NuFact2017, Uppsala
25-30 Sep, 2017

Muon g-2/EDM @J-PARC

K. Ishida (RIKEN)
for muon g-2/EDM at J-PARC group

Outline

muon g-2/EDM

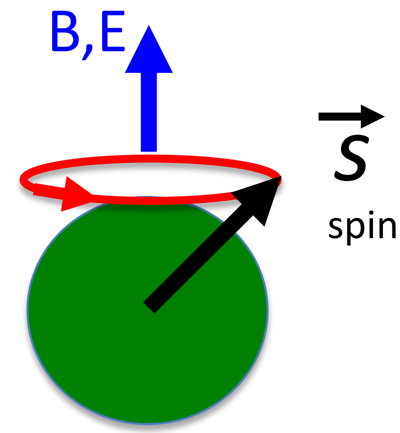
Overview of the experiment
  g-2/EDM based on storage of ultra-cold muon beam

Status of each major components

Our goals

Summary

muon g-2 and EDM



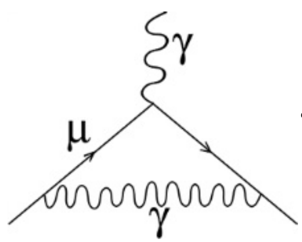
$\boldsymbol{\mu} = g_\mu \, (e/2m_\mu) \, \boldsymbol{s}$

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

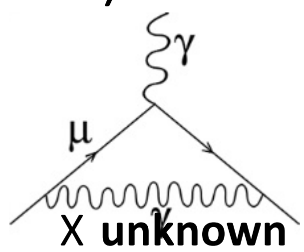
Dirac equation predicts g=2.

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.

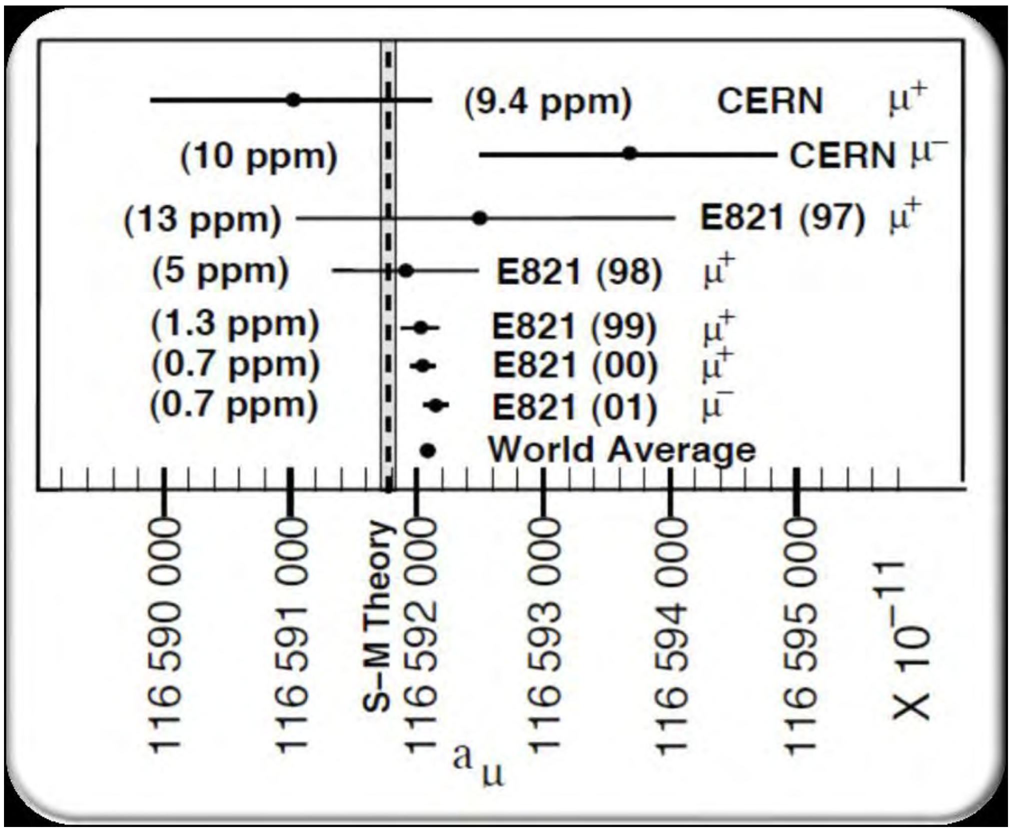
=> Indication of CP violation in the lepton sector.

muon g-2

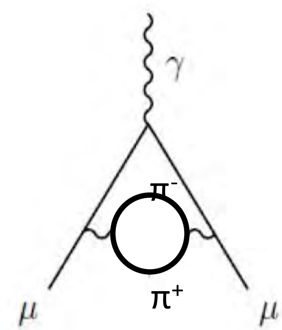
BNL E821 measured a_μ to 0.7 ppm for μ^+ and μ^- (sum 0.5 ppm)
Deviation of experiment and theory by 3~3.5 σ was observed.

$\Delta a_\mu = a_\mu(\text{Exp}) - a_\mu(\text{SM}) = (272\pm80) \times 10^{-11}$

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 large enough to explain the discrepancy.

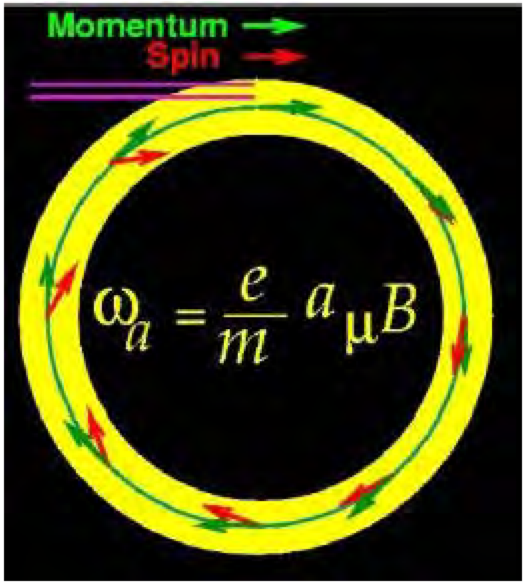


+...

muon g-2: method

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

make this zero



Measure ω_a under well controlled B.

Measurements BNL E821 and FNAL E989 use magic momentum (p=3.09 GeV/c)

14m

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 - different systematic errors.

g-2 measurement EDM

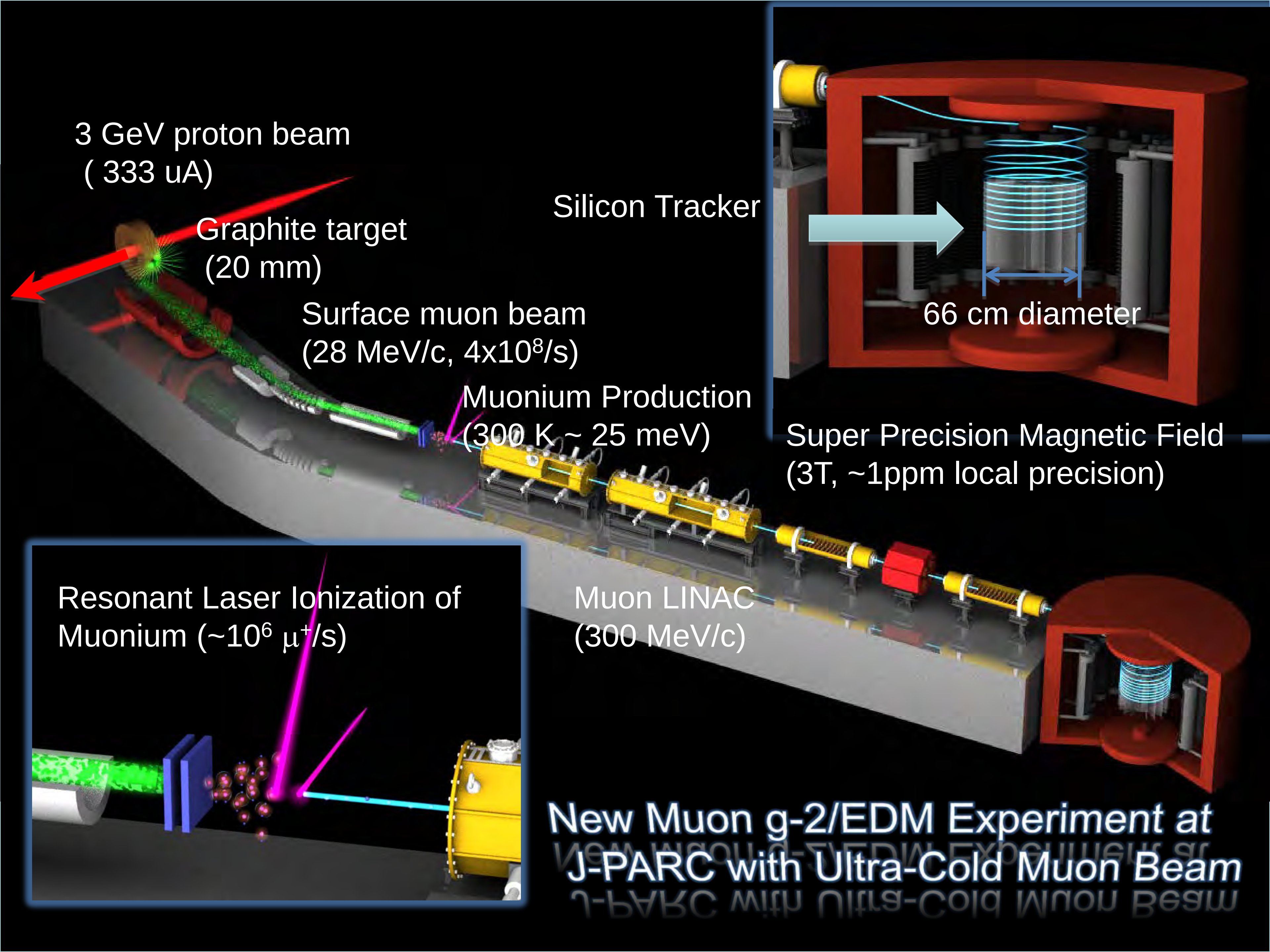
$$\omega = -\frac{e}{m}\left[a_\mu B - \left(a_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\beta \times E}{c} + \frac{\eta}{2}\left(\beta \times B + \frac{E}{c} \right) \right]$$

