2nd Workshop on EMuS Multidisciplinary Applications @Hefei Dec. 13-14, 2019

Introduction to J-PARC muon facility, MUSE

J-PARC MLF Muon Section/KEK IMSS

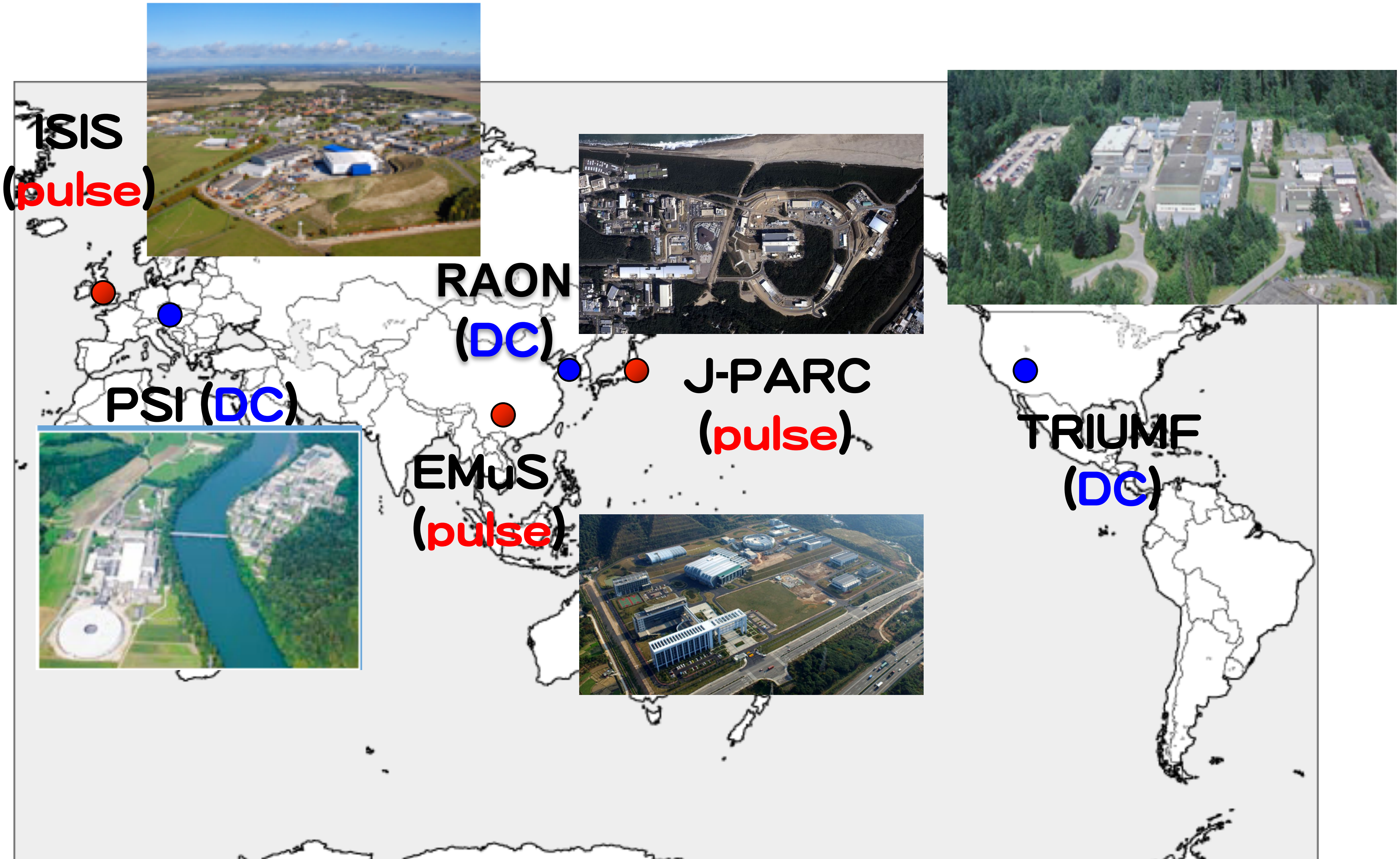
Yasuhiro Miyake

- J-PARC & J-PARC MUSE
- DC Muon & Pulsed Muon
- Summary

Only material science,

Muon fundamental physics to Prof. Kuno

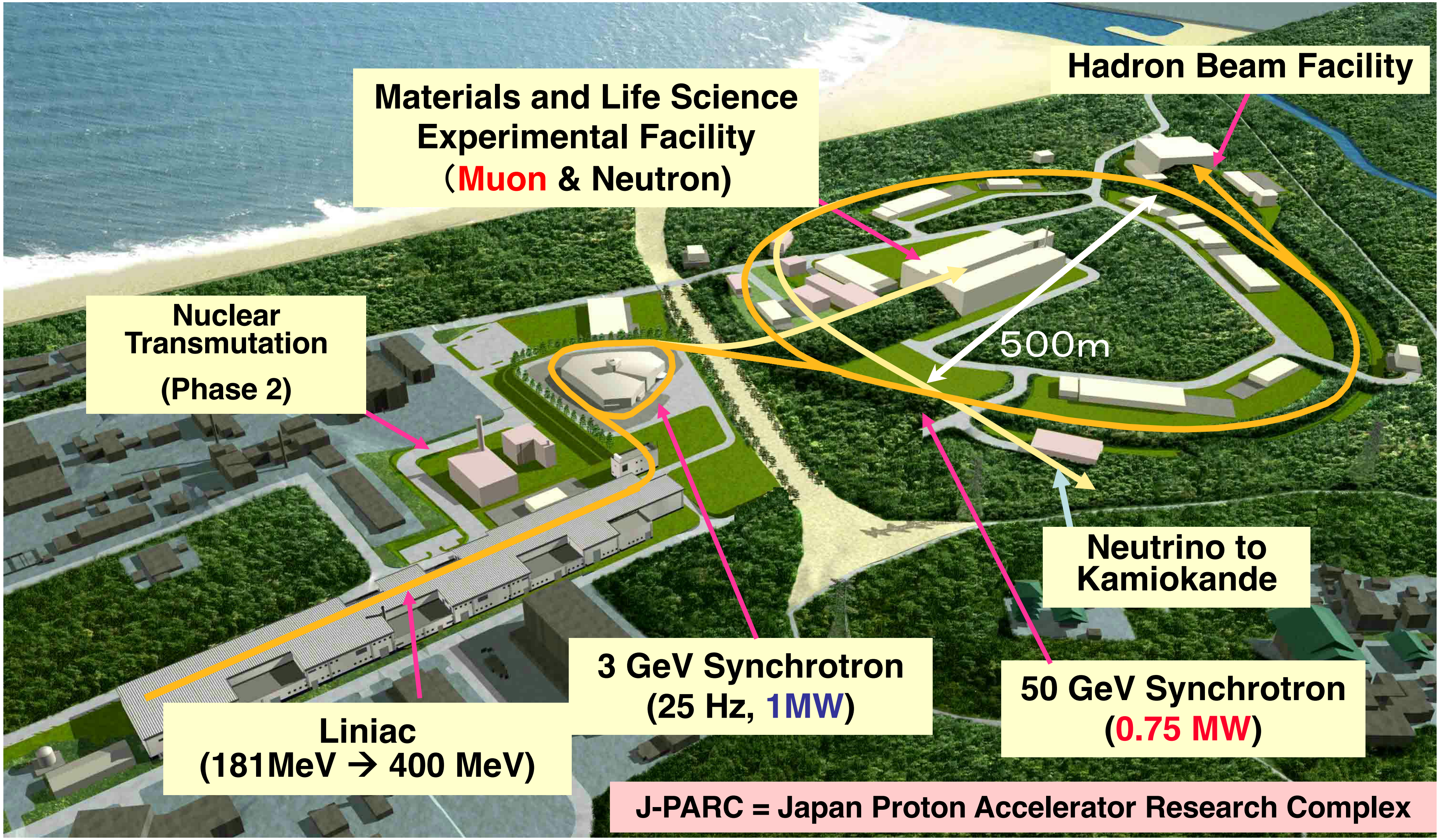
Muon Facilities in the world



$10^{6\text{-}8}$ muons/s by accelerator vs. cosmic muons about **1** muons/s on your hand

J-PARC Facility @Tokai

MUSE, pulsed (25Hz) muon source

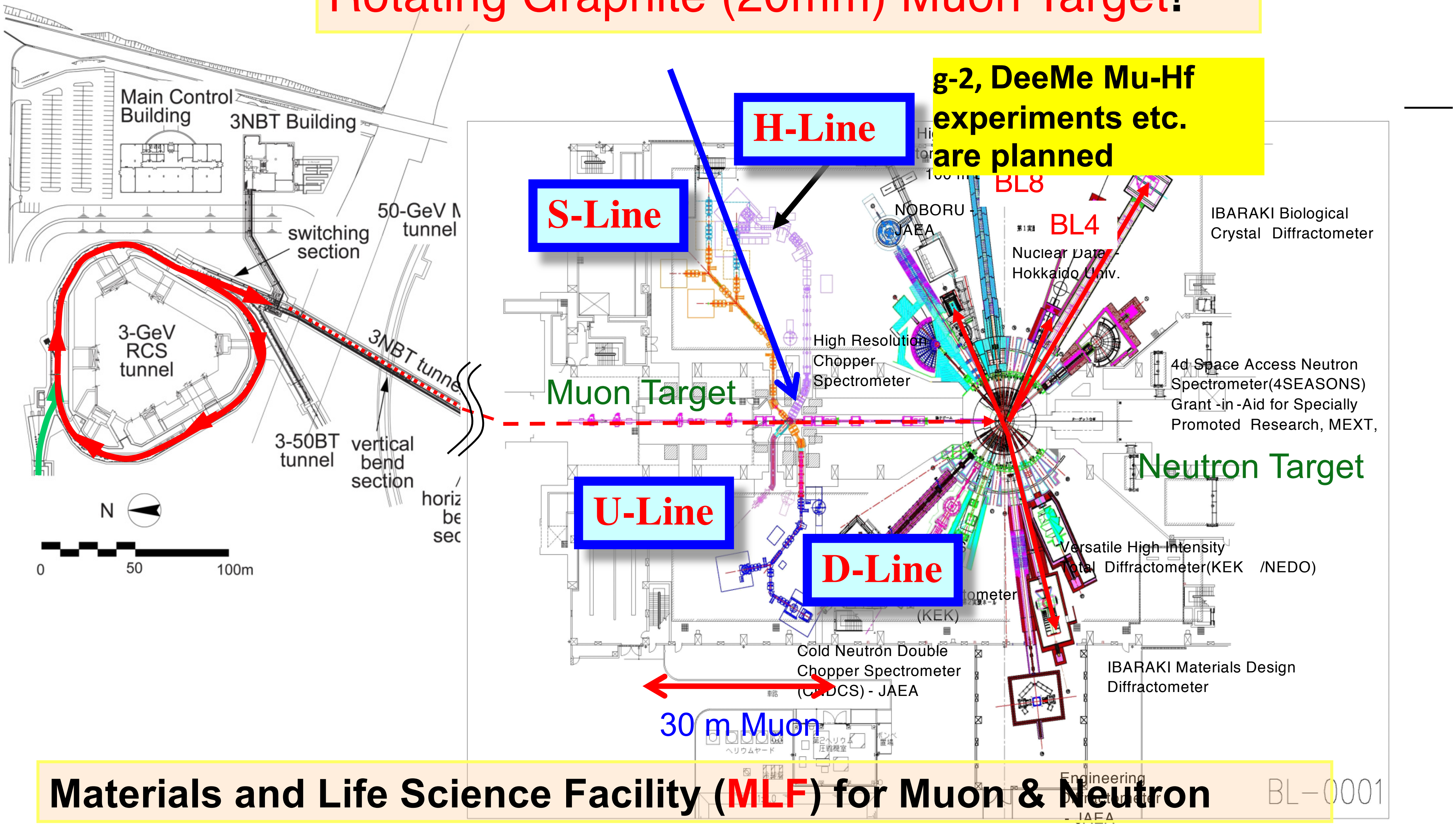


Joint Project between KEK and JAEA

Proton Beam Transport from 3GeV RCS to MLF

On the way, towards neutron source

Rotating Graphite (20mm) Muon Target!



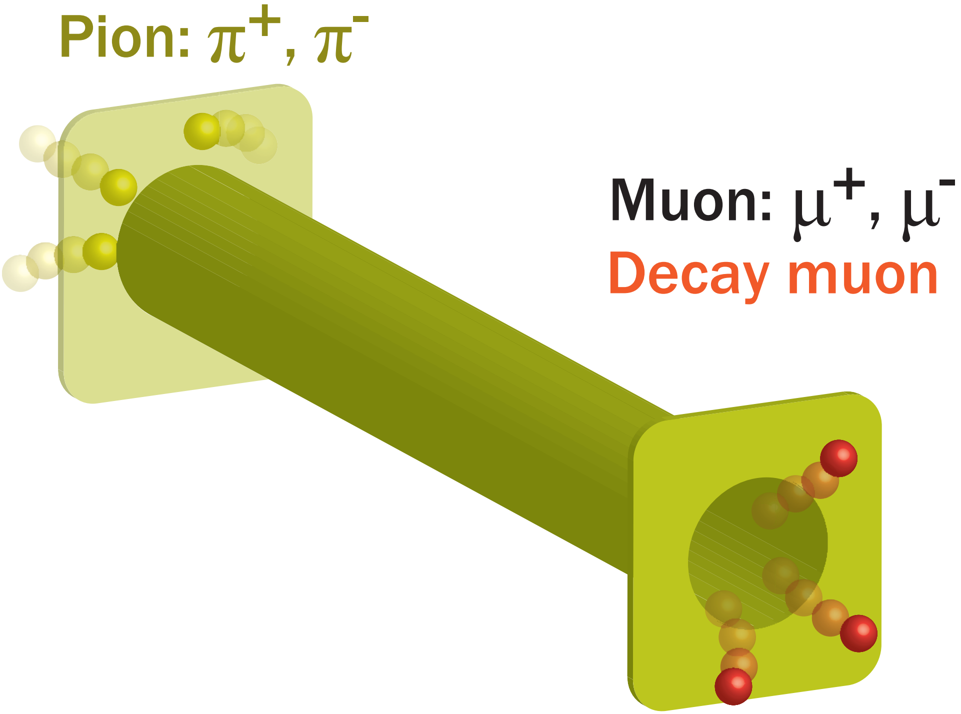
Materials and Life Science Facility (MLF) for Muon & Neutron

D-Line

Either Decay Muon or Surface Muon can be extracted!

Decay Muon **2.6 – 120 MeV/c**

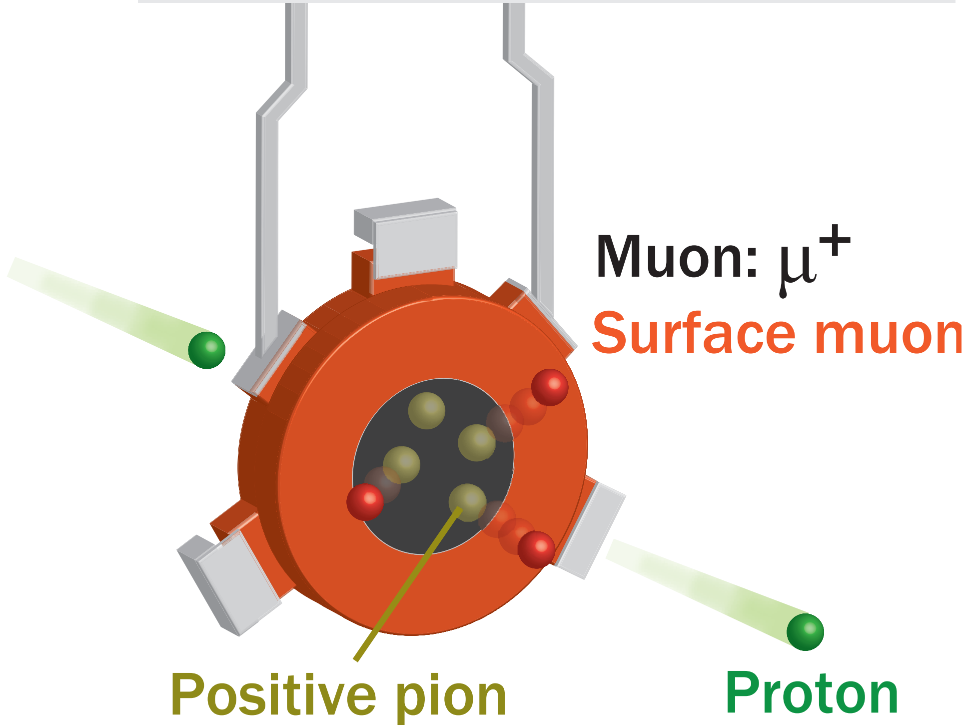
Muons from pion decay-in-flight



Confinement magnetic field
(Large-scale superconducting solenoid)

Surface Muon (30 MeV/c)

Muons from positive pions stopped at the target surface



Maily for the materials science

μ^+

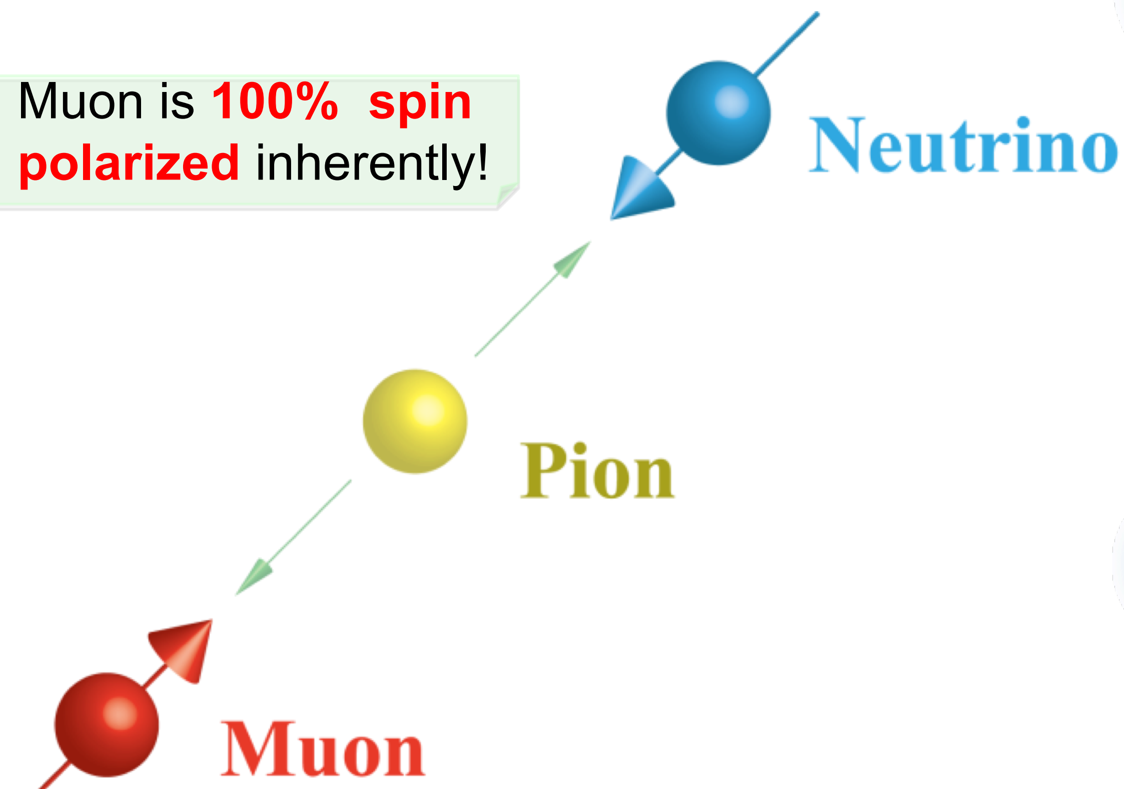
Positive Muon

A kind of **Lepton**.

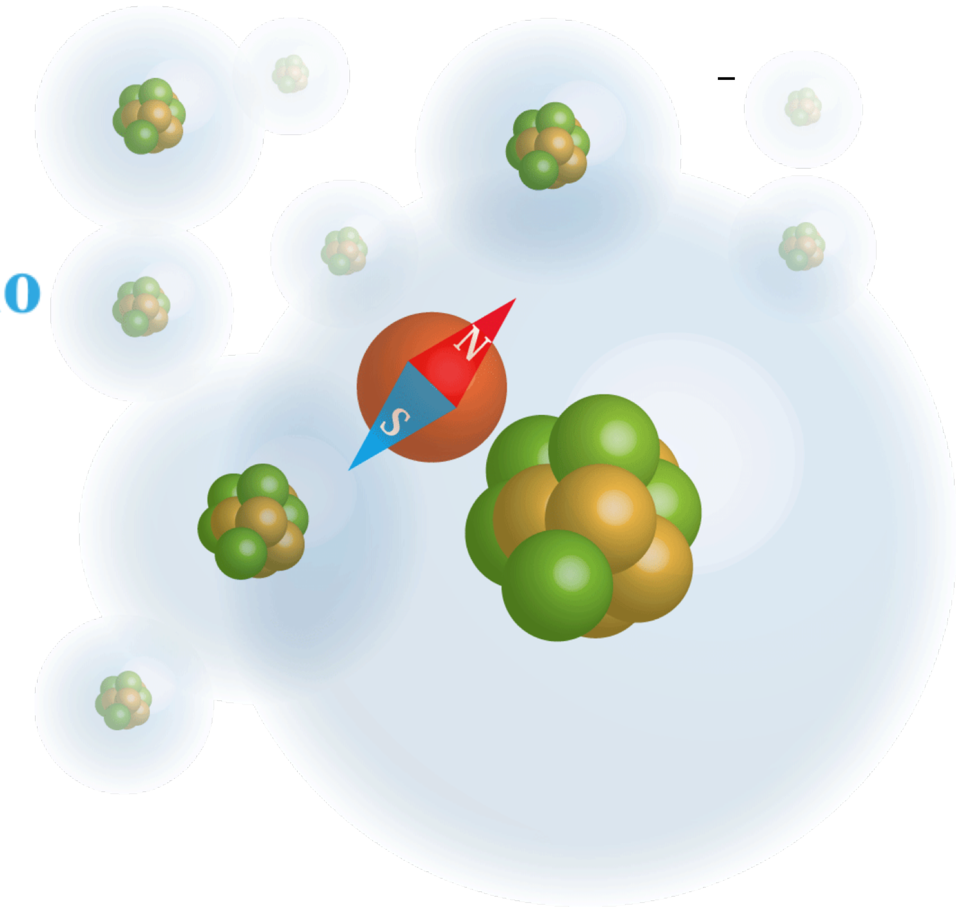
	Charge	Spin	Mass		Lifetime	
μ^+	+1	½	106 MeV/c²	（**1/9 of p⁺**）	2.2 μs	; 1/9 of p⁺, Spin Polarized!
μ^-	–1	½	106 MeV/c²	（**207 heavier e⁻**）	2.2 μs	: 200 times heavier e⁻

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

Muon is **100% spin polarized** inherently!



Spin Polarized Inherently



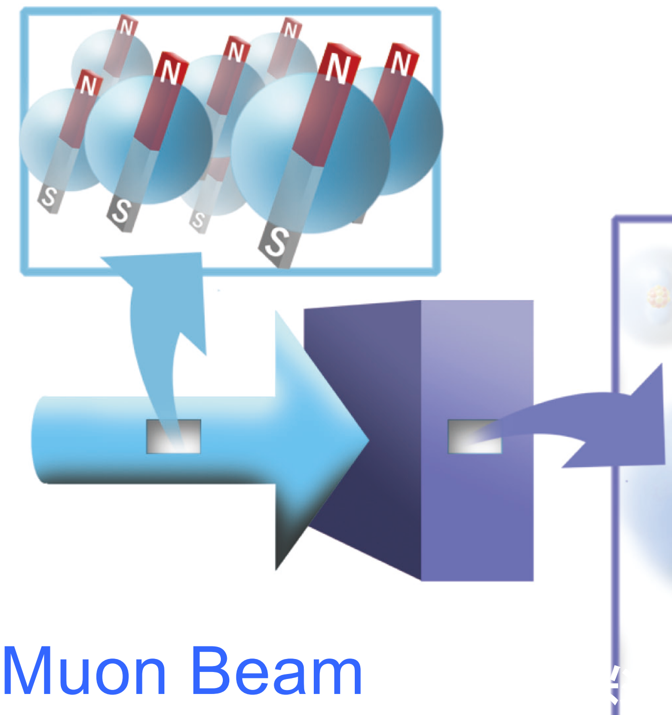
Like an **atomic-scale compass**

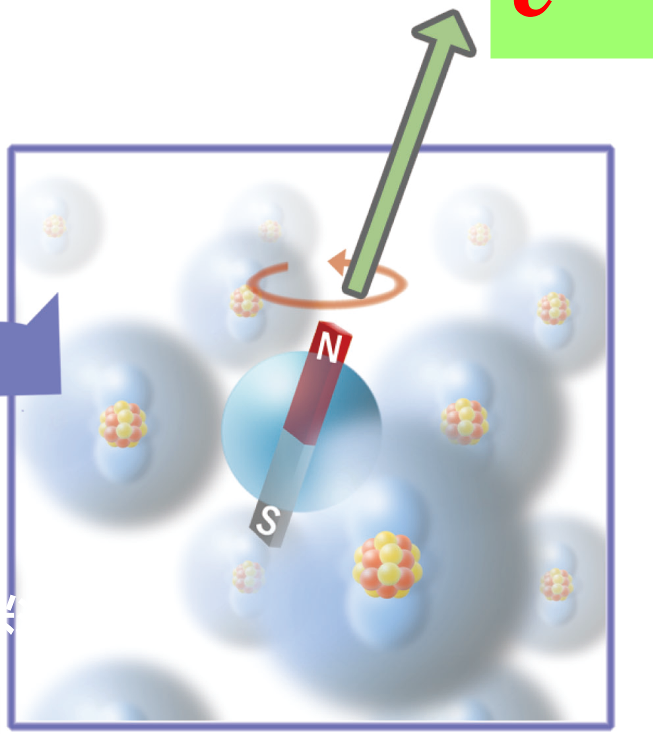
μ^+ μSR（Muon Spin Rotation ）Method

Muon Decay

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$
(2.2 μs)

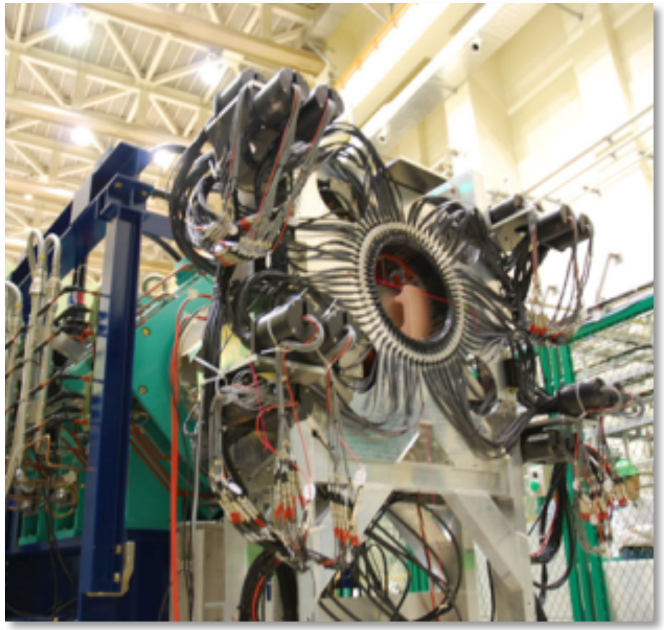
③Muons emit positrons to the direction when their spins were pointing upon decay, which are detected by scintillation counters.

