Photon Factory Activity Report
1997

Staff members and visitors of the Photon Factory gathered in front of the PF building.
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ACCELERATORS OPERATIONS, RESEARCH AND DEVELOPMENTS

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LIST OF PUBLICATIONS
Introduction

On April 1, 1997, a new organization, “High Energy Accelerator Research Organization”, was launched as a result of a merger of the National Laboratory for High Energy Physics, the Institute of Nuclear Studies of the University of Tokyo and the Meson Science Laboratory of the University of Tokyo. It consists of four research institutes (Institute of Particle and Nuclear Studies, Institute of Materials Structure Science, Accelerator Laboratory, and Applied Science Laboratory). The Photon Factory is now a part of the Institute of Materials Structure Science, along with two other user oriented facilities, the Neutron Science Laboratory (KENS) and the Meson Science Laboratory. This activity report is the first one after such an organizational change.

The biggest news at the Photon Factory during the period from April 1997 to March 1998 is the successful progress of the emittance upgrade project of the 2.5-GeV ring. This is an important milestone in the history of the Photon Factory. The emittance of the 2.5-GeV ring was 400 nmrad when the ring was first commissioned in 1982, and was once improved to 130 nm rad in 1987. The present upgrade program aims at improving the emittance down to 27-nmrad.

During the 9 month long shutdown from January to September, 1997, new components such as quadrupole and sextupole magnets, and vacuum chambers were installed into two-thirds of the storage ring namely between bending magnets B05 and B12, and between B19 and B26. Re-commissioning of the ring was successfully made in October, 1997 with familiar optics giving an emittance of 130 nmrad in order that we could restart user experiments quickly after the re-commissioning. In fact, user experiments were started from November, 1997. As described in the section of ACCELERATORS, ring machine study was repeatedly made every Monday and a ring current of 400mA was stored with emittances of 29 and 36 nm rad and life times of 12 and 20 hours, respectively. A further study to achieve the target value of 27 nmrad is being continued.

On this occasion of the major modification of the storage ring, a number of improvements of the storage ring have been made. Those improvements are the installation of new beam position monitors, a new feedback system for the stabilization of vertical position of the electron beam, a new vacuum monitors, a new control system, a refined kicker magnet system and two radio frequency damped cavities. The 16 years old storage ring is now almost renewed and is expected to have a longer life time as a unique synchrotron radiation source.

The electron beam size under the low emittance configuration was accurately estimated from the contrast of interference fringes produced by visible wavelength region of synchrotron radiation. It should be noted that this method of estimating electron beam size was developed at the Photon Factory and was...
proved to be very powerful. Test experiments were also carried out in December 1997 on beamlines and experimental stations to characterize synchrotron radiation beams with the low emittance operation. We observed an improvement of an energy resolution up to 10,000 on BL-2C undulator beamline equipped with a varied space grating monochromator, an increase of intensity at sample position of the undulator beamline, a better resolution on X-ray absorption spectrometry beamline, and better focuses at small angle X-ray scattering and macromolecular crystallography beamlines. With those observations and by taking into account of users' demand for a longer life, a decision was made to start the low emittance operation of the ring for user experiments from May, 1998 with machine optics giving an emittance of 36 nmrad.

Improvement of beamlines and stations has been continuously made during the shutdown of the ring. The double crystal monochromator on BL-10C was overhauled, and a mirror and its bending mechanism were also completely renewed resulting a better focus and 5-10 times more intense beam at the focal position. A vertically focusing mirror and its bender on the BL-15A small angle scattering beamline were replaced by new ones giving a better focus and 5-10 times more intense beam at the sample position. BL-15B was converted to a dedicated station for surface diffractometer which has been used at AR-NE3 undulator station. BL-11D was successfully commissioned, which covers an energy range of 10—1300 eV and is used for high resolution photoelectron spectroscopy.

Three experimental stations are under construction. Installation of beamline components of these stations will take place in 1998 summer shutdown and commissioning of those stations will be made in autumn of 1998. BL-1B will consist of a double crystal monochromator and a doubly focusing mirror and is dedicated for use of powder diffractometer at low temperature. BL-1C will cover an energy range of 20 eV—250 eV with an energy resolution of 5,000-10,000 and be used for photoelectron spectroscopic studies of nanostructured materials. BL-6C will be converted to a macromolecular crystallography beamline being equipped with a new automated image plate readout system in collaboration with Tsukuba Advanced Research Alliance (TARA) of University of Tsukuba. Fourteen pharmaceutical industries are taking part in TARA project.

Because of the long shutdown, operational hours of the 2.5-GeV ring logged only 3624 hours in fiscal year of (FY) 1997 which is shorter by approximately 700 hours than in FY 1996. PF-AR, a 6.5-GeV ring which used to be called TRISTAN AR, has been shut down since the fall of 1996 because the construction of a tunnel for direct injection of e-beam to KEK-B ring interfered with the operation of PF-AR. Re-commissioning of the PF-AR started in March, 1998 aiming at the restart of synchrotron
radiation program from April, 1998.

Despite the shorter operational hours of the 2.5 GeV ring in 1997, a number of scientific outputs have been obtained in various experimental programs. From the present volume of the Activity Report, we divide the volume into two, parts A and B. Reports from individual users experimental programs are separately given in part B. Some of highlights of experimental programs are given in part A.

Structural biology activities are continuously expanding. An atomic resolution structure of cytochrome c oxidase, which is one of the proton-pumping assemblies of the respiratory chain, was first obtained in 1996 by analyzing data acquired at the Photon Factory. During 1997, crystal structures of bovine heart cytochrome c oxidase in the fully oxidized, fully reduced, azide-bond, and carbon-monooxided-bond states were determined. From those structures, a new mechanism for redox-coupled proton pumping was proposed. Diffraction studies of another proton pump protein, bacteriorhodopsin, was made on BL-15A for various types of mutants. From difference Fourier maps and other spectroscopic measurements, a new mechanism of an interplay of local chemical changes and global structural changes of the protein was proposed.

Resonant scattering study of orbital ordering in perovskite-type manganite, which show various magnetic-field-induced phenomena such as colossal magnetoresponse, is being intensively continued. Since the first direct observation of orbital ordering by use of ATS scattering technique in December 1996 on BL-4C, various types of manganites having one, two or infinite number of MnO₆ octahedron layers have been studied revealing new features of orbital ordering in those materials. Such studies stimulated theoretical discussions of ATS scattering.

As a result of efforts in last 3 years to improve the soft X-ray undulator beamline (BL-2), a number of interesting outputs have been produced. Photoelectron angular distribution measurements from fixed-in-space CO molecules revealed the partial wave composition in the C K-shell continuum. A soft X-ray emission spectrometer on BL-2C is providing data on polarization and excitation energy dependence of soft X-ray Raman scattering from transition and rare earth metal compounds with a high resolution.

A perpendicular magnetic anisotropy in Co/Pt multilayers has been studied by measuring magnetic circular soft X-ray dichroism. Circularly or elliptically polarized synchrotron radiation is also used in non-resonant magnetic scattering study, magnetic EXAFS, and the study of circular dichroism in double photoionization of helium atom. Spin states of ferromagnetic Ni (110) were studied by spin-resolved photoelectron spectroscopy on BL-19.

An X-ray emission spectrometer named
“Escargo” reported in a previous Activity Report is now producing interesting results. An enhancement of magnetic effect in X-ray Raman scattering was found at the K-absorption edge of Co in Gd-Co compound.

The XAFS technique was very effectively used in the study of one (Na$_6$Co$_{13}$Fe$_7$(CN)$_{26}$.5H$_2$O) of prussian blue analogs which have attracted great interest because of their various characters as molecular magnets. Visible light irradiation and thermal annealing converts their spin states quite easily. From detailed analysis of XAFS spectra, a Co (II)/Co (III) composition ratio was determined and a drastic local structural change around Co atoms was detected. Studies of adsorbed SO$_2$ molecules on metal surfaces, Mo oxides on rutile TiO$_2$ surfaces, and coordination of Zn ions on a Langmuir monolayer were also carried out with the XAFS technique.

Microcrystals of interplanetary dust particles were examined using Laue diffraction method. The existence of a structure called NA type in nature was first confirmed with this experiment. Charge ordering and valence fluctuation in Fe$_3$O$_4$ at a low temperature (102K) were studied by measuring X-ray diffuse scattering and satellite diffraction peaks making use of the chemical shift of anomalous scattering factors between Fe$^{2+}$ and Fe$^{3+}$.

A number of interesting and important results in other disciplines are also described in HIGH LIGHTS section.
1. PS Preinjector
2. PS Injector Linac
3. PS Booster
4. PS Main Ring
5. PS North Experimental Hall
6. PS East Experimental Hall
7. Booster Synchrotron Utilization Facility
8. PF Injector Linac
9. PF Light Source/Experimental Hall
10. TRISTAN Accumulation Ring
11. TRISTAN Electron-Positron Colliding Ring
12. TRISTAN Experimental Hall: Fuji
13. TRISTAN Experimental Hall: Nikko
14. TRISTAN Experimental Hall: Tsukuba
15. TRISTAN Experimental Hall: Oho
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17. Cryogenics Center
18. Mechanical Engineering Center
19. Radiation Safety Control Center
20. Library
21. Dormitory
22. Guest House
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1 High-Brilliance Photon Factory Storage Ring.

1-1 Reconstruction Works

The reconstruction of the Photon Factory (PF) storage ring toward the low emittance light source was started in January of 1997. The reconstruction works took place mainly in normal cell sections. All the quadrupole and sextupole magnets were replaced in order to realize the new low emittance optics (Figure 1). They were doubled in number and were reinforced in field strengths. Two quadrupoles and two sextupoles were assembled and aligned within 100 μm on a common girder. Before installing the magnet assemblies in the ring tunnel, 28 standard points were surveyed and realigned. All the magnet assemblies were then installed and aligned within 100 μm (rms) relative to the standard points. The vacuum ducts were remodelled to

Figure 1.
Optical functions of the new low emittance optics.
match with the new magnetic lattice. They were pre-baked and installed in the ring, soon after all the magnets were settled. No in-situ baking were done. The new beam position monitors (BPM) in normal cells were also doubled in number. Each BPM unit was fixed mechanically to an end of the quadrupole magnet. All the BPM assemblies had been calibrated electrically and mechanically on a test stand. The accelerator components in a normal cell just after installation are shown in Figure 2.

All four radio frequency (RF) cavities were replaced with the newly developed damped cavities during the shut down. In these cavities, the dangerous higher-order-modes (HOM) propagate out to the beam duct and are absorbed by silicon carbide (SiC). Figure 3 shows these cavities installed in the ring.

All these works were successfully completed until the end of September in 1997.
1-2 Commissioning

Commissioning was started on the 1st of October in 1997. Since the operation time for the experimental users had been scheduled to start on the 4th of November, all the commissioning works should have been completed within one month. In order to make the commissioning works smoother, we decided to start the operation with optics very similar to the old ones.

On the first day of the commissioning, after adjusting the injected orbit by utilizing a single pass beam position monitor, we confirmed the beam circulation of about 100 turns without RF. On the second day, a beam could be stored with RF on and without steerers excited. After ten days, the maximum stored beam current reached to 500 mA. The vacuum conditioning through the SR irradiation in the high current operation gave a satisfactory result as shown in Figure 4. About one month later, the average pressure normalized by beam current reached to $1 \times 10^6$ [Torr/A].

New RF cavities were successfully commissioned. Any beam instabilities due to the HOM of the cavities was not observed for the beam current as high as 400 mA.

A new BPM system and a new orbit stabilization system were also successfully commissioned. The closed orbit could be measured with greatly improved accuracy ($1 \mu m$ (rms)) and faster sampling speed (100 Hz). By using these data, the electron orbit can be stabilized within 10 $\mu m$ with a feedback cycle of 10 Hz as shown in Figure 5.

The data of the correction parameters for the betatron tune shifts caused by the wigglers were newly taken for each insertion devices. The end correction parameters were also measured and the orbit movements were carefully checked for all the magnetic gap values of each insertion devices.

After all these machine tunings, the users operation was re-started on the 4th of November with an emittance of 130 nm-rad.

![Figure 4. The history of the vacuum conditioning.](highlight)

![Figure 5. Orbit stabilization with the global feedback.](highlight)
1-3 Low Emittance Operation

In parallel with the users operation, the machine studies on the low emittance optics were done on every Monday.

In Figure 6, the emittance is shown as a function of the horizontal phase advance of the normal cells. The ring emittance has a minimum at the phase advance of 135 degree. Since a tracking study showed that, as the phase advance increases, the dynamic aperture gets smaller, we started the low emittance operation at 90 degree optics.

Figure 6. Emittance curve as a function of the phase advance of normal cells.

During the first machine study, we could store a beam at 90 degree optics. Then we increased the phase advance step by step. We have succeeded to store a 400 mA beam for the phase advance between 90 and 125 degree so far. The designed emittance for 125 degree is 30 nm-rad. We tried to store the beam at around 135 degree, but it still remain the challenge for us. The main reason of this seems to be a small dynamic aperture.

In Table 1, the results of the machine studies are summarized. From a beam size measurement, the horizontal emittance was estimated to be 29 nm-rad for the 125 degree optics, that is not so far from the minimum emittance of the new lattice, 27 nm-rad. As for the vertical emittance, a measurement using an synchrotron radiation interferometer was carried out. The result indicated a XY coupling of about 1%.

A high current accumulation was tested for 105 degree optics (36 nm-rad). A 500 mA beam in multibunch mode and 100 mA in single bunch mode could be stored.

The beam lifetime was limited both by the gas scattering and by
the Touschek effect. The Touschek lifetime measured in single bunch operation is consistent with XY coupling of 1%.

In the multibunch operation, a vertical instability due to the ion trapping was observed. This was successfully suppressed with taking a ‘partial filling’ pattern (successive 250 of 312 RF bucket are filled and remainders are empty) and by exciting the octupole magnets.

The photon spectra of the undulator radiation was measured at a beam line BL02 both for the old (130 nm-rad) and the new optics (36 nm-rad). The increases of the photon flux densities observed for 1st, 3rd and 5th harmonics agreed well with the calculation.

After all these machine studies, we decided to start the low emittance users operation at 36 nm-rad. This moderately small emittance was chosen to keep average beam current higher than 300 mA with injection twice a day. The tune correction parameters and the end correction parameters were re-taken for all insertion devices. The orbit stabilization was carefully tested for that optics.

After these works, the users operation with low emittance started on the 15th of May in 1998. A typical beam current history in a week is shown in Figure 7. The beam injection is twice a day (9 a.m. and 9 p.m.). A run starts at 400 mA and ends at around 250 mA. The average beam current exceeds 300 mA.

![Figure 7. Typical beam current history in a low emittance operation.](image)

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<th>Table 1: Summary of the low emittance operation</th>
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Note; *) These values were obtained from a beam size measurement.
2 Atomic and Molecular Science

2-1 Atomic Spectroscopy

The double photoionization of a helium atom occurs through a direct process due to electron correlations. Therefore, it provides the ideal test case for theoretical understandings of three-body breakup in the double photoionization, if the energy- and angle-resolved triply differential cross section (TDCS) is measured. For this study, elliptically polarized light from the helical undulator (BL-28A) is a very powerful tool, because we can change the polarization quantities of it and examine the TDCS depending on the polarization quantities. The measured TDCS can be expressed as

\[ \text{TDCS} = \frac{1+S_1}{2} \text{TDCS}_x + \frac{1-S_1}{2} \text{TDCS}_y + \frac{S_3}{2} (\text{TDCS}_{\text{igh}} - \text{TDCS}_{\text{light}}), \]

where \( S_1 \) and \( S_3 \) are the Stokes parameters, which are defined by \( S_1 = \langle I_X - I_Y \rangle / I_0 \) (the photon beam along the Z axis) and \( S_3 = \langle I_{\text{igh}} - I_{\text{light}} \rangle / I_0 \). Because \( (\text{TDCS}_{\text{igh}} - \text{TDCS}_{\text{light}}) \) under the equal energy sharing condition for two outgoing photoelectrons, one can observe the \( S_1 \) dependence of the TDCS, i.e., the linear dichroism in the TDCS. Figure 1 (a) shows the TDCS measured with the elliptically polarized light of \( S_1 = 0.20 \) and \( S_3 = -0.95 \) and Figure 1 (b) the TDCS with the light of \( S_1 = -0.20 \) and \( S_3 = 0.95 \). From the Figs. 1 (a) and (b) the linear dichroism, the mirror symmetry relative to the e1 detection direction, is clearly seen. The solid curves in the Figs. are the fitting of the theoretical TDCS, which is obtained assuming the Gaussian function for the angular correlation between the electrons. As the angular correlation function is common for the both cases, the change of the pattern of TDCS is caused by the change of sign of \( S_1 \). This is the reason why one calls the mirror symmetry of the patterns the linear dichroism. Under the unequal energy sharing conditions, the TDCS has been successfully measured.
A hollow atom is any atom for which at least one of the inner shells is completely empty. To produce a hollow atom by exciting only two electrons, the inner shell must therefore be $1s^2$. The simplest hollow atom, and the one which has been known for the longest time is He in a doubly-excited state. Thanks to intense undulator radiation, a lot of investigations on the triple excitation of Li have appeared in these several years. However, they are limited to the K-shell empty hollow Li atom. Recently the K- and L-shell empty hollow Li atom has been observed in a Li$^+$ ion yield spectrum at the BL-16B undulator beamline. No corresponding resonance feature could not be observed within the signal-to-noise limit in the Li$^+$ channel. Figure 2 shows the resonance structure corresponding to the transition of $1s^22s\rightarrow 3s^3p^2$. The excited state is hollow, because the K- and L-shell is completely empty. It turns out that the observed spectrum of this transition exhibits a broad asymmetric Beutler-Fano profile similar in general appearance to the He doubly-excited transition. Apart from their exotic state, hollow atoms are interesting, because they can be in both highly correlated and highly symmetric states.

Figure 1.
Experimental and fitted TDCCS for the double photoionization of helium at $hv=90\text{eV}$ in the plane perpendicular to the photon beam; direction of electron $e_1$ indicated an arrow. The TDCCS is plotted in the polar coordinates with respect to the angle $\theta_2$ locating the second electron. (a) $S_1=0.20$ and $S_3=0.95$. (b) $S_1=-0.20$ and $S_3=0.95$ in the tilted X-Y coordinates. Soejima et al.
Highlights

Figure 2.
The 3s\(^{-1}\)3p resonance measured in the Li\(^{2+}\) channel. The solid line is the fitted Fano profile.
Azuma et al.

The 4d giant resonance was discovered experimentally in 1964 in the photoionization spectrum of Xe. The giant resonance is explained in terms of orbital collapse induced by a double-well effective potential and collective motions of electrons. The orbital collapse in certain atoms might be controlled externally by modifying the potential in the outer reaches through excitation or ionization of a valence electron. The observation of the controlled collapse remains as a challenge to experimental physicists. The isoelectronic sequence from Xe to Cs\(^{+}\) changes the character of the giant resonance completely, causing it to fall below threshold amongst the numerous bound states. These dramatic spectra are shown in Figure 3. Because the electronic structure of Xe and Cs\(^{+}\) are the same, the dramatic change cause by the change of effective nuclear charge is so surprising. This puzzling problem will attract the interest not only of theoreticians but also of solid state spectroscopists. The relaxation of 4d vacancies, froming

Figure 3.
The 4d giant resonance of Xe and Cs\(^{+}\). In the Cs\(^{+}\) spectrum, besides the many discrete resonances strong window-type resonances are observed.
Sano et al.
zones with high densities of excited states, play a crucial role in determining the luminescence of the solid, for example, CsI, both of whose constituent ions are in configurations equivalent to Xe.

2-2 Molecular Spectroscopy

One of the characteristics of threshold photoelectron spectrometry is the high sensitivity to ionization potentials, because a threshold electron spectrometer can detect almost all zero energy electrons, which are produced when photon energies coincide with the ionization potentials. For this reason, the threshold photoelectron spectrometry is widely used to study ionic molecular potentials those are embedded in many ionization continua. Figure 4 shows high-resolution threshold photoelectron spectra of O$_2$ in the valence region, which were measured at the beamline BL-20A equipped with a high-resolution normal incidence monochromator. The threshold electron analyzer with very narrow band path of less than 0.5 meV enables it possible to resolve the vibrational progression up to $v' = 45$ for the X state of O$_2^+$. The doublet structures of the X state are clearly seen. From these extremely fine spectra, the precise potential curve of the X state of O$_2^+$ has been determined for the first time. The potential curve is shown in Figure 5. The potential curve of the A state is also determined, and two new states are discovered owing to the high-resolution ability of the threshold electron analyzer.

Figure 4.
The high-resolution threshold photoelectron spectrum in the region of the X and a ionic state of O$_2^+$.
Akahori et al.
Highlights

Figure 5.
The potential energy curve of the X state determined by the high-resolution threshold photoelectron spectrum.
Akahori et al.

Angular distributions of photoelectrons from fixed-in-space molecules provide us detailed information on photoionization dynamics. If one considers the special cases of photoionization with the electric vector either parallel or perpendicular to the molecular axis, the angular distributions may be expressed as

$$ \frac{d\sigma}{d\Omega} = \sum_{k=0}^{N} A_{k} Y_{k}^{\ast} \left( \theta, \phi \right). $$

Because this equation is general, one can apply it to not only fixed-in-space molecules but also to any samples. Further simplification of this equation is obtainable when fixed-in-space linear molecules are considered. Namely in this case the angular distributions may be parameterized by

$$ \frac{d\sigma}{d\theta} = \sum_{k=0}^{N} A_{k} P_{k} \left( \cos \theta \right). $$

The AK coefficients include dipole matrix elements and phase shifts describing photoionization processes. The angular distribution of photoelectrons from C 1s of fixed-in-space CO molecules is shown in Figure 6, which was measured at BL-2B. The angular distribution indicates the forward and backward asymmetry and rich nodal structure. By the data analysis using the above equation, the AK coefficients

Figure 6.
Three dimensional representation of photoelectron angular distribution from the C K-shell of fixed-in-space CO molecules, which was measured at the shape resonance energy of 304.1 eV. The C and O atoms are positioned at right and left on the Z axis in the figure.
Shigemasa et al.
have been determined and the matrix elements and phase shifts derived. As the results of it, the nature of the $\sigma^*$ shape resonance in the C K-shell ionization continuum of CO has been revealed. That is, d and f partial waves give the main contributions to the cross section enhancement of the $\sigma^*$ shape resonance. The angular distribution pattern is so sensitive to the phase shift differences between the partial waves that this type of experiments is the best for the critical test of theoretical calculations, which are not so well developed for the shake of the difficulties to obtain correct continuum wavefunction in the multi-center molecular potential.

In the use of linearly polarized radiation, angle-resolved photofragment ion measurements can probe the geometries of photoexcited molecules or the core hole localization of them. Recently the fragment ions of $F^+$ from SF$_6$ molecules have been measured in the parallel and perpendicular direction relative to the electric vector of the incident light provided at BL-2B. The resonance structures and asymmetric parameters in the F K-edge region are shown in Figure 7. Despite the high symmetric structure of SF$_6$, the anisotropic angular distributions of $F^+$ fragment ions have been observed at each resonance as shown in the Figure 7. This anisotropy has been interpreted by the valence hole localization. That is, the localized F 1s core-hole, which is created by the excitation of linearly polarized light, is transferred to the localized valence hole via Auger decay. Then the SF$_6$ molecule with the localized valence hole is no longer the high symmetry of Oh, and dissociated in an anisotropic way.

Figure 7. (a) Fragment ion yield spectra measured parallel (solid curve) and perpendicular (dashed curve) to the electric vector of the incident light. The peaks of A, B, C, and D are due to the transitions of F 1s $t_u \rightarrow a_1^0$, F 1s $(a_1^0 + e_2^0) \rightarrow f_1^0$, F 1s $t_u \rightarrow f_1^0$, and F 1s $t_u \rightarrow e_1^0$; (b) Asymmetry parameter obtained from the ion yield spectra in (a).

Ueda et al.
3 Chemical Science

3-1 Coordination Structure of Zinc (II) Ions on a Langmuir Monolayer Observed by Total-Reflection X-Ray Absorption Fine Structure

The solvation structure of ions at the solution surface may not be the same as that in the bulk. This is especially true for the species concentrated at the surface by a surfactant or Langmuir Blodgett monolayer. Surface-active ions at the surface play important roles in the processes of solvent extraction, phase-transfer catalysis and the formation of LB films. Watanabe et al. have succeeded in investigating the solvation structures of the surface ions by using the total-conversion He ion-yield method under the total-reflection condition [5]. The experimental set-up is schematically shown in Figure 1, where the incident photon beam comes from a sagittal focus double-crystal monochromator via a 70 cm long bent mirror. The mirror focuses the beam vertically and changes the beam direction downward by 1 mrad to irradiate the solution surface. The essential requirement of this technique, a ripple-free liquid surface at an accurate position, was
attained by introducing a trough on a floating boat, continuous surface-level monitoring, and an automatic Z-stage control. As a typical application, they used this method to study the coordination structure of zinc(II) ions on a Langmuir monolayer [6]. Figure 2 shows XANES spectra from a Zn stearate Langmuir monolayer at different standing times after spreading stearic acid on the surface. The white line intensity for Zn(II) is known to be related to its coordination number, allowing us to estimate it at the monolayer to be 4. The white line gradually gains its intensity and becomes saturated after 12 hours, which corresponds to a coordination number of 5. EXAFS spectra were also measured and analyzed. The bond distance of Zn-O is 0.196 nm, which is fairly shorter than for the hexahydrate, 0.208 A. This is the first experiment to demonstrate that the coordination structure of Zn(II) ion beneath the fatty acid monolayer is different from that in bulk solution.

3-2 Polarization-Dependent Total-Reflection Fluorescence XAFS Study of Mo Oxides on a Rutile TiO$_2$ (110) Single Crystal Surface

Supported catalysts, where active species dispersed on a high surface area oxide, are widely used in both industry and daily life. There are many questions about the supported catalysts to be solved. For example, why does some support oxide create high-performance catalysts? The difficulty in answering this question arose from the difficulty in characterizing the structures of the supported catalysts. XAFS (X-ray absorption fine structure) is one of the powerful tools used to investigate the supported structure, but is limited in the sense that conventional XAFS is a one-dimensional structure-analysis tool.
Thus, the structure information derived from XAFS is complicated, and it is difficult to elucidate important information about the metal-support interaction. On the other hand, when a catalyst is prepared on a single-crystal oxide surface as a model support and polarized synchrotron radiation is applied with various orientations of the catalyst, one can obtain pseudo three-dimensional structure information from the polarization-dependent XAFS signal. Asakura et al. have developed a polarization-dependent total-reflection fluorescence XAFS system relevant to pseudo three-dimensional structure analyses of catalytic active species highly dispersed on single-crystal oxide. They found that a Pt one-atomic layer structure parallel to the surface developed on an Al₂O₃ (0001) surface and Co₃O₄ (001) particles epitaxially grown on Al₂O₃ (0001) at a beam line of BL-7C and BL-14A. [7,8]. They have applied it to Mo oxide on a TiO₂ (110) surface. The TiO₂ (110) surface has an anisotropic structure of an oxygen row run-
ning parallel to the (100) direction, as shown in Figure 3. They observed the Mo K-edge TPRF-XAFS signals in three different directions using a 4-circle goniometer installed at BL-14A. The TPRF-XAFS spectra had a strong polarization dependence. As a result of the analysis, it was revealed that the Mo dimer structure was produced on the TiO$_2$ (110) surface with the Mo-Mo direction perpendicular to the oxygen row of the TiO$_2$ (110) surface with 0.335 nm, as shown in Figure 4. The Mo-Ti distance was also found at 0.296 nm [9]. This TPRF-XAFS technique will give new insight about supported catalysts and key information about how to create new catalytic materials.