Out-of plane oscillation is an indication of EDM.

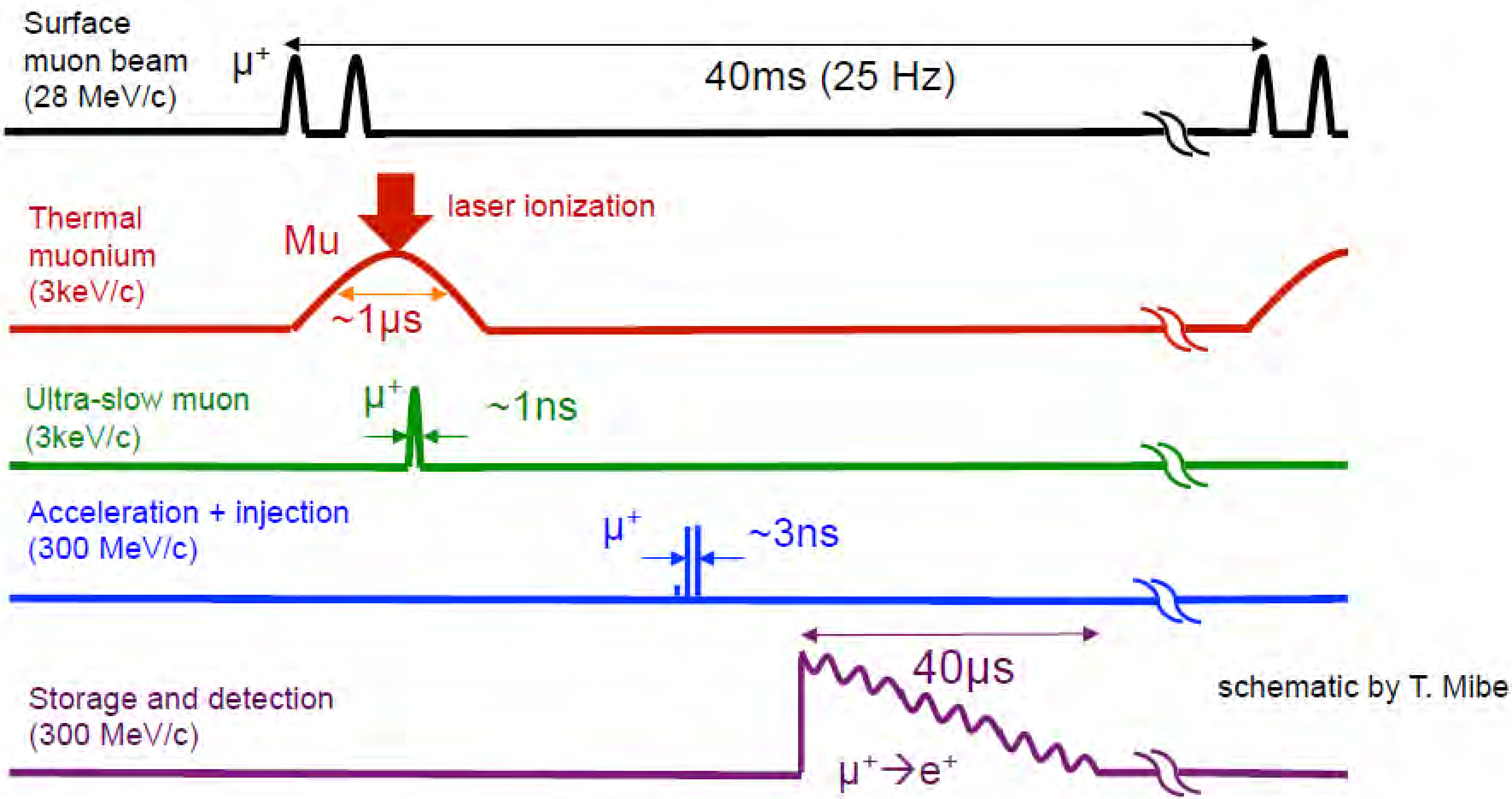
Make E=0 by making focusing needs low.
- no high "magic" momentum requirement.
Need of well controlled muon beam
- start with ultra cold muon beam.

Muon g-2/EDM@J-PARC

High intensity Japan Proton Accelerator Research Complex
1 MW at 3 GeV (0.2~0.5 MW at present), 0.75 MW at 30 GeV


3 GeV proton beam
(333 uA)
Graphite target
(20 mm)
Surface muon beam
(28 MeV/c, 4x10^8/s)
Silicon Tracker
66 cm diameter
Muonium Production
(300 K ~ 25 meV)
Super Precision Magnetic Field
(3T, ~1ppm local precision)
Resonant Laser Ionization of
Muonium (~10^6 μ+/s)
Muon LINAC
(300 MeV/c)
New Muon g-2/EDM Experiment at
J-PARC with Ultra-Cold Muon Beam

