Design and construction of the ultra-slow muon beamline at J-PARC/MUSE

P Strasser[1,2], Y Ikedo[1,2], S Makimura[1,2], J Nakamura[1,2], K Nishiyama[1,2], K Shimomura[1,2], H Fujimori[1,2], T Adachi[1,2], A Koda[1,2], N Kawamura[1,2], Y Kobayashi[1,2], W Higemoto[3,2], TU Ito[3,2], T Nagatomo[4], E Torikai[5], R Kadono[1,2] and Y Miyake[1,2]

[1] Muon Science Laboratory, Institute of Materials Structure Science, High Energy Accelerator Research Organization (KEK), 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan
[2] Muon Science Section, Materials and Life Science Division, J-PARC Center, 2-4 Shirane Shirakata, Tokai-mura, Naka-gun, Ibaraki 319-1195, Japan
[3] Advanced Science Research Center, Japan Atomic Energy Agency (JAEA), 2-4 Shirane Shirakata, Tokai-mura, Naka-gun, Ibaraki 319-1195, Japan
[4] Ion Source Team, Accelerator Group, RIKEN Nishina Center, RIKEN, Hirosawa-2-1, Wako, Saitama 351-0198, Japan
[5] Interdisciplinary Graduate School of Medicine and Engineering, University of Yamanashi, Takeda 4-3-11, Kofu, Yamanashi 400-8511, Japan

E-mail: patrick.strasser@kek.jp

Abstract. At the J-PARC Muon Science Facility (MUSE), a new Ultra-Slow Muon beamline is being constructed to extend the μSR technique from bulk material to thin films, thus empowering a wide variety of surface and nano-science studies, and also a novel 3D imaging with the "ultra-slow muon microscope". Ultra-slow muons will be produced by the re-acceleration of thermal muons regenerated by the laser resonant ionization of muonium atoms evaporated from a hot tungsten foil, a method that originated from the Meson Science Laboratory at KEK. The design parameters, construction status and initial beam commissioning are reported.

1. Introduction

The Muon Science Facility (MUSE) [1] is now under construction at J-PARC (Japan Proton Accelerator Research Complex) in the Materials and Life Science Facility (MLF) building. A new Ultra-Slow Muon beamline is being developed with the goal to expand the scope of the μSR technique from bulk material to thin films, multi-layers, surfaces and extremely small samples, enabling not only for a wide variety of surface and nano-science studies, but also a novel 3D imaging with the "ultra-slow muon microscope" [2].

Ultra-slow muons have been successfully produced at PSI using the technique of moderating a continuous surface muon beam in simple van de Waals bound solids to produce ultra-slow muons with epithermal energies down to 15 eV without any loss of the spin polarization [3]. This new beamline however is based on an alternative concept that was delevopped at the ultra-slow muon beamlines built at KEK in 1990 [4] and RIKEN-RAL in 1999 [5]. Intense ultra-slow muons will be produced by the re-acceleration of thermal muons regenerated by the laser resonant ionization of muonium atoms evaporated from the surface of a hot tungsten foil.

