For Project X muSR forum at Fermilab Oct 17th-19th, **2012**

J-PARC MLF MUSE
muon beams

J-PARC MLF Muon Section/KEK IMSS

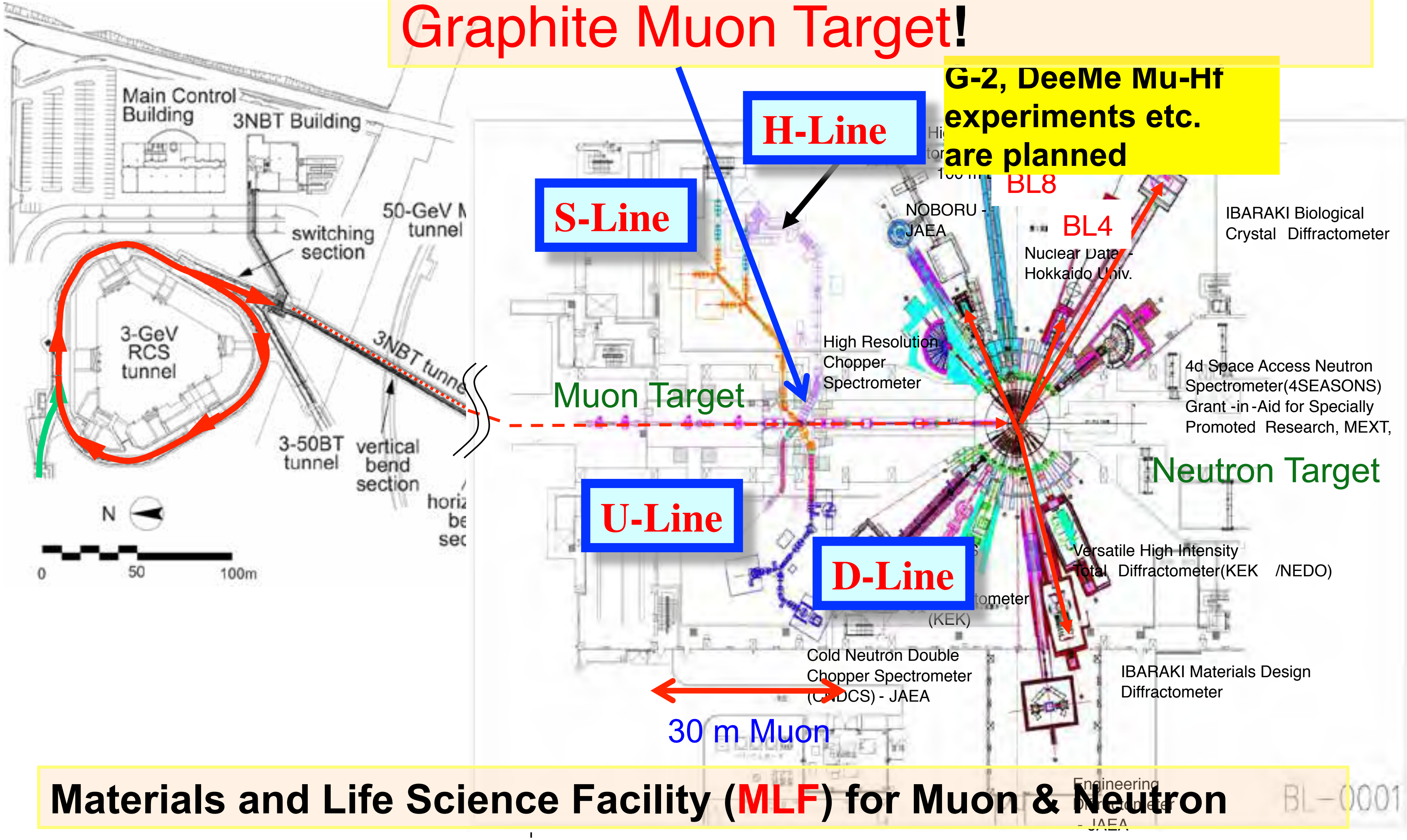
Yasuhiro Miyake

• D-Line	*In operation*
• U-Line	*Commissioning started!*
• S-Line	*Partially constructed!*
• H-Line	*Partially constructed!*

Proton Beam Transport from 3GeV RCS to MLF

On the way, towards neutron source

Graphite Muon Target!



G-2, DeeMe Mu-Hf experiments etc. are planned

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

Edge-cooling Graphite Fixed Target

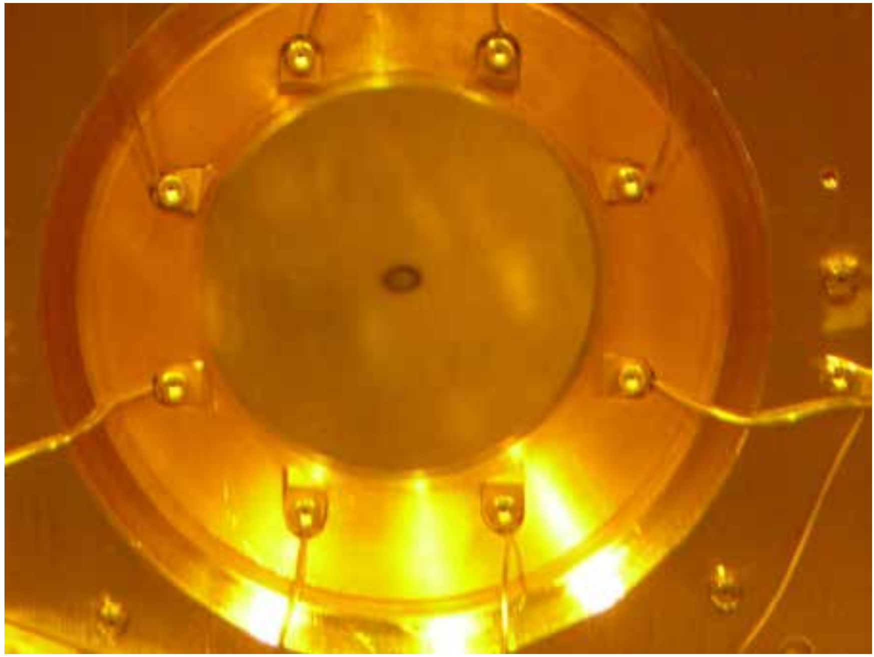
→

Rotating Graphite Target From January 2014!

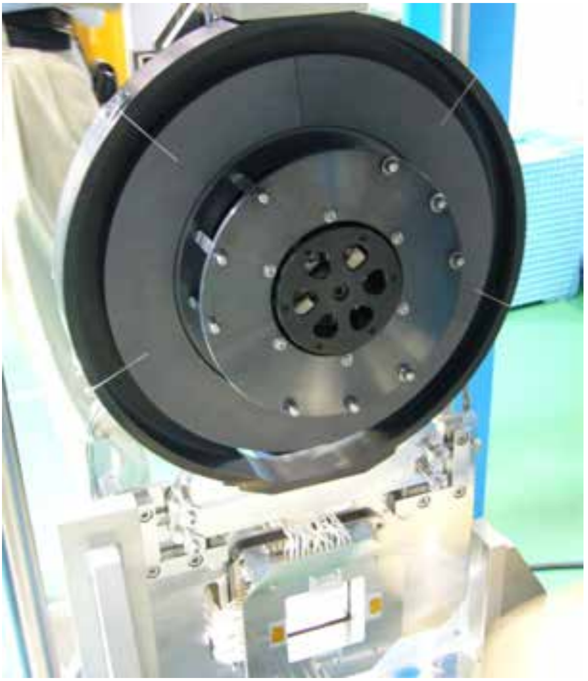
At Present!

Will be changed in Summer 2013!

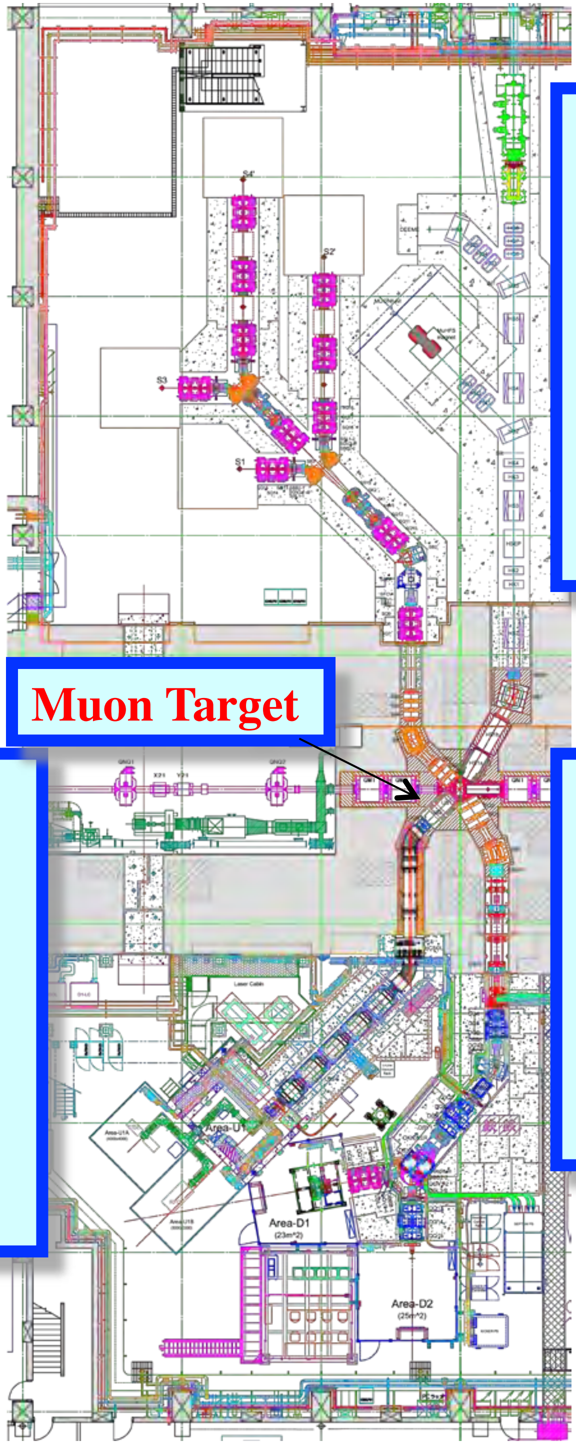
Investigated during shut-down!



Fixed Target



Rotating Target



S-Line

Surface μ^+(30 MeV/c)
For material sciences

H-Line

Surface μ^+ For HF, g-2 exp.
e^- up to 120 MeV/c For DeeMe
μ^- up to 120 MeV/c For μCF

Muon Target

U-Line

Ultra Slow μ^+(0.05-30keV)
For multi-layered thin foils, nano-materials, catalysis, etc

D-Line

Surface μ^+(30 MeV/c)
Decay μ^+/μ^-(up to 120 MeV/c)

Users' RUN, in Operation

MUSE

D-Line, since Sep., 2008

[The world-most intense pulsed muon beam achieved at J-PARC MUSE]

At the J-PARC Muon Facility (MUSE), the intensity of the pulsed surface muon beam was recorded to be 1.8 x 10^6/s on November 2009, which was produced by a primary proton beam at a corresponding power of **120 kW** delivered from the Rapid Cycle Synchrotron (RCS). The figure surpassed that obtained at the Muon facility of Rutherford Appleton Laboratory in the UK, pushing MUSE to the world frontier of muon science. It also means that the unprecedentedly high muon flux of 1.5 x 10^7/s (surface muons) will be achieved at MUSE when the RCS proton beam power reaches the designed value of 1 MW within a few years

（第3種郵便物認可）　2010年(平成22年)3月16日（火曜日）　讀賣新聞

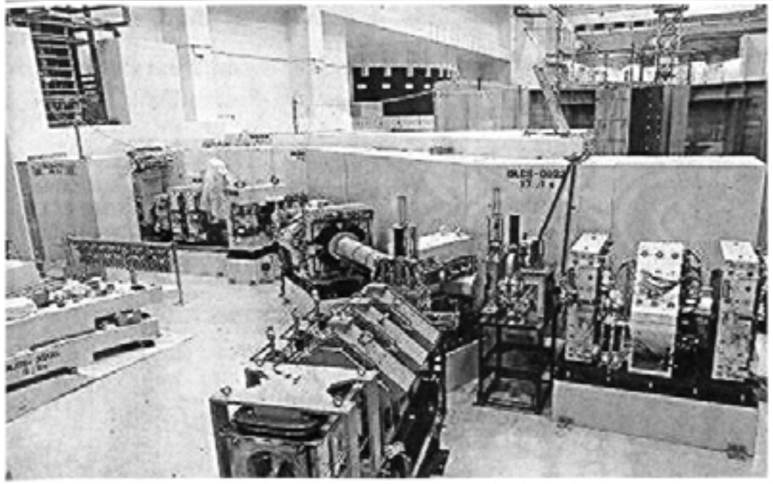
世界最高出力を達成

J—PARC「ミューオン」発生装置

東海村の大強度陽子加速器施設（J—PARC）物質・生命科学実験施設で、物質の微細な構造の測定などに使うミューオンの発生装置が昨年暮れ、世界最高の出力を達成していたことが、施設を運営するJ—PARCセンターの計測で分かった。

ミューオンは、光速近くまで加速した陽子を黒鉛に衝突させると発生する素粒子。磁気に敏感に反応するため、物質に当てることで、その物質内部の磁気がどうなっているかや、物質中に含まれる水素の状態などを、極めて高い精度で測定できる。新しい磁性材料をはじめ、超電導素材、燃料電池の材料開発などに威力を発揮すると期待されている。

ミューオンは断続的に発生するが、1回あたりの計測値は7万2000個に達しており、英国にある発生装置の2倍以上。高い効率での測定ができる。陽子加速器の出力を上げれば、同18万個のミューオンが得られることも確認。世界最高レベルの計測装置として、基礎科学や産業分野まで、幅広い利用が進みそうだ。



世界最高強度のミューオン発生が確認されたＪ—ＰＡＲＣの実験施設。左から延びるのがミューオンの通り道だ（Ｊ—ＰＡＲＣセンター提供。建設中の撮影）

We achieved World strongest pulsed surface muon beam at J-PARC MUSE D1&D2 area even with 120 kW intensity. on November,10th 2009

科学新聞

22年4月2日朝・夕
第　版6頁

世界最高強度 ミュオン発生

J—PARC 実験で成功

ミュオン（ミュー粒子）は、湯川秀樹博士がその存在を予言したパイ中間子が崩壊してできる不安定素粒子。大強度陽子加速器施設（J—PARC、茨城県東海村）では、昨年12月10日に試験的に行った陽子ビーム高出力運転において、物質・生命科学実験施設（MLF）に設置したミュオン実験装置で発生したミュオン数を実測した結果、世界最高強度のパルスミュオンが発生していることを確認した。

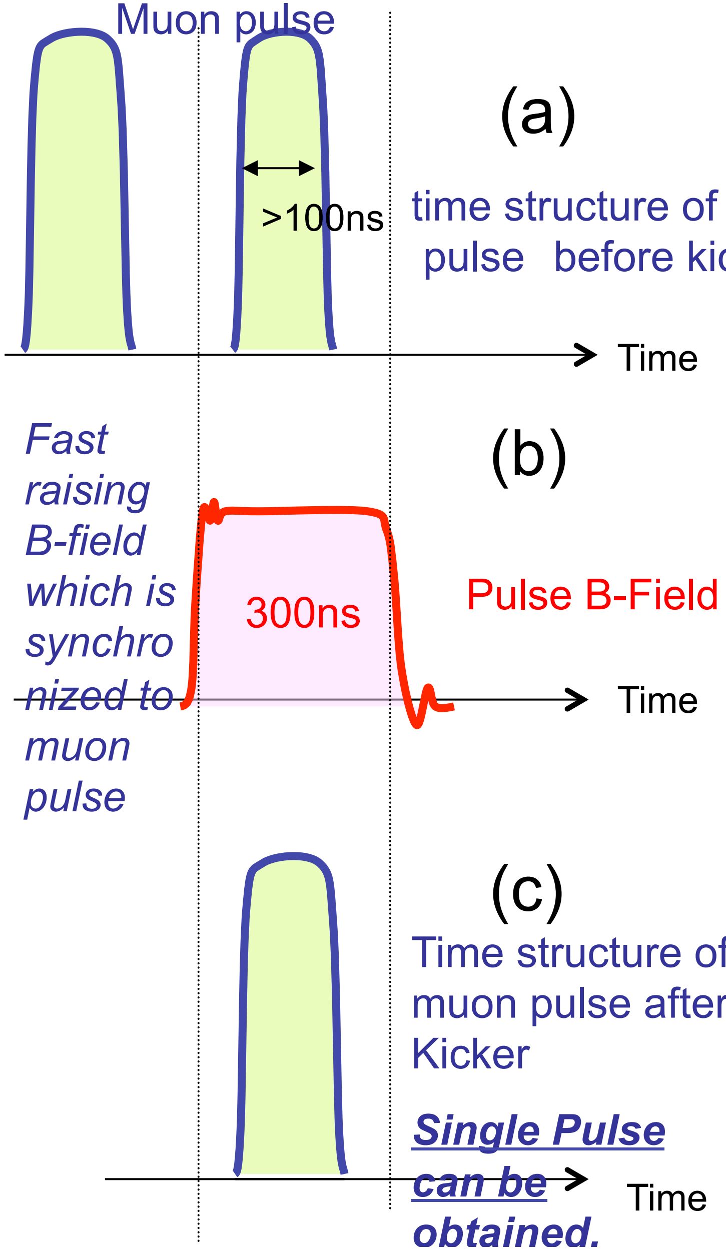
10日の運転では陽子ビーム出力を300キロワットに上昇させ、ミュオン装置に導き、高強度パルスミュオンの発生を行うとともに、陽子ビームの120キロワットでの定常運転を実施した。その際、検出器を用いてミュオン数を実測したところ、1パルス当たり7万2000個のミュオンが実験エリアに飛来してきていることが確認できたとしている。また300キロワット運転時では約18万個のミュオン強度が得られた。これは英国の同種のミュオン源で得られた1パルス当たり約3万個を上回る、世界最高強度パルスミュオンの発生となった。

今後、陽子加速器の一層の高出力化のための整備・調整を進め、1メガワットにまで上昇させる計画で、これによりさらなるミュオン強度の上昇が見込まれている。

高強度のパルスミュオン発生により、物性物理学や原子分子物理学の基礎研究がより加速すると同時に、磁性材料、超伝導材料、燃料電池などの環境技術につながる研究開発をはじめとする応用分野への利用が期待される。

$\mu^{\pm}$

Muon Kicker System



(a)

time structure of muon pulse before kicker

(b)

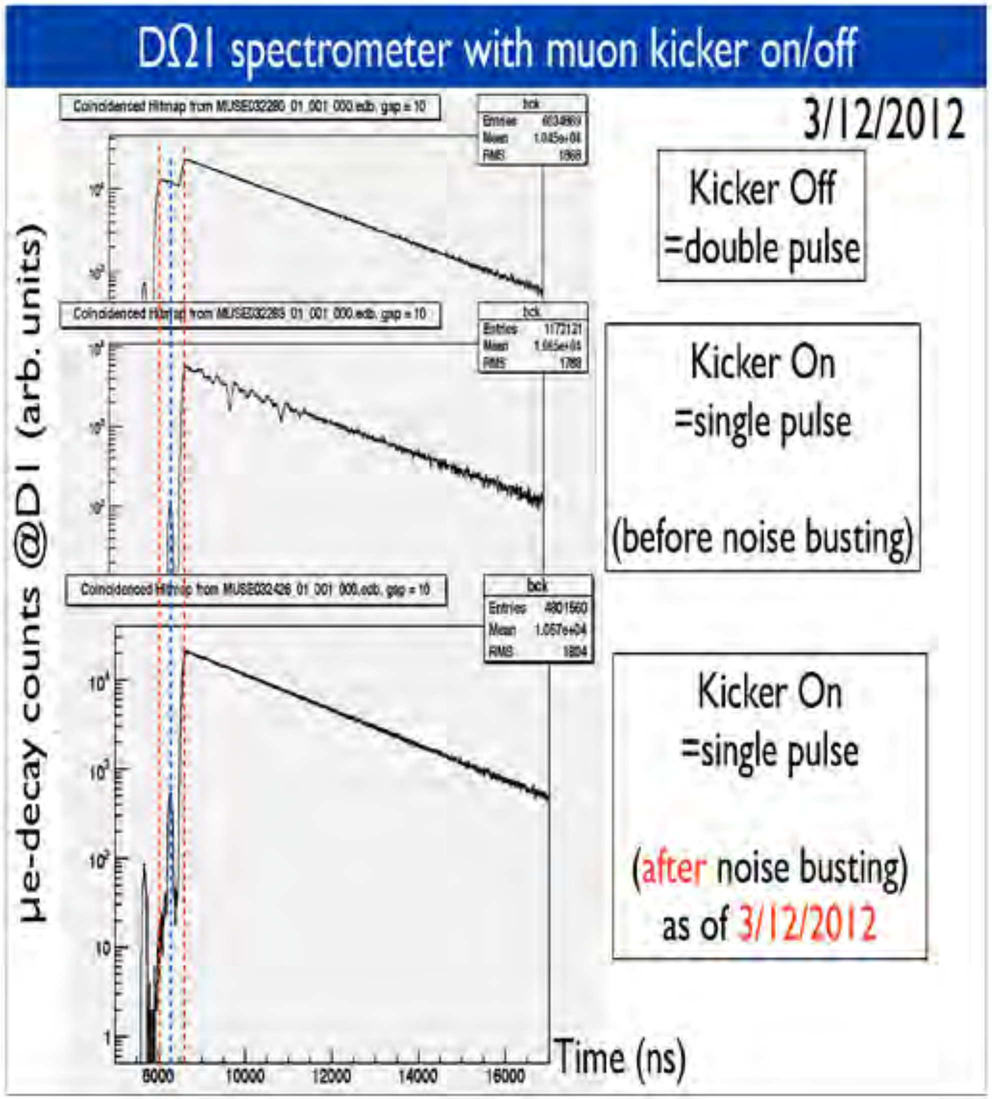
Fast raising B-field which is synchronized to muon pulse

Pulse B-Field

(c)

Time structure of muon pulse after Kicker

Single Pulse can be obtained.



