OPERATION and PROPOSALS

1. Outline of the Accelerators

Two electron storage rings, namely the PF ring and the PF-AR, have been stably operated as dedicated light sources at the Photon Factory. The KEK linear accelerator with a maximum electron energy of 8 GeV is employed to inject electron beams into the rings. The full energy injection at 2.5 GeV is carried out at the PF ring, while it is necessary to ramp up the injection energy of 3 GeV to the operation energy of 6.5 GeV at the PF-AR.

The machine parameters of the rings and the calculated spectral performances are listed in **Table 1** and **Table 2**, respectively. The spectral distributions of synchrotron radiation (SR) from the bending magnets and the insertion devices are shown in **Fig. 1**.

Table 1: Principal beam parameters of the PF ring and PF-AR.

	PF ring	PF-AR
Energy	2.5 GeV	6.5 GeV
Natural emittance	34.6 nm rad	293 nm rad
Circumference	187 m	377 m
RF frequency	500.1 MHz	508.6 MHz
Bending radius	8.66 m	23.2 m
Energy loss per turn	0.4 MeV	6.66 MeV
Damping time		
Vertical	7.8 ms	2.5 ms
Longitudinal	3.9 ms	1.2 ms
Natural bunch length	10 mm	18.6 mm
Momentum compaction factor	0.00644	0.0129
Natural chromaticity		
Horizontal	–12.9	–14.3
Vertical	–17.3	–13.1
Stored current	450 mA	60 mA
Number of bunches	252	1
Beam lifetime	20-25 h (at 450 mA)	20-25 h (at 60 mA)

Table 2: Calculated spectral performances of the bend source and all the insertion devices at the PF ring (2.5 GeV, 450 mA) and the PF-AR (6.5 GeV, 60 mA). λ_u: period length, *N*: number of the 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, Type of magnet, H: hybrid configuration, S.C.: super conducting magnet, σ_x,σ_y: horizontal or vertical beam size, σ_x',σ_y': horizontal or vertical beam divergence, $K_y(K_x)$: vertical (horizontal) deflection parameter, *D*: photon flux density (photons/sec/mrad^2/0.1%b.w.), *B*: brilliance (photons/sec/mm^2/mrad^2/0.1%b.w.), P_T: total radiated power. Different operating modes of undulator and wiggler are denoted by -U and -W, respectively.

Name	*E/I* GeV/mA	λ_u cm	*N*	*L* m	$G_y(G_x)$ cm	$B_y(B_x)$ T	Type of magnet	σ_x mm	σ_y mm	$\sigma_{x'}$ mrad	$\sigma_{y'}$ mrad	$K_y(K_x)$	$\varepsilon_1/\varepsilon_c$ keV	*D*	*B*	P_T kW
PF	**2.5/450**															
Bend								0.41	0.059	0.178	0.012		4	5.38E+13	3.48E+14	
SGU#01		1.2	39	0.5	0.4	0.7	P(NdFeB)	0.6	0.012	0.088	0.029	0.78		4.56E+16	9.90E+17	0.4
U#02-1		6	60	3.6	2.8	0.4	H(NdFeB)	0.65	0.042	0.054	0.008	2.3		2.73E+17	1.55E+18	1.07
U#02-2		16	17	2.72	2.6	0.33(0.33)	P(NdFeB)	0.65	0.042	0.054	0.008	4.93(4.93)		9.53E+15	4.58E+16	0.53
SGU#03		1.8	26	0.5	0.4	1	P(NdFeB)	0.6	0.012	0.088	0.029	1.68		2.50E+16	5.44E+17	0.82
MPW#05-W		12	21	2.5	2.64	1.4	H(NdFeB)	0.71	0.045	0.078	0.009	16	5.9	2.22E+15	1.10E+16	8.83
MPW#13-U		18	13	2.5	2.71	1.5	H(NdFeB)	0.74	0.02	0.094	0.019	2		1.70E+16	1.57E+17	0.06
VW#14					5	5	S.C.	0.53	0.045	0.128	0.008		20.8	5.42E+13	3.59E+14	
SGU#15		1.76	27	0.5	0.4	0.97	P(NdFeB)	0.6	0.012	0.088	0.029	1.37		4.38E+15	9.44E+16	0.75
U#16-1 & 16-2		5.6	44	2.5	2.1	0.6(0.38)	P(NdFeB)	0.654	0.042	0.055	0.008	3(2)		1.03E+18	1.82E+17	0.88
SGU#17		1.6	29	0.5	0.4	0.92	P(NdFeB)	0.6	0.012	0.088	0.029	1.37		7.88E+15	1.71E+17	0.69
Revolver#19B		7.2	32	3.6	2.8	0.4	H(NdFeB)	0.7	0.045	0.078	0.009	2.7		7.17E+16	3.52E+17	0.63
EMPW#28-U		16	12	1.92	3(11)		P(NdFeB)	0.53	0.045	0.127	0.008	3(3)		1.55E+16	1.00E+16	0.26
PF-AR	**6.5/60**															
Bend								1	0.2	0.593	0.036		26	3.90E+13	3.11E+13	
EMPW#NE1W		16	21	3.36	3(11)	1(0.2)	P(NdFeB)	1.07	1.07	0.268	0.032	15(3)	28(90%)	1.84E+15	2.54E+15	5.52
U#NE3		4	90	3.6	1	0.8	P(NdFeB)	1.57	0.17	0.312	0.029	3		1.29E+16	7.66E+15	3.708
U#NW2		4	90	3.6	1	0.8	P(NdFeB)	1.57	0.17	0.312	0.029	3		1.29E+16	7.66E+15	3.708
U#NW12		4	95	3.8	1	0.8	P(NdFeB)	1.57	0.17	0.312	0.029	3		1.29E+16	7.66E+15	3.912
U#NW14-36		3.6	79	2.8	1	0.8	P(NdFeB)	1.35	0.14	0.338	0.036	2.8		7.69E+15	6.49E+15	3.12
U#NW14-20		2	75	1.5	0.8	0.63	P(NdFeB)	0.75	0.07	0.383	0.038	1.17		7.69E+15	6.49E+15	0.936

