Report of the J-PARC
Muon Advisory Committee (MAC)

MAC-2020

April 2021

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MAC-2020 was held as a zoom virtual meeting on February 1st, 4th, 12th and February 22nd, 2021.

I Facility Overview

Greetings from IMSS

Professor N. Kosugi, Director of KEK-IMSS, introduced the activities of the Institute of Materials Structure Science (IMSS). IMSS is one of 17 inter-university national research institutes and it is in charge of operation and academic user programs of multi-probe research for life and materials science with photons, slow positrons, muons and neutrons. The scientific interest is on the investigation of a wide variety of geometric and electronic structures in bulk, surface, heterogeneous, and complex systems, with the goal to develop basic principles and concepts for the creation of new functional materials that are useful for the realization of a sustainable society. In recent years, the use of quantum beams such as muons, neutrons, synchrotron radiation, and slow positrons has become indispensable for the study of materials with widely different length and time scales of fluctuations. In particular, to understand the diversity and multifaceted nature of materials and life science, it is important to utilize various types of quantum beams in a combined and collaborative manner.

J-PARC Overview/Charge to MAC

J-PARC Director Professor N. Saito gave an overview of J-PARC status and activities, highlighting the J-PARC research focusing on the origin of matter and universe, and on exploring the diversity of matter and life. The J-PARC accelerator and MLF established stable operation at 600 kW in JFY 2020, delivering proton beam to MLF with a world class availability of 95.3%. Operation at 1 MW has been demonstrated for 36.5 hours, and preparations for routine operation at beam power > 600 kW are continuing. On the main ring (MR) side the J-PARC budget for JFY 2020/2021 will allow 1.5 months of operation of MR-SX (as requested), the production and installation of new power supplies for the MR to be completed in JFY2021, and facility and accelerator upgrades of MR up to 750 kW.

MEXT selected 15 of 31 Projects of The Japanese Science Council (JSC) Master Plan 2020, among them the J-PARC g_{μ}-2/μ_{edm} experiment at the H-line as “Important and Urgent Projects”. Finally, a set of charges was given to MAC to evaluate the facility operation and to make suggestions for improvements.

MLF Overview

Professor T. Otomo, the new Division Head of MLF, gave an overview of facility status and beam operations in FY2020. The MLF management staff has been renewed in FY2020: new executives were appointed for the IMSS Neutron Division (S. Itoh), MLF Deputy and IMSS Muon Division (K. Shimomura), and CROSS (M. Shibayama). The Neutron Science Section and Technology Development Section received new section leaders as well. MAC recognizes the increase of proton beam power from 500 kW to stable operation at 600 kW as a further important step towards stable operation at the design power of 1 MW. A successful 1 MW beam operation was achieved in June for 36.5 hours.

The facility was forced to shut down for about 4 weeks in April/May 2020 due to the Covid-19 pandemic. Most of the lost beamtime was compensated, and, due to limited user access to MLF, a mail-in service for samples and automation/remote operation of experiments has been set up in available beamlines.

MAC acknowledges the steady increase of the number of proposals submitted to MLF, the increase in scientific output, and the stabilization of the number of single users at a high level of about 1100/year. This indicates the large interest of the user community and increasing impact of MLF in science.

MUSE Facility Overview

Professor R. Kadono reviewed the present status of the MUSE facility with some highlights covering the latest developments since FY2019. The S2 area has been under construction by a group of Okayama University in FY2020. The major installation work for the radiation-controlled area is nearly completed. Approval from the Nuclear Regulatory Authority and local government is pending. The situation is similar for the H line and associated H1 area, where the installation work for the beamline magnets and associated infrastructure (cabling, cooling-water, etc.) has progressed during the summer shutdown. The rotating muon production target (which was renewed in FY2019) and its assemblies worked reliably, and suitability for 1 MW operation was confirmed in a 36.5-hour test operation in June 2020. At the D line, a leak in the outdoor He gas piping between the compressor building and MLF experimental hall No. 2 was uncovered during regular maintenance in the summer shutdown. Its cause was identified to be a result of corrosion from salt damage, and several measures were implemented to avoid such damage in future.