DΩ1 spectrometer with muon kicker on/off

3/12/2012

Kicker Off
=double pulse

Kicker On
=single pulse

(before noise busting)

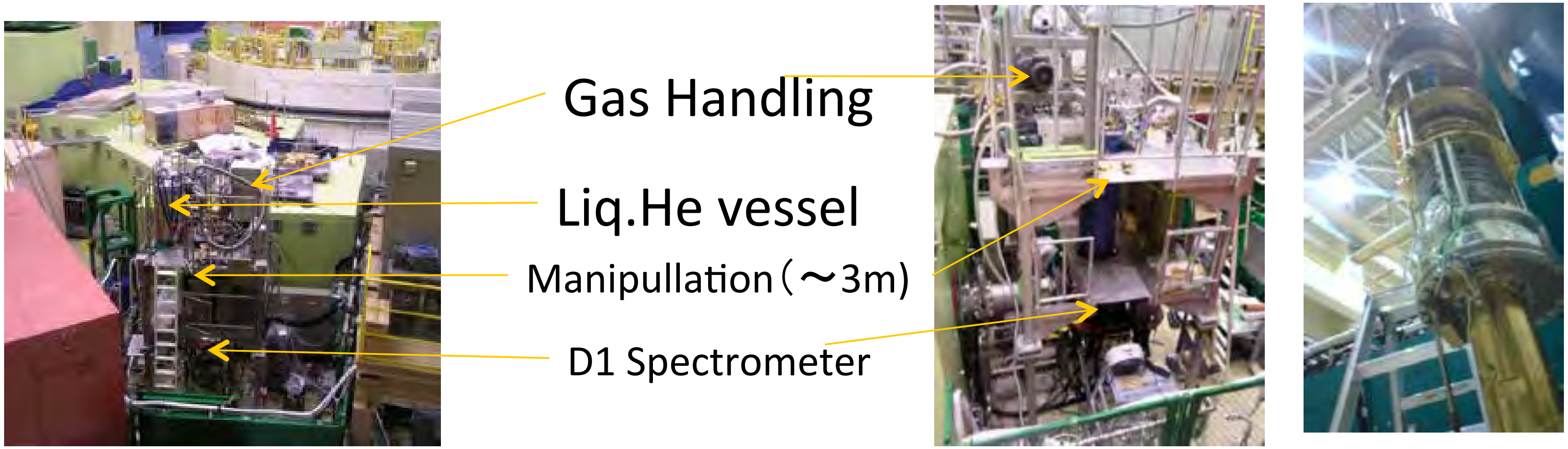
Kicker On
=single pulse

(after noise busting)
as of 3/12/2012

μ^+

Top loading Dilution Refrigerator

- Brought from KEK-MSL
- 25mK was achieved at D1 area on 4/30.
- It takes 3 days until achieving the lowest temperature.
- It takes 8-12 hours to exchange a sample.

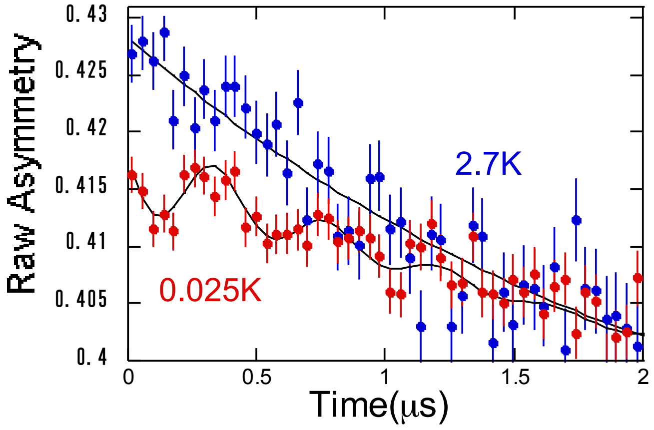


Gas Handling

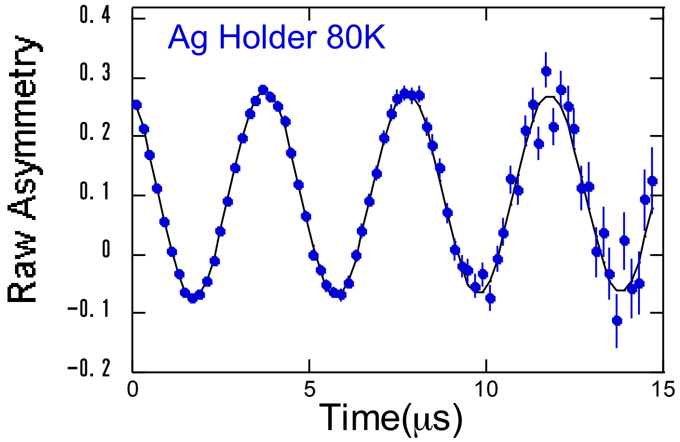
Liq.He vessel

Manipullation（～3m)

D1 Spectrometer



低温における4f電子系の磁気秩序の観測

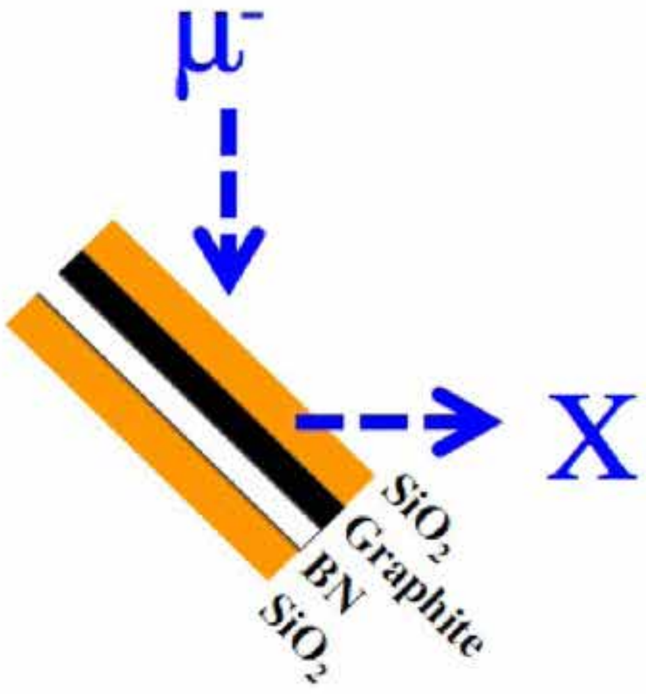


試料ホルダーのみ

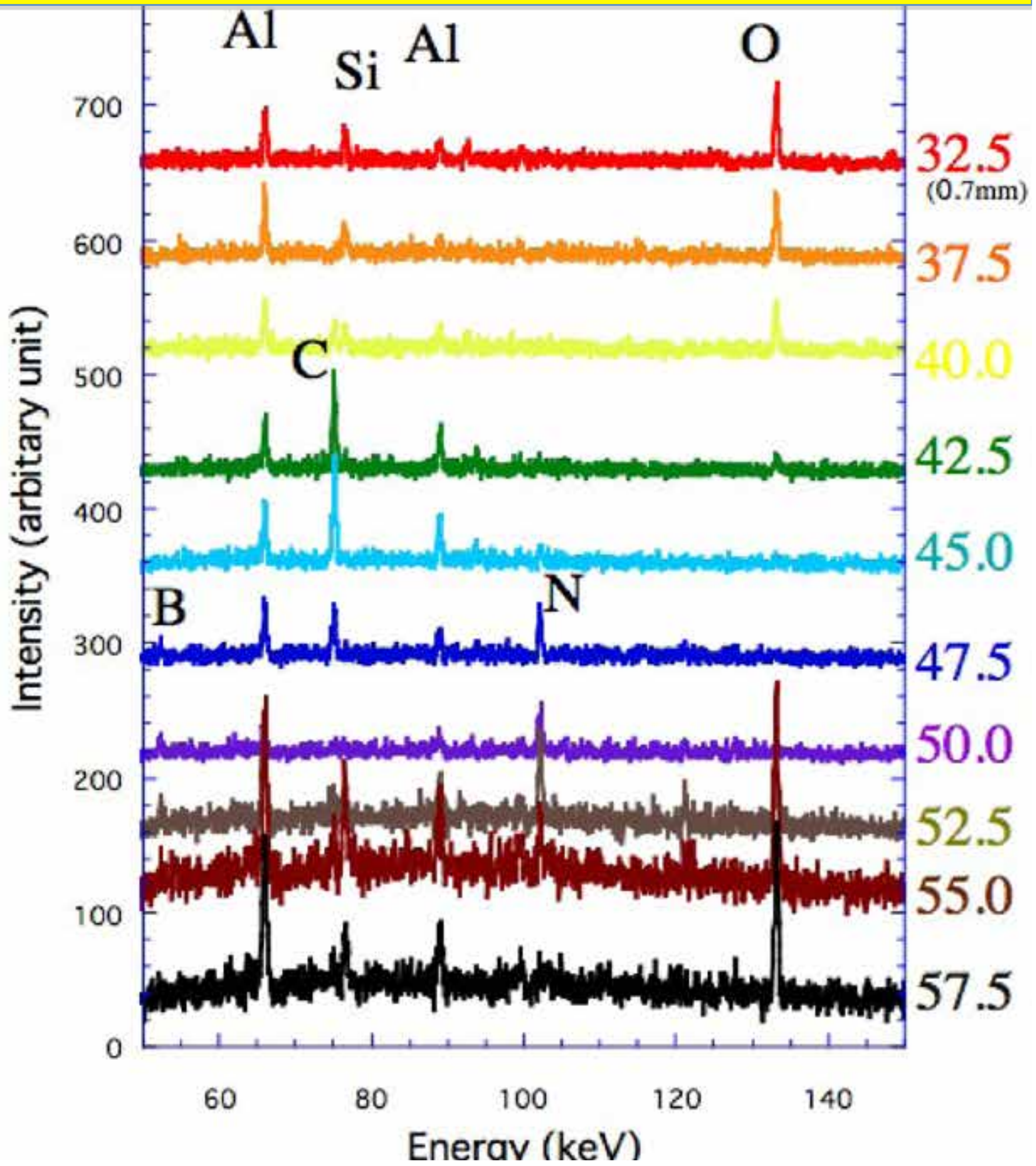
μ^-

Non-destructive analysis of Meteorite

Terada et al.



		thickness × √2
1st layer	SiO2	2.115
2nd layer	graphite	3.5391
3rdlayer	BN	5.3439
4th layer	SiO2	7.4166



D-Line

Studies explored at MUSE **D-Line**

Either Surface muon (μ^+) or Decay muon (μ^+/μ^-up to 120 MeV/c) available!

1. Solid State Physics（Magnetism・Superconductor）
    1. *μSR Study of Organic Antiferromagnet β'-(BEDT-TTF)$_2$IBrCl*
    2. μSR in Ironpnictide superconducto *Phys. Rev. Lett.* ***103*** *027002*←The first PRL @J-PARC
    3. μSR evidence for magnetic ordering in $CeRu_2Al_{10}$ *J. Phys. Soc. Jpn. At May, 2010*
    4. **novel phase transition in f-electron system - high-order “multipole” ordering**

    Phys.Rev. B 82, 014420 (2010),Phys. Rev. B 84, 064411 (2011).J.Phys.Soc.Jpn.80(2011)SA075,J. Phys. Soc. Jpn. 80, 113703 (2011). ,J. Phys. Soc. Jpn. 80, 033710 (2011).

    1. **Ba_2IrO_4: A novel spin-orbit Mott insulating quasi-2D antiferromagnet,**
        Phys.Rev. B83, 155118 (2011)
2. Material Science（Li Batteries、Alloy、Voids）
    1. Li_xCoO_2（Toyota）*Phys.Rev. B 82,224412 (2010), Phys.Rev. B84 054430 (2011)*
    2. **$CaFe_2O_4$-type $NaMn_2O_4$ and $LiMn_2O_4$**
    3. Li Diffusion in Li ion conductor
    4. Pre-martensitic phenomena of thermo elastic martensitic transformation in NiTi alloys studied by muon
    5. **μSR in Finemet → contribution towards J-PARC accelerator!**
3. Physical CHemistry
    1. Investigation of molecular effect in the formation process of muonic atom
    2. Mu(μ^+e^-) formation mechanism in condensed matters
4. Particle Physics
    1. $\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)$ rare decay
5. Non-destructive analysis, Radiography
    1. **Koban, Old coin** *J. Phys.: Conf. Ser.s 225 (2010) 012040* , Bull. Chem. Soc. Jpn. Bull. Chem. Soc. Jpn.(2012)
    2. **Muon Radiography**
6. Beam Development
    1. Slicer *J. Phys.: Conf. Ser. 225 012012(2010)*
    2. Ultra Slow Muon

U-Line

Dedicated to Ultra Slow Muon

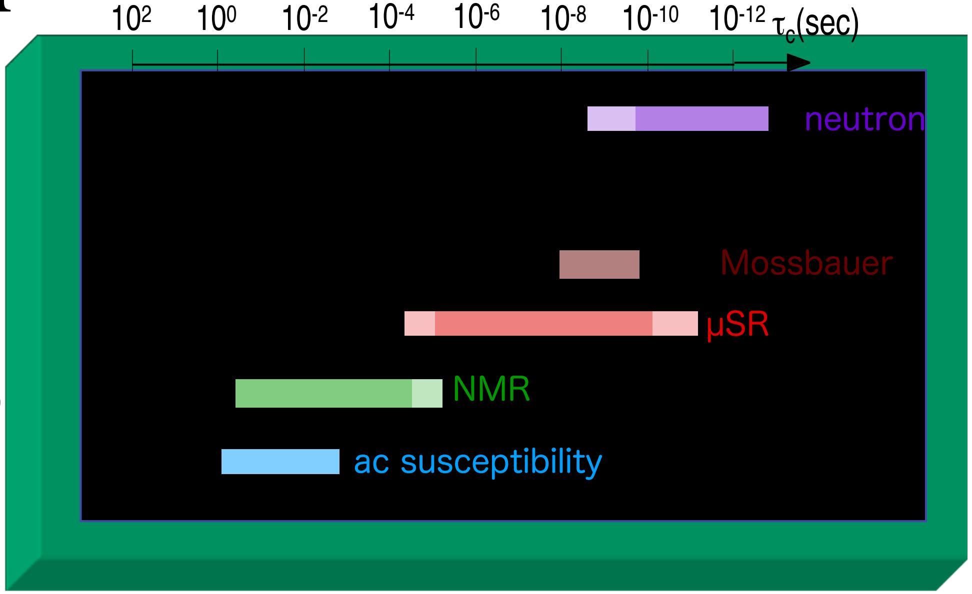
more than 10 times intense than D-Line

First goal of U-Line:
Surface muon source that produce Ultra Slow muon
(E= 0.05 eV – 30 keV) with high intensity and
high luminosity.

Motivation

Positive Muons (μ^+) very powerful tool

- As a probe for
  microscopic magnetism
- As a light isotope of H, D and
  T, its Diffusion and Reaction
- Specific Time Scale (μs order)



Strong Requirement for *Ultra Slow Muon Source*

- Study Nano-science(Interfaces or multi-layered film)
- Surface Chemistry-Catalysis on nano-particle

Cooling techniques to obtain *Slow Muon* Beam

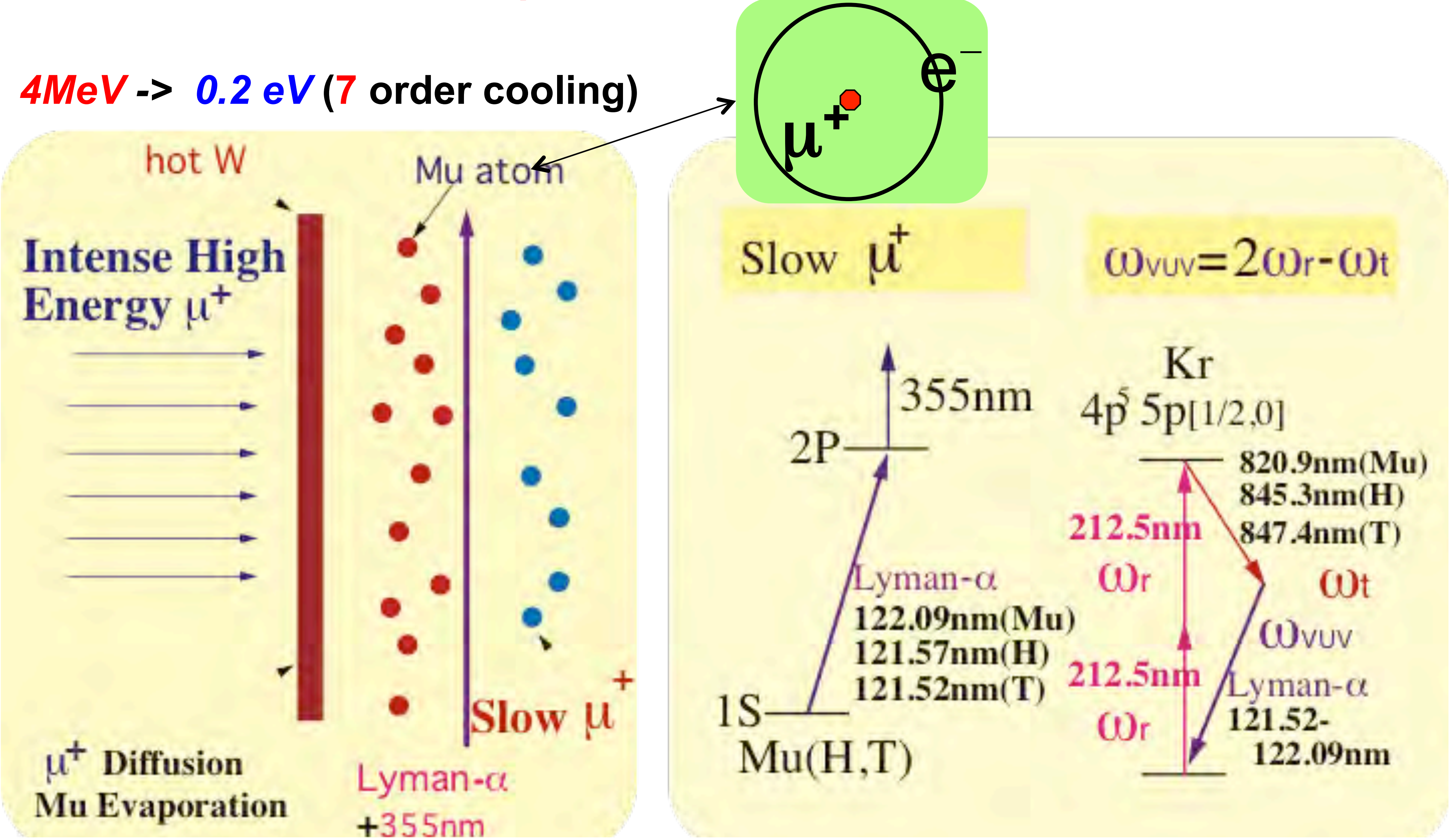
- *Slowing down through solid Ar or N_2 at PSI*
- *Laser Resonant Ionization of Mu at KEK, RIKEN-RAL&J-PARC*

Concept of ultra slow μ^+ generation by laser resonant ionization of thermal Mu from hot tungsten

Can be realized by synchronizing intense pulsed muon and pulsed laser

J-PARC MUSE ***(pulsed muon*** **source)** ***CAN MAKE IT !***

4MeV **->** ***0.2 eV*** **(7 order cooling)**



Ultra-slow Muon HISTORY

STEP1: Production of Thermal Muonium in vacuum (~*1985*) by Mills, Imazato, Nagamine et al. & Matsushita, Nagamine(Pt)

STEP2: Resonant Ionization of thermal Muonium by 1s-2s excitation(~*1987*)（QED confirmation） By Chu, Mills, Kuga, Yodh, Miyake, Nagamine et al.

STEP3: Ultra-slow Muon Project @KEK (*1990-1998*) by Miyake, Shimomura, Birrer Nagamine, et al.

STEP4: Ultra-slow Muon Project @理研RAL (*1999~*) by Bakule, Matsuda, Miyake, Shimomura, Nagamine et al.

STEP5: High-intensity Ultra-slow Muon @J-PARC (*2010-*） *Present project*

STEP 2 Thermal Mu1s-2s resonant excitation

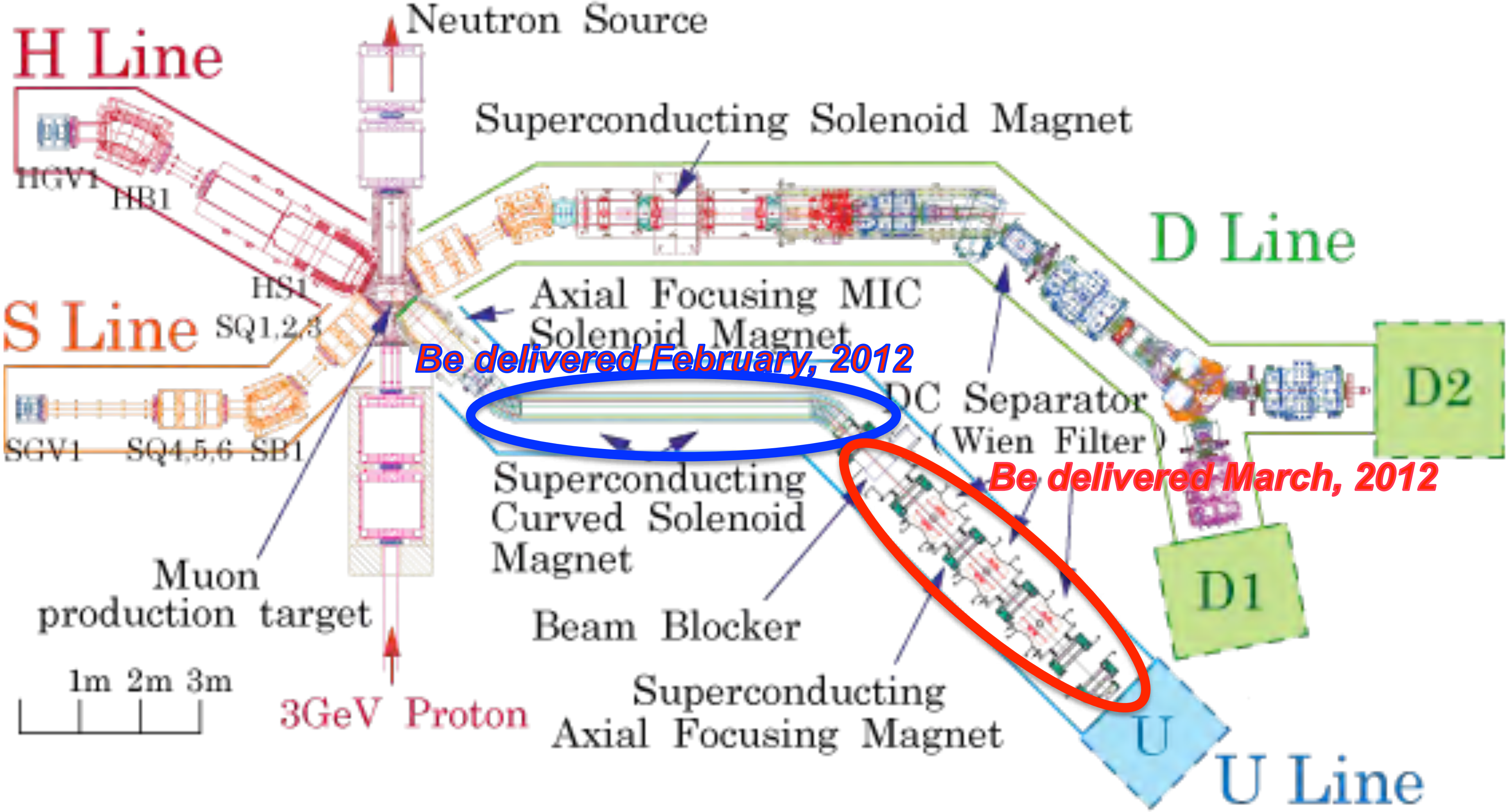
- **The first successful extraction of Ultra-slow Muon！**
- **consistent with QED expectation within 300MHz**

By S. Chu, Nobel prize (1997). Now Secretary of US-DOE.

