Advancement of the J-PARC muon facility

Overview of MUSE (Muon Science Establishment)

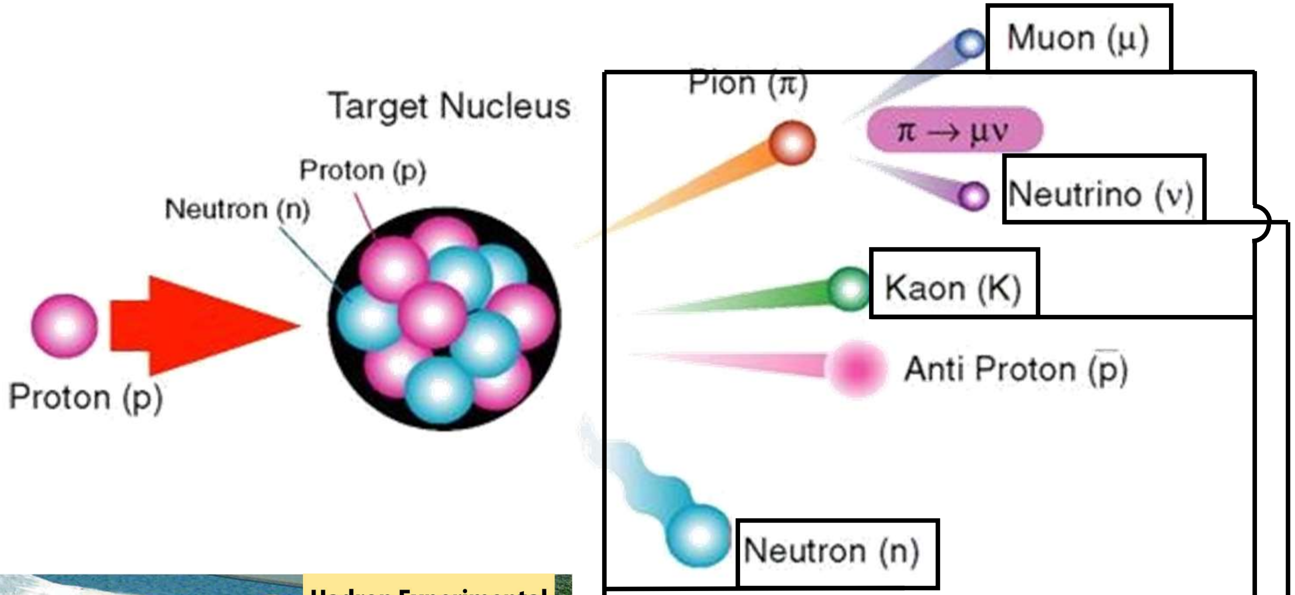
Muon4Future, 26/Mar/'25

Muon Sci. Sec. MLF Div. J-PARC Naritoshi Kawamura

J－PARC

3 accelerators

400 MeV linac
3GeV synchrotron (RCS)
30GeV synchrotron (MR)



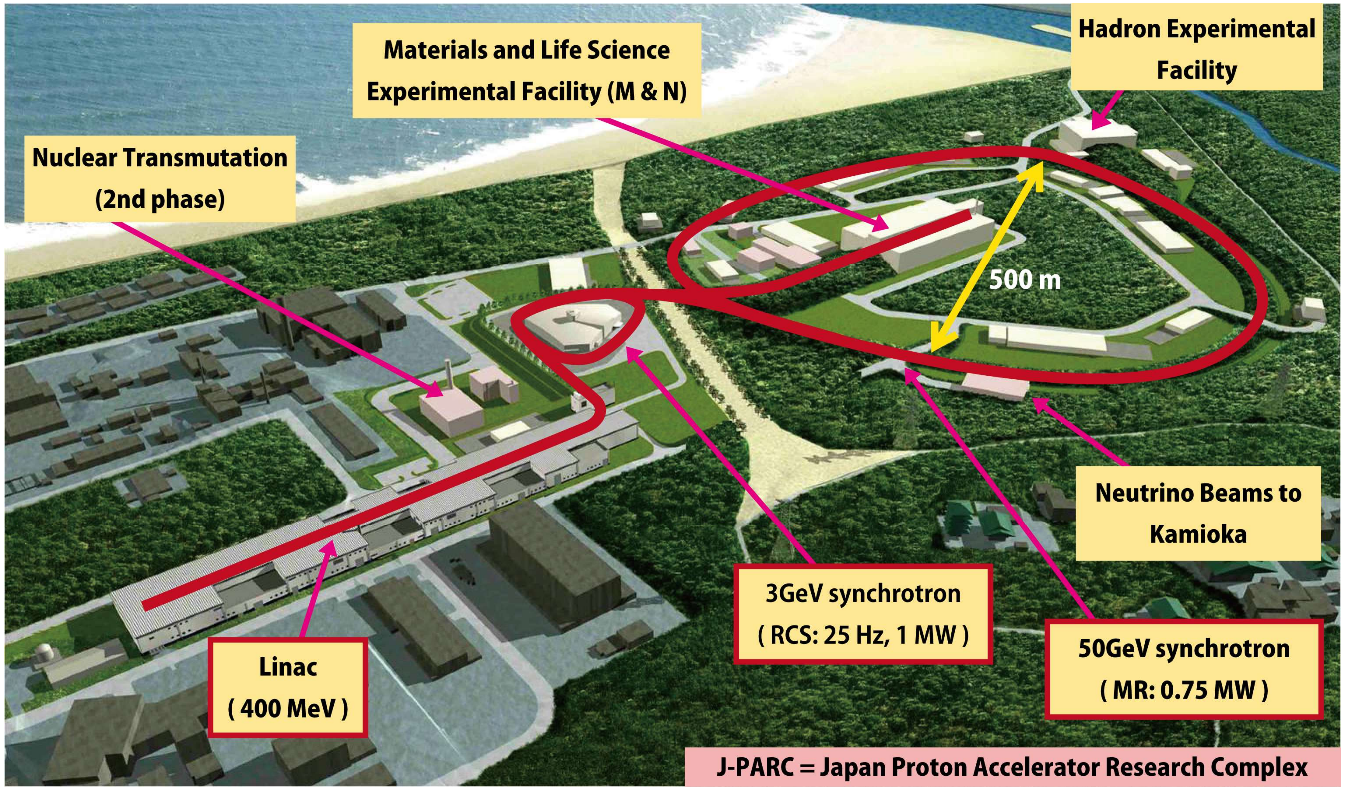
Materials and Life Science Facility

Hadron facility

Neutrino facility

Nuclear transmutation research (under design)

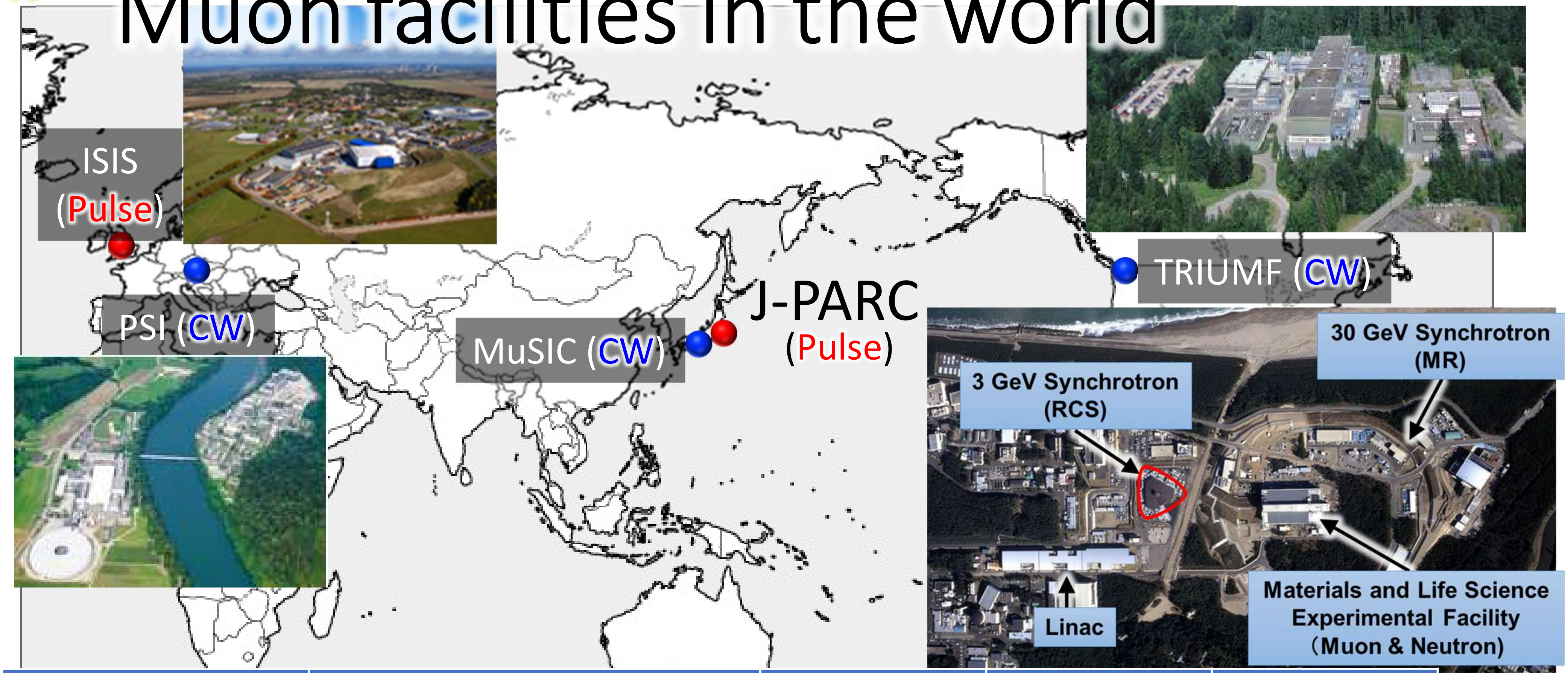
4 facilities



Requirements of a muon facility

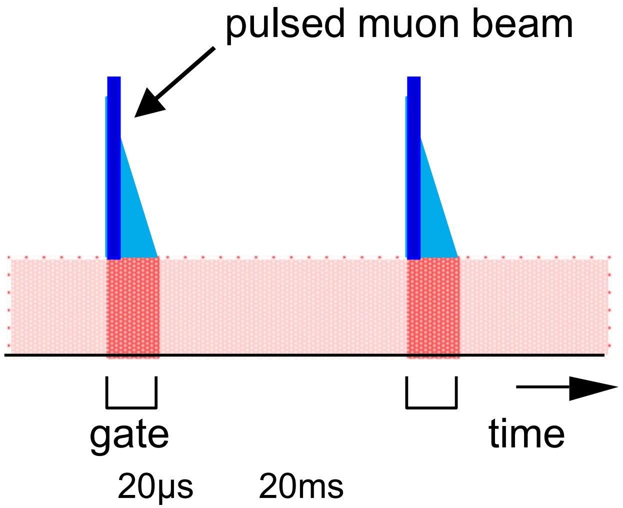
- A high-power proton driver with an energy of more than $E_{th} = 2m_\pi \left(1 + \frac{m_\pi}{4m_p}\right) \approx 290\ \mathrm{MeV}$.
  - Practically, more than 500 MeV accelerators
- A pion production target that can be operated safely and stably under high heat deposition and high radiation field
- A beamline with high transmission efficiency.
  - Particle physics: only a beamline for a specific purpose COMET@J-PARC Hadron, MU2E@Fermi, g-2@Fermi
  - Material science/General science: as much as a variety of beamlines to answer a variety of users' demands
- "Specialties" that characterizing the facility