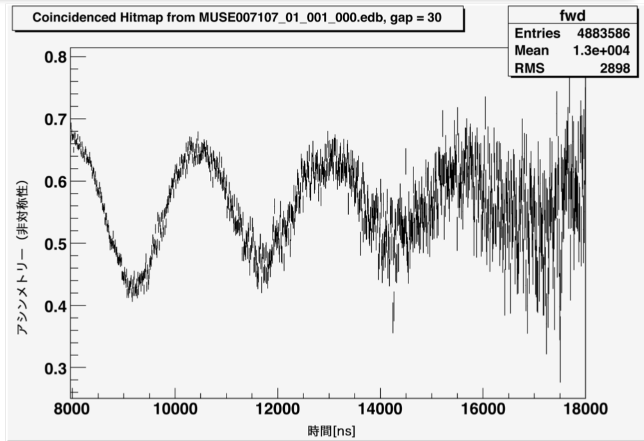




①Muons are produced with 100% spin polarizaion and transported by a beamline for implantention to sample.

②The implanted muons stop between atoms, where they start Larmor precession according to the local magnetic fields.





The signal of scintillation counters oscillates periodically due to the Larmor precession of muons

D1 μSR Spectrometer, Surface Muons

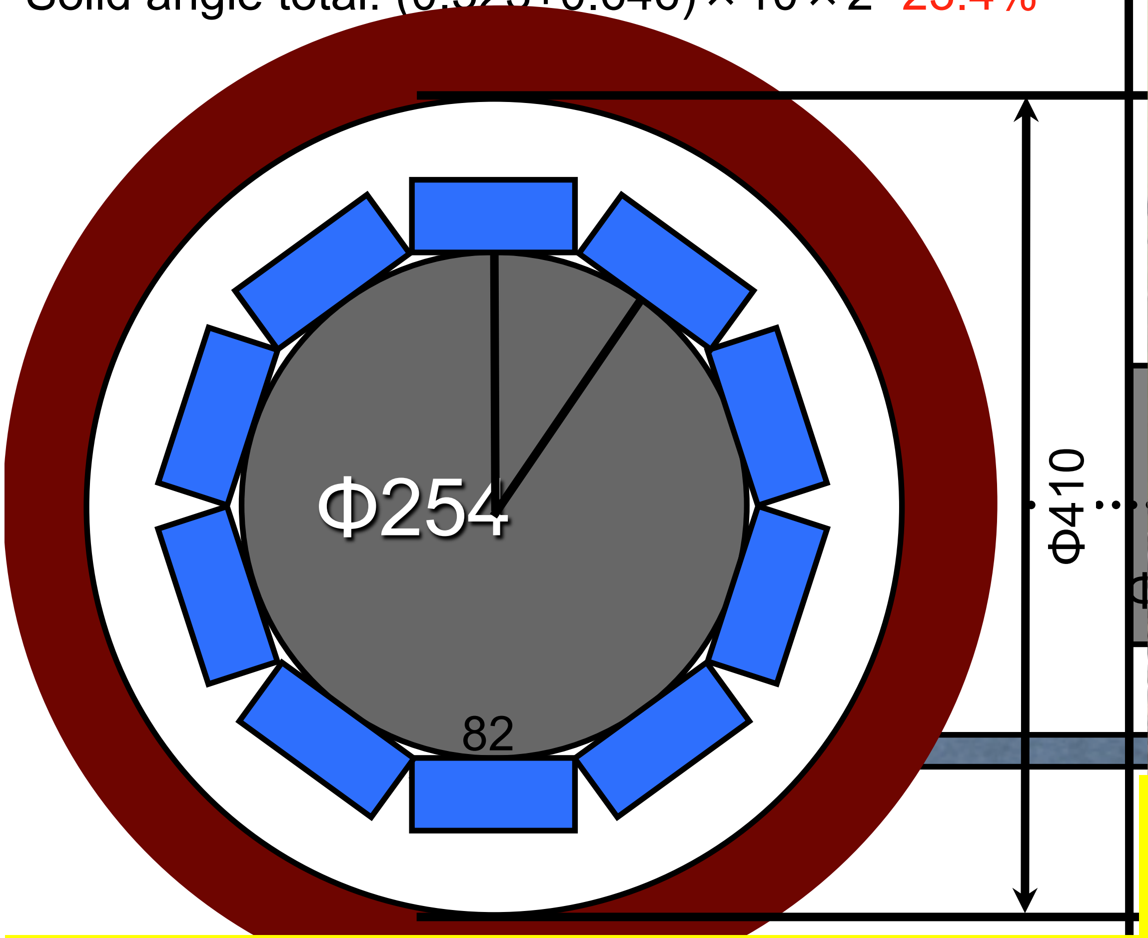
magnet inner bore : Φ410

magnet gap : 135mm

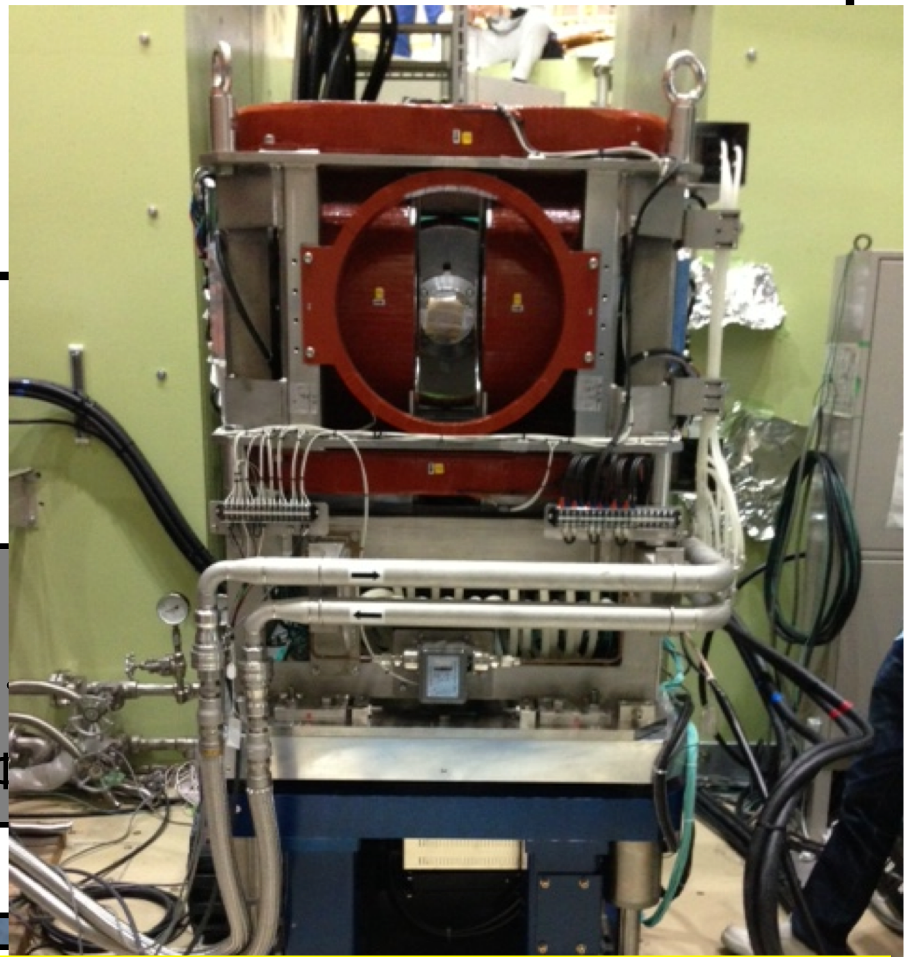
vacuum duct diameter : Φ254→10 sets/round

32ch × 40=1280channels.

Solid angle total: (0.523+0.646) × 10 × 2=23.4%



LF up to 4kG
GAP 135mm
Can be inserted up to Φ254



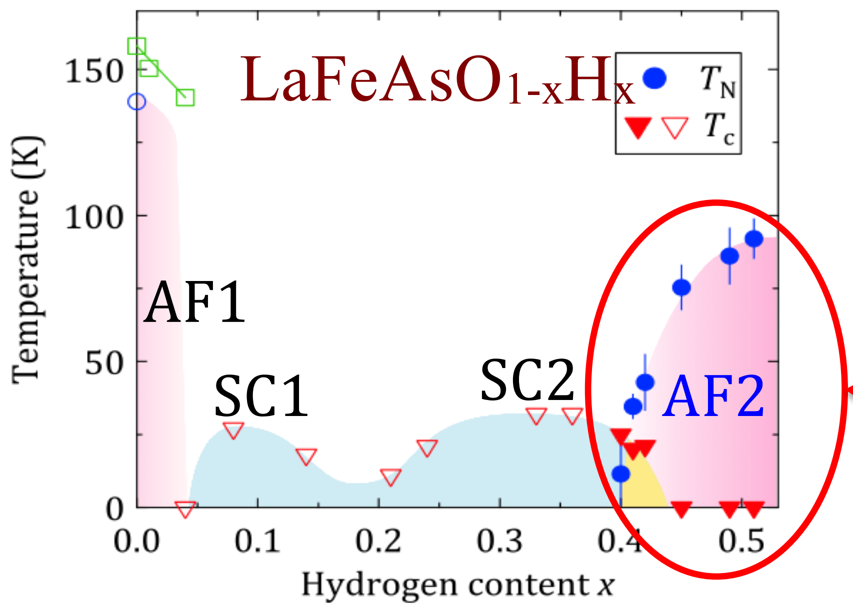
200 M of coincidence e^+ events/h
for 15 x 15 mm² with a 20 mm

Kojima, HIgemoto

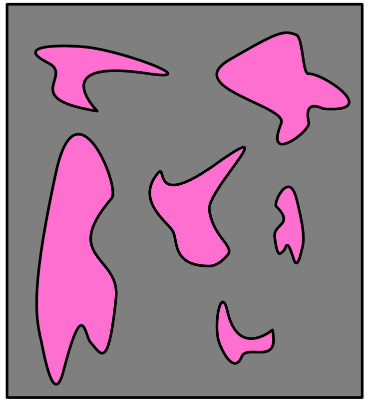
Solid Angle 23.4 %/7% ~ 3.3 times compared with DΩ1

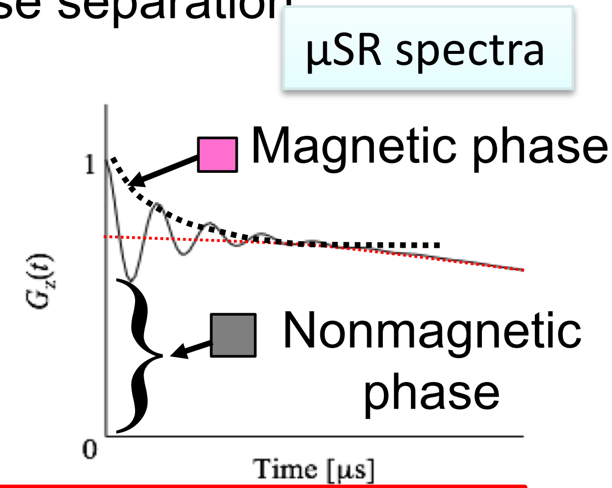
Element-Strategy-Initiative: Materials for electronic devices

Bipartite magnetic parent phases in the iron oxypnictide superconductor



Mesoscopic phase separation





Mapping out T_N versus H content x

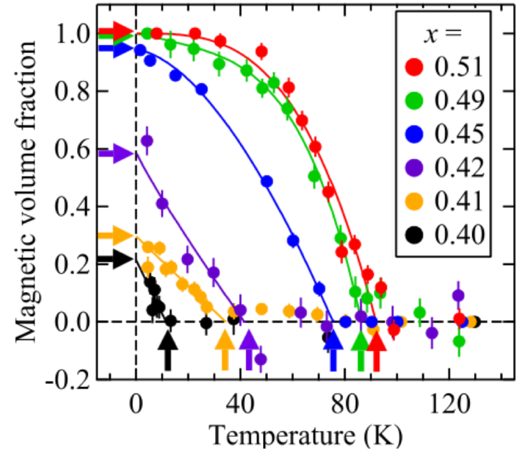
nature physics
LETTERS
PUBLISHED ONLINE: 16 MARCH 2014 | DOI: 10.1038/NPHYS2906

Bipartite magnetic parent phases in the iron oxypnictide superconductor

M. Hiraishi[1], S. Iimura[2], K. Kojima[1,3]*, J. Yamaura[4], H. Hiraka[1], K. Ikeda[1], P. Miao[1,3], Y. Ishikawa[1], S. Torii[1], M. Miyazaki[1], I. Yamauchi[1], A. Koda[1,3], K. Ishii[5], M. Yoshida[5,6], J. Mizuki[6], R. Kadono[1,3], R. Kumai[1,3], T. Kamiyama[1,3], T. Otomo[1,3], Y. Murakami[1,3], S. Matsuishi[4] and H. Hosono[2,4]

High-temperature superconductivity appears as a consequence of doping charge carriers into an undoped parent

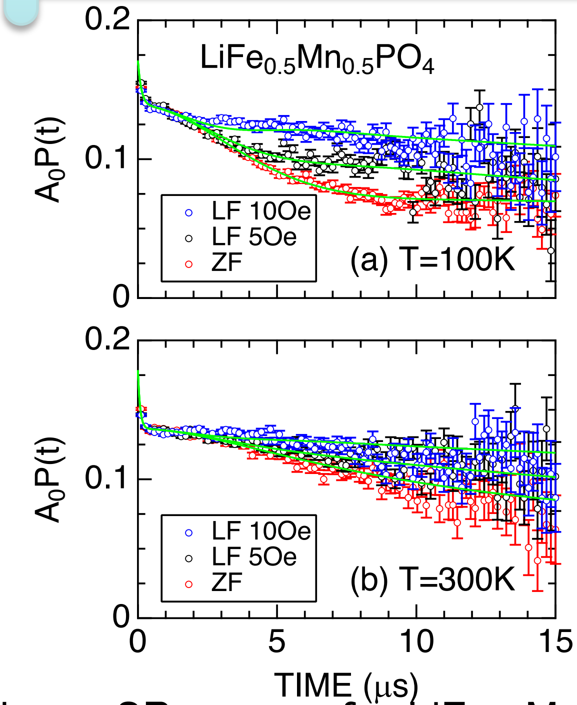
the tetragonal cell and m
determined to be unambig



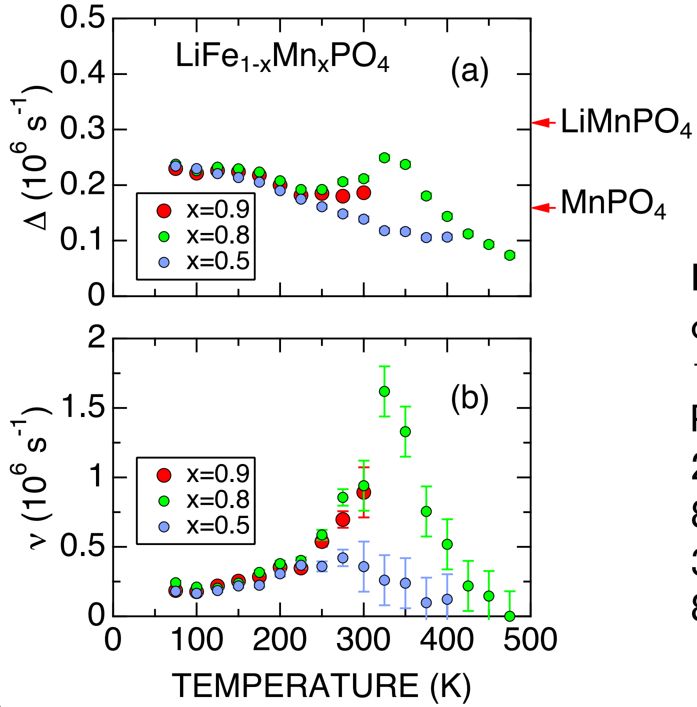
M. Hiraishi, S. Iimura *et al.*, Nat. Phys. **10**, 303 (2014).

Industrial Use of Muon～Li Battery～
Clarify Li diffusion behavior in the cathode materials

【Motivation】In order to develop a new cathode material with high working voltage, we have measured a Li-diffusion coefficient of several **olivine type compounds** with muSR, since mSR provides information on Li-diffusion even in the materials containing magnetic ions.



The muSR spectra for $LiFe_{0.5}Mn_{0.5}PO_4$ measured at (a) 100 K and (b) 300 K. The decrease in relaxation rate at 300 K is caused by Li-diffusion.



The temperature dependence of (a) the field distribution width Δ and (b) the hopping rate ν for $LiFe_{1-x}Mn_xPO_4$. The $\nu(T)$ curve shows that Li is the most mobile in the x=0.8 sample.

TOYOTA CRDL, INC.

Related papers using the data obtained in J-PARC;

1) M. Mansson and J. Sugiyama, Physica Scripta 88, 068509 (2013).
2) J. Sugiyama et al., Phys. Rev. B 85, 054111 (2012).
3) J. Sugiyama et al., Phys. Rev. B 84, 054430 (2011).

【Impact】 Such cathode material leads to a Li-ion battery with **safe and high energy capacity**, which is suitable for the future electric cars.

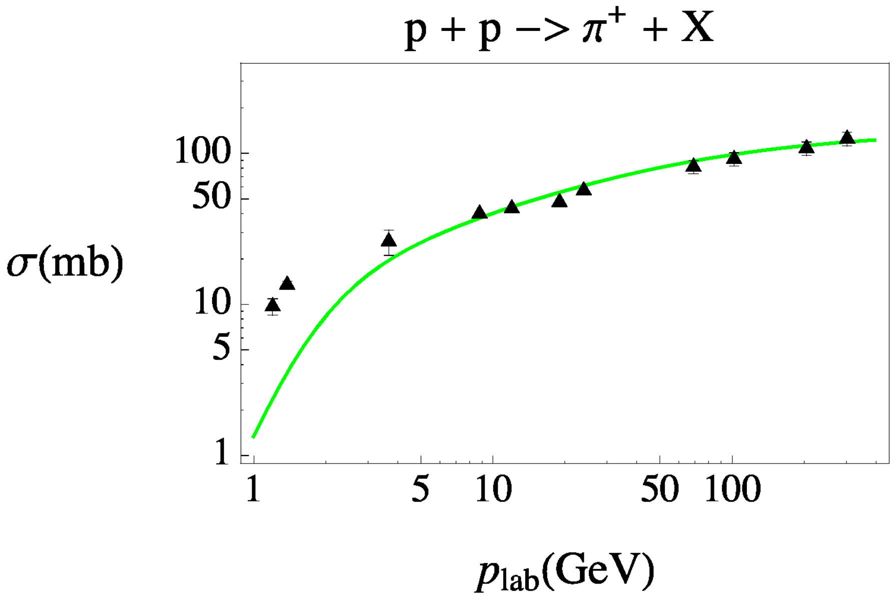


Figure 5: Log - log plot of the π^+ total inclusive cross section parameteriza solid line) of equation (1) versus experimental data (triangle symbols) of refe 6, 7, 9, 14].

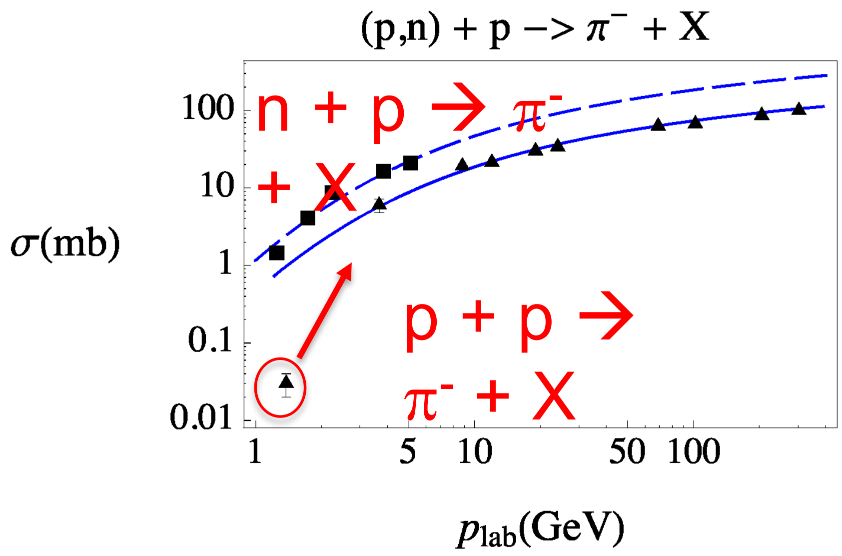


Figure 7: Log - log plot of total inclusive cross section parameterization (blue, s equation (2) for the reaction $p + p \to \pi^- + X$ versus experimental data (triang of references [3, 4, 7, 9, 14, ?]. Also shown is the cross section data (solid squ Abdivaliev [10], for the reaction $n + p \to \pi^- + X$, compared to the parameteriz dashed line) of equation (9).

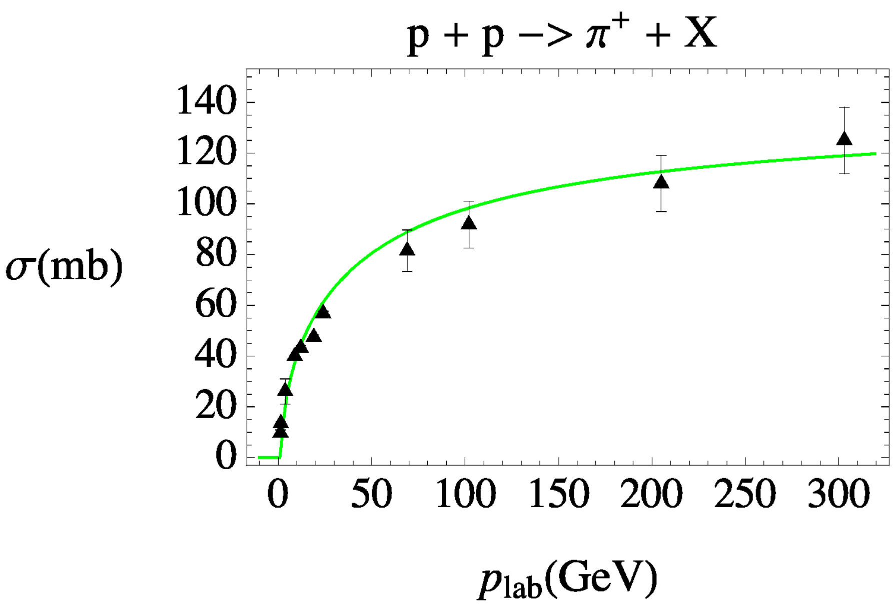


Figure 6: Same as figure 5, except for use of linear axes.

