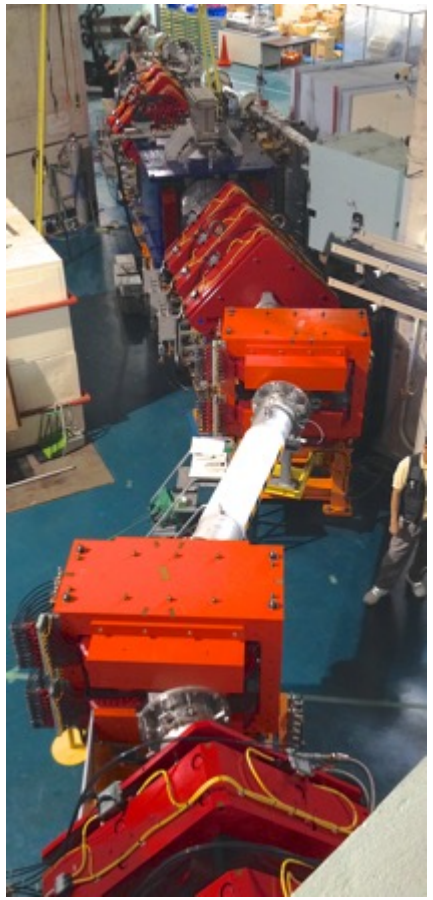
Status of MuSIC-RCNP Muon Facility



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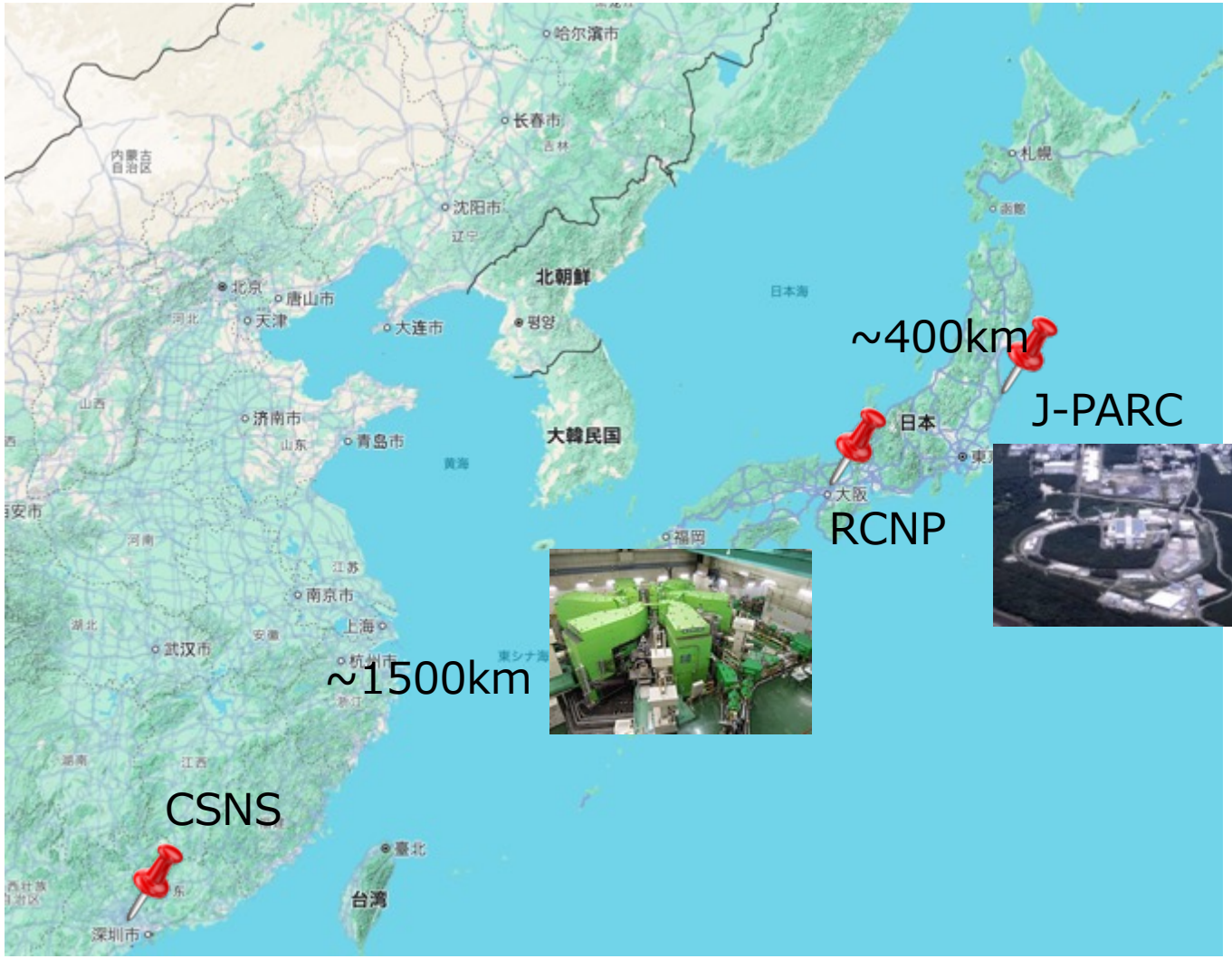
22nd July, 2025, μSR 2025@St John's

contents

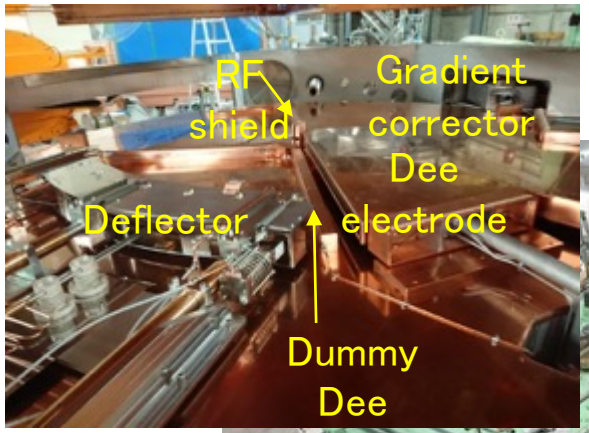
1. RCNP accelerator facility
2. MuSIC muon sourced and beamline
3. Physics resluts (before long shutdown)
4. Future MuSIC
5. Summary

RCNP, Osaka University

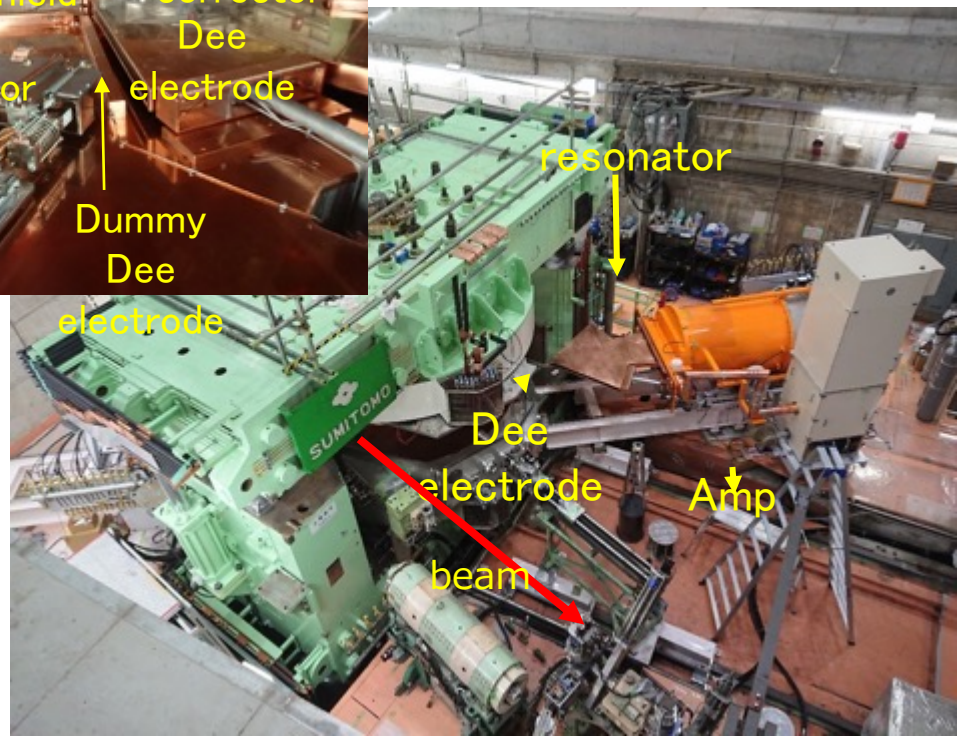


RCNP
from 1972

Two accelerators in RCNP



upgraded AVF accelerator



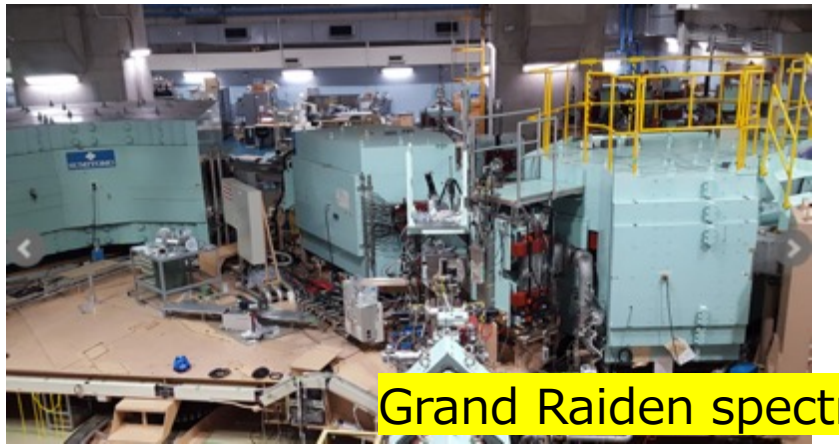
RING cyclotron

- Accelerate variable ions with variable energy for nuclear physics
- Proton 1.1 uA 392 MeV (Maximum) is used for muon beam production
- Parallel operation of experiments is not possible

