NuFact10, Mumbai
201010.22

Low emittance, slow muon source for new g-2 experiment

K. Ishida (RIKEN) for

New g-2/EDM@J-PARC collaboration

What is this for?

Requirement on ultra cold muon beam for new g-2

Development plans

Search of thermal muonium emission target

(S1249 Experiment @ TRIUMF)

Laser and acceleration developments

Motivation of this development

Realizing muon storage ring without focusing electric or magnetic field for muon g-2

1. new muon g-2 measurement
   complimentary and with higher precision to BNL E821

2. Requirement : ultra cold muon beam
   ~300 MeV, $\Delta p_T/p_L \sim 10^{-5}$

Why muon g-2?

magnetic moment

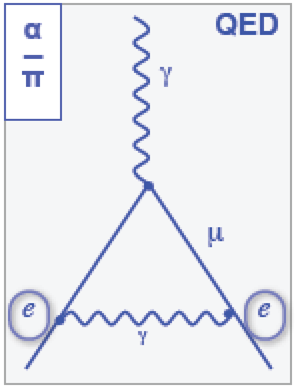
$$\vec{\mu} = g\left(\frac{e}{2m}\right)\vec{s}$$

m : magnetic moment

s : spin

g : gyromagnetic ratio

QED 1st order correction



Dirac equation : g=2

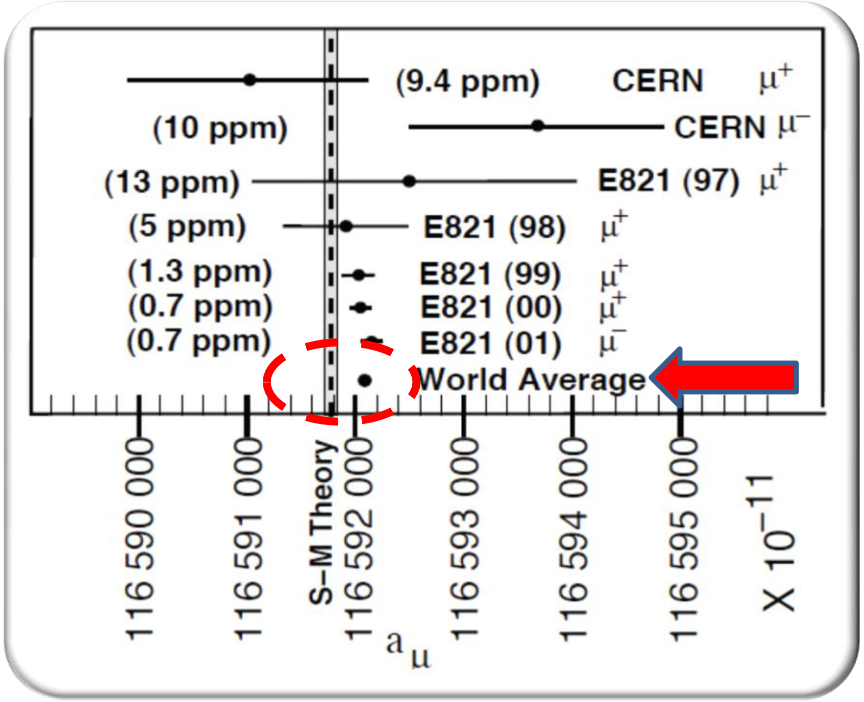
$$\mu = (1+a)\left(\frac{e\hbar}{2m}\right)$$

QED correction

$$a = \frac{g-2}{2} = \frac{1}{2}\left(\frac{\alpha}{\pi}\right) - 0.3248\left(\frac{\alpha}{\pi}\right)^2 + \ldots.$$

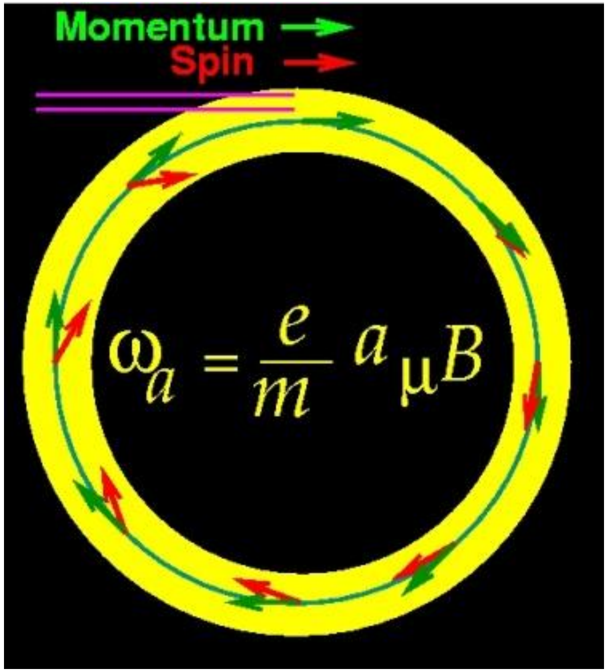
Inconsistency observed at BNL E821

$$\Delta a_\mu^{(\text{today})} = \Delta a_\mu^{(\text{Exp})} - \Delta a_\mu^{(\text{SM})} = (295 \pm 88) \times 10^{-11}$$



How to measure a_μ =(g-2)/2

Detect the muon precession frequency in the uniform magnetic field $\overrightarrow{B}$



$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = \frac{e}{m_\mu}\left(\frac{g_\mu - 2}{2}\right)\vec{B} \qquad \vec{\omega}_a = \frac{e}{m_\mu} a_\mu \vec{B}$$

$$\frac{\Delta a_\mu}{a_\mu} = \frac{\Delta\omega_a}{\omega_a} \oplus \frac{\Delta B}{B}$$

< 0.1 ppm

< 0.1 ppm

BNL muon g-2 experiment

Muon storage ring with homogeneous magnetic field

+ Muon focusing by electric quadrupoles

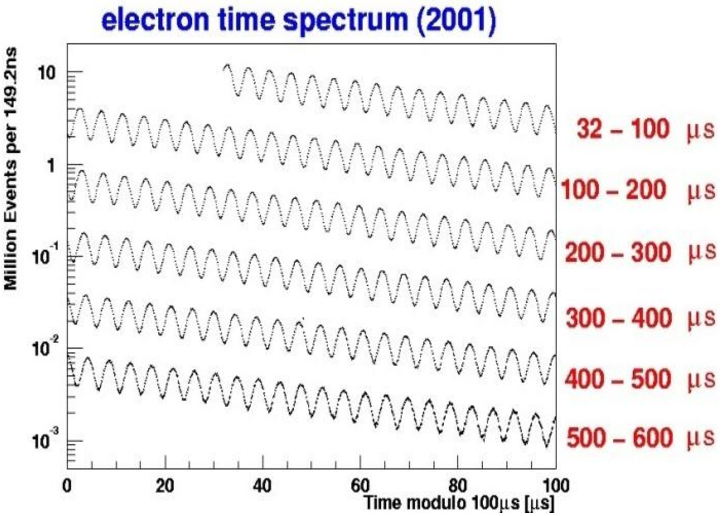
using magic momentum (3.09 GeV/c)

$$\vec{\omega}_a = -\frac{e}{m_\mu}\left[a_\mu \vec{B} - \cancel{\left(a_\mu - \frac{1}{\gamma^2-1}\right)} \frac{\vec{\beta}\times\vec{E}}{c}\right]$$

Typical storage ring diameter 14m

Statistically limited but systematic error will also contribute

high energy pion contamination, field homogeneity of large magnet, …



New muon g-2 proposal using ultra-cold muon beam

N. Saito's talk in WG4, NuFact09

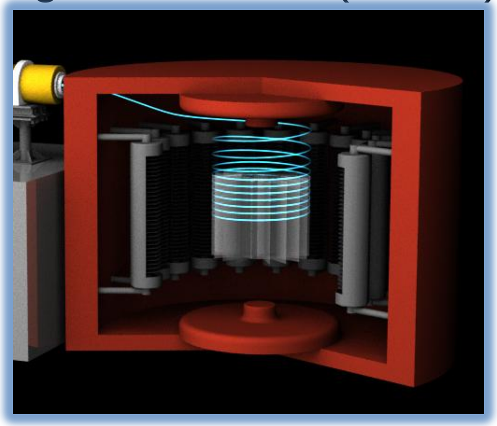
Muons with very small transverse momentum
stay in storage ring orbit
even without focusing electric field.
-> no need of magic momentum (3.1 GeV/c)

$$\vec{\omega}_a = -\frac{e}{m_\mu}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\cancel{\vec{E}}}{c}\right]$$

-> but reasonably high γ (300 MeV/c)
will help statistics (longer dilated lifetime)

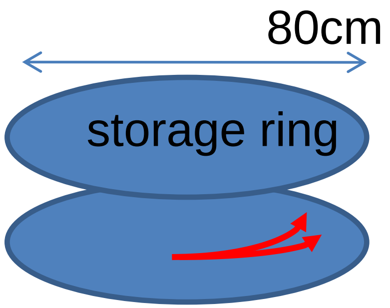
Benefits: Compact muon ring – better B field
Compact detectors – better resolution
Clean muon beam - no pion flash

Essential requirement is
high-intensity ultra-cold (well-aligned) muon beam



g-2@J-PARC (~0.8m)