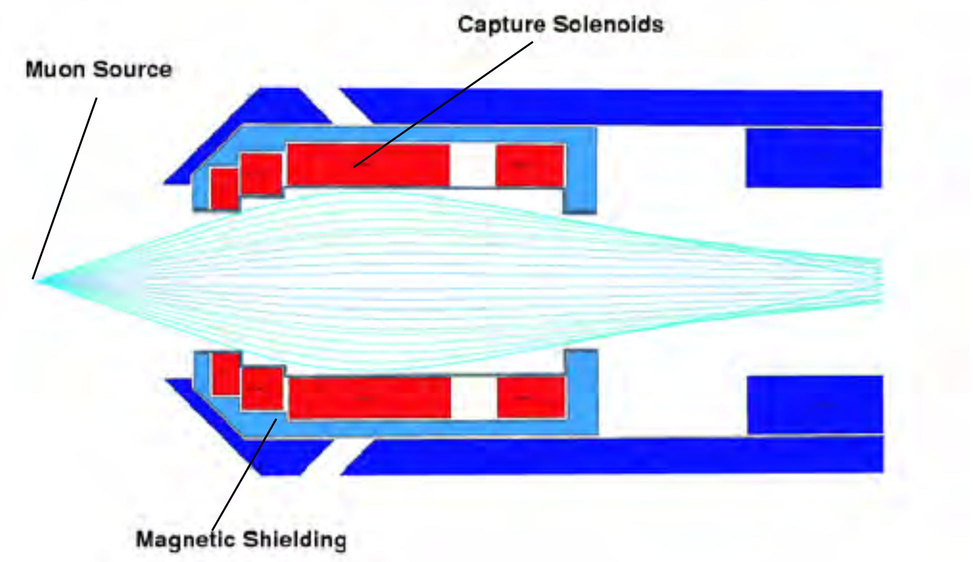
U-Line

5.0 x 10^8 /s surface muons, 20 times more intense than D-line which is the strongest at present!

Dedicated beam line to produce Ultra Slow muon (E= 0.05 – 30 keV) with high intensity and high luminosity.



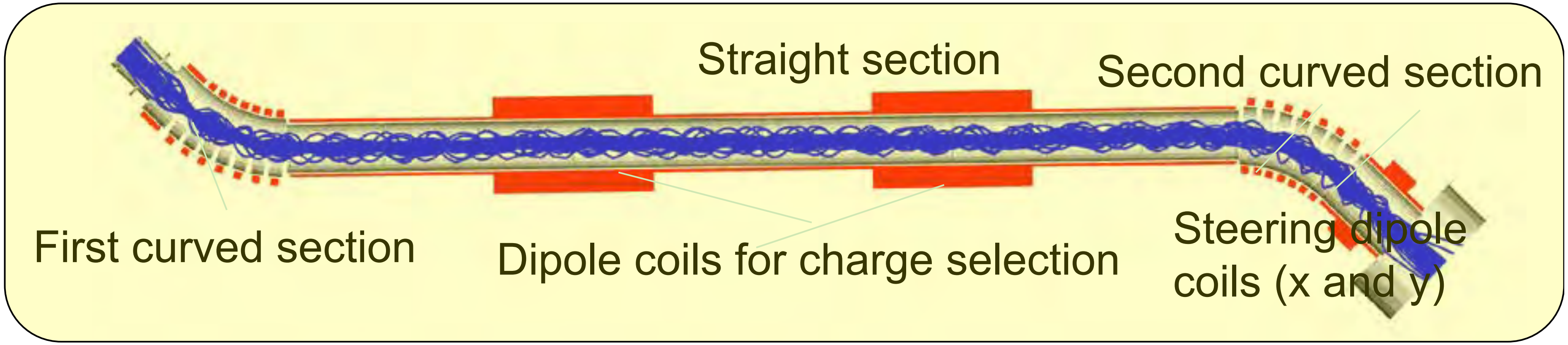
Normal Conducting MIC Capture Solenoid



Maximum current	1500A
Peak central field	0.3T
Coolant	130 l/s
Muon capture rate	$5\times10^{8}\ \mu^{+}$/s @ 30 MeV/c
Solid angle acceptance	400 mSr (±20^{o} initial angle, ~10 times larger)

Due to the high level of exposure to radiation, the solenoids are wound with radiation-resistant mineral insulation cables(MIC).

Superconducting Curved Transport Solenoid under fabrication @Toshiba deep collaboration with KEK cryogenic group!



Straight section

Second curved section

First curved section

Dipole coils for charge selection

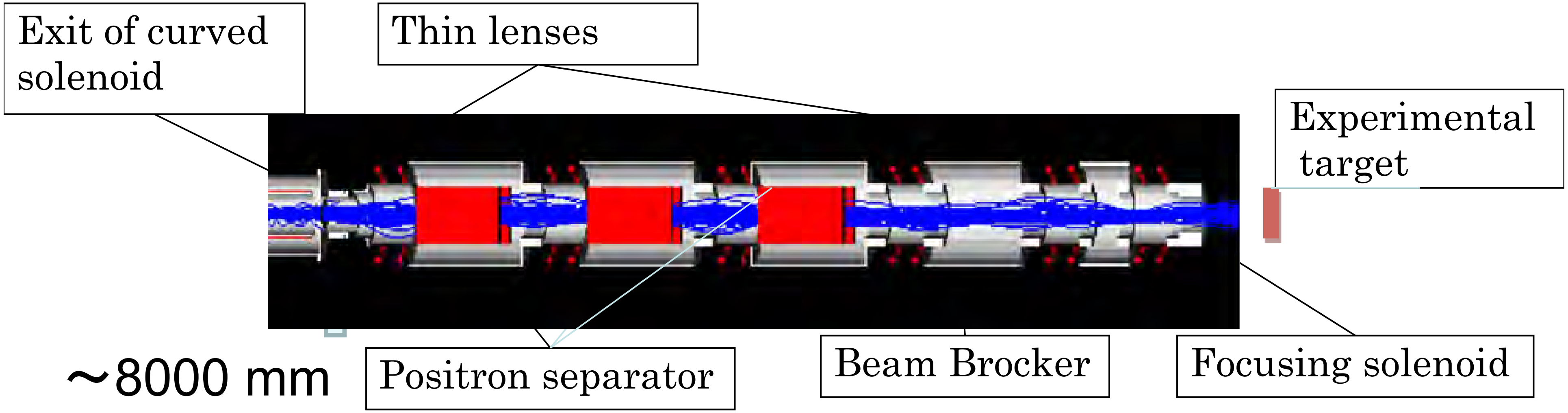
Steering dipole coils (x and y)

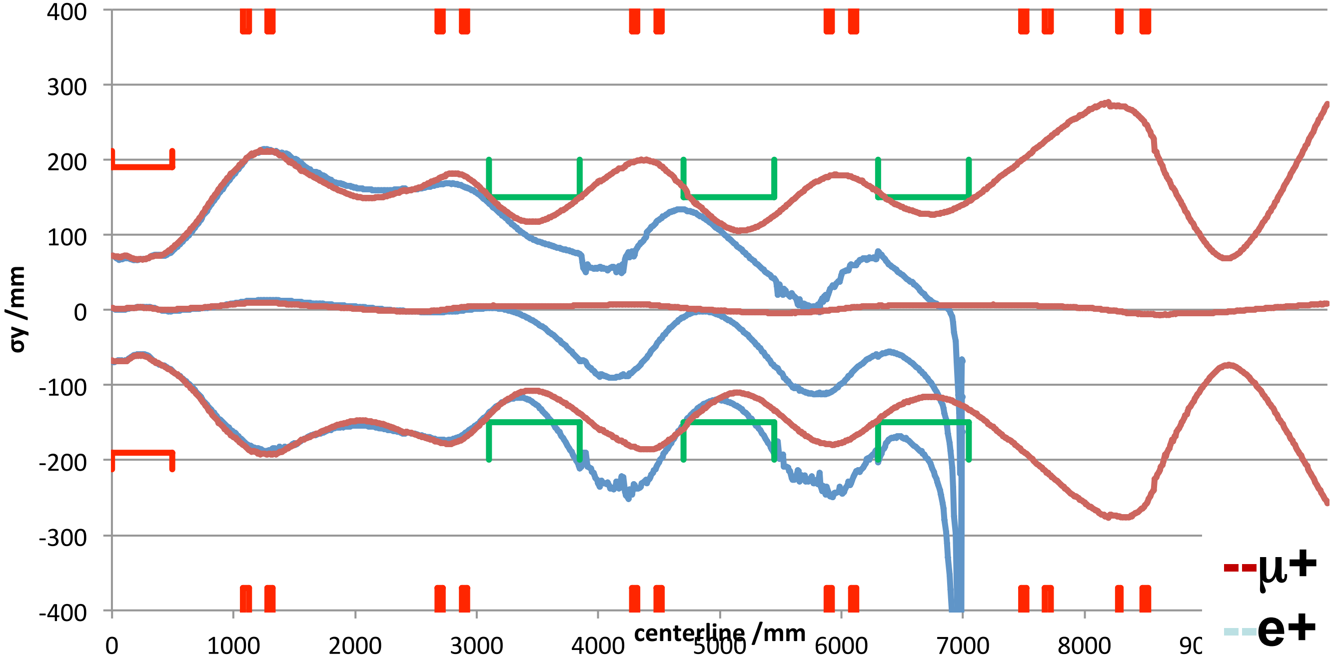
Cooled by Five Gifford-McMahon (GM) refrigerators

Should be delivered Oct.,2011, but Postponed to June. 2012

Superconducting Curved Solenoid is about to be installed into U-Line, On July 6th, 2012

Axial Focusing superconducting solenoids



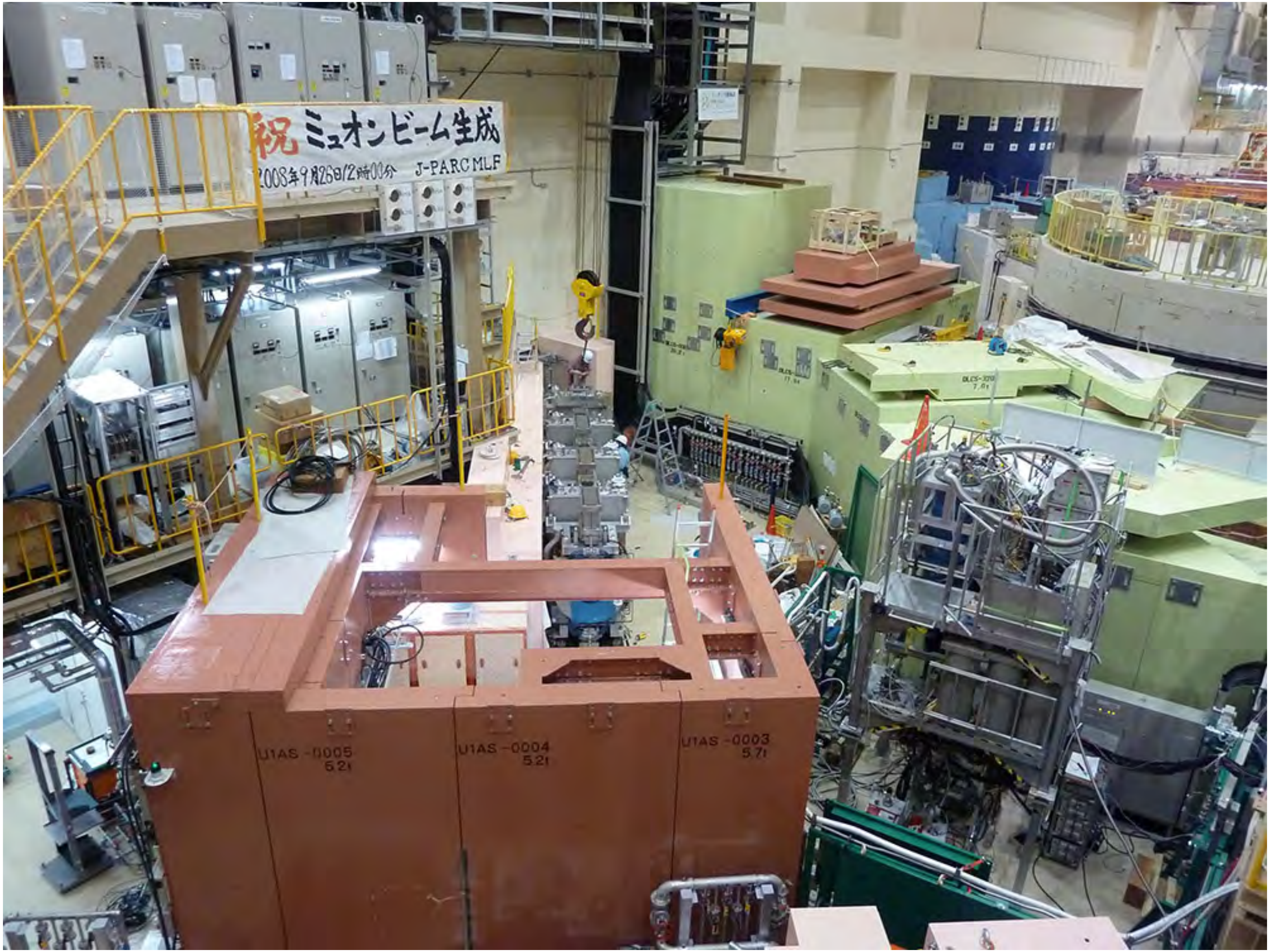


Positron separator

- Three-stage, Wien Filter type
- w= 450, l= 750,
- gap= 300 mm
- Max. Electric field +2.67 MV/m (**±400 kV**)
- Max. Correction dipole field -0.0375 Tm

Funded, Many thanks to KEK Directors & J-PARC Director

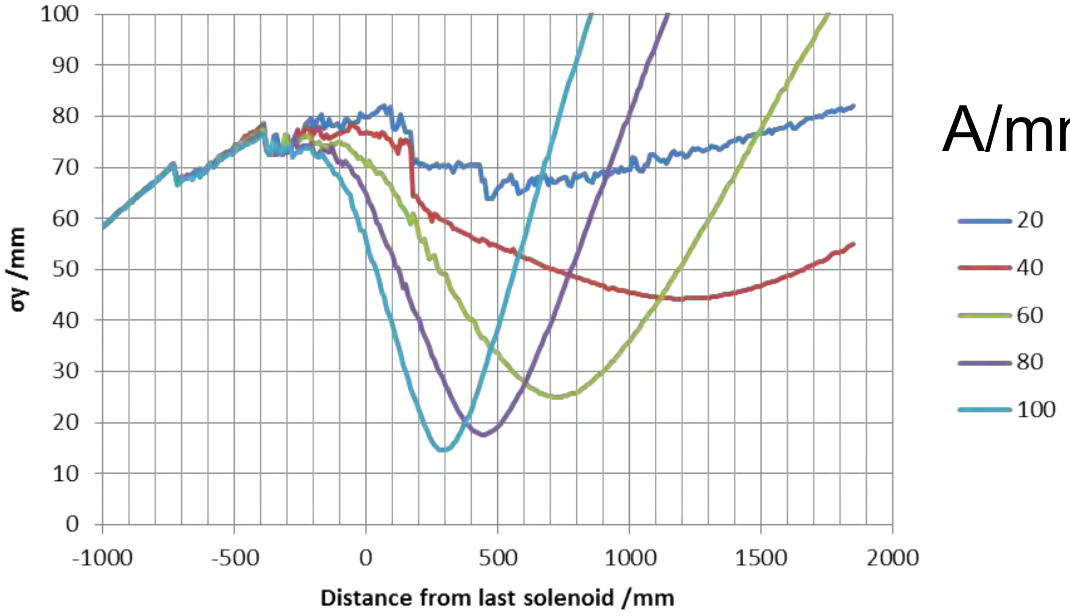
Superconducting Axial Focusing Magnets


祝 ミュオンビーム生成
2008年9月26日12時00分 J-PARC MLF
U1AS-0005 5.2t
U1AS-0004 5.2t
U1AS-0003 5.7t

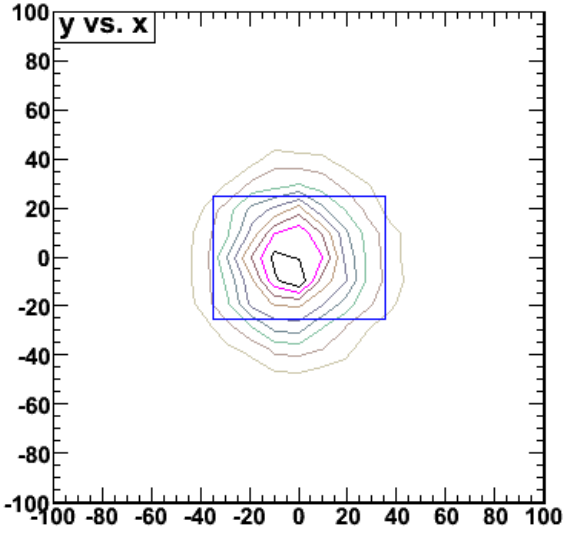
Surface μ⁺ stopping on W, Commissioning from Oct. 18th,

Beam size and focal length
Dependence of current density
of the last coil

σ = 18 mm, Focal length 460 mm
σ = 25 mm, Focal length 700 mm

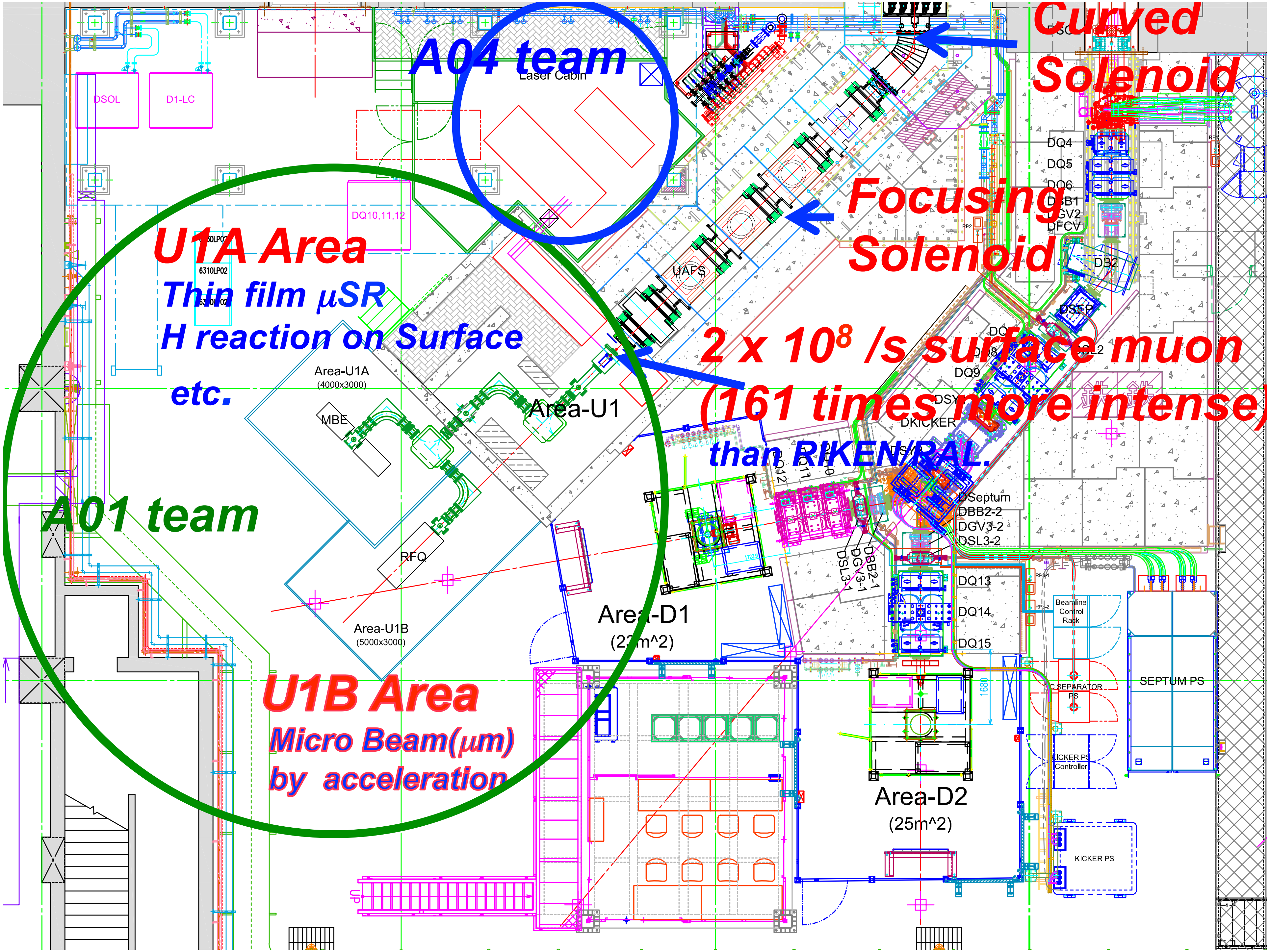


Beam profile at the final focusing point（700mm）



W Target (70 x 40 mm^2)

Intensity: **2 x 10^8 μ⁺/s**, on **W** (70 x 40 mm^2)(@1 MW)
Intensity: **1.2 x10^6** (→0.5 x 10^6) **μ⁺/s**, on **W** (40 x 35 mm^2)@RIKEN-RAL
1.2 x10^6/s is surface μ⁺ arriving at Port3, could be less than 0.5 x 10^6/s stopping on W



Curved Solenoid

A04 team

Focusing Solenoid

U1A Area

Thin film μSR

H reaction on Surface

etc.

2 x 10^8 /s surface muon (161 times more intense)

than RIKEN/RAL.