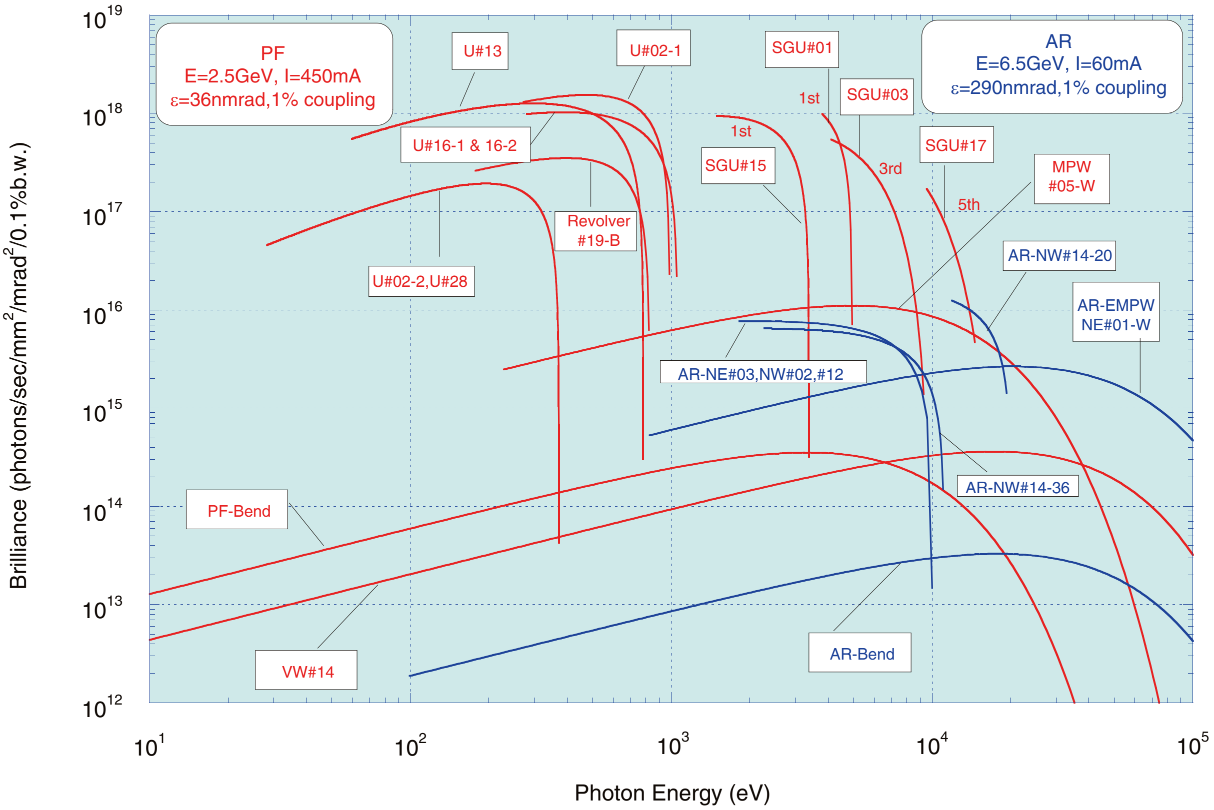

Figure 1: Synchrotron radiation spectra available at the PF ring (2.5 GeV) and the PF-AR (6.5 GeV). Brilliance of the radiation vs. photon energy is denoted by red curves for the insertion devices, SGU#01, U#02-1 & 02-2, SGU#03, MPW#05, U#13, VW#14, SGU#15, U#16-1 & 16-2, SGU#17, Revolver#19-B and U#28, and the bending magnets (PF-Bend) at the PF ring. Blue curves denote those for the insertion devices, EMPW#NE01, U#NE03, U#NW02, U#NW12, U#NW14-36 and U#NW14-20, and the bending magnets (AR-Bend) at the PF-AR. The name of each source is listed in Table 2. The spectral curve of each undulator (or undulator mode of multipole wiggler) is the locus of the peak of the first harmonic within the allowance range of K parameter. For SGU#01 and SGU#15, the first harmonic regions are shown. For SGU#03, the third harmonic region is shown. For SGU#17, the fifth harmonic region is shown. Spectra of Revolver#19 for surface B is shown.

2. Operation Summary

The operation schedule of the PF ring and PF-AR in FY2015 is shown in **Fig. 2**. The user time was secured in the winter period from February to March 2016. The statistics of the accelerator's operation for the past decade are shown in **Fig. 3**. The actual user times in both rings increased by about 800 hours compared with those in FY2014.

In the PF ring, more detailed operation statistics and the number of failures from FY2005 to FY2015 are listed in **Table 3** and **Table 4**, and a pie chart of the down time in FY2015 is shown in **Fig. 4**. The mean time between failures (MTBF) was shorter than 150 hours due to an increase of troubles of the magnet and injection, but the failure rate was maintained at 0.5% because recovery from the troubles was carried out quickly.

In the PF-AR, similar statistics are listed in **Table 5** and **Table 6**, and a pie chart of the down time in FY2015 is shown in **Fig. 5**. The MTBF was as long as 150 hours and the failure rate was 1.1%, which was improved from the rate of 1.9% in FY2014. In addition, troubles due to the dust trap have been drastically decreased since FY2013 and occurred only once in FY2015. Stable operation has been carried out in FY2015 compared with the ordinary annual operations.

In the PF ring, two new polarized undulators (U#13 and U#28) have been smoothly operated. Accelerator components for the new beam transport line to the PF-AR are being prepared and installation will start in June 2016.