In the open experimental areas, a variety of scientific activities were conducted under the Inter-University Muon Research Program (IUMRP) using instruments installed at D1/2, U1A/B, and S1. At S1, a first successful test of the new 5-T μSR spectrometer “CYCLOPS” was carried out at zero field. The impact of the COVID-19 pandemic on IUMRP is so far limited to the partial loss of beamtime, where many efforts have been taken to minimize the actual loss by postponing experiments for external users at the expense of beamtime for internal staff and for the beamline/instrument commissioning works. MAC highly appreciates the flexibility of the MUSE staff in ensuring the continuation of facility operation in this difficult time of the pandemic.

Inter-University Research Program

MAC is pleased to see that the number of submitted proposals and overbooking of 1.6 have now reached a high level, comparable with other international muon facilities: 106 (17 international, 6 P-type) in 2020A/B, after 108 proposals (20 international, 7 P-type) in 2019A/B. MAC evaluates that this is due to the continuing efforts of MUSE staff in improving instrumentation and to expand and support the user community, as well as to the world-class availability of the proton beam, providing long term stable conditions to run the experiments. MAC recommends a careful survey of the degree of satisfaction of the users. MAC also acknowledges the continuous progress of the 2nd-stage S-type proposals.

As in the previous years, the scientific results from the Inter-University Research Program maintain a high standard of productivity. MAC was again impressed to see several significant studies on a variety of topical subjects: μSR studies on the crystallization process of FINEMET nano-crystalline alloys, spin-1/2 random J1-J2 square-lattice Heisenberg antiferromagnets, spin dynamics in two-dimensional magnets, hydrogen trapping sites in Al-alloys, muon stopping sites in proteins, Na diffusion in $Na_{0.7}CoO_2$ by negative muons, i.e. μ–SR, irradiation tests of pixel detectors for the g_{μ}-2 experiment, and non-destructive negative muon elemental analysis on bottled Kampo medicines of archaeological interest.

MAC appreciates the promotions and addition of permanent staff of MUSE from ten to twelve. MAC considers it essential to have a large fraction of permanent staff in MUSE for the future operation of the facility, to ensure continuity of instrument development and user support, and to mitigate the risk of losing key know-how. Although the number of permanent staff increased, the total number of staff in MUSE remains unchanged, since the number of non-permanent staff decreased by two. MAC is still concerned about the shortage of manpower which may cause significant difficulty in keeping and developing the activity of MUSE in view of the planned expansion of the facility in S2 (S3/S4), H1, and H2 areas.

MAC recommends increasing efforts to establish new links between MUSE and other organizations, and to make collaborations tighter with universities and private companies, not only in Japan but also overseas, to establish a system for sharing human resource management, such as introducing cross-appointment positions, organizing and providing attractive career-paths.

II MUSE Facility Activity

Muon Source Facility: M1/M2 Area

The muon section is responsible for the safe operation of the proton transport tunnel in the vicinity of the muon production target. This task includes a substantial effort to mitigate radiological hazards related to activation by the proton beam. The primary concern has been tritium production and migration, but new hazards are beginning to emerge such as the short-lived ^{24}Na. With increasing beam intensity towards 1 MW, these hazards will continue to grow. At other facilities, this task is accomplished by a dedicated expert group in a coordinated site-wide manner. While there may be advantages to the existing strategy (for example, the muon section has the most direct interest in the safe operation of the M1/M2 tunnel), there are also disadvantages: the scientists are not experts of mitigating radioactive hazards, and the responsibility presents a substantial manpower demand on a section that is already significantly understaffed. MAC recommends using manpower and the specific expertise of staff more efficiently and effectively for the overall productivity and safe operation of J-PARC.

The muon section has admirably performed this role, designing and implementing the buffer tank system to control tritium venting, and forming a productive collaboration with Toyama University to better understand the production and migration of tritium in the muon target itself. Radiation monitoring and mitigation will certainly continue to be a challenge as the beam current increases.