Requirement on ultra-cold muon beam for g-2



Small beam divergence

$\sigma(p_T)/p_L = 10^{-5}$

will limit vertical spread in muon g-2 storage ring

to 80 mm after 4000 turns (~5 $\gamma\tau_\mu$)

For p_L=300 MeV/c (storage in 3T compact ring ~80cm),

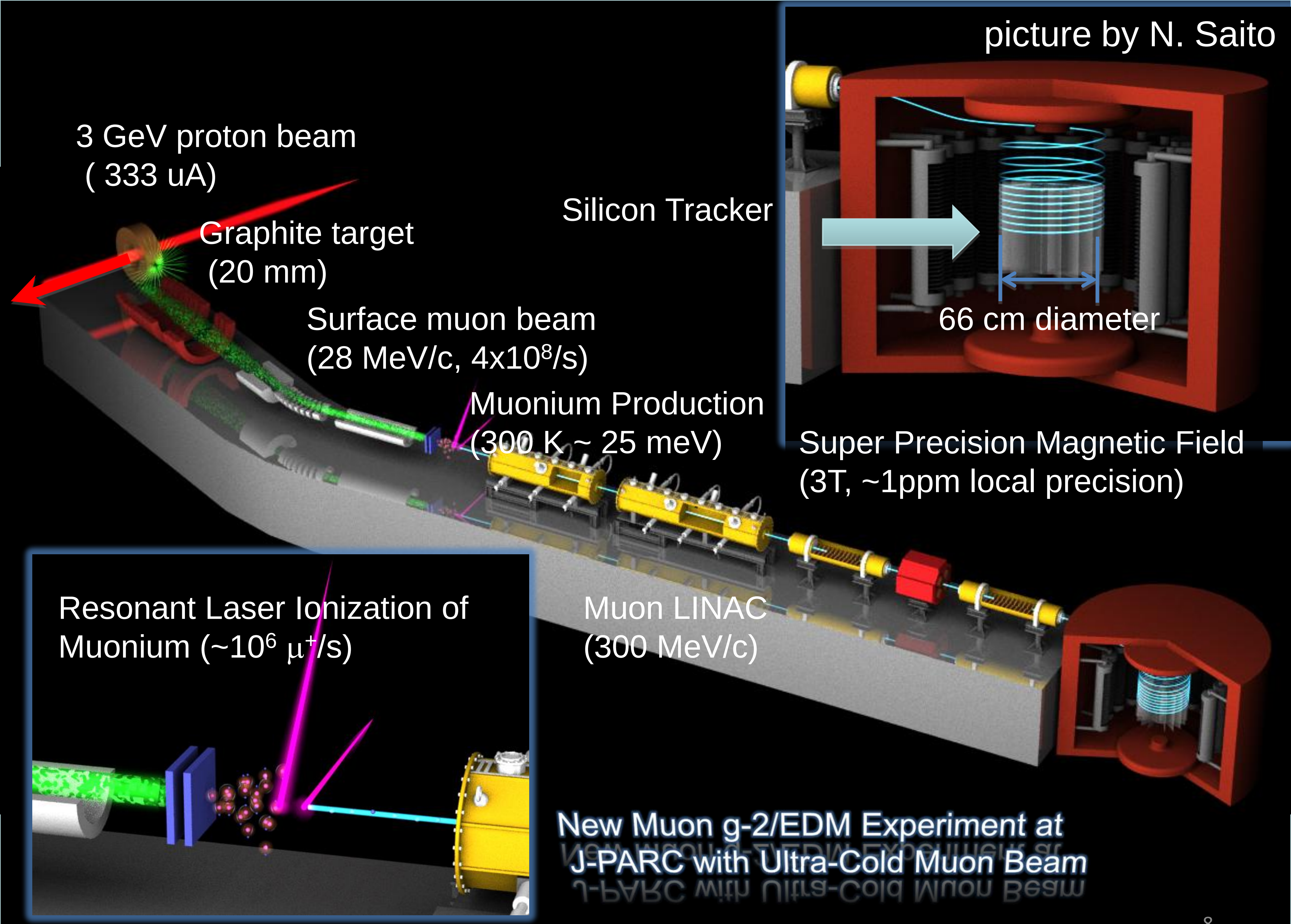
p_T should be < 3 keV/c (T ~ 0.045 eV = 500K)

This could be achieved by stopping muons in a target and accelerating muons reemitted from its surface.

Slow muon from hot tungsten (2100 K) is not cold enough without additional beam cooling.

We would better start with muonium emission at room temperature.

New Muon g-2/EDM Experiment at J-PARC with Ultra-Cold Muon Beam



picture by N. Saito

3 GeV proton beam
(333 uA)

Graphite target
(20 mm)

Surface muon beam
(28 MeV/c, 4x10^8/s)

Muonium Production
(300 K ~ 25 meV)

Silicon Tracker

66 cm diameter

Super Precision Magnetic Field
(3T, ~1ppm local precision)

Resonant Laser Ionization of
Muonium (~10^6 μ^+/s)

Muon LINAC
(300 MeV/c)

Comparison of g-2 measurements

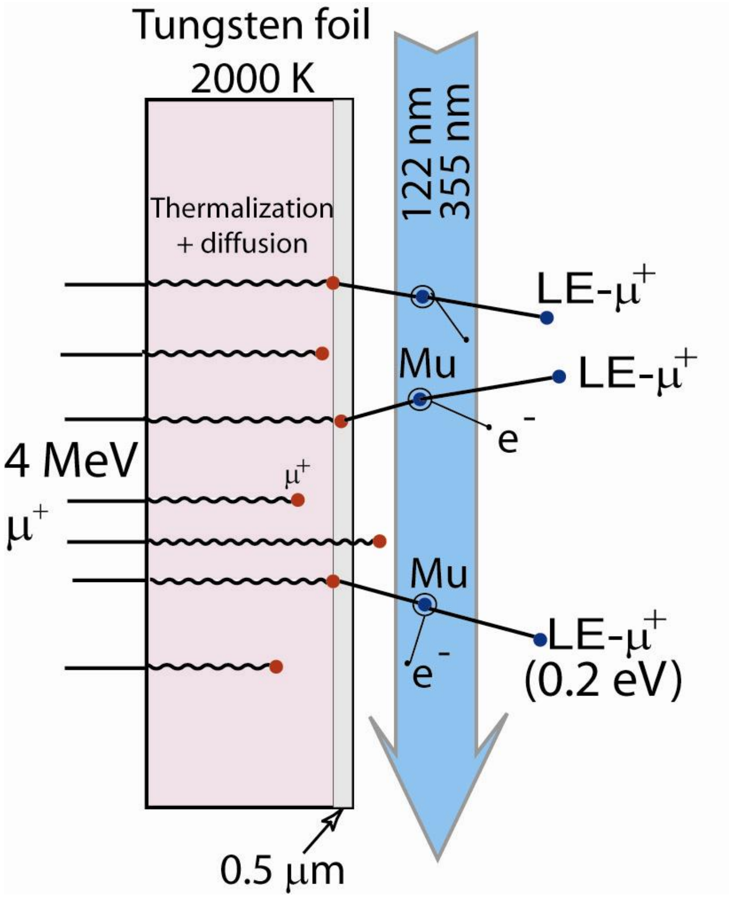
	BNL-E821	Fermilab	J-PARC
Muon momentum	3.09 GeV/c		0.3 GeV/c
gamma	29.3		3
Storage field	B=1.45 T		3.0 T
Focusing field	Electric quad		None
# of detected μ+ decays	5.0E9	1.8E11	1.5E12
# of detected μ- decays	3.6E9	-	-
Precision (stat)	0.46 ppm	0.1 ppm	0.11 ppm

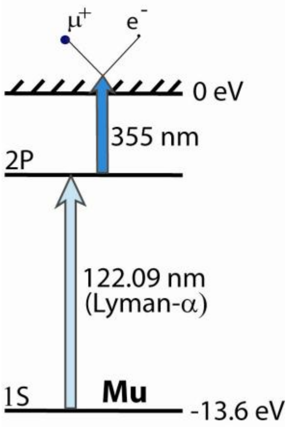
g-2@J-PARC based on 10^6 /s cold muons, 1 year run

How to achieve this?

Development of thermal muon source at KEK/RIKEN-RAL

4 MeV muons $\xrightarrow{2\%}$ 0.2 eV thermal Mu $\Longrightarrow$ 0.2 eV μ^+





122.09 nm (Mu)
121.57 nm (H)
121.53 nm (D)

- **two** laser beams necessary for resonant ionization
- required very broad laser bandwidth due to thermal movement of atoms

1S-2P saturation intensity

I_{sat}=2.3 W/cm^2 monochromatic<100MHz $\Longrightarrow$ I_{sat}=4.6 kW/cm^2 (Doppler 200GHz)

Main challenge: to generate VUV @ 122 nm and with 200 GHz (+ 1 ns jitter rel. to ext. trig.)