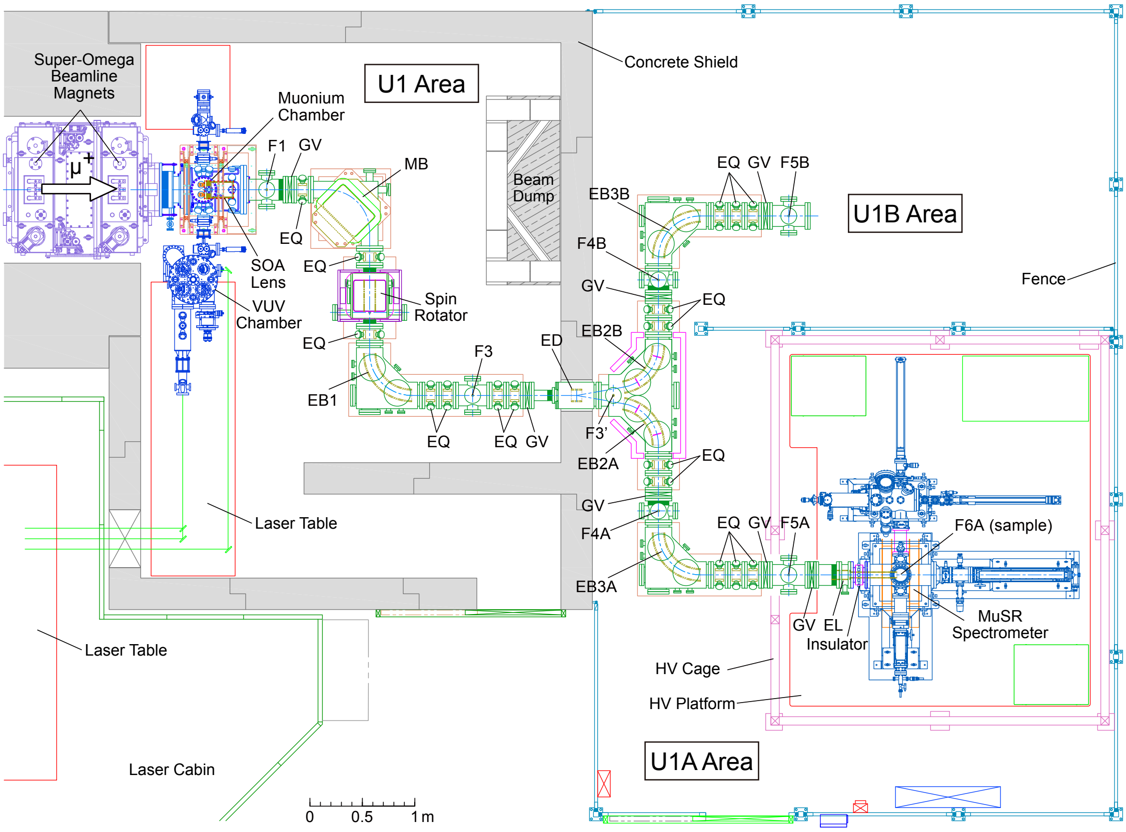

Figure 1. Layout of the new ultra-slow muon beamline at J-PARC/MUSE.

To efficiently ionize muonium atoms, a resonant ionization scheme via the "1s-2p-unbound" transition by a pulsed nanosecond laser was adopted. A new state of the art all solid-state laser system produces the VUV light of 122.088 nm (Lyman-alpha) needed to induce the 1s-2p transitions [6]. After laser ionization, the free muons have a mean thermal kinetic energy of only 0.2 eV with 50% spin polarization. They are extracted, re-accelerated up to 30 keV and focussed by an electrostatic lens. This re-accelerated beam has better energy resolution, time resolution and space distribution compared to the initial surface muon beam. The beam is then transported with a series of electric quadrupoles and electric bends to two experimental areas U1A (Ultra-Slow Muon μSR) and U1B (Re-acceleration, Microbeam μSR), respectively. The layout of this new ultra-slow muon beamline is shown in Fig. 1.

The now completed Super-Omega muon beamline (U-Line) in the MLF experimental hall No. 2 will be used as the primary muon source [7]. Muons up to 45 MeV/c can be extracted with a large acceptance solid angle of 400 mSr upstream from the muon target with an angle of 45 degrees by a normal-conducting capture solenoid. Captured muons are then transported to the experimental hall by a superconducting curved transport solenoid and an axial focusing solenoid to the experimental area U1 (see Fig. 1 of Ref. [8] for a layout of the Super-Omega muon beamline). The muon beam has a double-pulsed structure of 100 ns wide, separated by 600 ns with a repetition rate of 25 Hz. We achieved the world most intense pulsed muon source at the U-Line with a time-averaged surface muon intensity of 6.4 $\times$ 10^7/s at 212 kW proton beam, 20 times more intense than at the D-Line, which is already in operation since 2009, and corresponding in the future to 3.0 $\times$ 10^8/s with a beam power of 1MW.

The expected ultra-slow muon intensity is obtained by scaling the production rate from the R&D at RIKEN-RAL [5] where 20 μ^+/s were produced with an initial surface muon beam of 1.2×10^6/s. Comparing this intensity to the one that will be available at the U-Line, we gain a factor of 250. The new laser system was designed to achieve roughly 100 times the power of the previous laser [6]. And a factor of two is gained because the laser and the muon beam are synchronized to 25 Hz, whereas at RIKEN-RAL the laser was synchronized to every second muon pulse (50 Hz). Consequently, we can expect a maximum ultra-slow muon production rate of 1.0×10^6 μ^+/s, and about 50% at the sample position due to muon decay in-flight.

