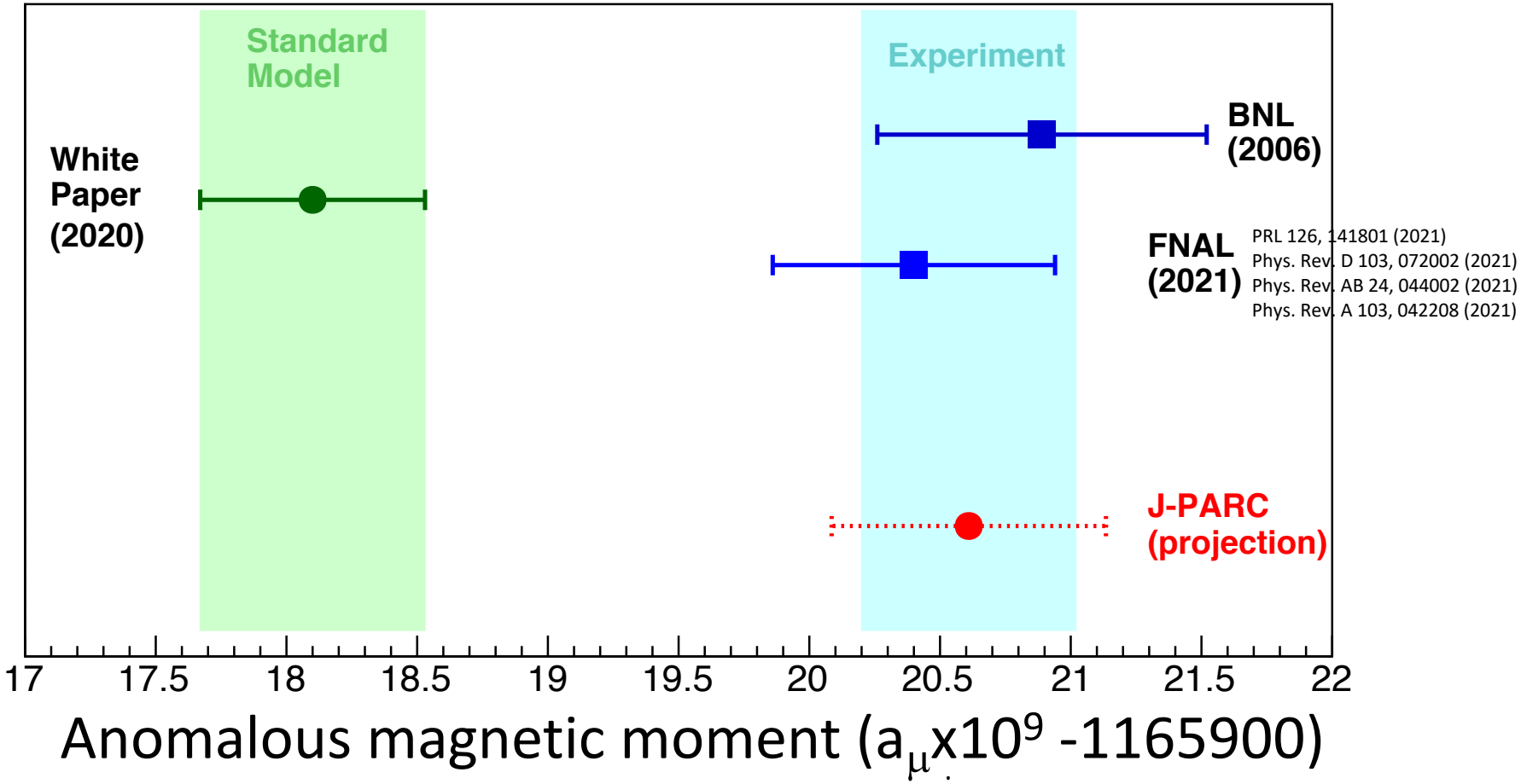
Muon g-2/EDM at J-PARC

October 20, 2022

PSI2022

Tsutomu Mibe (KEK)