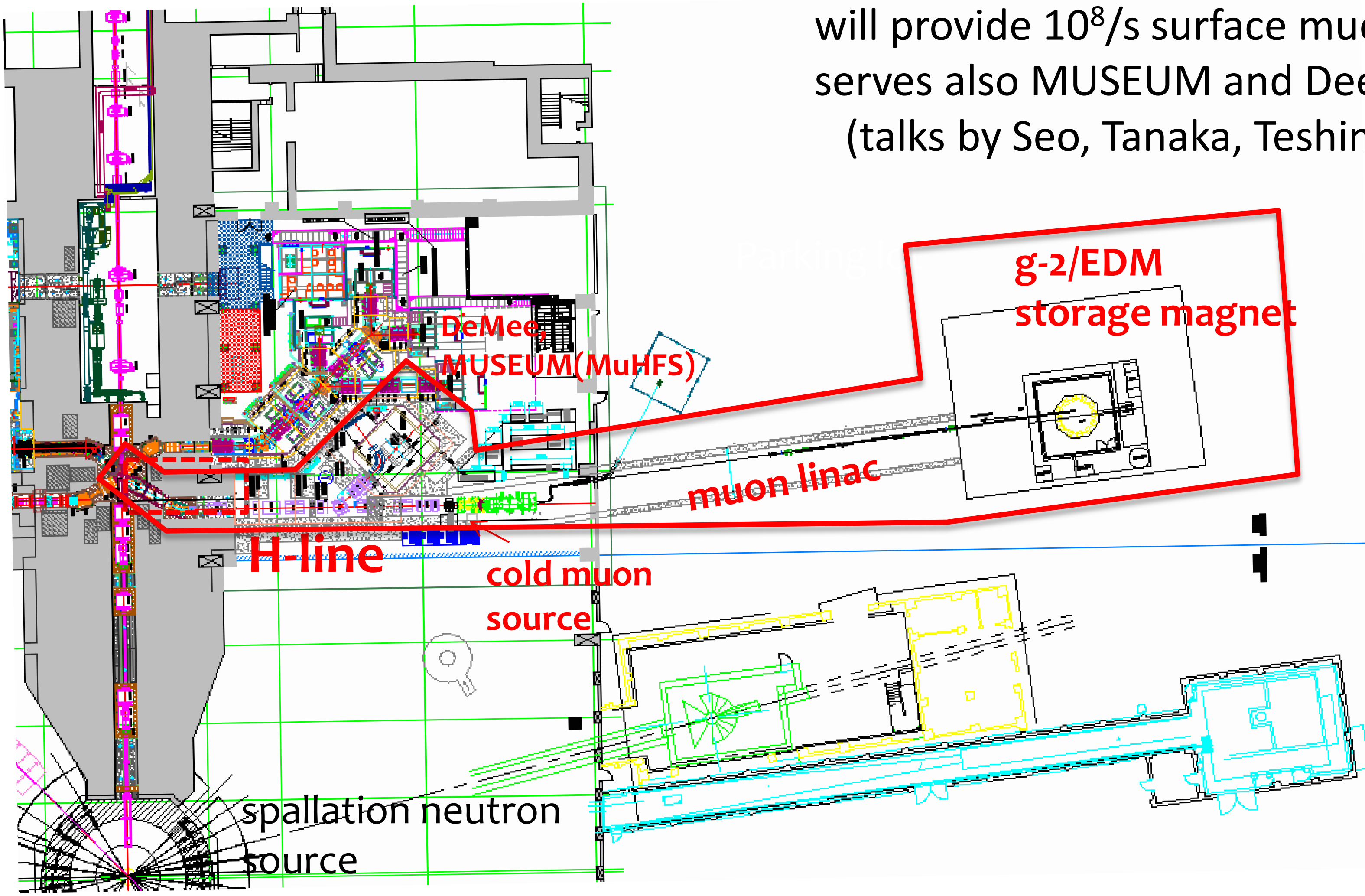
Time sequence



Surface muon beam

H-line@J-PARC MLF (Materials and Life Science Facility)

H-line is under construction.
will provide 10^8/s surface muons
serves also MUSEUM and DeeMe
(talks by Seo, Tanaka, Teshima)

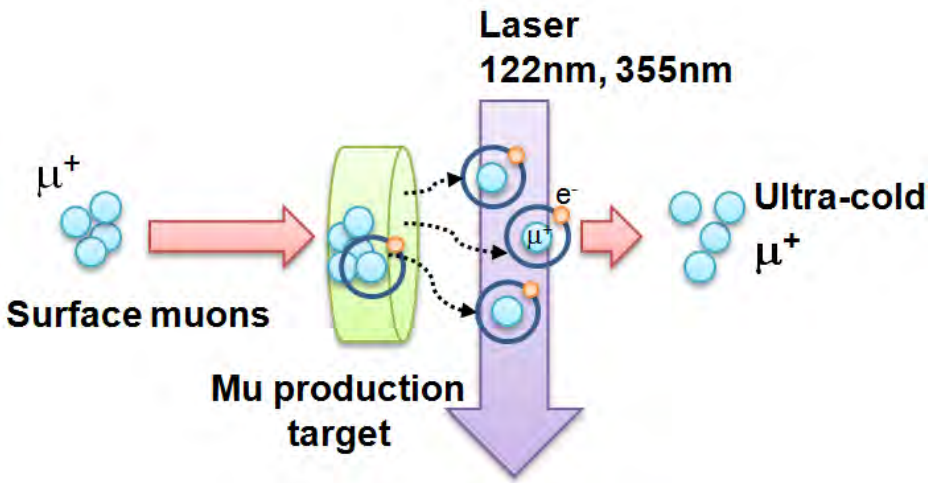


H-line construction

Shield structure completed
Installation of power station in progress

Ultra-slow muon from Thermal Muonium

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

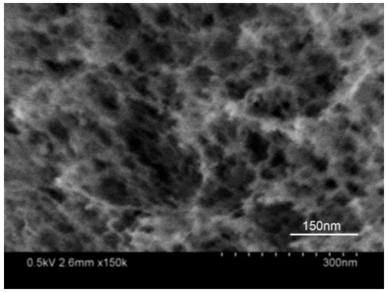


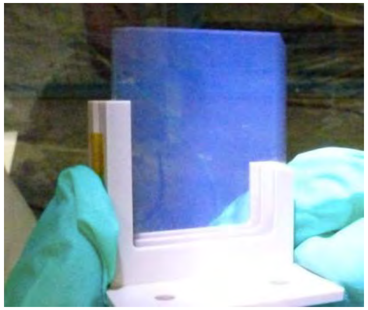
Stop muons in a material,
some diffuse out at thermal energy.
Good muonium emitter and
an intense laser to remove the electron
are essential.

(efficiency>1% required)

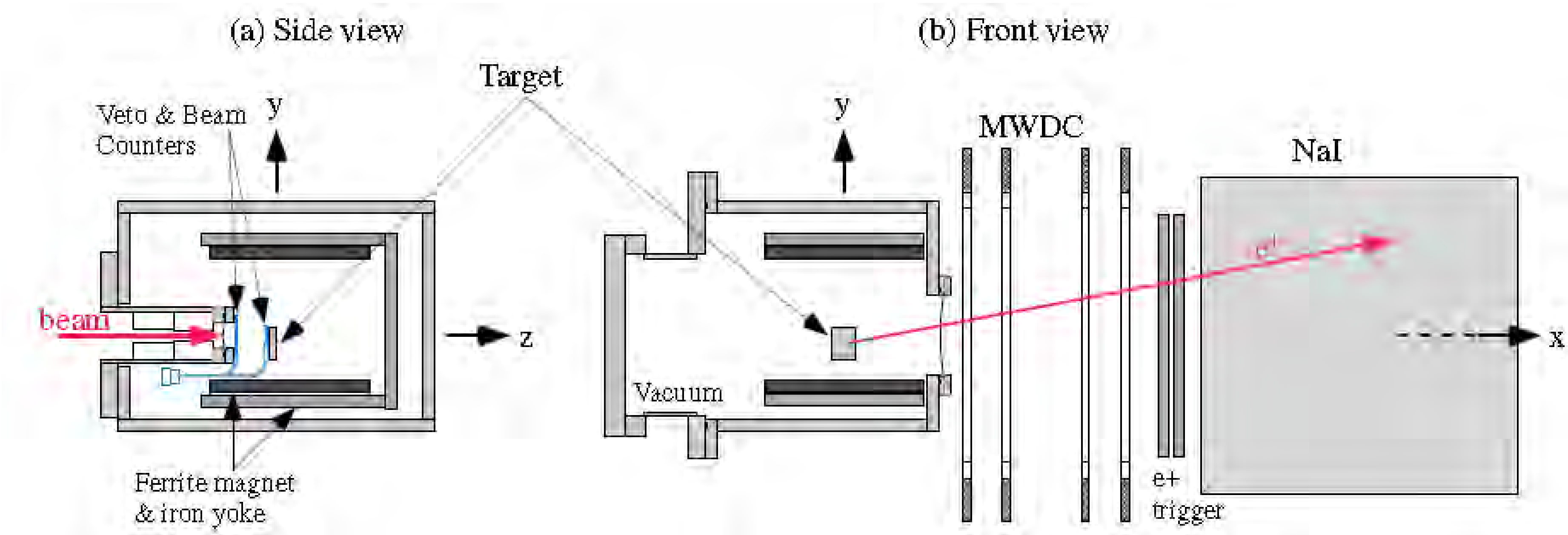
Silica powder has been known to be a good
Mu emitter (large surface area)

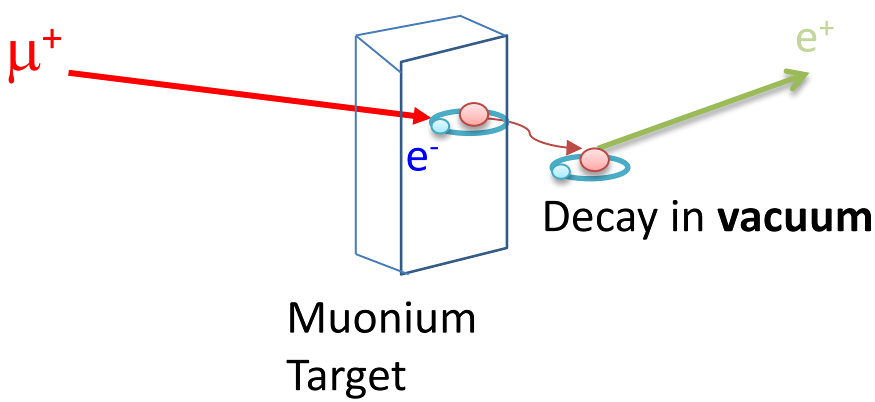
Silica aerogels with similar network structure
can be more easily handled and may fit better
our system
However, Mu yield was low
in the past





