# Report from the Muon Science Advisory Committee (KEK-IMSS) and Muon Advisory Committee (J-PARC Center)

**May, 2013**

**Report from the Muon Science Advisory Committee**
**(and the 11th J-PARC Muon Advisory Committee)**
**Held on February 22 - 23th 2013**
**at J-PARC, Tokai**

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# I. Overview Session

Prof. K. Yamada from KEK gave the welcome address and outlined the charges to the committee (MuSAC) from the part of the Institute of Material Structure Science IMSS. In his presentation he stressed the importance to find the right balance between science and beam line/ spectrometer developments for the small group of MUSE.

This talk was followed by the introduction of Prof. Y. Ikeda who as well presented questions to the committee (MAC) and overviewed J-PARC activities. An important part of work at the center during the year 2012 was still determined by the aftermath of the March 2011 earth quake. The committee was very impressed by the rapidity and efficiency of the recovery work of the damage suffered by infrastructure and buildings. Various pictures comparing the status after the earth quake with the present status gave an impressive testimony of the huge amount of work done. The revised operational plan, foreseeing a beam power of 300kW in FY 2012, could be implemented. Moreover, a 539 kW operation of the RCS at 25 Hz was successfully demonstrated during 35 sec. An updated 5 years plan concerning the various activities which involve J-PARC as well as KEK was presented. 2013 will be characterized by the Linac upgrade and the construction of a main user building, which will profit from a supplementary budget. A 6 cycle user operation for a total of 132 days is foreseen. Compared to the MUSE facility the neutron instrument facility is in a well advanced stage with 18 beam ports in operation and 3 in construction out of a total of 23. The committee was also pleased to hear about the status of the T2K experiment, which took data from October 2012 and has collected 11 candidate neutrino events.

Dr. Arai gave a detailed overview of the Materials and Life Science Facility activities. The number of proposals and users has been steadily increasing over the past year and the latter parameter exceeded the mark of 700 people. Of these about 10% are users (and correspondingly proposals) for muon experiments. Particularly the large number of students (about 30%) is encouraging in view of a future expansion of the user community and of the attractiveness of the facilities.

Prof. Myake summarized the activities of the MUSE facility.
The D-line is now in operation and can profit from the upgrade of the spectrometer that increased the usable event rate by a factor of two. The committee was also pleased to see that the kicker system of the D-line was improved and that the noise problem reported the previous year sizably

reduced. Essential progress was reported concerning the ultra slow muon beam line (U-line), a dedicated beam line designed to produce ultra slow muons in the eV to keV range with high intensity and luminosity. The superconducting Curved Solenoid and the Superconducting Focusing Solenoid were successfully installed in October 2012, so that commissioning of the U-line promptly started afterwards. First tests at about 200 kW power show a factor 20 higher intensity of surface muons than at the D-line. The committee was also pleased to hear that a supplemental budget was approved to construct the S1 area of the S-line. This will greatly enhance the possibility to perform bulk μSR studies in the next years. Crucial front end elements of the H-line could be successfully and timely installed before a too high radiation level around the target station was reached.

The Inter-University Research Program presented by Prof. Kadono was evaluated by MuSAC/MAC in the context of the ongoing development of the MUSE facility. At present there is a chronic shortage of manpower for development and construction work, and this personnel demand has limited the time and support for research activities in this program. Additional considerations include the reality that the scientific output from MUSE is currently reliant on a single beam line (D-line), and that the Great East-Japan Earthquake of 2011 caused a major interruption in the research of all program members. This event certainly had an adverse effect on the number of papers published in refereed journals over the past year.

Still there was a resurgence and growth in the number of Inter-University Research proposals in 2012, but insufficient beam time available at J-PARC MUSE for ~50 % of the requests. This is the case despite the number of days allocated for any particular experiment being generally much less than that assigned to experiments at the world's other muon facilities. While the lack of beam time is greatly limiting for current users, this is a good situation to have in these early stages of the MUSE facility, as it indicates a strong demand for the expansion of infrastructure that is currently taking place.

Some of the research published in 2012 was presented to the committee. This included a μSR study showing strong support for electric quadrupole ordering in superconducting $PrIr_2Zn_{20}$, measurements of the Li diffusion coefficient in battery electrode materials and non-destructive element analysis of historical coins. This work is representative of the diverse range of applications of the MUSE facility still in its infancy, and reflects the general makeup of approved Inter-University Research Program proposals. It is encouraging to see a continued growth of research initiatives in parallel with the construction of new beam lines and the development of instrumentation.

