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!**

- **S-Line**
- **H-Line**
- **U-Line**
- **D-Line**

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

G-2, DeeMe Mu-Hf experiments etc. are planned
Edge-cooling Graphite Fixed Target
At Present!

Investigated during shut-down!

Rotating Graphite Target
From January 2014!

Will be changed in Summer 2013!

Fixed Target

Rotating Target
**S-Line**
Surface $\mu^+(30\text{ MeV/c})$
For material sciences

**U-Line**
Ultra Slow $\mu^+(0.05-30\text{keV})$
For multi-layered thin foils, nano-materials, catalysis, etc

**D-Line**
Surface $\mu^+(30\text{ MeV/c})$
Decay $\mu^+ / \mu^-$ (up to 120 MeV/c)
Users’ RUN, in Operation

**H-Line**
Surface $\mu^+$ For HF, $g$-2 exp.
$e^-$ up to 120 MeV/c For DeeMe
$\mu^-$ up to 120 MeV/c For $\mu$CF
At the J-PARC Muon Facility (MUSE), the intensity of the pulsed surface muon beam was recorded to be $1.8 \times 10^6$/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 $1.5 \times 10^7$/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.
Muon Kicker System

- Muon pulse

(a) Time structure of muon pulse before kicker

(b) Fast raising B-field which is synchronized to muon pulse

(c) Time structure of muon pulse after Kicker

Single Pulse can be obtained.

Graphical representation showing the time structure of muon pulses before and after the Kicker, with Fast raising B-field synchronized to the muon pulse.
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.
Non-destructive analysis of Meteorite

Terada et al.

![Diagram showing layers and elements analysis](image)

<table>
<thead>
<tr>
<th>Layer</th>
<th>Material</th>
<th>Thickness $\times \sqrt{2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st layer</td>
<td>SiO$_2$</td>
<td>2.115</td>
</tr>
<tr>
<td>2nd layer</td>
<td>graphite</td>
<td>3.5391</td>
</tr>
<tr>
<td>3rd layer</td>
<td>BN</td>
<td>5.3439</td>
</tr>
<tr>
<td>4th layer</td>
<td>SiO$_2$</td>
<td>7.4166</td>
</tr>
</tbody>
</table>

![Graph showing energy levels and elements](image)
1. Solid State Physics (Magnetism•Superconductor)
   1. μSR Study of Organic Antiferromagnet $\beta'-(\text{BEDT-TTF})_2\text{IBrCl}$
   2. μSR in Ironpnictide superconducto Phys. Rev. Lett. 103 027002 — The first PRL @J−PARC
   4. novel phase transition in f-electron system - high-order “multipole” ordering


2. Material Science (Li Batteries, Alloy, Voids)
   2. CaFe$_2$O$_4$–type NaMn$_2$O$_4$ and LiMn$_2$O$_4$
   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 ChEmetry
   1. Investigation of molecular effect in the formation process of muonic atom
   2. Mu(μ$^+$/μ$^-$) formation mechanism in condensed matters

4. Particle Physics
   1. μ$^-$ + A(Z,N) → e$^-$ + A(Z,N) rare decay

5. Non-destructive analysis, Radiography
   2. Muon Radiography

6. Beam Development
   2. Ultra Slow Muon

Studies explored at MUSE D-Line

Either Surface muon (μ$^+$) or Decay muon (μ$^+$/μ$^-$) up to 120 MeV/c available!
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 ($\mu^+$) 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 ($\mu$s 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 $\mu^+$ 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!**

$4\text{MeV} \to 0.2\text{eV} (7\text{ order\ cooling})$
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.


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

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.
Dedicated beam line to produce **Ultra Slow muon**

(\(E = 0.05 - 30 \text{ keV}\)) with high intensity and high luminosity.

5.0 \(\times\) 10^8 /s surface muons, 20 times more intense than **D-line** which is the strongest at present!
Normal Conducting MIC Capture Solenoid

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum current</td>
<td>1500A</td>
</tr>
<tr>
<td>Peak central field</td>
<td>0.3T</td>
</tr>
<tr>
<td>Coolant</td>
<td>130 l/s</td>
</tr>
<tr>
<td>Muon capture rate</td>
<td>$5 \times 10^8 \mu^+ /s @ 30 \text{ MeV}/c$</td>
</tr>
<tr>
<td>Solid angle acceptance</td>
<td>400 mSr (±20° initial angle, ~10 times larger)</td>
</tr>
</tbody>
</table>

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!