Slow muon beam: present status

Achievement at RIKEN-RAL by KEK-RIKEN Collaboration

Low energy μ^+ beam

Slow muon beam intensity ~ **15-20 μ^+/s**

(starting from 1.5 x 10^6 muons)

Beam diameter (FWHM): **4 mm**

Energy at target region **0.2 eV**

Energy after re-acceleration **0.1-18 keV**

Energy uncertainty

after re-acceleration ~14 eV

Pulse repetition rate **25 Hz**

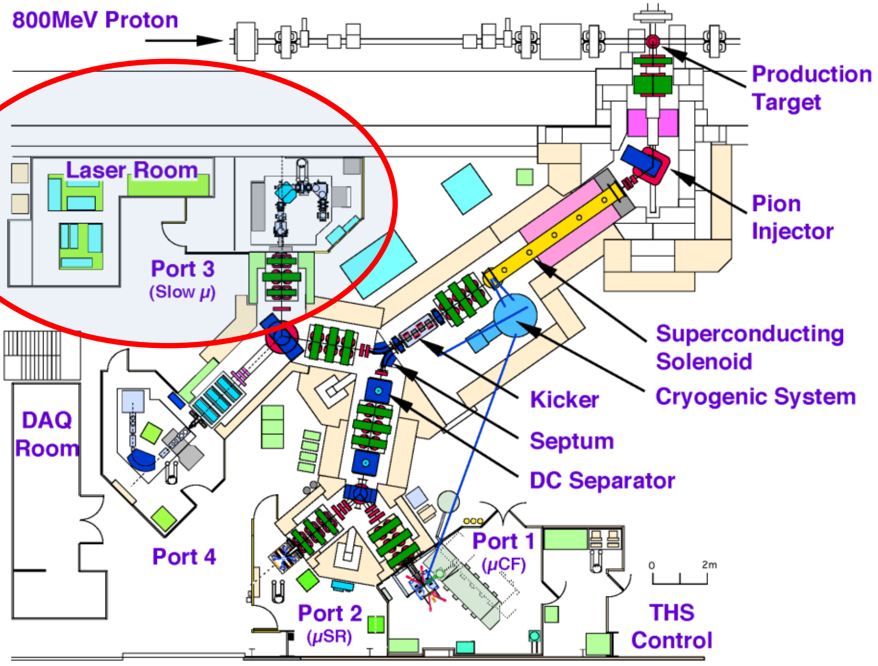
Single pulse structure

7.5 **ns** (FWHM) at 9.0 keV

Spin polarisation ~**50%**

Long time background < 1/250

Rutherford Appleton Laboratory
200 kW proton source



Overall efficiency was 10^{-5} based on hot tungsten target (2100 K)
We need lots of improvement in intensity and properties

Prospect for increasing the ultra-cold muon intensity for the new muon g-2

We aim 20/s => 10^6 /s ultra cold muon beam for muon g-2.

1. Stopped muon intensity (density)
    - -> Super omega & J-PARC (x300) (Miyake, Ikedo@NuFact10)
    - => 1~4 x 10^8
        - \+ Tapered tube (x2 ?) (Tomono@Nufact10 tomorrow)
2. Muonium emission efficiency (x1?)
    - 0.04 (@2100K) -> ? (room temperature materials)
    - test of candidate materials at TRIUMF
3. Laser ionization & repetition
    - S. Wada, Norihito Saito, K. Yokoyama, O. Louchev (x100 x2) => 0.2
4. Ultra-cold muon extraction optics (acceleration without heating)
    - design@RIKEN (M. Iwasaki, K. Tsukada) (~1 ?)

=> 10^6 /s

Mu producing materials

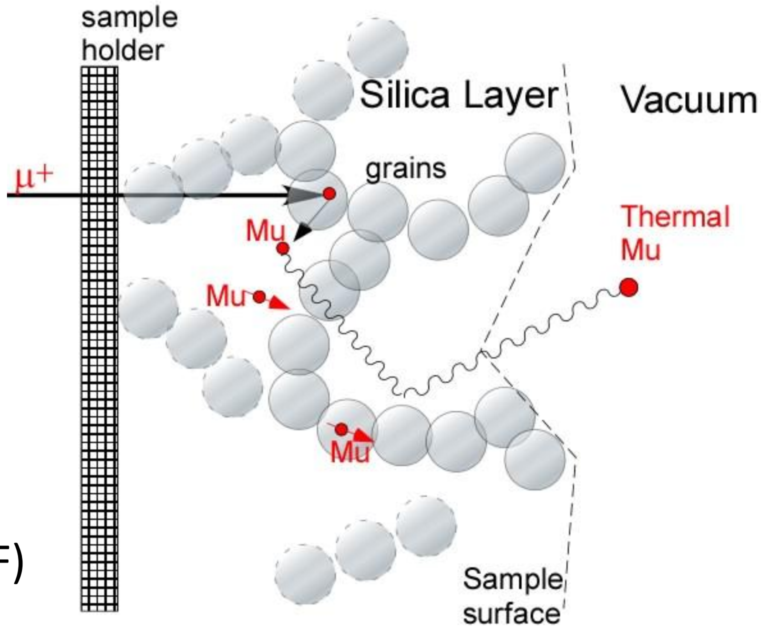
Two types of materials have been used so far

Hot tungsten (@2100 K)

Fast diffusion in thin W to surface at high temperature

Efficiency ~ 4% (4 MeV μ beam to Mu)

utilized for slow muon beam (KEK, RIKEN-RAL)



Silica Powder (@300 K)

Rapid diffusion in spaces between nano-particles

Efficiency ~4%

utilized for Mu 1S-2S(KEK, RAL), Mu-Mubar(PSI, LAMPF)

Comparison of Mu production from Hot W and Silica powder

	Hot W	Silica Powder
	2100K	300K
Energy spread	0.2 eV	x 1/7
Transverse momentum	6 keV/c	x 1/2.6
Doppler width	20 GHz	x 1/2.6
Mu area	large	small
Mu separation	large	small
Yield	3%	3%
Purity	High & stable	?
Heat emission	Large	none
Shape stability	could bend	need settle

-> Many advantages with room temperature target:
smaller source size, less Doppler broadening, …

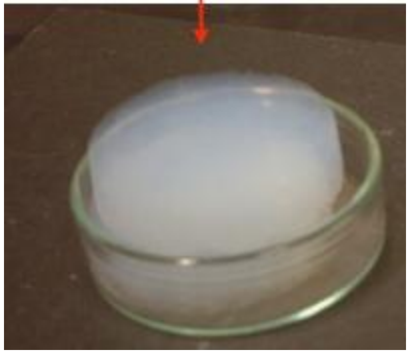
Plan for Muonium Production Target Study

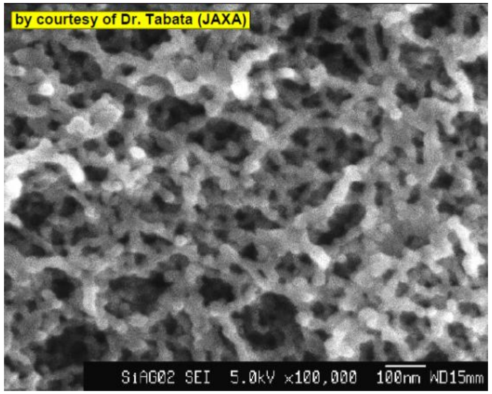
Silica powder is known to produce muonium
at room temperature
but it’s very fluffy and difficult to hold

2 G.M. Marshall

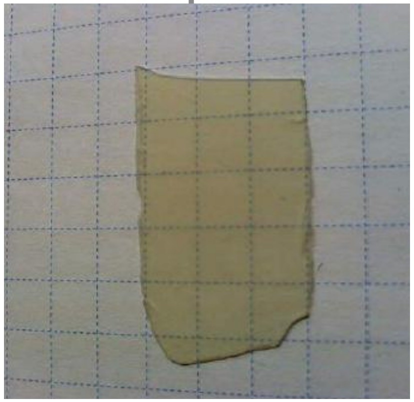
We made several new solid targets
with porous structure to study

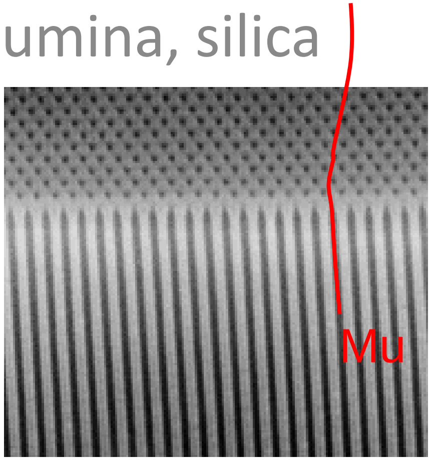
silica aerogel




by courtesy of Dr. Tabata (JAXA)

porous alumina, silica





Measurement of muonium emission yield by imaging

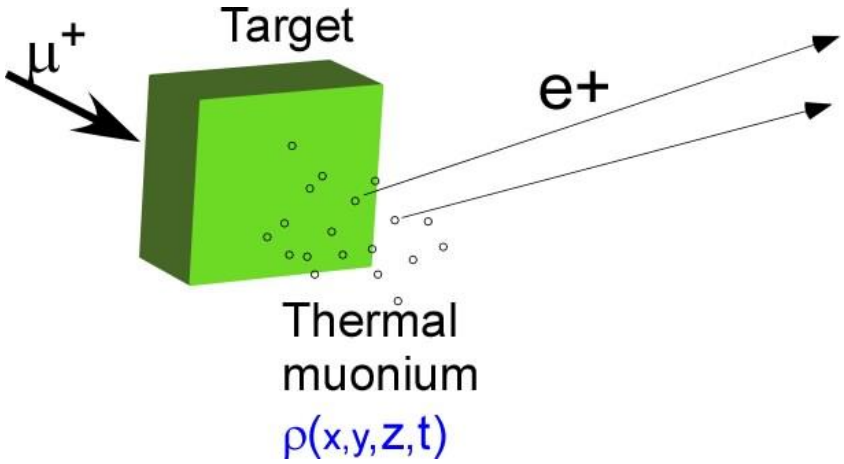
Muonium imaging to measure muonium yield and profile.