RCNP (Research Center for Nuclear Physics) accelerator facility

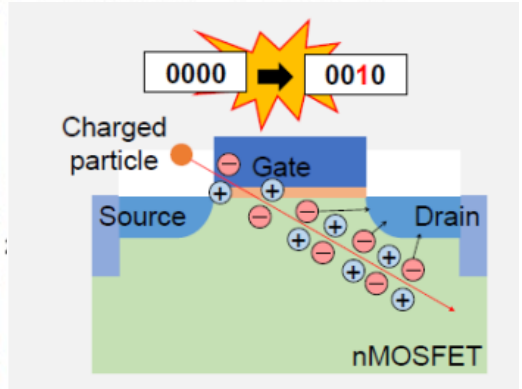
Physics at RCNP

nuclear physics



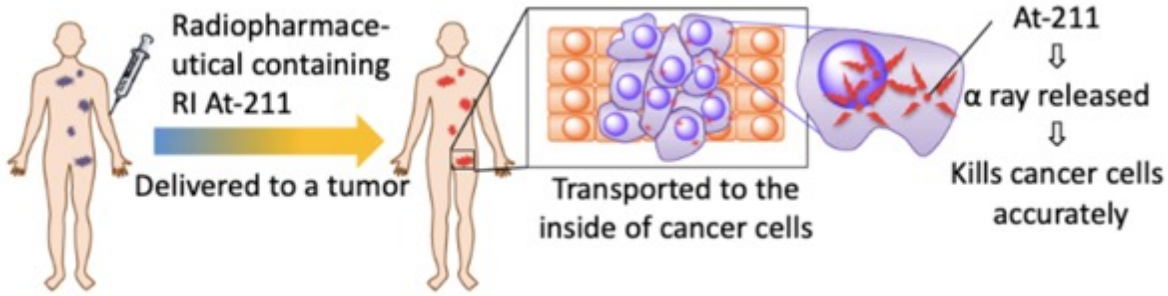
Grand Raiden spectrometer

white neutron irradiation

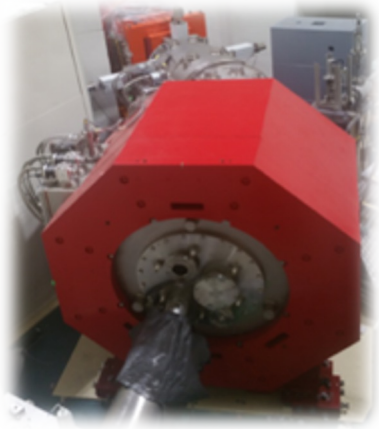


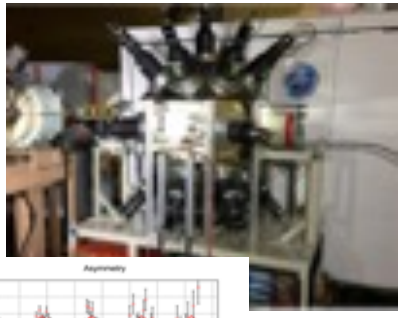
RI production (ex. α-targeted therapy)

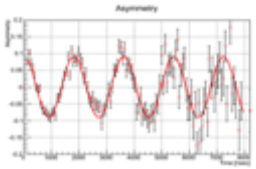
$^{209}Bi(\alpha,2n)^{211}At$



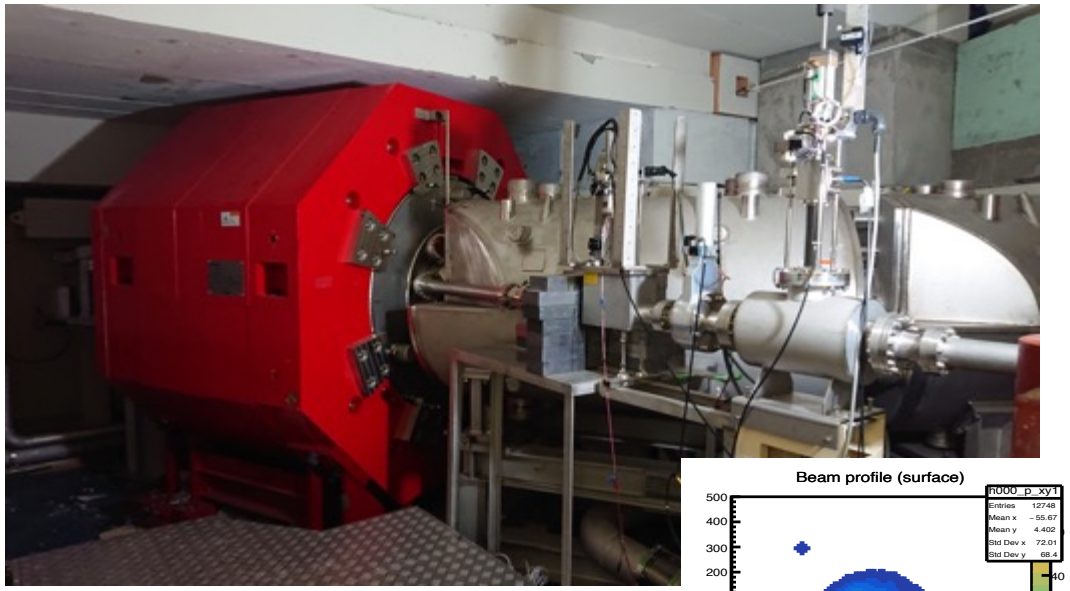
muon physics

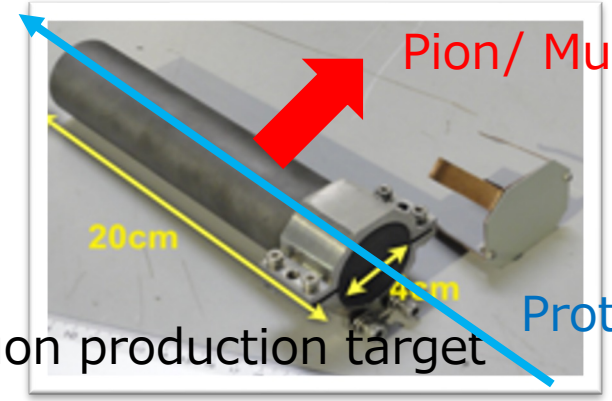


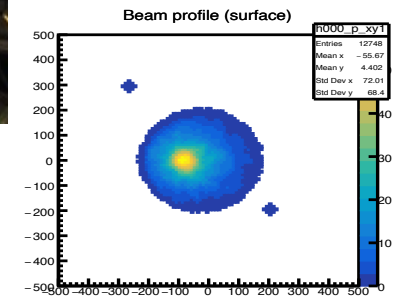


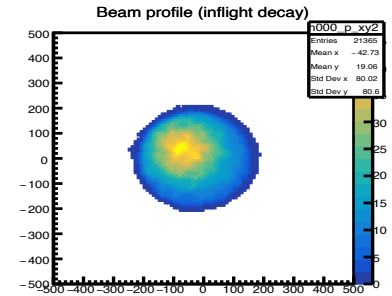


MuSIC capture solenoid





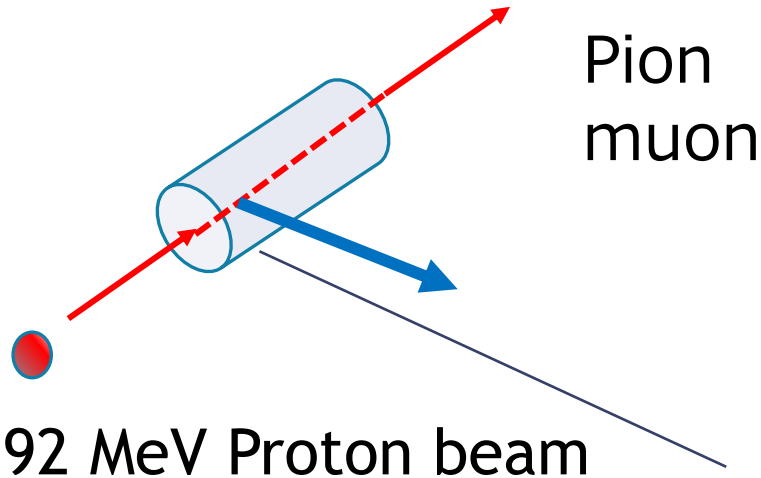




- MuSIC (Muon Science Innovative Channel)
  - Muon produced with 392 MeV, 1.1μA proton beam
  - efficient DC muon beam source with large acceptance solenoid system
  - ~ 4 x 10^8 μ/s was observed at solenoid exit Phys Rev Acc. Beams 20(2017)030101.
  - Originally designed for decay μ- use (prototype of COMET exp)
  - mirror field solenoid
  - The first pion capture solenoid + thick muon production target

