5th Plenary Workshop of the Muon g-2 Theory Initiatives
7 September 2022, Edinburgh

Muon g-2/EDM experiment at J-PARC

Katsu Ishida (RIKEN)

on behalf of the J-PARC muon g-2/EDM collaboration (E34)

Outline

- concept overview
- progress, update
- schedule, collaboration
- summary

Muon g-2/EDM experiment at J-PARC

Aims for

measurement of muon g-2 independent of BNL and FNL experiments

Phase 1 : 0.45 ppm

Phase 2 : 0.1 ppm

by quite different method

using several novel techniques

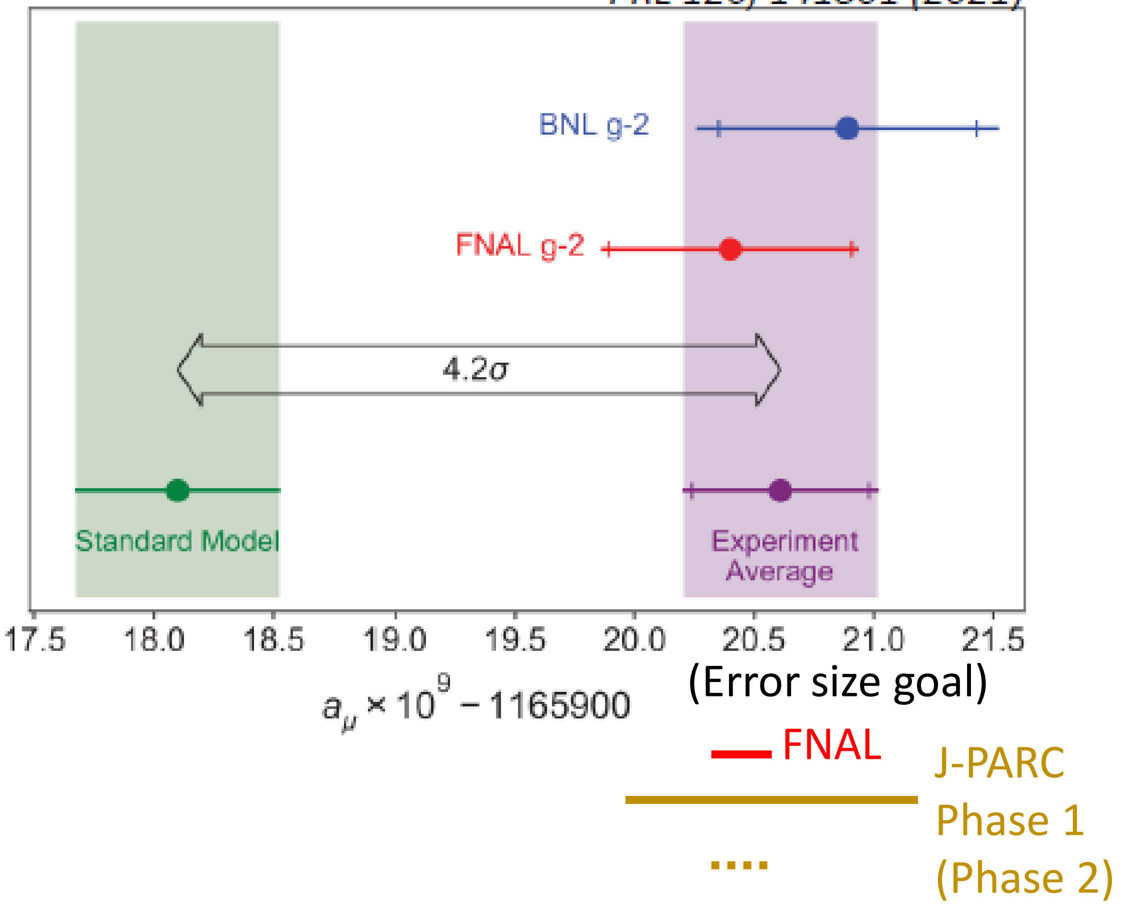
very low emittance muon beam

muon LINAC acceleration from thermal energy

MRI-type high-precision muon storage magnet

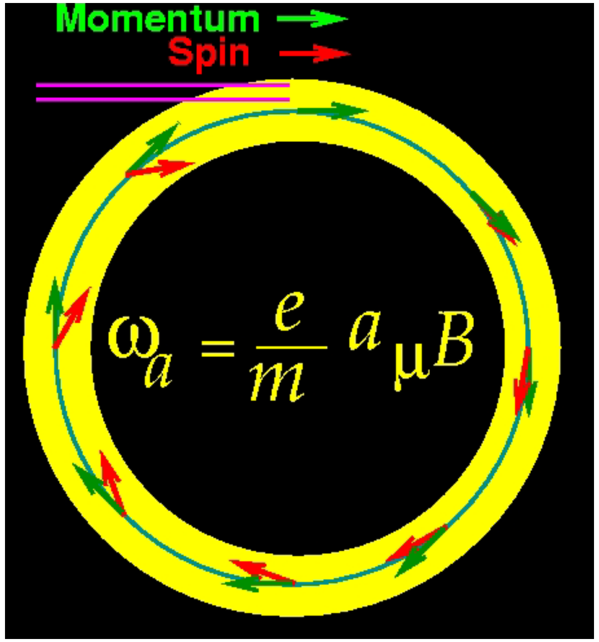
Full tracking detector

PRL 126, 141801 (2021)



muon g-2 and EDM measurements

In uniform magnetic field, muon spin rotates ahead of momentum due to g-2 ≠ 0



general form of spin precession vector:

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

BNL E821 approach
γ=30 (P=3 GeV/c)

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

FNAL E989

J-PARC approach
E = 0 at any γ

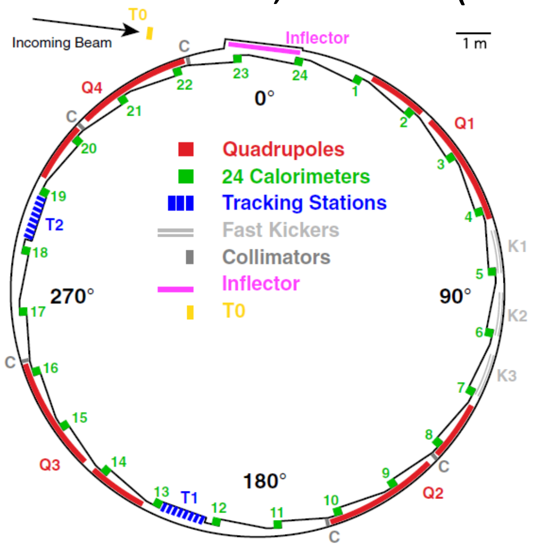
$$\vec{\omega}_a = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right]$$

J-PARC E34

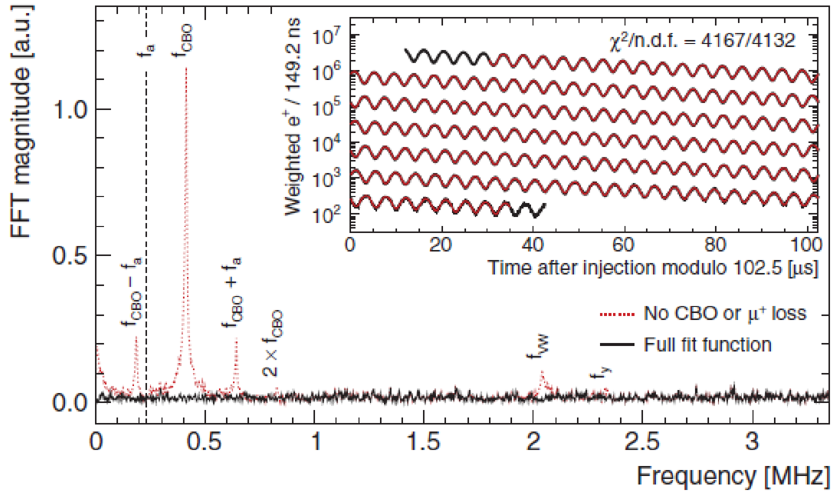
Fermi Muon g-2/EDM Experiment

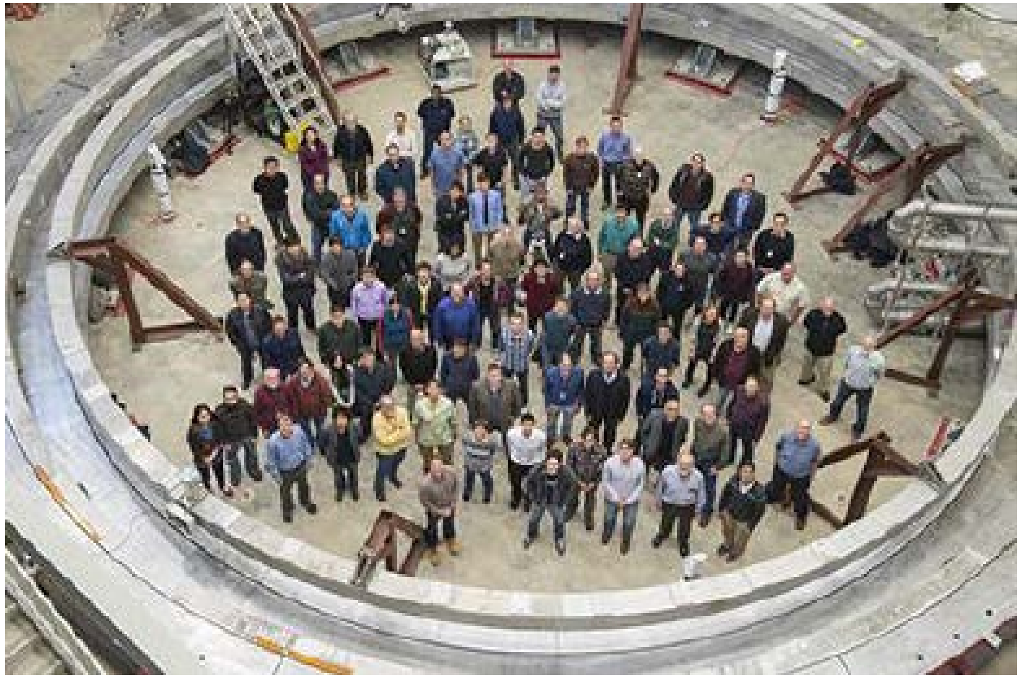
- Based on 3 GeV magic momentum muon beam
  - Muon from high-energy pion decay line at Fermi-lab
  - High precision muon storage ring with 14 m diameter
  - Muon injection kicker
  - Strong focusing with quadrupole electrode
  - Positron detection with calorimeters and tracking detectors

P.R.D. 103, 072002 (2021)



P.R.L. 126, 141801 (2021)