3-3 Characterization of Magnetic Materials of CoFe Cyanides by XAFS Spectroscopy

Prussian-blue analogs have recently attracted great interest because of their various characters as molecular magnets. Although structural information is important to understand the magnetic properties, the single-crystal x-ray diffraction technique is hardly applicable, since these materials are usually obtained only as a fine powder or thin films. Na$_{x}$Co$_{x}$Fe (CN)$_{6}$·5H$_2$O exhibits a spin phase transition at around 260 K, associated with the Fe-to-Co charge transfer of Fe$^{2+}$-Co$^{2+}$ (LT) and Fe$^{3+}$-Co$^{2+}$ (HT). This transition also undergoes upon visible-light irradiation, and the HT phase is preserved at low temperature. Recently, Yokoyama et al. studied the Fe and Co K-edge XAFS of these compounds at BL-7C by changing the temperature [10]. Co K-edge XANES (solid lines in XANES plots) were found to be expressed as a sum of the spectra of pure Co$^{2+}$ and Co$^{3+}$ species, thus allowing the determination of the Co$^{3+}$/Co$^{2+}$ ratio.
Highlights

In temperature-dependent experiments, the obtained Co$^2+$ ratios were 0.70 at 30 K and 0.34 at 296 K (see the XANES spectra: long- and short-dashed lines for Co$^2+$ and Co$^+$, respectively), indicating a clear phase transition. The Fe K-edge EXAFS spectra (in the $k^2\chi(k)$ plots, solid and dashed lines for 30 and 296K, respectively) verified the local structure around Fe of Fe(CN)$_6$Co$^+$$^+$ and clarified no noticeable structure change around Fe upon the phase transition. On the other hand, from the Co K-edge EXAFS, the local structure has been confirmed to be Co(NC)$_4$H$_2$O$_6$Fe$^3+$, and show drastic differences in the Co-N, O distances between the LT and HT phases. This difference originates from the transition between high spin (Co$^2+$) and low spin (Co$^+$).

References

4 Structure of Surfaces and Interfaces

4-1 SO₂ Adsorption on Monolayer Pd/Ni (111)

The electronic structure of thin metal films is expected to be significantly different from the corresponding bulk material. A monolayer Pd film on Ni(111) was investigated by employing adsorption of SO₂ as a molecular probe. S K-edge XAFS spectra of SO₂/Pd(1 ML)/Ni(111) were taken at Beamline 11B to study the adsorbate structure. The epitaxial growth of the Pd monolayer was verified by LEED and STM. The results obtained for SO₂/Pd(1 ML)/Ni(111) were compared to those of SO₂ on Pd(111) and Ni(111). The SO₂ molecule exhibits inclined orientation on Pd/Ni(111), as shown in the figure. Such an orientation is noticeably different from that on Pd(111) [1], where the molecular plane is almost perpendicular to the surface (see also the figure). On the contrary, it was established that the SO₂ molecule is lying completely flat on Ni(111) [2], this being more similar to the Pd/Ni(111) case. The present finding indicates large differences in the valence electronic structure between the monolayer Pd film and the Pd crystal surface. It is recognized from the molecular orientation that SO₂ act as a donor against Pd(111) and its acceptor nature is less important, while both the natures should be essential on Ni(111). This difference may
originates from the difference of the occupied and unoccupied d-band densities between Ni and Pd close to the Fermi level. Due to the direct contact with Ni, the monolayer Pd film should show modified d-band states close to Ni which allows the interaction with SO₂.

References

4-2 Total Reflection X-Ray Photoelectron Spectroscopy

X-ray photoelectron spectroscopy (XPS) experiment using total reflection incident X-rays has been performed at BL-11 B and BL-2A since 1991. This method discriminates the surface chemical state and probes a particular depth layer by changing the glancing angle and the wavelength of the incident X-rays. When the angle dependence of XPS peaks are measured, the surface layer chemical structure of a multilayer could be analyzed [1].

A typical example was Si (15 Å) and W (10 Å) 100 bilayers [4]; Si, SiO₂, and W XPS peaks were observed between 1890 and 1790 eV in binding energy, and these three XPS peak intensities showed differences in angular dependence, from which we could...
determine the surface oxide thickness and chemical composition.

The backgrounds in XPS spectra are usually very high because inelastically scattered photoelectrons lose their energy in a solid. When we measure the total reflection X-ray photoelectron spectra, the backgrounds can be deliberately reduced and photoelectron peaks can be enhanced. This is because we can control the X-ray penetration depth by changing the glancing angle of the incident monochromatic X-rays. Thus the photoelectron spectra of less than 5 Å surface are separately observable. Figure 1 shows the XPS spectra of copper phthalocyanine thin film on a silicon wafer [2]. Though conventional XPS spectra are overlapped by strong substrate silicon signal as shown in Figure 1a, the total reflection XPS spectra has extremely low backgrounds and relatively strong signal (copper) intensity (Figure 1b).

References

4-3 Surface X-Ray Diffraction Study Based on Absolute Reflectivity

Surface x-ray diffraction is one of powerful tools to determine the structure of crystal surfaces. One can obtain three dimensional surface structure by the measurement of intensity profile along the rods. Particularly the measurement of the integral order rods gives the surface structure with respect to the bulk crystal. Moreover we have showed usefulness of absolute reflectivity in the analysis of experimental data [1,2]. Here absolute reflectivity means the intensity ratio of the diffracted beam to the incident one. For instance, one can discriminate models with different coverages because they give quite different absolute reflectivity even if they happen to give similar profiles.

For this purpose, we have obtained theoretical expressions to calculate absolute reflectivity [1,2]. On the other hand, we have measured absolute reflectivity of the diffraction spot by a position sensitive proportional counter followed by normalization of the intensity by the incident beam. Using this analysis based on absolute reflectivity, we have successfully distinguished the structure corresponding to the coverage of 1 ML in the case of Si(111)-√3×√3 structure of Bi [1] and Ag [2]. If one accumulate such data as standards, one can determine more easily unknown structures from the analysis of absolute reflectivity. In Figure 1 absolute reflectivity of
the 00 rod obtained for a $\sqrt{3} \times \sqrt{3}$ structure of Sb is compared with those for the known structures of Bi and Ag with the coverage of 1 ML. This clearly indicates that Sb atoms make a trimer, corresponding the coverage of 1 ML.

Figure 1. Absolute reflectivity of 00 rod of Si(111) $\sqrt{3} \times \sqrt{3}$ (Sb, Bi, Ag).

References


4-4 Peierls Transition of One-Dimensional Metallic Chains on a Semiconductor Surface

One-dimensional metallic systems are important for their exotic physical properties. Recently we have found that the metallic 4x1 In overlayer on the Si(111) surface with a linear-chain structure undergoes a phase transition at ~130 K into a “4x2” phase with periodicity doubling along the linear chains through scanning tunneling microscopy and electron diffraction [1]. In order to identify the origin of this phase transition, detailed temperature-dependent angle-resolved photoelectron spectroscopy (ARPES) study was performed on BL-7B (Research Center for Spectrochemistry, the University of Tokyo). As shown in Figure 1, the 4x1 phase at room temperature has three metallic bands ($m_1$, $m_2$ and $m_3$ in the figure) crossing the Fermi level. These states are surfaces states localized on the In overlayers [2]. After the transition into the 4x2 low-temperature phase, the ARPES data exhibit that the spectral weights of the metallic surface states are quenched drastically near the Fermi level and that the 4x2 surface is not metallic any more. Although the
detailed interpretation of this spectral change is rather intriguing partly due to the limited energy resolution, it is thought to represent an opening of a band gap (of the order of ~100 meV) at the Fermi level. From this result and detailed Fermi surface measurements done in collaboration with BL 7.0.1 of Advance Light Source (which reveal a consistent one-dimensional nesting vector of the Fermi ‘lines’ of m[3]), this phase transition is unambiguously concluded to be an one-dimensional Peierls transition [1]. This finding provides a completely new type of one-dimensional materials based on a two-dimensional array of metallic quantum wires, where the charge density wave can be probed directly in the real space [1].

![Figure 1](image_url)

**Figure 1.**
ARPES spectra for the room-temperature 4x1 phase (open circles) and the low-temperature (~130 K) 4x ‘2’ phase (solid lines). The spectra are taken along the linear chain direction, that is along \( \overline{\Gamma}-\overline{X} \) in (a) the first and the (b) third surface Brillouin zone (\( \overline{\Gamma} \) at \( k_x = 0 \AA^{-1} \) and \( \overline{X} \) at \( k_x = 0.82 \AA^{-1} \)).

**References**
5 Materials Science

The investigation of the magnetic properties of matter by synchrotron radiation is a relatively new field, and has been developing rapidly in recent years. Synchrotron-radiation techniques used to analyze the magnetic properties are also developing, ranging from the technique based on X-ray diffraction / scattering to X-ray absorption and photoemission spectorscopy. The topics related to this research field presented here are the direct observation of orbital ordering in perovskite-type manganites by using resonant X-ray scattering; a non-resonant magnetic diffraction experiment, which enables one to obtain the orbital and spin part of the magnetic form factor separately; the resonant inelastic X-ray scattering from the ferrimagnetic amorphous Gd-Co compound, magnetic circular X-ray dichroism for the study of perpendicular magnetic anisotropy in a metallic multilayer; and the spin-resolved photoemission experiment of ferromagnetic Ni (110) using a newly developed compact spin polarimeter. Finally, we would like to introduce non-SR studies, i.e. positronium emission from a SiO₂ surface, which was done at the new low-energy positron facility commissioned in the linear accelerator.

5-1 Direct Observation of Orbital Ordering in Perovskite-type Manganites

Over the last few years, magnetic-field-induced phenomena in perovskite-type manganites, such as negative colossal magnetoresistance, have attracted a great deal of attention.[1] In these materials, the charge, spin, and orbital degrees-of-freedom each play important roles. However, the charge and spin configurations have been investigated by neutron and electron diffraction techniques, it has been proved difficult to observe the orbital ordering directly. Nevertheless, we have recently succeeded in detecting orbital ordering in the doped
layered-perovskite $La_{x}Sr_{y}MnO_3$ [2] and the undoped, three-dimensional perovskite $LaMnO_3$ [3] by using resonant x-ray scattering near to the Mn K-absorption edge.

The electronic configuration of $Mn^{3+}$ ions is $(t_{2g},e_g)$ using Hund's rule as a first approximation. The three $t_{2g}$ electrons are localized, while the $e_g$ electron orbitals are strongly hybridized with the oxygen p orbitals. Orbital ordering of the $e_g$ electrons was directly observed by exploiting the sensitivity of x-ray scattering to an anisotropic charge distribution. In the case of $LaMnO_3$, for the basis shown in the upper panel of Figure 1, the forbidden $(h,0,0)$ and $(0,k,0)$ reflections $(h,k: \text{odd})$ have appreciable intensities for incident photon energies near to the Mn K-absorption edge as a result of the asphericity of the Mn atomic electron density present in the orbitally ordered state. Figure 2 shows the energy dependence of the integrated intensity of the $(3,0,0)$ reflection together with the measured fluorescence at $T=10$ K. Besides the enhancement, resonant scattering from orbital ordering is expected to exhibit several distinctive features, as characterized by the azimuthal angle (for rotations around the scattering vector) and the final polarization. Namely, the dependence of the intensity on the azimuthal angle exhibits a characteristic oscillation with a two-fold symmetry, as shown in Figure 3 and the polarization of Mn 4P transition.

![Figure 1](image)

Figure 1.
Upper panel: Schematic view of the orbital and spin ordering in the a-b plane at the perovskite manganite, $LaMnO_3$. The orbital ordering along the c-axis is expected to repeat the same pattern.
Lower panel: Schematic energy level diagram of Mn 4P$_{1/2}$ in the orbitally ordered state.
Figure 2. Closed circles representing the energy dependence of the integrated intensity of the orbital ordering superlattice reflection (3,0,0) near to the manganese K-absorption-edge at \( T = 10.0 \) K. The open circles represent the measured fluorescence. Similar results were obtained at the (1,0,0) reflection.

Figure 3. Azimuthal-angle dependence of the intensity of the orbital ordering reflections (3,0,0) normalized by the fundamental reflection (2,0,0) and (4,0,0) at \( E = 6.555 \) keV and at room temperature. The solid curve is the calculated intensity from the theory. Inset: Schematic view of the experimental configuration and definition of the polarization directions.

The orbital ordering scattering is completely rotated from \( \sigma \) to \( \pi \).

These results can be naturally understood on the basis of a simple model of x-ray physics assuming the 4p level splitting due to the orbital ordering, which is shown in the lower panel of Figure 1. One possible mechanism is a Coulomb interaction between the 4p and 3d orbitals, which raises (lowers) the 4p\(_x\) (m:x,y,z) levels lying parallel (perpendicular) to the direction of extension of the orbital.

References

5-2 Non-resonant X-ray Magnetic Diffraction

The non-resonant X-ray magnetic diffraction of ferromagnets is a unique tool by which we can obtain the form factors of the spin and orbital magnetic moment separately. A Fourier transform of these form factors gives the densities of the spin and orbital magnetic moment in real space. The white-beam method of non-resonant magnetic diffraction has been proved to be quite effective for the spin and orbital magnetic form-factor measurements of ferromagnets[1]. This method of X-ray magnetic diffraction has been performed on beamline BL3C at the Photon Factory. The aims of this experiment...
are: (1) to establish this experimental method on this beamline, (2) to measure the spin and orbital magnetic form factor of various ferromagnets (especially the orbital magnetic form factor which can not be measured by the other methods), and (3) to reveal the role of the spin and orbital magnetic moments in the magnetism of ferromagnets.

The ferromagnet specimens in the experiment at the Photon Factory have so far been divided into three categories: (1) 3d transition metals (Fe, Co), (2) 4f rare earth metals and alloys (Tb, DyCo5, SmAl3), and (3) 5f actinides compounds (UTE, USE). Among these specimens, the experiment of Fe revealed that the non-resonant X-ray magnetic diffraction experiment at the BL3C was quite reliable, and that the measurement of Co gave the orbital magnetic form factor of this element for the first time. The spin and orbital magnetic form factors of 4f electrons of Tb and 5f electrons of UTe were successfully measured, which confirmed the usefulness of this experiment.

The result of the experiment of hcp Co is briefly discussed. The purpose of this experiment was (1) to measure the orbital magnetic form factor of Co for the first time, and (2) to show that magnetic form factor of a magnetic moment on the order of 0.1 $\mu_B$ (Bohr magneton) can be measured on this beam line. The observed orbital magnetic form factor of hcp Co, $L(k)$ ($k = h02h$, $h=1-5$) is shown in Figure 4. Here, the ordinate is represented in the unit of $\mu_B$. The solid line is a theoretical curve of the dipole approximation, which was fitted to the observed data with a fitting parameter of the net value of the orbital magnetic moment ($L(0)$). The fitted value of $L(0)$, 0.16 $\mu_B$, is comparable to that of the g-factor measurement, 0.147 $\mu_B$ [2], and to that estimation from the neutron-diffraction measurement, 0.13 $\mu_B$ [3].

So far, X-ray magnetic diffraction measurements of ferromagnets have been successfully demonstrated, and the first and second setp of the aims have been realized. In the near future we will measure more precisely the spin and orbital magnetic form factors of ferromagnets (for example, measure their temperature dependence etc), and will go to the third step of the above aims.

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Figure 4.
The orbital magnetic form factor of hcp Co determined from non-resonant X-ray magnetic diffraction.
5-3 Resonant Inelastic X-ray Scattering from the Ferrimagnetic Amorphous Gd-Co

We have found the magnetic circular dichroism (MCD) spectra of the resonant inelastic X-ray scattering (RIXS) associated with the Gd Lα, and Lα₂ fluorescence lines of the ferrimagnetic amorphous Gd-Co compound. [1] The RIXS spectra and those MCD-RIXS spectra around the Gd Lα fluorescence lines are shown in Figure 5 (a) and (b), respectively. The observed structures in these RIXS spectra can be divided into 5 groups (labeled A, B, C, D, and E in Figure 5 (a)). Peaks A, B, and C, whose incident photon energies were above 7250 eV, correspond to the normal fluorescence lines, Lα₂, Lα₁ satellite from multiplet splitting, and Lα₁, respectively. The peak energies of peaks A, B, and C, whose incident photon energies were below 7250 eV, and peaks D and E, increased with increasing the incident energy. These peaks correspond to the RIXS. Peaks A, B, and C below 7250 eV are associated with the normal fluorescence lines (Lα₂, Lα₁ satellite, and Lα₁). Peak D is the high-energy off-resonant RIXS relevant to the Lα₁ fluorescence line, which is an unusual structure in the hard x-ray region. Peak E is assigned to the multiplet of the 2p⁵4fⁿ⁺¹ quadrupolar excitation. The incident x-ray energy dependence of these spectra clearly show not only the normal

References

Figure 5.
(a) X-ray emission spectra around the Gd Lα fluorescence from Gd-Co. The incident photon energy at which the spectra were taken is given in the figure. They are divided into five groups labeled by the corresponding scaling factor.
(b) Magnetic effects of the x-ray emission spectra.
resonance effects, but also the magnetic resonance ones between the excited 2p_{3/2} electron and the 5d conduction state, i.e., an enhancement of the magnetic effects and the appearance of a new structure which corresponds to the magnetic effect of the total fluorescence yield. Although more than double enhancement the magnetic effects is clear evidence of magnetic resonance, the origin of this behavior is still not well understood.

Reference

5-4 Perpendicular Magnetic Anisotropy, Interfacial Hybridization, and Enhanced Orbital Moment in Co/Pt Multilayers Studied by Magnetic Circular X-Ray Dichroism

Perpendicular magnetic anisotropy (PMA) in metallic multilayers has not yet been fully understood. We have studied the origin of PMA by magnetic circular x-ray dichroism (MCXD) measurements on Co/Pt multilayers with varying Co-layer thickness (1.5 ≤ t_{co} ≤ 29ML) [1].

Figure 6(a) shows the MCXD spectra in the Co M_{2.3} and Pt N_{5.7} and O_{2.3} edge regions [1]. Only a negative MCXD is observed at the Co M_{2.3} edges for thin t_{co}, while a small positive MCXD as well as a strong negative MCXD is seen for thick t_{co}. This asymmetry increase

Figure 6.  
(a) MCXD spectra of Co/Pt multilayers around the Co M_{2.3} and Pt N_{5.7} and O_{2.3} core edges. The inset shows the normal absorption for t_{co} = 3 and 15 ML.  
(b) XAS and MCXD spectra of Co/Pt multilayers for t_{co} = 3 and 15 ML around the Co L_{2,3} core edges.
Perpendicular $m_{orb}$ as a function of $t_{Co}$, as determined from the Co L$_{2,3}$ MCXD spectra using the MCXD orbital sum rule. The solid curve represents a fit to the data based on the model shown in the inset. The dashed curve denotes an extrapolation for a supposed case of all fcc Co layers, being in clear disagreement with the experimental point.

Figure 6 (b) displays the Co L$_{2,3}$ XAS and MCXD spectra for $t_{Co}$ = 3 and 15 ML [1]. By applying the MCXD orbital sum rule to the data, we have determined the perpendicular $m_{orb}$. The result is shown as a function of $t_{Co}$ in Figure 7. We note that $m_{orb}$ increases rapidly with decreasing $t_{Co}$ for $t_{Co}$ $\geq$ 6-8ML, just corresponding to appearance of PMA, confirmed by our torque magnetometry. The $m_{orb}$ value does not monotonically decreases, but gradually increases with increasing $t_{Co}$ for $t_{Co}$ $\geq$ 6-8ML. This non-monotonic behavior is in sharp contrast to the monotonic $m_{orb}$ decrease observed in an Au/Co/Au (111) staircase and Co films on Cu (100), and strongly indicates a structural transition from fcc to hcp Co with increasing $t_{Co}$. A fitting to the data was made using the model shown in the inset by taking $m_{orb}$ of bulk fcc Co ($m_{orb}^{bulk}$), that of bulk hcp Co ($m_{orb}^{hcp}$), and the enhanced $m_{orb}$ of a single interface Co layer ($\Delta m_{orb}$) as parameters. The result is shown by the solid curve [1]. The fitting yields $m_{orb}^{bulk}$ = 0.110 $\mu$m/atom, $m_{orb}^{hcp}$ = 0.148 $\mu$m/atom and $\Delta m_{orb}$ = 0.064 $\mu$m/atom. Our result for $m_{orb}^{bulk}$ is the first experimental determination of $m_{orb}^{bulk}$. The analysis gives a magnetic anisotropy energy of $\Delta E_{an}$ = -(2.3-1.0) $\times 10^4$ eV/atom for $t_{Co}$ = 2-5ML. This value is larger than the spin-spin dipole interaction energy of $2\pi M_s^2=+0.92\times10^4$ eV/atom, and thus drives PMA, in good agreement with the result of the present torque magnetometry.

\[\text{Reference}\]

Spin-and angle-resolved photoelectron spectroscopy has been increasing in importance as one of the feasible experimental techniques to obtain direct information about the spin dependence of electronic structures of magnetic and non-magnetic materials. These experiments are achieved in combination with an angle-resolved photoemission and an electron-spin analysis. However, in many of the experiments carried out so far, photoelectrons emitted normal to the sample surface were analyzed, which provides information only along a spatial symmetry line of the bulk Brillouin zone (B. z.) or at the $\Gamma$ point of the surface B. z.

We have recently developed a new compact retarding-potential Mott spin polarimeter with an efficiency of $1.9 \times 10^{-6}$ for a gold target operating at 25 keV. A novel design of the electron optics with a 0.59 sr collection angle for scattered electrons was adopted based on Monte-Carlo calculations[1] and electron beam ray-tracing calculations. The new polarimeter could easily be attached behind a photoelectron energy analyzer, and be utilized to measure the spin- and angle-resolved photoemission spectra.[2]

Figure 8 shows the spin-resolved off-normal emission spectra of ferromagnetic Ni(110).[3] The spectra with emission angles of
42.5°, 48.5° and 52° correspond to the spectra from the S point of the surface B. z. In these spectra, we observe prominent peaks at the binding energy of 1.3 eV with negative spin polarization. Compared with a theoretical band calculation, these peaks are assigned to a pair of bands with $Q_1/Q_2$ spatial symmetry near to the Q line about 30% away from L to W point. For the $Q_2$ band, the exchange splitting is almost zero at the L point, and becomes larger when the band moves to W point, which results in a higher density of states for the minority spin states than for the majority ones and a considerable negative spin polarization was observed.

References

5-6 Positronium Emission from SiO₂ Surface

Various solids emit positroniums (Ps) when bombared with low-energy positrons. In the case of insulators, a Ps can be formed both in the bulk and on the surface. The Ps emission energy reflects the band structure of the material, the Ps state in the bulk, the Ps formation mechanism, and the work functions of the electrons and positrons. It has been a puzzle why the energies of the Ps emitted from SiO₂, measured by the time-of-flight (TOF) technique for single crystal surfaces[1] and by the angular correlation of annihilation radiation (ACAR) method for silica aerogel,[2] are different from each other. Both data show a single component, the former giving a distribution peaked at 3.27eV and the latter peaked at 0.8eV.

In order to investigate the discrepancy between these results, the TOF spectra of the o-Ps emitted from a single crystal and amorphous surfaces of SiO₂ have been measured using an intense, pulsed, monoenergetic positron beam at KEK.[3,4] The energy distributions of the o-Ps emitted from KI and MgO single crystals were also measured by using the same method. Figure 9 shows oscilloscopes traces (TOF spectra) averaged over 10⁴ linac pulses. The SiO₂ single-crystal data for the flight distance $d = 135$mm, and the positron incident energy, $E_0 = 0.5$keV show two components corresponding to Ps energies of about 3eV and 1eV. The two components exist consistently in the spectrum taken at $d = 90$ mm. The spectra for amorphous SiO₂ also show two components. The TOF spectra for KI and MgO show single components of the peak energies, 2.1 eV and 2.6
The 1 eV component from the SiO$_2$ surface is attributed to the emission of Ps formed in the bulk, and the 3 eV component to the emission of Ps formed on the surface. The reason why the 1 eV component was not observed in the previous TOF measurement [1] is probably because the Ps detection efficiency was too low for energies lower than 3 eV. The reason why the 3 eV component was not observed by the previous ACAR measurement [2] is probably because the emitted Ps reenters into another grain, and is reemitted with an energy of about 1 eV.

Figure 9.
Time-of-flight spectra. All of the data are normalized to the measurement time. The arrows in (a)-(d) show the time corresponding to 1 eV and 3 eV. In (e) and (f), the arrows show the peak positions.

References

5-7 Magnetic EXAFS with Spin Orientation Analysis

The spectrum of Magnetic EXAFS (MEXAFS) of DyFe$_2$ was measured at the Fe K-edge and a novel analysis was successfully applied to obtain the spatial distribution of spin polarization with the information of its orientation.

The measurement was performed at PF-BL28B of KEK with circularly polarized X-rays that were generated by an ellipsoid multi-pole wigler. The degree of the circular polarization was about 0.36 around Fe K-edge. Instead of switching helicity of the incident photons, the
applied magnetic field of about 0.6 T was reversed every 4 second to obtain magnetic circular dichroism (MCD) effects. The absorption profiles were measured as $\mu^+(E)$ and $\mu^-(E)$ for the direction of the applied magnetic field along the projection of the propagation vector of the incident x-rays and for the opposite direction, respectively.

A magnetic absorption $\mu_m(E)$ is defined as Eq. (1).

$$\mu_m(E) = \mu^+(E) - \mu^-(E)$$  \(1\)

An MEXAFS spectrum $\chi_m(E)$ is obtained from $\mu_m(E)$ with subtraction of the background profile $\xi_m(E)$.

$$\chi_m(E) = \mu_m(E) - \xi_m(E)$$  \(2\)

On the other hand, $\chi^+(E)$ and $\chi^-(E)$, the EXAFS spectra corresponding to $\mu^+(E)$ and $\mu^-(E)$ are defined as Eqs. (3) and (4).

$$\chi^+_m(E) = \mu^+_m(E) - \mu^-_m(E) - \frac{1}{2} \xi_m(E)$$  \(3\)

$$\chi^-_m(E) = \mu^-_m(E) - \mu^+_m(E) + \frac{1}{2} \xi_m(E)$$  \(4\)

In Eq. (5), the contributions from charge density are canceled between $\chi^+_m(k)$ and $\chi^-_m(k)$.

$$\chi^+_m(k) = \frac{1}{k^2} \frac{\mu^+_m(E)}{E}$$  \(5\)

In Eq. (5), the contributions from charge density are canceled between $\chi^+_m(k)$ and $\chi^-_m(k)$.

The results for DyFe$_2$ are shown in Figure 1 with those of calculation by FEFF6 code. Figure 1 (c) well reflects that the spin moment of Fe couples with that of Dy ferrimagnetically. $\sigma(r)$ also successfully reproduced the spin distribution in pure Fe. Thus, the $\sigma(r)$ profile retrieves the sign of the spin polarization, which is especially useful to see the orientation of spin moments.

Figure 1.
The solid lines in (a), (b) and (c) are $I_{FEF}(k^2\chi_m(k))$, $I_{FT}(k^2\chi_m(k))$ and $\sigma(r)$ profiles in DyFe$_2$ at 20K, respectively. The k-range of Fourier transformations was $k = [4.5-12.8]$ Å$^{-1}$. The broken lines in (a) and (c) are the simulated profiles with FEFF6 code.
6 Crystallography

Crystallographic studies on inorganic materials and minerals using SR have been promoted at the Photon Factory during this decade, especially in the fields of structure refinements to obtain accurate structures, the application of anomalous scattering to elucidate the site occupancies of solid solutions, and identification and structure refinements of submicrometer-sized specimens and the micro-areas of thin sections. From these studies, three topics are introduced below.

6-1 Identification of Interplanetary Dust Particles (L2005AE6)

Since the sizes of interplanetary dust particles are in general from submicrometer to 20 micron, there have been no X-ray diffraction studies on them. Synchrotron radiation can make possible to carry out diffraction experiments.