Measurement S1249@TRIUMF

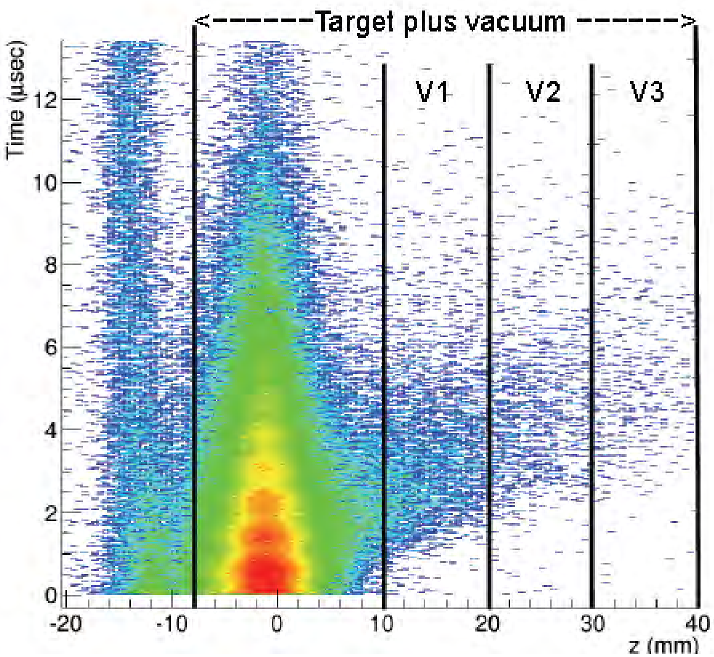


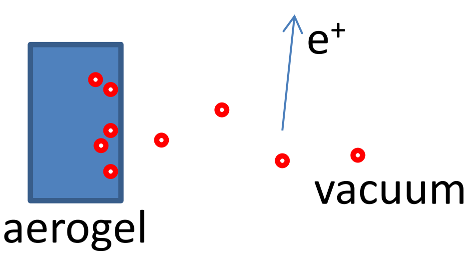


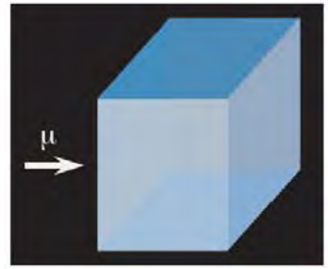
Mu velocity in vacuum ~5 mm/μs
MWDC intrinsic resolution ~0.1 mm
Track back resolution ~2mm
(from 0.1mm silica-plate data)

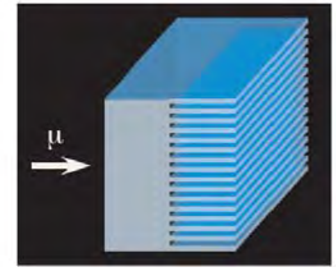
Muonium production in vacuum (S1249@TRIUMF 2013)

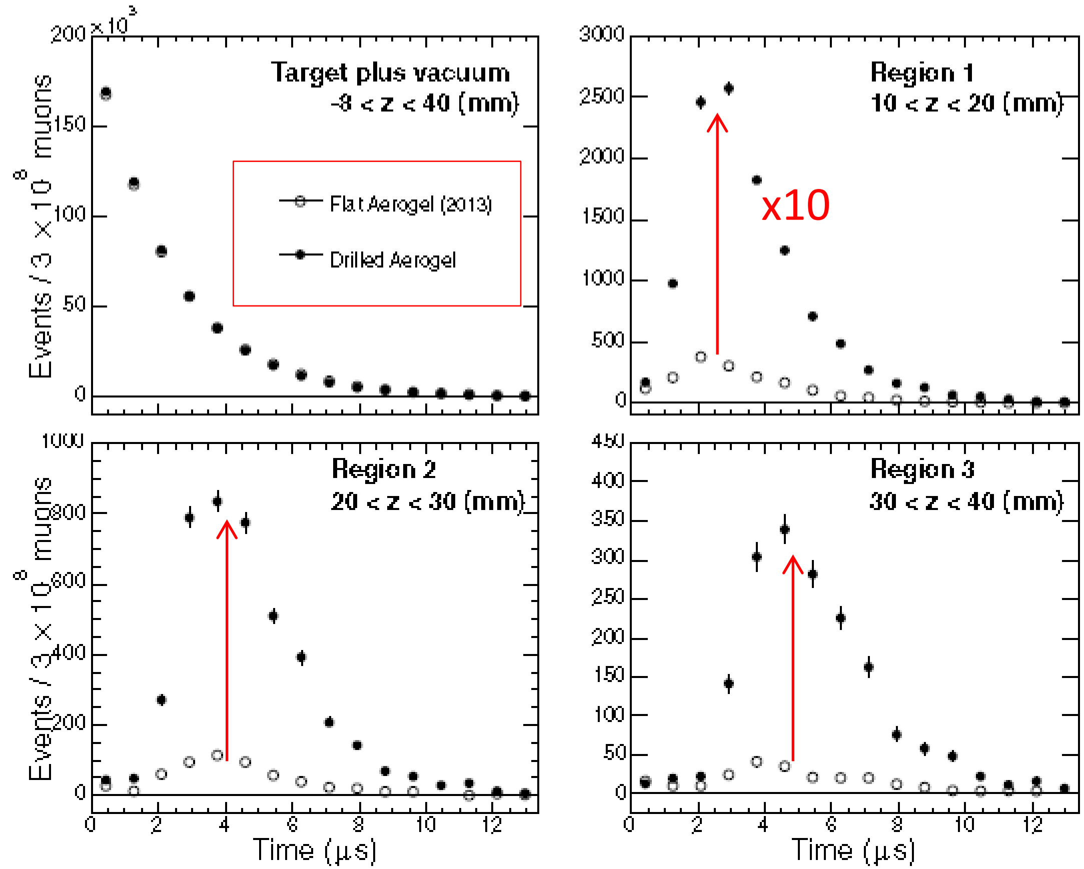
x10 enhancement of Mu emission
from laser ablated surface





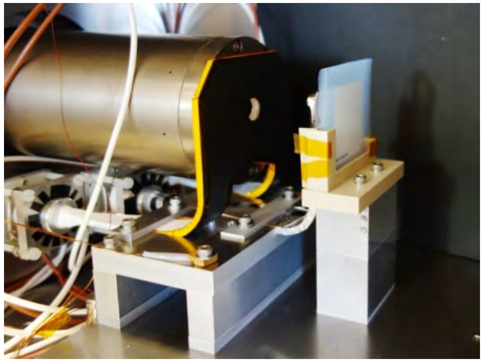


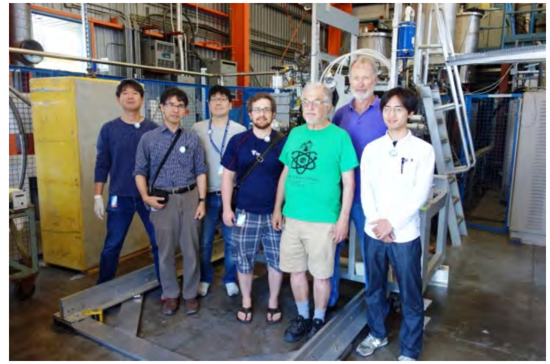


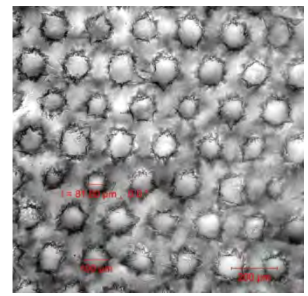


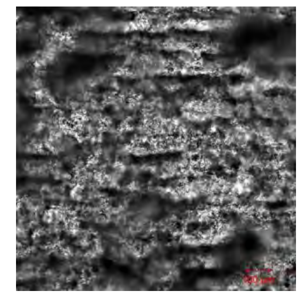
(to be published in PETP soon!)

