29 Aug, 2014
PANIC14 @ Hambrug

Ultra-slow muon production with room-temperature thermal-muonium-emitting material

Collaboration List

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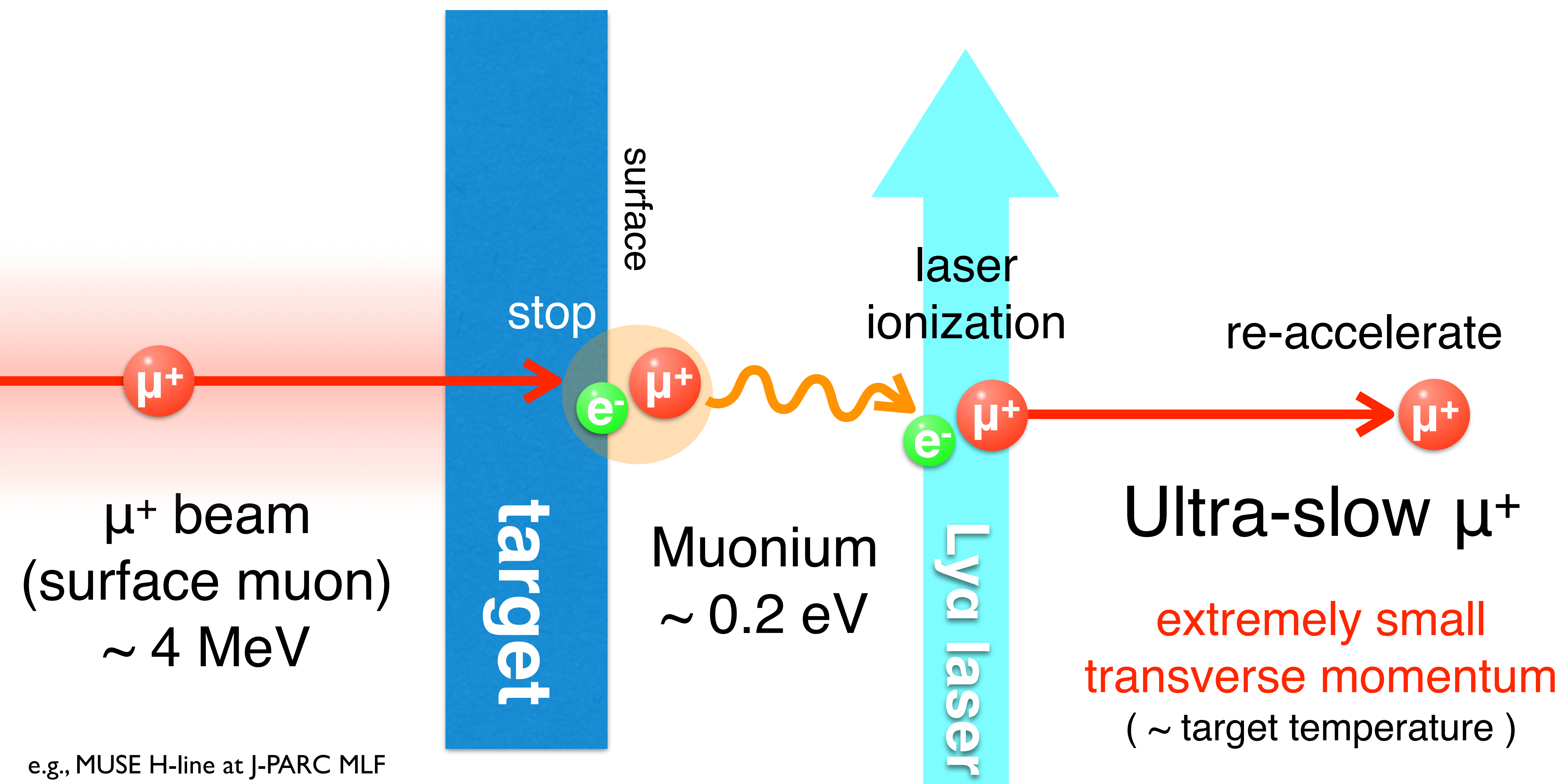
RIKEN Nishina Center
Shinji Okada

What is ultra-slow muon ?



e.g., MUSE H-line at J-PARC MLF
1 x 10^8 μ+/s at 28 MeV/c
in a 5% (rms) momentum bite

Applications

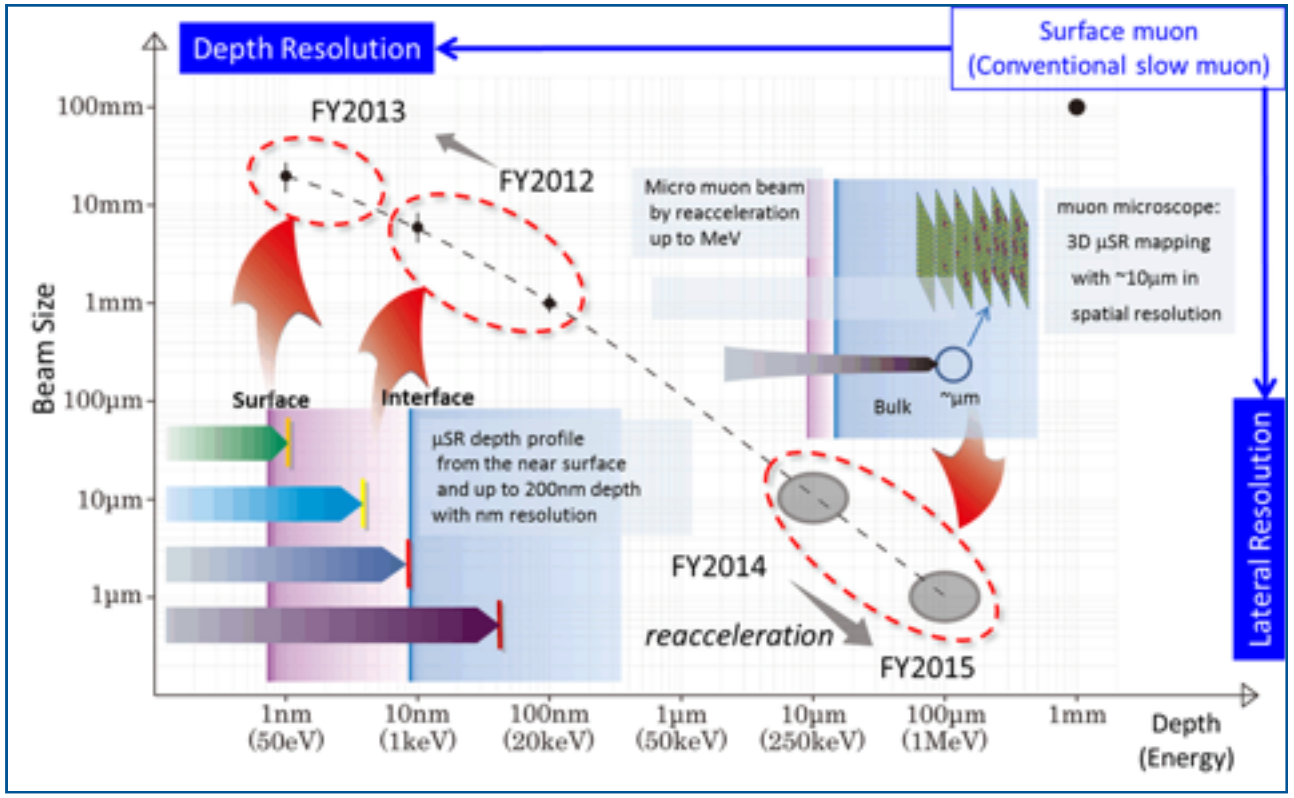
Condensed matter physics

Extended μSR

(muon spin rotation relaxation resonance)

- thin films, surfaces & interfaces, nano-structures -

for studying magnetism of the materials …

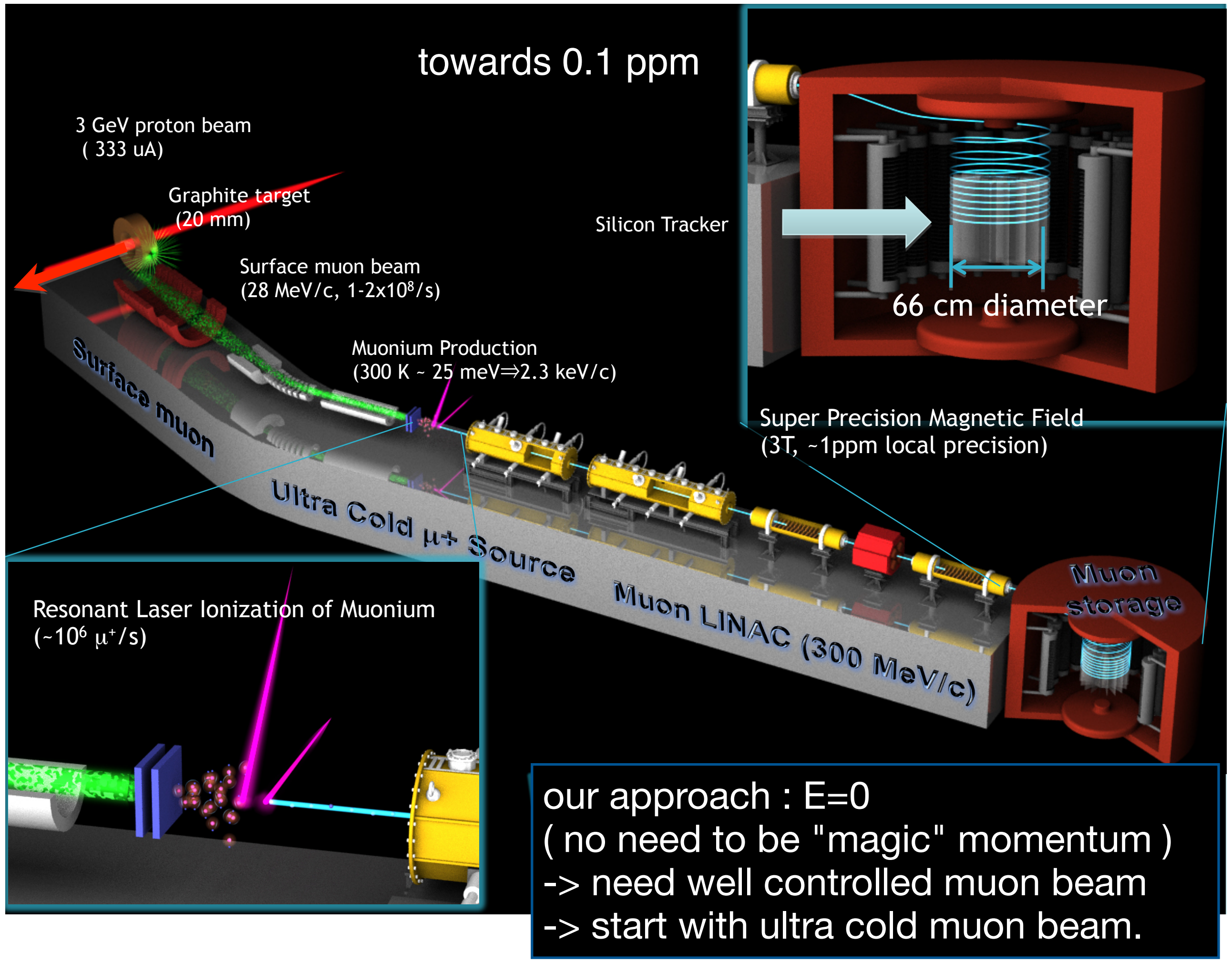


Grant-in-Aid for Scientific Research on Innovative Areas 2011-2015, "Ultra Slow Muon Microscope" (http://slowmuon.jp/english/index.html)

Particle physics

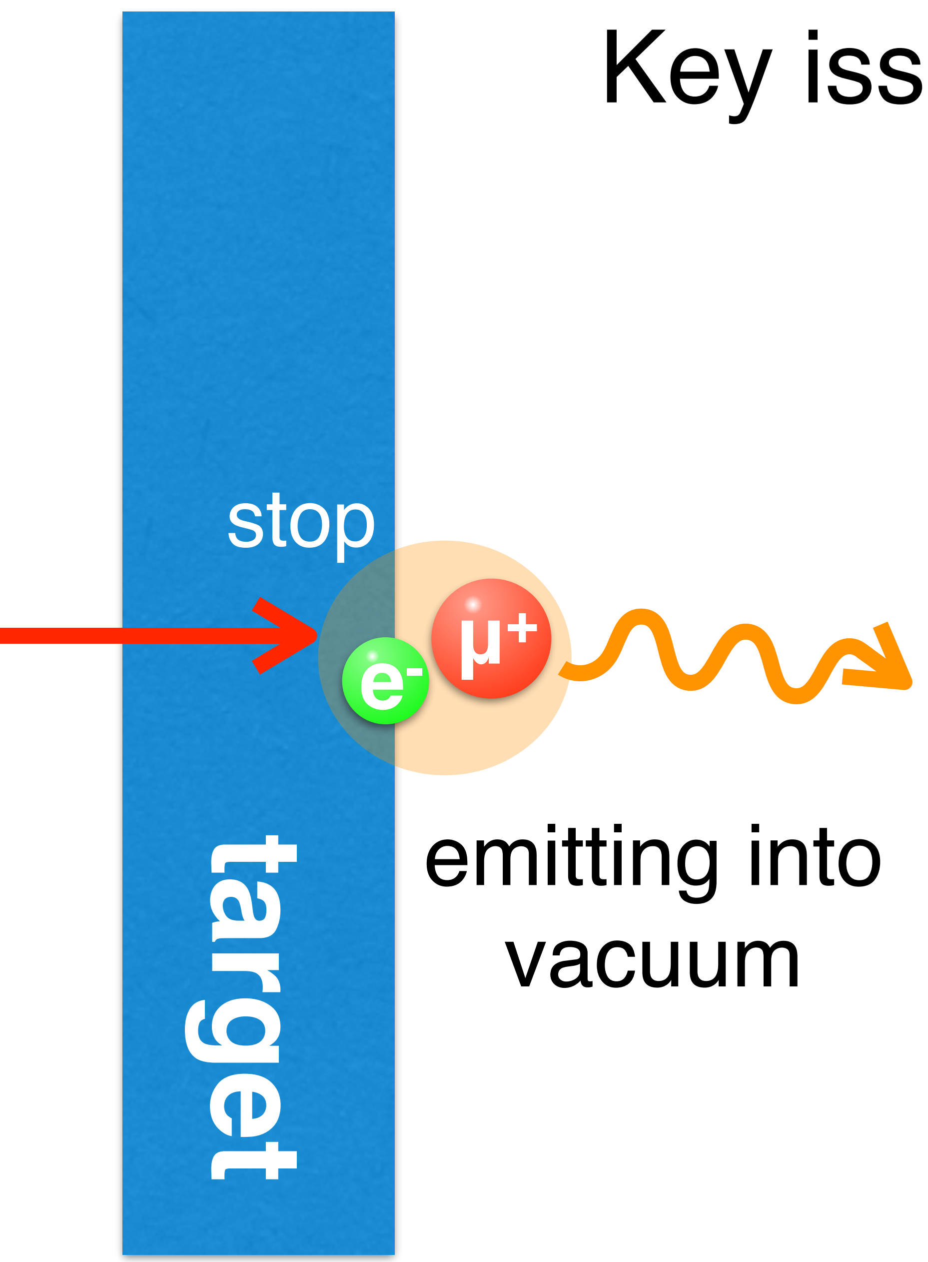
Measuring the **muon g-2** and EDM at J-PARC

-> talk by Prof. A.Denig on Tuesday



J-PARC E34 proposal http://j-parc.jp/researcher/Hadron/en/pac_1001/pdf/KEK_J-PARC-PAC2009-12.pdf

Muonium-emitting material



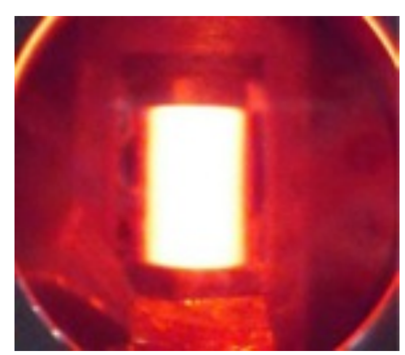
Key issue

Muonium in vacuum

(not only producing but emitting in vacuum for laser ionization)

so far we know only…

hot tungsten
~ 2300 K !



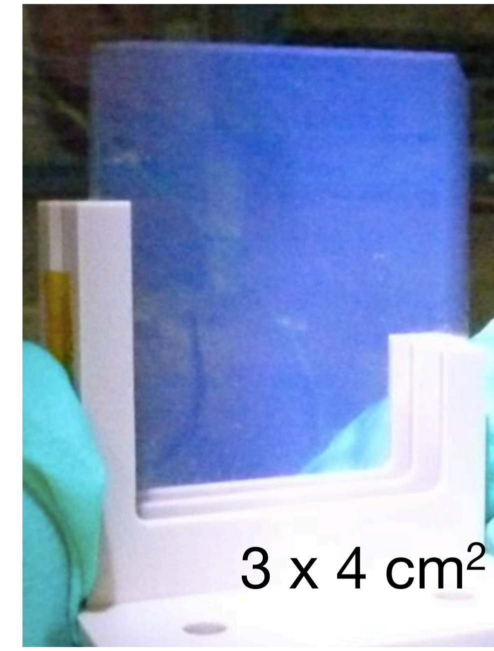
unhandy due to **significant heat**

silica powder
room temp.

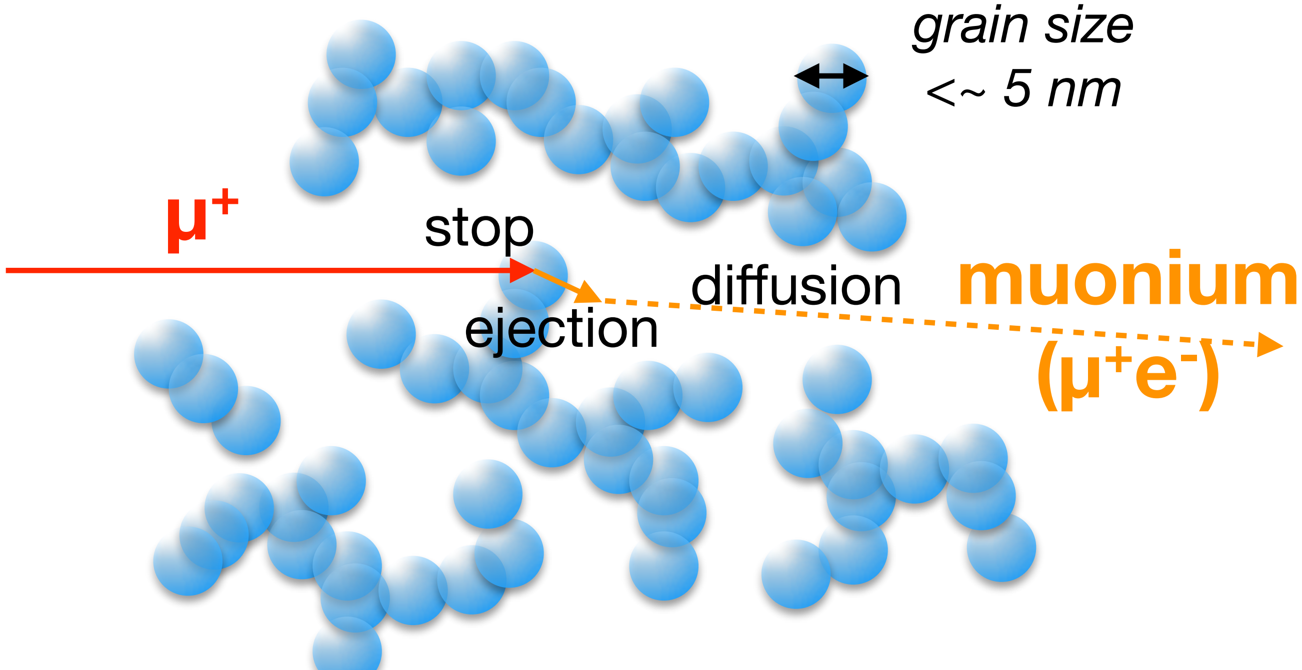
unhandy due to **powdery material**

New idea : Silica aerogel

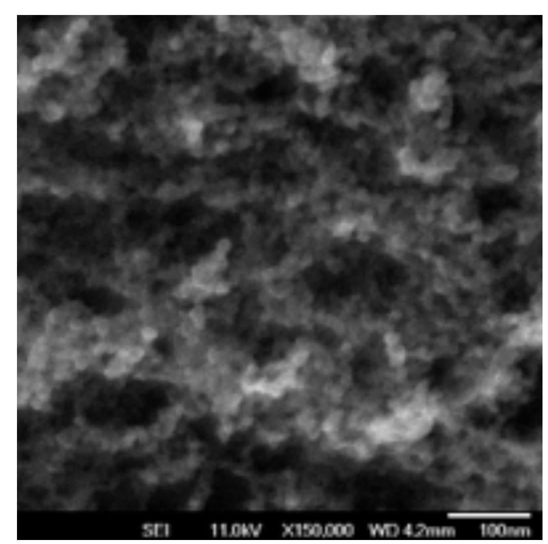
- ✓ Same chemical composition as silica powder
- ✓ Self standing
- ✓ Extremely low density



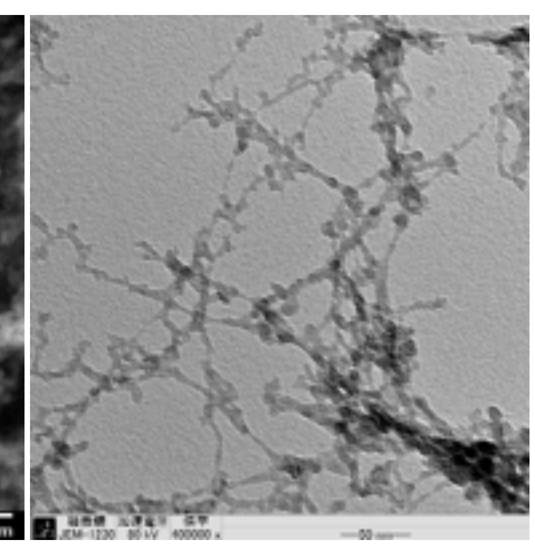
3D-network structure
of SiO_2 grains linked together



SEM
Scanning Electron Microscope



TEM
Transmission Electron Microscope



with help from "Advanced Technology Support Division" at RIKEN

Merit of room-temperature target

1. Handiness

   ➡ Easy to handle ⇔ hot-W radiating significant heat

2. Smaller Emittance

   ➡ lower energies of the produced Mu

   ➡ smaller transverse momentum of muon beam

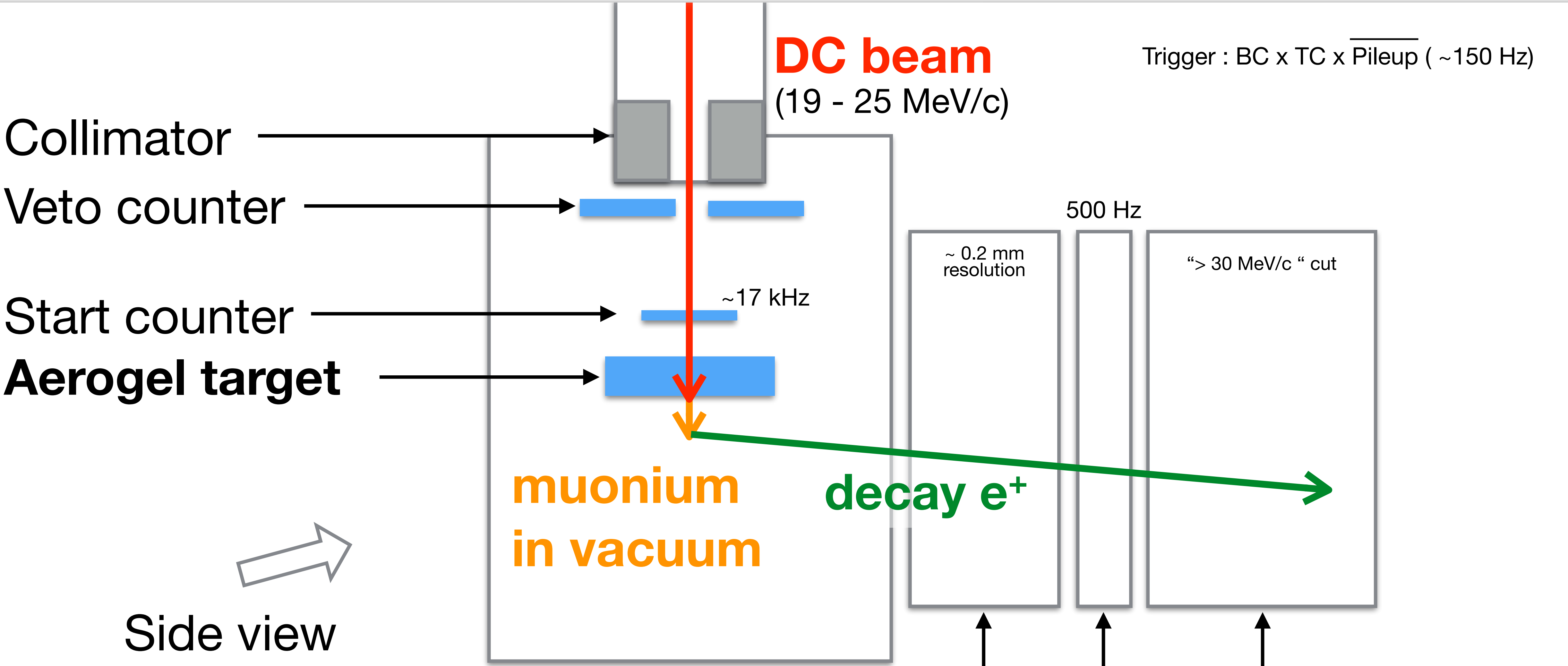
3. Smaller Spacial Spread & Doppler Broadening

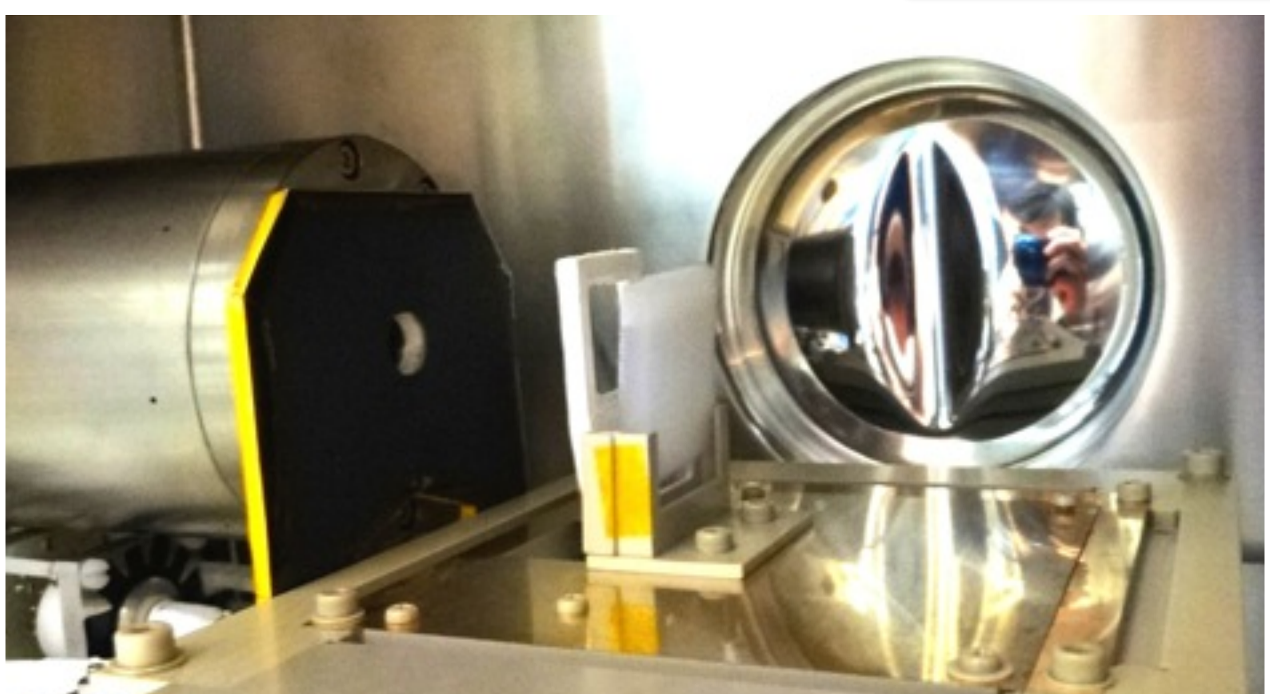
   ➡ Narrower energy distribution

   - smaller spatial spread of Mu in vacuum
   - smaller Doppler broadening of resonant line for Mu excitation