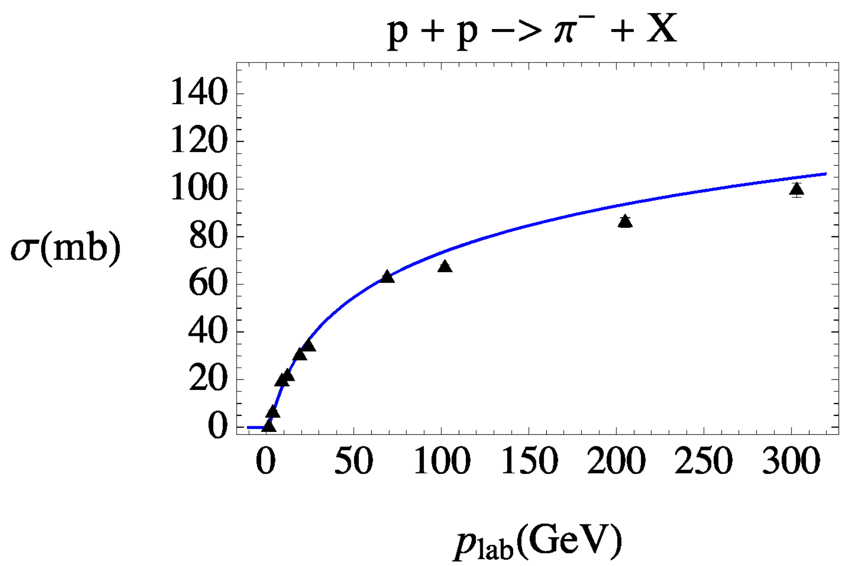
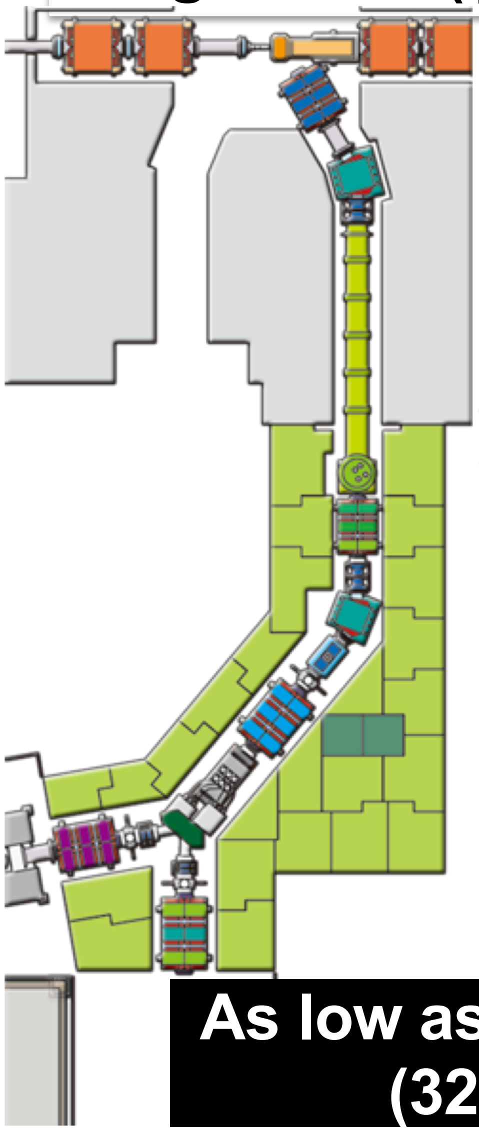


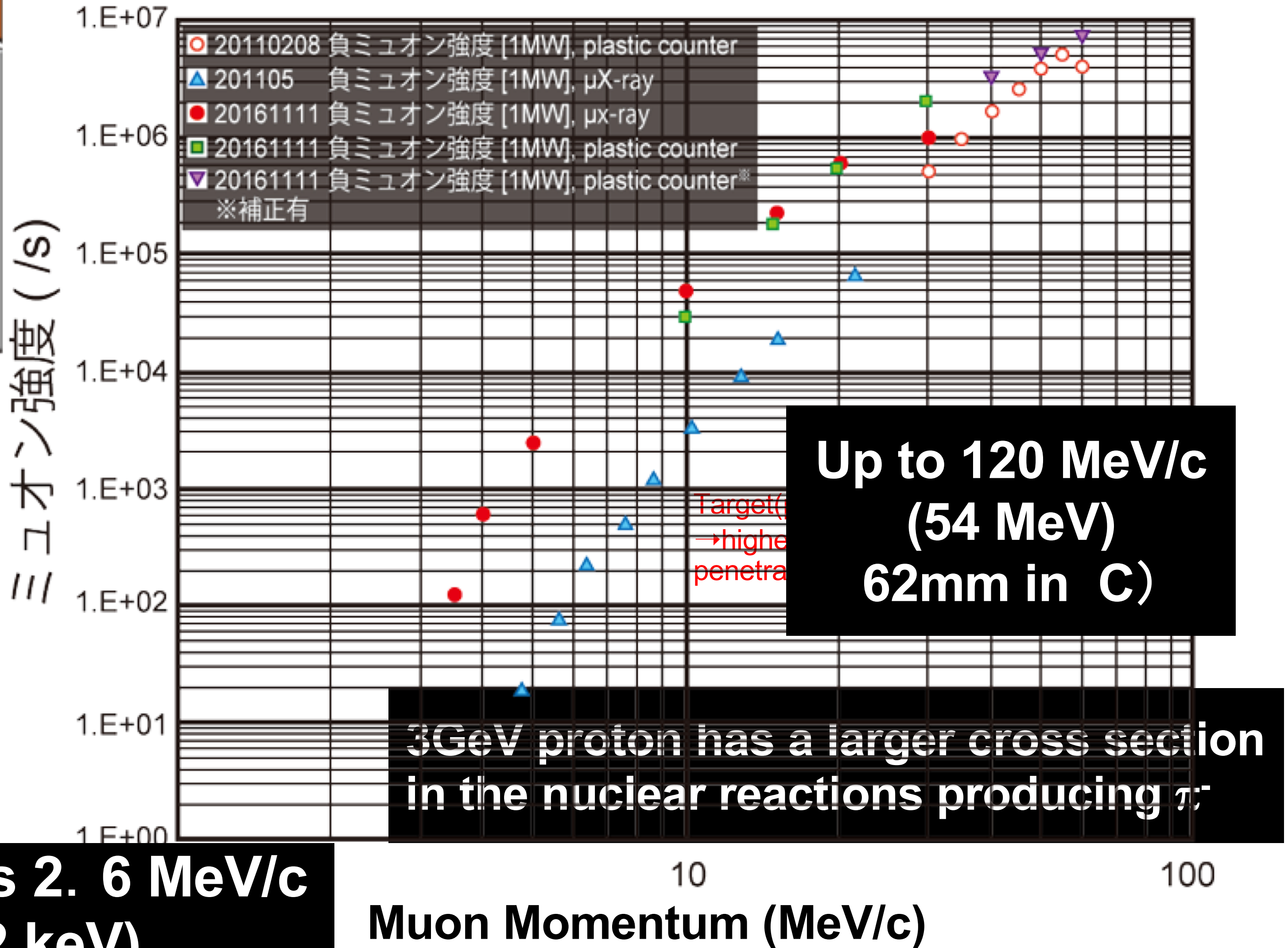
Figure 8: Same as Figure 7, except for use of linear axes and n+p reaction is

Pion Total Cross Section in Nucleon – Nucleon Collisions, John W. Norbury, NASA/TP–2009-215953

World Strongest Pulsed Negative Muon Source at J-PARC MUSE, Operated by KEK-IMSS

Larger Bore (ϕ12cm → ϕ24cm), Warm Bore（No Window）





Up to 120 MeV/c (54 MeV) 62mm in C）

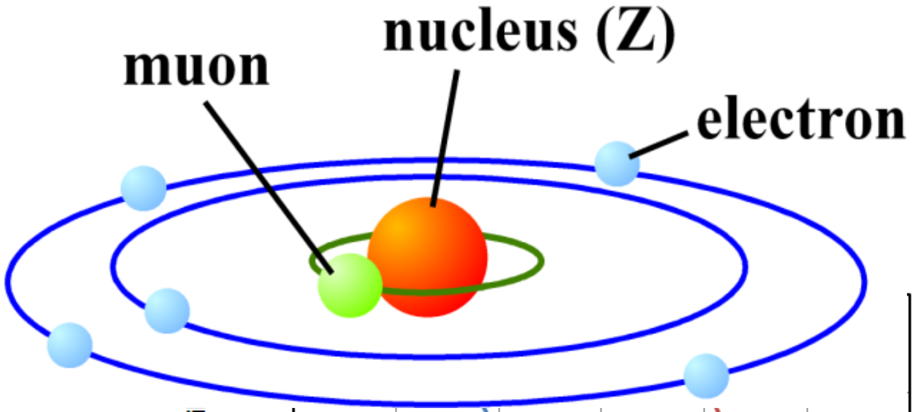
3GeV proton has a larger cross section in the nuclear reactions producing π^-

As low as 2. 6 MeV/c (32 keV)

μ^- 200 times heavier electron

μ^- (200 times heavier electron)

→forming **muonic atom**



200 times larger binding energy

||

~ 200 times higher muonic X ray

Cu Kα X-ray

Electron: 8 keV

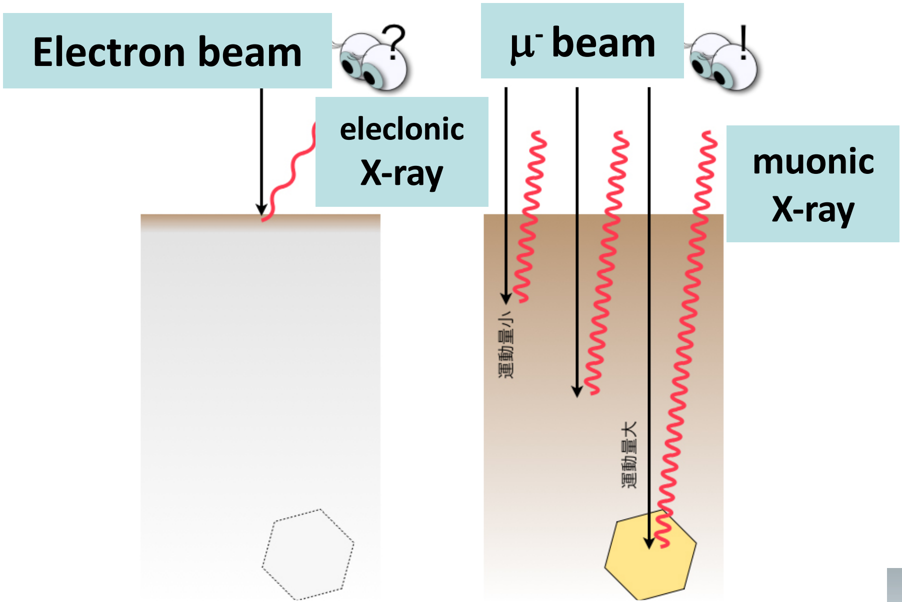
Muon : 1.5 MeV

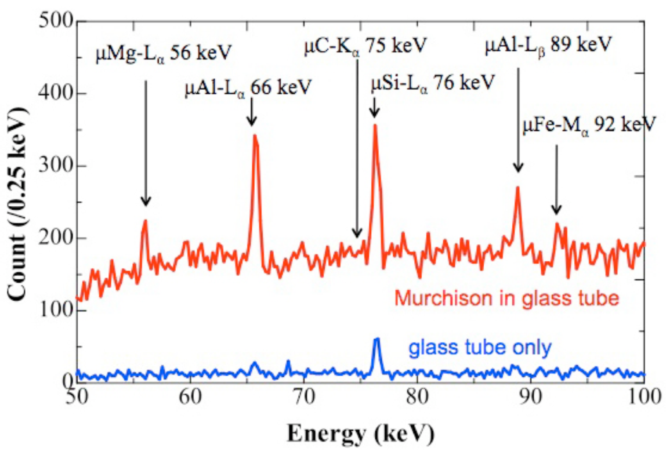
||

Deep penetration

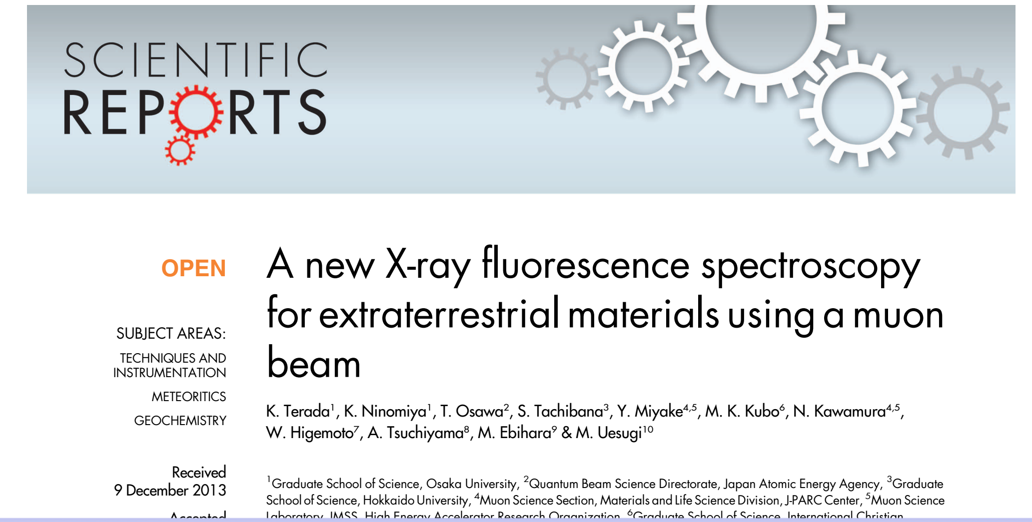
Non-destructive element analysis using μ^- X-ray

Demonstration of bulk sensitive light-element-analysis on interstellar object





It is demonstrated on a carbon-rich **meteorite** that the element-specific muonic X-ray spectroscopy can provide information on the **content of light elements deep** within the specimen, paving a path to the application of the technique to the specimens brought back by the **"Hyabusa II"** mission in the future.


SCIENTIFIC REPORTS

OPEN

SUBJECT AREAS:
TECHNIQUES AND INSTRUMENTATION
METEORITICS
GEOCHEMISTRY

Received
9 December 2013

A new X-ray fluorescence spectroscopy for extraterrestrial materials using a muon beam

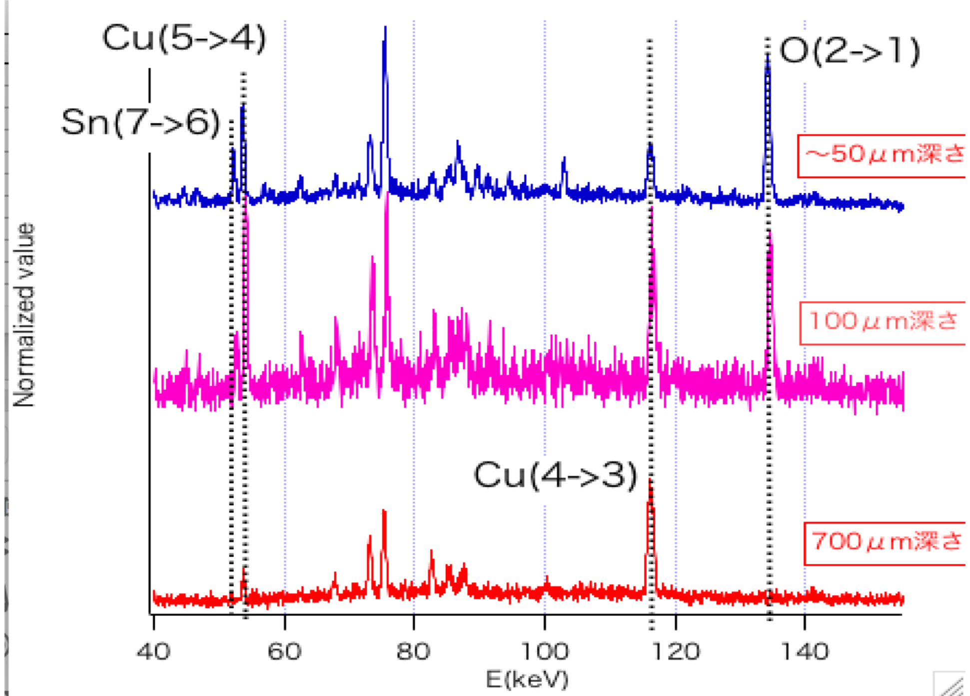
K. Terada[1], K. Ninomiya[1], T. Osawa[2], S. Tachibana[3], Y. Miyake[4,5], M. K. Kubo[6], N. Kawamura[4,5], W. Higemoto[7], A. Tsuchiyama[8], M. Ebihara[9] & M. Uesugi[10]

[1]Graduate School of Science, Osaka University, [2]Quantum Beam Science Directorate, Japan Atomic Energy Agency, [3]Graduate School of Science, Hokkaido University, [4]Muon Science Section, Materials and Life Science Division, J-PARC Center, [5]Muon Science

K. Terada, K. Ninomiya, T. Osawa, S. Tachibana, Y. Miyake, M. K. Kubo, N. Kawamura, W. Higemoto, A. Tsuchiyama, M. Ebihara & M. Uesugi, Sci. Rep. **4**, 5072 (2014).

Archeology by negative muons

Funded by collaborative research of Inter-University Research Institute Corporation,

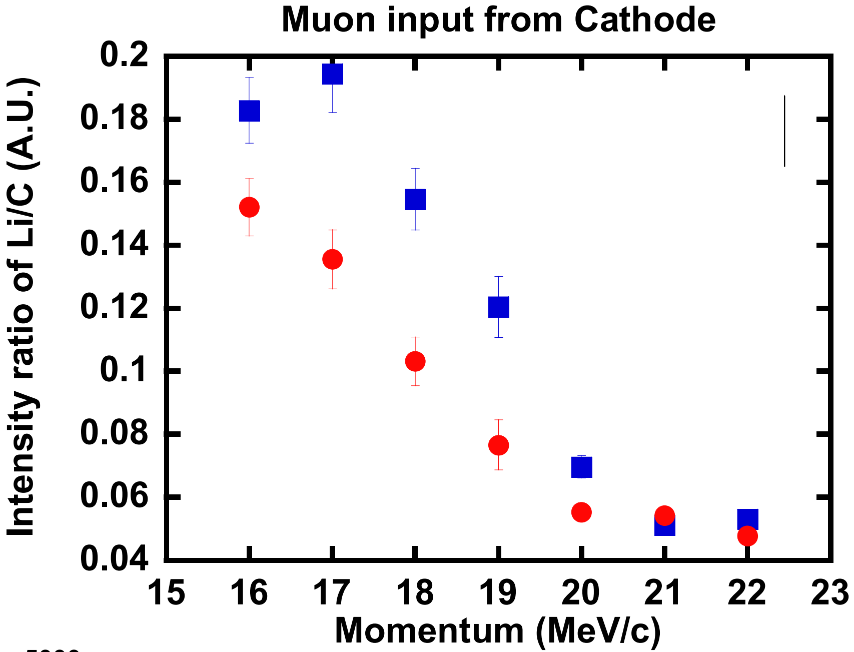


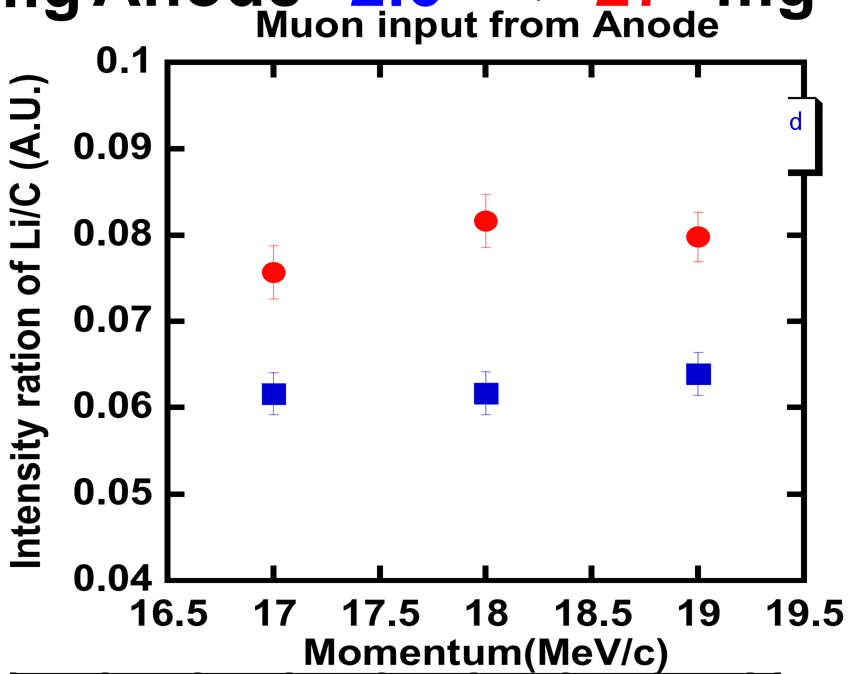
Many Old Coins, Bronze bell-shaped vessel, swords, etc., from 500 nm to 6 cm depth!

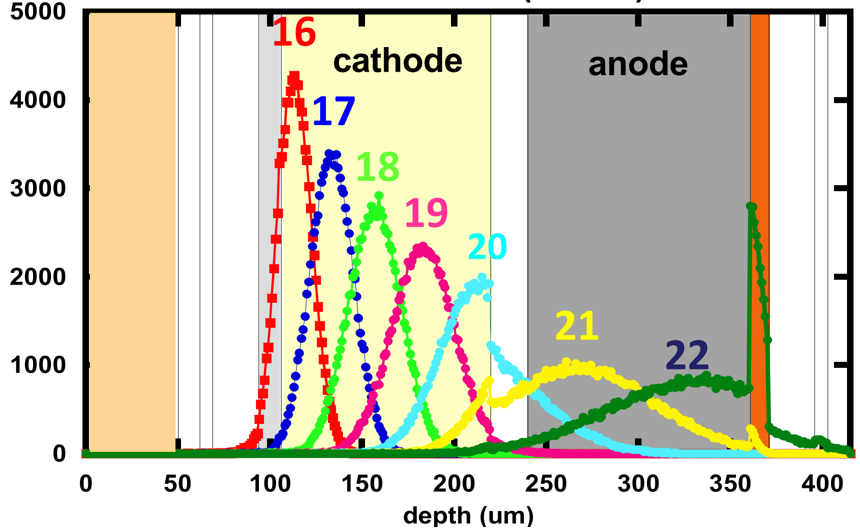
S-type; Operand Measurement of Li battery

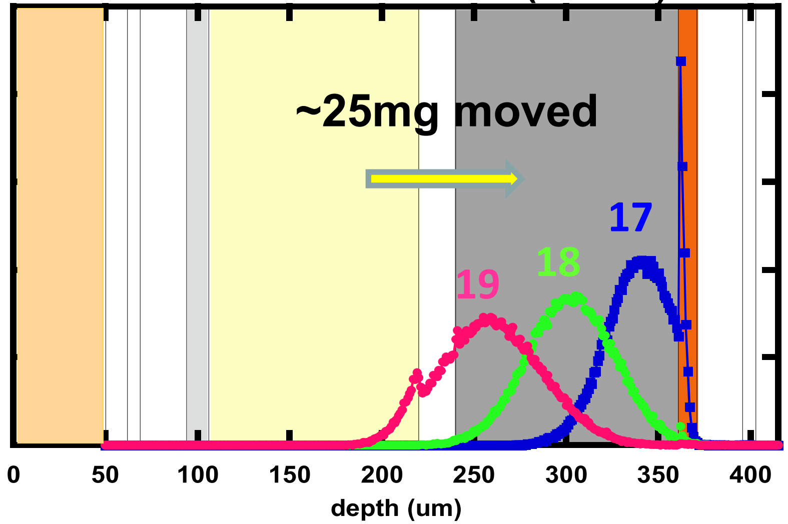
Depth profile of Li signals shows difference between discharged and charged in OPERAND!

Cathode(whole) 46 → 21 mg Anode 2.6 → 27 mg



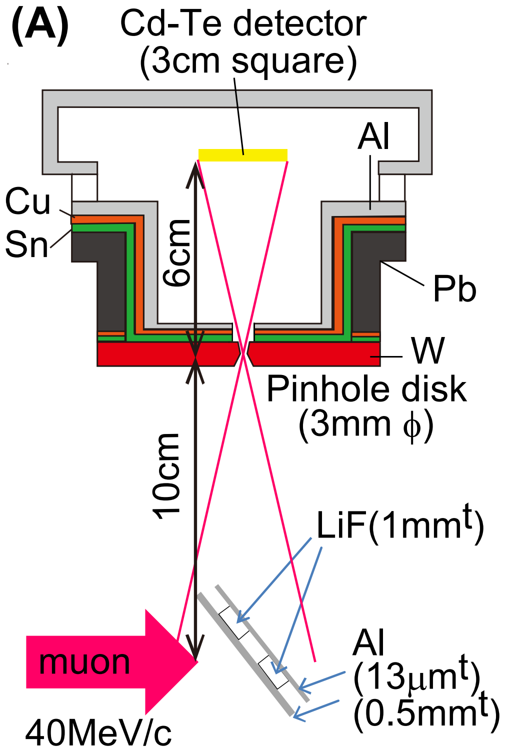


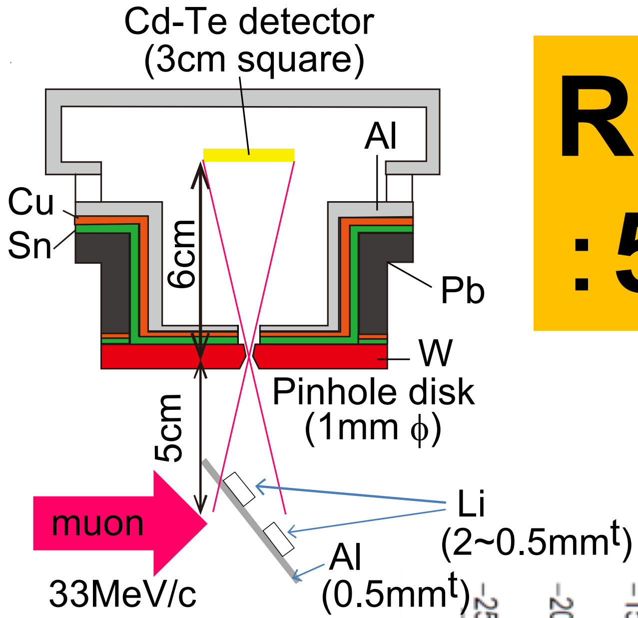




μ^-

Li, Muonic X-ray 3D-imaging demonstrated for the first time !