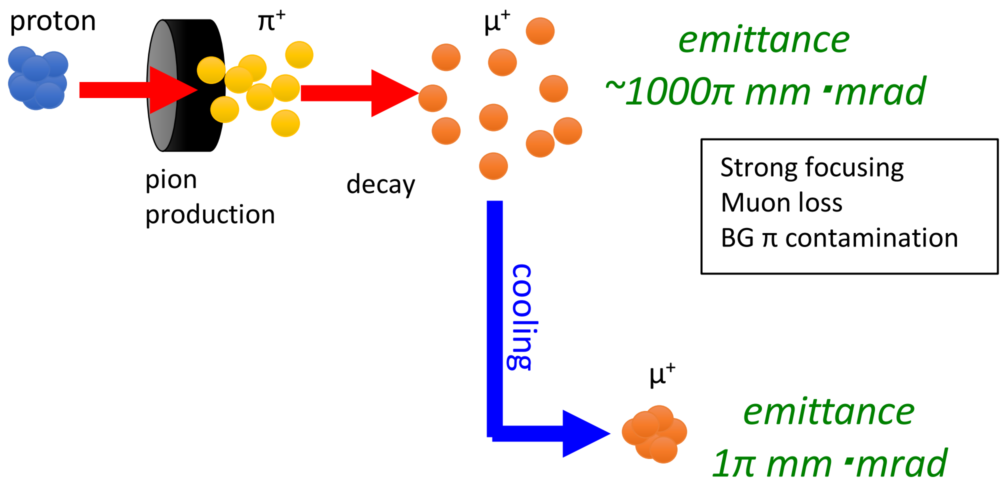


Basis of our method

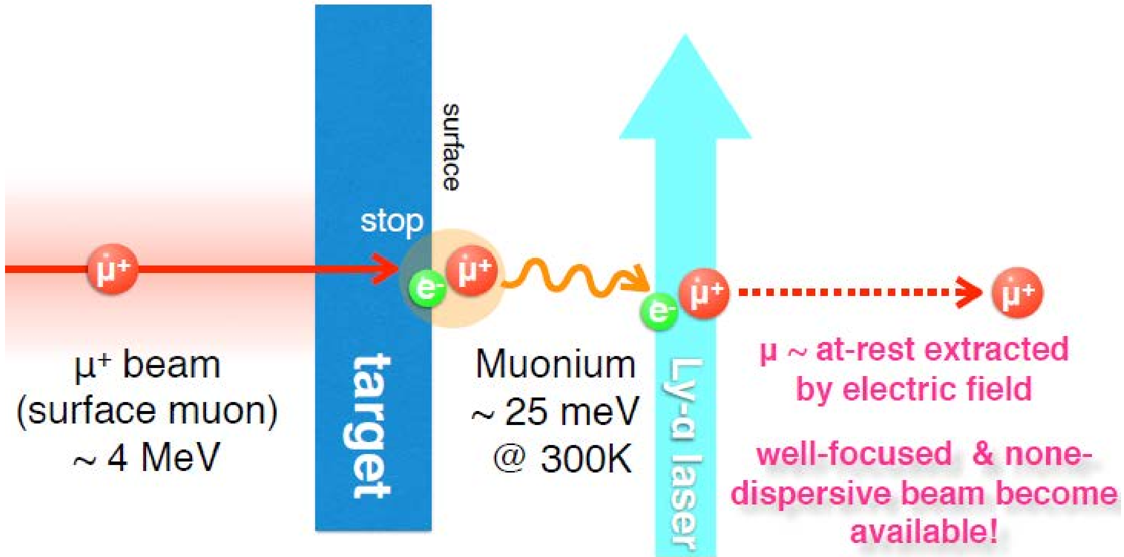
- Very low emittance (cooling) muon beam

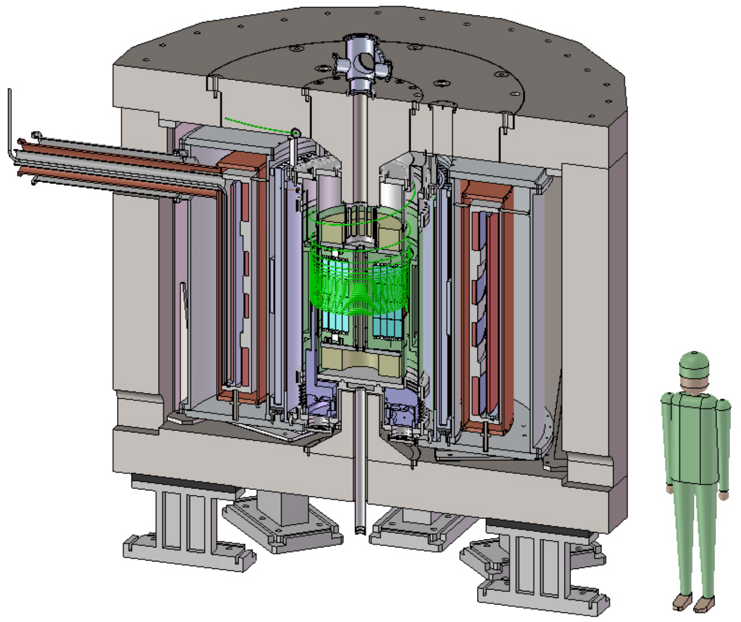
  by reacceleration of thermal energy muon
  - No need of strong focusing E-field

    no restriction on muon momentum
  - MRI type compact precision magnet
  - Full tracking detector

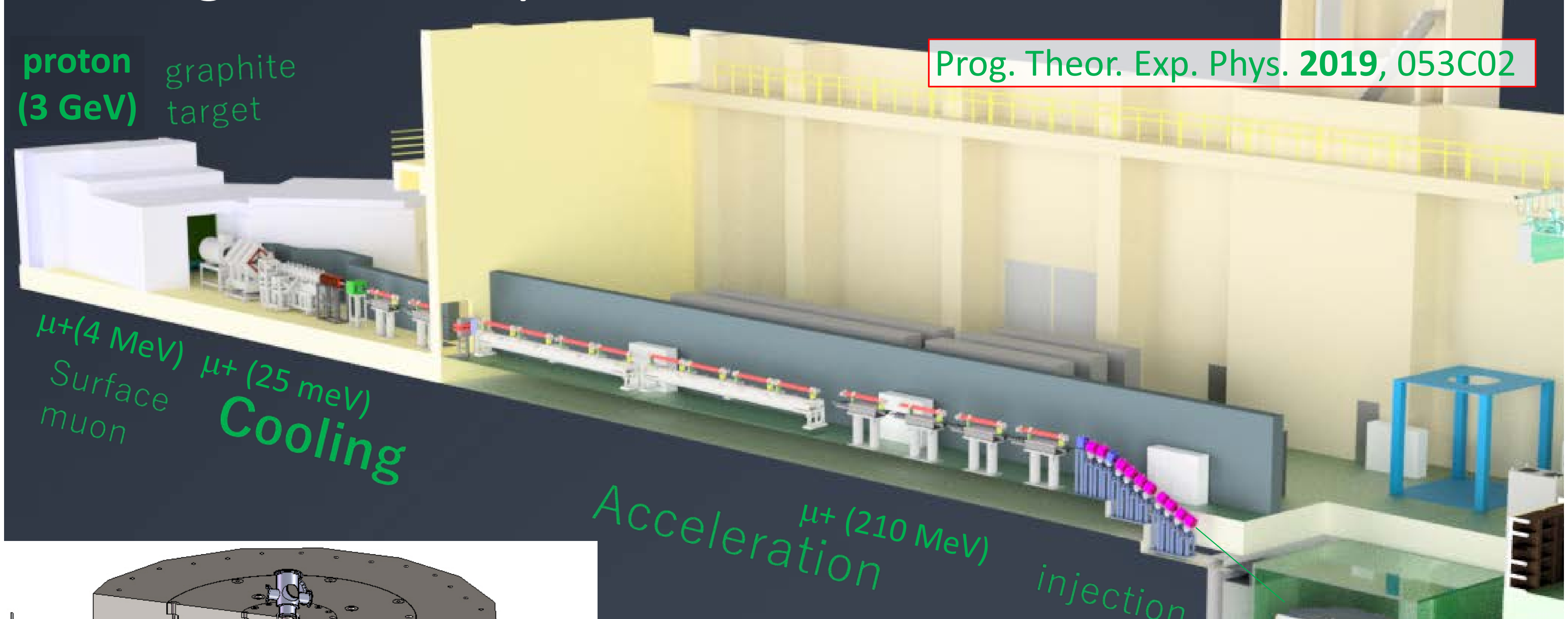


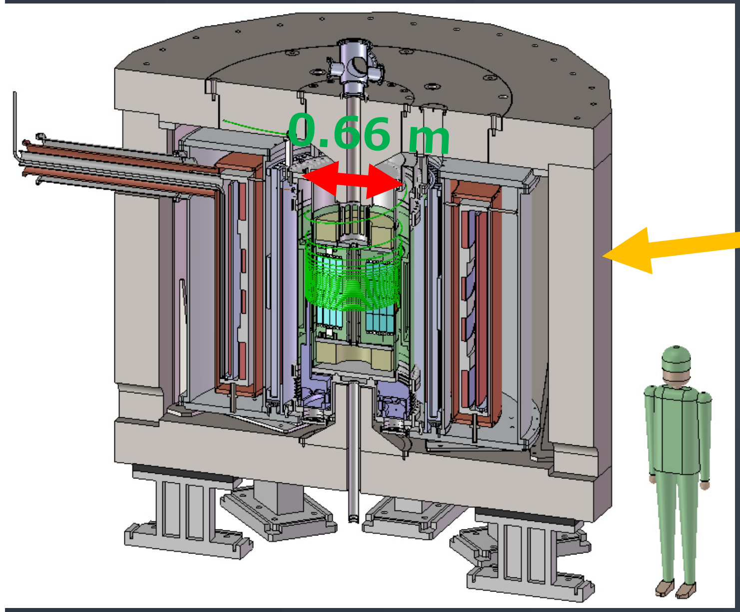
- Thermal energy muon source made by



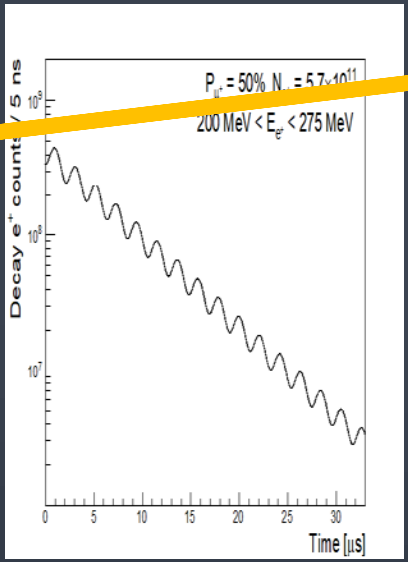


Muon g-2/EDM Experiment at J-PARC: overview





muon storage magnet



Goals:

g-2 450 ppb (~ BNL/FNAL run 1)

EDM 1.5 x 10^{-21} e・cm (x70 better)

Primary muon beam production: J-PARC MLF

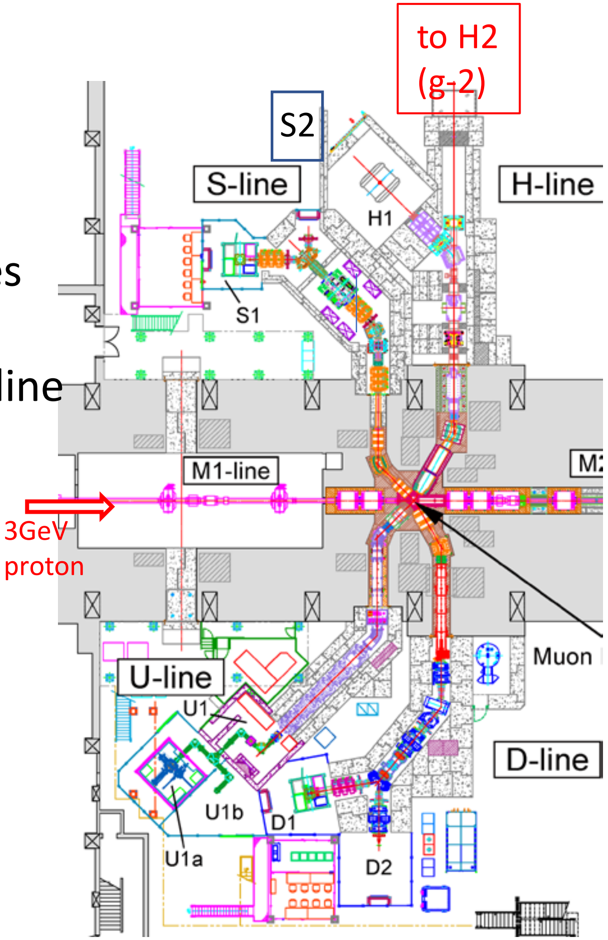
- J-PARC MLF (Materials and Life Science Facility)
  - 1 MW 3 GeV proton beam for neutron and muon production