   ➡ more efficient use of laser power

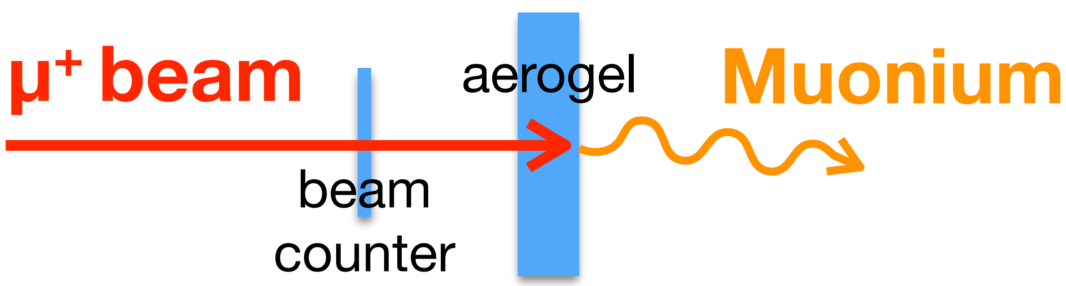
TRIUMF S1249 experiment





The first Mu observation from aerogel

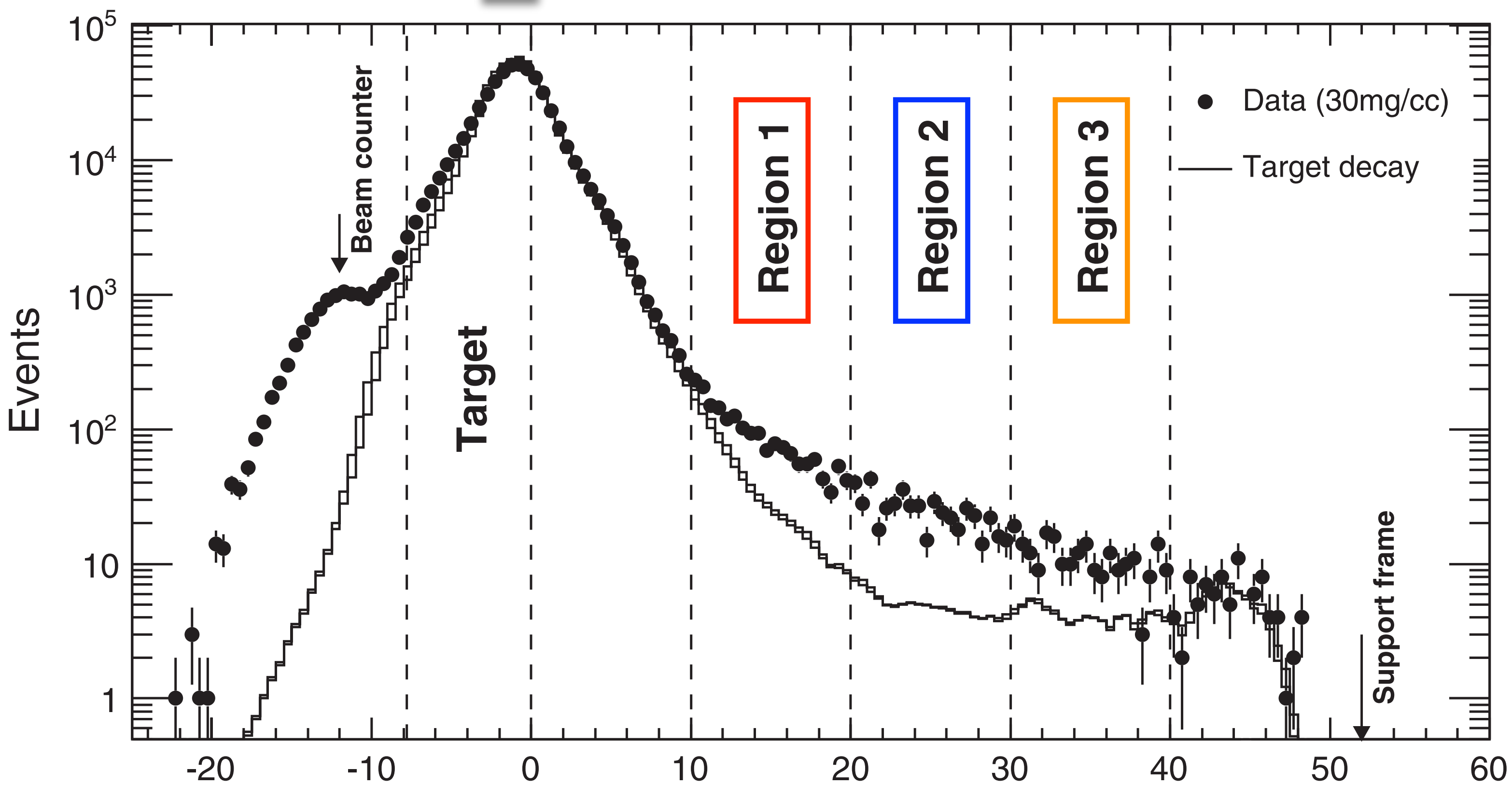
Prog. Theor. Exp. Phys. 2013, 103C01



~ 0.3 % per muon stop

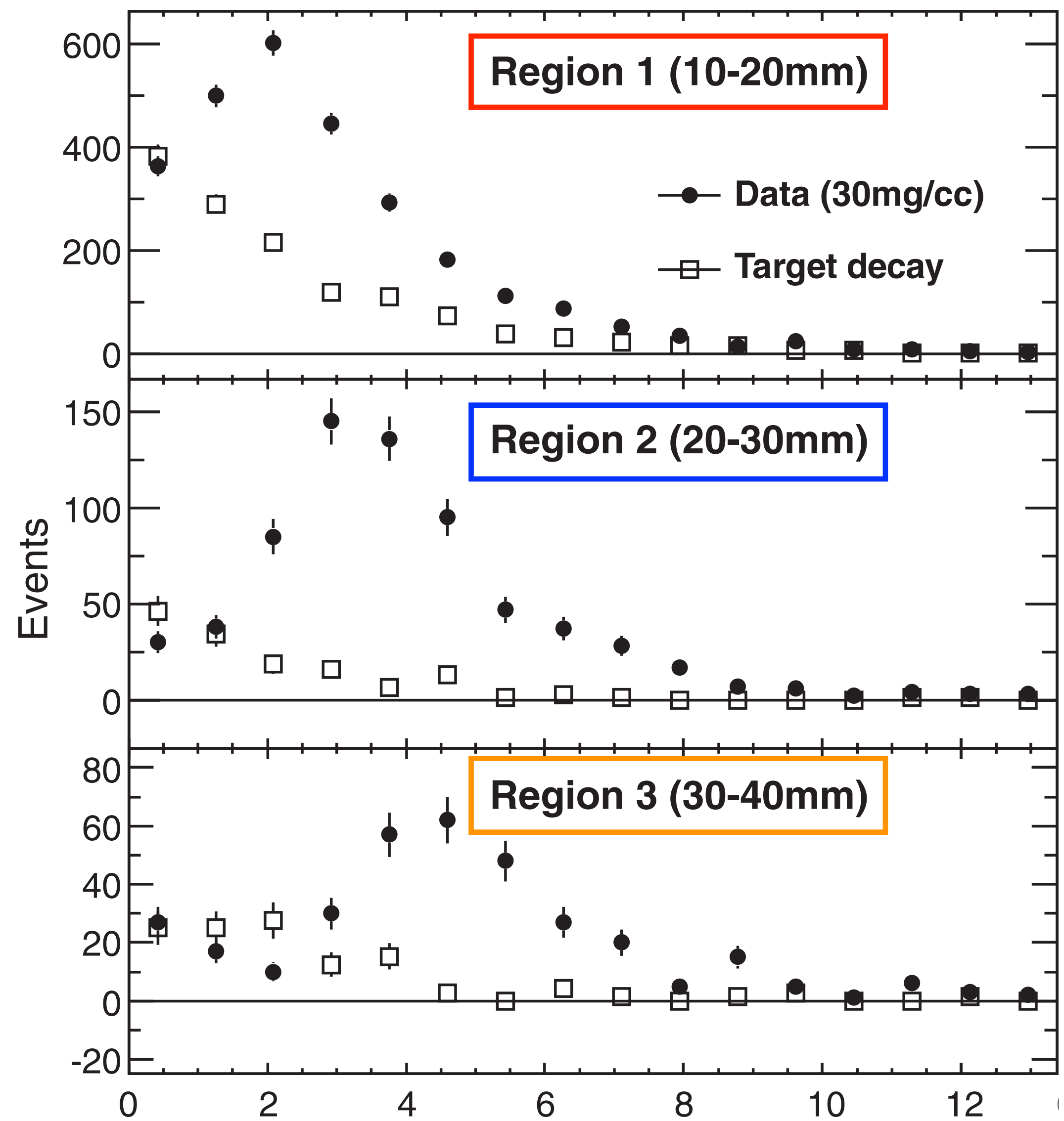
Table 1. Vacuum yield in the region 1–3 and mean free path

Density ($\mathrm{mg\,cm^{-3}}$)	Vacuum yield (per 1000 muon stops)	Mean free path (μm) (small chemical potential model)
29	$2.74 \pm 0.11^{+0.10}_{-0.13}$	$0.226 \pm 0.016^{+0.113}_{-0.079}$
47	$2.81 \pm 0.11^{+0.14}_{-0.08}$	$0.118 \pm 0.009^{+0.060}_{-0.034}$
97	$3.13 \pm 0.20^{+0.12}_{-0.09}$	$0.035 \pm 0.004^{+0.018}_{-0.012}$
178	$1.60 \pm 0.11^{+0.07}_{-0.10}$	$0.0050 \pm 0.0007^{+0.0020}_{-0.0014}$



Z distribution [mm]

Histogram : target decay distribution estimated from a simulation of muon stopping smeared by the extrapolation resolution

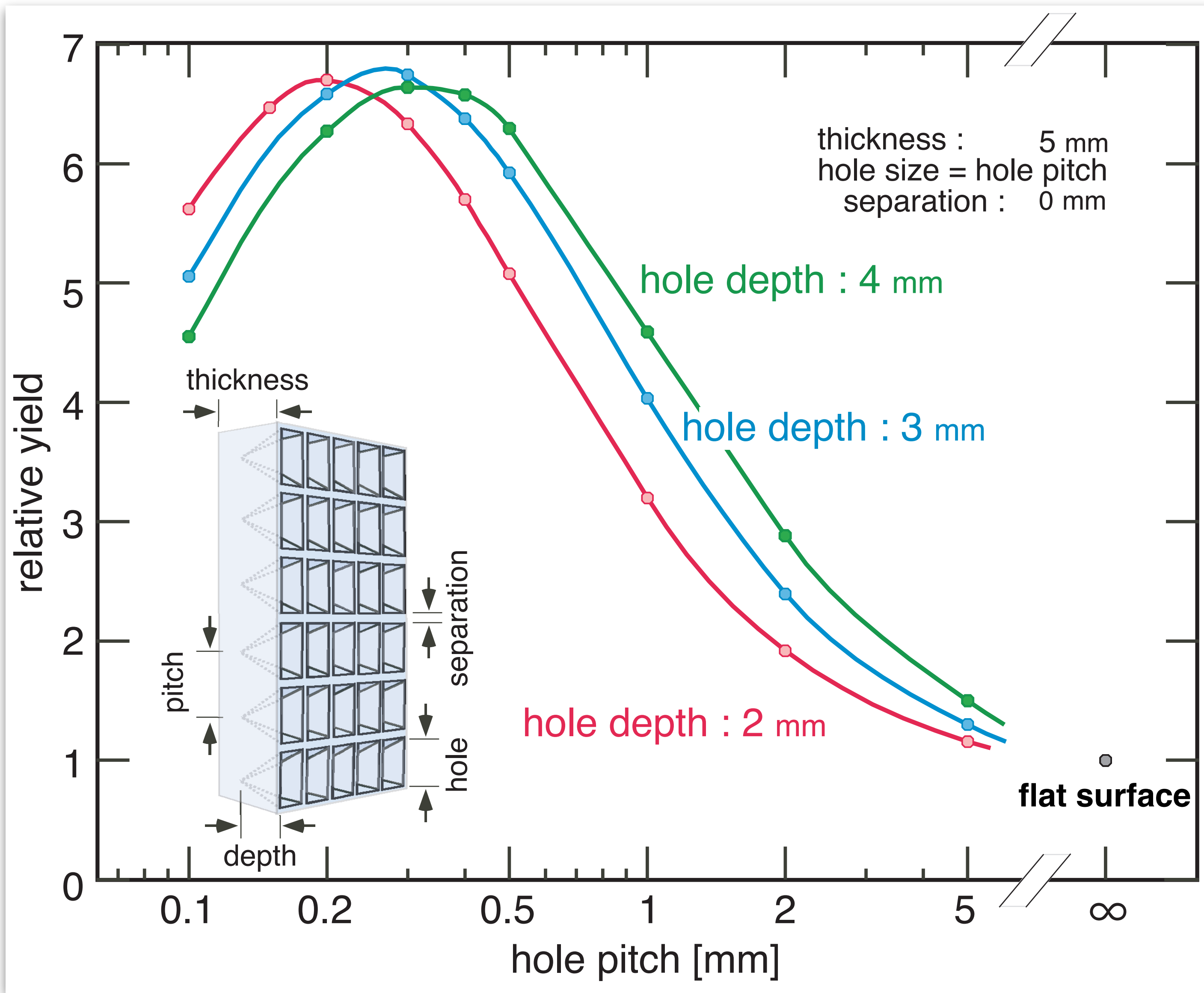


Time distribution [μs]

Toward more yields

→ increasing surface area

simulation with diffusion model



simulation:

aerogel :

5 mm thick

diffusion : thermal dump model

$m_\mu / M_X = 2.5 \times 10^{-5}$

$V_{chem} = +15$ eV (repulsive potential)

$\Delta l_{mfp} = 1.865 \times 10^{-4}$ mm

$\rho = 30$ mg/cc *equiv.*

initial muonium position

uniform over aerogel in z-direction

Gauss distribution in x / y-direction

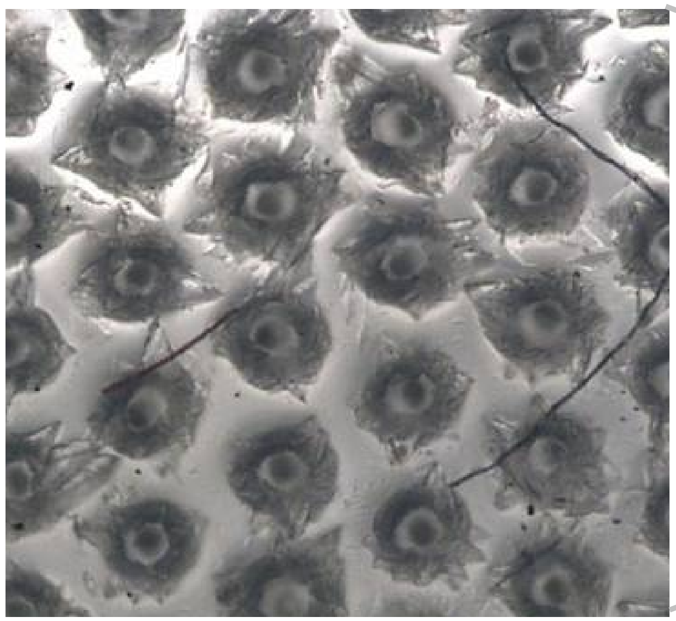
$\sigma_x = \sigma_y = 4.4$ mm

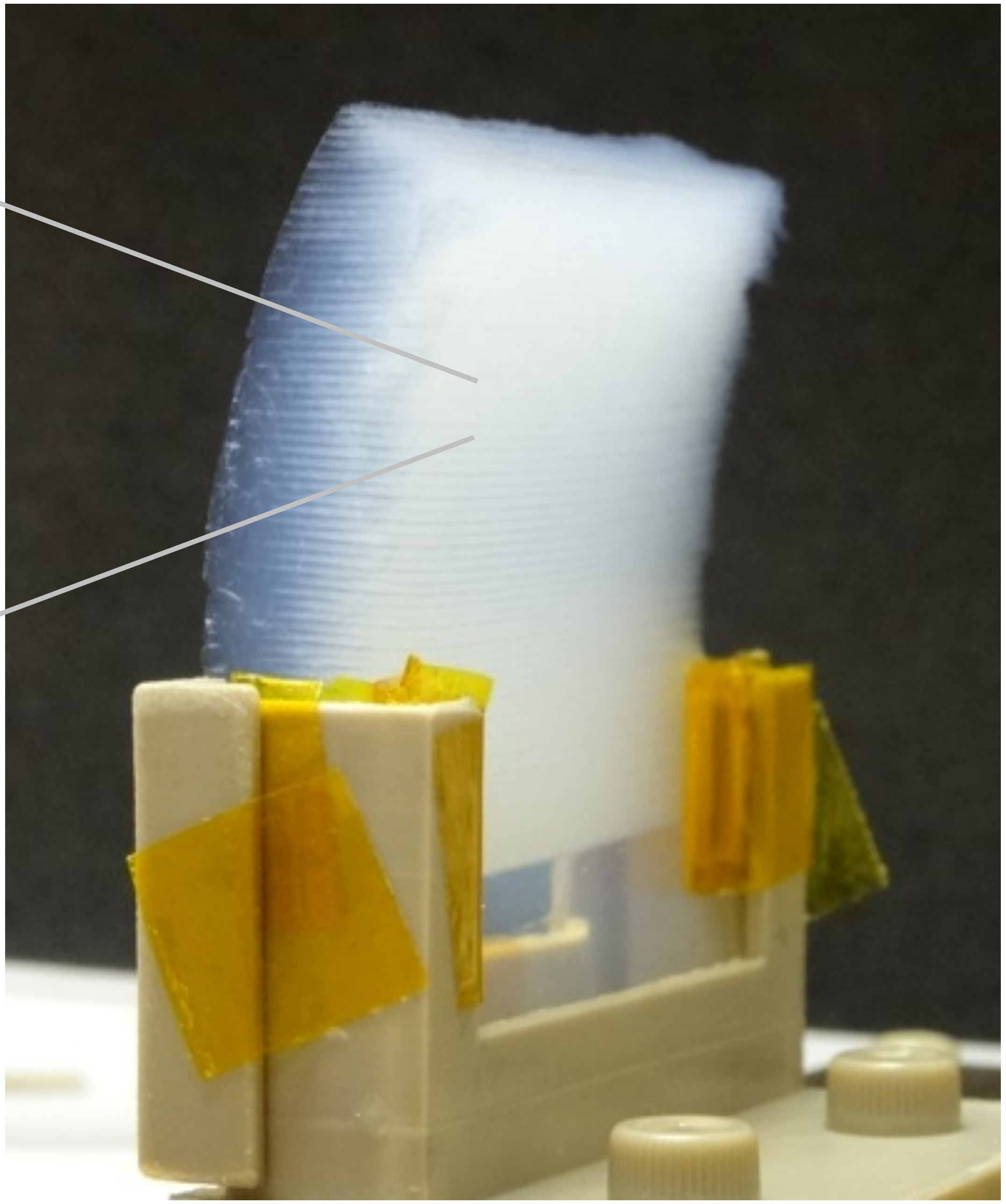
muoniums generated in a hole were rejected into garbage

simulated by M. Iwasaki

Laser-drilled aerogels

surface





Pitch : 300 - 500 μm
Hole size : ~ 300μm
Depth :~ 2mm

All silica-aerogel samples we used were prepared at Chiba Univ. by M. Tabata (Chiba/JAXA)) and drilled by Y. Oishi (RIKEN) & Y. Asakawa (LIGHTEC Inc.)

Result from laser-drilled aerogels

again at TRIUMF with the same experimental setup (in 2013)

arXiv:1407.8248

The emission probability for the laser-processed aerogel sample is at least **eight times higher** than for a uniform one.

Table 1 Yield of Mu in the vacuum region 1–3. For all laser processed samples, the diameter of the structure is 0.27 mm.

Sample	Laser-ablated structure (pitch)	Vacuum yield (per 10^3 muon stops)
Flat	none	3.72 ± 0.11
Flat (Ref. [5])	none	2.74 ± 0.11
Laser ablated	500 μm	15.98 ± 0.23
Laser ablated	400 μm	20.85 ± 0.73
Laser ablated	300 μm	30.50 ± 0.32

Vacuum yield : ~3 % per muon stop

-> ultra-slow muon rate ~ 0.2 × 10^6 /s
-> so now, the vacuum yield achieved the operational level for g-2 !

(though still 5 times smaller than the design intensity to achieve the final statistical sensitivity of 0.1 ppm)

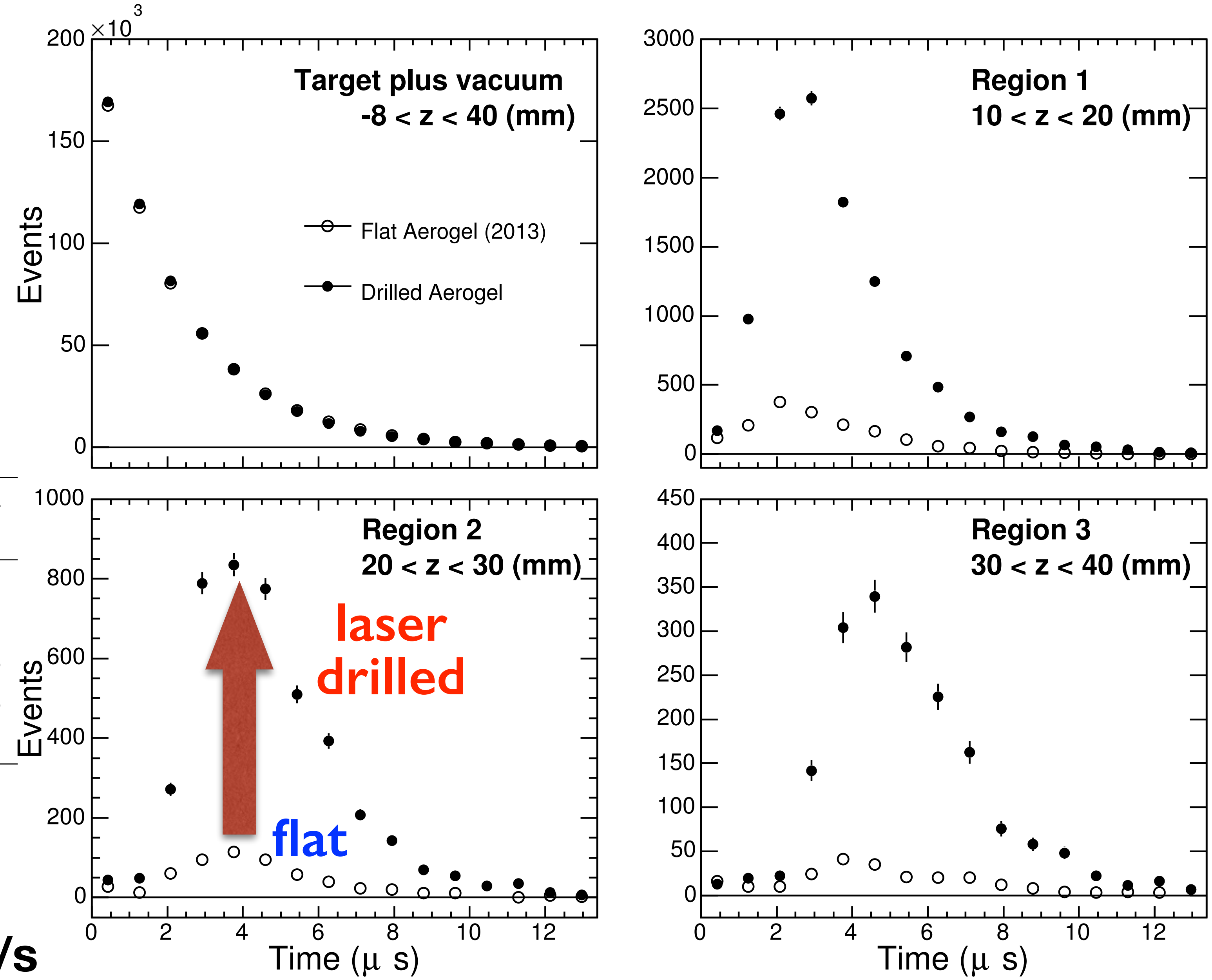
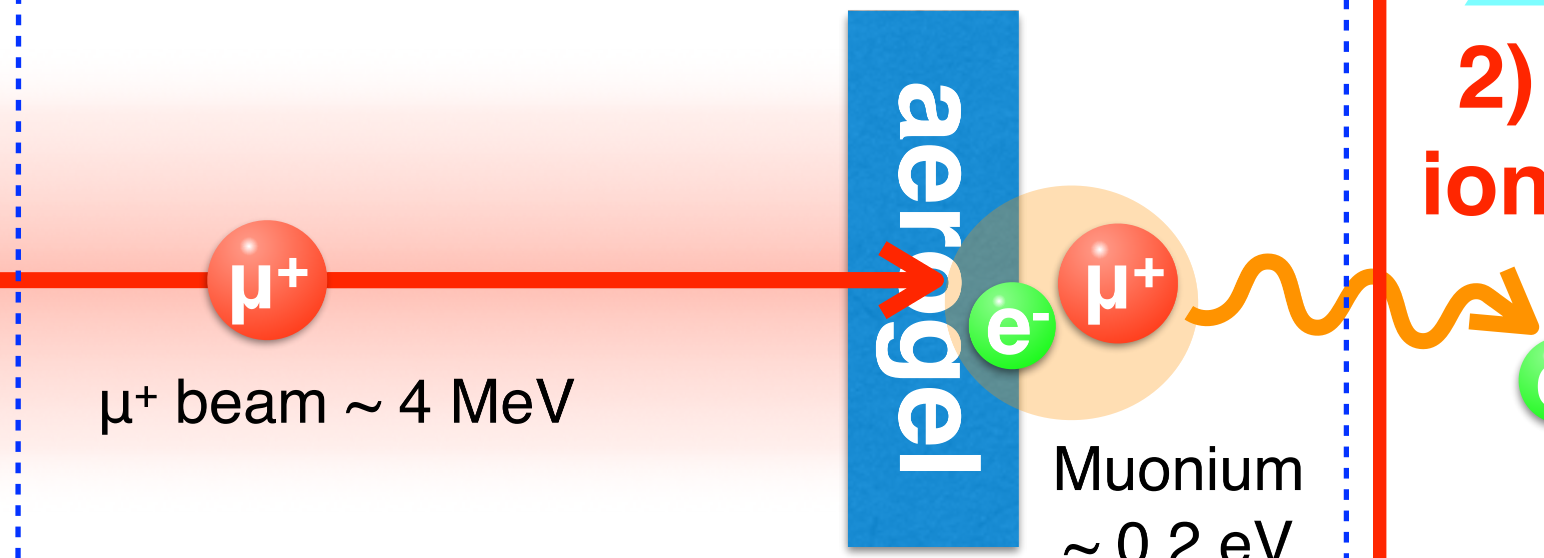


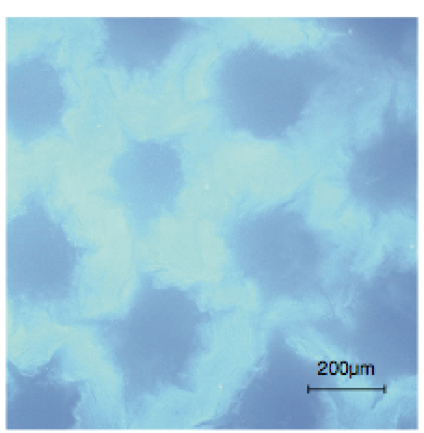
Fig. 3 Time distributions of positrons in the entire target region and in each of three vacuum regions, for flat aerogel (open circle) and laser-ablated aerogel with pitch of 300 μm (closed circle). No background has been subtracted

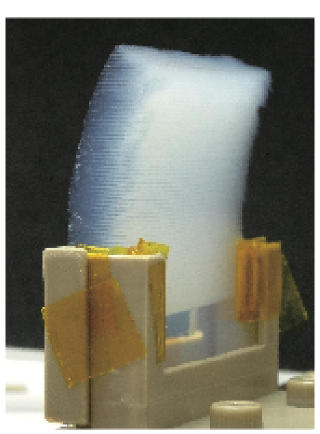
What’s next ?

