J-PARC muon g-2 experiment

Takayuki YAMAZAKI (KEK IMSS)

on behalf of

The J-PARC muon g-2/EDM collaboration

Muon *g*-2

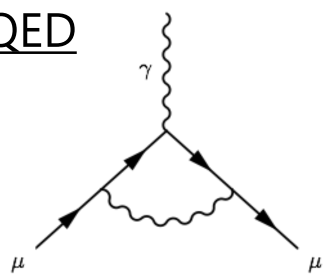
- Magnetic dipole moment

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

- The *g* factor is exactly 2 in tree level, but higher order terms make *g* larger
- $a_\mu = (g-2)/2$ is called anomalous magnetic moment

SM contributions

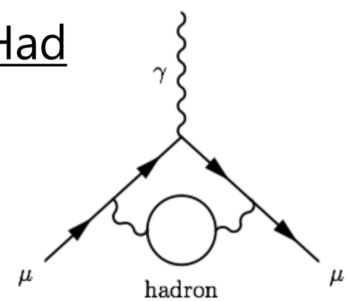
QED



$11658471.90\ (0.01) \times 10^{-10}$

Phys. Rev. Lett. **109** (2012) 111808

Had



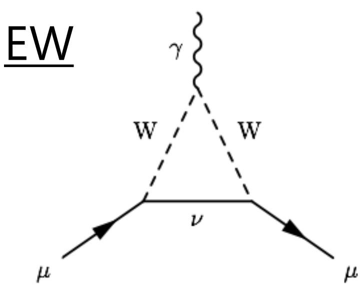
LO HLbL: 9.80 (2.60) $\times$ **10^{-10}**

EPJ Web Conf. **118** (2016) 01016

LO HVP: 692.23 (2.54) $\times$ **10^{-10}**

KNT17'

EW



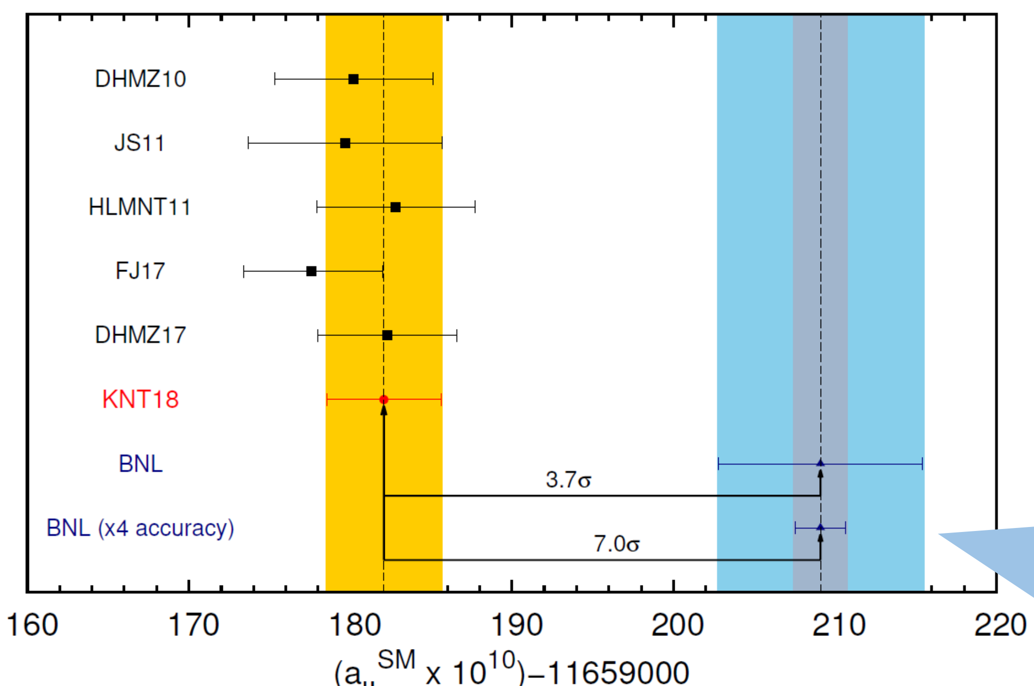
$15.36\ (0.10) \times 10^{-10}$

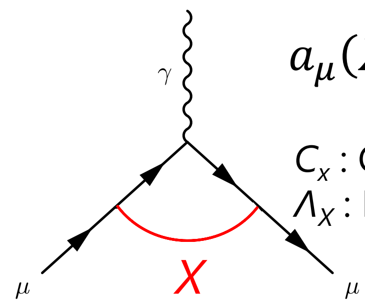
Phys. Rev. D **88** (2013) 053005

>3σ discrepancy

- Muon *g*-2 is one of the most sensitive targets to explore new physics
  - Precise experiment (BNL E821) : 0.5ppm
  - Precise theoretical calculations : 0.4ppm (2011) → 0.3ppm (2017)
- According to a recent theoretical calculation, the discrepancy between experiment and SM theory is 3.7σ → **New physics?**

c.f. arXiv:1802.02995



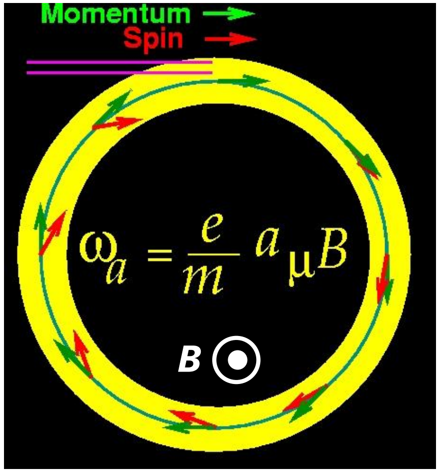


$$a_\mu(X) \sim C_X \left(\frac{m_\mu}{\Lambda_X}\right)^2$$

C_X : Coupling strength
Λ_X : NP energy scale

New muon *g*-2 measurements

- Now *experimentalists' turn* to update the historical plot
    - FNAL E989
    - J-PARC E34
- Measurement principle
    - Measure spin precession frequency $\boldsymbol{\omega}_a$ under uniform magnetic field ***B***



g-2>0

- More generally, $\boldsymbol{\omega}_a$ under ***B*** and ***E*** field is

$$\boldsymbol{\omega}_a = -\frac{e}{m_\mu}\left[\underbrace{a_\mu \boldsymbol{B}}_{g\text{-}2} - \underbrace{\left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\boldsymbol{\beta}\times\boldsymbol{E}}{c}}_{\text{Effect of } \boldsymbol{E} \text{ field}} + \underbrace{\frac{\eta_\mu}{2}\left(\boldsymbol{\beta}\times\boldsymbol{B} + \frac{\boldsymbol{E}}{c}\right)}_{\text{EDM}}\right]$$

Elimination of *E*-field effect is necessary for precise measurements

FNAL E989 / J-PARC E34

- Their difference is the way to eliminate ***E***-field effect.

General form

$$\boldsymbol{\omega}_a = -\frac{e}{m_\mu}\left[\underbrace{a_\mu \boldsymbol{B}}_{g\text{-}2} - \underbrace{\left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\boldsymbol{\beta}\times\boldsymbol{E}}{c}}_{\text{Effect of } \boldsymbol{E} \text{ field}} + \underbrace{\frac{\eta_\mu}{2}\left(\boldsymbol{\beta}\times\boldsymbol{B} + \frac{\boldsymbol{E}}{c}\right)}_{\text{EDM}}\right]$$

γ = 29.3 (P = 3 GeV)
"Magic momentum"

$$\boldsymbol{\omega}_a = -\frac{e}{m_\mu}\left[\underbrace{a_\mu \boldsymbol{B}}_{g\text{-}2} + \underbrace{\frac{\eta_\mu}{2}\left(\boldsymbol{\beta}\times\boldsymbol{B} + \frac{\boldsymbol{E}}{c}\right)}_{\text{EDM}}\right]$$

FNAL E989

Improvement of the BNL method

***E* = 0 at any γ**
Only very weak magnetic focusing

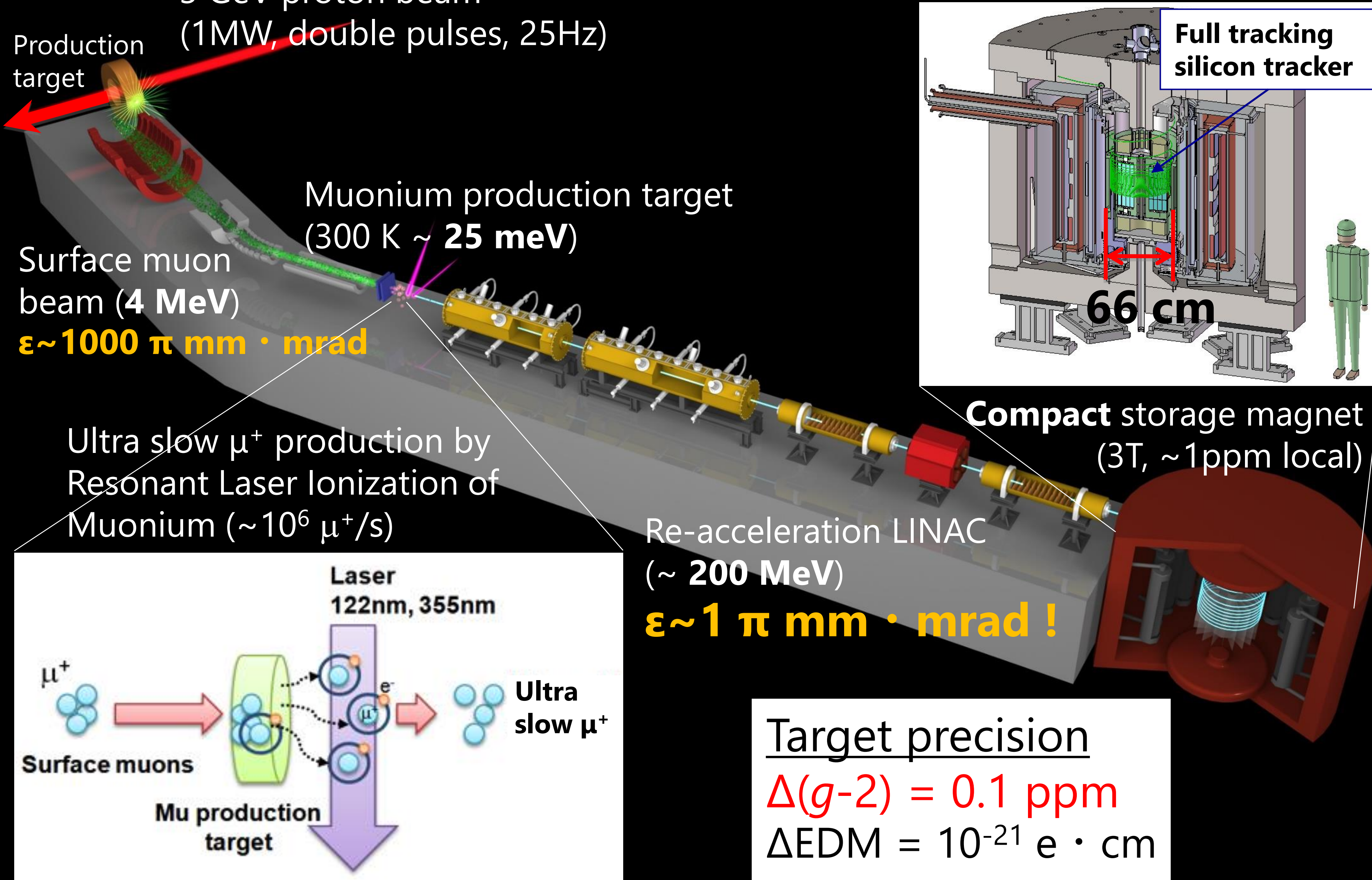
$$\boldsymbol{\omega}_a = -\frac{e}{m_\mu}\left[\underbrace{a_\mu \boldsymbol{B}}_{g\text{-}2} + \underbrace{\frac{\eta_\mu}{2}\boldsymbol{\beta}\times\boldsymbol{B}}_{\text{EDM}}\right]$$