An overview of the different aspects of this new ultra-slow muon beamline and the present status of the beam tuning and commissioning are presented.

2. Thermal muonium production chamber

The thermal muonium production chamber shown in Fig. 2 contains the hot tungsten target (W target) that will be used to produce muonium atoms. Thermal muons will be regenerated by the laser resonant ionization of the muonium atoms evaporated from its surface. Surface muons enter the chamber through a 50-μm thick stainless steel window placed at the end of a capillary device (conical shape) that enhances slightly the muon stopping distribution on the target. The muons are first moderated by a 50-μm thick W foil (moderator) and then stopped in a 50-μm thick W foil (target) that is heated up by a pulsed DC current. The moderator foil is also used to shield the stainless steel window from the heat of the target. The W foil dimensions (70-mm wide by 45-mm high) are determined by the beam parameters of the Super-Omega muon beamline at the focussing point to maximize the muon stopping distribution, while the total foil thickness is optimized to stop muons near the rear surface of the hot W target to maximize the muonium emission in vacuum. The W target was designed to be heated up to $\sim$2300 K in an ultra-high vacuum of 10^{-7} Pa, and have O_2 flow control for surface treatment of carbon removal. A pulsed interrupt heater power supply provides a DC current of up 1000 A (15 V max.) to heat the W target. It is turned off for 1 ms around the muon pulse arrival time to eliminate induced magnetic field from the target, and is also electrically insulated to apply 30 kV to the target for beam extraction. The entrance and exit flanges as well as the wall of the the muonium chamber are water cooled to remove the radiation heat from the target. A vacuum of 8.7×10^{-8} Pa with the W target at room temperature and a degassing rate of 3.2×10^{-7} Pa m^3/s were achieved.

A highly pure tungsten foil is essential because a clean tungsten surface is required to obtain intense muonium emission. The foil dimensions required for mounting on the target holder are 70 mm by 54 mm and 50-μm thick. Unfortunately, the companies, which had supplied highly pure (6 N, 99.9999%) tungsten foil in the past, discontinued their manufacturing. It used to be manufactured by a hot rolling technique of highly pure tungsten bulk material. Therefore the development of manufacturing methods was started instead of fabricating a new and expensive hot rolling apparatus. The feasibility was determined by utilizing 0.2-mm thick plates made of ordinarily pure tungsten material (3 N, 99.95%). The thickness was reduced up to 50 μm by two methods, etching and mechanical polishing, respectively. As a result, uniform 50-μm thick foils could be successfully obtained by the mechanical polishing method. Then mechanical polishing was introduced to highly pure tungsten bulk. The development of the manufacturing method of highly pure tungsten foil is described in details in Ref. [9].

The extraction and focusing optics for the ionized muons consists a SOA immersion lens [10] similar to that of the previous ultra-slow muon beamlines [4, 5]. All electrical electrodes can withstand a high-voltage of up to 30 kV. The ionized muons are initially extracted by a low electrical field gradient of typically 200 V between the W target held at 30 kV and the mesh electrode S1 held at 29.8 kV (mesh transmission efficiency of 90%). The gap between the target and S1 is 14 mm. It should be noted that a 1-mm thick laser ionization volume in front of the target will give to the muon beam an additional energy spread of 14 eV and a corresponding