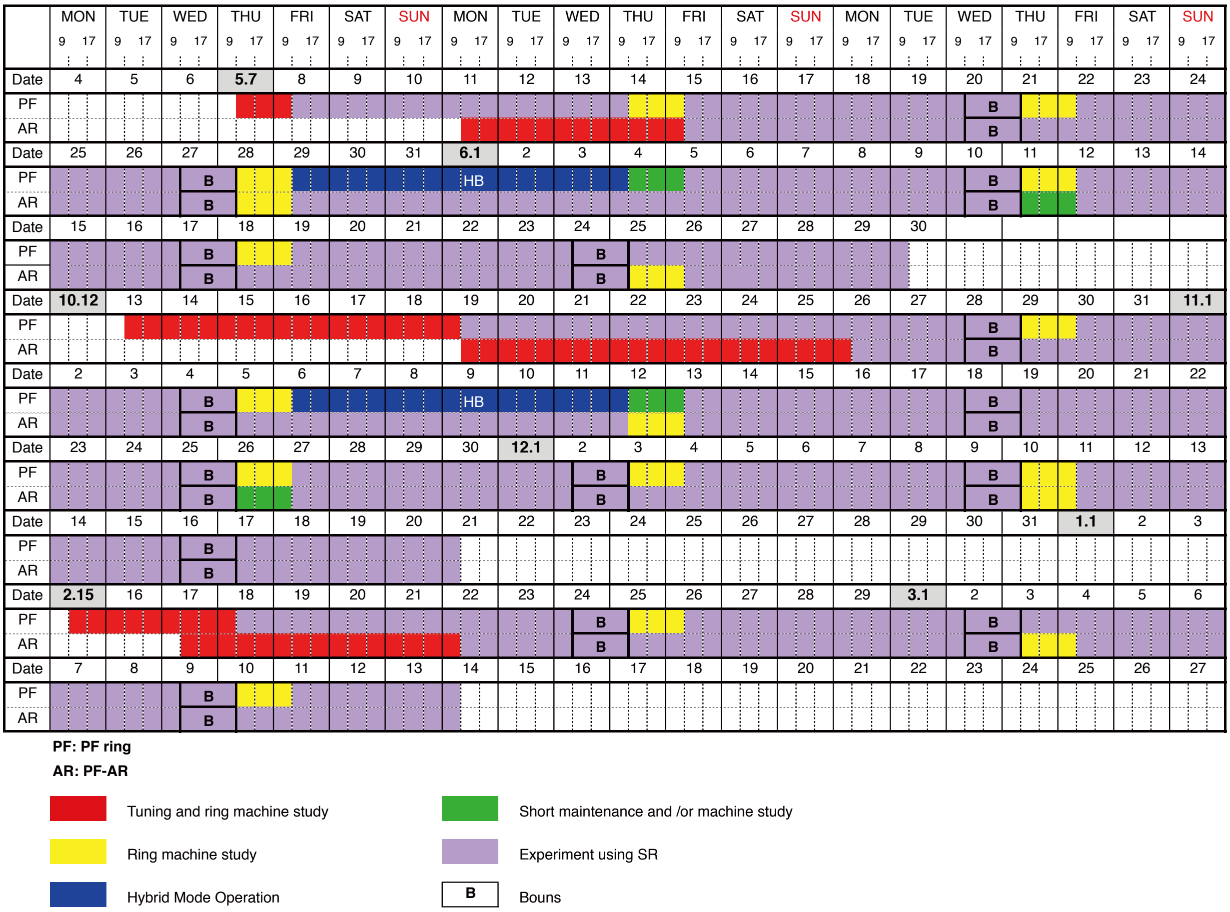

Figure 2: Operation schedule of PF ring and PF-AR in FY2015.

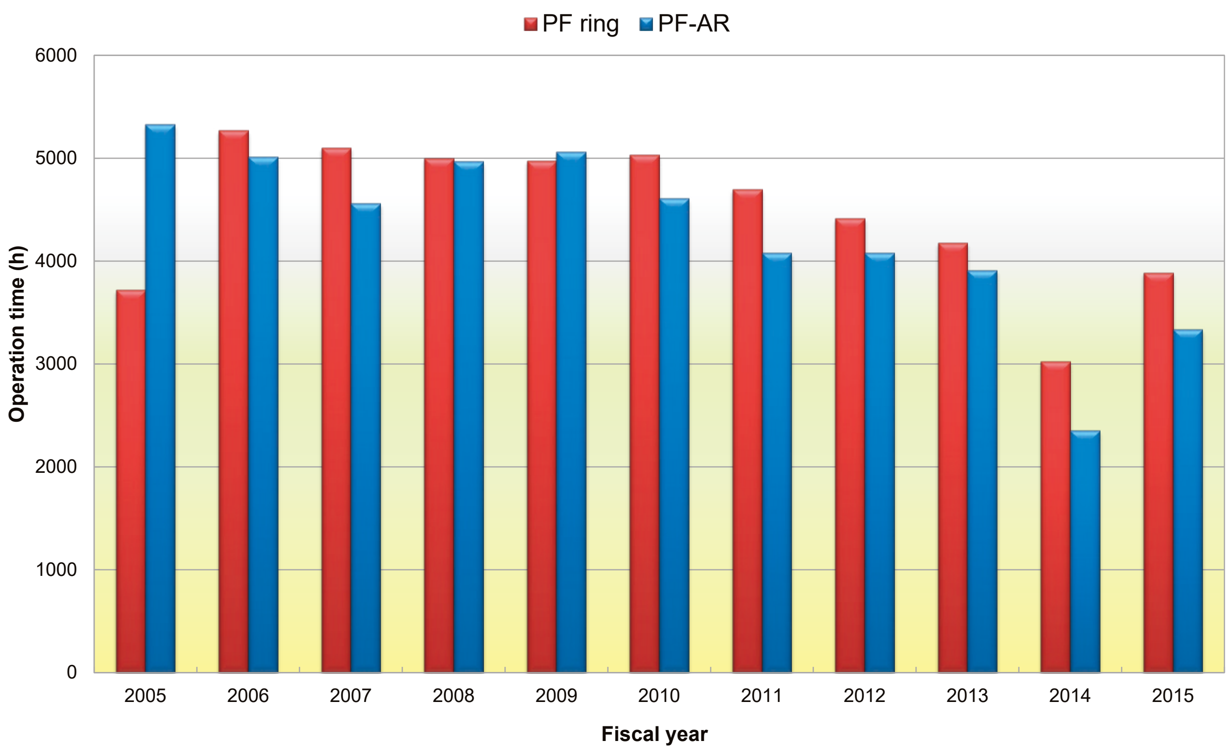

Figure 3: Total operation time for PF ring and PF-AR.

Table 3: Operation statistics for PF ring from FY2005 to FY2015.

Fiscal Year	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Total operation time (h)	3720	5272	5104	5000	4976	5064	4728	4416	4176	3024	3888
Scheduled user time (h)	2640	4248	4296	4032	4008	4080	2832	3792	3504	2328	3048
Ratio of user time (%)	71.0	80.6	84.2	80.6	80.5	80.6	59.9	85.9	83.9	77.0	78.4
No. of failures	33	25	23	18	24	18	18	23	22	15	23
Total down time (h)	27.5	44.6	91.1	23.8	42.7	29.2	14.9	37.6	52.1	11.4	14.4
Failure rate (%)	1.0	1.0	2.1	0.6	1.1	0.7	0.5	1.0	1.5	0.5	0.5
MTBF (h)	80.0	169.9	186.8	224.0	167.0	226.7	157.3	164.9	159.3	155.2	132.5
MDT (h)	0.8	1.8	4.0	1.3	1.8	1.6	0.8	1.6	2.4	0.8	0.6

Table 4: Number of failures for PF ring from FY2005 to FY2015.

Fiscal Year	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
RF	6	7	4	5	12	13	5	10	8	1	1
Magnet	3	3	2	3	4	0	2	0	2	4	7
Injection	1	2	3	4	0	1	0	0	1	3	6
Vacuum	1	2	1	0	0	0	0	0	0	0	1
Dust trap	11	0	1	0	1	0	0	0	0	0	0
Insertion Devices	5	3	4	3	1	1	4	3	0	1	1
Control/ Monitor	1	1	0	0	3	0	1	6	5	3	3
Cooling water	0	1	0	1	1	0	0	0	0	0	0
Safety/ Beamline	2	2	2	1	2	2	1	1	1	3	2
Earthquake	3	0	2	1	0	0	4	3	1	0	2
Electricity	0	4	4	0	0	1	1	0	4	0	0
Total	33	25	23	18	24	18	18	23	22	15	23