J-PARC E34

New method with different systematics

Super-low emittance muon beam (**ultra slow muon beam**)
is the key technique for the J-PARC E34 experiment

J-PARC *g*-2 experiment (E34)

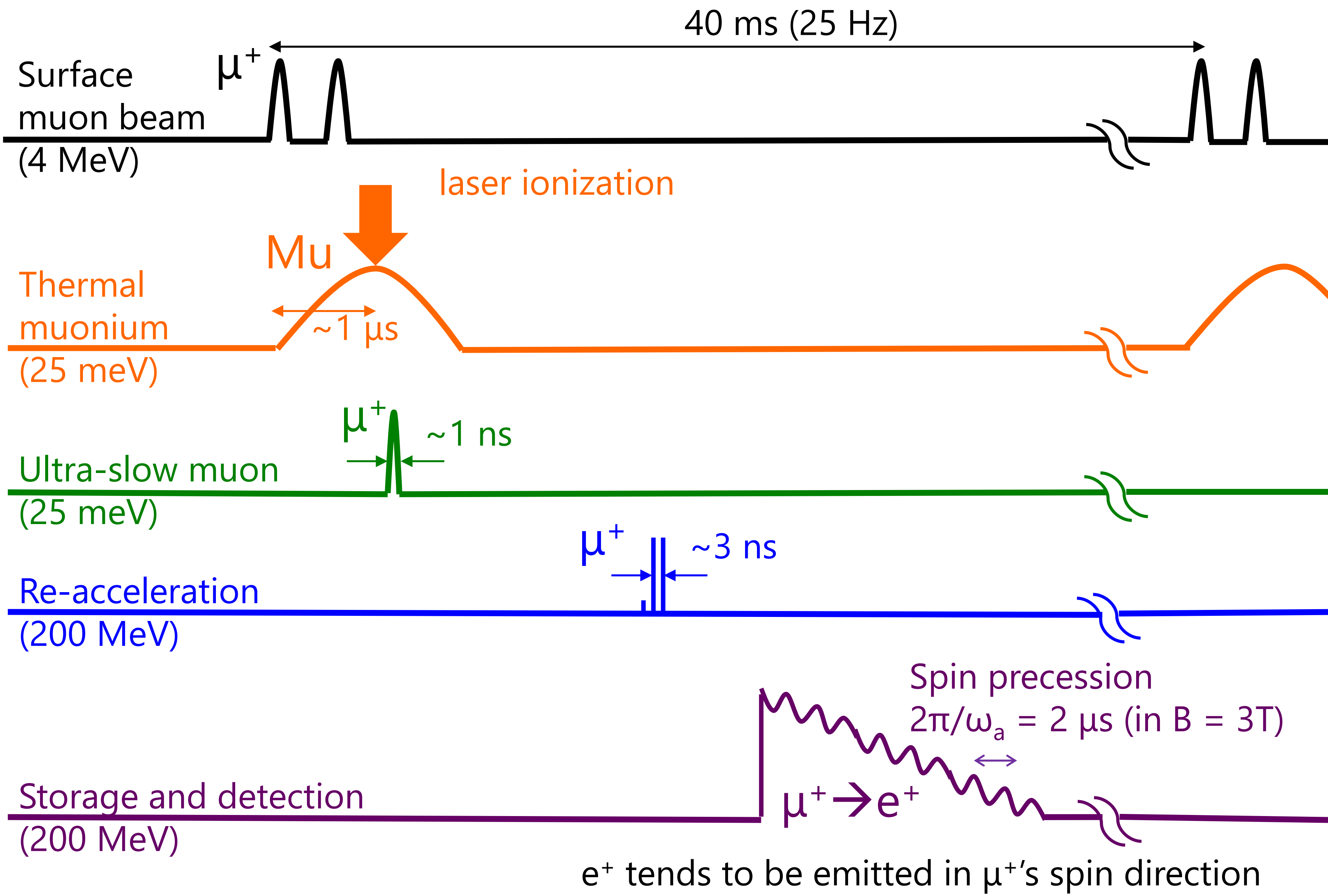


Target precision

$\Delta(g\text{-}2) = 0.1$ ppm

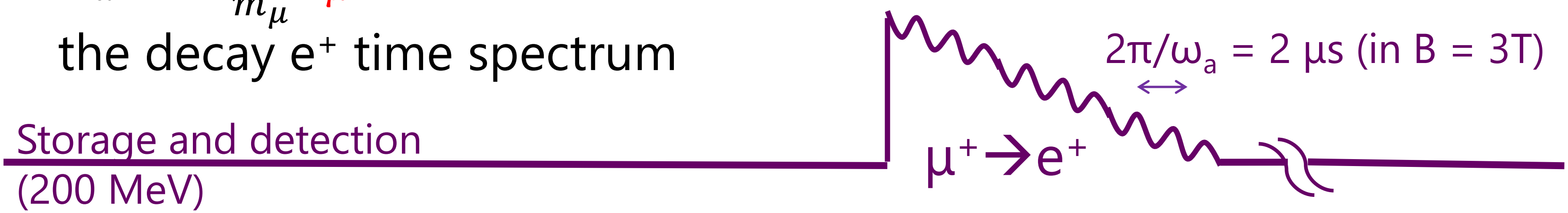
$\Delta EDM = 10^{-21}$ e・cm

Experimental sequence



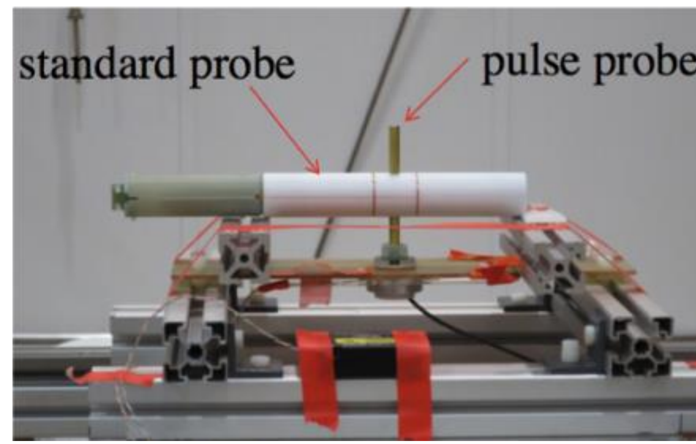
How to get a_μ

- $\omega_a = -\frac{e}{m_\mu} a_\mu B$ is extracted from the decay e^+ time spectrum



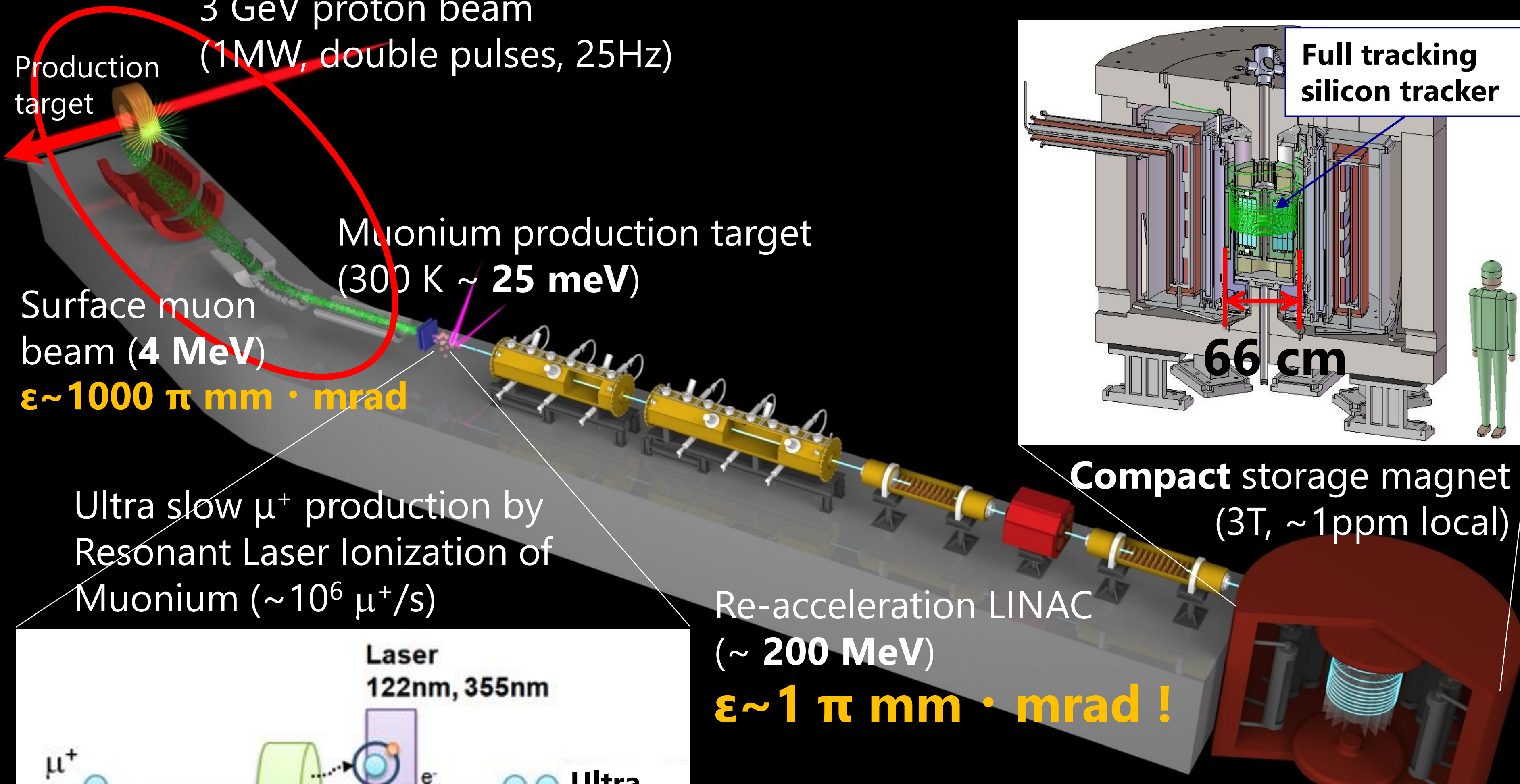
- Magnetic field B is measured in the form of NMR frequency ω_p, and a_μ is

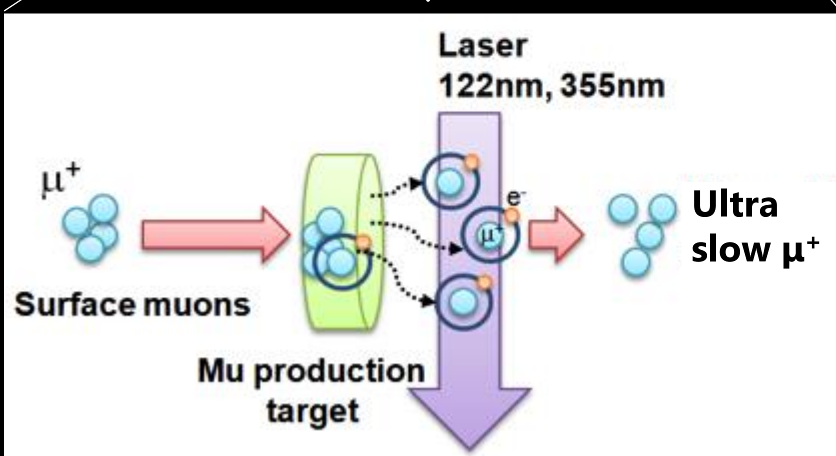
$$a_\mu = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p}$$



- Muon-to-proton magnetic moment ratio is obtained from muonium HFS measurement
  - μ_μ/μ_p = 3.18334524(37) : 0.12 ppm, LAMPF measurement
  - will be measured with a precision of 0.01 ppm at the MuSEUM experiment at J-PARC

J-PARC *g*-2 experiment (E34)