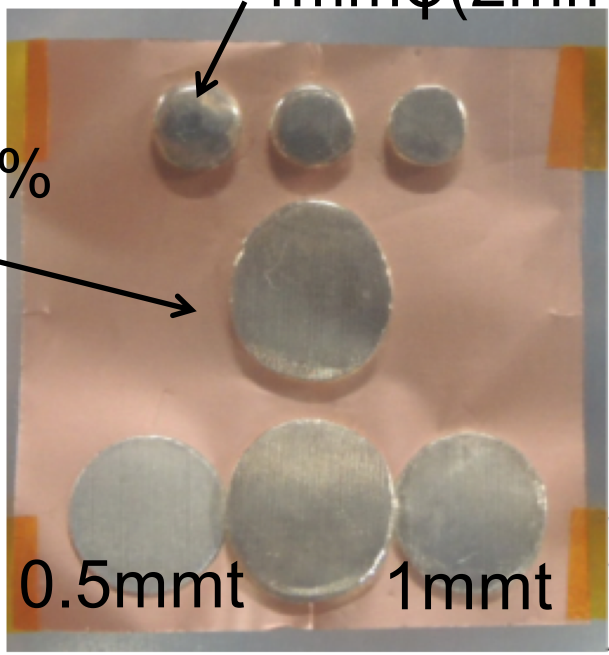


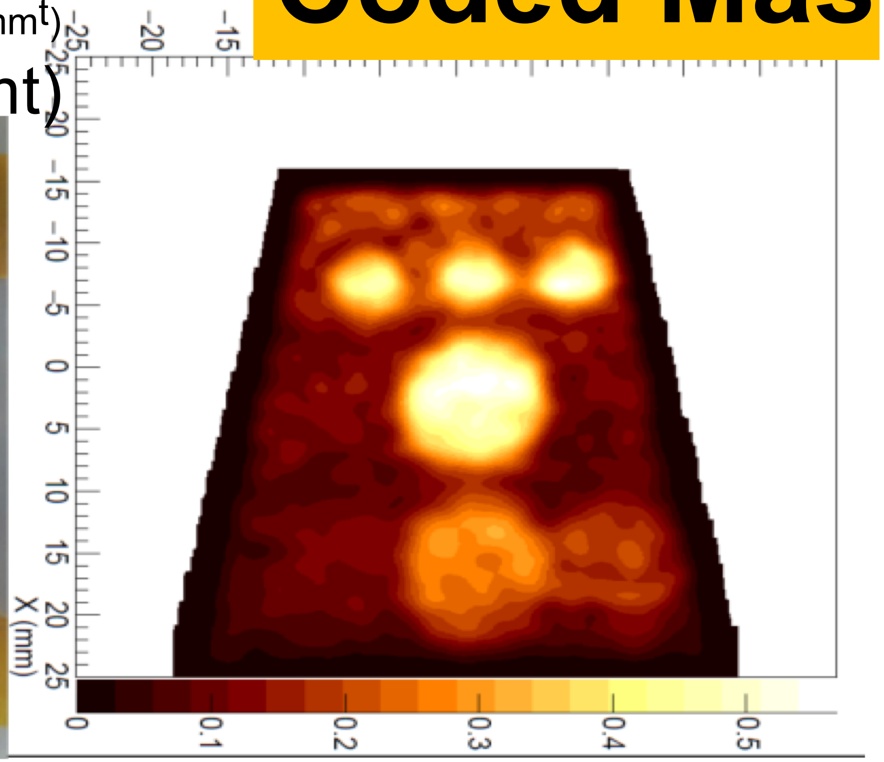
Resolution : 5mm → 2mm

↓

Coded Mask

Solid Angle : 50%





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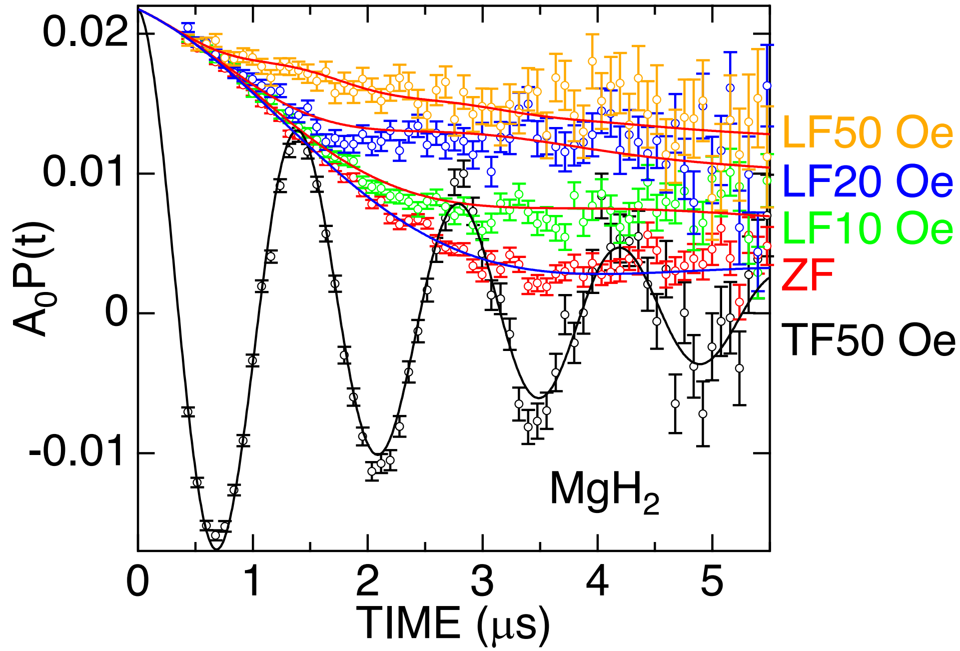
Jun Sugiyama

17B0137 : μ-SR experiment on MgH_2 and related compounds

Using a unique feature of J-PARC, we have successfully observed an internal nuclear magnetic field in MgH_2 with a negative muon spin rotation and relaxation (μ^-SR) technique. This will clarify the dynamics of H in solids from the fixed lattice site, while a positive muon behaves as a light isotope of H^+ and is sometimes delocalizing.



PHYSICAL REVIEW LETTERS 121, 087202 (2018)

Editors' Suggestion | Featured in Physics

Nuclear Magnetic Field in Solids Detected with Negative-Muon Spin Rotation and Relaxation

Jun Sugiyama,[1,*] Izumi Umegaki,[1] Hiroshi Nozaki,[1] Wataru Higemoto,[2,3] Koji Hamada,[4] Soshi Takeshita,[4] Akihiro Koda,[4] Koichiro Shimomura,[4] Kazuhiko Ninomiya,[5] and M. Kenya Kubo[6]

A01 Azuma et al.

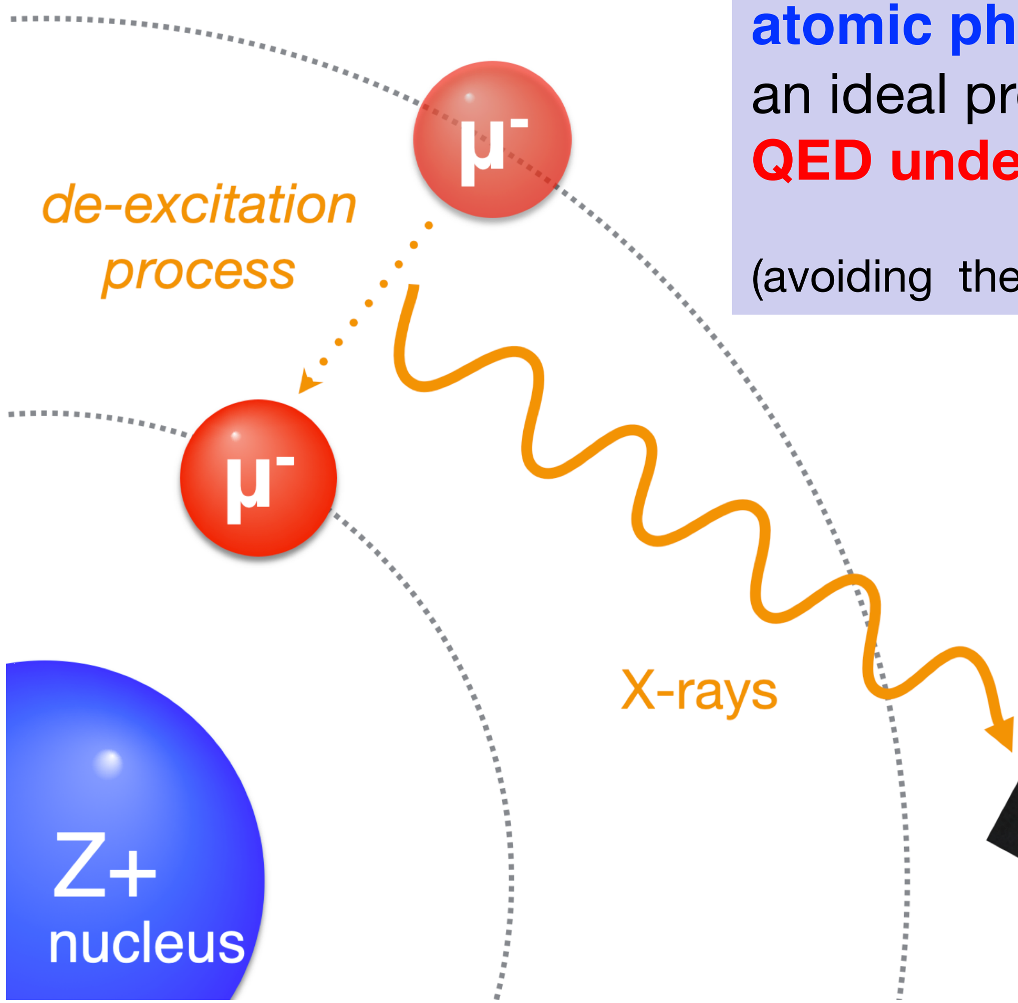
Precision x-ray spectroscopy of muonic atoms with TES detector

muonic atom ($\mu^- + N^{Z+}$): exotic highly-charged hydrogen-like ions
negative muon located very close to the nucleus feels
an **extremely strong electric field**

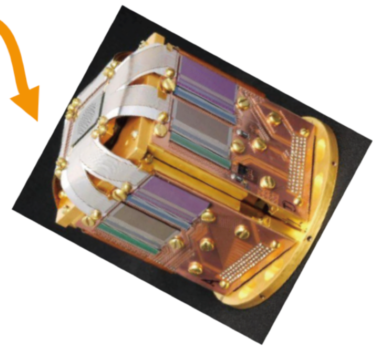
(200^2 times higher than normal hydrogen-like ions)

atomic physics
an ideal probe to explore
QED under an extremely strong electric field

(avoiding the nuclear size effect by selecting high l states)



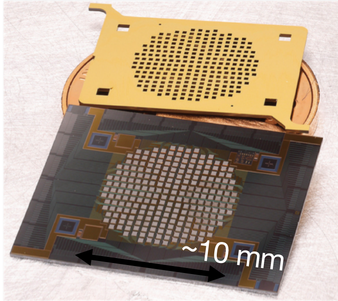
2-5 eV QED contribution
for muonic Ne 5f → 4d, 5g → 4f (~6keV)
(theoretical prediction)



high-precision
spectroscopy

A01 Azuma et al.
Precision x-ray spectroscopy of muonic atoms with TES detector

Superconducting Transition-Edge-Sensor Calorimeter (NIST,US)



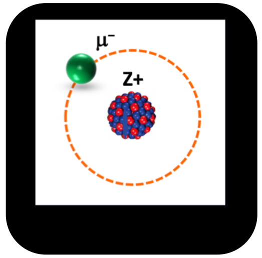
@ 50mK ADR cryostat

240 pixels = 23 mm² eff. area 1 pixel size : ~ 0.1 mm²

high-res (FWHM ~6 eV) for ~6 keV X-ray

×

Intense ultra-slow μ⁻ beam (J-PARC)

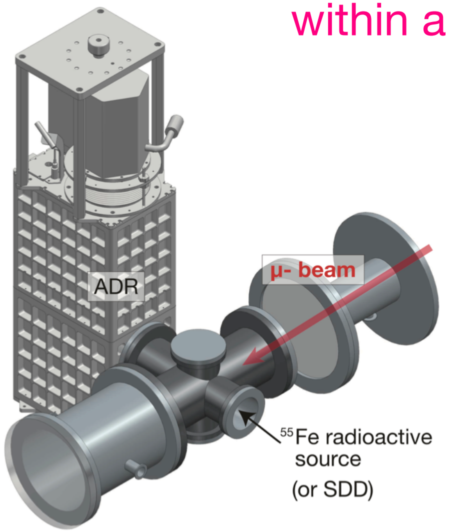


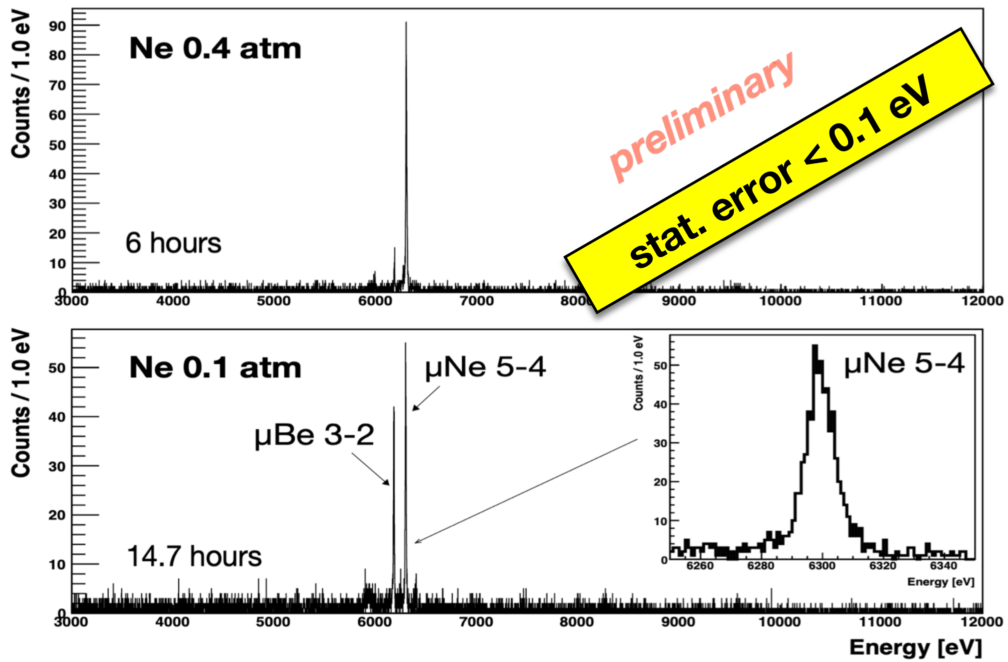
Energy: down to ~50 keV
Intensity: 10^6 per pulse for 20 MeV/c
Pulse repetition: 25 Hz

muonic atom isolated in vacuum (muonic Ne)

First experiment in April 2019

successfully observed very sharp peak within a half day !!





μ^-

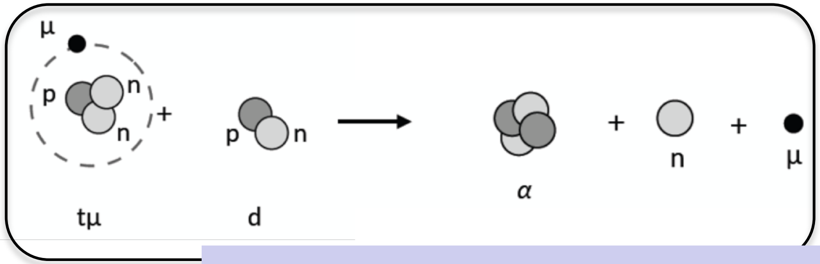
B02 Kino et al.

Basic Research of in-Flight Muon Catalyzed Fusion (IFMCF) in Mach Shock Wave Interference Region

Theory+Experiment:Elucidate the elementary processes in IFMCF

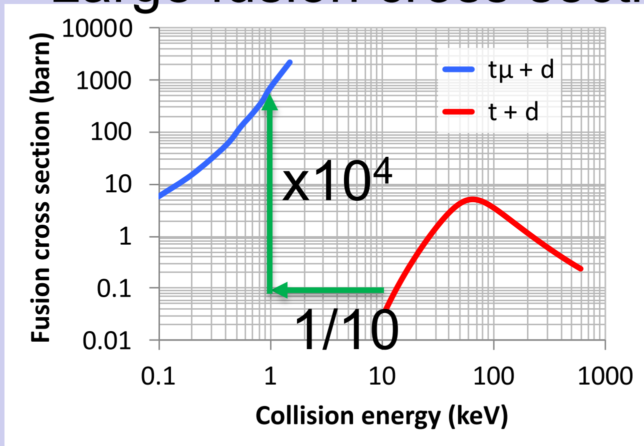
Precise four-body scattering theory

Non-adiabatic
(full four-body)
Multi channel
(rearrangement scattering)
Independent of system
(mass, interaction)



In-flight nuclear reaction

Large fusion cross section



tμ + d → ^{4}He + n + μ +17.6 MeV

Experiment@ JPARC/

Hydrogen isotope target

Application : Energy and neutron source

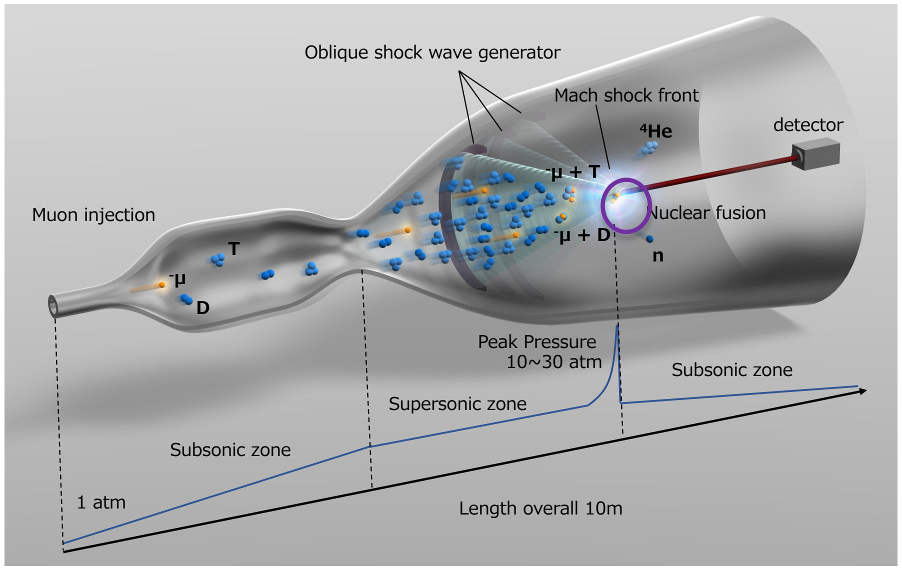
○ Interference region of Mach Shock wave

Flow

Shock wave

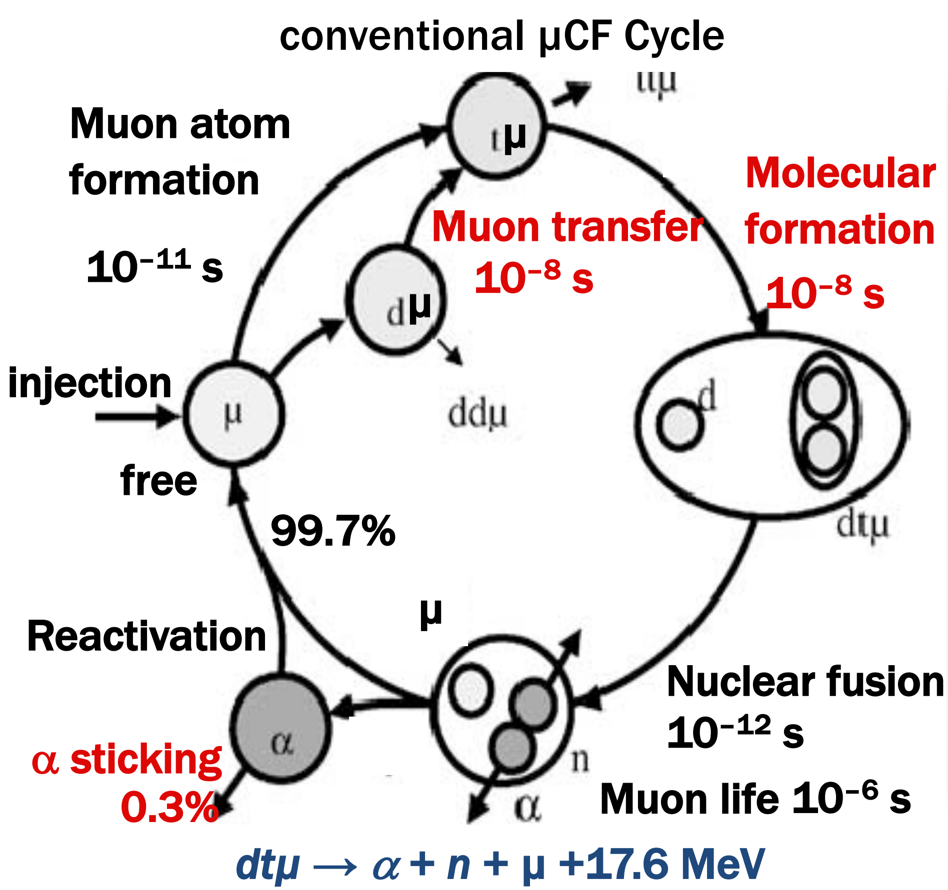
30 atm

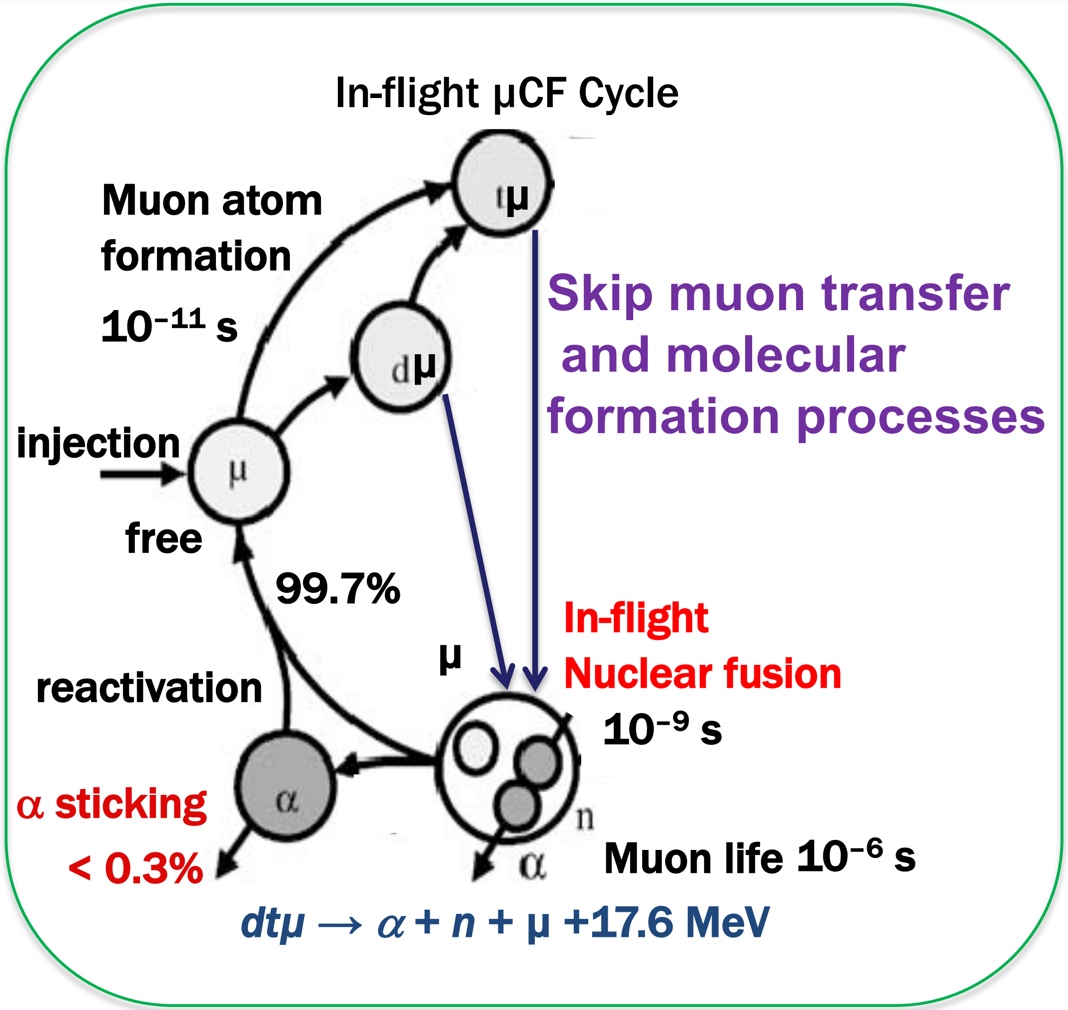
Schlieren pictures



B02 Kino et al.

Creation of In-flight Muon Catalyzed Fusion in Interference Region of Mach Shock Wave





New non-resonant in-flight muon catalyzed cycle has been propose

C02; Conversion from accelerator muon to micro beam

Muon generated by Acc. → Muon beam like LASER

Large Δ**p** bad special coherence, and
large ΔE bad temporal coherence.

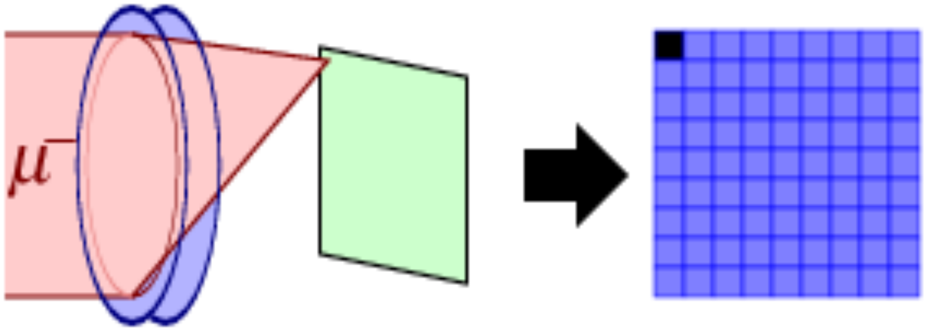
Flash-light

Coherent Muon Beam

Highly directive, and Monochromatic.
It can be focused into small spot.

Beam of LASER

Beam-cooling makes beam focusable into small spot!