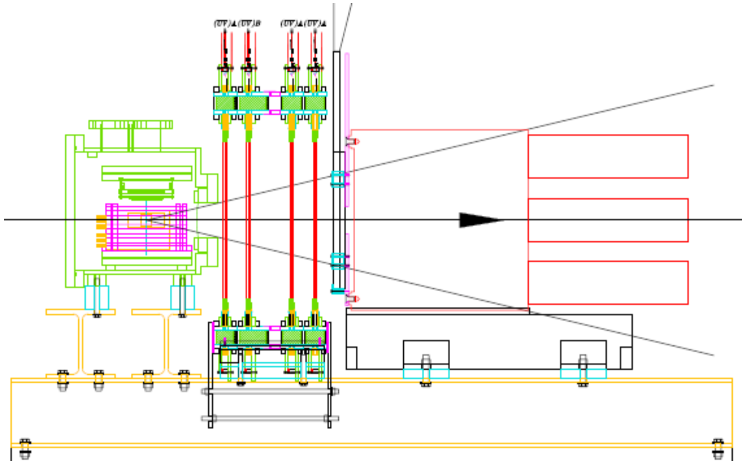
(Measurement at TRIUMF by RIKEN/KEK/TRIUMF collaboration
in this November)

1) Thermal muonium yield for various target => which gives best yield?

2) Spatial distribution of Mu vs timing (laser)

=> When and where can we effectively shoot ionizing laser?

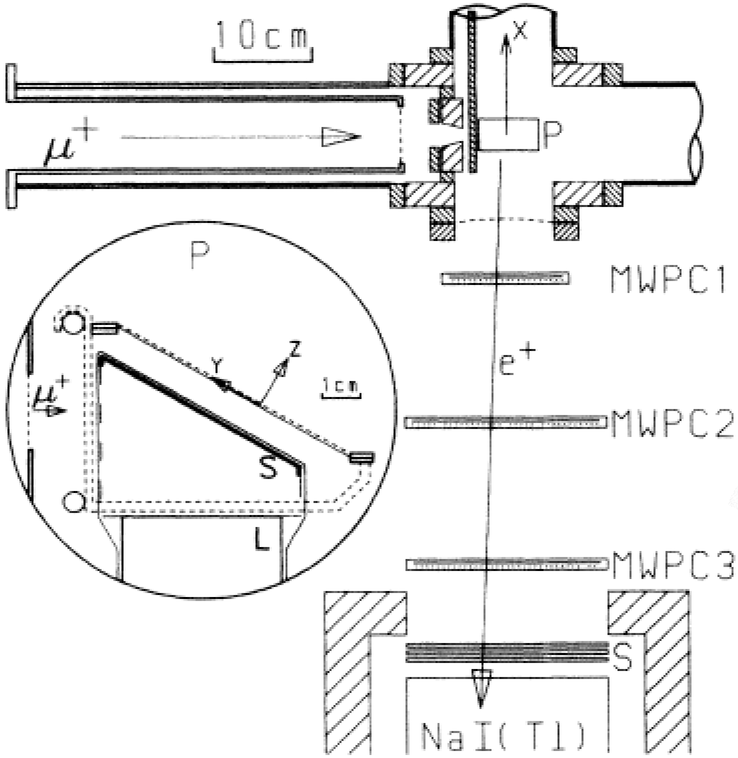


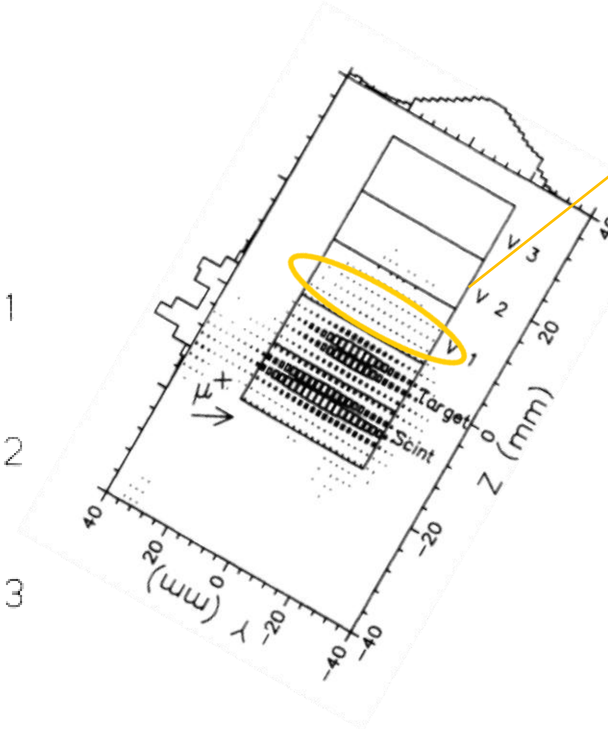


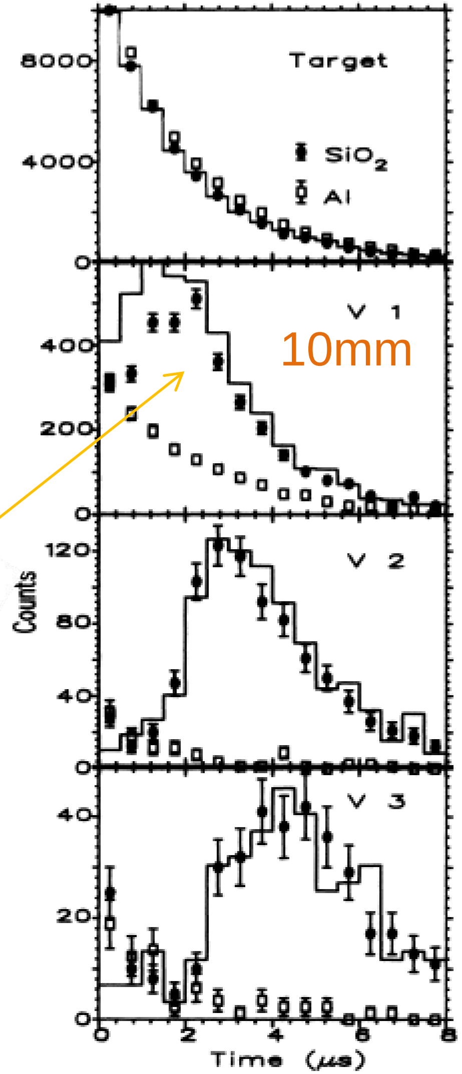
Previous measurement on SiO_2 powder

Typical measurement

- Beer et al, Phys.Rev.Lett. 57 (1986) 671
- Vacuum chamber + Target + MWPC
  - analysis based on 4 regions (each 10mm thick)
- measurement close target surface suffered from background