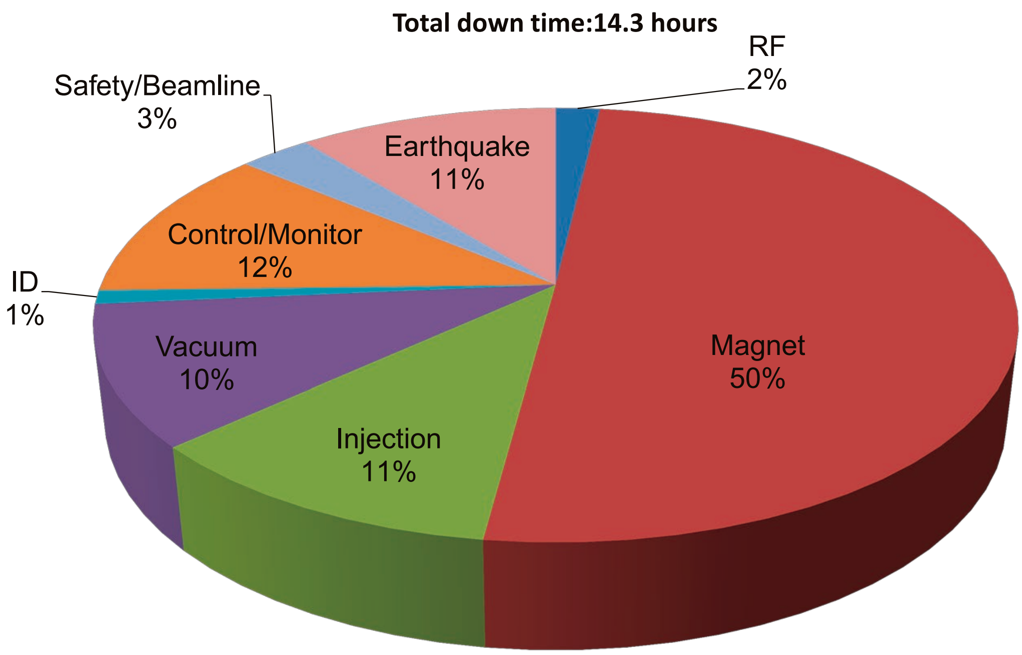

Figure 4: Pie chart of down time for PF ring in FY2015.

Table 5: Operation statistics for PF-AR from FY2005 to FY2015.

Fiscal Year	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Total operation time (h)	5313	5016	4561	4969	5063	4608	4080	4080	3912	2352	3336
Scheduled user time (h)	4456	4032	3624	4344	4392	4032	2904	3672	3478	1992	2784
Ratio of user time (%)	83.9	80.4	79.5	87.4	86.7	87.5	71.2	90.0	88.9	84.7	83.5
No. of failures	79	51	60	40	41	74	49	33	47	22	18
Total down time (h)	69.3	55.1	45.2	41.7	91.0	73.7	38.7	29.7	99.6	37.0	31.0
Failure rate (%)	1.6	1.4	1.2	1.0	2.1	1.8	1.3	0.8	2.9	1.9	1.1
MTBF (h)	56.4	79.1	60.4	108.6	107.1	54.5	59.3	111.3	74.0	90.5	154.7
Mean down time (h)	0.9	1.1	0.8	1.0	2.2	1.0	0.8	0.9	2.1	1.7	1.7

Table 6: Number of failures for PF-AR from FY2005 to FY2015.

Fiscal Year	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
RF	12	10	1	4	8	10	5	4	5	2	1
Magnet	4	1	1	2	2	10	8	3	4	9	4
Injection	4	3	8	9	1	6	4	3	18	7	1
Vacuum	2	6	2	0	2	1	0	1	0	0	1
Dust trap	37	24	39	15	16	24	20	13	3	2	1
Insertion Devices	0	1	0	0	0	0	0	0	0	0	0
Control/ Monitor	4	0	1	1	1	2	1	2	8	0	0
Cooling water	5	1	0	3	4	4	1	0	2	0	0
Safety/ Beamline	9	4	5	5	7	17	3	4	3	1	8
Earthquake	2	0	1	0	0	0	5	3	1	0	2
Electricity	0	1	2	1	0	0	2	0	3	1	0
Total	79	51	60	40	41	74	49	33	47	22	18

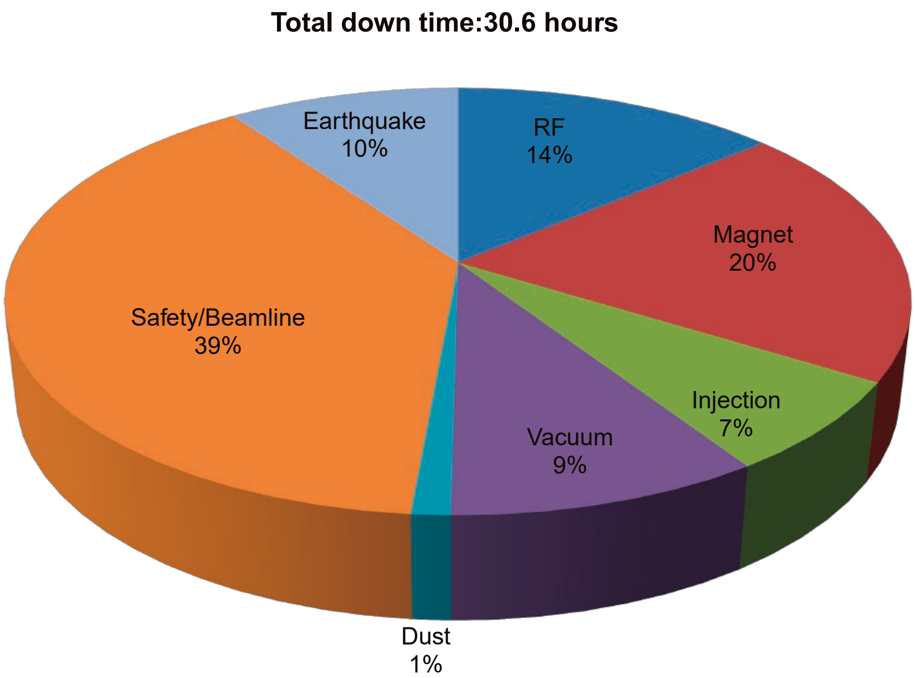

Figure 5: Pie chart of down time for PF-AR in FY2015.

3. Experimental Stations

Fifty-two experimental stations are operated at the PF ring, the PF-AR and the slow positron facility (SPF), as shown in **Figs. 6, 7** and **8**. Thirty-five stations are dedicated to research using hard X-rays, 14 stations for studies in the VUV and soft X-ray energy regions, and 3 stations for studies using slow positrons. **Tables 7, 8** and **9** summarize the areas of research carried out at the experimental stations at the PF ring, PF-AR and SPF.