Scanning by nano-focused μ^-

Scanning Muon Microscopy

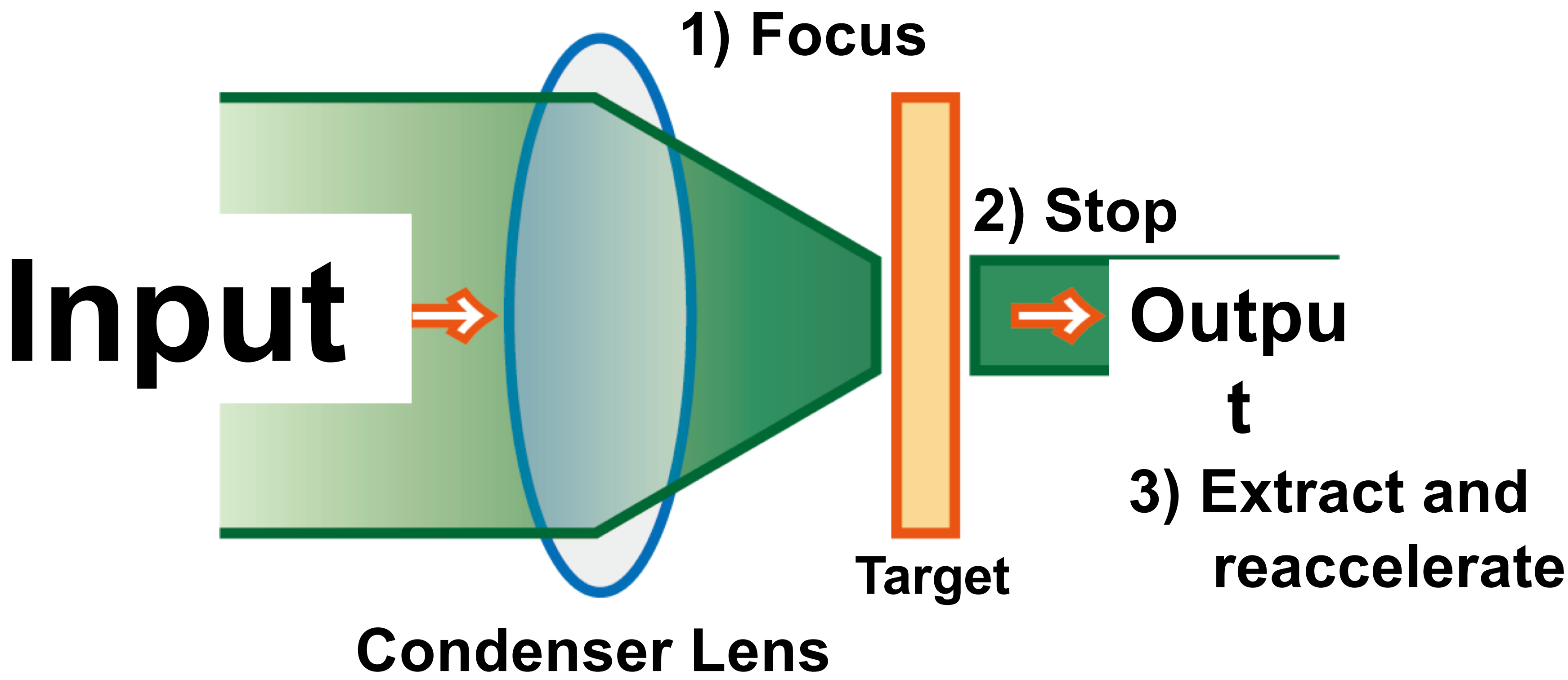
3-dim Mapping of Elements, Isotopes and Chemical-Status.

↓

Revolution in Mat./Life Sc.

μ^-

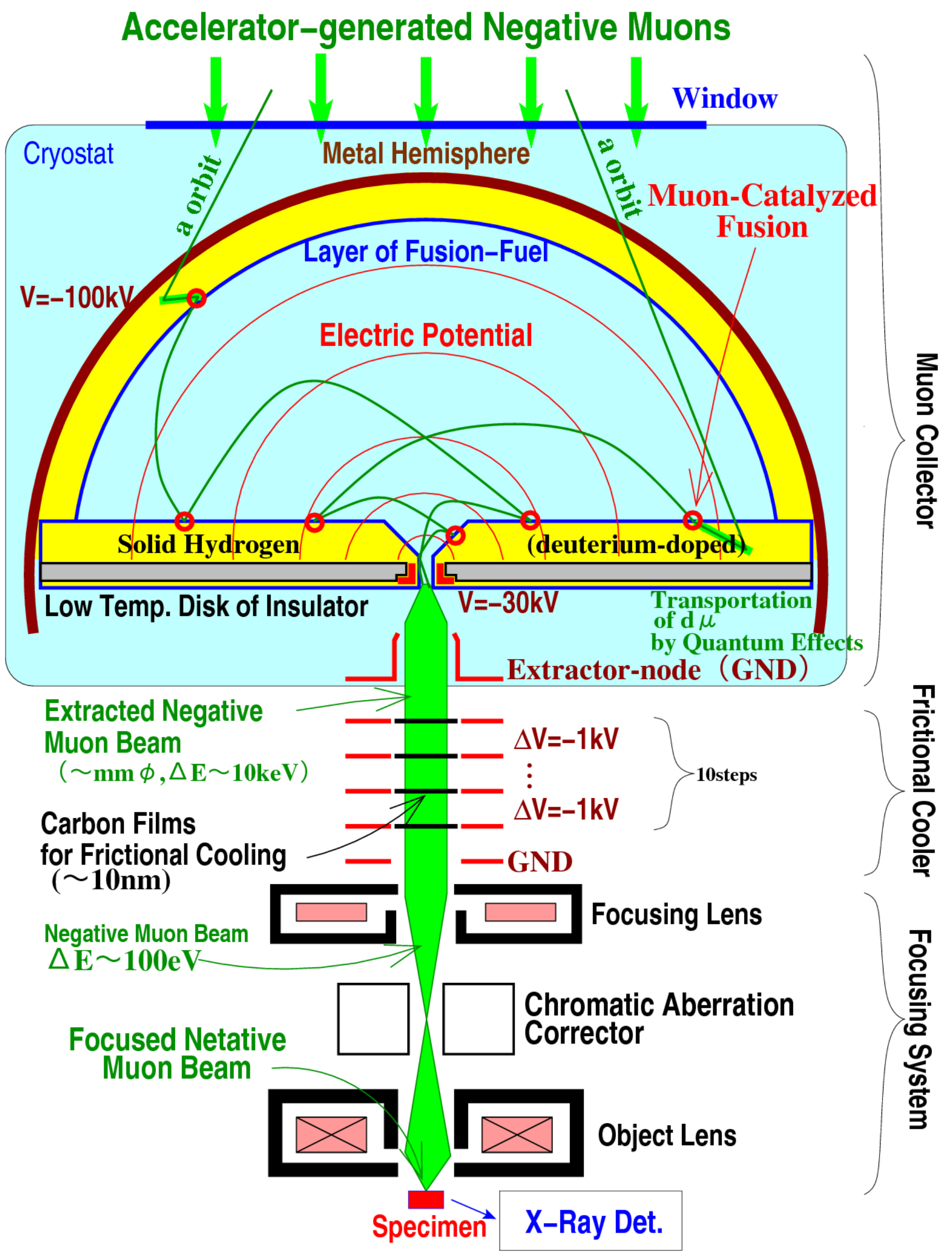
Principle of Beam-Cooling



- Momentum distribution is cleared by stopping.
- Volume in phase space (emittance) is shrunken.
- Beam is cooled down by this process (and iteration)

μ^-

Generation of Negative Micro Muon Beam.



1) **Muon Catalyzed Fusion** (**μCF**) is applied to the beam-cooling. Captured muon into atom is dissociated with low energy ～ 10keV after μCF .

2) Accelerator muon is captured by solid H_2 with mm-thickness. pμ is converted into dμ, and dμ diffuses in mm-range by **Ramsauer–Townsend effect**.

3) μCF on thin DT-layer on solid H_2 dissociates the muon. The muon is transported into center by E-field.

4) Muon beam is extracted, is cooled frictionally, and is focused on specimen.

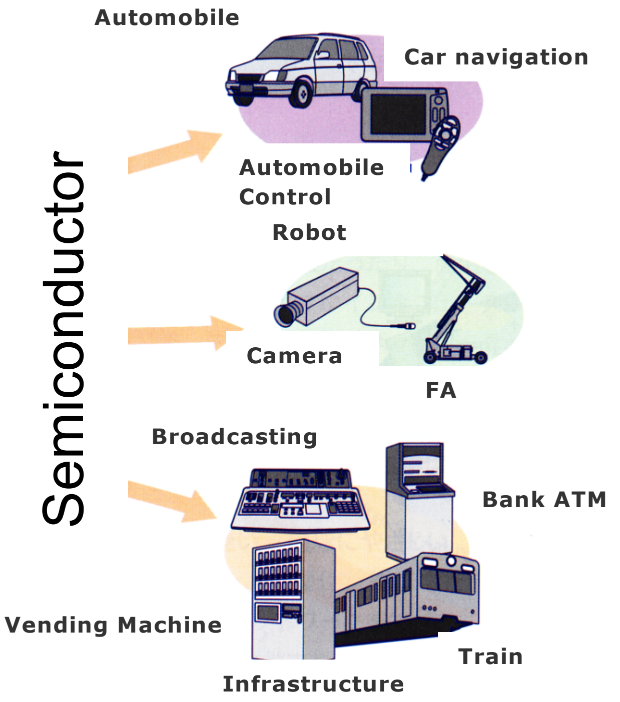
μ^{+} μ^{-}

Soft error of semiconductor

A soft error is an issue that causes a temporary condition in RAM that alters stored data in an unintended way.

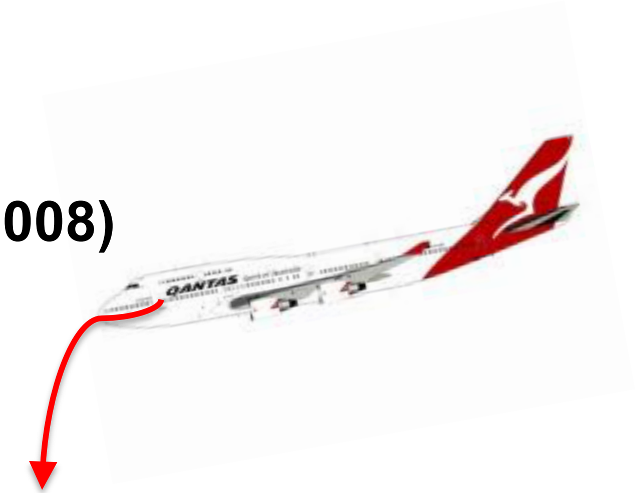
ICT supports base of Infrastructure

(Information and Communication Technology)



Qantas Flight 72、QF72

A steep dive(October, 2008)



Automatic Controlled Drive ：
existing GPU（Graphic Processing Unit) 10^{8} sets

- **1 soft error/ (10^{7} hours)**
- **10 accidents/h in the world**

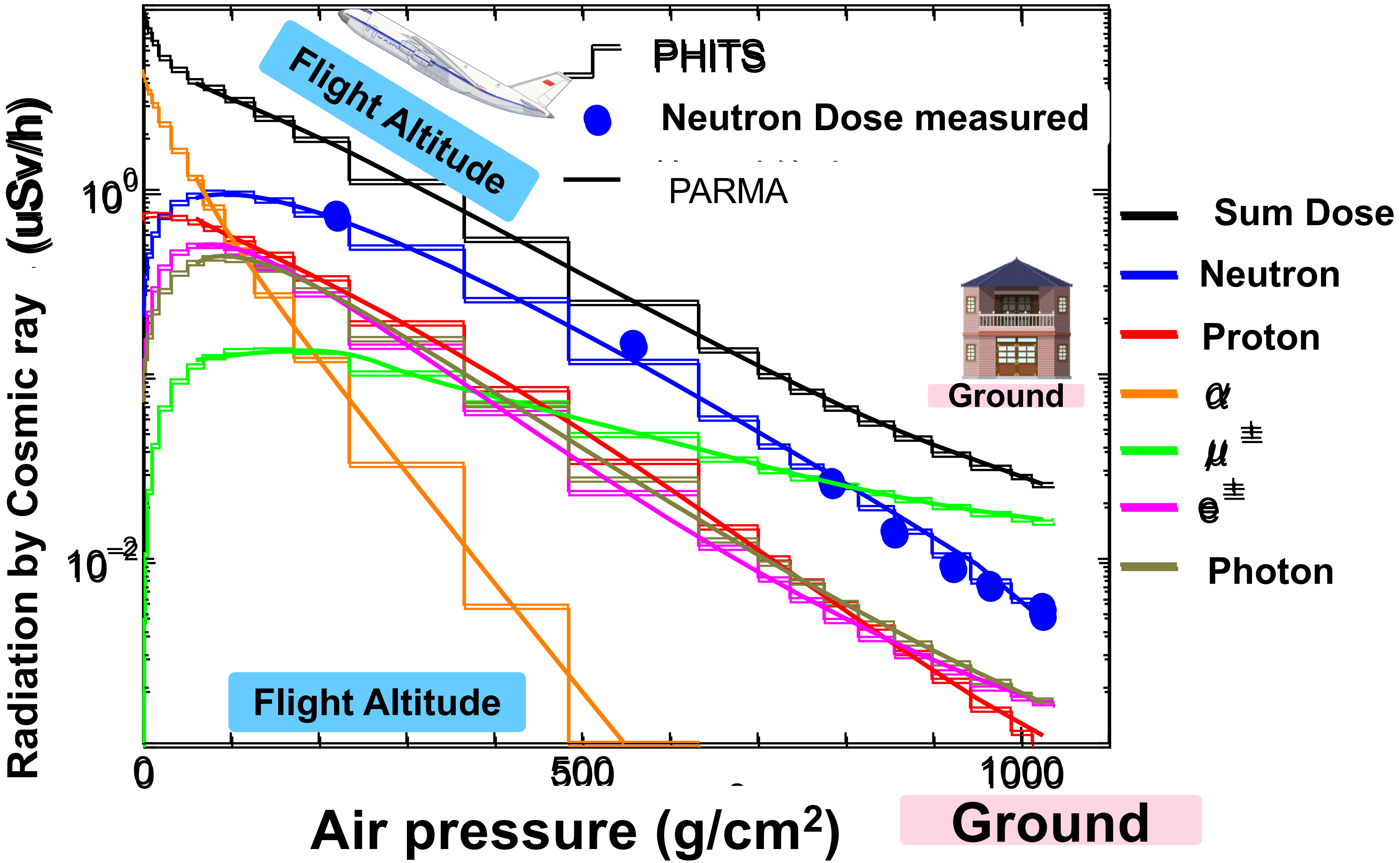
－＞80000 accidents/year

High reliability is essential for automatic control for the automobile, railway, airplane etc.

μ^+ μ^-

Soft error of semiconductor

Radiation by Cosmic ray against Altitude



On the grounds, contribution of μ is dominant!

1) T. Nakamura et al., (2005) 2) M. Kowatari et al., (2005)

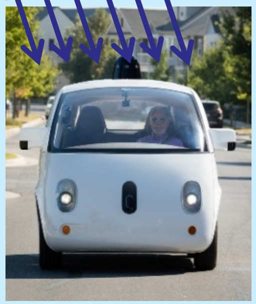
μ^+ μ^-

Negative and Positive Muon-Induced Single Event Upsets in 65-nm SRAMs

- The problem of **soft errors** in semiconductor devices subjected to terrestrial radiation environment (e.g., muons: 75%) has been recognized as a major threat for electronics used at ground .
- The soft error means a temporary malfunction in semiconductor devices due to **single event upsets (SEUs)** induced by energetic ionizing radiation.
- The **SEU cross sections** for 65-nm SOTB and Bulk SRAMs were measured with both low energy “positive” and “negative” muon beams.

Cosmic-rays at ground(muons : 75%)

Super Computer

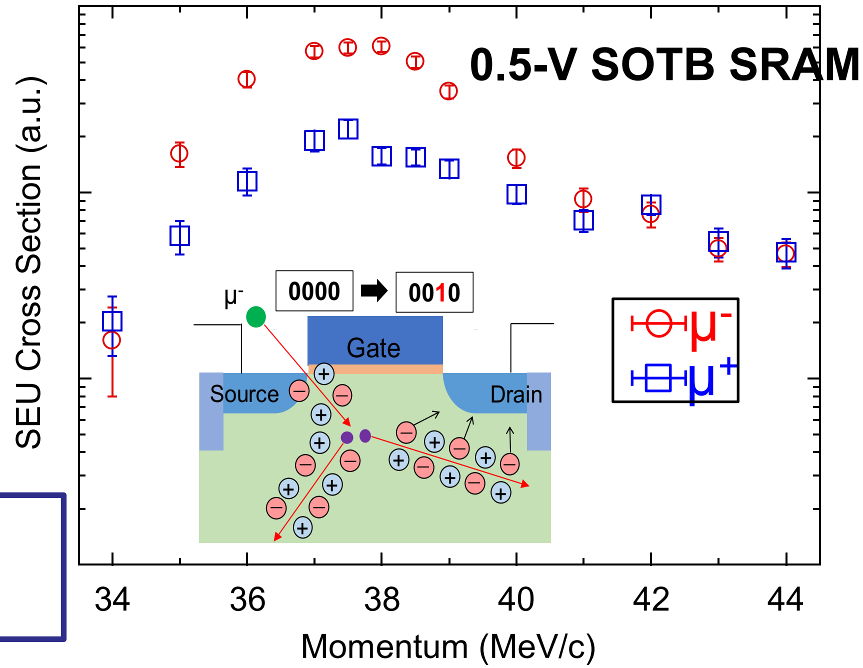


Automobile

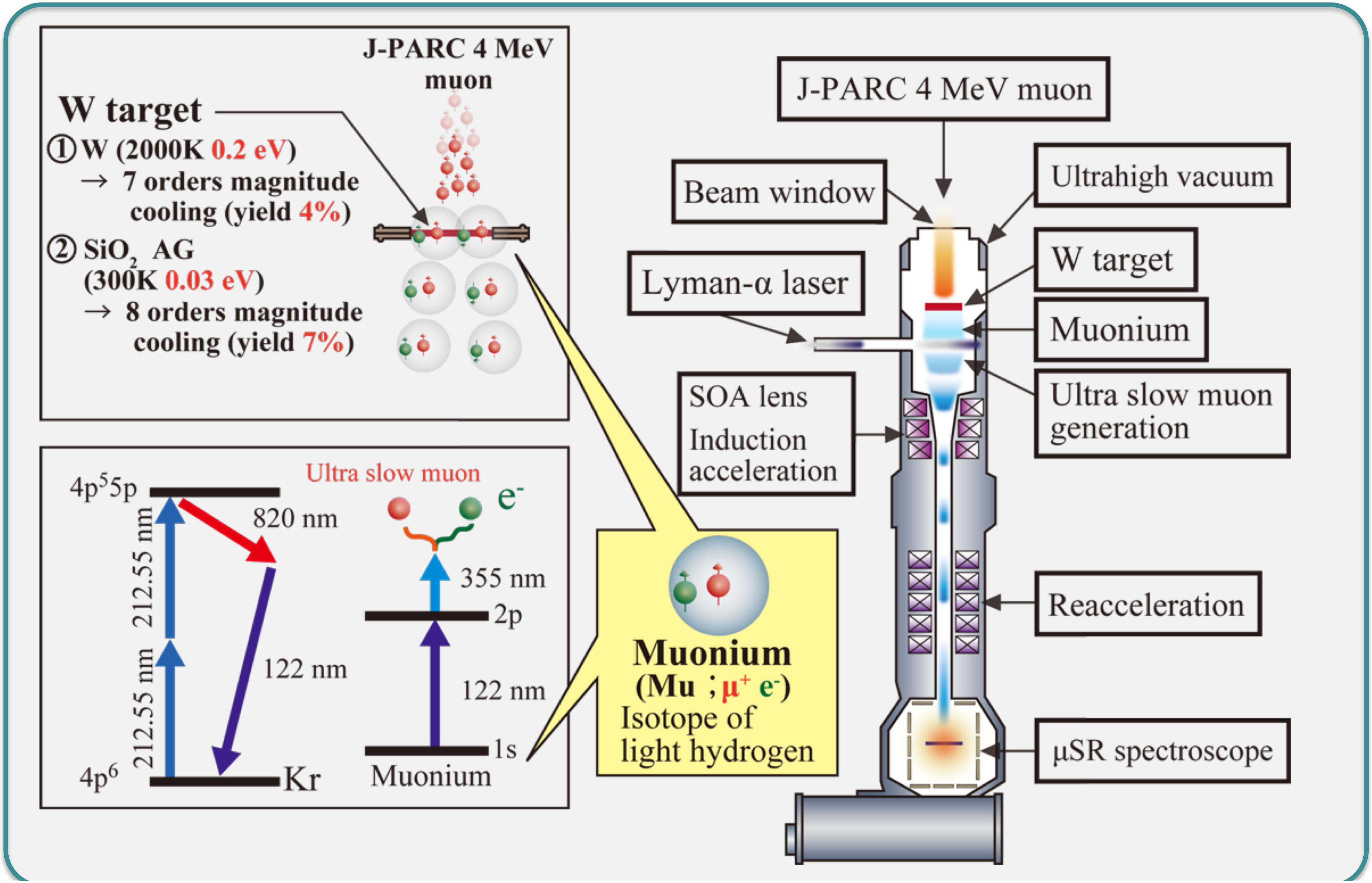
High reliability of semiconductor devices is necessary for safety and stable use.

The first experimental result :

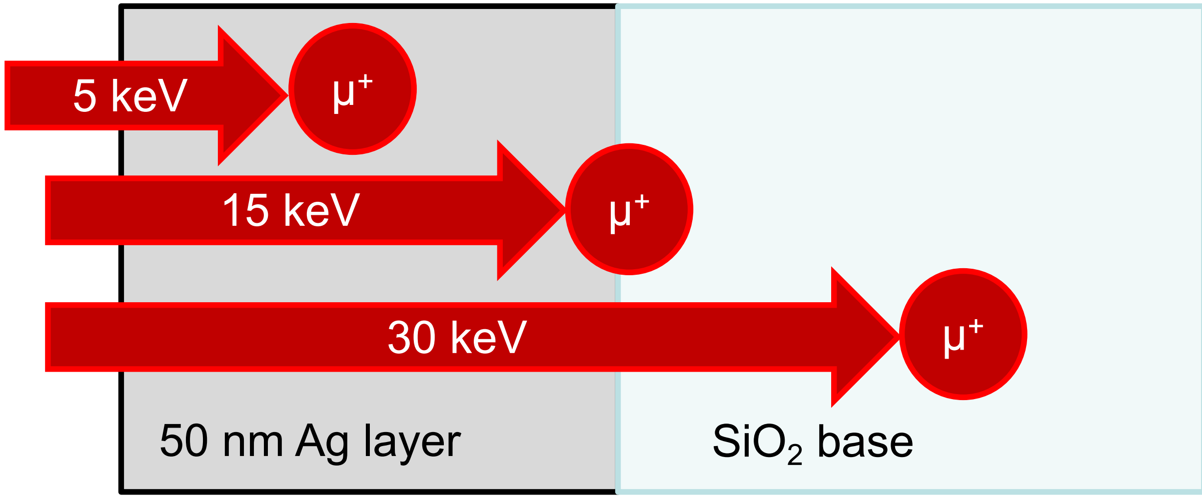
The negative muon SEUs occur at about three times higher rate than the positive muon ones.



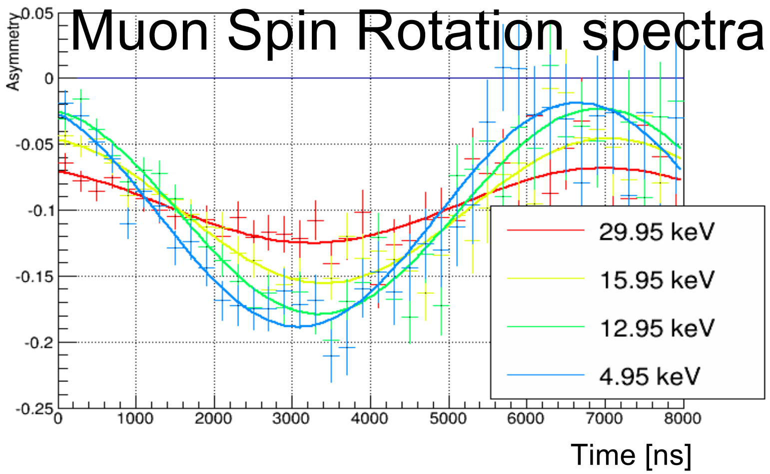
U-Line dedicated to Ultra Slow Muon *(0.1 - 30 keV)*



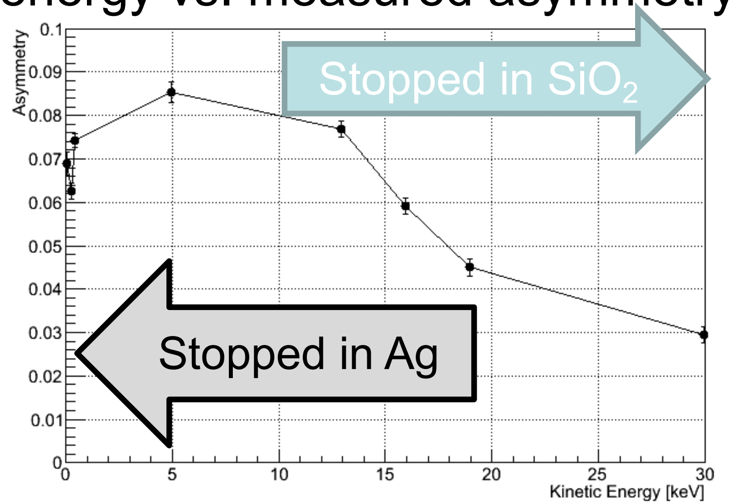
Ultra Slow μ^+



A μSR experiment was carried out with a sample made of 50 nm Ag-layer and SiO_2 base using Ultra Slow Muon beam.
As low as 100 eV(1nm in Au)



Kinetic energy vs. measured asymmetry



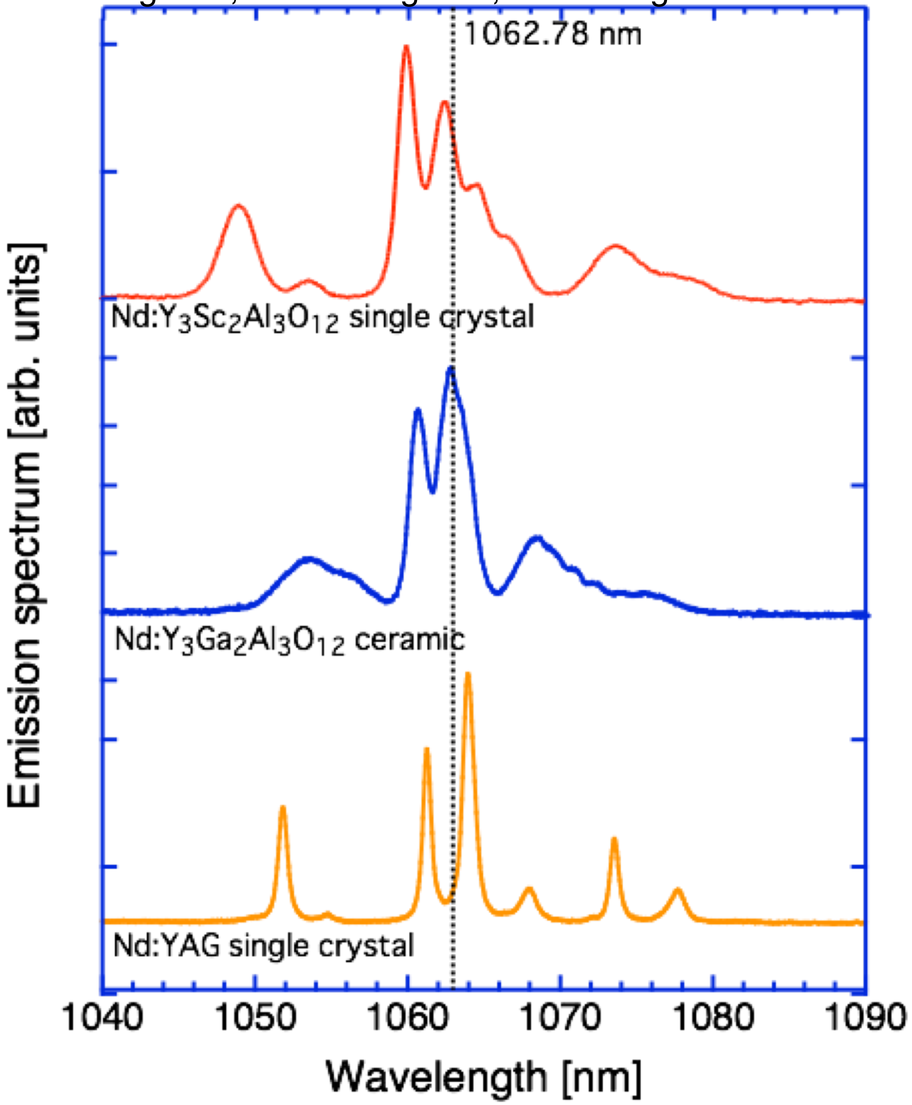
	Current state of USM
Maximum event rate by MCP	121 events/s
Size	~ 10 mm (FWHM)
Time distribution	~ 10 ns (FWHM)
Maximum hit rate by Kalliope	22 hits/s
Asymmetry	0.1
Polarization	At least 39%