Muon facilities in the world

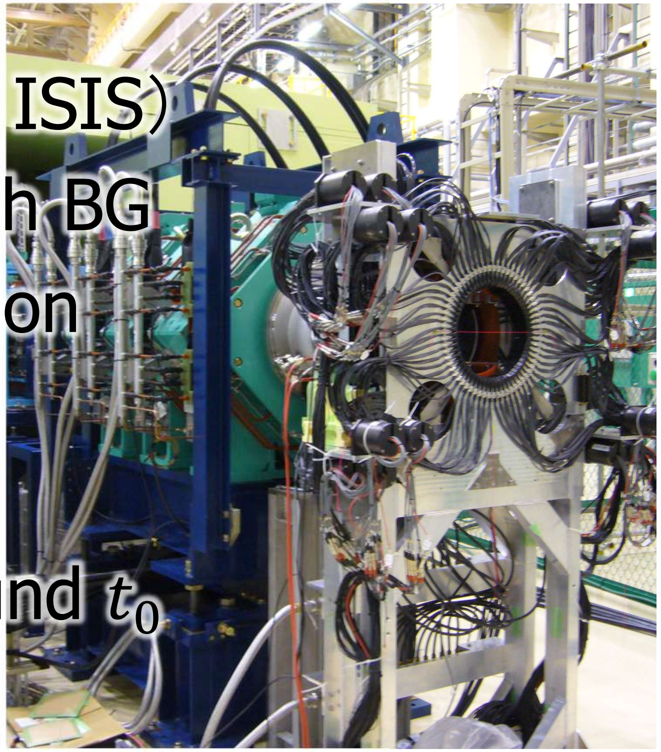


Country	Japan		The U.K.	Switzerland	Canada
Facility	J-PARC MUSE	RCNP MuSIC	RAL ISIS	PSI	TRIUMF
proton energy [GeV]	3.0	0.39	0.8	0.59	0.52
proton intensity [MW]	1.0	0.0004	0.16	1.4	0.05
μ^+ [/s] (surface)	3×10^8 (U line)	2×10^4 (50MeV/c)	6×10^5	6×10^8 (μE4)	2×10^5
μ^- [/s]	1×10^7	10^4	7×10^4	2×10^7	(5×10^4)
CW / Pulse	Pulse (25Hz)	CW	Pulse (50Hz)	CW	CW

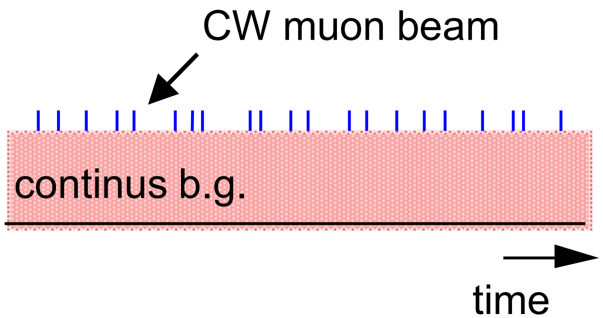
Time Structure - Pulse and CW



- Pulse beam
  (Synchrotron; J-PARC, ISIS)
  - ○ Good S/N under high BG
  - ○ Long-time observation (relaxation >10 μs)
  - × Event tracking
  - × Low time reso. around t_0 (Muonium rotation)

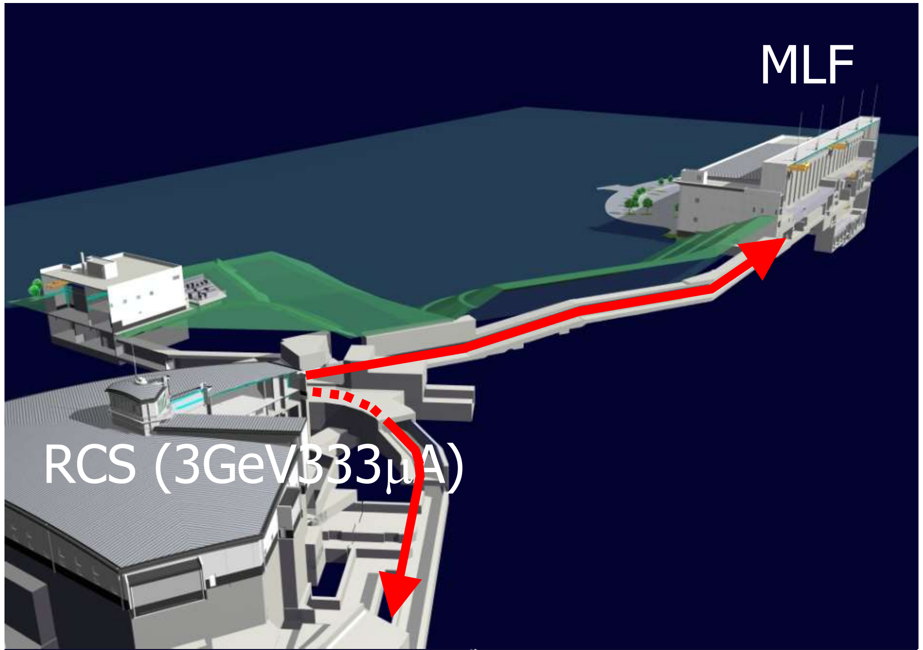


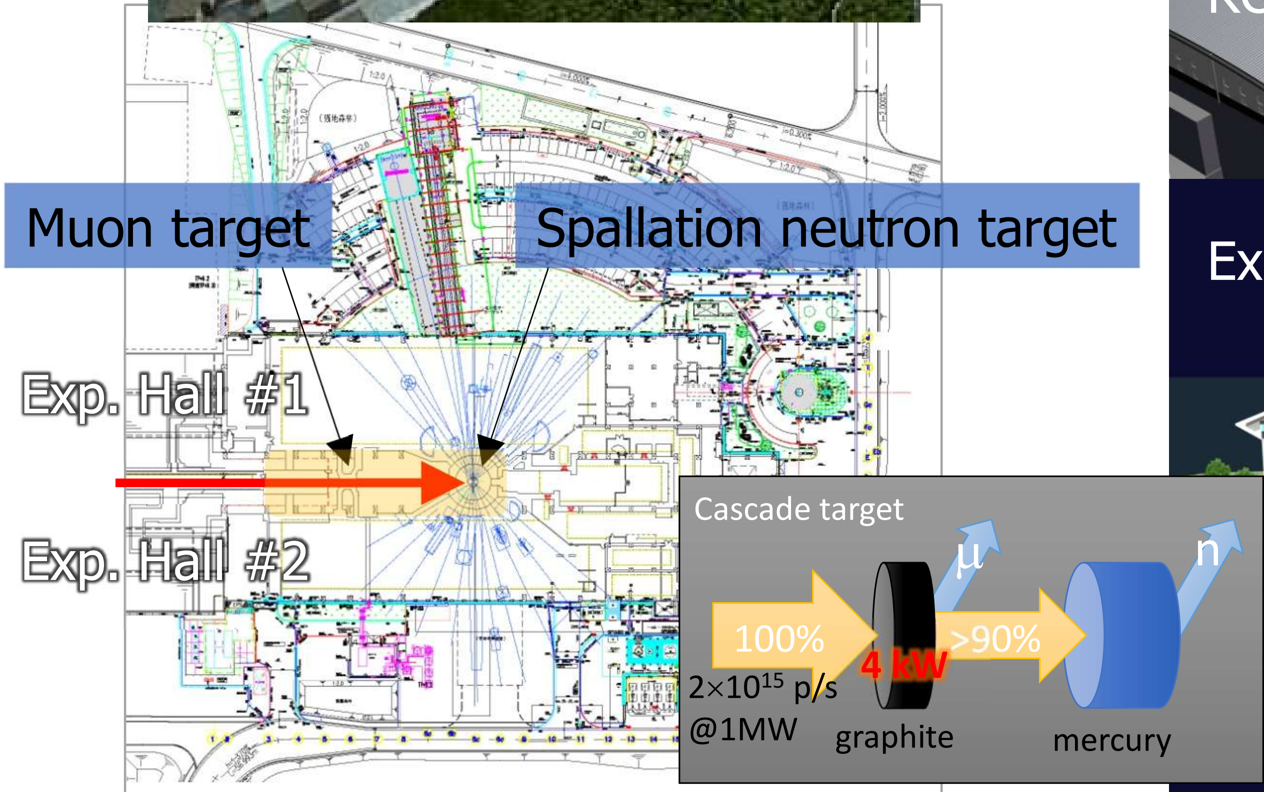
A highly segmented spectrometer is required

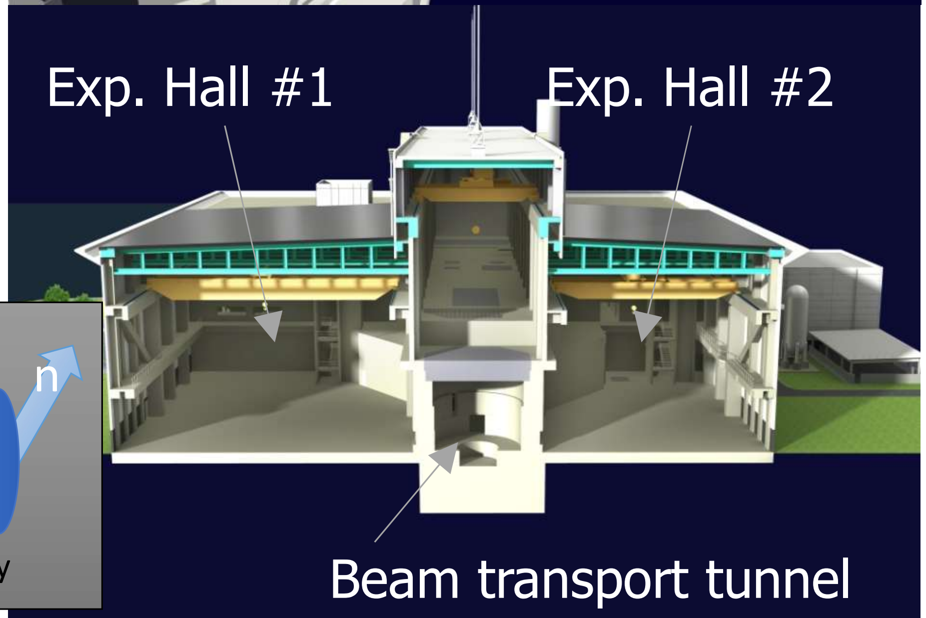


- CW beam
  (Cyclotron; PSI, TRIUMF)
  - × Practical limit in the beam int. due to pile up events.
    (MORE in PSI was solved.)