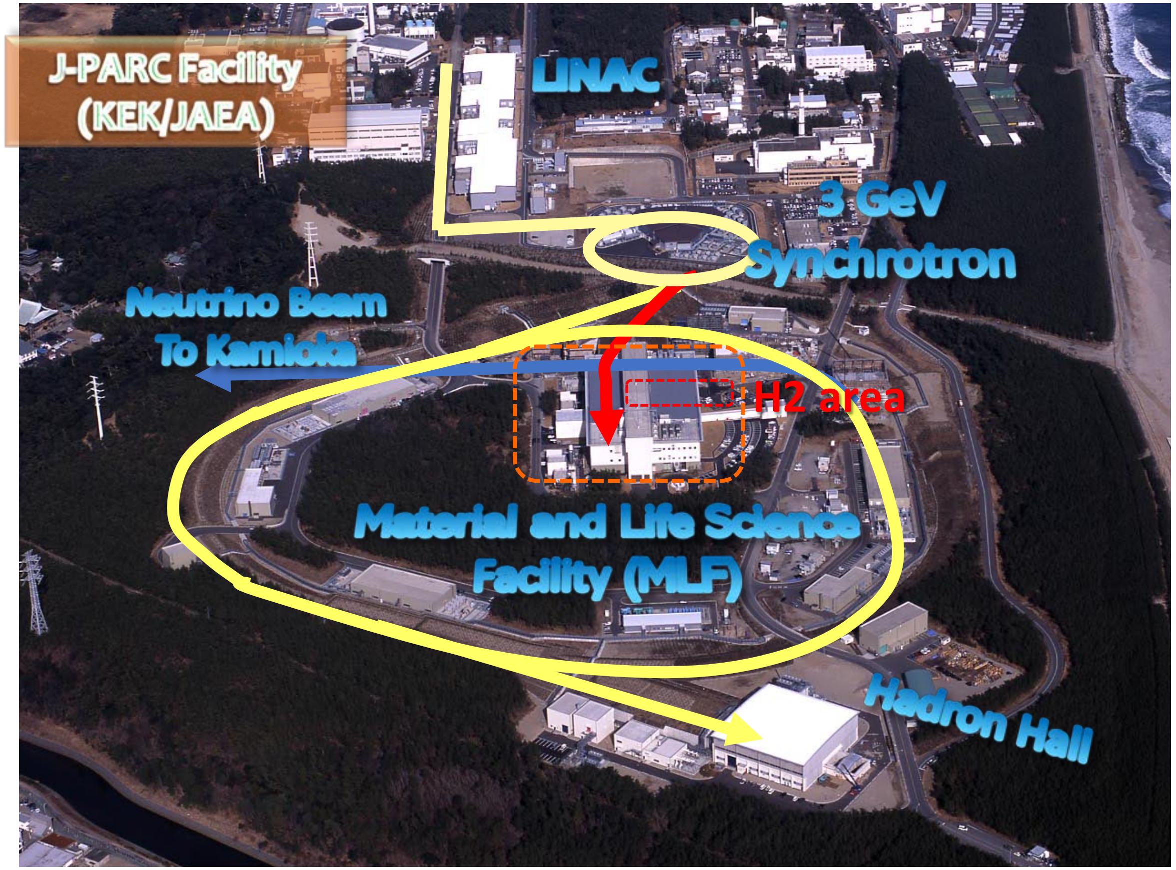
Muon Facility (MUSE)

Four muon beam lines

(D-, U-, S- and H-line)

Muon g-2/EDM at H-line





Muon Beam Line and Experimental Area

New muon beamline "H-line" is under construction

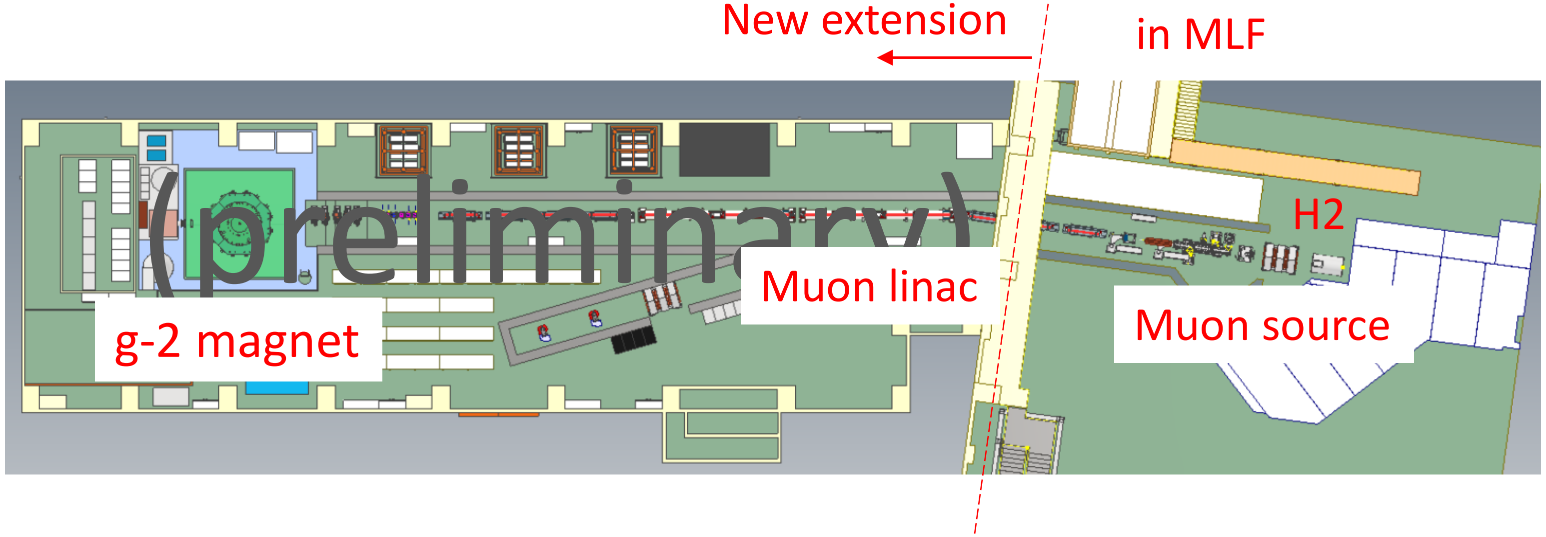
- Beam was delivered to H1 area in early 2022 :

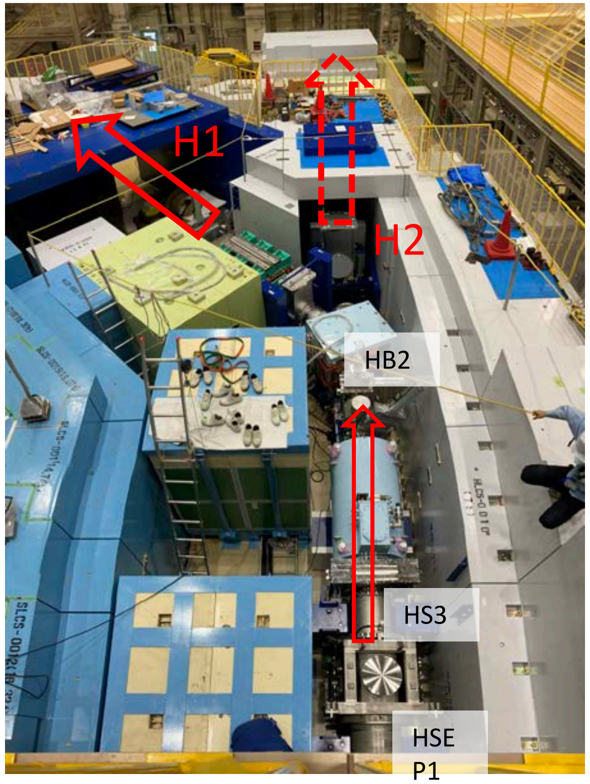
  for μe-conversion (DeeMe) and Mu-HFS (MuSEUM)

- Beam planned to H2 area (for muon g-2) in 2023

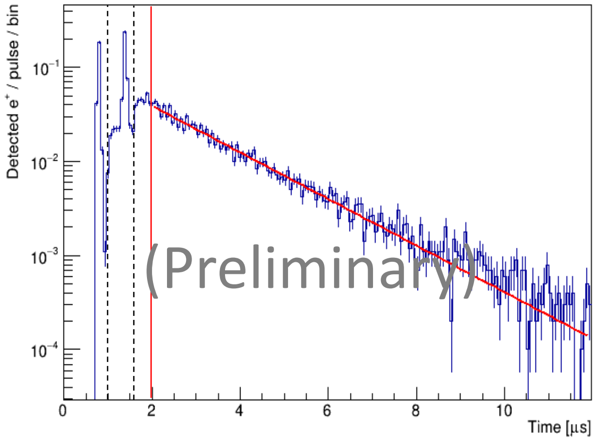
  beamline components, radiation shielding, …