1) Mu generation in vacuum



-> Confirmed at TRIUMF S1249



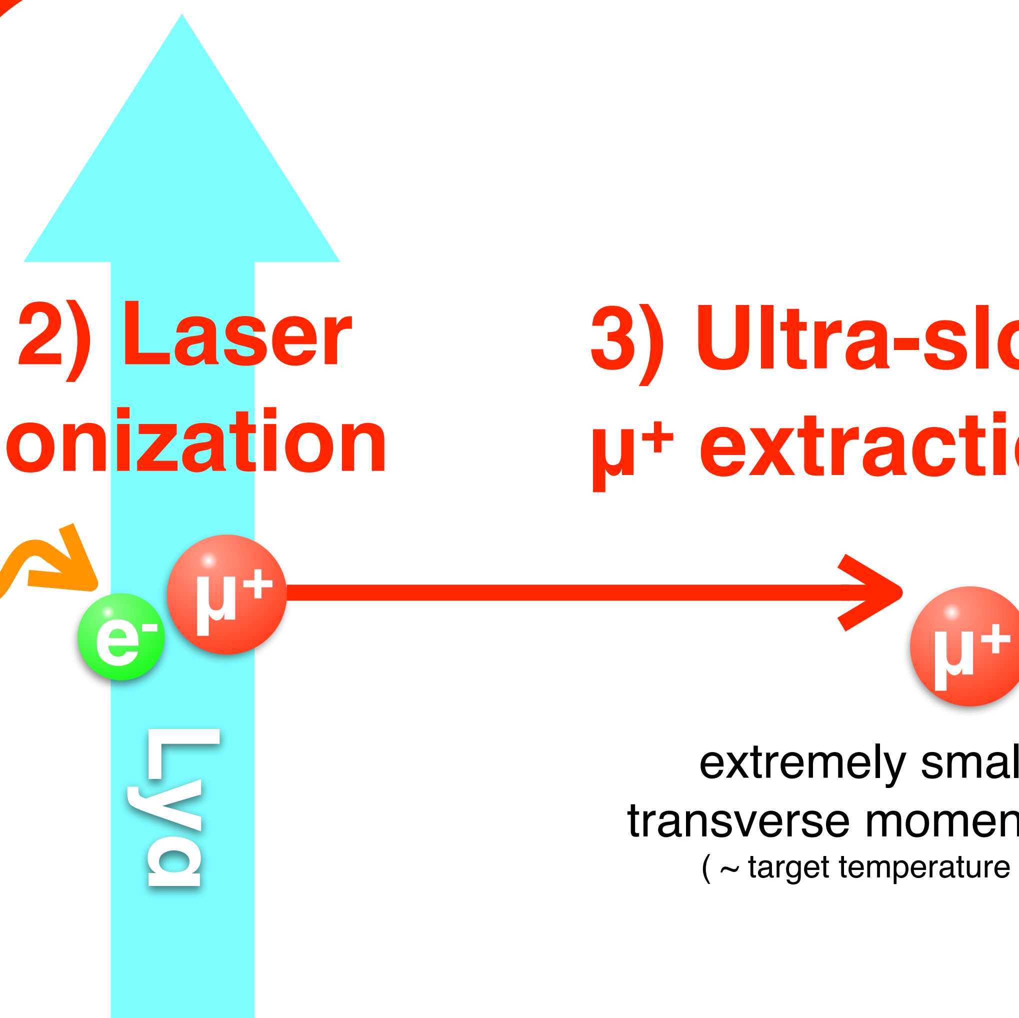


Laser ablated aerogel

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)

next step :

Actual ultra-slow muon production

Ultra-slow muon production at RAL

R & D of room-temperature target
to be developed to a practical level

(1) Production :

ultra-slow muon production with the room-temp.

(2) Extraction :

establishment of ultra-slow muon extraction scheme

Hot-W (electrode) vs. Aerogel (insulator)

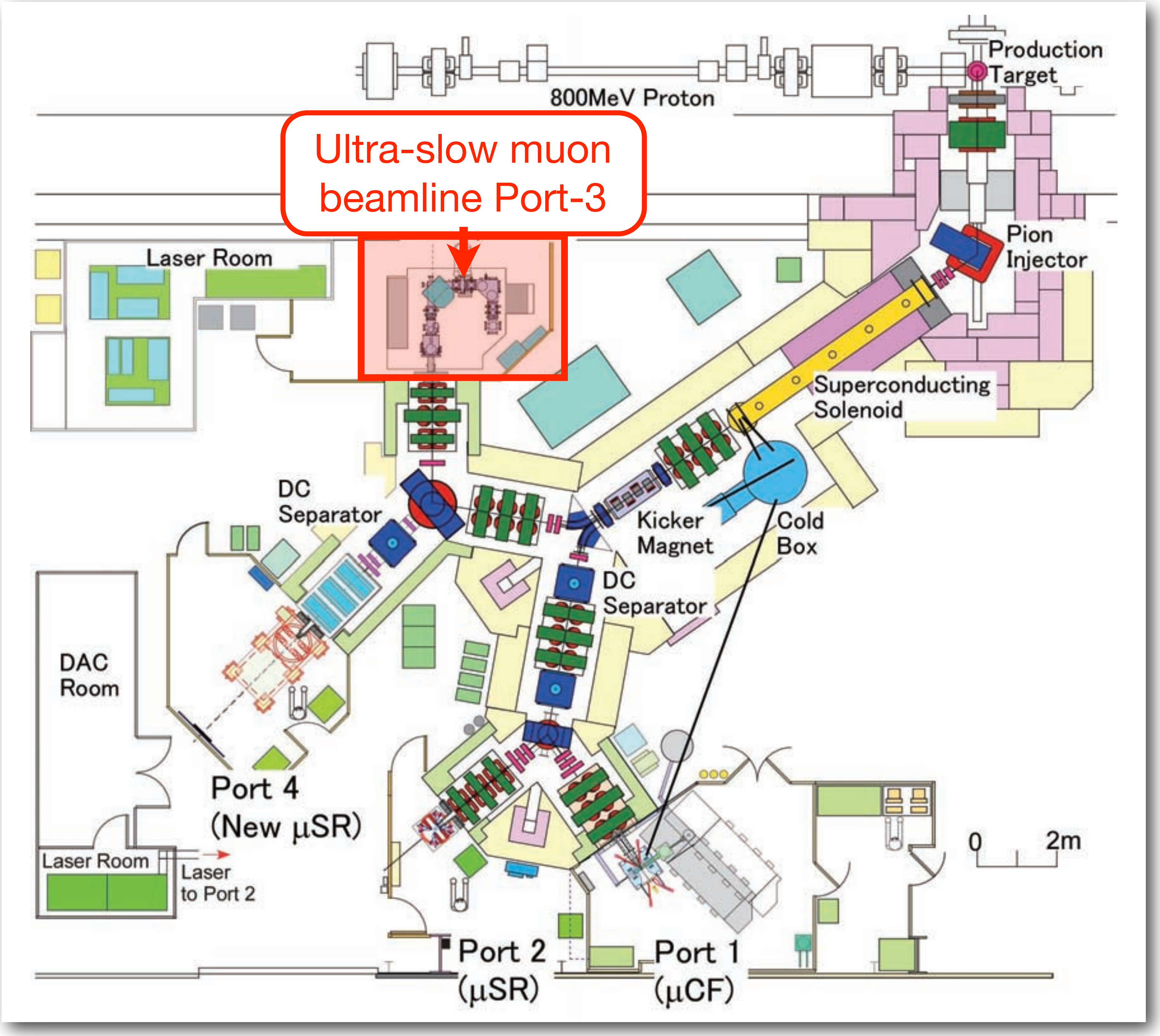
(3) Stability :

testing of the long term stability

(4) Optimization towards higher yield :

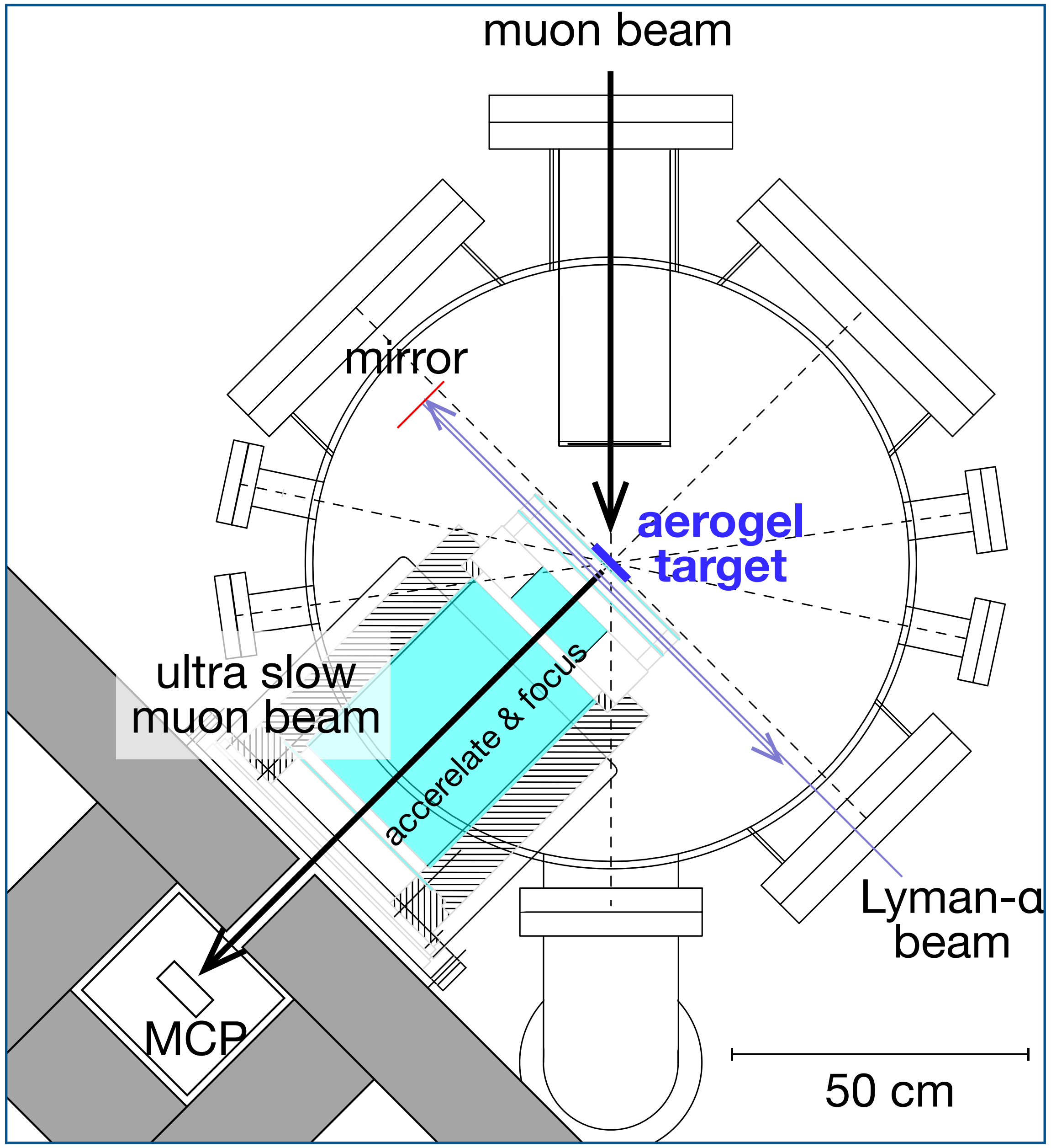
- structured-target shape
- laser with reflection mirrors installed near the target
- etc …

RIKEN-RAL Muon Facility (UK)

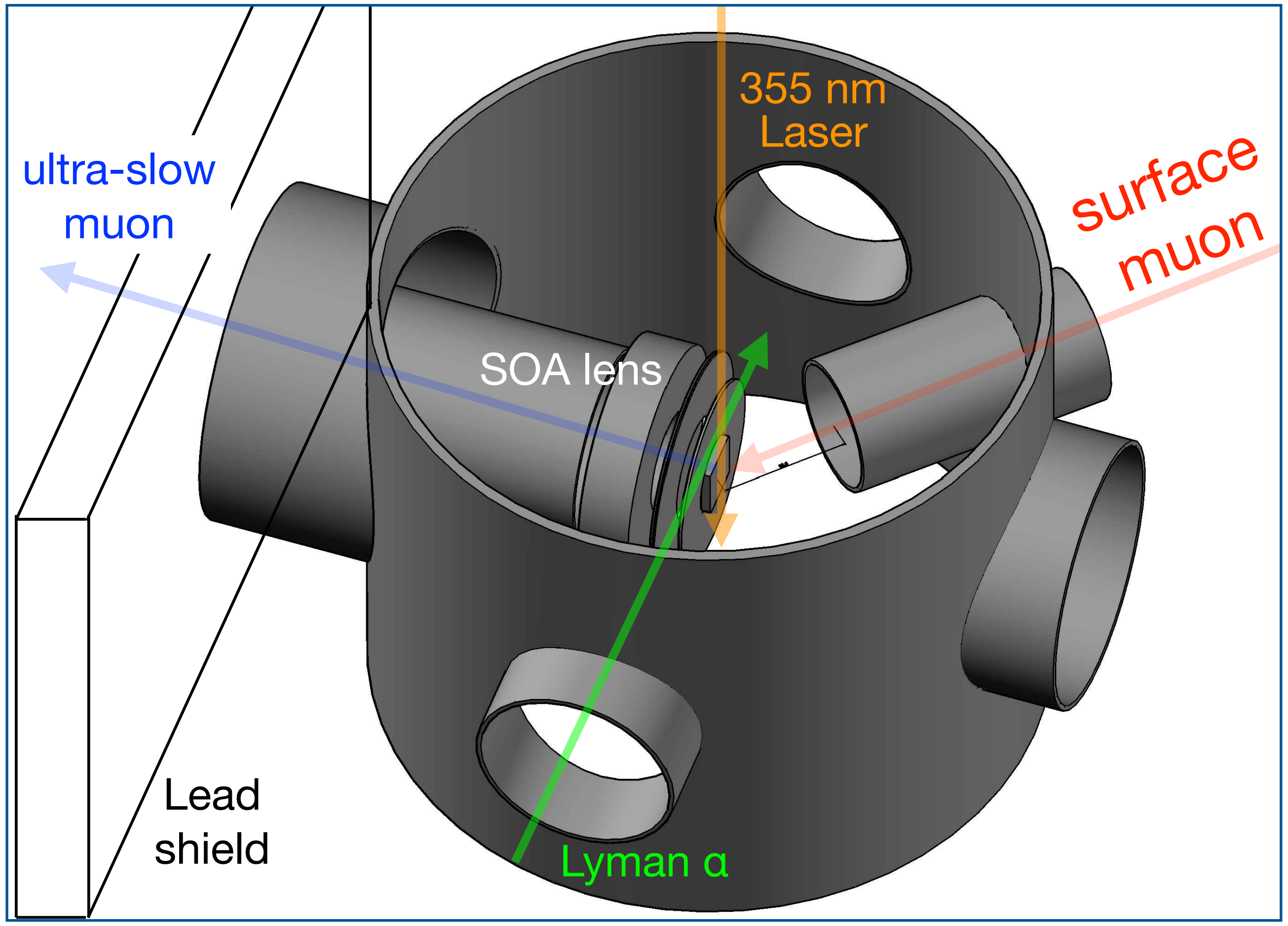


Experimental setup

top view



birds-eye view



preparing towards the first beam test
at RIKEN-RAL on **March, 2015**

Summary

✓ Ultra-slow muon for next generation μSR and muon g-2/EDM exp.

✓ Plenty of merit with room-temperature target

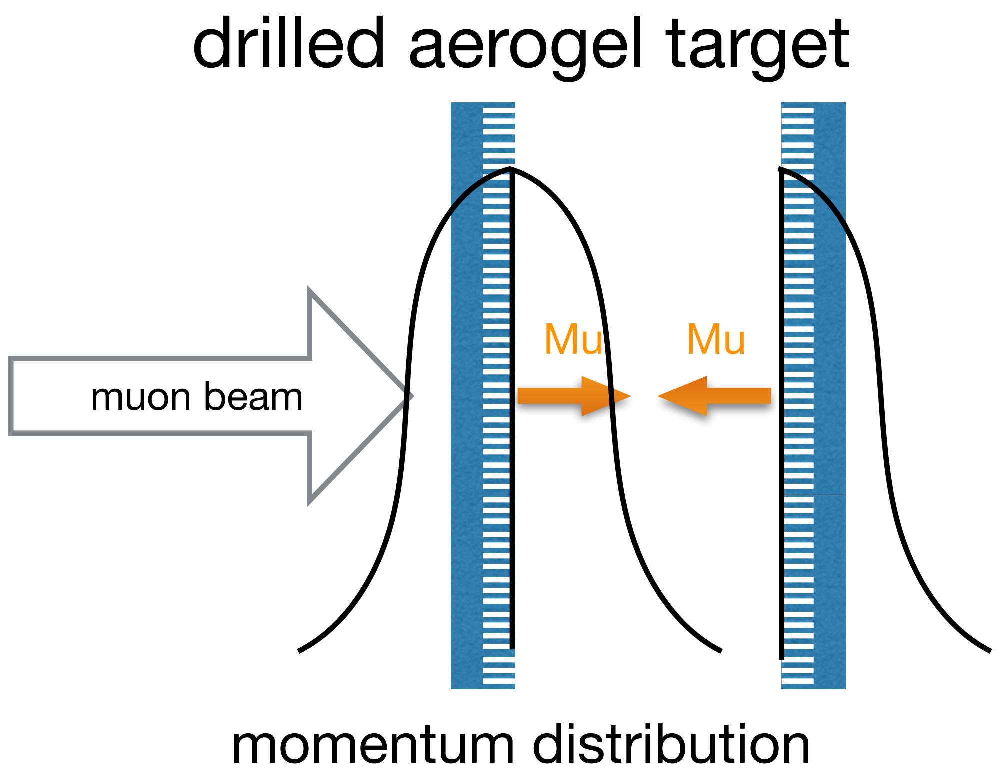
✓ Great performance with laser-drilled aerogel target (TRIUMF S1249)

✓ R & D of room-temp. target at RAL to be developed to a practical level

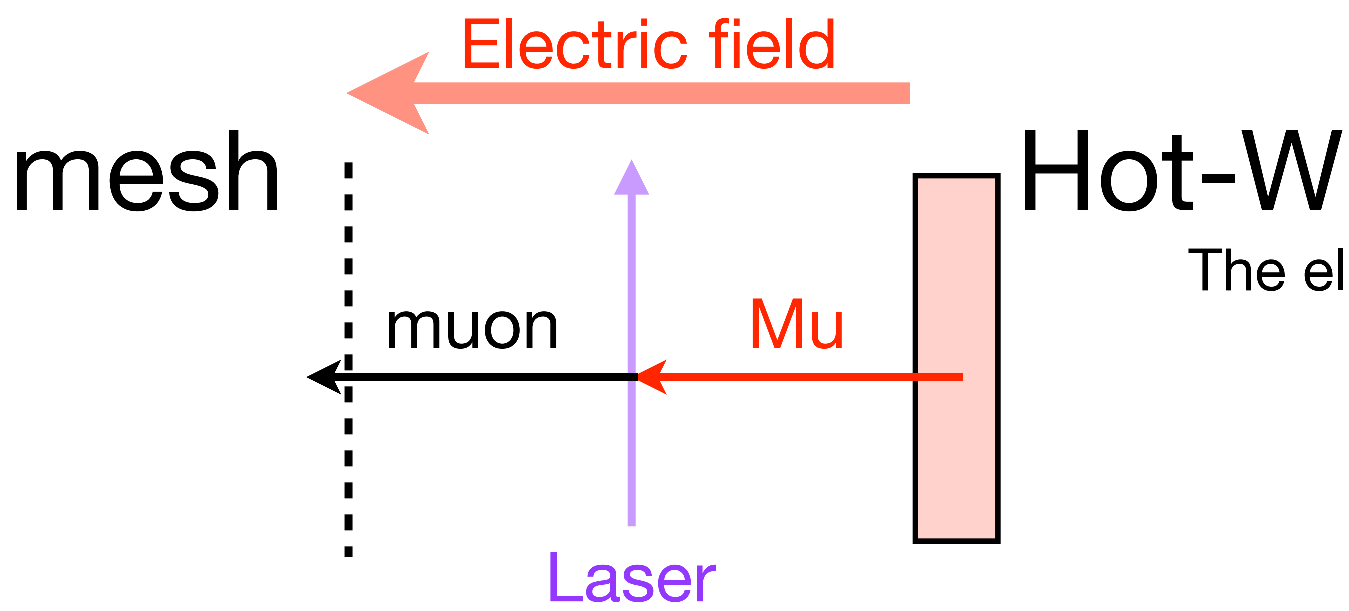
Backup slides

another idea for more yields

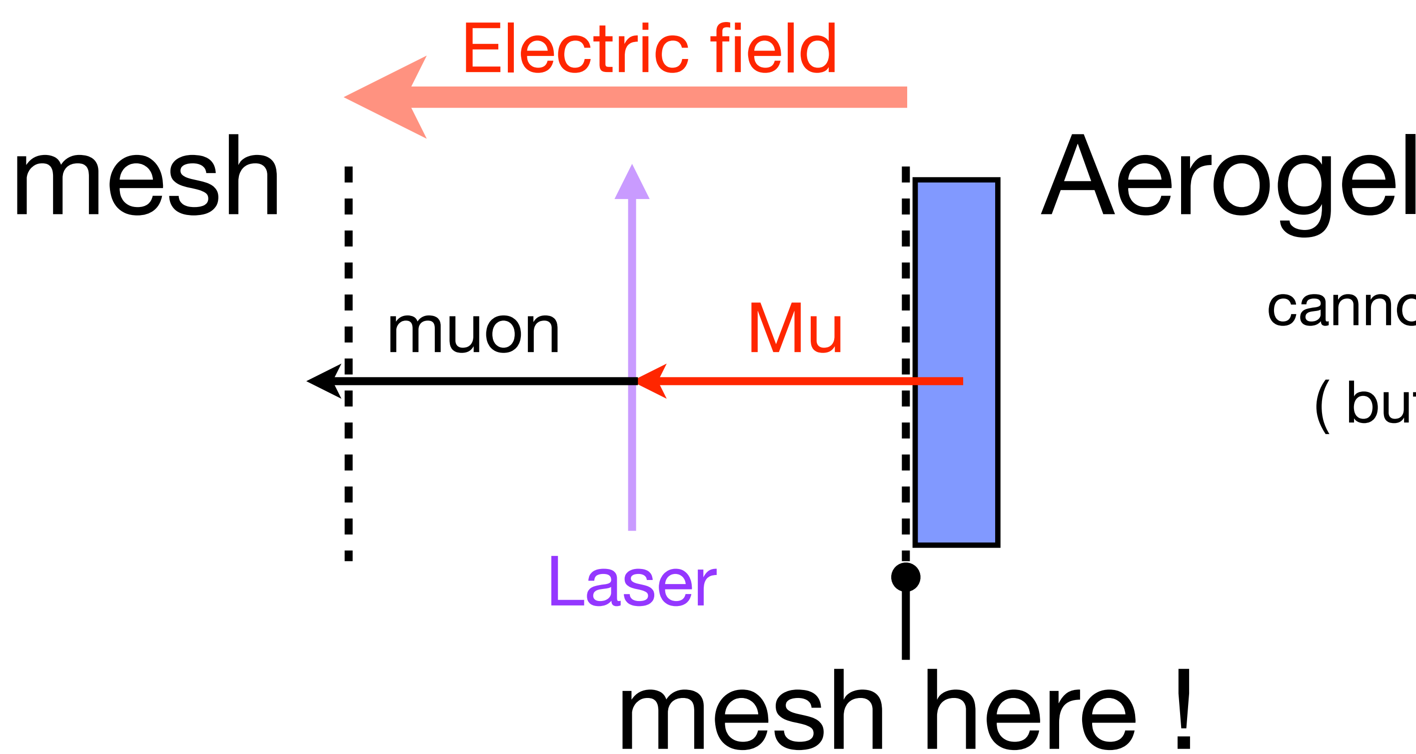
sandwiched aerogel target



Muon extraction after laser ionization



The electrode is Hot-W itself

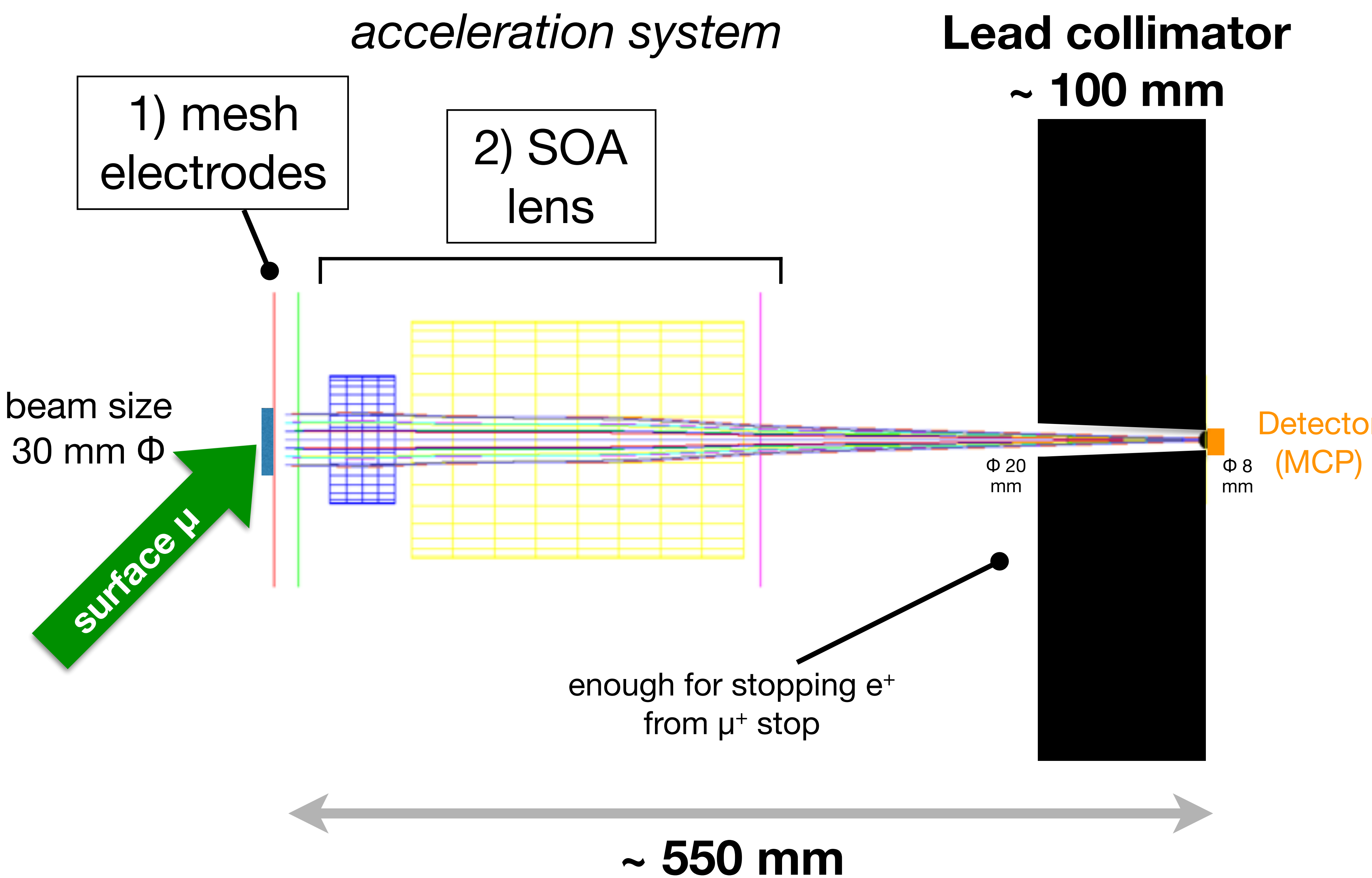


cannot be an electrode

(but dielectric body)

to be sure that the electrical potential

Beam trajectories



g-2

muon g-2 and EDM

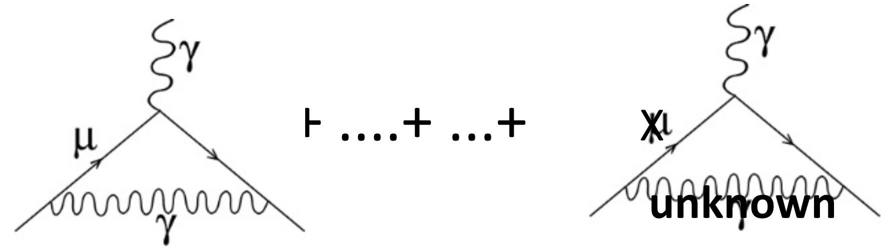
$\boldsymbol{\mu} = g_\mu \, (e/2m_\mu) \, \boldsymbol{s}$

$a_\mu = (g_\mu - 2)/2$: anomalous magnetic moment

Dirac equation predicts g=2.