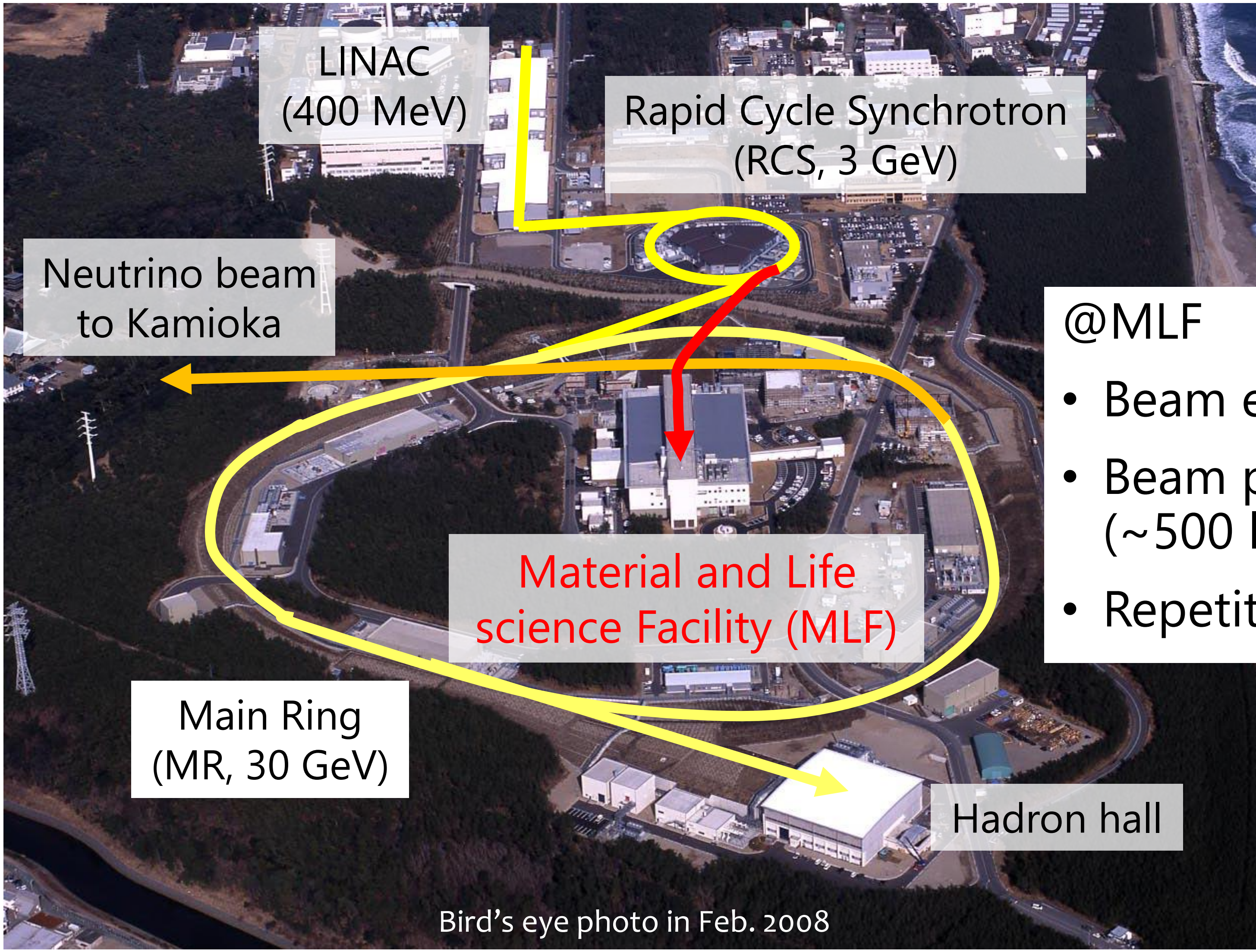
Target precision

$\Delta(g\text{-}2) = 0.1$ ppm

$\Delta EDM = 10^{-21}$ e・cm

J-PARC

J-PARC = Japan Proton Accelerator Research Complex



@MLF

- Beam energy 3 GeV
- Beam power 1 MW (~500 kW at present)
- Repetition rate 25 Hz

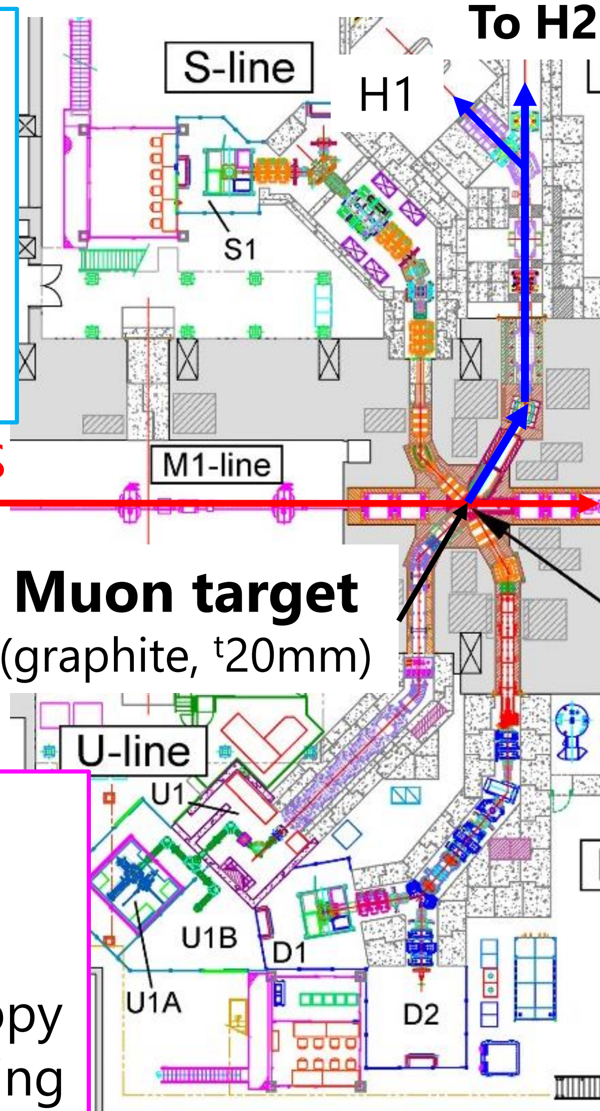
J-PARC muon facility

- MUSE (MUon Science Establishment) in the MLF

S-line
- surface μ^+
- dedicated to μSR
- S1 area is available
- S2/S3/S4 will be constructed

3GeV proton from RCS

2e15 /s @1MW

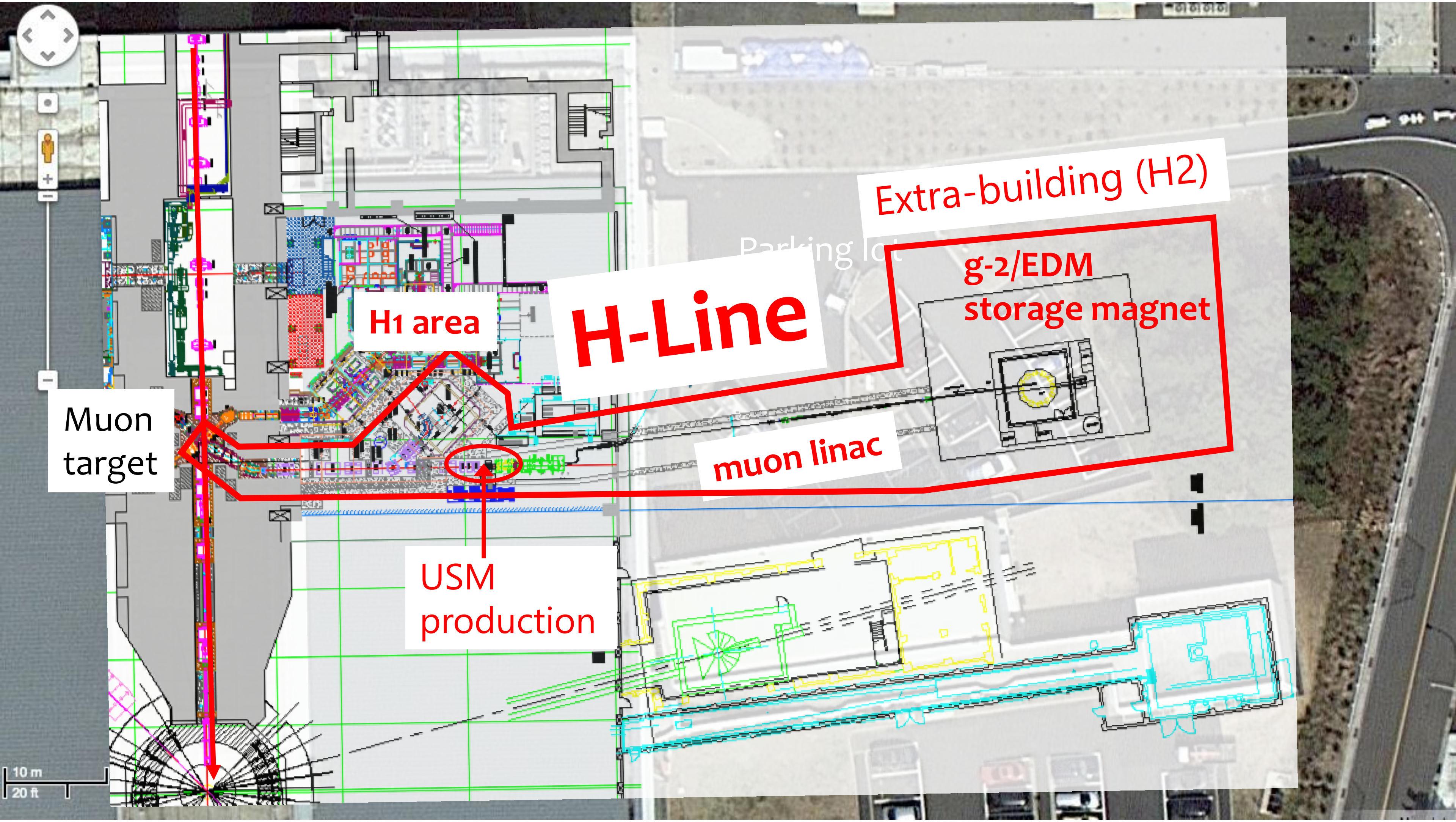


H-line
- **surface μ^+ (>10^8 μ^+/s)**, decay μ^+/μ^-, e^-
- **for high intensity & long beamtime** experiments
- H1 for DeeMe & MuSEUM
- **H2** for **g-2/EDM** & transmission muon microscopy
- **under construction**

U-line
- ultra slow μ^+
- U1A for nm-μSR
- U1B for μ microscopy
- under commissioning

D-line
- decay μ^+/μ^-, surface μ^+
- D1 area for μSR
- D2 for variety of science

Proposed experimental site (H2)