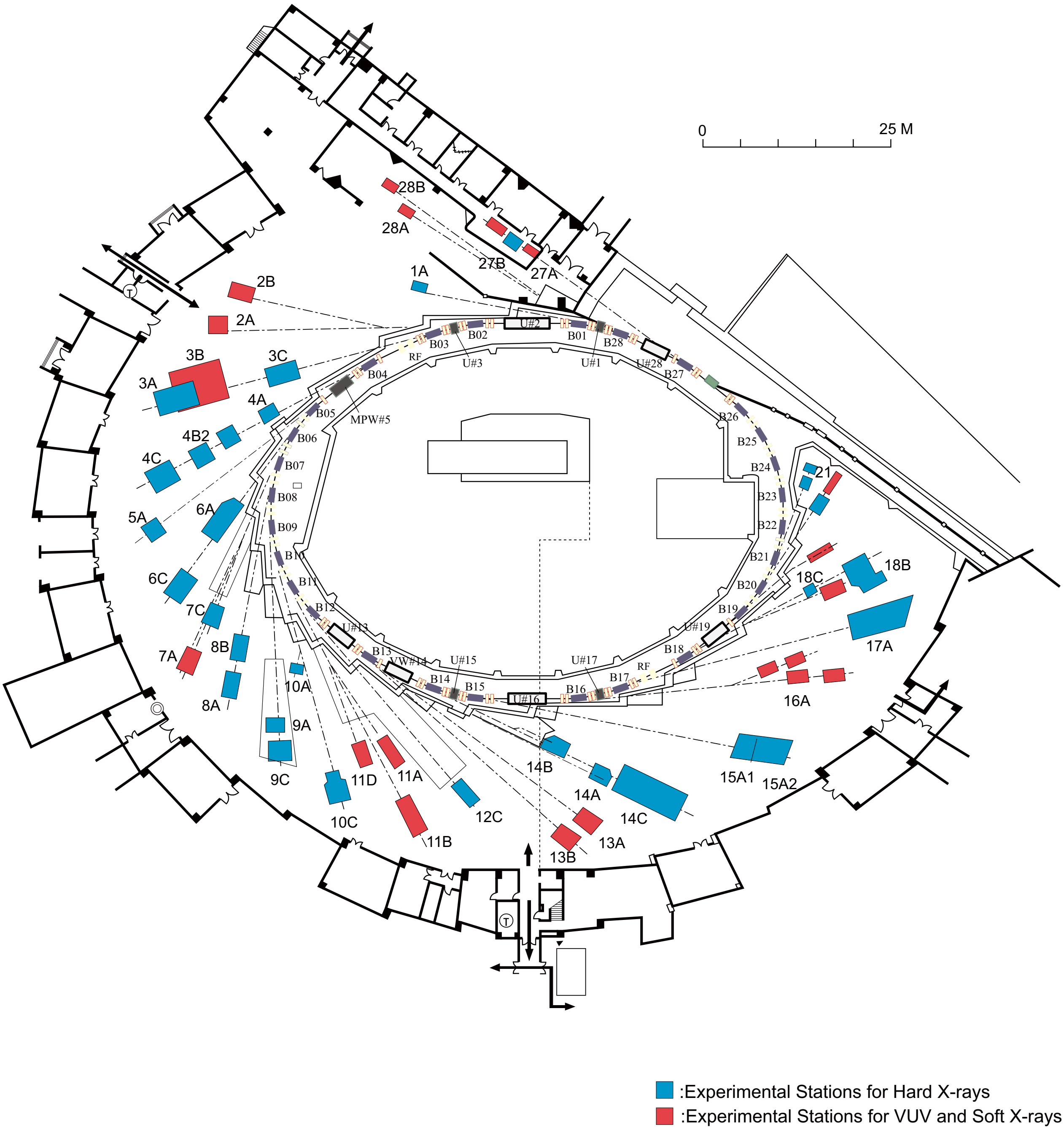

Figure 6: Plan view of the PF experimental hall, showing hard X-ray experimental stations (blue), and VUV and soft X-ray experimental stations (red).

Table 7: List of experimental stations available for users at the PF ring.

Experimental Station			Person in Charge
BL-1		(Short Gap Undulator)	
	A	Macromolecular crystallography	N. Matsugaki
BL-2		(Undulator)	
	A	Soft X-ray spectroscopy	H. Kumigashira
	B	Soft X-ray spectroscopy	H. Kumigashira
BL-3		(A: Short Gap Undulator)	
	A	X-ray diffraction and scattering station for materials science	H. Nakao
	B	VUV and soft X-ray spectroscopy (♠)	K. Edamoto [Rikkyo Univ.], J. Yoshinobu [The Univ. Tokyo], K. Mase
	C	Characterization of X-ray optical elements/White X-ray magnetic diffraction	K. Hirano
BL-4			
	A	Trace element analysis, X-ray microprobe (♠)	Y. Takahashi [The Univ. Tokyo], M. Kimura, Y. Niwa
	B2	High resolution powder diffraction (♠)	H. Uekusa [Tokyo Inst. Tech.], H. Nakao
	C	X-ray diffraction and scattering	H. Nakao
BL-5		(Multipole Wiggler)	
	A	Macromolecular crystallography	N. Matsugaki
BL-6			
	A	Small-angle X-ray scattering	N. Igarashi
	C	Macromolecular crystallography (♠)	M. Okube [Tokyo Inst. Tech.*], H. Kawata
BL-7			
	A	Soft X-ray spectroscopy (♦)	J. Okabayashi [RSC, The Univ. Tokyo], K. Amemiya
	C	X-ray spectroscopy and diffraction	H. Sugiyama
BL-8			
	A	Weissenberg camera for powder/Single-crystal measurements under extreme conditions	H. Sagayama
	B	Weissenberg camera for powder/Single-crystal measurements under extreme conditions	H. Sagayama
BL-9			
	A	XAFS	H. Abe
	C	XAFS	H. Abe
BL-10			
	A	X-ray diffraction and scattering (♠)	A. Yoshiasa [Kumamoto Univ.], R. Kumai
	C	Small-angle X-ray Scattering	N. Shimizu
BL-11			
	A	Soft X-ray spectroscopy	Y. Kitajima
	B	Soft X-ray spectroscopy	Y. Kitajima
	D	Characterization of optical elements used in the VSX region♠	K. Mase
BL-12			
	C	XAFS	H. Nitani

Experimental Station			Person in Charge
BL-13		(Undulator)	
	A/B	VUV and soft X-ray spectroscopies	K. Mase
BL-14		(Vertical Wiggler)	
	A	Crystal structure analysis and detector development	S. Kishimoto
	B	High-precision X-ray optics	K. Hirano
	C	Medical applications and general purpose (X-ray)	K. Hyodo
BL-15		(Short Gap Undulator)	
	A1	Semi-microbeam XAFS	H. Nitani
	A2	High brilliance small-angle X-ray scattering	N. Shimizu
BL-16		(Variable Polarization Undulator)	
	A	Soft X-ray spectroscopies with circular and linear polarization	K. Amemiya
BL-17		(Short Gap Undulator)	
	A	Macromolecular crystallography	Y. Yamada
BL-18			
	B	Multipurpose monochromatic hard X-ray station (♦)	A. Singh [SINP], R. Kumai
	C	High pressure X-ray powder diffraction (DAC) (♠)	H. Kagi [The Univ. Tokyo], T. Kikegawa
BL-20			
	A	VUV spectroscopy (◊)	N. Kouchi [Tokyo Inst. Tech], J. Adachi
	B	White & monochromatic X-ray topography and X-ray diffraction experiment	H. Sugiyama
BL-27			
	A	(Beamline for radioactive samples) Radiation biology, soft X-ray photoelectron spectroscopy	N. Usami
	B	Radiation biology, XAFS	N. Usami
BL-28		(Elliptical / Helical Undulator)	
	A	High-resolution VUV-SX beamline for angle-resolved photoemission	K. Ono
	B	High-resolution VUV-SX spectroscopy	K. Ono

♠ User group operated beamline
♦ External beamline
◊ Operated by University

RCS: Research Center for Spectrochemistry, the University of Tokyo
SINP: Saha Institute of Nuclear Physics
* Current affiliation: Tohoku Univ.

