Oct, '04
Setting the proton beamline and MLF base
Feb, '06
Installing the alignment plates
May, '06
Installing the target chamber
Jun, '06
(top) A shield guide and a monitor
(left) MUSE proton beamline tunnel view
Dec, '06
Installing a correction mangnet
May, '07
Installing a gate valve equiped with pillow seal flanges
July, '07
MUSE Group photo celebrating the completion of the MUSE proton beamline installation
Dec, '07
Solenoid coil arrival
Jan, '08
(left) Installing solenoid
(right) Target exchange test
Feb, '08
Installing the cryogenic helium buffer tank
Mar, '08
Remote control test in hot cell
May, '08
(left) Installation of the secondary muon beamline (decay and surface muon lines)
(right) A view of quadrupole magnet

New milestone at MUSE

[MUSE Construction, Ultra-Slow Muon, Pillow Seal, Super Omega]

The Muon Science Establishment, MUSE, at the Japan Accelerator Research Complex (J-PARC) recently produced the world's highest intensity pulsed muon beam. Read on to learn the team's hard work, and their plans for the future.

The muon is an elementary particle that is much like an electron, but is 200 times heavier. Because of the larger mass, it is less likely to lose energy from radiation when interacting with matter, and is less affected by electromagnetic fields. Thus, muons can penetrate deeper into matter than electrons would. Muons are uniquely useful because their magnetic spin can map the local magnetic environment inside matter. Alongside the light and the neutron beam, the muon beam is one of three complementary tools used in material science. Muon beams are useful for probing properties such as magnetism and superconductivity (read about it in superconductivity and physicist's MUSE).

The scope of applications of muon science goes beyond just material science. The wide range of its applications include fundamental sciences such as particle physics, condensed matter physics, and chemistry; as well as applied sciences such as muon catalyzed fusion, biophysics, non-destructive analysis, and beam technology.

Take muon-catalyzed fusion, a potential green power source. When a room temperature mixture of hydrogen isotopes—such as deuterium and tritium—is irradiated by negatively charged muons, fusion occurs.

This intriguing process utilizes the fact that muons are 200 times heavier than electrons, while carrying the same electric charge. When a normal atom is bombarded by negatively charged muons, some of the electrons are replaced by muons, which orbit 200 times closer to the nucleus. This means that those atoms need to come 200 times closer to experience same strength of Coulomb repulsion as ordinary atoms would, and so these muonic atoms can get much closer to other nucleus. This makes it much easier for molecules of muonic hydrogen to form. In these muonic molecules, hydrogen nuclei fuse to produce energy. The process is cyclical in nature, catalyzed by negatively charged muon.

Currently, muon-catalyzed fusion is an unpractical power source, as the process consumes more energy than it produces. To fix this problem, scientists need to find a way to produce muons more efficiently. To increase the number of cycles muons can undergo before decaying, it turned out that it is also crucial to deal with the muon loss by the fusion product called alpha particle. The studies found that intense pulsed muon beam can unveil the muon loss process.

The key to most of these applications is having a more intense, pulsed muon beam. The Muon Science Establishment, MUSE, at the Japan Accelerator Research Complex (J-PARC) in Tokai, Japan, has just taken another step towards creating such a beam and enabling this kind of science. The 100-kilowatt power for the proton beam which was achieved last month is another milestone for the MUSE program, marking the world's highest pulsed muon beam intensity.

MUSE's challenge

The muon beamline at J-PARC extracts protons from a rapid cycle synchrotron (3GeV) ring, and hurls them at a graphite target. The resulting collision produces large numbers of pions. These pions then decay into muons in one of two ways. First, lower energy pions stopped at the graphite target decay inside the target. These muons are called surface muons and have energies around 4 MeV. Second, the higher energy pions that emerge from the target decay while travelling through a six-meter superconducting magnet that extends to muon experimental areas. These muons are called decay muons, and have energies of 5 MeV to 50 MeV.

"We were designing and constructing a beamline for a muon intensity level with which no one has any experience," says Prof. Yasuhiro Miyake of KEK, the leader of the MUSE construction team. "The challenge was to design everything to be radiation proof." Not only do the components require radiation hardening, but all components require remote handling capability, because no one can enter the facility when handling radioactive equipment.

Sealing with pillow

The beam of protons can easily be scattered by just a smattering of air molecules. This contaminates the environment with the resulting radiation. The accelerator scientists, therefore, need to make sure their beam pipe can seal tightly, and maintain a high vacuum. For the beam ducts of the primary proton beamline and the extraction beamline, the team uses a vacuum sealing technology called a pillow seal.