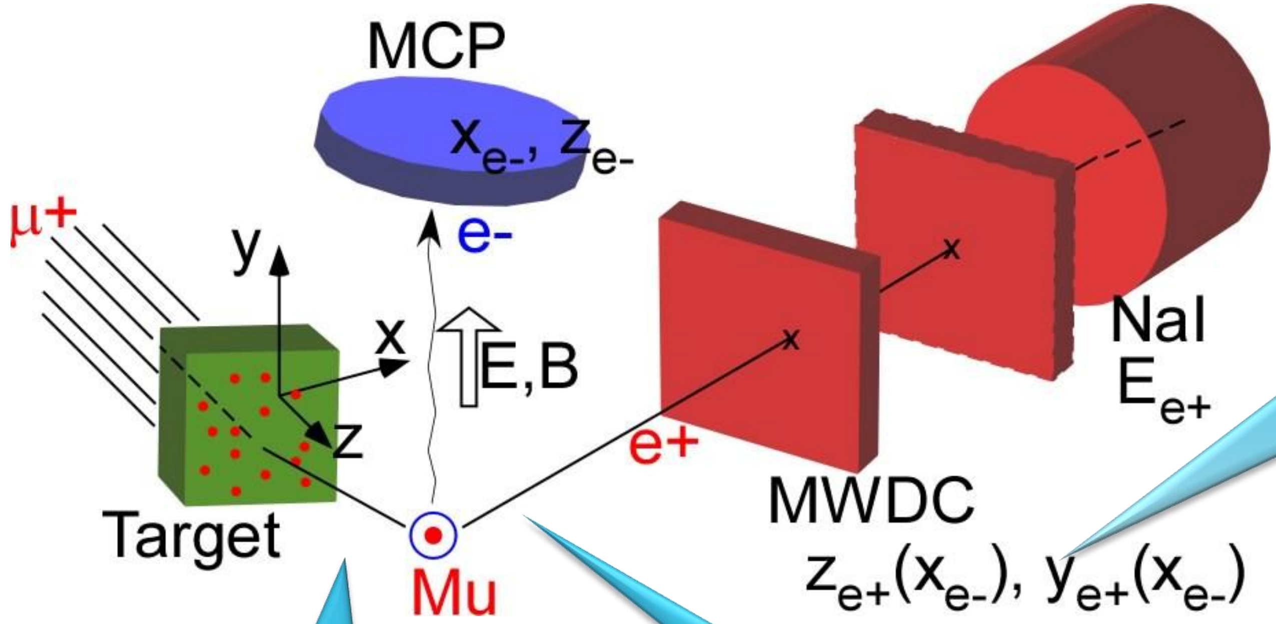






10mm

Significant improvements expected with MWDC, MCP



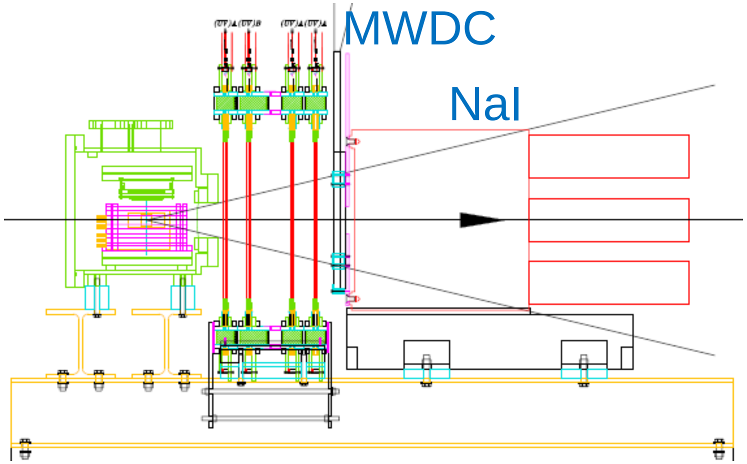
Good resolution with drift chamber

Detection of electron also rejects a huge BG from μ decay in target without e-

Complete reconstruction of 3D coordinates of decay vertex from e^+ in coincidence with e^-

Status of Preparation (1)

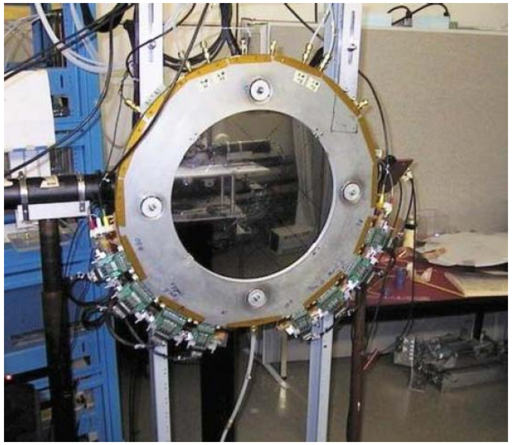
at TRIUMF



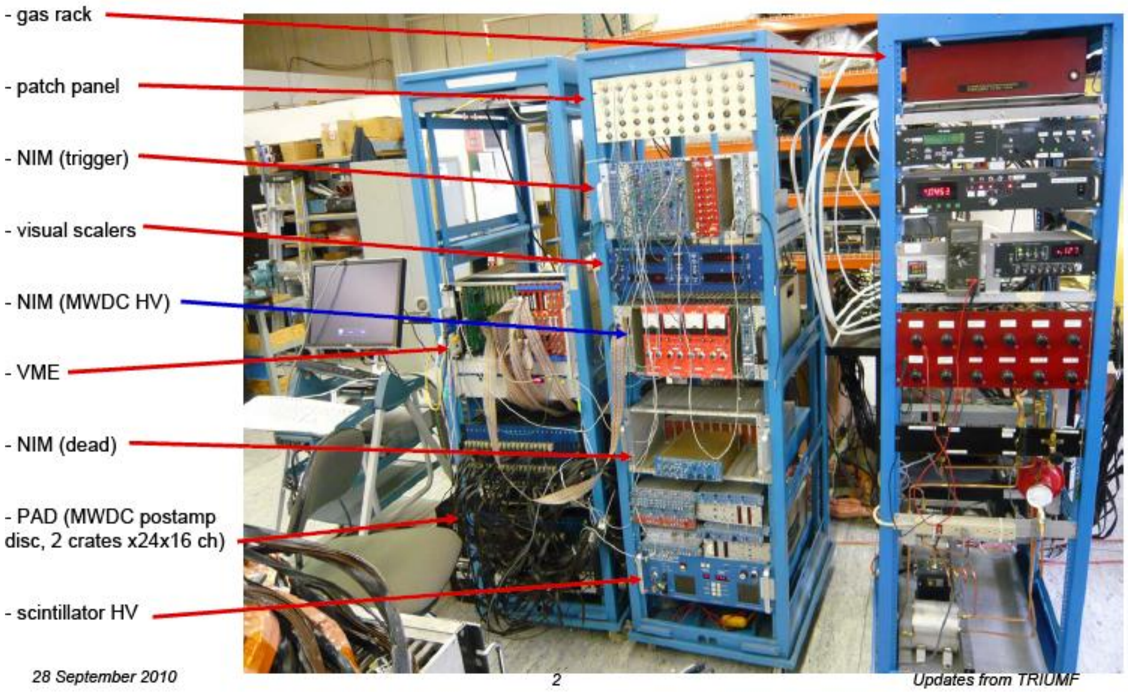
MWDC

NaI

MWDC
(from TWIST)



Mount table
(from Tokyo Group, keV μ-)

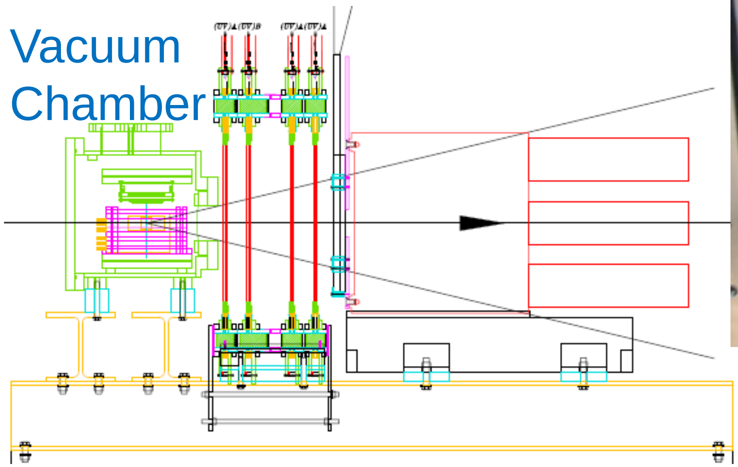


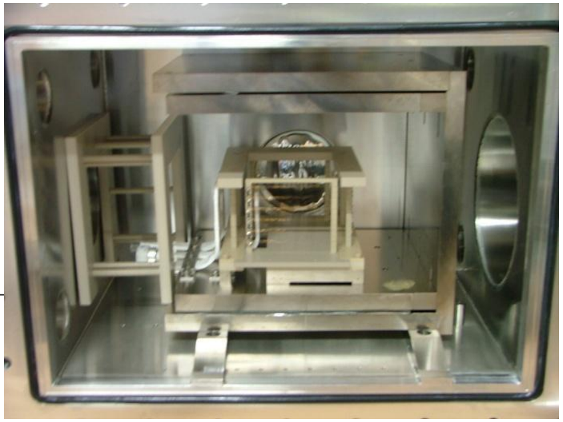
- gas rack
- patch panel
- NIM (trigger)
- visual scalers
- NIM (MWDC HV)
- VME
- NIM (dead)
- PAD (MWDC postamp disc, 2 crates x24x16 ch)
- scintillator HV

28 September 2010 2 Updates from TRIUMF

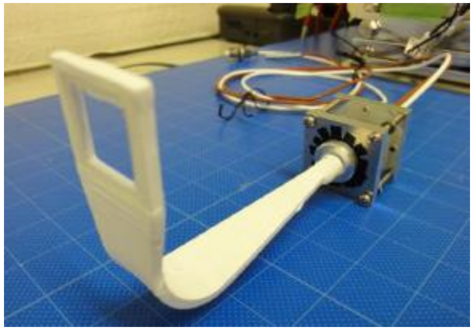
Status of Preparation (2)

at RIKEN /KEK



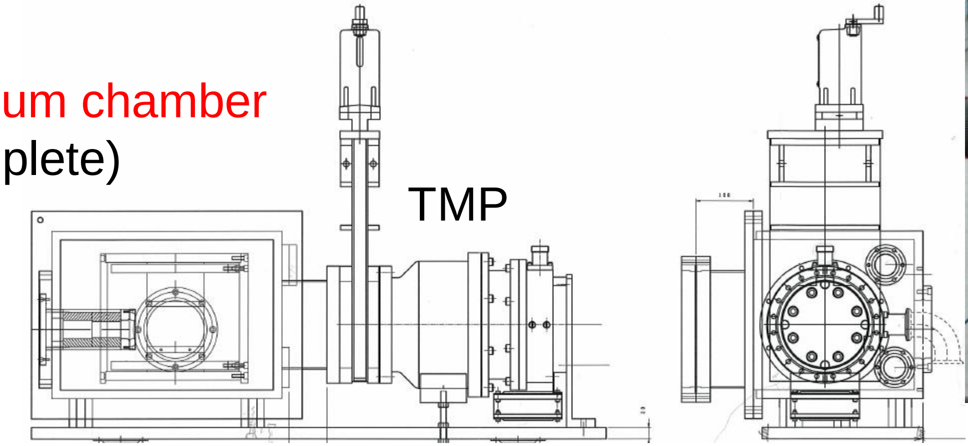


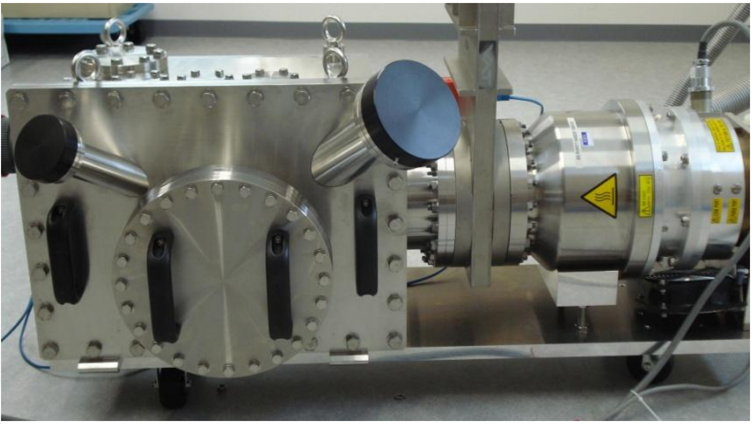
magnet, field cage (ready)



