Future muon sources
Huddersfield, UK 2015/1/13

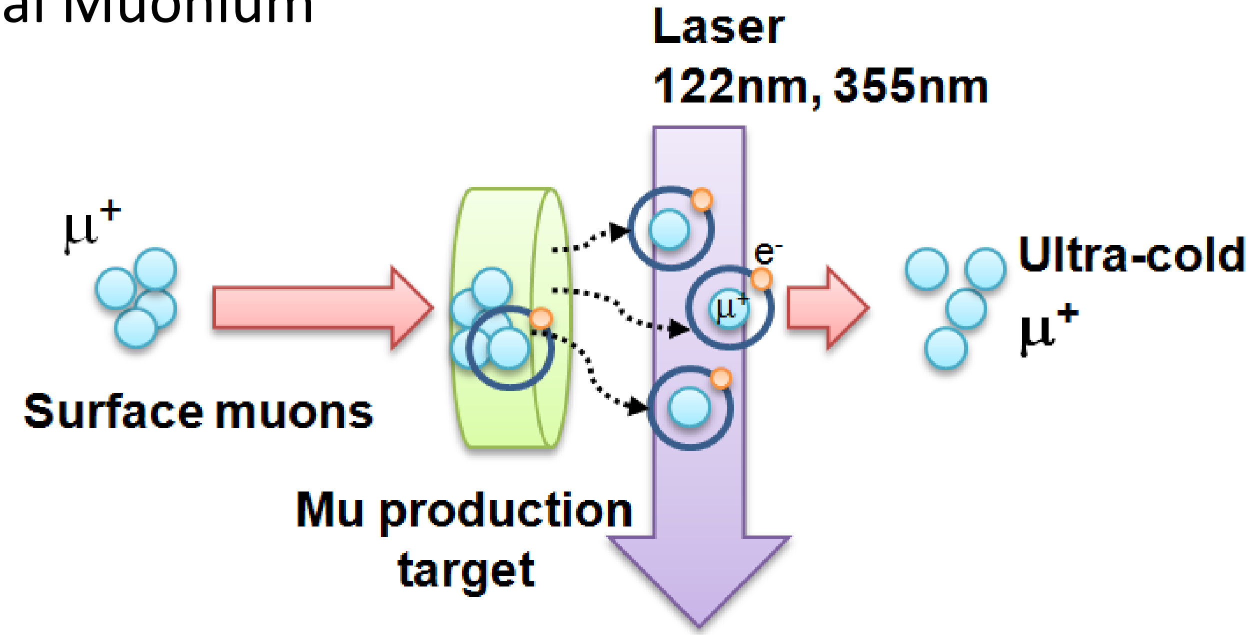
Low energy muons using laser ionization

K. Ishida (RIKEN)

Outline
- Principle and past developments
- Ultra Slow Muon Microscope (USMM) project
- New progress

Principle of the method

Ionization of thermal Muonium



Advantages

Thermal energy initially => small beam spread in space and momentum

Possibly high efficiency (depends laser and target)

Disadvantage

laser cost/operation

spin polarization (~50%)

History

Ionization of thermal Muonium (back ~30 years)

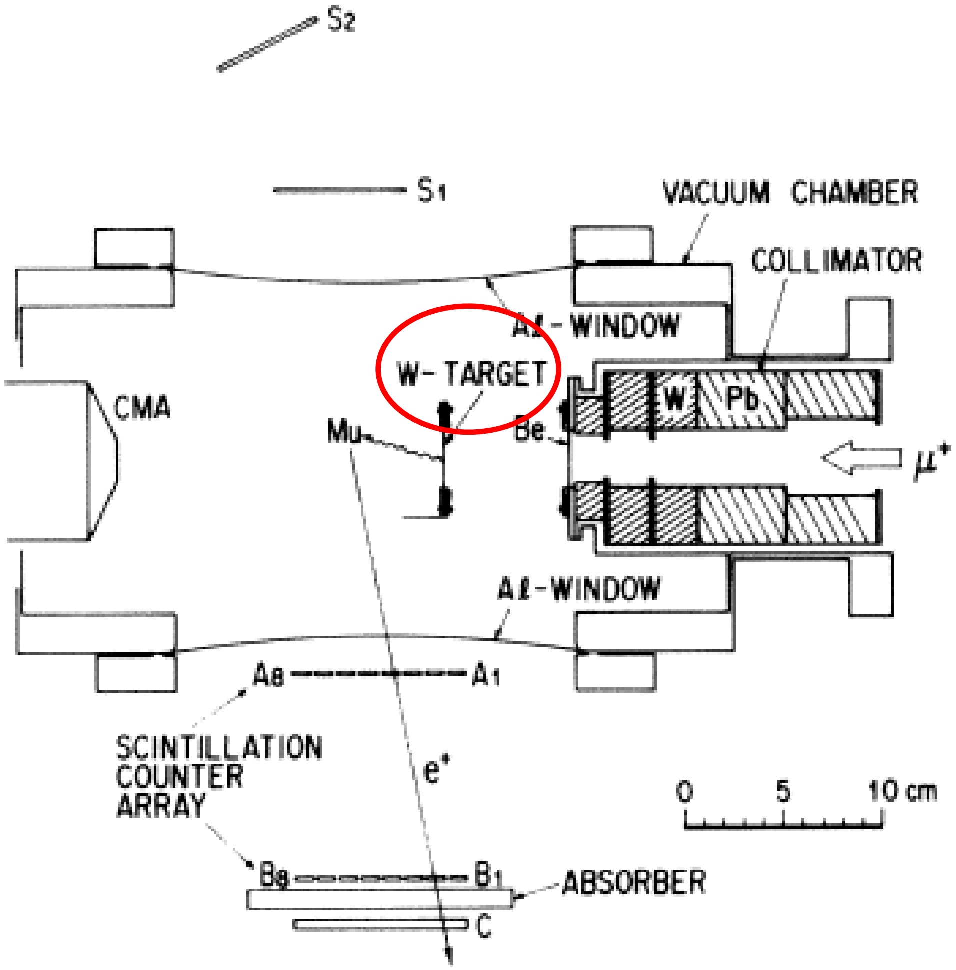
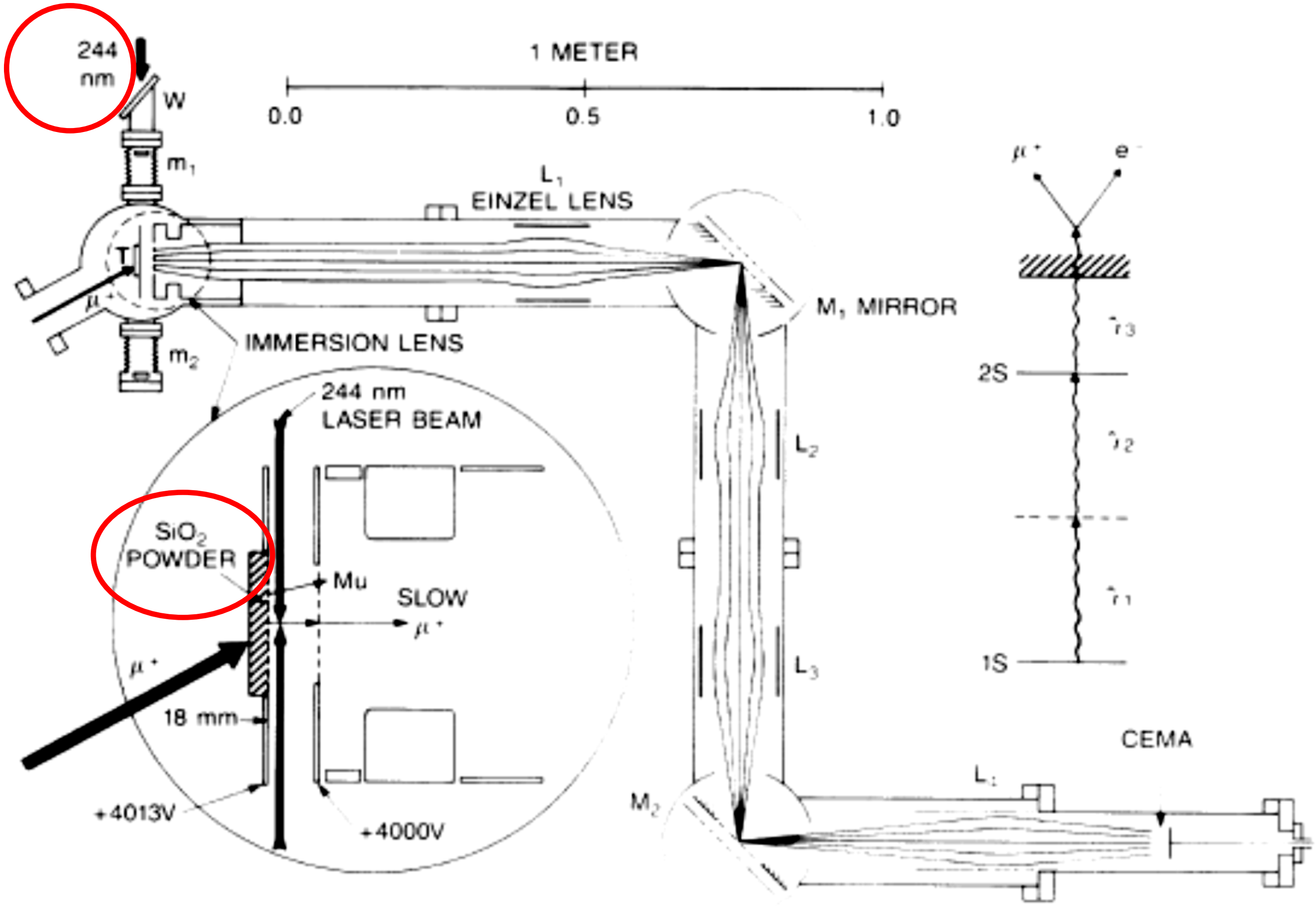


FIG. 1. Apparatus for observing muonium in vacuum. A_i, B_i, C, and S_i are scintillation counters.

Generation of thermal Mu
from Hot W
UT-MSL@KEK 1986

History

Mu 1s-2s and ionization
KEK-MSL 1988

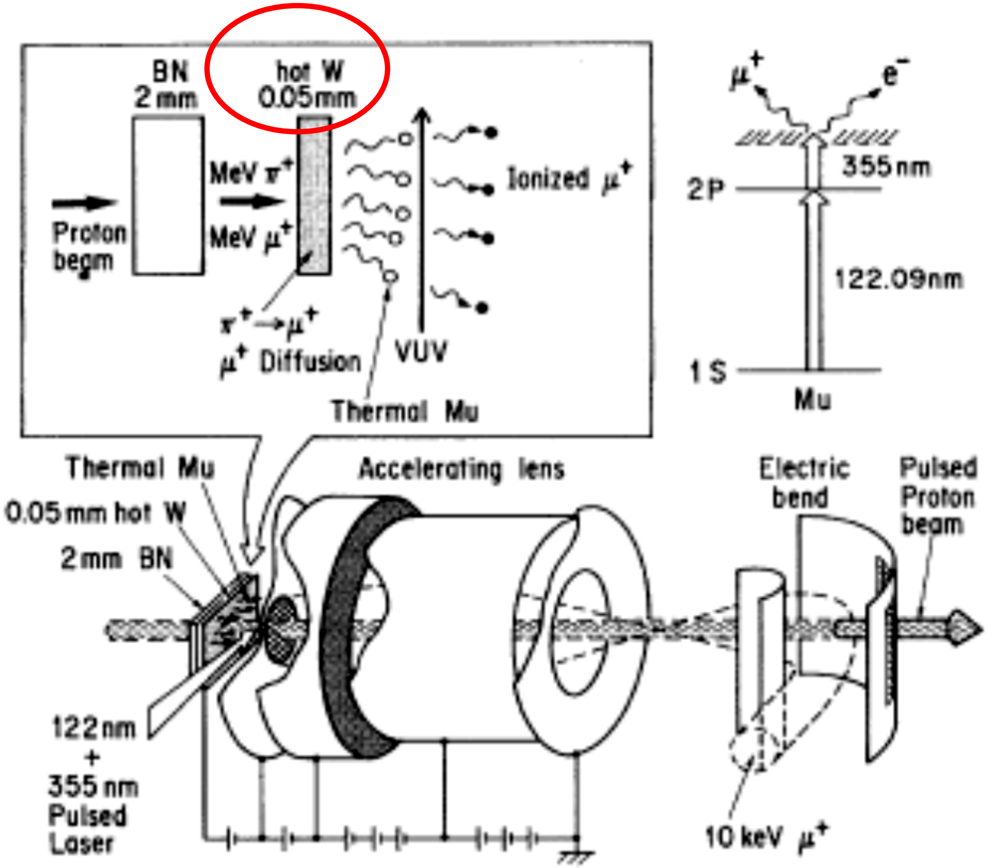


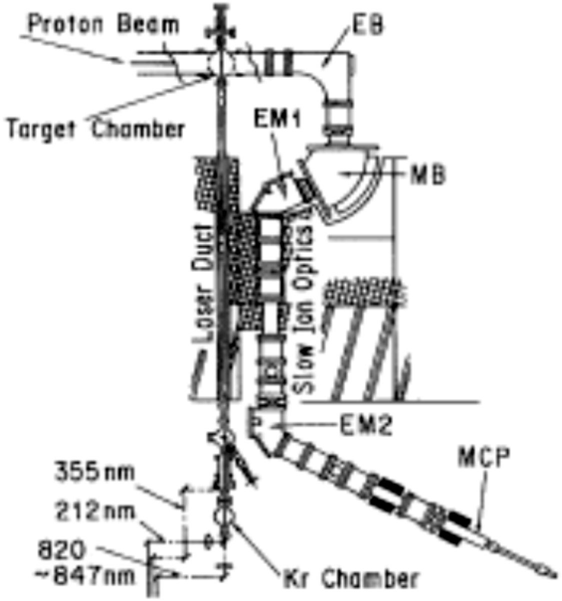
History

Dedicated slow muon beamline (Target in proton beam)

KEK-MSL

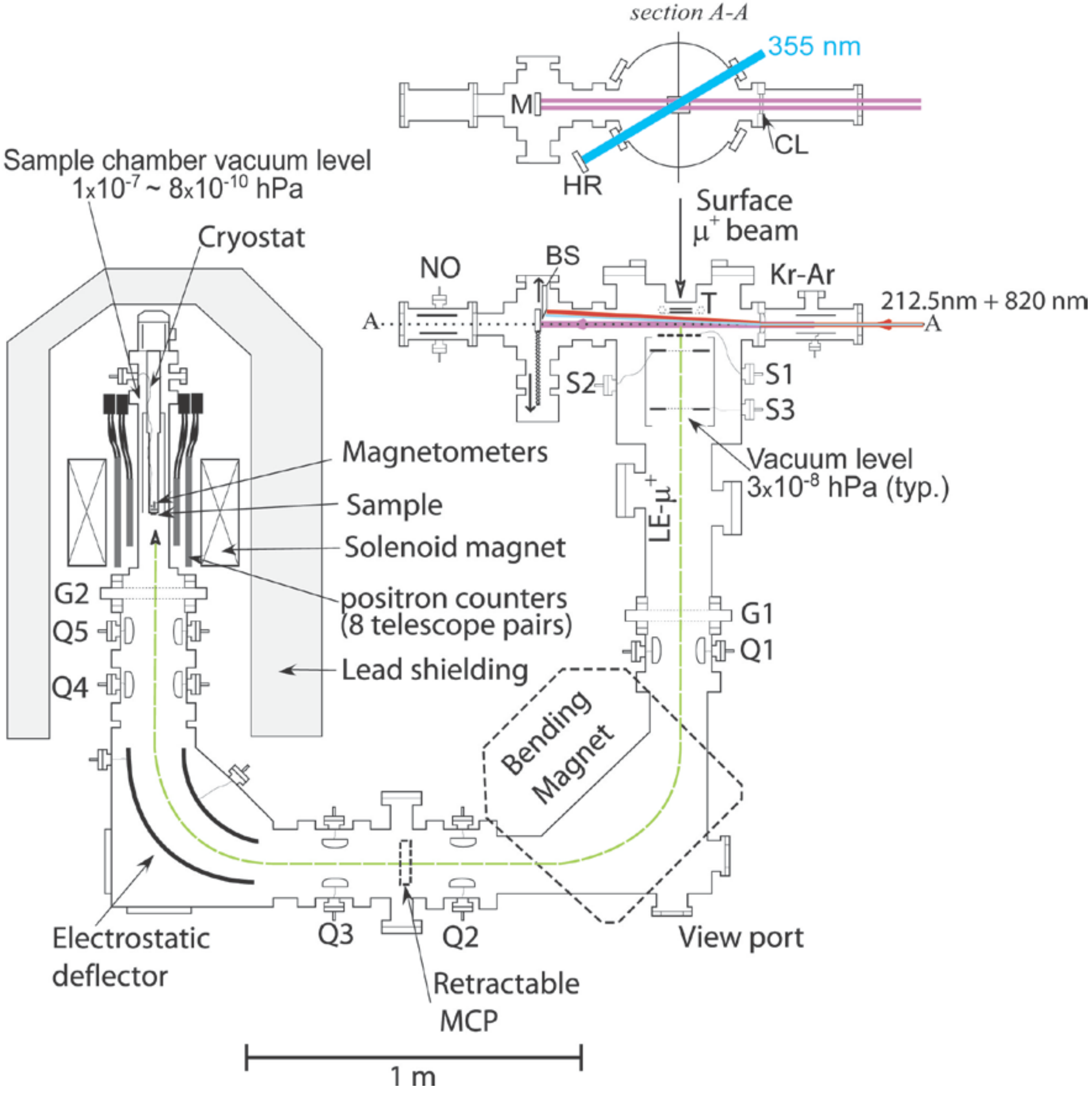
K. Nagamine et al, PRL74(1995)481



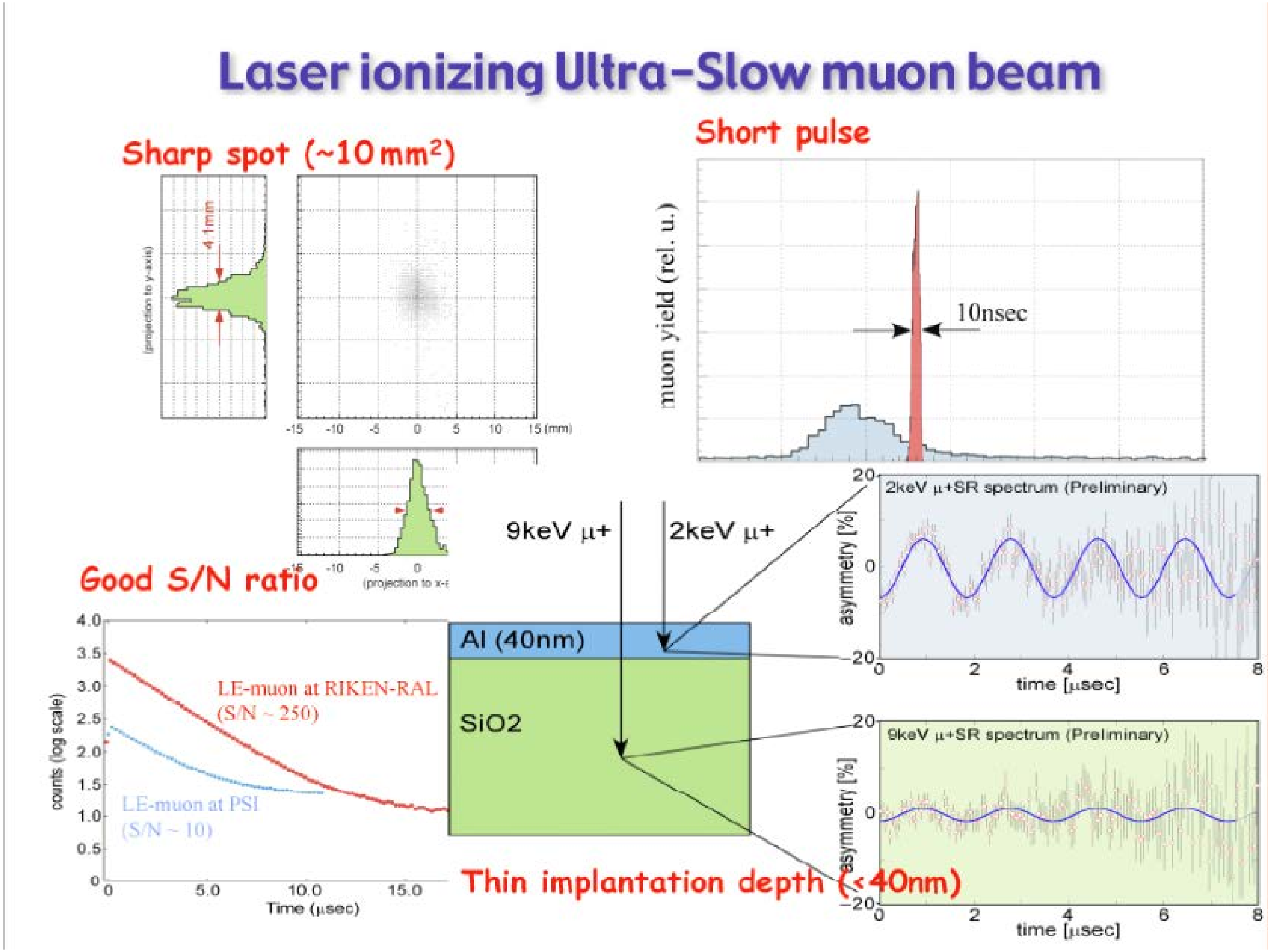


History

Slow muon beam line
RIKEN-RAL (2000-2008)
P. Bakule et al.,
NIM B266(2008)335



Achievement at RIKEN-RAL (2000~2008)