Radiative corrections deviates g from 2.

a = a(QED) + a(Hadronic) +a(Weak) + ...



Contributions from all particles, even undiscovered

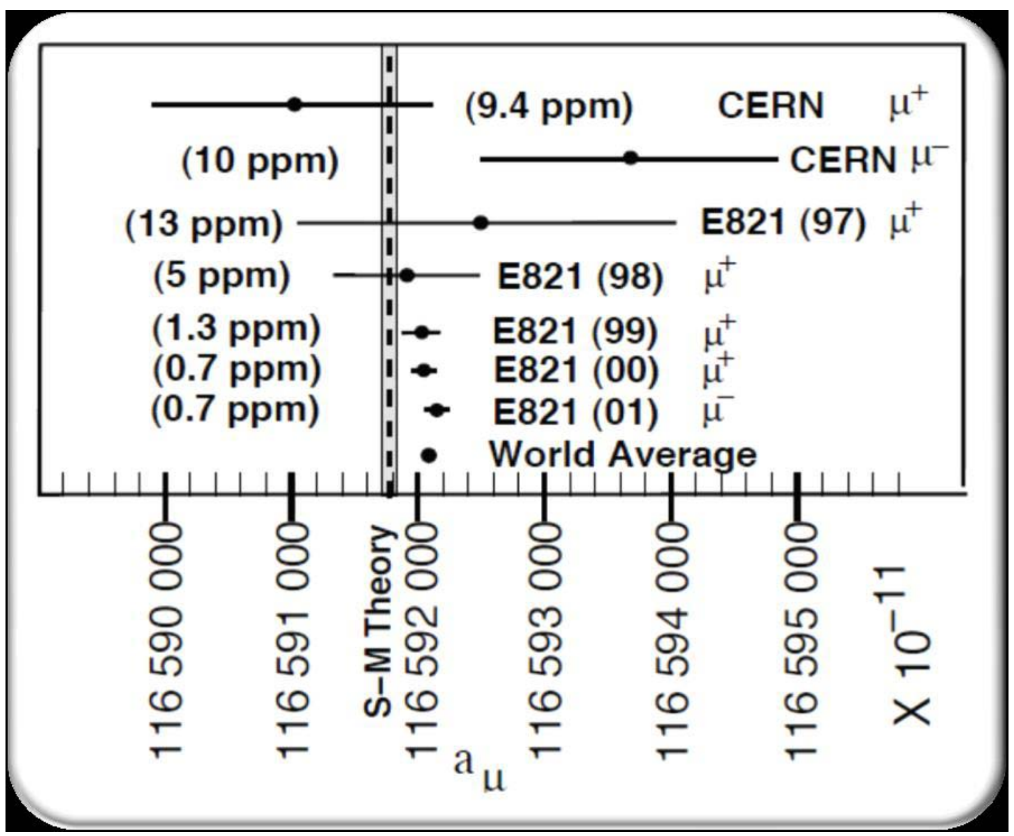
$\boldsymbol{d} = \eta \, (e/2mc) \, \boldsymbol{s}$

If EDM is nonzero -> T reversal is violated.

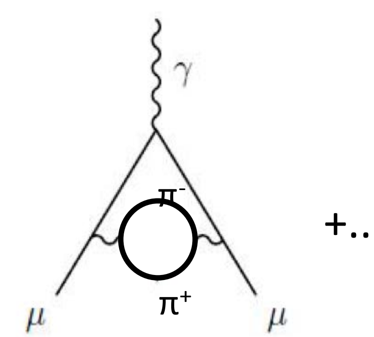
=> First indication of CP violation in the lepton sector.

muon g-2

BNL E821 measured a_μ to 0.7 ppm for μ^+ and μ^- (sum 0.5 ppm)
Deviation of experiment and theory by 3.4 σ was observed.
New physics?
Experiment and theory to better precision is waited for.



Hadronic contribution (experimental input) study by several groups and methods ("e+e- →γ^*→ hadrons" and tau-decay).
=> Some variations but not enough large to explain the discrepancy.



Muon g-2/EDM@J-PARC

We plan an independent measurement at J-PARC
based on ultra-cold muon beam and MRI-type storage ring.

with different scheme - in systematic errors.

g-2 measurement

EDM

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} \boxed{ - \left(a_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} } + \frac{\eta}{2}\left(\vec{\beta} \times \vec{B} + \boxed{\frac{\vec{E}}{c}} \right) \right]$$

Out-of plane oscillation is
an indication of EDM.

Make E=0 by making focusing need low.
- no high "magic" momentum requirement.
Need of well controlled muon beam
- start with ultra cold muon beam.

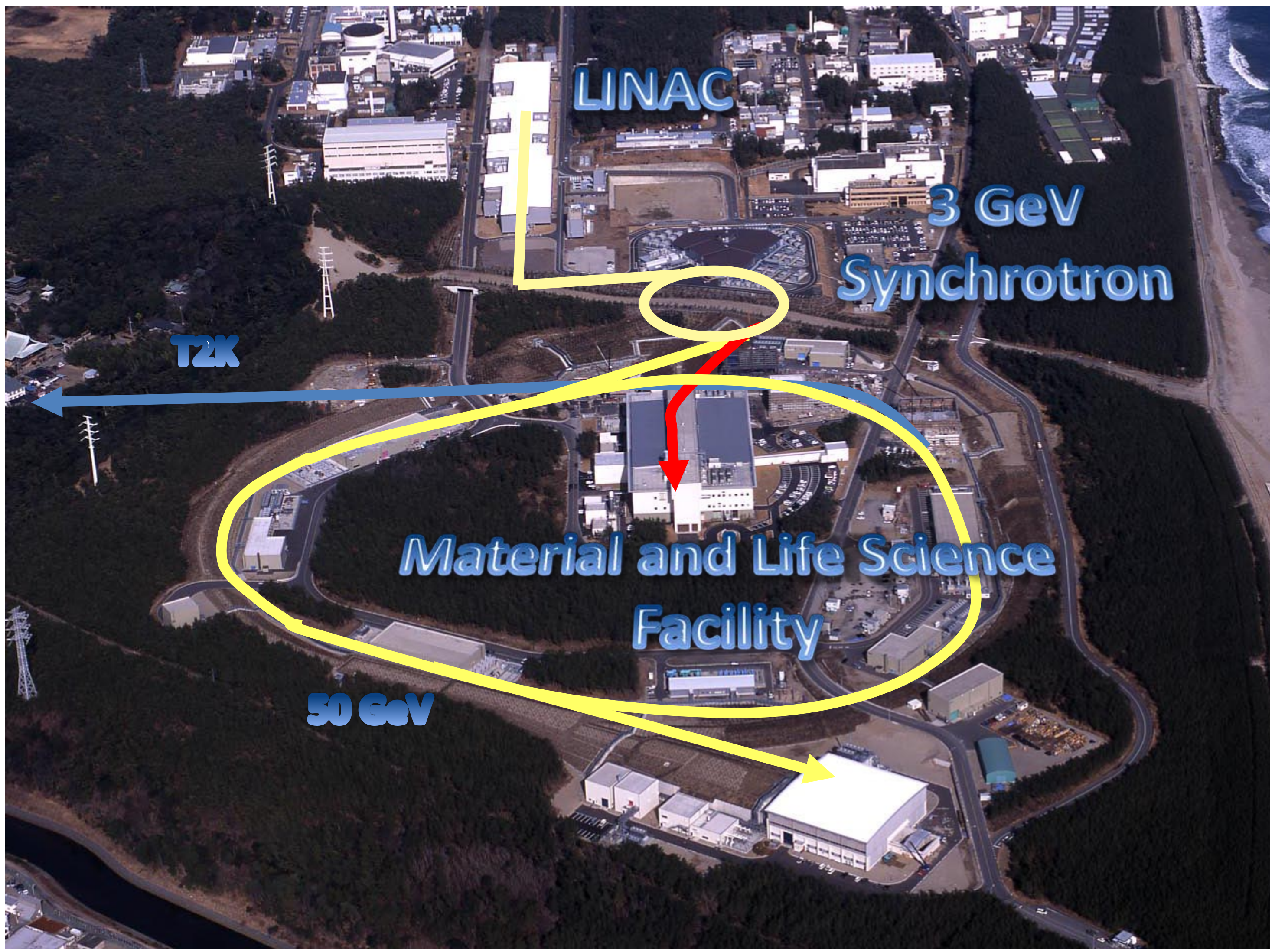
Our goal: comparison

	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		Very weak magnetic
# of detected μ+ decays	5.0E9	1.8E11	1.5E12
# of detected μ- decays	3.6E9	-	-
Precision (stat)	0.46 ppm	0.1 ppm	0.1 ppm*

* Based on 1 x 10^6/s stored muons x 1 year data taking (10^7 s).

Muon g-2/EDM@J-PARC

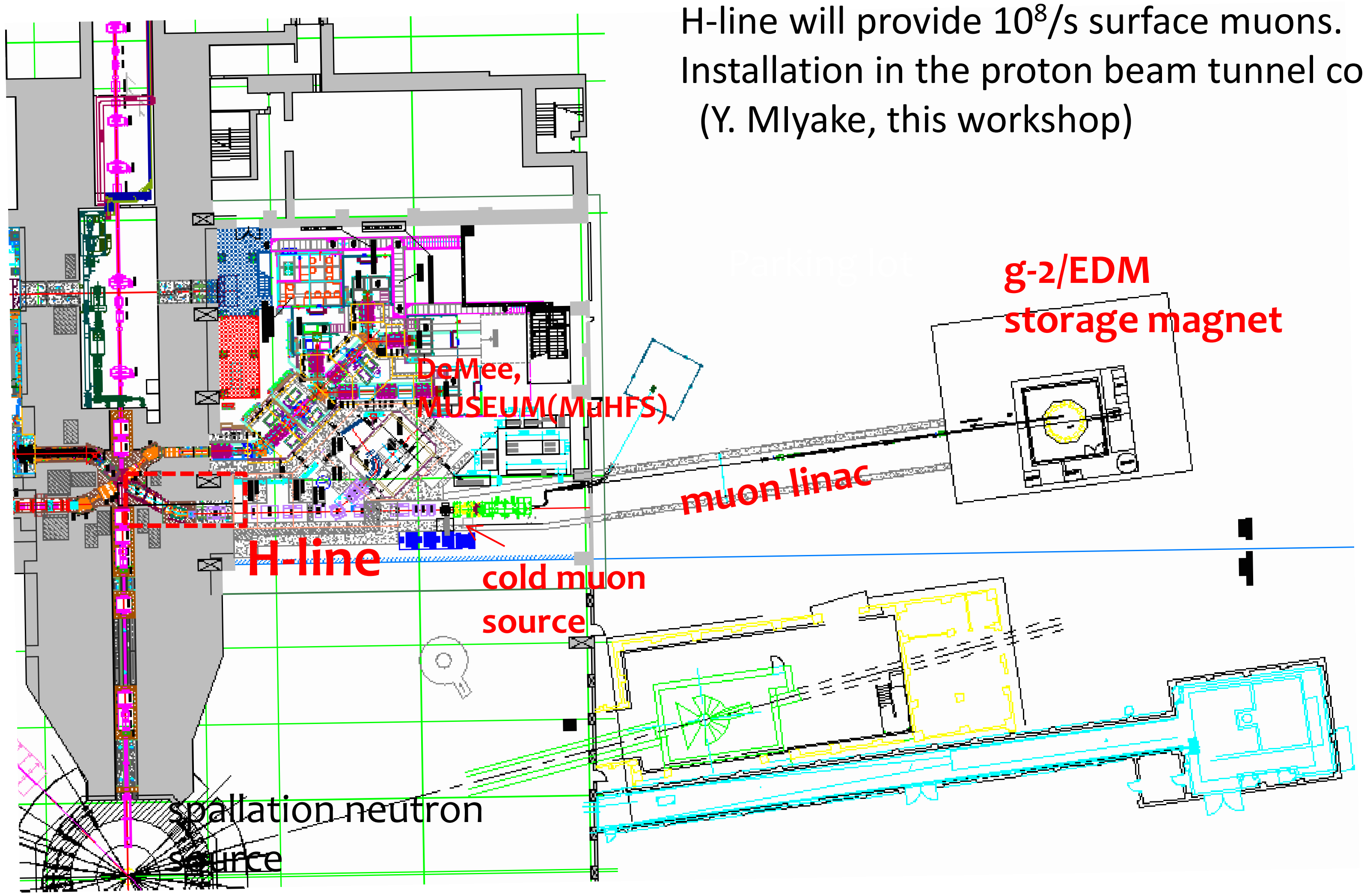
High intensity Japan Proton Accelerator Research Complex
1 MW at 3 GeV (0.3 MW at present), 0.75 MW at 50 GeV



proposed experimental site

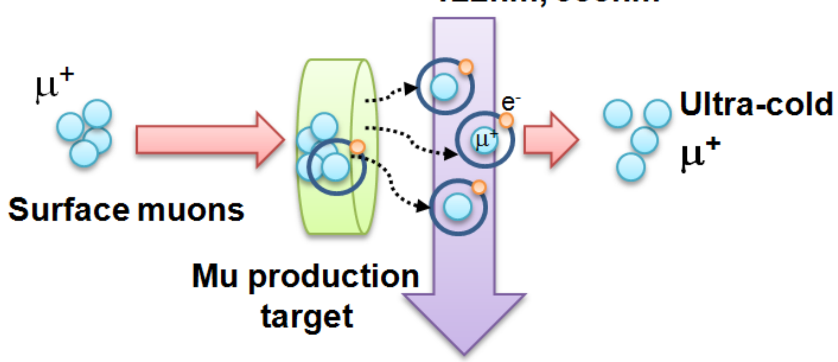
J-PARC MLF (Materials and Life Science Facility)

H-line will provide 10^8/s surface muons.
Installation in the proton beam tunnel completed
(Y. MIyake, this workshop)



Ultra-slow muon from Thermal Muonium

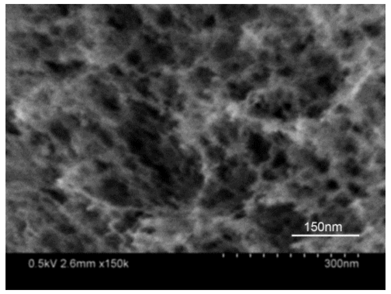
Typical surface muon beam (4 MeV, Δp~2%, 4cmϕ, 50 mr)

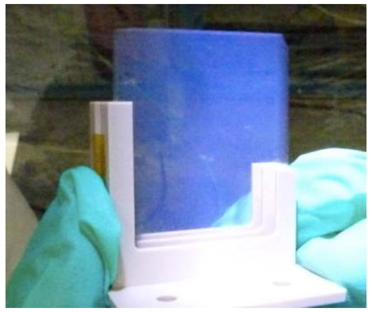


Stop muons in a material,
some diffuse out at thermal energy.
Good muonium emitter and
an intense laser to remove the electron
are essential.

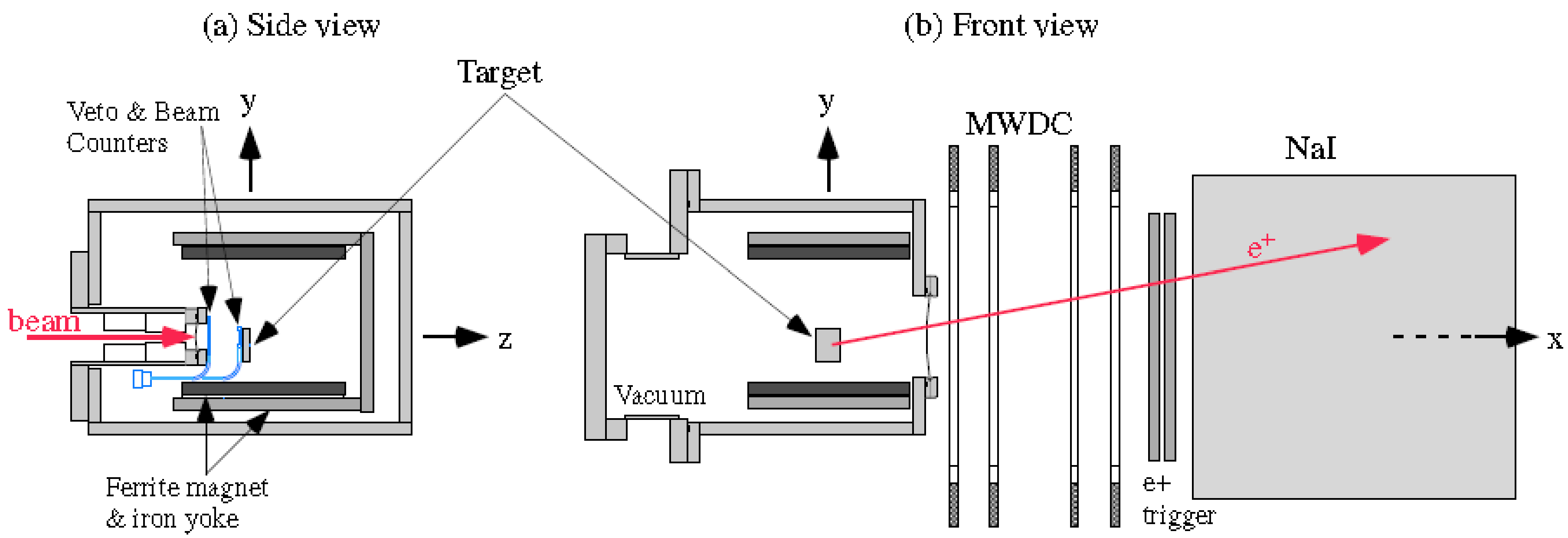
Silica powder has been known to be a good
Mu emitter at room temperature
Mu diffuse out through network of SiO_2 grains
(large surface area)

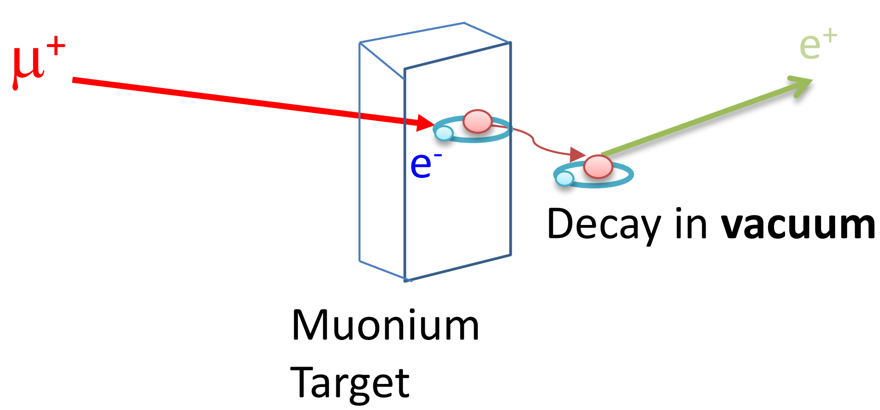
Silica aerogels with similar network structure
can be more easily handled and may fit better
our system





Measurement S1249@TRIUMF

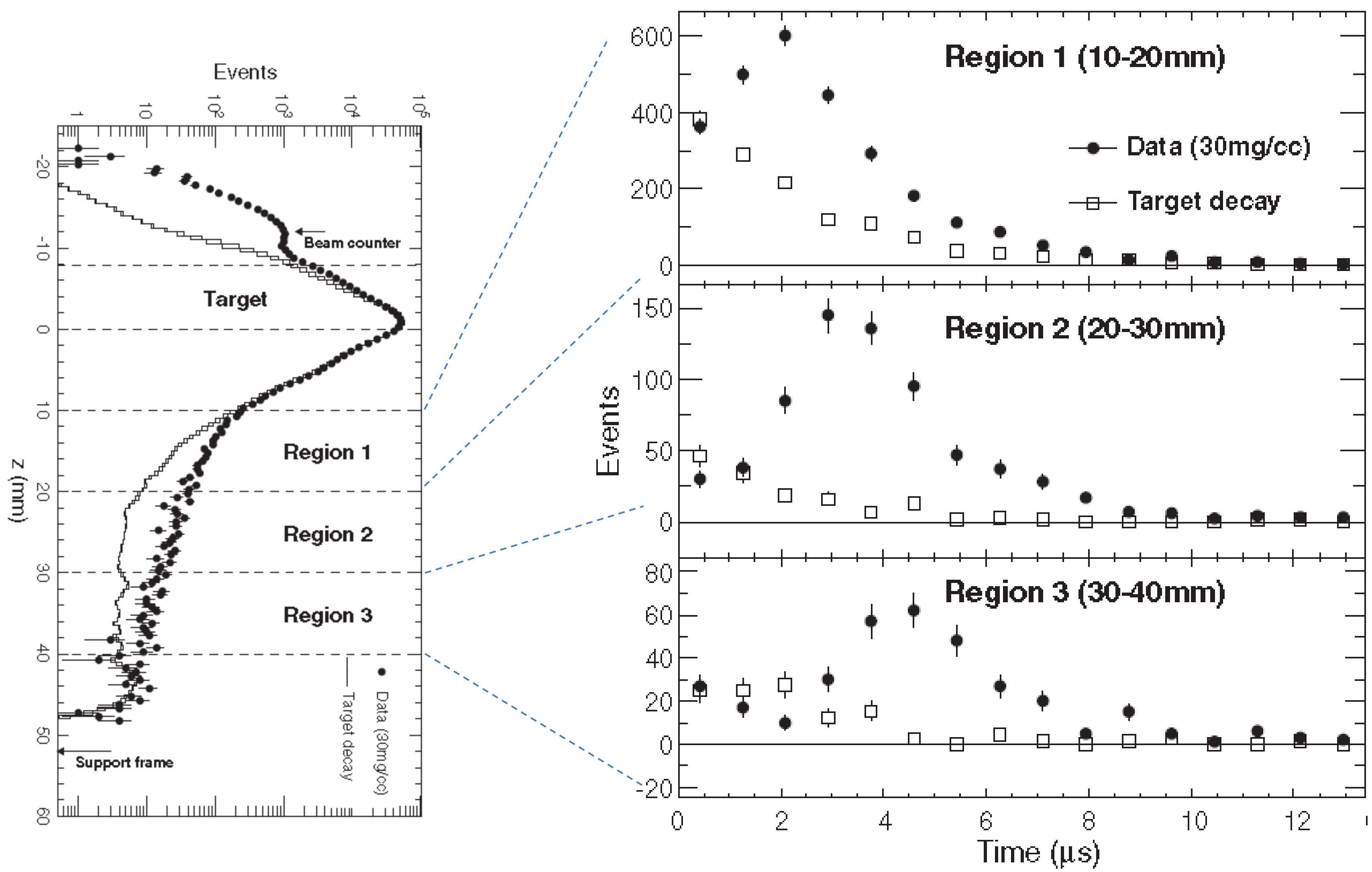




Mu velocity in vacuum ~5 mm/μs
MWDC intrinsic resolution ~0.1 mm
Track back resolution ~2mm
(from 0.1mm silica-plate data)

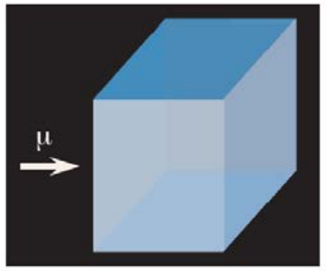
First results S1249@TRIUMF 2010-2011

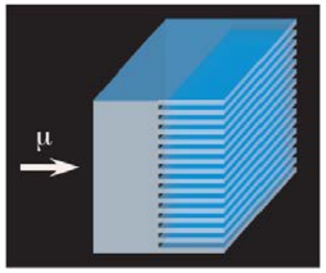
Mu excess over reference target was observed
Yield was "not" satisfactory (~1% emission per stopped μ)

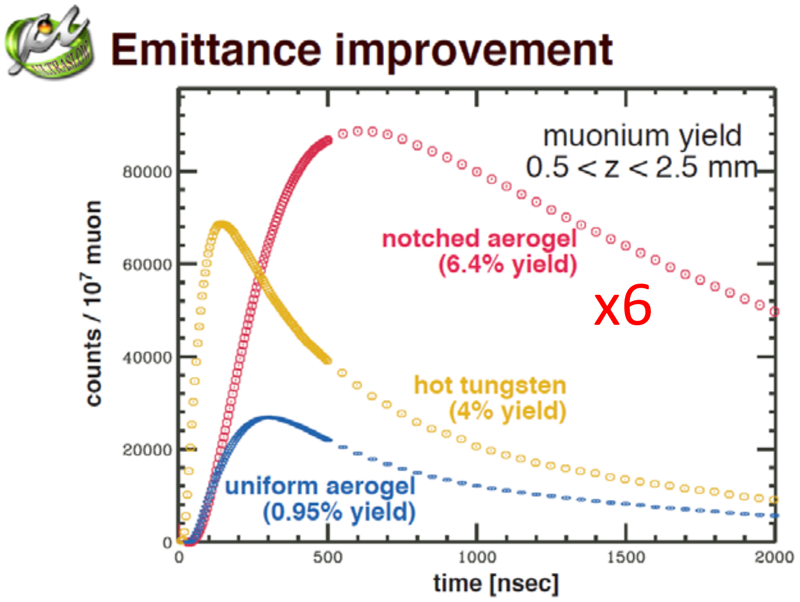


More muoniums wanted

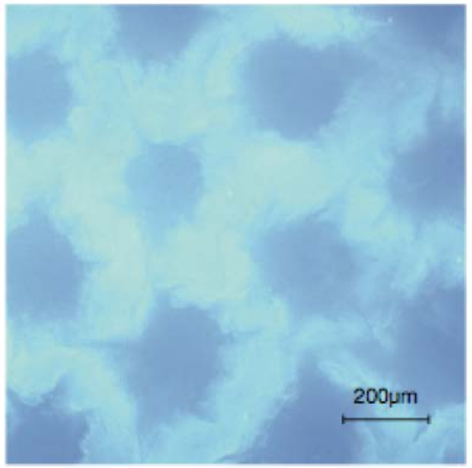
Muon should stop near surface (<0.1mm) to come out!
Simulation with structured surface by M. Iwasaki (Ultra Slow Muon Microscope Meeting, Sapporo, 2012)

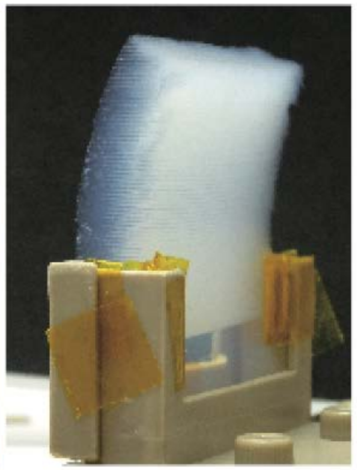




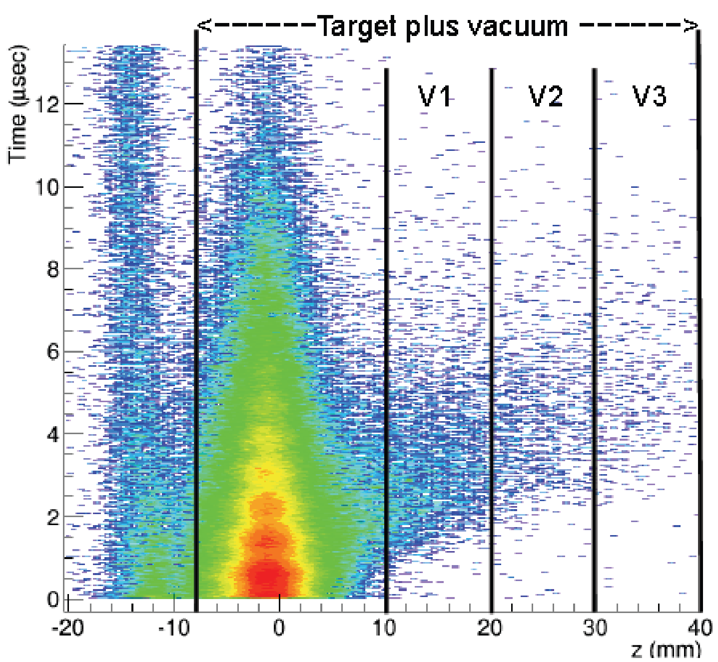


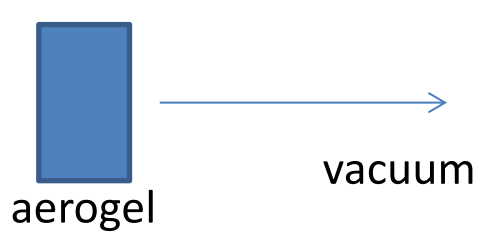
How to make it?
Ion beam, dust-gun, mold, push-pin, ...
Laser ablation was successfully applied.