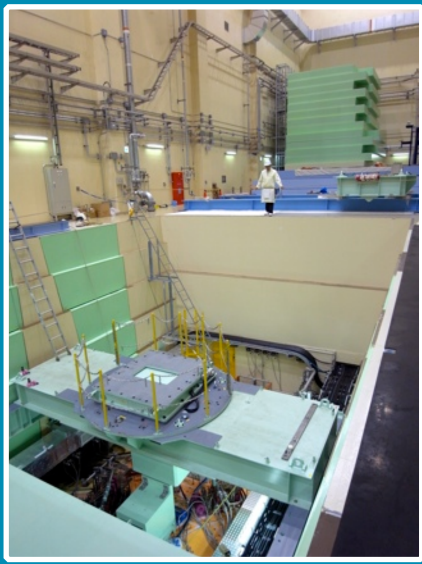
The pillow seal was originally developed at the Paul Scherrer Institute (PSI) in Switzerland. The ingenious feature of this vacuum sealing mechanism is the thin foil bag inserted between the flanges that connect vacuum ducts. The foil is filled with compressed air to shut the tiny openings between flanges.

However, the original pillow seal did not satisfy MUSE's requirement for a leak rate of less than 10^{-7}Pascal–m^3/s. "To develop the KEK pillow seal, we had an intense period of research and development," says Miyake who was in charge of the MUSE construction as well as the development of the pillow seals.

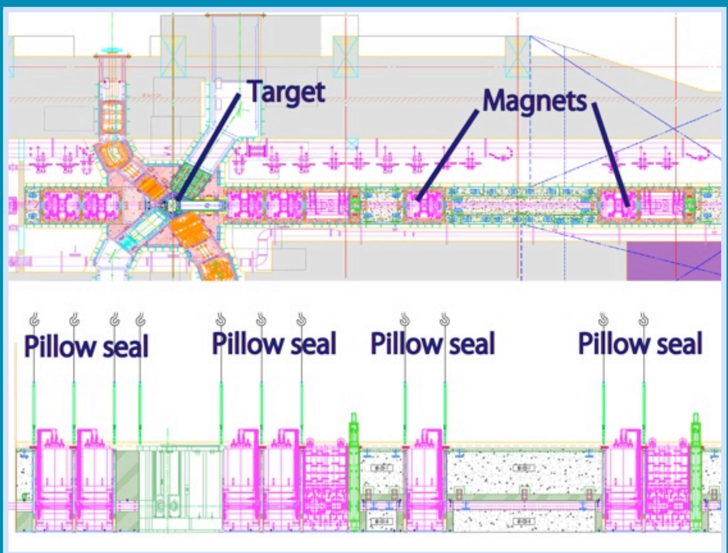
To decrease the leak rate, Miyake, KEK mechanical engineer Nobuhiko Sato, and his collaborators from PSI came up with several sophisticated ideas. The pillow seal has two sets of pillow rings, inner and outer, on each side. Between the inner and outer pillow rings on the supporting flanges, they cut a miniscule groove. The groove is connected to a vacuum pump that vacuums the tiny volume of the groove, so that the pillow can seal the ducts even more tightly. Moreover, the team has found that the smoothness of the flange surface affects the performance. "The design was a success," says Miyake. "With polished surface of flange, we have found that the leak rate can be brought as low as 10^{-9} Pascal–m^3/s."

It was also necessary to make the pillow seals' thickness adjustable to gaps that range from 70 millimeters to 90 millimeters. The team developed a way to use a device called a pantograph to extend or contract the flanges using a bellow and compressed nitrogen gas. The final product successfully fulfilled all requirements, and can adjust itself to the appropriate thickness.

The successful pillow seal design has also been applied to other experiments at J-PARC.



Many layers of thick concrete shield the upper-floor facility from radiation produced at the MUSE target station beneath.



The top view (above) and the cross sectional view of muon beamline at MUSE. 23 pillow seals connect beam ducts in the vicinity of the muon target to maintain the vacuum in excellent condition.

A pillow seal with the radiation shield structure attached above.

↓Prof. Yasuhiro Miyake of KEK is the leader of the MUSE construction team.

↑Dr. Koichiro Shimomura of KEK explains the refrigeration system he is in charge of during the beamline development. He also took charge of the superconducting magnet.