Muon Production Target

Following a mechanical failure of the rotating feedthrough linkages, the spare target (with improved linkages) was installed in 2019. It appears to be operating well and has shown no signs of problems so far. However, there is now *no backup target*. In case of a failure of the present target, this risks the entire muon program. The muon section has taken two approaches to mitigate this risk: 1) enhancing in situ monitoring of the operating target to anticipate and avoid failures on the fly, and 2) to begin the process of generating a new spare target. The first approach is making excellent progress with a radiation resistant IR camera able to monitor the target temperature distribution during operation and the development of an autonomous machine learning system to monitor the rotary mechanical system. These are particularly important strategies and MAC recognizes these as evidence of strong progress. Approach 2) is, however, lagging, largely due to budgetary limitations. The task has also been made more difficult by a loss of expertise in design and fabrication specific to the target. Manufacture of a new target is eventually essential, as its lifetime is finite. Despite expectations that the normal lifetime will be quite long, there is little actual experience with targets of this kind. From this point of view, MAC considers it quite urgent that a spare target should be constructed now, particularly since the full stress of 1 MW operation may reveal unanticipated problems.

μSR Spectrometer and sample environment

On the S-line, the S1 kicker is required to select the time structure (single versus double pulse) at the S1 end-station. There have been ongoing problems with the HV driver for the S1 kicker, causing about 5 failures per year, with the risk of beam time loss for several hours every time. Since August 2019, a new smoothing capacitor has been inserted, and the failure rate has been strongly reduced. This improvement is not only important for smooth operation of S1, but it will also be essential for the operation of the S2 beamline.

A remarkable progress was achieved for the D1 spectrometer. Among many things, two major improvements have been done concerning the deviation of the zero-field condition along with identifying the origin of the distortion of the early time domain in the μSR time spectra, especially for thicker samples.

Efforts to develop new measurement techniques and equipment are also ongoing. The μSR spectrometer for high fields (CYCLOPS) has been tested using the muon beam in S1. A new technique was also developed to reconstruct the time spectrum with continuously varying temperature and/or magnetic field without waiting for stabilization. This method could potentially improve the efficient use of high intensity muon beams and is called the transient μSR technique. For the sample environment, a particularly notable addition is the newly commissioned ^{3}He cryostat, Heliox ACV. In 2020B term, four proposals using Heliox ACV were approved, which is 16% of all proposals at the S1 area. In addition, in June 2020, an experiment using Heliox ACV was successfully conducted in fully remote operation. Some bad news is that the closed-cycle cryostat (CCR), the so-called "Dry Lemon", is not available for user experiments due to a cold leak problem. The Dry Lemon system indeed had some issues since it was installed. It is rather slow to stabilize, and the highest reachable temperature was limited to about 470 K. However, for several important research areas with high societal impact (e.g., energy materials) it is important to conduct systematic and efficient measurements in the broader temperature range 20 – 700 K using a stable CCR system. MAC recommends that priority is given to achieve such capabilities (either by repairing and improving the Dry Lemon system and/or by finding some alternative).

The overall progress on the spectrometers is very impressive and MAC congratulates the team for their excellent and hard work.

Negative Muons @ D-line

Due to COVID-19, the beam was shut down in April/May 2020. As a result, the number of beam days at the D-line was reduced to 73% of the days planned for JFY 2020. By exchanging the beamtime of external users with that of the internal staff, the number of beamtime deferred days could be reduced to 14.5 days (7 users) in the D-line. However, this caused a big load for the internal staff. In order to prepare for similar situations in the future, a more efficient operation system and environment are required.

Significant progress is reported in the negative muon elemental analysis program by improving the X-ray detection efficiency based on the pulsed character of the muon beam, where the instantaneous rates are very high. This has been achieved by increasing the number of detectors with multiple pixels and large solid angle coverage. Last year, two 100-pixel detectors were kindly transferred from the Photon Factory and Spring-8. New DSP modules are used to develop a signal processing circuit system for multi-pixel detectors at much lower cost compared to the conventional read-out system: 0.1 million Yen versus 200 million Yen per multi-pixel detector – clearly a substantial savings! Test operation of a set of DSP modules for one 100-pixel detector showed a more accurate timing information, but the observation of an unexpected background component requires further investigation.