New extension building ready for construction



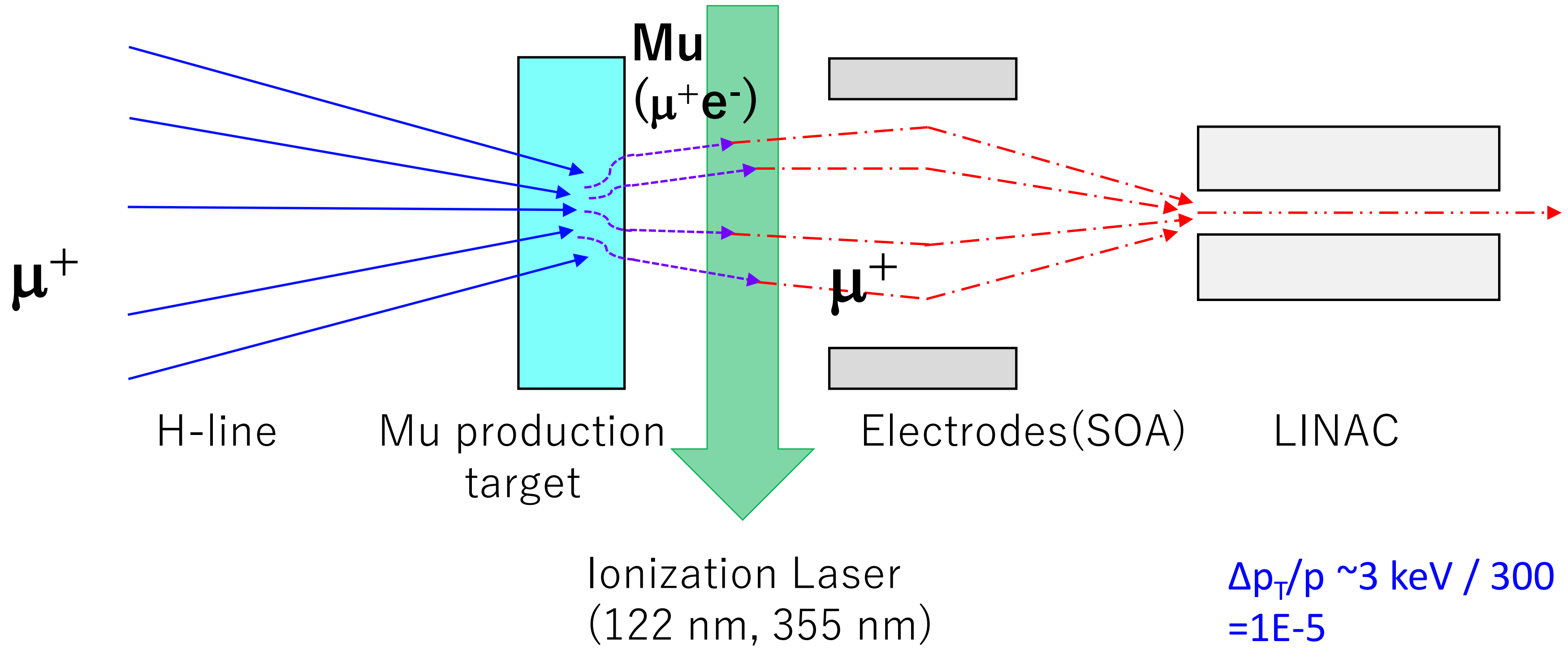


Confirmation of muon intensity (~10^8/s) by muon decay events in H1



Concept of low emittance muon beam production by reacceleration of thermal muon

	surface muon	thermal muon	accelerated muon
E	3.4 MeV	30 meV	212 MeV
p	27 MeV/c	2.3 keV/c	300 MeV/c
Δ p/p	0.05	0.4	4×10^{-4}



$\Delta p_T/p$ ~3 keV / 300 MeV
=1E-5

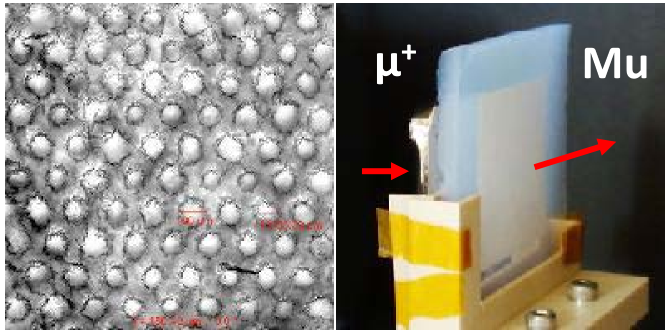
Making thermal energy muon

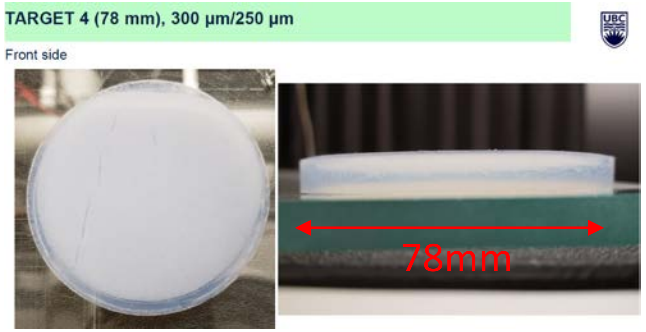
- Silica Aerogel as Muonium (=μ^+e^-) source

Surface muons (~4 MeV) are converted to thermal muonium

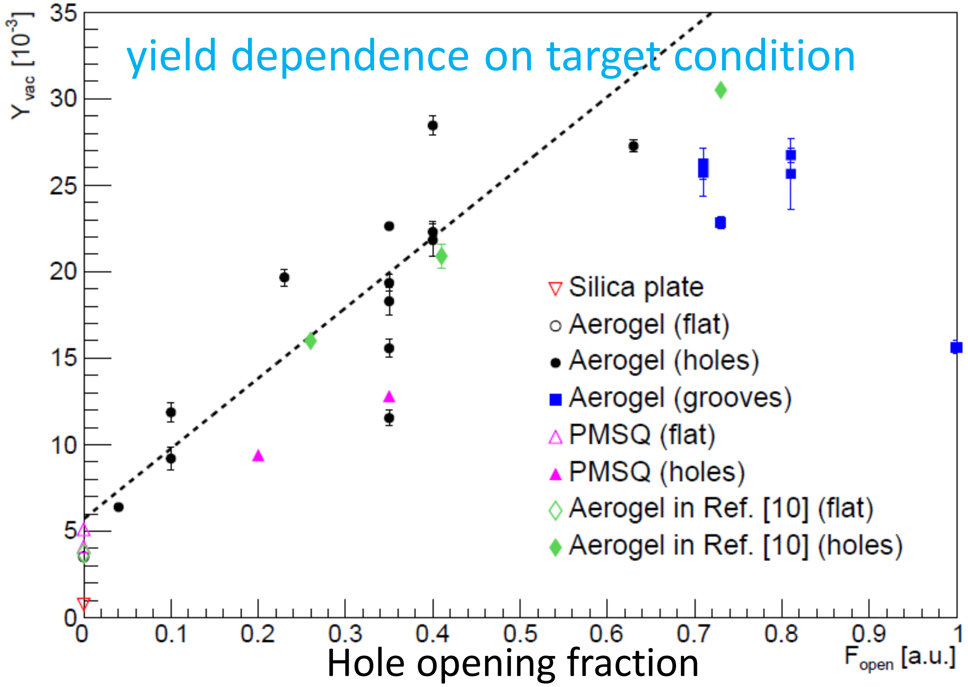
- Cooling from 4 MeV to 0.03 eV (x10^{-8})
- Laser ablation of silica aerogel increased thermal Mu efficiency

P. Bakule etal., PTEP 2013, 103C01
G. Beer et al., PTEP 2014, 091C01
G. Beare et al., PTEP 2020, 123C01





Larger size and less deforming ablated aerogel (at UBC)



Making muon source with laser Ionization

- Mu **ionization** with laser (for μ^+ acceleration)

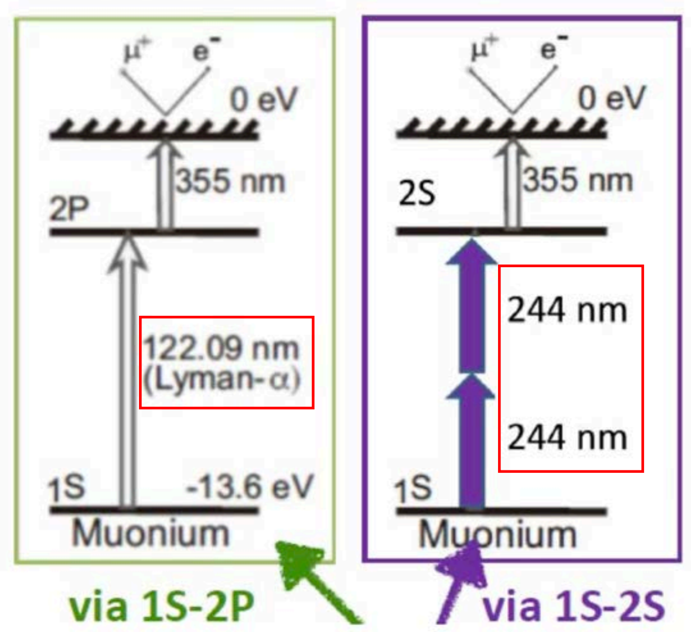
Two schemes are considered for Mu ionization

Mu 1S-2P excitation at U-line

- Efficient single photon excitation
- Challenging 100 μJ Lyman-α laser development

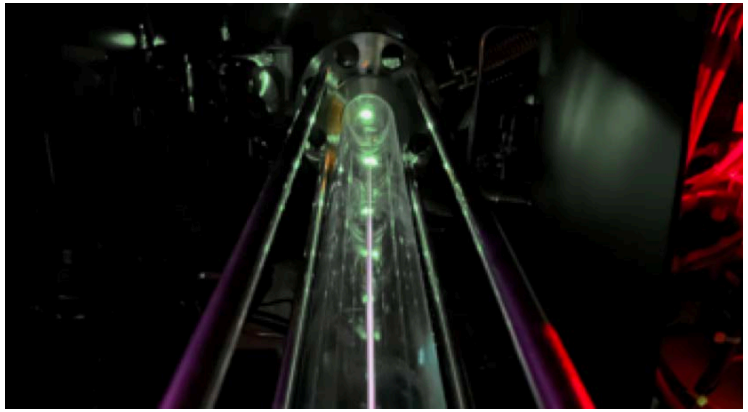
Mu 1S-2S excitation at S-line

- Established 244 nm laser technology
- Demonstration started in S2-line



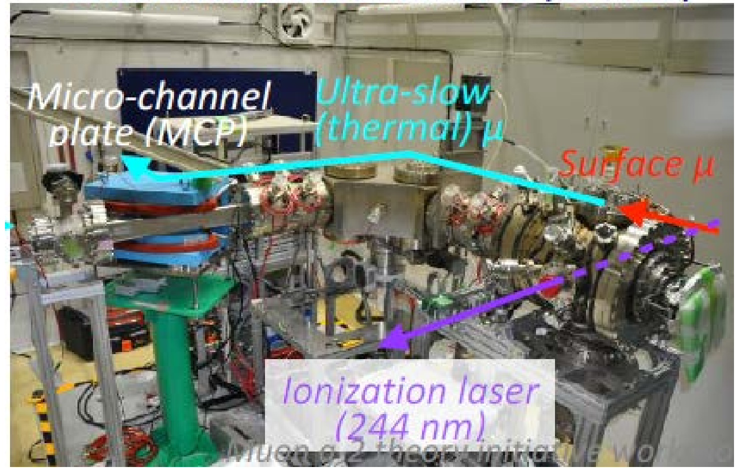
Ionization of Mu form silica aerogel was confirmed this year by both methods

Now comparing the measured efficiency with simulation



Intense Lyman-α 4 μJ at U-line (goal 100 μJ with longer wave mixing chamber in H-line)

Slow muon beam line (SMBL)