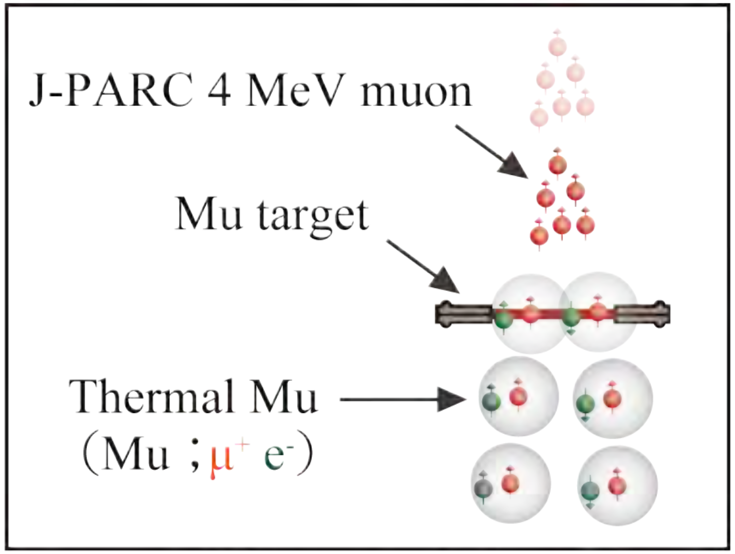
A01 team

U1B Area

Micro Beam(μm)

by acceleration

A01：Generation of Ultra Slow Muons

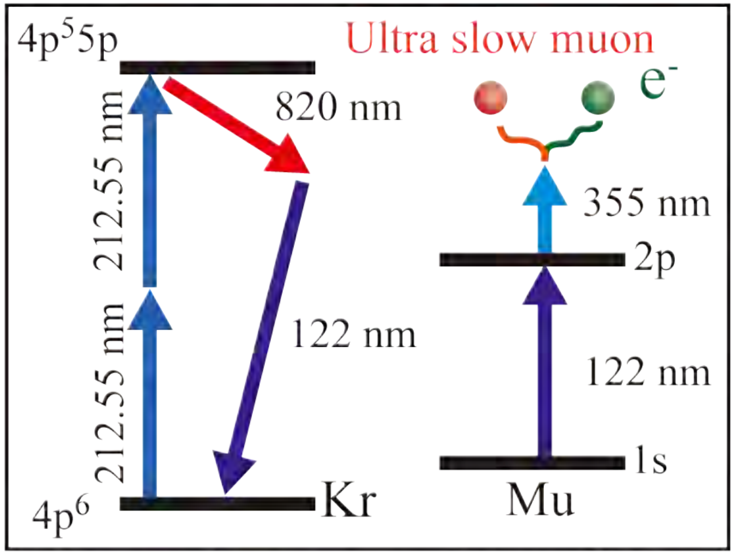


J-PARC 4 MeV muon

Mu target

Thermal Mu
(Mu ; $\mu^+ e^-$)

Mu generator



$4p^55p$

Ultra slow muon

e^-

820 nm

212.55 nm

212.55 nm

122 nm

355 nm

2p

122 nm

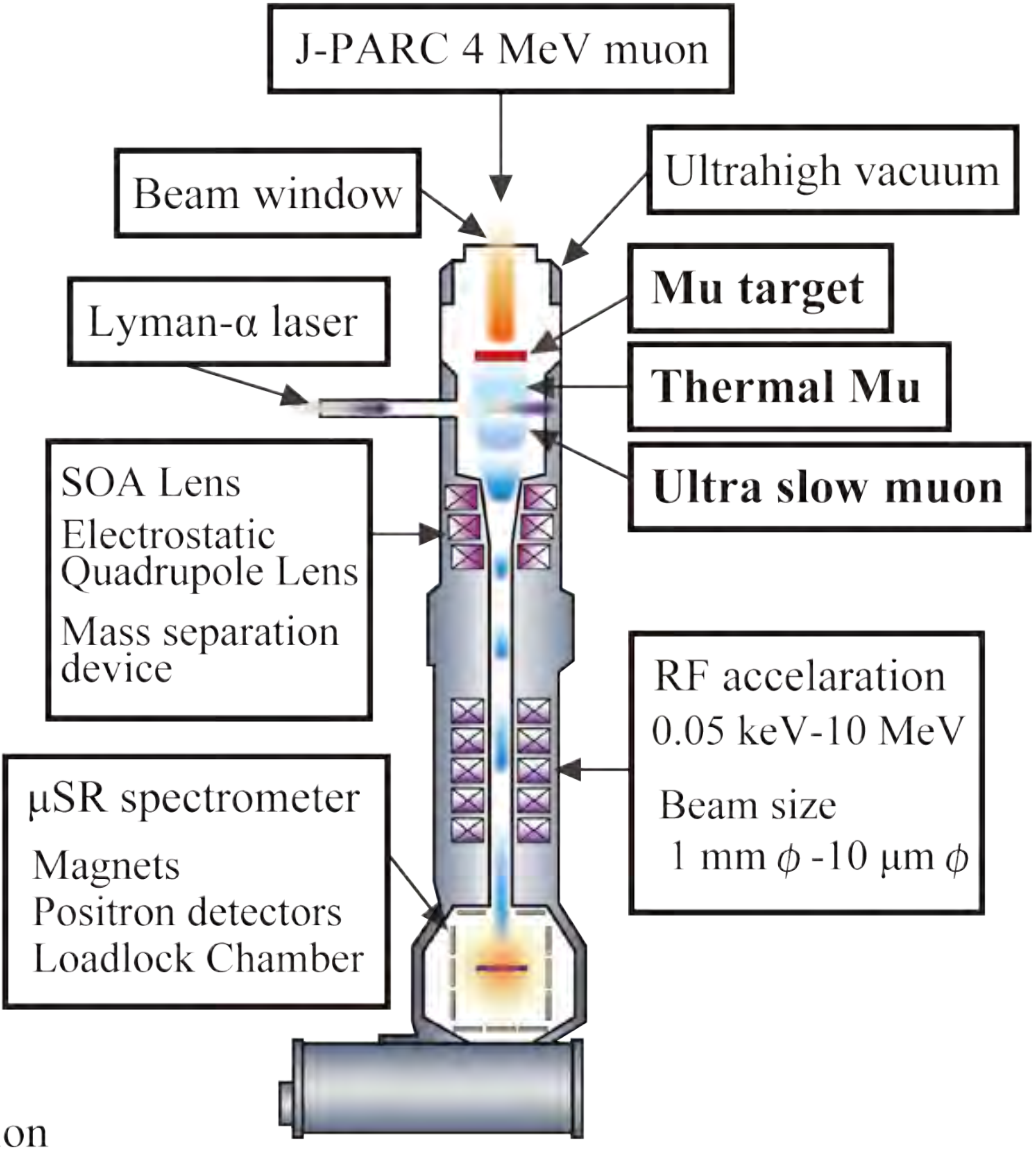
1s

$4p^6$

Kr

Mu

Lyman-α laser generation and Mu dissociation by laser resonant ionization method



J-PARC 4 MeV muon

Beam window

Ultrahigh vacuum

Mu target

Lyman-α laser

Thermal Mu

Ultra slow muon

SOA Lens
Electrostatic Quadrupole Lens
Mass separation device

RF accelaration
0.05 keV-10 MeV

Beam size
1 mm ϕ -10 μm ϕ

μSR spectrometer
Magnets
Positron detectors
Loadlock Chamber

ULTA SLOW MUON GENERATION

Grants-in-Aid; Frontier of Materials, Life and Elementary Particle Science Explored by Ultra Slow Muon Microscope
Lead by Prof. E. Torikai

A01:Ultra Slow Muon Microscopy & Microbeam (Y. Miyake)

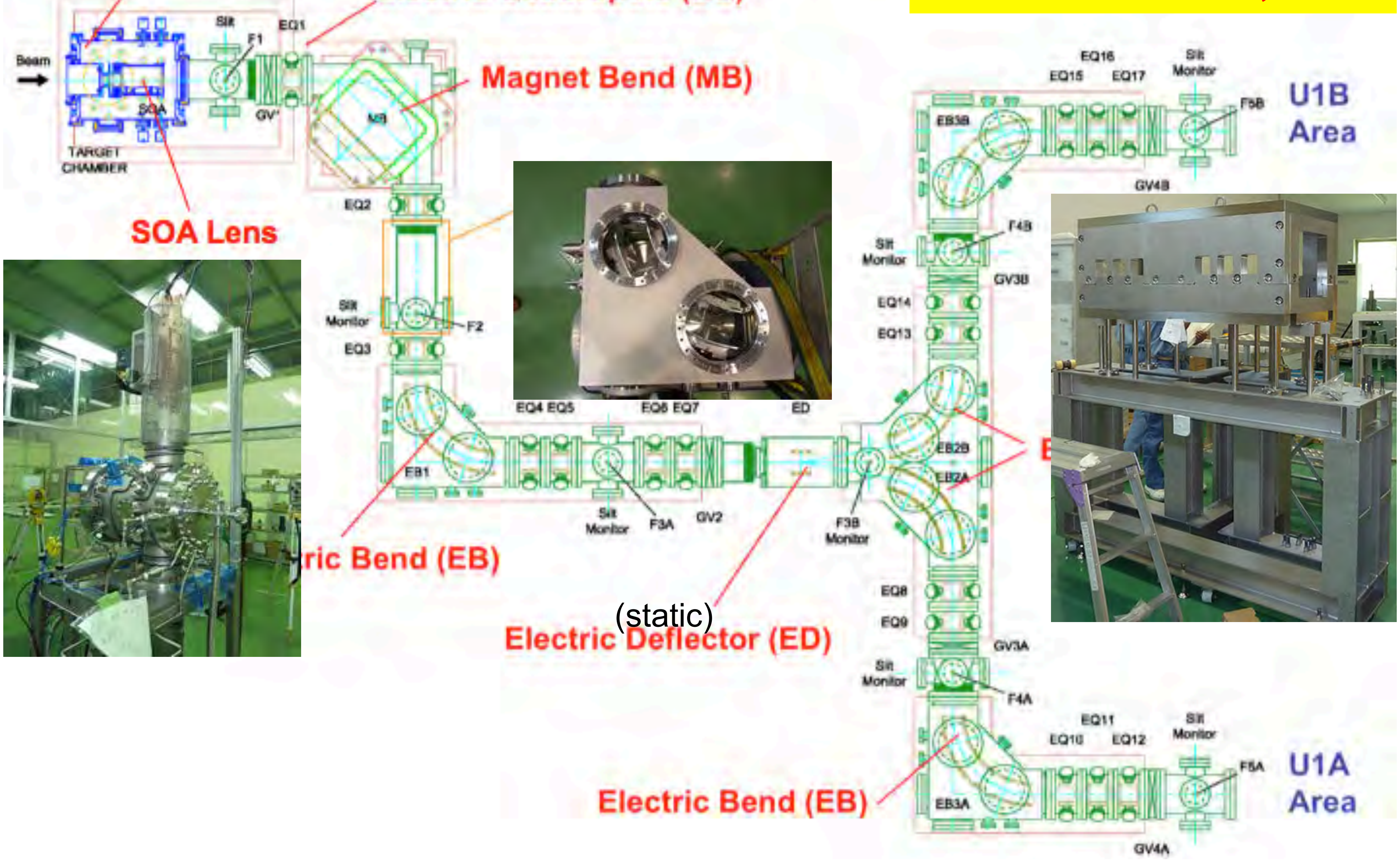
A02：Spin Transport and Reaction at Interface (E. Torikai)

A03：Heterogeneous correlation of electrons over the boundary region between bulk and surface (R. Kadono)

A04:Ultra Cold Muon beam (M. Iwasaki)

Ultra-Slow Muon Beamline Layout

Will be installed
On Nov. 19-30th,2012



Target Chamber

Electric Quadrupole (EQ)

Magnet Bend (MB)

SOA Lens

ric Bend (EB)

(static)

Electric Deflector (ED)

E

U1B Area

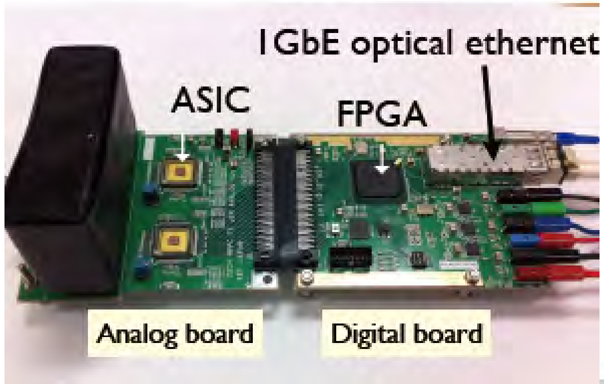
U1A Area

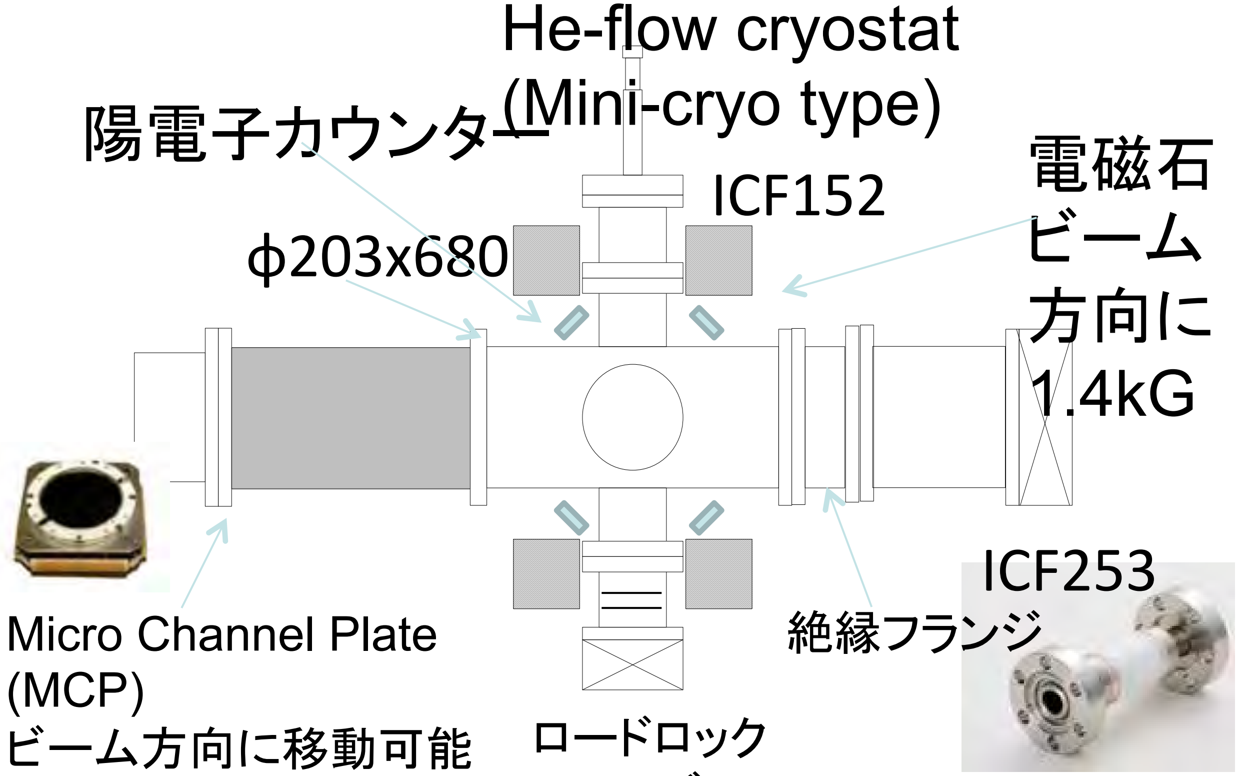
Electric Bend (EB)

Spectrometer

Specification of Spectrometer(1st stage)

- Magnetic Field0-1400G（Normal conducting）
- Temperature　10-15K以上 (He flow cryostat)
- Vacuum（10^{-8}Pa）
- e^+ counters, MPPC　(256ch)
- Floated by 30kV



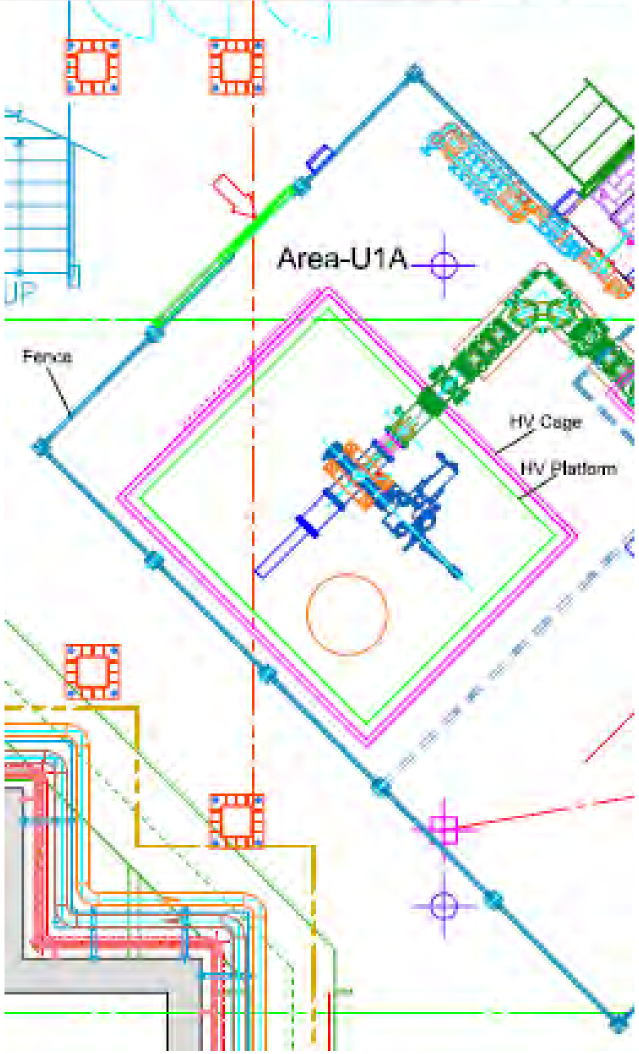


電磁石
ビーム
方向に
1.4kG

Micro Channel Plate
(MCP)
ビーム方向に移動可能
プロファイルの測定

絶縁フランジ

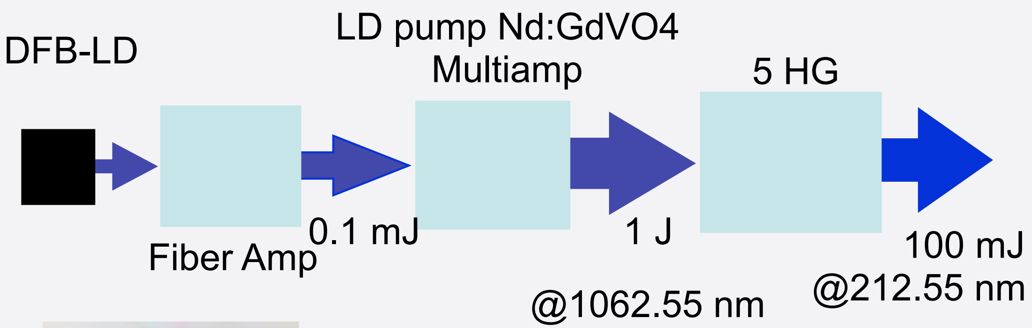
ロードロック
チャンバーへ
試料の挿入、分析（RHEED等）

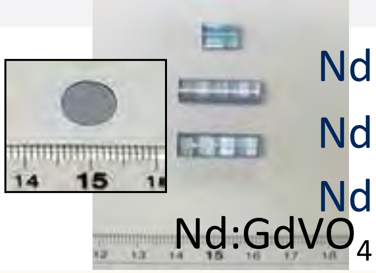


A04

Laser Diagram

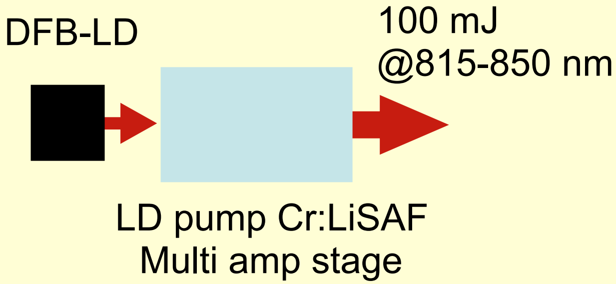
Pump Laser1 : 2photon resonance frequency＝ 212.55 nm

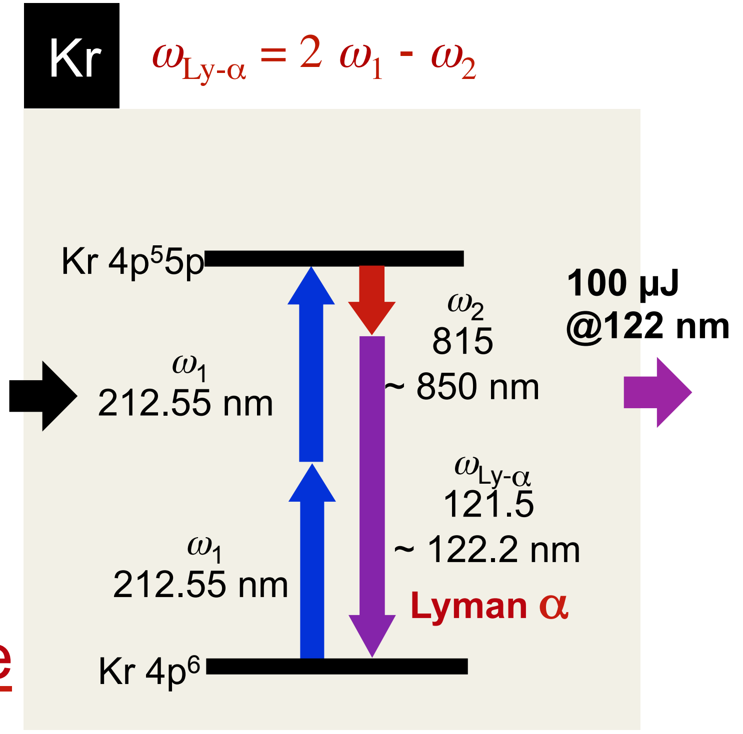




Nd:GdVO$_4$Laser Crystal
Directly emitting 212(x5)nm
Much better efficiency(Wada)

Pump Laser2 : 815-850 nm variable





Lyman-α Intensity 100 times

Ultra Slow Muon for sure **$10^{5\text{-}6}$/s**

S.WADA, N. Saito & M.IWASAKI RIKEN

U-Line

Expected Yield of Ultra Slow Muon

20 slow muons/second at RIKEN-RAL→J-PARC, MUSE

1) **Repetition Rate**

25 Hz (At RIKEN-RAL *50 Hz*) factor **2** ***times*** ***(1.5)***

2) Surface Muon Yield by **Super Omega Channel**

2.0×10^8 /s / 1.2×10^6 /s (RIKEN-RAL) = ***161*** *times (400)*

3) Lyman-α Intensity by **Laser Development**

71 μJ/p / <1 μJ/p (RIKEN-RAL) ~ ***100*** *times*

Our Goal of Ultra Slow Muon Yield is

20 /s x 2 x 161 x 100 = 0.6 x 10^6/s (Maximum)