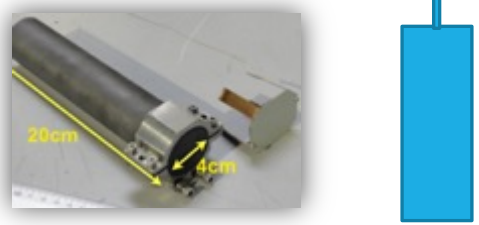
Muon production at solenoid

thick target + large acceptance solenoid



Pion
muon

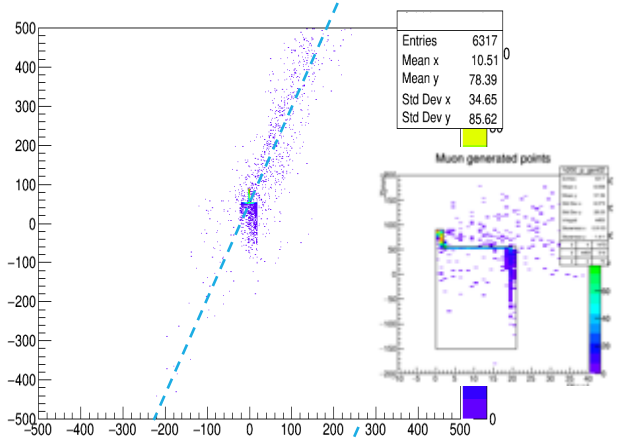
392 MeV Proton beam



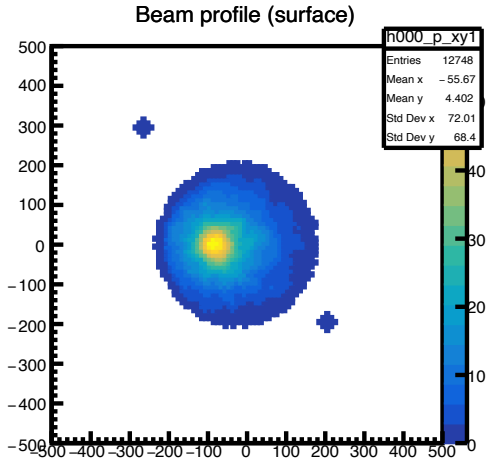
needle target currently used

surface muon

solenoid axis

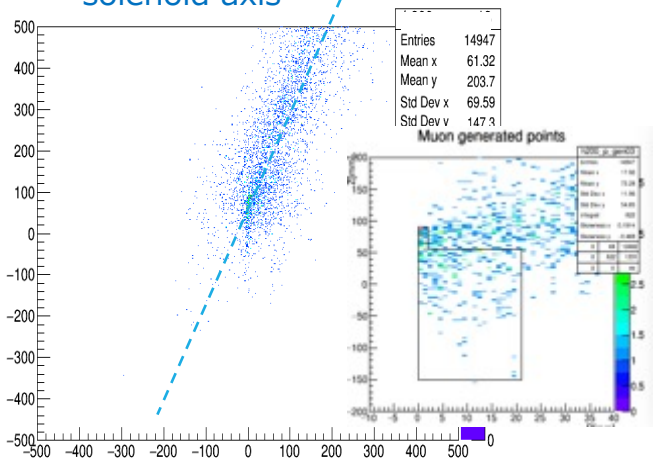


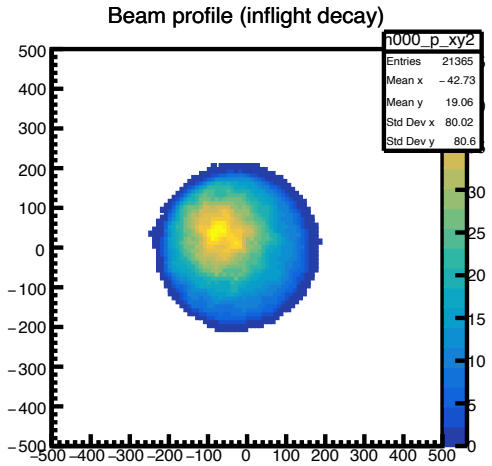
real space



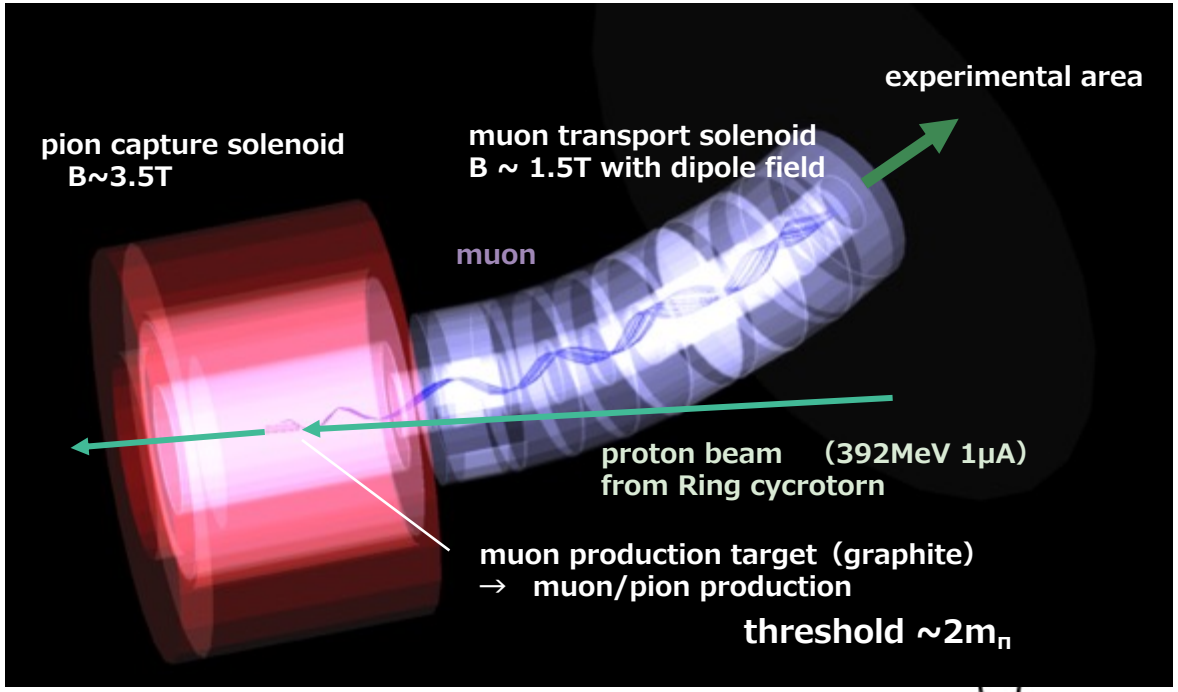
decay muon

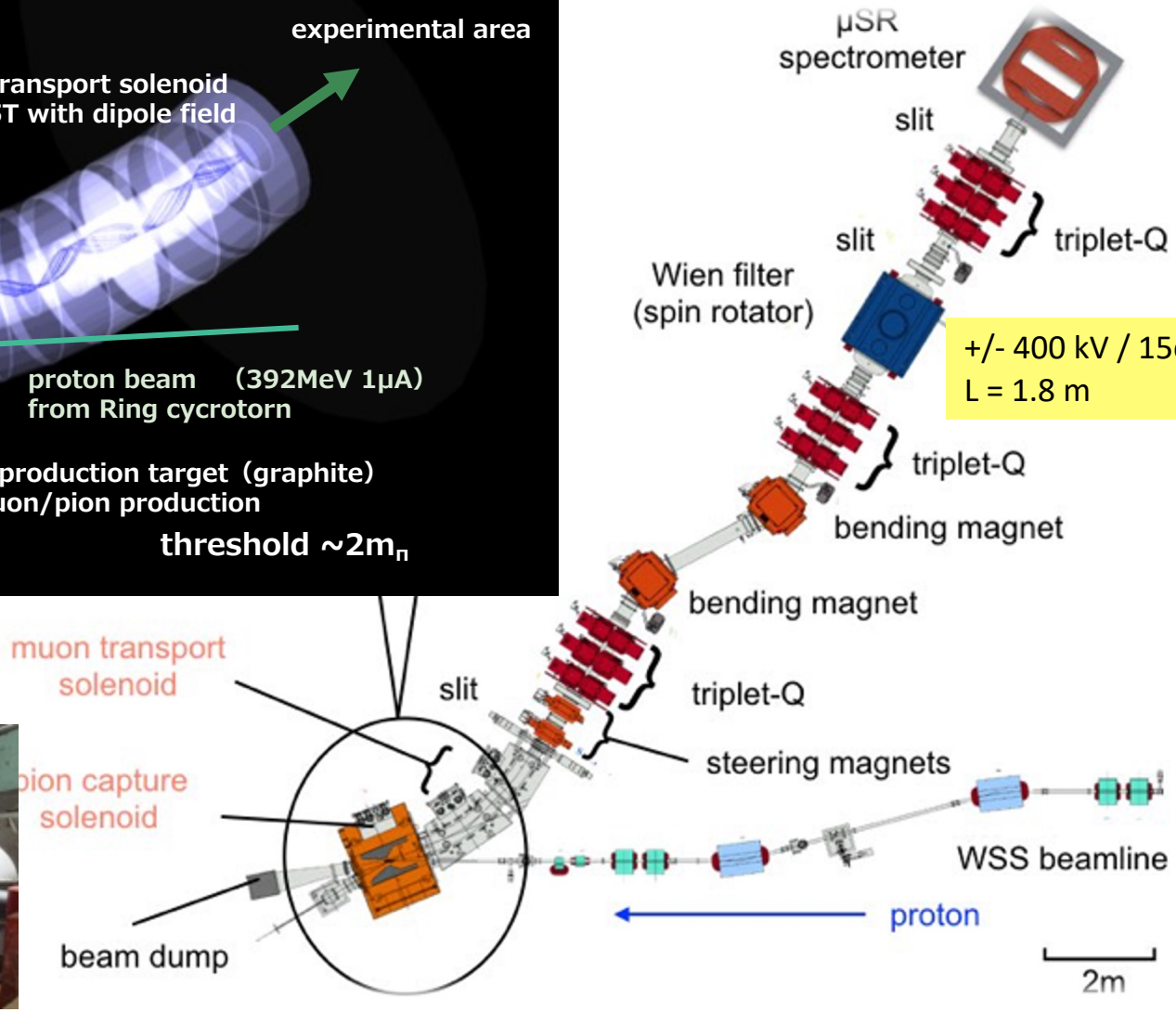
solenoid axis



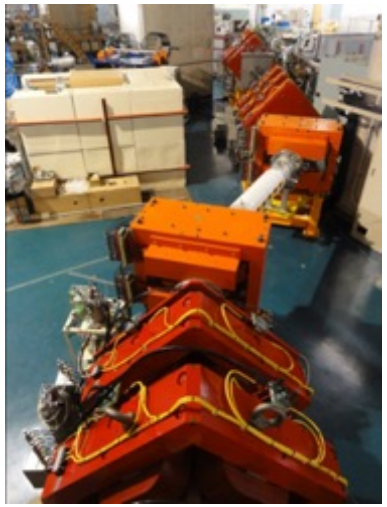


Muon beamline





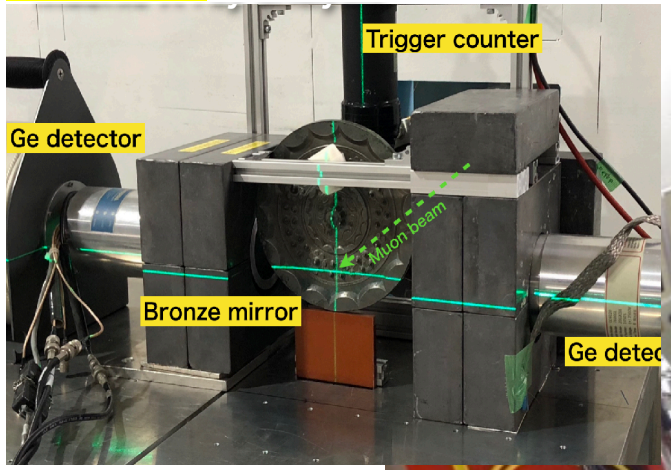
74 deg@28MeV/c



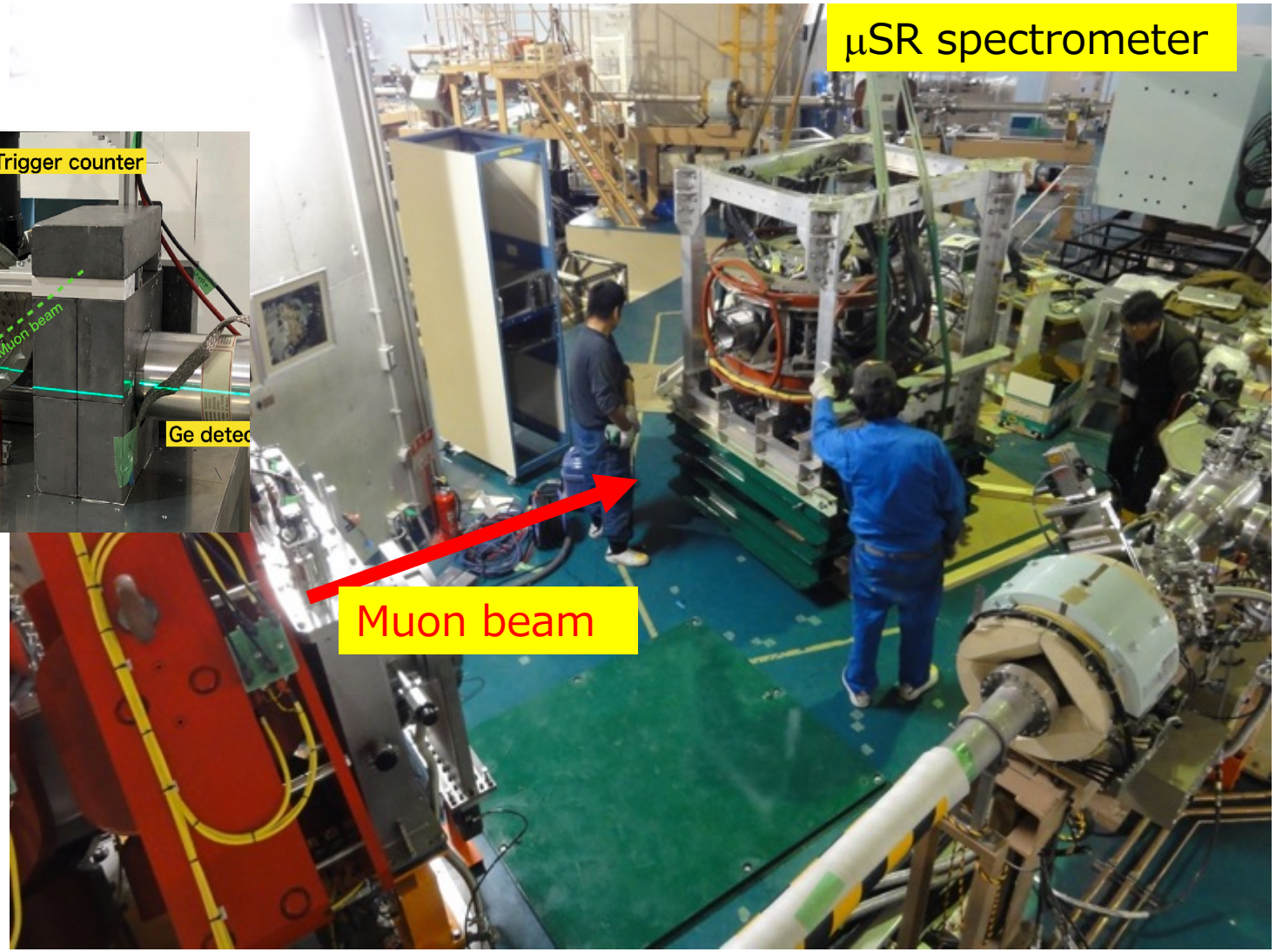
392 MeV 1.1uA proton beam