beam counter

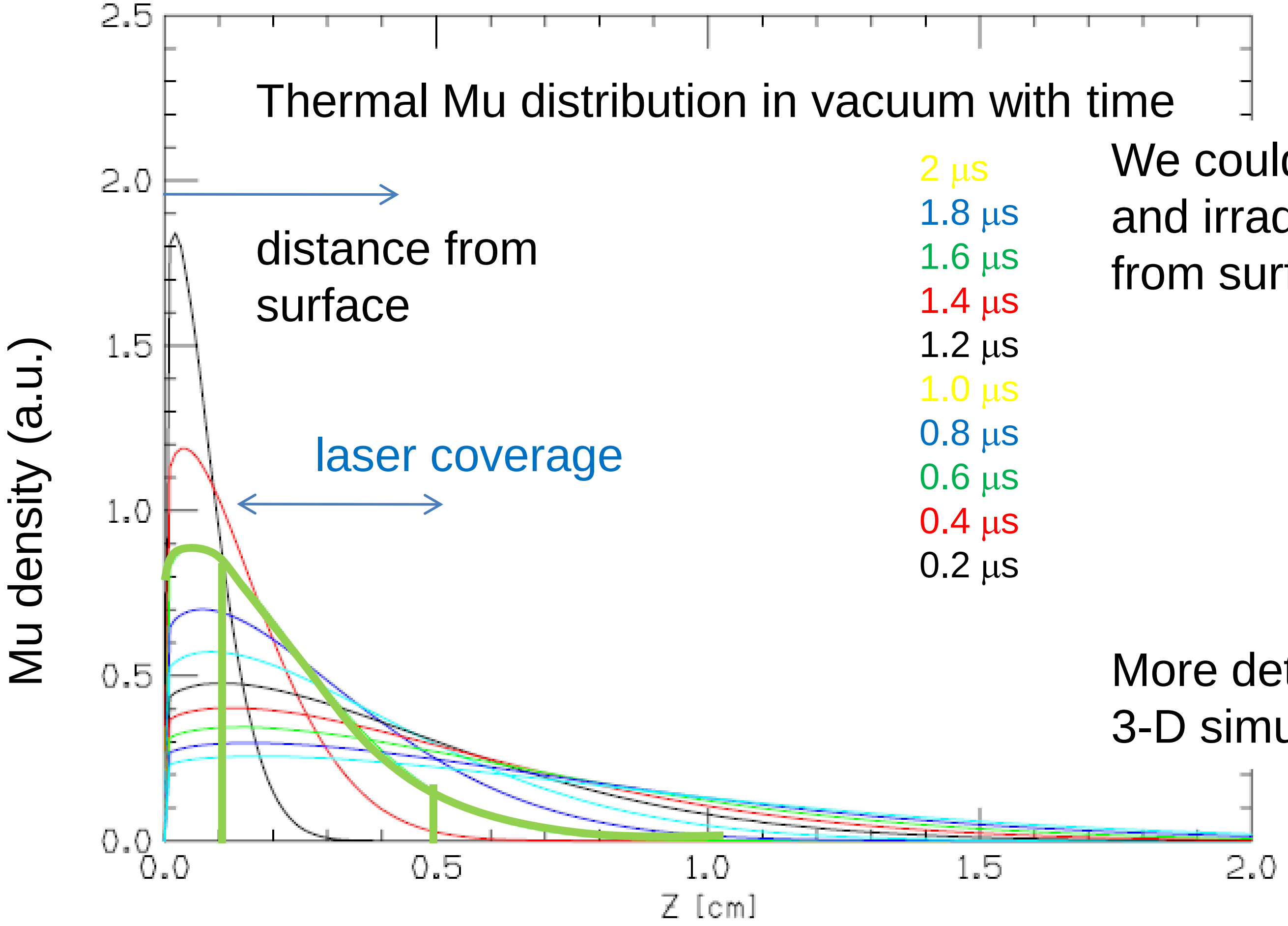
Vacuum chamber
(complete)





Laser overlap with muonium

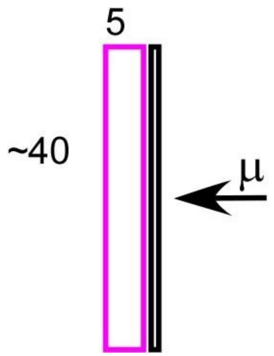
Typical model calculation on Muonium distribution in vacuum (model assumption)


Thermal Mu distribution in vacuum with time

distance from surface

laser coverage

We could wait ~0.6 μs and irradiate 1 – 5 mm from surface by laser



More detailed
3-D simulation is in progress

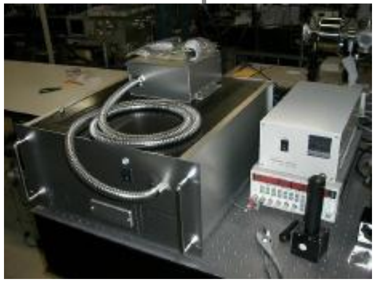
Parameters to describe Mu distribution will be obtained from the measurement

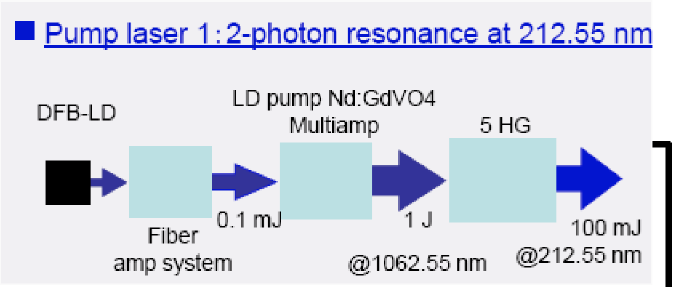
Then, we can design the ionizing laser (timing and laser beam shaping)

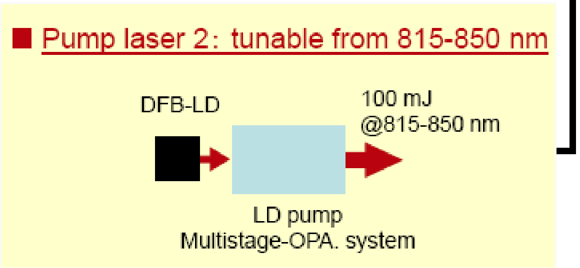
Ionizing laser development at RIKEN

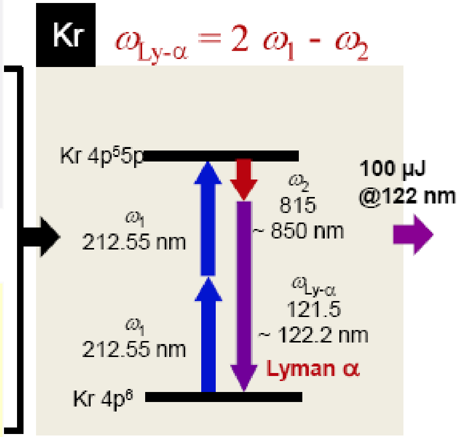
Under development by RIKEN laser group (S. Wada, Nori Saito) and K. Yokoyama

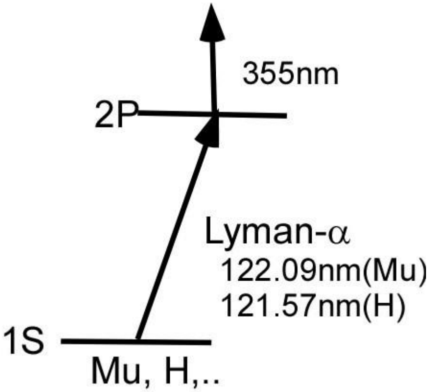
<= expertise of building stable laser systems, in house technique of special crystal growing, energy compact system, 4 wave mixing simulation