## II. MUSE Facility

### Muon Production Target:

The status of the current fixed muon target and the progress with the development and commissioning of a new rotating muon target were reported in a presentation by Mr. S. Makimura and Mr. Y. Kobayashi.

For a stable long term operation of the target under the high level of proton irradiation at 1 MW power, the installation of a rotating muon target is mandatory and has to be performed without delay. Continuous durability tests with the mock-up target will be performed soon and some further work on testing procedures for decommissioning the target and support structure is under way. The expected lifetime, essentially determined by the bearings, is 10 years. After detailed commissioning studies it is planed to install the final version of the rotating target in the summer of 2013. The importance of working out a scenario for disposal of the radioactive parts and to define a disposal area was stressed at the end of the talk. MuSAC/MAC was again impressed by the high level of engineering of the small team involved in this important project. MuSAC/MAC feels that some sharing of expertise and staff effort with the neutron target group would be highly desirable to coordinate arrangements for the storage and disposal of the used targets. Sharing resources could also assist with meeting the tight target installation schedule in the summer of 2013, which should be the current top priority for the facility.

### U-line:

Dr. Y. Ikedo presented an update on the current status of development for the Super Omega muon beam line. MuSAC/MAC was pleased to hear that an axial focusing solenoid system was successfully installed in October 2012 as scheduled. The system is composed of a muon beam blocker, six cryostats with respective pairs of superconducting magnets, a three-stage positron separator, and two focusing solenoids, all of which were in good mechanical and operating conditions meeting specifications. MuSAC/MAC was impressed to learn that the first beam extraction experiment was satisfactorily completed. Beam commissioning has led to a very good initial surface muon beam with the world strongest pulse intensity of ~ $2.5\ 10^{6}\ \mu^{+}$/pulse at the present power level of the proton accelerator, which corresponds to more than $2\ 10^{8}\ \mu^{+}$/s for 1 MW power. Using the second stage of the positron separation system a large fraction of background positrons could be eliminated. MuSAC/MAC is delighted that the Super Omega project is reaching the final stage towards the production of a very intense thermal muonium source.

**Ultra Slow Muon Beam Line:**

In a related talk, Dr. T. Nagatomo and Mr. J. Nakamura presented the situation at the instrument side of the U-line, namely, at the ultra slow muon set-up (USM), a project supported by the Kakenhi.

The Muonium production chamber and the transport system were delivered and recently aligned. Tests were performed to search for the most effective metals for the production of thermal Muonium. Beside very pure Tungsten, Iridium appears a promising candidate. An issue was found in the temperature homogeneity of the hot metal foil, which affects the profile and stability of USM-beam. Beam optics parameters have to be optimized and adapted to the properties of the surface muons delivered by the U-line. This optimization process appears to the committee of primary importance in order to achieve the proposed beam quality and intensity.

**D1/D2 μSR Spectrometer Upgrade:**

The D-line continues to be the only operational muon channel at the MUSE facility, and the committee was delighted to hear that in addition to the D1 experimental area, the D2 leg is now being fully utilized. In 2012, MuSAC/MAC recommended a targeted effort to improve the quality of the D-line beam and the available sample environments, with an understanding that such work would have to be done in parallel with the heavy workload demand from the continued construction of the other muon beam lines.

The most significant development over the past year has been the testing of a new low-cost modular positron detector system (Kalliope) based on semiconductor-based multi pixel photon counters (MPPC). By integrating Kalliope as add-on detectors into the existing DΩ1 spectrometer, this new system has been demonstrated to yield low-noise and distortion-free μSR spectra, with a data collection rate exceeding that of the general-purpose ARGUS instrument at the pulsed muon RIKEN-RAL facility in the United Kingdom. Hence a major hurdle has been cleared for implementation of this technology into muon instruments at MUSE.

A strategy for installing Kalliope detectors into existing magnets on both the D1 and D2 legs in the upcoming year was presented at the current meeting. There are additional plans for further development of these detectors for eventual use in high magnetic field μSR. These initiatives are not only valuable for improving experimental capabilities on the existing D-line for current users, but also will ensure minimal delay between the completion of the S-line and the establishment of functional experimental areas there. Consequently, the committee strongly urges a continued commitment to bolstering the spectrometer and sample environment capabilities in the D-line experimental areas.

**S Beam Line:**

The construction of the surface muon beamline (S-line), which is one of key elements of the J-PARC/MUSE facility to increase the number of users and foster the scientific output took shape in 2012. Dr. P. Strasser presented the present status of the project and the future strategy of the beam line construction. The S-lines consist of four experimental areas (S1, S2, S3, S4) in the final stage. Installation of two kicker systems together with spin rotators are planned to provide large versatility and flexibility.