Muonium production in vacuum (S1249@TRIUMF 2017)



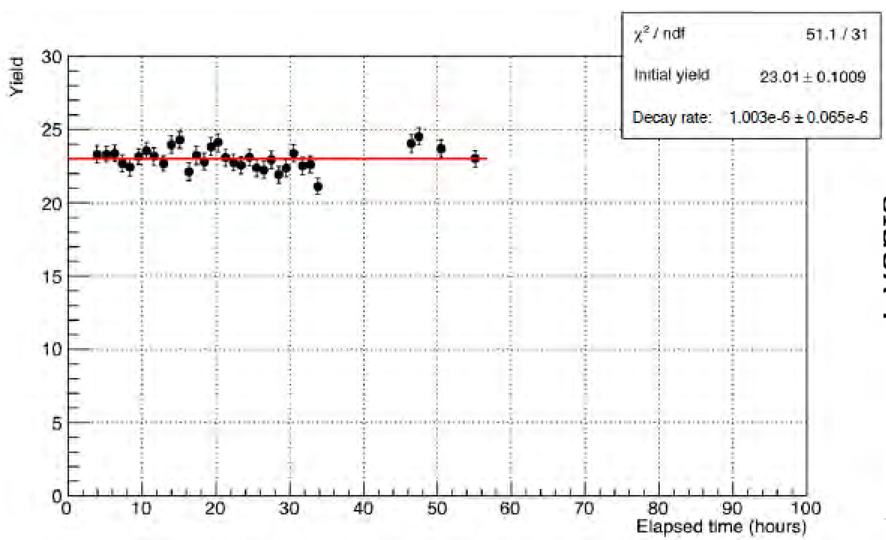




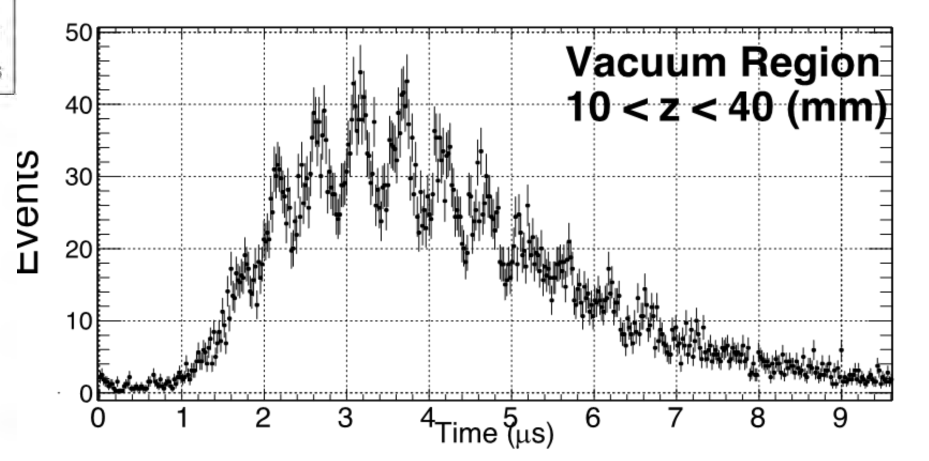


1) Systematic study of Mu yield laser-ablated silica aerogel (22 samples)
- data under detailed analysis

2) No deterioration of Mu yield up to 2.5 days

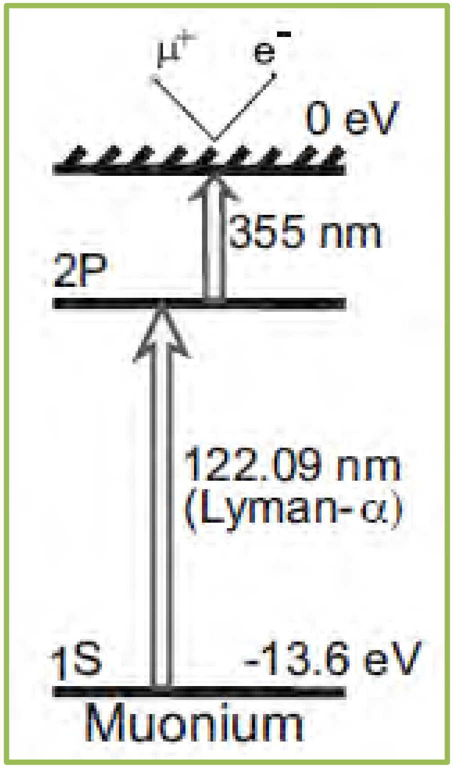


3) Confirmation of Mu polarization in vacuum

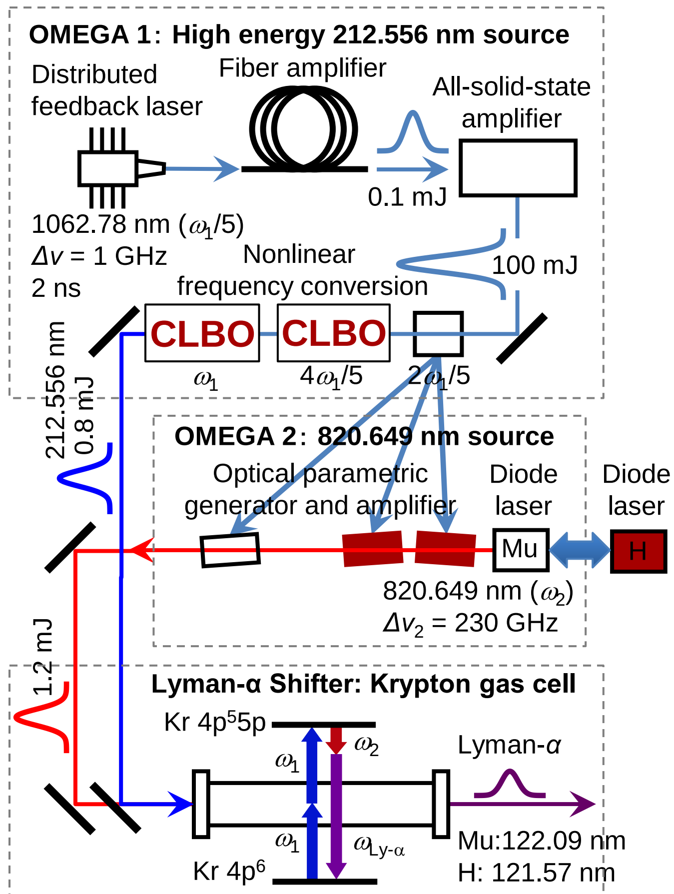


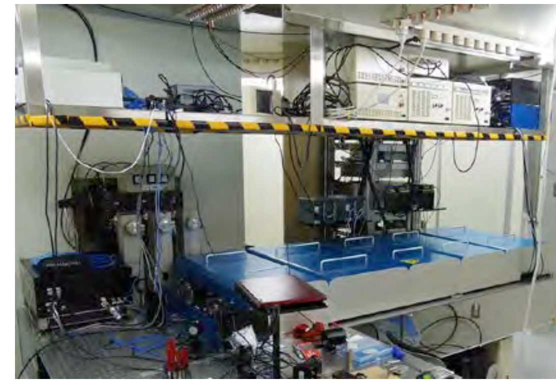
Laser ionization of Mu

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



Improved Coherent Lyman-α System Configuration



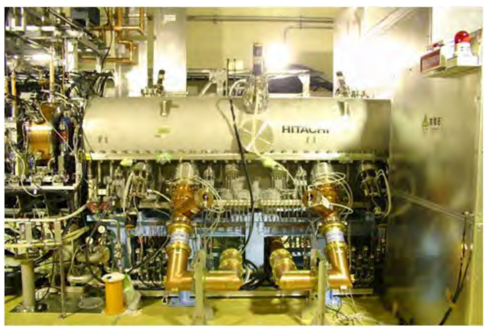


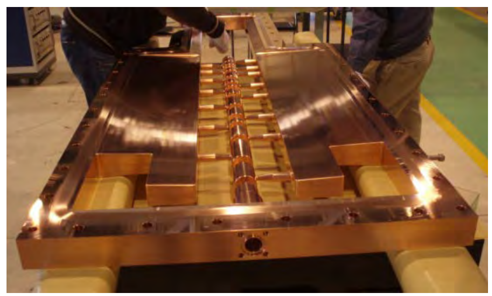
Laser was developed in collaboration with another project (USMM in U-line). Large laser crystal for main amplifier is under development in order to achieve 100 μJ goal (10 μJ without amplifier). Will give ~75% ionization efficiency in 2 cm^2 laser area.