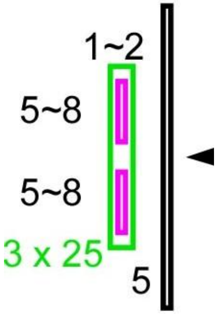
Ionization Process

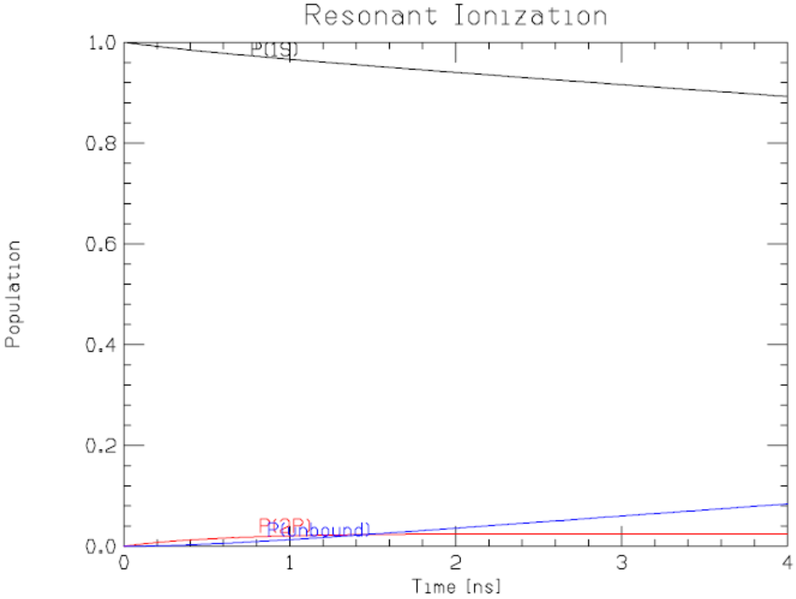
Estimation of ionizing process versus

laser intensity

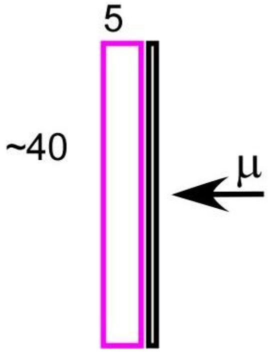
based on rate equation & transition rate

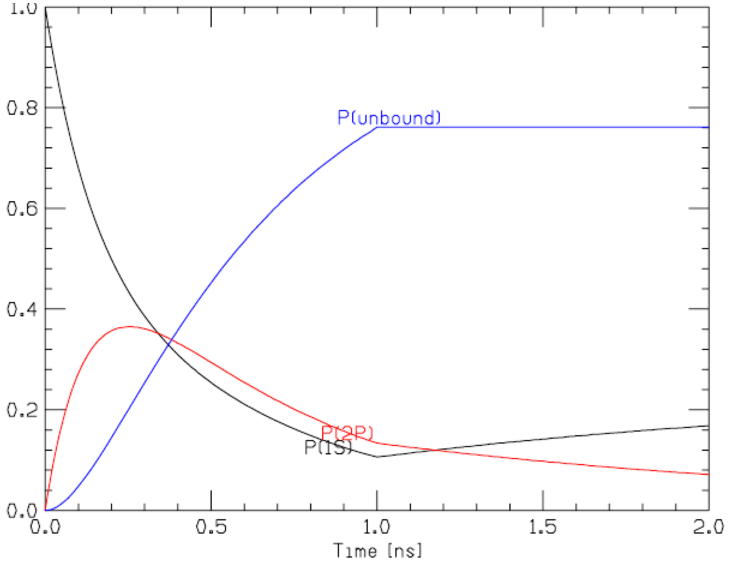
Case for *I*(Lyman-α) = 1 μJ,
I(355) = 300 mJ
length=4ns
ionization 0.11 (??)





Case for I(Lyman-α) = 100 μJ
I(355) = 300 mJ
length = 1ns
gives ionization efficiency = 0.76 after 1 ns





x 7 ionization
x 10 larger area (& higher density)
linear increase
with the expense of larger source size

Acceleration of muons

Acceleration without heating

keep the low transverse momentum spread as low as possible.

Present scheme (collaboration with linac experts)

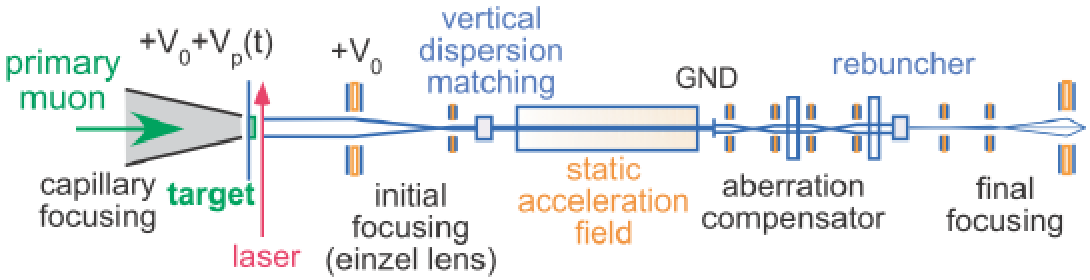
Initial acceleration (a few 100keV)

-> low beta linac (β~0.1-0.5, to 14MeV)

-> high beta linac (up to 300 MeV)

Design of initial acceleration without higher order aberration (by K. Tsukada)

working with electron/ion microscope experts



Initial acceleration with cooling, phase rotation

Various possibilities depending on what we need:

ionizing timing controlled by laser

1) transverse momentum suppression [Iwasaki]

Only muons with a fixed P_T ionized

Doppler shift from resonance for a λ(laser)