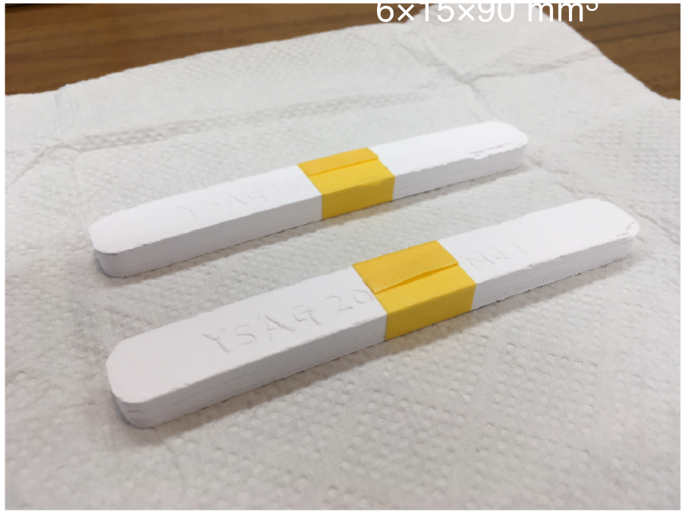
Ultra Slow μ⁺

Newly fabricate Nd:YSAG ($Nd:Y_3Sc_{1.5}Al_{3.5}O_{12}$) ceramic

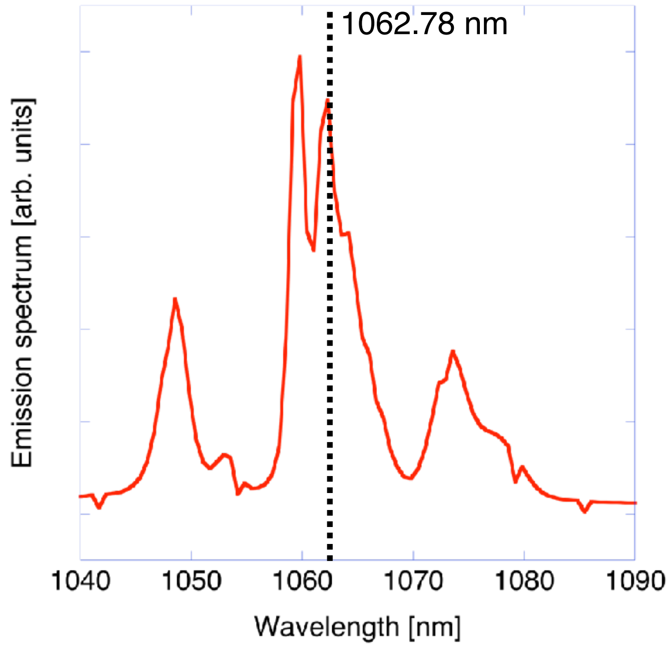
density of Ga, Sc and Al

Ga : 5.91 g/cm³, Sc : 2.99 g/cm³, Al : 2.70 g/cm³





after several trial, small size (5×5×15 mm³) transparent ceramic was delivered

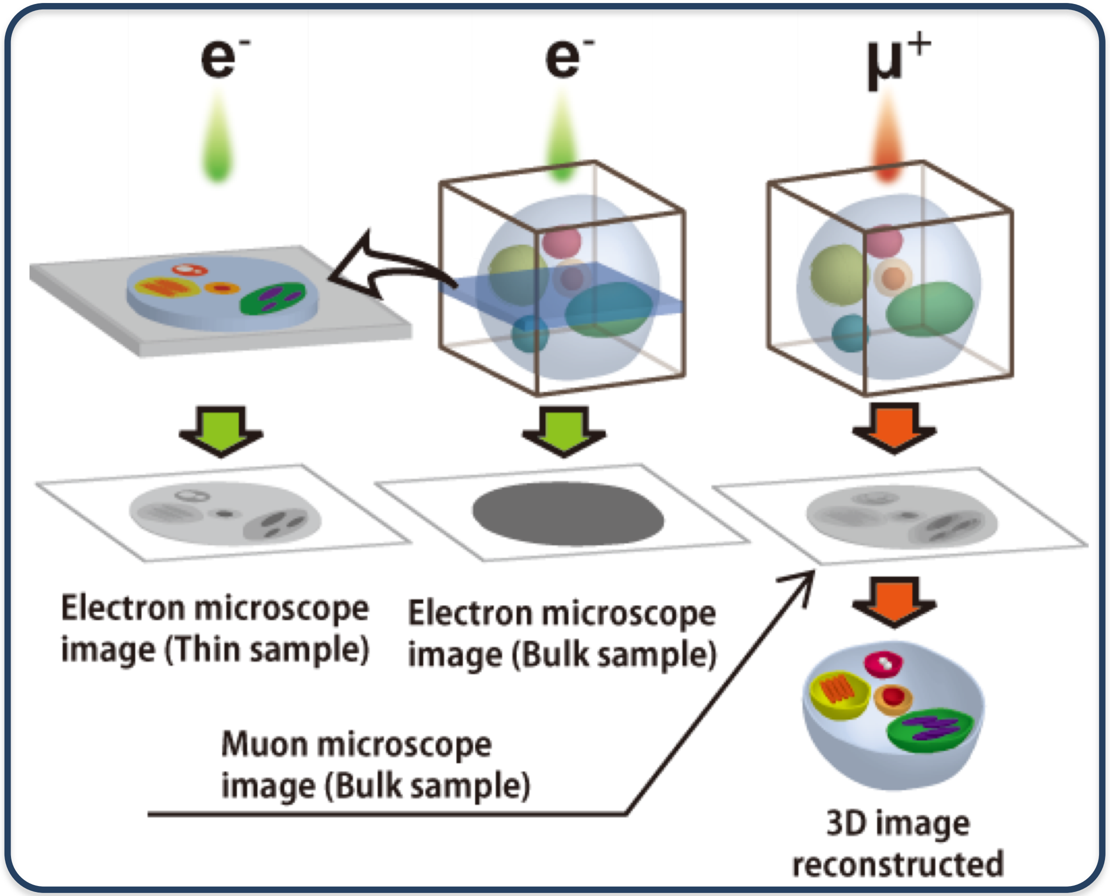


Better sintering condition is searching to make ø12, 80mm long Nd:YSAG

Ultra Slow μ^+

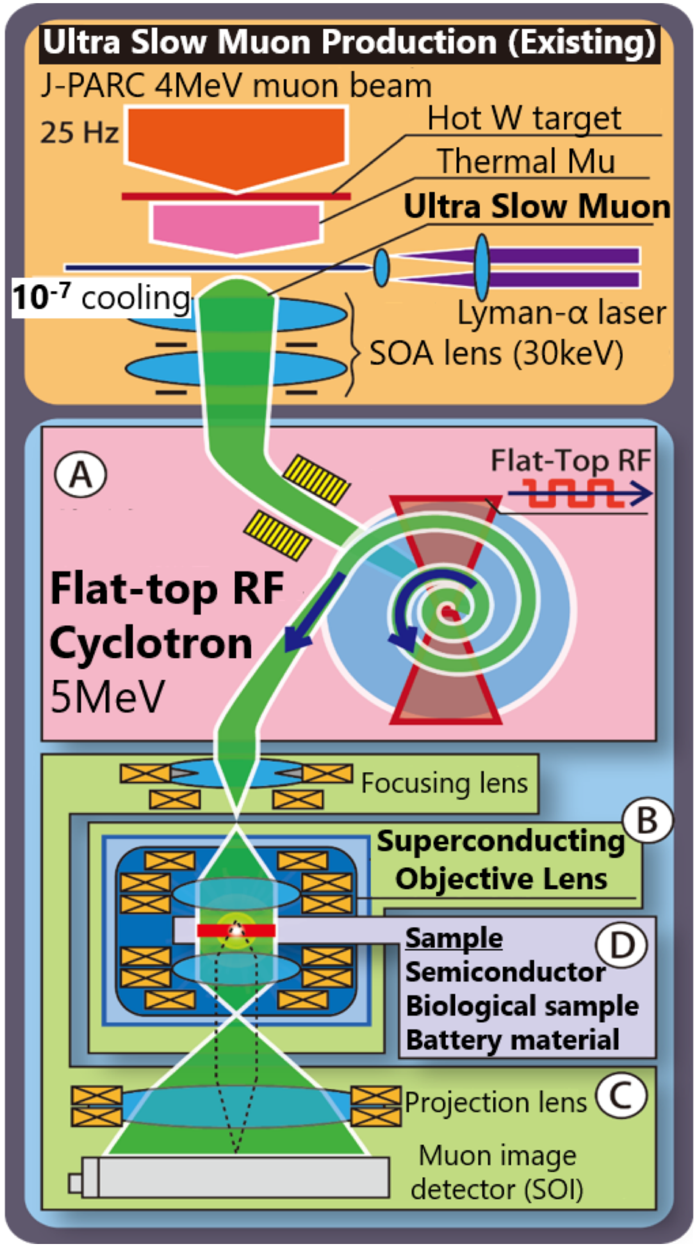
Transmission muon microscope 3D Imaging

Applying re-accelerated muons, utilizing its feature of "Wave", for a new type of "eye" !



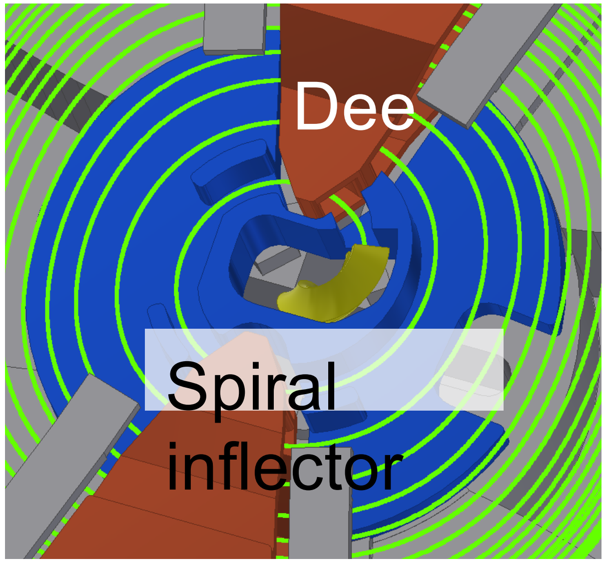
Electron Microscope can observe sample less **than 1μm thickness**, on the other hand, **Muon Micoscope** may be able to observe **200 times thicker** samples, because of **200 times heavier mass,** enabling us to observe **alive cell through a window!**

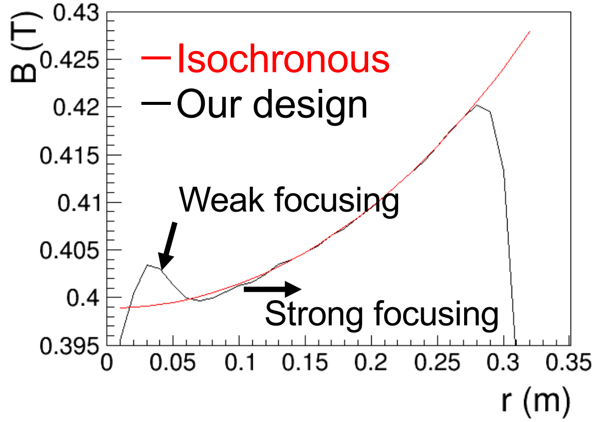
Ultra Slow μ+ Transmission Muon Microscope

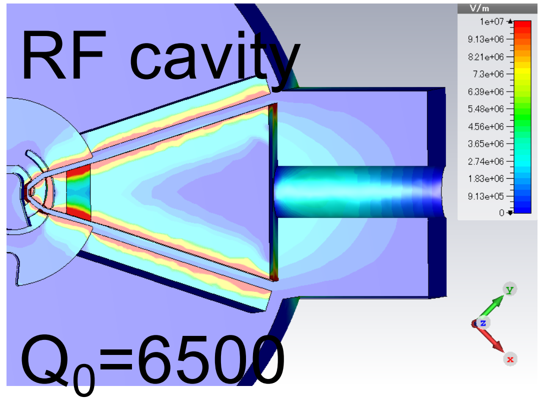


FY2018: Detail design & partial fabrication

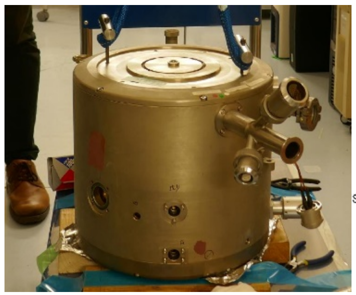
Cyclotron beam dynamics

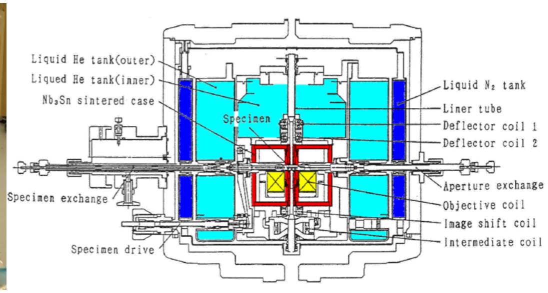


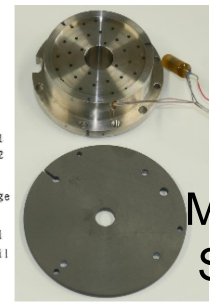




Superconducting Lens by Meissner Shield





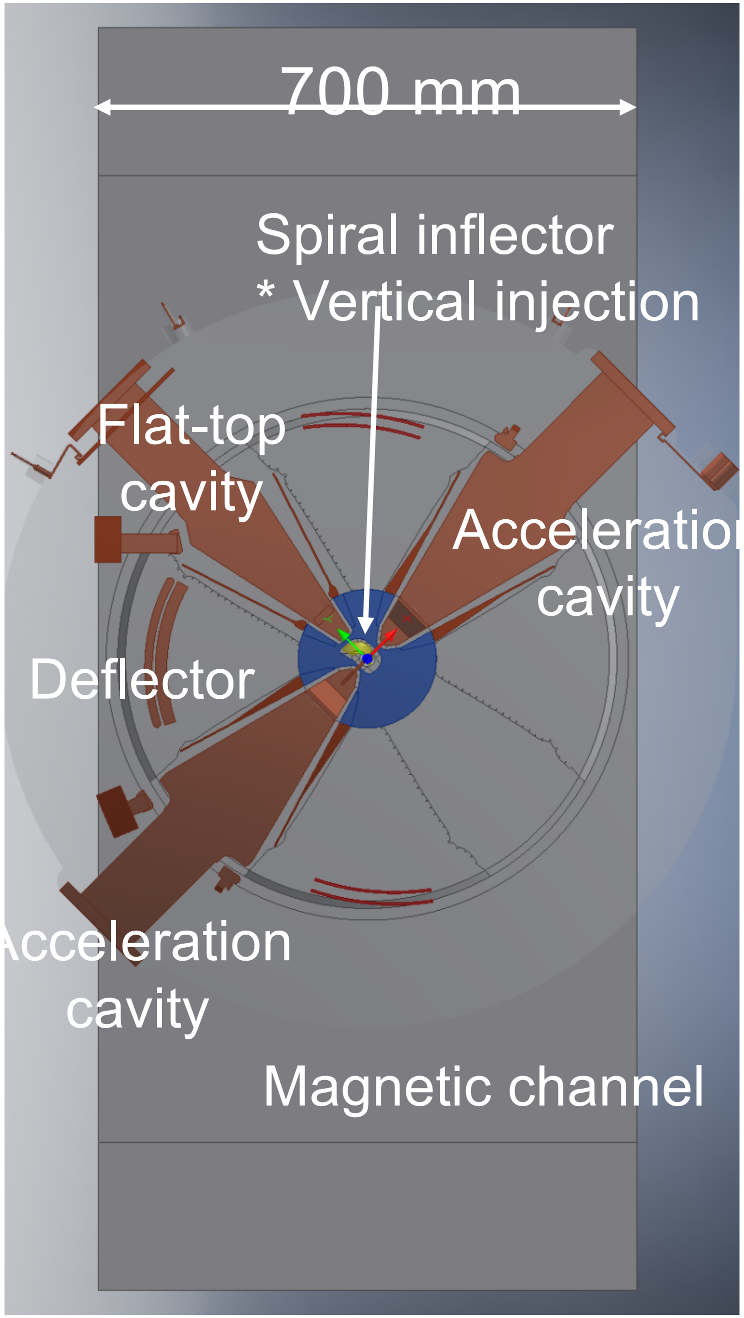


SC Coil 140kAT

Meissner Shield

FY2019: Full fabrication, FY2020: beam@MLF

Muon Cyclotron; now fabricating → will be delivered soon



Magnet

- B_{ave} = 0.4 T
- # of sectors = 4
- Extraction radius R_{ext} = 262 mm

RF

- Harmonic number = 2
- RF frequency = 108 MHz
- Dee voltage = 50 kV
- Flat-top RF(3F) frequency = 324 MHz

Injection

- Spiral inflector ±4.5 kV

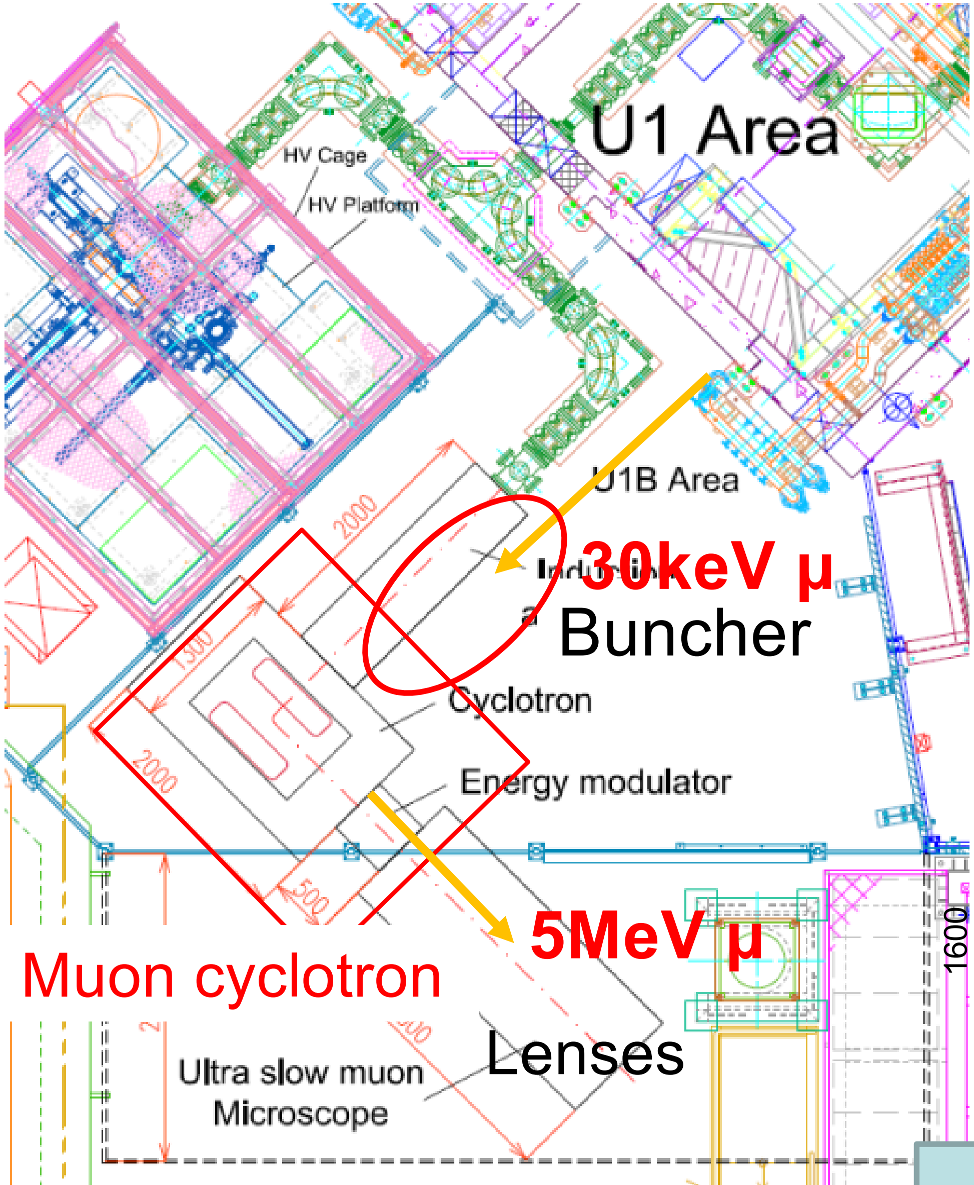
Extraction

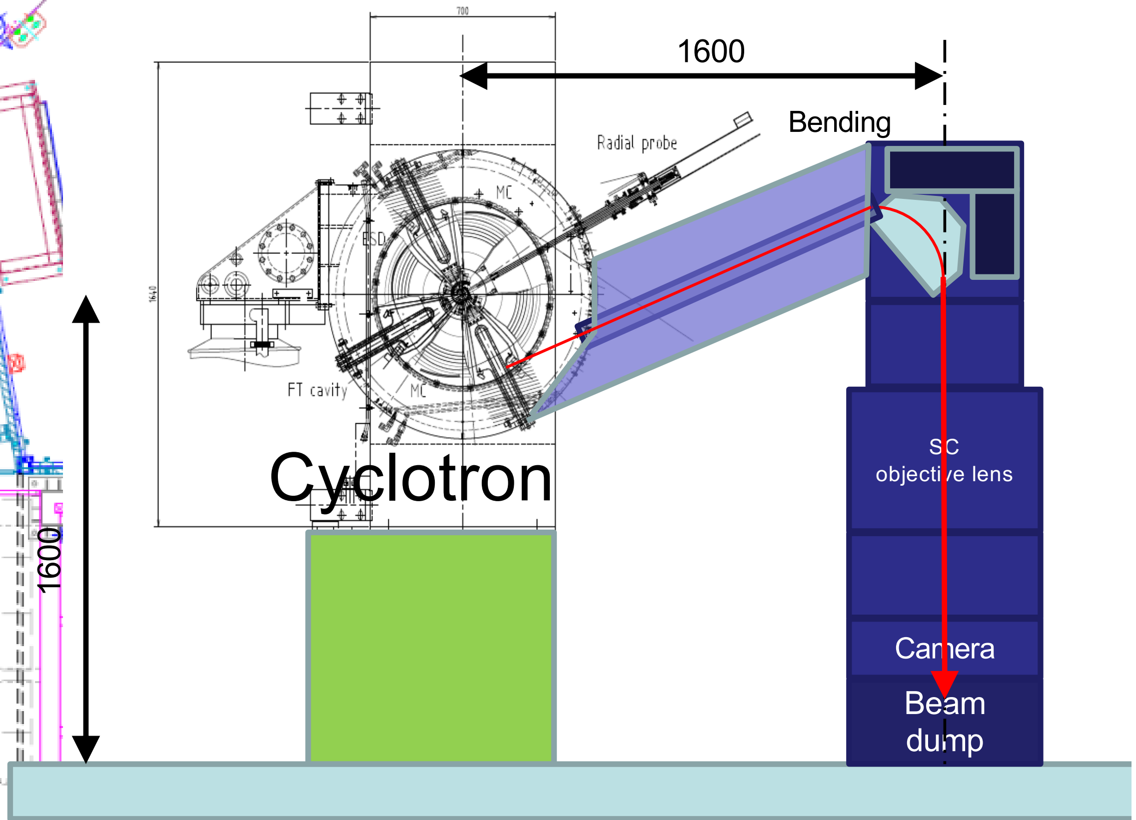
- Electrostatic deflector ±7.5 kV/mm
- Passive magnetic channel

- Accelerated **up to 5 MeV** by 59 turns ~ 1μs
- **Flat-top** initial phase acceptance and
- $\Delta E/E = 1 \times 10^{-4}$ is achieved