Laser ionizing Ultra-Slow muon beam

Sharp spot (~10 mm^2)

Short pulse

Good S/N ratio

Thin implantation depth (<40nm)

Achievement at RIKEN-RAL (2000~2008)

Good beam characteristics
However,
slow muon intensity ~20/s

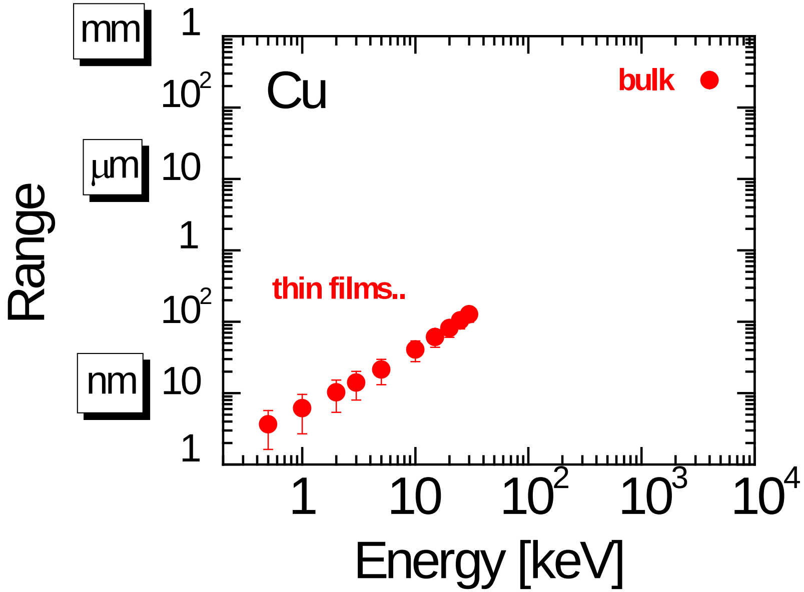
Limiting factors
1. primary muon beam intensity (~10^6/s)
2. efficiency (Mu emission and laser ionization) (~10^{-5})

These can be changed by
  J-PARC (1MW) and new U-line (x100)
  New laser (x100)
more than 10^5 /s slow muons expected

Ultra-slow muon for μSR and muon g-2

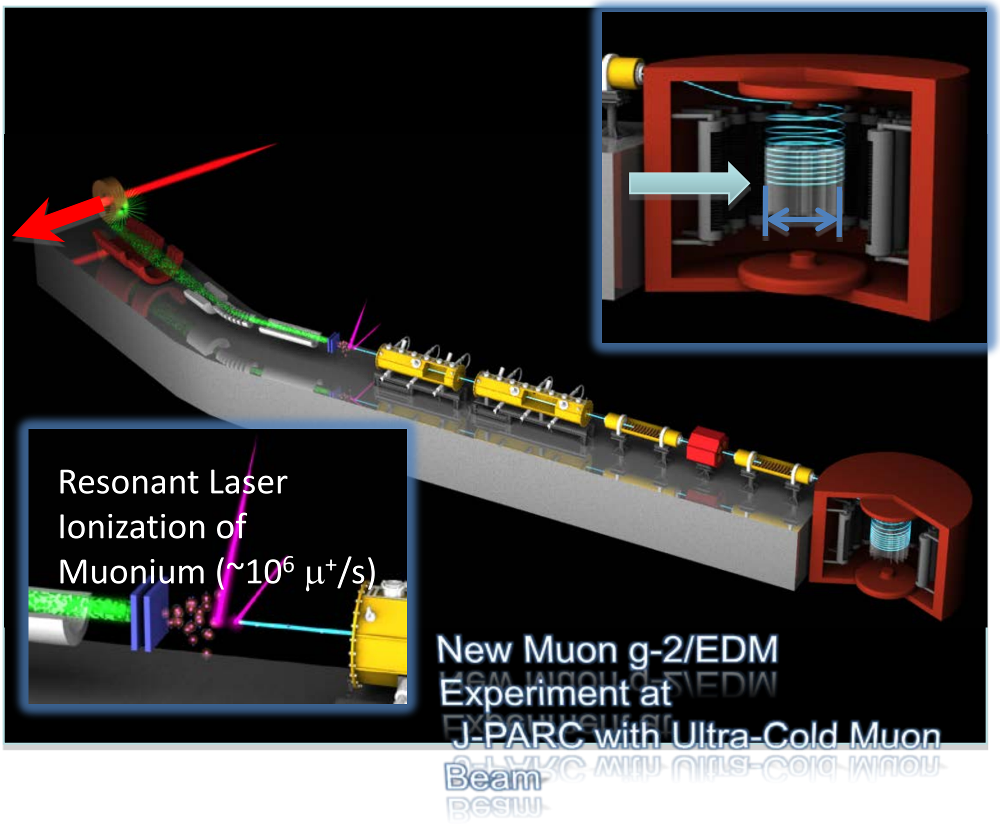
For μSR

implantation depth control.
small beam size



For muon g-2/EDM

Sharp ultra-cold accelerated muon beam
Store in muon g-2/EDM ring



Strong interest by several groups

Ultra Slow Muon Microscope : Grant-in-Aid program

"Ultra Slow Muon Microscope" (USMM)
A fund was granted for all-Japan ultra-slow muon collaboration
of about ~91 members
project leader: E. Torikai (Univ. Yamanashi)
for FY2011-2015 totaling 1 billion-yen (6M STG).

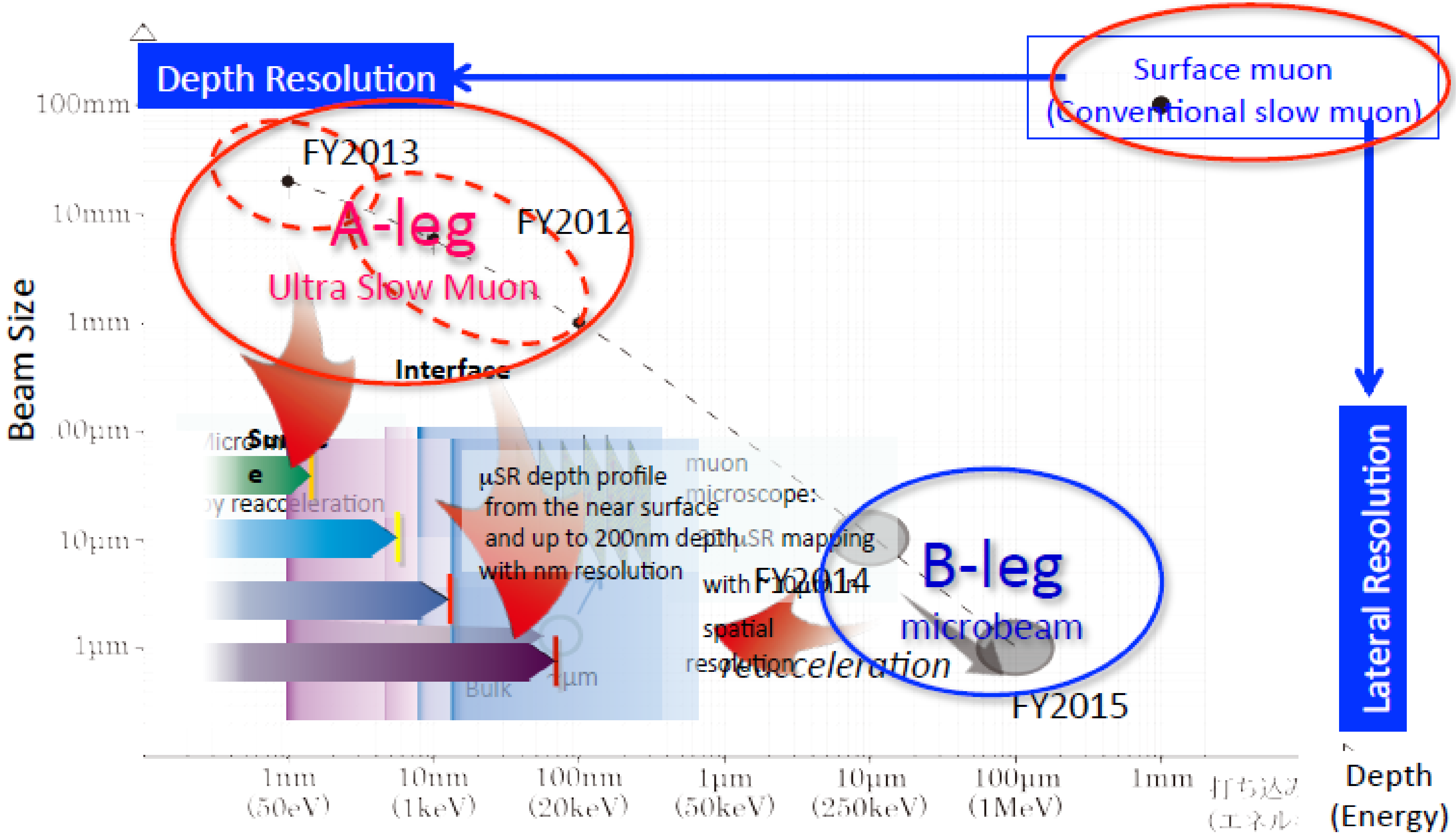
ULTRASLOW
MUON
MICROSCOPE

USMM : Objective at a glance

ULTRASLOW
MUON
MICROSCOPE

Small beam size + depth resolution

by USMM project



USMM : programs

ULTRASLOW MUON MICROSCOPE

generation and application of ultra-slow muons

ionizing laser

beamline and acceleration

μSR spectrometer

sample conditions

4 main programs headed by program leaders

A01 Establishment of the Ultra Slow Muon Microscope and Micro-scale μSR. (Y. Miyake)

A02 Spin transport and catalytic reactions in the boundary regions. (E. Torikai)

A03 Heterogeneous electron correlation in the surface-bulk boundary and across thin layered structures. (R. Kadono)

A04 Extreme cooling and sharpening of the beam towards the “new physics” frontier beyond the standard model. (M. Iwasaki)

4 programs are collaborating to achieve maximum output.

U-line @J-PARC MUSE

Large solid angle surface muon beam line

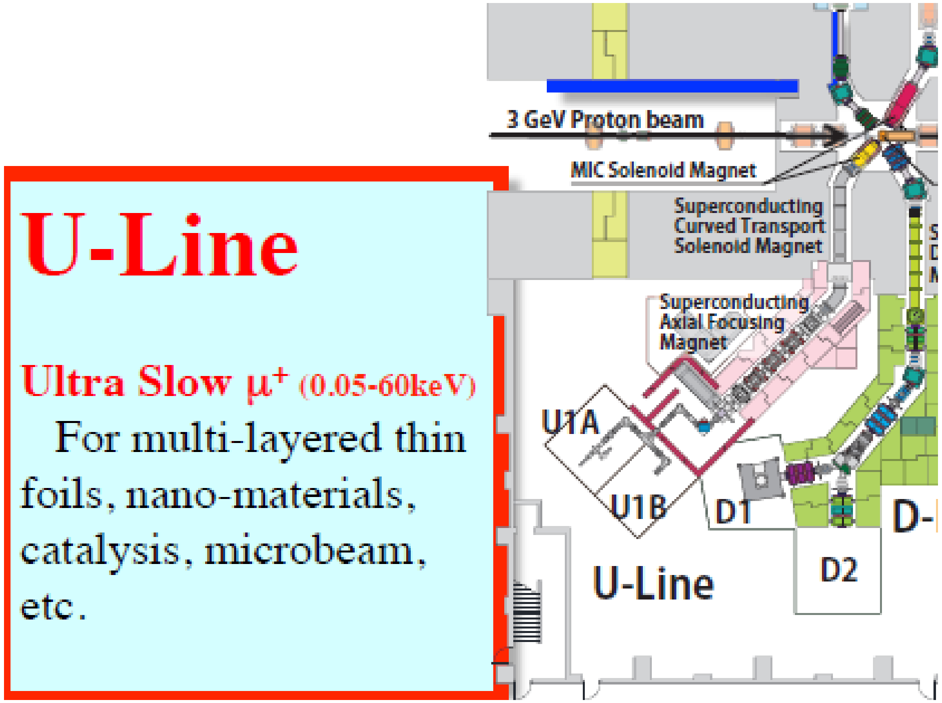
as a source of ultra-slow-muon beam

more than 2 x 10^8 muon/s@1MW

- front end collection by solenoid lens
- curved solenoid muon transport
- focusing solenoid section
- (all superconducting except front)

See also talk by N. Kawamura

Y. Ikedo, Y. Miyake, ..
@RCNP Workshop
Osaka, 2015.



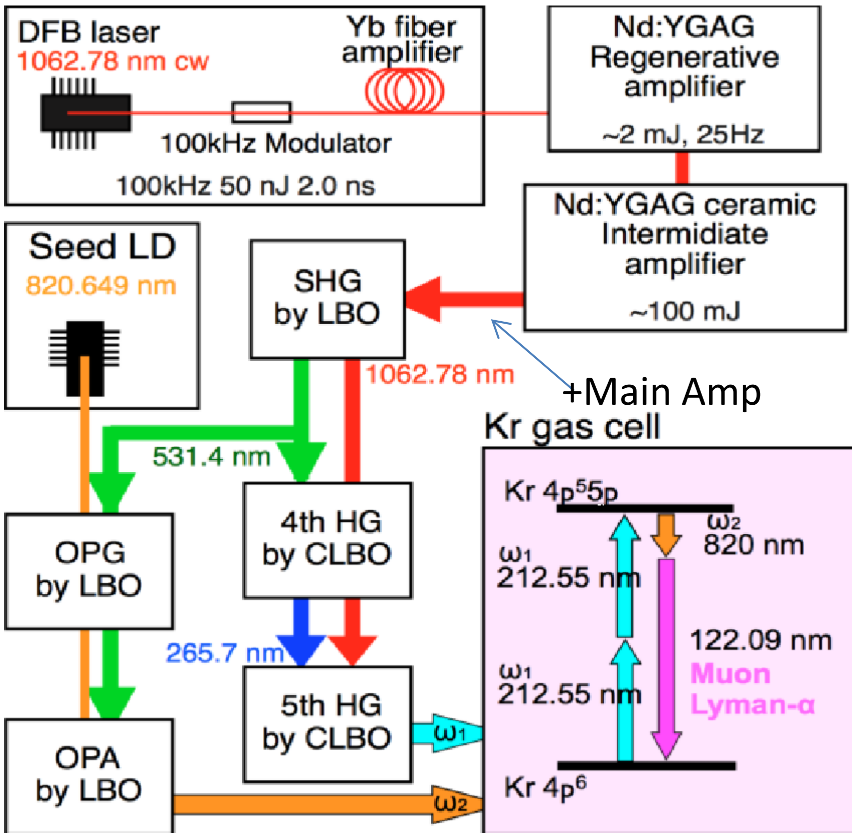
U-Line

Ultra Slow μ^+ (0.05-60keV)

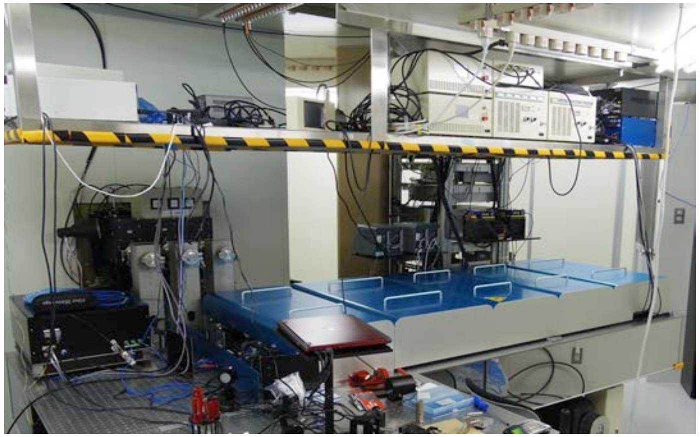
For multi-layered thin foils, nano-materials, catalysis, microbeam, etc.