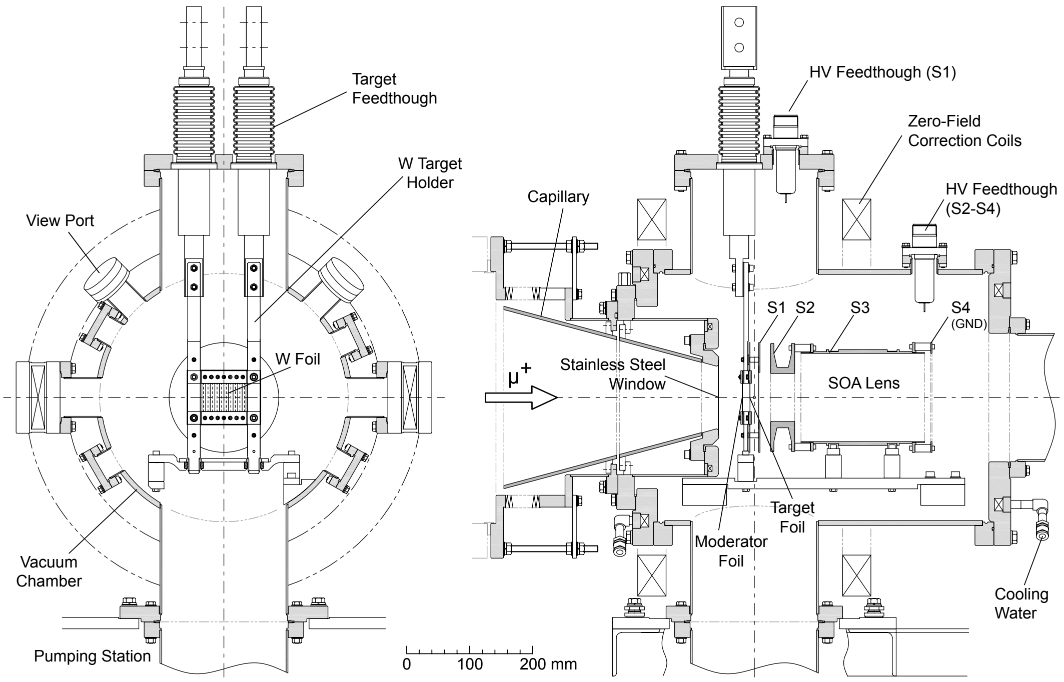

Figure 2. Schematic view of the thermal muonium production chamber with the hot W target.

time spread of 1.9 ns. Lower field gradient will reduce the energy spread but increase the time spread, and vice versa. A possible workaround is using a short HV pulse between the target and S1 to accelerate muons before they reach S1 so that all muons have the same initial extraction energy when passing the mesh. A typical 10-ns long pulse of 2 kV would give almost no energy spread while limiting the time spread to 1.0 ns. The required accuracy of the pulse should be $< 10^{-3}$. The mechanical alignment of the target, laser and S1 is also important.

3. Stray field from Super-Omega muon beamline

The W target for the production of ultra-slow muons is located 700-mm downstream from the last solenoid of the Super-Omega muon beamline. The residual magnetic field at the W target position has a critical effect to the muon beam properties, such as extracting and focusing the beam. In addition, the magnetic field normal to the beam direction reduces seriously the muon spin polarization. To minimize these effects, a magnetic shield was installed to enclose almost entirely the muonium production chamber. The magnetic shield is made of 20-mm thick iron plates, three plates normal to the beam axis, and two plates on the sides. The first plate (1.2-m wide and 2.2-m high) made of ordinary iron is placed right downstream of the last magnet of the axial focusing solenoid. The other plates (1.0-m wide and 2.4-m high) made of extra-low carbon steel are located 250 mm away from the first plate, 150 mm further downstream of the second one, and 500 mm from the beam axis on both sides, respectively. Each plate normal to the beam has a hole for the beamline duct with a diameter of 500, 400, and 300 mm, respectively.

The code OPERA-3D (TOSCA) was used for the magnetic field analysis. Figure 3 shows a top view of the magnetic shield around the W target illustrating the last two solenoid magnets of the Super-Omega muon beamline and the two zero-field correction coils. The muon beam is coming from left, and the W target is located at the center position (Z=0) in between the two zero-field correction coils. Initially, the calculated stray field at the W target position is 240 G, but can be reduced down to ∼40 G with the magnetic shield. This residual stray field

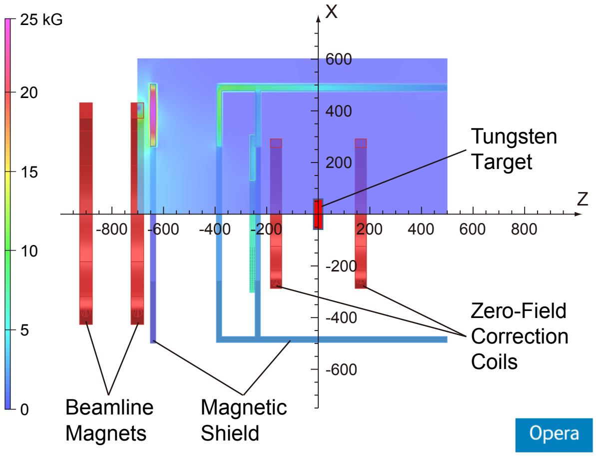

Figure 3. Opera-3D model of the magnetic shield showing the last beamline solenoid magnets and the zero-field correction coils.