Ultra Slow μ+

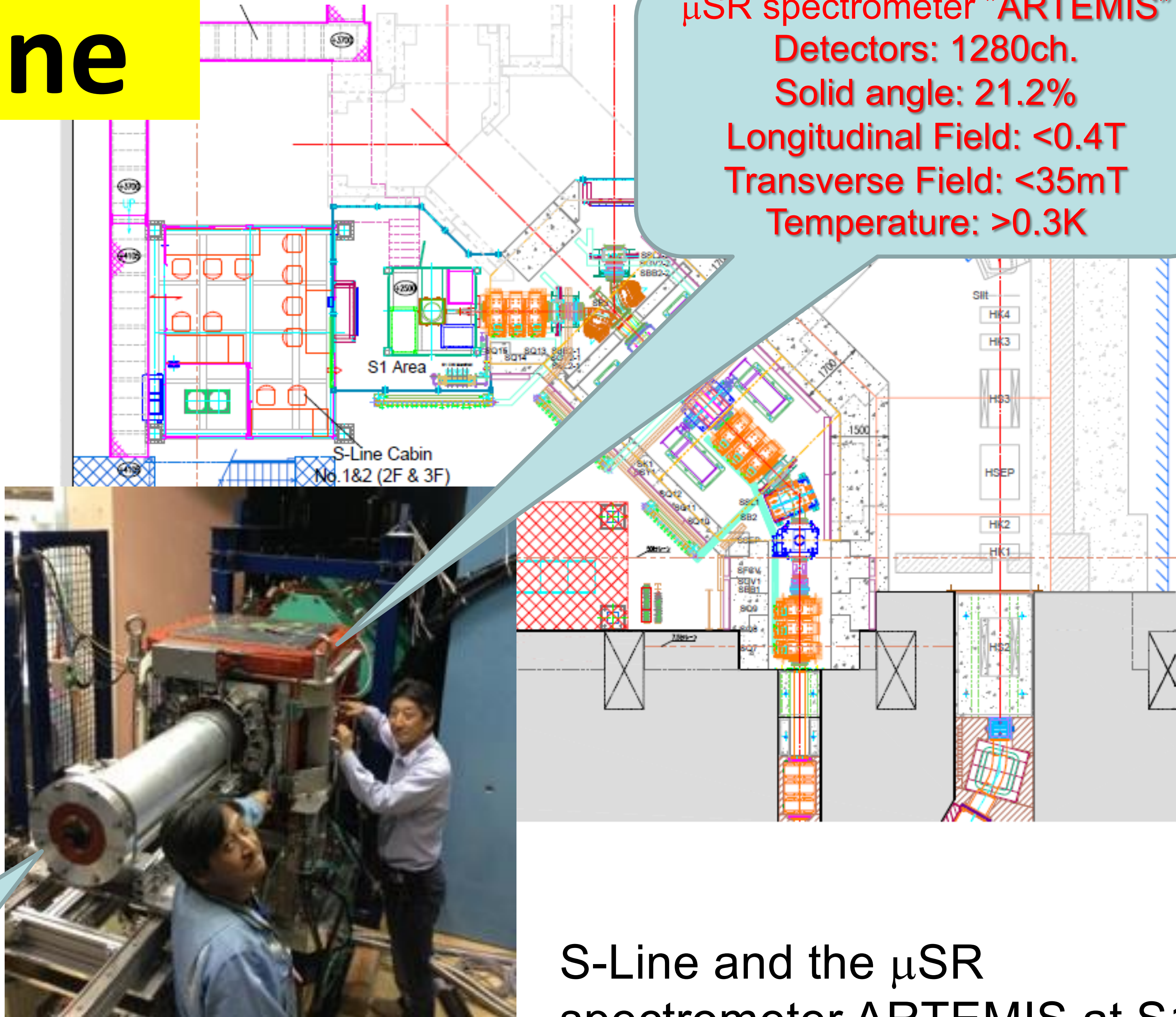
Layout @U1B area





S-Line

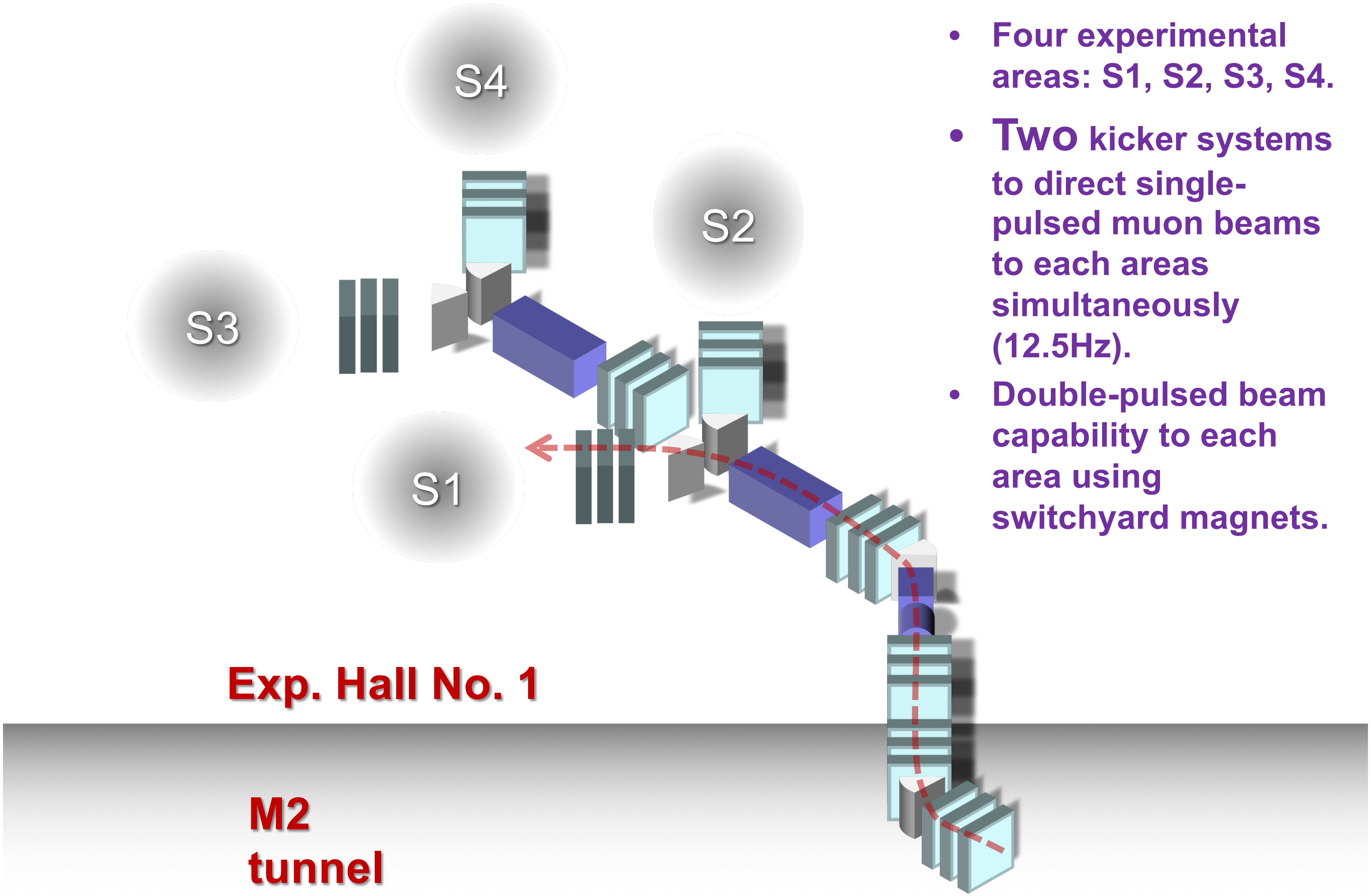
μSR spectrometer "ARTEMIS"
Detectors: 1280ch.
Solid angle: 21.2%
Longitudinal Field: <0.4T
Transverse Field: <35mT
Temperature: >0.3K



past
chamb

S-Line and the μSR spectrometer ARTEMIS at S1.

S-Line: dedicated to **materials science**



- **Four experimental areas: S1, S2, S3, S4.**
- **Two kicker systems to direct single-pulsed muon beams to each areas simultaneously (12.5Hz).**
- **Double-pulsed beam capability to each area using switchyard magnets.**

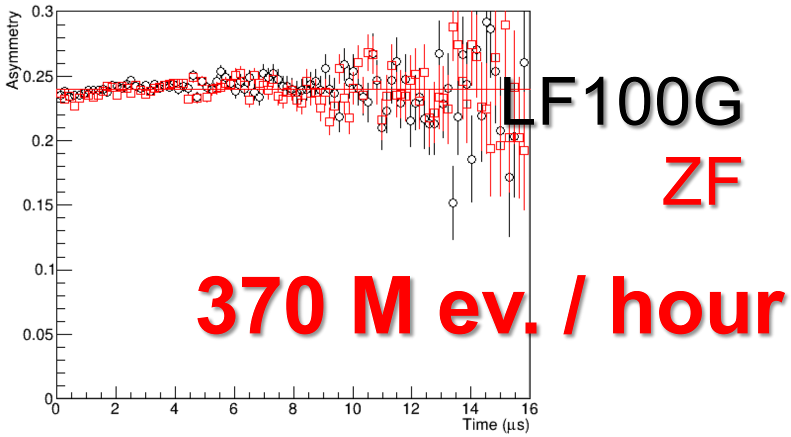
μ^+

S-Line

Steady operation at the S1 area is ongoing.

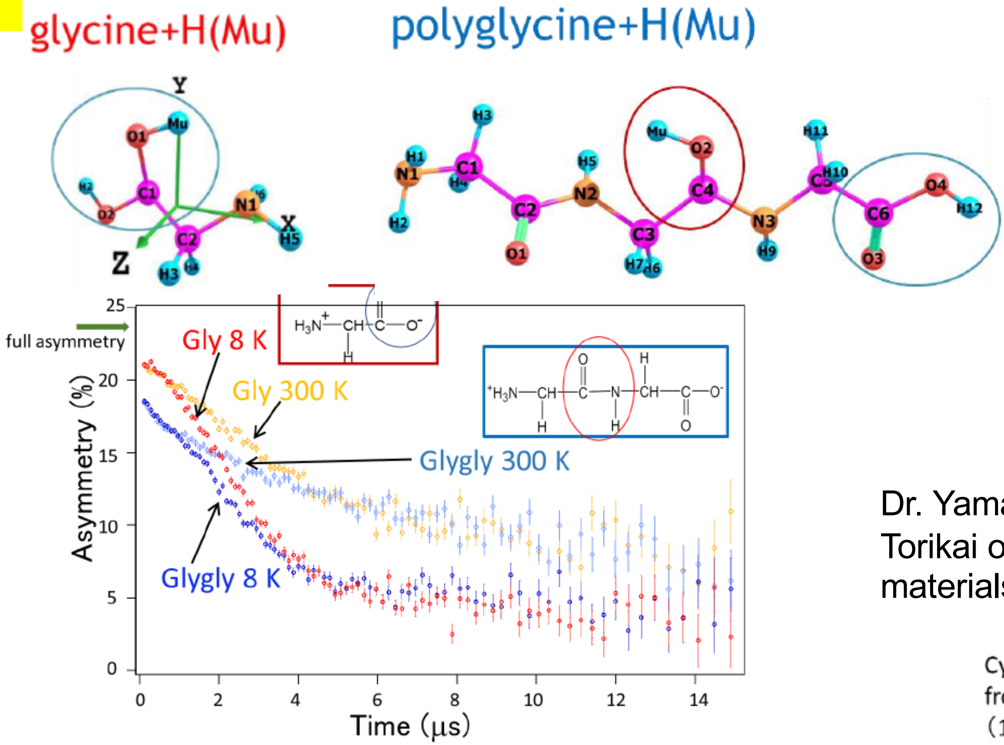
- A roughly half number of the approved exp. proposals by Muon PAC in 2018 has been carried out at the S1 area, including ONE urgent proposal and THREE P-type proposals.
- FOUR journal papers and TWO conference proceedings are published in 2018.
  - K. Horigane et al., PRB 97, 064425; K. Kurashima et al., PRL 121, 057002; I. Yamauchi et al., PRB 97, 134410; H. Okabe et al., PRB 97, 075210.
- Press release: “Magnetic fluctuation of Bi-2201 high-Tc cuprates at the over-doped region” by Prof. Adachi, Sophia Univ.

Dr. Tanaka and students are mounting their sample on the cryostat.



The integrity of the μSR DAQ system was confirmed during the 1MW test operation in Jul. 2018. The above time spectra were obtained in ONE minute.

On-going Science Activity at S-line
- μSR on bio-materials -



Sugawara et al.(2018)

Dr. Yamamura of Kitasato Univ., Dr. Nihimura of KEK, and Prof. Torikai of Yamanashi Univ. carry out measurements on bio-materials at S-line.

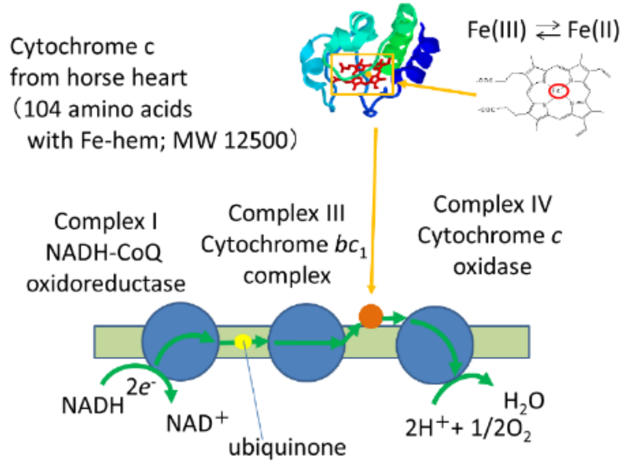


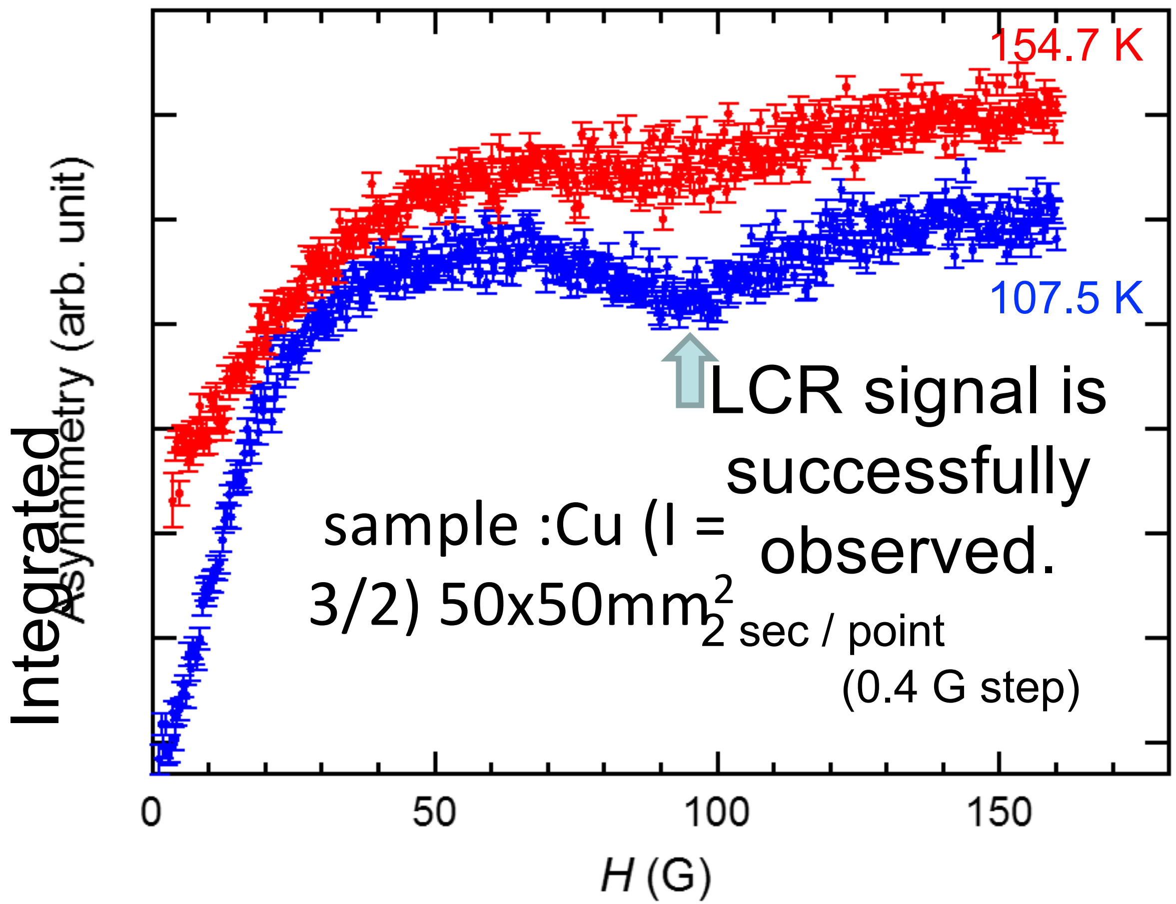
図1　ミトコンドリア内膜における呼吸鎖の模式図とシトクロム*c*

<u>Bio-material μSR group</u>

Kitasato Univ.: Sugawara, Yamamura
Yamanashi Univ.: Torikai, Shiraki, Fujimaki
Hokkaido Univ.: Miwa
Kwansei gakuin Univ.: Kusunoki, Yamaguchi
Ibaraki Univ.: Pant, Iinuma, Yamaguchi, Kozuma
KEK: Shimomura, Nagamine
JAEA: Higemoto

High intensity beam→necessary for tiny samples like bio-materials

S-Line: μ-LCR test measurement @1MW

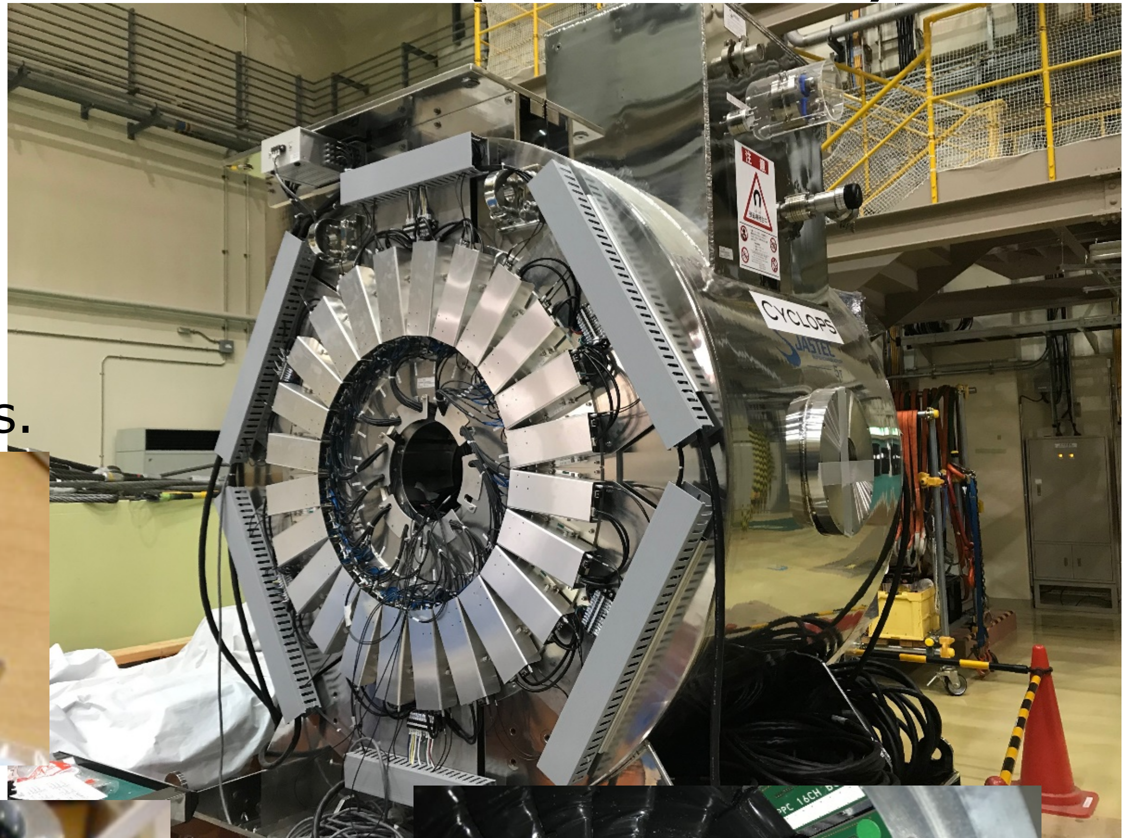


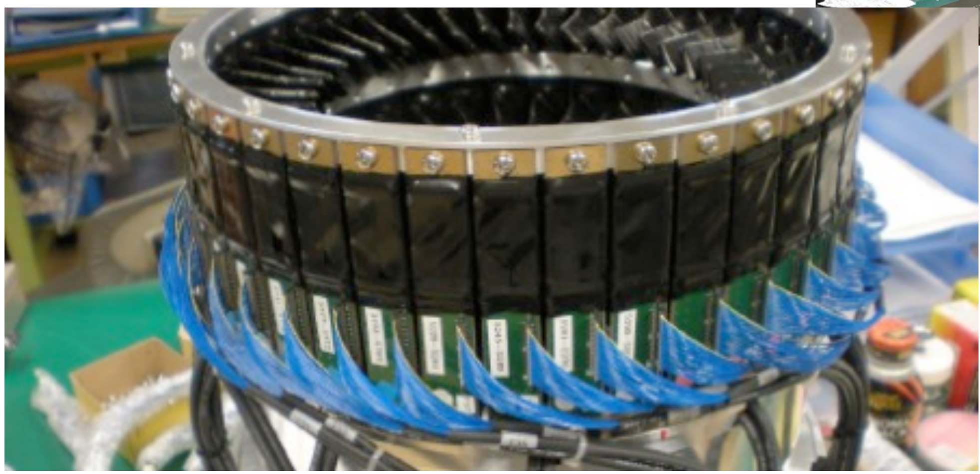
Muon decay events were accumulated for **2 Sec.** at each point.

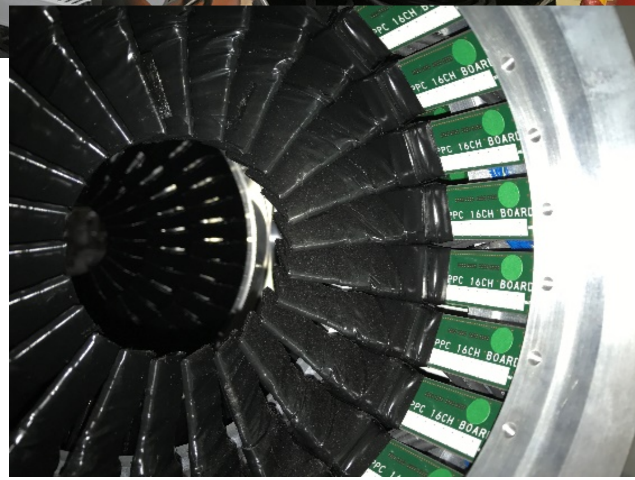
400 points were measured with increasing or decreasing field, roughly taking 14 min.

5T μSR spectrometer (CYCLOPS)

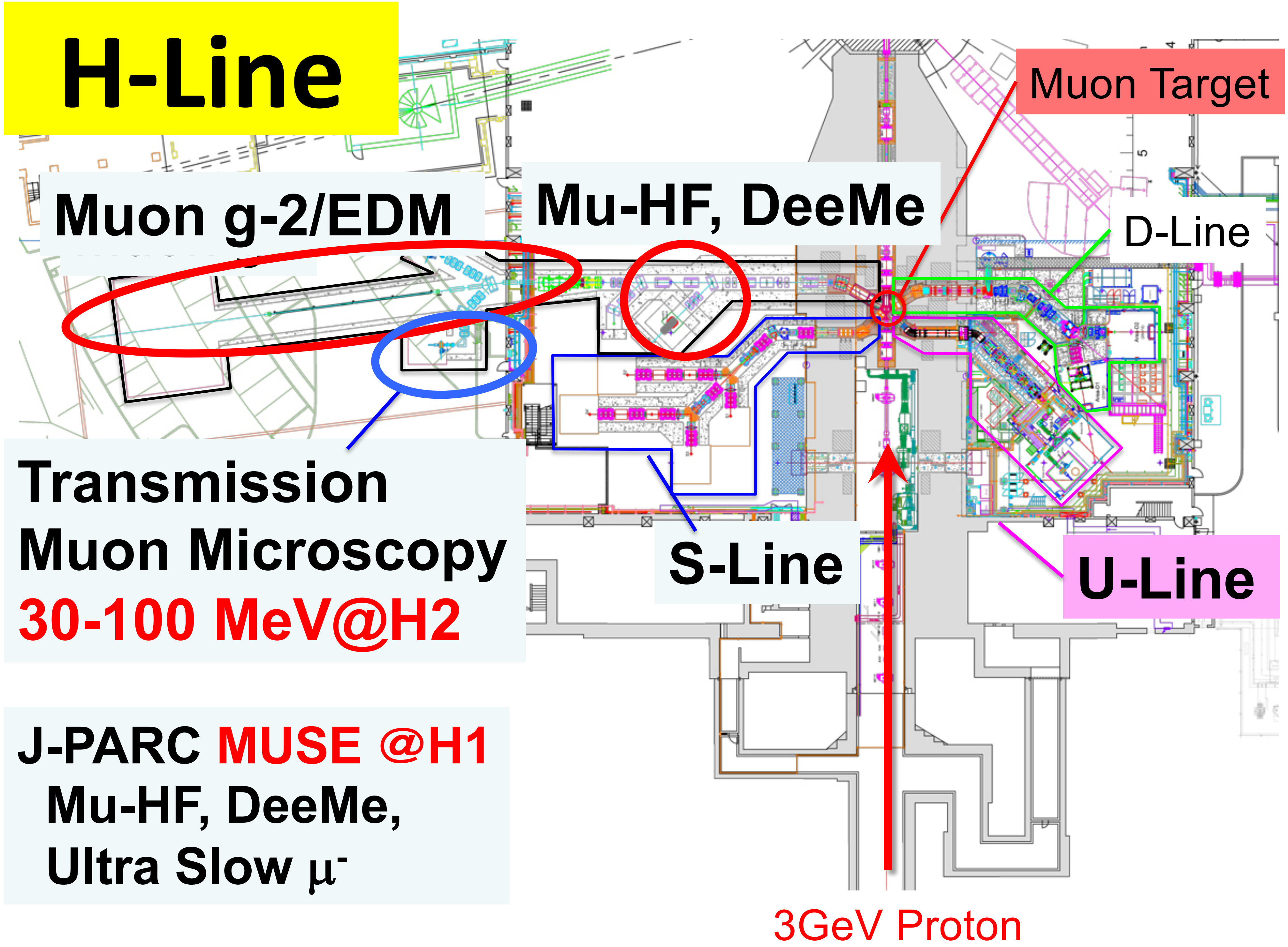
Dry-type superconducting magnet (max. 5T) cooled by 2 GM refrigerators.
3008ch. positron detectors consisting of 96 KALLIOPE modules.