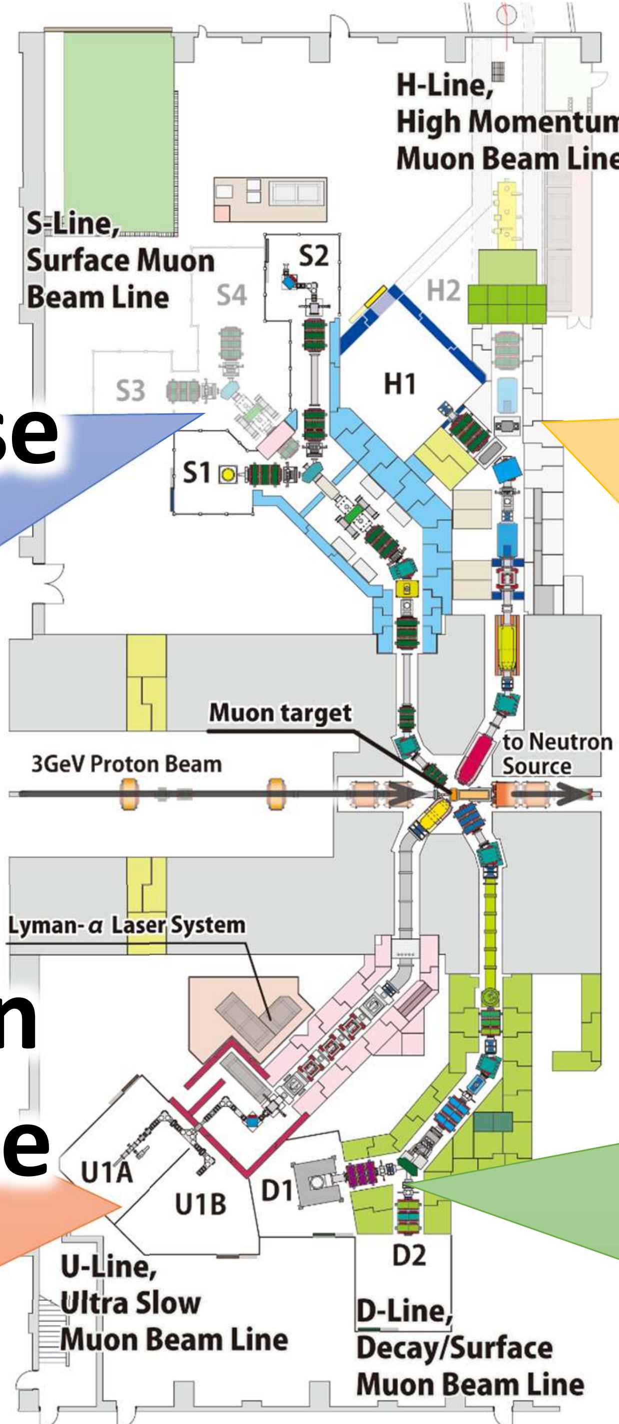
Materials and Life Science Facility







Muon Facility in MLF, MUSE



S-line μ^+

Surface muon (4 MeV)

4 areas

Simultaneous use

ultra-low temperature
high magnetic field
pulsed excitations *etc.*

H-line μ^+/μ^-

High-intensity surface

High Intensity

muon (<4 - 50 MeV)

General Use

"fundamental physics"

requiring high precision,
high sensitivity

U-line μ^+

Ultra Slow Muon

(0.1 - 30 keV)

Surface/Interface

/interface sciences (U1A)

Test-bench for TμM (U1B)

D-line μ^+/μ^-

Decay and surface muon

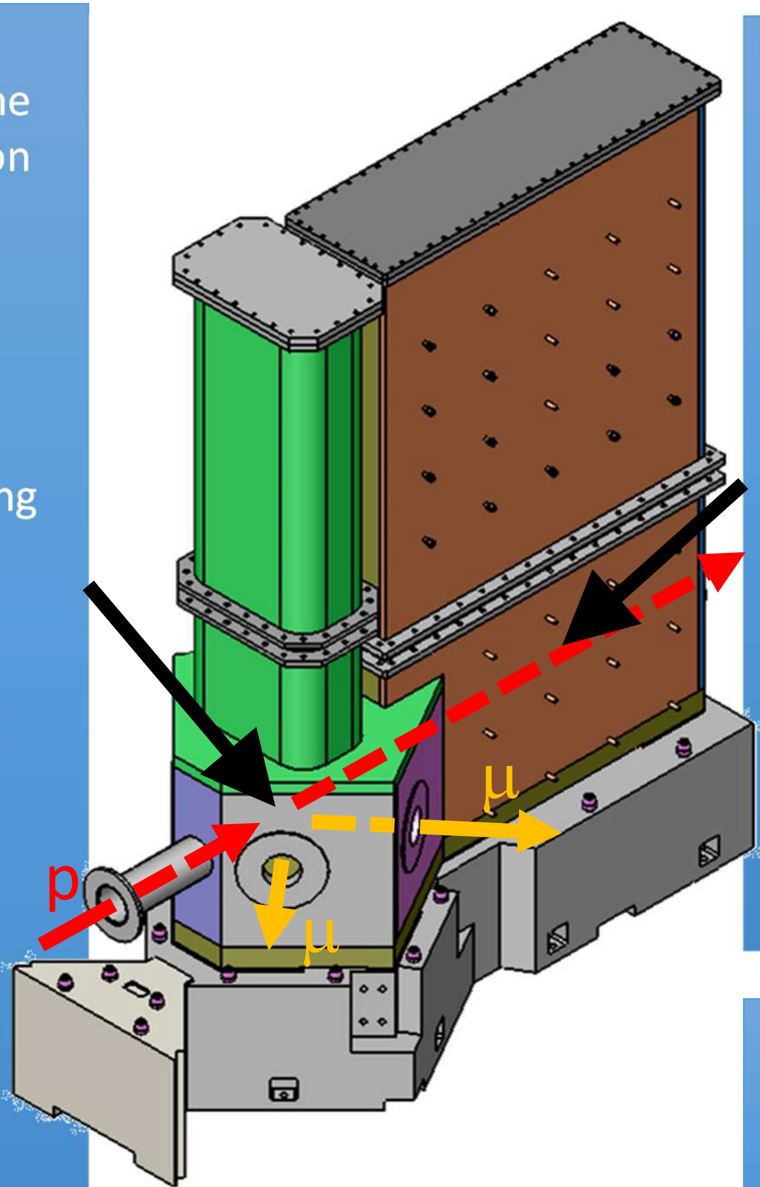
General Use

to answer a variety of users' demands with μSR spectrometer (D1) general purpose (D2)

Muon Production Target

<u>Rotating target</u>

- To prolong the lifetime of the target against DPA, operation started.
  #1: 2014-2019
  #2: 2019-
- Heat deposit : 4 kW
- Graphite disk: rad. cooling
  Bearing, jacket: water cooling
- Monitors: motor torque, vacuum level, Q-mass for outgas. IR-Radiation thermometer is going to be operated.



<u>Two Scrapers (proton collimator)</u>

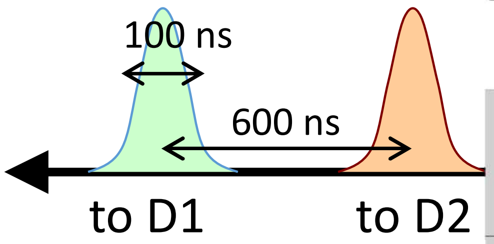
- Scrape the scattered protons by the target
- Renewed in 2015.
- Heat deposit : 20 kW@No1
- Water cooling
- Thermocouple thermometers

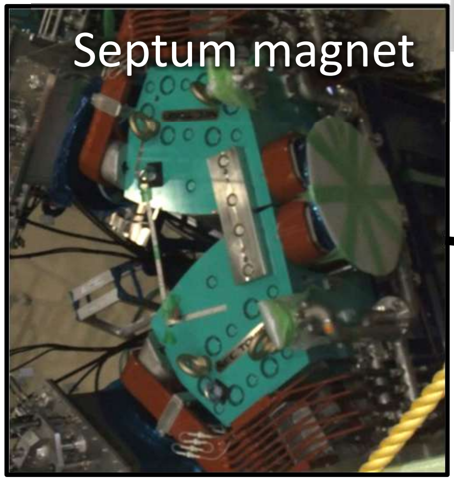
<u>Vacuum vessel</u>

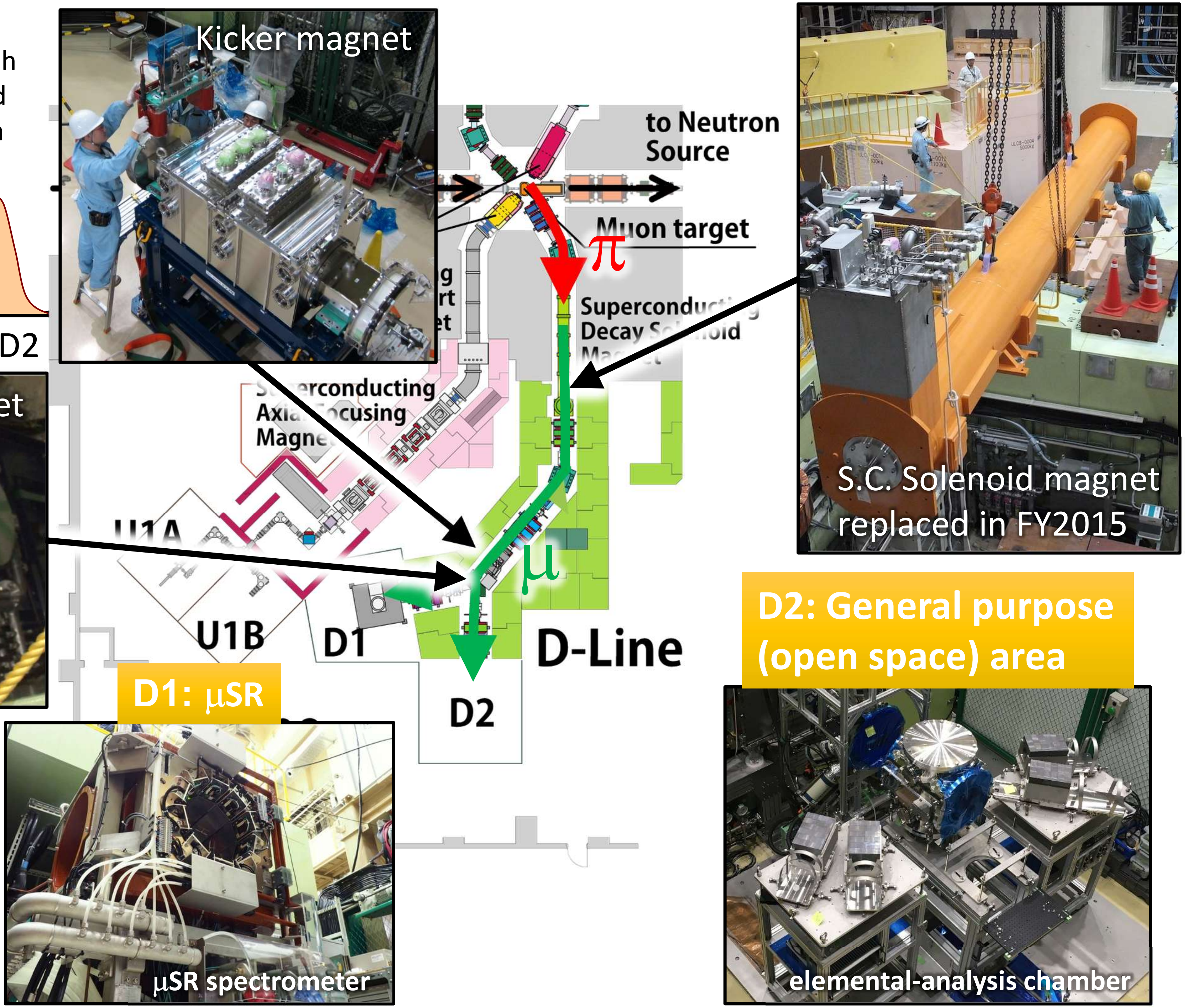
- In service since 2008
- Hea deposit : 10 kW
- Water (>90%) and air cooling
- Thermocouple thermometers