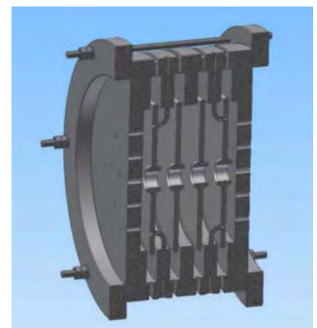
Muon acceleration

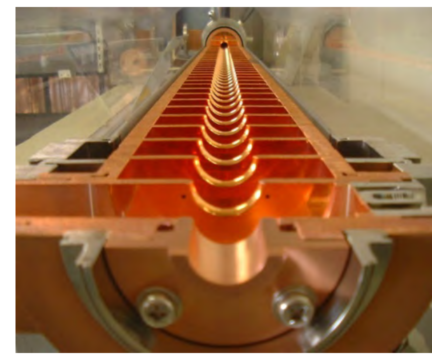
	5.6 keV, β=0.01		0.3 MeV, β=0.08		4.5 MeV, β=0.3		40 MeV, β=0.7		212 MeV, β=0.9
USμ	→	RFQ	→	IH-DTL	→	DAW CCL	→	Disk-loaded	→
		3.2 m	324 MHz	1.4 m		16 m	1296 MHz	15 m	

Total ~ 40m

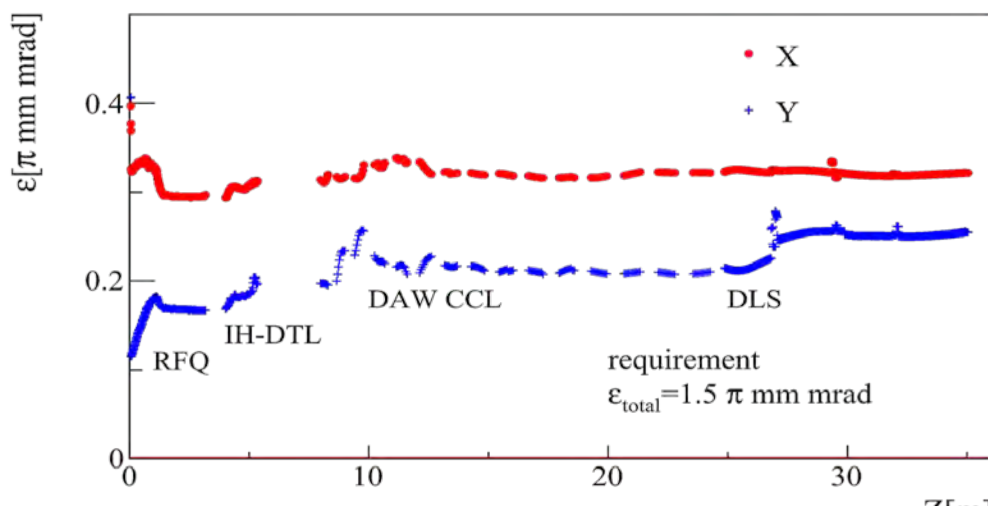






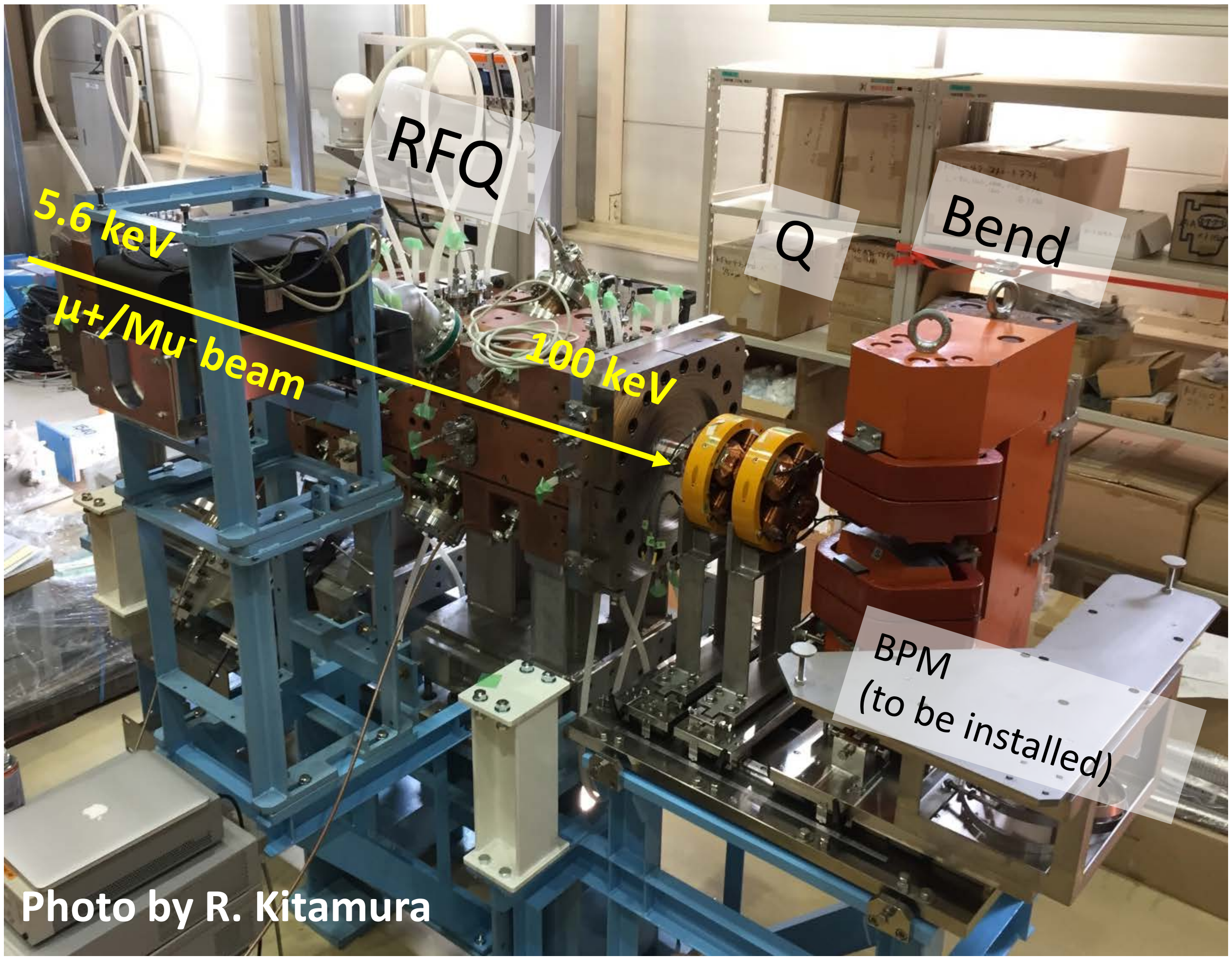


End to end simulation
- for ex. decay loss before RFQ ~30%
- transmission loss ~7%
- decay loss during acceleration ~20%
- emittance growth is small