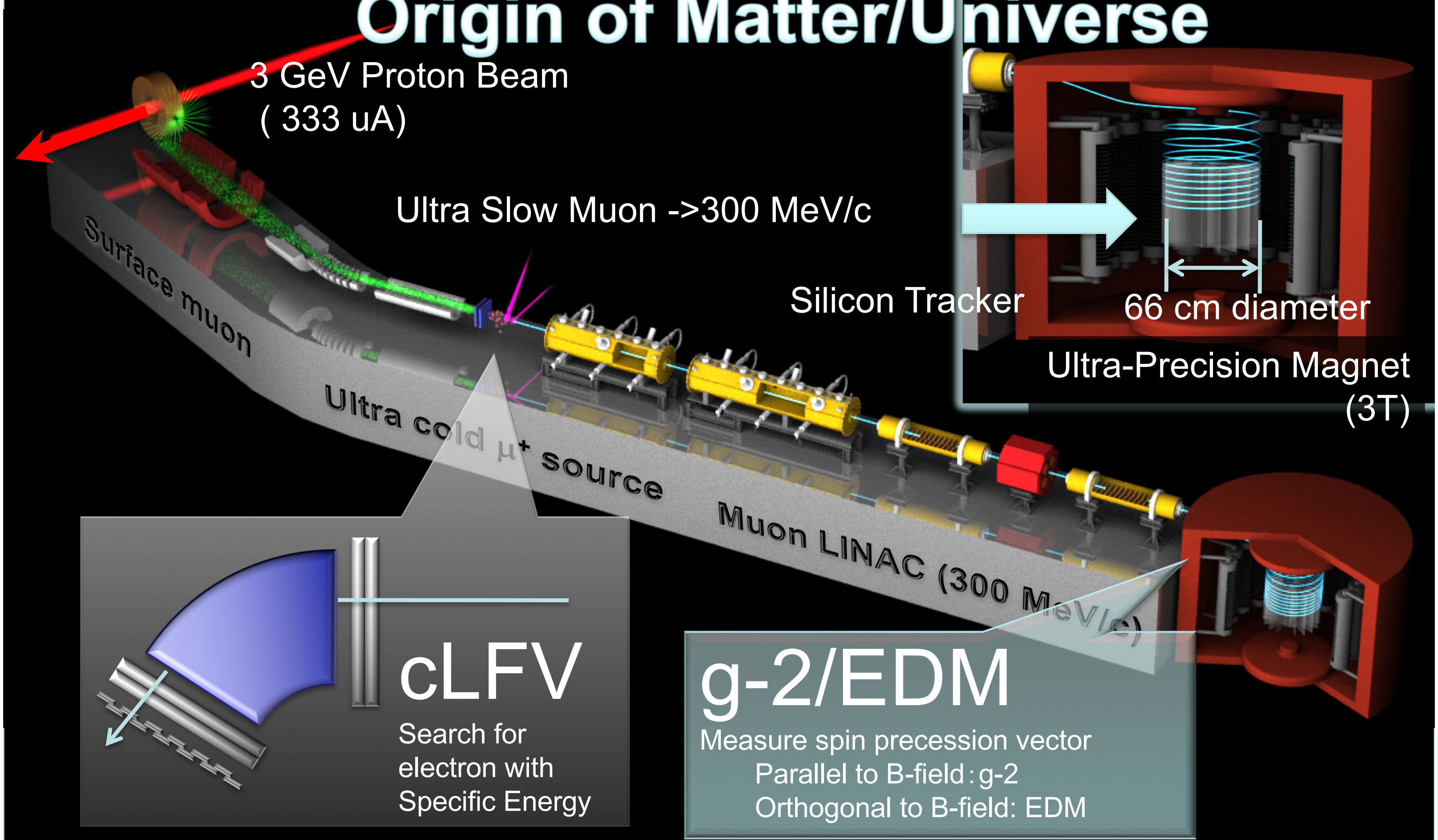




1x1 mm^2 scintillating fibers are aligned in a spiral to meet the e^+ track under high fields.


H-Line
Muon Target
Muon g-2/EDM
Mu-HF, DeeMe
D-Line
Transmission
Muon Microscopy
30-100 MeV@H2
S-Line
U-Line
J-PARC MUSE @H1
Mu-HF, DeeMe,
Ultra Slow μ-
3GeV Proton

High Intensity Muon Beam for
Space-time Symmetry and Origin of Matter/Universe

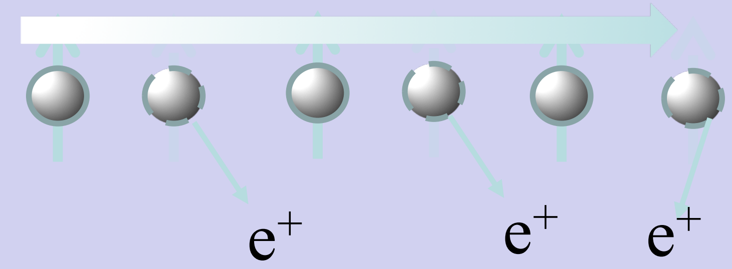


According to Prof. Saito, Iwasaki

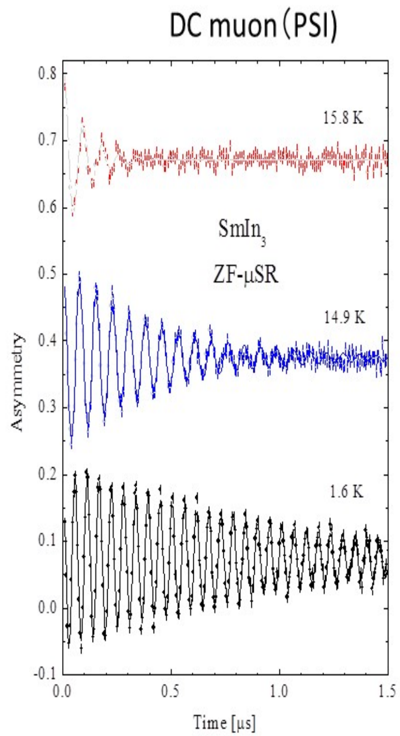
DC Muon vs. Pulsed Muon

DC Muon

Time



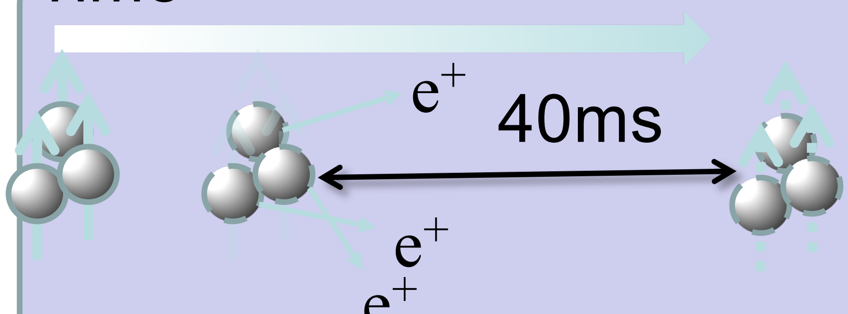
- **High time-resolution**
  - Fast relaxation/precession
- Defining-/Veto-Counter
  - Low BG
- Limited time window



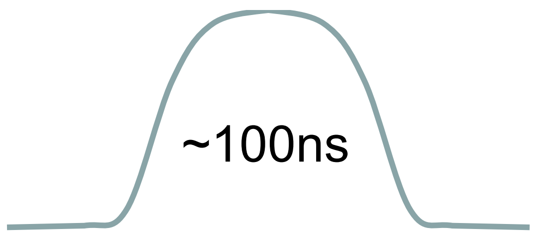
T.U.Ito, W.Higemoto et al.,
J. Phys. Soc. Jpn. 80 (2011) 033710

Pulsed Muon

Time



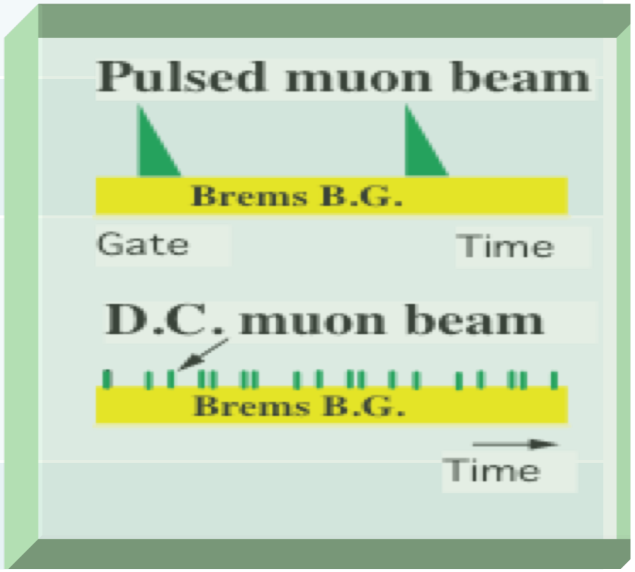
- Virtually unlimited time window
  - Slow relaxation
  - Fast fluctuation
- Pulsed condition



10^4-10^5 muon/pulse/1MW

DC Muon vs. Pulsed Muon *(Complementary probe)*

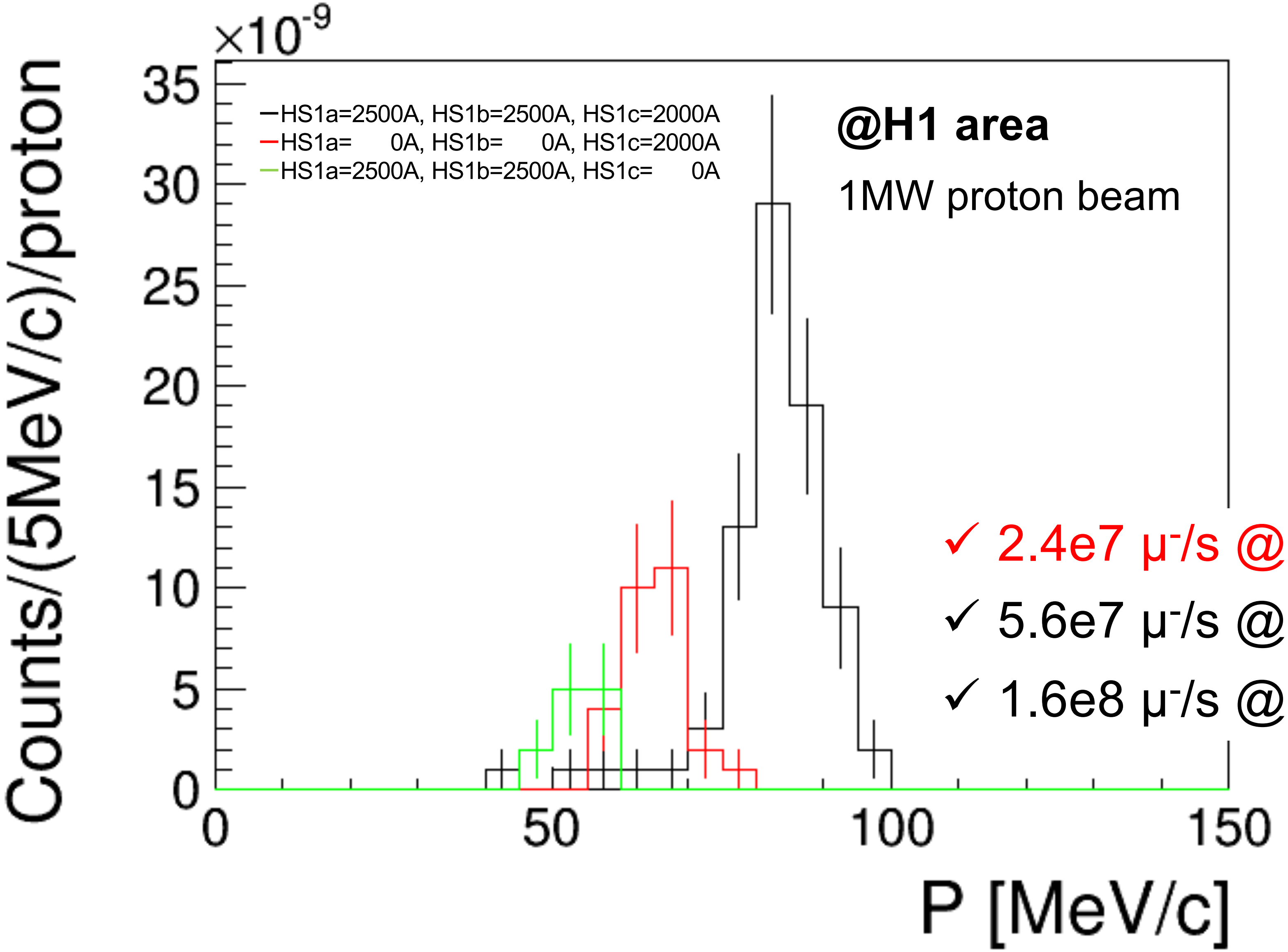
	DC muon	Pulsed muon
Time resolution	◎	×
Detectors	～10ch	Segmented (~1000ch)
Event by event	◎	△（pulse by pulse）
Slow relaxation	△	○
Beam Intensity	○	◎
Synchronization with perturbation	△	◎
DC BG	△	○



Summary

- D-Line, Operating User's Runs
  - μ^+SR
  - μ^-SR
  - μ^- Non-destructive analysis
- U-Line, Under commissioning,
  - nm-μ^+ SR, 100 eV - 30 keV
  - Transmission Muon Microscopy
- S-Line, Operating User's Runs
  - μ^+SR @S1
  - Mu, 1s-2s precision measurement@S2
- H-Line,
  - Fundamental physics(g-2/EDM, DeeMe, Mu-HF etc.!)
  - Transmission Muon Microscopy

Negative muon beam @H-line



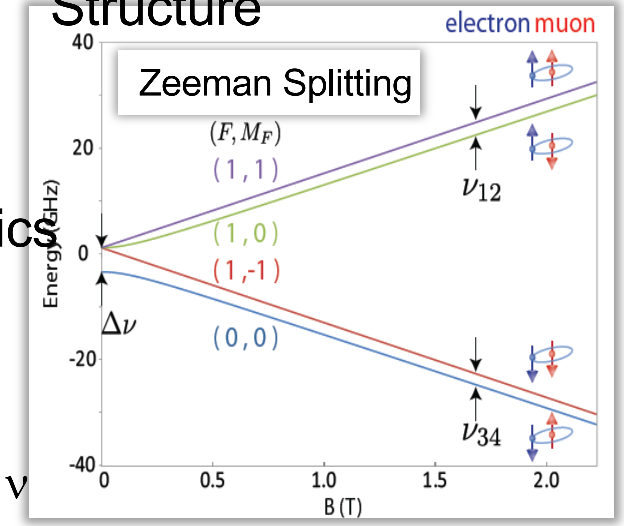
- ✓ 2.4e7 μ^-/s @54MeV/c
- ✓ 5.6e7 μ^-/s @65MeV/c
- ✓ 1.6e8 μ^-/s @82MeV/c

2011MS-01 Precise Measurement of Mu HFS and magnetic moment

@H1

- Most precise check of bound QED
- Most precise measurement of muon mass and magnetic moment
  →Basic parameter for fundamental physics
  g-2, $\mu^{-}p$ Lamb shift
- Exotic particle Search
- Search of Lorentz and CPT symmetry breaking

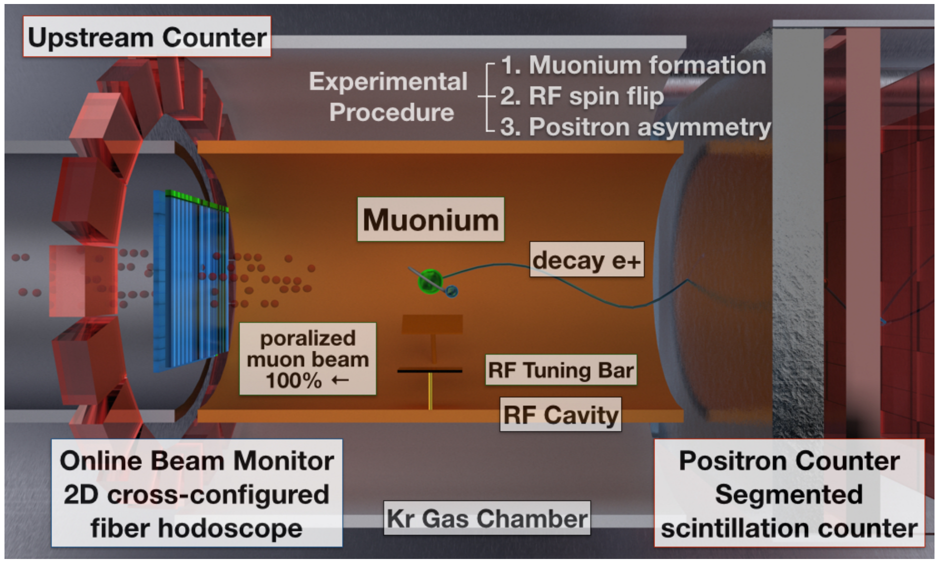
$h\Delta\nu_{HFS}$: Mu Hyperfine Structure



$\nu_{12}+\nu_{34}=\Delta\nu_{HFS}$

$\nu_{12}-\nu_{34} \propto \mu_\mu/\mu_p$

To improve the previous measurement at LAMPF, Intense pulsed muon beam (10^8/S) is necessary. H line is a unique beam line in the world for this measurement !



$\Delta\nu$ **12ppb→2ppb**

μ_μ/μ_p **120ppb→20ppb**

2011MS-03 μ-e Conversion Search: DeeMe

@H1

$$\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)$$

Forbidden in the Standard Model of particle physics

- Observation ⬄ Clear Proof of physics beyond the SM
- Hints to: neutrino oscillation, matter-antimatter asymmetry
- Current upper bounds(TRIUMF, SINDRUM-II@PSI)
  - BR[μ^- Ti→ e^- Ti] < 4.3 × 10^{-12}, BR[μ^- Au→ e^- Au] < 7 × 10^{-13}
- Theoretical Predictions: BR = 10^{-13}~10^{-16}

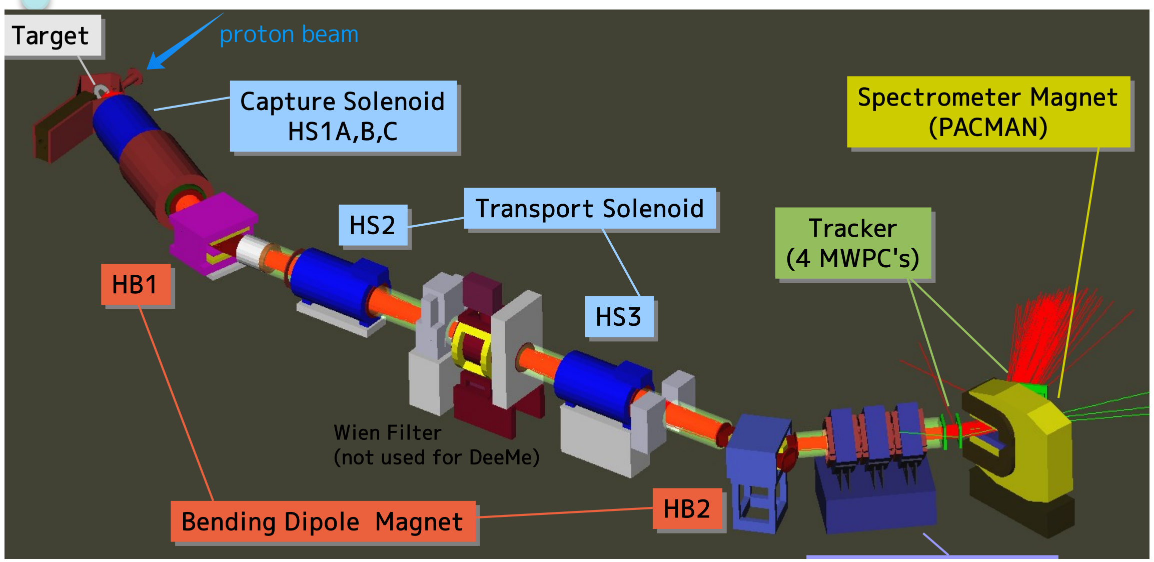
GO $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$

	μ^-		e^-	ν_μ	$\bar{\nu}_e$	
L_μ	1		0	1	0	$\Delta L_\mu = 0$
L_e	0		1	0	-1	$\Delta l_e = 0$

$\mu^- A \rightarrow e^- A$

	μ^-	A		e^-	A	
L_μ	1	0		0	0	$\Delta L_\mu = -1 \neq 0$
L_e	0	0		1	0	$\Delta l_e = +1 \neq 0$

<u>DeeMe</u>: unique idea utilizing J-PARC features
Update the sensitivity by more than 10 to find a signal.



- Utilize high-power high-purity pulsed proton beam from RCS.
- Make use of a generic muon beam line.
- No beam-time conflicts with T2K and Hadron-Hall programs.
- Diversity: different method from COMET and Mu2E
- It is critically important to utilize J-PARC as much as possible

2014MS04 Measurement of the proton radius from the hype @H1 splitting energy in the ground-state muonic hydrogen

Proton radius puzzle

From Lamb shift (2s-2p energy) of muonic hydrogen (PSI 2010)

Proton charge radius was smaller by 7 sigma from other measure

New proposal

Determine **proton magnetic radius** using muon spin

Method : measure **hyperfine splitting energy** of muonic hydroge

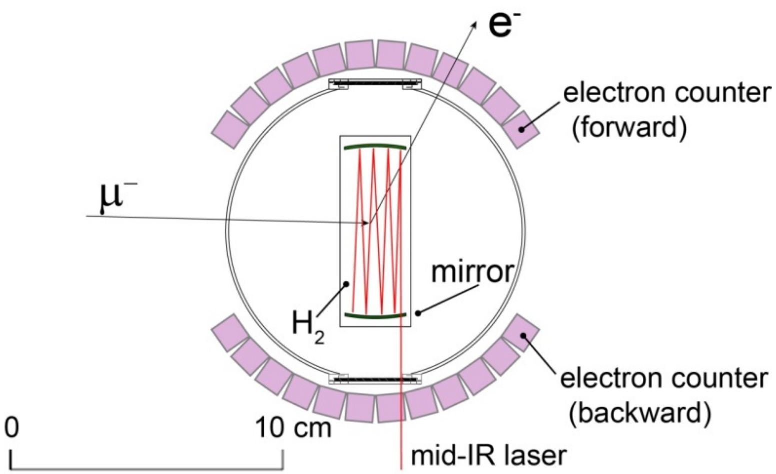
laser resonant pumping of polarized spin state

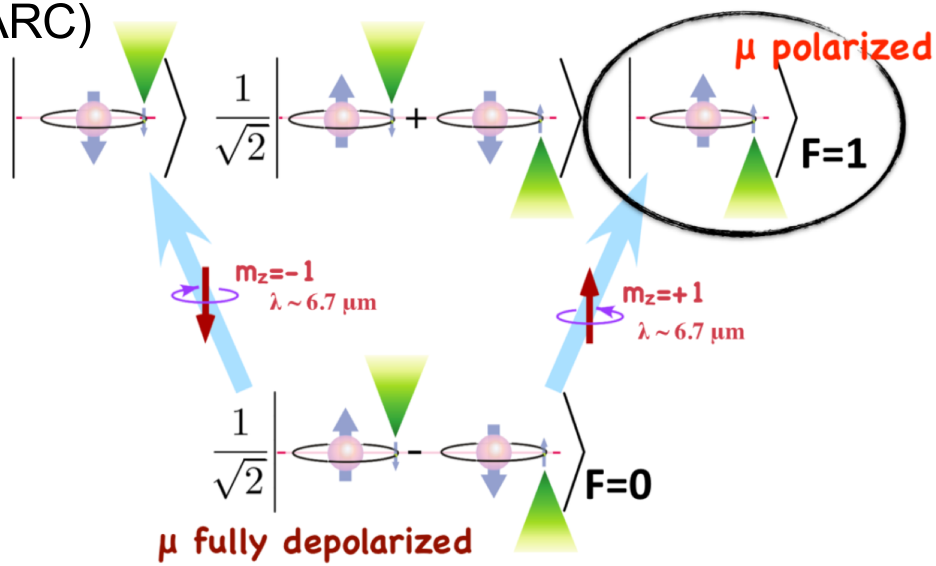
and probe with muon decay

Keys:

High power 6.7 μm infra-red laser and Hydrogen target system (by RIKEN)

High intensity negative muon beam (J-PARC)





Motivation of Mu Laser Experiment at S2-area

- **Present uncertainty of muon mass limits theoretical 1S-HFS frequency**

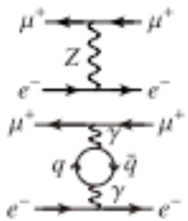
m_μ
mass uncertainty
$u_r[m_\mu] = 120$ ppb (exp)

→

Uncertainty in transition frequency of Muonium
$u[\Delta\nu_{\text{1S-HFS}}]_{\text{theo.}}$ 515 Hz

$$\Delta\nu_{\text{1S-HFS}} \simeq \frac{16}{3}\alpha^2 R_\infty \frac{\mu_\mu}{\mu_B}\left(1+\frac{m_e}{m_\mu}\right)^{-3}$$

Theoretical prediction of frequency shift in $\Delta\nu_{\text{1S-HFS}}$



Electroweak: -65 Hz
Hadronic: 232.7 Hz

- Electroweak and Hadronic contribution has been predicted and they are sufficiently large to observe the actual experiment
- However, they cannot be evaluated under the present u_{theo} of 515 Hz
  → Reduce the mass uncertainty is very important

- $u_r[m_\mu]$ **can be reduced by precise measurement of 1S-2S transition frequency**
  - Since the reduced mass contribution is large, the mass can be determined precisely from the precise $\Delta\nu_{\text{1S2S}}$ measurement

e.g. $u[\Delta\nu_{\text{1S2S}}]_{\text{exp.}} = 10$ kHz → $u_r[m_\mu]_{\text{exp.}} =$ **1 ppb**

$$\Delta\nu_{\text{1S2S}} \simeq \frac{3\alpha^2}{8h} m_e c^2 \left(1+\frac{m_e}{m_\mu}\right)^{-1}$$

Reduced mass contribution: 0.48%