D-line: A decay/surface muon beamline

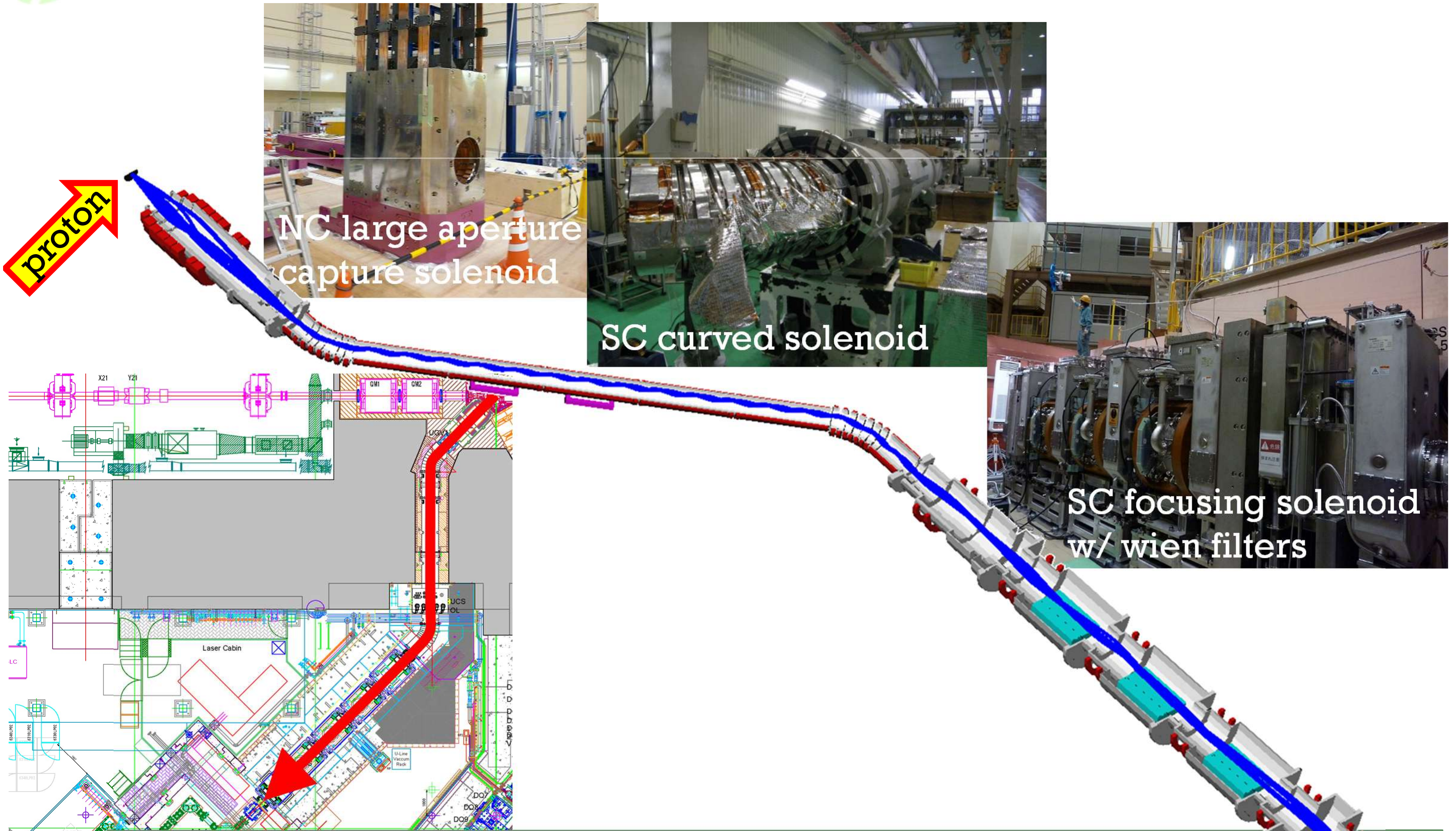
Double pulse structure due to accelerator bunch
Each pulse is distributed to D1 and D2 areas with a kicker magnet.