MAC recognizes that the research program with negative muons is very broad, comprising general proposals, industrial applications, joint projects of humanities and sciences, and educational experiments, and that this is a strong point for MUSE and, indeed, for all of J-PARC.

U-line/Ultra Slow Muons: Beamline

The Ultra Slow Muon (USM) project is in progress. The μSR spectrometer at the U1A experimental area has been commissioned, making it ready for DAY-1 experiments. Muon spin rotation was observed in a multilayer sample of platinum and silica, with available implantation energies of 0.5 – 30 keV, energy and time resolution of ΔE ~ 50 eV and Δt ~ 10 ns, respectively. Due to expected improvements on 1) the USM generation efficiency 2) beam transport and 3) detection efficiency, enhanced beam characteristics are expected within the next three years (1000 Hz rate, energy range of 0.1 – 30 keV, ΔE ~ 10 eV and Δt ~ 1 ns). With these parameters, a user program comparable to the LEM facility at PSI can be envisaged.

Decay positrons from the upstream beamline cause background, which will be shielded by a new wall of lead in front of the spectrometer. The effect of the shielding will be evaluated in February 2021. A problem with electric noise on the high-voltage stage caused fluctuation in the implantation energy of the beam. This was solved by modifying the power supply path of the spectrometer's magnet, to reduce the noise from 30 V to 4 V peak-to-peak. In preparation for the start of user experiments using USM, optimization of the extraction scheme and transport optics to increase the beam intensity is under study. A detailed comparison of experiments and simulations of beam transport will provide a quantitative and comprehensive understanding of the entire system. The goal is to carry out test experiments of USM-μSR by the end of 2021, and to start user programs within about three years.

MAC congratulates the team for the progress and appreciates the presentation of a clear project plan.

Laser System

Continuous investigations of the final amplification stage at the primary wavelength of 1062.78 nm have been carried out. The team received newly fabricated Nd:YSAG laser ceramics for the crucial power amplifier optimized at the precise wavelength required for the muonium ionization scheme. The ceramic shows good amplification gain at 1062.78 nm. But some level of wave form distortions is found in the transmitted wave front. This could lead to low conversion efficiency and possible damage to the crystal. The adoption of a deformable mirror helps to compensate the wave front distortion without laser pumping. The feedback software of the deformable mirror has been optimized for amplifying operation. To reduce manpower and costs for maintenance, the team changed the light source from a commercial flash lamp to an all-solid-state 1062.78 nm laser. The number of USM is measured to be almost same as with the previous configuration used last year. The lifetime of Lyman-α optics was also studied for higher power operation. It was found that there are several life-time issues for the Kr/Ar mixture gas, the UV transparent LiF gas cell window and steering mirrors. Countermeasures are under investigation.

MAC is pleased to see the significant progress by the team, especially by the newly assigned two persons for laser maintenance. Additional support by laser experts is especially important for further improvements of the laser power.

H-line

Completion of the H-line is essential for the approved science program in fundamental physics with DeeMe and MuSEUM in the H1 area, and later with TμM and g_{μ}-2/μ_{EDM} in the future H2 and extension hall. MAC congratulates the involved teams for the major progress in the construction of the H-line and the H1 area in 2020. Most beamline components, magnets, separator and vacuum system have been installed. The necessary electrical and cooling connections for some of the beamline magnets (HB1/2) were put in place for a minimal configuration, to enable initial beam tuning at lower rates after the operation approval by the Nuclear Regulation Authority. It is of utmost importance that the rest of the beamline installations can be completed in the summer shutdown of 2021. MAC urges the management to assure the necessary resources are available. Beam commissioning at the highest rates will be possible in fall of 2021. MAC welcomes the further involvement of the experimental collaborations DeeMe and MuSEUM in the necessary setup and commissioning work. Careful and complete characterization of the beam properties in the H1 area and in various operation regimes will be important for a full understanding of systematics and should be planned and scheduled.

Considerable progress was made towards establishing the building for the H2 area. Important in this respect is a new six-year Grant-in-Aid funding for g_{μ}-2/μ_{EDM} and the submission of a KEK request for full construction funding.