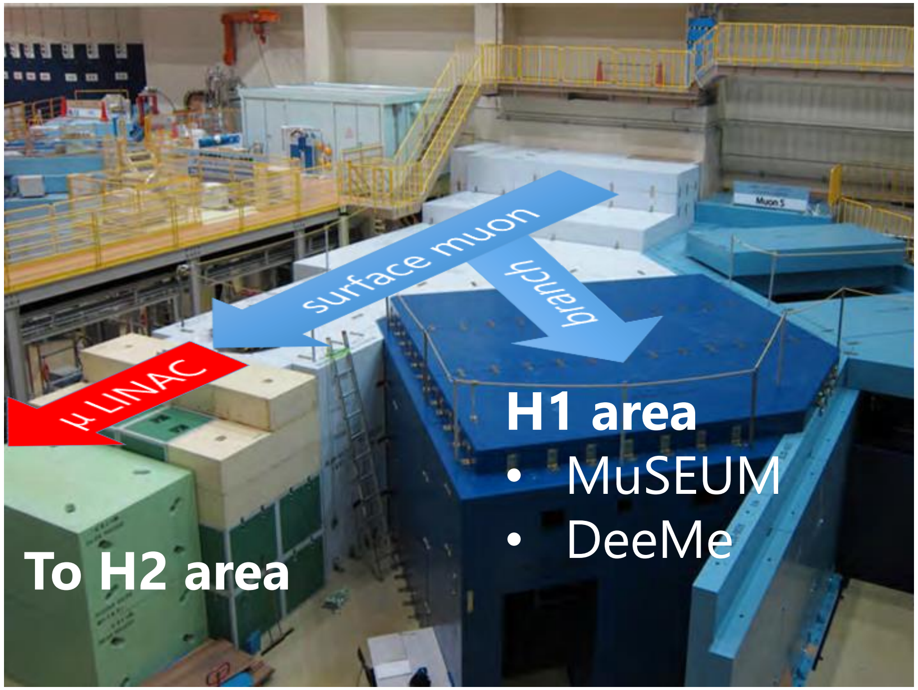
Construction status of H-line

Ready

- Main beamline magnets were already fabricated.
- Frontend devices were already installed in the proton beam tunnel.
- Beamline shield blocks in the existing experimental hall were installed

Proton beam tunnel

MLF experimental hall #1

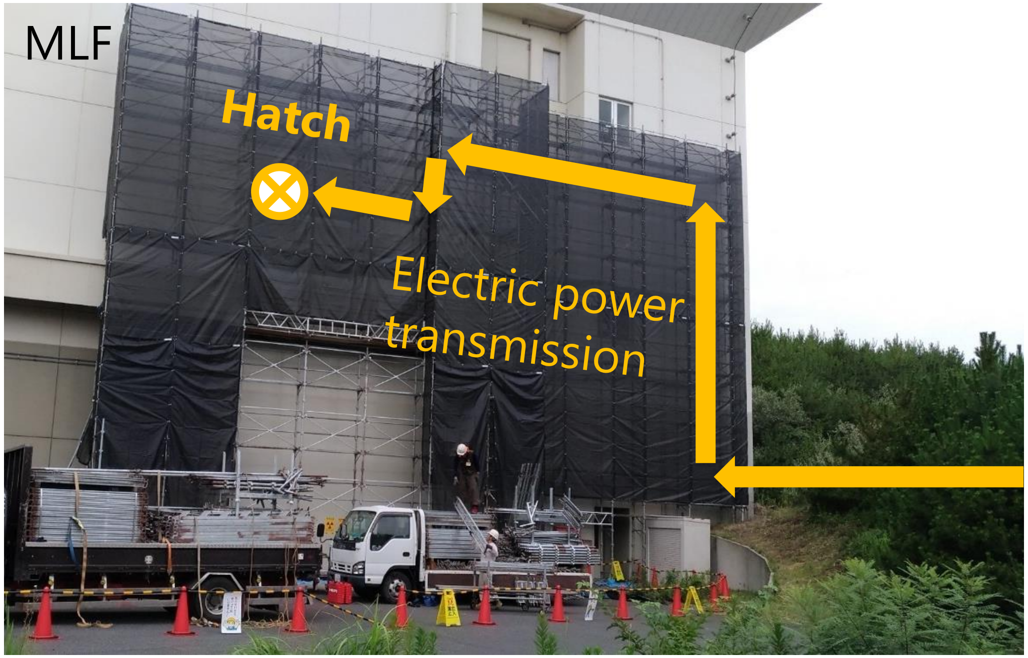


Construction status of H-line

On-going

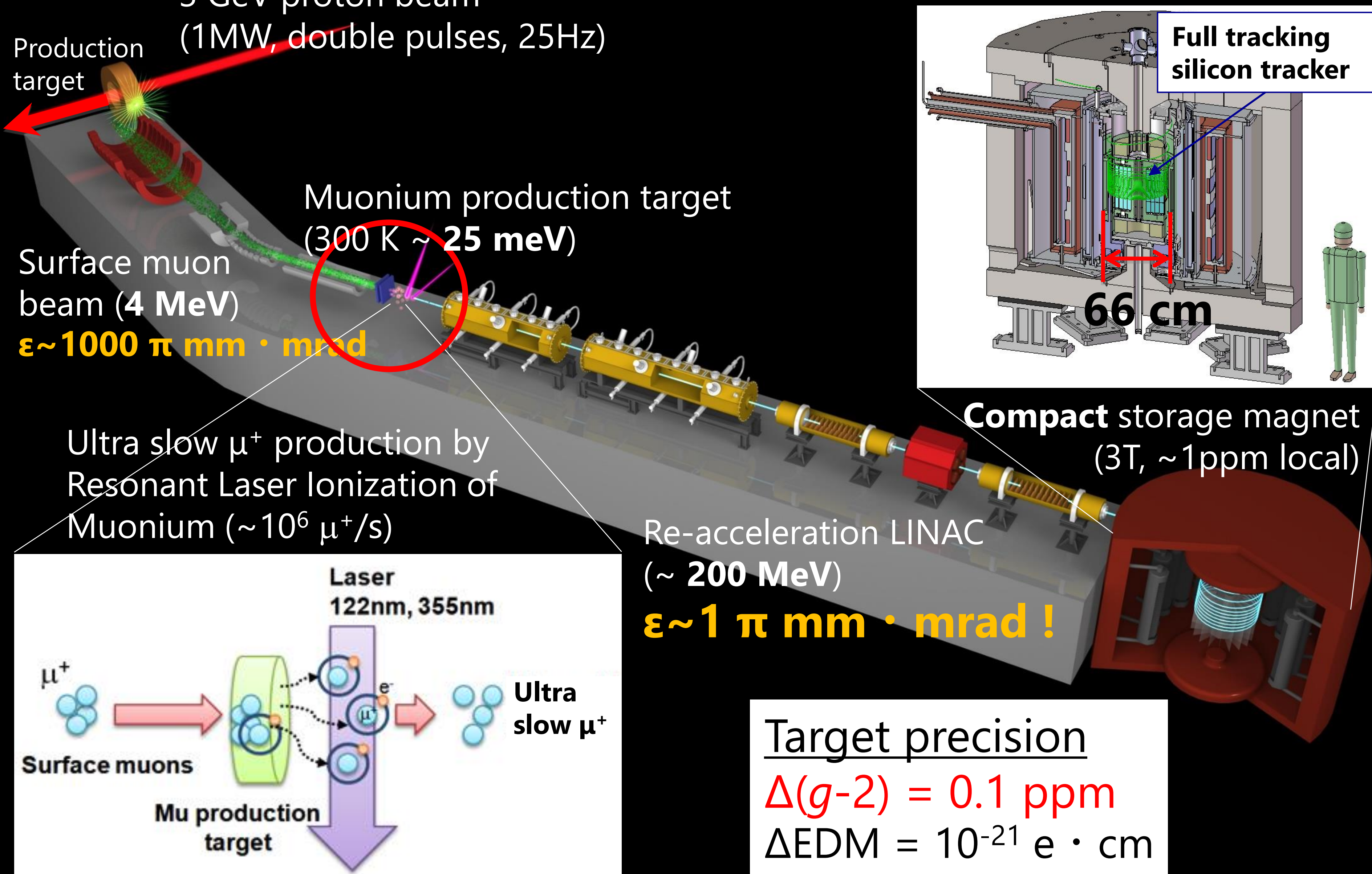
- Construction of a new electric power sub-station for H-line has started!
  - H-line needs about 5 MW electricity, but the surplus power of existing electric sub-stations in the MLF is only 1 MW.

Renovation of the MLF wall for electric power transmission line



Construction of the bedding of the electric sub-station

J-PARC *g*-2 experiment (E34)

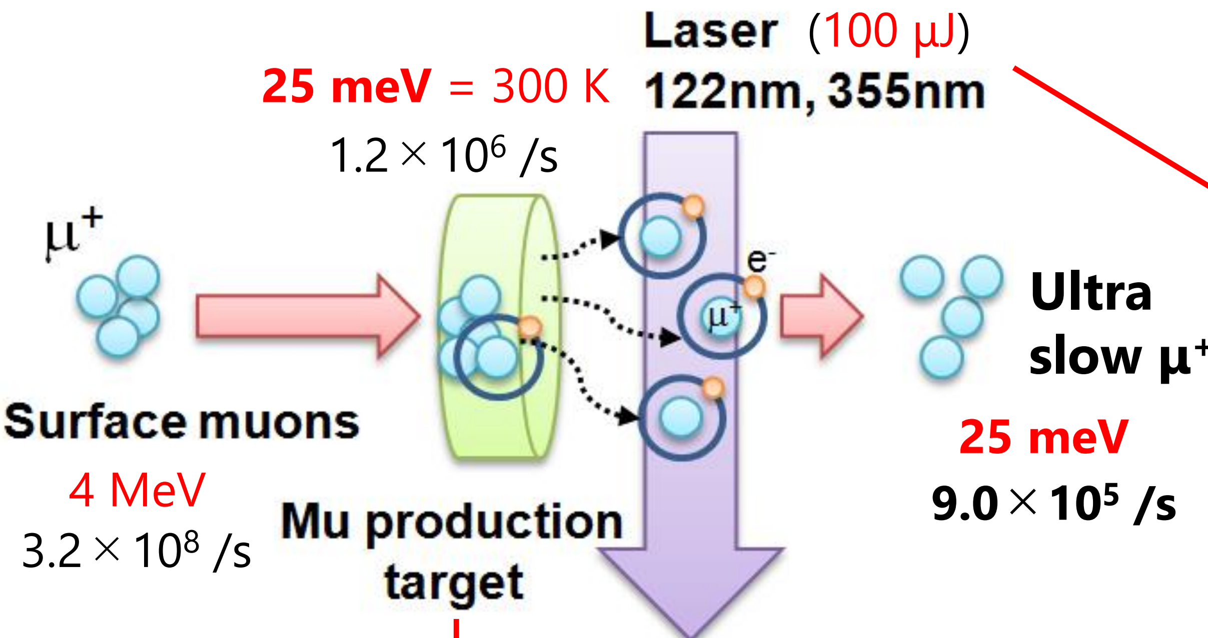


Target precision

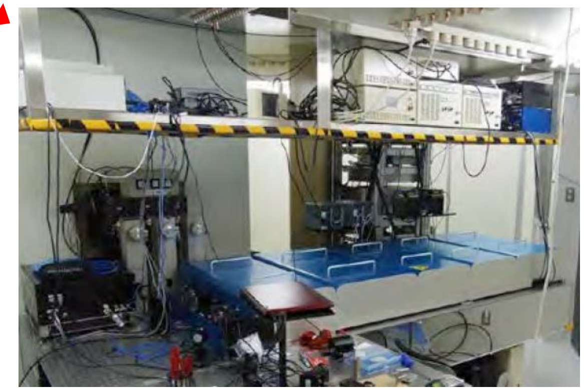
$\Delta(g\text{-}2) = 0.1$ ppm

$\Delta\mathrm{EDM} = 10^{-21}$ e・cm

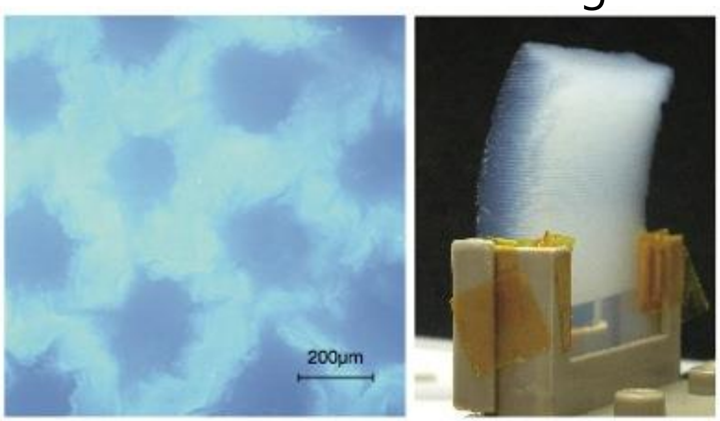
Ultra-slow muon (USM)



Laser system is currently being developed at U-line, and 10 μJ was achieved.