USMM: laser

Laser was developed at RIKEN
(Advanced Meson Science Laboratory and Center for Advanced Photonics)



+Main Amp



laser system installed in J-PARC

all-solid-state laser system

newly synthesized ceramic Nd:YGAG

(amplification at the right wavelength)

~10 μJ already achieved

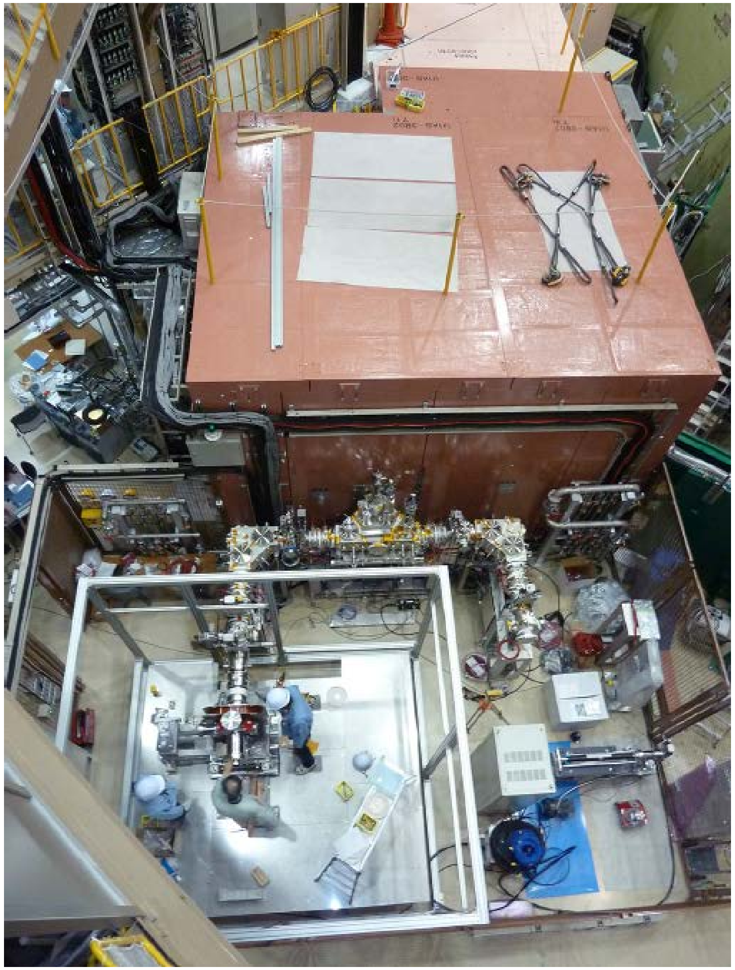
>100 μJ expected soon

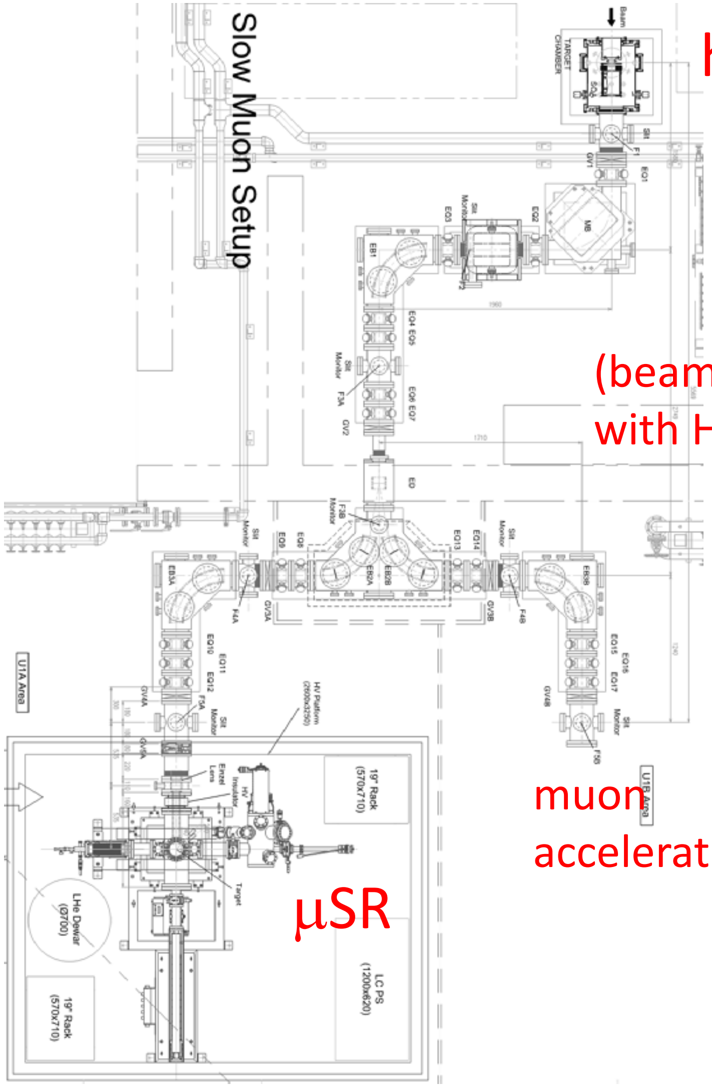
(add main amp, further tune etc)

USMM: beamline

ULTRASLOW
MUON
MICROSCOPE

Slow muon beamline and μSR spectrometer





surface muon

hot-W

(beamline tested with H^+ beam)

muon acceleration

μSR

USMM: status

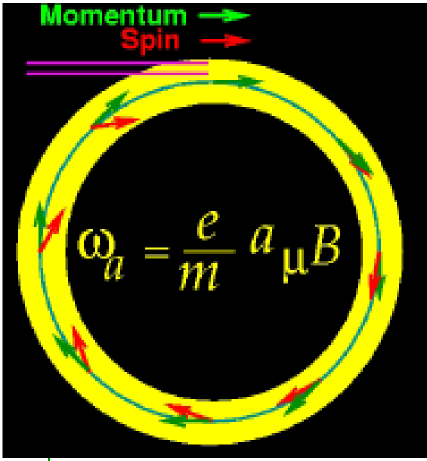
2011 : start of the project
Aug 2013: International symposium in Matsue, Japan
May 2014: First generation of Lyman-a at J-PARC
Jul 2014: Laser ionization of H and beam transport study
Dec 2014 : Starting commissioning

Status of key components

- U-line (primary muon source) was commissioned.
- Slow muon beam line was tuned with H beam.
- Lyman-α ready (full power operation will come later).

J-PARC beam to restart on 17 Jan.
We expect to observe slow muons even in a week!

slow muon development for moun g-2



Muon's *g* value deviation from 2 by vacuum polarization
Anomalous magnetic moment: $a=(g-2)/2$

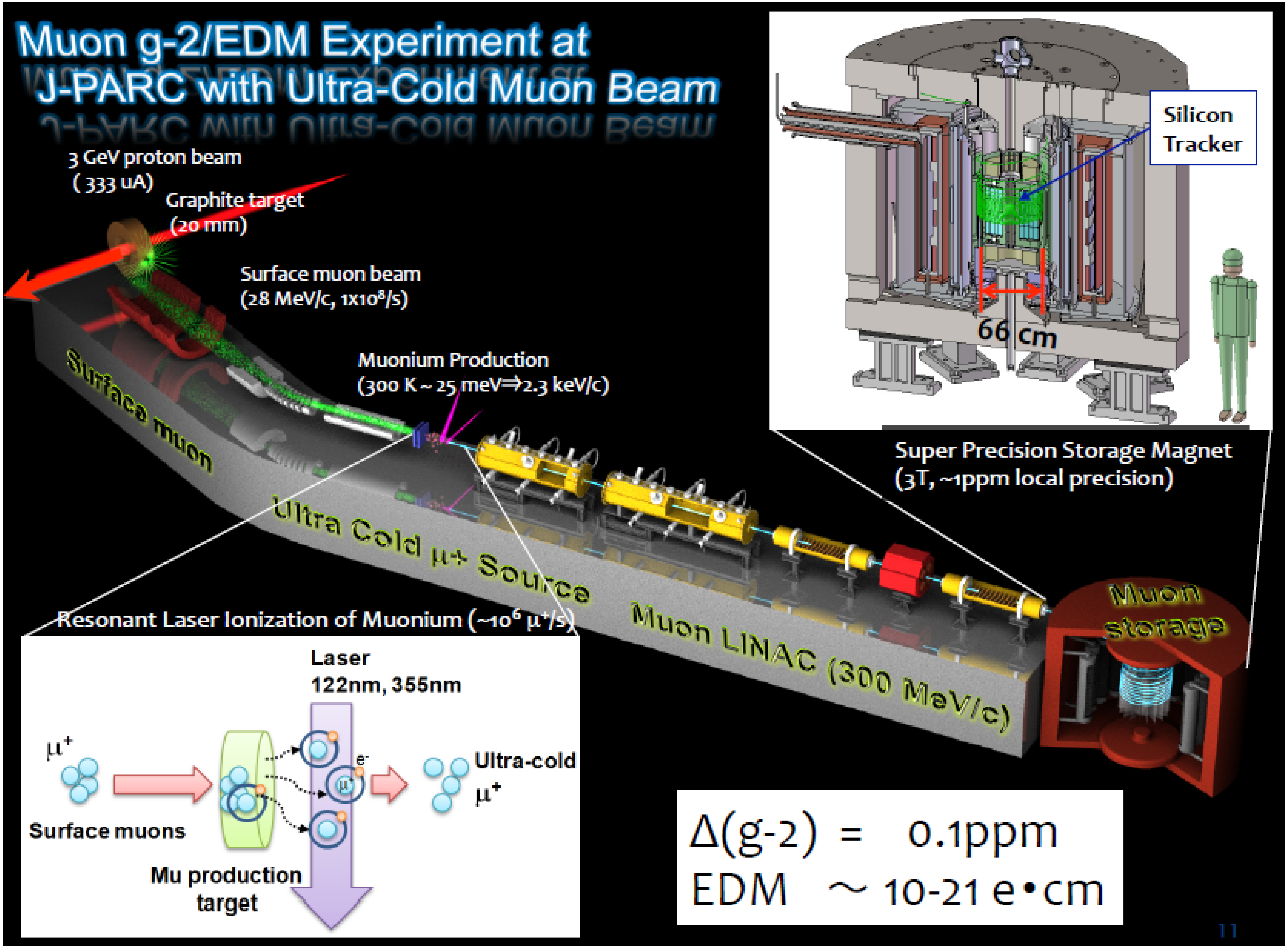
a_μ = 11 659 208.9 (6.3) x 10^{-10} (BNL E821 exp) **0.5 ppm**
11 659 182.8 (4.9) x 10^{-10} (standard model)

Δa_μ= Exp - SM = 26.1 (8.0) x 10^{-10} **3σ anomaly**

loop contributions from new interaction/particles ??

An improved measurement is planned (FNAL E989)
the same magic momentum
the same muon storage ring transferred from BNL.
We plan a new independent measurement (J-PARC E34)
lower momentum and beam storage in compact MRI magnet
This requires a much colder muons than available from hot W.

Muon g-2 at J-PARC H-line



Δ(g-2) = 0.1ppm

EDM ～ 10-21 e•cm

Need of new target development

Requirement for zero E-field:

Muons should be kept stored without E-focusing

→ Beam with ultra-small transverse dispersion,

i.e. $\Delta p_T/p$ <10-5 => PT~300K

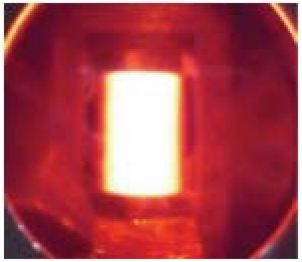
We go for room temperature target instead of hot tungsten

0) Small beam spread for muon g-2 ring storage <– essential

1) Easier handling and flexibility without heat radiation

2) Possibility of higher yield <= need to be tested

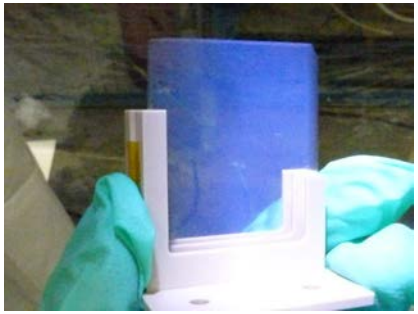
3) Better ionization efficiency <= smaller Doppler broadening, space spread



vs

Silica powder was traditionally used at RT
but we go for silica aerogel for better handling

→

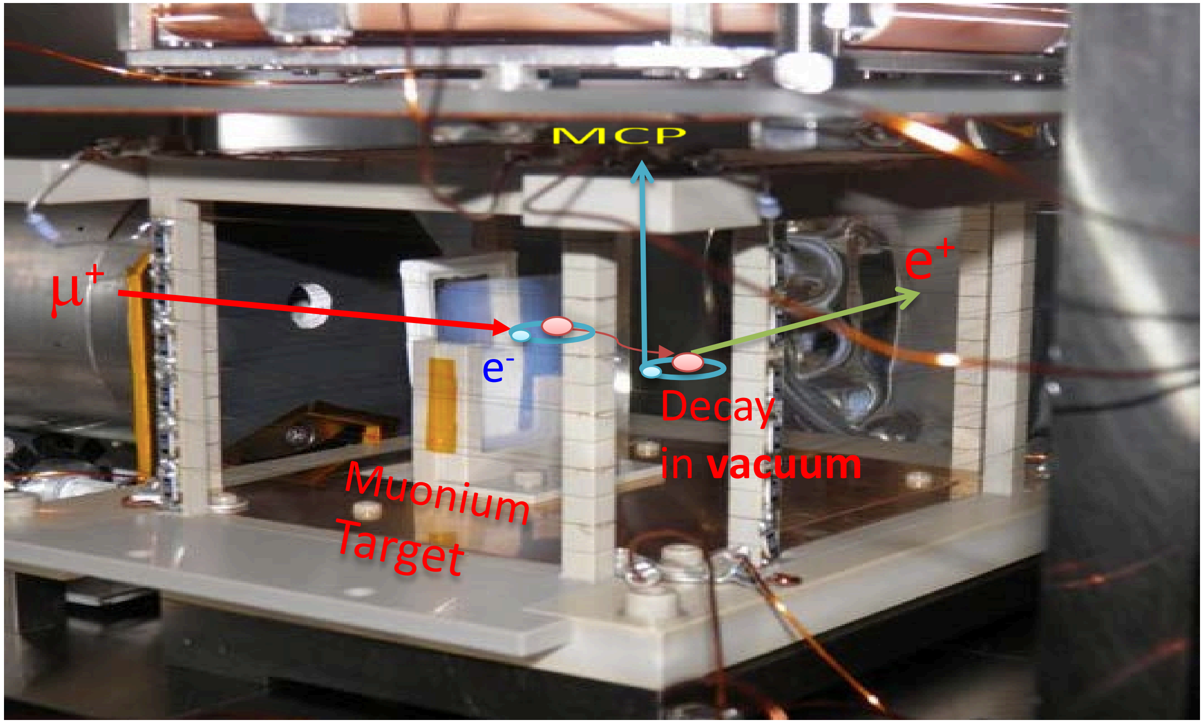


Initial measurement S1249 : 2010-2011

Measurement of Mu emission yield from silica aerogel

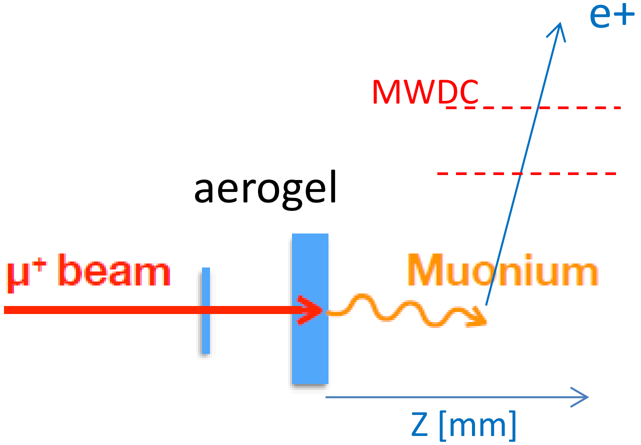
d.c. muon beam at TRIUMF

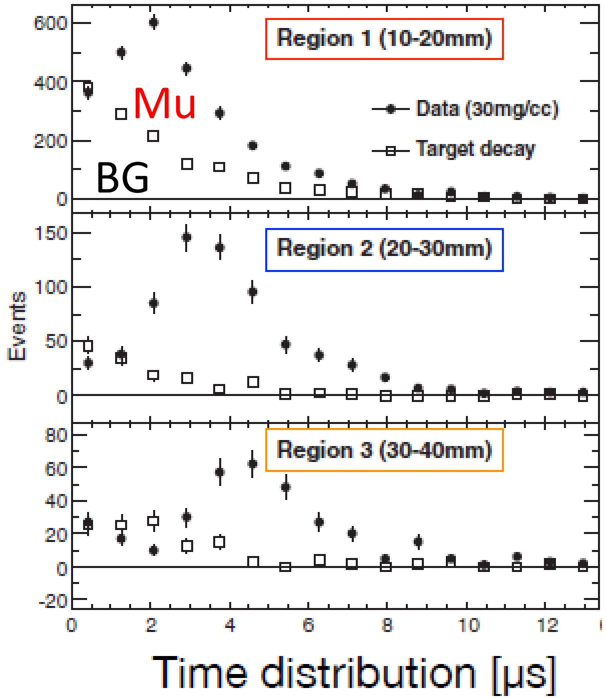
single μ-e decay tracking method with MWDC



Publication in JTEP 2013, 103C01

The measurement was successful, disappointingly small yield



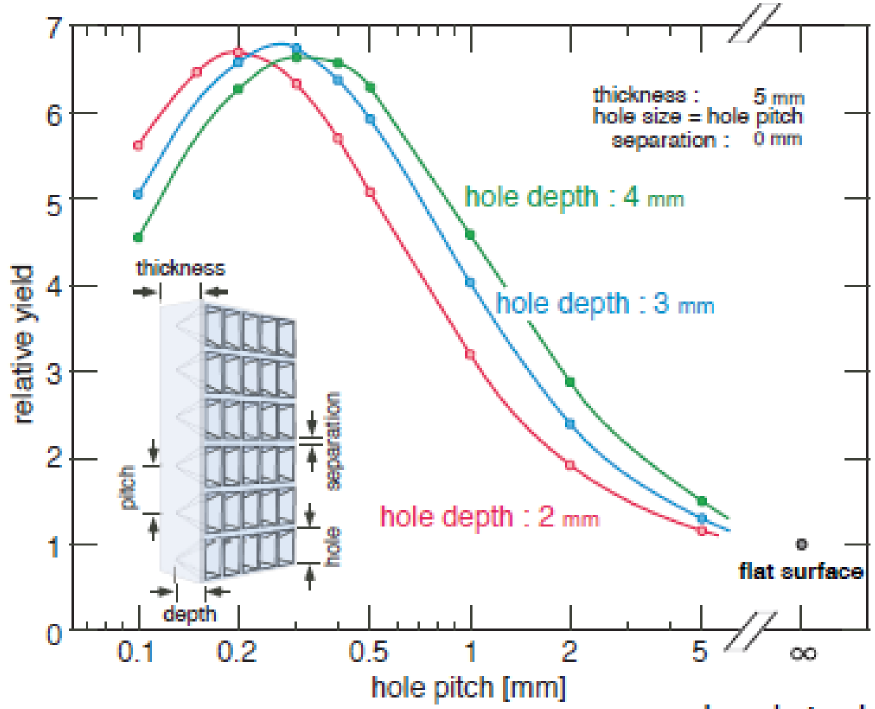


Aerogel target development – enhanced surface

First result on silica aerogel was "disappointing"
Much less than expected from silica powder reports.