MAC recommends reviewing the readiness of the important experiments DeeMe and MuSEUM, both for the hardware and their analysis strategies, and to schedule their respective commissioning runs and provide perspectives for data taking. Both fundamental particle physics experiments, if they achieve their envisaged performances, can soon take the lead in their field and provide world-leading results from J-PARC.

III Research Projects (S-type proposals)

The presented research reports demonstrate the rich field of muon applications, from fundamental particle physics to condensed matter physics, materials science, elemental analysis, and ideas to use the muons as novel microscopy/tomography probe. This broad field of topical applications is a strength of MUSE.

Development of D1 spectrometer instruments and μSR experiments in strongly correlated electron systems

The development of the μSR spectrometer and related instrumentation at the D1 area for research on strongly correlated electron systems is continuing. Recently, a lower background set up for μSR measurements has been realized. In FY2020, following items were studied:

1) Origin of distortion of μSR data: when the kicker is operated, a significant distortion of μSR spectra was observed at D1. This distortion is remarkable in thicker samples. It was established to be due to positrons originating downstream of the DC separator.
2) Zero field μSR is an extremely important class of experiments, particularly in the investigation of magnetic materials. At D1, a zero magnetic field is achieved by active field compensation using magnetic field probes and a feedback coil system. A residual magnetic field of several tens of μT, observed under zero magnetic field condition, is now significantly reduced by improving the feedback system, and continuous monitoring during data taking.
3) μSR measurements on strongly correlated electron systems are being carried out on following topical subjects: novel magnetism in the BiS_2 superconductor, time reversal symmetry broken superconductivity in non-centrosymmetric superconductors, and evolution of magnetism and superconductivity towards quantum critical point.

Microscopic mechanism of hydrogen-sensitive properties in inorganic materials

Progress has been made on the S2-type research project entitled “Microscopic mechanism of hydrogen-sensitive properties in inorganic materials” started in 2019B. The project is a part of the “Element Strategy Initiative to form Core Research Centres for Electronic Materials” (headed by H. Hosono, TITech, under support from the MEXT under Grant No. JPMXP0112101001, 2013-2022) for which KEK-IMSS serves as a satellite core for the materials analysis of using multiple quantum beams including synchrotron X-rays, neutrons, and muons. In this muon S2-type project, the materials analysis using muons is conducted with special focus on the role of hydrogen in semiconductors and ferroelectrics, using the well-known tendency of the positive muon to form the light hydrogen-like muonium atom in such materials. This comprehensive project is clearly an optimal target for using the unique properties of muons, and the complementary utilization of other quantum beams (X-rays and neutrons) makes this an important flagship venture. Ideally, in the future this project could also act as a platform for additional developments and studies of other hydrogen related materials (e.g., in situ studies of dynamics in H-storage materials, etc.). MAC acknowledges the importance of this project and congratulates the team for the excellent progress and prompt scientific output.

Applications of Muon Radiography for the "Photon and Quantum Basic Research Coordinated Program"

The current status of the development and application of "negative muon radiography" was presented. Negative muon radiography is a non-destructive elemental depth-profiling analysis in materials using muonic X-rays emitted during the formation of muonic atoms. Thus far, this method has been applied to the development of lithium batteries and to archaeological research, as well as soft error research. Current developments focus on improving the beam intensity in the low momentum regime around 2.6 MeV/c to allow investigating samples closer to the surface. An important improvement is the installation of 100-pixel and 13 array Ge detectors, which are expected to make a significant contribution to archaeological research, particularly, for the near surface.

Examples of the current archaeological research program are the analysis of tin and lead concentration in a bronze mirror and Buddhist chant bottle, which were excavated from an abandoned temple in the 12th century, and the study of silver and copper coins, so called Cho-gin, used in the Edo period in Japan. An example of soft error research is the study on bulk planar 20 nm SRAMs, where muon induced SEUs (Single Event Upsets) and MCUs (Multi Cell Upsets) were much more affected by the capture reactions induced by the negative muons.