Riken-RAL Slow Muon Intensity

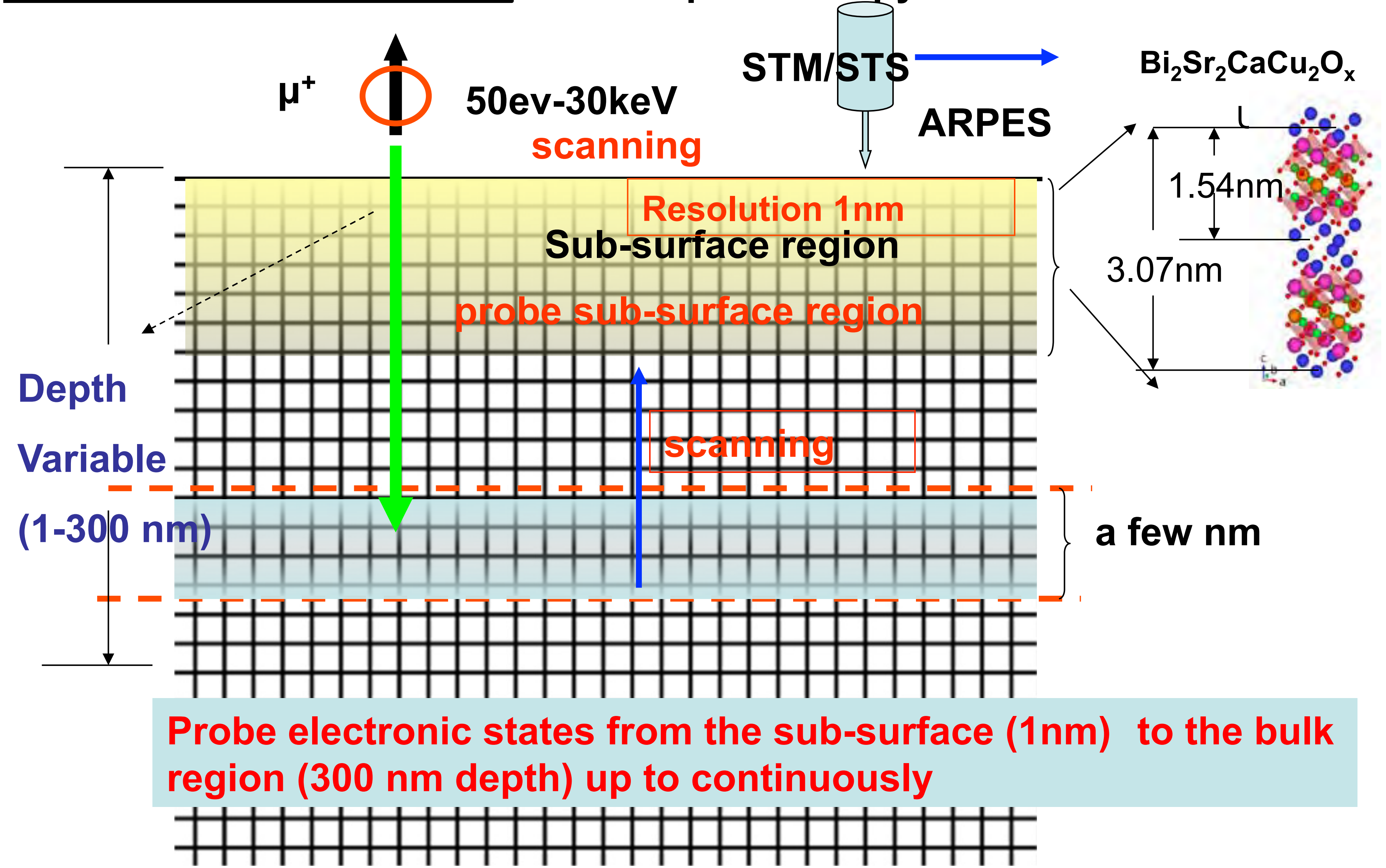
Started with realistically, 10^3/s !

Sub-Surface/Boundary Magnetism

utilizing variable implantation depth
(1 nm to 300 nm)

Sub-Surface/Boundary Magnetism

Scanning tunneling microscopy and spectroscopy on the surface



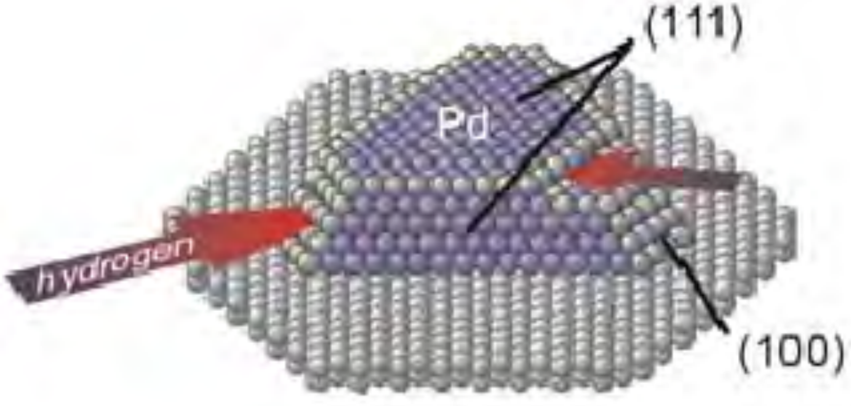
Probe electronic states from the sub-surface (1nm) to the bulk region (300 nm depth) up to continuously

According to Prof. Nishida

Surface/Sub-Surface H chemistry

Surface/Sub-Surface H chemistry

H reaction on the nano Surface quite different from bulk



- Surface H ⟹ Isomerization
- Adsorbed H ⟹ Hydrization

M. Wilde et al., ACIE 47 (2008) 1.

Chemical Evolution in Cosmic May occur on the surface of ICE

Main Cast is H

$$CO + 3H \rightarrow CH_3O$$

$$H + H \rightarrow H_2$$

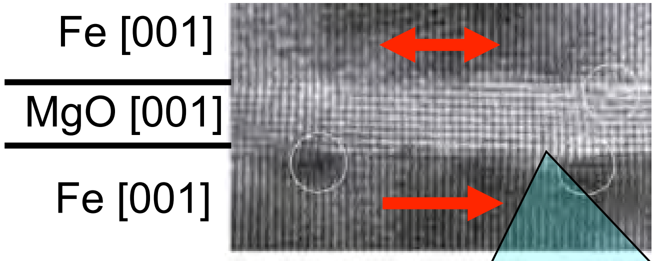
N. Watanabe, A. Kouchi, PSS 83 (2008) 439

Clarify
- Electronic state of H on the surface
- Role of the surface H on Ice/Cluster
- Diffusion Constant of H

According to Prof. Fukutani

A02 Spin Transport and Reaction at Interface

Spin direction of the Ultra Slow Muon can be easily controlled by Spin Rotator

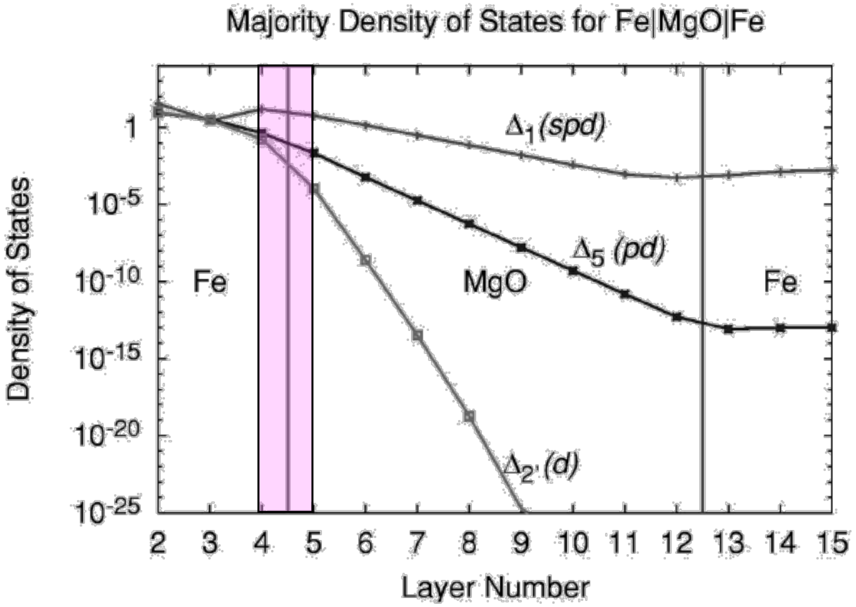


Spin implantation depends upon Atomic spin state on the boundary

磁気トンネル接合には絶縁体・強磁性体
界面のスピン状態の理解が重要

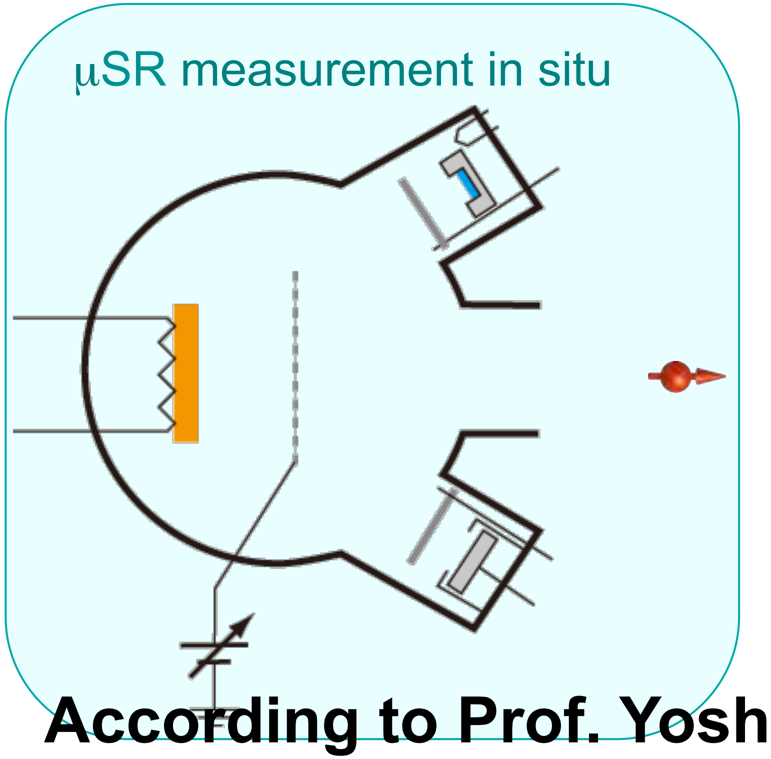
- ◆Extension towards half metal etc.
- ◆Spin Implantation to semiconductor

Observing spin state on the boundary between Ferro/insulator



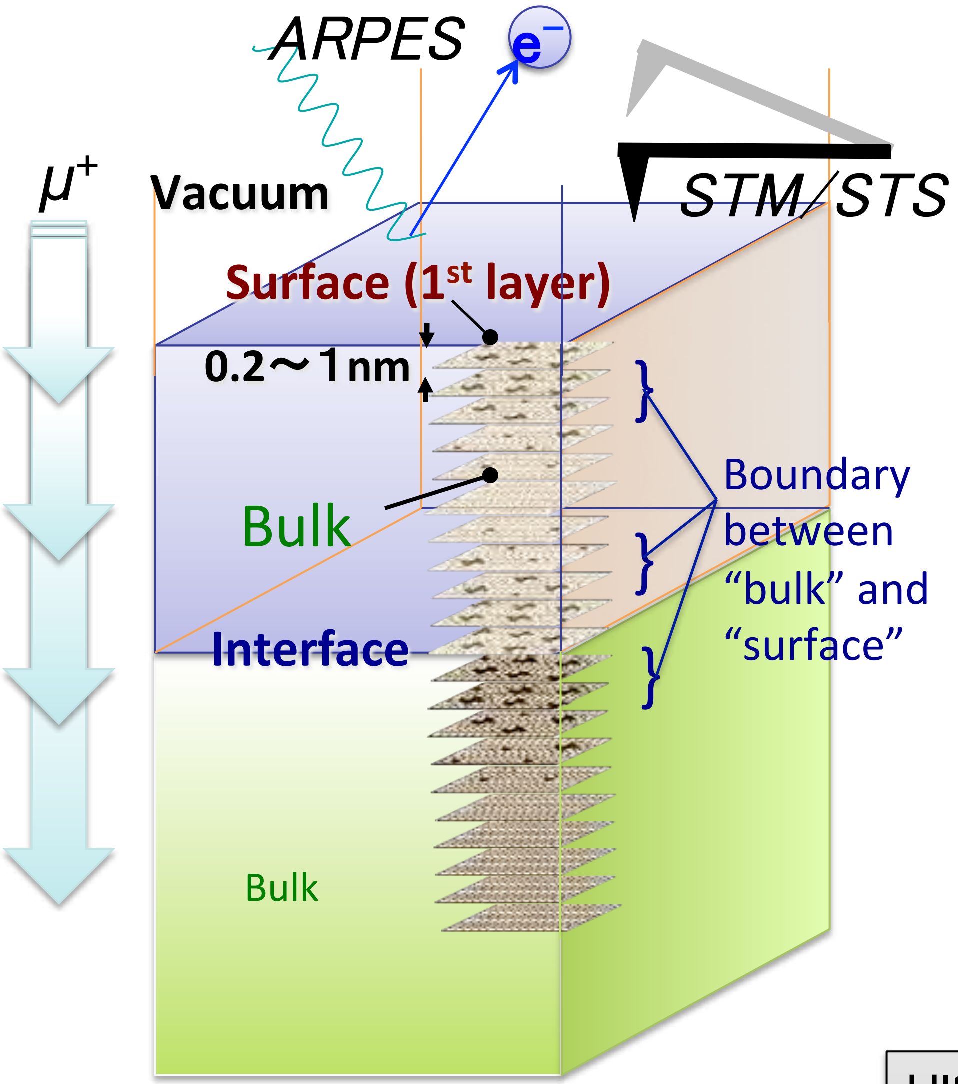
Butler et al. PRB 63, 056614 (2001).

μSR measurement in situ



According to Prof. Yoshino

A03: “Heterogeneous electronic correlation at sub-surface & interface”



Remarkable difference in the electronic property between surface and bulk

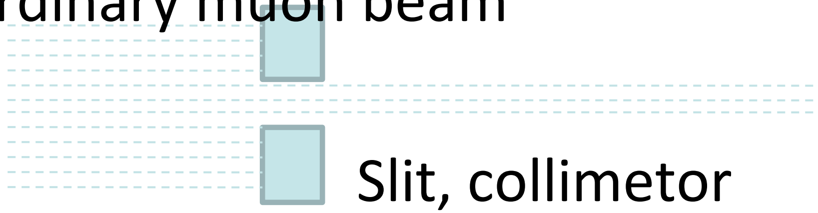
- Breakdown of inversion (mirror) symmetry at surface/interface → “Recovery of orbital angular momentum” near the surface
- Spatial constraint over the motion of electrons → “Enhancement of quasi-two-dimensional character and associated change in the electronic state

…Novel electronic property (“heterogeneous electronic correlation”) may be realized on the hetero-structure composed of transition metal compounds that are subject to strong electronic correlation.

Ultraslow muon serves as a unique tool to probe the electronic state of subsurface and interface in the real space.

A01：Microbeam: Muon Microscopy, requiring only μg to ng sample

Ordinary muon beam



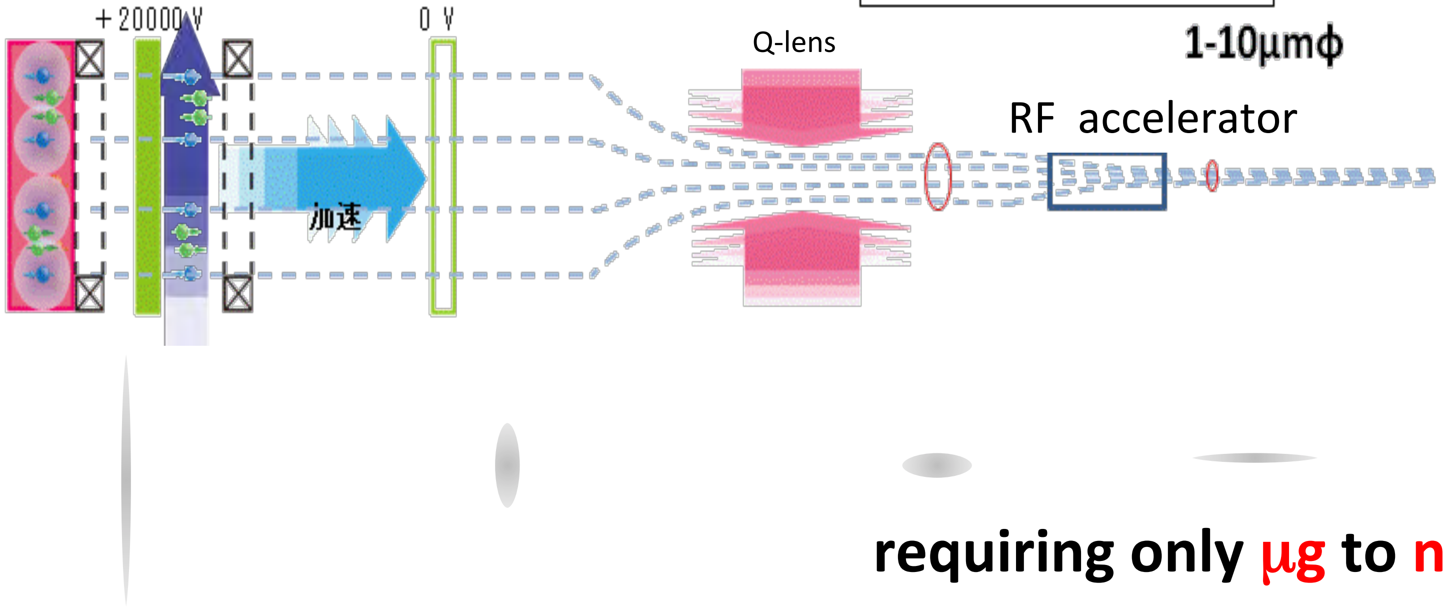
Slit, collimetor

Beam is scraped away
by beam slit or collimeter.
Beam size >a few cm.
Beam intensity is reduced.

So far, requires 1 g sample

ultra-slow muon

Beam Focusing



Reduction of
beam size
without any
reduction of
beam intensity!

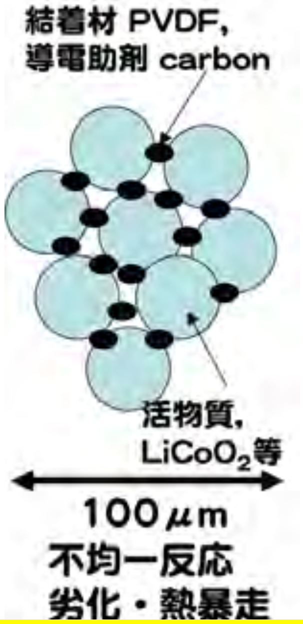
requiring only μg to ng sample

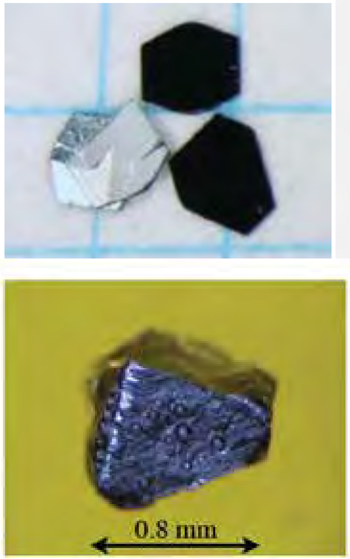
Beam size -> ~Φ70mm
Depth resolution -> a few nm

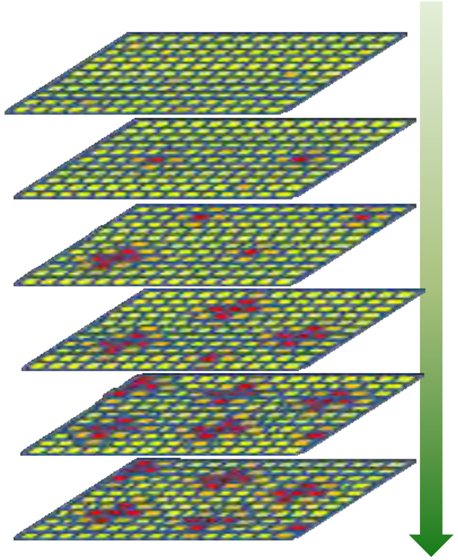
Minimum beam size -> ~Φ1μm
Depth resolution -> order of μm

Realization of muon microscope

A01;Study of materials and life science by micro muon beam







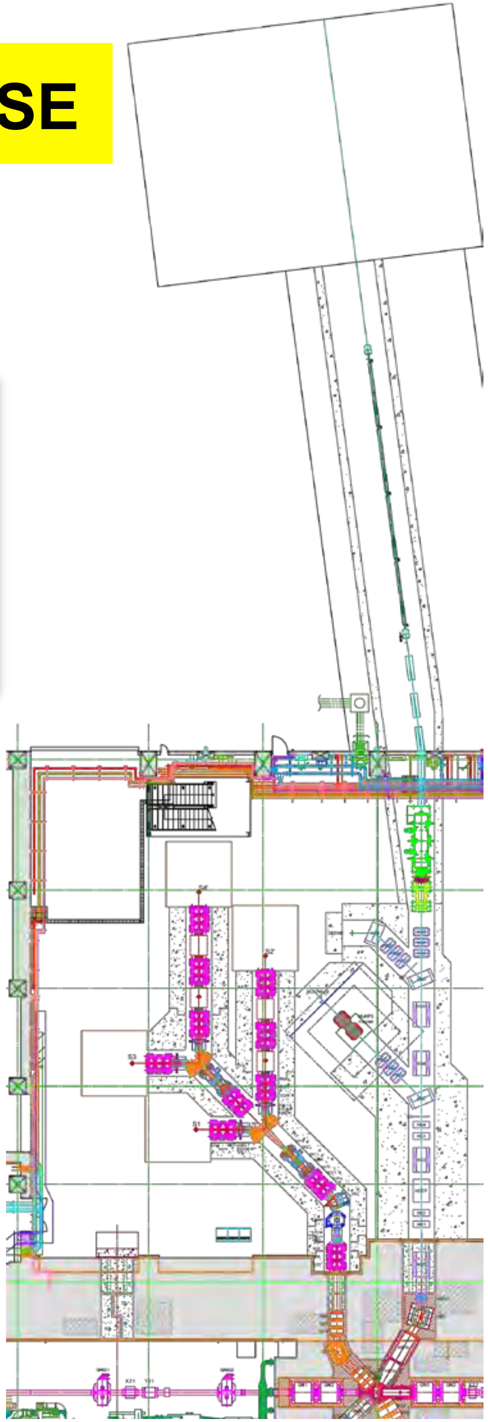
3D mapping of magnet domain inside sample

Particle property change vs. non-uniformity
･Non-uniform Li diffusion in battery
･Non-uniformity in permanent magnet domain

Micro-scale sample、Micro-size region (grain, domain)
Study of undeveloped scientific or engineering field!