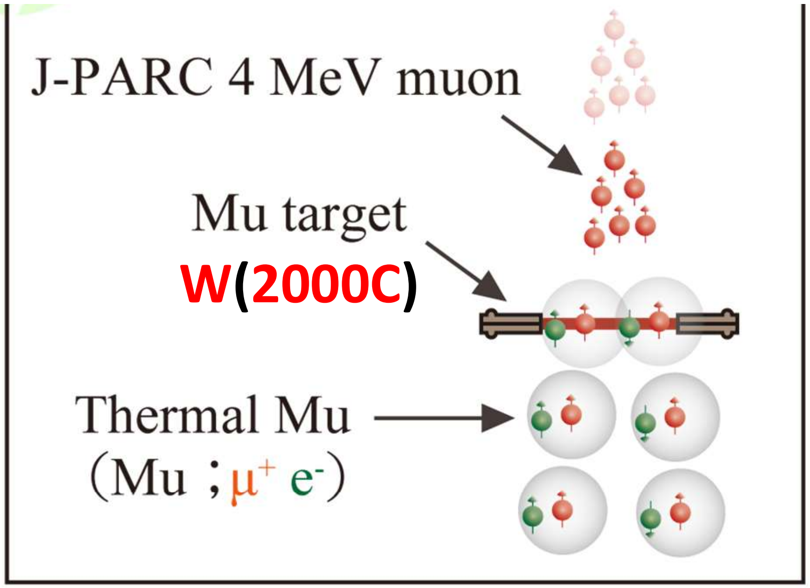


U-line: The highest intensity beamline for USM

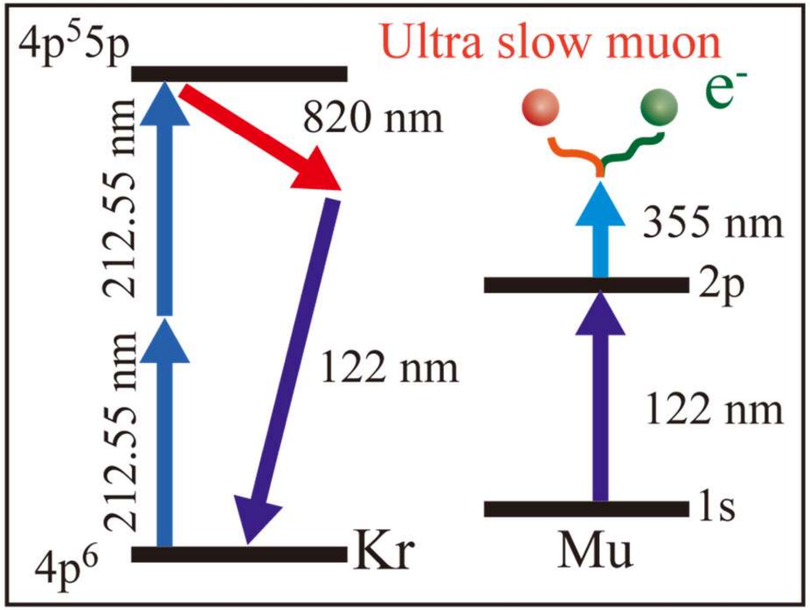


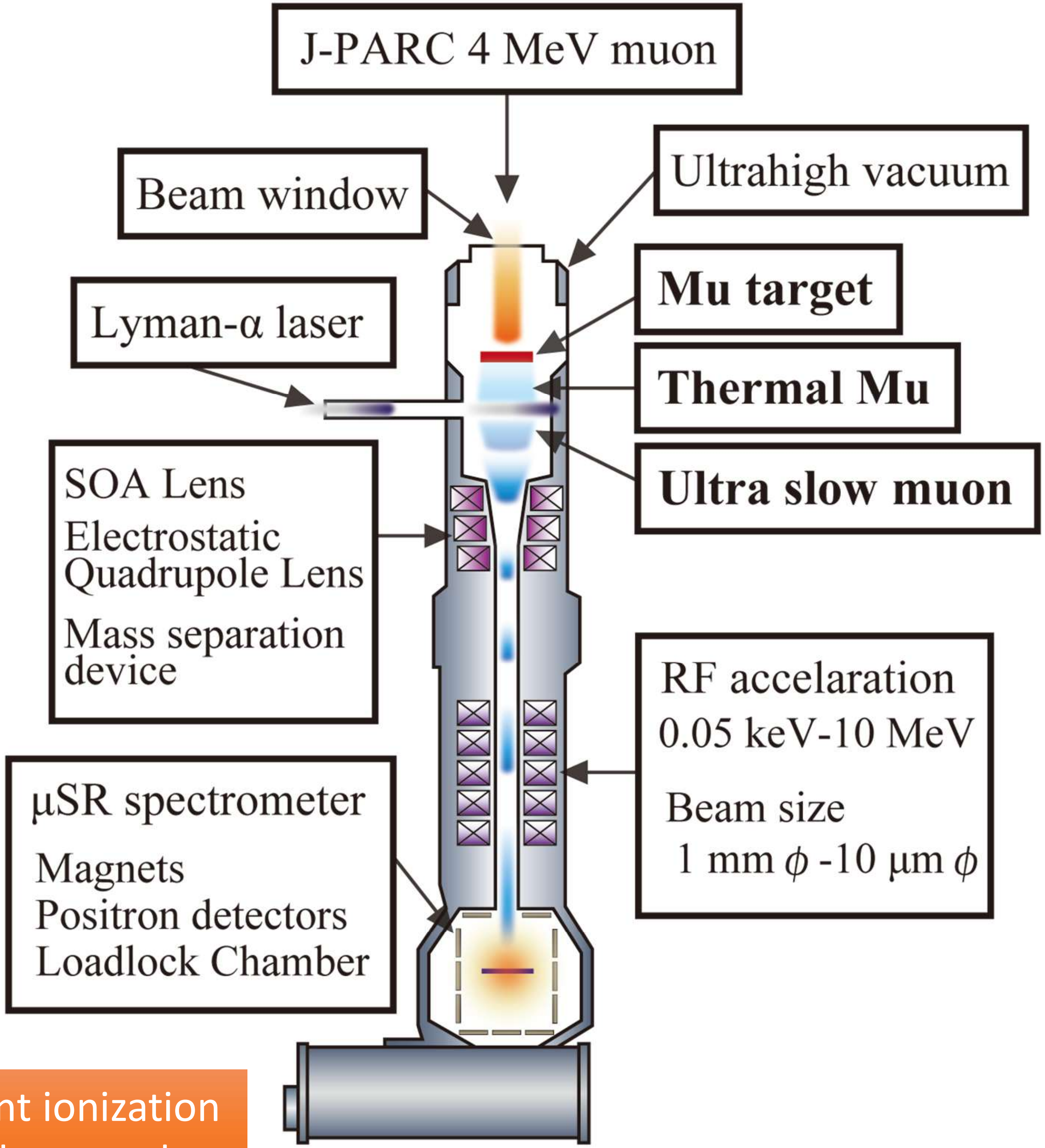
- All beamline magnets are axial focusing
- The world strongest pulsed muon: $2\times10^{8}\ \mu^{+}/s$, $1\times10^{7}\ \mu^{-}/s$

U-line: Generation of Ultra slow muon (USM)



Mu generator



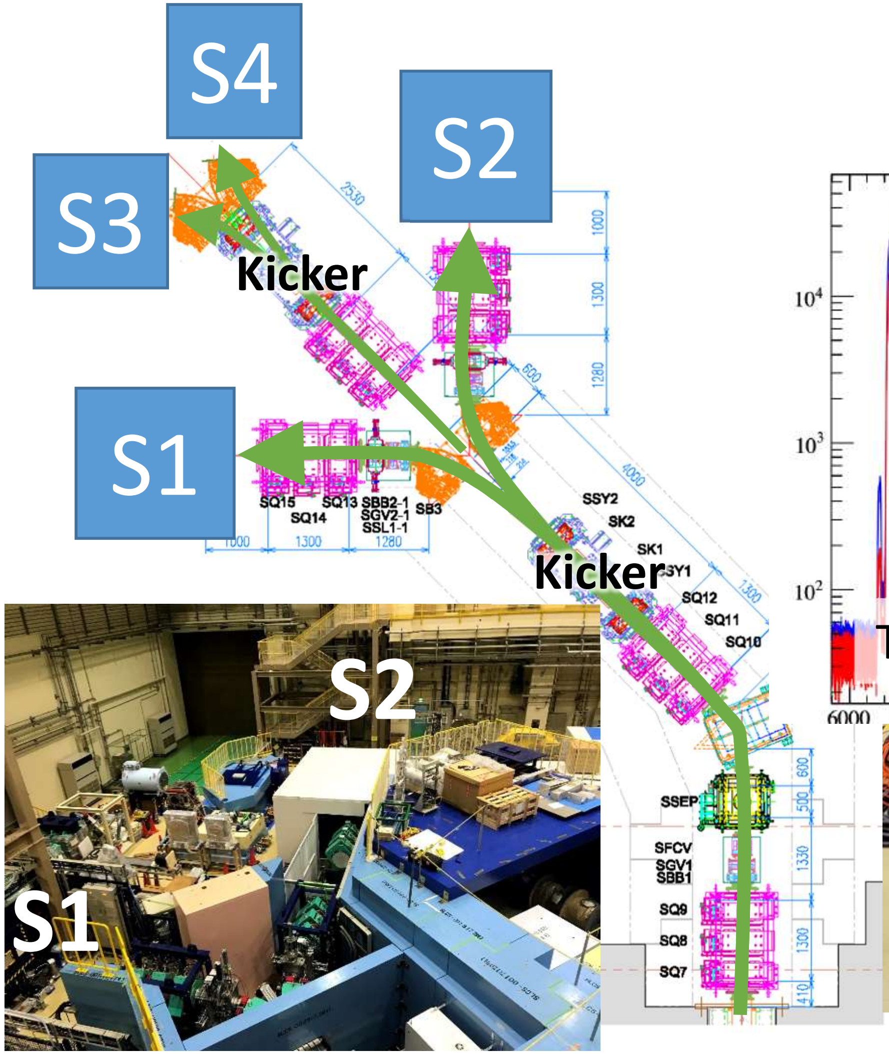


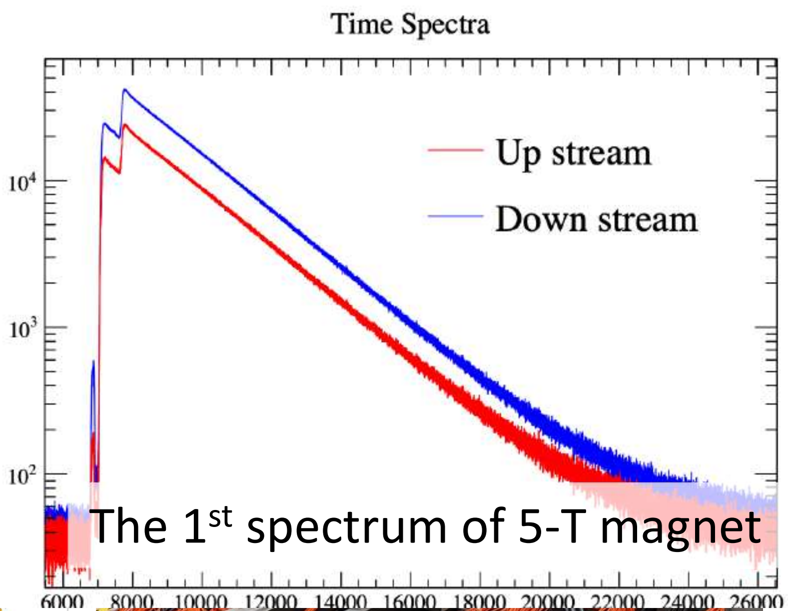
USM is generated by the laser resonant ionization method synchronized with the muon beam pulse.

S-line: A surface muon beamline

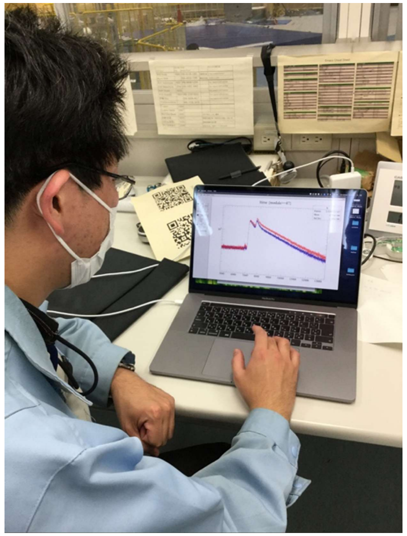
S line is dedicated to transport surface muon beam. By using two kicker system, S line provides muon beams to all 4 areas simultaneously.
At present two experimental areas, S1 and S2, were completed.

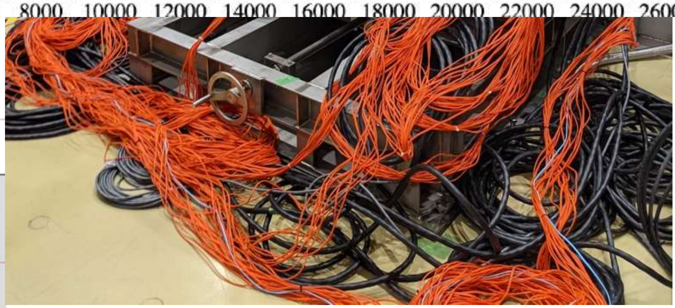
In the S1 area, a μSR spectrometer was equipped for material science.
In the S2 area, the Mu 1s-2s level is measured with ultra-high precision, applying two photon absorption.