By sweeping laser wave length

=> P_T of ionized muons varies with time

by chirped laser

=> dispersion of arriving time vs P_T

=> compensate P_T spread

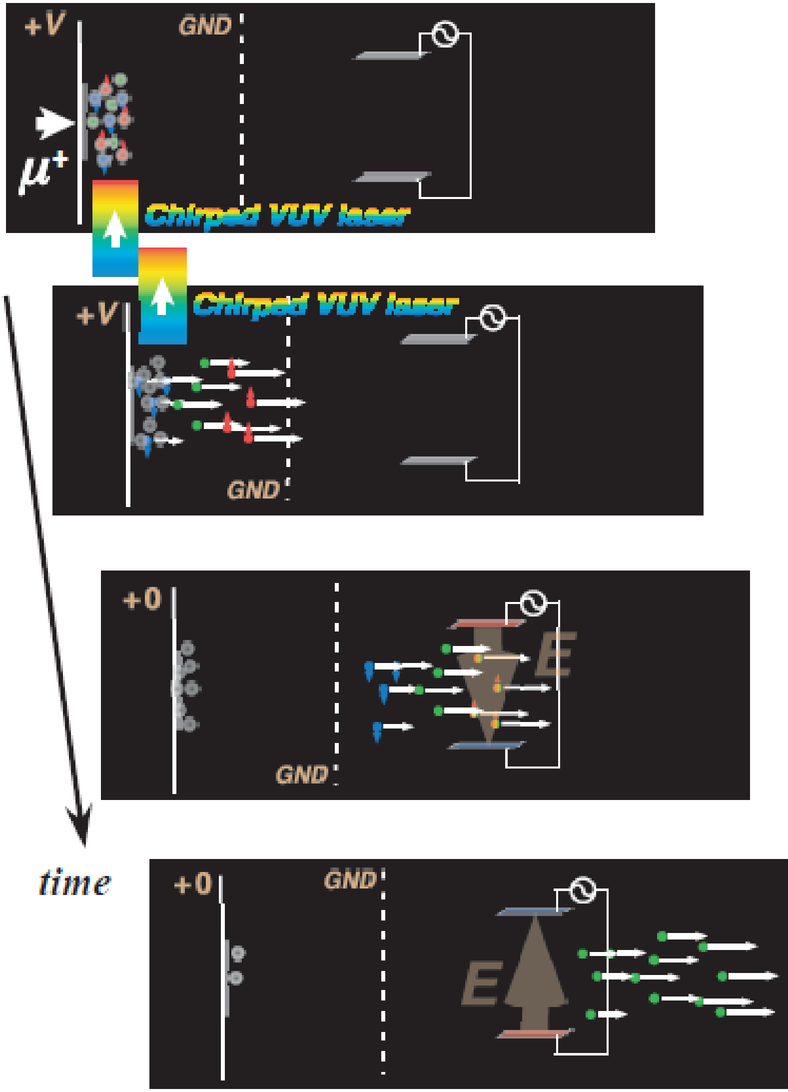
by varying transverse E field

or

2) Making short bunch for injection to linac

3) Reduce energy spread due to ionized position

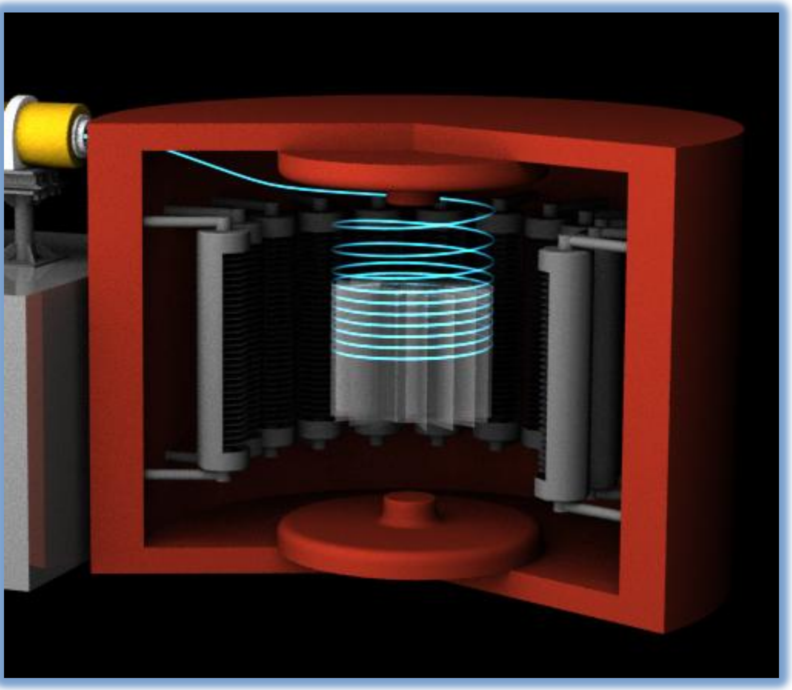
etc

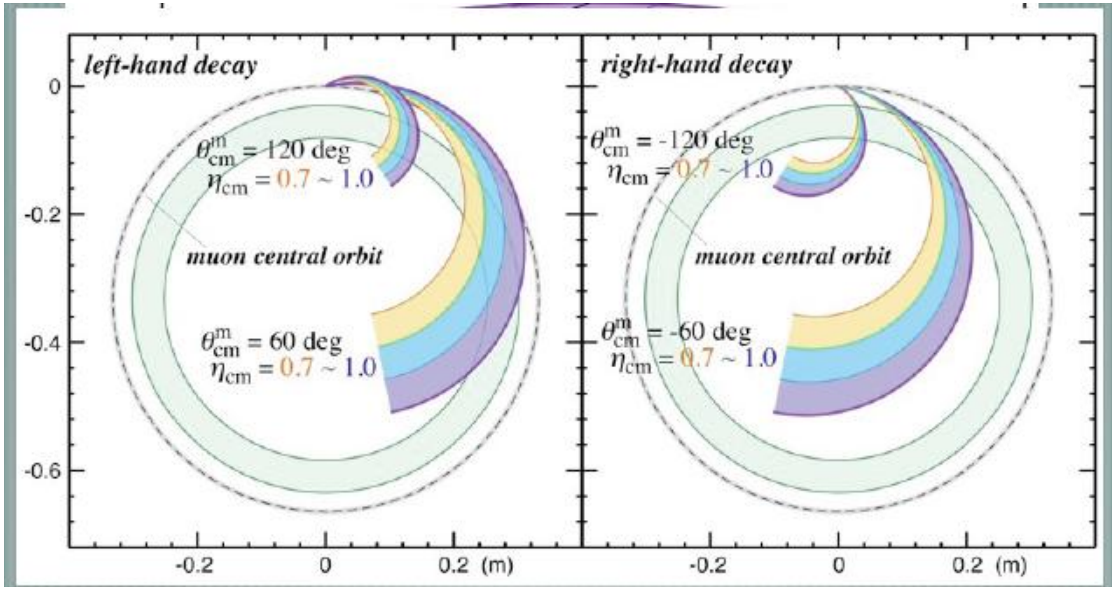


Storage ring and detectors

Progress mostly at KEK

- Storage ring magnet (based on MRI technology)
- Precision field measurement (working on NMR with NIRS)
- Beam injection scheme (Iinuma, Nakayama)
- Detectors for muon-decay tracking (Mibe, Iinuma)





Summary

A new g-2 experiment was proposed at J-PARC
It is based on ultra-cold muon beam
We plan to increase beam intensity to 10^6/s
and improve beam properties

Room temperature muon source should be developed
  Measurement is planned at TRIUMF to study

Intense laser is likely to promise x100 improvement
  RIKEN is developing laser and will test at RIKEN-RAL next year.

We are also working on muon acceleration, storage ring etc.

There are still a lot many to do. We welcome your collaboration.

Modeling of Mu diffusion

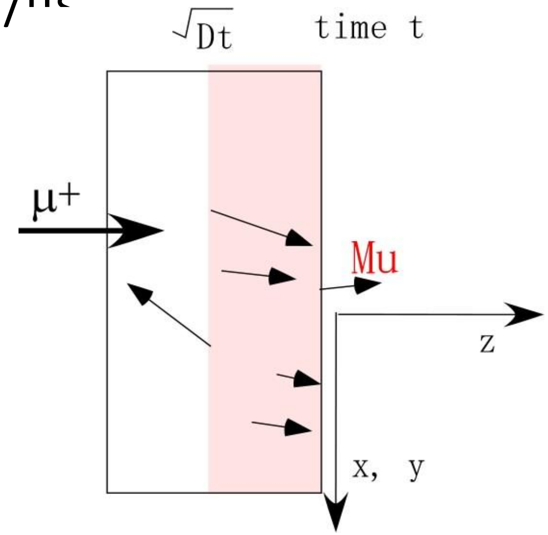
TRIUMF and PSI model of Mu emission from SiO2

"effective diffusion rate" for Mu diffusion in target

- time for muon to diffuse to surface layer, delayed emission
- 500 cm^2/s (G. Marshall)
  - 1mm thick -> 20 μs ! very slow (10% yield)
  - 0.1 mm thick -> 200 ns

emitted Mu moves with Boltzman velocity of σ_{vz}=0.5 cm/

- z distribution is Gaussian with σ_z=0.5cm after 1μs,
- Mu spreads in region z = 0 ~ 5 mm



Mu distribution is convolution of these two

Laser overlap with Mu: Modeling of Mu emission

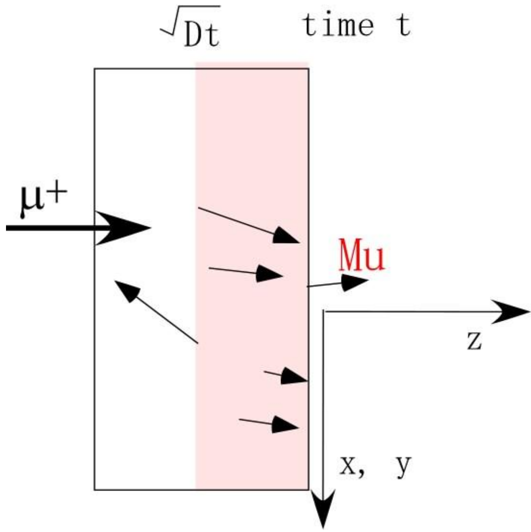
- TRIUMF and PSI model of Mu emission from SiO2
- "effective diffusion rate" D_2 is one of the parameters
  - time for muon to diffuse to surface layer, delayed emission
  - 500 cm^2/s (G. Marshall)
    - 1mm thick -> 20 μs ! very slow (10% yield)
    - 0.1 mm thick -> 200 ns
- emitted Mu moves with Boltzman velocity of σ_{vz}=0.5 cm/μs
  - z distribution is Gaussian with σ_z=0.5cm after 1μs,
  - Mu spreads in region z = 0 ~ 5 mm
- with this diffusion model and uniform muon stopping,

  muonium in vacuum increase

  with $(D_2 t)^{1/2}$ (if ignoring muon decay)
  - emission rate is its derivative $(D_2/t)^{1/2}$
- Mu distribution is convolution of these two
  - adding up Gaussian of different width ($\sigma_z(t-t_e) = 0.5(t-t_e)$ cm)

    with weight $t_e^{-1/2}$

This region contributes to emission at time t



Keys for intense cold muon

1. Target materials

   Muonium measurement at TRIUMF (June and Nov 2010)

2. Intense Lyman-α laser

   1+2 Combined test at RIKEN-RAL (March 2011-)

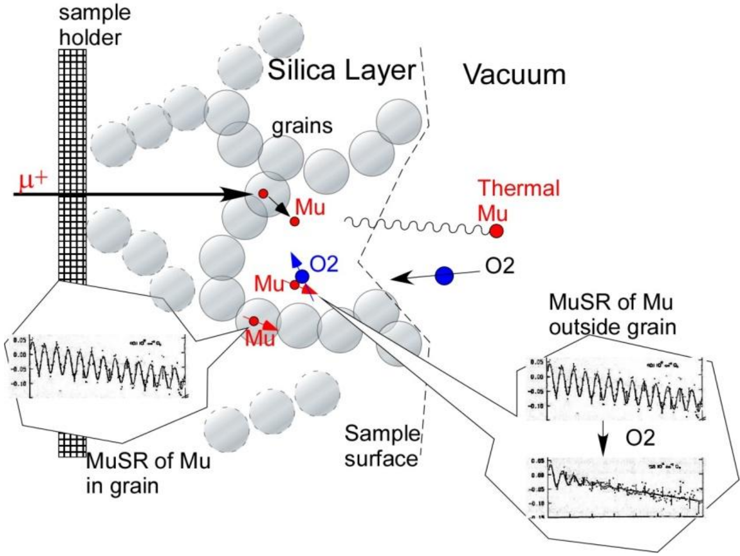
3. Initial acceleration scheme

   1+2+3 Combined measurement at RIKEN-RAL

4. Highest intensity muon channel at J-PARC (Miyake, Ikedo)

   1+2+3+4 Realization of cold muon source for g-2 at J-PARC

Hints for high Mu yield



While the understanding is far from complete,
material with large surface area seems essential

1. diffuse out of muon from substance
   fine particle (size a), diffusion in bulk (D_{bulk})
   yield $\sim D_{bulk}^{0.5}/a$

2. Mu diffusion in void channels
   target thickness (b), diffusion through voids (D_{void}) ,
   yield $\sim D_{void}^{0.5}/b$
   large mean free path (l) & interconnecting void channels
   - high void/material ratio
   free interacting gas model ($D = 1/l \sim \rho^{-1/3}$)

whereas high muon stopping density ($\sim\rho$)