→ increasing surface area

simulation with diffusion model



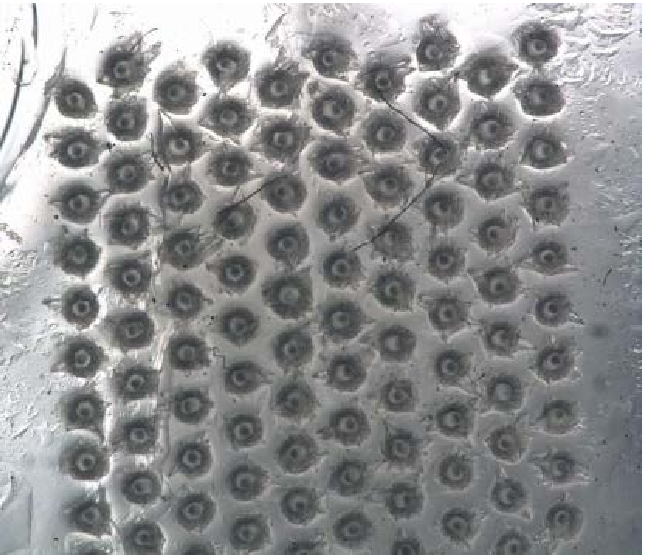
simulated by M. Iwasaki

We then tested
Surface area increase by artificial channels
Model simulations => 6 times increase?

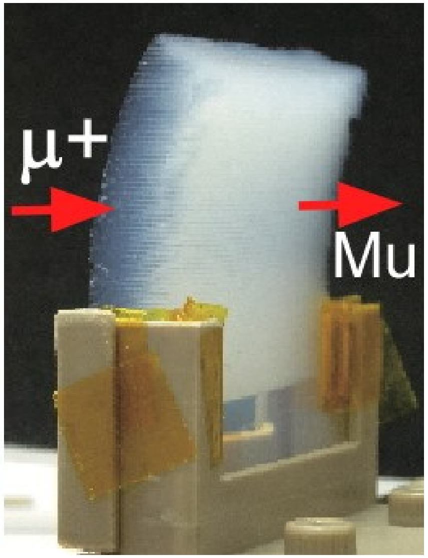
Silica aerogel supplied by Chiba University
Drilled with laser by Y. Oishi (RIKEN)

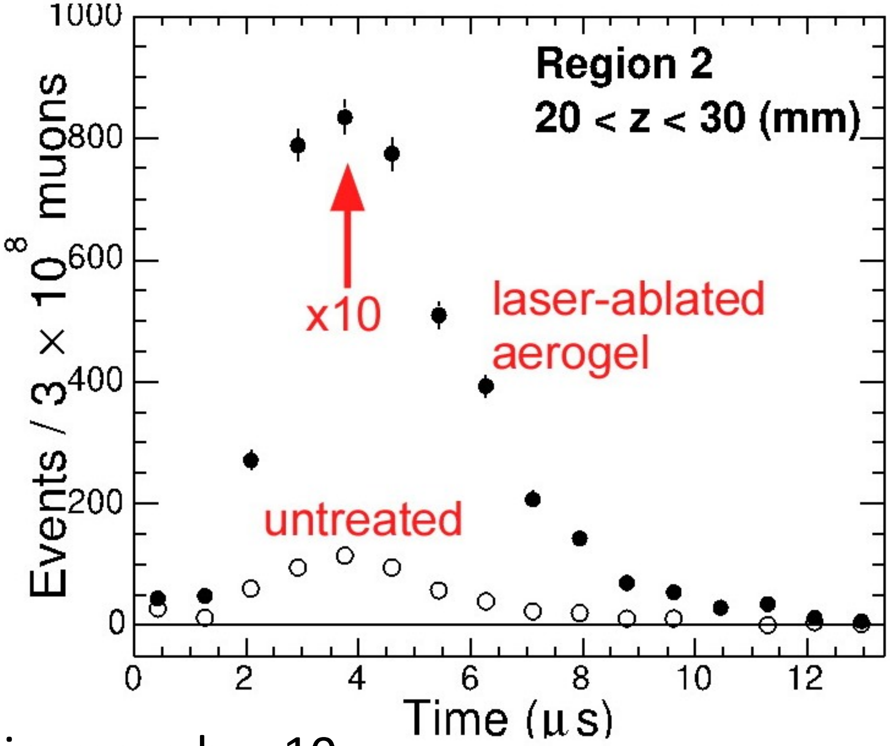
Result

Measurement at TRIUMF Oct 2013



500 μm pitch surface dip





Mu emission increase by x10

Publication in JTEP 2014, 091C01

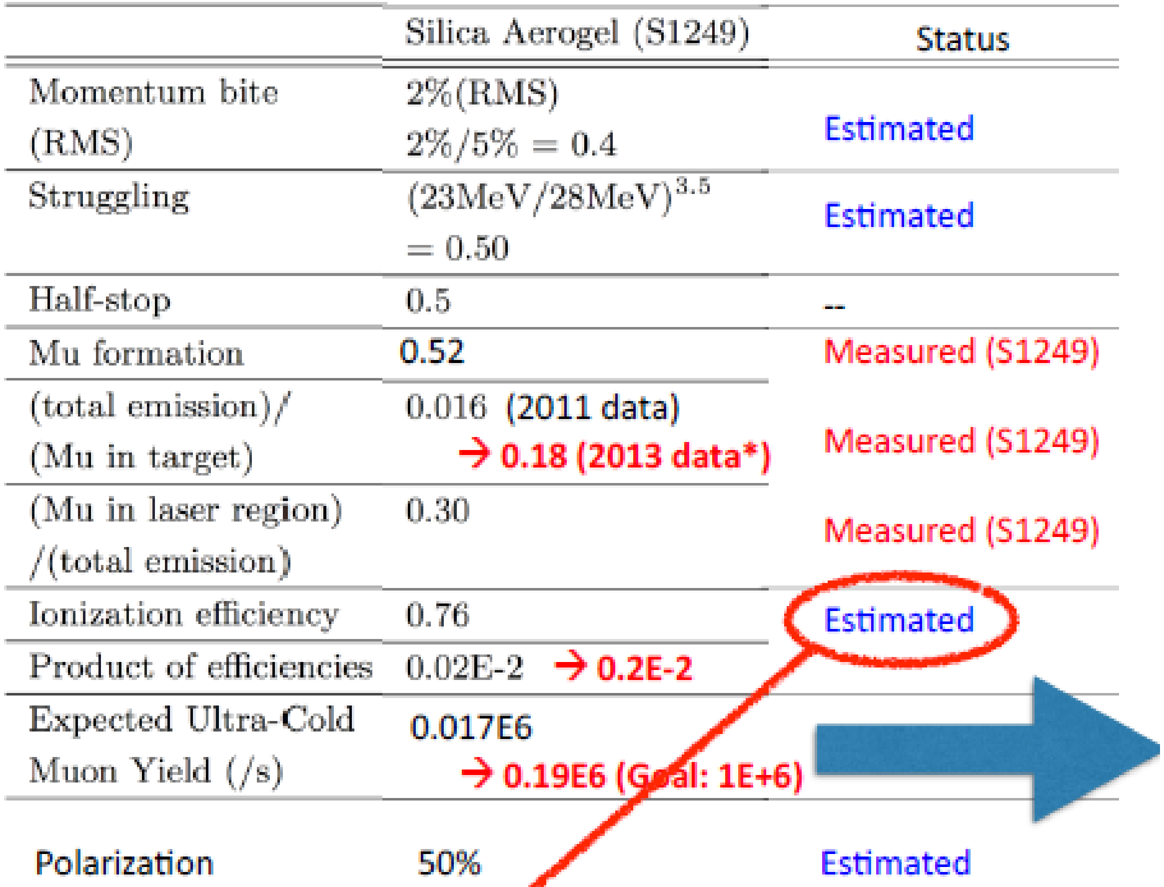
Further target study at J-PARC D-line

Mu yield correlated to the surface area

Mu rate is almost reproducible (after even a year)

Implication to Muon g-2 at J-PARC

Muon source R&D status



	Silica Aerogel (S1249)	Status
Momentum bite (RMS)	2%(RMS) 2%/5% = 0.4	Estimated
Struggling	$(23\text{MeV}/28\text{MeV})^{3.5} = 0.50$	Estimated
Half-stop	0.5	--
Mu formation	0.52	Measured (S1249)
(total emission)/(Mu in target)	0.016 (2011 data) → 0.18 (2013 data*)	Measured (S1249)
(Mu in laser region)/(total emission)	0.30	Measured (S1249)
Ionization efficiency	0.76	Estimated
Product of efficiencies	0.02E-2 → 0.2E-2	
Expected Ultra-Cold Muon Yield (/s)	0.017E6 → 0.19E6 (Goal: 1E+6)	
Polarization	50%	Estimated

* Prog. Theo. Exp. Phys. 091C01 (2014)

measurement preferred

gives 0.44 ppm statistics
(better than previous BNL E821)
in 1 year RUN
Further improvement is expected.

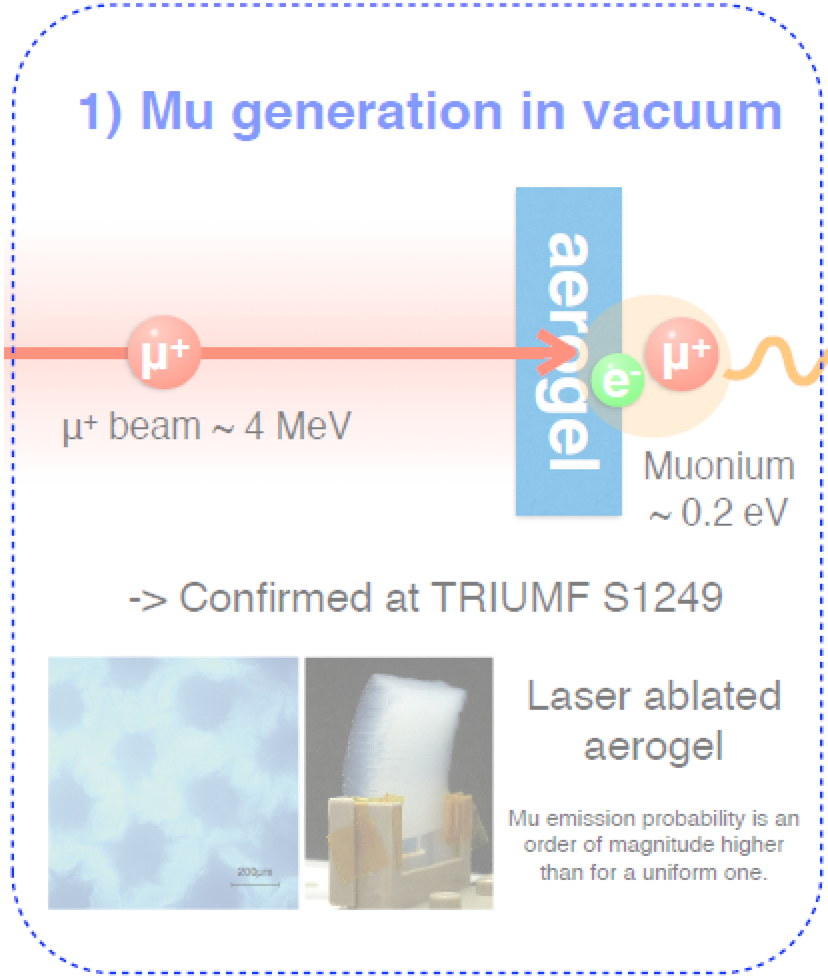
Comparison of hot-W and silica aerogel

	Hot W	**Silica aerogel**
Density [g/cm^3]	19.25 (one of the highest)	~0.03 (very low)
muon state in bulk	μ^+	Mu(60%?) and μ^+
Diffusion coefficient [cm^2/s]	2×10^{-3} (2000K)	5.0 (for ρ=0.03)
Diffusion length [μm in μs]	0.5	20
Release from surface	Activation type	Rapid (<5ns)
Strength	Very hard	fragile
Conductivity [nΩ m]	52.8	insulating
Thermal conductivity [W/m K]	173	0.017
Temperature [K]	2000	300 (no optimization yet)
Mu Emission efficiency (depends beam condition)	4%	~10%
Usage for slow muon	almost established	need demonstration !

So different!
but gives similar yield

Next step

Demonstration and optimization of slow muon production based on silica aerogel

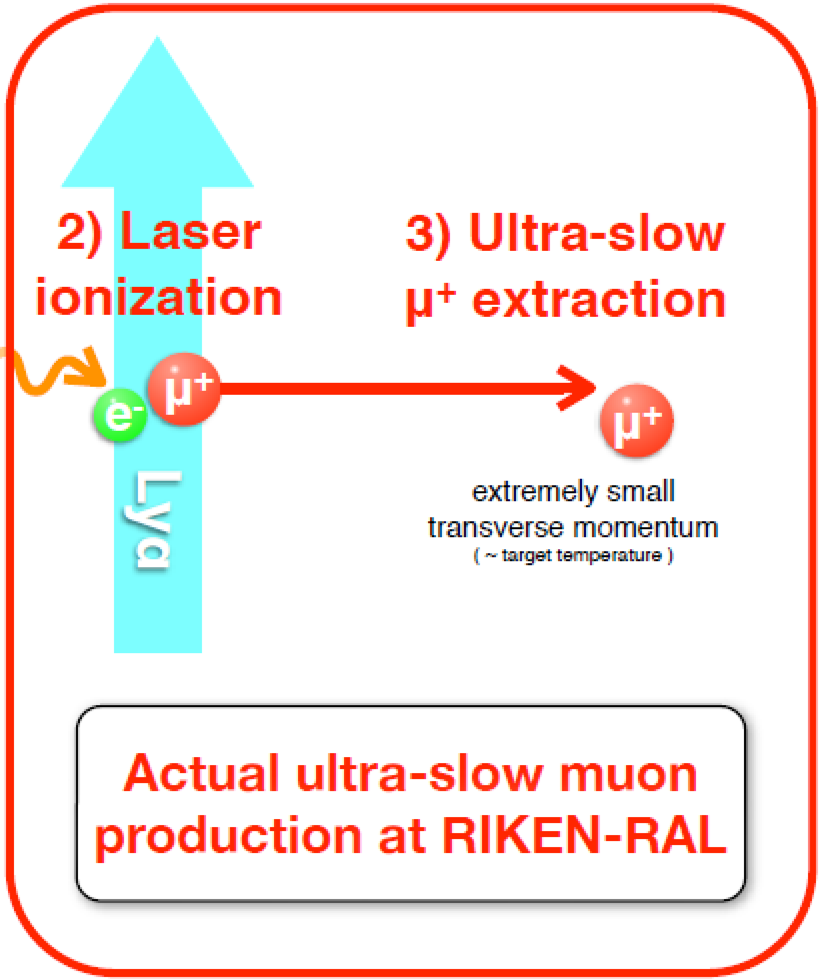


1) Mu generation in vacuum

-> Confirmed at TRIUMF S1249

Laser ablated aerogel

Mu emission probability is an order of magnitude higher than for a uniform one.



2) Laser ionization

3) Ultra-slow μ^+ extraction

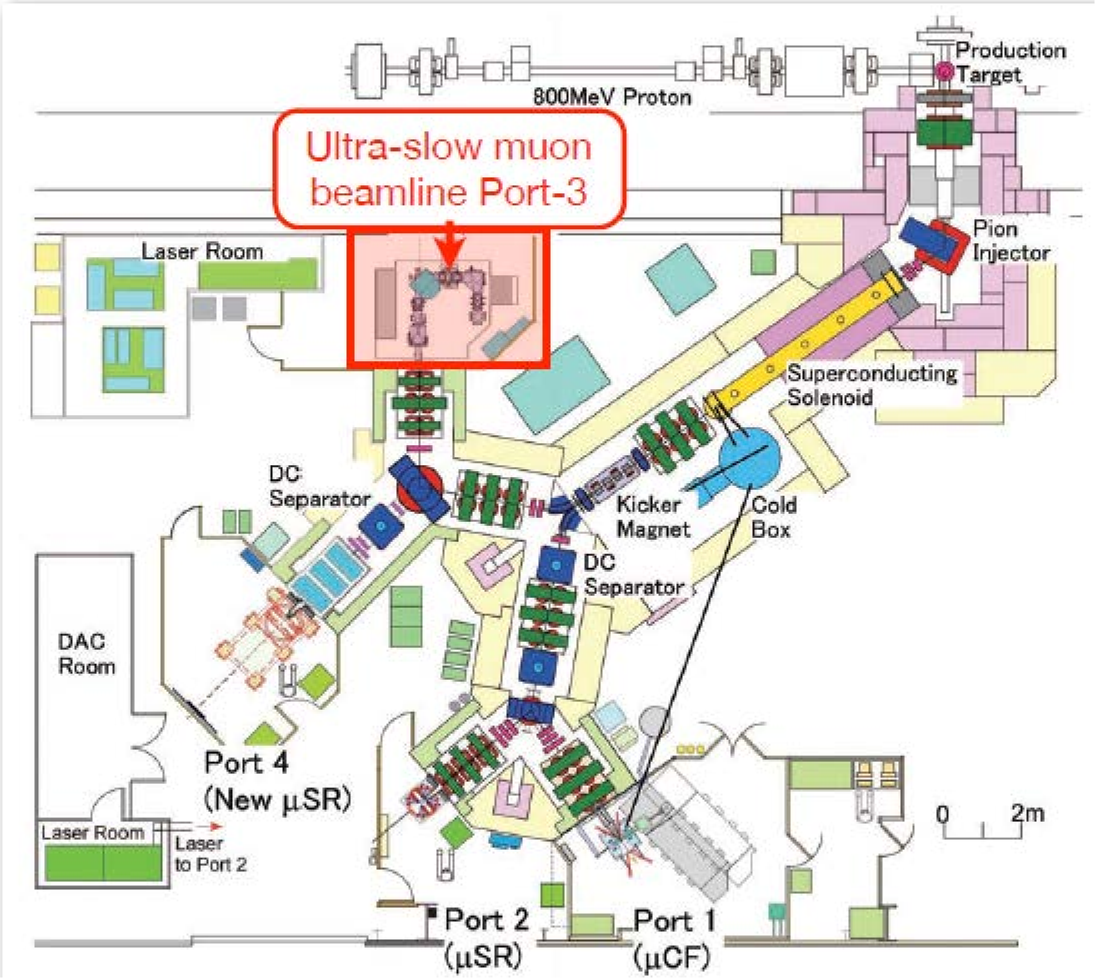
extremely small transverse momentum
(~ target temperature)