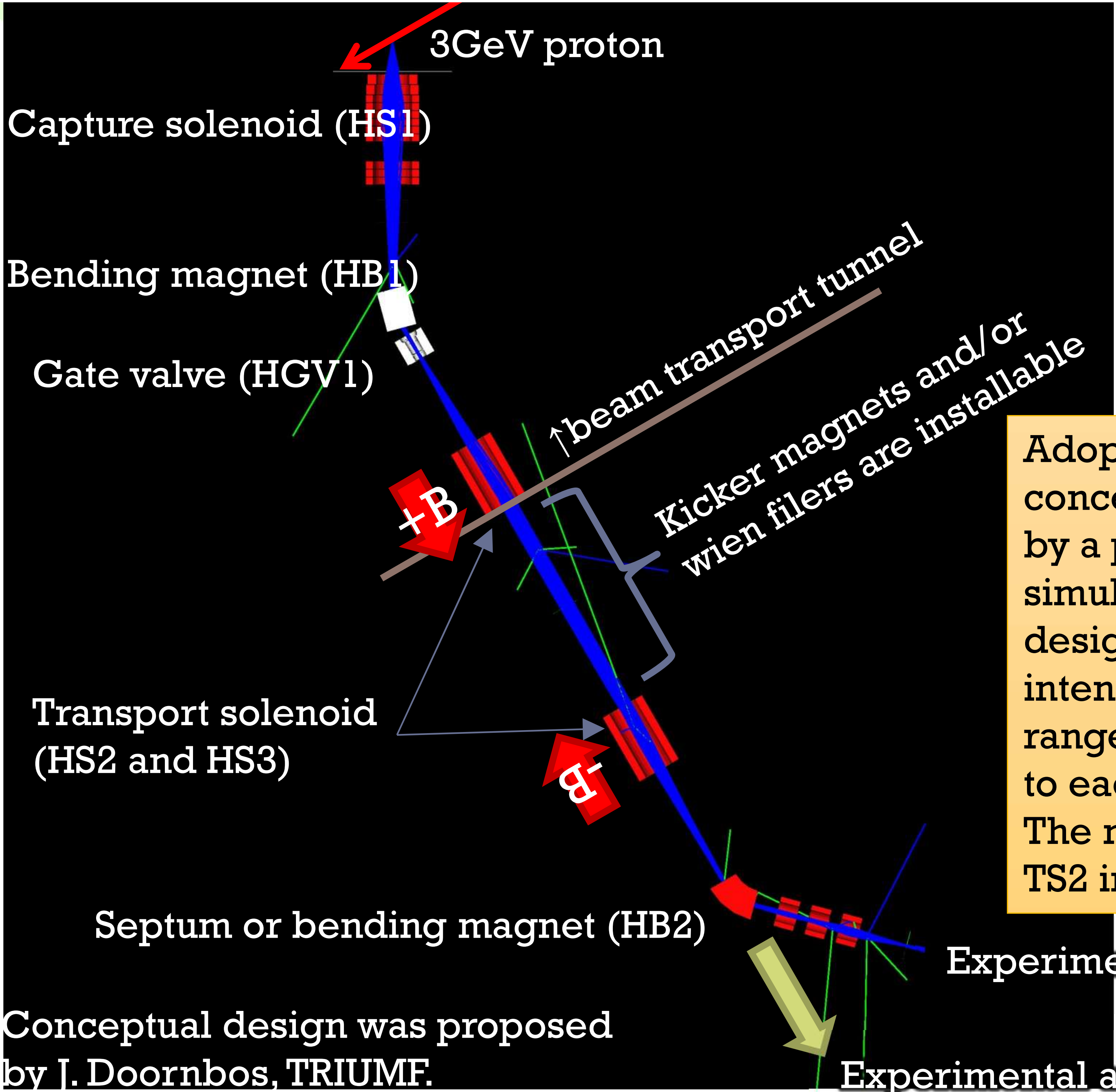
The 1st spectrum of 5-T magnet





Pulse μSR: Highly segmented spectrometer is necessary to avoid the distortion of time spectrum due to pileup.
Cf. 5-T magnet needs 3008-ch

H-line: Generic-purpose High-intensity beamline



Instrument specification of H1

Beam Intensity:

1×10^8 μ^+(surface)/s

2×10^6 μ^-(28 MeV/c cloud)/s

2×10^7 μ^-(40 MeV/c cloud)/s

4×10^7 μ^-(>50 MeV/c cloud)/s

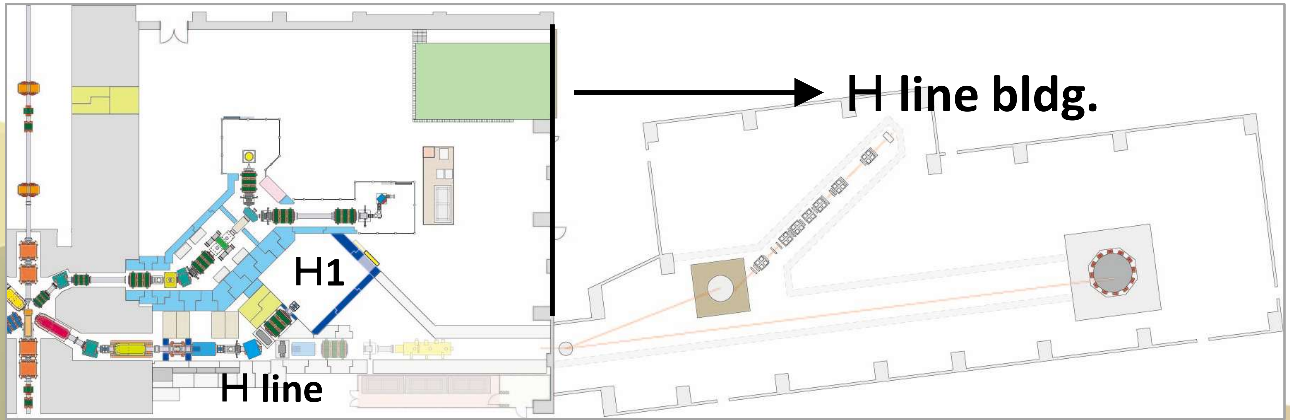
Beam spot size:

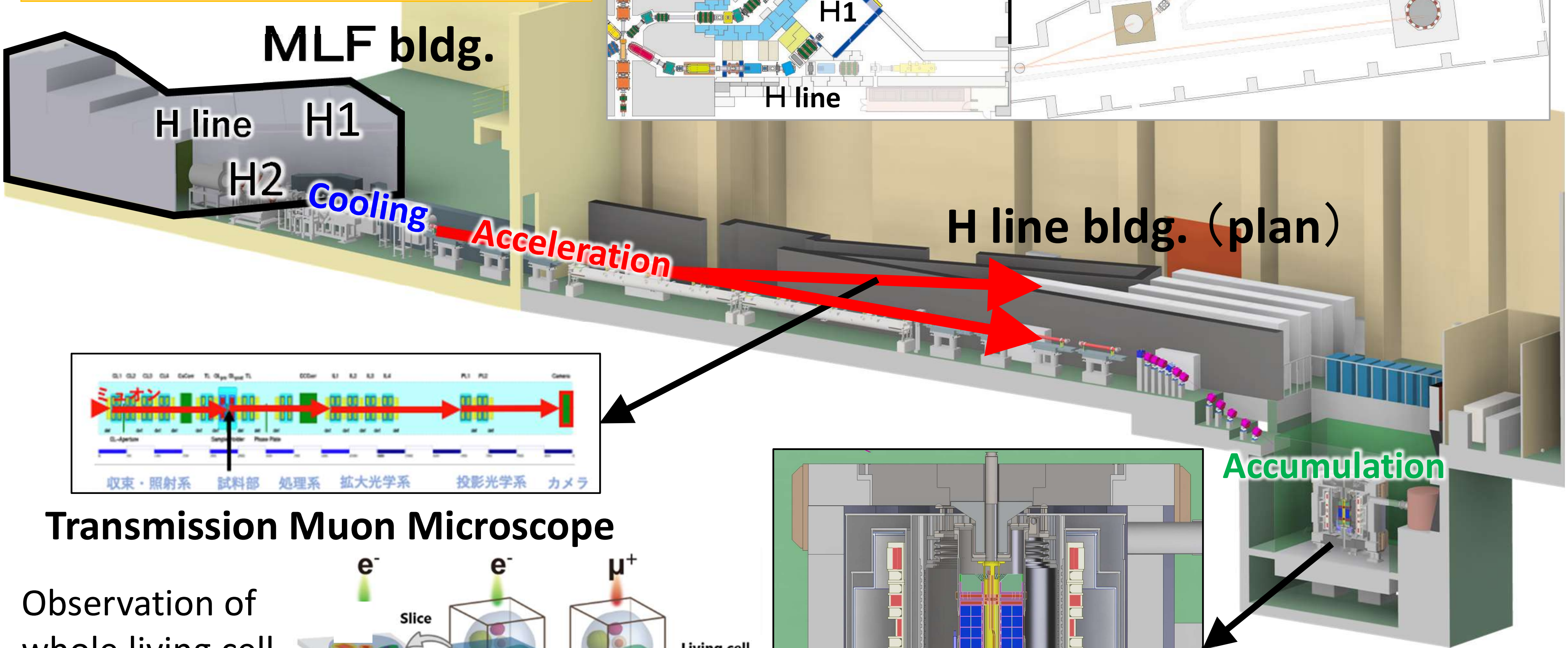
∅30-35 mm

Adopting a new beamline concept which is confirmed by a particle tracking simulation, the H line is designed to provide a high-intensity beam with a wide-range momentum tunability to each of several areas. The muon beamline of MLF-TS2 inherited this concept.

H-line: feature prospects (the world's first muon acc.)

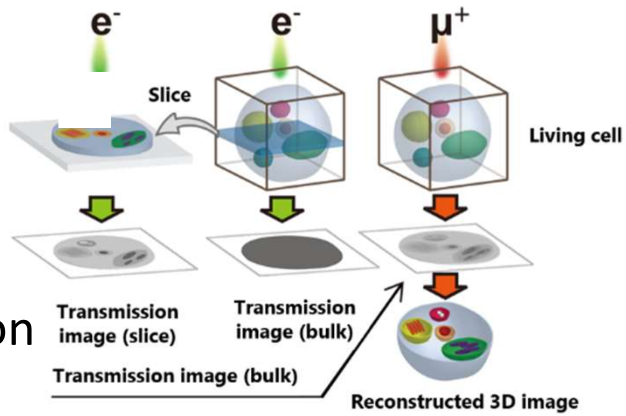
The studies in the H1 area
DeeMe:
muon-to-electron conversion search
MuSEUM:
High-precision measurement of muonium

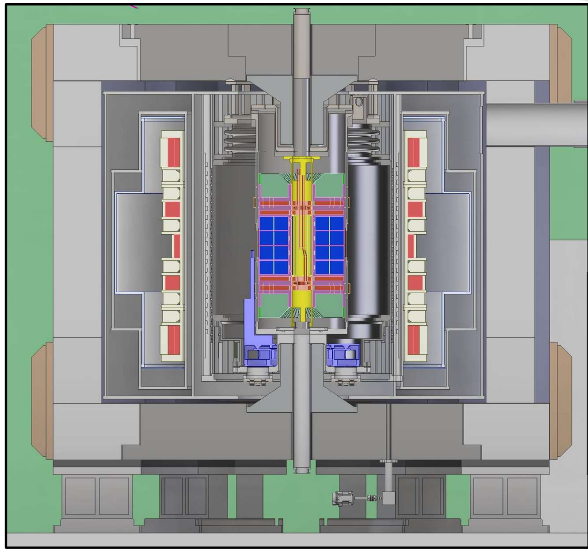




Transmission Muon Microscope

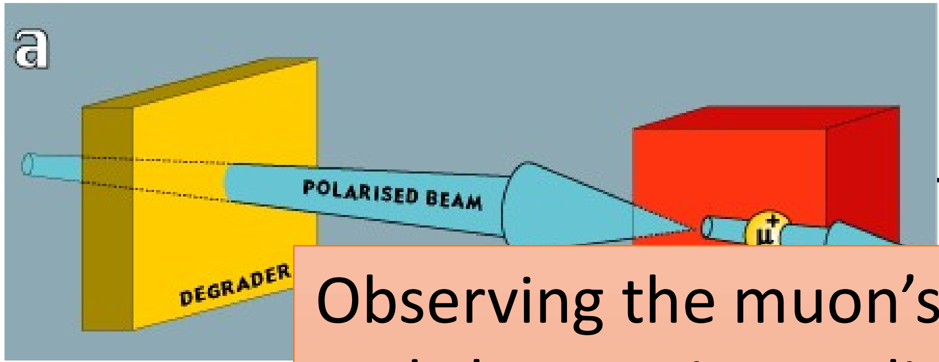
Observation of whole living cell owing to high transmittance capability of muon





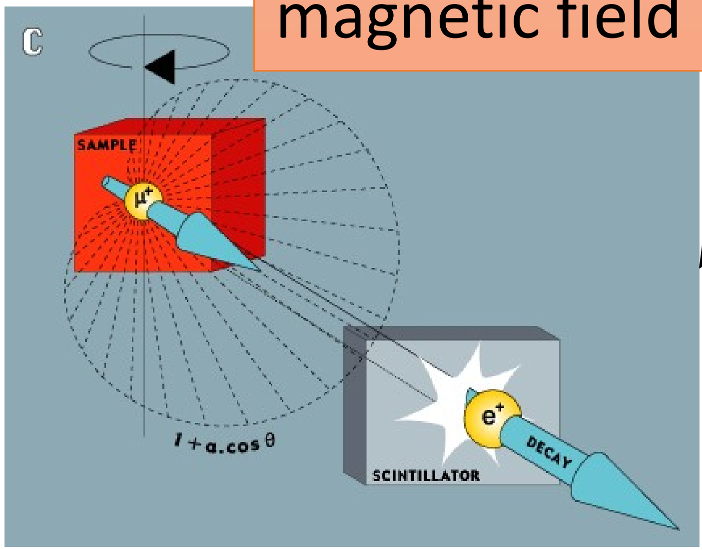
g-2/EDM exp.
Searching for BSM.