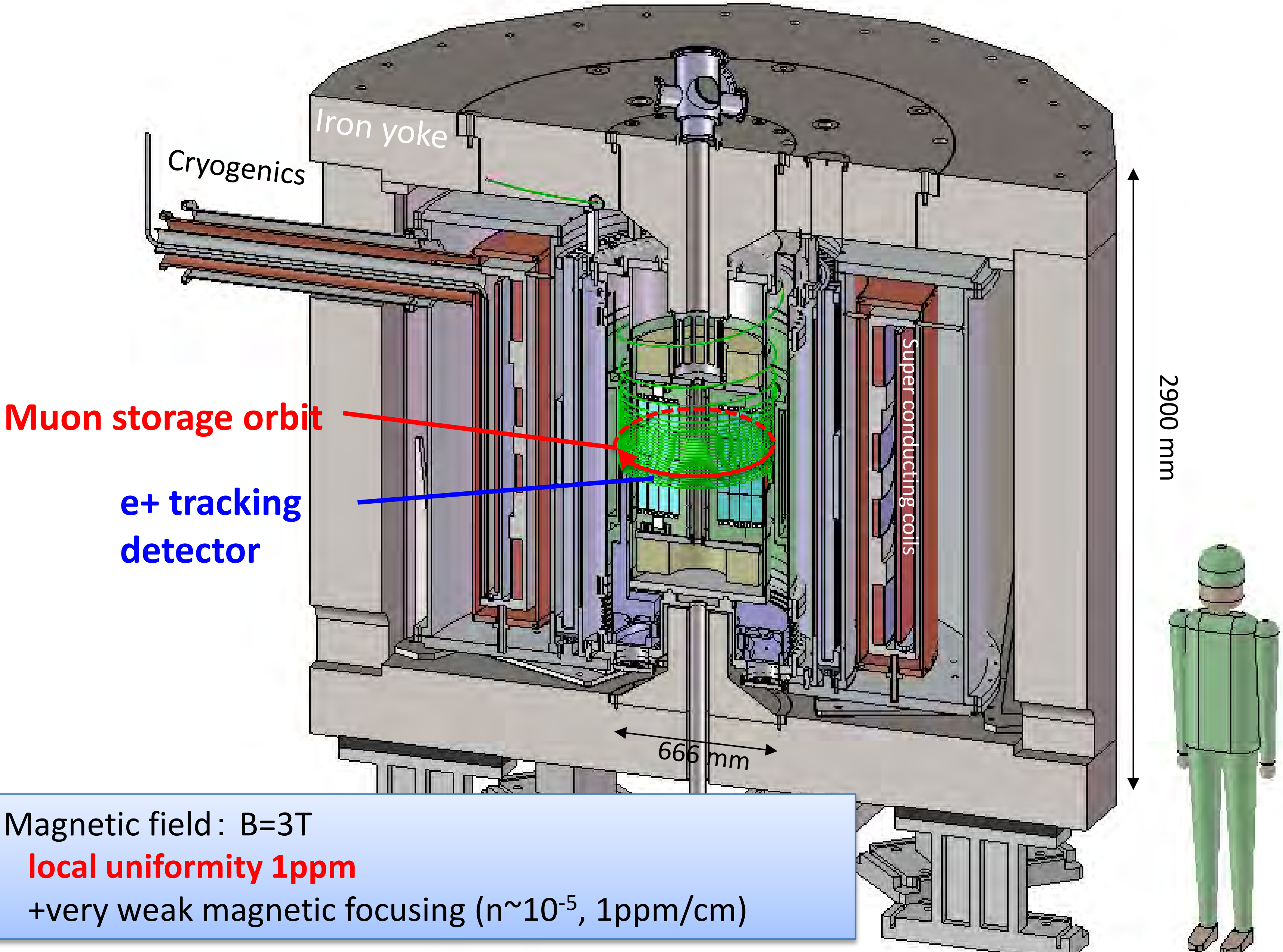


RFQ acceleration test

Muon RFQ acceleration test using slowed down muon beam
scheduled at D-line in October, 2017



Muon storage magnet and detector



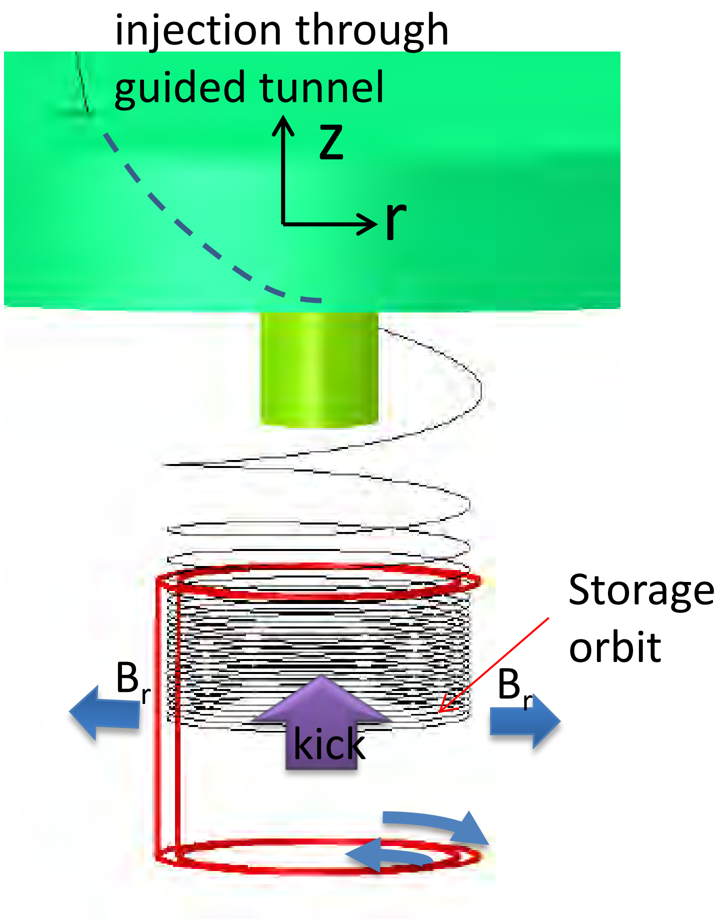
Magnetic field : B=3T

local uniformity 1ppm

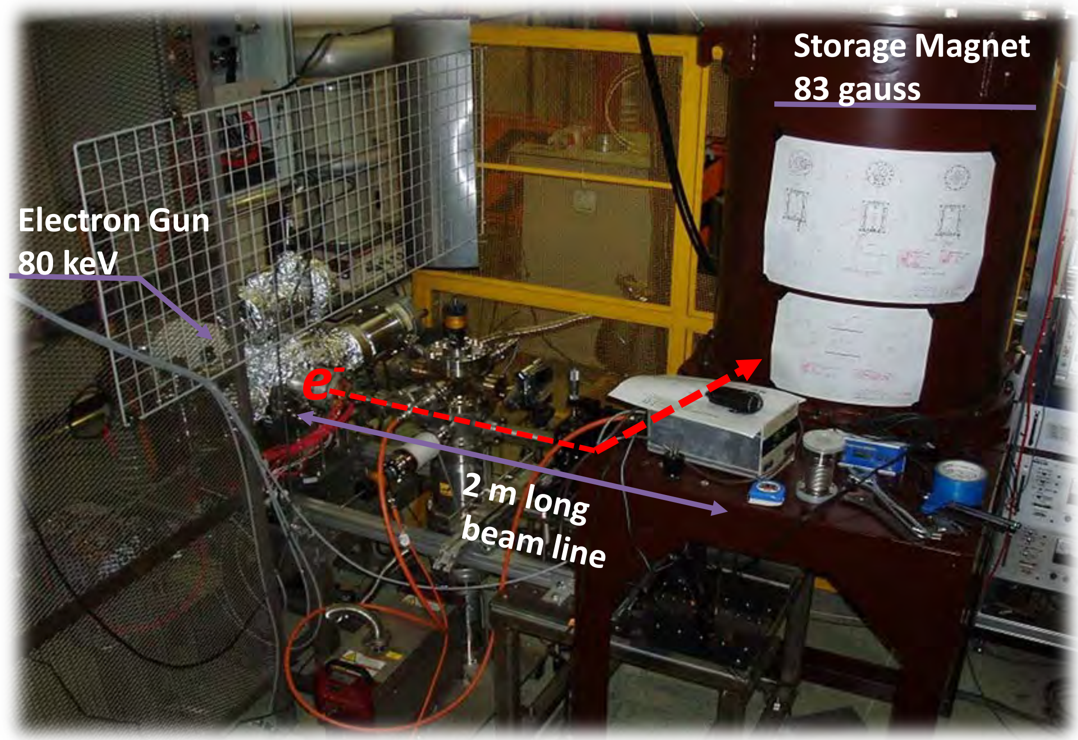
+very weak magnetic focusing ($n \sim 10^{-5}$, 1ppm/cm)

Spiral beam Injection

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



Detailed trajectory design with OPERA field



Spiral injection test with mini-solenoid and electron gun - in progress (observed two turns)

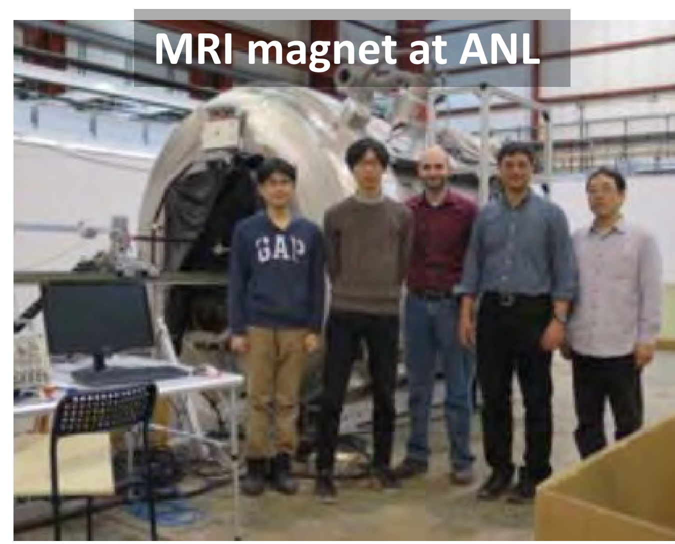
Muon storage magnet and field monitor

Good synergy with MUSEUM (S. Seo and T. Tanaka, MuHFS talks)