↓Prof. Ryosuke Kadono of KEK is the head of KEK-MSL laboratory and the leader of the KEK-Muon Spin Rotation / Relaxation / Resonance (muSR) group.

For example, the underground neutrino experiment at J-PARC, T2K, has applied the new pillow seal design to their vacuum chambers at the target station.

Guiding and shielding

The proton beamline runs through multiple dipole and quadrupole magnets to skew and focus the beam. To manage this intense beam of protons, the magnets need be aligned with a 0.1 millimeters precision. However, the real difficulty is that no one is allowed in the facility for maintenance by hand, because of the severe radiation conditions that can fry living things instantly.

To deal with this problem, the team designed remote-control mechanisms. However, to manipulate beamline components with the needed high precision, the team developed guide shields. These are huge blocks of iron with rails on them to guide magnets and other beamline components to exactly right positions when they are lowered by crane. The thick iron blocks shield the surroundings from the radiation coming from the beamline, and the guides allow operators to remotely mount and dismount 60-ton magnets with 0.1-millimeter precision.

Cooling the target

The heart of the muon beamline is the graphite target that produces pions from the intense proton beam. The 3 GeV proton beam will ultimately have a power of one megawatt. This beam will deposit 4 kilowatts of heat at the graphite target, which translates to 1,500 degrees Celsius. Without any cooling, however, the target would reach above 2,000 degrees Celsius.

To deal with the heat, the team fabricated an edge-cooled graphite target. A copper frame goes around the 2 centimeters-thick graphite target, and it contains a water pipe that spirals around inside the copper frame three times. This structure keeps the frame under 150 degrees Celsius.

One big challenge was the physical stress between the graphite target and the copper frame. The heat of the proton beam causes both materials to expand, but the graphite expands more than the copper. To relieve the stress, the team inserted a 2 millimeters-thick titanium strip in the area in between. "When heated, the titanium expands to just right degree so as to relieve the stress between the graphite and the frame," explains Miyake. The team also had to take into account the irradiation effects that can lower heat conduction rate and even change graphite's crystal structure, making it shrink. "Our analysis of thermal and dimensional stress showed the edge-cooled graphite target with titanium buffer interface can endure 4 kilowatt of heat deposit and radiation damage."

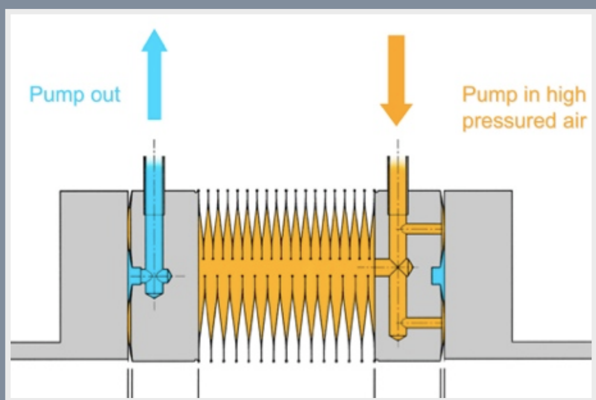
Because of the intense radiation, the current target would not last longer than six months under the expected 1-megawatt proton beam. The team just performed the target exchange operation test in September using J-PARC's radiation shielding containment box, which is known as a hot cell. The hot cell allows MUSE team members to safely handle radioactive materials using robotic manipulators. J-PARC is the first accelerator facility in Japan that requires a hot cell.

The MUSE team performs target exchange operation in the hot cell developed by J-PARC neutron group. To remotely control the target mounted on the 2-ton stainless steel shield to 0.5-millimeter precision requires a careful design around the target.

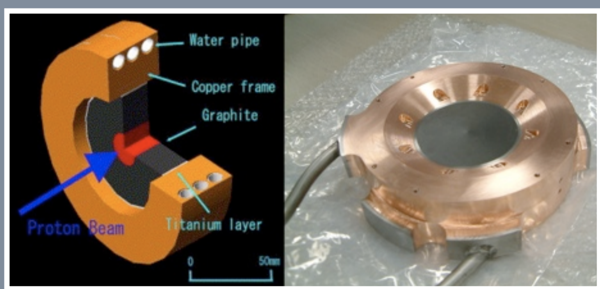
"We visited other facilities that handle radioactive materials to learn from them, and collaborated closely with oversea laboratories such as PSI to carefully design the target," says KEK engineer Shunsuke Makimura. He was in charge of the development of the muon source and the beam transfer line to the neutron source. "We did not have previous experience with this, so we repeated many cycles of test-and-modify to improve our equipments." Operating the manipulators takes some getting used to. However, with good training and the operation guidelines developed by the team members, the team now efficiently manages target exchange operations.