The chemical formula of this sample is Fe\(_{x}\)Ni\(_{1-x}\)S, analyzed by an electron prove micro analyzer (EPMA). According to the formula, L2005AE6 is conceived to be one of the intermediate series of pyrrhotite (FeS, 0\(<\)x\(<\)0.125). The structures of the pyrrhotite series are regarded as being a modification of the niccolite (NiAs)-type structure (P6 \(_{3} \) : a = 3.43, c = 5.79, Z = 2) which is stable at high temperature over a wide range of chemical compositions. The structure is built up with an alternation of hexagonal sheets of Fe and those of S stacking along the c-axis. Vacancies of Fe sites in an ordered or random manner cause many types of complicated modulated structures at low temperature corresponding to various chemical compositions. Therefore, the purpose of this study was to identify the crystal structure with the greatest possible precision.

The Laue pattern was obtained at BL-481 by a 30-minute exposure with the average ring current being 297 mA under the ring oper-
Highlights

Figure 1. A and B are paired satellites associated with the missing spot of 2-1 -1, and C and D with 2-1 -2. E is a subcell diffraction spot with index 4-2 6 which is a higher order diffraction of index 2-1 3.

The experiment was carried out in a vacuum of 6x10⁻² Torr. More than 40 Laue spots were recorded on the imaging plate. One feature of the Laue pattern is that some satellite reflections accompanied by missing main spots are observed. Two satellites among them are paired and located on a line in reciprocal space from its origin through the missing spot as they are split from the missing spot. With the exception of the satellites, the Laue spots were rather well indexed based on a hexagonal 3C-type pyrrhotite with cell parameters of a = 6.867 and c = 17.062Å. By taking into account the lower indices to l, the axial ratio (c/a) is obtained as being 0.828, which can be compared with the average value for pyrrhotites of 0.832.

The indices of the missing spots with a pair of satellites are 2-1 2, 2-1 1, 2-1-1, 2-1-2 and 2-1-4. One of the paired satellites is shown in the figure. This type of pyrrhotite is classified as the NA type, and the c-axis of this type is three-times longer than that of the niccolite (NiAs)-type subcell, while modulation takes place in the a-axis direction.

From the positions of the satellite reflections and the distribution of the missing spots, the periodicity of the a-axis is obtained as N involved in the notation of NA. The periodicity of the a-axis direction was calculated to be 41.84 -times (N = 41.84) longer than that of the niccolite-type FeS subcell.

The structure of NA-type pyrrhotite should be analyzed using a higher dimensional space group, but has not been determined. In the present case, only five crystallographic-independent diffraction spots were obtained, which does not enable us to solve the structure. This type of pyrrhotite has been obtained only by synthesis experiments, and was never been discovered in nature. Therefore, the present NA type of interplanetary dust particle is the first from nature.
6-2 Valence Contrast

The valence-difference contrast method is a fairly old concept, but a new technique to observe the behavior of ions in different valence states, where the use of synchrotron X-rays is essential, and the determination ability depends on the difference in the atomic-scattering factors. The difference can be enhanced when the anomalous-scattering effect is dominant at a wavelength close to the absorption edge. There have been only several reports about how to use anomalous scattering on different valence states since 1990 [1, 2]. Most of the reports focused on refining the values for anomalous scattering factors in a normal crystallographic way. Such studies were still empirical and far from a quantitative treatment. A threshold has come when the anomalous scattering factors can be calculated with relatively accurate values for realistic beams and crystals.

It is known that a change in the energy levels of valence electrons give a chemical shift of up to several eV on the pre- and main-edge peaks in the XANES (X-ray absorption near-edge structure) spectra. Based on them algorithm by Cromer and Liberman [3] and the absorption data in the XANES region, anomalous scattering factors (f') were half-experimentally obtained for Fe\(^{2+}\) and Fe\(^{3+}\) ions [4]. Surprisingly, there is a large difference of 2.5 between the factors of the two ions (I = 1.7415 Å). The famous Kramers-Kronig transformation is theoretically perfect, it may have a technical problem to obtain an absolute value close to the edge, because of the lack of full absorption data for the requirements for scaling.

The establishment of the valence-difference contrast (VDC) method was made based on the observation of diffuse scattering related to valence fluctuation in magnetite, Fe\(_2\)O\(_4\) [5]. The VDC method can clearly distinguish Fe\(^{2+}\) ions from Fe\(^{3+}\) in X-ray diffuse intensities at the FeK absorption edge (BL-10A). Figure 1 (a) shows the iso-diffusion surface around a 440 reciprocal lattice point of magnetite at I = 1.7425 Å. Two-dimensional contour maps were
Figure 1.
Observed intensity distribution of X-ray diffuse scattering around 440: (a) $T=130K$, $\lambda=1.7421\AA$, $f'(\text{Fe}^3\cdot)-f'(\text{Fe}^2\cdot)=-1.60$, $\Delta E/E \approx 10^4$ and (b) $T=130K$, $I=1.7421\AA$, $\Delta E/E \approx 10^3$.

Highlights

Figure 1.
Observed intensity distribution of X-ray diffuse scattering around 440: (a) $T=130K$, $\lambda=1.7421\AA$, $f'(\text{Fe}^3\cdot)-f'(\text{Fe}^2\cdot)=-1.60$, $\Delta E/E \approx 10^4$ and (b) $T=130K$, $I=1.7421\AA$, $\Delta E/E \approx 10^3$.

obtained by the fixed-time counting method at each point of 20 x 20 reciprocal grid with an exposure time of 10 sec per point. The horn-like diffuse streak pattern, elongated along $[110]^*$, was clearly observed at 150 K, but disappeared at room temperature. Similar diffuse streaks along $[110]^*$ were reported in the neutron and electron diffraction [6,7], but the reason of the appearance is quite different from that in the X-ray case. The neutron diffuse streaks were well explained by introducing a molecular polaron model with a local displacement of the oxygen atoms [8]. The X-ray diffuse streaks significantly differed in the elongating direction from neutron, ones and disappeared when the valence contrast was removed (Figure 1 (b)). Thus, the X-ray diffuse streaks shown in Figure 1 (a) were deeply related to the local charge ordering, thus, a Huang scattering analysis was introduced to determine the partial pairing of Fe$^3\cdot$ and Fe$^2\cdot$. The results showed that the iso-diffusion surface elongating toward $[110]^*$ was reproduced to have a partial ordering of Fe$^3\cdot$ and Fe$^2\cdot$ in the ratio of 1:3 (or 3:1) along $[110]$ in the B sites.

Recently, the VDC method has been applied for measuring the Bragg diffraction, especially for observing satellite peaks related to charge ordering. Figure 2 (a) shows the intensity profiles of superlattice reflections indexed as 07/24 and 09/24 at 102 K, which were measured with an $f'$ difference of 1.6 at $\lambda=1.7421\AA$ in the BL-10A station [9]. The half-integer reflections are caused by (1) the charge ordering of Fe$^3\cdot$ and Fe$^2\cdot$ ions as well as (2) the lattice deformation associated with atomic position shifts. X-ray intensity measurements were performed for low magnetite with various X-ray energies near to the FeK absorption edge. The energy dependence in the diffracted intensity was clearly observed for the 07/24 reflection (Figure 2 (b)). Especially in the energy region from 7.12 to 7.13 keV, the characteristic energy dependence in the integrated intensity (solid circles) was very comparable with calculations based on the $f'$ difference.
between Fe$^{2+}$ and Fe$^{3+}$ [4]. This implies that the superlattice peak contains the intensity component due to the valence difference. Similar studies are in progress for RFe$_2$O$_4$ (R = Y, Dy, Ho, Er, Tm, Yb, Lu) [10].

Figure 2.
(a) Variation of the logarithmic intensity versus the momentum transfer for superlattice reflections near to 044 at T=102K and l=1.7421Å.
(b) Energy dependence of the diffracted intensity for the 07/24 superlattice reflection near to the FeK absorption edge at T=102K, where the dashed curve gives the calculation values.

References

6-3 What is the Best Way to Obtain Accurate Structural Parameters from Powder Diffraction Data?: High-Resolution Powder Diffraction Data Weighted with a New Weight Function in Rietveld Refinement

Crystal structure analysis using powder diffraction data presently constitutes one of the very active fields in crystallography, and is very
important in the fields of materials sciences and engineering. One of the main reasons for strong demand on the powder method may be that single crystal for diffraction study cannot be so easily obtained when materials were revealed to have interesting physical properties. The other reason may be that materials often exhibit useful properties only in powder or polycrystalline state including thin film. Interpretation of physical properties will be promoted by understanding the crystal structure, and it can be practiced by obtaining accurate structural parameters in the analysis. We have started a S1 project from 1998 fiscal year as a post project after the construction of a synchrotron radiation powder diffractometer with multiple-detector system [1]. Our purpose is to re-examine a system of crystal structure analysis using powder diffraction data in order to answer the question posed at the title of this report.

The Rietveld method is widely used as an indispensable technique for crystal structure refinement using powder diffraction data. Structural parameters can be determined by the least-squares fitting of a whole observed diffraction pattern. Profile intensity data are used as observations, and thus the technique can be applied irrespective of peak overlaps. It is, however, our belief that high-resolution data have high quality of information and thus they should give more accurate results than low resolution data. Accuracy of better than 0.005Å in average may be required for refined atomic coordinates to discuss detailed crystal chemistry, such as of a distortion of coordination polyhedron, of the structure. In practice, however, accuracy of refined parameters is often contrary to the expectation [2].

A new weighting scheme for the minimization function used in Rietveld refinement was proposed [3, 4]. It has a form $w = Y^2$ with $e = 2 (Y_o : \text{observed profile intensity})$, and gives relatively heavier weights on weak intensities than those currently used in the form $w = Y_o$ in Rietveld refinement. The accuracy of structural parameters was measured by using the mean squared deviation of structural parameters ($\sigma$) obtained by Rietveld refinement from those of single crystal values. Figure 1 shows plots of $\sigma$'s of Mg$_2$SiO$_4$ (11 positional parameters) against the diffraction data sets with various angular resolutions. The number of peaks in CuK$\alpha_1$ data set is reduced to a half of CuK$\alpha_1$-K$\alpha_2$ doublet data set without losing information density. Peak widths observed with synchrotron radiation (SR) were less than a half of those obtained by laboratory systems (CuK$\alpha$) at mid-angle region. Moreover, the number of peaks for SR1.2Å is about twice as large than that of SR1.54Å. By the use the new weight function, the accuracy could be improved with improving the resolution of diffraction data. However, as long as we use the conventional weight by $w = Y_o$, the accuracy is independent of the resolution.

We are now accumulating the data, and many experimental observations in weighted error distributions have confirmed the validi-
ty of the new weight function. A subtitle of this report “high-resolution powder diffraction data weighted with the new weight function” will be one of the clues for answering the question posed first.

Figure 1.
Plots of $\sigma$'s of Mg$_2$SiO$_4$ against the diffraction data sets with various angular resolutions. Symbol SR means synchrotron radiation data and number followed represents a wavelength used.

References
7 High Pressure Science

X-ray diffraction studies under high pressures are carried out by using two different types of high-pressure devices. One is a diamond-anvil cell (DAC), which is commonly used at most of the SR facilities in the world. The other is a cubic-anvil press, which is a kind of multi-anvil press system developed in Japan. MAX80 and MAX90 are nicknames for the high-pressure systems designed for SR experiments at the Photon Factory. The characteristics of the DAC device are advantageous for realizing ultra-high pressure, but with a very small sample volume; that of the cubic anvil press is the capability of a large sample volume, which can generate uniform conditions, such as pressure, temperature and stress field. The experimental station for DAC is a bending-magnet beamline, BL18C, which is equipped with a double-crystal monochromator and focusing mirrors. On the other hand, MAX80 and MAX90 are installed in BL14C (superconducting magnet wiggler beamline) and AR-NE5C (bending magnet in the high-energy storage ring PF-AR). These beamlines generate high-energy synchrotron radiation suitable for the large sample volume high-pressure device.

MAX80 and 90 have shown many excellent performances, which are interesting and original in high-pressure science field; i.e. fundamental physics, materials science, crystal chemistry and geophysics. In the first topic, Dr. Takashi Taniguchi (National Institute for Research Inorganic Materials) has carried out a new investigation of the high-pressure phase transition of boron nitride [1], and is a diamond related isoelectronic compound, which is also widely used in industrial applications as a super-hard material. The next topic is a typical experiment of the crystal chemistry of FeS under high-pressure and high-temperature conditions performed by Keiichi Kusaba (Institute for Materials Research, Tohoku Univ.) [2]. It shows a full performance of our high pressure system.
7-1 Effect of Nonhydrostaticity on the Pressure-Induced Phase Transformation of Rhombohedral Boron Nitride.

Pressure-induced phase transformations of low-pressure poly­morphs of boron nitride (BN) and carbon have been the subject of study for many years. Two types of stacking sequences of a hexagonal network with twofold and threefold structures are known in their ambient-pressure phase. At room temperature and high pressure, hexagonal boron nitride (hBN) and graphite, with a twofold layered structure, are known to transform to wurtzite-type BN (wBN) and hexagonal diamond (h-diamond), respectively. The h-diamond structure has the same atomic coordination as the wurtzite structure by ignoring the difference of atomic kind. In the case of a threefold layered structure of the rhombohedral form, although a significant amount of rhombohedral graphite has not yet been obtained, rhombohedral BN (rBN) has been successfully synthesized.

An in-situ x-ray diffraction study of the room-temperature compression of rBN was performed up to 10GPa. Although no phase

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Figure 1.
Variation of the x-ray diffraction profiles with pressure using a solid-state pressure-transmitting medium at room temperature. A: Starting material: rBN (a) Starting condition, (b) 0.35GPa, (c) 5.3GPa, (d) 6.1GPa, (e) 7.0GPa, (f) 9.5GPa, (g) release the pressure to 0.25GPa, (h) 0.15GPa, (i) ambient pressure. B: Starting material: hBN (a) Starting condition, (b) 7.8GPa, (c) 10.5GPa, (d) 11.0GPa, (e) 11.8GPa, (f) release the pressure to 0.3GPa, (g) ambient pressure.
transformation of rBN was observed in a liquid pressure-transmitting medium, the structure of rBN changed to become disordered within the layered stacking sequence at less than 1 GPa with a solid-state pressure-transmitting medium. A further transformation to the wurtzite structure (wBN) was observed at 6 GPa, and was unquenchable upon the release of pressure at room temperature. Graphite is known to transform to h-diamond at room temperature, and is unquenchable upon the release of pressure. Because of the structural analogy of h-diamond and wBN, the disordered rBN structure due to compression seems to be similar as that of graphite. On the contrary, it is known that wBN is also transformed from hBN and is quenchable upon the release of pressure at room temperature. It should be emphasized that the observed crystallographic orientation relationship in the phase transformation of rBN to wBN was different from that of hBN to wBN. Such a different nature of the phase transformation may cause a structural instability of h-diamond and wBN transformed from rBN.

7-2 Compression Behavior and Phase Equilibria of FeS

There have been many investigations concerning the high-pressure behavior of stoichiometric FeS (troilite) from the viewpoints of

Figure 2.
Iso-c/a ratio curves for the fundamental NiAs type cell in P-T phase diagram of FeS.
earth and planetary science, solid-state physics and crystal chemistry, since a high-pressure phase was found in 1970. This is because, iron sulfide (FeS) including troilite is considered to be an important compound in the core of the earth and planets, and it also shows a variety of magnetic properties and crystal structures.

We have also investigated the high-pressure and high-temperature behavior of FeS by an in-situ X-ray diffraction method using a large-volume press apparatus.

The high-pressure phase was first confirmed to have a monoclinic cell; also, a large volume change at the phase transition at 7GPa could be explained by a 'high spin - low spin transition' of the iron atom. A pressure-and-temperature phase diagram of FeS up to 16GPa and 800°C was also determined, as shown in Figure. 1, which had some different points from previous investigations. The most important point to consider the core of the earth and planets is that the phase boundary between the simple NiAs type phase and the hexagonal phase is described by a straight line up to 11GPa.

In the present study, two other interesting behaviors of the hexagonal phase were found. One was an inflection at 7.5GPa in the compression curve at 300°C, the other was a minimum thermal expansion observed at 5.7GPa. These two observations suggest that the hexagonal phase changes its property due to the pressure and temperature. We considered that these phenomena were caused by a spin order - disorder transition in the hexagonal phase similar to that of the invar-type alloys.
8 Biological Science

With the rapid expansion of this field, many new atomic-resolution structures of biological macromolecules have been solved in the Photon Factory during the preceding years. Clearly, synchrotron radiation is now considered to be an essential tool for the study of biological science. The demand for beam time is ever more increasing, particularly concerning macromolecular crystallography, as more biologists become aware of the importance of the atomic-resolution structure of macromolecules in order to study structure-function relationships. This demand is not likely to decrease in the near future, when genome projects are expected to elucidate many unknown protein genes whose structures must be investigated.

The highlights here do not attempt to cover all of the important results, but rather to introduce a very limited area of this rapidly expanding field. The highlights include the structure analysis of L-isoleucyl-tRNA synthetase, cytochrome c oxidase, and hydrogenase. It should be mentioned that many other new structures were solved using beam lines in the Photon Factory, and appeared in the literature. Two other sciences in the biological field using synchrotron radiation are also highlighted here. They are the study of the proton pumping mechanism of bacteriorhodopsin by X-ray diffraction measurements and research on radiobiological processes.

8-1 Enzyme Structure with Two Catalytic Sites for Double-Sieve Selection of Substrate

High-fidelity transfers of genetic information in the central dogma can be achieved by a reaction called editing. The crystal structures of L-isoleucyl-tRNA synthetase (IleRS) in complexes with L-isoleucine and L-valine demonstrate that the editing is processed by two-step selection or by a "double-sieve" mechanism. The first sieve is on the aminoacylation domain containing the Rossman fold, whereas the
second, editing sieve exists on a globular $\beta$-barrel domain that protrudes from the aminoacylation domain.

The crystal structure of *thermus thermophilus* IleRS (1045 amino acid residues, 120kD) and those of the complexes of IleRS with L-isoleucine and L-valine were determined at resolutions of 2.5, 2.8, and 2.8 Å, respectively [1]. IleRS belongs to the class I synthetases [2], which are characterized by an ATP-binding domain constructed with a Rossmann fold. *Thermus thermophilus* IleRS is a thick, L-shaped molecule with an approximate size of 100Å x 90Å x 45Å. The structure exhibits the Rossmann-fold domain at the center, $\beta$-rich intervening domains at the top, and an $\alpha$-rich cylindrical domain at the bottom (Figure 1).

In the L-isoleucine/IleRS complex, one L-isoleucine molecule is bound at the bottom of a catalytic cleft in the Rossmann-fold domain. The hydrophobic side chain of L-Ile is recognized by a pocket consisting of conserved amino residues through van der Waals interactions. The L-leucine side chain does not fit into this pocket, because of the steric hindrance of one of the terminal methyl groups. Naturally, larger
amino acids are occluded from this pocket. In contrast, in the L-valine/IleRS complex structure, an L-valine molecule is actually bound to the same site. The hydrophobic contact area of the L-valine side chain with those of conserved amino residues at the pocket is slightly smaller than that of the L-isoleucine side chain. All of these observations agree with the concept of the first, coarse sieve in the double-sieve mechanism of editing [3].

The Rossmann-fold domain has a β-rich insert consisting of four structural domains (Ins-1 to Ins-4). A β-barrel core and a protruding β-ribbon of the Ins-2 domain form a deep cleft, the size of which is comparable to that of the catalytic cleft of the Rossmann-fold domain. The "CP1" fragment [4] (corresponding to the present Ins-1 and Ins-2 domains) cloned from E. coli IleRS retains the specific Val-tRNA editing activity [5].

In the present L-valine/IleRS complex structure, a second L-valine molecule was identified at the bottom of the deep cleft in the Ins-2 domain. In contrast, in the L-isoleucine/IleRS complex structure, no electron density was observed in this second pocket. Therefore, the second pocket on the Ins-2 domain is specific for L-valine, indicating that this pocket is the site for the second, fine sieve of the double-sieve mechanism of editing [3].

8-2 Atomic-Resolution Structure of Cytochrome c Oxidase and its Functional Mechanisms

Cytochrome c oxidase, one of the proton-pumping assemblies of the respiratory chain, catalyzes the reduction of O₂ to H₂O. Four electrons from ferrocytochrome c are funneled into O₂ and completely reduce it to H₂O with concomitant pumping of protons from the matrix to the cytosolic side of the inner mitochondrial membrane. The reduction of molecular oxygen to water is carried out at the site involving heme a₃ and Cu₃. The electrochemical potential thus generated causes protons to flow back into the matrix resulting in the synthesis of
ATP, the biological molecular device to store energy.

The crystal structure of bovine heart cytochrome c oxidase was determined \([6,7]\). This remarkable achievement was already reviewed in a previous report \([8]\). The whole protein moiety consists of 13 different polypeptide chains, five phosphatidyl ethanolamines, three phosphatidyl glycerols, two cholates, two hemes \(a\), three copper, one magnesium and one zinc (Figure 2). To understand the mechanism of the proton pumping by this enzyme, however, a careful comparison of the crystal structure in various oxidation and ligand binding states at high resolution is needed. For this purpose, the crystal structures of bovine heart cytochrome c oxidase in the fully oxidized, fully reduced, azide-bound and carbon monoxide-bound states were determined at 2.30, 2.35, 2.9, and 2.8 angstrom resolution, respectively \([9]\).

On reduction of the metal sites of the fully oxidized enzyme, the most notable change occurred at a segment from Gly49 to Asn55, which moved toward the cytosolic surface by about 4.5 Å at the position of the carboxyl group of Asp51. The hydrogen bond between the peptide amide of Ser441 and the carboxyl group of Asp51 was broken, and Asp51 lost its accessibility to the matrix side through the hydrogen-bond network. Based on these results and on other biological evidences, Yoshikawa et al. proposed a new mechanism for redox-coupled proton pumping \([9]\).

8.3 High-Resolution X-ray Structure of Hydrogenase from Desulfovibrio sp.

The hydrogenase of \textit{Desulfovibrio} sp. catalyzes the reversible oxidoreduction between molecular hydrogen and a specific electron acceptor, cytochrome \(c_3\). The Ni-Fe active center of \textit{Desulfovibrio} hydrogenase has an unusual ligand structure with non-protein ligands. The X-ray structure of the hydrogenase from \textit{Desulfovibrio} sp. Miyazaki has been solved at 1.8Å and refined to a crystallographic R
factor of 0.229 [10] (Figure 3). The structure was determined using techniques of multiple isomorphous replacement (MIR) and multiple anomalous diffraction (MAD). The phases were obtained from MIR information at 4.0 Å combined with MAD information at 3.5 Å from the data collected using the X-rays of 1.743, 1.730, 1.750 and 1.487 Å. Twelve anomalous scatterers (eleven Fe and one Ni) were used for MAD phasing.

On the basis of the refined structure of the Ni-Fe hydrogenase, three diatomic ligand species coordinating the Fe atom in the Ni-Fe active center have been proposed to be S=O, C=O, and C=N, and a sulfur atom has been postulated to be the bridging ligand between the Ni and the Fe atoms. These assignments are supported by data from pyrolysis mass spectroscopy and infrared spectroscopy. The non-protein ligands to the Fe atom should cooperatively participate in the system of hydrogen metabolism, for example, as an electron sink during the electron-transfer reaction between the hydrogenase and the biological electron carrier protein, cytochrome c. Another possible role of these ligands might be to stabilize the redox state of Fe(II), which may not change during the catalytic cycle, and is independent of the redox transition of the Ni.

8-4 Structures of the Photointermediates of Bacteriorhodopsin and the Implication for the Proton Pump Mechanism

Bacteriorhodopsin (BR) is a light-driven proton pumping machinery found in the membrane of halophilic bacteria, which transports an ion across a membrane against a chemical potential. The molecular events during the photo-reaction have been extensively by
a variety of techniques. The results indicate that the translocation of a proton from the cytoplasmic side to the extracellular side comprised of a series of local proton transfers (Figure 4).

An important question is how the sequence of chemical reactions is controlled to prevent a back reaction. Another issue is how the sidedness is determined for the release and the uptake of protons. To reveal the global structural changes during the reaction and the relationships between the global structural change and the local chemical reactions, X-ray diffraction measurements have been carried out for BR under various conditions. The obtained results are summarized below (ref. Figure 4):

1. Structural changes at the M, MN and N intermediates were clarified. The structural changes suggest opening of the cytoplasmic channel. Further, small but significant differences between the M and the N intermediate were revealed [11, 12].

2. In the original structure, the proton channel opens to the extracellular side. The major determinant of the open side, thus the conformational change, is the local electrostatic interaction, but not retinal

Figure 4.
Schematic model of molecular events during photo-reaction.
Highlights

3. The structural transition between the M and N intermediates is hydration dependent. This result reasonably explains the efficient proton transfer from D96 to the Schiff base [13, 15]. These results suggest that the local chemical reaction and the global structural changes are tightly coupled to each other. The alternative conformational changes regulate the sidedness of the Schiff-base reaction; and simultaneously, deprotonation of the Schiff base, itself, induces conformational changes. The vectorial proton translocation is reasonably explained based on this concept.

8-5 Research on Radiobiological Processes

A monochromatized photon beam from synchrotron radiation has been proved to be a powerful tool for investigating radiobiological processes from the viewpoint that we can control the local ionization density through photoelectrons having monoenergetic energy. Among the various included processes, chemical processes in an aqueous system would be more important, since living cells contain more than 80% water. The determination of the yields of reactive intermediates, such as the OH radical or solvated electrons, is one of the main projects of the radiation-biology group at the Photon Factory, since they are known to play important roles in producing DNA damages. The yields of these species depend upon the microscopic density of the energy deposited. As a measure of these species, the oxidation yield of Fe$^{3+}$ from Fe$^{2+}$ in a Fricke solution was measured by Watanabe et al. (1995), in the photon energy range from 1.8 to 10 keV. The measured yields decreased along with a decrease in the photon energy. This photon-energy dependence can be reproduced by computer sim-
ulations. The decrease in the yields can be explained by an enhanced recombination of the primary radiolytic products that are produced more densely by photons with lower energies. Recently, some data points of vacuum ultraviolet photons (6.0 - 8.5 eV) were added to the spectrum (photon energy dependence) of Fricke yield. The ultraviolet photons used can produce only one isolated pair of dissociated radicals, or ions, which means that the highest yields of the reactive intermediates will be expected from an energetic point of view. As shown in figure 5, the yields were much higher than the data obtained in the region above 1.8 keV, as expected, and also in accordance with theoretical simulations. According to the simulations, there would be a minimum around or less than 1 keV due to the highest energy density deposited by electrons having these energies. The chemical reactions and yields included in the microscopic region to which radiation energy is deposited with high density are attracting much attention, since energy deposition with high density causes higher biological effects. In order to investigate the effect of photons from 10 eV to 1 keV on aqueous systems, we need to develop methods to irradiate with photons which are generated in a vacuum. The group has just developed an irradiation apparatus for this purpose, and is expected to measure the yields in the 10-to-1 keV region.

Radiation acts on biomolecules mainly towards their decomposition. It is also known, however, that radiation energy is used to synthesize large organic molecules from inorganic or small ones, although the efficiencies are very small. Before the appearance of life, large amounts of accumulated organic molecules were necessary; radiation is considered to contribute very much to the synthesis and accumulation of various biomolecules, known as "chemical evolution". In order to demonstrate the non-biological synthesis of nucleotides,
which are known to be components of deoxyribonucleic acid (DNA), the use of monochromatic photons was planned by taking advantage of selective absorption by a specified element in samples. Adenosine containing 14C-labelled deoxyribose was mixed with phosphate and irradiated with monochromatic photons of K-shell resonance absorption energy in aqueous solution. Irradiated samples were analysed by thin-layer chromatography combined with the autoradiogram technique. The preliminary results suggest that 3'-AMP, 5'-AMP, 2'-AMP and 3',5'-ADP were synthesized along with the irradiation of phosphorus K-shell resonance absorption (Figure 6).