μSR (muon spin Rotation, Relaxation, Resonance)



a) Almost 100%
is transported
target to the s

Observing the muon's precession frequency and changes in amplitude gives information on the internal magnetic field of the sample.
Muon is a unique tool proving the local magnetic field inside the sample.



c) The muon de
emitted to the
→The time dist
(forward–backw
magetic Field.

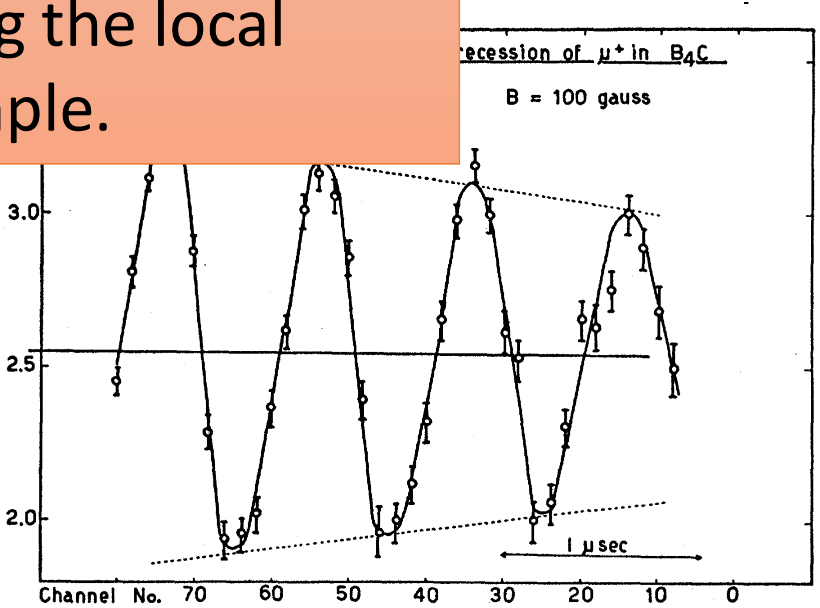


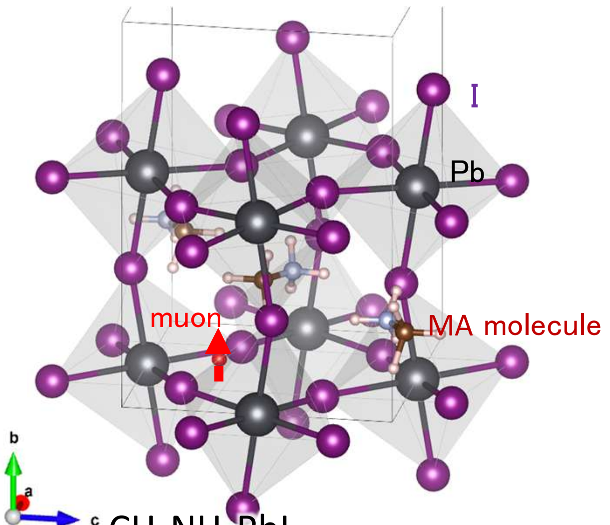
FIG. 7. Muon precession in boron carbide after decay and background correction.

Scientific Highlight (Material Science)

μSR study on the hybrid perovskite solar cell

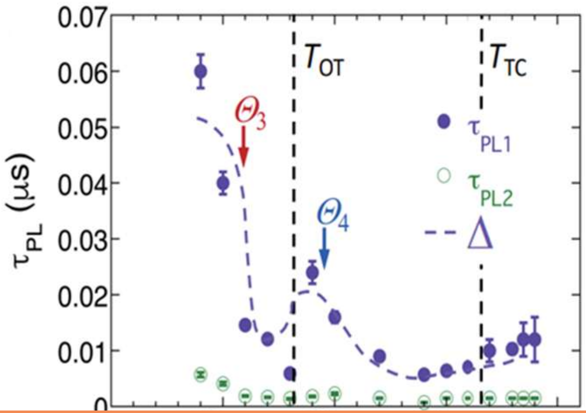
One promising next-generation solar cell material is a hybrid organic-inorganic perovskite (HOIP) compound. They are attracting attention because of their extremely high energy conversion efficiency of more than 25%.

A μSR study on archetypal H… $MAPbI_3$, reveals that the ch… carrier lifetime correlates w… the rotation of organic molecules.



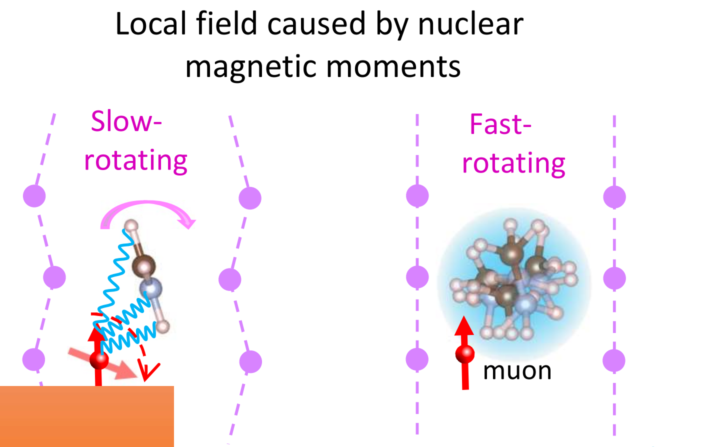
$CH_3NH_3PbI_3$

MA(Methyl Ammonium)PbI_3



Material Science

…determined from photoluminescence measurements and muon spin relaxation rate (dashed curves). The vertical dashed lines indicate the structural transition temperatures.



…n of … n from … t constant.

The orientation of molecules seen from the muon is averaged out.

The muon spin exhibits relaxing behavior due to the local magnetic field from MA molecules.

Muon spin polarization is unchanged. (Unable to follow changes in magnetic field)

The result indicates that the moderate suppression of the speed of free rotational motion of organic molecules is important for the long charge carrier lifetime.

We demonstrated the μSR study can contribute to the development of efficient and low-price next-gen. solar cell, optical device, *etc*.

A. Koda *et al.*, *PNAS* 119, *e2115812119* (DOI:10.1073/pnas.2115812119)

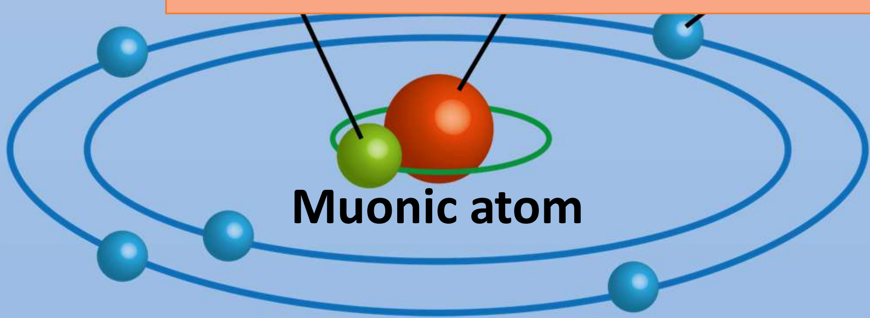
Muonic X-ray measurements

A muon is 200 times heavier than an electron

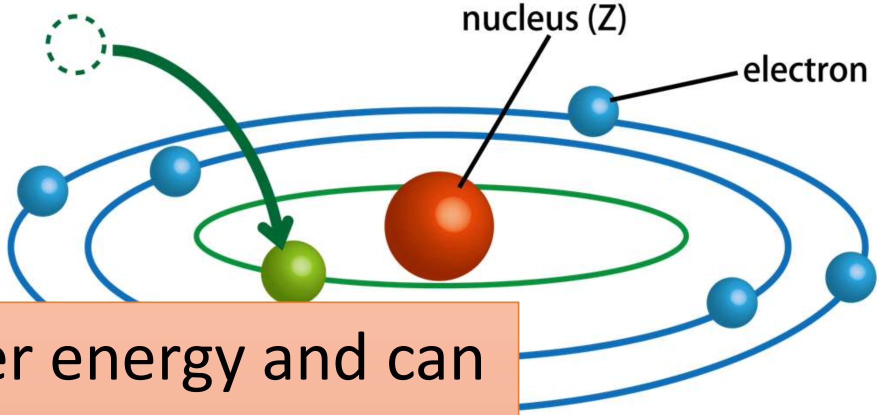
The or

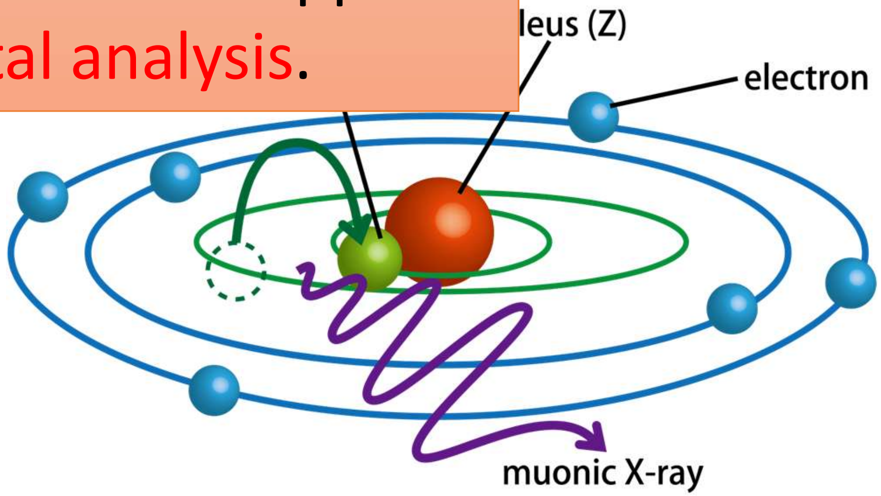
is

The muonic X-ray has higher energy and can come out of the inside of the sample where the muon stops. This feature can be applied to non-destructive elemental analysis.