Laser-ablated silica aerogel



G. Beer et al., Prog.Theor.Exp.Phys. (2014)091C01

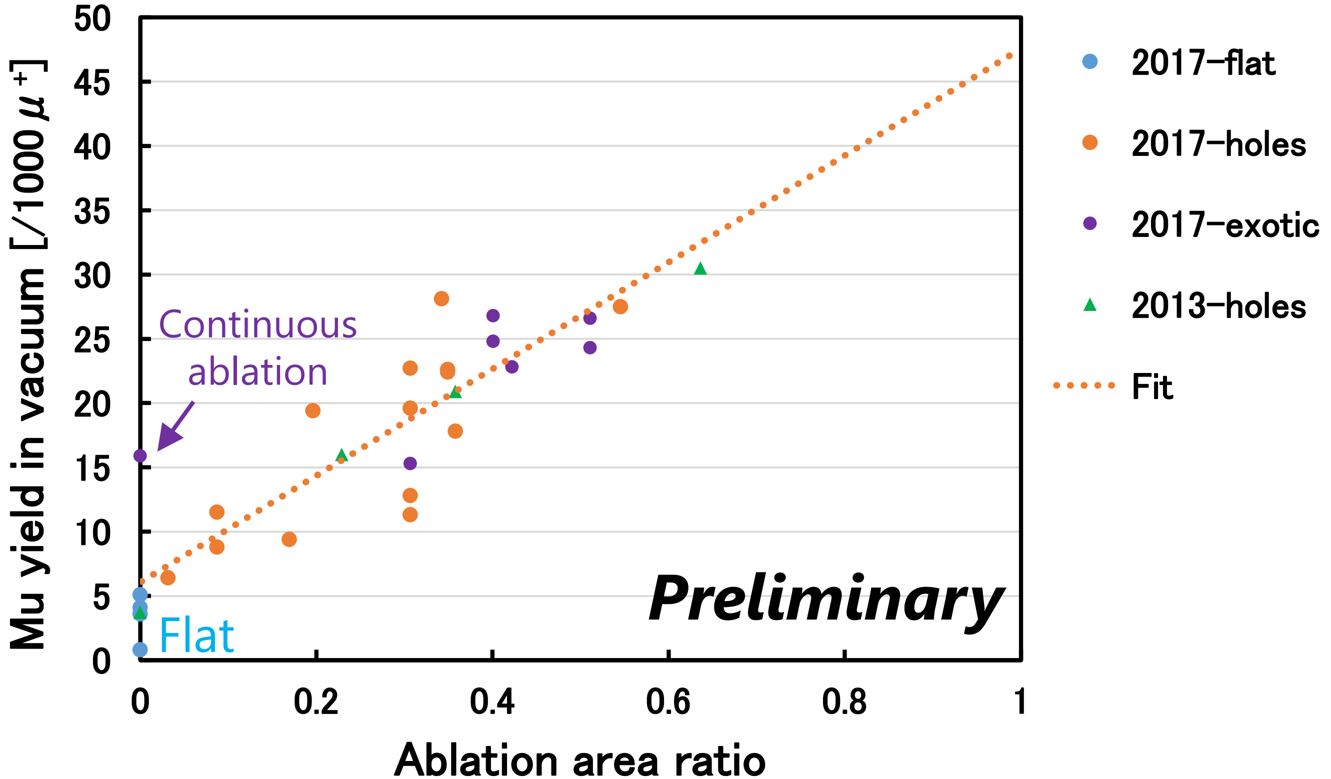
- Muonium (Mu, μ^+e^-) is produced in silica aerogel target at room temperature and then ultra slow μ^+ is extracted by laser ionization.

Mu production experiment at TRIUMF (June-July, 2017)

- Measured muonium yields of 25 samples in 3 weeks
- Tested long term stability of Mu yield

Mu yields vs ablation parameters

- Systematic study of Mu yield of various samples

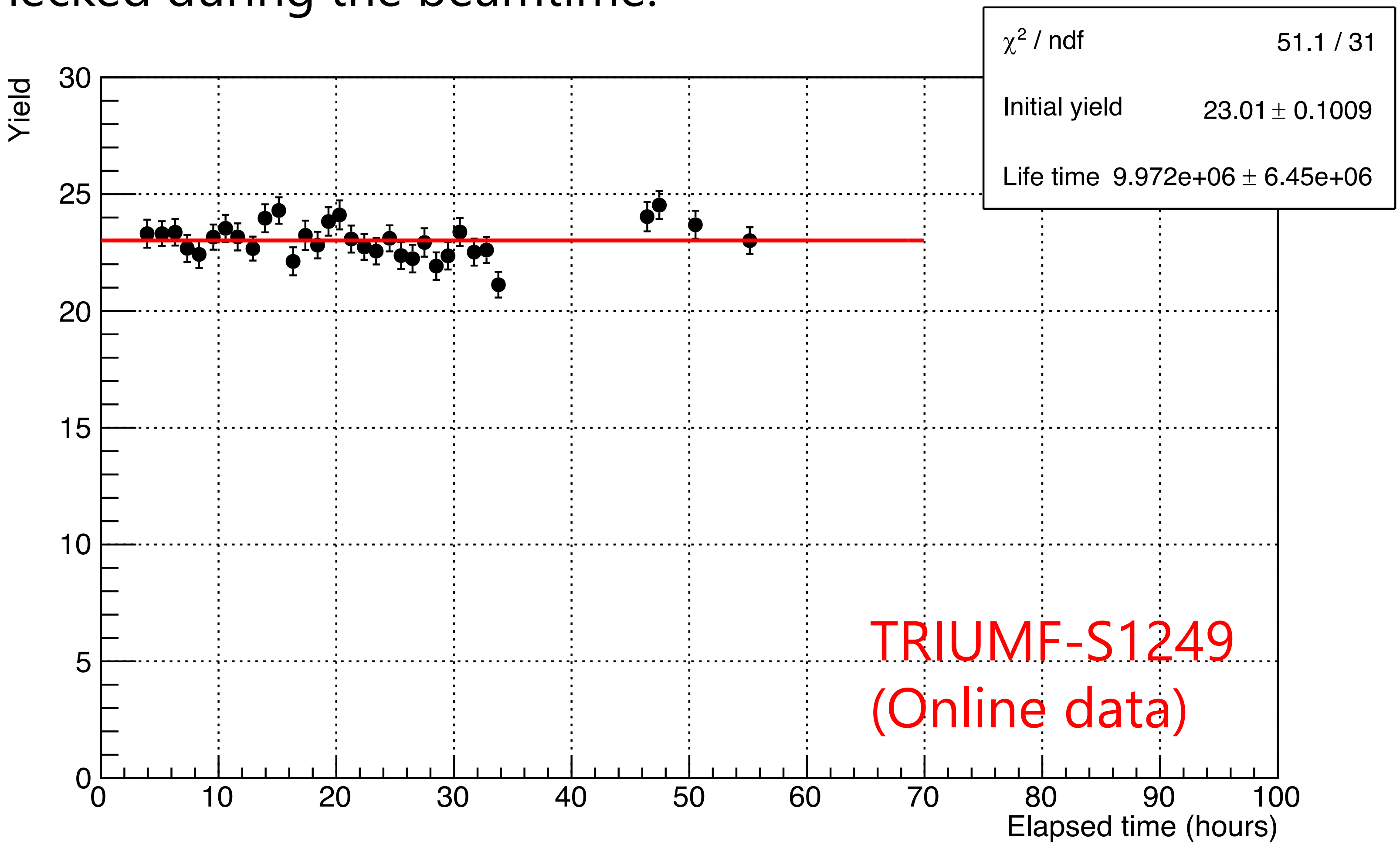


= [hole base area] / [emission face area] ∝ [aspect ratio]^2

- There seems to be correlation between yield and ablation area ratio.
  - Detailed analysis is on-going to understand the emission mechanism.

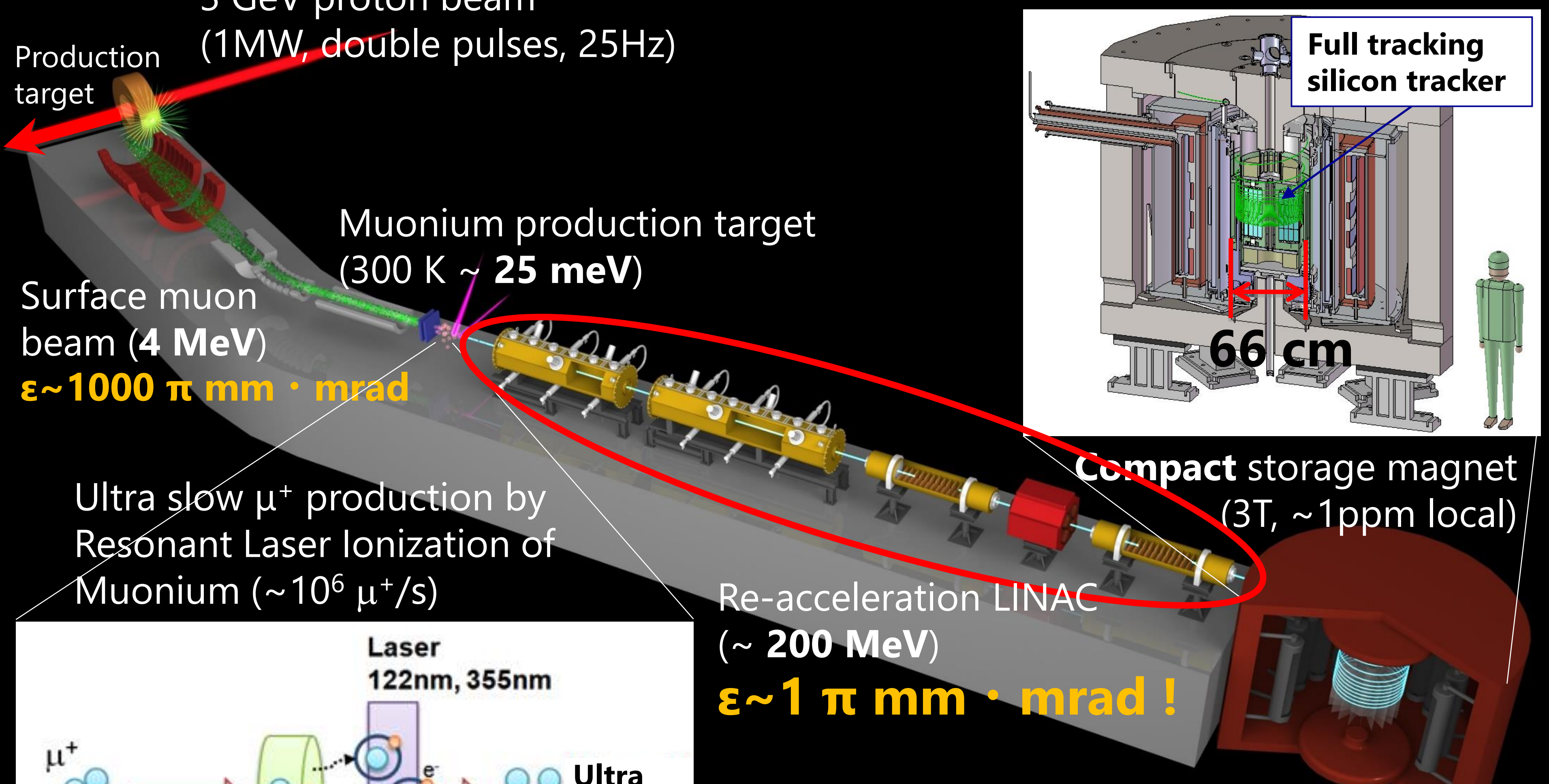
Long-term stability of Mu yield

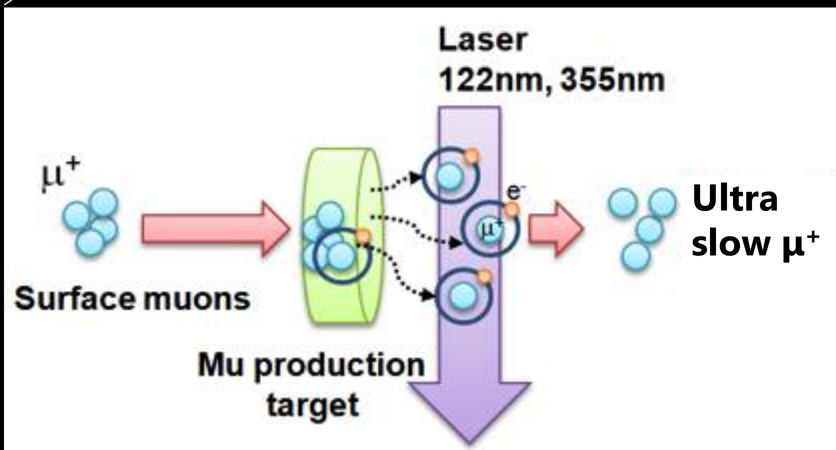
- Long term stability is important for J-PARC E34 experiment, so checked during the beamtime.