References
9 Medical Application

9-1 First Clinical IVCAG (Intravenous Coronary Angiography) Using 2D Monochromatic Synchrotron Radiation

A first clinical application of synchrotron radiation (SR) to IVCAG was successfully performed in May 1996. This system may meet clinical requirements of screening patients with coronary artery (CA) disease such as myocardial infarction and/or angina pectoris, which are major causes of death in the modern industrialized societies.

The SR from an elliptical multipole wiggler at the accumulation ring was used. Its acceleration energy and the stored current was 5.0 GeV and 30 mA, respectively. The photon beam with energy of 37 keV used for a patient was that reflected from an asymmetrically cut silicon crystal with 3,1,1 reflection so that the magnified size of 150mm X 80mm was available. The intensity enhancement was achieved by silicon surface polishing.

The patients received an intravenous injection of contrast agent via a catheter introduced from left cubital vein or from right internal jugular into the central veins. 2D images were acquired with a 9 inch image intensifier coupled to a CCD camera. SR IVCAG seems to be promising not only as anatomical diagnosis but also for functional diagnosis of coronary heart disease due to the 2D beam.

Four patients in total, two with previous PTCA (percutaneous transluminal coronary angioplasty) and other two with complain of chest pain but no experience of coronary angiography were selected together with the from of consent. All were male whose ages range between 55 and 72 years old.

The human study programme was proceeded after approval of three concerned ministries and other two local organizations.

One of the typical IVCAG images is shown in Figure 1. That is
obtained in right anterior oblique projection with caudal angulation in a patient with PTCA at the proximal portion of the LAD. The temporal subtraction was done. The large arrow indicates the site of previous PTCA and the small arrows the LAD and the left circumflex CA. The IVCAG obtained can provide enough quality and useful information for clinics. The irradiation dose was about 25 cGy per projection.

This work done as a joint work between Tsukuba University and KEK by the authors in ref[1] was awarded the "Tsukuba Encouragement Prize" in 1997.

Reference

Ulthathin SiO₂ layer formation is a key technology in fabrication of advanced metal-oxide-silicon large-scale integrated circuit devices. Thus, the SiO₂ layer structure has been intensively studied to understand the electrical properties of the oxide layers. Recent studies using X-ray diffraction measurements show that SiO₂ crystallites exit in the amorphous SiO₂ layer on the Si substrates [1,2]. There is an extra peak located exactly on the line of the crystal-truncation-rod (CTR) scattering elongated from the 111 Bragg point. The intensity of the peak depends on the thickness of the oxide layer, and the peak was not observed after etching of the oxide film. In order to obtain the fine structure of the peak along the CTR scattering, high-resolution measurements using the four-circle diffractometer with a Si crystal analyzer installed on the beamline 4C have been performed [2,3]. In addition, Sakabe's camera and Weissenberg camera with imaging plate detector installed on the beamline 6A2 and 18B, respectively, were used to investigate the whole aspect of the X-ray diffraction pattern in

Figure 1.
The intensity profile around q=0.54 exactly on the line of the CTR scattering from the 111 Bragg point for the extra peak of the SiO₂/Si (111) 4° off sample with the oxide layer of 34 nm in thickness.
Highlights

reciprocal space. The peak profile has a Laue-function-like oscillation-fringe pattern as shown in Figure 1. The distance between the adjacent interference fringes corresponds approximately to the inverse of the film thickness. These results suggest that the crystallites are located at the SiOx/Si interface and widely distributed in the amorphous Si layer on the Si substrates [2]. A proposed model for the structure of the crystallites implies that the lattice is elongated along the surface-normal direction with the lateral lattice spacing fitted that of the substrate and thus the crystallites have an epitaxial relationship with the Si substrates [3]. It was concluded that microcrystallites coexist in amorphous SiOx films on Si substrates. It is crucial to understand the oxidation process mechanism and the electronic breakdown properties of the thermally oxidized SiOx thin films.

References

10-2 Soft X-Ray Standing Wave

Silicon is the most widely used n-type dopant for growth of GaAs (001) by molecular beam epitaxy (MBE) because the high electron mobilities were achieved in this system. It has been reported previously that Si-doped GaAs epitaxial layer exhibits an n- or p-type conductivity which depends on the crystallographic orientation of GaAs, growth temperature, and V/III flux ratio [1]. Furthermore, it has been reported recently that the character of the Schottky barrier between metals and GaAs can be controlled by a thin Si interface layer. Interaction between Si atoms and a GaAs surface or depositing Ga and As atoms plays an important role in the Si doping during GaAs growth and in the initial stages of Si epitaxial growth on GaAs. Heun et al. reported that Si-As chemical bondings are dominant at the Si/GaAs
interface deposited Si on the GaAs surface from the results of in situ surface sensitive synchrotron radiation photoelectron spectroscopy installed on the beamline 1A [2]. However, the lattice position of the Si dopants in the Si-doped GaAs grown by MBE and the structure of the Si/GaAs interface grown by MBE has not yet been explored in detail to understand the nature of the Si atoms adsorbed on the GaAs surface. The X-ray standing-wave (XSW) measurement is a powerful technique to study the lattice position of particular atomic species on a crystal surface. To determine the three-dimensional arrangement of the Si atoms deposited on the GaAs (001) surface with a sub-monolayer thickness, the back-reflection XSW experiments of both GaAs (1-11) and (111) reflections were performed by scanning photon energy using a pair of InSb (111) crystals across the normal incidence Bragg reflection condition at the beamline 1A as shown in Figure 2 [3]. Two types of back-reflection XSW results show that Si atoms occupy both the Ga site and the As site, and that the occupancy of the Ga and As sites can be estimated to be about 75% and 25%, respectively. Si atoms were deposited at 400°C without As flux. Thus, Si adsorption site is mainly affected by the top layer As coverage, which is consistent with conductivity dependence on the substrate orientation.

Figure 2.
Experimental setup for (1-11) and (111) back-reflection XSW study for Si/GaAs (001) surface.

References
11 Instrumentation and Techniques

Recently, the polarization of synchrotron radiation has been widely used for experiments in atomic spectroscopy and material science. New instruments and techniques are being developed for such experiments. The x-ray phase plate controls the polarization of x-rays. Undulator beamline BL-2C has a new spectrometer for polarized soft-x-ray Raman scattering. A high-resolution monochromator of BL-2C shows good performance due to an improvement in the beam emittance of the PF ring.

11-1 Application of the X-Ray Phase Plate to Non-Resonant X-Ray Magnetic Diffraction

Non-resonant x-ray magnetic diffraction is a powerful tool to separately measure the orbital and spin parts of the magnetic form factor of ferromagnets. To date, the white-beam method has been mainly used to measure the magnetic form factors of ferromagnets of 3d, 4f and 5f electron systems. Although this method is powerful and convenient, an unstable electron-beam orbit in a storage ring and
strong fluorescent x rays from a specimen are apt to deteriorate the statistical accuracy. One of the most promising ways to improve the statistical accuracy is to use the monochromatic-beam method instead of the white-beam method. Recently, the monochromatic-beam method was developed by utilizing an x-ray phase plate [1].

The experiment was performed on BL-3C1 (Figure 1). The white beam was monochromated at an energy of 8.65 keV by a Si (111) double-crystal monochromator. The polarization of the x rays was then transformed by an x-ray phase plate of a diamond single crystal slab. The polarization was controlled through the offset angle (Δφ) of the phase plate. The monochromatic and polarized x rays were incident upon a Fe (110) single crystal where 220 Bragg diffraction took place (θ = 45°). The iron specimen was magnetized by a C-type electromagnet. The diffracted-beam intensity for one magnetization direction (I+) and that for the reversed magnetization direction (I−) were measured with a solid-state detector. The flipping ratio was obtained by R = (I+−I−)/(I+−I−). Figure 2 shows the observed flipping ratios at various values of Δφ. The observation (open circles) and calculation (solid line) agree well. The maximum value of R was 3 x10−3.

![Figure 1. Experimental setup for the non-resonant x-ray magnetic diffraction.](image)

![Figure 2. The flipping ratio R of the Fe 220 reflected intensity.](image)

Reference

Figure 3.
Nitrogen K-edge emission spectrum of h-BN. The group of structures observed below 396.0 eV derives from fluorescence and Raman scattering. The sharp peak at 401.1 eV is the elastic scattering peak of the incident photon. The total energy-resolution is determined by the full width at half maximum (FWHM) of the elastic-scattering peak.

11-2 Spectrometer for Polarization Dependent Soft X-ray Raman Scattering

A soft x-ray emission spectrometer for the polarized soft x-ray Raman scattering spectroscopy has been designed and installed on the undulator beamline BL-2C. The spectrometer was designed based on the Rawland circle geometry, comprising an incident slit, spherical grating, and a 2-dimensional position-sensitive detector.

Measurements on some transition-metal compounds, rare-earth compounds, and other materials have been performed to observe the polarization dependence and excitation energy dependence with high energy-resolution using a 20 µm incident slit width. Figure 3 shows the nitrogen K-emission spectrum of hexagonal BN excited at the nitrogen K-edge threshold energy. The sharp peak at 401.1 eV is the elastic scattering peak of the incident photon. The peak width comprises the energy width of the incident photon and the resolution of the spectrometer. The total energy width of the peak is 0.4 eV (FWHM) at 400 eV.

Measurements of the polarization dependence and excitation-energy dependence at the Ca L edge of CaO have also been carried out. The results of the excitation energy dependence show the Raman scattering peak. It is assigned to the excitation of the valence electron-hole pair. This excitation occurs along the energy-band dispersion curve from the Γ-point to the L-point. The spectra of the polarization dependence show a difference in the Raman peak intensity between the polarized and depolarized configurations. 'Depolarized' means that the polarization of the electric field is not conserved between the incident photon and that of the emitted photon. The intensity difference of the Raman peak is interpreted as that the polarization of the soft x-ray is not conserved during decay from the core exciton to the valence exciton.

We have already set up the soft x-ray emission spectrometer with high energy-resolution to obtain the polarization-dependence spectra, and have started to explore the polarization dependence of the soft x-ray Raman scattering.
Undulator beamline BL-2C has been designed to meet the demands for sophisticated experiments with very high resolving power. One can say "high-resolution monochromator", when the bandpass of a monochromator is narrower than the natural widths of the spectra. When this demand is satisfied, the monochromator can suggest a new opportunity in the field of soft x-ray spectroscopy.

The beamline has benefited from an improvement of the beam emittance of the Photon Factory storage ring. A comparison of the throughput of the beamline between the low-emittance operation and the normal-emittance is shown in Figure 4. The black line shows the spectrum under low-emittance operation, and the red line under normal-emittance, respectively. The photon flux at the first harmonic increases by 1.6, and the flux at the second harmonic decreases.

The 1s→π⁺ photoabsorption spectrum of nitrogen molecules, which is widely used to demonstrate the high-resolution ability of soft x-ray monochromator, is shown in Fig 5(a). Seven vibrational peaks are clearly resolved. By the deconvolution procedure, a resolving power of 10000 is recognized at 400 eV. Figure 5(b) shows the 1s→π⁺ photoabsorption spectrum of oxygen molecules. Many vibrational peaks are also observed. The broken lines display the fourteen vibrational peaks, but only seven peaks are drawn in the figure. The resolving power is estimated to be more than 10000. These results of the high-resolving power have been accomplished only in the third-generation storage ring. It reveals that the BL-2C is equipped with one of the highest performance monochromators with the highest resolving power.

From October 1998, BL-2C will be opened for general users.
Figure 5.

(a) The $1s \rightarrow \pi^*$ absorption spectrum of nitrogen molecules. It was measured with a grating having 1000 lines/mm and slit widths of $S_1=70 \, \mu m$ and $S_2=15 \, \mu m$.

(b) The $1s \rightarrow \pi^*$ absorption spectrum of oxygen molecules. It was measured with a grating having 2200 lines/mm and slit widths of $S_1=50 \, \mu m$ and $S_2=5 \, \mu m$. The dots represent the data, the solid line is the fitted curve, and the broken lines show the vibrational peaks, respectively.
12 Theory

Theory Group, see a photograph below, are performing various kinds of researches including secondary optical processes in soft X-ray region, strongly correlated electron systems, structural changes by photoexcitation and doping, and so on. In the following we briefly introduce doping effects in a three-dimensional charge-density-wave.

12-1 Melting of a Three-Dimensional CDW-Unified Theory for Structure and Spectroscopy

In this section we briefly introduce the melting mechanism of a three-dimensional (3D) charge-density-wave (CDW) state, with Ba$_{1-x}$K$_x$BiO$_3$ as an example [1]. The parent material BaBiO$_3$ is well known to be a 3D-CDW with a frozen breathing-type distortion of each oxygen octahedron.

The bismuth ion, which resides in the center of the octahedron, takes the valences of nearly +3 or +5, depending on the “breathing in” or “breathing out” of the octahedron, respectively. This means that an electronic gap, namely, a Peierls gap, opens around the Fermi surface. It is nearly 2 eV as a direct gap and 0.5 eV as an indirect one. Such a large direct gap suggests the existence of a strong electron-lattice coupling and its nonlinear effect.

Substituting Ba with K, extra holes are doped and cause the melting of the CDW. In the figure, the known facts and the theoretical interpretation are summarized. In particular, the latter is characterized by the following four steps of the hole-doping process:

1. Extra holes are still extended.
2. Hole bipolarons (BP’s) are formed, coexisting with the extended holes already formed.
3. No more long-range order of the CDW, but the system is still an insulator with a quasi electronic gap.

4. The system is now metallic. Even in this step, local CDW domains are still surviving.

Part of these phase changes, namely, $2 \rightarrow 3 \rightarrow 4$ explains systematic changes in neutron scattering data, light absorption spectra, conductivity, and the magnetic susceptibility, observed when the degree of doping ($x$) increased. The first step, on the other hand, is not confirmed yet, although we believe that detailed studies of the early doping stage will reveal the missing step.

Reference

Table 1 List of Experimental Stations at PF Storage Ring

<table>
<thead>
<tr>
<th>Experimental Station</th>
<th>Spokesperson</th>
</tr>
</thead>
<tbody>
<tr>
<td>BL-1</td>
<td></td>
</tr>
<tr>
<td>A [NTT] Solid surface analysis (under construction)</td>
<td>Y. Watanabe [NTT]</td>
</tr>
<tr>
<td>B X-ray spectroscopy (under construction)</td>
<td>H. Kato (until Mar. '98)</td>
</tr>
<tr>
<td>C Soft X-ray photoelectron spectroscopy (under construction)</td>
<td>A. Kakizaki (since Apr. '98)</td>
</tr>
<tr>
<td></td>
<td>Y. Murakami</td>
</tr>
<tr>
<td></td>
<td>A. Kakizaki</td>
</tr>
<tr>
<td>BL-2</td>
<td></td>
</tr>
<tr>
<td>(Undulator)</td>
<td>Y. Kitaizumi</td>
</tr>
<tr>
<td>A Soft X-ray spectroscopy</td>
<td>M. Watanabe</td>
</tr>
<tr>
<td>C Soft X-ray spectroscopy</td>
<td>M. Watanabe</td>
</tr>
<tr>
<td>BL-3</td>
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<tr>
<td>A X-ray diffraction and scattering</td>
<td>M. Tanaka</td>
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<tr>
<td>B VUV and soft X-ray spectroscopy</td>
<td>Y. Azuma</td>
</tr>
<tr>
<td>C1 X-ray diffraction</td>
<td>H. Kawata</td>
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<tr>
<td>C2 X-ray magnetic Bragg scattering by means of white X-rays</td>
<td>M. Adachi, H. Kawata</td>
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<td>BL-4</td>
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<td>A. Iida</td>
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<tr>
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<td>BL-6</td>
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<td>A Macromolecular crystallography by Weissenberg camera</td>
<td>N. Igarashi</td>
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<tr>
<td>B [TARA] Macromolecular crystallography by Weissenberg camera</td>
<td>N. Sakabe [TARA], M. Suzuki</td>
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<td>C1 X-ray diffraction at low temperatures</td>
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<td>C2 Accurate lattice spacing measurement</td>
<td>M. Ando</td>
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<tr>
<td>BL-7</td>
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<tr>
<td>B [RCS] Surface photochemical reaction and angle resolved photoelectron spectroscopy</td>
<td>H. W. Yeom [RCS], K. Ito</td>
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<td>C X-ray spectroscopy and diffraction</td>
<td>M. Nomura</td>
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<td>BL-8</td>
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<td>B [Hitachi] EXAFS</td>
<td>Y. Hirai [Hitachi], A. Yagishita</td>
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<tr>
<td>C1 [Hitachi] X-ray lithography</td>
<td>Y. Hirai [Hitachi], A. Yagishita</td>
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<tr>
<td>C2 [Hitachi] X-ray tomography and X-ray microscopy</td>
<td>Y. Hirai [Hitachi], A. Yagishita</td>
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### Experimental Stations

<table>
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<tr>
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<th>Facilities</th>
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<tr>
<td><strong>BL-9</strong></td>
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<tr>
<td>A</td>
<td>XAFS (under construction)</td>
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<td>I. Nishiyama [NEC], M. Nomura</td>
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<tr>
<td>C</td>
<td>[NEC] EXAFS and X-ray topography/diffraction</td>
<td>H. Kimura [NEC], M. Nomura</td>
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<td><strong>BL-10</strong></td>
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<tr>
<td>A</td>
<td>X-ray diffraction/scattering, crystal structure analysis</td>
<td>M. Tanaka</td>
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<td>B</td>
<td>XAFS</td>
<td>N. Usami</td>
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<tr>
<td>C</td>
<td>Small-angle X-ray scattering of enzymes, surface diffraction</td>
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<td><strong>BL-11</strong></td>
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<td>A</td>
<td>Soft X-ray spectroscopy</td>
<td>Y. Kitaima</td>
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<td>B</td>
<td>Surface EXAFS, soft X-ray spectroscopy</td>
<td>Y. Kitaima</td>
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<td>VUV spectroscopy (solid state)</td>
<td>H. Kato (until May '97)</td>
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<td>D</td>
<td>Angle-resolved photoelectron spectroscopy</td>
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<td>K. Ito (until May '97)</td>
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<td>VUV high-resolution spectroscopy</td>
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<td>XAFS</td>
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<td>A</td>
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<td>High pressure &amp; high temperature X-ray diffraction</td>
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<td>C</td>
<td>[NMC] Soft X-ray photoemission spectroscopy and XAFS</td>
<td>E. Shigemasa</td>
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<td>B</td>
<td>High-precision X-ray optics</td>
<td>K. Hirano</td>
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<td>C</td>
<td>General purpose (X-rays)</td>
<td>K. Hyodo</td>
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<td>A</td>
<td>Small-angle X-ray scattering of muscle and alloys</td>
<td>K. Hirano (until Mar. '98)</td>
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<tr>
<td>B1</td>
<td>White X-ray topography and X-ray magnetic Bragg scattering</td>
<td>H. Kamikubu (since Apr. '98)</td>
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<td>B2</td>
<td>Surface and interface diffraction</td>
<td>H. Sugiyama, H. Kawata</td>
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<td>High-resolution X-ray diffraction</td>
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<td><strong>BL-16</strong></td>
<td>(Multipole wiggler/Undulator)</td>
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<td>Y. Murakami</td>
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<td>A</td>
<td>[Fujitsu] XAFS</td>
<td>S. Komiya [Fujitsu], A. Iida</td>
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<td>B</td>
<td>[Fujitsu] photochemical vapor deposition</td>
<td>S. Komiya [Fujitsu], A. Iida</td>
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<tr>
<td>C</td>
<td>[Fujitsu] Grazing incident X-ray diffraction, X-ray fluorescence analysis</td>
<td>S. Komiya [Fujitsu], A. Iida</td>
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<tr>
<td><strong>BL-18</strong></td>
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<tr>
<td>B</td>
<td>Macromolecular crystallography (Weissenberg and Laue)</td>
<td>A. Yagishita (until May '97)</td>
</tr>
<tr>
<td>C</td>
<td>X-ray powder diffraction at non-ambient conditions</td>
<td>A. Kakizaki (since Jun. '97)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N. Watanabe</td>
</tr>
<tr>
<td></td>
<td></td>
<td>T. Kikegawa</td>
</tr>
</tbody>
</table>
### Experimental Facilities

#### Table 2 List of Experimental Stations at AR

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<thead>
<tr>
<th>Experimental Station</th>
<th>Spokesperson</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BL-19</strong> (Revolver undulator)</td>
<td>A. Kimura  [ISSP]</td>
</tr>
<tr>
<td>A [ISSP] Spin-resolved photoelectron spectroscopy (Mott detector)</td>
<td>A. Yagishita (until May '97)</td>
</tr>
<tr>
<td>B [ISSP] Spin-resolved photoelectron spectroscopy (SPLEED)</td>
<td>A. Kakizaki (since Jun. '97)</td>
</tr>
<tr>
<td>[ISSP] Soft X-ray emission spectroscopy</td>
<td>S. Shin  [ISSP]</td>
</tr>
<tr>
<td><strong>BL-20</strong></td>
<td>A. Kakizaki</td>
</tr>
<tr>
<td>A VUV spectroscopy</td>
<td>K. Ito</td>
</tr>
<tr>
<td>B [ANBF] White and monochromatic beam general purpose X-ray station</td>
<td>G. Foran  [ANBF], K. Ohsumi</td>
</tr>
<tr>
<td><strong>BL-21</strong> [Light Source Div.] Beam position monitoring</td>
<td>T. Katsura  [Light Source Div.]</td>
</tr>
<tr>
<td><strong>BL-27</strong> (Beamline for experiments using radioisotopes)</td>
<td>K. Kobayashi</td>
</tr>
<tr>
<td>A Radiation biology, soft X-ray photoelectron spectroscopy</td>
<td>K. Kobayashi</td>
</tr>
<tr>
<td>B Radiation biology, X-ray diffuse scattering</td>
<td>K. Kobayashi</td>
</tr>
<tr>
<td><strong>BL-28</strong> (Elliptical multipole wiggler/Undulator)</td>
<td>T. Koide</td>
</tr>
<tr>
<td>A VUV and soft X-ray spectroscopy with circularly polarized undulator radiation</td>
<td>T. Iwazumi</td>
</tr>
<tr>
<td>B Spectroscopy and scattering with polarized X-rays</td>
<td></td>
</tr>
<tr>
<td><strong>NTT</strong> Nippon Telegraph and Telephone Corporation</td>
<td></td>
</tr>
<tr>
<td><strong>TARA</strong> Tsukuba Advanced Research Alliance</td>
<td></td>
</tr>
<tr>
<td><strong>RCS</strong> Research Center for Spectrochemistry, The University of Tokyo</td>
<td></td>
</tr>
<tr>
<td><strong>ANBF</strong> Australian National Beamline Facility</td>
<td></td>
</tr>
</tbody>
</table>

**Spokesperson**

- A. Kimura  [ISSP]  
- A. Yagishita (until May '97)  
- A. Kakizaki (since Jun. '97)  
- S. Shin  [ISSP]  
- K. Ito  
- G. Foran  [ANBF], K. Ohsumi  
- T. Katsura  [Light Source Div.]  
- K. Kobayashi  
- K. Kobayashi  
- T. Koide  
- T. Iwazumi  
- H. Kawata  
- T. Iwazumi  
- T. Koide  
- X. Zhang  
- K. Hyodo  
- T. Kikagawa  
- K. Kanazawa  [Acc.Dept.]
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<tr>
<th>Branch Beamline</th>
<th>Acceptance Horiz. (mrad)</th>
<th>Type of Monochromator</th>
<th>Mirror</th>
<th>Photon Energy (keV)</th>
<th>Beam Size (H×V) (mm)</th>
<th>Photon Flux at Sample Position</th>
<th>Energy Resolution (ΔE/E) ×10¹⁰</th>
<th>Reference</th>
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<tbody>
<tr>
<td>BL-3A</td>
<td>4</td>
<td>Double Crystal Si(111) Sagittal Focusing</td>
<td>Collimating Focusing Mirrors (Fused Quartz)</td>
<td>4 - 25</td>
<td>100×5</td>
<td>−2</td>
<td>1 - 3</td>
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<td>BL-3C1/C2</td>
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<td>None</td>
<td>None</td>
<td>4 - 30</td>
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<td>4, 5</td>
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<td>−2</td>
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<td>4 - 35</td>
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<td>−2</td>
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<td>15×3</td>
<td>−2</td>
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<td>BL-4C</td>
<td>3</td>
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<td>Bent Cylinder</td>
<td>6 - 23</td>
<td>1.0×0.6</td>
<td>−5</td>
<td>8, 9</td>
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<td>BL-6A</td>
<td>4</td>
<td>Bent Si(111) (a = 0, 6.0°, 7.8°, 9.5°, 11.4°, 13.7°, 16.5°)</td>
<td>Bent Plane Fused Quartz</td>
<td>5 - 25</td>
<td>2.5×1</td>
<td>−2</td>
<td>10</td>
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<td>Double Mirror Fused Quartz Focusing</td>
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<td>1×10⁷/smm² (8 keV, 300 mA) (1×10⁷ when focused)</td>
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<td>Mirror</td>
<td>Photon Energy (keV)</td>
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<td>9×10&lt;sup&gt;5&lt;/sup&gt;/6mm&lt;sup&gt;2&lt;/sup&gt; Ge(111) (a = 8.0°)</td>
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## Experimental Facilities

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<th>Mirror</th>
<th>Photon Energy (keV)</th>
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<td>Pre-mirror Bent Cylinder Si Pt- &amp; Ni-coated Post-mirror Bent Plane Fused Quartz Pt- &amp; Ni-coated</td>
<td>2 - 10</td>
<td>2.4 × 0.3</td>
<td>3 × 10⁻³ (9 keV, 300 mA) Si(220) Pc - 0.5</td>
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<td>15 × 2</td>
<td>1 × 10⁻³ (14.4 keV) High-resolution Monochromator Nuclear Monochromator of Single Crystal ⁵²Fe,0 (777)</td>
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<td>5 × 10⁻⁹ Single Crystal Si(311) (α = 4° - 6°) Double Crystal Si (311)</td>
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Branch | Beamline | Acceptance | Type of | Mirror | Photon | Beam Size | Photon | Energy | Energy |
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References

## Experimental Facilities

### Table 4: VUV and Soft X-ray Beamline Optics

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<tr>
<th>Branch Beamline</th>
<th>Acceptance (mrad)</th>
<th>Type of Monochromator</th>
<th>Groove Density (l/mm)</th>
<th>Photon Energy (keV)</th>
<th>Beam Size (mm)</th>
<th>Typical Resolving Power (E/ΔE) and Photon Flux (/s)</th>
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<td>BL-7B (RCS)</td>
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<td>1m Seya-Namioka</td>
<td>2400</td>
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<td>1m Seya-Namioka</td>
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<td>5 3.6</td>
<td>6.65 m Off-Plane Eagle</td>
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<td>10⁵</td>
<td>3 - 5</td>
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<td>BL-20A</td>
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<td>3m Normal Incidence</td>
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<td>K = 0.55 – 2.2</td>
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<td>2200</td>
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<td>5000 – 10000</td>
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Table 5: Timetable of the Machine Operation in FY 1997.

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Legend:
- **PF**: PF ring
- **AR**: PF-AR
- **B**: KEKB
- **Machine Study**
- **Photobaking of Beamline**
- **Users Beam Time**
- **SR Use of AR**
- **Machine Tuning/Photobaking**

**Notes:**
- The timetable includes machine operation cycles for FY 1997.
- Each cycle includes a schedule for Linac 1, Linac 2, and Linac 3.
- Specific dates are marked with shaded boxes indicating different operations and maintenance activities.