The committee appreciates the successful installation in the M2-tunnel of elements (e.g. quadrupole triplets) during the last shutdown period and supports the strategy to concentrate the effort onto the so-called phase 1 stage. Additionally, the committee was very pleased to hear that funding for the construction of this area (including phase S1) has been recently approved as a special supplemental budget. To cope with the double pulse at the S beam line, two methods are being envisaged; a RF pulse technique to obtain high time resolution measurements at S1, and a beam slicer at S2, which is similar to the one that has been already successfully installed in the D-line. As next step, a kicker system will be installed. An electric kicker instead of a magnetic kicker (which is sometimes accompanied by noise) is under detailed consideration. The committee agrees with this choice. Finally, the plan for the beam transport optimization and for phase 2 were shortly outlined. In summary, important steps have been taken and the importance of a well-suited handling of the double−pulsed structure of the muon beam, for a versatile instrument suite at the S-line has been recognized.

**H Beam Line:**

Dr. N. Kawamura presented a status report on the development of the H beam line. The initial potential users have now converged to a design of the front end part of the channel that can provide a high flux of positive and negative muons with variable momenta from 30 MeV/c to 120 MeV/c. Thanks to the support from KEK and J-PARC, all the front end components including HS1a, HS1b, HB1 and HGV1 have been fabricated and installed in the summer 2012 shutdown.

The three active proposed experiments for the H line are 1) MuHFS, designed to measure the muonium hyperfine parameter to the high precision needed for the analysis of g−2 experimental data, 2) DeeMe, the search for $\mu^{-}$e conversion in a nuclear field, a process that is forbidden by the standard model of particle physics and 3) g−2/EDM, an experiment aiming to measure the anomalous magnetic moment of the muon to a precision of 0.1 ppm. Design work is under way to find a flexible arrangement of separator elements and kicker magnets compatible with the requirements of all these experiments.

# III. Research Projects

## Element-strategy with high-performance μSR:

The committee was impressed with the S-type Inter-University Research proposal presented by Prof. K.M. Kojima aimed at using μSR to help in a comprehensive search for new functional materials that do not contain rare-earth metals and are composed solely of non-toxic elements. Such materials would alleviate the demand for rare-earth elements in technologically sophisticated products, and by removing toxic substances pave the way for environmentally safe disposal.

The proposal is one component of an overall experimental strategy centered about materials synthesized in the laboratory of Prof. Hideo Hosono at the Tokyo Institute of Technology, who is internationally recognized for his discovery of iron-based superconductors and pioneering work in the development of transparent oxide semiconductors. The approach involves the use of light elements in newly developed functional materials and characterization of these materials by several different methods, including μSR and neutron scattering at J-PARC MLF, and X-ray diffraction at the KEK Photon Factory. Here μSR can provide unique information on hydrogen states and diffusion, and complementary information on local electronic and magnetic states. It was exciting to learn that the new MUSE facility will play an integral role in the effort to find next-generation materials with the potential to revolutionize several technologically important areas.

Tied to this proposal is the development of a μSR spectrometer for the S-line that more fully exploits the very high intensity of the J-PARC muon beams. The goal is to have the ability to measure numerous samples in a substantially shorter period of time to provide rapid feedback on exploratory sample synthesis. A constraint of this endeavor is the desire to measure small-size samples. While the design goal of measuring 10 milligram size samples per night seems ambitious, it is unclear at this early stage of this project whether such high sample throughput is at all necessary. The detector will incorporate a version of a new positron detector system (Kalliope), a prototype of which has already been demonstrated to work. Hence there is reasonable probability that a spectrometer can be built that comes close to having the desired specifications. The committee was delighted to hear that there is already funding committed to the muon component of the Element Strategy project, which is sufficient to build this spectrometer.