experimental port shared with various exp.

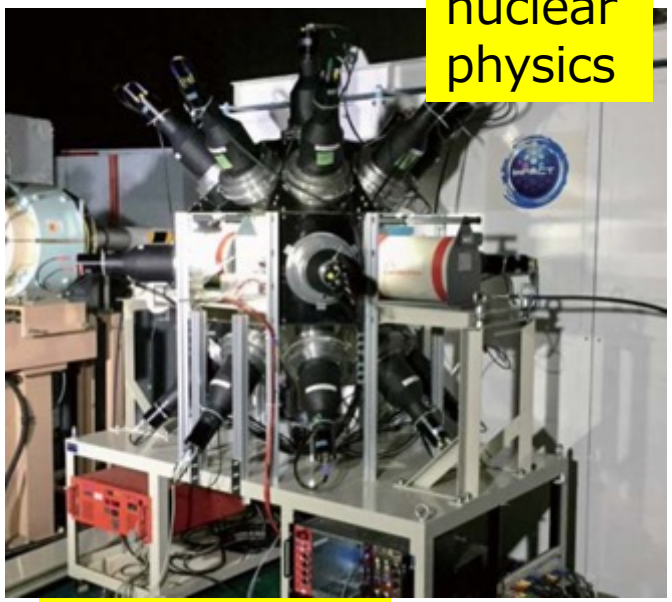
MIXE



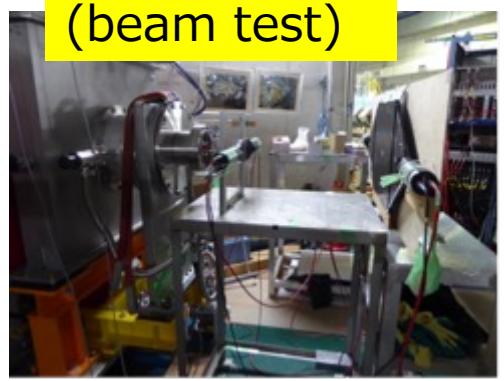
μSR spectrometer



nuclear physics



TOF setup (beam test)



Muon beam

proton 1.1 uA operation (full intensity)

At the experimental port,

Decay muon (<100 MeV/c)

~ 10^5 cps positive muon @ 60 MeV/c

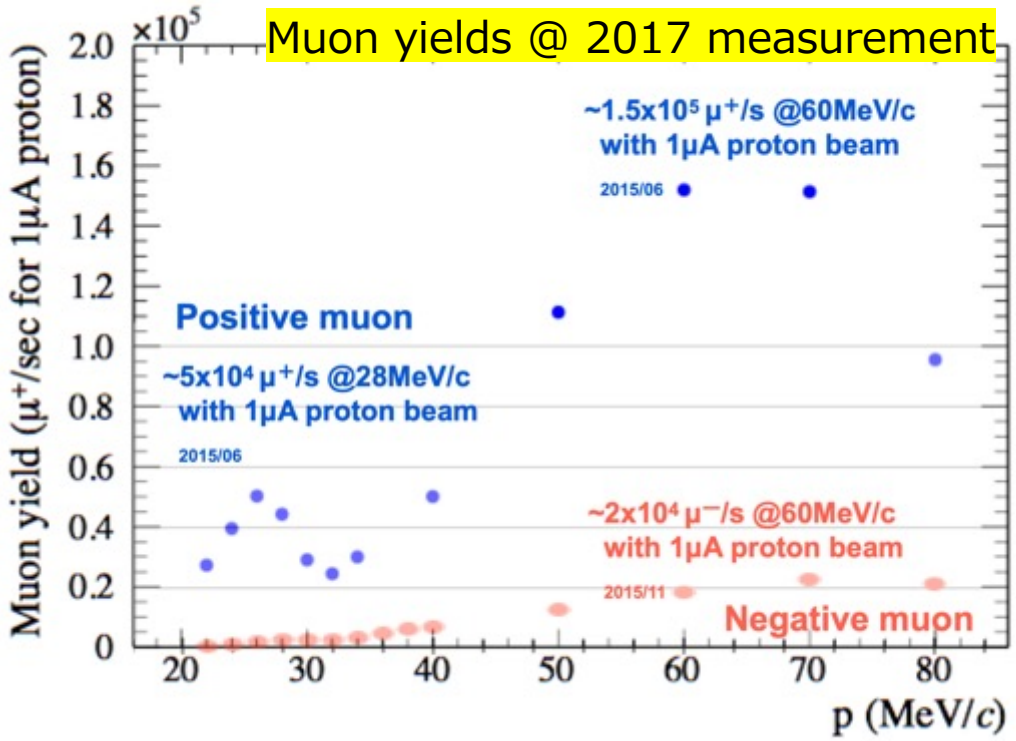
~ 10^4 cps negative muon @ 60 MeV/c

- beam size : 50 mmφ without end collimator
- polarization ~ 60 % @ 60 MeV/c

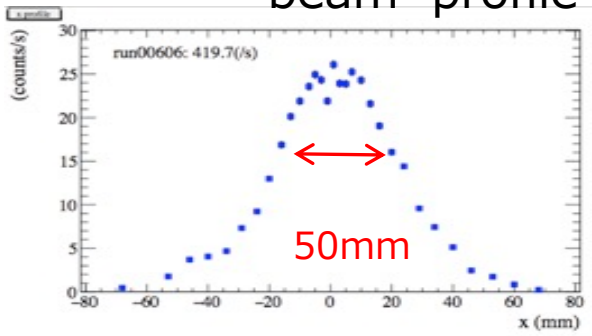
Surface muon (μ+)

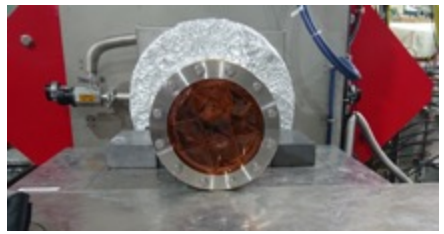
~ 3 x 10^4 cps @ 28 MeV/c

- polarized but not 100 % due to contaminated decay muon
- depend on decay / surface muon ratio