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

- Exit of curved solenoid
- Thin lenses
- Experimental target
- Beam Brocker
- Focusing solenoid
- Positron separator

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

≈ 8000 mm

Funded, Many thanks to KEK Directors & J-PARC Director
Superconducting Axial Focusing Magnets
Surface $\mu^+$ stopping on W, Commissioning from Oct. 18th,

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

$\sigma = 18$ mm, Focal length 460 mm
$\sigma = 25$ mm, Focal length 700 mm

Beam profile at the final focusing point (700mm)

Intensity: $2 \times 10^8$ $\mu^+$/s, on W (70 x 40 mm$^2$) (@1 MW)
Intensity: $1.2 \times 10^6$ ($\rightarrow 0.5 \times 10^6$) $\mu^+$/s, on W (40 x 35 mm$^2$) @RIKEN-RAL

$1.2 \times 10^6$/s is surface $\mu^+$ arriving at Port3, could be less than $0.5 \times 10^6$/s stopping on W
U1A Area
Thin film $\mu$SR
H reaction on Surface
eq etc.

2 x $10^8$/s surface muon
(161 times more intense)
than RIKEN/RAL.

A01 team

A04 team

Curved Solenoid
Focusing Solenoid

U1B Area
Micro Beam($\mu$m)
by acceleration
A01 : Generation of Ultra Slow Muons

J-PARC 4 MeV muon
Mu target
Thermal Mu (Mu ; $\mu^+ e^-$)

Mu generator

J-PARC 4 MeV muon
Beam window
Ultrahigh vacuum
Mu target
Thermal Mu
Ultra slow muon
SOA Lens
Electrostatic Quadrupole Lens
Mass separation device

RF acceleration
0.05 keV-10 MeV
Beam size
1 mm $\phi$ - 10 $\mu$m $\phi$

Lyman-$\alpha$ laser generation and Mu dissociation by laser resonant ionization method
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. 19-30\textsuperscript{th}, 2012
Spectrometer
Specification of Spectrometer (1st stage)
- Magnetic Field 0-1400G (Normal conducting)
- Temperature 10-15K (He flow cryostat)
- Vacuum (10⁻⁸Pa)
- e⁺ counters, MPPC (256ch)
- Floated by 30kV
Pump Laser1: 2photon resonance frequency = 212.55 nm

DFB-LD → LD pump Nd:GdVO₄ Multiamp → Fiber Amp → 5 HG

100 mJ @212.55 nm

Kr 4p⁵⁵p → ω₁

ω₁ = 212.55 nm

ω₂ = 815 nm

ω₁ - ω₂

Lyman-α intensity 100 times

Ultra Slow Muon for sure 10⁵-⁶/s

Pump Laser2: 815-850 nm variable

DFB-LD → LD pump Cr:LiSAF Multi amp stage

100 mJ @815-850 nm

Kr 4p⁶

ω₁

212.55 nm

ω₂

815 nm

ω₂ - ω₁

Lyman-α

100 µJ @122 nm

Nd:GdVO₄ Laser Crystal

Directly emitting 212(x5)nm

Much better efficiency (Wada)
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
   \[2.0 \times 10^8 \text{ /s} \div 1.2 \times 10^6 \text{ /s (RIKEN-RAL)} = 161 \text{ times (400)}\]

3) Lyman-α Intensity by Laser Development
   \[71 \mu\text{J/p} \div <1 \mu\text{J/p (RIKEN-RAL)} \sim 100 \text{ times}\]

Our Goal of Ultra Slow Muon Yield is

\[20 \text{ /s} \times 2 \times 161 \times 100 = 0.6 \times 10^6 \text{/s (Maximum)}\]

Riken-RAL Slow Muon Intensity Started with realistically, 10³/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

STM/STS µ+

50ev-30keV scanning

Bi$_2$Sr$_2$CaCu$_2$O$_x$

Unit cell

Resolution 1nm

1.54nm

3.07nm

Depth

Variable

(1-300 nm)

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
Chemical Evolution in Cosmic May occur on the surface of ICE

H reaction on the nano Surface quite different from bulk

- Surface H → Isomerization
- Adsorbed H → Hydrization


Main Cast is H

\[ \text{CO} + 3\text{H} \rightarrow \text{CH}_3\text{O} \]

\[ \text{H} + \text{H} \rightarrow \text{H}_2 \]

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

Fe [001]  
MgO [001]  
Fe [001]

Spin implantation depends upon Atomic spin state on the boundary

Observing spin state on the boundary between Ferro/insulator

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

Spin Transport and Reaction at Interface


According to Prof. Yoshino
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 \( \mu \)g to ng sample

Ordinary muon beam

- 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 size -> \( \sim \Phi 70 \text{mm} \)
- Depth resolution -> a few nm

- Minimum beam size -> \( \sim \Phi 1 \mu \text{m} \)
- Depth resolution -> order of \( \mu \text{m} \)

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

- 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 Battery compound etc.)