No hint of degradation was observed for 2.5 days

J-PARC *g*-2 experiment (E34)



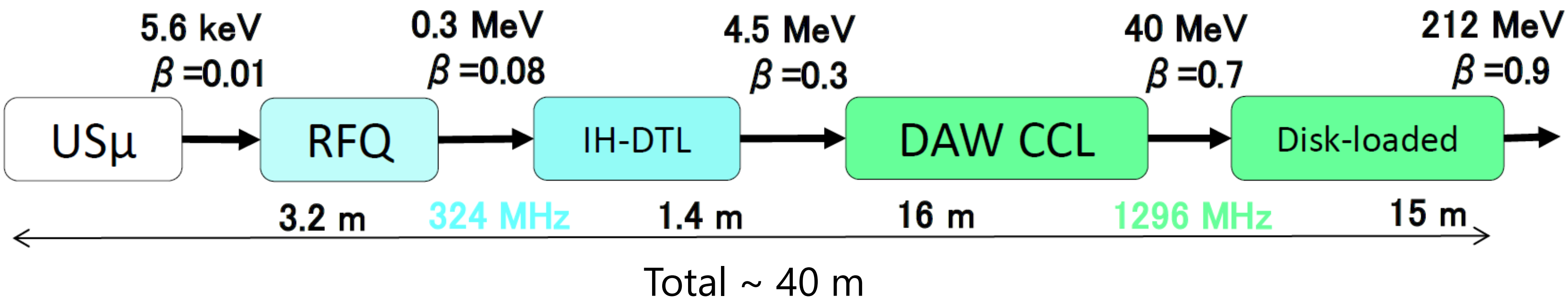


Target precision

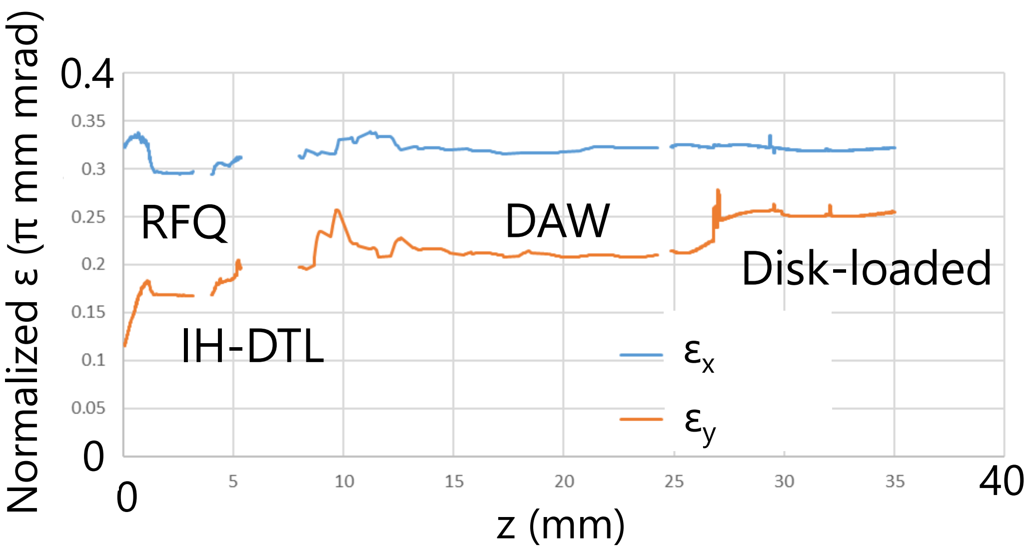
$\Delta(g\text{-}2) = 0.1$ ppm

$\Delta EDM = 10^{-21}$ e・cm

Muon acceleration

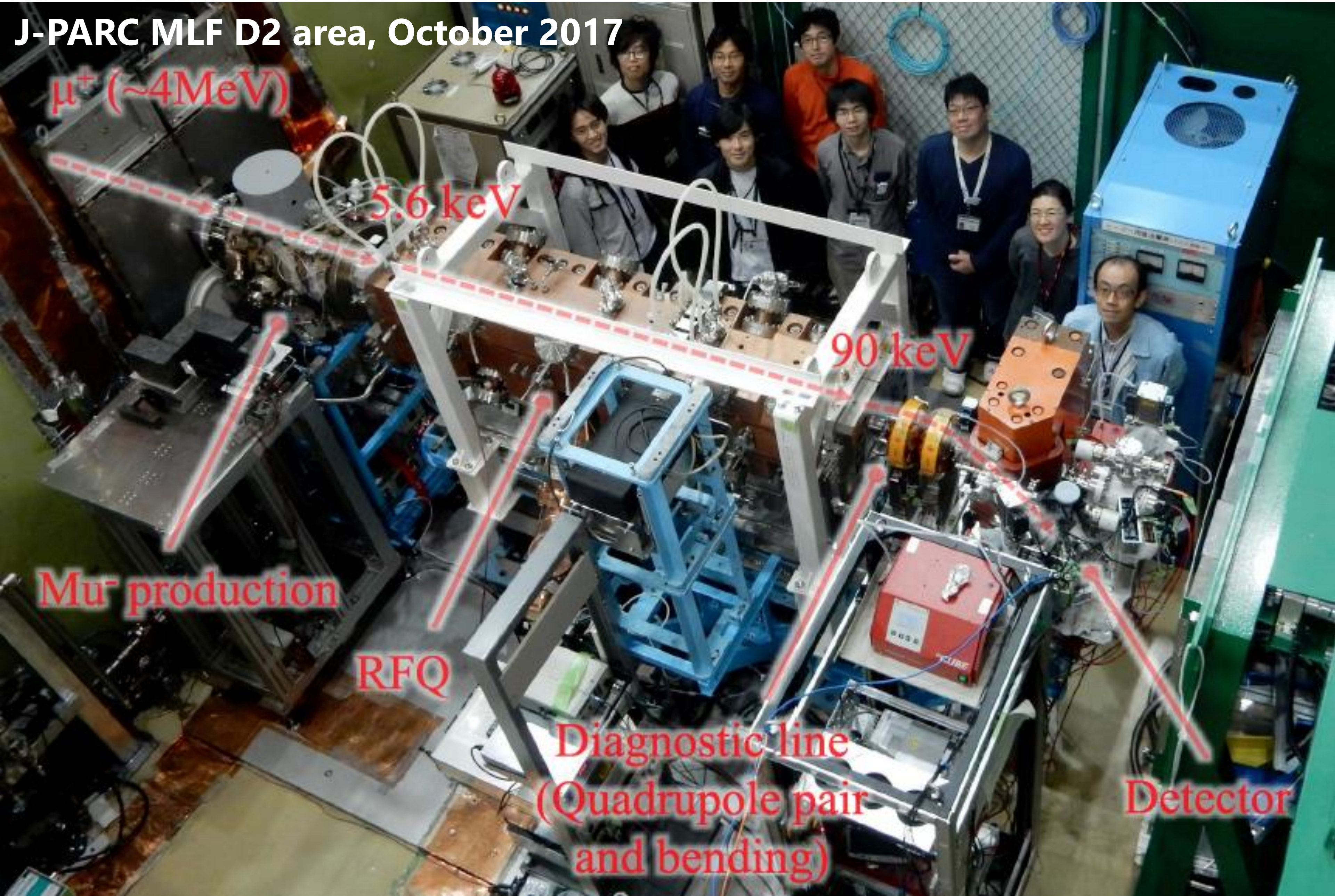


- Beam acceleration and transportation were simulated from USM source to the exit of muon LINAC, and emittance growth is not significant.

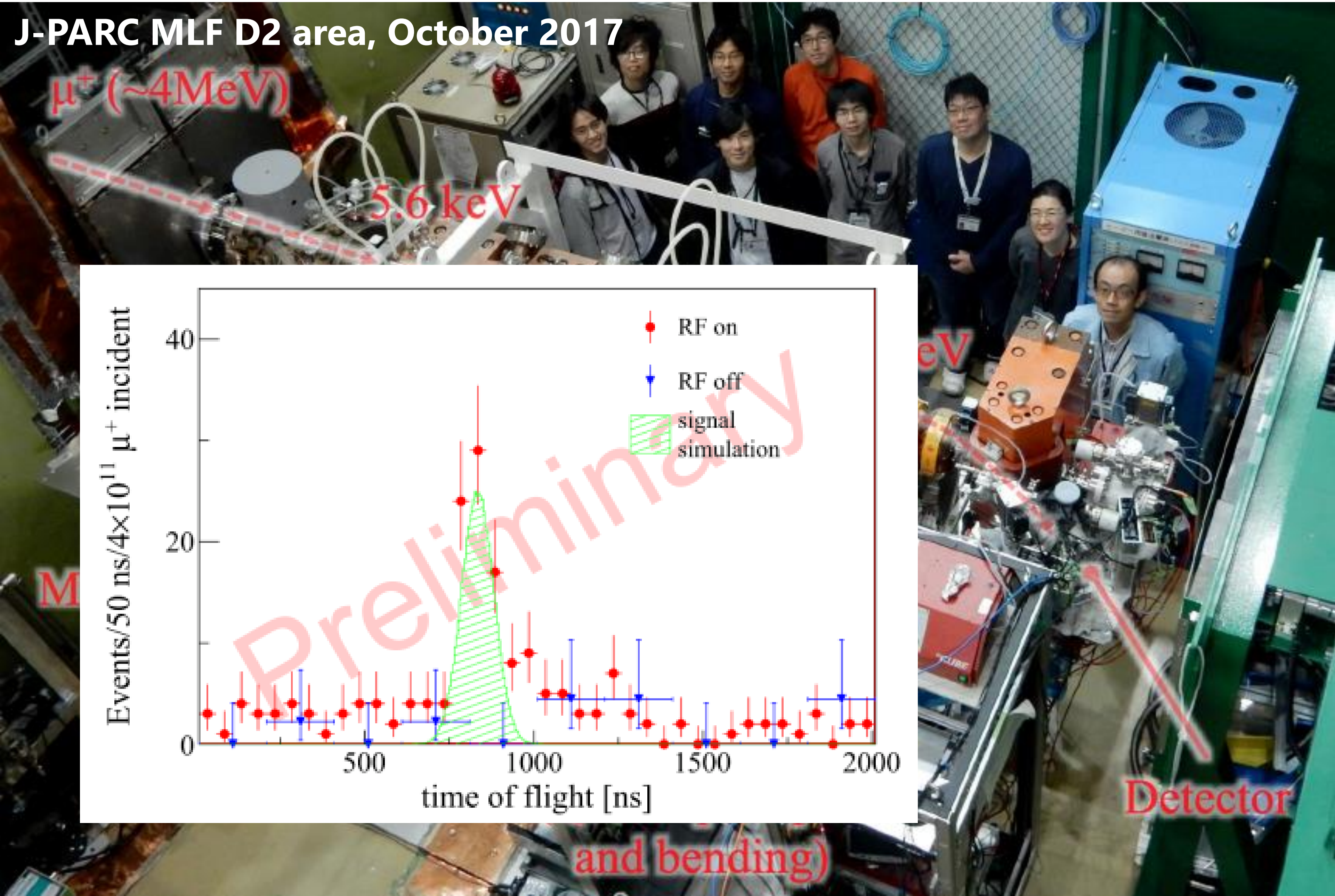


- Construction of each structure and demonstration of muon acceleration is next step.
- Muon acceleration using RFQ was demonstrated in Oct. 2017.