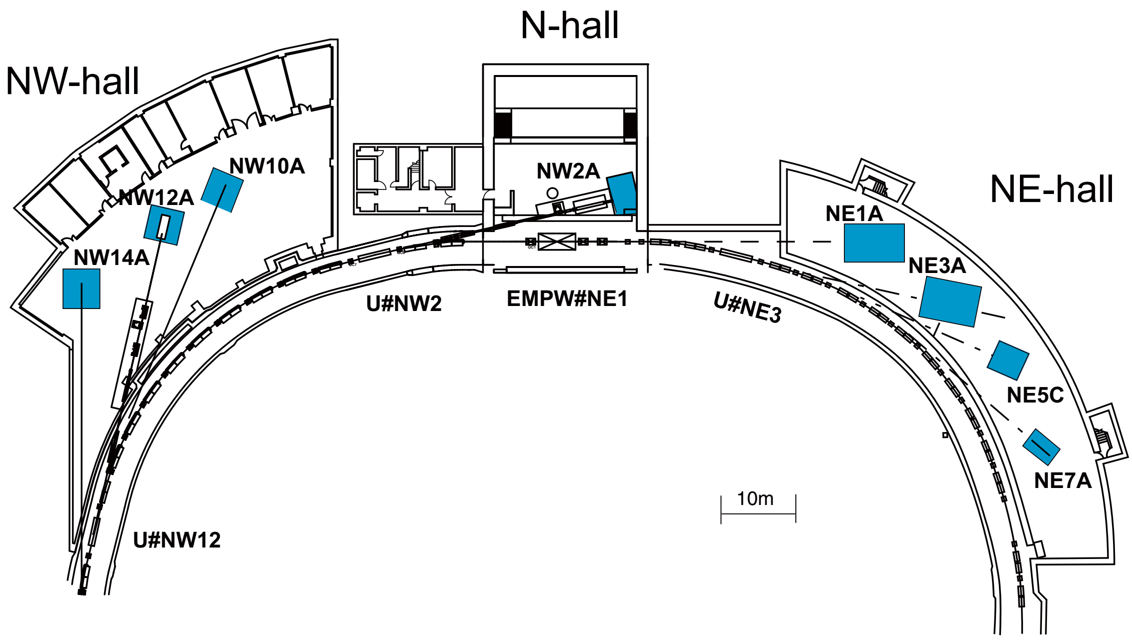

Figure 7: Plan view of beamlines in the PF-AR north-east, north, and north-west experimental halls.

Table 8: List of experimental stations at the PF-AR.

Experimental Station		**Person in Charge**
AR-NE1	(Multipole Wiggler)	
A	Laser-heating high pressure X-ray diffraction and nuclear resonant scattering (DAC)	T. Kikegawa
AR-NE3	(Undulator)	
A	Macromolecular crystallography	Y. Yamada
AR-NE5		
C	High pressure and high temperature X-ray diffraction (MAX-80)	T. Kikegawa
AR-NE7		
A	High pressure and high temperature X-ray diffraction (MAX-III), X-ray imaging	K. Hyodo
AR-NW2	(Undulator)	
A	Time-resolved Dispersive XAFS/XAFS/X-ray Diffraction	Y. Niwa
AR-NW10		
A	XAFS	H. Nitani
AR-NW12	(Undulator)	
A	Macromolecular crystallography	Y. Yamada
AR-NW14	(Undulator)	
A	Time-resolved X-ray diffraction, scattering and absorption	S. Nozawa

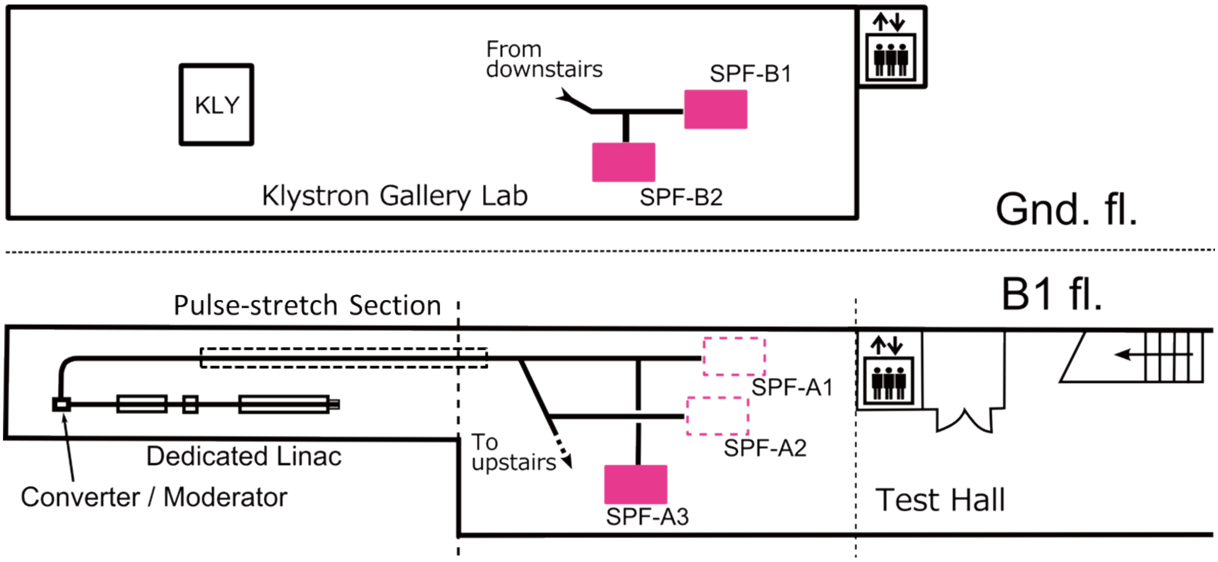

Figure 8: View of beamlines in the Slow Positron Facility.

Table 9: List of experimental stations at the Slow Positron Facility.

Experimental Station		Person in Charge
SPF-A3	Total-reflection high-energy positron diffraction	T. Hyodo
SPF-B1	General purpose (Positronium negative ion)	T. Hyodo
SPF-B2	Positronium time-of-flight	T. Hyodo

3. Summary of User Proposals

The Photon Factory accepts experimental proposals submitted by researchers mainly at universities and research institutes inside and outside Japan. The PF Program Advisory Committee (PF-PAC) reviews the proposals, and the Advisory Committee for the Institute of Materials Structure Science formally approves those that are favorably recommended. The number of accepted proposals over the period 2004–2015 is shown in **Table 10**, where S1/S2, U, G, P, MP denote Special, Urgent, General, Preliminary, and Multi-Probe proposals, respectively. Category T is a new type of proposal for supporting researches by PhD students.

Category MP is also a new type of proposal in which no less than two of the four beams, synchrotron radiation at the PF, slow positron at the Slow Positron Facility, and neutron and muon beams at the Materials and Life Science Experimental Facility (MLF) in J-PARC, are required to be used, as a multi-probe experiment.