Actual ultra-slow muon production at RIKEN-RAL

RIKEN-RAL

RIKEN-RAL is the best place for this demonstration/development

dedicated area
laser utilities



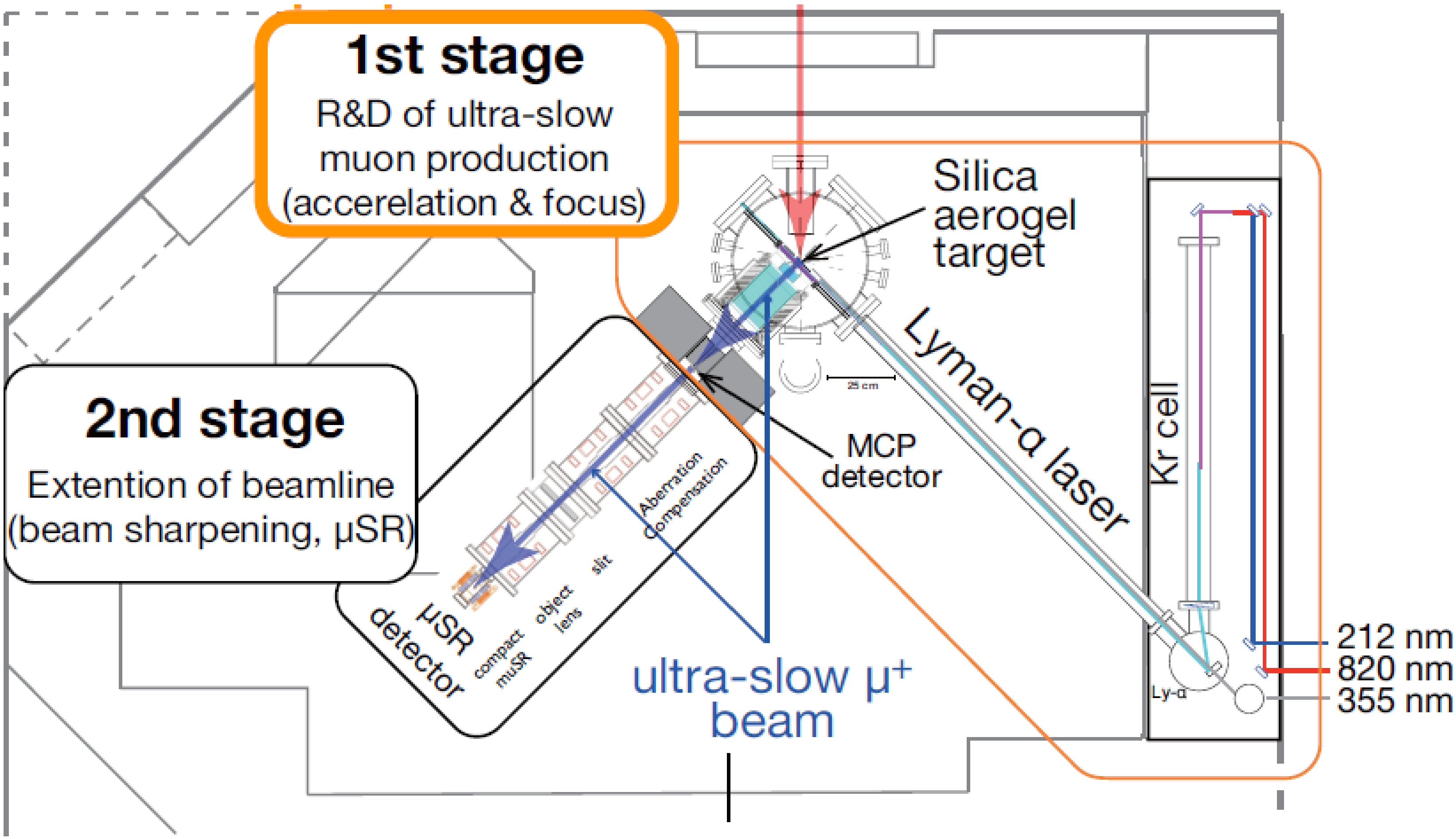
RIKEN-RAL

Redesigned beamline

take advantage of room temperature target

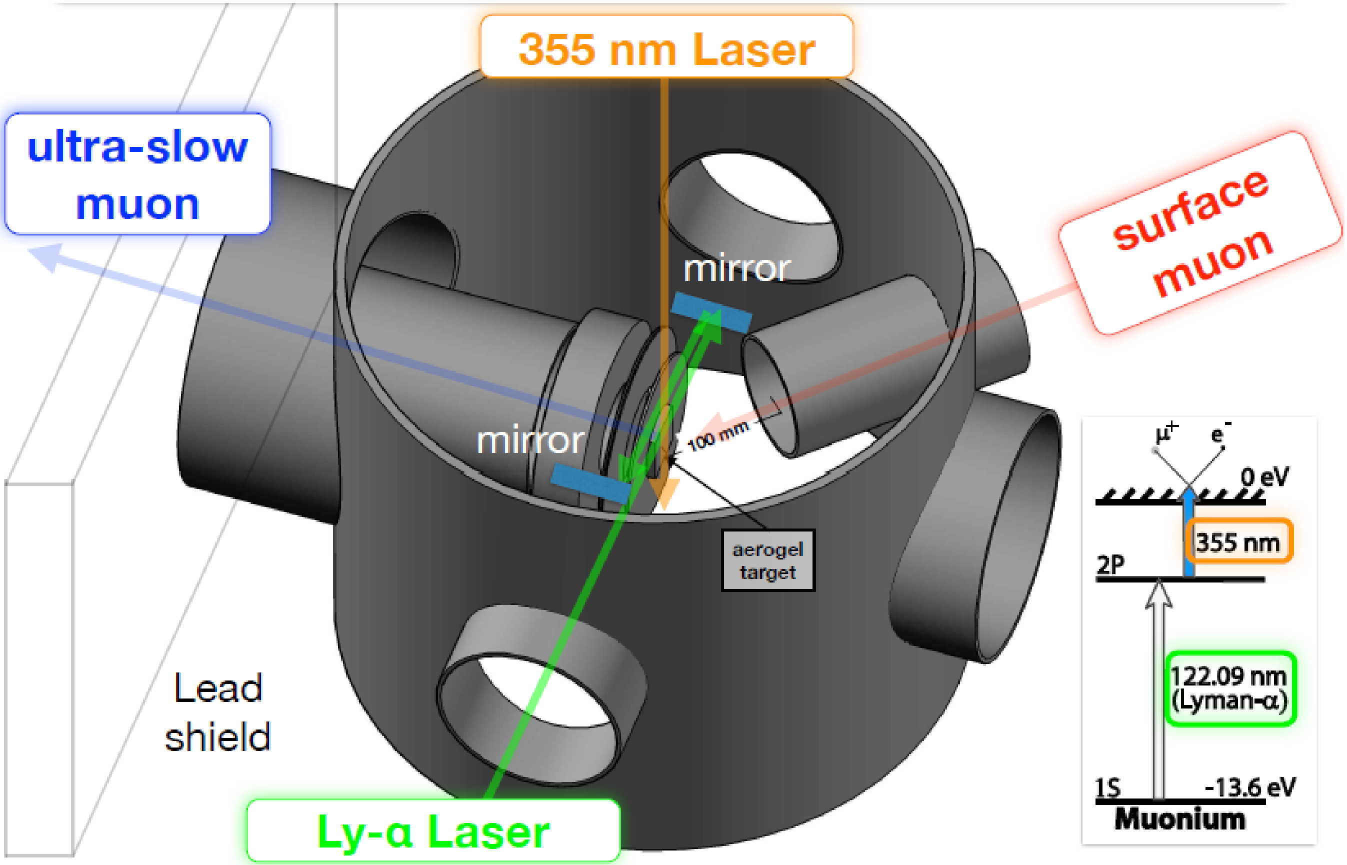
Try to remove complex optics components

Proto-type design for muon g-2 muon source



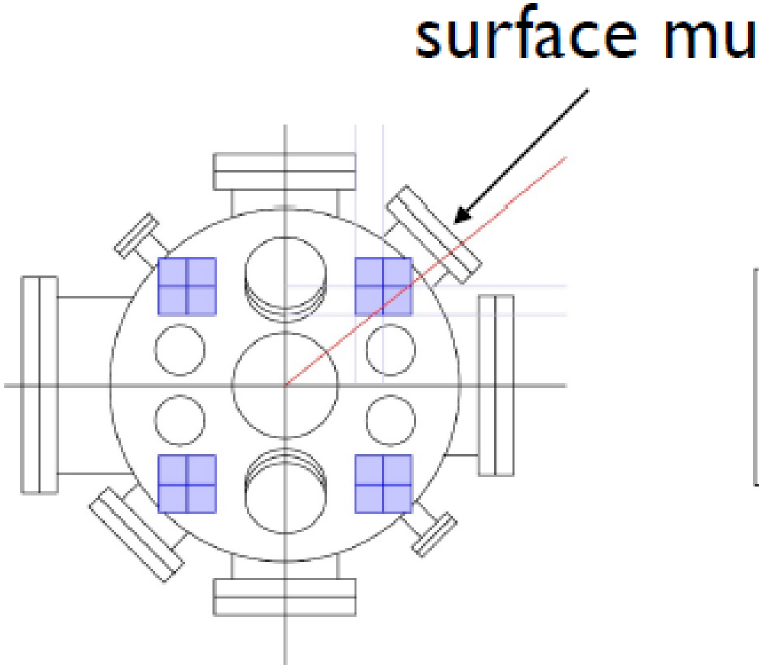
Study with new beamline at RIKEN-RAL

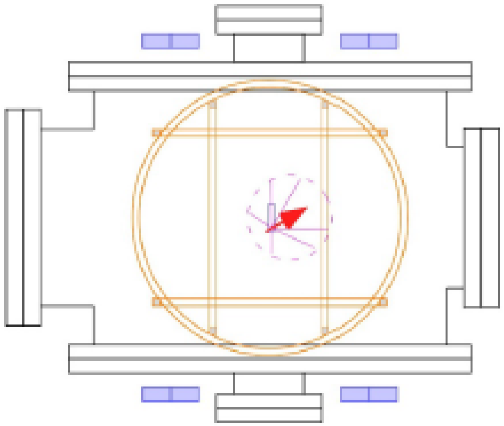
1. New chamber/beamline optimized for room temperature target
2. 45 degree extraction and lead shield to reduce background
3. Laser upgrade and mirror

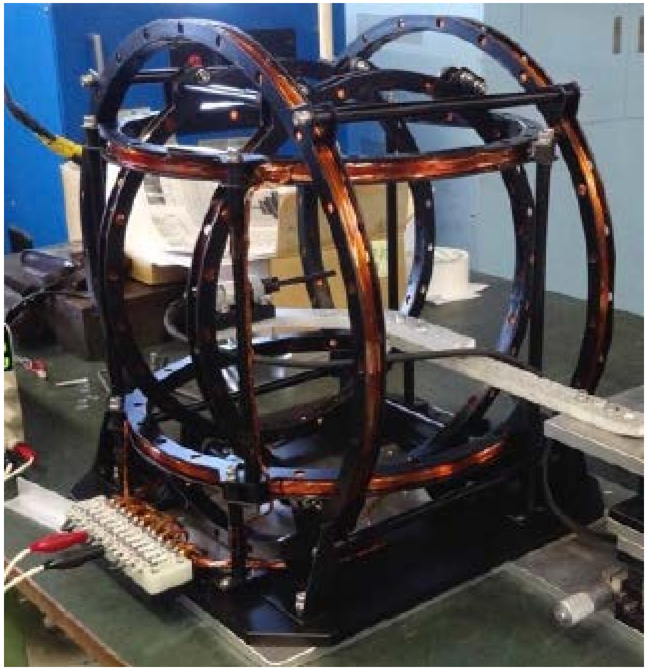


RIKEN-RAL slow muon : spin control magnetic field

Spin holding/reorientation/flip field coil and probe
μSR monitors muon stopping and spin status



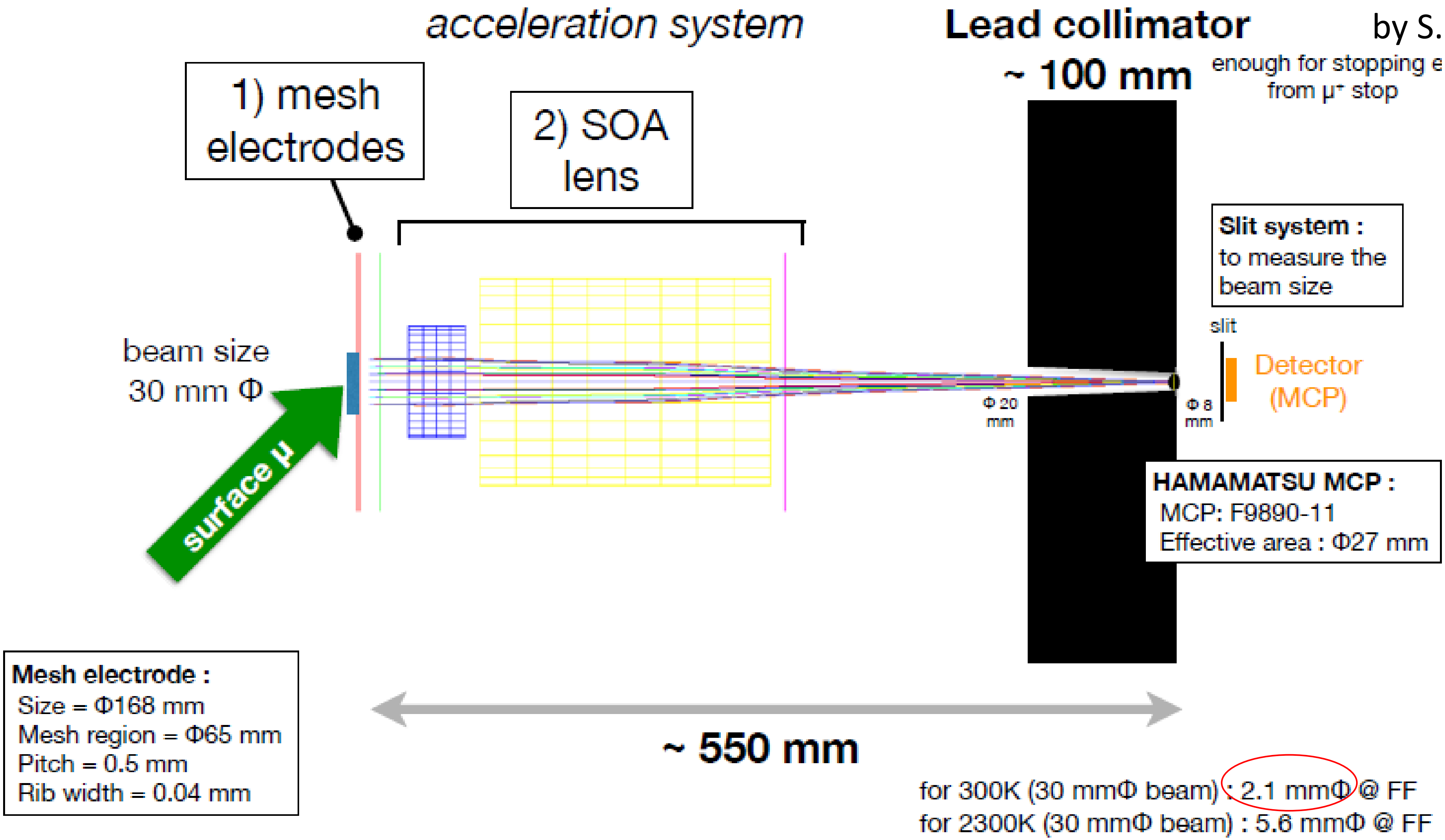




Reorient the muon spin utilizing x100 precession while in Mu state

Cylindrical optics and background

by S. Okada



Slit system : to measure the beam size

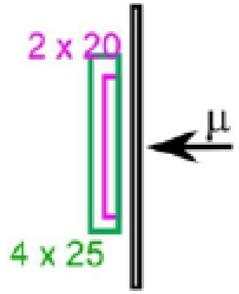
HAMAMATSU MCP :
MCP: F9890-11
Effective area : Φ27 mm

Mesh electrode :
Size = Φ168 mm
Mesh region = Φ65 mm
Pitch = 0.5 mm
Rib width = 0.04 mm

for 300K (30 mmΦ beam) : 2.1 mmΦ @ FF
for 2300K (30 mmΦ beam) : 5.6 mmΦ @ FF

beam shaping optics may be added in beam extension

Expected yield at RIKEN-RAL



Surface muon beam intensity: 1.5 x 10^6/s (x1/2 @25Hz, x1@50Hz)

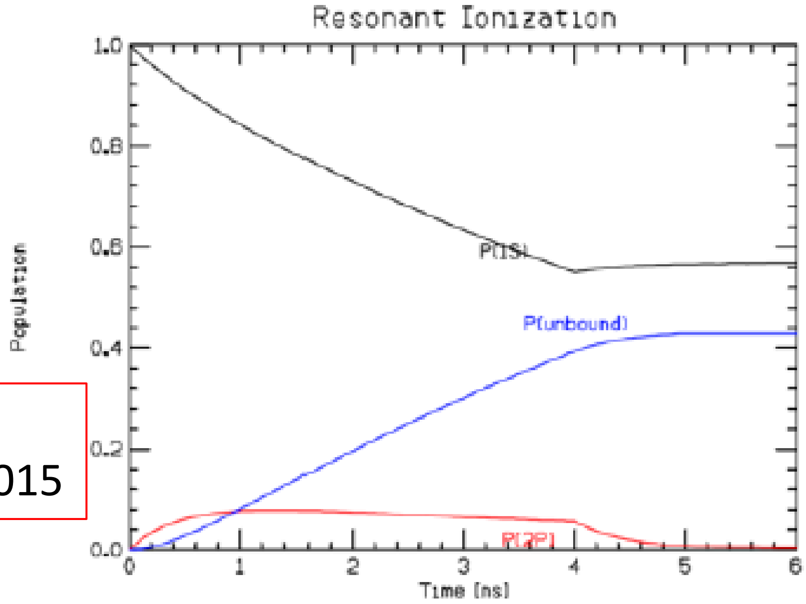
Total Mu emission: 0.09(S1249) * 0.5(half stop) * 0.5(Port 3 vs M15) = 0.0225

Mu in laser covered region (2 cm(Y) and 1~3 mm(Z)@ 600 ns): 0.5 x 0.2 = 0.1

Laser ionization: ~0.42

- 1s->2p by 122 nm with 4 μJ/pulse,
- 80 GHz, 4 ns, spot size 2 mm x 2 cm
- 2p->unbound by 355 nm, 300 mJ
- 5 ns in 4 mm x 2.5 cm

Mesh grid and transport: 0.8 * 0.8 = 0.64



Overall efficiency 0.06%

to be tested around June 2015

Intensity 1.5 x 10^6/s * 0.0006 = 900/s

c.f. ~15 /s (previous RAL expt.)

x 50 increase (laser power x4, Doppler x2.5, Mu Spread x2, 50Hz x2 etc)

more yields with laser reflection mirror in future

Future prospects

Towards more yield, betterquality

Mu target material

Larger surface/volume ratio

Artificial surface structure - straight exit channels

Multiple target -> multiple beamline

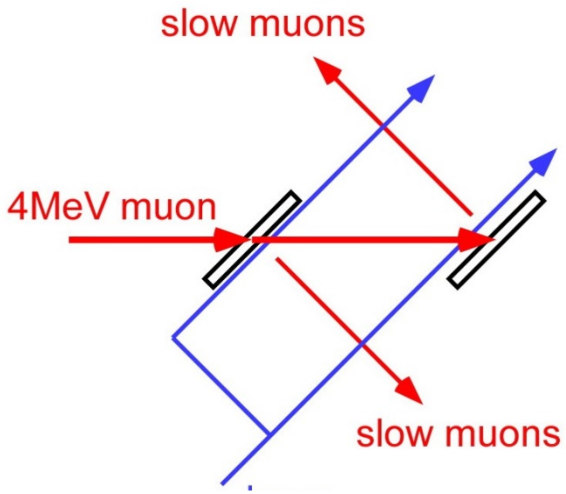
Two-step phase space compression

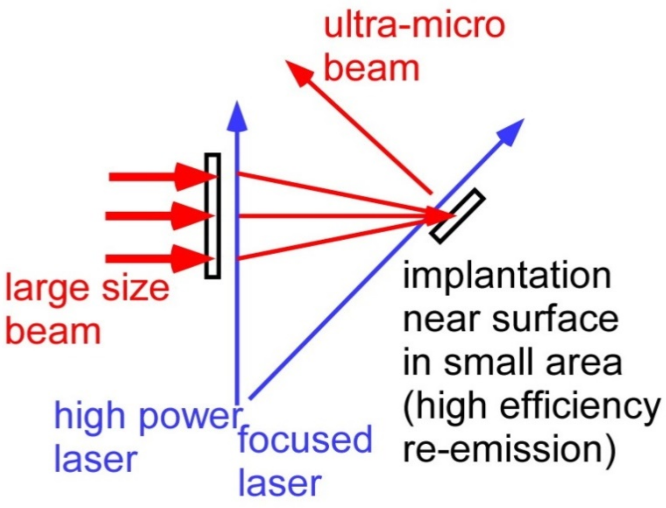
Surface muon (4 cmϕ)

-> First target -> slow muon

-> focus on Second target (2 mmϕ)

-> ultra micro beam (<100 μm)





Summary

Low energy muon beam is about to be obtained at J-PARC
by Ultra Slow Muon Microscope collaboration.
Expected yield is about the order of 10^5/s.