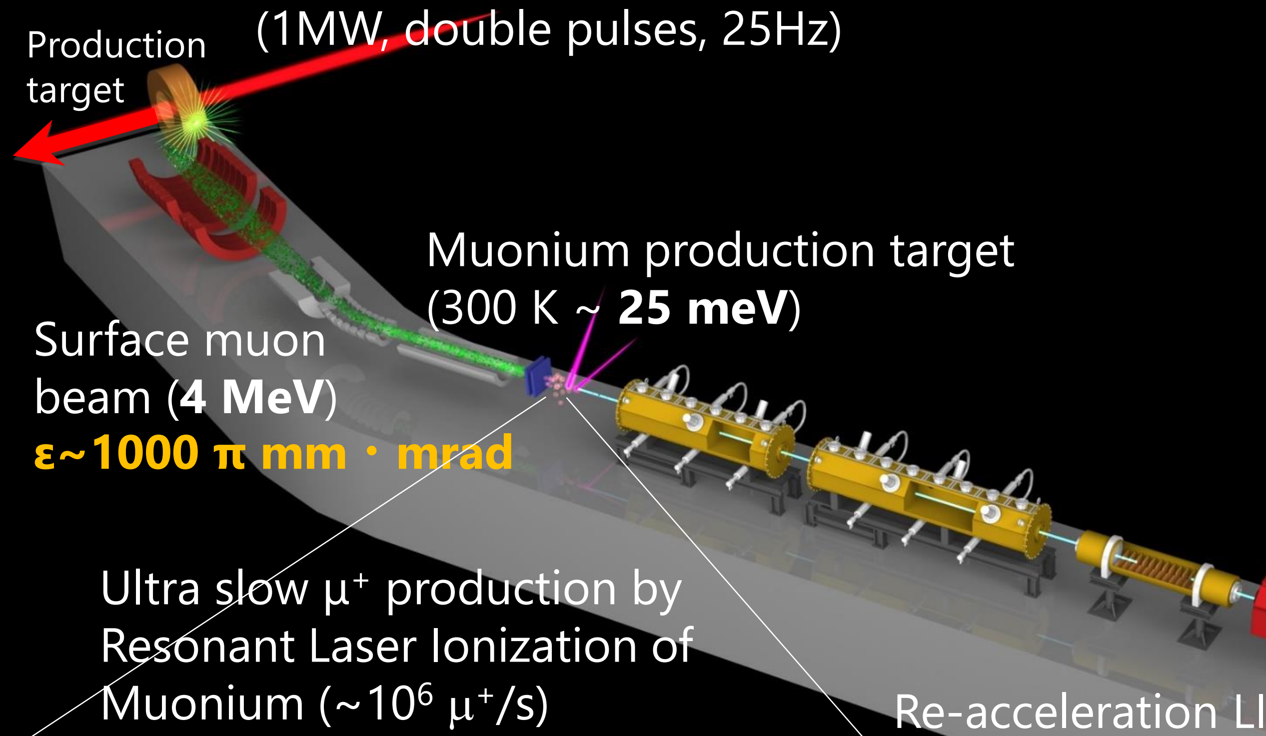
Muon RF acceleration for the first time!

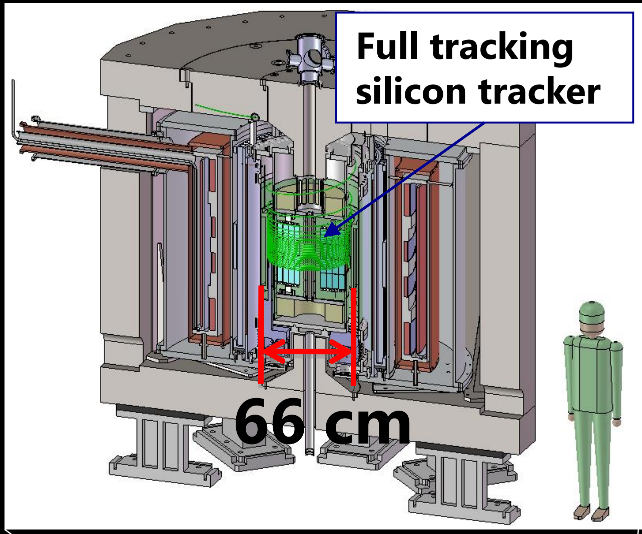


Muon RF acceleration for the first time!

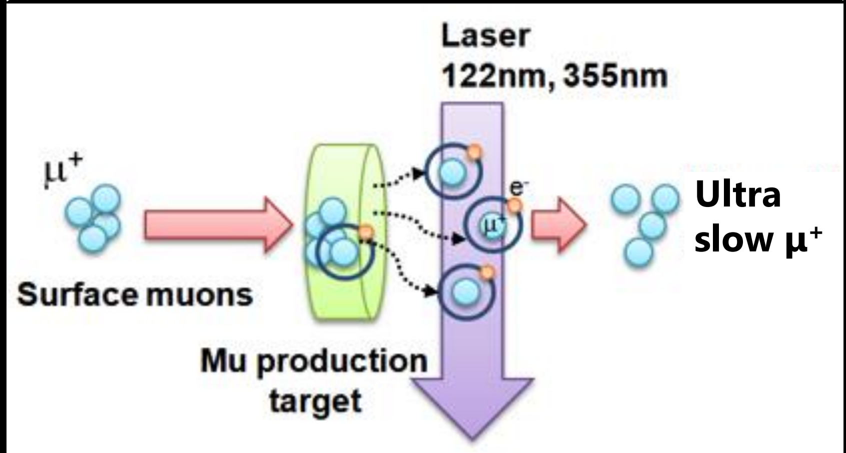


J-PARC *g*-2 experiment (E34)





Ultra slow μ⁺ production by Resonant Laser Ionization of Muonium (~10^6 μ⁺/s)



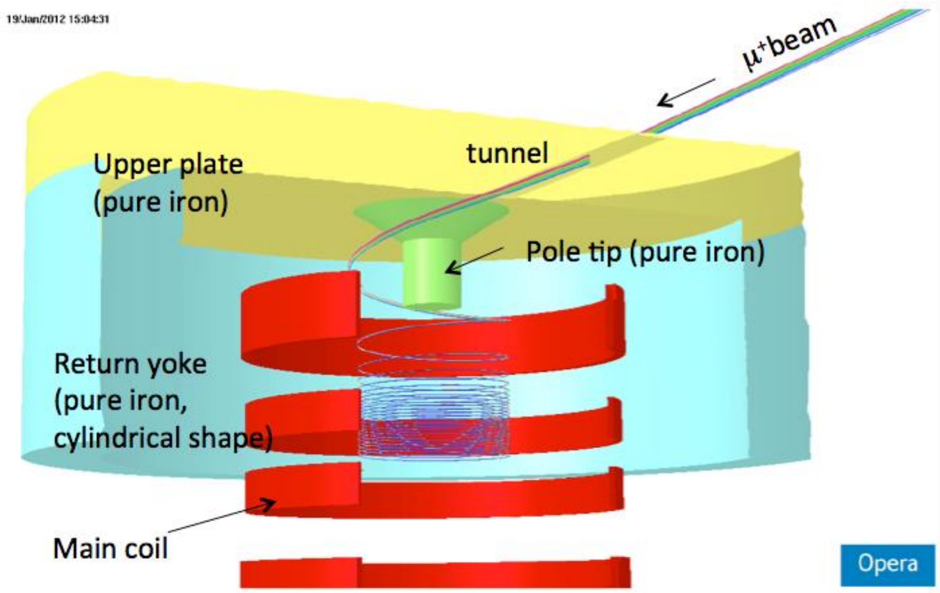
<u>Target precision</u>

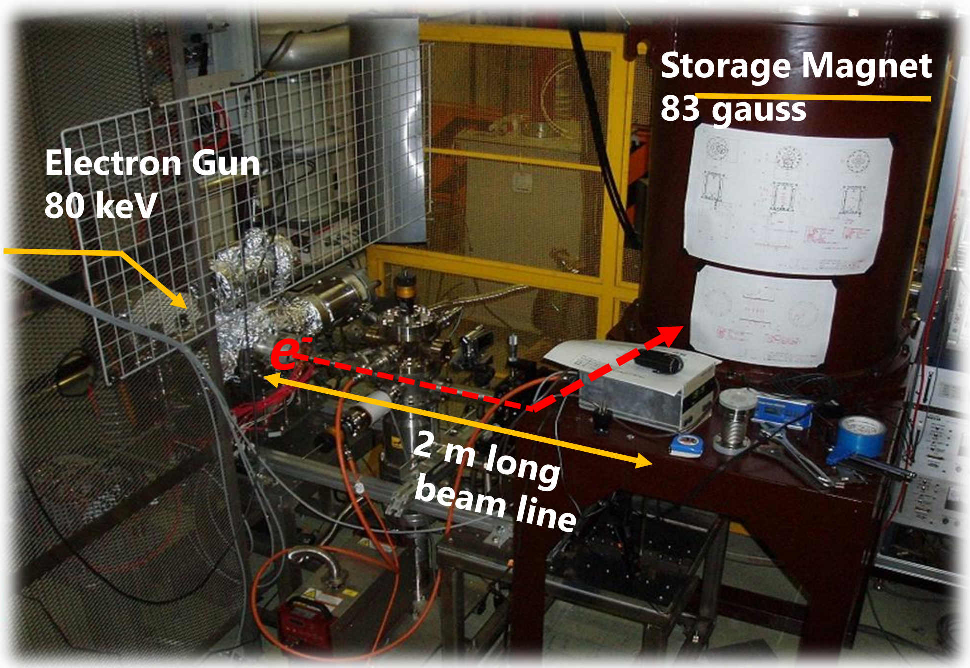
$\Delta(g\text{-}2) = 0.1$ ppm

$\Delta\text{EDM} = 10^{-21}$ e・cm

Spiral injection to storage magnet

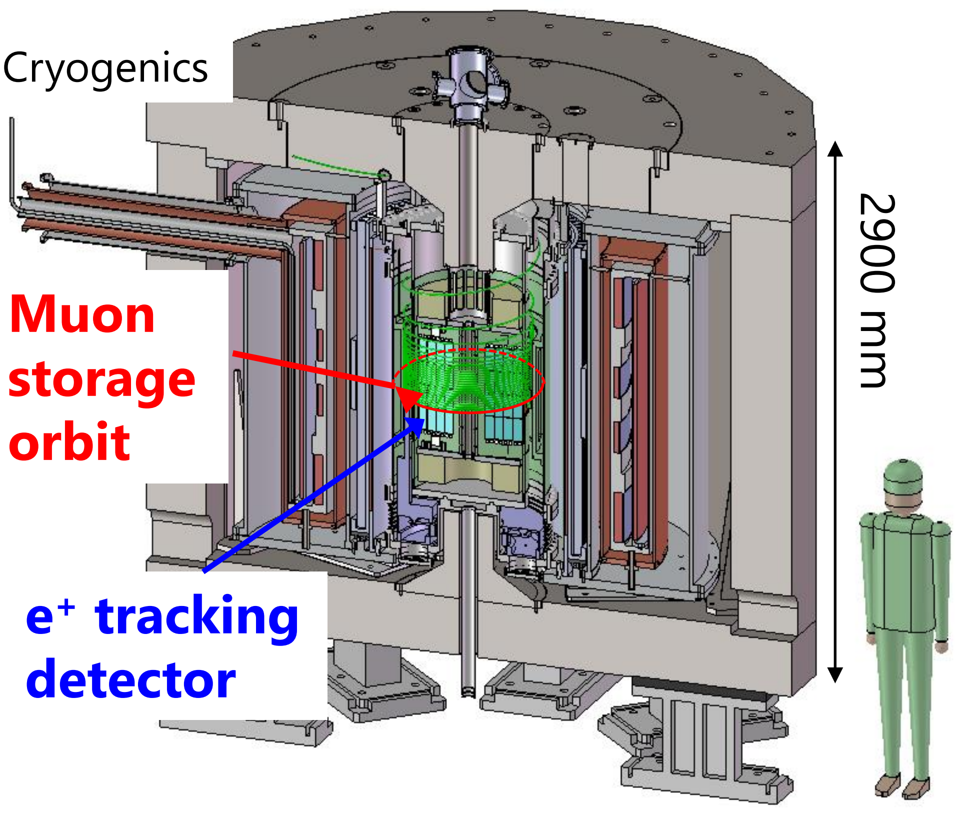
- Ultra slow muon beam (~200MeV) is injected to the storage magnet using spiral injection and weak magnetic kick.
  - ✓ Injection efficiency ~90% (c.f. NIMA 832 (2016) 51-62)
  - ✓ Test experiment using electron beam is on-going.