**Experimental Facilities**
Experimental Facilities

Figure 1.
Operation Time of Photon Factory Ring

Figure 2.
Operation Time of PF-Accumulation Ring
2 Reconstruction and Upgrading of Beamline

2-1 BL-2A, Improved Performance of an Undulator Soft X-ray Station for 1.8-5keV

BL-2A, which was equipped with a double-crystal monochromator [1-3] to utilize high-order (3rd or higher) harmonics of the undulator #02, was modified in accordance with the reconstruction of the grazing-incidence monochromator station from BL-2B [4] to BL-2C [5].

Figure 1 schematically shows the layout of the beamline. Because the sample position has moved downstream by ~5.5 m to avoid interference with the optical components of BL-2C, a cylindrical mirror Mv has been introduced for vertical focusing in addition to another cylindrical mirror Mh for horizontal focusing. Both the mirrors are coated by Ni and the incident angles are 0.6°.

The electron beam emittance $\epsilon$ of the Photon Factory storage ring has been reduced from 130 nmrad to 37 nmrad since May, 1998. This increases brilliance of the synchrotron radiation, especially in the undulator source. Source size of the undulator radiation was sufficiently small even at $\epsilon = 130$ nmrad so that the measurable photon flux within a limited area near the center of radiation (Figure 2) can...
be compared with the calculated photon flux density (Figure 3). The peak intensity of the 5th harmonics has reached at ~2.8 times as much as before. On the other hand, the total photon flux in a rather wide area, which can be utilized by the two focusing mirrors for most experiments, has become ~1.5 times.

References


Figure 2.
Measured photo-current from a Ni plate. Only the center of the undulator radiation (gap = 32.9 mm) was passed by apertures whose acceptances are 60 mrad (horizontal) and 20 mrad (vertical).

Figure 3.
Calculated photon flux density at K = 1.7 [by the courtesy of Dr. K. Tsuchiya (Light Source Division)].
2-2 Improvement of X-ray Magnetic Scattering Beamline, BL-3C2

At beam line 3C, magnetic Bragg scattering using white X-rays is performed, making use of the small vertical emittance of electron beams. Since station 3C1, where the experiments had been mainly done before, has insufficient space for further development of this activity, a 4-axis diffractometer has been newly introduced at the end station, 3C2, and has been prepared for use. Thereby, the quality of the data has actually, been, greatly improved, despite the lower flux density of the incident beams.

Another big change is the installation of a double-crystal monochromator in front of the downstream shutter. Ducts and some components have also been remade so that both white and monochromatic beams can pass through to the end station, 3C2. The monochromatic X-rays will be utilized in the not distant future along with a phase-retarder system. This method of polarity reversal is not only helpful when the target is a hard magnetic material, but has also been recently found to be quite efficient with an enhancement of the polarization factor. We are also now planning to combine the diffractometer with a super-conducting magnet, for the preparation of samples which require higher magnetic fields and lower temperatures.

2-3 Experimental Hutch Remodeling of BL-10A

The hutch of BL-10A experimental station (inorganic single crystal structure analysis) was remodeled during the long shutdown of the Photon Factory ring in 1997. The 10A 4-circle diffractometer was installed in the small hutch on the carriage base which moved according to the Bragg angle of monochromator. Therefore, when we try to perform the diffraction experiment under extreme condition using such equipment as a cryostat, a heater or so on, the great difficulty was occurring because of the narrow work
Experimental Facilities

space. We extended the hutch to obtain enough work space around the diffractometer and to make the structural analysis experiments under extreme conditions easily perform.

The former small hutch was disposed and new one which covers both of the 4-circle diffractometer and its carriage base was built.

The size of the hutch is about $4 \times 2.5 \times 2.5$ m (Figure). Heat insulating materials were stuck on the wall and keep inside temperature constant. Beam line components, such as beam pipes and the $\gamma$-stopper, were reconstructed and the interlock system was refined.

This new hutch already has been used from November, 1997. The space around the diffractometer and sample became remarkably wide compared with the former. We can easily set up sample environment setting equipment and easily perform the crystal structure analysis experiment under extreme conditions, now.

2-4 BL-10C, A Renewed Solution X-ray Scattering Beamline

BL-10C has been renewed as a dedicated station for solution X-ray scattering experiments. Improvements of the beamline optics and of X-ray camera were made during a long shutdown in 1997 [1], and the renewed beamline was opened for users from January, 1998.
BL-10C was constructed in 1982 to serve experiments using focused monochromatic X-rays, and had optics comprising a double flat-crystal monochromator followed by a bent cylindrical focusing mirror[2]. Since this type of optics is still appropriate for accepting synchrotron radiation from the low-emittance ring, the optical system, itself, was conserved as before upon the renewal.

The bent cylindrical focusing mirror was renewed. The original mirror bender, which had a classical four-point bending mechanism and was manually operated, was replaced by a new one having an updated bending mechanism; also, a new reflecting mirror (Pt-coated fused quartz) was installed. The specifications of the mirror were modified so that the system could be operated at a lower glancing angle (7mrad) than that used before (8mrad). This alteration in the glancing angle resulted in the use of a 100cm long mirror having a cylindrical radius of 11.2cm and at a bending radius of 2290m.

The performance of the new mirror system is as follows. With an angular acceptance of 0.38 mrad (vertical) × 3.6mrad (horizontal), which is the practically maximum acceptance of the beamline, the throughput of the mirror is 5×10¹¹ photons/s for 8.4keV X-rays at 400mA ring current. This flux is at least 3-times higher than that
Experimental Facilities

Figure 1. New small angle X-ray scattering camera for BL-10C.

achieved with the old mirror. Also, the intensity of the beam at the sample position has been increased by a factor of 5-10, depending on the aperture size of the first collimator slit located downstream of the mirror. For example, with the typical aperture size of 0.8mm (v) x 15mm (h), photon fluxes on the order of 1×10^{11} photons/s are available at the samples. The size of the focal spot magnified at a 1:1 ratio was 0.64mm (v) x 2.4mm (h) by FWHM, while the theoretical value is 0.58mm x 2.0mm. This result reveals that the new mirror system works well as a focusing device.

The double Si(111) crystal monochromator was overhauled. The gear unit of the goniometer for the first crystal was replaced by a new one having a higher mechanical precision. The backlash of the goniometer in the scanning mode was suppressed to less than 0.002° for $\theta$-rotation. The first crystal right exposed to white radiation is cooled by circulating chilled water into the crystal holder. In order to enhance the cooling efficiency, the water-pass inside of the monochromator chamber was widened by exchanging tubes of 6mm diameter for ones of 8mm diameter. A decrease in the beam intensity due to thermal deformation of the first crystal, which used to be observed near to the full ring current (around 400mA), became not so severe that the adjustment of the first crystal to the second one on repeated occasions came not to be a crucial operation.

The X-ray camera in the experimental hutch was reconstructed (Figure 1). In order to secure smooth movements of the camera components on the bench, a steel bench and carriers containing linear ball bearings as moving guide were employed. Most of the components, i.e., sample slit, sample stage, X-ray stop and detector stage, became capable of being remotely driven by stepping motors. Consequently, the new camera became easier to manipulate. It has also become feasible to incline the camera chamber to the beam axis at an angle of up to 20°. This improvement made it possible to record scattering patterns of 4.4×10^{-2}<Q<5.5×10^{-1}Å^{-1} for a 2m camera length and 1.5×10^{2}<Q<2.10^{3}Å^{-1} for a 0.6m length.
2-5 BL-11A, Progress in the Commissioning of the Soft X-ray (70-1900eV) Station

As reported in the previous volume, BL-11A was reconstructed by a new grazing-incidence monochromator equipped with a varied-line-spacing plane grating (VLS-PG) [1,2].

In FY1997, two improvements concerning the beamline performance were achieved. The first one is the availability in a higher energy region. It has been clarified that highly pure soft X-rays up to 1900 eV are obtainable with a holographically recorded grating at the included angle of 176.2° (Figure 1). Although the resolving power is not so high because of the low groove density of the present grating (800 l/mm), some EXAFS spectra on Na, Mg, or Al K-edge were measured for the first time at the Photon Factory. Figure 2 shows an example spectrum of Al metal. A 1200-l/mm grating will be installed in

![Figure 1.](image1)

Spectral distribution of the monochromator with an 800-l/mm holographic grating at the included angle of 176.2°.

![Figure 2.](image2)

Al K-edge EXAFS spectrum of aluminum plate. The I₀ intensity was monitored by the photo-current from a gold-coated mesh.
Experimental Facilities

FY1998 to achieve higher energy resolution for the high energy region.

The other progress in FY1997 is the installation of a double-mirror system for harmonic rejection. It was clarified that typically 5-10% of the second- and third-order components exist in the low energy region. This is not negligible for electron-yield measurements especially on low concentration samples such as surface adsorbates. Thus a double-mirror system was designed and constructed, where two plane mirrors are arranged as shown in Figure 3. Incident angle is variable in the range from 1.5° to 10° by rotating the two mirrors around an axis at the symmetry center, which can keep the output-beam position fixed. The 130 mm long mirrors are made of silicon and halves of their surfaces are coated with MgF2. By sliding the mirror set along the rotation axis, bare silicon or MgF2-coated surface can be selected to reflect the SR beam. The mirrors can be removed away from the beam path, though the exit beam position becomes lower by 8 mm. Figure 4 demonstrates how the higher order harmonics are eliminated with this mirror system. For a very wide scan in the EXAFS measurements on C, N, or O K-edge, the cut-off energy must be varied during the measurements so that a computer program was prepared for the simultaneous scan of the incident angle of the double mirror and the grating by stepping motors. Figure 5 shows an example spectrum of such EXAFS measurements using this double-mirror system for a surface adsorbate CH3CN/Ni (111) [3].

Figure 3.
Schematic drawings (incident angles of 2° and 5°) of the optical path in the double-mirror system.

Figure 4.
Photoelectron spectra of a partially oxidized Si wafer measured with the Si double-mirror at incident angles of 1.5° and 4.95°.
References


2-6 Reconstruction of Solid State Spectroscopy Beamline, BL-11D

Beamline BL11D is used for photoemission measurements for both solids and solid surfaces. The designing specifications of the new beamline are as follows: monochromator type, negative incident-length valid deviation angle spherical grating monochromator; energy range, G1 200-1300eV, G2 50-700eV, G3 20-280eV, G4 10-90eV; resolution, 5000-10000; spot size, less than 0.5mm diameter; photon flux, $10^8$-$10^{10}$ photons/sec at 400mA ring current.

Figure 1. Top and side view of the focusing mirror chamber and the plane mirror/grating chamber.

Figure 5. N K-edge surface EXAFS spectrum (partial electron yield) of submonolayer adsorbed CH$_2$CN on Ni(111).
Figure 1 shows top and side views of the focusing-mirror chamber and the plane-mirror/grating chamber. In this beamline, four focusing mirrors have been used following the first mirror inside the shield wall. The basic design for the vacuum chambers and the five-axis motor-controlled alignment mechanism of the mirrors is the same that for four focusing mirrors, except for the mirror size, refraction direction and holder.

The scanning mechanism for changing the deflection angle and incident angle of the grating simultaneously is very complex. We usually use 3 motions: one rotation axis for the grating; one rotation axis and one linear translation axis or two linear motions for the plane mirror. To simplify the scanning mechanism we used an off-center rotation of the plane mirror shown in Figure 2 instead of two motions. This mechanism is simulate the half-angle motion.

All of the equipment was completed in the autumn of 1996. Unfortunately, the plane mirror hit the grating and the scanning mechanism became damaged. During a long shutdown in 1997 the scanning mechanism was fixed and a collision-protect system was installed. Although the plane mirror/grating chamber has four grating holders, there are only two gratings (G1 and G3) in it.

The exit photon energy of the monochromator has been calibrated by photoemission measurements at the Fermi level and the 4f core of a Au evaporated on a Si wafer at liquid-nitrogen temperature. The functions of the rotation angle of the grating and the plane mirror versus the photon energy were different from analytical calculations.

In the range of photon energy from 70 to 150 eV more than $10^{11}$ photons/sec were measured at a ring current 400 mA in a spot size of less than 1 mm$^2$ with a resolving power of approximately 2000. The wide range spectrum of photoemission measurements of Au shows its excellent higher order rejection rate. The ratio of the 1st to 2nd order signal of a Au valence band is $1/50$~$1/100$ in the range of photon energy from 30 eV to 80 eV, and the 2nd order signal has not been detected at greater than 100 eV.

The energy resolution of the monochromator has been tested by the photoelectron yield of nitrogen gas and rare gases. The total yield spectrum of N$_2$ at the N 1s is shown in Figure 3, where the width of the entrance slit is 30 µm and the exit slit is 20 µm. Because of a
mechanical problem, the minimum width of the exit slit is limited to more than 20 µm. And the motion of the scanning mechanism is quite unstable, so that the spectrum is scattered with data points.

2-7 Improvement of the Mirror Bending System of BL-15A

This report describes a mirror bending system and a reflecting mirror which have recently been installed at BL-15A.

The BL-15A station was designed for small-angle x-ray scattering experiments, and was commissioned in 1982 when the PF started operation. Since then it has been actively used by many user groups. The X-ray optical system of BL-15A consists of bent mirrors for vertical-beam focusing and a triangle-bent Ge(111) monochromator for horizontal-beam focusing, and realizes high-flux X-ray intensities (>10¹⁰ xph/s) sufficient for time-resolved measurements. The existing bent mirror system comprised two mirrors (non-coated fused quartz) of 70 cm long and a 1.5 m-long beam with a H-shaped cross-section on which the two mirrors were tightly clamped. The H-shaped beam is bent by the so-called “four points method” and the two mirrors clamped onto the H-shaped beam are expected to be bent simultaneously. The vertical beam size at the focal plane (9.1 m downstream from the mirrors) was 0.8 mm, which is about three-times larger than the expected values. The degradation of the beam focusing is larger than the expected values. The degradation of the beam focusing is attributed to an over bending of the H-shaped beam due to sagging because of gravity, resulting in a split focusing beam with two mirrors.

It is clear that the improvement of the emittance of the PF ring does not benefit with the existing bent mirror system; therefore, we have decided to replace it with a new system.

The newly installed mirror bending system was fabricated based on an “arm method” (Figure 1) by Toyama Co. Ltd. The advantage of the “arm method” over the “four-points method” is that 1) reverse bending is available, and therefore over bending of the mirror...
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Figure 1.
Bending mechanism of 1) the “four points” method, and 2) the “arm” method.

can be avoided, and 2) the effective length of the bent area along the mirror 1 x 10⁻⁴ to 1 x 10⁻⁵ torr with an identical vacuum pumping system.

The mirror has been fabricated, polished and Pt-coated by Cannon Co. Ltd. The size of the mirror, which is made from fused quartz, is 1000 mm long, 100 mm wide, and 60 mm thick. The surface figure is 3 - 5λ along the mirror and λ/2 - λ/4 across the mirror. The surface roughness is 10 Å rms. The surface of the mirror is coated with 1000 Å-thick Pt with a Cr thin layer (200 Å) sandwiched.

The mirror bending system was installed at BL-15A in January, 1998, when the PF ring was shutdown, and its characteristic performance was evaluated during the first run in the same month. For 8 keV x-rays, the largest incident angle possible for total reflection with the Pt-coated mirror is about 8 mrad. However, for the time being, the mirror has been set with an incident angle of about 4 mrad, which is about two-times larger than the previous set-up (2.4 mrad) with a non-coated mirror. The reason why the incident angle was set to 4 mrad instead of 8 mrad is that the existing set-up of the downstream beam pipes is not available for eluciating the beam with the 8 mrad incident angle to the mirror and that the 4 mrad incident angle is just enough for rejecting the third higher harmonics with the Ge(111) monochromator. The focus beam size in the vertical direction was measured as a function of the mirror bend using a CCD-based X-ray detector.

Figure 2.
Full width of the half maximum of the focus beam size as a function of the mirror bending. Measured integrated intensities are also plotted.
detector (Figure 2). The horizontal beam sizes are also plotted as references in Figure 2. The minimum vertical beam size in the full width of half maximum (fwhm) was 0.35 mm, which was slightly larger than the theoretical value (0.23 mm). We are going to evaluate the focus beam size again after the emittance of the PF ring is improved in May 1998. The theoretical focus beam size with the improved beam emittance is 0.11 mm.

Control of the mirror bending system is achieved with a stepping-motor controller (Tsuji-Densi Co., Ltd.).

2-8 Improvements of BL-15B for Surface X-ray Diffraction Experiments

BL-15B is to be used mainly for three purposes: white Laue topography, X-ray magnetic resonance scattering and surface X-ray diffraction. Since surface X-ray diffraction is a newly adopted S1 project, improvement of the experimental hutch and the beamline optics were necessary.

First, in the 1997 summer shutdown, the hutch was enlarged and separated into two rooms in tandem; the upstream room is BL-15B1 for white Laue topography and X-ray magnetic resonance scattering and the downstream room is BL-15B2 for surface X-ray diffraction. After that a double crystal monochromator and a bent cylindrical mirror, whose performances had already been verified at other beamlines, were installed.

The mirror can be removed from the X-ray beam path because a highly collimated beam is often required for experiments in BL-15B1. The monochromator is also removable because of white Laue topography.

The specifications of these optical elements are as follows:

Monochromator: Si (111)
- Energy range: 6keV to 20keV
- Mirror: Rhodium-coated silicon
  - Size: 1000mm x 100mm x 60mm
  - Radius of curvature: 56.87mm x 5553mm

The monochromator system was tested and adjusted in the last November. First the beam height drifted 0.3mm while the energy was being changed from 6keV to 20keV. Later the cause of the drift proved to be the heat of pulse-motors in the monochromator chamber. Now the drift is limited within 0.1mm by adjusting the motors. It was also confirmed that the deviation angle from an ideally parallel position of two crystals was less than 6 sec of arc in this machine time. In the following machine time, the mirror was adjusted. The shape of the beam at the focus point was measured by scanning a 1mm x 1mm slit vertically and horizontally. As shown in Figure 1, the measured result
Experimental Facilities

agrees well with that simulated by ray tracing method. The vertical and horizontal FWHMs are 0.63mm and 0.38mm, respectively. It was confirmed that the size and the position of the focused beam were almost independent on its energy. Finally the absolute flux of the beam was measured by an exactly calibrated PIN diode. As shown in Figure 2, more than $10^{11}$ photons / sec was guaranteed around the energy of 10keV.

The performance of the optical system in the BL-15B ensures the prospect for experiments of the S1 project. Now an ultra high vacuum chamber is being adjusted for the experiments.

Figure 1.
The shape of the beam at the focus point obtained by measurement and simulation.

Figure 2.
The absolute photon flux measured by PIN diode.
3 Beamlines under Construction and Planning

3-1 BL-1C, a New Beamline for Photoelectron Spectroscopy Experiments

The new beamline BL-1C is now being constructed as the PF special-proposal beamline for 97S1-002: “Formation processes and new properties of quantum nano-structures” led by Prof. M. Oshima of the University of Tokyo. This proposal is valid for five years starting from fiscal 1997.

The objectives of this project are to investigate the surface/interface properties of semiconductors/magnetic materials/superconductors by means of high-resolution photoelectron spectroscopy, and to elucidate the electronic properties of quantum nano-structures fabricated using nano-technologies.

In nano-electronics, which is a kind of meso-scopic electronics, very precise control techniques on the atomic scale are strongly required. For that purpose, a surface/interface control technique, atomic-layer epitaxy and etching, self-organization crystall growth and nano-lithography are now being developed. By utilizing these advanced techniques, quantum nano-structures can be formed, and novel properties in low-dimensional systems, such as quantum wires and dots, have been discovered. By combining semiconductor electronics with spin electronics, “meso-scopic spinics” is becoming a new key phrase for next-generation devices. In order to develop these advanced technologies, atomic-scale characterization is also required. Therefore, in this project various kinds of quantum nano-structures, such as InAs dots, GaN dots and ZnO quantum nanocrystals for laser diodes, MnAs, MnSb and GaMnAs magnetic quantum structures for T-bit storage devices, novel silicide optical devices for space technology, magnetic quantum wires for fundamental understanding of magnetic properties, giant magnetic resistance multilayered materials for spin valve transistors and storage system will be formed and in situ analyzed with angle-resolved photoelectron spectroscopy at low tempera-
Experimental Facilities

The "97S1-002" group consists of the Oshima Lab and the Tanaka Lab (Univ. of Tokyo), the Koinuma Lab and the Kawasaki Lab (Tokyo Inst. of Technology), the Akimoto Lab (Univ. of Tsukuba), Dr. H. Akinaga (JRCAT), the Hirose Lab (Space and Aeronautics Lab), the Nozaki Lab (Elec. Commun. Univ.), the Niwano Lab (Tohoku Univ.) and Dr. Y. Aiura (ETL).

So far, the optical design and mechanical design have been settled. The layout of BL-1C is shown in Figure 1. The optical parameters are listed in Table 1. A varied-spacing plane grating monochromator (VS-PGM) has been adopted to provide high-resolution monochromatic beams ranging from 20 eV to 250 eV without changing the exit-slit (S2) position. Construction of the beamline will be started just after the summer shutdown in July, 1998. In order to study the magnetic properties of magnetic quantum nano-structures, a circular polarization aperture (CPA) will be set between M0 and S1 for MCD measurements.

An in situ angle-resolved photoelectron spectroscopy system consisting of an ARUPS-10 chamber with LEED, a molecular-beam epitaxy chamber with RHEED and 6 K-cells, a Schottky contact chamber for silicide formation and a laser MBE mini-chamber is now being constructed, and will be set at the BL-1C end-station, probably at the end of 1998.

Table 1 Optical parameters of BL-1C

<table>
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<tr>
<th>Component</th>
<th>Position (m)</th>
<th>Type</th>
<th>Angle (°)</th>
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<td>Toroidal</td>
<td>86.5</td>
<td>32,6325</td>
<td>196.547</td>
</tr>
</tbody>
</table>

Figure 1. Layout of the BL-1C beamline.
Tsukuba Advanced Research Alliance (TARA) Sakabe Project is a cooperative effort involving industry, government and universities to pursue an understanding of the maintenance of life through a study of the crystal structure and functionality of basic biological materials. The experimental station of TARA was constructed at BL-6B and experiments there began in May, 1996. We have 45 members from 15 universities, 10 members from 5 government institutions and 90 members from 20 companies of which 14 have donated funding to the project. Thirty seven papers have already been published.

Since the number of members in the TARA Sakabe Project has increased extensively and a shortage of beam-time became a serious problem, the PF accepted the request from TARA Sakabe project to reconstruct BL-6C as a TARA station in Feb. 1998. BL-6C will be reconstructed from the end of June, 1998, in cooperation with PF members. This work is due to be completed in October, 1998.

BL-6C has been designed as a beamline for monochromatic macromolecular crystallography using a screenless Weissenberg camera and imaging plates. The beam-line is to be reconstructed downstream of the beam monitor, as illustrated in Figure 1. The BL-6C experimental hutch will be built downstream of BL-6B and will use the downstream wall of BL-6B as the front wall of the BL-6C hutch (Figure 1). The ceiling level of both BL-6B and BL-6C, is the same and computers and other equipment for the experiments will be installed there. Users can access the ceiling space using the stairs which are already in place at BL-6B.

The beam-line consists of a Pt-coated bent-plane Si single-crystal mirror and an asymmetrically cut Si (111) monochromator. The mirror and the monochromator are located at a distance of 21.0 m and 26.5 m from the source, respectively. The monochromator is located in the experimental hutch and is newly designed to provide a focused beam over a wide wavelength range with one crystal by simultaneous tuning
the asymmetry factor and the radius of curvature for focussing (a paper of the new type monochromator will be published elsewhere soon). The specifications of the mirror and the monochromator are as follows:

Mirror:
- Material: platinum-coated (1000 Å) silicon single crystal
- Size: 1000 x 100 x 50 mm³
- Radius curvature: ca. 3.5 km

Monochromator:
- Method: new type (see text)
- Material: Si (111)
- Maximum tilt cut angle: \( \alpha_c = 19.7° \)
- Minimum radius of curvature: \( R_0 = 37.9 \text{ m} \)

A fully automated (on-line) protein data-collection system[1], which is being developed by the Sakabe group supported by JSPS-RFTF96R 14501, will be installed in the station. This system consists of a Weissenberg-type camera, an imaging-plate reader equipped with multi-reading heads, which will be set at intervals of 90 mm, an imaging-plate eraser, and a cassette transportation table, as shown in Figure 2. A specially ordered large imaging-plate is fixed onto the inside of a movable cylindrical cassette, which has 36 small rectangular holes for the primary beam path at equal intervals along the circumference of the cylinder. The exposure area on the imaging-plate can be selected with upper and lower screens. After a diffraction pattern (maximum 36 frames) has been recorded on the imaging-plate, the cassette is automatically moved to the reader via the transportation table. Another cassette which has already been erased is transported from the eraser to the camera, and recording will start again while the first cassette images are being read. The total time for transportation, reading images, and erasing is designed to be shorter than 18 minutes. For 18 frames, where 2.88 Å resolution data will be collected using 1.0 Å X-rays, the time for reading and erasing a single frame will be 1 minute.

Reference
4 New Instrumentation

4-1 CCD X-ray Detector Coupled with Fiber-Optic Tapers for Macromolecules

We have been developing CCD X-ray detectors coupled with fiber-optic tapers for an X-ray diffraction study of macromolecules. The advantage of the CCD-based detectors involves a much higher duty-cycle ratio of the measurement, due to the shorter readout time of the CCD-based detectors compared with the imaging plate. With the conventional readout system of the imaging plate, the readout time is about 120 - 180 seconds, which is much longer than the typical exposure time (5 - 10 seconds) using synchrotron radiation. On the other hand, the readout time of the CCD detector is about 1 - 10 seconds, which is comparable to the exposure time.

Since the experimental stations for macromolecules at PF are usually over subscribed and fully booked by users, it is very important to increase the duty-cycle ratio of the detecting system by introducing CCD-based X-ray detectors to the stations.

A project to develop CCD-based X-ray detectors for macromolecules was started in 1994 in collaboration of PF and TARA project headed by Prof. Sakabe. The aimed specifications of the CCD-based detector are that: F1) the detective quantum efficiency should be comparable to that of the imaging plate, 2) the effective-area size is comparable to that of the imaging plate (200 mm x 250 mm), 3) the readout time should be negligibly short (less than 1 second) so as to increase the duty-cycle ratio, 4) the dynamic range is 4 orders of magnitudes, and 5) measurements by the CCD are automatically synchronized with the rotation of a specimen crystal. Special emphasis has been given to item 3), which makes our system design unique. In our system, a half-frame readout scheme of a CCD is adopted, in which a full-frame CCD is divided into two regions, the upper-half region as an image sensor and the bottom-half region as an image storage (Figure 1). The image recorded on the upper-half region of the CCD is transferred to the bottom-half region of the CCD within 2.048 ms. Then, the image transferred to the bottom-half region is readout to the computer within a time of 1.9 seconds, during which the next image is recorded in the upper-half region. Therefore, there is apparently no dead time imposed between two exposures, thus resulting in a 100% duty-cycle ratio of the measurements.

The basic module of our CCD detector consists of a thin phosphor sheet applied on an aluminized PET film, a high-transmittance fiber-optic taper and a half-frame cooled CCD (Figure 2). As the final goal, we aim to build a 18-module (3 x 6) arrayed CCD detector with an active area of 221 mm x 221 mm. In order to realize this final goal through R & D, we started with developing a single-module CCD
Experimental Facilities

detector in the first stage, and a $2 \times 2$ arrayed CCD detector in the second stage in due course. The half-frame CCD which we used in the single-module CCD has $512 \times 512$ pixels, and each pixel size is 24 microns x 24 microns (Hamamatsu S5466). Based on an evaluation of the performance characteristics of the single-module CCD system, the following basic parameters were chosen for arrayed CCD detectors: a demagnifying ratio of the fiber-optic taper of 3.2; type of phosphor, Gd$_2$O$_2$S: Tb, and thickness of the phosphor, 15 mg/cm$^2$. With the above parameters, a single X-ray photon incident to the detector creates 3.5 - 4.0 electron-hole pairs in the CCD. The readout noise of the CCD is about 8.0 - 8.5 electron rms., and the dark current of the CCD is 0.2 - 0.3 electron/s/pixel at -40. The measured DQE (detective quantum efficiency) of the single-module CCD detector is shown in Figure 3 together with the DQE of the imaging plate. The full width at half maximum (fwhm) is mm.