Silica aerogel was developed as a new candidates
that may further improve the beam quality
and will be applicable to new muon g-2 measurement.
Slow muon demonstration is planned soon at RIKEN-RAL.

Spare Slides

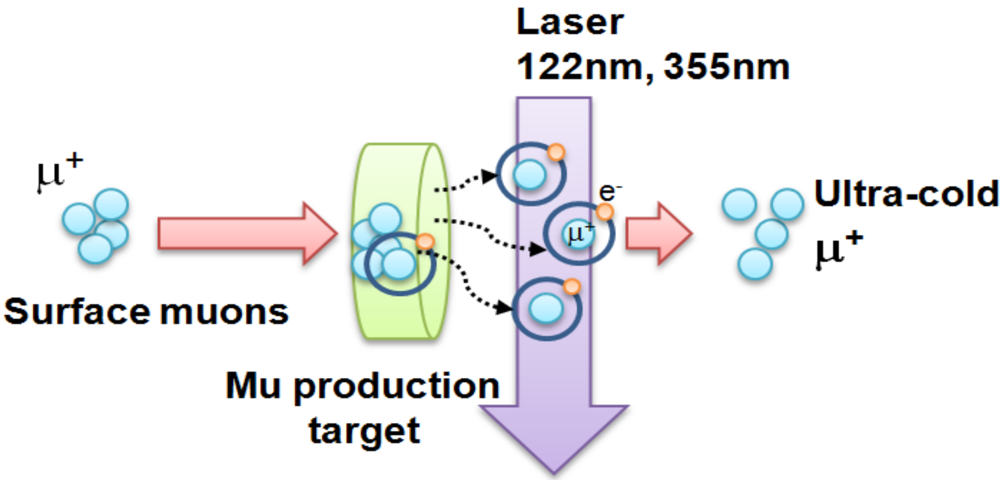
Summary - Port 3 characteristics@2008

Low energy μ^+ beam	μSR spectrometer
Intensity at sample **~ 15-20 μ^+/s** 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	Background: <0.01 per 15 μs after μ^+ pulse Count rates: ~ **50 kev/hour** (compared to 20-50 Mev/hour @ bulk μSR at ISIS) TF : < **60 mT** ZF compensation to 0.1 μT Sample temperature: **10K-300K** **External LE-μ^+ trigger**

To be solved
- Small intensity
- Loss of spin polarization
- Beam quality - good but not fully

Ultra-slow muon from Thermal Muonium

Starting from surface muon beam (4 MeV, Δp~2%, 4cmϕ, 50 mr)

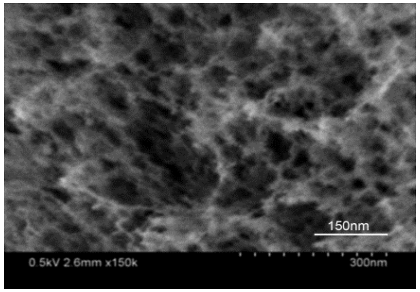


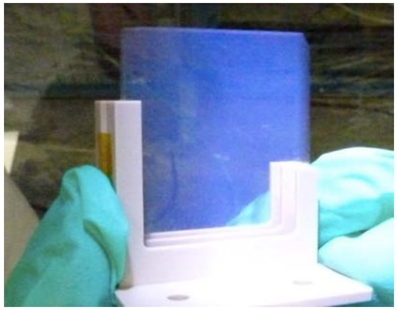
Stop muons in a material,
some diffuse out at thermal energy.
Good muonium emitter and
an intense laser to remove the electron
are essential.

(efficiency>1% required)

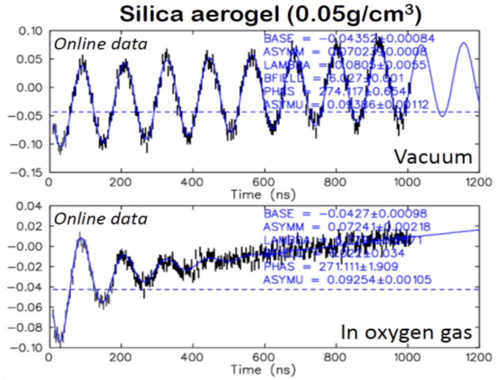
Silica powder has been known to be a good Mu emitter at room temperature
Mu diffuse out through network of SiO_2 grains (large surface area)

Silica aerogels with similar network structure can be more easily handled and may fit better our system





S1249 Mu Imaging Experiment



First MuSR measurement in June 2010

Quick screening of bad samples (no Mu or polarization)

First Imaging measurement (Nov 18 – 23, 2010)

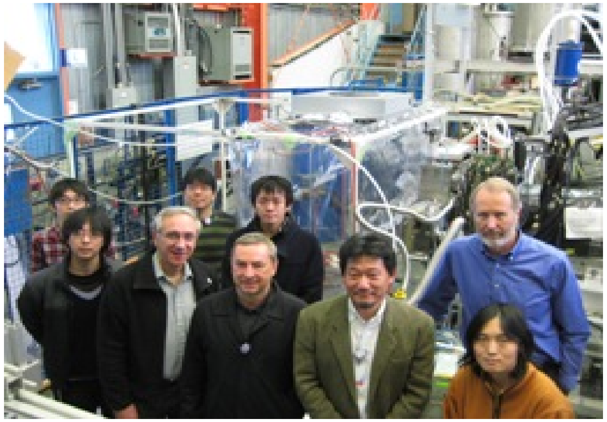
MWDC and MCP commissioning was successful

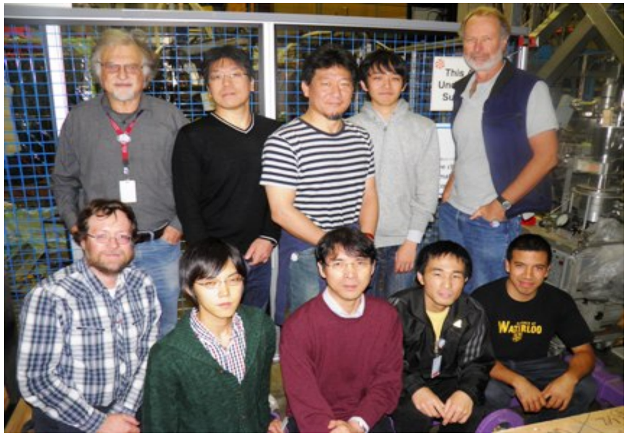
Data taken just for one aerogel sample

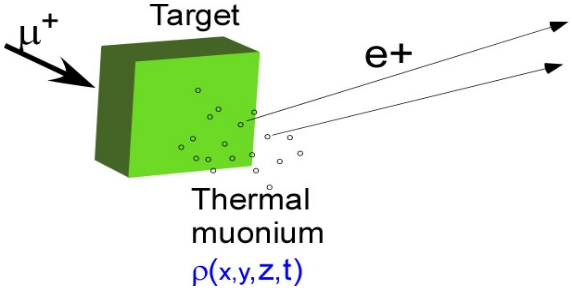
Second Imaging measurement (Oct 20 – 30, 2011)

Data were taken for 4 silica aerogel samples (0.027, 0.05, 0.1, 0.18 g/cm^3)

and one SiO_2 plate (2.2 g/cm^3) as a reference, x15 statistics obtained

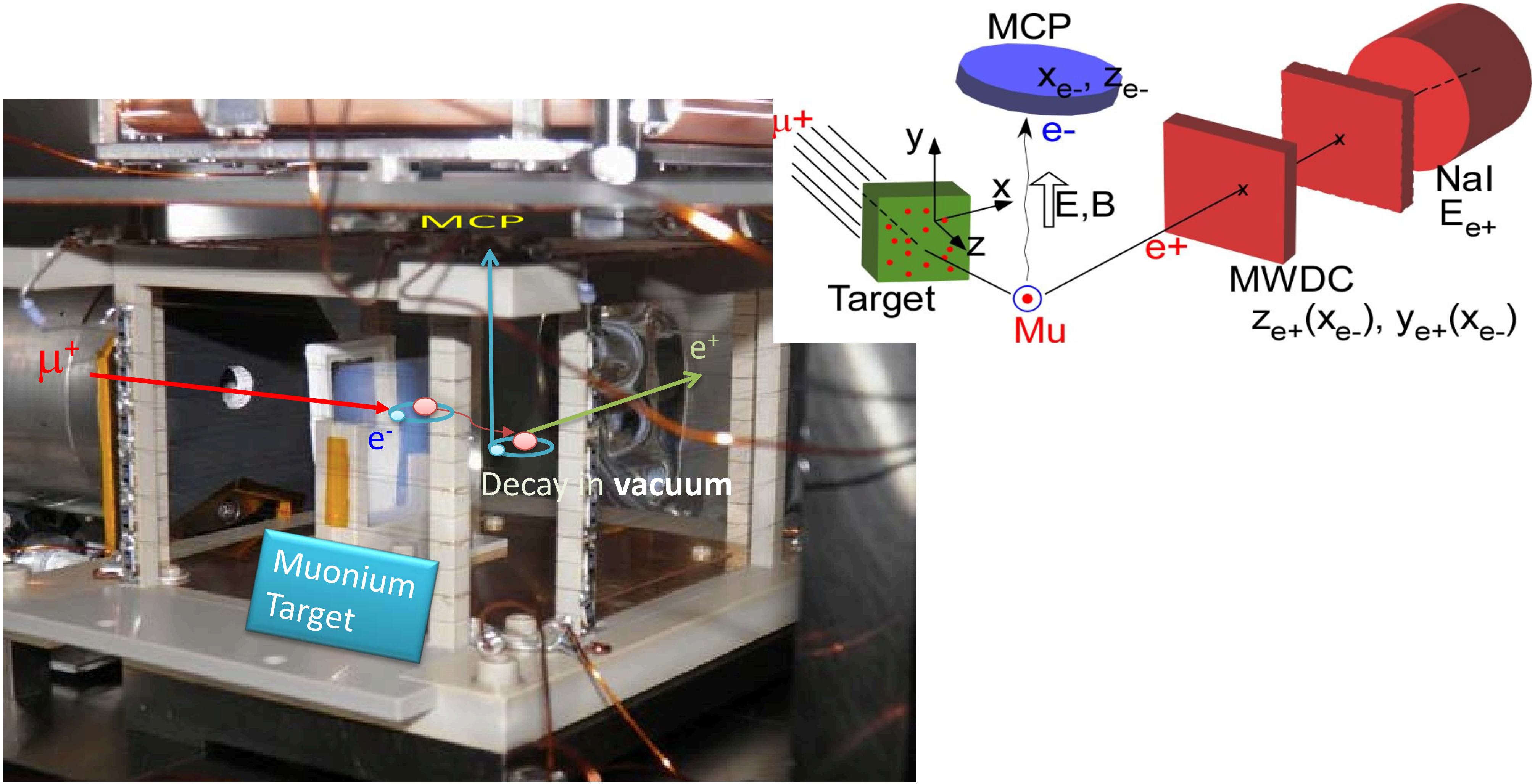






2010 & 2011 (not all members are shown)

Mu Imaging Setup



Modeling of Mu diffusion: simple geometry

Test of the diffusion model is one of the important issue of S1249.
We determine what parameter well describes the observation and apply the result for further design of the material or the target geometry.

First approach is by just mathematical equation of diffusion

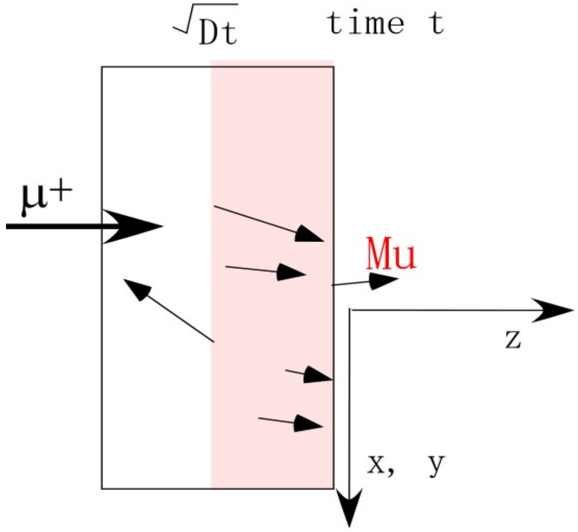
Mu diffusion in target

- time for muon to diffuse to surface layer, delayed emission
- Integrated emission by time = $(Dt)^{1/2}$
- => Distribution of mission timing is $(D/t)^{-1/2}$

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

Mu distribution is convolution of these two



Easiest for quick estimation of efficiency
D is a parameter specific to the target material
but no direct connection to physics

Modeling of Mu diffusion: extended

Diffusion simulation with microscopic random walk

see G. Marshall's presentation in CM4 and CM5

Simulate random walk with mean free path of L_{MFP}

If z>0 move in vacuum with constant velocity

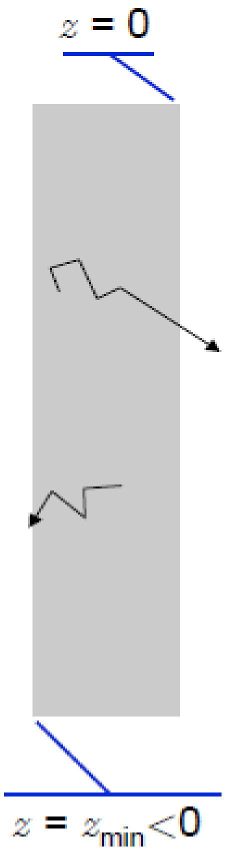
Capable to input detailed physics

(velocity distribution, step length distributions, etc)

and practical parameters

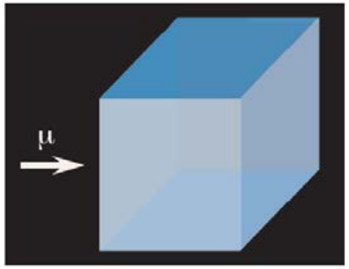
(muon stopping distribution, surface boundary etc)

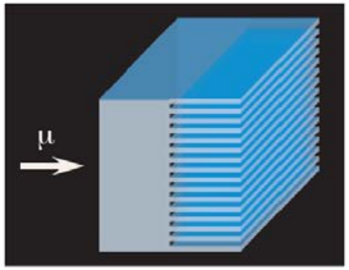
Most of the analysis is based on comparison of this simulation and the data