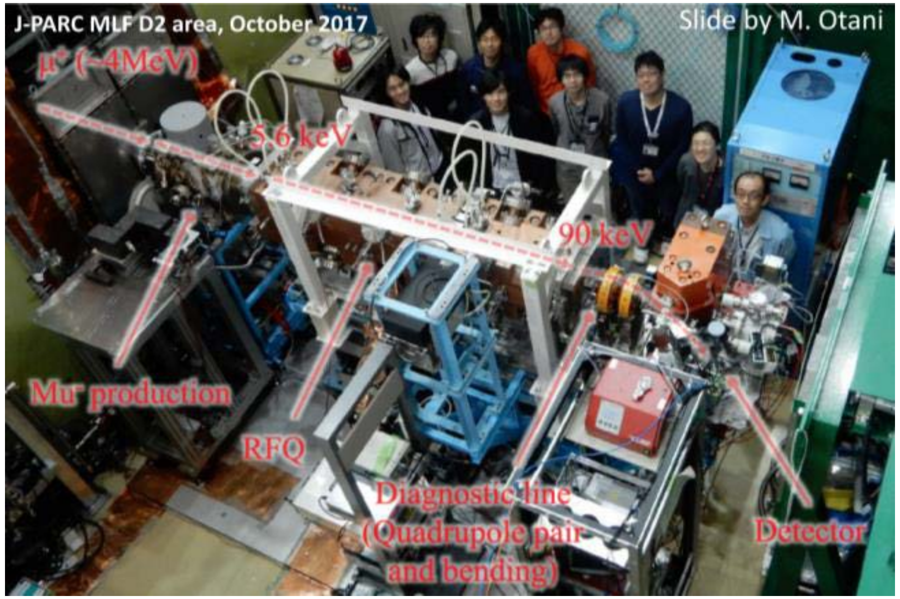


Mu Ionization in S2-line for 1S-2S spectroscopy

High power 244 nm laser development in progress

Muon acceleration : initial stage

- From thermal energy to MeV
  - First step : degraded sub-keV Mu- to RFQ (89 keV)
    - demonstration in 2017
    - bunch structure measurement 2018



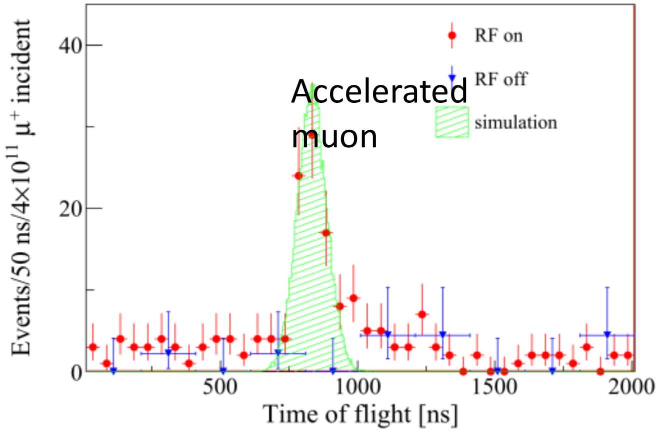
  - Second step : thermal energy muon (~0.03 eV) to RFQ
    – high efficiency and high-quality beam
    - demonstration planned in S2-line in early 2023

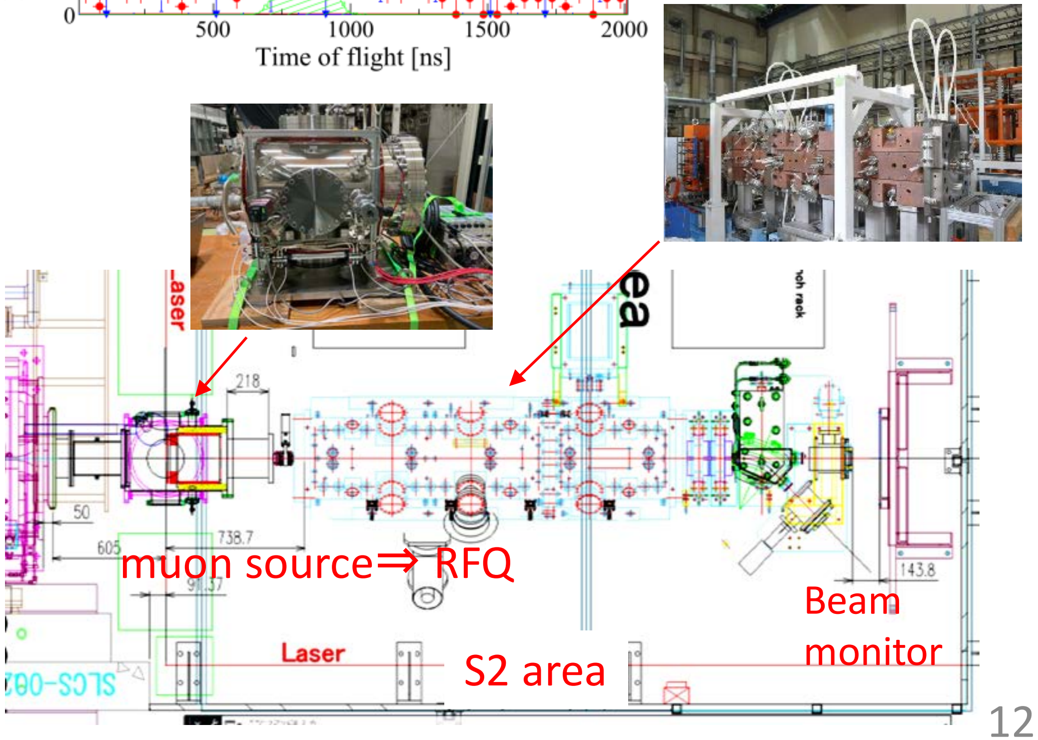
World first muon RF acceleration

S. Bae et al., Phys. Rev. Accel. Beams 21, 050101 (2018)

Bunch width monitor

Y. Sue et al., Phys. Rev. Accel. Beams, 23, 022804 (2020)

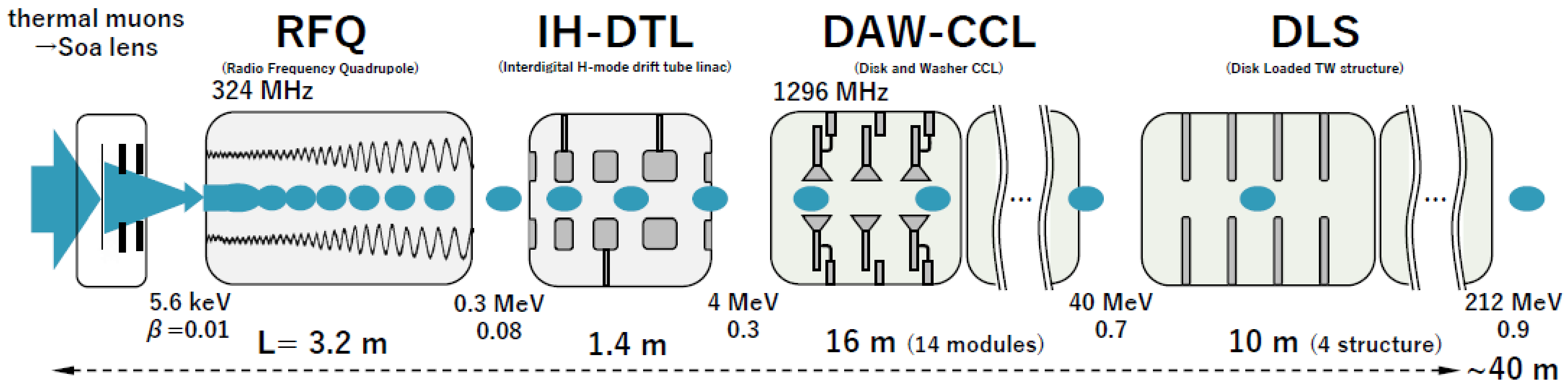




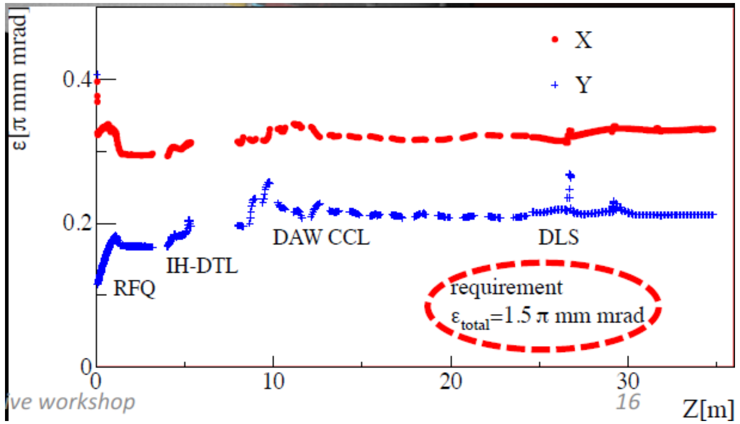
Further acceleration of muons with LINAC

- The rest of muon LINAC cavities are designed and evaluated for acceleration to 212 MeV (300 MeV/c)

Staging design for fast muon acceleration covering wide β region



(Emittance growth simulation)

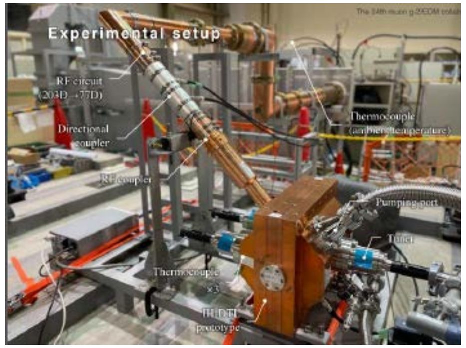


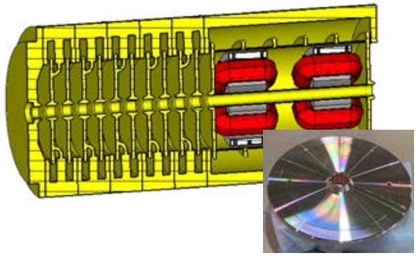
Test with thermal muon in 2023

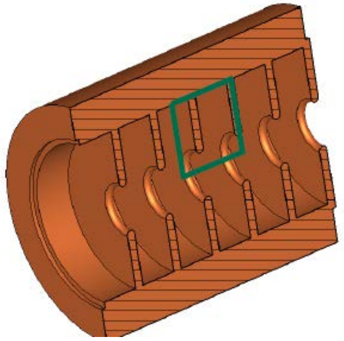
Proto-cavity power test, Real cavity production

First real tank is fabricated

Prototype fabrication in 2022FY







Thanks to Special Promotion Grant-in-aid 2020-2025 (Kakenhi)

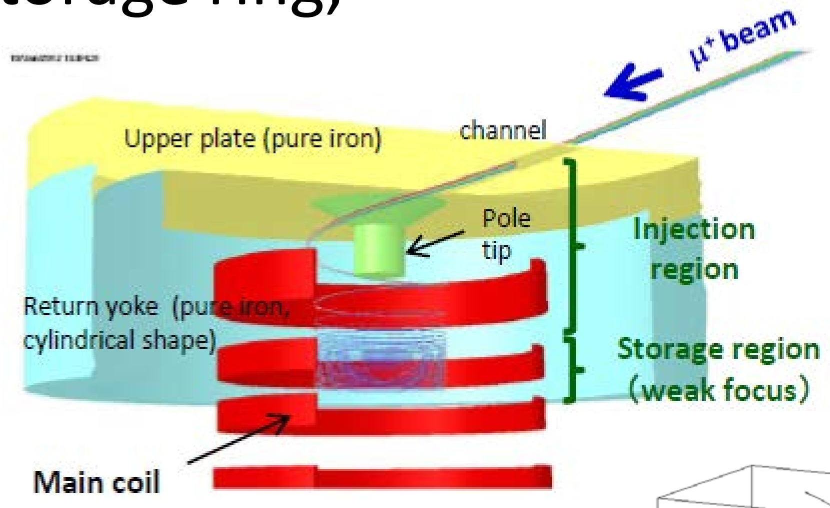
Spiral Muon Injection

- For injection of muon beam into compact storage ring,

  3D spiral injection scheme has been invented
  - Smooth connection between injection and storage regions
  - Pulsed magnetic kicker to guide muons to stable orbit
  - Weak-focusing magnetic field to control muons in a few cm