Category C is a proposal to carry out a joint experiment between KEK and a research institute including a private company. Category I is a non-proprietary proposal for integrated promotion of social system reform and research and development, supported by the Ministry of Education, Culture, Sports, Science and Technology. Category V is a non-proprietary grant-aided proposal that has already been reviewed and approved for a research grant; beam time for these proposals is allocated with high priority, and the applicants are required to pay the regulation fees for the beam time. Category Y is a proprietary proposal; the applicants are required to pay the regulation fees for the beam time. The number of current G-type proposals each year has exceeded 800 for the past few years. In addition to these proposals, 50 projects in the Platform for Drug Discovery, In-

Table 10: Number of proposals accepted for the period 2004–2015.

Category	FY-2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
S1	1	0	1	0	0	0	0	0	0	0	0	0
S2	0	3	6	1	4	6	3	2	4	5	4	7
U	4	0	1	7	3	2	2	0	4	1	0	0
G	382	310	386	403	402	397	407	415	454	447	407	361
P	13	10	22	14	14	14	16	11	18	18	5	16
T											6	4
MP												4
C	26	28	25	24	18	12	15	19	20	20	25	24
I						9	17	13	17	13	16	11
V									1	2	2	2
Y	2	2	23	23	22	29	31	30	30	41	22	33

formatics, and Structural Life Science were performed at the PF in FY2015. A full list of the proposals effective in FY2015 and their scientific output can be found in the Photon Factory Activity Report (http://www2.kek.jp/imss/pf/science/publ/acrpubl.html).

S-type proposals consist of two categories, S1 and S2. S1 proposals are self-contained projects of excellent scientific quality, and include projects such as the construction and improvement of beamlines and experimental stations which will be available for general users after the completion of the project. S2 proposals are superior-grade projects that require the full use of synchrotron radiation or long-term beam time. Proposals are categorized into five scientific disciplines, and reviewed by the five subcommittees of PF-PAC: 1) electronic structure, 2) structural science, 3) chemistry and materials, 4) life science I (protein crystallography), and 5) life science II (including soft matter science). Figure 9 shows the distribution by research field of the proposals accepted by the subcommittees in FY2015.

The number of users, for all types of proposals, now exceeds 3,100. Although the number of experimental stations has decreased, the approved scientific proposals and number of users have increased annually, as shown in Fig. 10. This indicates a high and increasing demand for synchrotron radiation and can be attributed to continuous improvements in the storage rings, beamlines, and experimental stations. The synchrotron has become one of the most important research tools for carrying out advanced science experiments and development. About 22% of the proposals are conducted by new spokespersons, which indicates that the Photon Factory is open to public academic scientists.

Figure 11 shows the distribution of users by institution and position. About three-quarters of the users belong to universities, of whom approximately 73% are associated with national universities. Over two-thirds of the national university users are graduate and undergraduate stu¬dents; this indicates that the Photon Factory plays an important role in both research and education. The geographical distribution of the Photon Factory users is shown in Fig. 12 and Fig. 13, which also indicates the immense contribution of the Photon Factory to research and education throughout Japan. The registered number of papers published in 2015 based on experiments at the PF was 478 at the time of this writing (July 1st, 2016). In addition, 41 doctoral and 119 master theses have been presented.

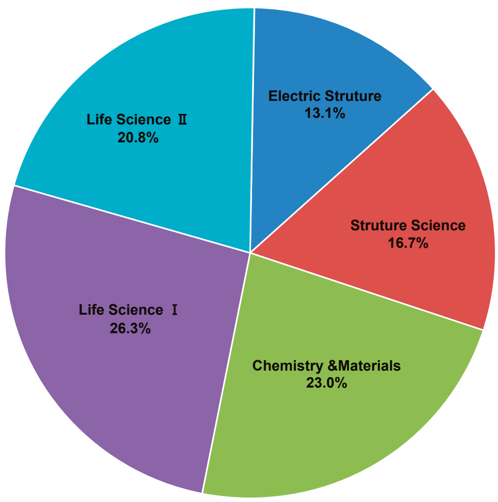

Figure 9: Distribution by scientific field of experimental proposals accepted in FY2015.

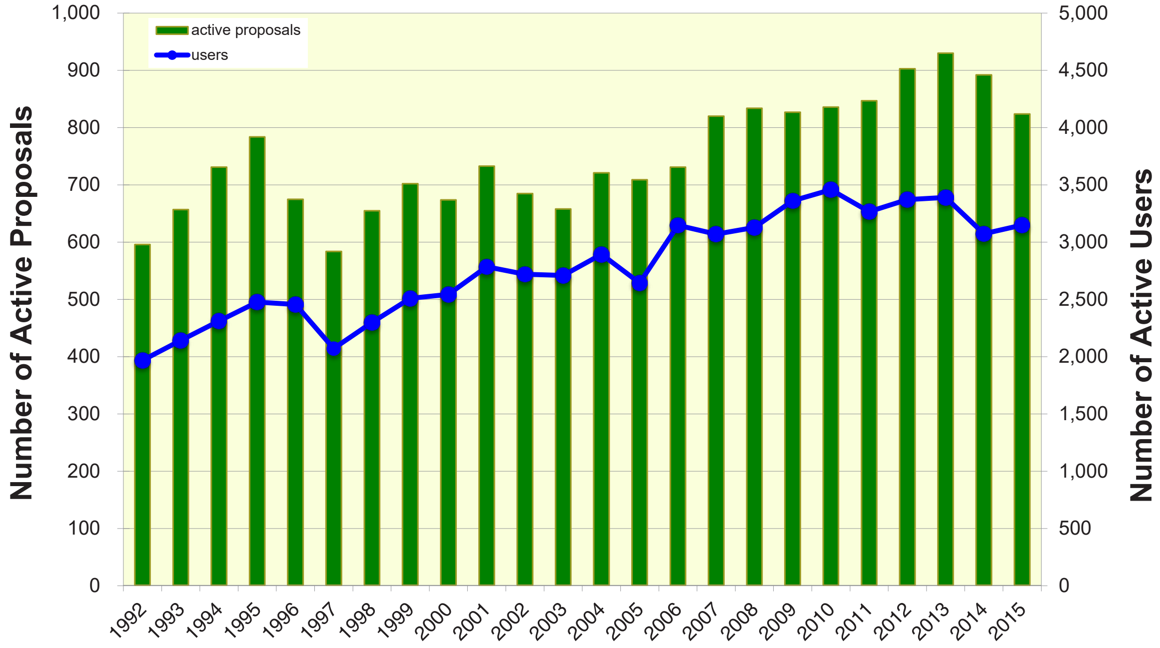

Figure 10: Number of registered PF users and scientific proposals over the period 1992–2015.