Development of Negative Muon Experiments using Cosmic X-Ray Gamma-Ray Detection Technique. From Atomic Physics to High-Precision 3D Non-Destructive Elemental Analysis

This S1 proposal has been carried out under the Grant-in-Aid for Scientific Research on Innovative Area, entitled ``Toward new frontiers: Encounter and synergy of state-of-the-art astronomical detectors and exotic quantum beams". By using the negative muon beam at MUSE, two types of experiments were started by the team which consists of members from completely different research communities:

(1) Precise spectroscopic measurements in atomic and molecular physics to test, for example, quantum electrodynamics (QED) predictions. By using a multi-pixel high resolution transition-edge-sensor (TES) calorimeter, the team observed the 5g-4f and 5f-4d transitions of the muonic

Ne atom at E=6298.5 eV with an energy resolution of 6-7 eV (FWHM). Such an energy resolution is required to verify results of theoretical calculations.

(2) Non-destructive elemental analysis of extra-terrestrial samples. Muonic X-rays are ideally suited for studying the amount and distribution of light elements. The method will be used to quantify C, Mg, Si and O concentrations in asteroids. Asteroid samples are small, so the sensitivity must be improved to detect the faint muonic X-ray lines by reducing background. In addition to the present setup with Ge detectors, the team has started to implement 3D imaging by utilizing newly developed CdTe imagers and image reconstruction methods which are used in the field of medical imaging.

Transmission Muon Microscopy

The aim of the proposal is to realize the transmission muon microscopy (TμM) to visualize sub-millimeter-thick objects with nm resolution. In the 1st phase, TμM of an object with a thickness of about 10 μm by a 5 MeV beam was set as the goal. An AVF-type cyclotron with flat-top RF field is employed to accelerate the 30 keV USM beam to 5 MeV with a small energy dispersion $\Delta E/E \sim 10^{-5}$. Such a small ΔE reduces aberrations of the objective lens and provides a high resolution comparable to that achieved in electron microscopy. In this fiscal year, a 3D magnetic field measurement system using a search coil, which can measure steeply varying field with high linearity, was constructed, and the magnet of the cyclotron was tuned by shimming. Finally, the team succeeded in confirming the cyclotron's isochronous magnetic field which is needed to provide the required energy dispersion.

The team tried to obtain muon-diffraction using a prototype of TμM and the 30 keV ultraslow muon beam. However, before obtaining meaningful data, problems of the Lyman-α laser system must be solved. The team presented a clear timeline to accomplish their goal in three years.

MAC is pleased to see that this particularly challenging project has started as one of the competitive programs of MUSE. MAC acknowledges that the project needs more resources to keep the schedule and suggests defining clear milestones and critical paths.

Precision Measurement of Muonium Hyperfine Structure and Muon Magnetic Moment

The MuSEUM collaboration aims at a new precision determination of the ground state hyperfine splitting (HFS) in muonium (Mu) through measurements at, both, very low ('zero') magnetic field and at a high magnetic field. Together with a separate determination of the muon mass from an improved measurement of the Mu 1S-2S transition frequency, the muon magnetic moment can be determined and the most precise test of QED in a bound system performed. The measurement is extremely timely, given the upcoming 1S-2S measurements and the FNAL g_μ-2 experiment, and should be pursued with high priority.

The collaboration has performed ever improving zero field measurements over the past years and plans to perform a final zero field run in 2021. They have shown impressive first results and now depend on moving to the H1 area to perform the high field experiments at high muon intensity. Timely completion of the H-line is therefore mandatory.

In order to prepare for an immediate start in the H1 area, the MuSEUM collaboration is working towards the completion of their experimental setup. They are pursuing a very promising effort in shimming the magnetic field of their large MRI magnet, they are completing the development and inter-comparison of magnetometers and started R&D for future upgrades using ^{3}He probes. They are working on the stabilization of the microwave cavity, implementing modifications to the gas target for higher density measurements including an improved pressure measurement, and they will add an upstream positron detector that will contribute to an improvement of the statistical sensitivity.

Because of the importance of the accuracy of the future result of the MuSEUM measurement, MAC would like to reiterate its request for the MuSEUM collaboration to establish upfront a robust scheme for an unbiased, blind analysis.