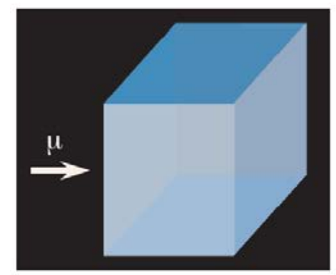


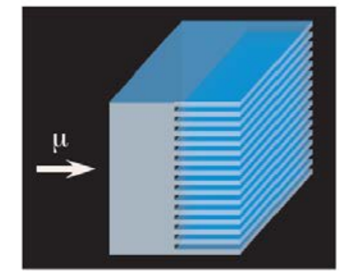


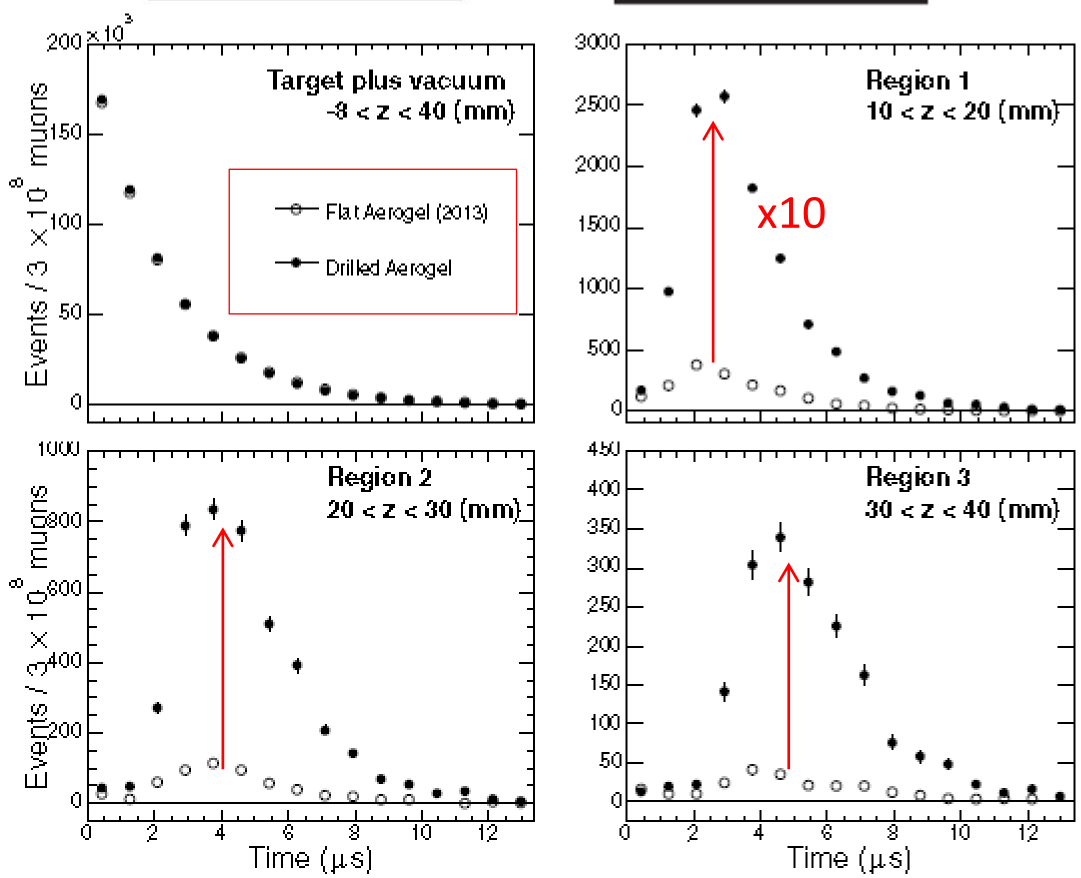
New measurement (S1249@TRIUMF 2013)











(to be published in PETP soon!)

Muon source

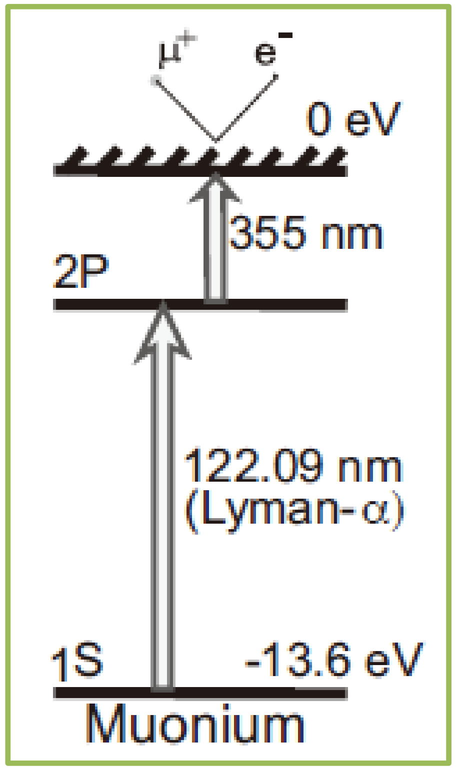
Huge increase (x10) of Mu yield in measurement last October.
We now have about 10% of muons coming out in vacuum.
(from 23 MeV/c, σp=2%)
Expected ultra-cold muon yield is only factors away from requirement.
(present estimate is 0.2 x 10^5/s assuming other conditions are fulfilled)

=> Further optimization of target condition (density, hole size/pitch, ...)
(we initially tested only four samples)
is now feasible at J-PARC

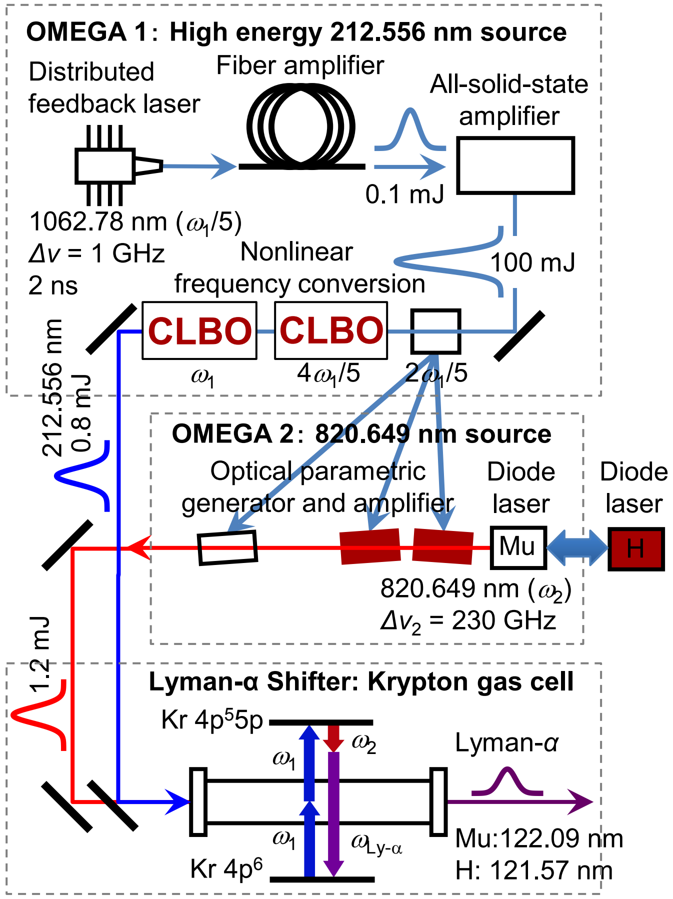
=> Demonstration of ionization from silica aerogel
is planned at RIKEN-RAL.

Mu Ionization Laser

Remove e- for g-2 measurement (and acceleration) with lasers



Improved Coherent Lyman-α System Configuration

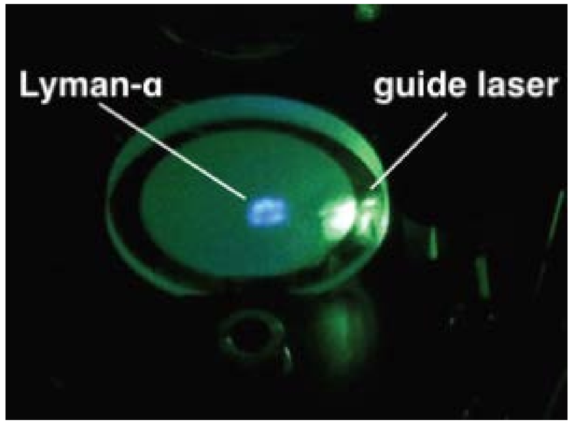


Lyman-α laser progress

New Lyman-α laser developed by RIKEN laser group
for ultra-slow-muon-microscope project (USMM by Grant-in-Aid)
aimed for use of ultra-cold-muons for materials study
=> Laser intensity goal is 100 μJ (x100 improvement over record)

Lyman-α was introduced to the USMM beamline this year.
Laser tuning and calibration progressing
=> Good R&D for muon g-2/EDM laser
Ionization test (with Mu source from hot-W) this autumn

laser system installed in J-PARC (for USMM)



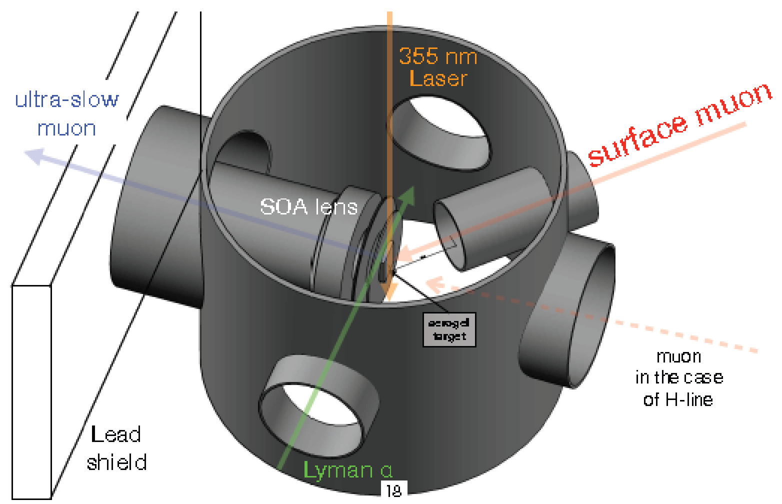
laser fluorescence in the source chamber

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, ...)



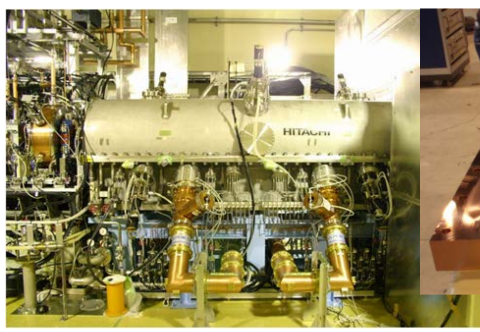
A new Muon Source chamber will be constructed for evaluation study.

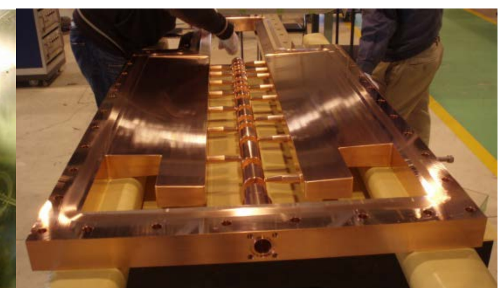
Baseline for muon g-2 accelerator

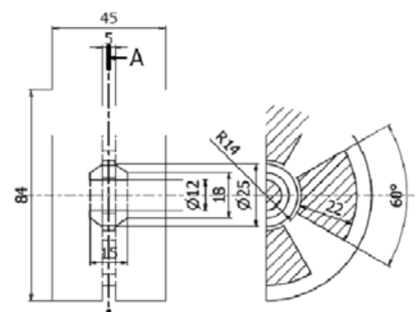
テキスト

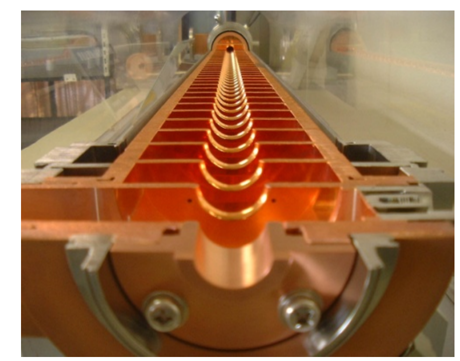
5.6 keV	0.34 MeV	5.1 MeV	42.3 MeV	200 MeV
β≈0.01	β≈0.08	β≈0.3	β≈0.7	β≈0.94

	Bunching Section	Low-β	Middle-β	High-β
μe⁻	RFQ (324 MHz)	Interdigita-H (324 MHz)	CDS or DAW (1300MHz)	Disk loaded structure (1300MHz)



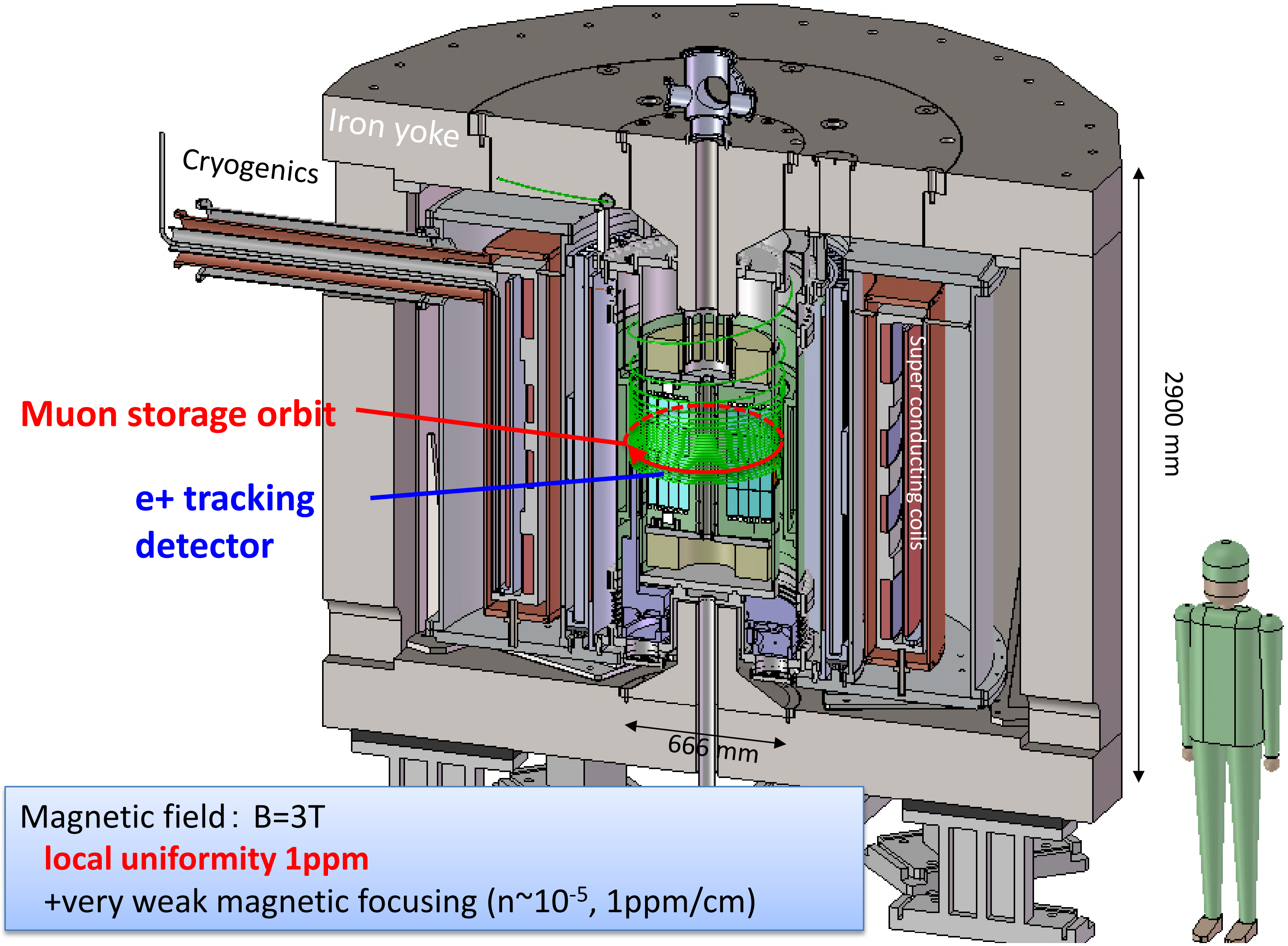






Initial acceleration simulation
for ex. RFQ capture loss~30%, muon decay x 0.7

Muon storage magnet and detector

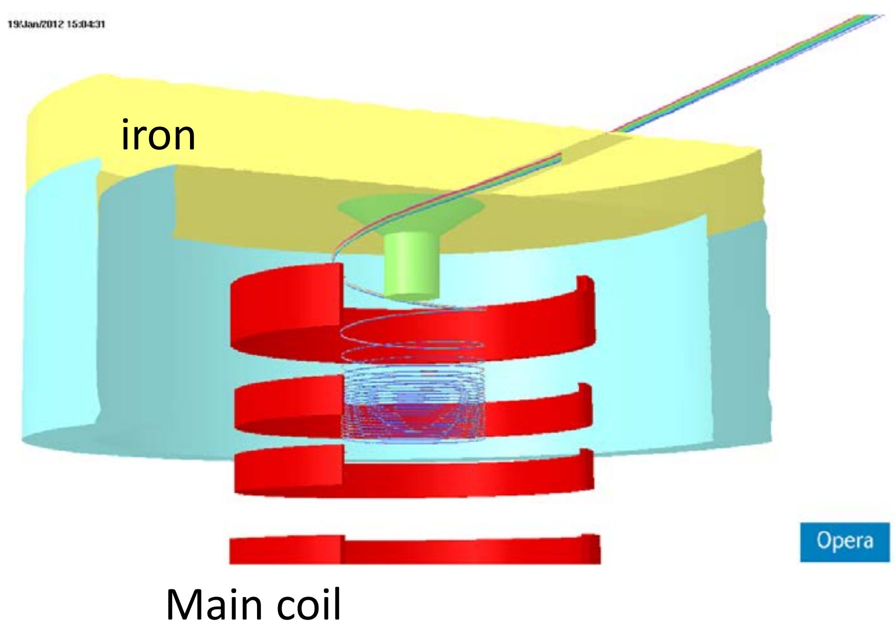


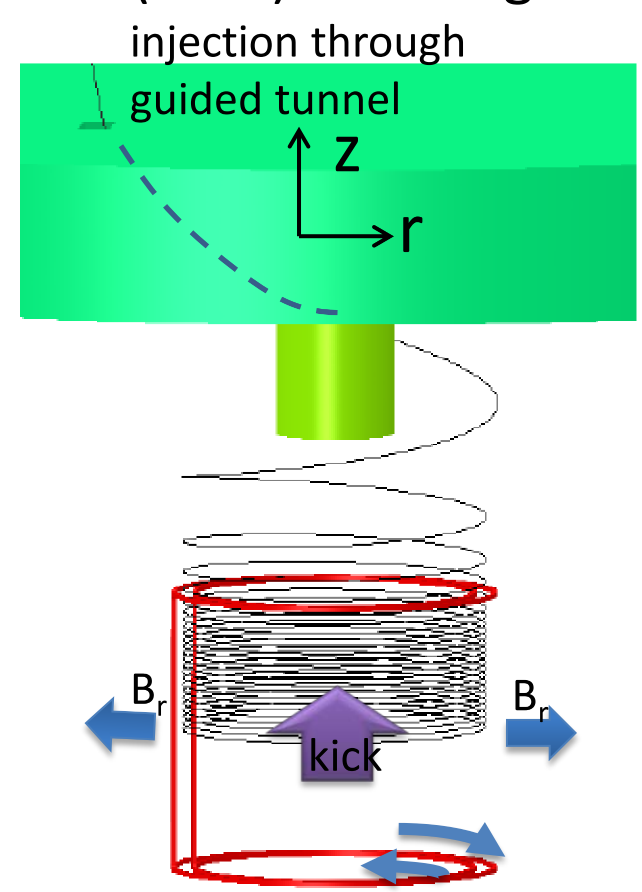
Magnetic field : B=3T
local uniformity 1ppm
+very weak magnetic focusing (n~10^{-5}, 1ppm/cm)

Beam Injection

Injection scheme

Spiral injection + weak magnetic kick (8 mr) to storage-orbit





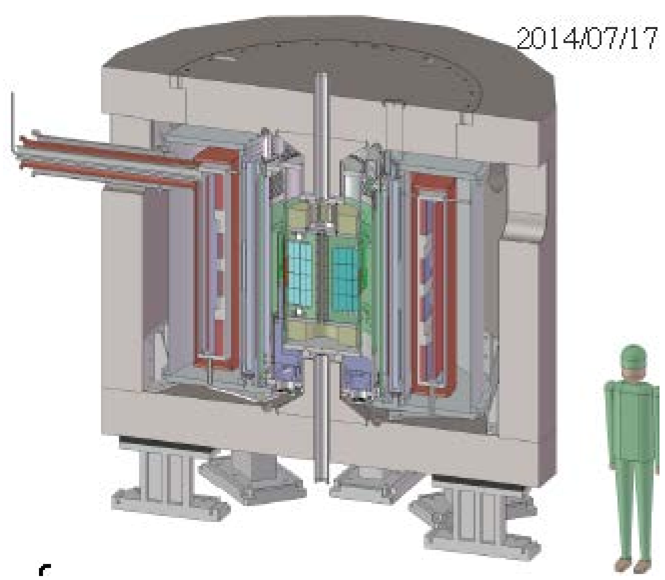
Design of injection-matching transport beamline.
Spiral injection test with mini-solenoid and electron gun soon

Muon storage magnet and field monitor

Good synergy with MUSEUM (P. Strasser, MuHFS talk)

in physics ($\lambda=\mu_\mu/\mu_p$ needed for g-2)

ultra-precision magnet (3T vs 1.7 T)
 shimming method of MuHFS magnet

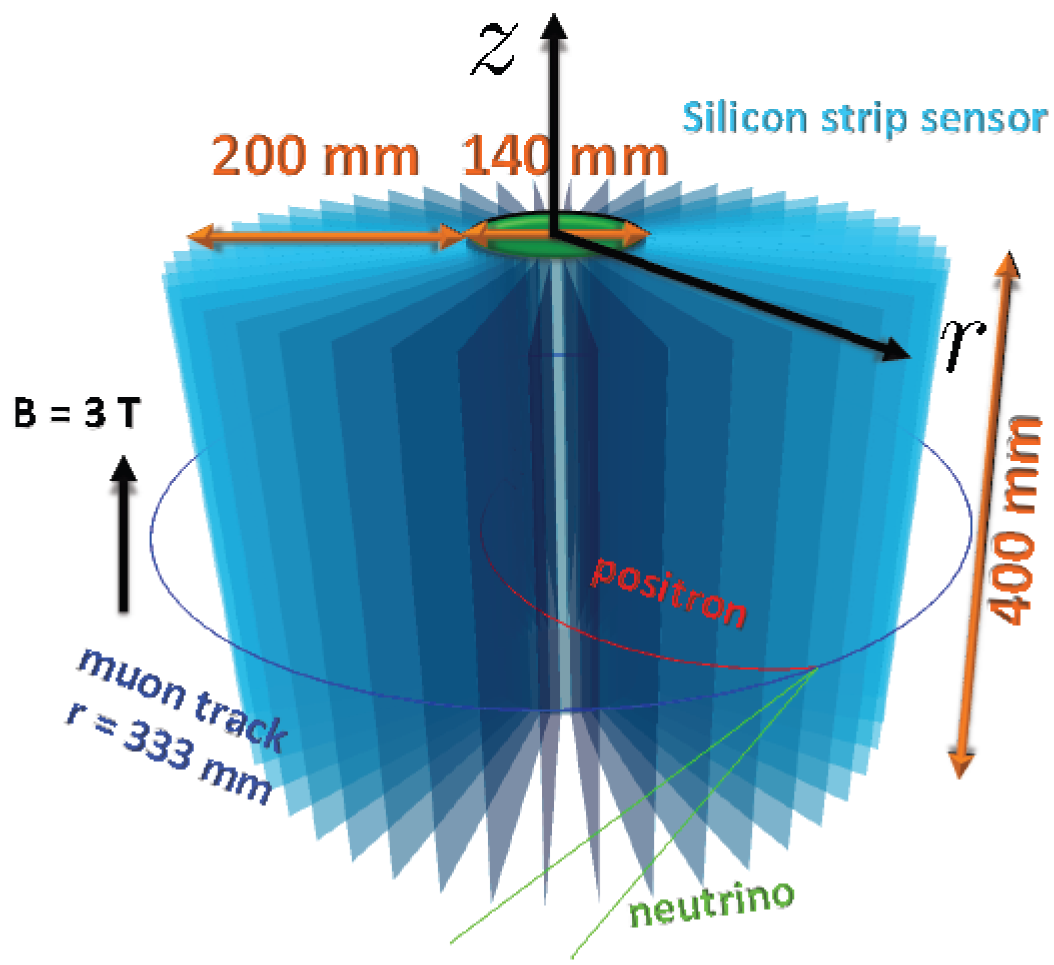



MuHFS magnet 1.7T

and field measurement
 monitoring system, NMR probe

Detector

measure muon decay positron tracks with Silicon-strip detectors
forward/backward decay gives different positron momentum



beam test with test sensor
muon beam at J-PARC
and electron at Tohoku-U
in progress

Collaboration

- > 98 members (…still evolving)
- > 21 Institutions
- Academy of Science, BNL, BINP, CRNS-APC, UC Riverside, Charles U., KEK, Korea U, NIRS, UNM, Osaka U., PMCU, RCNP, STFC RAL, RIKEN, Rikkyo U., SUNYSB, CRC Tohoku, U. Tokyo, TITech, TRIUMF, U. Victoria
- 9 countries
- Canada, China, Czech, France, Japan, Korea, Russia, UK, USA (alphabetic order)

Masaharu Aoki[8], Pavel Bakule[20], Bernd Bassalleck[24], George Beer[26], Gerry Bunce[27], Abhay Deshpande[19], Simon Eidelman[4], Douglas E. Fields[24], Miloslav Finger[6], Michael Finger Jr.[6], Yuya Fujiwara[17,14], Yoshinori Fukao[10], Noriyosu Hayashizaki[16], Seiko Hirota[10,14], Hiromi Iinuma[10], Masanori Ikegami[10], Masahiro Ikeno[10], Katsuhiko Ishida[17], Masa Iwasaki[17], Ryosuke Kadono[10], Takuya Kakurai[12], Takuya Kamitani[10], Yukihide Kamiya[10], Sohtaro Kanda[12], Frédéric Kapusta[5], Naritoshi Kawamura[12], Takashi Kohriki[10], Sachio Komamiya[14], Kunio Koseki[10], Yoshitaka Kuno[8], Alfredo Luccio[12], Oleg Luchev[2], Muneyoshi Maki[12], Glen Marshall[22], Mika Masuzawa[10], Yasuyuki Matsuda[9], Teijiro Matsuzaki[17], Tsutomu Mibe[10], Katsumi Midorikawa[2], Satoshi Mihara[10], Yasuhiro Miyake[10], William M. Morse[2], Jiro Murata[17,13], Ryotaro Muto[10], Kanetada Nagamine[23,10,18], Takashi Naito[10], Hisayoshi Nakayama[10], Megumi Naruki[10], Makiko Nio[21], Hajime Nishiguchi[10], Daisuke Nomura[10], Hiroyuki Noumi[15], Tomoko Ogawa[2], Toru Ogitsu[10], Kazuki. Ohishi[17], Katsunobu Oide[10], Masahiro Okamura[2], Art Olin[22,26], Norihito F. Saito[2], Naohito Saito[10,14], Yasuhiro Sakemi[7], Ken-ichi Sasaki[10], Osamu Sasaki[10], Akira Sato[12], Aurore Savoy-Navaro[5], Yannis K. Semertzidis[2], Yuri Shatunov[12], Koichiro Shimomura[10], Boris Shwartz[4], Wilfrid da Silva[25], Patrick Strasser[10], Ryuhei Sugahara[10], Michinaka Sugano[10], Ken-ichi Tanaka[10], Manobu Tanaka[10], Nobuhiro Terunuma[10], Nobukazu Toge[10], Dai Tomono[17], Eiko Torikai[12], Toshiyuki Toshito[11], Akihisa Toyoda[10], Kyo Tsukada[12], Tomohisa Uchida[10], Kazuki Ueno[17], Vlasov Vrba[1], Satoshi Wada[2], Akira Yamamoto[10], Kaoru Yokoya[10], Koji Yokoyama[17], Makoto Yoshida[10], Mitsuhiro Yoshida[10], Koji Yoshimura[10]

9

Muon g-2/EDM@J-PARC : Status

J-PARC PAC
Conceptual Design Report at J-PARC PAC (13 Jan 2012)
Stage 1 approval as E34 (21 Sep 2012)
Most recent PAC report highly recognized
our progress in muon source.