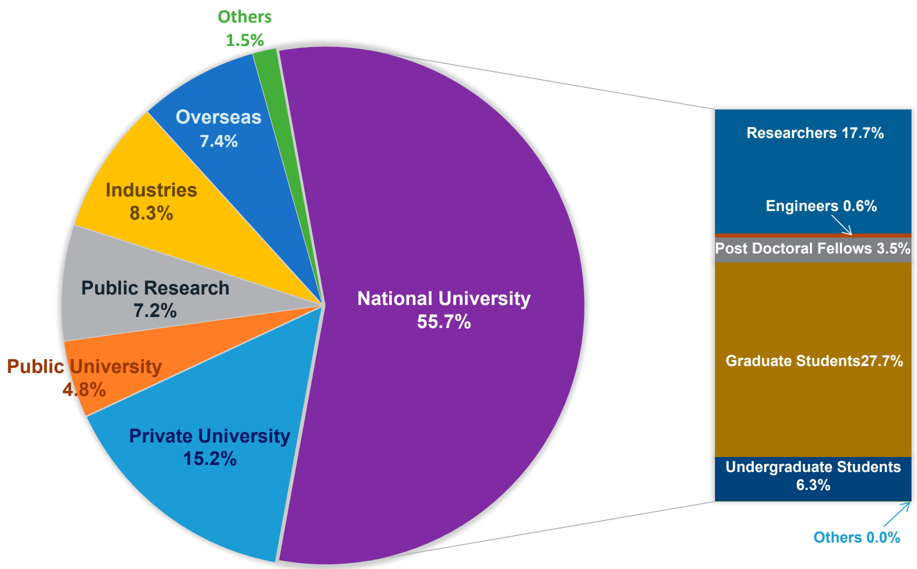

Figure 11: Distribution of users by institution and position.

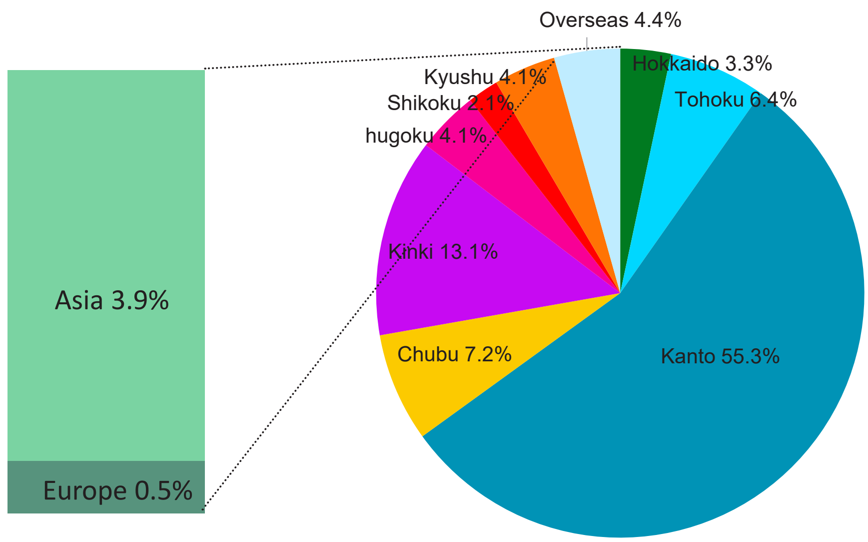

Figure 12: Regional distribution of spokespersons of proposals accepted in FY2015. We corrected the pie chart on 2019/09/02.

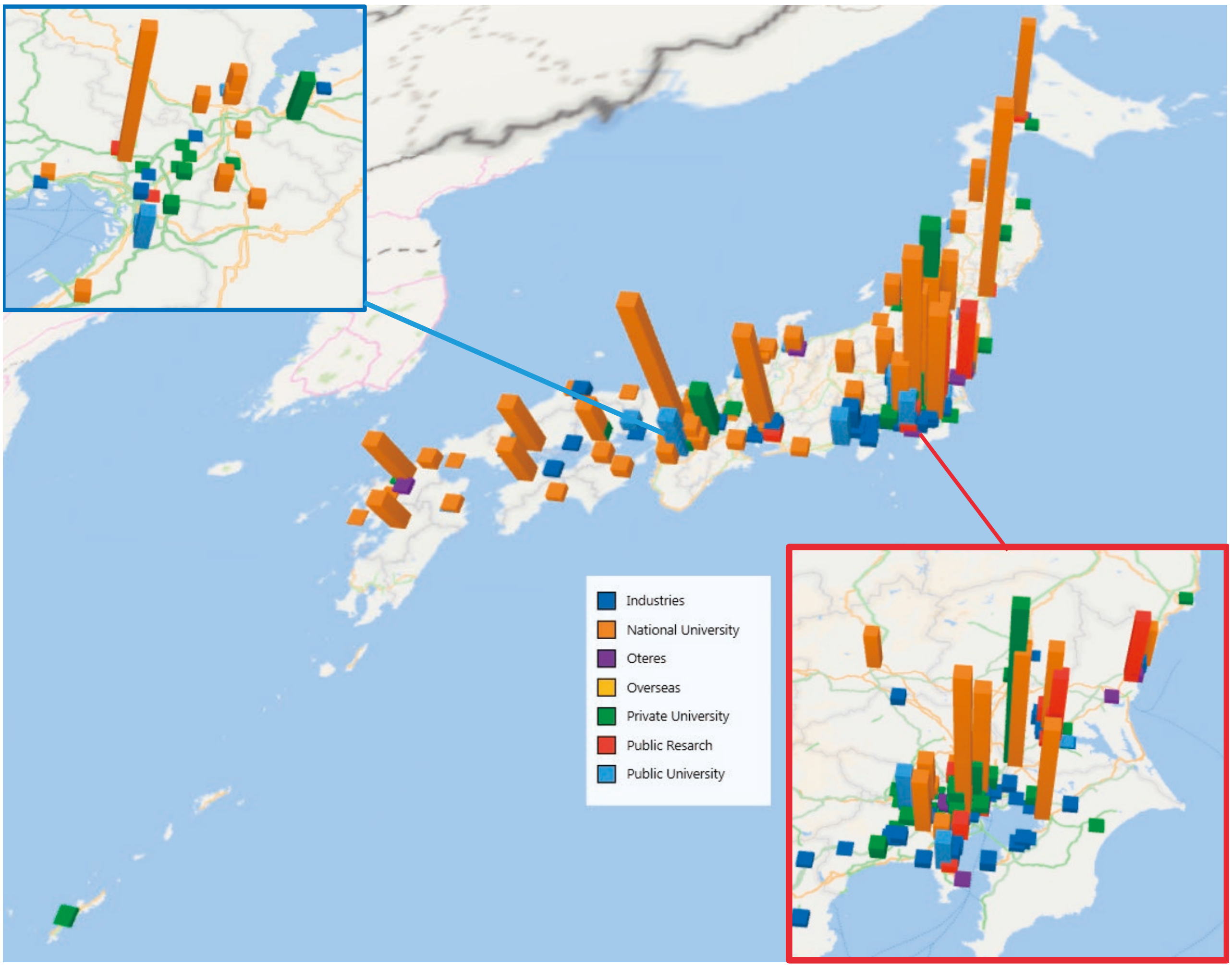

Figure 13: Geographical distribution of Photon Factory users in FY 2015 (domestic users only).