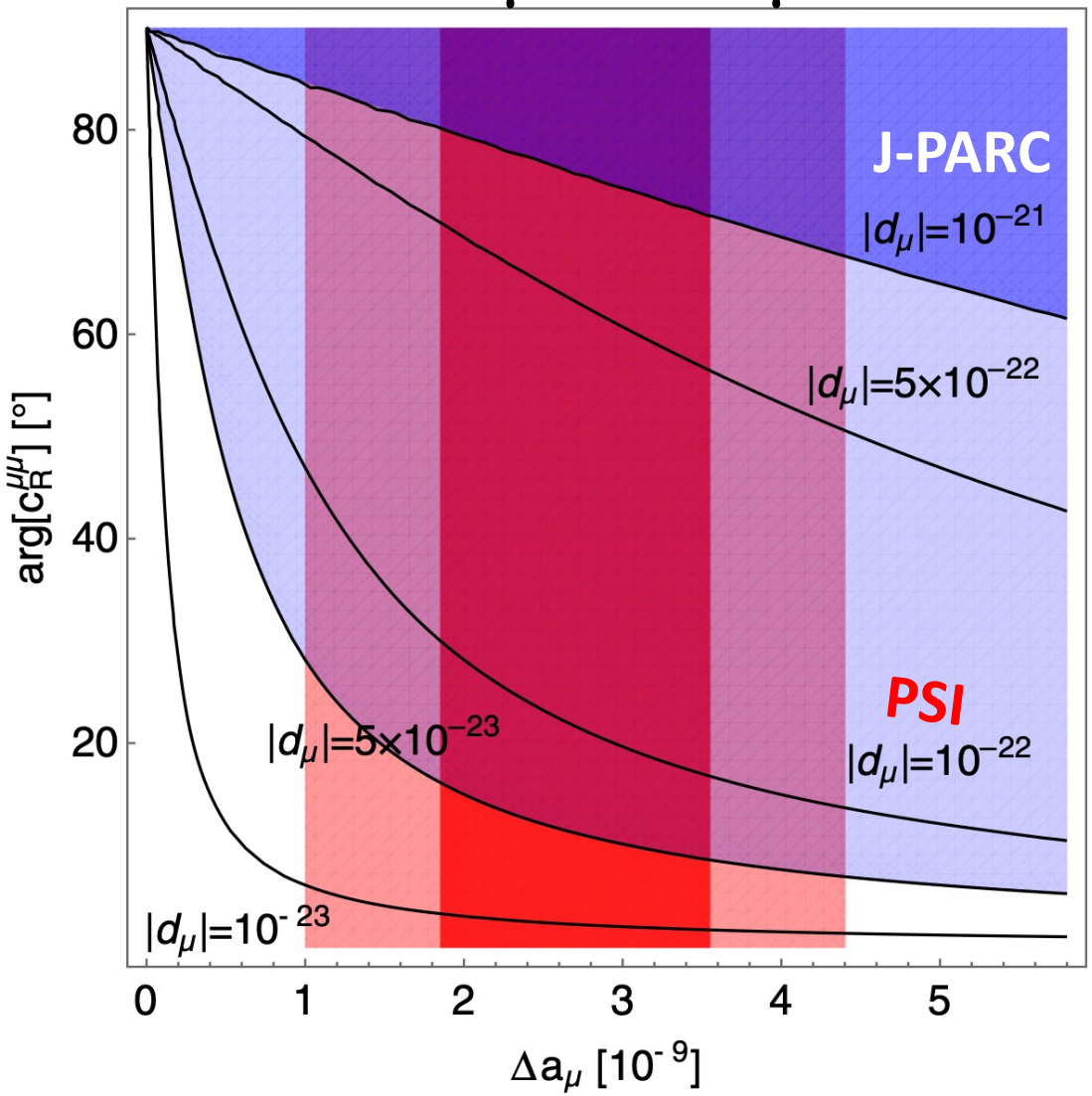
Current status and J-PARC projection



Muon EDM

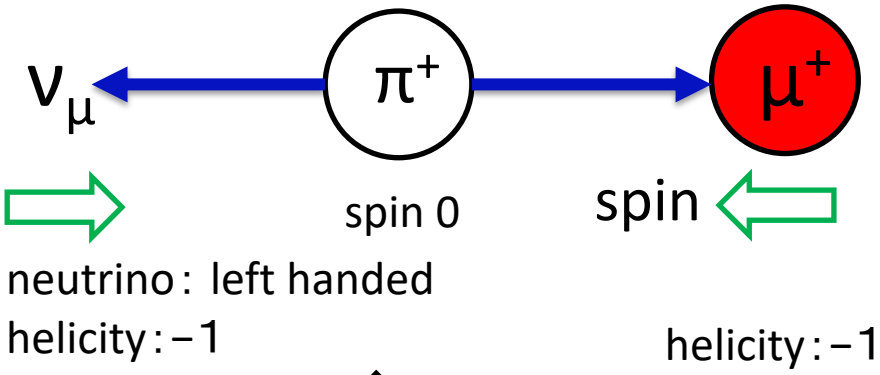
EDM(d_μ) vs a_μ

A. Crivellin et al., PRD 98, 113002 (2018)

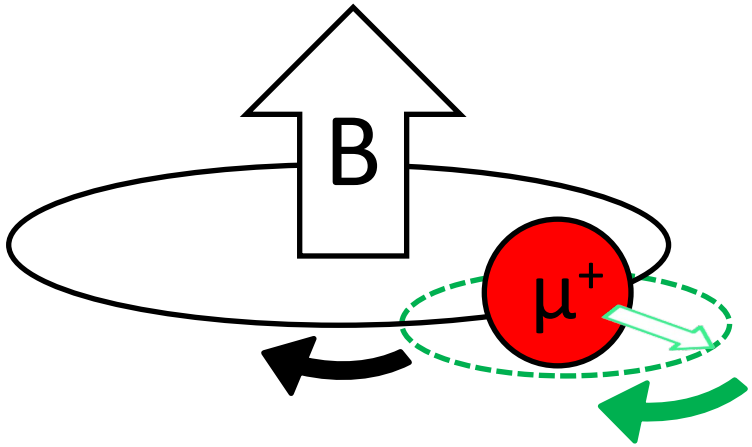


Three steps of g-2 & EDM measurement

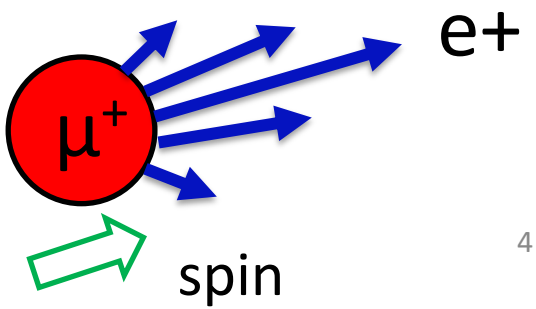
1. Prepare a polarized muon beam.



2. Store in a magnetic field (muon's spin precesses)

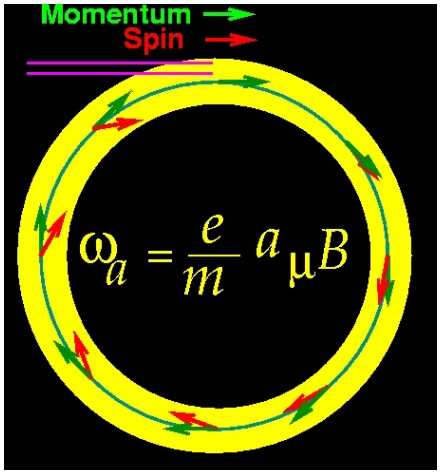


3. Measure decay positron



Spin precession of muon

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



Spin precession vector w.r.t momentum :

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

g-2 precession in B-field

g-2 precession in motional B-field

EDM precession

BNL/FNAL approach
γ=30 (P=3 GeV/c)