Examples：Trans-uranium compound（Novel Np, Am compound etc.、）
Life science（Electron transfer in DNA etc.,）
Industrial application（Inhomogeneity of reaction in Buttery compound etc.,）

S & H-Lines at MUSE



S-Line

Surface μ⁺
For material sciences

H-Line

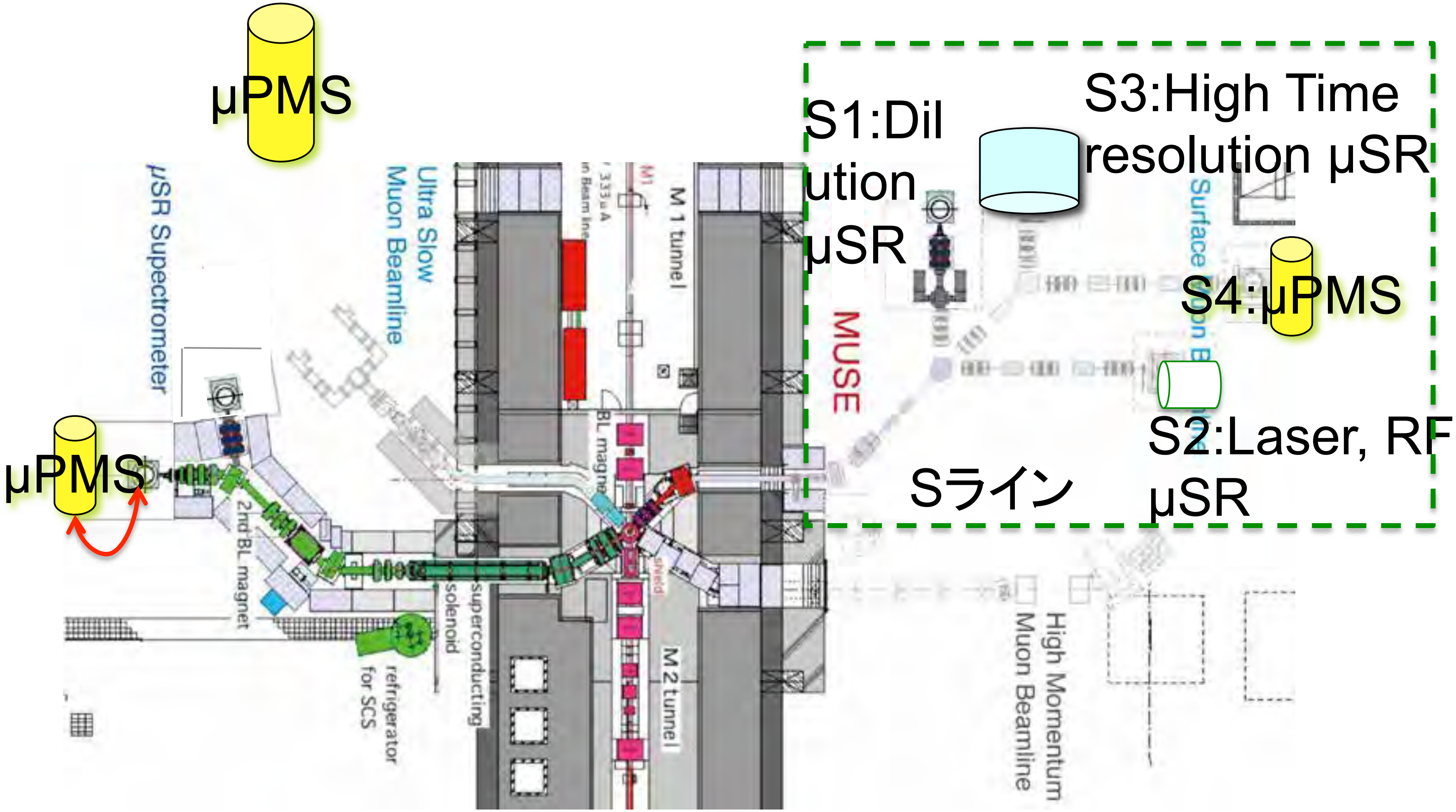
Surface μ⁺ For HF, g-2 exp.
e⁻ up to 120 MeV/c For DeeMe
μ⁻ up to 120 MeV/c For μCF

Installation in the vicinity of production target @Summer, 2012

S-Line

「μSR利用拡大」

例：高速汎用装置「μPMS」…時間積分法で大強度をフル活用



μPMS

μPMS

S1:Dilution μSR

S3:High Time resolution μSR

S4:μPMS

S2:Laser, RF μSR

Sライン

H-Line; Projects submitted to IMSS MUSE

○Mu Hyperfine precise measurement(*30MeV/c*)

○“g-2”(*30MeV/c*)→*Ultra Slow Muon*:

Improve Sensitivity by
x 100 (10^{-14})

Precision Measurement of Anomalous Magnetic Moment

Muon Precision Experiment to search for New Physics

○“μ-e” Conversion(DeeMe) (*105MeV/c*):

Improve Precision by
x 5 (0.1 ppm)

Search for Charged Lepton Flavor Mixing

Charged Lepton Flavor Mixing and Origin of Matter

○Pencil Beam Production(*30MeV/c*)

○μCF Under High Press. and Temp.(*120MeV/c*)

:For the experiments of μCF high pressure and high temperature.

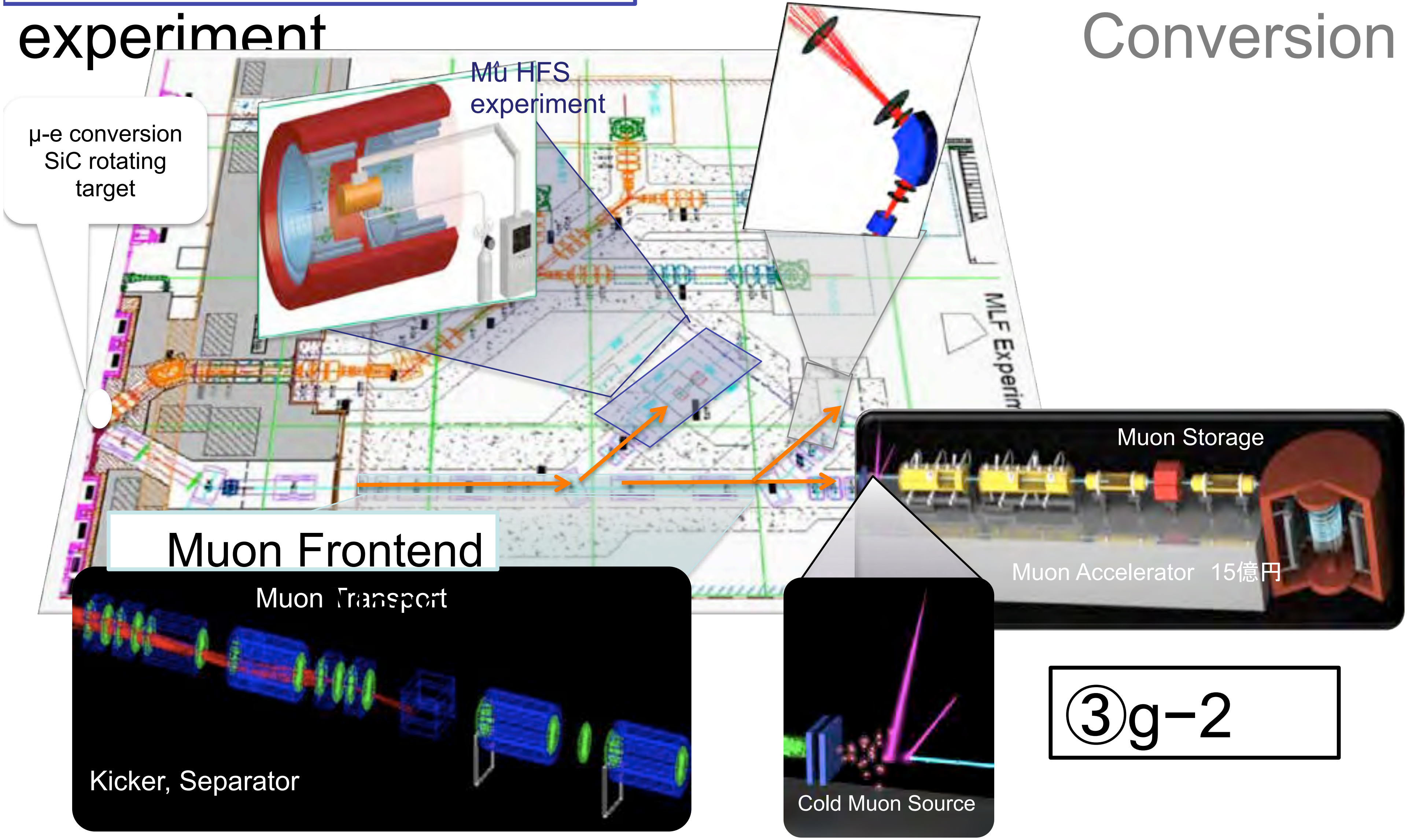
Welcome not only material sciences, but also fundamental physics!

Design H-Line extracting μ or e Up to *120 MeV/c*

H-line Plan step by step

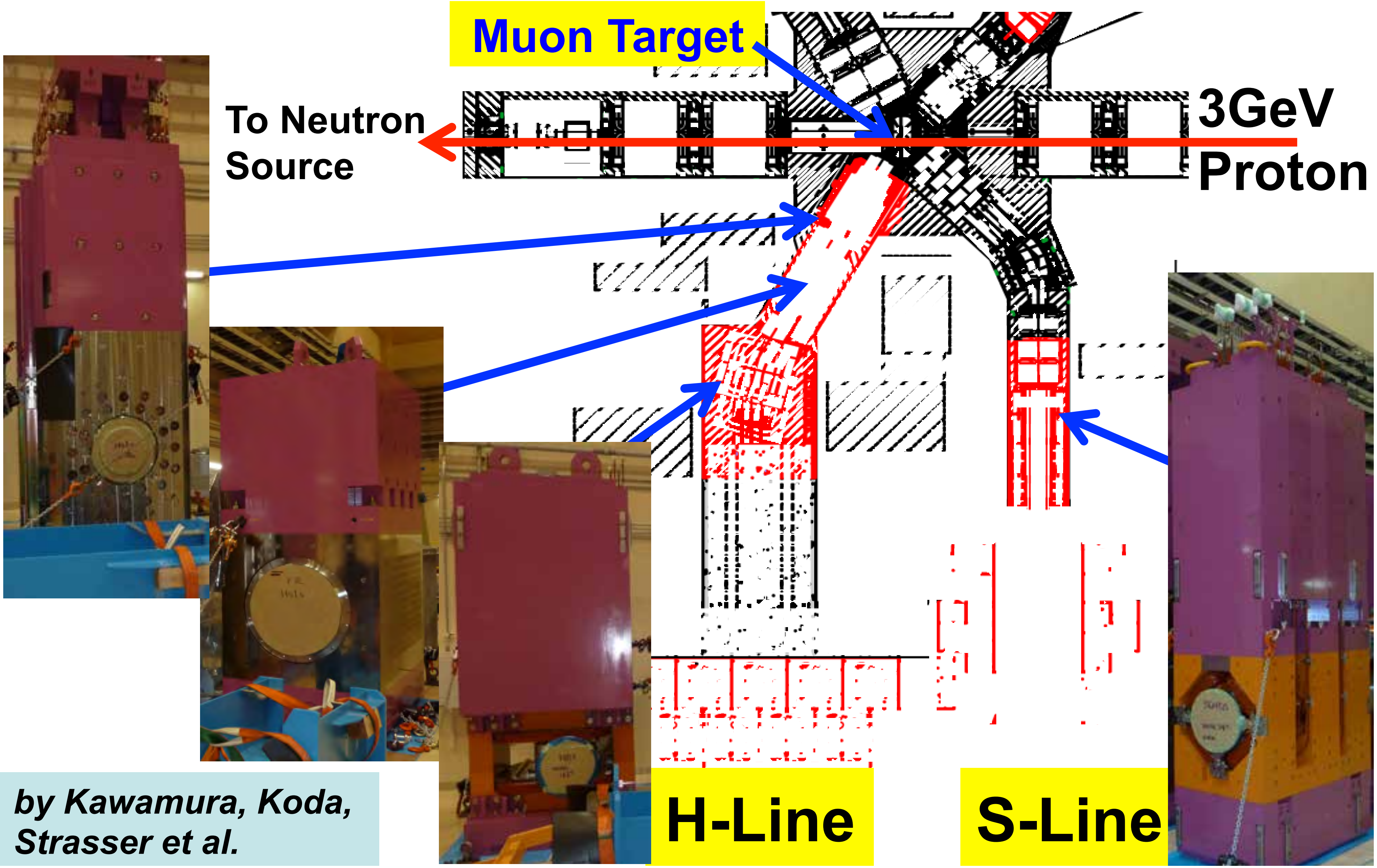
①Mu HFS experiment

②Deeme; μ-e Conversion



③g−2

Installation of the Beam Line Components in the M2 tunnel this Summer, 2012



Muon Target

To Neutron Source

3GeV Proton

H-Line

S-Line

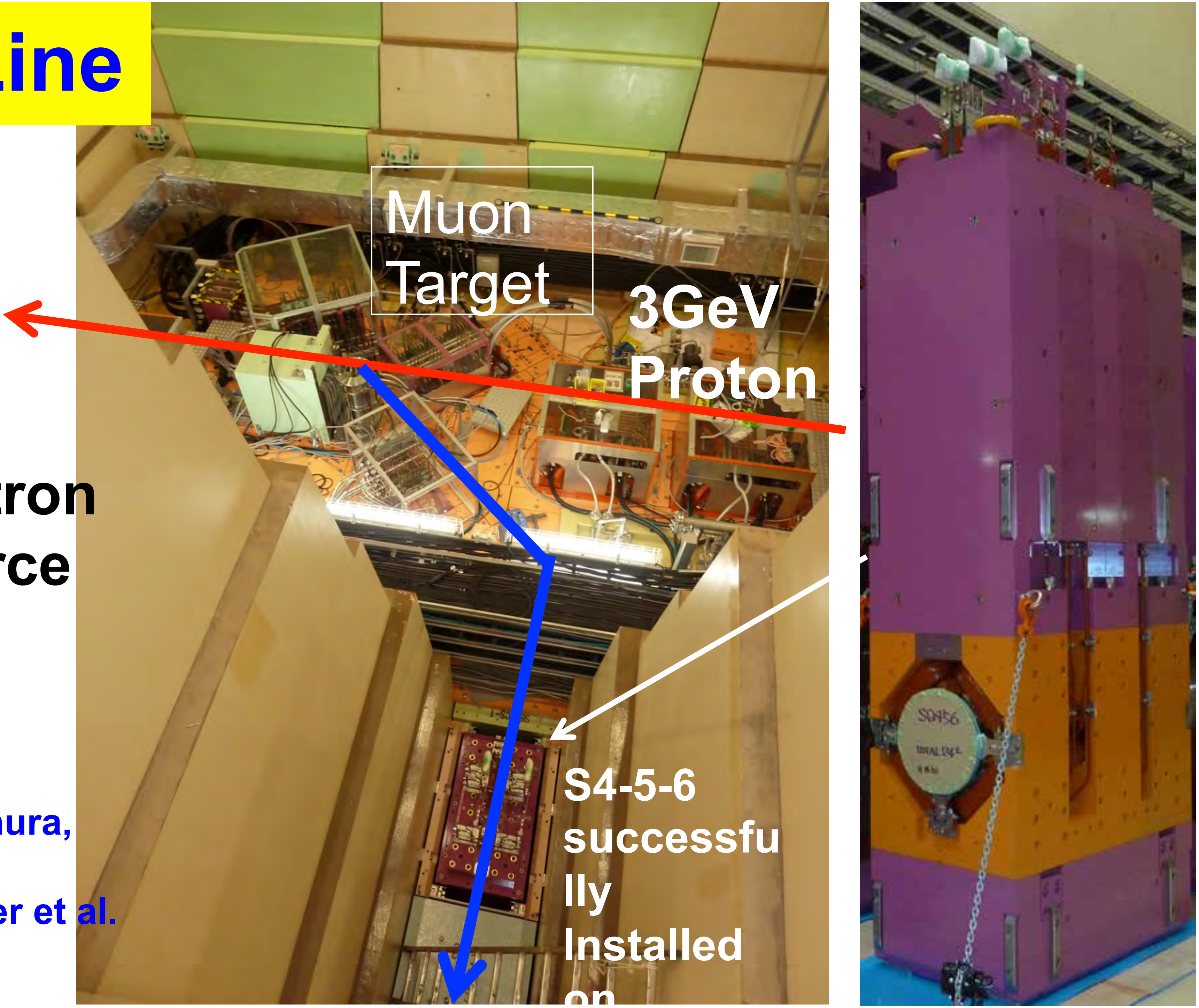
by Kawamura, Koda, Strasser et al.

Summary

- (Muon Target, Operating well → Rotating Target!)
- D-Line, Operating User's Run → Kicker operation
- U-Line, Constructing now!
  +Grant-in-Aid (Innovative Areas)
- S-Line, Partially fabricated! → to KEK/MEXT!
  +Competitive Budget (Rare Earth Program?)
- H-Line, Partially fabricated! → to KEK/MEXT!
  +Grant-in-Aid (Kiban-S)

Welcome to J-PARC MUSE !

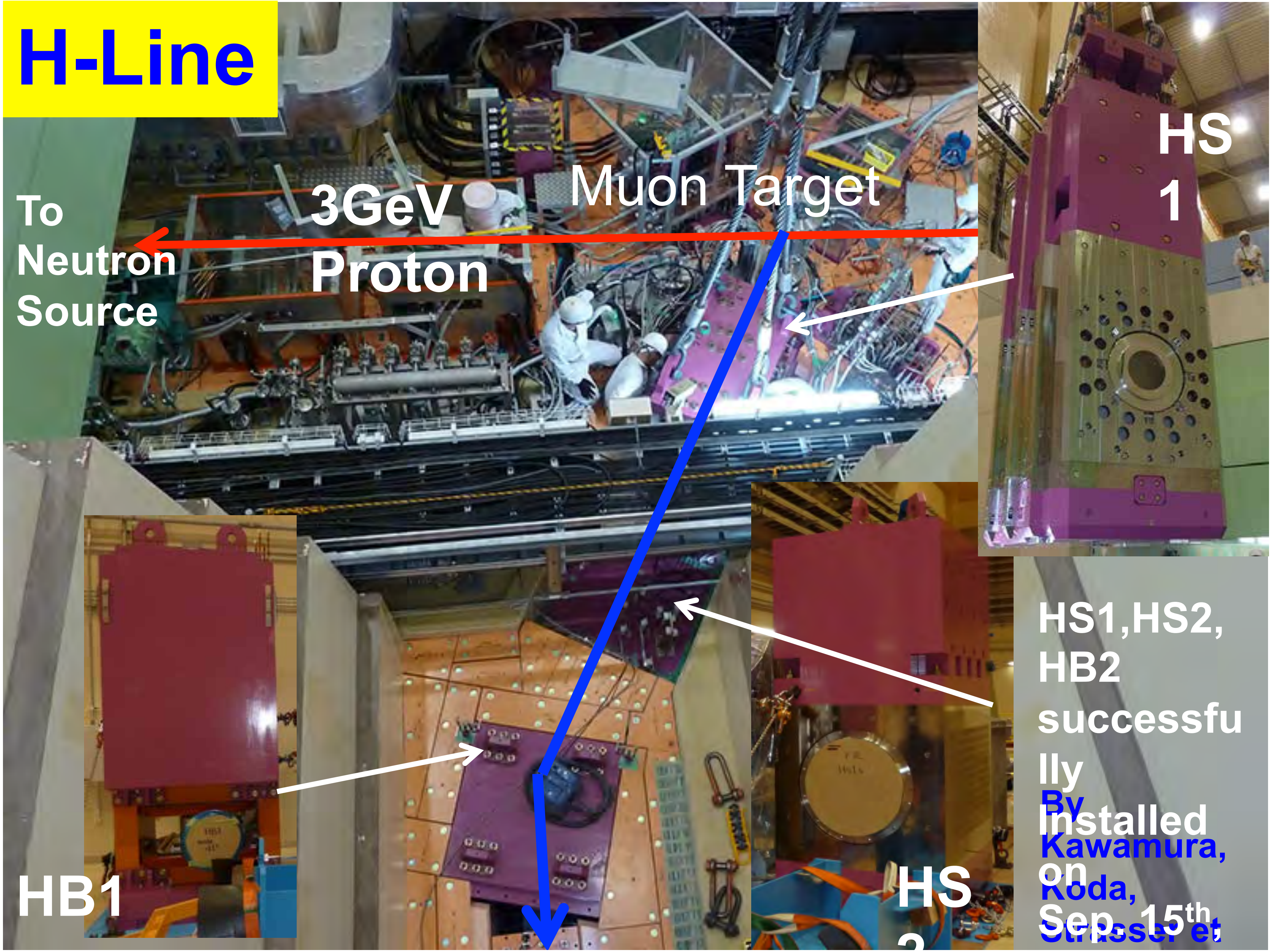
S-Line



To Neutron Source

By Kawamura, Koda, Strasser et al.