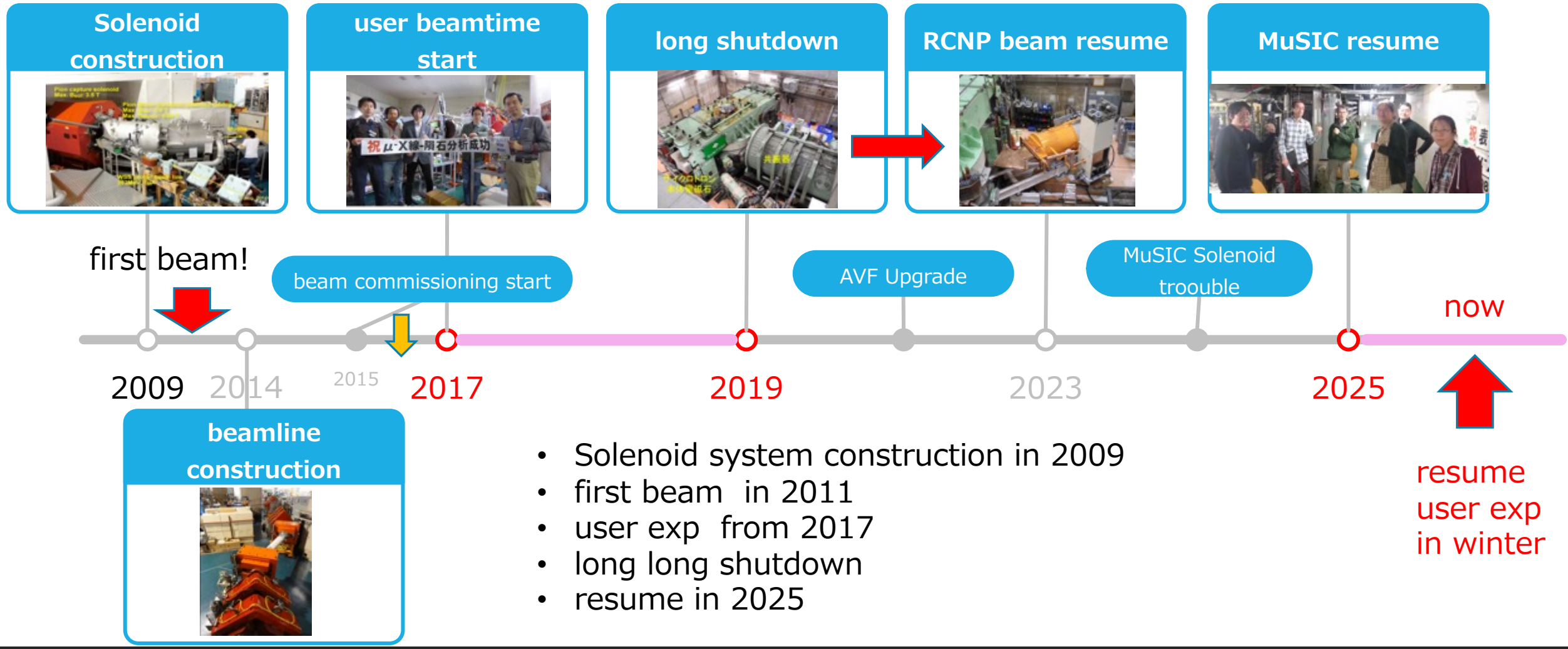


beam profile μ+





history

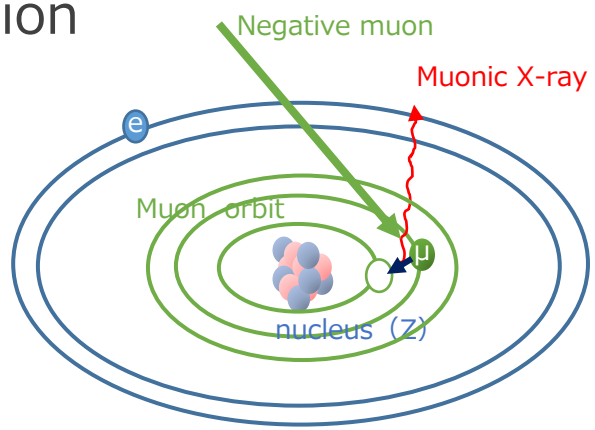


- Solenoid system construction in 2009
- first beam in 2011
- user exp from 2017
- long long shutdown
- resume in 2025

Science at MuSIC (-2019)

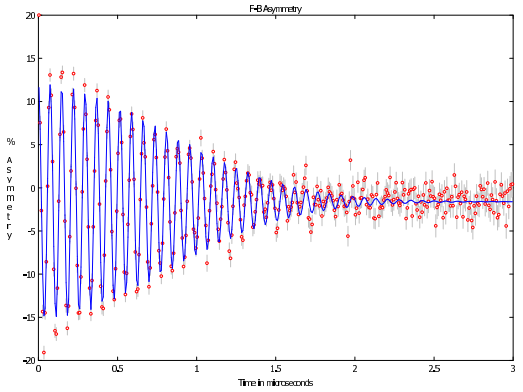
Negative Muon

- MIXE
  - archeology, radio chemistry etc
  - non-destructive elemental analysis
- Nuclear Physics
  - nuclear capture
  - transmutation
- Others



Positive Muon

- μSR
- software test of semiconductor

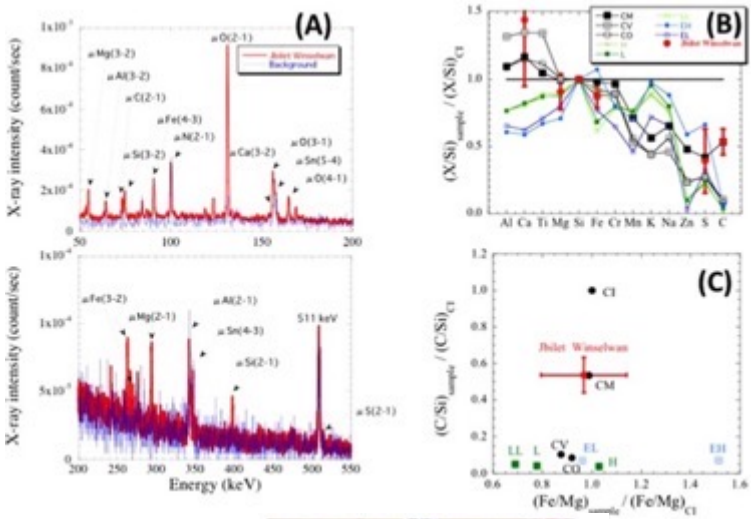


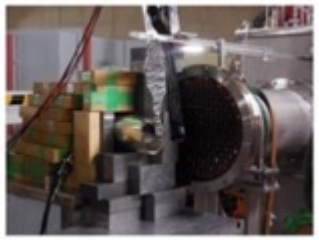
MIXE

meteorite

Non-destructive elemental analysis of a carbonaceous chondrite

K. Terada et al., Sci. Rep. 7 (2017) 15478.

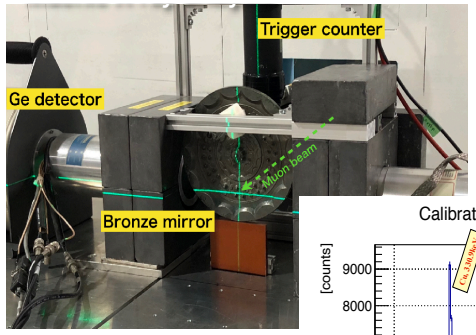


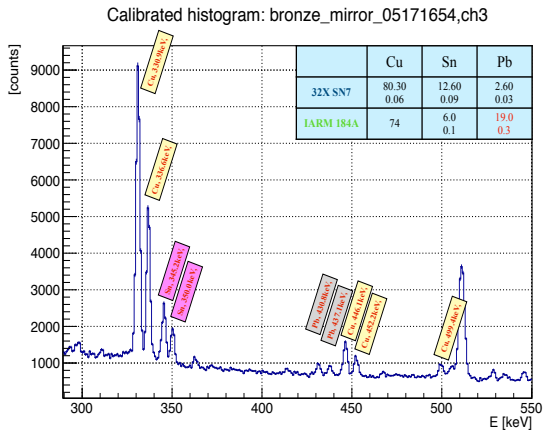


archeology

Non-destructive and non-contact substance analysis of archaeological materials using muonic X-rays

K. Minami et. al.,Society for the History of Asian Casting Technology 14 (2021)16.



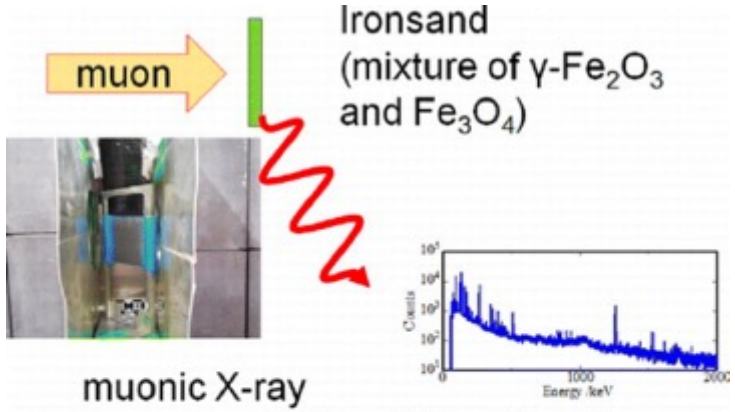


Determinec composition

chemistry

composition identification of mixtures of the Iron compounds

K. Ninomiya et al.,
Bull. Chem. Soc. Jpn., 95(2022)1769

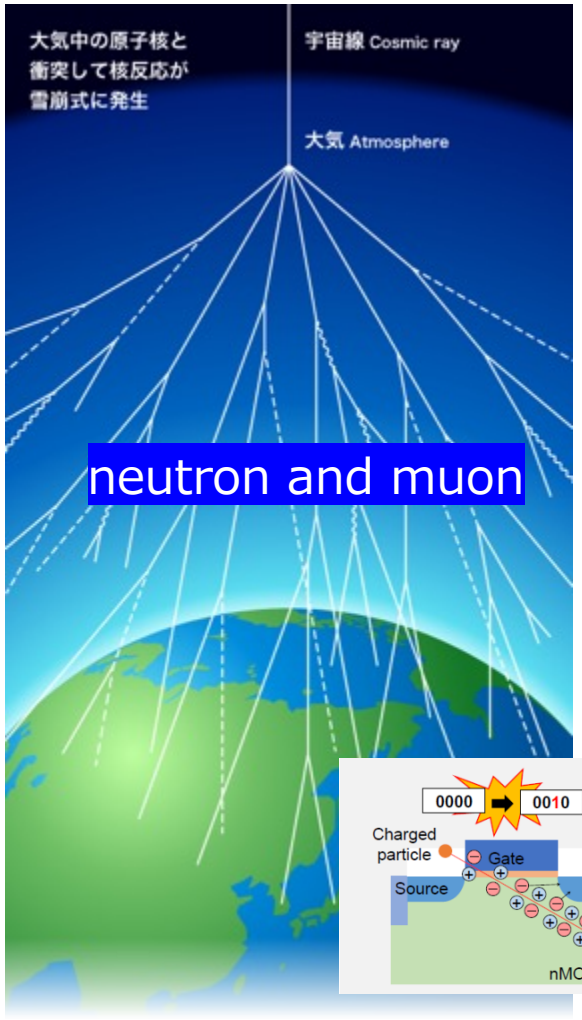


muonic X-ray

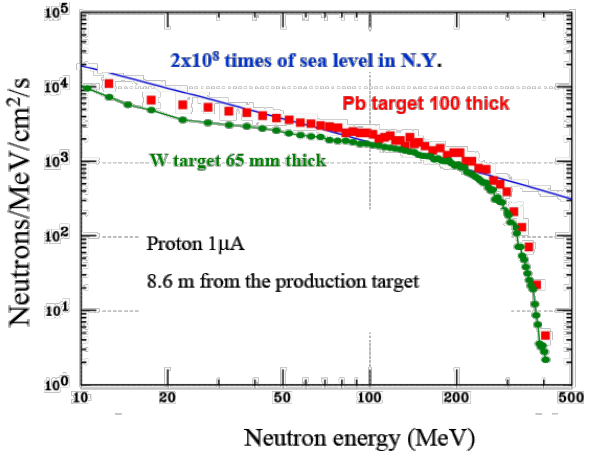
- muonic X-ray intensity ratio
- muon capture ratio of Fe to O

non-destructive identification of chemical state of the sample

Software and hardware test of the semiconductor devices



White neutron source



muon source

- In RCNP, Both white neutron and muon source are available
- high intensity cosmic ray muon and neutron reproduced from proton beam
- In the muon case, charges are significantly affected
- This is caused by the muon nuclear capture reaction.