Search for Muon-Electron Conversion Utilizing Pulsed Proton Beam from RCS (Rapid-Cycle Synchrotron)

The DeeMe project has further progressed preparing their apparatus for the phase of the search for muon to electron conversion with improved capabilities. The physics goal is very topical, and the project should be pursued at high priority. DeeMe urgently needs the H-line at full intensity to commission, in sufficiently long beam-times, their full system and investigate in detail all backgrounds. DeeMe presented first results from the 2019 measurement campaign and demonstrated excellent progress with their novel HV-switching MWPCs. As their grant runs up to 2023, it is of utmost importance that they reach physics data taking as soon as possible. They have been involved already and will continue to strongly support the construction and commissioning of the H-line. From the side of the facility every effort should be made that the completion of the H-line can proceed without further delays in this year.

On the side of the collaboration, it would be good to carefully analyse the decay-in-orbit data of 2019 and show the results. Towards physics data taking, MAC encourages the collaboration to present a detailed plan for the analysis, including the concept for data blinding. As the experiment would soon enter uncharted territory and have a considerable discovery potential, it appears important to develop and vet the analysis scheme upfront.

Precision Measurement of Anomalous Muon Magnetic Moment

The muon g_{μ}-2 anomaly remains an important agenda item in particle physics. The prediction from the standard model of particle physics was updated in 2020 by the muon g_{μ}-2 theory initiative. Currently, the difference between theory and experiment is 3.7 standard deviations. A new experiment is running at Fermilab. An international workshop will be hosted at KEK in 2021 to discuss physics in the post Fermilab g_{μ}-2 era.

The collaboration worked with the muon science laboratory and the J-PARC centre on preparation for the extension of the H-line. In FY2020, a survey of buried cultural property, ground survey, area levelling survey, design of rerouting control cables in the area was completed at the proposed site adjacent to the main MLF hall. In parallel, the collaboration has made progress on development of the experimental apparatus towards the targeted start of the experiment in 2025.

The collaboration received a new Grant-in-Aid funding for 6 years. This grant allows full construction of the positron detector, DAQ, B-field monitors, and to develop the software. The grant allows implementing part of the computing resources, injection beam transport line, low-beta and medium-beta acceleration RF cavities. The remaining parts rely on funding from KEK which will request funding from MEXT for the full construction.

Precision Measurement of the Muon Mass by 1S-2S Laser Spectroscopy of Muonium

In order to reduce the muon mass uncertainty, laser spectroscopy of the 1S-2S transition of muonium (Mu) is highly suitable. The experiment of two-photon excitation of Mu using a 244 nm pulsed-laser is planned to start this year as the first step. For the experiment, a new beam area (S2 area) was designed and constructed. A laser booth was also designed to house the 244 nm laser system safely and appropriately within the MLF experimental hall. The S2 muon beam optics was optimized by G4Beamline simulations. The muon beam profile has a Gaussian shape with a FWHM of about 77 mm horizontally and 29 mm vertically at the end of the final quadrupole triplet. The detection system of laser-ionized slow muons was re-configured and re-aligned to obtain a 33% improvement of the transport efficiency, which was checked by H^+ transport. A pulsed laser system with narrow-linewidth (<100 MHz) and high pulse energy (~5 mJ) at 244 nm is required for the experiment. There are several schemes to obtain narrow-linewidth laser pulses. Two schemes based on Ti:Sapphire laser cavities and regenerative amplifiers using Yb doped fibres are most promising. The pulsed laser system is under development at the moment.

IV General Comments and Recommendations

MUSE pursues a well-balanced program between materials science, fundamental physics and developing new research directions (e.g., use of negative muons, muon microscopy). Such a stimulating environment allows for the development of first-class scientists with broad perspectives, and the training of young scientists. The excellent achievements of the MUSE facility are only possible thanks to the outstanding work of the MUSE team, which became particularly evident in the way the team managed the difficult situation of the Covid-19 pandemic.

MAC appreciates the continuing interest from broad scientific communities in muon science at J-PARC, the increasing scientific output, and we recognize the continuous efforts on providing safe operation of the facility.