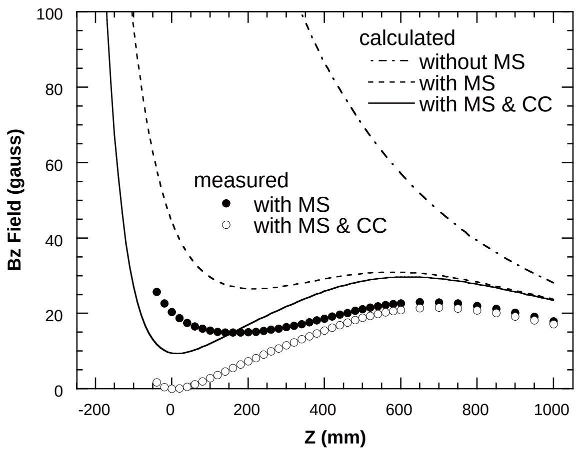

Figure 4. Magnetic field distribution results without and with magnetic shield (MS) and zero-field correction coils (CC), respectively.

originates mainly from the large hole in the magnetic shield for the beamline duct. The field can be further canceled by using three orthogonal zero-field correction coils placed on the W target chamber. Measurements were performed after the installation of the W target chamber and the magnetic shield using a three-dimensional Hall probe mounted on a XYZ positioning stage. The measured and calculated stray fields along the beam axis are shown in Fig. 4. Although an offset exists between measured and calculated fields, the data are in good agreement. The offset originates probably from the magnetization effect of the magnetic shield. The residual stray field was suppressed by the zero-field correction coils to less than 1.5 G over the W target region. Then the field gradually increases with increasing Z, showing a peak structure of 20 G, and then decreases again. The major field component is along the beam axis, in the same direction as the muon spin, and will therefore not affect the spin depolarization of the muons. The normal component is sufficiently small (< 0.2 G) to affect any changes to the muon spin.

4. Beam Transport Line

The complete layout of the new ultra-slow muon beamline is shown in Fig. 1. After laser ionization, the thermal muons are extracted, re-accelerated and focussed to an intermediate focusing point, F1, located 600 mm from the W target. From there, the beam is transported with a series of electric quadrupoles (EQ) and electric bends (EB) to two experimental areas U1A and U1B, respectively. A magnetic bend (MB) placed just after F1 carries out the mass separation of the beam to eliminate positrons and also select $^2H^+$ and $^7Li^+$ ions for off-line beam tuning. The C-shaped magnetic bend allows the direct monitoring of the hot W target through a viewport located at the end of the magnet vacuum chamber. A 90 degrees magnetic bend was preferred so that the muon spin rotates perpendicular to muon beam direction, allowing μSR measurements with transverse field similarly to RIKEN-RAL and PSI low energy muon beamlines. A dedicated spin rotator will soon be installed in between MB and EB1 to rotate back the muon spin for longitudinal field measurements.

The general shape of the beamline was decided based on the space available in the MLF experimental Hall No. 2 and to satisfy the requirement for two experimental areas for "Ultra-Slow Muon μSR" and "Reacceleration/Microbeam μSR", respectively, with sufficient distance in between for experimental instruments like a spectrometer, a high-voltage platform, etc. The ultra-slow muon beam is sent to the desired experimental area by an electric deflector (ED) that deflects the beam by 10 degrees and directs it to one of the entrance of the double electric bend (EB2). At first, the operation of the ED will be static directing the full beam (25 Hz) either to U1A or U1B. In the future, a pulsed operation is thought to allow every other pulse to be sent to both areas with a repetition rate of 12.5 Hz. Five beam monitor and slit assemblies are located along the beamline (F1–F5) for monitoring and tuning purposes. Both horizontal slit mechanisms (left and right) are remotely activated from the same side, while the vertical slits (top and bottom) are both mounted from below. This compact arrangement leaves space for a beam monitor transfer mechanism to be placed at the top of the vacuum chamber. Presently, either a standard MCP detector (micro-channel plate, ϕ40 mm, single anode) or a two-dimensional MCP detector (with delay-line anode for high resolution 2D-imaging) can be mounted. The detector is lowered behind the slits that can be used to evaluate the beam profile with a single-anode MCP. The total beamline length becomes around 8.5 meters from the hot W target to F5. The ultra-slow muon beam energy of 30 keV was decided to minimize the beam loss due to muon decay in-flight. At 30 keV, the time-of-flight is approximately 1.3 μs, and about 45% of the ultra-slow muons will decay before reaching the sample position.