muon irradiation in semiconductor devices (@RCNP)

65-nm bulk SRAMs、DC muon beam

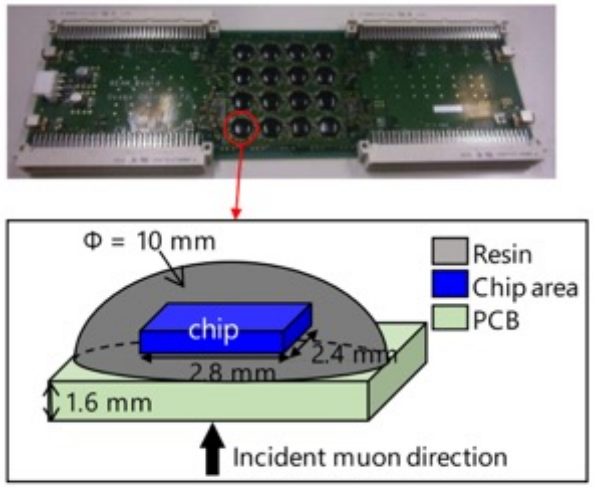
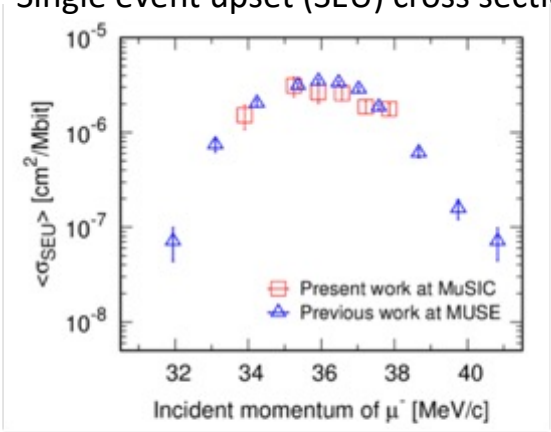
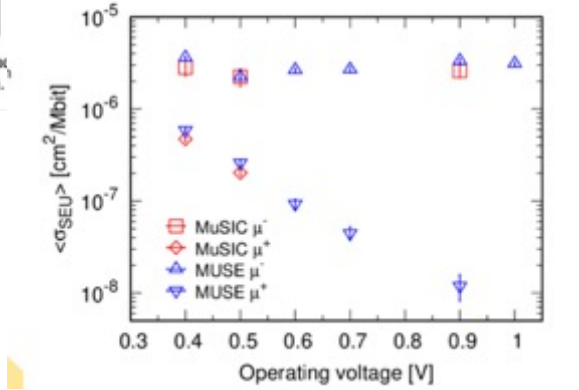


Fig. 1. Structure of the device board. Sixteen chips are bonded on the 1.6-mm-thick PCB. The thickness of tested chips is approximately 0.3 mm.

Single event upset (SEU) cross section





- different behavior between μ+ and μ-

T. Mahara, et al.,
IEEE Trans. On Nucl. Sci 67, 7(2020)1555

Emissions of Hydrogen Isotopes from the Nuclear Muon Capture Reaction in ^{nat}Si

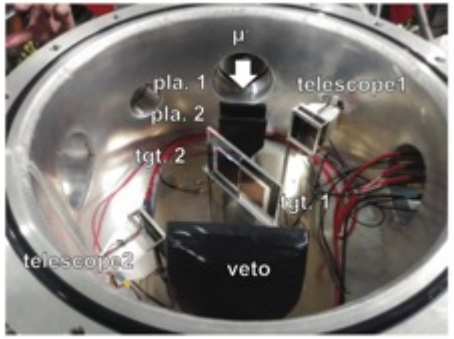


Fig. 1. Experimental setup placed at the beam exit of the M1 beamline of MuSIC.

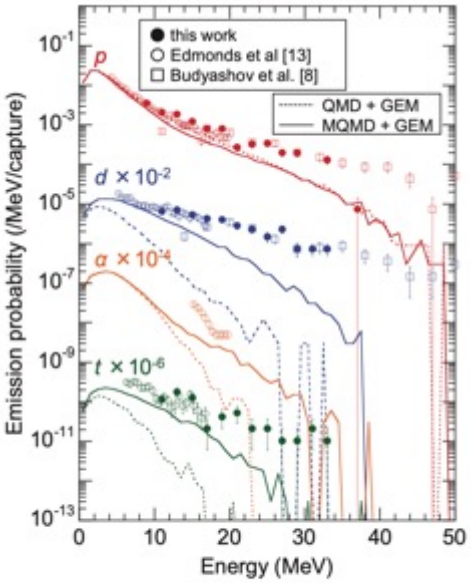


Fig. 5. Comparison of the measured and simulated energy spectra of proton, deuteron, tritons, and alpha particle from the μNC reaction on silicon. The orange open circle denotes the energy spectrum of alpha particle measured in

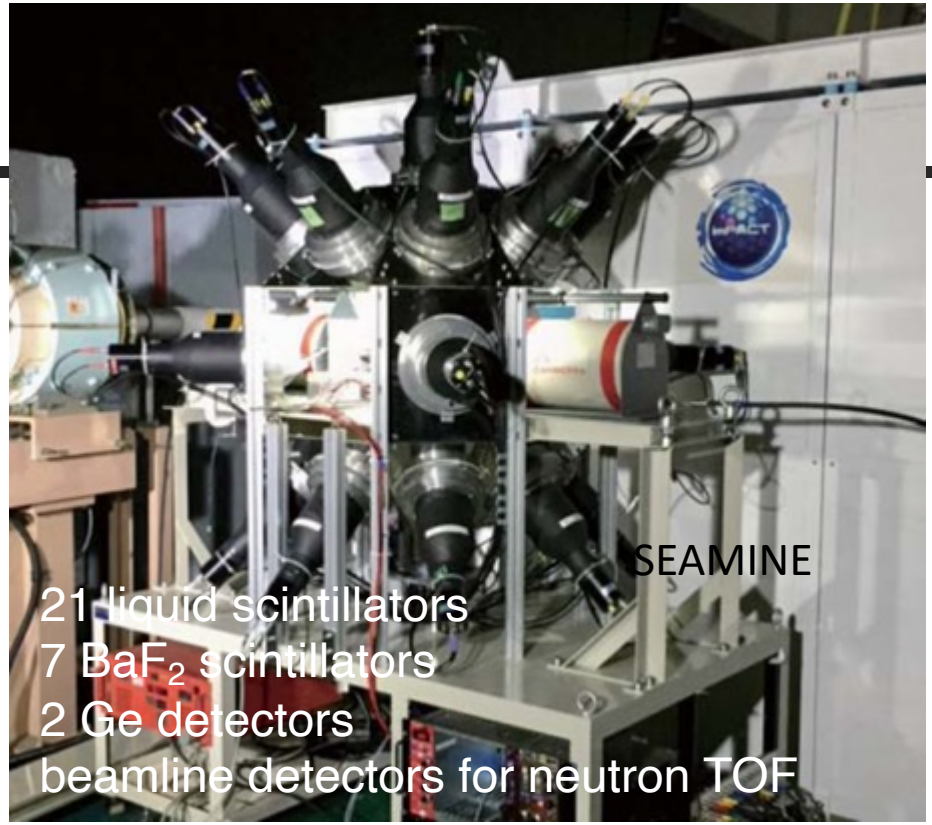
- directly observed secondary emitted particles from Si
- fundamental study for μ- capture in semiconductor

S. Manabe et al.,
EPJ Web. Conf. **284**, 01029 (2023)

Nuclear physics

Muonic X-Ray Measurement for the Nuclear Charge Distribution: the Case of Stable Palladium Isotopes

- Muonic X-ray spectroscopy
  Nuclear size (nuclear charge radius)
- Neutron emission following nuclear muon capture
  measured neutron energy spectra for palladium isotopes



Pd (A= 104,105,106,108, 110)
Measured at MuSIC

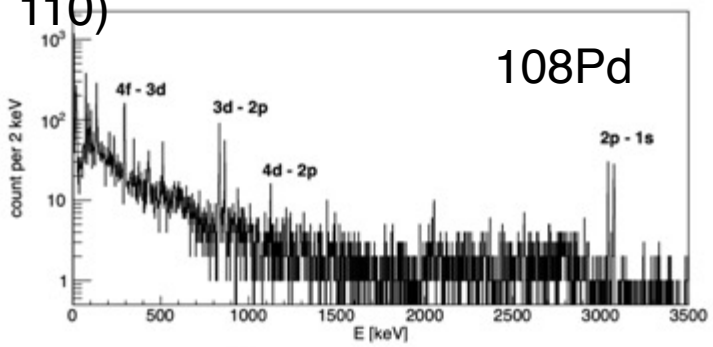
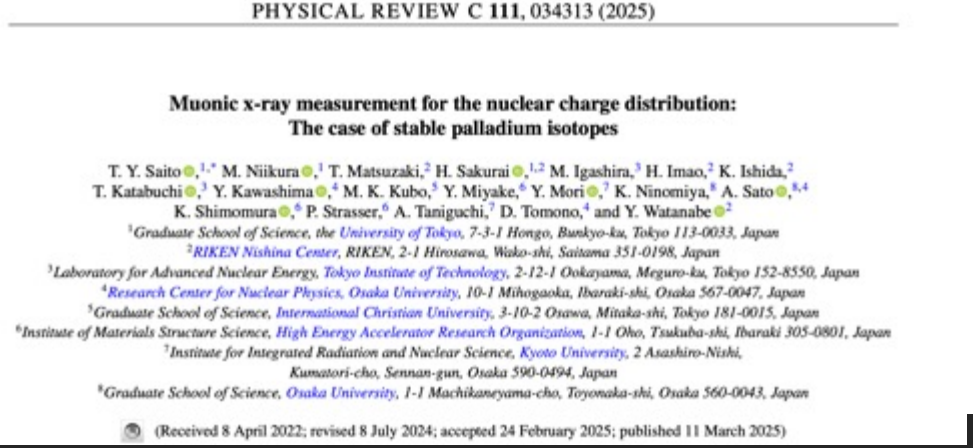


FIG. 4. The entire spectrum of the ^{108}Pd measurement gated on the X-ray timing. The intense peaks are indicated.