MAC is pleased to see the very stable operation at 600 kW proton beam power with an outstanding availability of 95.3%. In 2020, another test at 1 MW for 36.5 h demonstrated, that the MUSE beamlines and instruments are ready for the 1 MW operation, and MAC is looking forward for stable long-term operation at 1 MW planned for 2023.

MAC acknowledges the efforts in finishing the S2- and H-lines: these are especially important steps to start/continue the long-awaited particle physics programs at these lines.

MAC appreciates the progress in the Mu laser ionization program for the generation of USM, which is of pivotal importance for MUSE (USM μSR, TμM, g_μ-2). The Mu 1S-2S two-photon transition could be a promising backup scheme to the Lyman-α 1S-2P transition. MAC acknowledges the report and supports the recommendations of the Laser Advisory Committee which met at J-PARC in January 2020. MAC recommends a re-evaluation of the laser system by the Committee within the next two years. MAC reiterates its recommendation to setup a "laser development team" under the responsibility of J-PARC to ensure long-term stable laser operation for all experiments requesting USM.

MAC is pleased to see the increase of permanent staff by two – which MAC considers as an extremely important step in the transition of MUSE to a users' facility. However, additional staff are still needed with part of their duties assigned to the 'instrument scientist' role that includes assisting new users in preparing proposals and learning to run their experiments. Developing a strong and stable muon user community relies on such support from the facility. The reduction by two non-permanent staff does not alleviate the critical manpower shortage at MUSE. This is one of the most important concerns about the operation and further development of the facility.

Therefore, MAC reiterates its recommendation to make available additional staff. As a first step, MAC recommends strengthening the group of MUSE staff responsible for the M1/M2 proton beam line and muon production target. On a medium-term, MAC recommends managing the safe delivery of proton beam by a J-PARC group with the expertise and capabilities to deal with these issues in a uniform site-wide manner, which would also correspond to international standards. In this manner, additional manpower can be released for running the muon science program at MUSE. Additionally, MAC strongly recommends that MUSE management establishes new links with other organizations to widely support the muon activities and community by increasing the number of staff to keep and enhance the current and future activities. As a further step, MAC encourages the management to establish joint appointments with universities and companies, to take up some of the tasks of user support. Besides helping in manpower, this would strengthen connections in various research areas.

MAC considers it urgent that a spare target should be constructed now, particularly since the full stress of 1 MW operation may reveal unanticipated problems. MAC recommends that MUSE works on a spare muon target with very high priority, and to provide the necessary funding. As the new target is developed, a clear record should be kept preventing future losses of how-to expertise. MAC recognizes that some efforts are already underway, including planning for a storage vessel for the spare target, but MAC encourages that a budgetary plan for rapid production of a spare target should be considered now in order to be prepared for any unanticipated failure of the current target.

Despite the recent budget reductions since 2019, MAC is pleased to know that MUSE has acquired an additional budget for the construction of H-line.

In view of the various projects and limited manpower, MAC reiterates its recommendation that the MUSE management clearly articulates the priorities of various projects in order to ensure their efficient completion and timely scientific output. It is also essential to develop a plan for the resources required to run MUSE as a user facility with all beamlines completed.

APPENDIX I

Members of MAC:

Hiroshi Amitsuka (Hokkaido University)

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Andrew MacFarlane (University of British Columbia)

Martin Mansson (KTH Royal Institute of Technology)

Takashi Nakano (Research Center for Nuclear Physics)

Thomas Prokscha (Paul Scherrer Institute) Chair

Tadayuki Takahashi (University of Tokyo)

APPENDIX II

Charges given to MAC:

- Evaluate the appropriateness of the facility operation and its upgrades with respect to the following points:
  - safe, stable, and efficient operation towards the production of science in timely manner
  - timely construction of beamlines and its preparation to maintain the uniqueness of the facility attracting not only domestic users, but also international users.
  - operation and maintenance of proton beamline up- and downstream of the muon target
- Any suggestions for improvements are appreciated. Our particular concerns include but not limited to the followings:
  - limited manpower to operate and maintain the muon beamlines,
  - Urgency of the muon target back-up, commissioning of U-line, and preparation for H-line construction, and remaining S beamlines.