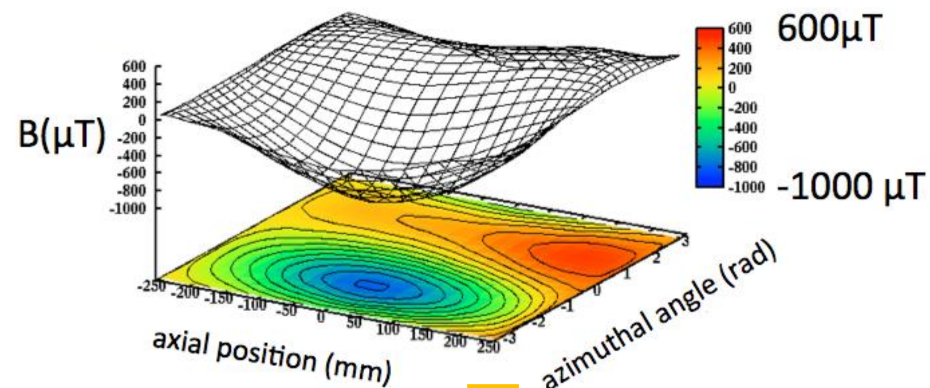


Muon storage magnet

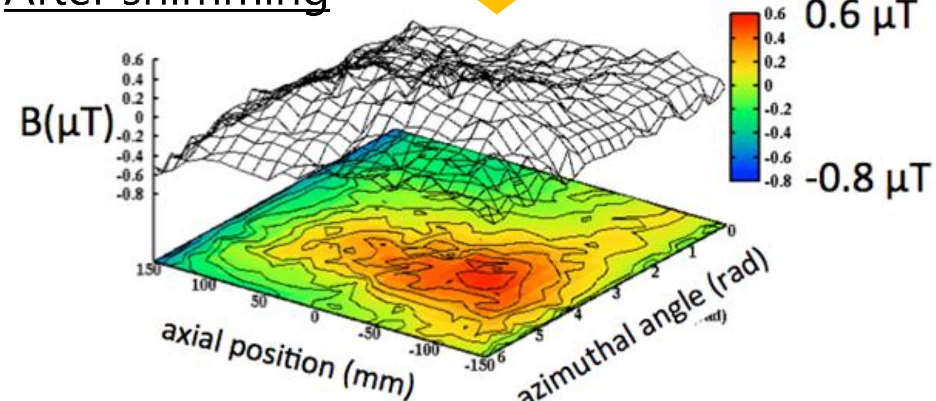
- Compact MRI-type solenoid (3 T)
  - ✓Shimming technique to achieve local uniformity of 1 ppm was confirmed using the same type magnet



Before shimming



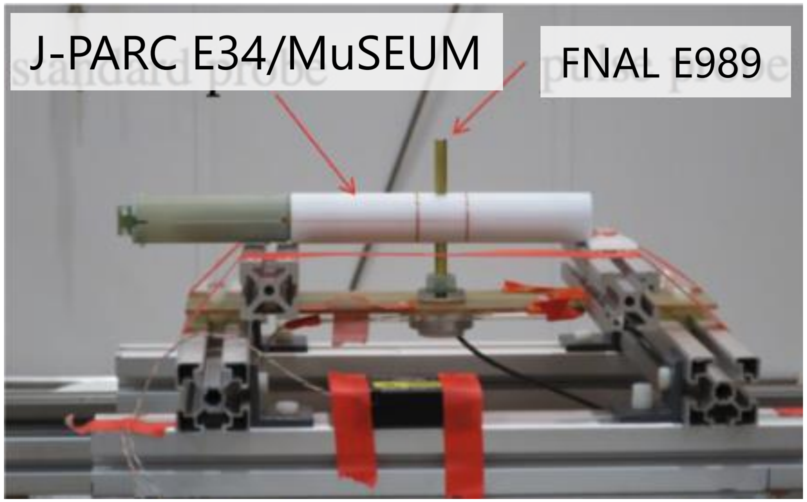
After shimming



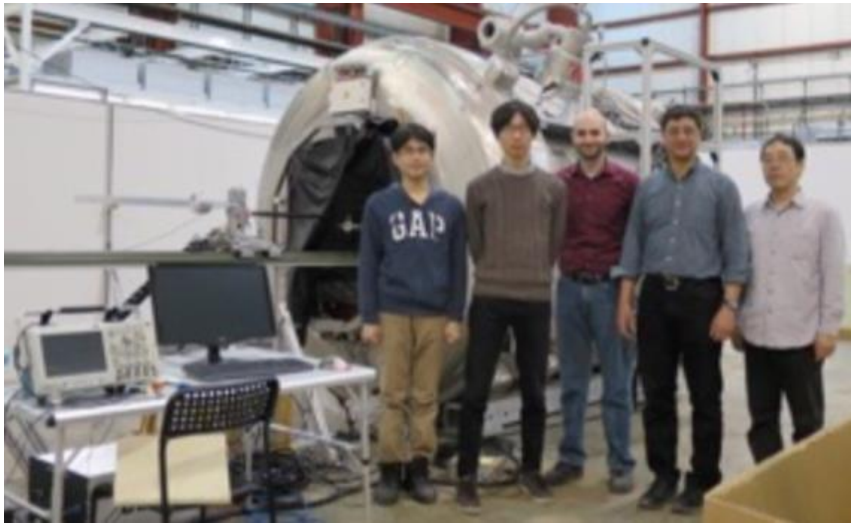
Cross calibration of NMR probes

- NMR probes to measure B (ω_p) were cross-calibration at ANL.

The NMR probes (J-PARC, FNAL E989)



MRI magnet for calibration at ANL (1.45 T)

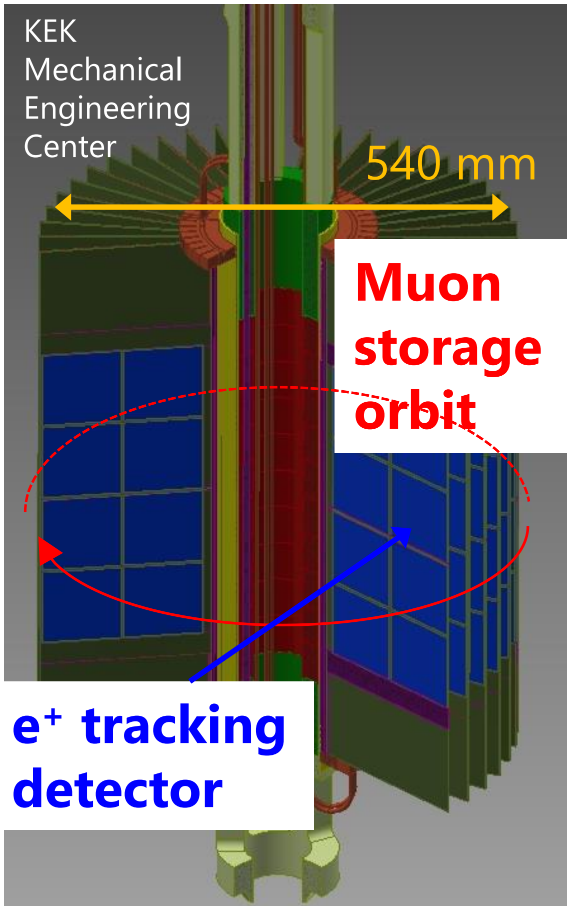


Probe type	Frequency (Hz) *Preliminary*
J-PARC	617 176 44.5 ± 1.0 (0.015 ppm)
Fermilab	617 176 44.9 ± 0.9 (0.015 ppm)
Difference	0.4 ± 1.3 (0.021 ppm)

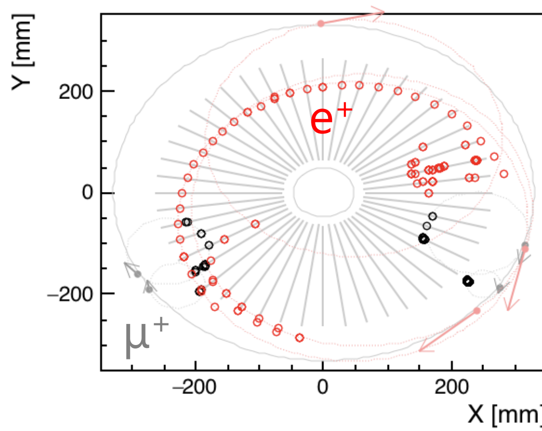
- They agreed within 0.021 ppm!

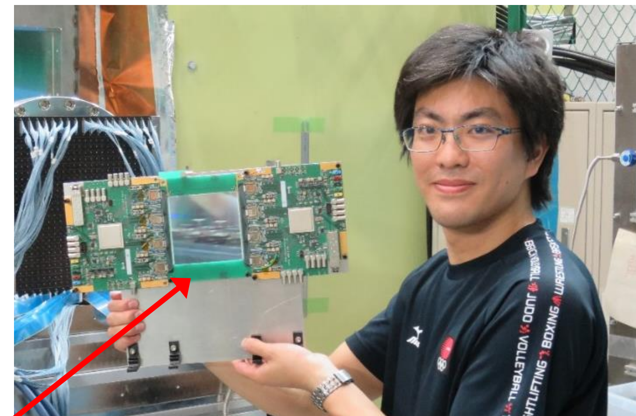
Decay e^+ tracking detector

- Decay e^+ tracks are measured using silicon strip sensors.



Event display





- Prototype module was already used in real experiment (MuSEUM) with muon beam in Jun. 2017.
  - ✓ One silicon strip sensor (512ch x 2 block)
  - ✓ Prototype readout ASIC

Technical Design Report (TDR) 2017

- We revised the TDR responding to focused review committee's recommendations and submitted to PAC in Dec. 2017.

Date	Events
July, 2009	**LOI** submitted to PAC8
January, 2010	**Proposal** submitted to PAC9
January, 2012	**CDR** submitted to PAC13, Milestones defined.
July, 2012	Stage-1 status recommended by PAC15 Stage-1 status granted by the IPNS director
May, 2015	**TDR** submitted to PAC
Oct, 2016	**Revised TDR** submitted to PAC and FRC
Nov, 2016	**Focused review on technical design**
Dec 15, 2017	**Responses and Revised TDR submitted to PAC**

Summary

- J-PARC g-2 experiment (E34) is under preparation to measure muon g-2 with an independent method using ultra slow muon beam.

physics
data & results **construction**

TDR

- **Construction phase is starting and there were many achievements in the last year.**

- Further information : http://g-2.kek.jp

Squamish, BC (Canada)

The collaboration

Collaboration meeting in Kyushu University (December, 2017)

92 “current” members from 40 institutions signed up for the collaboration bylaws (2017)