**Superconductivity Probed by HTF μSR:**

Dr. Koda described a new S type proposal to study superconductors using high transverse field μSR. Such measurements have previously been undertaken by KEK researchers at the M15 beamline of the TRIUMF dc source and these have proved highly fruitful over many years. Particular advantages of a new high flux pulsed source compared to a dc source for such measurements are the high data rates and the ability to study superconducting penetration depths $\lambda$ that are relatively long, either for intrinsic reasons or more generally in the region approaching $T_c$ where $\lambda$ diverges. Conversely, a pulsed source presents problems in covering a wide field range for the measurements due to the limited frequency response associated with the width of the pulse. Two solutions are presented in this proposal. In the first method the width of the pulse is reduced by slicing using a fast kicker. When used in conjunction with a spin-rotator, transverse field measurements may be taken up to 0.4 T, assuming a 10 ns width for the pulse slice. In order to extend the limit of fields above 0.4 T the proposed method is to use a $\pi/2$ RF pulse. Since the time origin is defined by the edge of the RF pulse, the timing resolution is greatly increased and the possibility of working up to 5 T is envisaged. Seven spot frequency RF systems are now available to cover the range from 0.37 T to 3.5 T. The disadvantage of this method is that powder samples must be used to ensure penetration of the RF field. MuSAC/MAC recommends that initial priority should be given to the low-field pulse slicing and static spin rotator method, as this is compatible with single crystals and will allow measurements to be made in a regime where the high flux pulsed source has a clear advantage over the dc sources.

**Muonium Hyperfine Structure:**

Muonium is a purely leptonic atom. The absence of any known inner structure for leptons makes muonium a very well suited system for high precision QED tests and for determining fundamental constants. This includes the fine structure constant $\alpha$ from bound states, muon properties such as its mass ($m_\mu/m_e$) and the muon magnetic moment ($\mu_\mu/\mu_p$). Furthermore, muonium provides a stringent test for the validity of CPT and Lorentz invariance with sensitivity at the Planck scale; the system particularly enlarges the spectrum of sensitively tested particles to such from the second generation. At this time a new series of precision experiments is coming up which are strongly interrelated: the muonium hyperfine structure, muon g−2, and rare muon decays. In particular, the muonium hyperfine structure provides the ratio of the muon to proton magnetic moments which is of crucial importance for the evaluation of the upcoming muon g−2 experiments at Fermilab and at J-PARC.

This experiment aims at a very precise determination of the hyperfine structure interval of Muonium in its ground state and the muon magnetic moment from Zeeman transitions in a strong magnetic field. For this, polarized muons will be stopped in a Kr gas target inside of a microwave cavity which is tuned to two Zeeman transition frequencies at one particular magnetic field. Neutral muonium atoms are formed by elelectron capture from Kr atoms. Electromagnetic transitions are induced by microwaves. The signals from the chosen transitions are associated with a flip of the muon spin polarization and can be observed through the change in the decay distribution of the positrons from muon decays. The experiment will improve over the previous similar experiment by Liu et al. at LAMPF, which was the most accurate muonium spectroscopy measurement so far. It provides a basis for other fundamental muon experiments and for the system of adjusted fundamental constants. For the new experiment it will be important to conduct a larger number of measurements at several different pressures, particularly at the lowest possible ones, in order to obtain a reliable extrapolation of the measurements towards the vacuum values of the transition frequencies.

The collaboration has made good progress in the development of experimental apparatus. This includes, e.g., simulations, a segmented positron detector and a newly designed longer microwave cavity. The latter addresses a crucial point by reducing the muon stops in the walls which prepares for conducting the experiment at the lowest possible gas pressures. This way the influence (and uncertainty) of a nonlinear pressure dependence of the transition frequencies can be minimized, respectively eliminated. In the large bore superconducting magnet a sufficiently homogeneous magnetic field can be provided. With the higher muon beam flux and realistically available beam time it appears possible to gain one order of magnitude improvement over the LAMPF result. This would be a very important advance both for the verification of QED dominated theoretical calculations on a most fundamental pure two-body system and the determination of the muon magnetic moment/muon mass which is to a very large part independent of the correctness of theory. The latter is centrally required for the success and the interpretation of ongoing muon g-2 experiments. For the present hyperfine structure experiment the full exploitation of the high intensity muon beam at the H-line of J-PARC-MUSE will be essential. A narrow momentum bite at high muon flux will be important to optimize the experiment's accuracy. It goes without saying, constant refinement of the experiment by, e.g., GEANT simulations is essential to optimally utilize the beam time.

The design of the apparatus (magnet, cavity), detector system and the beam line (H line) have been making further good progress. The collaboration has a solid strategy, in particular towards minimization of systematic uncertainties. MuSAC/MAC recognizes that this project must be realized at J-PARC. The anticipated results are of highest importance for fundamental physics and other experiments. The committee strongly supports further efforts to get the funding and resources which are necessary to realize this important experiment. It will be crucial to maintain speed and assure the quality of the results which are internationally awaited. For efficient progress we recommend to exploit fully the possible synergies with the other users of the upcoming H-line.