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

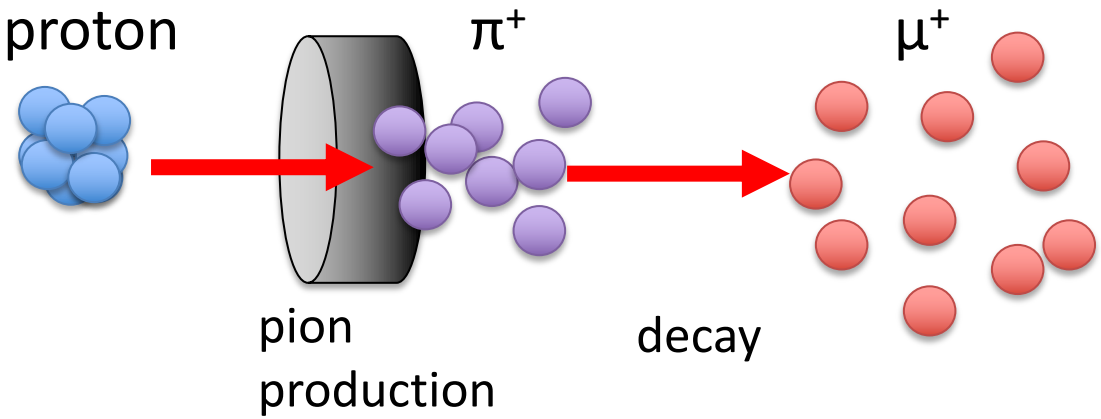
BNL & FNAL E989

J-PARC approach
E = 0 at any γ

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

J-PARC E34

Conventional muon beam



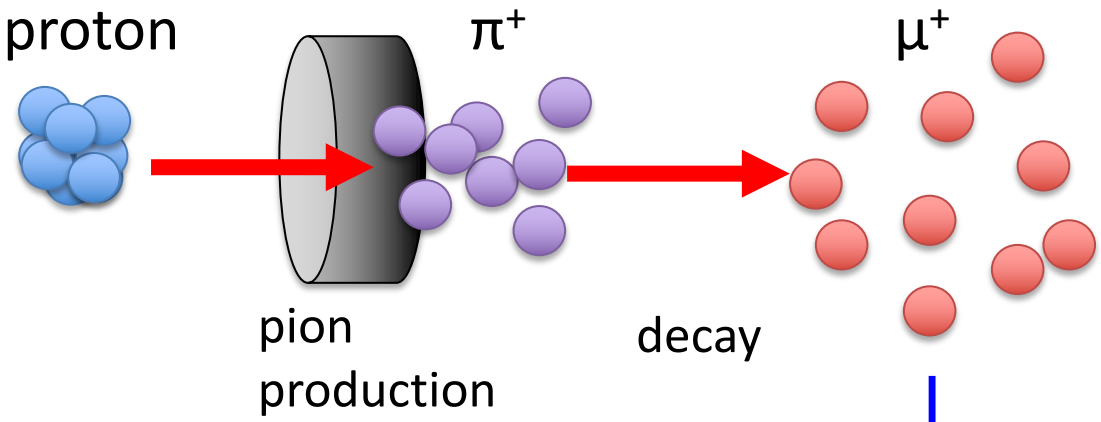
emittance