Collaboration Meeting held every half year.
9th C.M. will be in 6-8 Nov at KAIST in Daejon, Korea

Technical Design Report to be made this year
Expect to start running in 3~4 years (dep. on budget)

Several small grants obtained for development.
Overall budget is still a issue.

Summary

New muon g-2/EDM measurement is under preparation at J-PARC.
Since last year, there has been significant progresses.

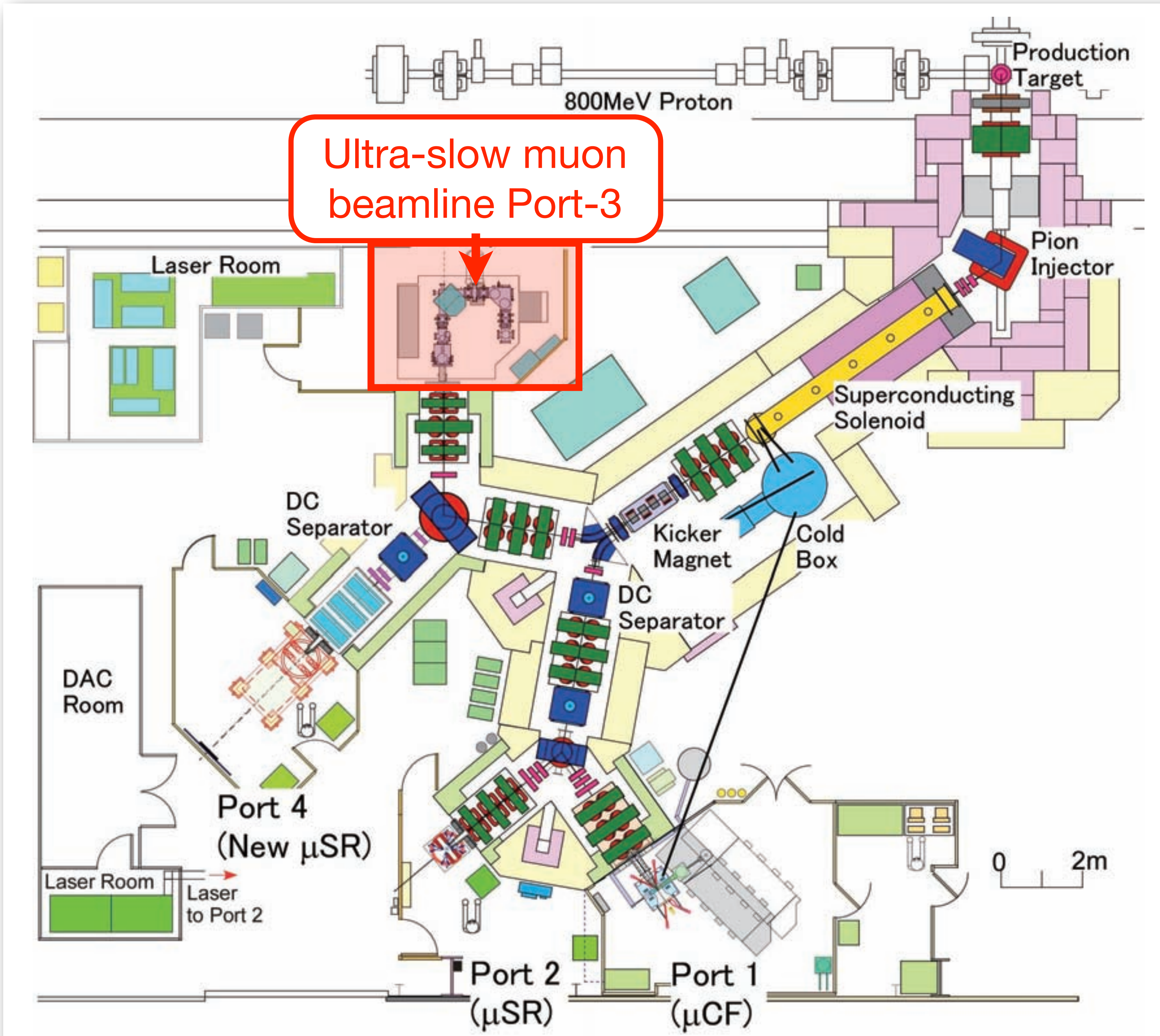
Muon Source (x 10 Mu emission)
Practical Mu ionization study will follow

New Lyman-α Laser progressing in collaboration with USMM group

Also progress in accelerator, storage magnet, injection, detection.

Concept of new beamline at RAL port-3

RIKEN-RAL Muon Facility



Motivation for new beamline

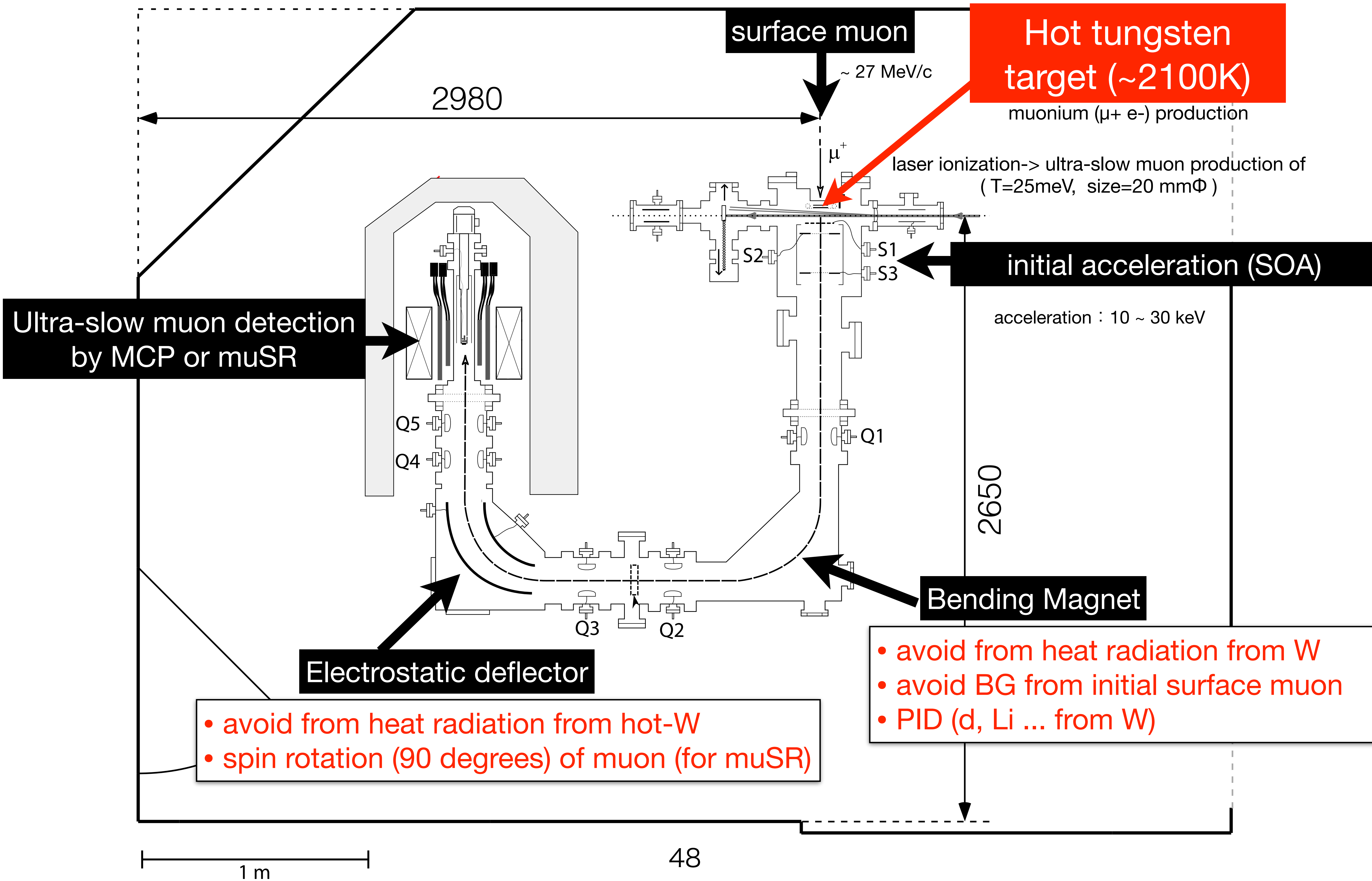
Hot tungsten
~ 2100 K

room-temp. target
~ 300 K

No radiating significant heat

Optimal beamline design is different

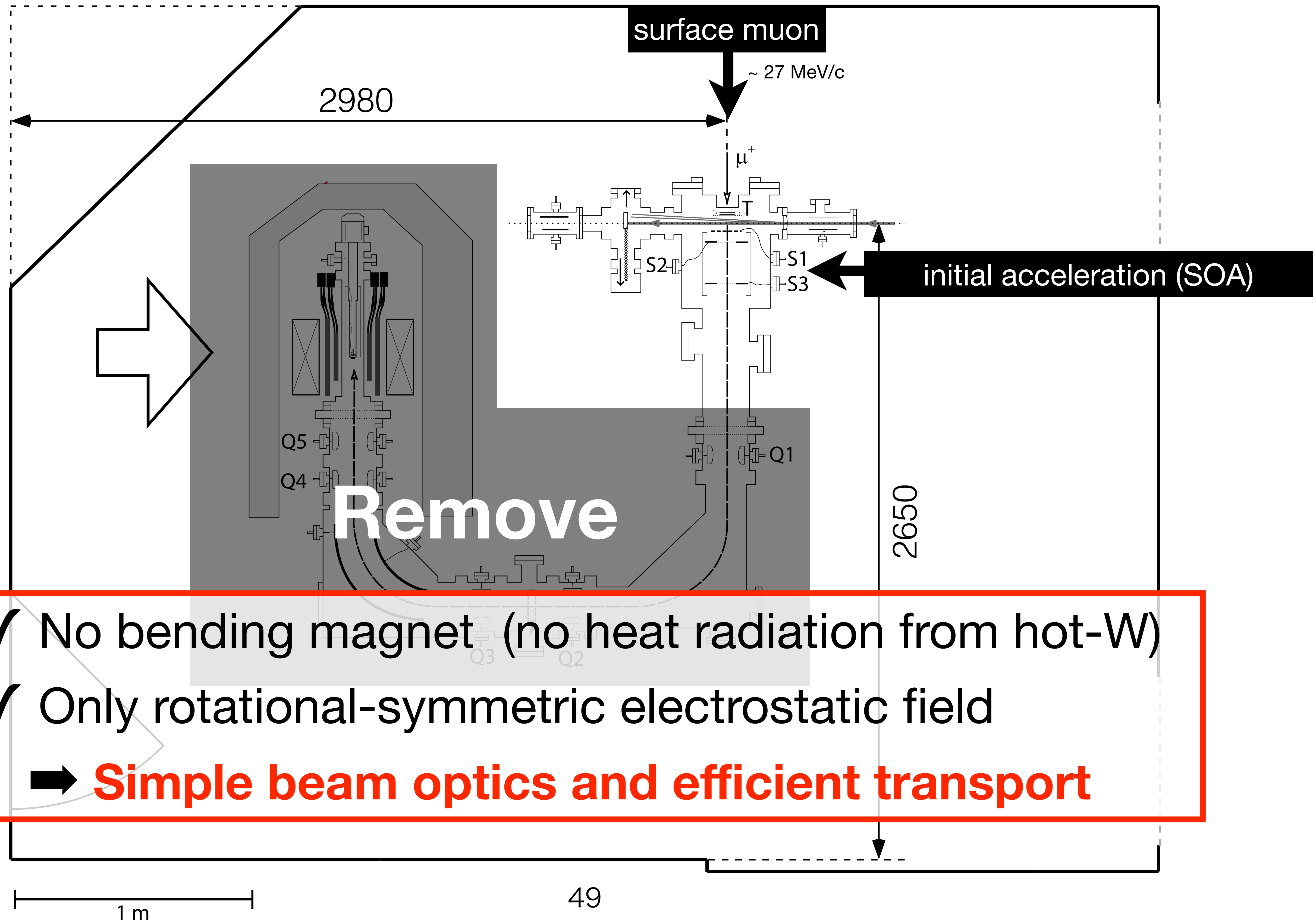
Present beamline port-3



- avoid from heat radiation from hot-W
- spin rotation (90 degrees) of muon (for muSR)

- avoid from heat radiation from W
- avoid BG from initial surface muon
- PID (d, Li ... from W)

Concept of new beamline (1)

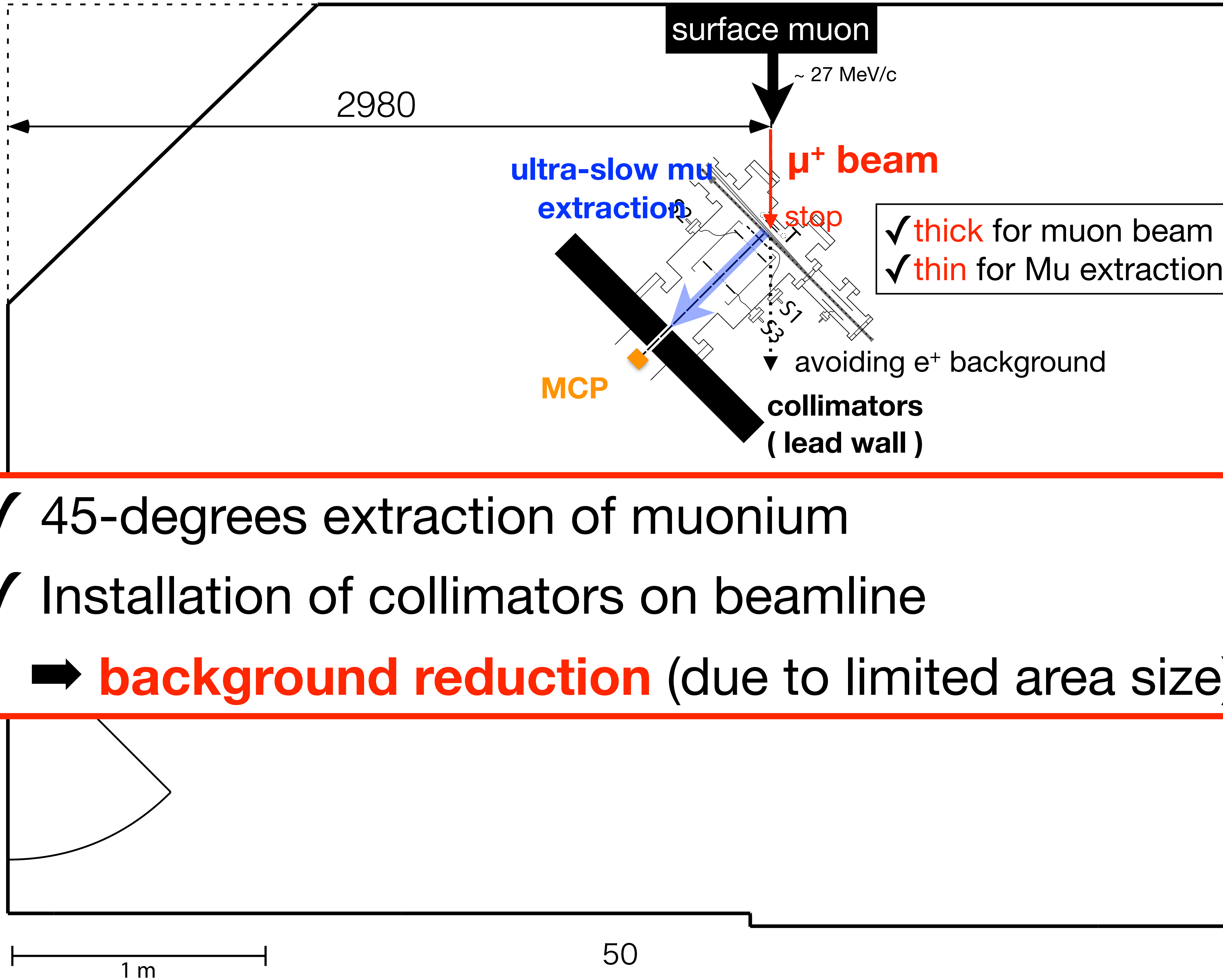


✓ No bending magnet (no heat radiation from hot-W)

✓ Only rotational-symmetric electrostatic field

➡ **Simple beam optics and efficient transport**

Concept of new beamline (2)



- ✓ 45-degrees extraction of muonium
- ✓ Installation of collimators on beamline
  - ➡ **background reduction** (due to limited area size)

Final design

Main chamber / beamline design

(A) Minimum setup

➡ Only meshed electrodes and SOA lens

➡ Enough for R&D of laser ionization and mu+ extraction

➡ Beamline extension is possible for more study of sharpening

(B) Lyα reflection mirrors

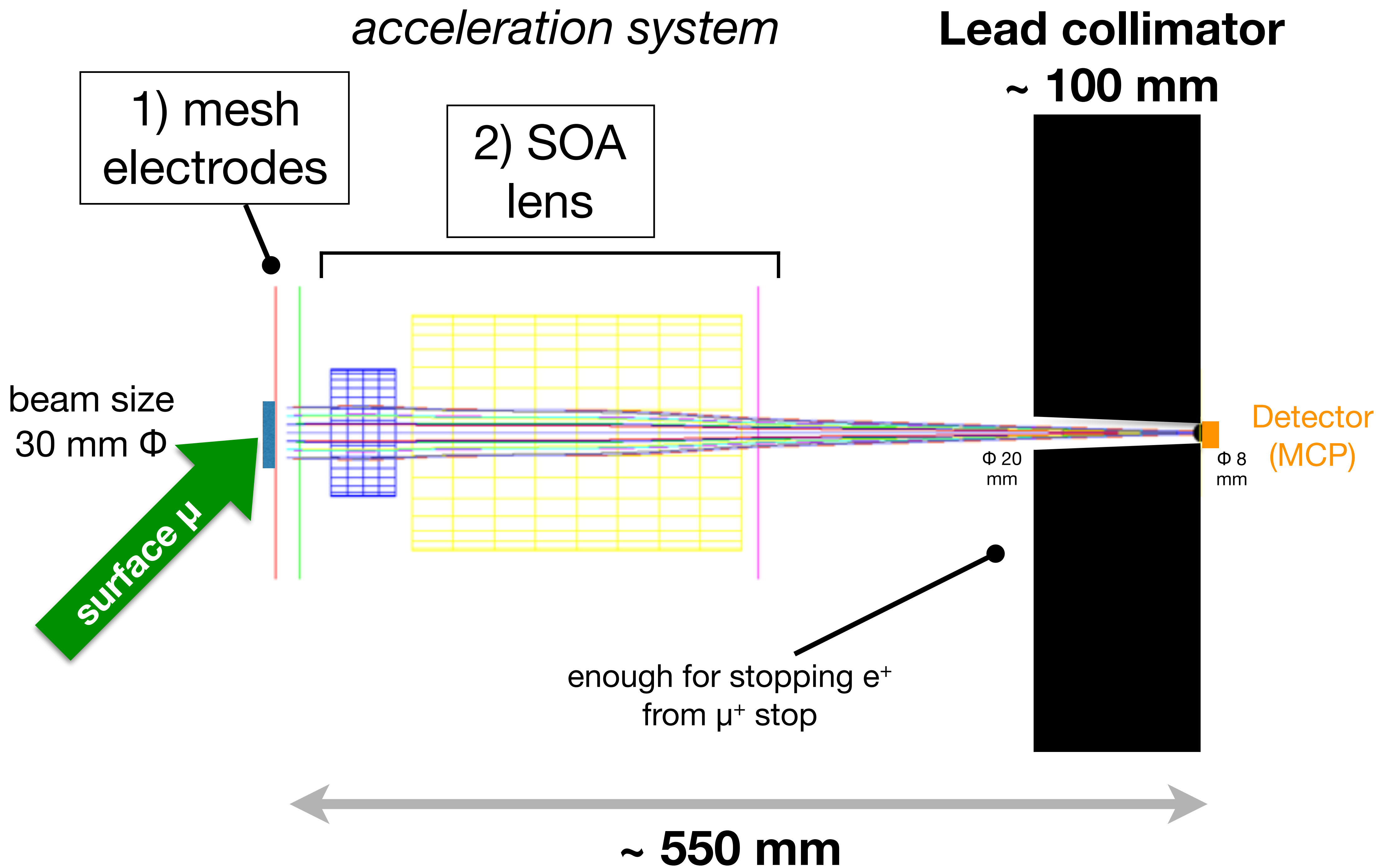
(C) Minimization of incident surface muon size

(D) Magnetic coils (for control of spin and earth magnetism / fringing field)

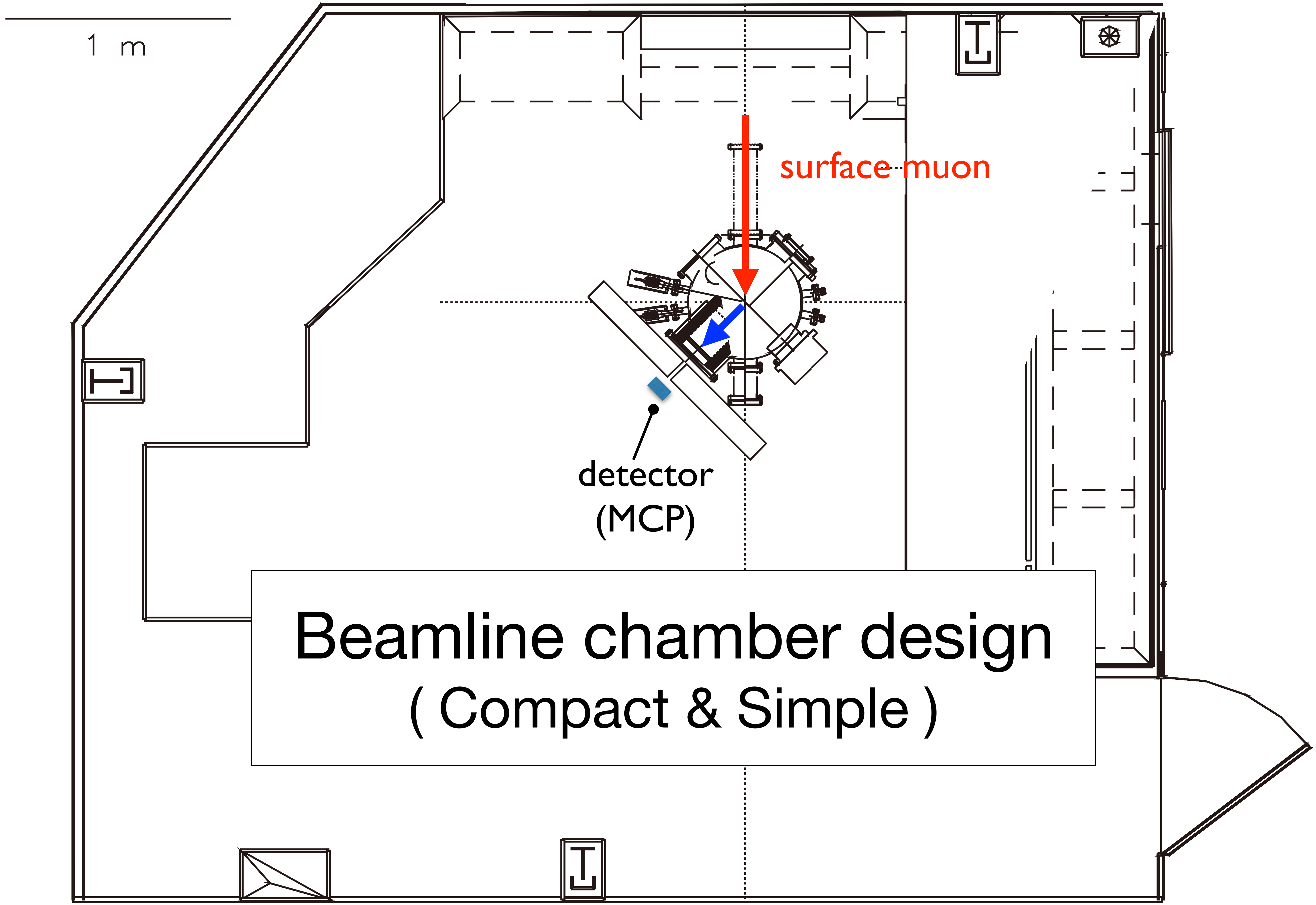
(A) Minimum setup

Beam trajectories

calculated by CPO (Charged Particle Optics)