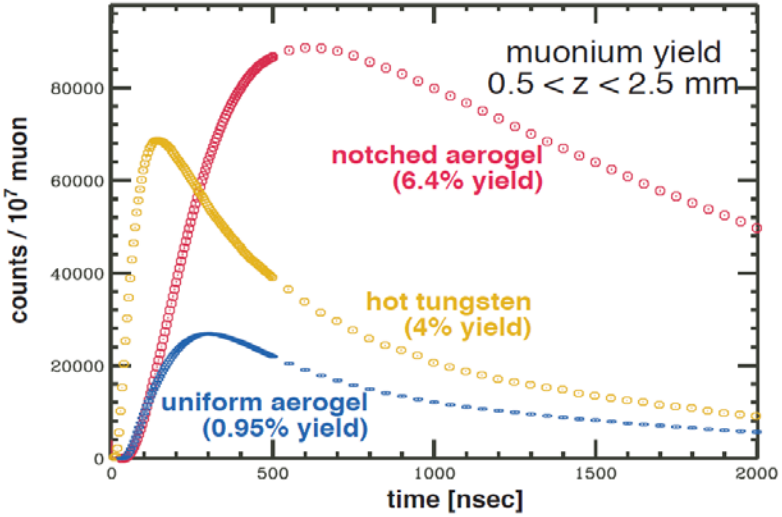
Simulation of gain by Sub-structure

by M. Iwasaki at ultra Slow Muon Microscope Meeting, Sapporo

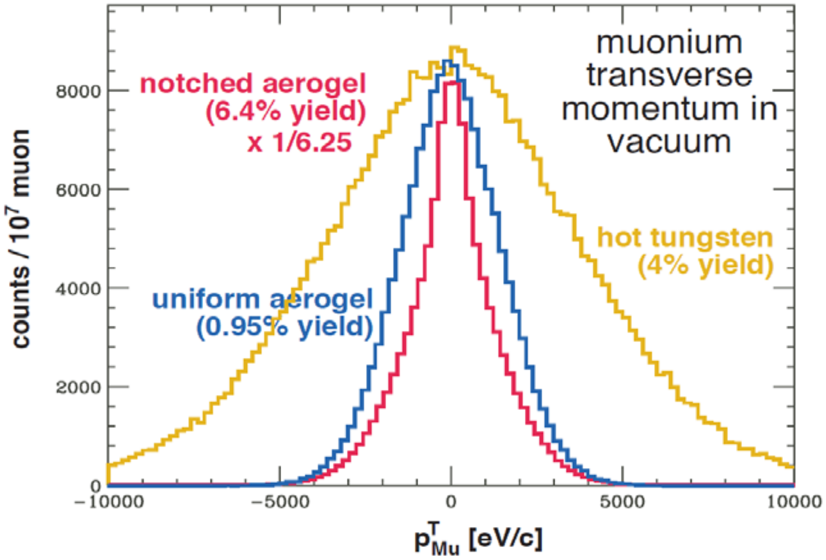


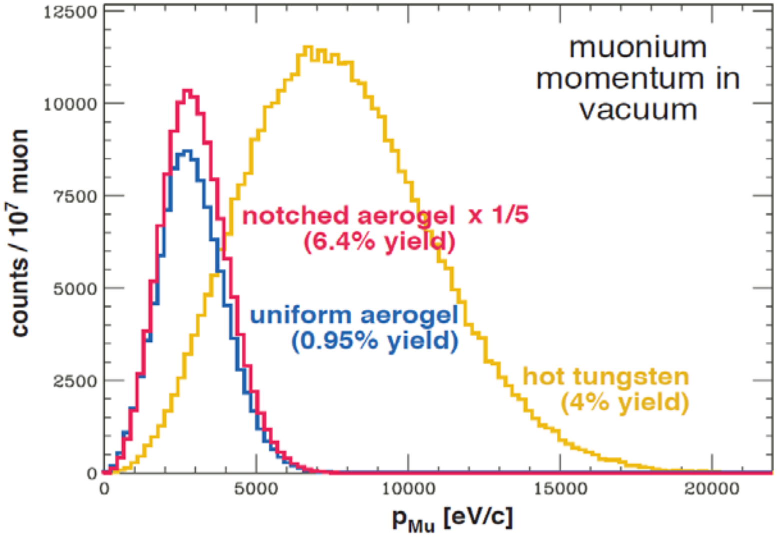


Emittance improvement



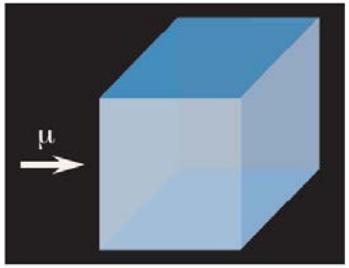
Emittance improvement

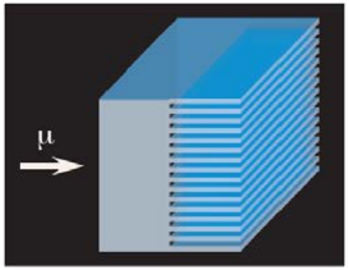


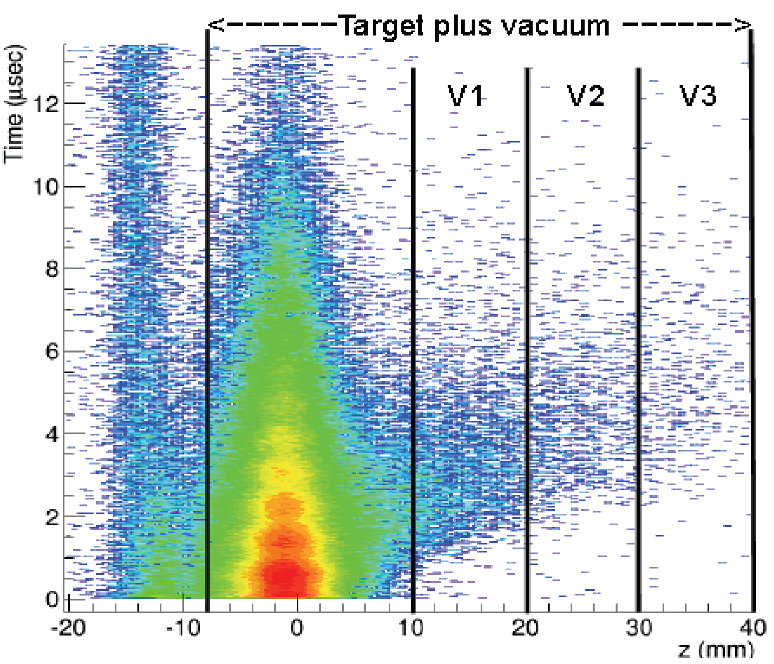


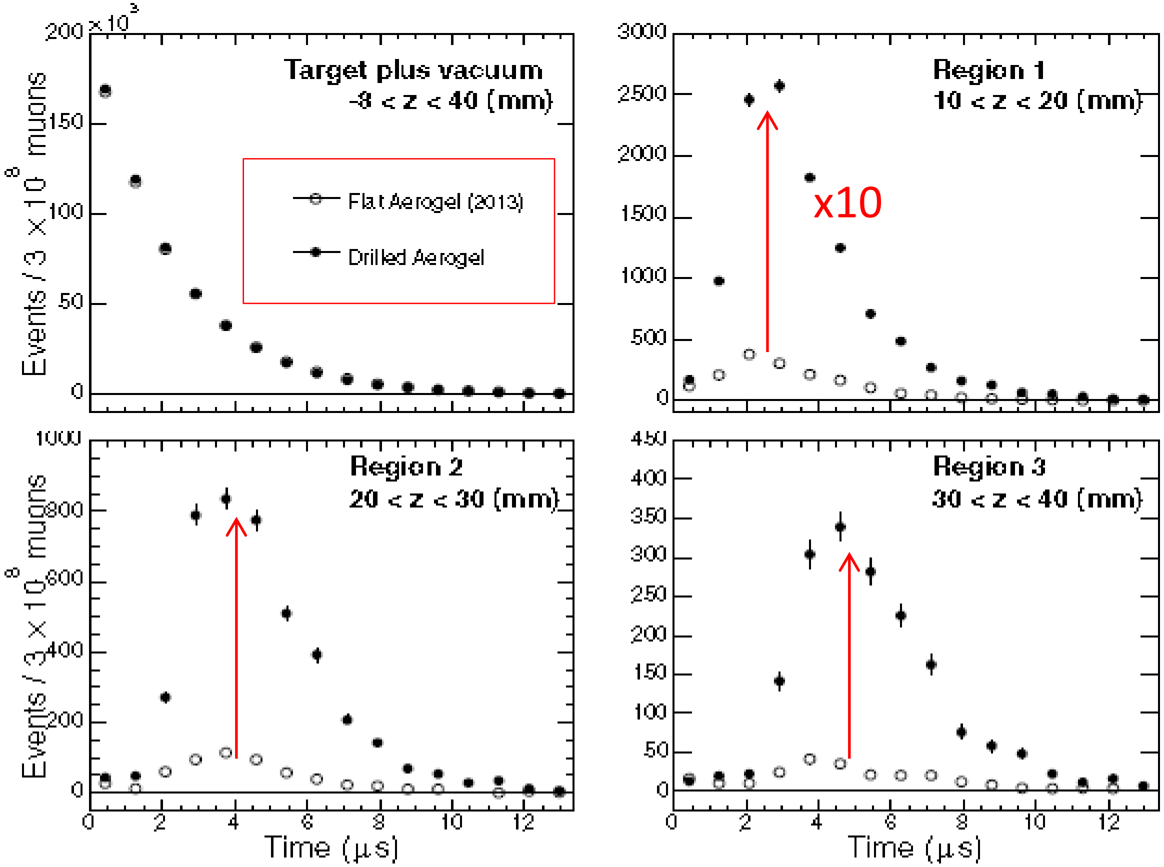
typically x6(preliminary) improvement

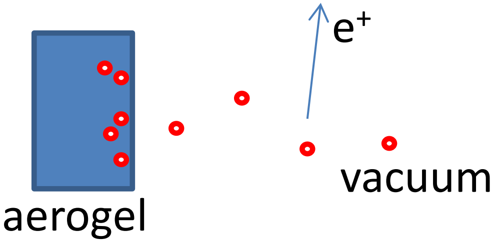
New measurement (S1249@TRIUMF 2013)





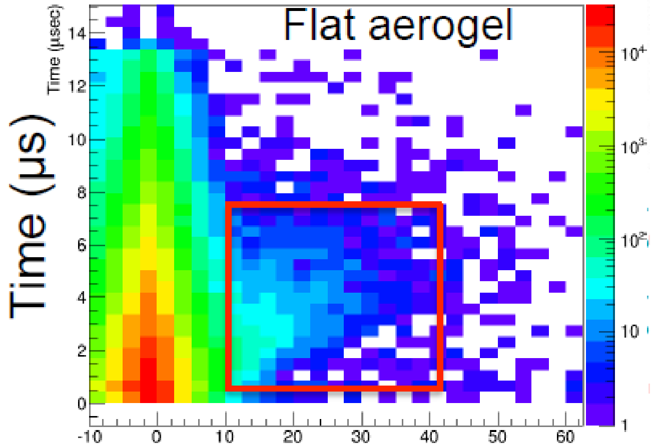




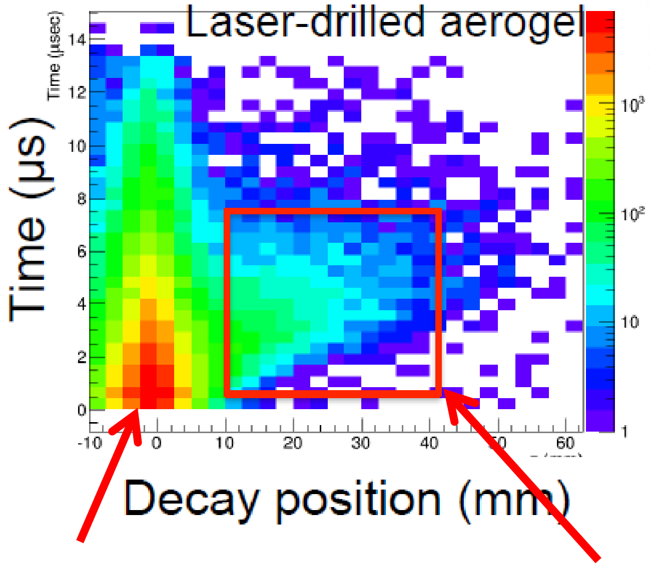


(to be published in PETP soon!)

New measurement with aerogel in Oct 2013



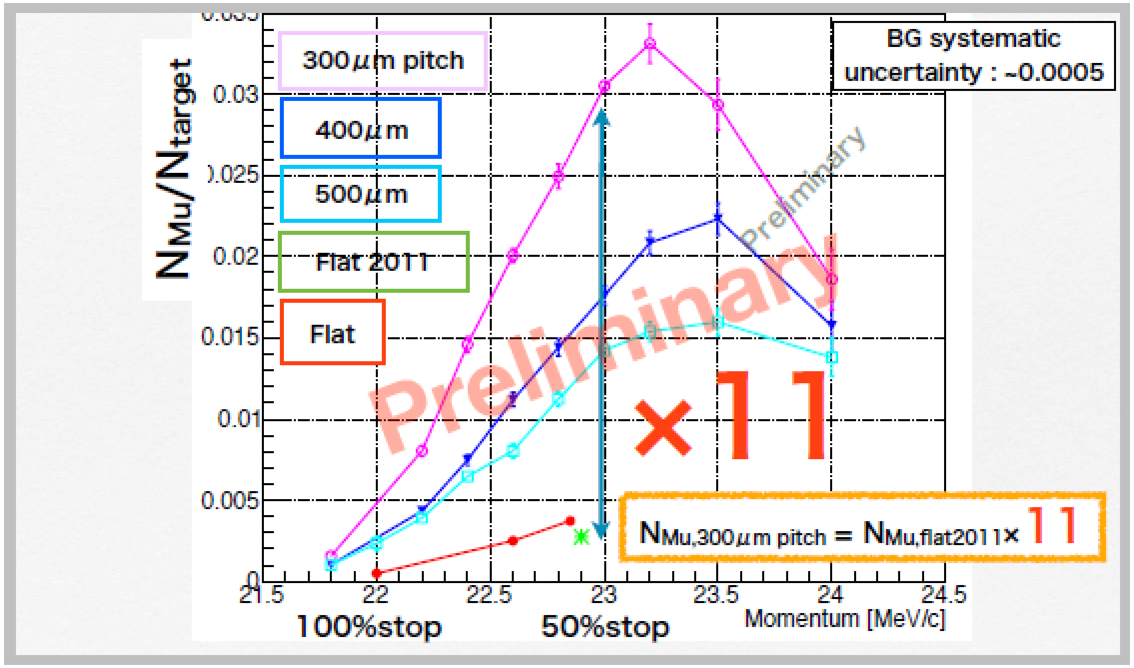
analysis of T. Mibe



Mu in target

Mu in vacuum

Mu in vacuum vs Mu in target



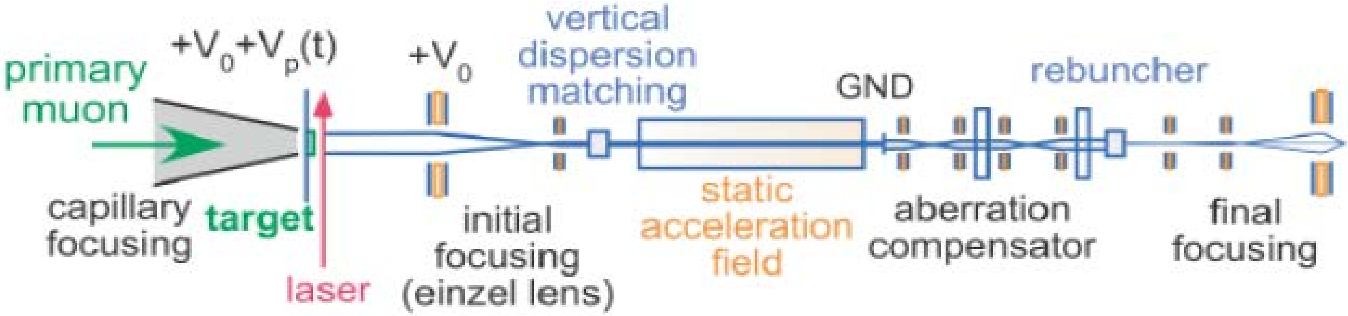
Report in JPS meeting
R. Kitamura 29 Mar 2014

x 11 Mu increase by surface increase with laser drilling consistently increasing with more hole density (narrower pitch)

Study of beam sharpening by “Grant-in-Aid”

One of the missions to RIKEN is "Super cooling and sharpening of ultra slow muon beam for fundamental/particle physics” in “Ultra Slow Muon Microscope”

- Cold muon source =>S1249
- New Intense Lyman-α Laser for Ionization
- Initial Acceleration – scheme shown in

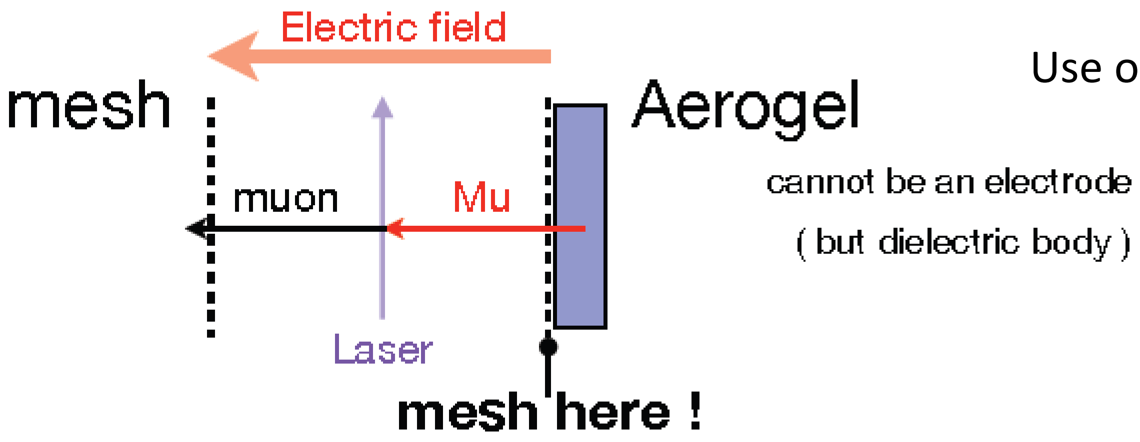


pulsed electric extraction field - ΔE

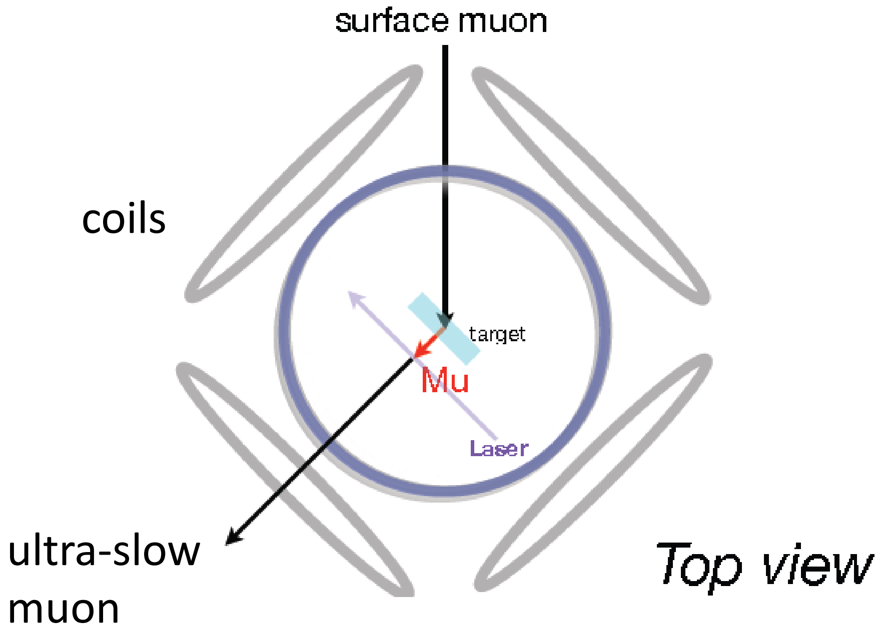
chirped laser - pT

RF compression - timing

New target section designs



Use of metal meshes to form good E-field



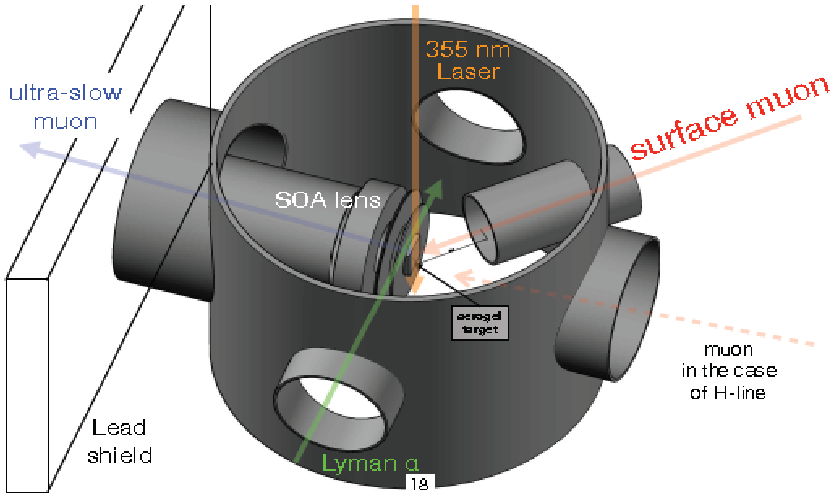
Control of Mu spin with weak magnetic field (~1 G)
(and also stray field cancellation)

Ultra-cold muon from silica aerogel

Muonium to ultra-cold muon beam by ionization and acceleration
So far all the ultra-cold muon beam at KEK and RIKEN-RAL Muon Facility
was based on Mu from hot-W (~2000K) and with static field (~10 keV).