TY Saito et.al., Phys. Rev. C **111**, 034313


PHYSICAL REVIEW C 111, 034313 (2025)

Muonic x-ray measurement for the nuclear charge distribution: The case of stable palladium isotopes

T. Y. Saito,[1,*] M. Niikura,[1] T. Matsuzaki,[2] H. Sakurai,[1,2] M. Igashira,[3] H. Imao,[2] K. Ishida,[2] T. Katabuchi,[3] Y. Kawashima,[4] M. K. Kubo,[5] Y. Miyake,[6] Y. Mori,[7] K. Ninomiya,[8] A. Sato,[8,4] K. Shimomura,[6] P. Strasser,[6] A. Taniguchi,[7] D. Tomono,[4] and Y. Watanabe[2]
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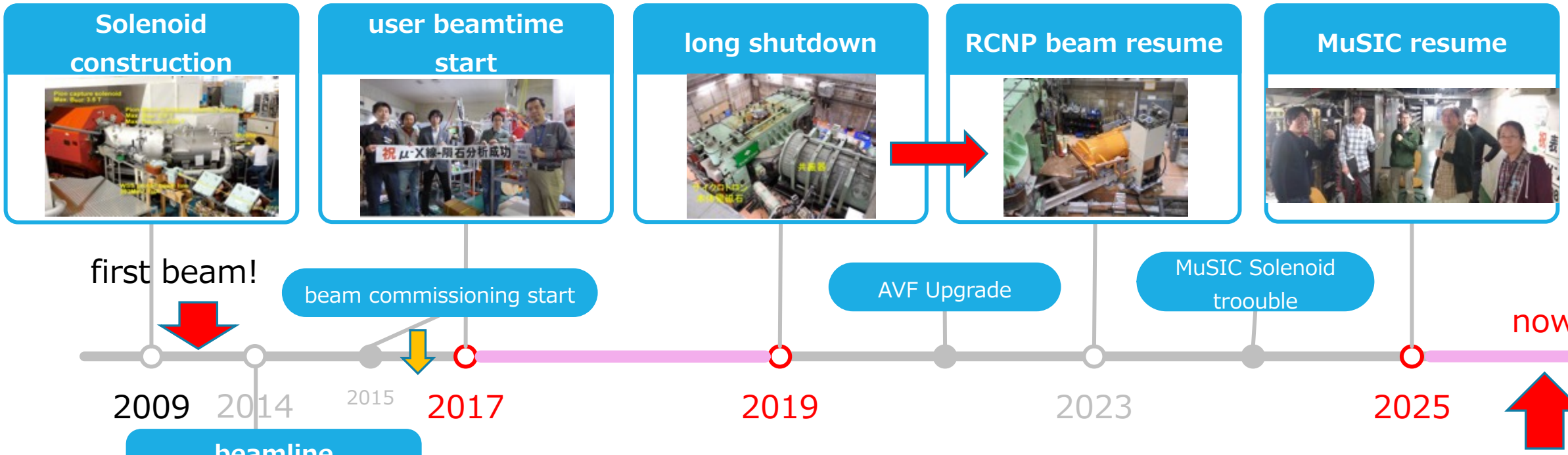
history



- Solenoid system construction in 2009
- first beam in 2011
- user exp from 2017
- long long shutdown
- resume in 2025

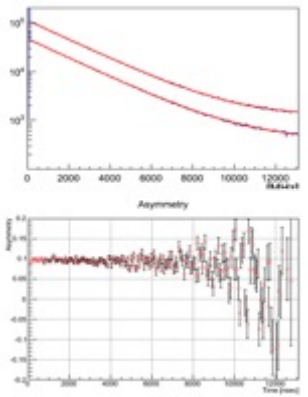
Solenoid troubles(2023-)

Troubles in the cryogenic system of the solenoid magnet

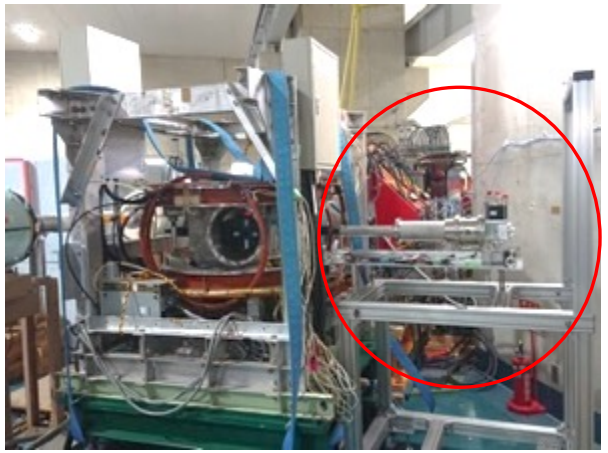
- Troubles occurred in the refrigerator of the solenoid system.(15 years old)
- Some power contacts were shorted due to the overcurrent.
- Burned points were located (three areas identified) and repaired.
- Ground contacts were improved in several locations.
- The solenoid cooling test was successfully completed.
- Muon beam operation resumed in April 2025.
- User experiments resume this winter.

positive muon (μSR)

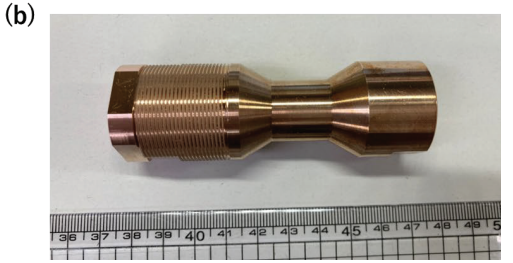
μSR spectrometer (with microstat)



- A conventional μSR spectrometer was installed.
- A microstat (>4 K) and a new GM refrigerator (>4 K) are available.
- Two experiments were conducted in 2019.
- Experiments are planned to resume, including studies under high pressure, taking advantage of decay muons at MuSIC.