The characteristic X-ray energy is 200 times higher.

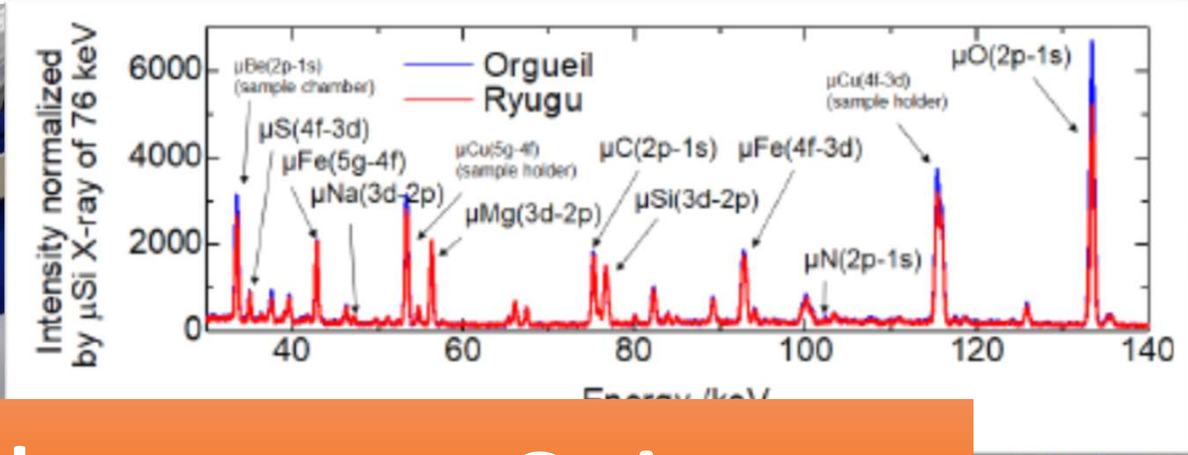




A negative muon captured by an atom loses its energy down to the ground state by emitting X-rays.

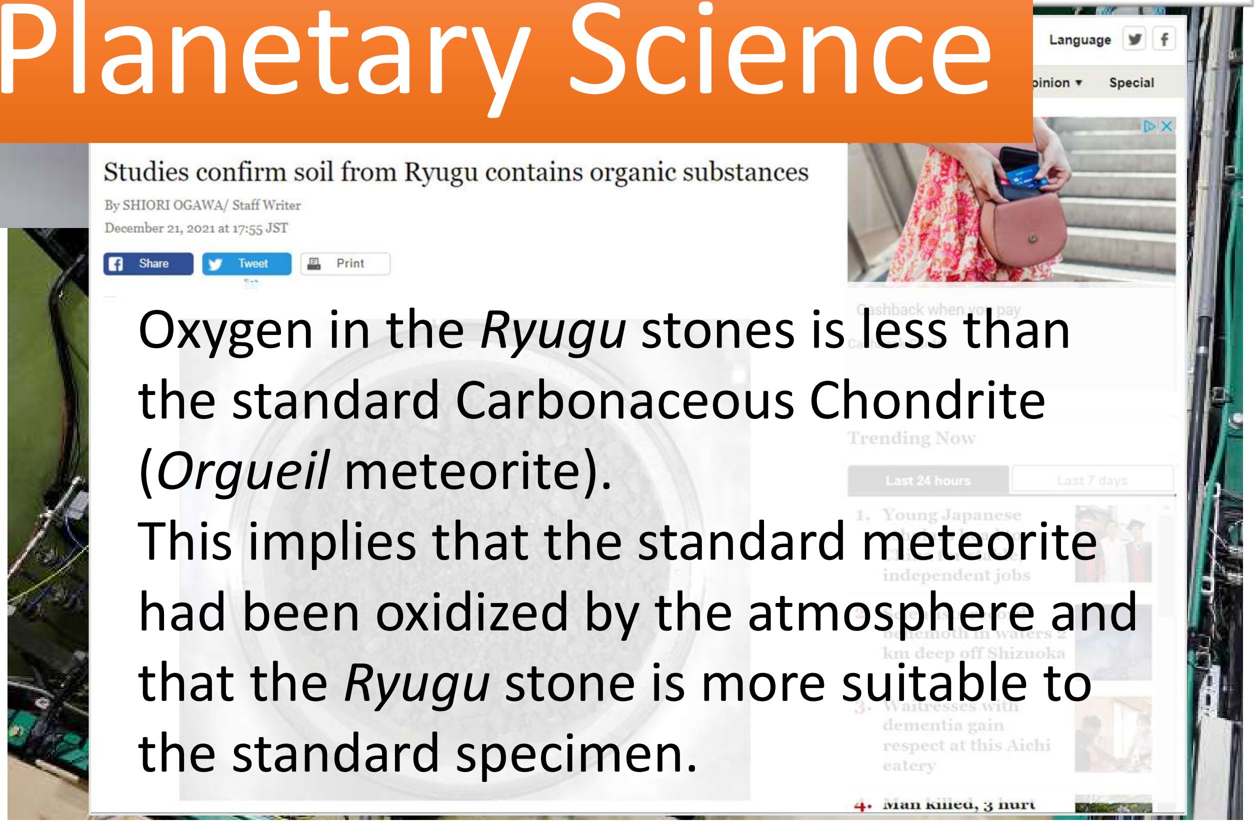
Scientific Highlight (Element Analysis)

Muonic X-ray non-destructive element analysis



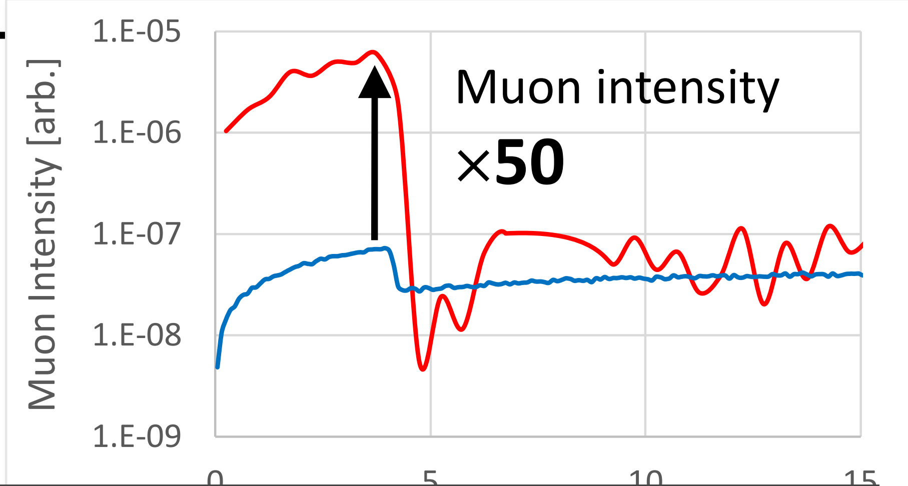
Earth and Planetary Science

Hayabusa-II (CG image)

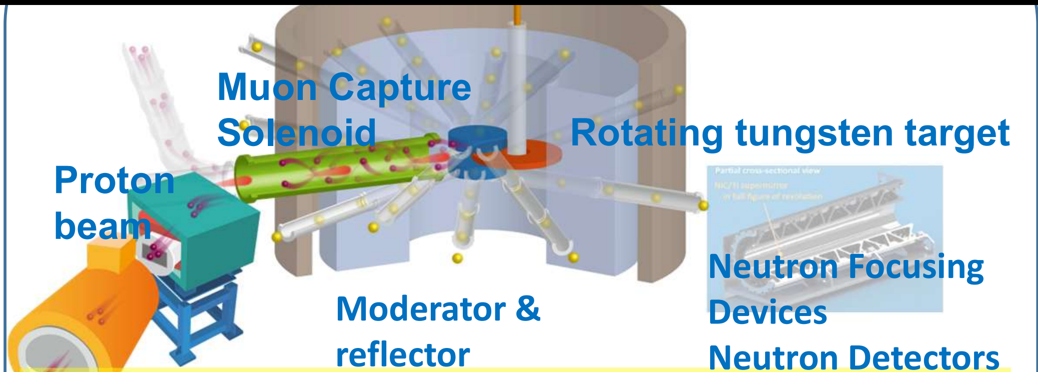


Oxygen in the *Ryugu* stones is less than the standard Carbonaceous Chondrite (*Orgueil* meteorite).
This implies that the standard meteorite had been oxidized by the atmosphere and that the *Ryugu* stone is more suitable to the standard specimen.

MLF Target Station2

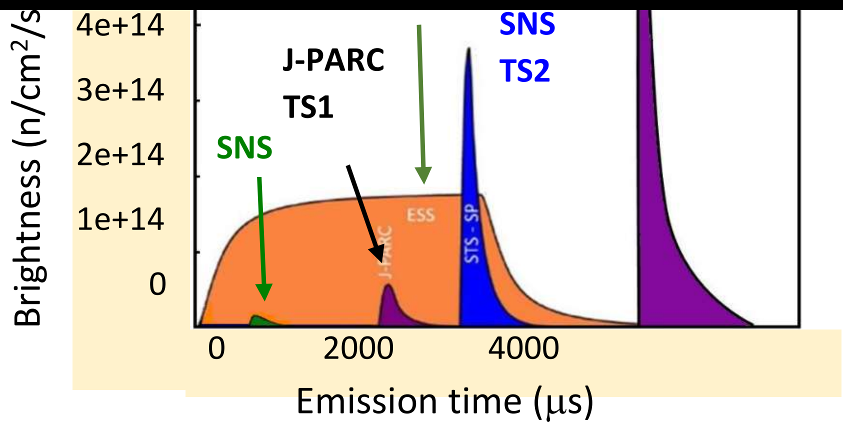


This project was selected as one of “The Medium- to the Long Term Academic Research Strategy” by the Science Council of Japan, although the budget has not been guaranteed yet.



Neutron:
10 (target) x 2 (device) → 20 times gain of brightness

Muon: :
10 (target) x 5~10 (Muon capture solenoid) → 50 ~100 times gain of flux



Brightness of MLF TS2 will be the world's highest compared to the next plan of overseas facilities

“Specialties” of MUSE

- High-intensity pulsed beam
  → beam distribution by kicker systems (D & S line)
  → devices synchronizing the pulse
    → flashlight *etc*. for μSR spectroscopy (SE)
    → ultra-slow muon generation by pulse-laser
      → g-2/EDM exp., transmission muon microscope

- pion generation by 3-GeV proton beam
  → relatively high yield of π^- and thus μ^-
    → promotion of non-destructive elemental analysis
      → application to heritage science *etc*.

Summary

- The world's highest-intensity pulsed muon facility, MUSE, provides high-intensity muon beams to 4 unique beamlines to answer the demand of various muon sciences; material science, atomic and molecular physics, particle physics, industrial application, elemental analysis, heritage science, *etc*.

- Thank you very much for your attention.   Grazie