## μN-eN Rare Process:

An improved search for the lepton flavor violating process μ+Z -> $e^-$+Z is suggested for the H-line at J-PARC. The experiment aims for the observation of a possible process which is suggested in a number of scenarios beyond the present Standard Model of Particle Physics. It is highly motivated and has a robust discovery potential for lepton number violation. For its full success this experiment needs to have results before other experiments (COMET/Phase-2, Mu2e) aiming to observe the same process at higher precision come into a production stage. With the sensitivity goal of $10^{-14}$ the proposed experiment is very timely right now. It can be considered also an important step on the way towards ultimate higher accuracy.

MuSAC/MAC recognizes the progress in the ongoing R&D such as wire chambers, kicker, SiC target which are carried out in part in collaboration with international recognized laboratories. This approach is applauded and essential for fast progress. Proton background outside the beam pulses is studied and the tests and studies so far are very encouraging. The tests prove that the aimed for accuracy can be achieved. MuSAC/MAC further acknowledges that resources have been allocated to the μ+Z -> $e^-$+Z project and that the collaboration is increasing. In particular, the hiring of two dedicated post-docs is a step in the right direction.

In view of the new precision territory ahead the optimistic time schedule can only be met, if the experiment will have large, strong, and lasting commitment of both the researchers and the laboratory. Such a most demanding experiment can only be a full success, if there is no interference with other projects and the resources are sufficient and steady. For a project of this size in a field, with strong international competition aiming for an ultimate sensitivity beyond the present project, a clear work breakdown schedule with clear responsibilities and accompanied by a realistic time schedule with contingencies is considered essential.

The experiment can be expected to beneficially share the large acceptance H-line with the muonium hyperfine structure and g−2 experiment. Collaboration on this issue between the experiments is recognized and appreciated. Further progress will require sufficient resources to be allocated towards both the experiments and the beam line. It appears very important that the present concentration on most promising projects is maintained and that full dedication of the researchers in the collaborations in fundamental muon physics is met with adequate manpower and resources.

## Muon Microscope (Kakenhi):

Prof. E. Torikai overviewed the present status of the muon microscope project supported by the grant-in aid for scientific research in innovative area (KAKENHI, Shin-Gakujyutsu-Sousei) involving a large community of applied muon scientists. This program using an ultraslow muon microscope aims for real-space imaging and probing spin-related properties and their dynamics covering physics, chemistry and biology. The committee highly evaluates this ambitious and attractive program based on the long-term developments for an ultra-slow muon beam in Japan.

The microscope basically consists of a source of thermal muonium, an ionization stage by a Lyman alpha laser and a transport system. An intense pulsed muon beam, a necessary prerequisite for a powerful source, of 2.5 Mevents/pulse at 212 kW was recently obtained. The second crucial element is the laser setup. A scheme using two-photon resonance and four waves mixing with a combination of solid-state lasers and a Kr gas cell was adopted. After substantial efforts, Lyman alpha 122 nm photons were produced (at 100 μJ power). However, a drastic enhancement of the intensity and of the stability is necessary and a vigorous development effort is required to reach the final goal in the performance of the laser system. Following Prof. Torikaii's report, Dr. Ohishi showed the advantage of a ceramic crystal over the previous single crystals for amplifying the laser beam. During this year long shutdown, we recommend the collaboration to select prioritary experiments among the proposed ones in accordance with the envisaged scientific impact. The International Symposium on Science Explored by USM (IUSM2013), which will be held in Matsue for August 9-12 2013, is a suitable opportunity to discuss these issues.

## ASRC(JAEA)-KEK Project:

Dr. W. Higemoto presented recent progress in the instrumental development for μSR measurements in D1 area, and reviewed the results of his leading JAEA-KEK project entitled "Microscopic study of novel properties of f-electron systems by means of μSR". As for cryogenic techniques, the temperature range covered by a compact $^4$He cryostat has been extended down to 2.5 K, leading to a useful improvement of the connectivity to the lower-temperature experiments with a dilution refrigerator. Other developments in a Fly-Past system, a Kicker Control system and an Image Intensifier (IIT) muon-beam profile monitor have allowed to improve the quality of the μSR experiments. Scientific research activities in FY 2012 have mainly focused on investigations of the coexistence of superconductivity and on antiferro-quadrupolar ordering in the caged-structure compounds $PrIr_2Zn_{20}$ and $PrTi_2Al_{20}$, which are currently the most attractive materials in the f-electron physics. MuSAC/MAC was impressed by the work presented by the ASRC group: their careful ZF- μSR studies demonstrated that the former shows no change in the relaxation rate at the superconducting transition temperature, while the latter displays a slight increase suggesting the possible presence of odd-parity superconductivity. MuSAC/MAC acknowledges that the project has progressed very successfully, and after hearing about the research plan expects that further progress will be obtained in the future.