H-Line



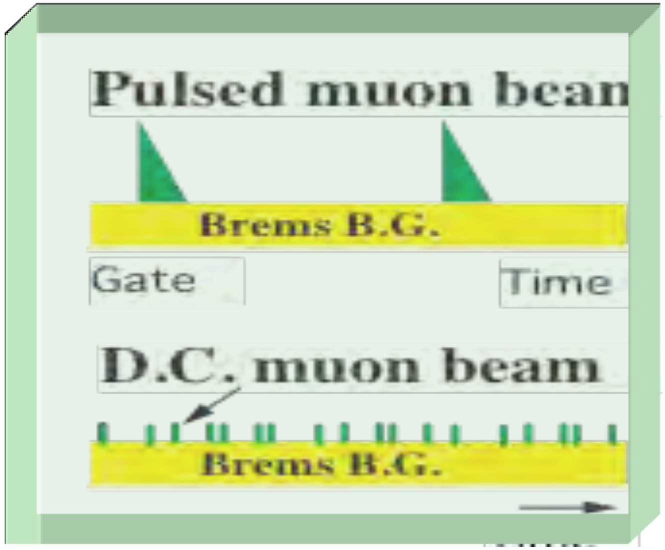
HS1,HS2, HB2 successfully Installed on Sep. 15th,

By Kawamura, Koda, Strasser et

What is Pulsed Muon compared with DC Muon *(Complementary)*

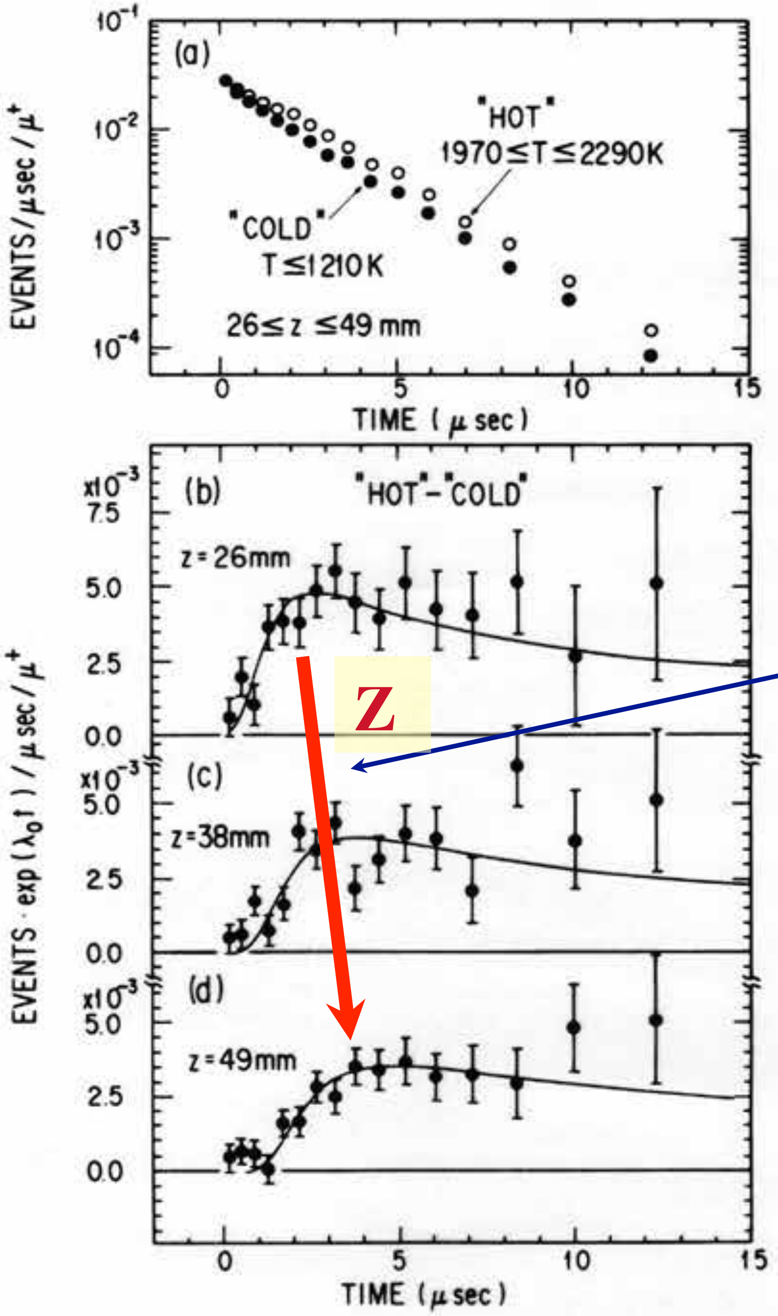
1. **Time Resolution is determined by proton beam, to be as large as 100 ns.**
   →Development of Beam Slicer
   →Ultra Slow Muon Generation
2. **Synchronization with pulsed perturbation**
   Can be synchronized with pulsed RF or Laser
   →Ultra Slow Muon Generation by Laser Resonant Ionization of Mu
3. **Long time Measurement (in particular, slow relaxation)**
   The higher intensity, the better, since no pile up occurs (μ decay or μSR)
4. **Phase Sensitive Measurement**
   Even under a large white noise, μ related signal can be observed efficiently, such as μCF experiment under a large Bremstraulung from Tritium.
5. **Instrument should be segmented!**
   →Expensive Spectrometer

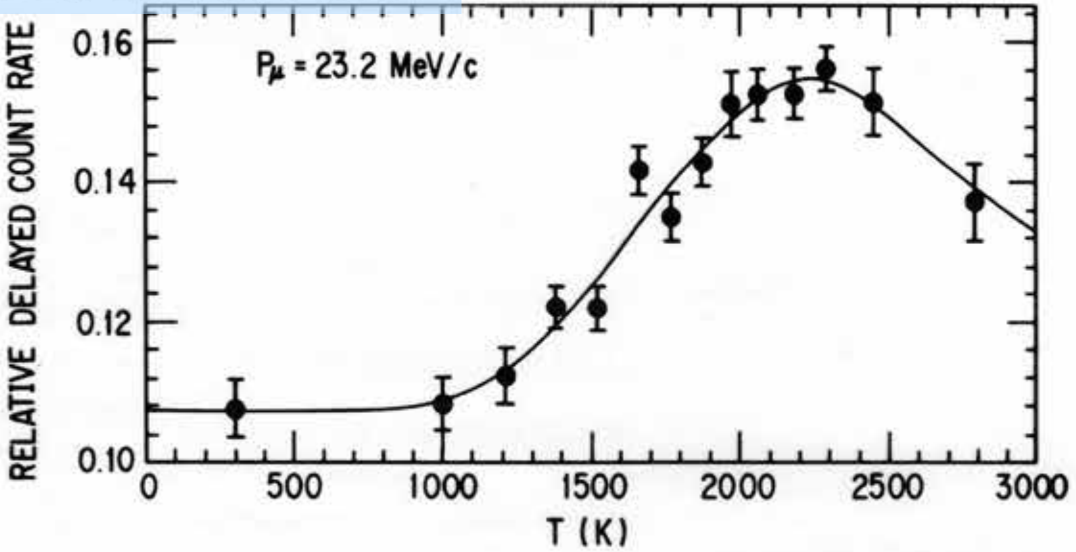
Complementary to Continuous Beams



STEP1:Generation of themal Mu in vacuum

From Mills et al.



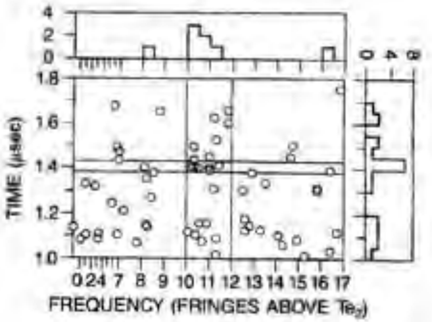


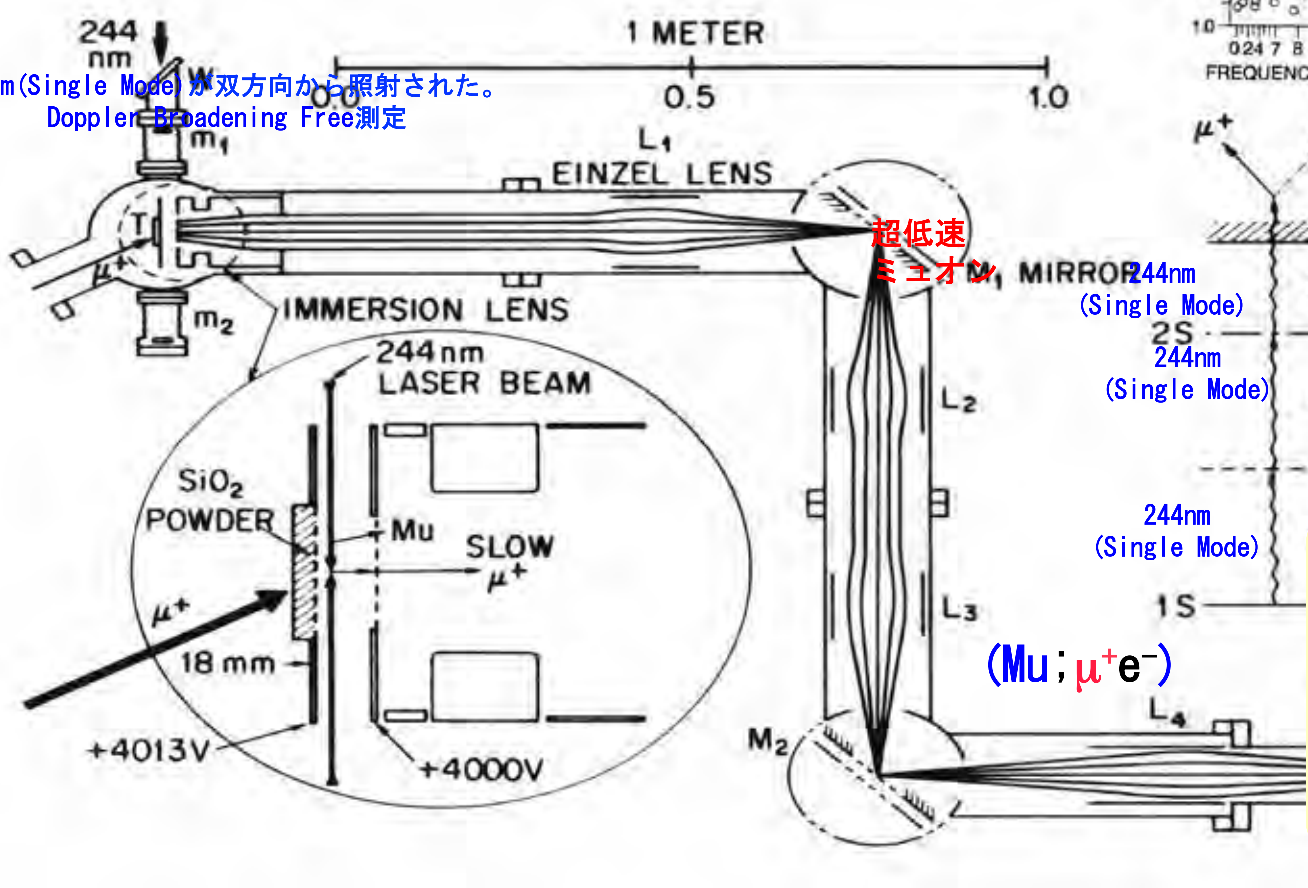
- **Z**：Distance from hot target, Mu takes more time to reach further distance

- About **4%** of stopped muons evaporate into vacuum, as thermal Mu

STEP2：STEP2: Resonant Ionization of thermal Muonium by 1s-2s excitation(*~1987*)（QED confirmation）By Chu, Mills, Kuga, Yodh, Miyake, Nagamine et al

- **The first successful extraction of Ultra-slow Muon！**
- **consistent with QED expectation within** 300MHz





244nm(Single Mode)が双方向から照射された。
Doppler Broadening Free測定

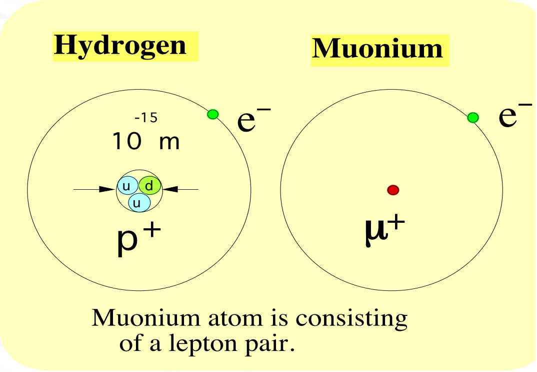
超低速
ミュオン

244nm
(Single Mode)

244nm
(Single Mode)

244nm
(Single Mode)

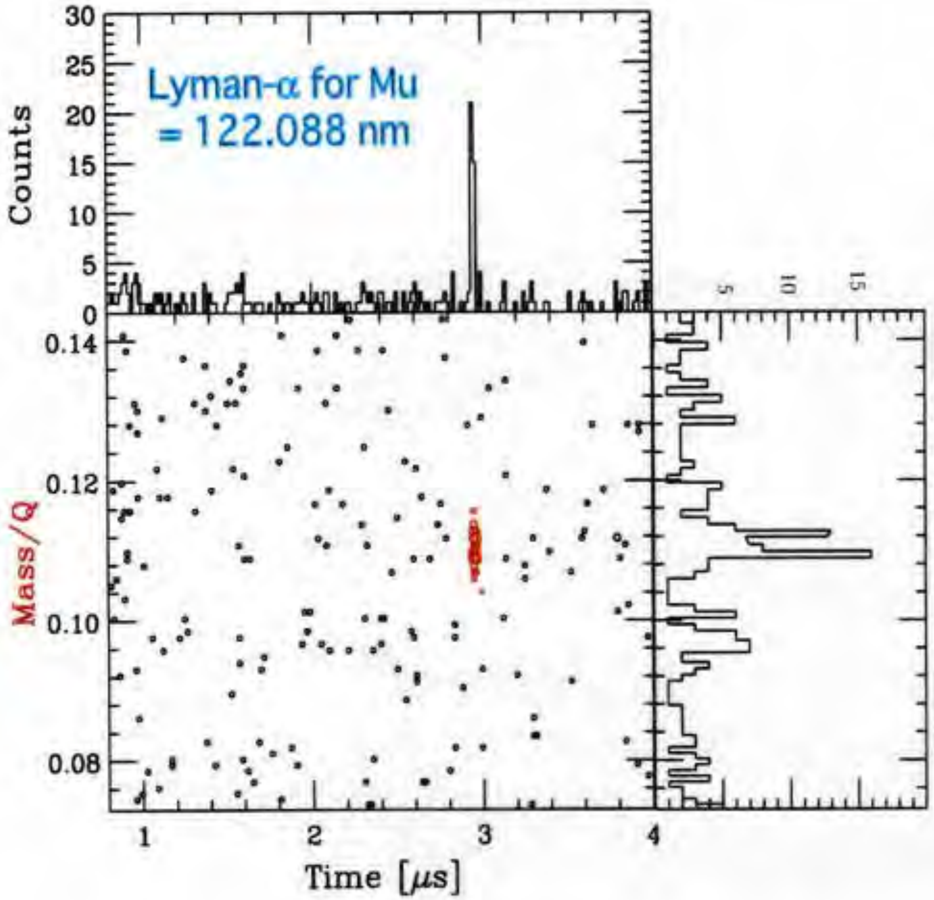
(Mu；μ^+e^-)

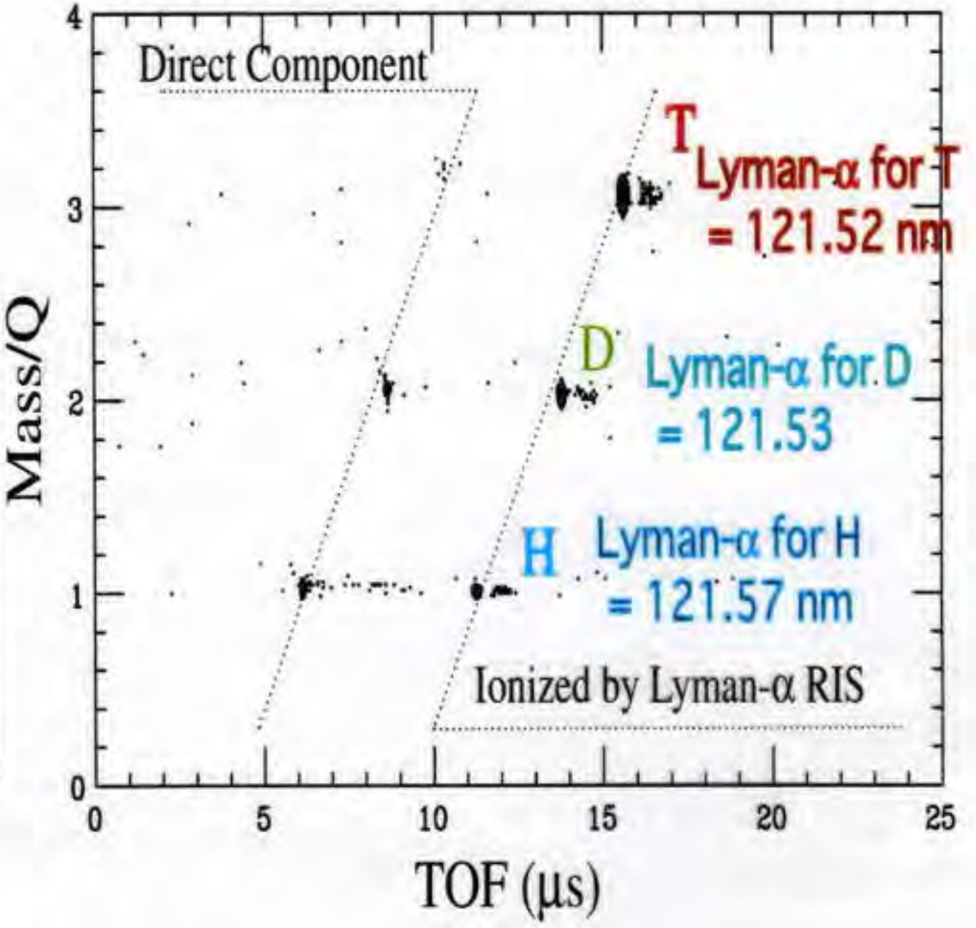


Muonium atom is consisting of a lepton pair.

STEP3: Generation of slow μ^+ and t^+, d^+, p^+ @KEK

@KEK 5 μA Muon Source





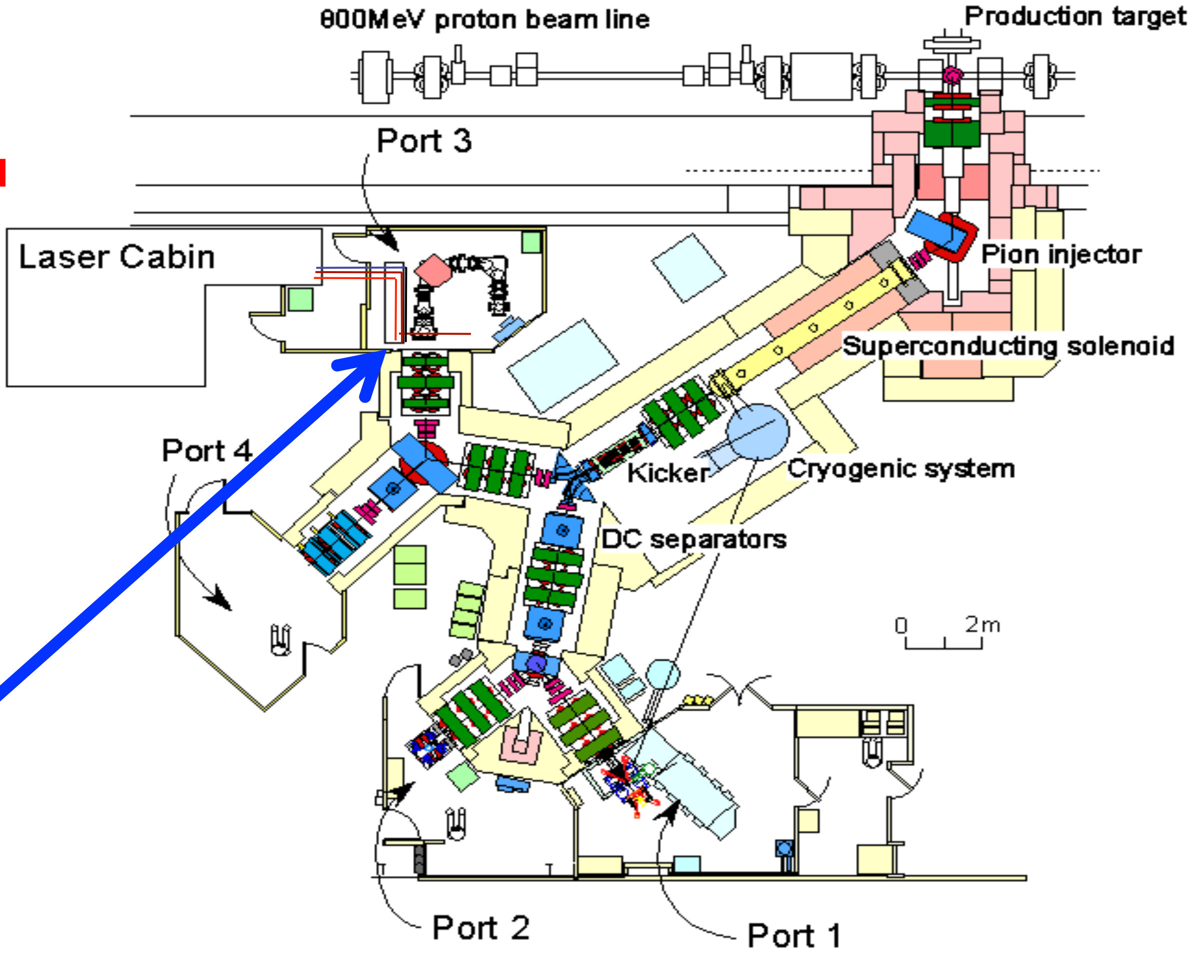
Mu resonant ionization

T,D, H resonant ionization

STEP4: **Performance** investigated through Preliminary Experiments held at RIKEN-RAL, **UK**

We established the way of how to generate Ultra Slow Muon by the Resonant Ionization of Mu at KEK, but Muon Intensity at KEK-MSL was too low!

From KEK, We brought all the slow optics and Laser system to Port3 (RIKEN-RAL) in order to do R&D efficiently!