At present, only the construction of U1A area is almost completed. A new μSR spectrometer has been constructed and installed on a high-voltage platform ($\pm$ 30 kV) allowing the muon beam to be decelerated down to a few tens of eV on the sample, or further accelerated up to 60 keV. Because of the residual magnetic field from the μSR spectrometer along the beam axis, an Einzel lens (EL) was preferred to mirror the beam image from F5A to the sample position (F6A). This Einzel lens is also used to adjust the focussing position when changing the high-voltage at the sample. This new ultra-slow muon μSR apparatus is described in details in Ref. [11].

The optimization of the initial beam extraction and acceleration with the SOA lens was performed using a Monte Carlo simulation with calculated electric field by the code RELAX3D. A source of 4 cm in diameter can be focused at F1 with a FWHM of 1 mm at 30 keV. A distance of 600 mm to the intermediate focusing point F1 was decided to minimize the beam aperture to 30 mrad for easier beam transport, while increasing its size to about 2 mm (FWHM). Then from F1 the beam was optimized using the transport codes WINGIOS2 and GICOSY. A 30-keV beam with a source radius of 2 mm and an aperture of 30 mrad can be fully transported with very little beam aberration.

5. Present status and future plans

The full Geant4 beamline transport simulation of the ultra-slow muon beam is in progress using the PSI simulation package musrSim [12]. Magnetic and electric field distributions of each individual component were calculated using the code OPERA-3D (TOSCA), and incorporated into the simulation code. Preliminary simulation results [13] are consistent with the initial beam calculation. In parallel, off-line beam tuning and commissioning is proceeding using a $^7Li^+$ beam. Lithium atoms originate from impurities in the W foil that are evaporated and surface ionized when the target is heated up. Results were already reported in Ref. [13]. Li beam has now been successfully transported to the last focal plane (F5A) located just before the μSR spectrometer. Optimization of the beam transportation and properties is ongoing. As soon as the laser system will be operational, beam tuning will continue with ionized $^2H^+$, followed by the first ultra-slow muon beam expected in Autumn of 2014.

Acknowledgments

This work was supported by a Grant-in-Aid for Scientific Research in Innovative Area "Ultra Slow Muon" (No. 23108002) of the Ministry of Education, Culture, Sports, Science, and Technology, Japan.

References

[1] Miyake Y *et al. J. Phys.: Conf. Ser.* this issue
[2] Miyake Y *et al.* 2014 *JPS Conf. Proc.* **2** 010101; Torikai E *et al* unpublished
[3] Prokscha T *et al.* 2001 *Appl. Surf. Sci.* **172** 235
[4] Nagamine K *et al.* 1995 *Phys. Rev. Lett.* **74** 4811
[5] Bakule P *et al.* 2008 *Nucl. Instr. and Meth.* B **266** 335
[6] Oishi Y *et al.* 2014 *JPS Conf. Proc.* **2** 010105; Nakamura J *et al. J. Phys.: Conf. Ser.* this issue
[7] Y. Ikedo *et al.* 2014 *JPS Conf. Proc.* **2** 010103, 2013 *Nucl. Instr. Meth.* B **317** 365, 2012 *Phys. Procedia* **30** 34
[8] Strasser P *et al.* 2013 *Nucl. Instr. Meth.* B **317** 361
[9] Makimura S *et al.* 2014 *JPS Conf. Proc.* **2** 010104
[10] Canter K F *et al.* 1986 Modified Soa immersion lens positron gun *Positron Studies of Solids, Surfaces and Atoms* ed A P Mills Jr *et al* (Singapore: World Scientific) pp 199-206
[11] Higemoto W *et al.* unpublished
[12] Sedlak K. *et al.* 2009 Physica B **404** 970 (`http://www.psi.ch/lmu/geant4-simulations`)
[13] Nagatomo T *et al.* 2014 *JPS Conf. Proc.* **2** 010102