Rotating target

One goal of the MUSE team has been to increase the lifetime of the target so that target exchange would be less frequent or altogether unnecessary. The team has been working on an alternative target called the rotating target. With the current fixed target, the proton beam hits only one spot. By rotating the target, the effects of the beam are spread over larger areas. This reduces the heat deposit and irradiation effects dramatically, thereby increasing the lifetime of the target.



To seal the vacuum more effectively, the team cut grooves between the outer and inner pillow rings, and pumped out the air inside.



The graphite target has a cooper frame with water pipes inside to keep the target cool.

The MUSE hot cell crews at work to replace the muon graphite target using manipulators (the arm structures).

KEK engineer Shunsuke Makimura is in charge of the the muon source and the beam transfer line from muon source to neutron source

The bottleneck of the rotating target development is the axle bearing. The lifetime of the rotating target would depend on the lifetime of the bearing rather than the lifetime of the graphite target. The team has just begun testing of their bearing's lifetime.

"The bearing must endure extreme conditions such as high temperature, high radiation, and the use in vacuum," says Makimura. "The rotating target will decrease the cost of target exchange, the amount of exposure to radiation, and the amount of machine downtime."

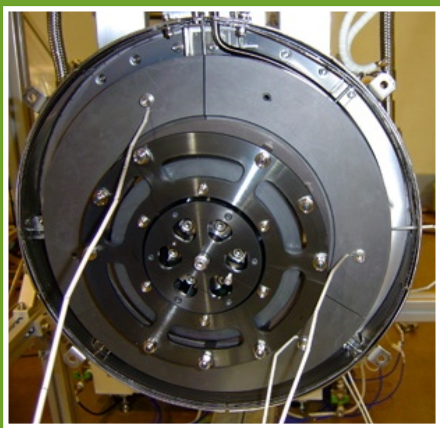
Ultra-slow muon source

MUSE is a small group of just a dozen physicists and engineers. Every member of the team worked hard to pull off the successful construction of the world's most intense pulsed muon source in just a few years. "Even though it was planned, it feels good that we achieved the world's highest intensity at 100 kilowatts," says Prof. Ryosuke Kadono of KEK, the head of KEK-MSL laboratory and the leader of the KEK-Muon Spin Rotation / Relaxation / Resonance (muSR) group. "In terms of science, however, this is just the start." The team is now preparing for the various science projects that will be made possible once the target 1-megawatt proton beam intensity is achieved.

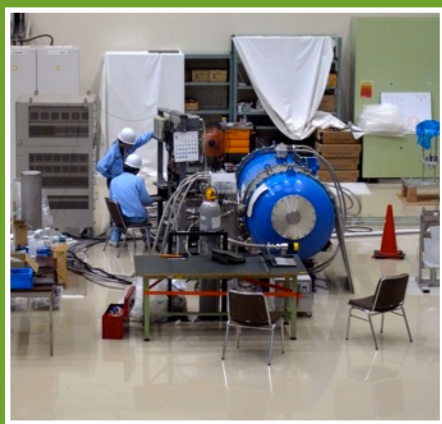
The team's next step is to create a source of ultra-slow muons. These are muons with even lower energy than the surface muons. As the surface muons take 1 millimeter of matter to come to a complete halt, they can only be used to measure the properties of materials at a depth of around 1 millimeter. They cannot be used to explore the surface properties of materials. The proposed super omega muon channel at MUSE will deliver ultra-slow muons with energies in the range of 30 eV to a few tens of keV. This means that physicists will be able to implant muons anywhere from 1 nanometers to 300 nanometers into material, and thereby measure the surface properties of materials.

"The super omega is a dream machine that will bring unprecedented time resolution, beam size, and yield," says Miyake.

"With the startup of MUSE, we have already taken the first step towards the science of the ultra-slow muons," says Kadono. "It is up to Japan whether it should continue its strong tradition of pulsed muon beams." As muon experts around the world would admit, the actual installment of the super omega channel would bring important breakthroughs in muon science.



The MUSE team is currently developing and testing the rotating target.



Research and development of the superconducting magnet for the super omega channel is ongoing in the back of the MUSE station.

Related Link:
MUSE
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Related Issue:
Superconductivity and the physicist's
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