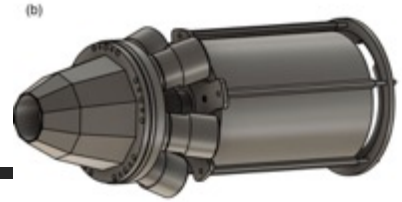


new GM refrigerator installed



high pressure cell
by W. Higemoto（JAEA）

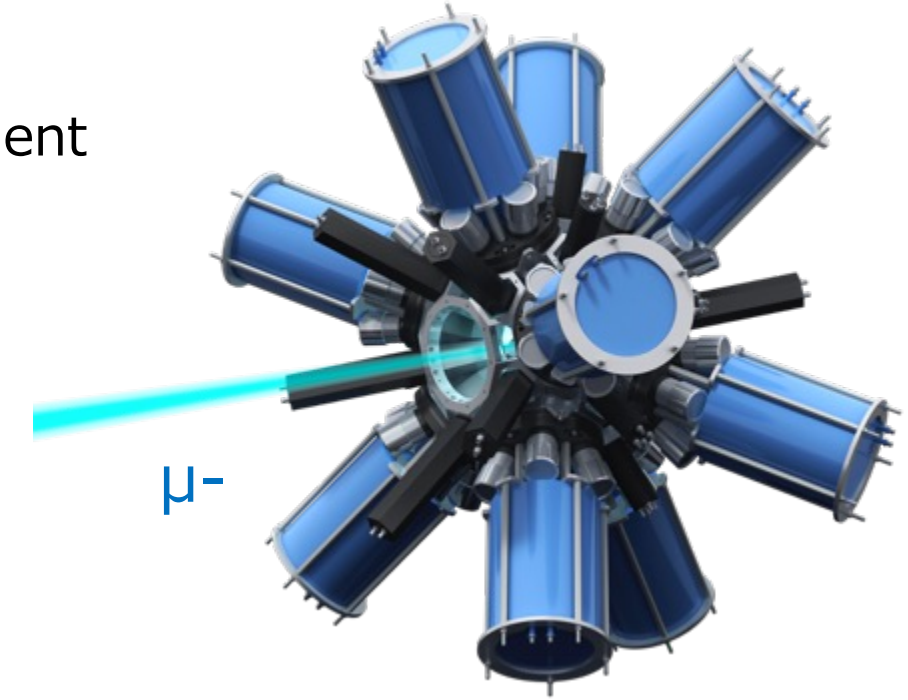
negative muon



X- and γ-ray measurement

- MIXE
- nuclear physics
- chemistry
- muon capture

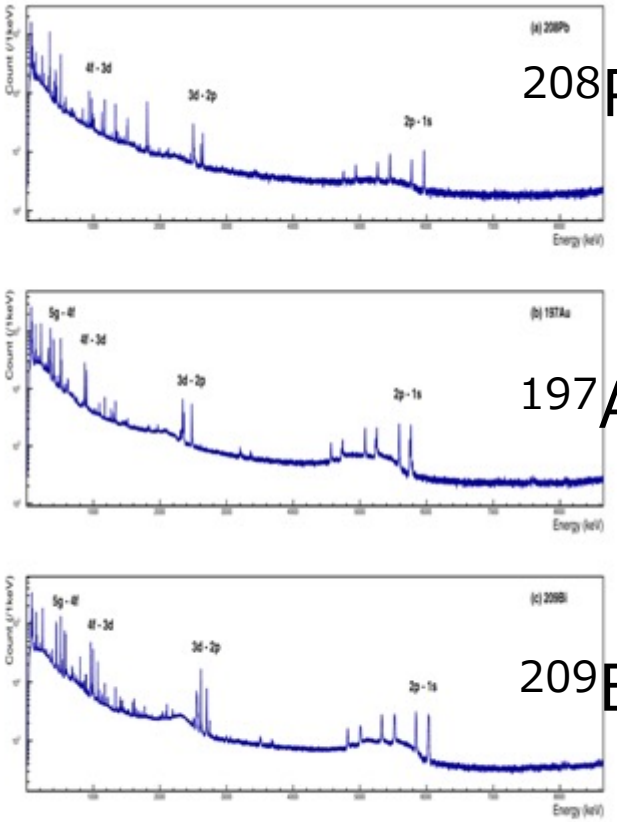
New Ge Array



from M. Niikura

HPGe x 10
neutron counter x 10
BaF_2 x 10

4 sets are now available



208Pb

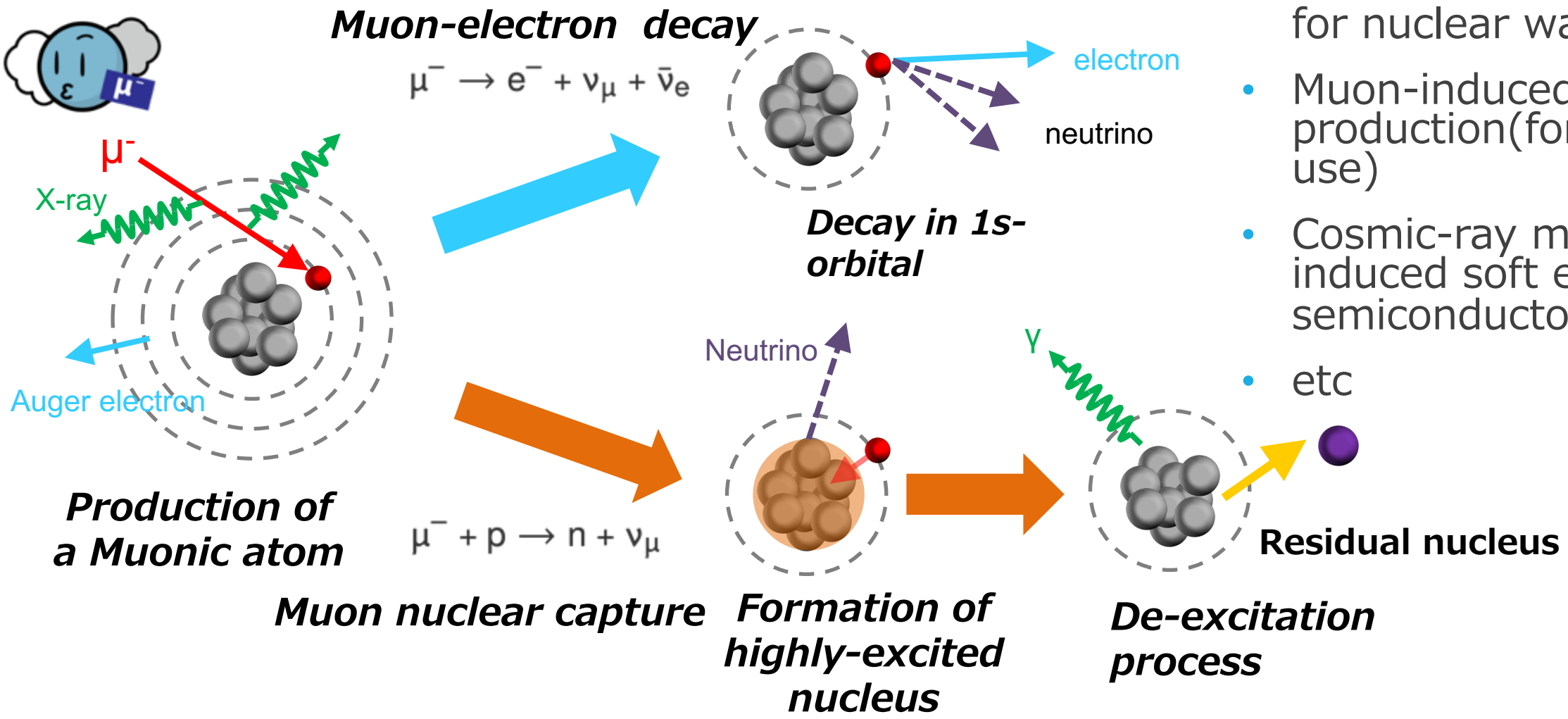
197Au

209Bi

Fig. 15. Energy spectrum of the muonic X-rays of ^{208}Pb (a), ^{197}Au (b), and ^{209}Bi (c). X-rays from the K, L, M, and N series are identified. The SE and DE peaks are shown in the spectra.

R. Mizuno et al.,
NIM A 1060, 169029 (2024).

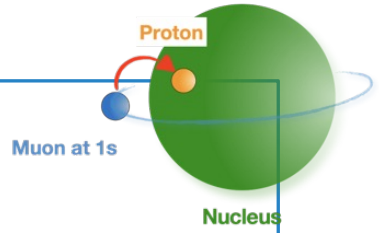
Muon capture reaction



- Nuclear transmutation for nuclear waste
- Muon-induced RI production(for medical use)
- Cosmic-ray muon induced soft errors in semiconductor devices
- etc

muon nuclear data

A new project to develop evaluated muon nuclear data (μND) has recently been launched in Japan



μND

consisting of the four sub-libraries:

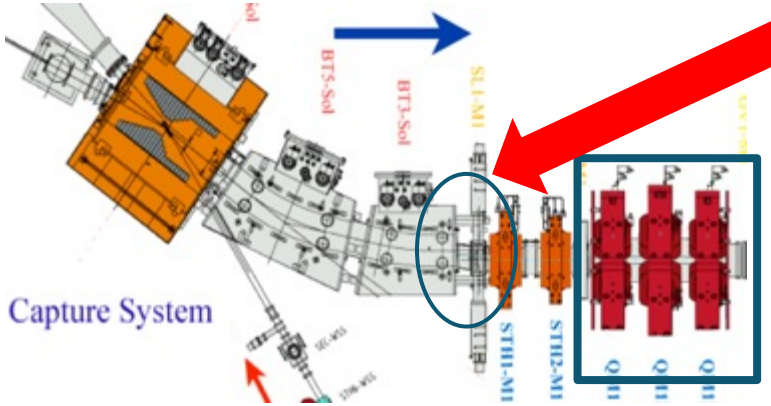
- Muonic X-ray Energies and Intensities (XEI)
- Lifetime of muonic atoms (Nuclear Capture Rate: NCR)
- Energy Spectra of emitted Particles (ESP)
- Residual Production Branching ratios (RPB)

μND library through theoretical, experimental, and machine-learning approaches

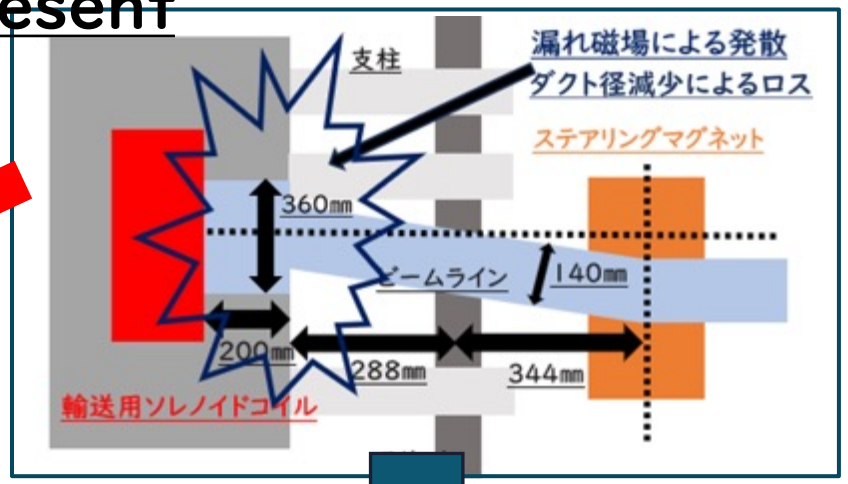
Ref. M. Niikura et al., JAEA Conf. 2024-02, 29-34 (2024).

- This fundamental dataset is essential for all negative-muon analyses supporting emerging scientific and technological developments.
- The project is experimentally supported by MuSIC.

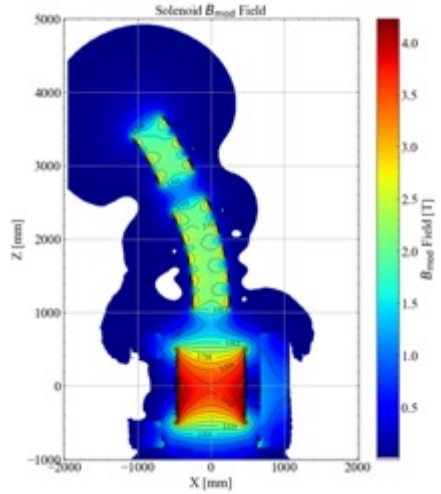
Muon beamline improvement

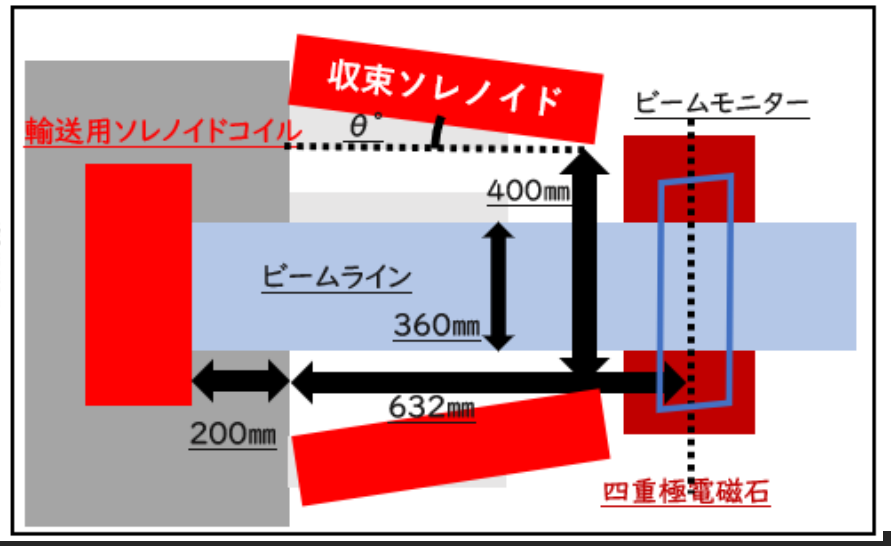


present



new





- Severe muon loss observed at the solenoid exit due to magnetic field leakage.
- Low-energy muons diverge significantly, reducing transport efficiency.
- A new focusing component is essential
- Design study for the connection and beam transport improvement has now started.
- also considering white muon port for RI production

(K. Watanabe, S. Matsui, K. Yokota, etc)

Summary

- Operational since 2017, providing DC muon beams for user experiments.
- Solenoid refrigerator issue resolved; beam confirmed in April 2025.
- User beamtime resumes in winter 2025 (limited due to shared use with nuclear physics).
- Supports μSR(ex. high pressure etc, originally designed for decay muon experiment) MIXE, nuclear physics (μND development, capture reaction, RI production), etc.
- Beamline upgrades and development of white muon beamline for RI production under consideration.

- New experiment proposals using MuSIC are welcome.