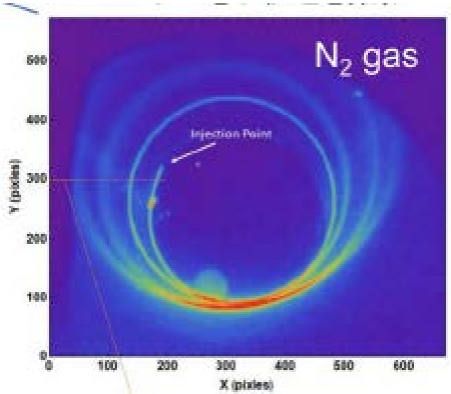
  Injection efficiency : ~85%

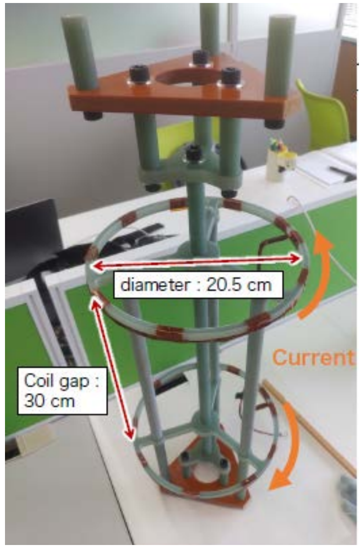
  H. Iinuma et al., Nucl. Instr. And Methods. A 832, 51 (2016)

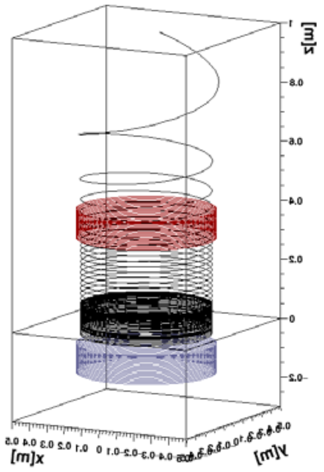


Test experiment using electron beam is progressing

- 297 keV/c e- and 8.25 mT, 24cmϕ (versus 300 MeV/c and 3 T, 66cmϕ)
- visualization of 3-D spiral geometry with CCD camera
- Test of beam shape effect and proto-type kicker



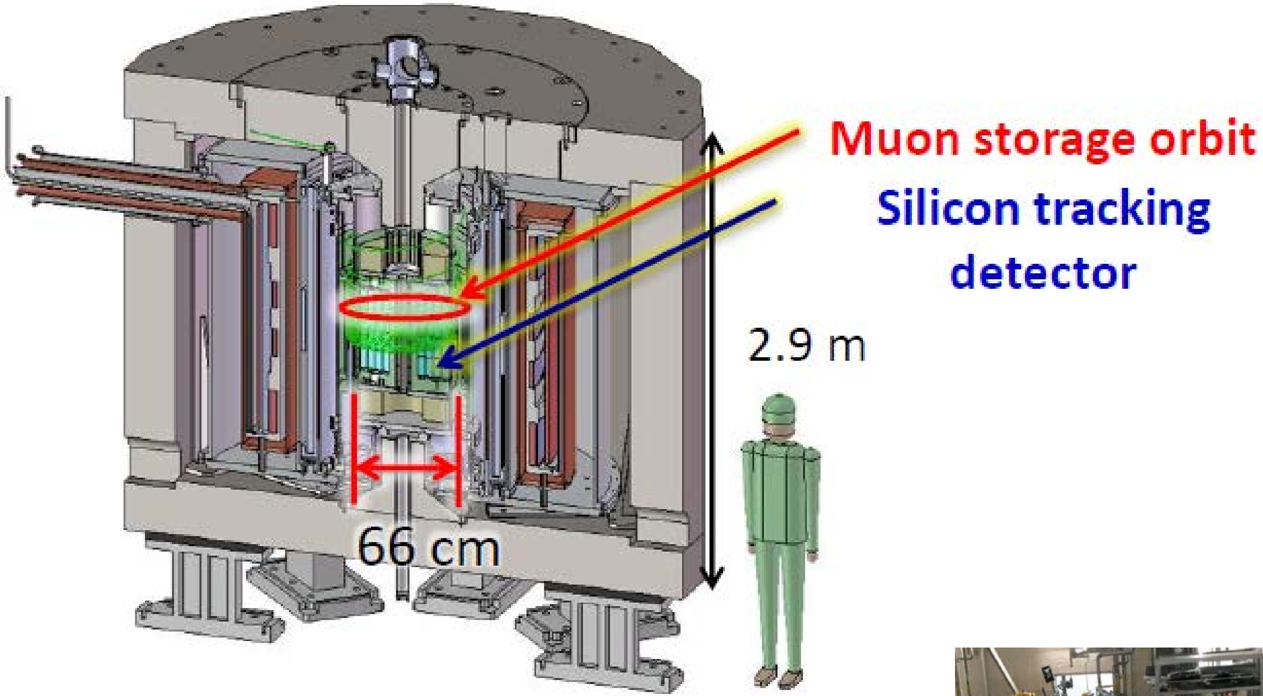




Injection, kicker and storage simulation

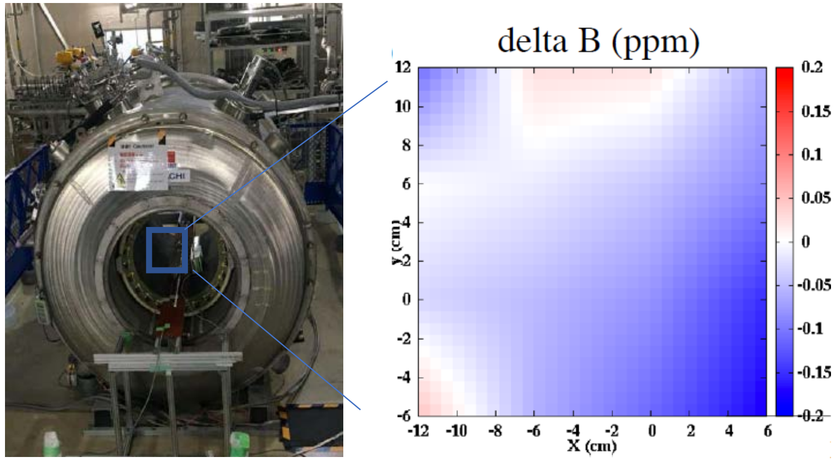
Muon Storage Magnet and Field Measurement

- 3T MRI-type superconducting solenoid magnet



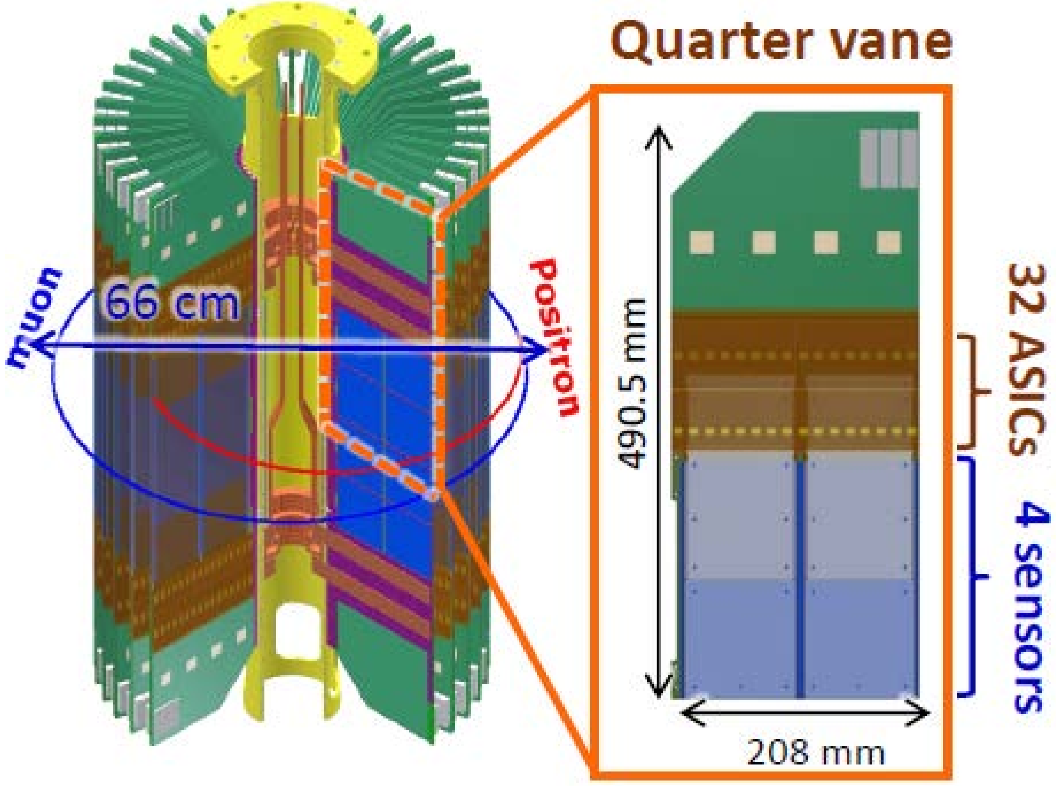
Cross-calibration of FNAL and J-PARC field probes at ANL at 1.45 and 1.7 T in 2019 (3 T study planned)

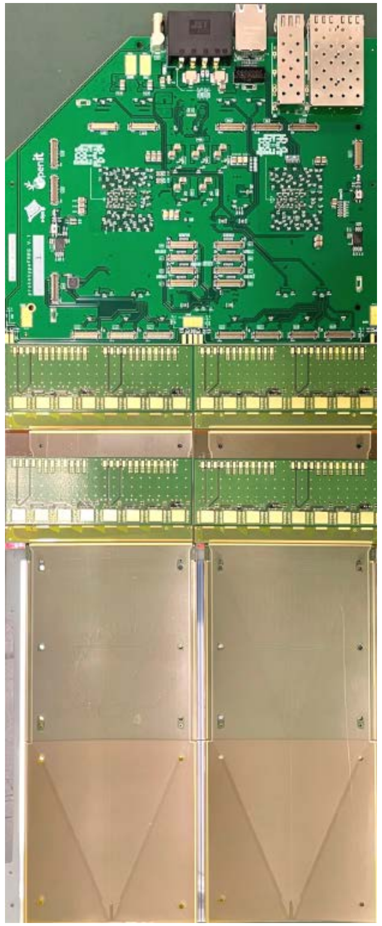
Demonstration of sub-ppm field shimming at 1.2 T using MuSEUM magnet



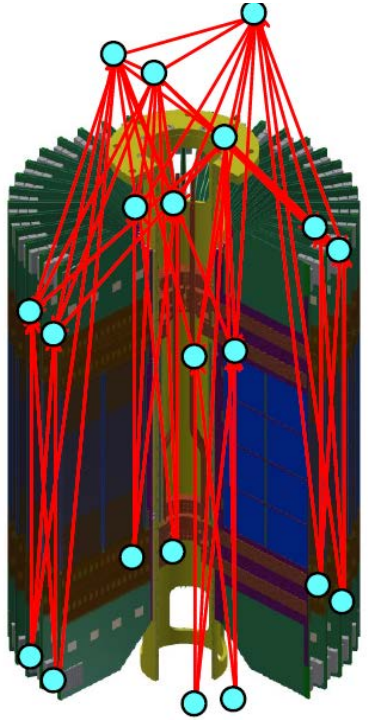
Detector and Analysis

- Positrons tracks are reconstructed by Silicon-strip detector
  - Mass production in progress
  - Readout ASIC was developed for this detector (*IEEE TNS 67, 2089(2020)*)
  - Prototype modules were tested at J-PARC and ELPH (*JINST 15 P04027 (2020)*)