~1000π mm ·mrad

Strong focusing
Muon loss
BG π contamination

Source of systematic uncertainties

Muon beam at J-PARC

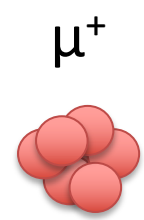


emittance
~1000π mm ･mrad

Strong focusing
Muon loss
BG π contamination

Source of systematic uncertainties

cooling



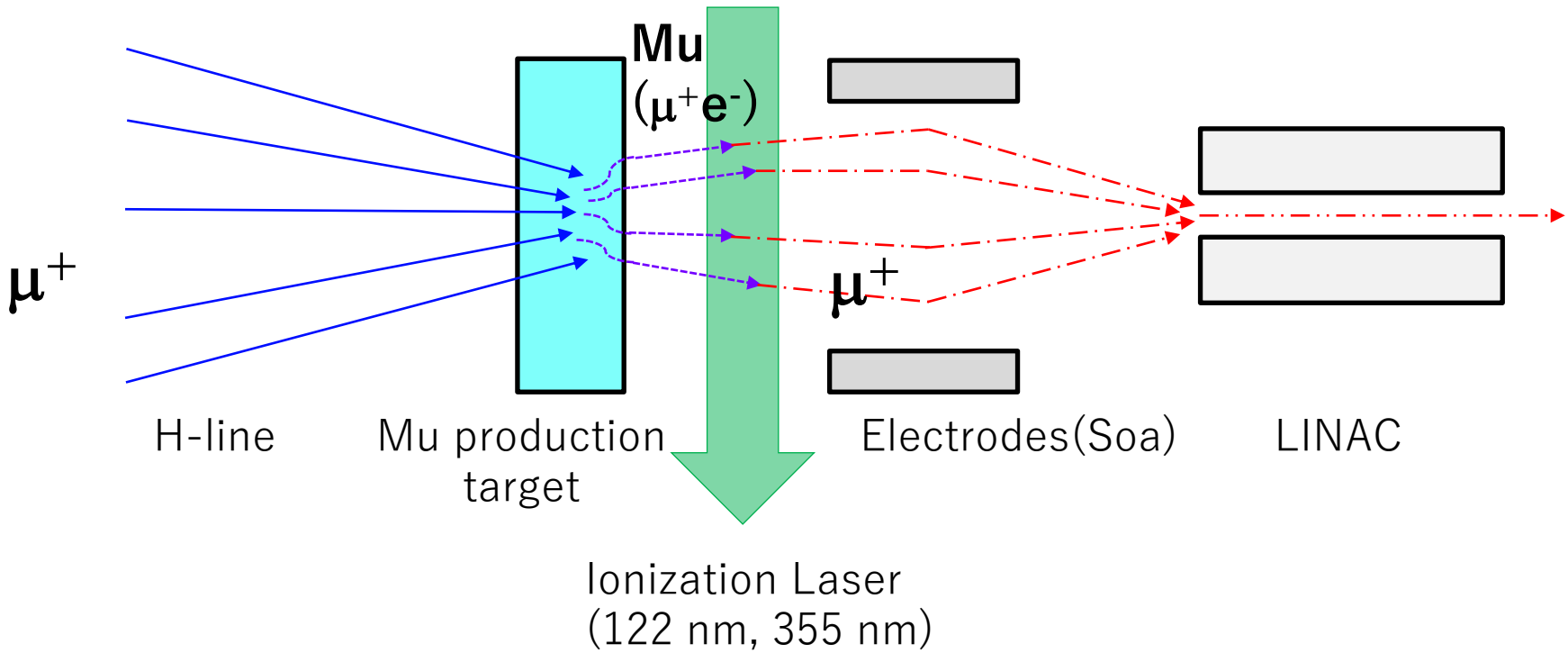
emittance
1π mm ･mrad

Reaccelerated thermal muon

Free from any of these

Re-accelerated thermal muon

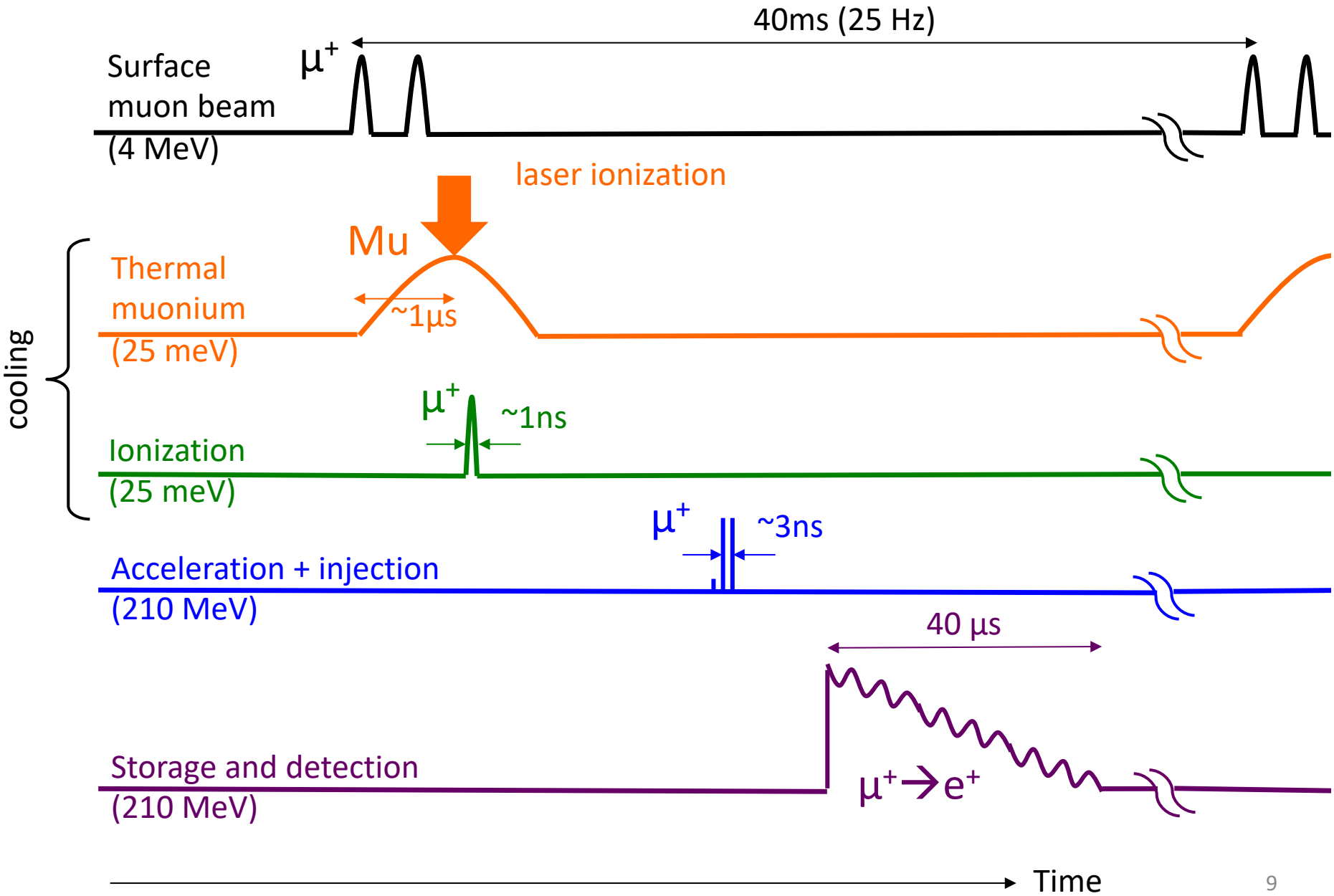
	surface muon	thermal muon	accelerated muon
E	3.4 MeV	30 meV	212 MeV
p	27 MeV/c	2.3 keV/c	300 MeV/c
Δ p/p	0.05	0.4	4×10^{-4}