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

3D mapping of magnet domain inside sample
S-Line

Surface $\mu^+$

For material sciences

H-Line

Surface $\mu^+$ for HF, g-2 exp.

e$^-$ up to 120 MeV/c for DeeMe

$\mu^-$ up to 120 MeV/c for $\mu$CF

Installation in the vicinity of production target @Summer, 2012
S-Line
例：高速汲用装置「μPMS」…時間積分法で大強度をフル活用

S1：Dilution μSR
S2：Laser, RF μSR
S3：High Time resolution μSR
S4：μPMS

μPMS
Sライン
「μSR利用拡大」
H-Line; Projects submitted to IMSS MUSE

○ Mu Hyperfine precise measurement (30MeV/c)

○ “g-2” (30MeV/c) \(\rightarrow\) Ultra Slow Muon:
  Precision Measurement of Anomalous Magnetic Moment
  Muon Precision Experiment to search for New Physics

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

① Mu HFS experiment

μ-e conversion
SiC rotating target

Mu HFS experiment

Muon Frontend

Muon Transport

Muon Accelerator 15億円

Muon Storage

② Deeme; μ-e Conversion

③ g−2

Kicker, Separator

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

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

Muon Target

3GeV Proton

S4-5-6 successfully Installed

By Kawamura, Koda, Strasser et al.
H-Line

To Neutron Source

3GeV Proton

Muon Target

By Kawamura, Koda, Strasser et al.

HS1, HS2, HB2 successfully installed on Sep. 15th
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 thermal Mu in vacuum

- Z: Distance from hot target, Mu takes more time to reach further distance.
- About 4% of stopped muons evaporate into vacuum, as thermal Mu.

From Mills et al.
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
STEP3: Generation of slow $\mu^+$ and $t^+$, $d^+$, $p^+$ @ KEK

@KEK 5 $\mu$A Muon Source

Mu resonant ionization

T, D, H resonant ionization
STEP 4: 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!
STEP4: High Temporal Resolution (8.3 ns (Now we are using ns laser system to ionize Mu.) → 1 ns)

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 ($\phi \sim 4 \text{ mm (Now)} \rightarrow \phi 1 \text{ mm}$) 

$\rightarrow \phi 10 \mu\text{m}$ 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 $\phi 50 \text{ mm}$ 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 ($\phi \sim 4$ mm (Now) $\rightarrow \phi 1$ mm)
3. High Temporal Resolution (8.3 ns (Now we are using ns laser system to ionize Mu.) $\rightarrow 1$ ns)
4. Synchronized with pulsed perturbation
5. Very Low Bg. $\rightarrow$ Very small Relaxation

But, only 20 slow muons/s at RIKEN-RAL $\rightarrow$ J-PARC U-Line
Depth and Beam Size Scanned by Ultra Slow Muon Microscope with Development Scenario
Comparison of features of slow muon beam obtained by the cryogenic moderator using solid Ne, or Ar and the laser resonant ionization

<table>
<thead>
<tr>
<th>Muon Facility</th>
<th>Laser Resonant Ionization</th>
<th>Cryogenic Moderator (Ar, N$_2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J-PARC(U-LINE), KEK, RIKEN-RAL</td>
<td>PSI, TRIUMF</td>
<td></td>
</tr>
<tr>
<td>Beam Energy</td>
<td>0.05 - 30 keV $\rightarrow$ 1 - 200 nm</td>
<td>0.5 - 30 keV $\rightarrow$ 10 - 200 nm</td>
</tr>
<tr>
<td>monochromacity</td>
<td>14 eV(before acceleration 0.2 eV)</td>
<td>400 eV</td>
</tr>
<tr>
<td>Beam Size</td>
<td>$\phi$ 1 mm $\rightarrow$ aiming at $\phi$ $\sim$ $\mu$m</td>
<td>$\phi$ 10 - 15 mm</td>
</tr>
<tr>
<td>Temporal resolution</td>
<td>several sub ns $\sim$ ns</td>
<td>$\sim$ 10 ns</td>
</tr>
<tr>
<td>Polarization</td>
<td>50% (100 % under 3 kG LF)</td>
<td>92%</td>
</tr>
<tr>
<td>Intensity</td>
<td>20/s (RIKEN RAL), $\sim$ $10^{5-6}$/s (J-PARC)</td>
<td>$10^{3-4}$/s</td>
</tr>
<tr>
<td>Synchronization</td>
<td>Possible (can be synchronized)</td>
<td>not possible</td>
</tr>
</tbody>
</table>
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