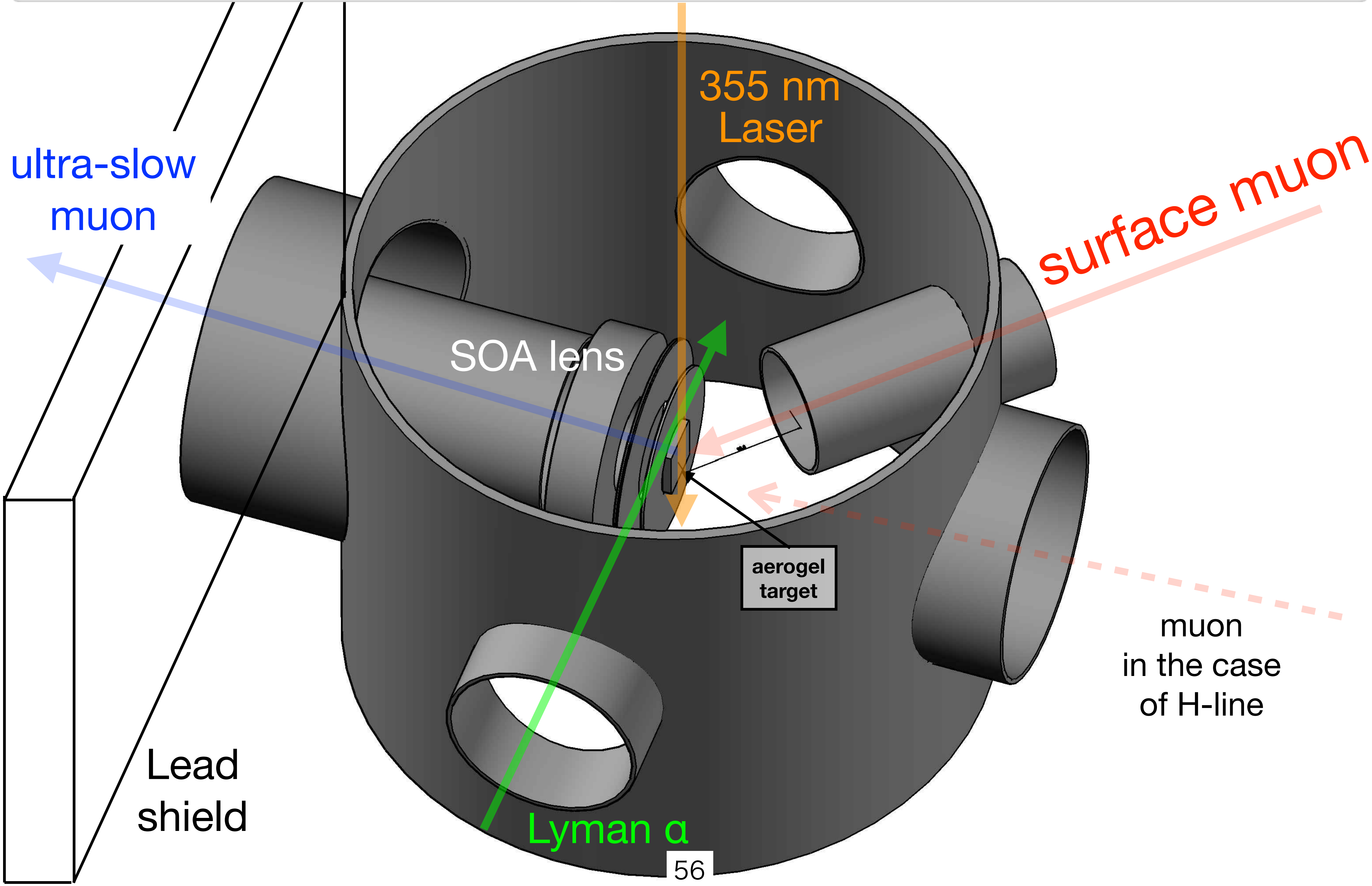


for 300K (30 mmΦ beam) : 2.1 mmΦ @ FF
for 2300K (30 mmΦ beam) : 5.6 mmΦ @ FF

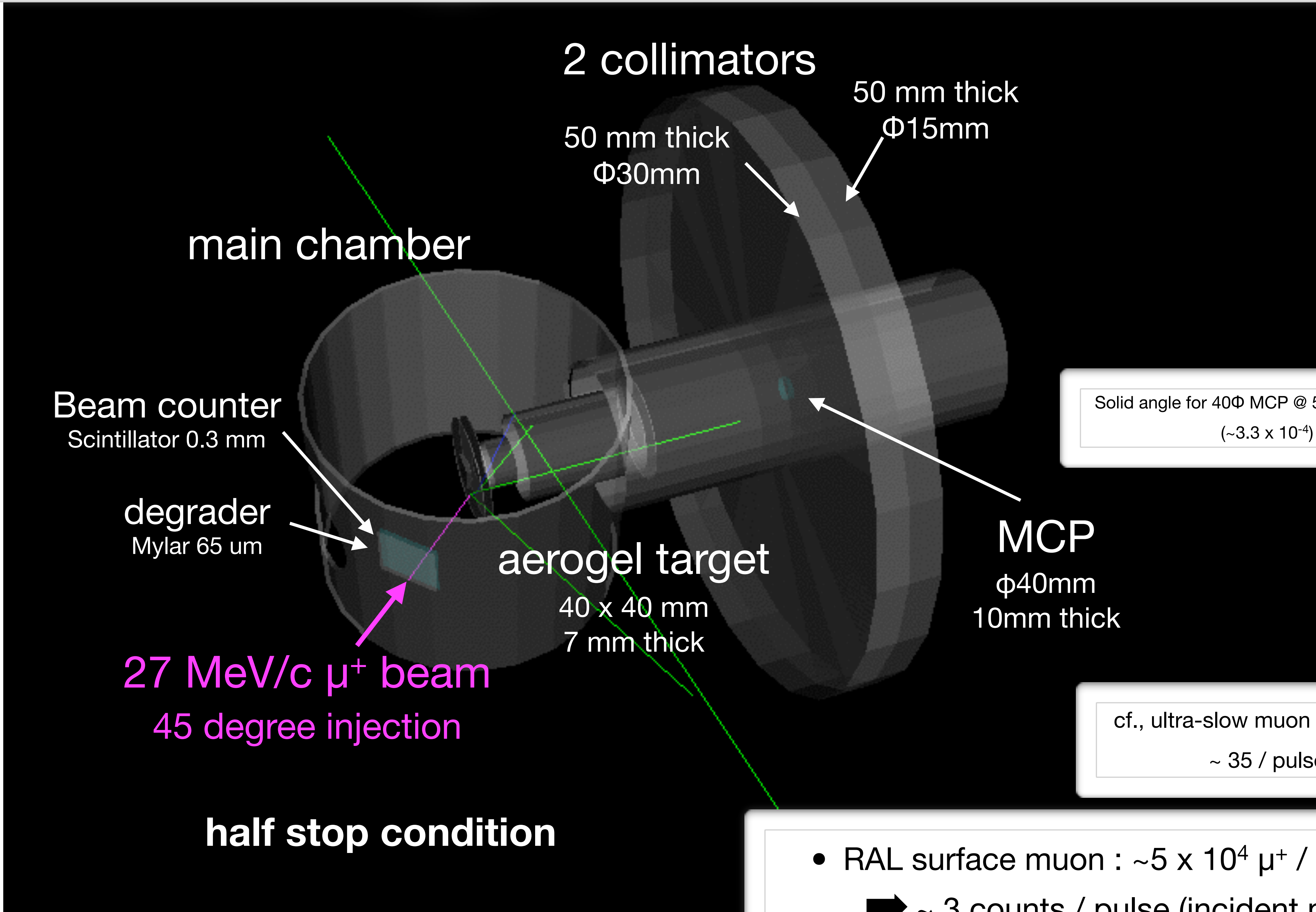


Beamline chamber design
(Compact & Simple)

Setup overview



Background simulation



Solid angle for 40Φ MCP @ 550 mm = 4 msr (~3.3 x 10^{-4})

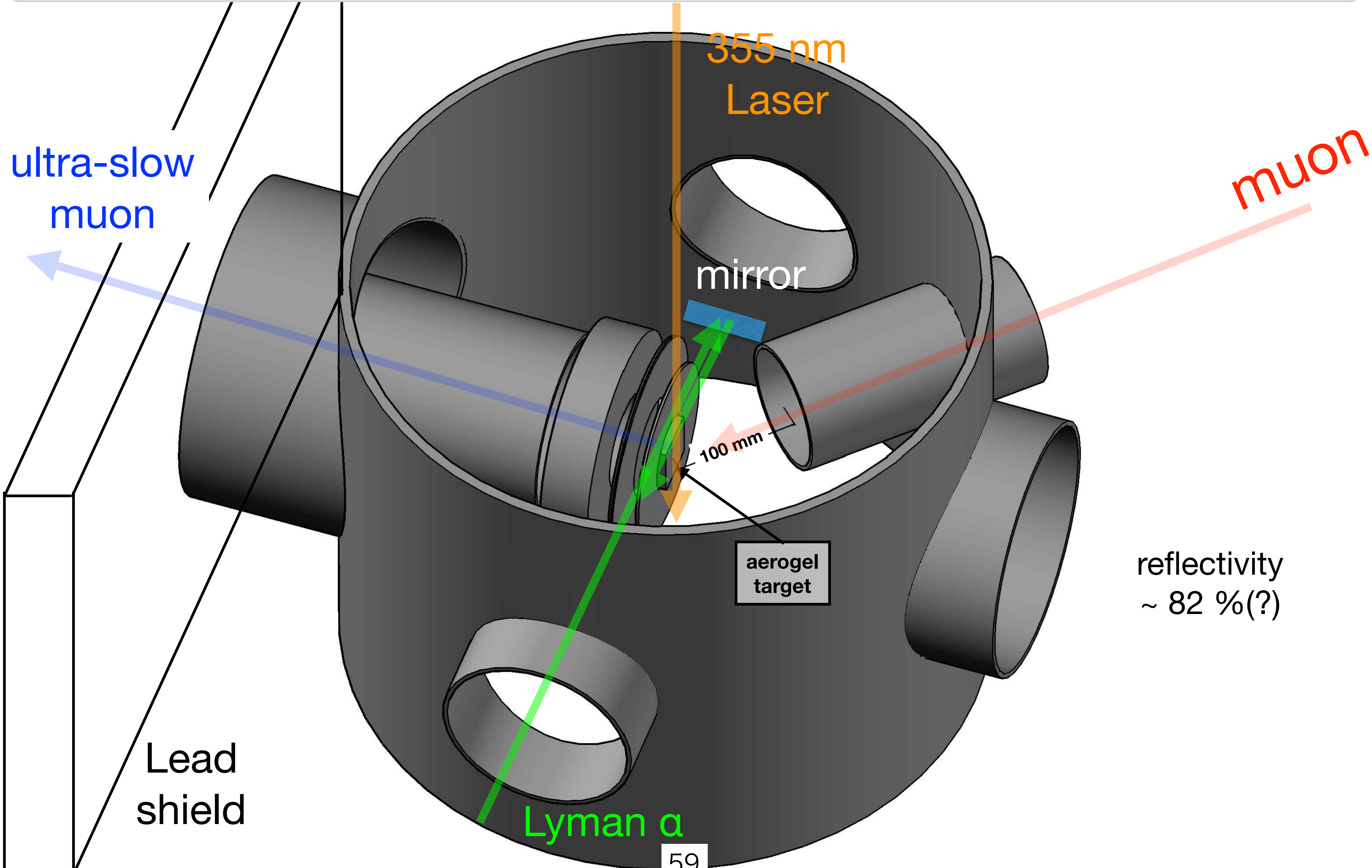
cf., ultra-slow muon : 900 / sec ~ 35 / pulse

- RAL surface muon : ~5 x 10^4 μ^+ / pulse
  - ➡ ~ 3 counts / pulse (incident mu+)
  - ➡ ~ 0.5 counts / pulse (incident e+)

(B) Lyα reflection mirrors

(w/ circularly polarized laser?)

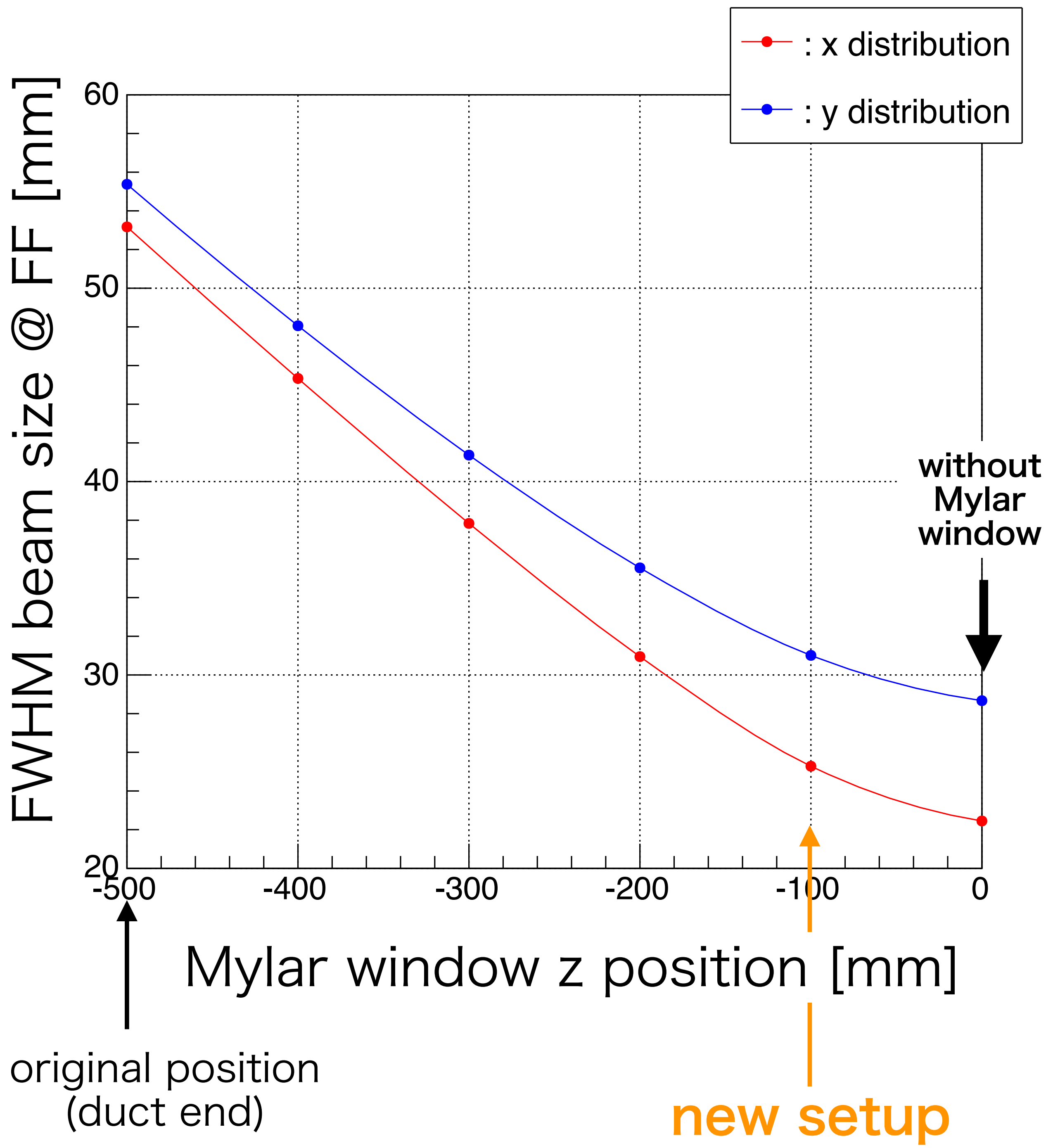
Setup overview

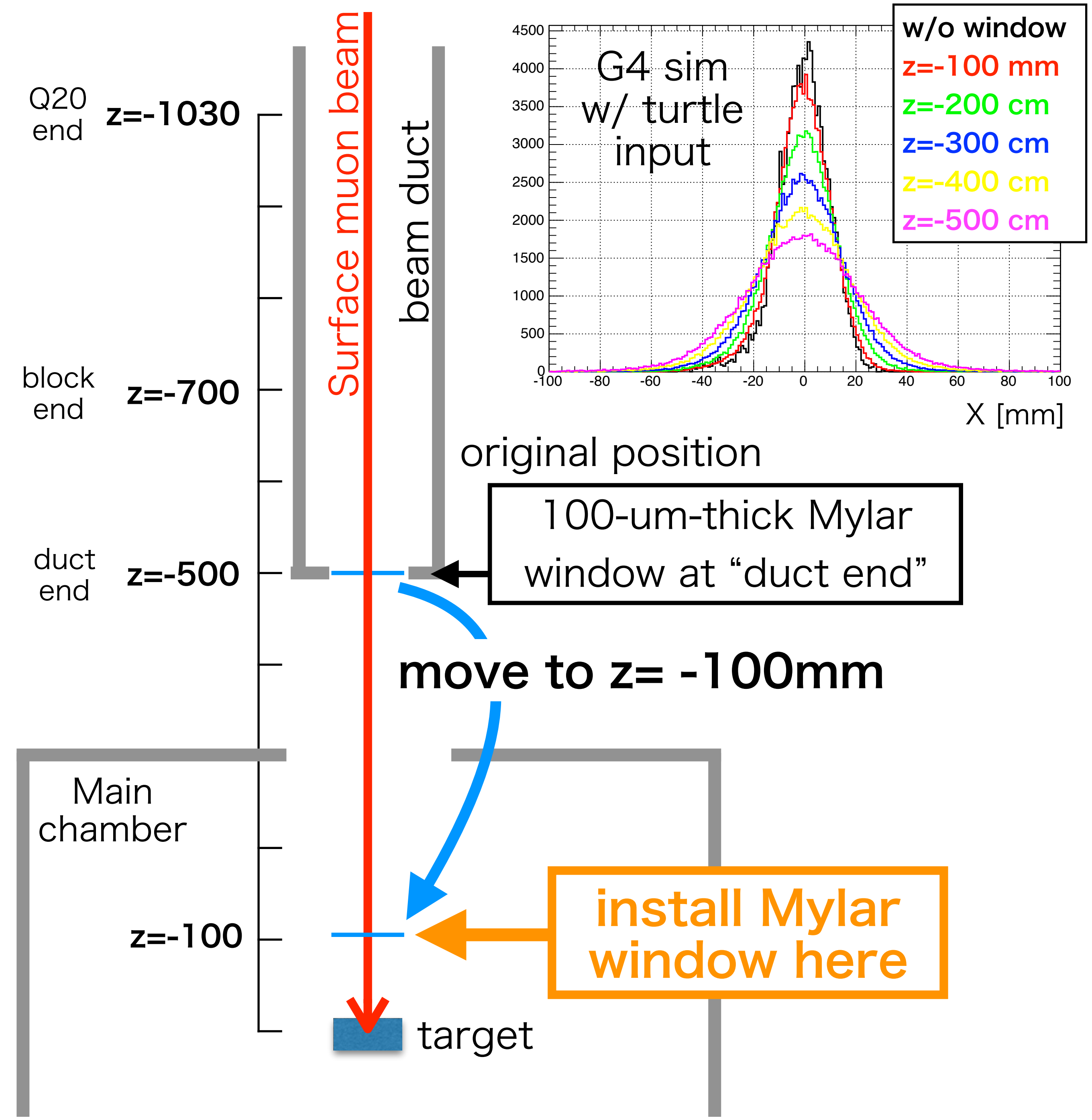


(C) Minimization of incident surface muon size

Surface muon beam size at final focus

FWHM beam size by changing the Mylar window position from -100 to -500 mm



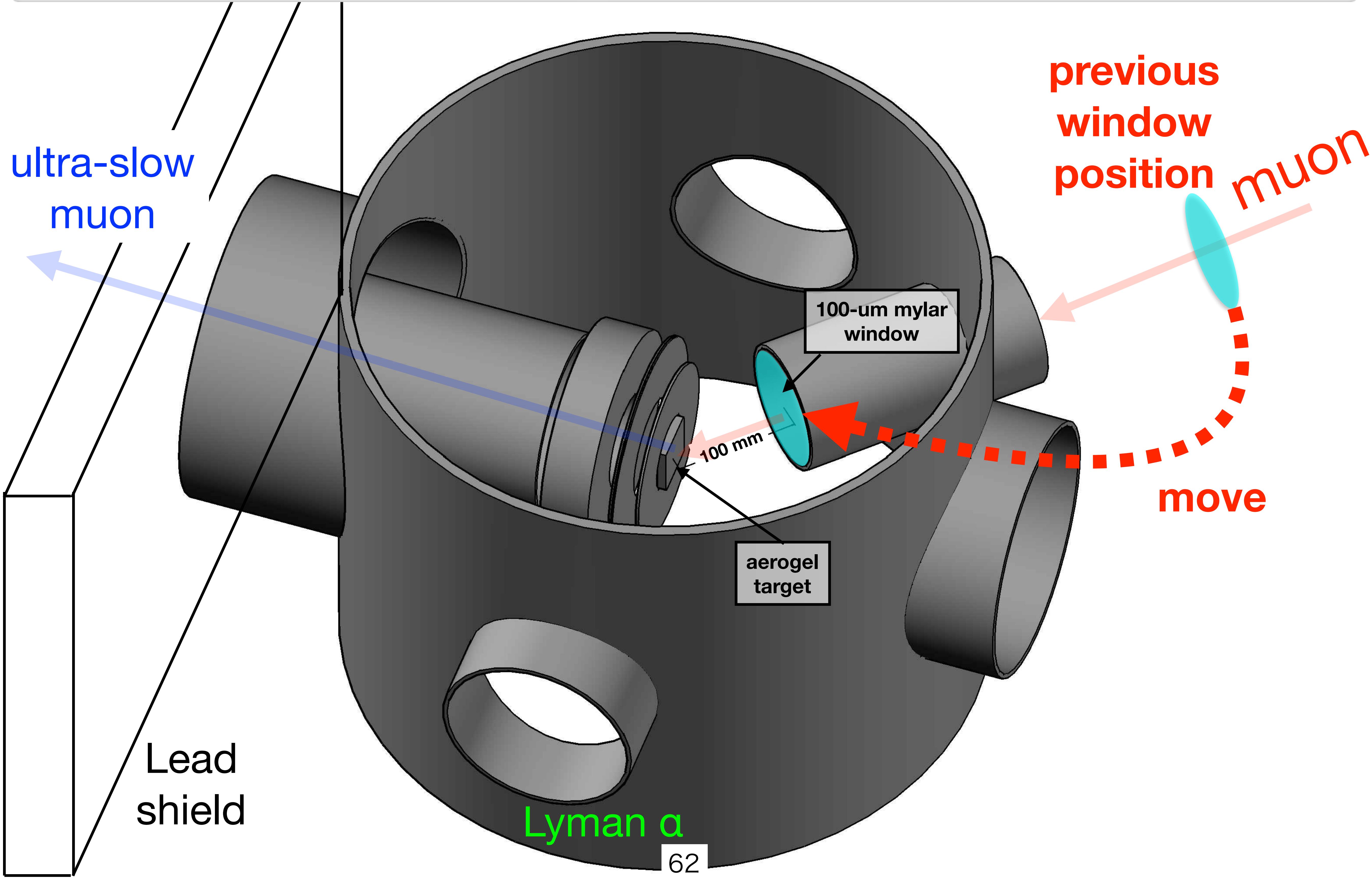


Mylar position : -500 mm -> -100 mm

Beam size x(FWHM) : 53 mm -> **25 mm**

Beam size y(FWHM) : 55 mm -> **31 mm**

Setup overview



(D) Magnetic coils

An idea of spin control at target

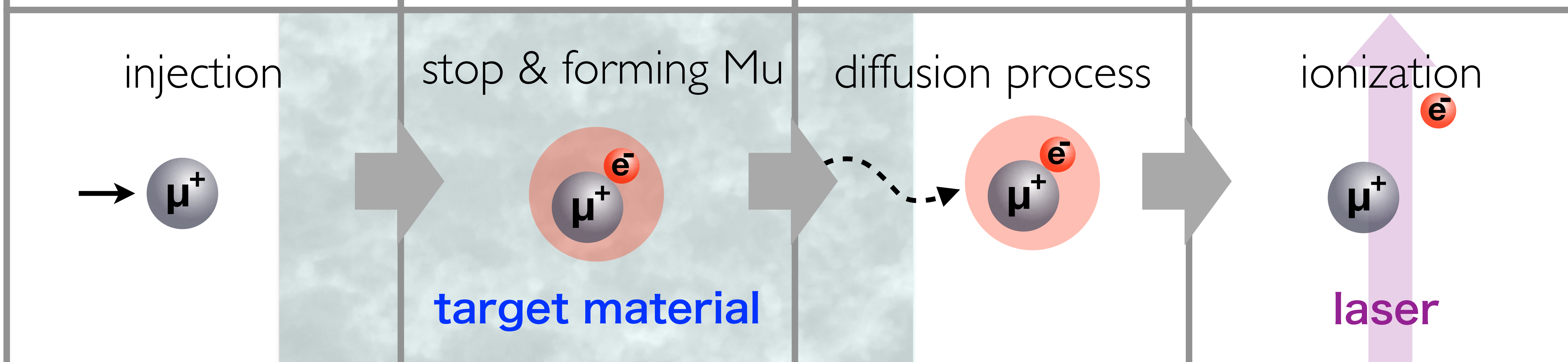
Gyromagnetic ratio

muon
~ 14 kHz / Gauss

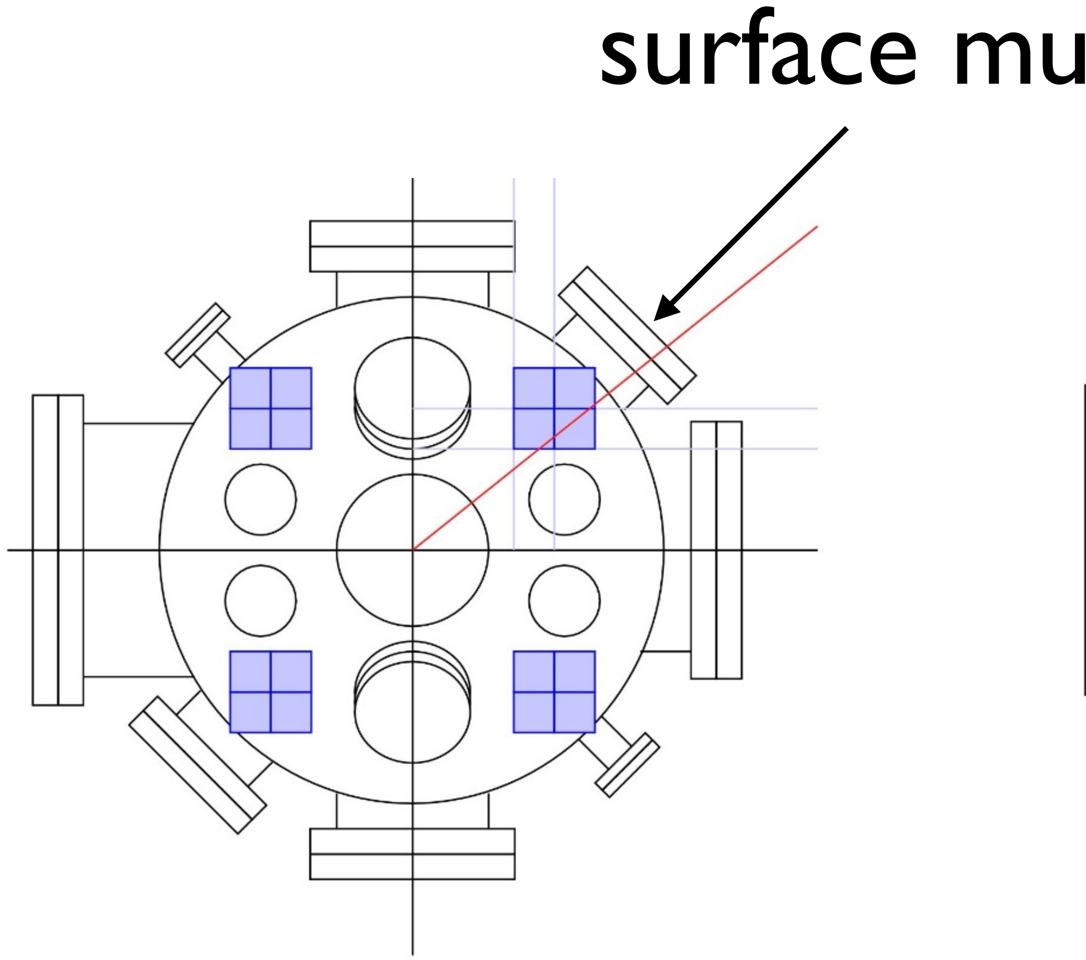
x 100 →
reduced mass : x 200
spin : 1/2 -> 1