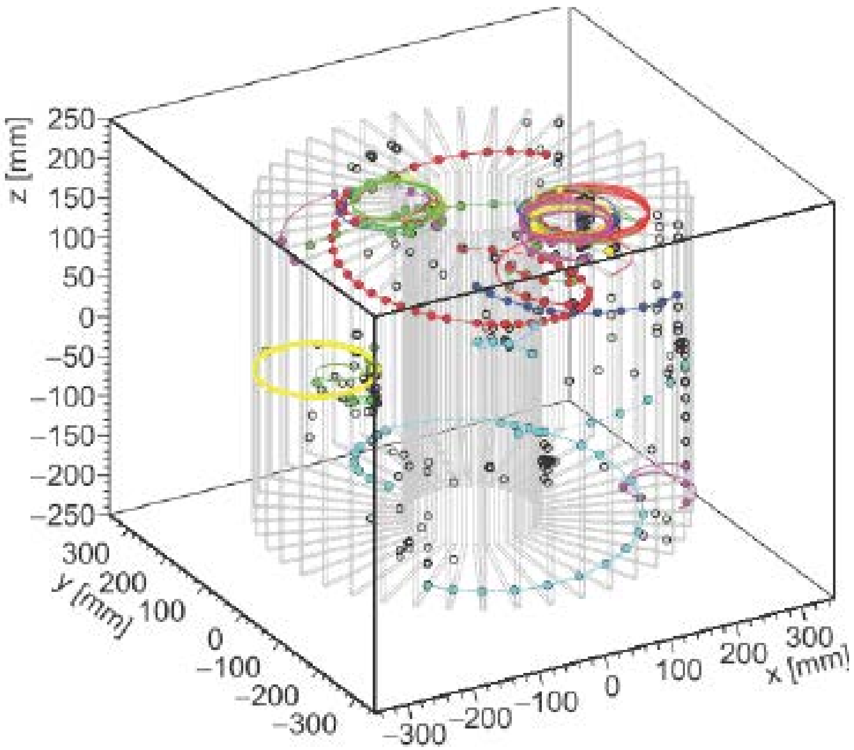


Alignment monitor

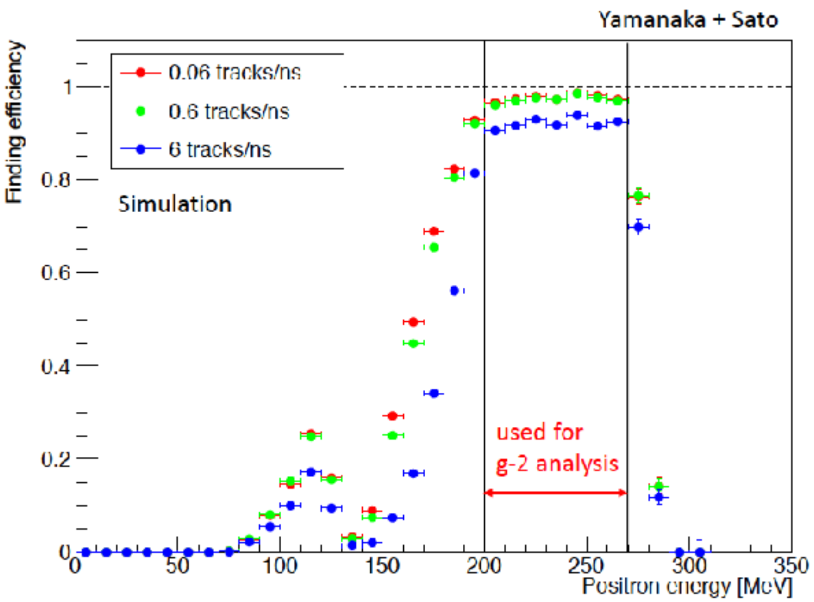


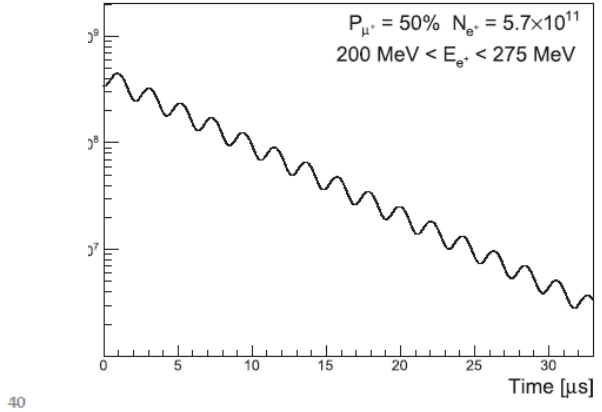
Detector and Analysis

- Simulation and track reconstruction software package being developed



Reconstruction efficiency





Reconstruction of positron energy and timing gives g-2 precession pattern

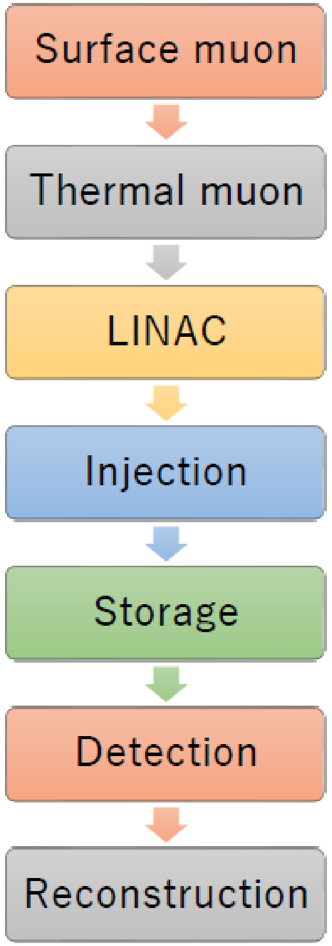
End to end simulation

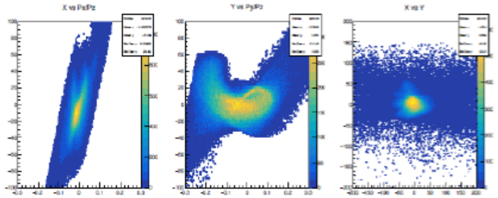
- Software package is being developed to make end-to-end simulation
  - 1.8 x 10^6 muons simulated at LINAC exit in 2020
  - 10 times more in 2022

    will be used for statistics and systematics study
  - ~10^9 will be needed for systematics in

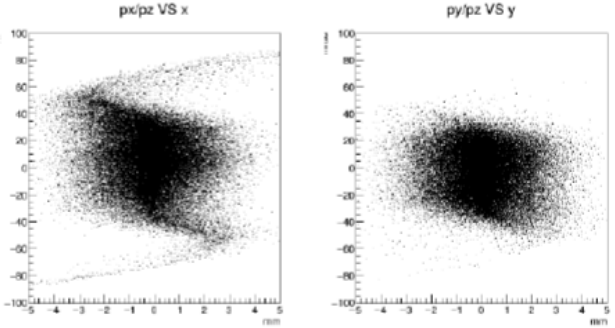
    timing shift by pile-up, sensor alignment using tracks

End-to-end simulation flow



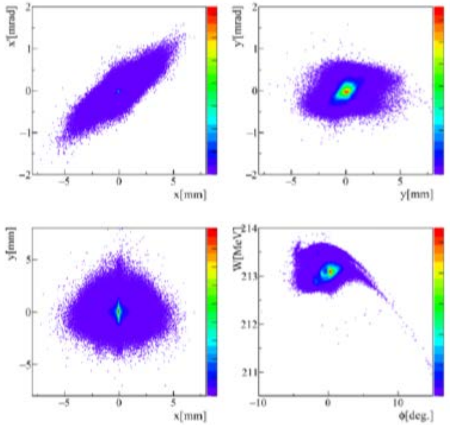


Surface muon

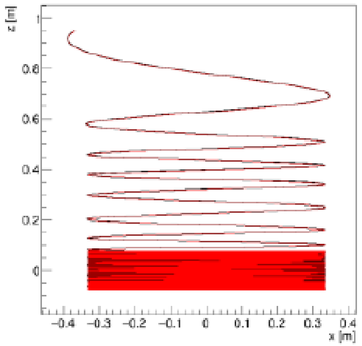


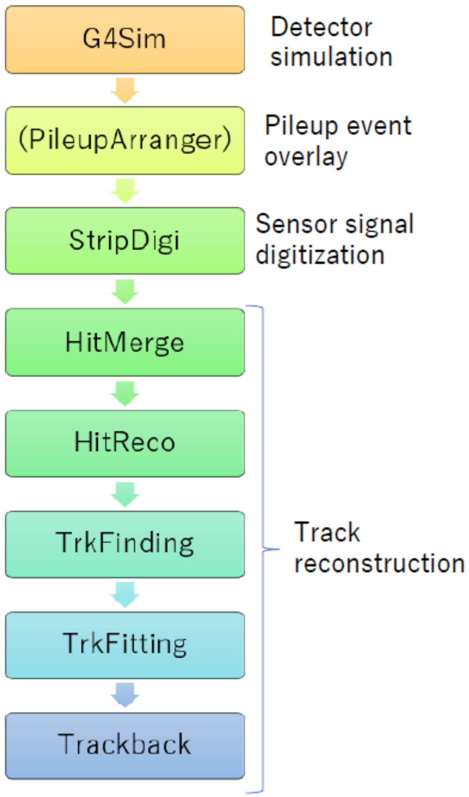
RFQ input

LINAC exit



Spiral injection





Truck reconstruction
g2esoft

Statistical and systematic uncertainties

E34 TDR Summary Paper,
Prog. Theor. Exp. Phys. 2019, 053C02

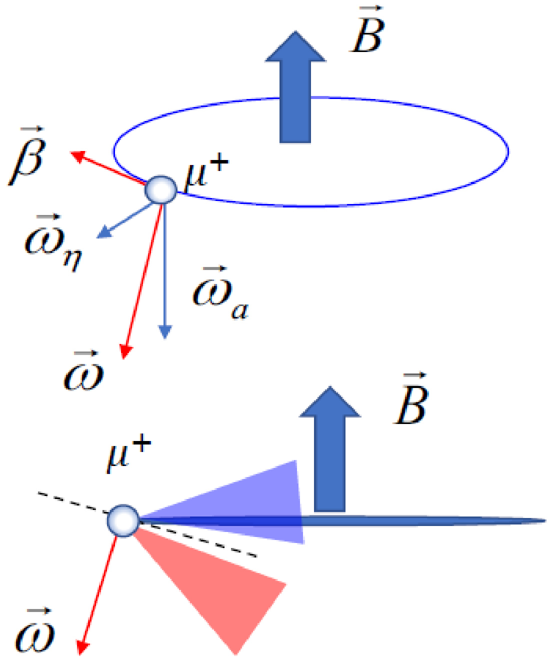
Summary of statistical uncertainties

	Estimation
Total number of muons in the storage magnet	5.2×10^{12}
Total number of reconstructed e^+ in the energy window [200, 275 MeV]	5.7×10^{11}
Effective analyzing power	0.42
Statistical uncertainty on ω_a [ppb]	450
Uncertainties on a_μ [ppb]	450 (stat.)
	$<$ 70 (syst.)
Uncertainties on EDM [10^{-21} $e\cdot$cm]	1.5 (stat.)
	0.36 (syst.)