The $2 \times 2$ arrayed CCD detector uses four CCDs (Hamamatsu S5467) each of which has $1024 \times 1024$ pixels of 24 $\mu$m x 24 $\mu$m. Each CCD is individually cooled to -40°C by three stages of a Peltier device, and is installed in a vacuum chamber to minimize the heat conductance due to convection. Experiments to evaluate the performance characteristics are now being carried out.

Figure 1.
Schematic drawing of a single-module CCD X-ray detector coupled with a fiber-optic taper.

Figure 2.
Measured DQE (detective quantum efficiency) of a single-module CCD X-ray detector together with that of the imaging plate.
4-2 Structure Analyses Under High Pressure and Low Temperature at BL-18C

BL18C became to be a dedicated station for the high pressure experiment by moving the activity of the group of materials science to BL6C. Accordingly, we made a new experimental stage for the diamond-anvil cell (DAC) including a system for the low temperature high pressure experiment.

DAC is the very compact high pressure device which generates pressure in a microscopic sample area by applying a load through the diamonds. Though the pressure is attained more than a 100GPa, the volume which realizes such ultra-high pressure is limited to the area where a diameter and thickness are slight of less than 40 µm and 20 µm respectively. Therefore, the high pressure diffraction experiment became possible by using the synchrotron radiation and a high-performance detectors such as an Imaging Plate, X-ray CCD and so on. This new DAC stage was made by SIGUMA KOKI Co., Ltd., and installed in BL18C last winter. The stage is designed in the size of 1200mmL×750mmWX755mmH to introduce it in the experimental hutch. It was composed by the following four parts; i.e. DAC stage, detector stage, microscope stage and base table.

DAC is placed on a pulse motor drive XYZ-motion stage to adjust a sample in DAC to the X-ray collimated by a pinhole slit of several ten microns size. Here, the direction X is parallel to the incident X-ray, Y and Z are perpendicular to it. The stage and the pinhole slit are mounted on the base table with YZ θ adjustable mechanism to align the X axis and the pinhole to the incident beam direction.

The IP (two kinds of sizes of 250mm and 400mm) and an X-ray CCD (an effective diameter φ200mm) are used to record diffraction patterns. Both detectors are being installed on a slide table with a 500mm length stroke which is monitored with linear-encoder precisely.

A microscope optical device is installed to adjust the sample position for pressure measurement and X-ray diffraction. The pressure is determined by measuring the pressure induced wavelength-shift of the ruby fluorescence. In order to excite the fluorescence an Ar laser is applied to the ruby minute particle (around one micron size) that it was put on the sample part of DAC. The microscope is mounted on a pulse motor drive stage, and through the optical fiber ruby fluorescence is led to the monochromator system which equipped on the experiment hutch roof. Laser light is introduced with the optical fiber conversely in the microscope head from the generator put on the roof. The CCD is fitted to the microscope head in order to monitor the sample. Before the X-ray exposure, the microscope is placed on the incident X-ray axis to adjust the sample position and measure the pressure, it focuses on the sample inside DAC and the ruby minute particle. After this procedure, the microscope takes shelter to the pos-
Experimental Facilities

A handy remote controller is used for operating in and out of the microscope head and the movement of the detector stage inside the experiment hutch. Collimators having $25, 40, 60, 80, 100 \mu m$ sizes pinhole slit are provided for the various experiments. When the finest collimator of $25 \mu m$ was used for the synchrotron radiation of a energy $20keV$, exposure time was sufficient for one hour with the powder Nb sample at the pressure around $150GPa$. (Dr.Takemura of National Institute for Research Inorganic Materials) However, it took about five hours for the experiment with HCl sample at $60GPa$ by the same X-ray. (Dr.Fujihisa of National Institute of Materials and Chemical Research) The trial operation of the new DAC stage has been almost finished at the moment in March, excepting the low temperature experimental system and an X-ray CCD. After the calibration procedures are finished, the whole system will be open to users.

4-3 BL-16A2 Station with a 6-Circle Diffractometer

A 6-circle diffractometer (Huber 5020) was installed in the BL-16A2 station in 1997. A new control system has been introduced, and some accessories have been prepared. Test experiments have been carried out in order to check and improve the system, and the work is almost finished. This station will be open from the autumn beamtime in 1998.

Since this beamline has a 53-pole multi-pole-wiggler, it will be dedicated for diffraction experiments to detect a very small signal, like that in magnetic diffraction. The system in this station is very similar to
that in BL-4C, which is a bending-magnet beamline. These stations should be chosen according to the experimental purpose. Although the diffractometer is powerful for detecting the precise profile of diffuse scattering, very small superlattice points and so on, they are not suitable for crystal structure analysis, due to the slow motion.

Figure 1 shows a side view of the diffractometer, which stands on the base. Beam alignment is easily carried out by remote control of the motors of the base. A cryostat or furnace can be installed on the Phi-circle, which is attached to the off-center Chi-circle. The temperature can be controlled from 7 K to 1300 K. A polarimeter can also be installed on a 2-Theta arm for a polarization analysis of the scattered beam, which is effective in diffraction from spin and orbital ordering.

The control system is shown in Figure 2. A control software, SPEC, was chosen because it is popular around the world. The measurements and simple data analysis can be done on a workstation. Since the monochromator and the temperature controller are also controlled by SPEC on this computer, the energy and temperature dependence can be automatically measured by some prepared macros.

In this station an 18 kW X-ray generator is installed. This X-ray generator is used with the 6-circle diffractometer, when synchrotron X-rays are not available. All setup with cryostat of furnace, can be finished by this X-ray generator before synchrotron experiment to save the beamtime.

**Figure 2.**
Control system for diffraction experiment
5 Slow Positron Facility

An intense pulsed positron beam source, built at the 3rd beam switchyard of the PF Injector Linac, was used to measure the time-of-flight (TOF) spectra of orthopositronium (o-Ps) emitted from a SiO$_2$ surface, to generate a continuous beam utilizing Penning-trap electrodes and to perform brightness-enhancement measurements of slow positron beams.

The PF linac is now undergoing a reformation process relevant to the KEKB project. With this project, we must relocate our slow-positron facility to the 1.5-GeV point of the KEKB J-linac. There are two primary-electron beam sources for the relocated slow-positron facility; the 1.5-GeV beam of the KEKB linac and the 45-MeV beam from a test linac. The nominal beam power of the 1.5-GeV beam is 0.75 kW (an energy of 1.5 GeV, charge of 10 nC, pulse length of 10 ps and pulse-repetition rate of 50 pulse/s). Since the injection interval of the J-linac for the KEKB rings might be relatively short, a dedicated linac for only slow positrons use (the slow positron generator linac i.e. test linac) was installed utilizing the remnants of the J-linac upgrade plan. An average beam power of 1 kW can be expected from latter linacs.

Figure 1 shows the relocated new slow positron facility, which is located at the 1.5 GeV point of the KEKB J-linac. It comprises beam lines for the primary electron beams, an electron-positron converter-moderator assembly, a slow-positron beam-transport line and several experimental stations. The primary electron beam is injected into the electron-positron converter. The electrically extracted slow positron beam is directed by a 30-m long beam transport line with an axial magnetic field of 100 G to an experimental hall. Ion pumps and SORB-AC cartridge pumps, which sorb active gases with a non-evaporable getter material, were used to attain an ultra-high-vacuum condition. A high-voltage station capable of applying 60 kV was installed in order to vary the energy of the positron beam. A device controller, combining a personal computer and a programmable sequence con-
troller through optical fiber, has been adopted to control the monitors
and power supplies at a high-voltage potential. As for the positron
beam monitors, we introduce retractable positron monitors using
phosphor screens with tandem microchannel plate by which images of
the positron beams were observed.

We are now waiting for beamtime to detect slow-positrons with
the positron beam monitor mentioned above at the end of the beam-
transport line.

Reference
Materials Science Forum Vol. 255-257 (Trans Tech Publications,
Switzerland, 1997) pp.689-691.

Figure 1.
Slow-positron source and a magnetically guided beam transport line at the 1.5-GeV point of the KEKB J-
linac. Slow positrons are guided through the beam transport to the experimental hall at the inner side of the
KEKB ARC section.
6 PF AR Project

6-1 Time-Resolved Protein-Crystallography Beamline

Biological activity is invariably accompanied by changes in structure in which atoms, groups of atoms or domains which move very rapidly under near-physiological conditions. However, macromolecular crystallography provides space- and time-averaged structure alone. Here, time-resolved crystallography in less than a microsecond is planned in order to clarify the mechanism of the reaction of biological macromolecules by combining a single-bunch operation of PF-AR and diffraction experiments.

Figure 1 shows the final plan view of the experimental halls for the PF-AR project. The shaded areas correspond to the present buildings of an experimental hall (NE-experimental hall), or that which can be reconstructed to an experimental hall (N-experimental hall). The hatched areas correspond to new experimental halls which can be constructed after the PF-AR project is completely approved. Figure 2 shows an enlargement of the North experimental hall. This experimental hall was originally constructed for colliding experiments for high-energy physics. There is no radiation shield, and also the level of the floor is almost 4 m lower than that of the ring components. If we reconstruct this building as a synchrotron-radiation experimental hall, it is necessary to construct the radiation shield and an experimental floor before starting preparations of the beamline components. In this figure, the black-shaded region corresponds to the new radiation shield and the red part corresponds to the experimental floor. The radiation shield is made of concrete block, whose thickness is 70 cm. We will start construction of these shields and the floor at the beginning of September, 1998 and finish the by the end of December, 1998. The blue-marked parts correspond to the beam line components: Insertion device, front end, beam shutter, X-ray mirror,
monochromator, and experimental hutch, respectively. The insertion device will be an in-vacuum X-ray undulator, and the X-ray optics will be the combination of a focusing X-ray mirror and an X-ray monochromator. These details are being designed.

6-2 Light Source

Before operation of the AR as a dedicated light source, "PF-AR" was started, and several improvements had been carried out. Concrete walls and lead panels for radiation shielding were installed between the PF-AR tunnel and the direct beam-transport line to the B-Factory. They ensure not only safe access to the PF-AR during the injection period of the BF, but also safe access to the beam-transport line during the PF-AR storage mode. In addition, the shielding between the tunnel and the south experimental hall was reinforced for a higher stored beam current. Stabilization of the cavity temperature is essential for reliable operation of the ring, especially in the summer. A precise temperature controller of cooling water for the RF cavities [1] was completed.

Recommissioning the PF-AR after a long shutdown was begun by
a joint team including the Accelerator Laboratory and the Light Source division in March, 1998. Since the ring was left as it was for more than one year after the final operation for machine development, we encountered several problems, especially in reopening the vacuum system. Unfortunately, no machine time for users was available in the 1997 fiscal year, because the schedule was delayed and it took almost half a month to start the machine up and to clean the vacuum system with the aid of the stored beam.

As described in a previous Photon Factory Activity Report [1], we have a plan to improve the present ring, which was designed as a booster of TRISTAN in order to make it suitable as a dedicated X-ray source. Although the essence of the plan has not been changed, we organized a task force to refine the design as well as the schedule of the project. The main parameters and the lattice of the proposed ring are shown in Table 1 and Figure 3.

The author would like to express his appreciation to all members of the AR commissioning group of the Accelerator Laboratory who have been devoting themselves to starting up the AR.

**Experimental Facilities**

**Figure 3.**
Lattice of the PF-AR

**Table 1.**
The time spectrum of the transmission light of the shutter.
ACCELERATORS
OPERATIONS,
RESEARCH
AND
DEVELOPMENTS
1 PF Storage Ring

1-1 Summary of the Storage Ring Operations

The PF electron storage ring was operated according to the operation program after nine months improvements for high brightness project. The ring improvements started in January of 1997 and successfully finished at the end of September in 1997. On the first of October in 1997, we began commissioning of the improved ring without in-situ baking. We adopted the old optics, i.e., about 130nmrad optics, because it is sure that we could re-start operation smoothly and accumulate the integrated beam current in only one-month commissioning. On the fourth of November in 1997 we could begin autumn user run with the emittance of 130nmrad. Initial beam current was 400 mA, the product of beam current and beam lifetime $I \cdot \tau$ was 205A-min, and beam was injected every eight hours a day. On the first of December in 1997, it was increased to 400A-min and the integrated beam current of 400A-hr. On the first of April in 1998, it reached 500A-min at 1000A-hr. We changed the operation optics to low emittance mode and the user run with high brilliance started on the 13th of May in 1998.

The operation statistics during this fiscal year are shown in Figures.1 to 4, and Table 1. Difference between operation time and user scheduled time is more and injection interval is shorter, and the both were based on commissioning after upgrading working on high brilliance project.

Table 1 Statistics of the storage ring operation during fiscal year 1997 (from Apr. 1997 to Mar. 1998)

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<td>--</td>
<td>626.0</td>
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<tr>
<td>Average current in T</td>
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<tr>
<td>Number of injections</td>
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<td>--</td>
<td>215</td>
</tr>
<tr>
<td>Interval between injections</td>
<td>10.2</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

Figure 1. Operation Times of the storage ring.
Accelerators

Figure 2. Rate of failure time of the storage ring operation.

Figure 3. Average stored currents and injection intervals.

Figure 4. Plot of $I \cdot \tau$

1. Vent for reducing beam emittance
2. Rearrange magnet system
3. MPW16
4. Vent for positron injection
5. Renovation of the rf-cavity for reducing beam instabilities
6. MPW15
7. EMPW29
8. New VW14
9. New LI
10. Thermal insulation
11. Low I operation
12. Single bunch test 36GeV final run
13. Vent for isolation valves, RPO
14. New lines
15. VW4 chamber
16. ISR chamber, isolation valves with rf shield
17. Water leak (absorber for V4 radiation)
18. Optical system, Feedback system
19. Blocker feedback cavity
20. B01 mirror, B04-06 scraper
21. B04 mirror absorber
22. B13, 11, 12, 14, 16, 11 renewal
23. Electrons operation
24. Damped cavity
25. Improvement for low emittance
1-2 High Brilliance Project

1-2-1 Low-emittance Operation

The low emittance optics was studied in parallel to the users operation, by utilizing the machine study time assigned on every Monday.

The emittance is shown in Figure 5 as a function of the horizontal phase advance of the new normal cells. The emittance has a minimum at 135 degree. A tracking study showed that, as the phase advance is increasing, the dynamic aperture gets smaller[1]. Thus,

![Figure 5](image.png)

Figure 5.
Beam emittance as a function of the horizontal phase advance of the normal cell. The blue line is for the case of normal cells only. The red line is for the whole ring.
 Accelerators

Figure 6.
Tune Diagram. We could store 400 mA beam at the green area. We could store a few mA beam at the yellow area, without the sextupoles but still cannot inject with the sextupoles on.

We started the low emittance operation at 90 degree. Then we increased the phase advance step by step as shown in Figure 6.

We could store a 400 mA beam for the phase advance between 90 degree and 125 degree. The design emittance for 125 degree optics is 30 nm-rad. We tried to store a beam at 135 degree, but we still cannot. The main reason of this seems to be a small dynamic aperture. A further study will be done in near future by utilizing a dynamic aperture measurement system [2].

In Table 2, the results of the low emittance operation are summarized. From a beam size measurement [3], the horizontal emittance was estimated to be 29 nm-rad for the 125 degree optics, that is very close to the design value, 30 nm-rad and is not so far from the minimum emittance of the new lattice, 27 nm-rad. As for the vertical emittance, a preliminary measurement by using an interferometer was carried out. The result suggests a XY coupling of about 1%.

The beam lifetime was somewhat shorter than expected. In the low emittance optics, the gas scattering and the Touschek effect have almost same beam loss rate [4]. Since the ring vacuum is still not recovered completely, the gas scattering lifetime is shorter than expected at present. By continuing the operation, this will be gradually improved. Touschek lifetime, which was estimated from the observed lifetime in single bunch operation, is also shorter than expected. This is most likely because of the smaller X-Y coupling than 2% that we had assumed in the design report [4].

| Table 2. Summary of the low emittance operation |
|-------------|-------------|-------------|
| design goal | achieved    |
| Emittance   | 27 nm-rad   | 29 nm-rad*  |
| XY coupling | < 2%        | —1%*        |
| Max. Beam Current | 400 mA | 400 mA |
| Beam Lifetime | 40 hr | —12 hr (29 nm-rad) |
|               | ( @ 300 mA ) | —20 hr (36 nm-rad) |

Note; * These values were obtained for the 125 degree optics.
An undulator spectrum was measured at a beam line both for old and new optics. The measured intensity change agreed well with the calculation.

References

1-2-2 Magnet System

In April 1997, new quadrupoles and sextupoles were transported and installed in the normal cell sections. As the first stage of the alignment, all these magnets were aligned with a precision of better than 1 mm, that was just enough for the vacuum chamber installation. In parallel to the vacuum works, power cables, interlock signal cables and cooling water pipes were connected. After completing these works, all the magnets were aligned with a precision of 100 µm rms.

Running tests and the polarity checks of the magnets were started soon after the alignment. Developments and running test of the control program were followed. Until the end of September 1997, all the necessary works were completed and the magnet system was ready for the beam.

1-2-3 Vacuum System

Fabrication and improvement of the beam ducts were continued from FY 1996 in parallel with pre-baking of the completed ones. Every beam duct was pre-baked in our facility and filled with dry nitrogen until the installation to the ring. After rough alignment of the magnets, the beam ducts were installed one by one. First priority of positioning is given for the BPM, which was mechanically mounted on the quadrupole magnet within accuracy of 100 µm. Other components such as photon stopper and BA gauge were mounted in the duct after pre-baking as well as the beam duct.

During the exposure of the installed vacuum ducts to the atmosphere, the dry nitrogen gas was always flowing through the ducts. Almost whole ring was exposed to the atmosphere more than once during the shutdown, and about half of the whole ducts including all ducts of the normal-cell sections were replaced by new or improved ones.
The ring ducts were evacuated section by section which was isolated by gate valves. The evacuation of the last section started at the beginning of September 1997. The averaged pressure of the ring became $2 \times 10^{-7}$ Pa just before the start up of the operation on 1 October. The averaged pressure was mainly determined by the pressure at the normal-sections where the local pressure was higher than that at the other sections roughly by one order. No bake-out was took place after the installation, except for the section where the RF cavities installed. The operating pressure of the ring is determined mainly by the photon stimulated desorption process due to the synchrotron radiation. In the beginning of the ring operation, the outgassing was very large and the beam was stored as high current as possible not so far as every local pressure exceeded $1 \times 10^{-6}$ Pa in order to degas the ring. After 1A·h of operation, the outgassing rate decreased enough to continue the degassing at 500 mA of initial current. The sublimation pump was refreshed whenever the pumping speed went down.

Since the distribution of the pumps and the pumping speed along the ring were almost same as before, the same pressure has to be achieved in the ring. The history of the averaged pressure of the ring is shown in Figure 7, where the operation time is represented by time-integrated stored current. The operation time of 1A·h is equivalent to averaged photon dose of $3.89 \times 10^{22}$ photons/m. The pressure quickly decreased with the operation as expected. Abrupt decrease of the stored current due to dust trapping was observed during the first stage.
of the operation. The beam lifetime was expected to be slightly longer than before if the pressure was same. The change of the lifetime is also shown in the figure. The lifetime increased inversely proportional to the pressure. However it was shorter by factor 2-3 than expected, though the required pressure was achieved. The behavior suggests as if the actual acceptance was smaller than expected. The degradation of the lifetime is partly explained by the Touschek effect. It is, therefore, suggested that the emittance coupling became smaller than expected due to precise alignment of the magnets. The user mode operation started at the operation time of 210 A·h. Pressure and lifetime reached to $1 \times 10^6$ Pa/A and 500 A·min in March 1998, respectively. No serious dust trapping was observed during user mode operation.

During the high-current operation with the low emittance optics, the large outgassing due to the heat-up of the duct components was observed. Local pressure was high especially in the sections where a number of surface irregularities such as flange gap remained. The beam lifetime was restricted to a short value by the Touschek effect and this large outgassing. The Touschek effect became more effective because of the small beam size in the low emittance optics. The large outgassing due to the heat-up is decreasing speedly.

There are 48 BA gauges around the ring and seven cold cathode gauges along the beam transport line to measure the local pressure. Those readings were monitored and displayed by a personal computer. The necessary time for monitoring was eight second per one scan. Accompany with the renovation of the beam ducts, the monitoring system was improved in order to be compatible with new data acquisition system of the ring and to be speeded up for the real-time monitoring. The necessary time is reduced below one second in the new system and each datum is transferred to the data-channel server of the ring every second. The real-time monitoring can be possible also on a universal network.
1-2-4 New Beam Position Monitor

The new BPM system comprises electrostatic pickup units, a signal-processing system, digitizing unit and timing system[1]. The pickup units for the normal-cell sections were doubled in number and these 42 new-type pickup units had four button-type electrodes and had been mounted on newly fabricated vacuum chambers. There were also 23 old-type units unchanged, to the amount of 65 BPMs in total. The whole BPM location in the upgraded PF ring was shown in Figure 8. As for the signal-processing system, the circuit units are to be distributed in 12 local control racks around the ring. The beam position signals from the pickup electrodes are transmitted to the processing system and at the front end of the system, one of the signals is selected by PIN diode switches. The detection signals are multiplexed and digitized in the VME module situated near the controlling computer. The timing signals to switch the electrode and to digitize the detection signal were originated from the timing system and sent to the electrode switching units and digitizing unit by the optical fiber.

After the calibration of the electrical offsets of the pickup units [1], the beam ducts were installed in the ring. Each pickup unit was fixed directly to the end of the quadrupole magnet. The setting error of each pickup unit was measured and recorded in order to correct the measured beam position. In parallel with the installation, the wiring of the signal cables and timing cables were carried out.

In the commissioning of the new BPM system, the switching period was set to the 250 µs and beam position measuring time was 10 ms. This measuring time was limited by the synchrotron frequency of about 30 kHz which changed the beam position during the electrode switching. The display and storage of the beam position data was performed at every 1 s by averaging 100 measurements.
1-2-5 New Feedback System

A fast global feedback system was installed to the ring in order to stabilize vertical orbit movements, and its performance has been tested [1]. The system that consists of 65 beam position monitors and 28 correctors is designed to suppress the beam position fluctuation due to the building vibrations with the spectral range up to 20 Hz. The whole closed orbit distortion is measured and excitation currents of the correctors are calculated with the singular value decomposition (SVD) method using floating-point DSPs on a VME system every 10 ms.

Figure 9 shows the closed orbit distortion (COD) relative to the standard orbit of the PF-ring. The solid line shows the COD measured just after the injection and the dashed line shows the COD at eight hours after the injection. The two graphs on the right side and those on the left side are the COD with/without the global feedback, respectively. The two graphs on the bottom are the drifts of the beam position at the BPM #50. As seen in the figures, the drift of the orbit is completely suppressed. The 3D plots of the vertical beam motion is shown in Figure 10. The feedback system was turned off at 52 min and the kick angle of all correctors were set to be zero. It is clearly seen that the beam fluctuation starts as soon as feedback was turned off. The excursion of the beam at the BPM #50 is shown in Figure 11. When the feedback is turned off, the beam excursion due to the temperature change of the magnet cooling water is observed. In this case, the variations in the water temperature was about 0.1 to 0.3°C and its period is about 10 minutes.

Figure 9.
Change in COD without feedback (upper left) and with feedback (upper right) in eight hours. The peaks at the BPM #11 and #47 are due to the trouble of the electrodes. Lower left and right graphs show the position change at BPM #50.
Accelerators

The global feedback system works quite well to suppress the vertical beam fluctuation up to 0.3 Hz. At present, the system bandwidth is limited by the LPF to avoid the synchrotron oscillation. If we can remove the LPF (if the synchrotron oscillation is suppressed) and optimize the PID coefficient, the feedback bandwidth will be improved up to 50 Hz.

Reference


Figure 10.
Vertical beam motion with and without global feedback.

Figure 11.
Beam motion at BPM#50.
1-2-6 Measurements of Beam Size by the Use of SR Interferometer

In the high brilliant configuration (105° lattice) of PF ring, the estimated beam sizes are 263 µm in the horizontal (BL-27) and 81 µm (BL-21) in the vertical directions (2% coupling is assumed) at the source point. Because of the diffraction effect of light, it is difficult to measure such a small beam size with the conventional imaging method using the visible light. The synchrotron radiation (SR) interferometer[1] has a good sensitivity for measurements of the small beam size. The principle of the measurement by means of the spatial coherency of the light is previously reported[2]. We apply this technique to the measurement of both the vertical and the horizontal beam sizes at PF ring.

Figure 12. Observed vertical interferogram taken at double-slit separations of 10 mm.

(a) Vertical Beam Size Measurement at BL21

The interferogram for the vertical direction was measured at BL21. A result of observed interferograms is shown in Figure 12. Under the assumption of a gaussian distribution for the beam profile, we can evaluate the rms beam size from the degree of spatial coherence obtained from the visibility of the interferogram. The beam size \( \sigma_v \) is given by Eq. (1)

\[
\sigma_v = \frac{\lambda \cdot f}{\pi \cdot D \cdot \sqrt{2 \ln(\gamma)}}
\]

where \( \lambda \) denotes wavelength of SR beam, \( f \) denotes distance from the source point to the double slit of interferometer, \( D \) denotes distance between the two slits, and \( \gamma \) denotes visibility of interferogram. Visibility of observed interferogram is 0.792, then result of the beam size is 63.4 µm.
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(b) Horizontal Beam Size Measurement at BL27

The absolute value of the complex degree of spatial coherence for horizontal direction was measured at BL27 with the double-slit assembly rotated by 90°. The interferogram was measured by changing the distance between the two slits from 2.5 mm to 5.3 mm. The observed interferograms and the absolute value of the complex degree of coherence are shown in Figures 13 and 14, respectively.

Figure 13.
Observed horizontal interferograms taken at double-slit separations of 2.5 mm.

Figure 14.
Absolute value of the complex degree of spatial coherence in the horizontal plane. The dots denote measured values of $|\gamma|$ and the solid line denotes the best-fit value of 268 $\mu$m.

In the measurement of the spatial coherence of the SR beam in the horizontal direction, we must take into account the effects of field depth. The configuration of the measurement in the horizontal direction is shown in Figure 15. Two effects are introduced due to the field depth. The first one is an effect of curvature of the trajectory in the bending magnet, and the second one is an imbalance between the intensities of the two modes of light that illuminate the double slit of
the interferometer, as shown in Figure 15. Then $|\gamma|$ will be given by Eq. (2)

$$\gamma = \sqrt{2 \cdot I_1(\phi) \cdot I_2(\phi)} \cdot \left( \int f(x) \cdot g(\phi) \cdot \rho \cdot (1 - \cos(\phi)) \cdot d\phi \right)$$

where $g$ denotes the angular distribution of the SR beam in the horizontal plane as a function of observation angle $\phi$, $I_1$ and $I_2$ denote intensities of the two modes of the light that illuminate double slit of the interferometer, $f$ denotes the beam profile distribution, $\rho$ denotes the bending radius. The first part in Eq. (2) represents the imbalance between the intensities of the two modes of light and the last parts represent the effect of curvature of the trajectory. In this calculation we assumed a gaussian distribution for both the beam profile $f(x)$ and the angular distribution of the SR beam $g(\phi)$. By fitting Eq. (2) to the observed $|\gamma|$, we can obtain the rms beam size in the horizontal direction. The result of such a fit is also shown in Figure 14, and we obtained a horizontal beam size of 268 $\mu$m.