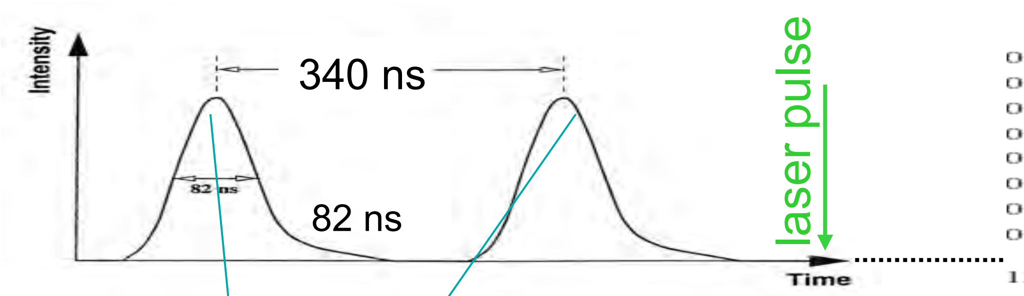


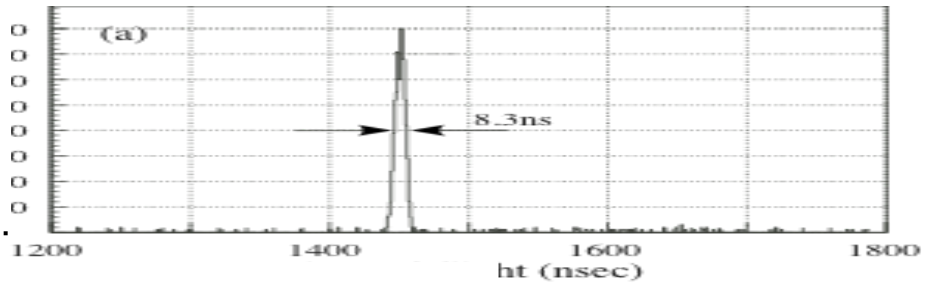
The RIKEN-RAL Muon Facility

STEP4: High Temporal Resolution (8.3 ns (Now we are using ns laser system to ionize Mu.) → 1 ns)

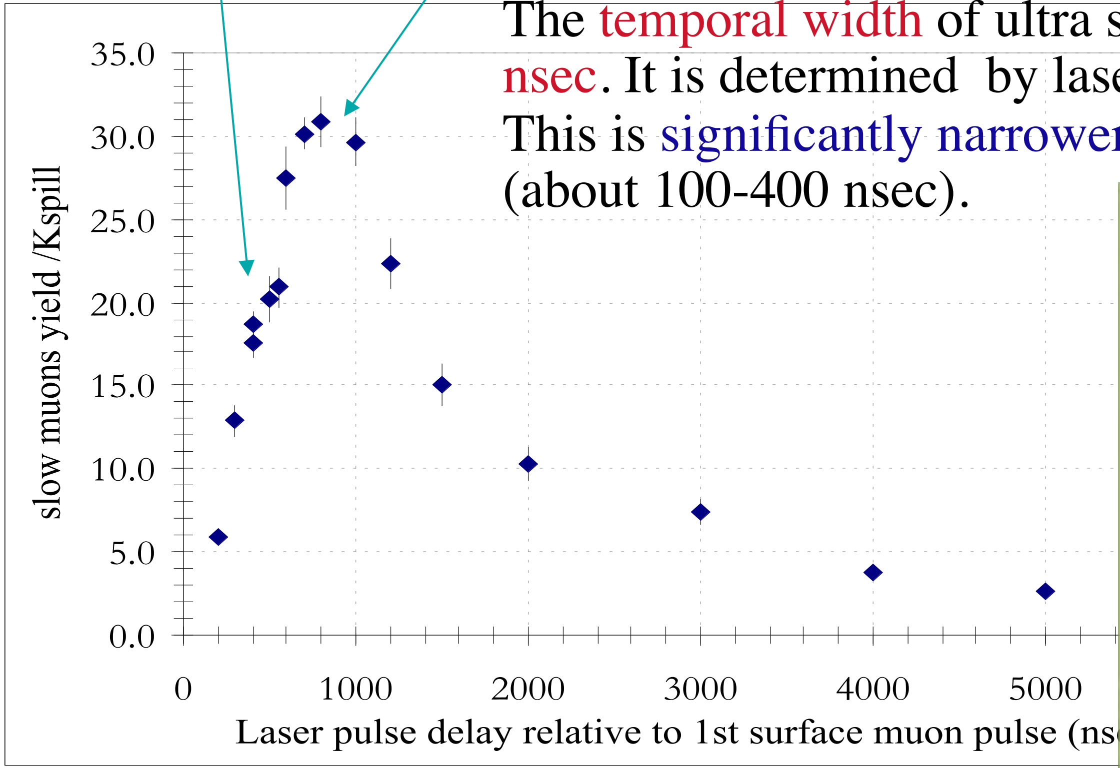
ISIS muon pulse structure

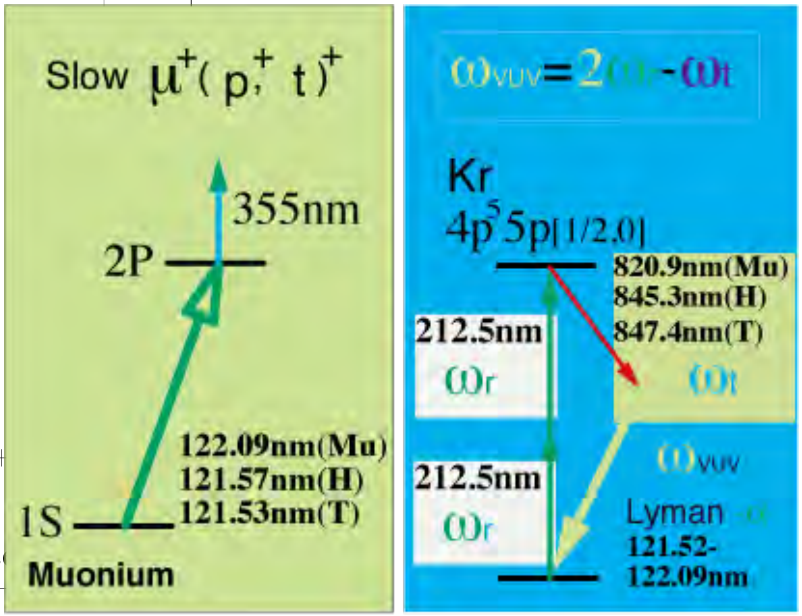
LE muon TOF





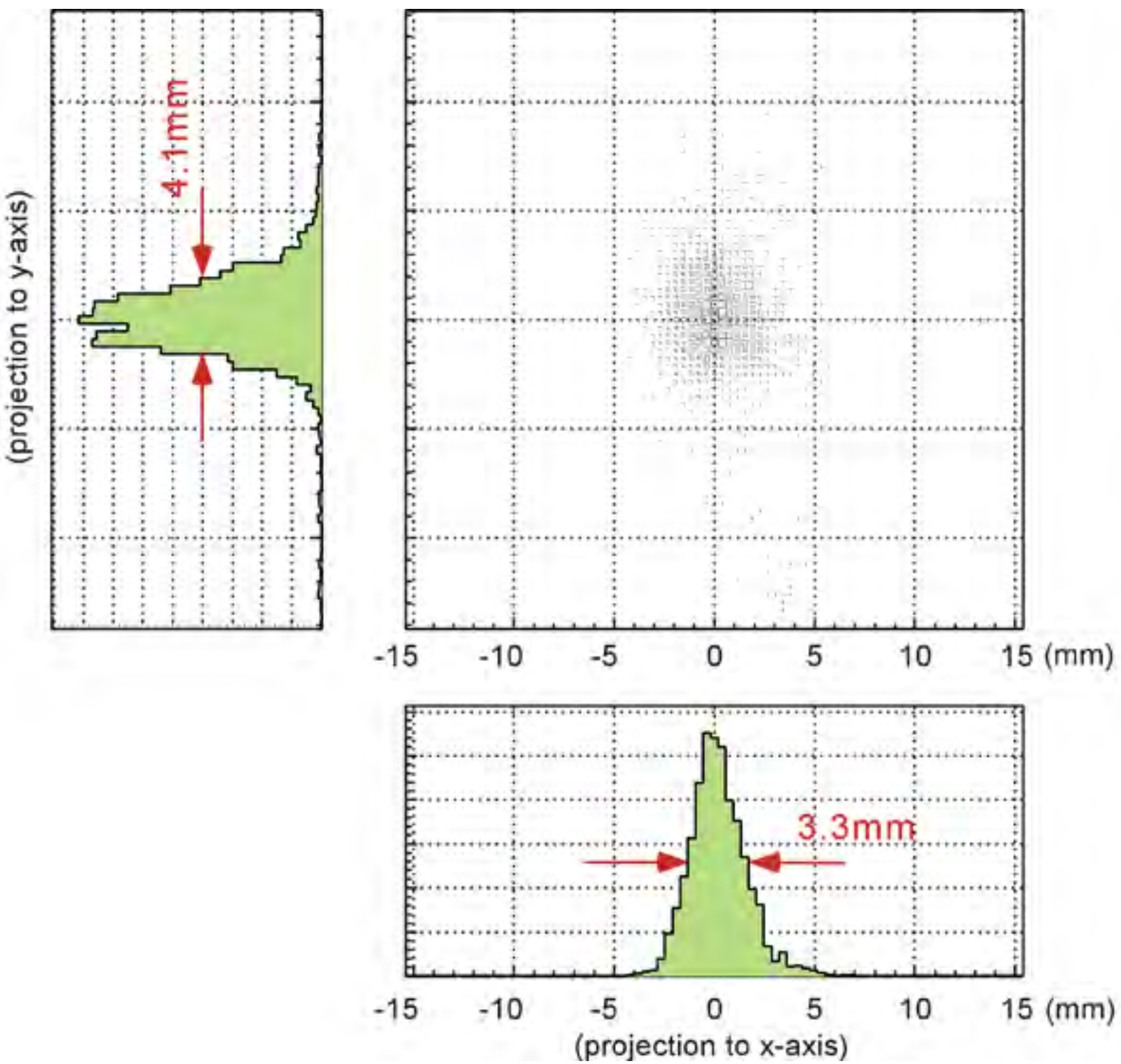
The temporal width of ultra slow muon beam was about 8.3 nsec. It is determined by laser pulse width!
This is significantly narrower than that of initial muon beam (about 100-400 nsec).





STEP4: Small Beam Size (ϕ ~ 4 mm (Now) → ϕ 1 mm) → ϕ 10 μm by accelerating 1MV at J-PARC

Demonstrated at RIKEN-RAL



The beam profile was measured by a position sensitive MCP at the sample position.

The beam width was **4.1mm (x-axis)** and **3.3mm (y-axis)** with 9.0keV beam energy.

(The size of initial muon beam was about **ϕ 50 mm** at 4.1MeV beam energy.)

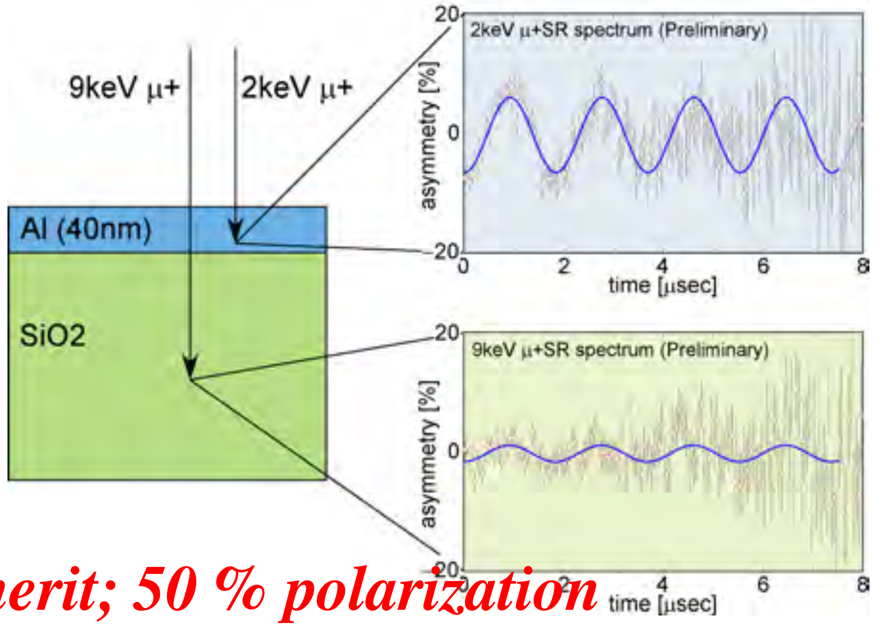
STEP4: Variable Implantation Depth (from 1 – 18 keV)

Demonstrated at RIKEN-RAL

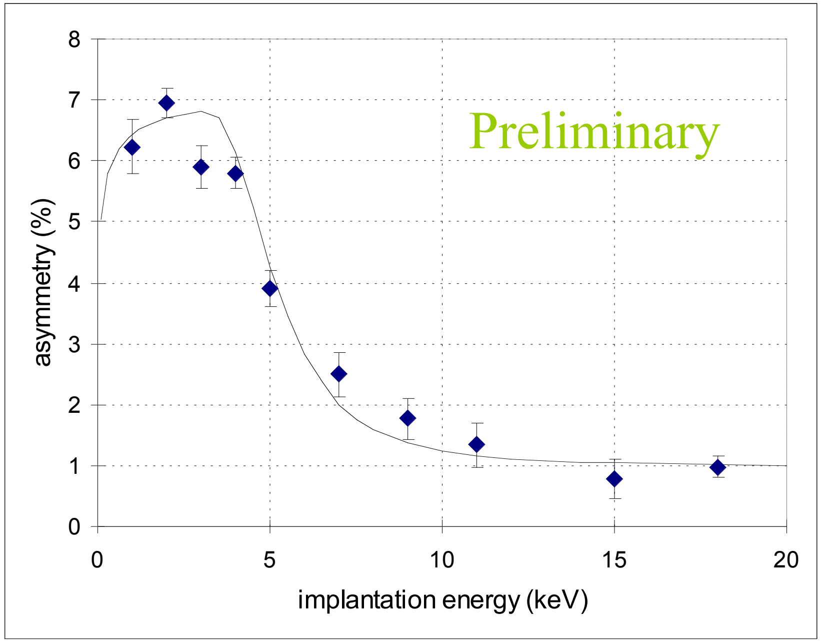
- We have demonstrated that we can control muon's range within 10nm resolution by changing implantation energy from **1~18keV**. (→ 0.05 -30 keV at J-PARC)

→ provides magnetic probe with depth resolution

→ application for study of surface/interfaces and multilayers



Demerit; 50 % polarization



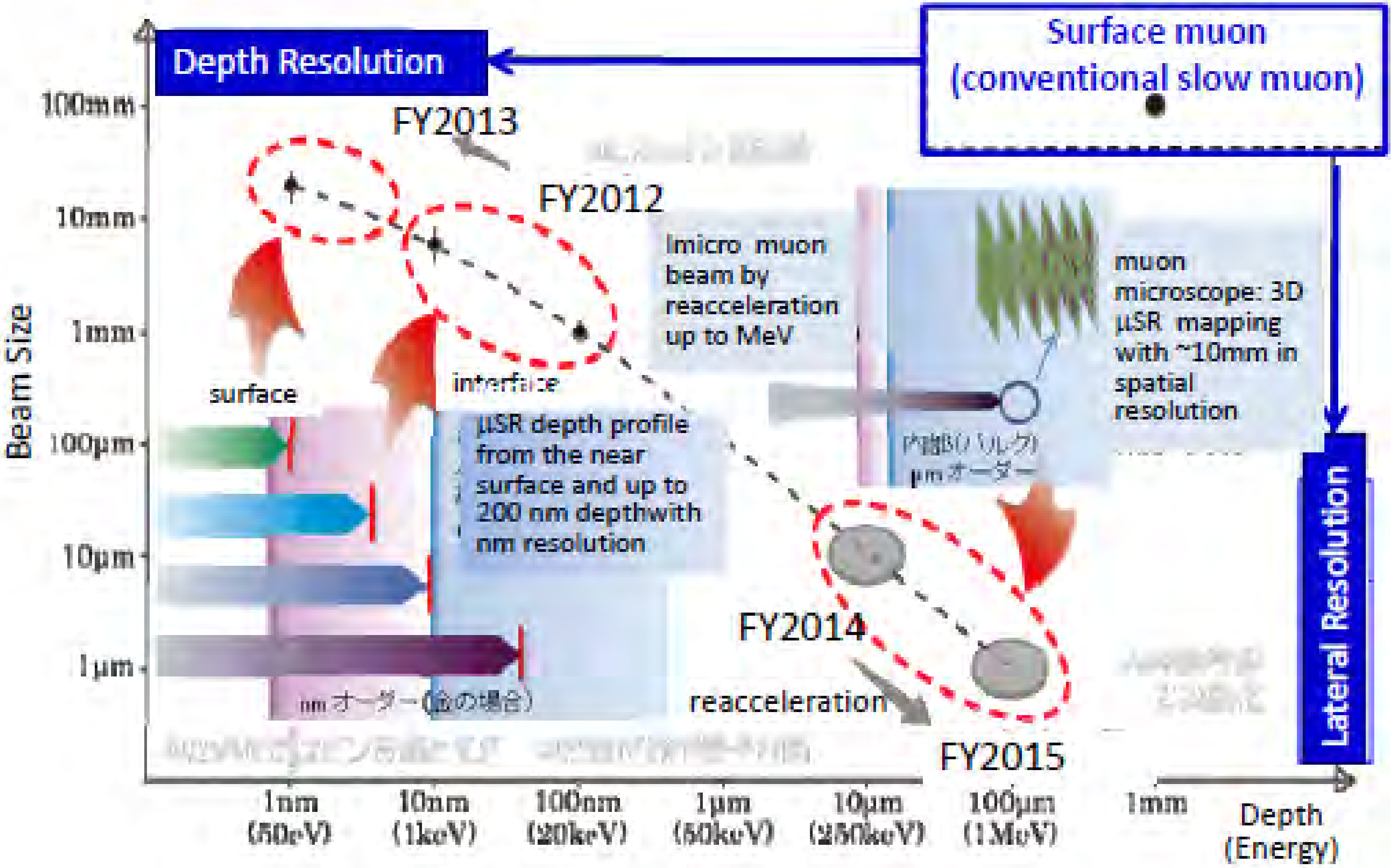
STEP4: Features of Ultra Slow Muon by Laser Resonant Ionization, *featuring three kind of Shortening!*

1. Variable Implantation Depth (~nm resolution)
2. Small Beam Size (ϕ ~ 4 mm (Now) → ϕ 1 mm)
3. High Temporal Resolution (8.3 ns (Now we are using ns laser system to ionize Mu.) → 1 ns)
4. Synchronized with pulsed perturbation
5. Very Low Bg. --> Very small Relaxation

But, only 20 slow muons/s at RIKEN-RAL→J-PARC ***U-Line***

Depth and Beam Size Scanned by Ultra Slow Muon Microscope

with Development Scenario



Surface muon (conventional slow muon)

Imicro muon beam by reacceleration up to MeV

muon microscope: 3D µSR mapping with ~10mm in spatial resolution

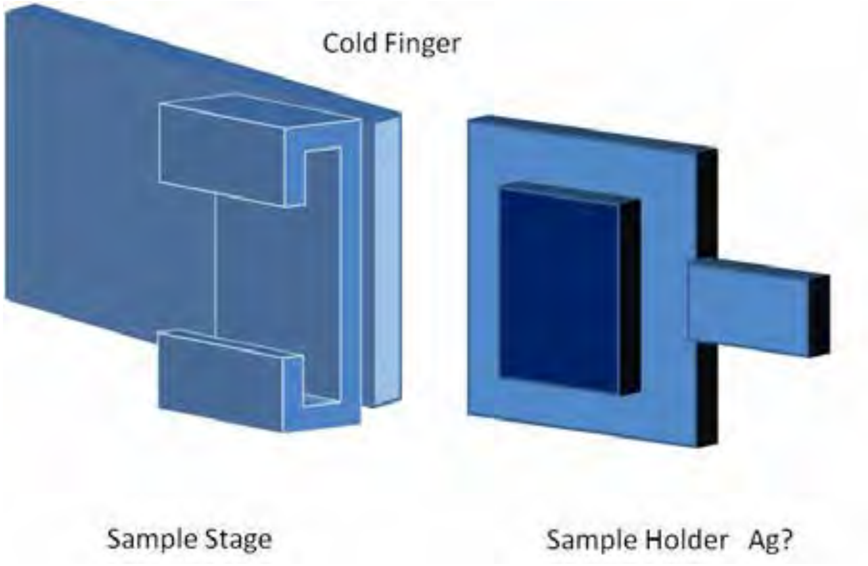
µSR depth profile from the near surface and up to 200 nm depthwith nm resolution

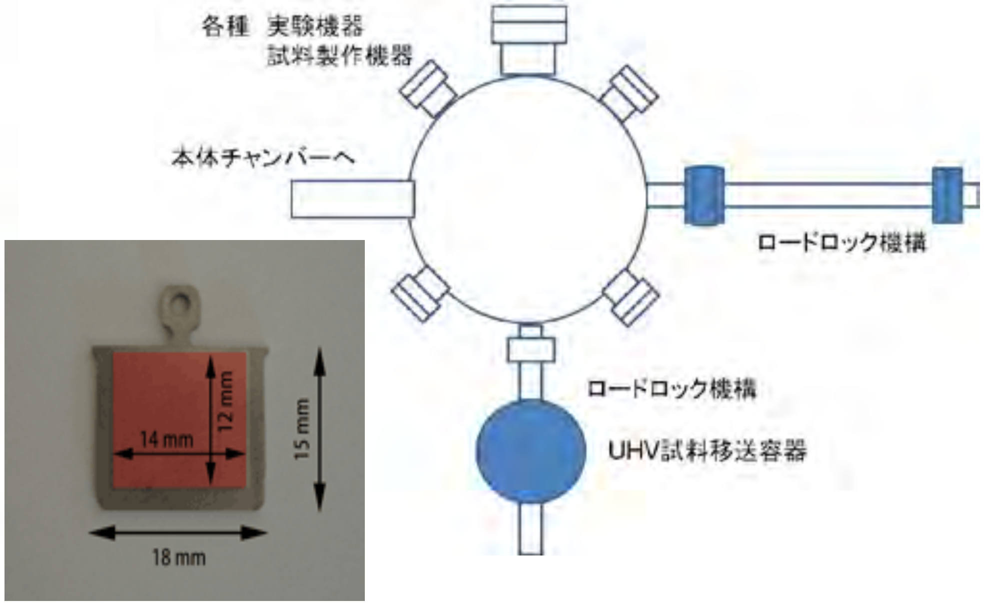
Comparison of features of slow muon beam obtained by the cryogenic moderator using solid Ne, or Ar and the laser resonant ionization

	Laser Resonant Ionization	Cryogenic Moderator (Ar, N_2)
Muon Facility	J-PARC(U-LINE),KEK, RIKEN-RAL	PSI, TRIUMF
Beam Energy	0.05 - 30 keV -> 1 - 200 nm	0.5 - 30 keV -> 10 -200 nm
monochromacity	14 eV(before acceleration 0.2 eV)	400 eV
Beam Size	ϕ 1 mm --> aiming at ϕ ~ μm	ϕ 10 - 15 mm
Temporal resolustion	seveal sub ns ~ ns	~ 10 ns
Polarization	50% (100 % under 3 kG LF)	92%
Intensity	20/s (RIKEN RAL), ~10^{5-6}/s (J-PARC)	10^{3-4}/s
Synchronization	Possible (can be synchronized)	not possible

試料ホルダーを共通化、交換を容易に（試料の付け方などは個々の試料で検討）

ロードロック機構　　真空を壊さずに試料の移送と挿入を可能に





磁石等　製作中

中心磁場分布　電流=417A