Estimated systematic uncertainties on a_μ

Anomalous spin precession (ω_a)		Magnetic field (ω_p)	
Source	Estimation (ppb)	Source	Estimation (ppb)
Timing shift	$<$ 36	Absolute calibration	25
Pitch effect	13	Calibration of mapping probe	20
Electric field	10	Position of mapping probe	45
Delayed positrons	0.8	Field decay	$<$ 10
Diffential decay	1.5	Eddy current from kicker	0.1
Quadratic sum	$<$ 40	Quadratic sum	56

EDM Measurement

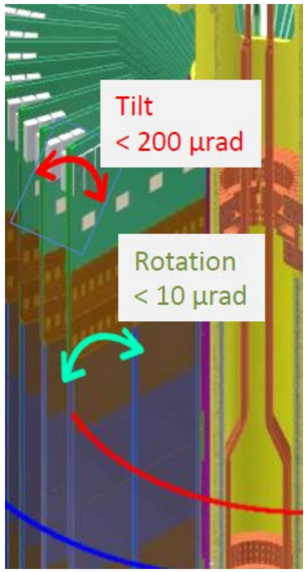


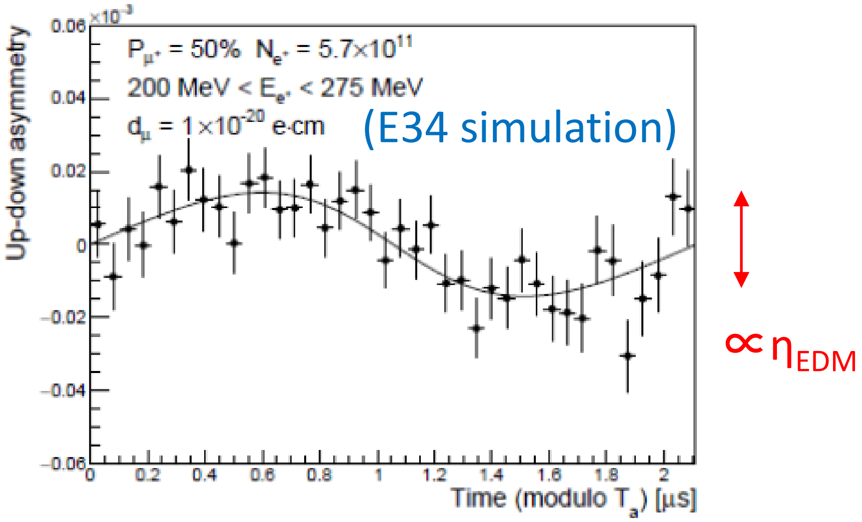
EDM measurement relies on the tilt of muon precession to the mid plane

- No E-field simplifies the measurement

$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_\eta = \underbrace{-a\frac{q}{m}\vec{B}}_{\text{g-2}} - \underbrace{\eta\frac{q}{2m}(\vec{\beta}\times\vec{B})}_{\text{EDM}}.$$

- To be observed in up-down asymmetry
- $\tan\delta = \omega_\eta/\omega_a = \eta\beta/2a$
- Good detector alignment precision is essential
- to aim at 10^{-21} e cm sensitivity (10^{-5} rad)
- 1 μm detector alignment is developed





Comparison of Parameters

	BNL-E821	Fermilab-E989	Our experiment
Muon momentum	3.09 GeV/c		300 MeV/c
Lorentz γ	29.3		3
Polarization	100%		50%
Storage field	$B = 1.45$ T		$B = 3.0$ T
Focusing field	Electric quadrupole		Very weak magnetic
Cyclotron period	149 ns		7.4 ns
Spin precession period	4.37 μs		2.11 μs
Number of detected e^+	5.0×10^9	1.6×10^{11}	5.7×10^{11}
Number of detected e^-	3.6×10^9	–	–
a_μ precision (stat.)	460 ppb	100 ppb	450 ppb
(syst.)	280 ppb	100 ppb	<70 ppb
EDM precision (stat.)	0.2×10^{-19} $e \cdot$ cm	–	1.5×10^{-21} $e \cdot$ cm
(syst.)	0.9×10^{-19} $e \cdot$ cm	–	0.36×10^{-21} $e \cdot$ cm

phase 1
~250 days

Collaboration Status

110 members from Canada, China, Czech, France, India, Japan, Korea, Netherlands, Russia, USA

Collaboration board (CB)
Chair: Seonho Choi

Executive board (EB)
Spokesperson: T. Mibe

Subgroups

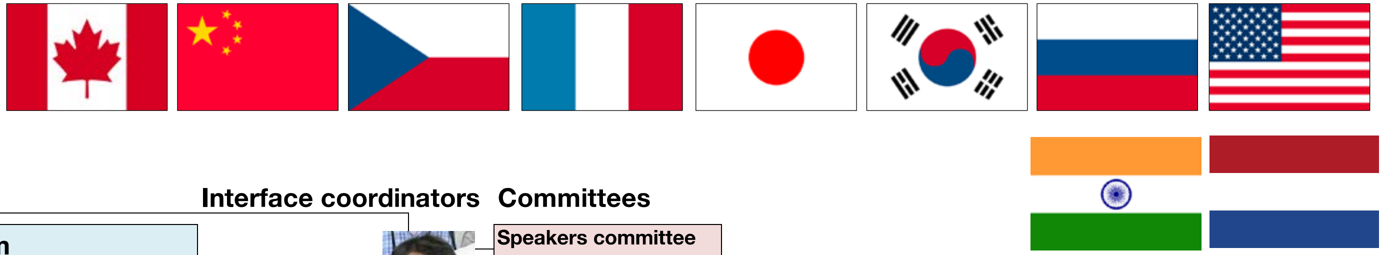
- **Surface muon beam** leader: T. Yamazaki, N. Kawamura
- **Ultra-slow muon** leader: K. Ishida, G. Marshall
- **LINAC** leader: Y. Kondo, M. Otani
- **Injection and storage** leader: H. Iinuma
- **Storage magnet, field measurements**
- **Detector** leader: T. Yoshioka
- **DAQ and computing** leader: Y. Sato, (K. Hayasaka)
- **Analysis** leader: T. Yamanaka

Interface coordinators

K. Ishida, M. Otani, Y. Kondo, H. Iinuma, T. Kume, Y. Sato, T. Suehara, T. Yamanaka

Committees

- **Speakers committee** chair: K.Ishida
- **Publication committee** chair: B. Shwartz



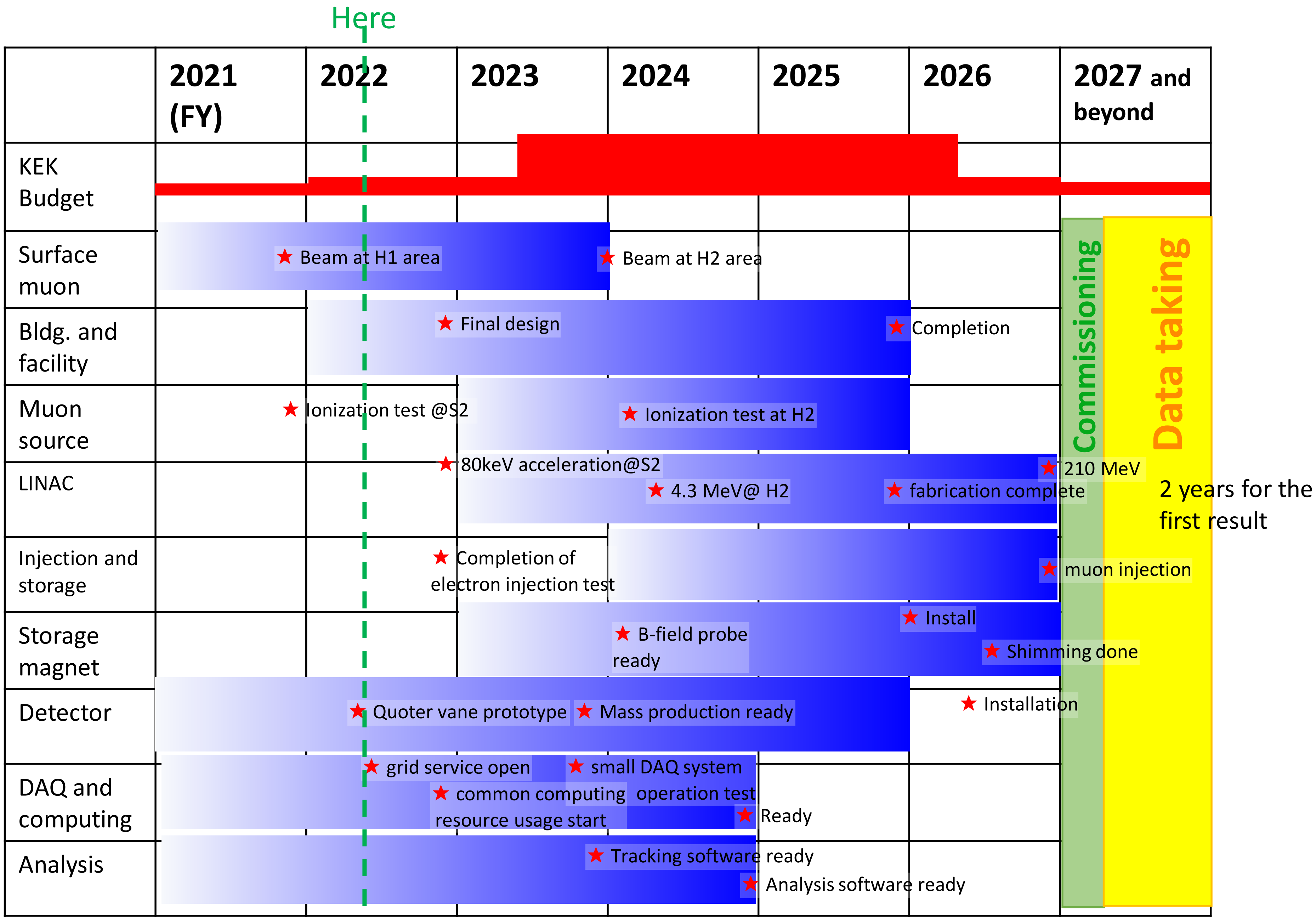
New

Welcome University of Groningen

Domestic institutes：
Kyushu, Nagoya, Tohoku, Niigata, Tokyo, Ibaraki, RIKEN, JAEA, etc.
KEK: IPNS, IMSS, ACC, CRY, MEC, CRC

The 24th J-PARC muon g-2/EDM collaboration meeting, June 8-10, 2022

Schedule



★ miles stones – many in this FY

Summary

- muon g-2/EDM experiment at JPARC aims to measure muon g-2 and EDM with a new experimental approach
  - Low emittance muon beam
  - MRI-type storage ring with good injection efficiency and highly uniform B-field
  - Full tracking detector with large acceptance

- The experiment is getting ready for realization
  - Construction of new muon beam line (H-line) and building design
  - Achieving many R&D and test milestones
  - Production of the subsystems are on going

- Expecting data taking to start in FY2027

  + 2 years run for 1st result

Thank you for your attention.