The estimated horizontal beam sizes from the designed emittance are 263 $\mu$m (using design values of energy spread and measured $\beta$ and $\gamma$-functions). The observed beam size in the horizontal direction agreed with the estimated one. From the observed vertical beam size, we can evaluate vertical and horizontal emittance coupling of 0.81%.

Figure 15.
Geometrical configuration of the horizontal beam size measurement.

References

1-2-7 Refinement of the Kicker Magnet System

Recently, the traveling-wave type kicker (TW-kicker) magnet is often used to produce a pulse bump orbit in the injection system. In
In order to realize a short rise time kicker pulse, we developed the epoxy-resin insulated 6.5Ω TW-kicker system with a line pulser power supply [1]. But the TW-kicker has the difficulty in the insulation for high voltage pulse. Our developed TW-kicker often breaks its insulation of epoxy-resin around 20 kV (sometimes about 15 kV). This insulation problem was also reported in Ref.1. To improve this problem without reducing the output of TW-kicker, we adopted the totally-reflection concept for the system. The totally-reflection concept was developed and tested to increase the output twice as much [2]. A block diagram of our design for totally-reflection type TW-kicker system is shown in Figure 16. The totally-reflected pulse is produced by the shortage of the output lead. The summation of the input and the totally-reflected pulse makes the strength of the magnetic field peak twice as much, too. In Figure 17, the resultant pulse shapes measured by the current transformer (Pearson 110A) at the input and output lead of the TW-kicker is shown. The totally-reflected pulse is seen clearly, and total height of the pulse becomes twice. The magnetic field output measured by a single-turn search coil is shown in Figure 18. The pulse length is about 1.6 µs. Since the revolution time of the PF ring is 0.624 µs, the magnetic field remains its 20% of the peak value at the second turn of the injected beam. In spite of the remaining field that makes the magnetic bump of 3.4 mm height for the second turn of the injected beam, we have enough aperture for the injection. The new type kicker system will be installed during the summer shutdown in 1998.

Figure 16.
A block diagram of the totally-reflection type TW-kicker system.

Figure 17.
The resultant pulse shapes measured by the current transformers at the input and output lead.
References


1-2-8 Operation of New RF Damped Cavities

Two of four cavities working in the Photon Factory (PF) storage ring were replaced with the new damped cavities during the summer shutdown in 1996 and were successfully operated during the user run in the autumn. The remaining two cavities were replaced with new ones during the long shutdown scheduled for the reconstruction for the low emittance configuration of the PF ring in 1997.

The damped structure rf cavity has been developed for two low emittance electron/positron storage rings. One is a high brilliance configuration of the PF storage ring. The other is a third generation VUV-SX synchrotron radiation source which is a future project of the University of Tokyo. For these storage rings, the coupled-bunch instability due to higher-order-modes (HOM’s) in rf cavity is a serious problem when a stable beam with high current is required.

The damped cavity which we developed has large beam duct, a part of which is made of an SiC microwave absorber. The HOM’s propagating out from the cavity through the beam duct are expected to be damped by the SiC part (Figure 19).

The nominal operating voltage of the cavity system is 1.5 to 1.7 MV for both the PF ring and the VSX ring. In case of the PF ring, four
Accelerators

Figure 19. Schematic view of the damped cavity. The unit is in mm.

Cavities are used. Therefore the nominal gap voltage per cavity is about 0.4 to 0.45 MV. Taking into account the reduction of Q-value of 10% for the actual cavity, the gap voltage requires the power of about 30 kW to be dissipated in the cavity. The value of the wall loss of 150 kW which is the maximum input power that we achieved has large safety margin and operational flexibility.

The high power model cavity was manufactured at Keihin Product Operations of Toshiba Corporation. The main part of the cavity was made of class1-OFHC copper which had been treated with Hot Isostatic Press (HIP) before. The cooling-water flow of 200 l/min is available with a pressure drop of 0.4 MPa. The cavity has two beam ports and four side ports for an input coupler, a movable tuner and two fixed tuners. U-light seal gaskets are adopted as rf contacts between each port and the attached equipment. The input coupler was newly designed being based on that for the 508 MHz APS cavity of TRISTAN ring, KEK. We changed the shape of the top of coaxial line where a coupling loop is placed and optimized the positions of the short plates of the rectangular waveguide and the coaxial line in order to obtain low reflection for 500 MHz. The movable tuner is the similar type to that used in the PF cavity. The fixed tuner is a cylindrical copper block with an ICF-flange to pad the port of the cavity. Two fixed tuners are attached to the bottom port and the side port of the cavity. These fixed tuners are used for the frequency shift of HOM’s by properly choosing the length of the copper block. As mentioned above, HOM’s whose frequencies are above the cutoff frequency of the beam duct propagate out to the beam duct and absorbed by SiC. HOM’s below the cutoff frequency of the beam duct still remain in the cavity with high Q-values. However, these can be detuned so as not to introduce any coupled-bunch instability. This frequency shift method, using two fixed tuners to detune the HOM’s, was first developed at the Photon Factory. The unloaded Q of the accelerating mode was 39500 with all equipment described above attached. The shunt impedance of the accelerating mode was estimated to be 6.9 MΩ. The SiC is made by Toshiba Ceramics Co. Ltd. and the trade name is CERASIC-B which is fabricated by sintering in an argon atmosphere under normal pressure. The dimension of the SiC is an inner diameter of 140 mm, an outer diameter of 160 mm and a length.
of 150 mm. The resistivity of the SiC was about 50 $\Omega$cm in the frequency range of 1–5 GHz. The SiC is fixed inside the copper duct by shrink-fit process. The copper duct has a water cooling channel on the outer surface. Since the SiC has good thermal conductivity of 100 W/mK, the temperature rise of the SiC duct is negligible under the usual operation of the PF ring.

Figure 20.
New damped cavities installed in the ring.

Figure 20 shows the cavities installed in the ring. Between two cavities, an evacuation chamber is placed which has two 400 l/s ion sputter pumps, two Titanium sublimation pumps, three vacuum gages and a quadrupole residual gas analyzer. The base pressure was $10^{-6}$ Torr after baking. Conditioning of these cavities was carried out in both CW and pulse modes. An rf power of up to 90 kW (CW) and 120 kW (pulse) was put into the cavities during the conditioning. The operation of the new cavities during the first beam storage after the installation is reported in Ref. 1. The operation of the ring started on Oct. 3 in 1997. The scheduled user run started on Nov. 4. Figure 21 shows the change of vacuum pressure at the cavity section where two new cavities were installed. The elapsed time in the figure does not include the scheduled shut down period. The vacuum pressure ranged around $10^{-8}$ Torr at first, however, decreased to $10^{-11}$ Torr range about one month after. At present, the vacuum pressure at the cavity section is below $10^{-9}$ Torr at a stored current of 400 mA, the nominal stored current in user run. Figure 22 shows the number of beam dump which took place during the operation from Oct. 3 in 1997 to Mar. 20 in 1998. Roughly speaking, the rf trip (shown in black bars in Figure 22) takes place only once or twice a month.

The detuning of the HOM’s was quite successful. We could not detect any coupled-bunch instability due to the HOM’s of cavities at the present operation point. However, the weak longitudinal coupled-bunch instabilities are still observed. They might be due to the compo-
Accelerators

Figure 21.
Change of vacuum pressure at the cavity section.

Figure 22.
Number of beam dump during beam storage.

Reference

1-2-9 Insertion Devices

All insertion devices of the PF storage ring (U#02, MPW#13, MPW#16, Rev#19, EMPW#28) were aligned in the summer of 1997 accompanied with the re-alignment of the magnets for the high brilliance project. During the reconstruction of the ring, EMPW#28 was put aside from the ring in order for the ring components to be transported into the ring and it was re-installed in July, 1997.

Before the start of the user operation in November 1997, the correction current data for all insertion devices had been taken for the independent tuning. To acquire these data, the new BPM system was
used for the horizontal correction and the four Photon-BPMs (BL04, 06, 12, 21) were used for the vertical correction. Using the new BPM data through the Data Channel (DCh), the data acquisition for the independent tuning was done more efficiently and reliably. The total time for the studies was shortened to nearly half comparing with the previous system and the accuracy of the orbit correction was better than 5 µm at each BPMs. For the operation of the high brilliance optics, we used the new BPM data for the horizontal and vertical correction. The number of BPMs used for the acquisition of the correction data was three for each direction. The four Photon-BPMs (BL04, 06, 12, 21) were used only for the check of the correction. This data acquisition system for the independent tuning will be unified to the new control system of the insertion devices during 1998.

The operation of the new control system[1] only partly for a multipole wiggler, MPW#13, started at the beginning of February in 1998. This system allows users to change the gap of MPW#13 where they do experiment and whenever they want in the user-run. Every time that the gap is changed, the logging data are saved in the database. The current gap can be seen with a web browser at any time.

About one month later, the operation of the new control system was stopped for some troubles and the control system was changed to the old one. Some troubles were caused by a few bugs in both a computer code for the control system of MPW#13 and a routine related to the DCh[1] which is data storage in the server computer. It was planned that these bugs were fixed during the short shutdown for the maintenance in March 1998 and then the new control system of MPW#13 started again.

The renewal of control system for two other insertion devices (U#02 and EMPW#28) are still under way.

Reference

1-2-10 Control System

The control system of the PF storage ring is under renewal construction. A replacement from old system to new one is gradually performed as keeping the storage ring in operation. In a first stage of a series of upgrades, the new control system of the magnet power supplies[1] was completed and has been successfully operated from October, 1997.

The operator console of the magnet power supplies was replaced from a touch screen to a window-based graphical user interface. Figure 23 shows a schematic view of the new operator console system. Various graphical objects such as buttons, switches and poten-
Accelerators

Figure 23. Schematic view of operator console system.

Figure 24. Example of control screen.

Meters for inputs and lights, meters and numerical value fields for outputs are prepared in workstations for operator consoles. These input/output objects have "plugs" to communicate with application softwares. We placed input/output mediator processes between objects and application processes. These mediators exchange data with application processes by TCP/IP protocol, so console processes are able to control any application processes distributed through a network. Application level user interfaces to operator consoles are very simple, because mediator processes absorb differences in handling various input/output objects. Application programmers use only several simple service routines as shown in Table 3 to communicate with input/output objects on operator consoles. We used VAPS (from Virtual Prototypes corp.) as GUI tool to develop object oriented control screens. Figure 24 shows an example of control screen.
Renewals of the control systems for such as the rf system and pulse magnets, which are still using old minicomputers, are in proceeding. The replacement of whole control system will be completed in March, 1999.

Table 3 User interface routines for console objects.

<table>
<thead>
<tr>
<th>Name</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>csl_opn</td>
<td>open communication port to console</td>
</tr>
<tr>
<td>csl_cls</td>
<td>close communication port</td>
</tr>
<tr>
<td>csl_put</td>
<td>send data to output object</td>
</tr>
<tr>
<td>csl_get</td>
<td>receive data from input object in blocking mode</td>
</tr>
<tr>
<td>csl_get_a</td>
<td>receive data from input object in non-blocking mode</td>
</tr>
</tbody>
</table>

Reference


1-3 Developments and Machine Studies

1-3-1 Measurements of Coherent Beam Centroid Motion due to Octupole Magnetic Fields

In order to measure the coherent beam centroid motion, single-bunch electron beam was excited horizontally by a fast kicker [1]. The beam position was measured over 16000 turns using a turn-by-turn beam-position monitor [2]. The initial beam position was controlled by the kicker voltage to be about 5 mm at a center of a long straight section ($\beta x = 5$ m). The initial stored beam currents were set to be in the range from 0.5 to 10 mA. The resolution of the position measurement was less than 0.08 mm at a current of more than 3 mA, but over 0.16 mm at a current of 0.5 mA. The eight octupole magnets [3] were excited in the current range from -1.0 to +1.0 A. The horizontal chromaticity was kept to be positive during the measurements with the
Figure 25. The horizontal beam centroid motions measured at stored beam currents of 0.5 mA (a,b and c) and 10 mA (d,e, and f) are shown as a function of time represented by the turn numbers. The octupole currents are settled at +1.0 A (a and d), 0.0 A (b and e), and -1.0 A (c and f).

The coherent centroid motion rapidly damps in the zero or the negative polarity of the octupole currents for both currents of 0.5 and 10 mA. This behavior is nonlinear smear. On the other hand, two different behaviors are observed between 0.5 and 10 mA in the positive polarity; one is a rapid damping for 0.5 mA, and the other is much slower damping for 10 mA. Former behavior is nonlinear smear, but latter one is head-tail damping, whose phenomena were also observed at TRISTAN Main Ring[4]. However, these phenomena seemed to be so strange for us, because the head-tail damping has occurred in the positive polarity of the octupole currents in spite that it has never occurred in negative polarity at a current of 10 mA. Now we are going to understand the phenomena through theoretical approach in detail [5].

References
A bunch-by-bunch beam diagnostic system which consists of a high speed light shutter and an optical beam detector has been developed. Since the open/close time of the shutter is comparable to the bunch spacing of 2 ns, it is capable of picking out the light pulses from a particular bunch in a bunch train. The selected pulses can be analysed with conventional optical beam diagnostic methods in order to measure beam properties of the individual bunch.

The schematic diagram of the high speed light shutter is shown in Figure 26. A pockels cell is placed between two polarization filters whose polarization angles are perpendicular to each other. The incident light can pass through the shutter while a high voltage pulse is applied to the cell because the cell rotates the polarization plane of the light. Since the time response of the cell is fast enough, the operation speed of the shutter is determined by the rise/fall time of the pulser. The pulser generates pulses with a width (FWHM) of about 1.5 ns, which is shorter than the bunch spacing of PF ring (2 ns), and a height of 550 V. We operated the shutter with a repetition rate of 534 kHz, which corresponds to the frequency of 3-revolutions in PF ring (1.60 MHz / 3 = 534 kHz), in considering the maximum repetition of the pulser (600 kHz).
We installed the shutter in BL-21 and observed the time structure of the light passed through the shutter using the photon counting method in the multi-bunch mode. The result is shown in Figure 27. In the figure, peaks show count rates of photons from successive 3 bunches. The count rate of the central peak, which corresponds to the selected bunch, is about 300 times larger than those of others although an electron number in each bunch is almost equal. The fact shows the shutter works properly, namely, it is capable of picking out a particular bunch in the bunch train in the multi-bunch mode.

Then we tried to observe the betatron oscillation of the individual bunch. The light passed through the shutter is focused on a photodiode using a lens with a focal length of 100 mm. If the image is focused on the edge of the sensing area of the photodiode, the amplitude of the output signal varies with the betatron oscillation because the image moves with the transverse motion of the bunch. The avalanche photodiode (Hamamatsu, S2381) with a frequency response of 1 GHz was used, and its output was observed by a spectrum analyzer. Figure 28 shows the result of the experiment when the betatron oscillation was excited by the RFKO method. The middle peak in the figure corresponds to the betatron upper sideband (about 500 kHz) of the repetition rate of the shutter (500 kHz + 534 kHz = 1034 kHz). The betatron oscillation of a particular bunch in the bunch train was detected by the optical method.

Alignment of the optical system was done and basic performance of the system was checked using the avalanche photodiode. However, dependence of the tune on the bunch position in the bunch train was measured using a photomultiplier (Hamamatsu, H6779) because the sensitivity of the avalanche photodiode was not sufficient for this purpose. A bunch train with 250 bunches was stored, and tunes of bunches were measured with RFKO method. During the measurement several bunches were lost due to over-excitation of the RFKO and the train was split into 4 bunch trains. Figure 29 shows tunes of several bunches in the 1st and 4th bunch train. In these
trains, the tunes of the head bunches are slightly larger than those of the rears. A bunch current of each bunch was 1.3-1.9 mA. Influence of a deviation of bunch currents on the tune measurement is negligible because the beam current dependence on the tune is $-2 \times 10^{-4}/\text{mA}$ \cite{1}. Therefore, the tune difference is quite significant. However, we need more systematic investigations to understand the origin of the phenomenon.

![Graph showing tunes of several bunches in the 1st and 4th bunch train.](image)

**Reference**

\cite{1} PHOTON FACTORY ACTIVITY REPORT, 1990

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**1-4 Storage Ring Specifications**

This section contains principal specifications of the 2.5 GeV PF ring to provide quick and handy information for users and machine physicists. These parameters are under the new low-emittance lattice. Detail specifications and parameters are available through the World Wide Web (URL: http://pinecone.kek.jp/pfring.status.html).
Accelerators

Figure 30.
Beam transport line.

Figure 31.
Ring lattice components.
Figure 32.
Synchrotron radiation spectra.
Brilliance of radiation vs. photon energy for the insertion devices (U#02, MPW#13, VW#14, MPW#16, Revolver#19 and EMPW#28) and the bending magnet (Bend) of the PF, and for the insertion device (EMPW#NE1 and MPW#NE3) of the AR. The name of each source is assigned in Table 10. Several insertion devices have both undulator and wiggler modes, which are denoted by U or W, respectively. The spectral curve of each undulator (or undulator mode of multipole wiggler) is a locus of the peak of the first harmonic within the allowable range of K-parameter. Spectra of Revolver#19 are shown for four kinds of period lengths.

Figure 33.
Vacuum system components.
Figure 34.
Beam position monitors.
Table 4  Insertion devices
Calculated spectral performances of the bend source and 6 insertion devices at the Photon Factory. E/\text{l}: beam energy and current, \( \lambda_u \): period length, N: number of periods, L: length of undulator or wiggler, \( G_y \) (\( G_x \)): minimum vertical (horizontal) gap height, \( B_y \) (\( B_x \)): maximum vertical (horizontal) magnetic field, P: pure configuration, H: hybrid configuration, S.C.: superconducting magnet, \( \sigma_x \), \( \sigma_y \): horizontal or vertical beam size, \( \sigma_x' \), \( \sigma_y' \): horizontal or vertical beam divergence, \( K_y \) (\( K_x \)): horizontal (vertical) deflection parameter, \( \varepsilon/\varepsilon_c \): photon energy of the first harmonic (critical energy in the case of bend source or wiggler), D: photon flux in unit solid angle (photons/s \cdot \text{mrad}^2 \cdot 0.1\%\text{b.w.}) , B: brilliance (photons/s \cdot \text{mm}^2 \cdot \text{mrad}^2 \cdot 0.1\%\text{b.w.}), P_T: total radiated power, \( \frac{dP}{d\Omega} \): power in unit solid angle. Different operating modes of undulator and wiggler are denoted by-U and-W, respectively.

<table>
<thead>
<tr>
<th>Name</th>
<th>E/\text{l} GeV/nA</th>
<th>( \lambda_u ) cm</th>
<th>N ( L ) m</th>
<th>( G_y ) (( G_x )) cm</th>
<th>( B_y ) (( B_x )) T</th>
<th>Type of magnet</th>
<th>( \sigma_x ) mm</th>
<th>( \sigma_y ) mm</th>
<th>( \sigma_x' ) mrad</th>
<th>( \sigma_y' ) mrad</th>
<th>( K_y )</th>
<th>( \varepsilon/\varepsilon_c ) keV</th>
<th>D</th>
<th>B</th>
<th>P_T kW</th>
<th>( \frac{dP}{d\Omega} ) kW/\text{mrad}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bend</td>
<td>2.5/300</td>
<td>0.96</td>
<td>0.39</td>
<td>0.059</td>
<td>0.186</td>
<td>0.013</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td>3.60E+13</td>
<td>2.48E+14</td>
<td>0.061</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U#02</td>
<td>2.5/300</td>
<td>6.60</td>
<td>3.6</td>
<td>2.8</td>
<td>0.4</td>
<td>H(NdFeB)</td>
<td>0.42</td>
<td>0.042</td>
<td>0.084</td>
<td>0.008</td>
<td>2.25</td>
<td>0.2</td>
<td>1.12E+17</td>
<td>9.73E+17</td>
<td>0.68</td>
<td>2.9</td>
</tr>
<tr>
<td>MPW#13-W</td>
<td>2.5/300</td>
<td>18.13</td>
<td>2.5</td>
<td>2.7</td>
<td>1.5</td>
<td>H(NdFeB)</td>
<td>0.86</td>
<td>0.019</td>
<td>0.117</td>
<td>0.018</td>
<td>25</td>
<td>6.2</td>
<td>9.70E+14</td>
<td>8.83E+15</td>
<td>6.48</td>
<td>2.53</td>
</tr>
<tr>
<td>MPW#13-U</td>
<td>2.5/300</td>
<td>18.13</td>
<td>2.5</td>
<td>2.7</td>
<td>1.5</td>
<td>H(NdFeB)</td>
<td>0.86</td>
<td>0.019</td>
<td>0.117</td>
<td>0.018</td>
<td>2</td>
<td>0.108</td>
<td>8.09E+15</td>
<td>6.94E+16</td>
<td>0.041</td>
<td>0.19</td>
</tr>
<tr>
<td>VW#14</td>
<td>2.5/300</td>
<td>5</td>
<td>5</td>
<td>S.C.</td>
<td>0.58</td>
<td>0.036</td>
<td>0.083</td>
<td>0.01</td>
<td></td>
<td>20.8</td>
<td></td>
<td>3.63E+13</td>
<td>2.75E+14</td>
<td>0.32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MPW#16-W</td>
<td>2.5/300</td>
<td>12.26</td>
<td>3.12</td>
<td>1.9</td>
<td>1.5</td>
<td>H(NdFeB)</td>
<td>0.42</td>
<td>0.042</td>
<td>0.084</td>
<td>0.008</td>
<td>16.8</td>
<td>6.2</td>
<td>7.69E+14</td>
<td>6.71E+15</td>
<td>8.17</td>
<td>4.84</td>
</tr>
<tr>
<td>MPW#16-U</td>
<td>2.5/300</td>
<td>12.26</td>
<td>3.12</td>
<td></td>
<td></td>
<td>H(NdFeB)</td>
<td>0.42</td>
<td>0.042</td>
<td>0.084</td>
<td>0.008</td>
<td>2</td>
<td>0.163</td>
<td>3.17E+16</td>
<td>2.72E+17</td>
<td>0.12</td>
<td>0.56</td>
</tr>
<tr>
<td>Revolver#19</td>
<td>2.5/300</td>
<td>5.46</td>
<td>2.3</td>
<td>3</td>
<td>0.28</td>
<td>H(NdFeB)</td>
<td>0.85</td>
<td>0.056</td>
<td>0.088</td>
<td>0.008</td>
<td>1.3</td>
<td>0.639</td>
<td>7.86E+16</td>
<td>2.60E+17</td>
<td>0.21</td>
<td>1.42</td>
</tr>
<tr>
<td>2.5/300</td>
<td>7.232</td>
<td>2.3</td>
<td>3.1</td>
<td></td>
<td></td>
<td>H(NdFeB)</td>
<td>0.85</td>
<td>0.056</td>
<td>0.088</td>
<td>0.008</td>
<td>2.7</td>
<td>0.176</td>
<td>3.29E+16</td>
<td>1.08E+17</td>
<td>0.42</td>
<td>1.44</td>
</tr>
<tr>
<td>2.5/300</td>
<td>10.23</td>
<td>2.3</td>
<td>3</td>
<td>0.54</td>
<td></td>
<td>H(NdFeB)</td>
<td>0.85</td>
<td>0.056</td>
<td>0.088</td>
<td>0.008</td>
<td>5</td>
<td>0.0437</td>
<td>9.63E+15</td>
<td>3.01E+16</td>
<td>0.77</td>
<td>1.52</td>
</tr>
<tr>
<td>2.5/300</td>
<td>16.414</td>
<td>2.3</td>
<td>3</td>
<td>0.62</td>
<td></td>
<td>P(NdFeB)</td>
<td>0.85</td>
<td>0.056</td>
<td>0.088</td>
<td>0.008</td>
<td>9.5</td>
<td>0.0078</td>
<td>1.28E+15</td>
<td>3.22E+15</td>
<td>1.01</td>
<td>1.06</td>
</tr>
<tr>
<td>EMPW#28-W</td>
<td>2.5/300</td>
<td>16.12</td>
<td>1.92</td>
<td>3(11)</td>
<td>1(0.2)</td>
<td>P(NdFeB)</td>
<td>0.58</td>
<td>0.036</td>
<td>0.083</td>
<td>0.01</td>
<td>15(1)</td>
<td>4.1(90%)</td>
<td>2.30E+14</td>
<td>1.71E+15</td>
<td>2.13</td>
<td>0.35</td>
</tr>
<tr>
<td>EMPW#28-U</td>
<td>2.5/300</td>
<td>16.12</td>
<td>1.92</td>
<td></td>
<td></td>
<td>P(NdFeB)</td>
<td>0.58</td>
<td>0.036</td>
<td>0.083</td>
<td>0.01</td>
<td>1(1)</td>
<td>0.182(99%)</td>
<td>1.36E+16</td>
<td>9.98E+16</td>
<td>0.02</td>
<td>0.064</td>
</tr>
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</table>
Table 5  General parameters of the storage ring.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Energy</td>
<td>2.5 GeV (max 3 GeV)</td>
</tr>
<tr>
<td>Initial stored (multi-bunch) current</td>
<td>400 mA (max 500 mA at 2.5 GeV)</td>
</tr>
<tr>
<td>(single bunch)</td>
<td>65 mA (max 100 mA)</td>
</tr>
<tr>
<td>Emittance</td>
<td>36 nm · rad (horizontal)</td>
</tr>
<tr>
<td></td>
<td>~0.4 nm · rad (vertical)</td>
</tr>
<tr>
<td>Circumference</td>
<td>187 m</td>
</tr>
<tr>
<td>RF frequency</td>
<td>500.1 MHz</td>
</tr>
<tr>
<td>Injection</td>
<td>2.5-GeV Linac</td>
</tr>
<tr>
<td>Beam lifetime</td>
<td>30 h (at 300 mA)</td>
</tr>
<tr>
<td></td>
<td>1 · τ ≥ 9 A · h (at 300 mA)</td>
</tr>
<tr>
<td>Vacuum pressure</td>
<td>≤5 × 10⁻⁷ Pa (at 300 mA)</td>
</tr>
<tr>
<td></td>
<td>5 × 2 × 10⁻⁸ Pa/A (at 300 mA)</td>
</tr>
<tr>
<td></td>
<td>~3 × 6 × 10⁻⁹ Pa (at 0 mA)</td>
</tr>
<tr>
<td>Insertion devices</td>
<td>Superconducting vertical wiggler 5T</td>
</tr>
<tr>
<td></td>
<td>60 period undulator K= 1.78 ~ 0.1</td>
</tr>
<tr>
<td></td>
<td>26 period multipole wiggler/undulator 1.5T ~ 0.04T</td>
</tr>
<tr>
<td></td>
<td>Four way revolver type undulator</td>
</tr>
<tr>
<td></td>
<td>14 period multipole wiggler</td>
</tr>
<tr>
<td></td>
<td>Elliptically polarized multipole wiggler</td>
</tr>
<tr>
<td>SR channels</td>
<td>SR experiment 22</td>
</tr>
<tr>
<td></td>
<td>Beam diagnosis 3</td>
</tr>
</tbody>
</table>