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

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

MuSEUM magnet 1.7T

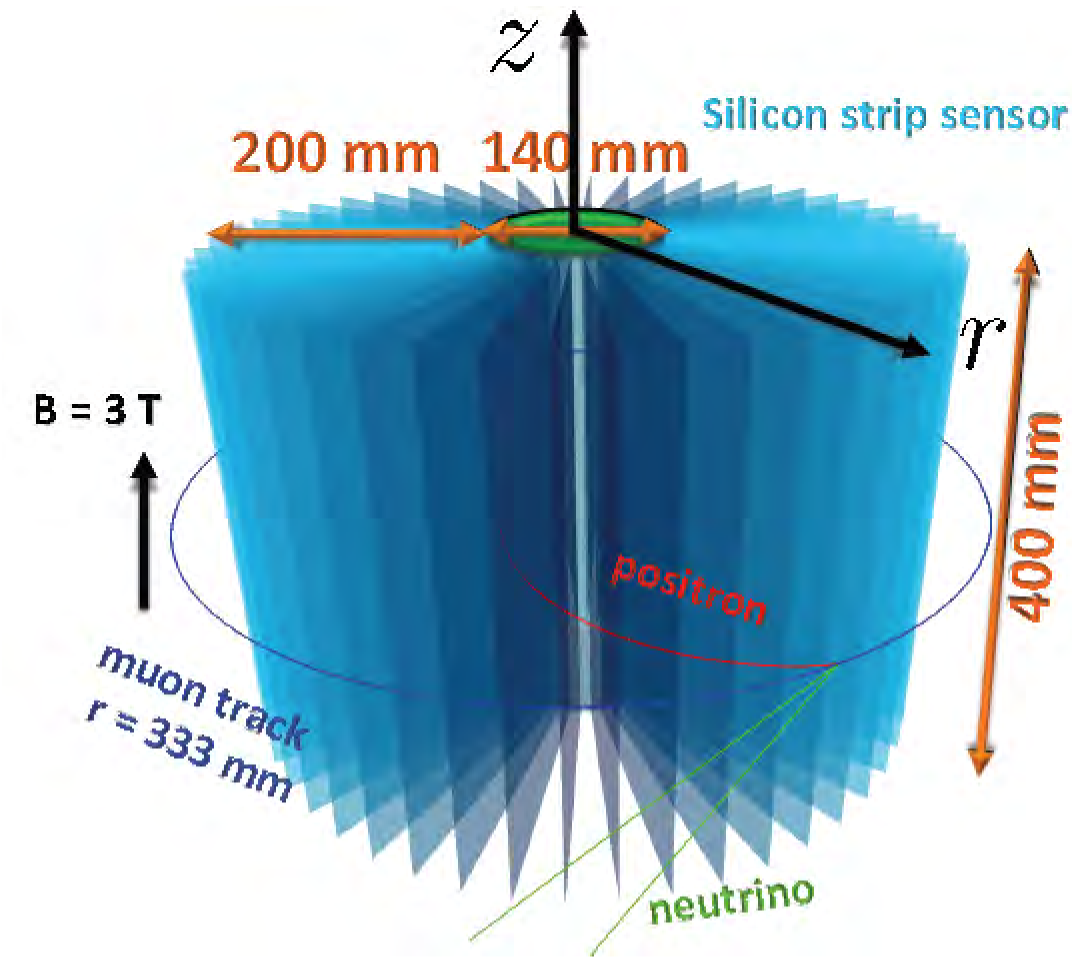


Cross calibration of J-PARC and FNAL B-field probes

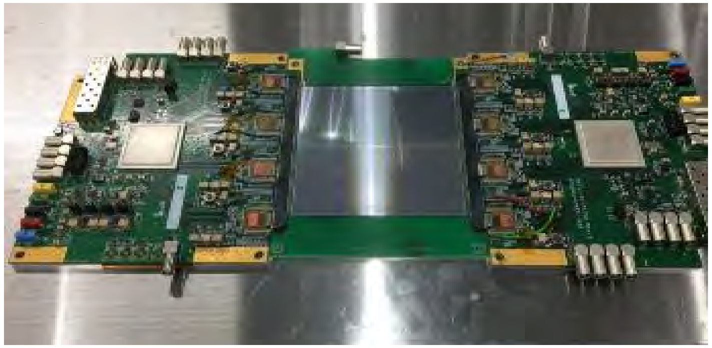
and field measurement
 monitoring system, NMR probe

Detector

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



Partial funding available to construct a part of the detector system



Beam test with muon beam at J-PARC and electron at Tohoku-U were carried out

Precise optical alignment system is being developed.

Expected beam intensity and statistical error

Table 13.1: *Efficiency and beam intensity*

Quantity	Reference	Efficiency	Cumulative	Intensity (Hz)
Muon intensity at production target	[2]			1.99E+09
H-line transmission	[2]	1.62E-01	1.62E-01	3.22E+08
Mu emission	[3]	3.82E-03	6.17E-04	1.23E+06
Laser ionization	[4]	7.30E-01	4.50E-04	8.97E+05
Metal mesh	[5]	7.76E-01	3.49E-04	6.96E+05
Init.Acc.trans.+decay	[5]	7.18E-01	2.51E-04	5.00E+05
RFQ transmission	[6]	9.45E-01	2.37E-04	4.72E+05
RFQ decay	[6]	8.13E-01	1.93E-04	3.84E+05
IH transmission	design goal	1.00E+00	1.93E-04	3.84E+05
IH decay	[7]	9.84E-01	1.90E-04	3.78E+05
DAW transmission	design goal	1.00E+00	1.90E-04	3.78E+05
DAW decay	[8]	9.94E-01	1.88E-04	3.76E+05
High beta transmission	design goal	9.80E-01	1.85E-04	3.68E+05
High beta decay	[9]	9.88E-01	1.83E-04	3.64E+05
Injection transmission	design goal	1.00E+00	1.83E-04	3.64E+05
Injection decay	[10]	9.90E-01	1.81E-04	3.60E+05
Detector start time	[10]	9.27E-01	1.67E-04	3.34E+05
Muon at storage				3.34E+05

(from TDR)

Statistical error in 2 years run - 0.35 ppm

(and Δdμ < 10-21 e cm)

Needs further improvement towards <0.2 ppm

Muon polarization recovery (0.5->0.9), improving Mu emission, ...

Our systematic error goals

Source	E821 (ppm,R01)	J-PARC (ppm)	
Pileup	0.08	<0.05	tracking rather than calorimeter
Beam background	<0.1		only muons stored
Lost muons	0.09	<<0.09	requires low emittance beam
Timing shifts	<0.1	<<0.1	no PMTs, track
E-field, pitch	<0.1	<<0.01	no E field, small divergence
Fitting/binning	<0.1	<<0.1	fewer oscillation cycles
CBO	0.07	<<0.1	small focusing field
Track reconstruction		<<0.1	must maintain rate independence
Gain changes	0.12	<<0.1	assess with spin flip comparison
Others		TBD	beginning to utilize simulations
Total	**0.21**	**<0.07**	

in ωa (Precession measurement)

Source	E821 (ppm,R01)	J-PARC (ppm)	
Absolute probe calibration	0.05	<0.03	sphericity of probe, common with E821 and E989
Moving probe calibrations	0.09	<0.03	better field uniformity
Moving probe measurements	0.05	<0.05	better uniformity so less sensitive to position corrections
Fixed probe interpolations	0.07	<0.07	better field uniformity
Muon distribution	0.03	<0.03	all decays tracked, bunched beam
Weak focusing field		<0.05	weak magnetic field gradient in storage region
Decay of persistent field		?	0.01 ppm/h, measured and corrected in ω_a analysis
Others	0.10	<0.1	temperature, kicker eddy currents, higher multipoles
Total	**0.17**	**<0.07**	

in ωp (B-field)

More detailed study in progress on each item.

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

J-PARC PAC

Letter of Intent (July, 2009)

Conceptual Design Report at J-PARC PAC (Jan 2012)

Stage 1 approval as E34 (21 Sep 2012)

Technical Design Report (TDR) (May 2015)

Focused Review on TDR (Nov 15-16, 2016)

Valued as independent approach that should be done ASAP

Many follow-up works done to respond recommendations

Selected as one of priority project in KEK Project Implementation Plan (PIP)

Selected as one of 28 in "Master Plan 2017" by Science Council of Japan ("Origin of Matter" with COMET and Hadron extension)

Several grants obtained for each development.

Overall budget is still a issue.

Muon g-2/EDM Collaboration

Collaboration Meeting held every half year.
15th C.M. will be in 11-14 Dec 2017 at Kyushu University

Collaboration structure

Collaborative board (7 representing institutes, regions) Chair - Seonho Choi (SNU)
Bylaws (Jan 2017)
Selection of Spokesperson - Tsutomu Mibe (KEK)

Currently, 90 members from Canada, Czech, Germany, Japan, Korea, USA, France, Russia
We look for new collaborators.

Summary

New muon g-2/EDM measurement is under preparation at J-PARC.

Many good progresses in each basic component
Surface muon beam, muonium emission and laser,
acceleration, injection, storage magnet, detectors

Overall simulation and detailed evaluation of error in progress

Construction to data taking stage in ~4 years
once budget/resource is available