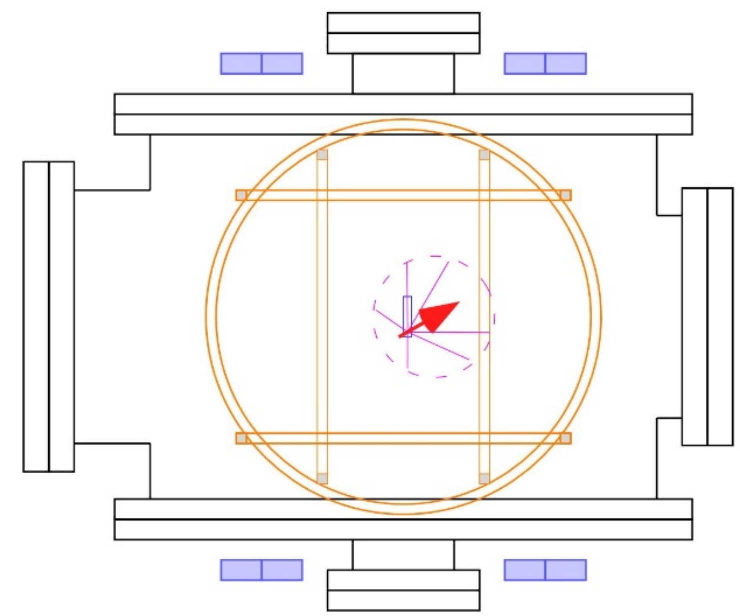
Mu
~ 1.4 MHz / Gauss

14 kHz / Gauss	1.4 MHz / Gauss		14 kHz / Gauss
slow μSR	fast spin rotation		slow μSR
(surface)	Mu	Mu (in vacuum)	(Ultra-slow)



Magnetic field coils (& MuSR counters)





~0.2 Gauss

Aim:

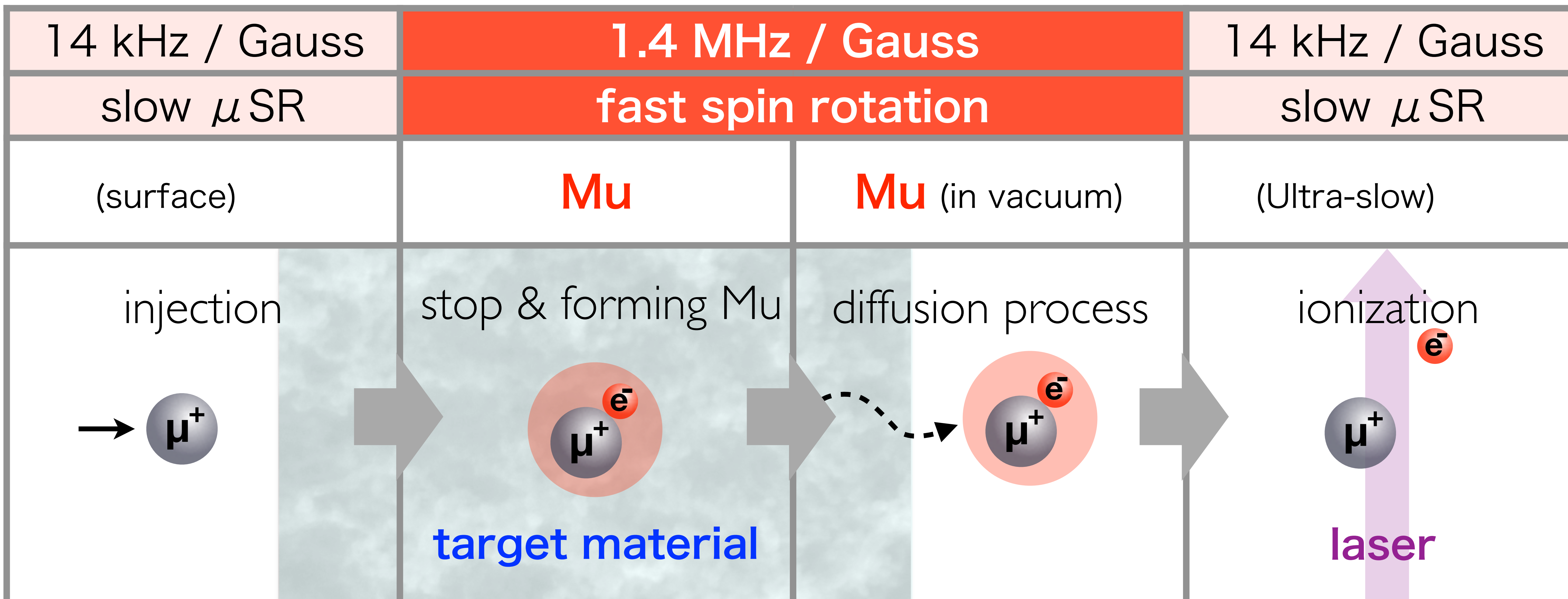
- Stabilize spin against earth & leakage magnetic field
- Measure the field at the sample directly
  (Calibrate field sensor relative to center field)
- Optimize muon stopping condition by MuSR

Muonim spin control at target

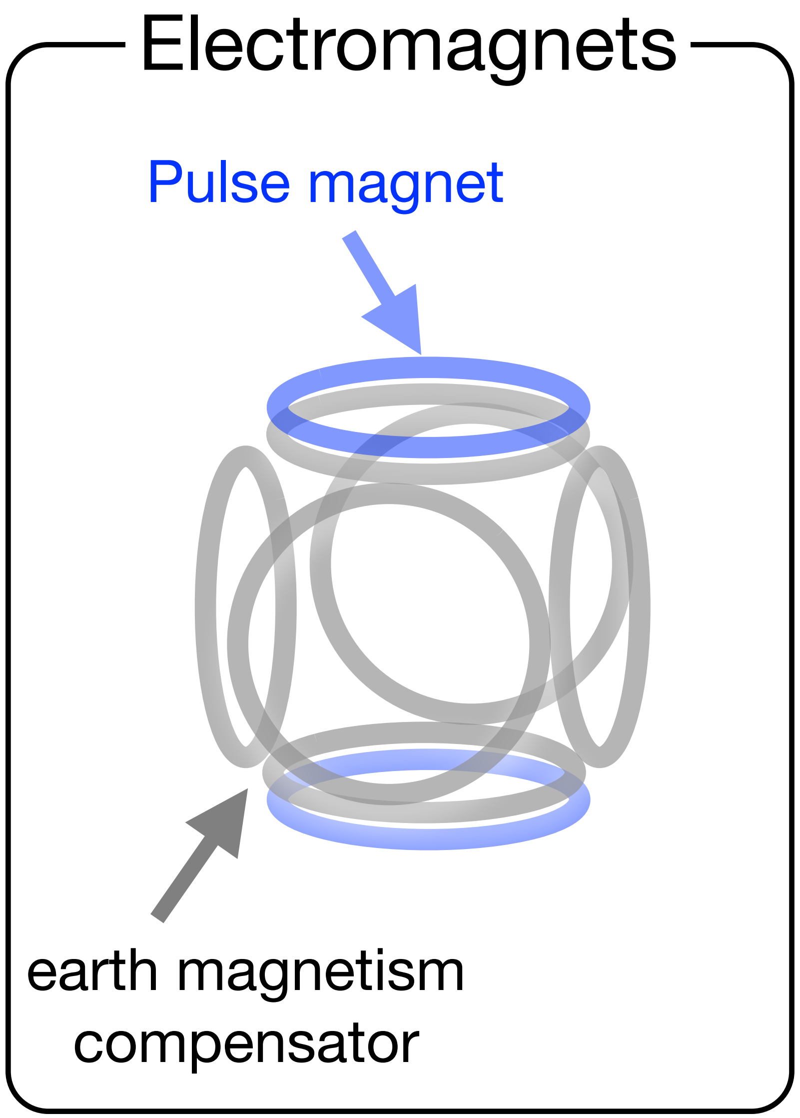
An idea of spin control at target

Gyromagnetic ratio

muon	x 100	Mu
~ 14 kHz / Gauss	reduced mass : x 200 spin : 1/2 -> 1	~ 1.4 MHz / Gauss



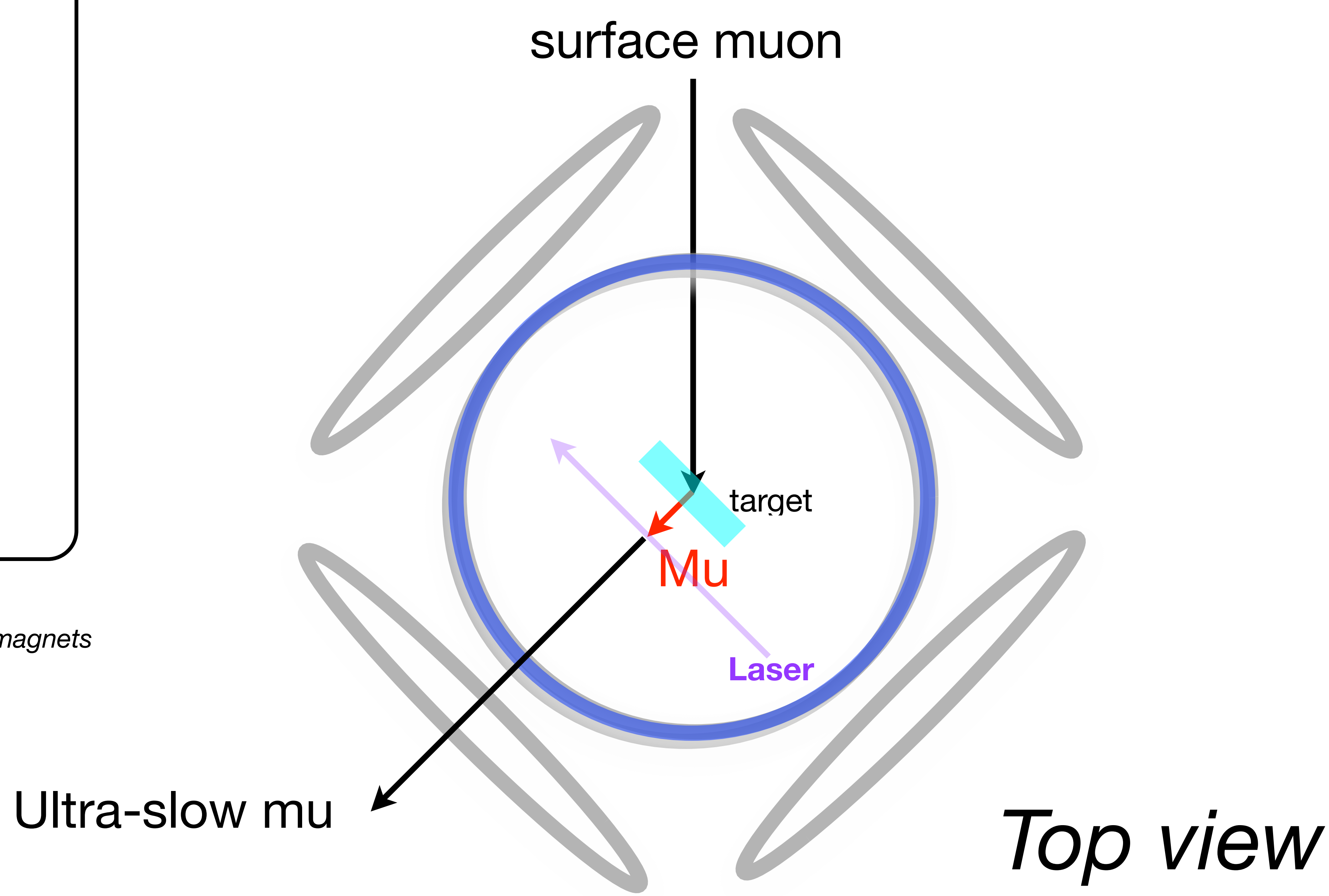
Mu spin control



might be better to install those electromagnets inside as much as possible.

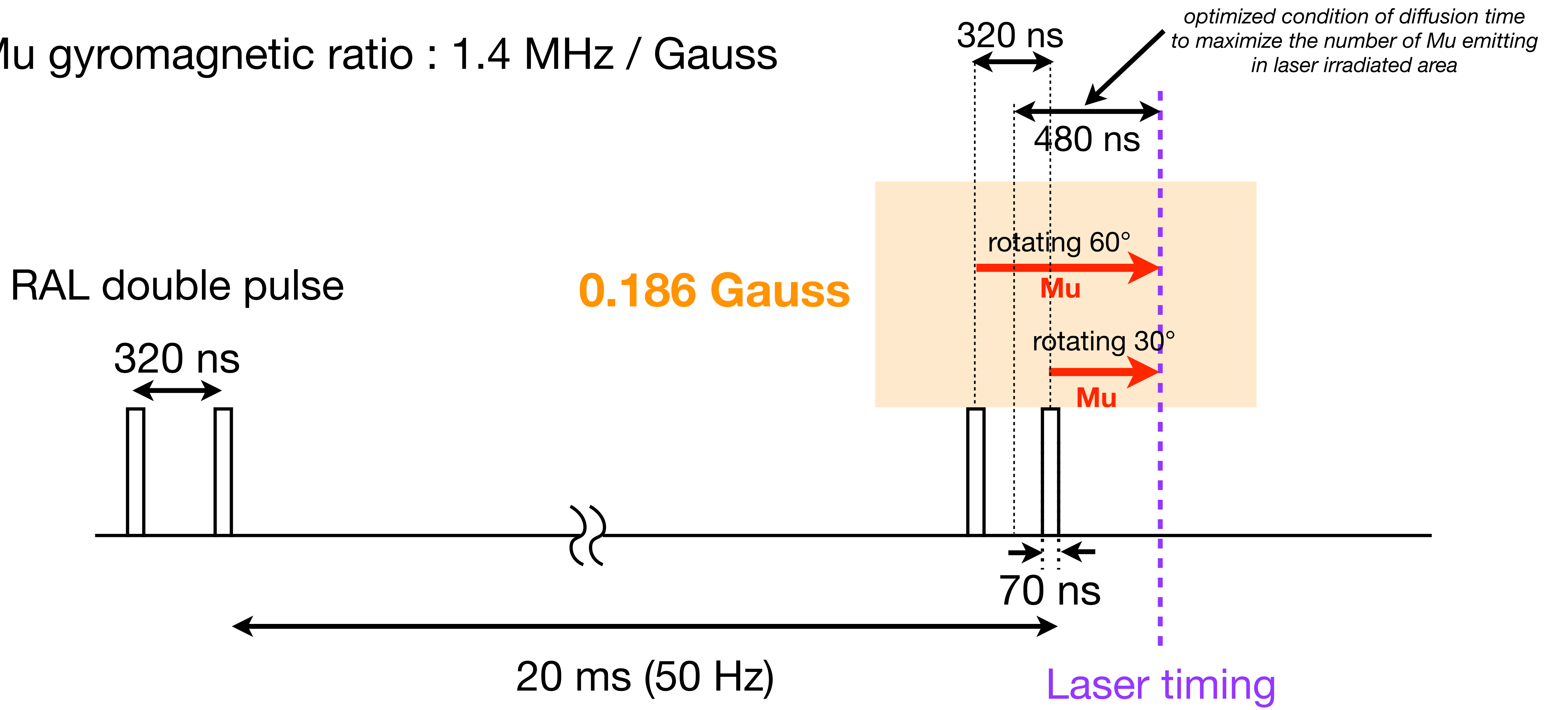
(1) Duration of being Mu => Laser irradiation timing

(2) Strength of a magnetic field applied



Mu spin control

Mu gyromagnetic ratio : 1.4 MHz / Gauss



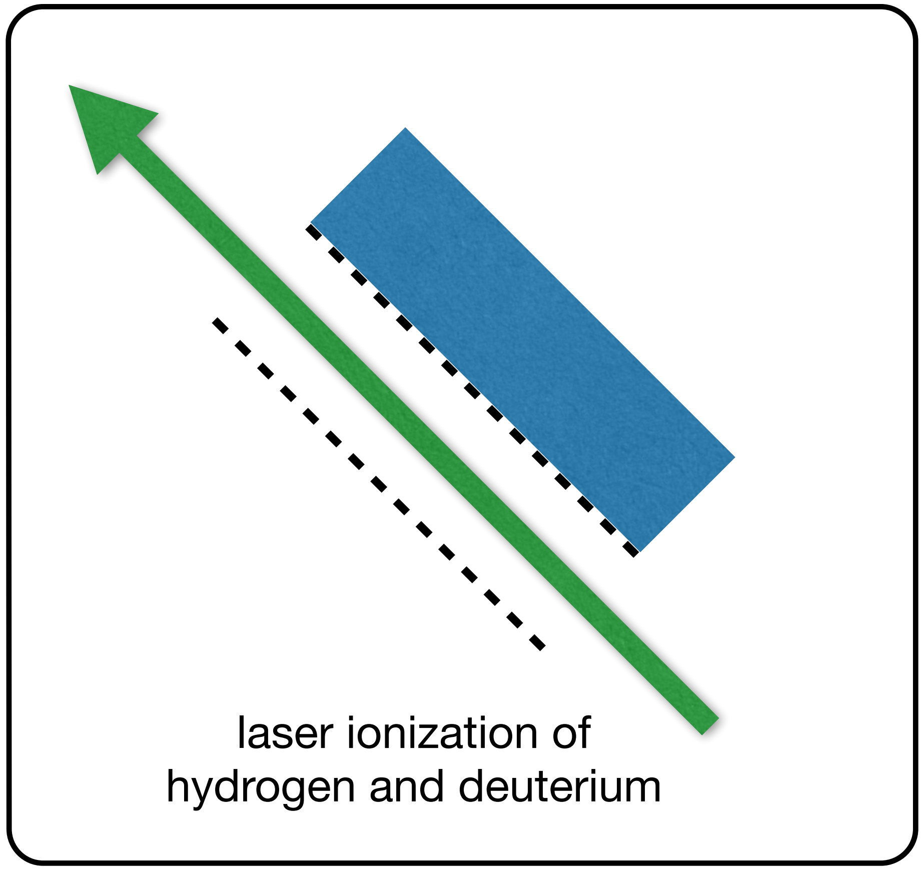
Polarization -> [cos(15)+cos(-15)]/2 = cos(15) ~ 0.97

(for transversal polarization, just changing the sign of the magnet)

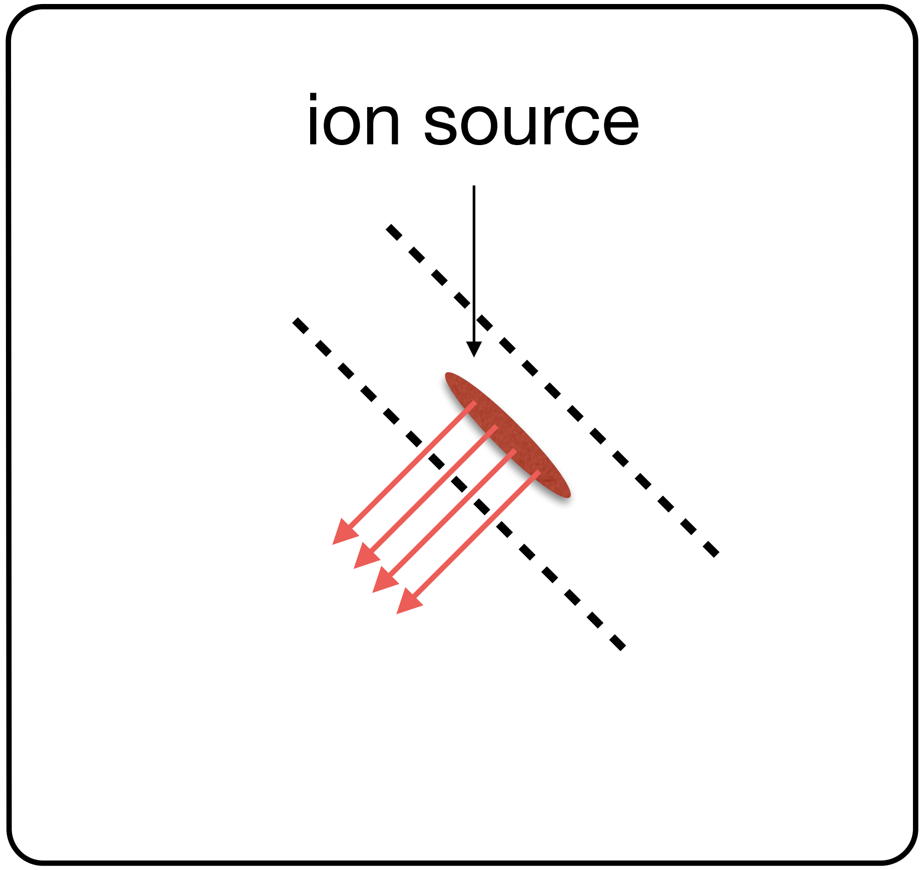
Ion source for beam tune

beam tune without muon beam

with laser



without laser



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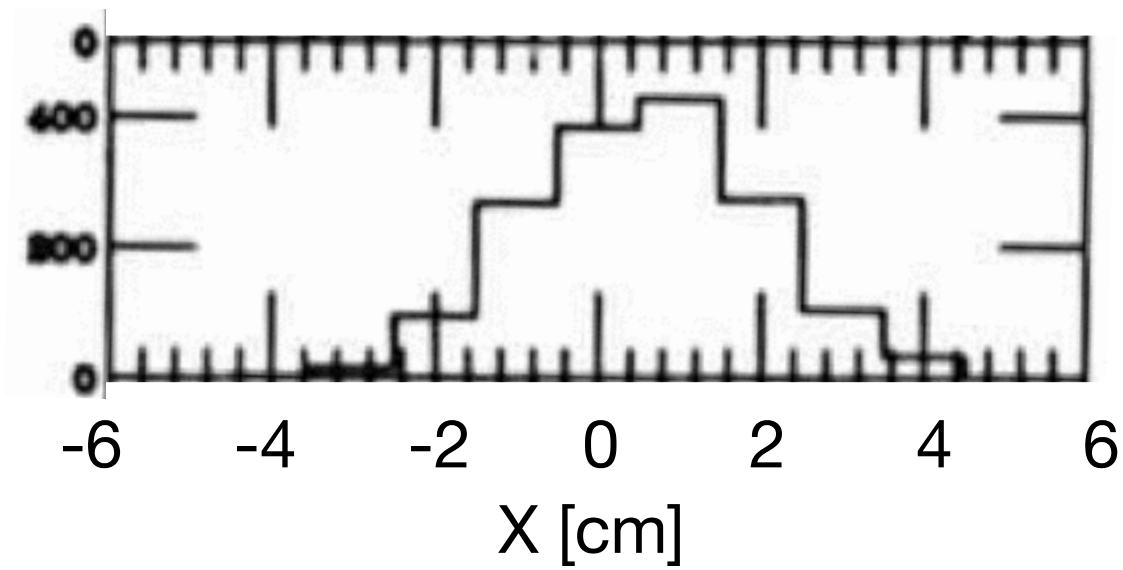
The first laser is operating at 212.5 nm and is tuned to a two-photon resonance in Kr, while the second laser operating in the range of 810 - 850 nm provides the tuneability of the Lyman-a output and is designed to have sufficient bandwidth to cover the Doppler width of muonium. The wide tuneability of the output allows us to ionize under the same conditions **not only muonium, but also hydrogen or deuterium**. This provides a useful tool for testing the whole apparatus without need for the muon beam.

Since we cannot use Li^+ or D^+ dissociated by the hot tungsten target, we **need ion sources**.
(just a filament for bulb?)

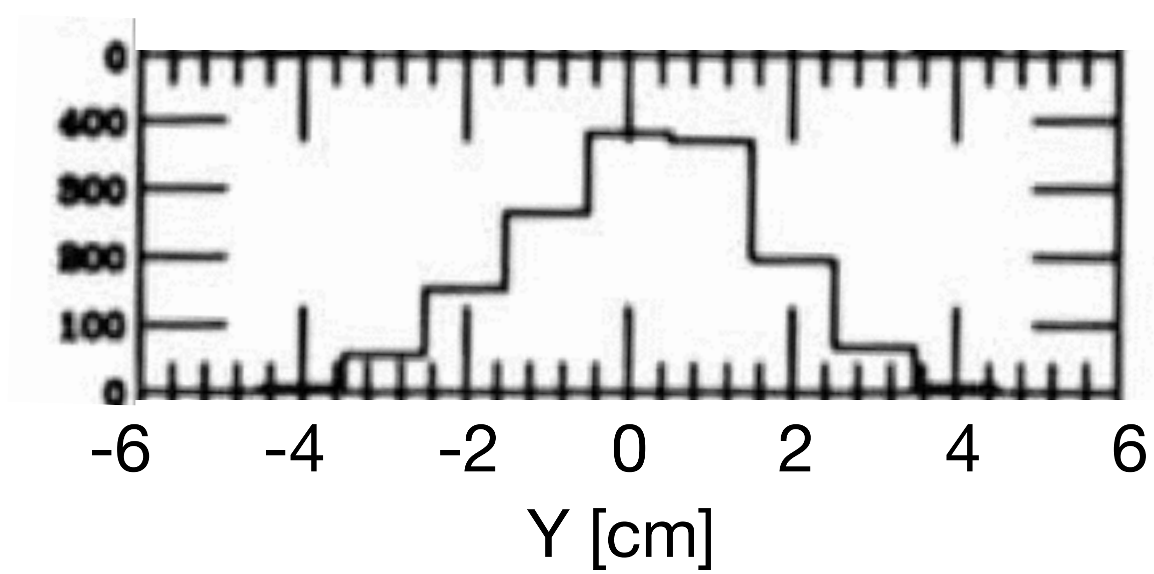
Capillary

Measured surface muon profile of RAL port-3 beamline

on 7-8 April, 2011

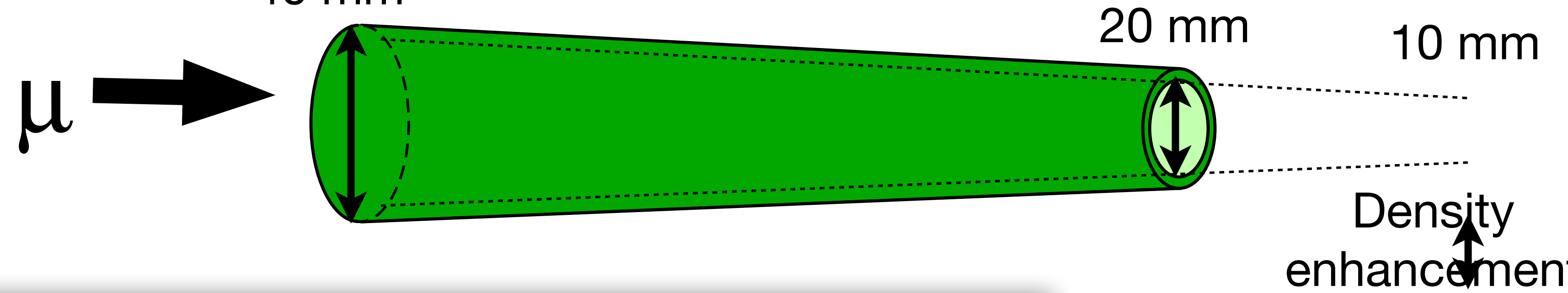


σ = 1.5 cm



σ = 1.5 cm

Focusing with tapered capillary method



Beam density enhancement ~ 1.7

Material	Outlet	Initial muon beam momentum (MeV/c)				
		30	35	40	45	Average
Plates						
Polished copper	20 mm	1.268(6)(63)	1.404(5)(70)	1.142(3)(57)	1.221(3)(61)	1.24(3)
Rough copper	20 mm	1.231(6)(62)	1.360(5)(68)	1.154(3)(58)	1.187(4)(59)	1.22(3)
	10 mm	1.520(9)(152)		1.446(6)(145)		1.48(11)
Gold-coated copper	20 mm	1.364(6)(68)	1.481(6)(74)	1.209(3)(60)	1.282(4)(64)	1.32(3)
Glass	20 mm	1.137(5)(57)	1.223(4)(52)	1.046(3)(52)	1.110(4)(56)	1.13(3)
Initial beam intensity (muons/s)	20 mm	1.6×10^3	2.8×10^3	5.2×10^3	5.8×10^3	
Tubes						
Conical glass	20 mmϕ	1.477(6)(103)		1.415(4)(99)		1.44(7)
	10 mmϕ	1.508(10)(211)		1.586(6)(222)		1.55(15)
Trapezoid glass	10 mm square	1.542(9)(216)		1.336(5)(187)		1.42(14)
Trapezoid copper	10 mm square	1.825(10)(256)		1.652(5)(231)		1.73(17)
Initial beam intensity (muons/s)	10 mm square	6.0×10^2		1.4×10^3		

D. Tomono et al, JPSJ 80 (2011) 044501