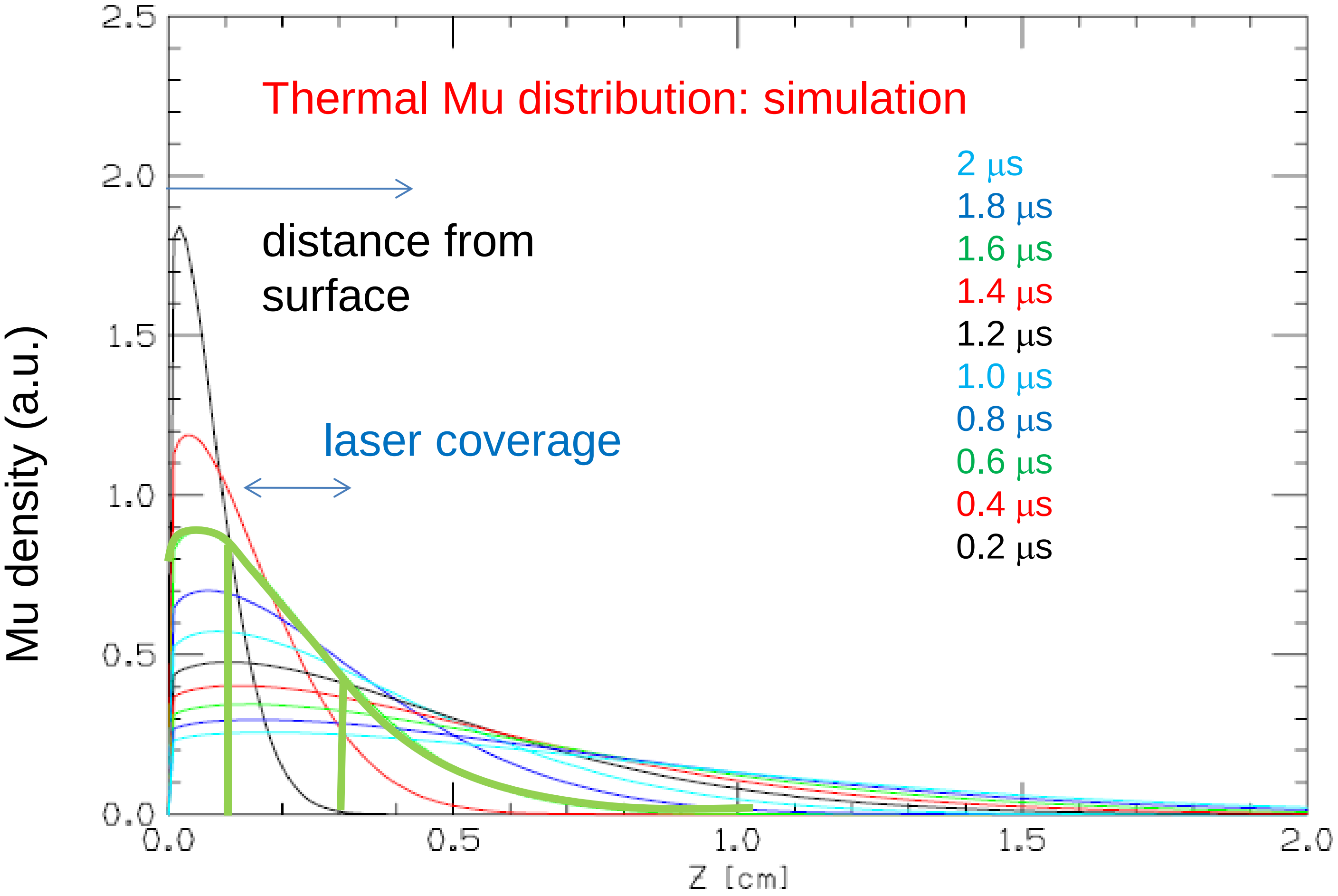
Ultra-cold muon beam from silica-aerogel source need to be demonstrated.

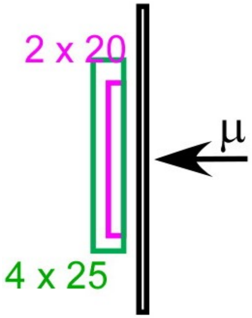
Silica aerogel will be evaluated for
1) long term stability of Mu yield
2) brittleness and vacuum
3) electrical field stability
(use of meshed metal container)
and also we try good things
1) colder beam spread
2) multiple-pass laser mirror
3) other functions (spin control, ...)



A new Muon Source chamber will be constructed for evaluation study.

Laser overlap with muonium



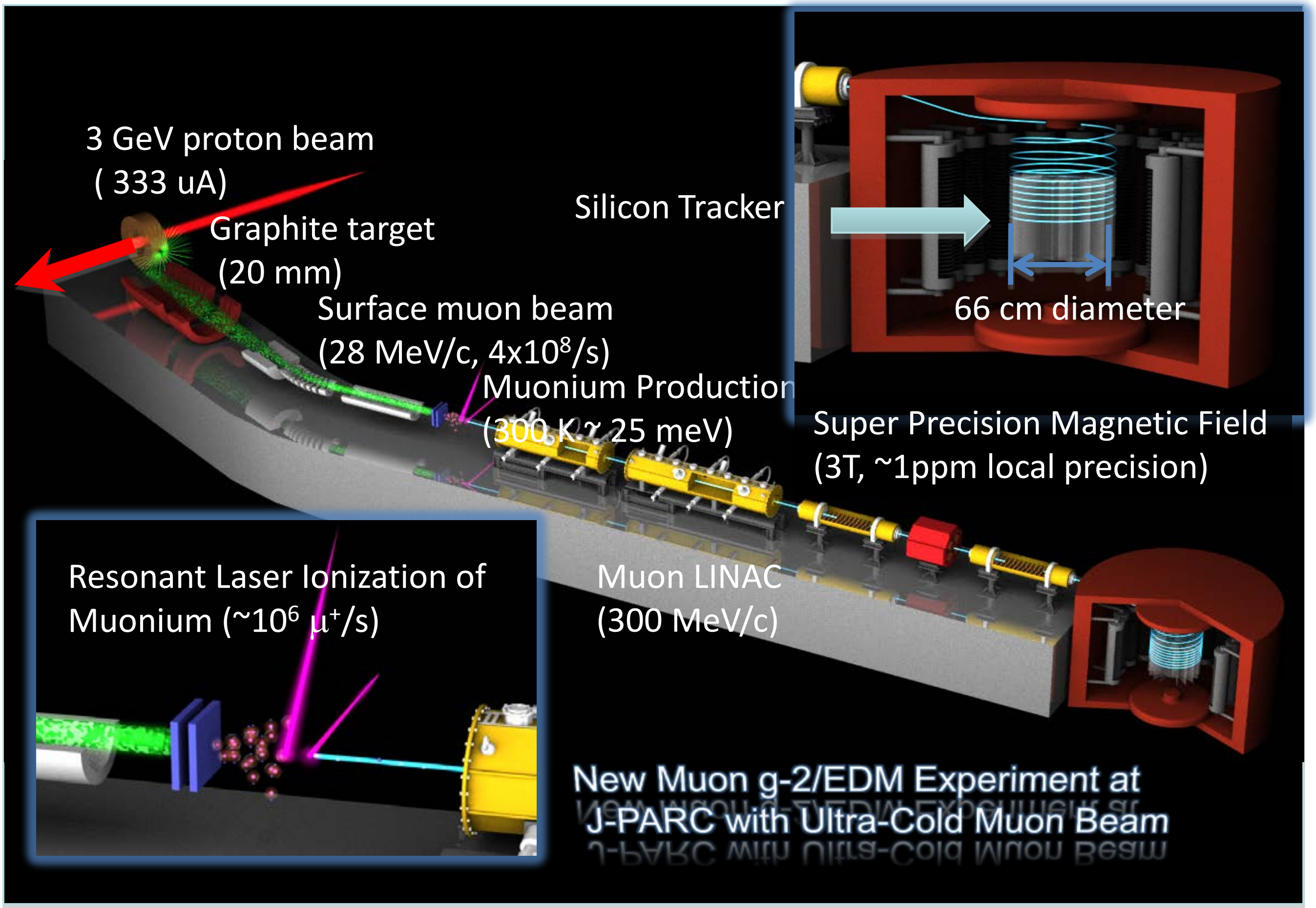


We could wait ~0.6 μs and irradiate 1 – 3 mm from surface by laser
This covers 20% of the total Mu emitted.

Motivation

g-2/EDM needs a good muon beam to store in the storage ring

We should start with very low energy muons and accelerate.



What target can be used here?

Ultra-slow muon : g-2 CDR 2011 and recent progress

Goal intensity is 1E6

in g-2 collaboration meeting 2014

2011

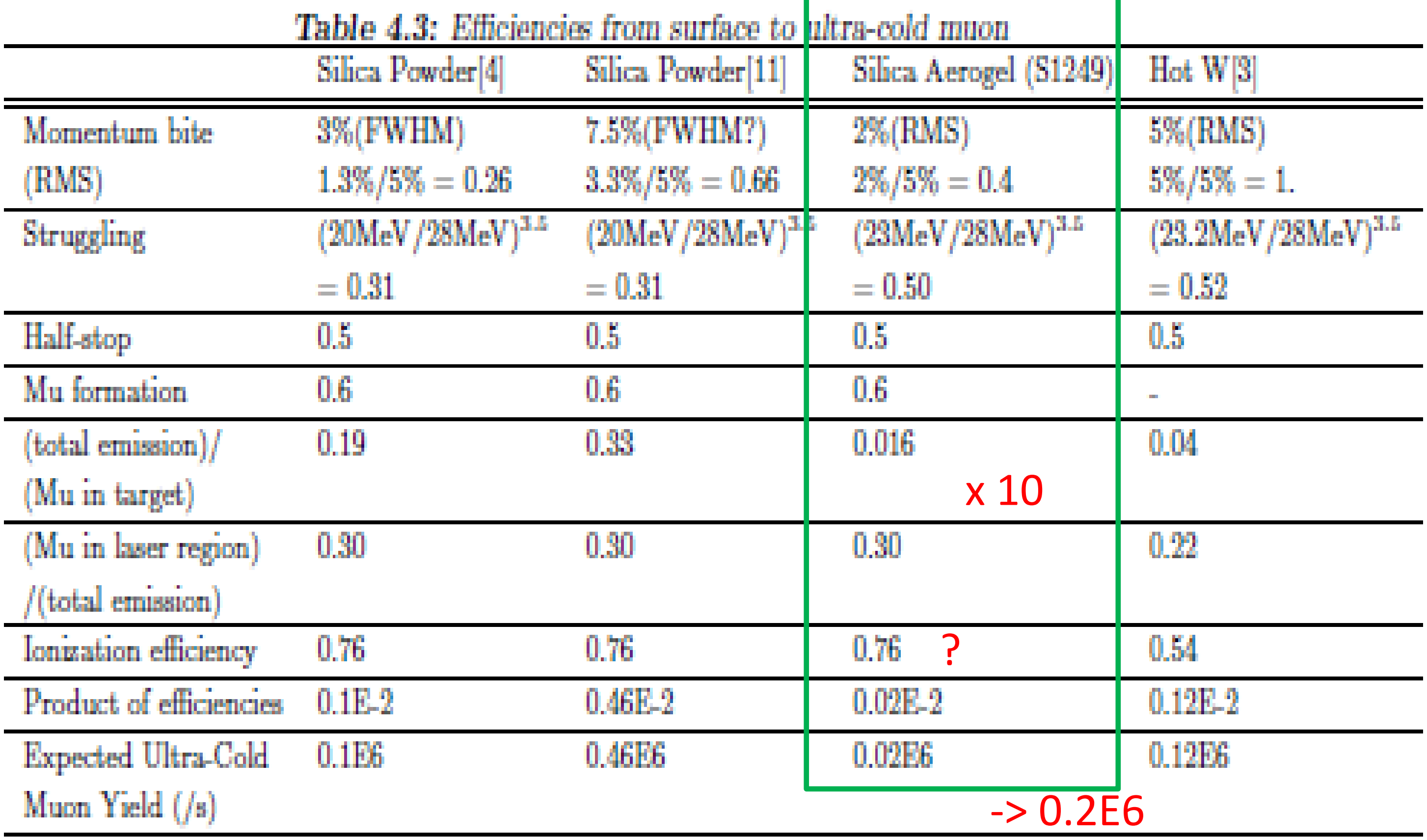


Table 4.3: *Efficiencies from surface to ultra-cold muon*

	Silica Powder[4]	Silica Powder[11]	Silica Aerogel (S1249)	Hot W[3]
Momentum bite (RMS)	3%(FWHM) 1.3%/5% = 0.26	7.5%(FWHM?) 3.3%/5% = 0.66	2%(RMS) 2%/5% = 0.4	5%(RMS) 5%/5% = 1.
Struggling	$(20\text{MeV}/28\text{MeV})^{3.5}$ = 0.31	$(20\text{MeV}/28\text{MeV})^{3.5}$ = 0.31	$(23\text{MeV}/28\text{MeV})^{3.5}$ = 0.50	$(23.2\text{MeV}/28\text{MeV})^{3.5}$ = 0.52
Half-stop	0.5	0.5	0.5	0.5
Mu formation	0.6	0.6	0.6	-
(total emission)/ (Mu in target)	0.19	0.33	0.016	0.04
(Mu in laser region) /(total emission)	0.30	0.30	0.30	0.22
Ionization efficiency	0.76	0.76	0.76	0.54
Product of efficiencies	0.1E-2	0.46E-2	0.02E-2	0.12E-2
Expected Ultra-Cold Muon Yield (/s)	0.1E6	0.46E6	0.02E6	0.12E6

x 10

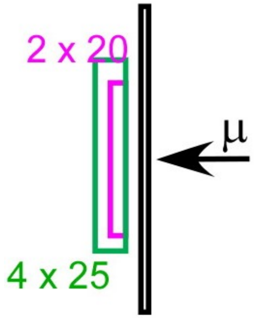
?

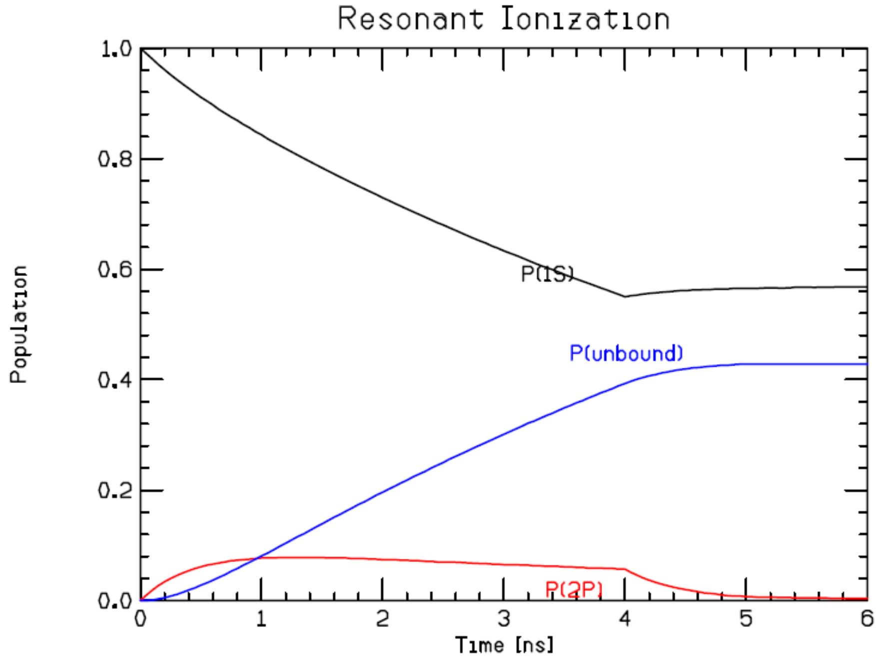
-> 0.2E6

Situation is much better than half a year ago.
But still missing factor 5.

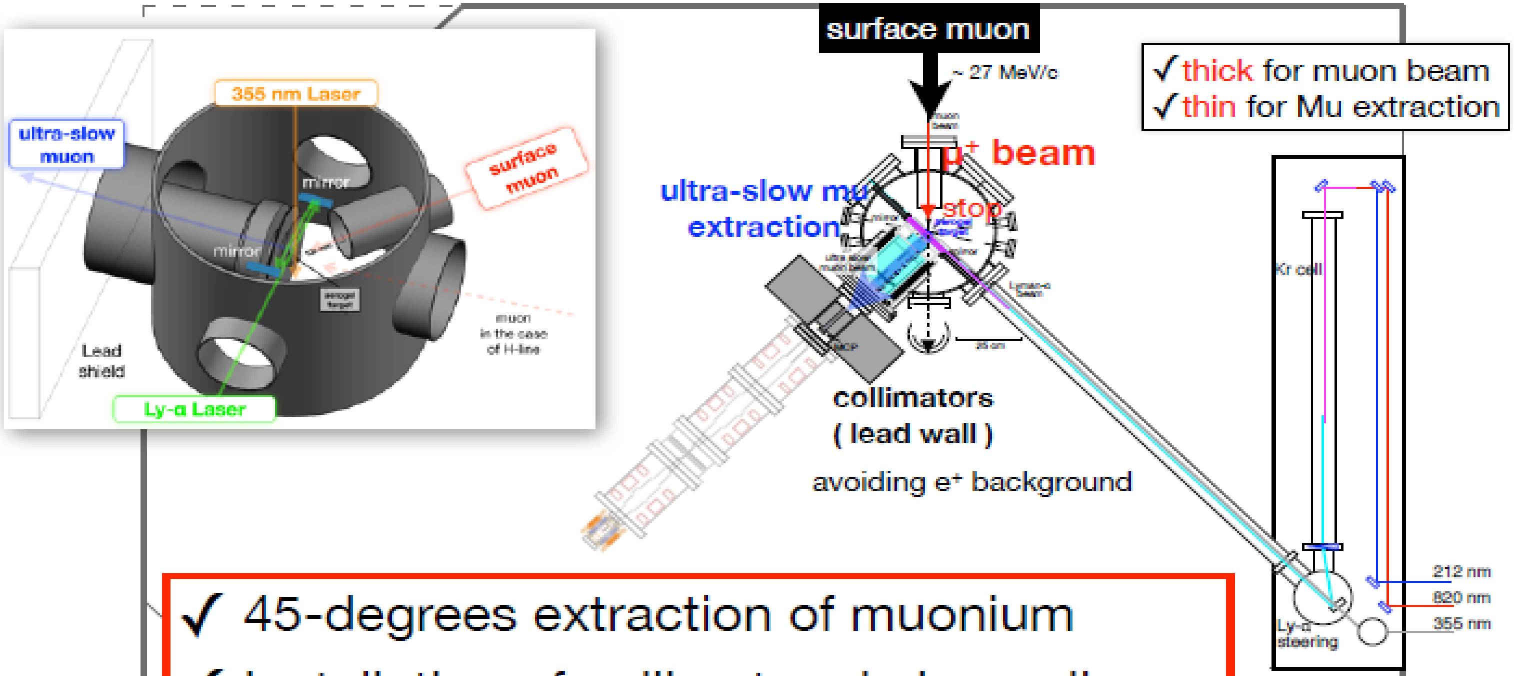
Laser ionization of Mu (Calculation) with 4 μJ laser

Time development of population of muonium in 1s, 2p and unbound states
Initial condition : all in 1s state $P_1(0) = 1$
Case for I(Lyman-α) = 4 μJ, I(355) = 300 mJ
Both lasers are switched on t=0
and stopped at 4ns and 5ns
=> ionization efficiency = 0.42 after 5 ns





Concept of new setup



- ✓ 45-degrees extraction of muonium
- ✓ Installation of collimators in beam line

➡ **background reduction**

Benefit at RIKEN-RAL

Semi-permanent setup in Port-3

Laser utilities

R&D without upsetting users