Table 6  Beam parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal tune νₓ</td>
<td>9.62</td>
</tr>
<tr>
<td>Vertical tune νᵧ</td>
<td>4.29</td>
</tr>
<tr>
<td>Momentum compaction factor α</td>
<td>0.061</td>
</tr>
<tr>
<td>Natural chromaticity εₓ</td>
<td>-12.5</td>
</tr>
<tr>
<td></td>
<td>-12.3</td>
</tr>
<tr>
<td>Bunch length σₓ</td>
<td>1.0 cm</td>
</tr>
<tr>
<td>Transverse damping time</td>
<td>7.8 msec</td>
</tr>
<tr>
<td>Longitudinal damping time</td>
<td>3.9 msec</td>
</tr>
<tr>
<td>Energy spread</td>
<td>7.3 × 10⁻¹</td>
</tr>
<tr>
<td>Radiation loss</td>
<td>400 keV</td>
</tr>
<tr>
<td>Table 7 Principal parameters of the accelerator system.</td>
<td></td>
</tr>
<tr>
<td>-----------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>Magnet system</td>
<td></td>
</tr>
<tr>
<td>Bending</td>
<td>number of magnets</td>
</tr>
<tr>
<td>28</td>
<td>1</td>
</tr>
<tr>
<td>Quadrupole</td>
<td>74</td>
</tr>
<tr>
<td>Sextupole</td>
<td>32</td>
</tr>
<tr>
<td>Octupole</td>
<td>4</td>
</tr>
<tr>
<td>Vertical steerers</td>
<td>24</td>
</tr>
<tr>
<td>Fast vertical steerers for global orbit FB</td>
<td>30</td>
</tr>
<tr>
<td>Backleg windings</td>
<td></td>
</tr>
<tr>
<td>on bendings for horizontal steerers</td>
<td>28</td>
</tr>
<tr>
<td>on sextupoles for vertical steerers</td>
<td>28</td>
</tr>
<tr>
<td>on sextupoles for skew quadrupoles</td>
<td>4</td>
</tr>
<tr>
<td>on sextupoles for field compensation</td>
<td>32</td>
</tr>
<tr>
<td>Electronic shunts on quadrupoles</td>
<td></td>
</tr>
<tr>
<td>for optics matching and tune compensation</td>
<td>34</td>
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<tr>
<td>RF system</td>
<td></td>
</tr>
<tr>
<td>Number of RF stations</td>
<td>4</td>
</tr>
<tr>
<td>Number of klystrons</td>
<td>4 (180kW/klystron)</td>
</tr>
<tr>
<td>Number of RF cavities</td>
<td>4 (single cell cavity)</td>
</tr>
<tr>
<td>Shunt impedance</td>
<td>27.6 MΩ (four cavities)</td>
</tr>
<tr>
<td>Unloaded Q</td>
<td>39000</td>
</tr>
<tr>
<td>Total power dissipated in cavity wall</td>
<td>10.5 kW</td>
</tr>
<tr>
<td>Total cavity gap voltage</td>
<td>1.7 MV</td>
</tr>
<tr>
<td>Synchrotron frequency</td>
<td>20 kHz</td>
</tr>
<tr>
<td>Vacuum system</td>
<td></td>
</tr>
<tr>
<td>Main pumping system</td>
<td></td>
</tr>
<tr>
<td>pump</td>
<td>pumping speed</td>
</tr>
<tr>
<td>SIP(Sputter Ion Pump)</td>
<td>128 l/sec</td>
</tr>
<tr>
<td>DIP(Distributed Ion Pump)</td>
<td>150 l/sec</td>
</tr>
<tr>
<td>Ti sublimation</td>
<td>...</td>
</tr>
<tr>
<td>NEG(Non-Evaporable Getter)</td>
<td>...</td>
</tr>
<tr>
<td>total effective pumping speed = 2 × 10^6 l/sec (for CO)</td>
<td></td>
</tr>
<tr>
<td>Rough pumping system</td>
<td></td>
</tr>
<tr>
<td>TMP(Turbo Molecular Pump)</td>
<td>300 l/sec</td>
</tr>
<tr>
<td>Measurement</td>
<td></td>
</tr>
<tr>
<td>B-A gauge</td>
<td>number</td>
</tr>
<tr>
<td>mass filter</td>
<td>4</td>
</tr>
<tr>
<td>cold cathode gauge</td>
<td>16 (for baking)</td>
</tr>
<tr>
<td>Sector gate valve</td>
<td>number</td>
</tr>
<tr>
<td>all metal with RF shield</td>
<td>4</td>
</tr>
<tr>
<td>viton seal with RF shield</td>
<td>11</td>
</tr>
<tr>
<td>Injection system</td>
<td></td>
</tr>
<tr>
<td>Septum magnet</td>
<td></td>
</tr>
<tr>
<td>name</td>
<td>Septum I (S1)</td>
</tr>
<tr>
<td>core material</td>
<td>laminated silicon steel (passive type)</td>
</tr>
<tr>
<td>length [mm]</td>
<td>1500</td>
</tr>
<tr>
<td>maximum current [A]</td>
<td>6000</td>
</tr>
<tr>
<td>deflection angle [degree]</td>
<td>7.0</td>
</tr>
<tr>
<td>pulse width [msec]</td>
<td>88</td>
</tr>
<tr>
<td>Kicker magnet</td>
<td></td>
</tr>
<tr>
<td>name</td>
<td>K1, K2, K3, K4</td>
</tr>
<tr>
<td>core material</td>
<td>ferrite (window frame type)</td>
</tr>
<tr>
<td>core length [mm]</td>
<td>3900</td>
</tr>
<tr>
<td>maximum deflection angle [mrad]</td>
<td>4.4</td>
</tr>
<tr>
<td>pulse width [msec]</td>
<td>5</td>
</tr>
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</table>
### Accelerators

**Superconducting vertical wiggler**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum field strength on the beam orbit</td>
<td>5 Tesla</td>
</tr>
<tr>
<td>Magnet gap</td>
<td>66 mm</td>
</tr>
<tr>
<td>Magnet pole size (widthxheight)</td>
<td>40 mmx260 mm</td>
</tr>
<tr>
<td>Number of magnetic poles</td>
<td>5 poles (3 poles at normal operation)</td>
</tr>
<tr>
<td>Rated exciting current</td>
<td>210 A at 4.8 Tesla</td>
</tr>
<tr>
<td>Superconducting wire size</td>
<td>NbTi/Cu 1:1</td>
</tr>
<tr>
<td>Cross section of coils</td>
<td>65 mmx70 mm</td>
</tr>
<tr>
<td>Number of turn</td>
<td>2520</td>
</tr>
<tr>
<td>Liquid helium consumption in the permanent current mode</td>
<td>0.7 L/h</td>
</tr>
<tr>
<td>Damping rate of the permanent current</td>
<td>1.4x10^-7/h</td>
</tr>
<tr>
<td>Inductance</td>
<td>1.31 H/coil</td>
</tr>
</tbody>
</table>

**Monitor system**

1. **Orbiting Beam Monitors**

<table>
<thead>
<tr>
<th>Monitor Type</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM (Position Monitor)</td>
<td>65</td>
</tr>
<tr>
<td>DCCT (Direct Current Current Transformer)</td>
<td>2</td>
</tr>
<tr>
<td>RFKO (Radio Frequency Knock-Out system)</td>
<td>1</td>
</tr>
<tr>
<td>WCM (Wall Current Monitor)</td>
<td>1</td>
</tr>
<tr>
<td>LS (Loss monitor)</td>
<td>30</td>
</tr>
<tr>
<td>Visible Light Monitor</td>
<td>1</td>
</tr>
<tr>
<td>CCD TV camera</td>
<td>1</td>
</tr>
<tr>
<td>CCD profile monitor (H&amp;V)</td>
<td>1</td>
</tr>
<tr>
<td>light profile monitor (H&amp;V)</td>
<td>1</td>
</tr>
<tr>
<td>four-element profile monitor for oscillation detection</td>
<td>1</td>
</tr>
<tr>
<td>streak camera</td>
<td>1</td>
</tr>
<tr>
<td>photon counting system</td>
<td>1</td>
</tr>
</tbody>
</table>

2. **Photon beam position monitors installed in beamlines**

<table>
<thead>
<tr>
<th>Beamline</th>
<th>Source</th>
<th>Upstream</th>
<th>Downstream</th>
<th>Ver./Hor.</th>
</tr>
</thead>
<tbody>
<tr>
<td>BL2 U</td>
<td>DSPM</td>
<td>DSPM</td>
<td>V, H</td>
<td>V</td>
</tr>
<tr>
<td>BL3A</td>
<td>B</td>
<td>SPM</td>
<td>SPM</td>
<td>V</td>
</tr>
<tr>
<td>BL3C</td>
<td>B</td>
<td>SPM</td>
<td>SPM</td>
<td>V</td>
</tr>
<tr>
<td>BL4C</td>
<td>B</td>
<td>SPM</td>
<td>SPM</td>
<td>V</td>
</tr>
<tr>
<td>BL6B</td>
<td>B</td>
<td>SLIT</td>
<td>SPM</td>
<td>V</td>
</tr>
<tr>
<td>BL6C</td>
<td>B</td>
<td>SLIT</td>
<td>SPM</td>
<td>V</td>
</tr>
<tr>
<td>BL6C</td>
<td>B</td>
<td>SPM</td>
<td>SPM</td>
<td>V</td>
</tr>
<tr>
<td>BL7C</td>
<td>B</td>
<td>SLIT</td>
<td>SPM</td>
<td>V</td>
</tr>
<tr>
<td>BL10A</td>
<td>B</td>
<td>SIC</td>
<td>SPM</td>
<td>V</td>
</tr>
<tr>
<td>BL10B</td>
<td>B</td>
<td>SLIT</td>
<td>WM</td>
<td>V</td>
</tr>
<tr>
<td>BL12A</td>
<td>B</td>
<td>SVW</td>
<td>SPM</td>
<td>H</td>
</tr>
<tr>
<td>BL14C</td>
<td>B</td>
<td>MPW</td>
<td>MPM</td>
<td>V</td>
</tr>
<tr>
<td>BL21</td>
<td>B</td>
<td>WM</td>
<td>SPM</td>
<td>V</td>
</tr>
<tr>
<td>BL27</td>
<td>B</td>
<td>SPM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BL28</td>
<td>EMPW</td>
<td>Under constr.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Note:**
- SPM: Split Photoemission Monitor
- SIC: Split Ion Chamber
- WM: Wire Monitor
- DSPM: Dual SPM for insertion device line
- DSPM: DSPM
- V: Vertical
- H: Horizontal
- B: Bending magnet
- U: Undulator
- SVW: Superconducting Vertical Wiggler
- MPW: Multipole Wiggler
- EMPW: Elliptical MPW

**Control system**

<table>
<thead>
<tr>
<th>Component</th>
<th>Number</th>
<th>Memory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control computers</td>
<td>4</td>
<td>16 Mbyte</td>
</tr>
<tr>
<td>Library computers</td>
<td>1</td>
<td>32 Mbyte</td>
</tr>
</tbody>
</table>

**Computer network:** (type: optical token ring)

- Number of nodes = 5 (max. 256)
### Table 8. Beam parameters at source points.

<table>
<thead>
<tr>
<th>B.L.</th>
<th>Source</th>
<th>$\sigma_x$ [mm]</th>
<th>$\sigma_y$ [mrad]</th>
<th>$\sigma_y$ [mrad]</th>
<th>$\sigma_y$ [mrad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BL01</td>
<td>B01(+2.5)</td>
<td>0.203</td>
<td>0.245</td>
<td>0.061</td>
<td>0.0125</td>
</tr>
<tr>
<td>BL02</td>
<td>U#02</td>
<td>0.422</td>
<td>0.084</td>
<td>0.042</td>
<td>0.0094</td>
</tr>
<tr>
<td>BL03</td>
<td>B02(-0.0)</td>
<td>0.238</td>
<td>0.263</td>
<td>0.066</td>
<td>0.0125</td>
</tr>
<tr>
<td>BL04</td>
<td>B03(+0.0)</td>
<td>0.288</td>
<td>0.228</td>
<td>0.084</td>
<td>0.0096</td>
</tr>
<tr>
<td>BL05</td>
<td>B04(+2.5)</td>
<td>0.319</td>
<td>0.161</td>
<td>0.066</td>
<td>0.0173</td>
</tr>
<tr>
<td>BL06</td>
<td>B06(+2.5)</td>
<td>0.391</td>
<td>0.185</td>
<td>0.059</td>
<td>0.0129</td>
</tr>
<tr>
<td>BL07</td>
<td>B07(+2.5)</td>
<td>0.391</td>
<td>0.185</td>
<td>0.059</td>
<td>0.0129</td>
</tr>
<tr>
<td>BL08</td>
<td>B08(+2.5)</td>
<td>0.391</td>
<td>0.185</td>
<td>0.059</td>
<td>0.0129</td>
</tr>
<tr>
<td>BL09</td>
<td>B09(+2.5)</td>
<td>0.391</td>
<td>0.185</td>
<td>0.059</td>
<td>0.0129</td>
</tr>
<tr>
<td>BL10</td>
<td>B10(+2.5)</td>
<td>0.391</td>
<td>0.185</td>
<td>0.059</td>
<td>0.0129</td>
</tr>
<tr>
<td>BL11</td>
<td>B11(+2.5)</td>
<td>0.391</td>
<td>0.185</td>
<td>0.059</td>
<td>0.0129</td>
</tr>
<tr>
<td>BL12</td>
<td>B12(+2.5)</td>
<td>0.447</td>
<td>0.138</td>
<td>0.054</td>
<td>0.0092</td>
</tr>
<tr>
<td>BL13</td>
<td>MPW#13</td>
<td>0.859</td>
<td>0.115</td>
<td>0.020</td>
<td>0.0168</td>
</tr>
<tr>
<td>BL14</td>
<td>VW#14</td>
<td>0.580</td>
<td>0.083</td>
<td>0.036</td>
<td>0.0098</td>
</tr>
<tr>
<td>BL15</td>
<td>B15(+2.5)</td>
<td>0.203</td>
<td>0.245</td>
<td>0.061</td>
<td>0.0125</td>
</tr>
<tr>
<td>BL16</td>
<td>MPW#16</td>
<td>0.422</td>
<td>0.084</td>
<td>0.042</td>
<td>0.0094</td>
</tr>
<tr>
<td>BL17</td>
<td>B16(0.0)</td>
<td>0.238</td>
<td>0.263</td>
<td>0.066</td>
<td>0.0125</td>
</tr>
<tr>
<td>BL18</td>
<td>B18(+2.5)</td>
<td>0.319</td>
<td>0.161</td>
<td>0.066</td>
<td>0.0173</td>
</tr>
<tr>
<td>BL19</td>
<td>U#19</td>
<td>0.847</td>
<td>0.088</td>
<td>0.057</td>
<td>0.0078</td>
</tr>
<tr>
<td>BL20</td>
<td>B20(+2.5)</td>
<td>0.391</td>
<td>0.185</td>
<td>0.059</td>
<td>0.0129</td>
</tr>
<tr>
<td>BL21</td>
<td>B21(+2.5)</td>
<td>0.391</td>
<td>0.185</td>
<td>0.059</td>
<td>0.0129</td>
</tr>
<tr>
<td>BL22</td>
<td>B27(+1.2)</td>
<td>0.259</td>
<td>0.218</td>
<td>0.090</td>
<td>0.0176</td>
</tr>
<tr>
<td>BL23</td>
<td>Empw#28</td>
<td>0.580</td>
<td>0.083</td>
<td>0.036</td>
<td>0.0098</td>
</tr>
</tbody>
</table>

### Table 9. Summary of Beamline Front Ends in FY 1997.

<table>
<thead>
<tr>
<th>Beamline</th>
<th>Affiliation</th>
<th>Source</th>
<th>Spectral Range</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>BL-1</td>
<td>KEK-PF and NTT</td>
<td>Bending magnet (B1)</td>
<td>VUV and soft X-ray</td>
<td>in operation</td>
</tr>
<tr>
<td>BL-2</td>
<td>KEK-PF</td>
<td>B0-period undulator</td>
<td>soft X-ray</td>
<td>in operation</td>
</tr>
<tr>
<td>BL-3</td>
<td>KEK-PF</td>
<td>Bending magnet (B2&amp;B3)</td>
<td>VUV and soft X-ray</td>
<td>in operation</td>
</tr>
<tr>
<td>BL-4</td>
<td>KEK-PF</td>
<td>Bending magnet (B4)</td>
<td>X-ray</td>
<td>in operation</td>
</tr>
<tr>
<td>BL-5</td>
<td>KEK-PF</td>
<td>Multipole wiggler/undulator</td>
<td>-</td>
<td>under installation</td>
</tr>
<tr>
<td>BL-6</td>
<td>KEK-PF</td>
<td>Bending magnet (B6)</td>
<td>X-ray</td>
<td>in operation</td>
</tr>
<tr>
<td>BL-7</td>
<td>KEK-PF and University of Tokyo</td>
<td>Bending magnet (B7)</td>
<td>VUV and X-ray</td>
<td>in operation</td>
</tr>
<tr>
<td>BL-8</td>
<td>Hitachi Ltd.</td>
<td>Bending magnet (B8)</td>
<td>VUV and X-ray</td>
<td>in operation</td>
</tr>
<tr>
<td>BL-9</td>
<td>Nippon Co. (NEC)</td>
<td>Bending magnet (B9)</td>
<td>VUV and X-ray</td>
<td>in operation</td>
</tr>
<tr>
<td>BL-10</td>
<td>KEK-PF</td>
<td>Bending magnet (B10)</td>
<td>X-ray</td>
<td>in operation</td>
</tr>
<tr>
<td>BL-11</td>
<td>KEK-PF</td>
<td>Bending magnet (B11)</td>
<td>VUV and soft X-ray</td>
<td>in operation</td>
</tr>
<tr>
<td>BL-12</td>
<td>KEK-PF</td>
<td>Bending magnet (B12)</td>
<td>VUV</td>
<td>in operation</td>
</tr>
<tr>
<td>BL-13</td>
<td>KEK-PF</td>
<td>27-pole wiggler/undulator</td>
<td>Soft and hard X-ray</td>
<td>in operation</td>
</tr>
<tr>
<td>BL-14</td>
<td>KEK-PF</td>
<td>Superconducting</td>
<td>hard X-ray</td>
<td>in operation</td>
</tr>
<tr>
<td>BL-15</td>
<td>KEK-PF</td>
<td>Bending magnet (B15)</td>
<td>X-ray</td>
<td>in operation</td>
</tr>
<tr>
<td>BL-16</td>
<td>KEK-PF</td>
<td>53-pole wiggler/undulator</td>
<td>Soft and hard X-ray</td>
<td>in operation</td>
</tr>
<tr>
<td>BL-17</td>
<td>Fujitsu Ltd.</td>
<td>Bending magnet (B16&amp;B17)</td>
<td>VUV and X-ray</td>
<td>in operation</td>
</tr>
<tr>
<td>BL-18</td>
<td>ISSP and KEK-PF</td>
<td>Bending magnet (B18)</td>
<td>VUV and X-ray</td>
<td>in operation</td>
</tr>
<tr>
<td>BL-19</td>
<td>ISSP and KEK-PF</td>
<td>Multi-undulator</td>
<td>VUV</td>
<td>in operation</td>
</tr>
<tr>
<td>BL-20</td>
<td>KEK-PF</td>
<td>Bending magnet (B20)</td>
<td>VUV and X-ray</td>
<td>in operation</td>
</tr>
<tr>
<td>BL-21</td>
<td>KEK-PF</td>
<td>Bending magnet (B21)</td>
<td>Beam diagnosis</td>
<td>in operation</td>
</tr>
<tr>
<td>BL-22</td>
<td>KEK-PF</td>
<td>Bending magnet (B22)</td>
<td>Soft X-ray and X-ray</td>
<td>in operation</td>
</tr>
<tr>
<td>BL-23</td>
<td>KEK-PF</td>
<td>25-pole wiggler/undulator</td>
<td>Circularly polarized</td>
<td>in operation</td>
</tr>
<tr>
<td>BL-24</td>
<td>KEK-PF</td>
<td>30-pole wiggler/undulator</td>
<td>VUV and soft X-ray</td>
<td>in operation</td>
</tr>
</tbody>
</table>
PF-AR Storage Ring

PF-AR, which was originally the booster synchrotron of TRI-STAN electron-positron collider, is now operated as a dedicated synchrotron light source with the electron beam of 6.5 GeV. In PF-AR there are four beam lines, BL-NE1, -NE3, -NE5 and -NE9. BL-NE1 has an ellipsoidal multipole wiggler and BL-NE3 has an X-ray undulator. The remaining two beam lines accept synchrotron light from the bending magnets in the normal cells. The machine and beam parameters of PF-AR is shown in Table 1.

From Jan. 1997 to Feb. 1998 PF-AR stopped the operation to construct a beam transport line for KEK B factory (KEKB). The operation started again in Mar. 1998. Now the beam from the linac is transported through the new electron transport line of KEKB.

Table 1. Machine parameters of PF-AR.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>6.5 GeV</td>
</tr>
<tr>
<td>Injection energy</td>
<td>2.5 GeV</td>
</tr>
<tr>
<td>Natural emittance</td>
<td>293 nm rad</td>
</tr>
<tr>
<td>Circumference</td>
<td>377 m</td>
</tr>
<tr>
<td>RF frequency</td>
<td>508.6 MHz</td>
</tr>
<tr>
<td>Bending radius</td>
<td>23.2 m</td>
</tr>
<tr>
<td>Energy loss per turn</td>
<td>6.66 MeV</td>
</tr>
<tr>
<td>Damping time</td>
<td></td>
</tr>
<tr>
<td>horizontal</td>
<td>2.5 ms</td>
</tr>
<tr>
<td>vertical</td>
<td>2.5 ms</td>
</tr>
<tr>
<td>longitudinal</td>
<td>1.2 ms</td>
</tr>
<tr>
<td>Natural bunch length</td>
<td>18.6 mm</td>
</tr>
<tr>
<td>Momentum compaction factor</td>
<td>0.0129</td>
</tr>
<tr>
<td>Natural chromaticity</td>
<td></td>
</tr>
<tr>
<td>horizontal</td>
<td>-14.3</td>
</tr>
<tr>
<td>vertical</td>
<td>-13.1</td>
</tr>
<tr>
<td>Stored current</td>
<td>40 mA</td>
</tr>
<tr>
<td>The number of bunches</td>
<td>1</td>
</tr>
<tr>
<td>Beam lifetime</td>
<td>240 min.</td>
</tr>
</tbody>
</table>
3 Injector Linac

Operation statistics for fiscal year 1997 are summarized in Table 1.

Table 1 Operation and failure time during this period.

<table>
<thead>
<tr>
<th>Date</th>
<th>Operation time (hrs)</th>
<th>Failure time (hrs)</th>
<th>Operation rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sep. 16 - Dec. 24</td>
<td>2289.2</td>
<td>65.4</td>
<td>97.1</td>
</tr>
<tr>
<td>1998</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jan. 12 - Mar. 23</td>
<td>1498.9</td>
<td>44.4</td>
<td>97.0</td>
</tr>
<tr>
<td>Mar. 30 - Mar. 31</td>
<td>49.0</td>
<td>0.5</td>
<td>98.8</td>
</tr>
<tr>
<td>total</td>
<td>3828.1</td>
<td>110.3</td>
<td>97.1</td>
</tr>
</tbody>
</table>

Table 2 Cumulative usage hours of klystrons during the past years.

<table>
<thead>
<tr>
<th>Period</th>
<th>Total No.of tubes</th>
<th>Unused No.of tubes</th>
<th>Failed No.of tubes</th>
<th>Mean age (hours)</th>
<th>Living No.of tubes</th>
<th>Avg. op. time (hours)</th>
<th>MTBF (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>up to 1987/7</td>
<td>106</td>
<td>4</td>
<td>52</td>
<td>4,400</td>
<td>50</td>
<td>9,600</td>
<td>13,600</td>
</tr>
<tr>
<td>up to 1988/7</td>
<td>120</td>
<td>2</td>
<td>67</td>
<td>4,500</td>
<td>51</td>
<td>11,400</td>
<td>13,500</td>
</tr>
<tr>
<td>up to 1989/7</td>
<td>140</td>
<td>5</td>
<td>82</td>
<td>6,400</td>
<td>53</td>
<td>12,400</td>
<td>14,400</td>
</tr>
<tr>
<td>up to 1990/7</td>
<td>158</td>
<td>6</td>
<td>98</td>
<td>8,500</td>
<td>54</td>
<td>11,200</td>
<td>14,700</td>
</tr>
<tr>
<td>up to 1991/7</td>
<td>176</td>
<td>14</td>
<td>107</td>
<td>10,100</td>
<td>55</td>
<td>11,100</td>
<td>15,800</td>
</tr>
<tr>
<td>up to 1992/7</td>
<td>191</td>
<td>24</td>
<td>113</td>
<td>10,800</td>
<td>54</td>
<td>13,400</td>
<td>17,100</td>
</tr>
<tr>
<td>up to 1993/7</td>
<td>203</td>
<td>19</td>
<td>123</td>
<td>10,800</td>
<td>56</td>
<td>15,300</td>
<td>17,700</td>
</tr>
<tr>
<td>up to 1994/7</td>
<td>217</td>
<td>30</td>
<td>130</td>
<td>10,900</td>
<td>57</td>
<td>17,800</td>
<td>18,700</td>
</tr>
<tr>
<td>up to 1995/7</td>
<td>230</td>
<td>34</td>
<td>138</td>
<td>11,200</td>
<td>58</td>
<td>19,000</td>
<td>19,200</td>
</tr>
<tr>
<td>up to 1996/7</td>
<td>266</td>
<td>47</td>
<td>159</td>
<td>13,900</td>
<td>58</td>
<td>11,500</td>
<td>18,400</td>
</tr>
<tr>
<td>up to 1997/3</td>
<td>285</td>
<td>12</td>
<td>167</td>
<td>15,000</td>
<td>58</td>
<td>7,600</td>
<td>18,400</td>
</tr>
</tbody>
</table>

The cumulative usage hours of klystrons and the averaged fault rate with averaged applied anode voltage are shown in Tables 2 and 3, respectively. Cumulative status of klystrons up to the end of this term are summarized in Table 4.

Table 3 Averaged fault rate and averaged applied voltage to klystrons.

<table>
<thead>
<tr>
<th>Period</th>
<th>Fault rate ( faults/day.tube )</th>
<th>Applied voltage (kV)</th>
<th>Operation Total (tube.days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1987/8-1988/7</td>
<td>1.0</td>
<td>240</td>
<td>9,990</td>
</tr>
<tr>
<td>1988/8-1989/7</td>
<td>0.6</td>
<td>241</td>
<td>10,510</td>
</tr>
<tr>
<td>1989/8-1990/7</td>
<td>0.3</td>
<td>244</td>
<td>10,690</td>
</tr>
<tr>
<td>1990/8-1991/7</td>
<td>0.2</td>
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<td>1991/8-1992/7</td>
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<td>1993/8-1994/7</td>
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<td>1994/8-1995/7</td>
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<td>1997/4-1998/3</td>
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<td>244</td>
<td>6,360</td>
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Table 4  Cumulative status of Bi-cathode klystrons up to March 1998 corresponding to the year of production. Unused tubes are those which have never been used in the klystron gallery. STB (stand-by) tubes are those which have been used in the gallery and can be used there again.

<table>
<thead>
<tr>
<th>Fiscal year of product</th>
<th>Total No. of tubes</th>
<th>Unused No. of tubes</th>
<th>Living No. of (STBWorking) tubes</th>
<th>Av. op. time (hours)</th>
<th>Failed No. of tubes</th>
<th>Causes aging window others</th>
<th>Mean age operation (hours)</th>
<th>Cumulative MTBF</th>
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</thead>
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<tr>
<td>1993</td>
<td>14</td>
<td>1</td>
<td>13</td>
<td>2 11</td>
<td>8,484</td>
<td>0 0 0 0</td>
<td>110,297</td>
<td>303,114</td>
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<tr>
<td>1994</td>
<td>13</td>
<td>0</td>
<td>13</td>
<td>1 12</td>
<td>6,058</td>
<td>0 0 0 0</td>
<td>78,758</td>
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<tr>
<td>1995</td>
<td>23</td>
<td>0</td>
<td>23</td>
<td>1 22</td>
<td>3,989</td>
<td>0 0 0 0</td>
<td>91,741</td>
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<tr>
<td>1996</td>
<td>15</td>
<td>2</td>
<td>13</td>
<td>0 13</td>
<td>1,594</td>
<td>0 0 0 0</td>
<td>22,318</td>
<td></td>
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<tr>
<td>total</td>
<td>65</td>
<td>3</td>
<td>62</td>
<td>4 58</td>
<td>4,811</td>
<td>0 0 0 0</td>
<td>303,114</td>
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</table>
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