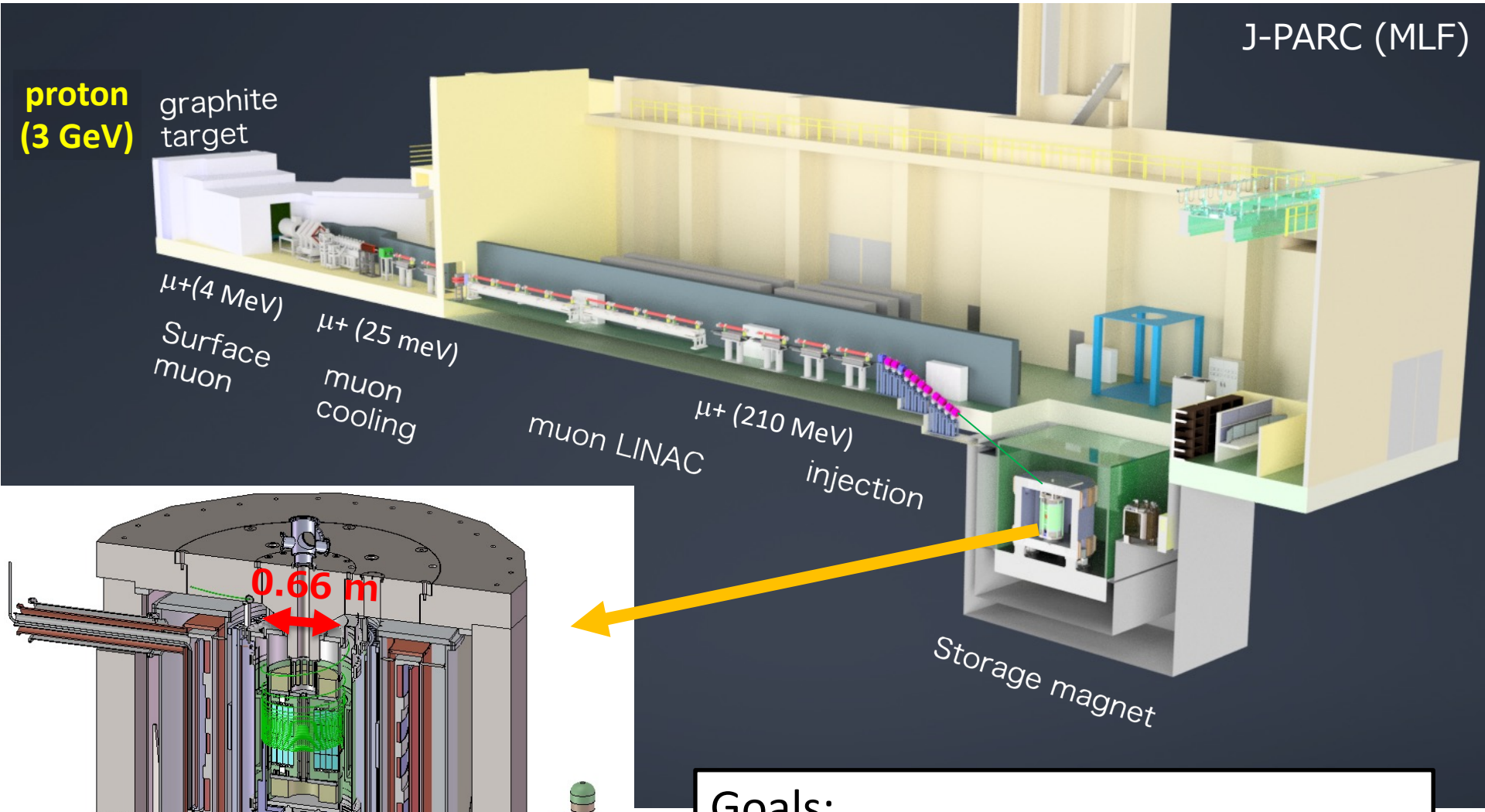
Muonium : a bound state of μ^+ and e^-

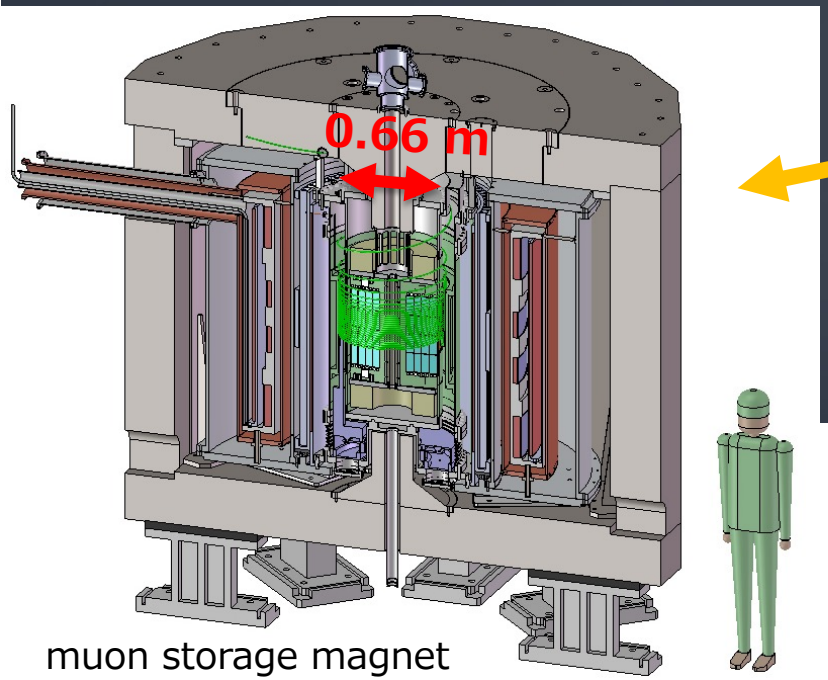
Cooling + LINAC → The world-first muon accelerator

Experimental sequence



Muon g-2/EDM experiment at J-PARC



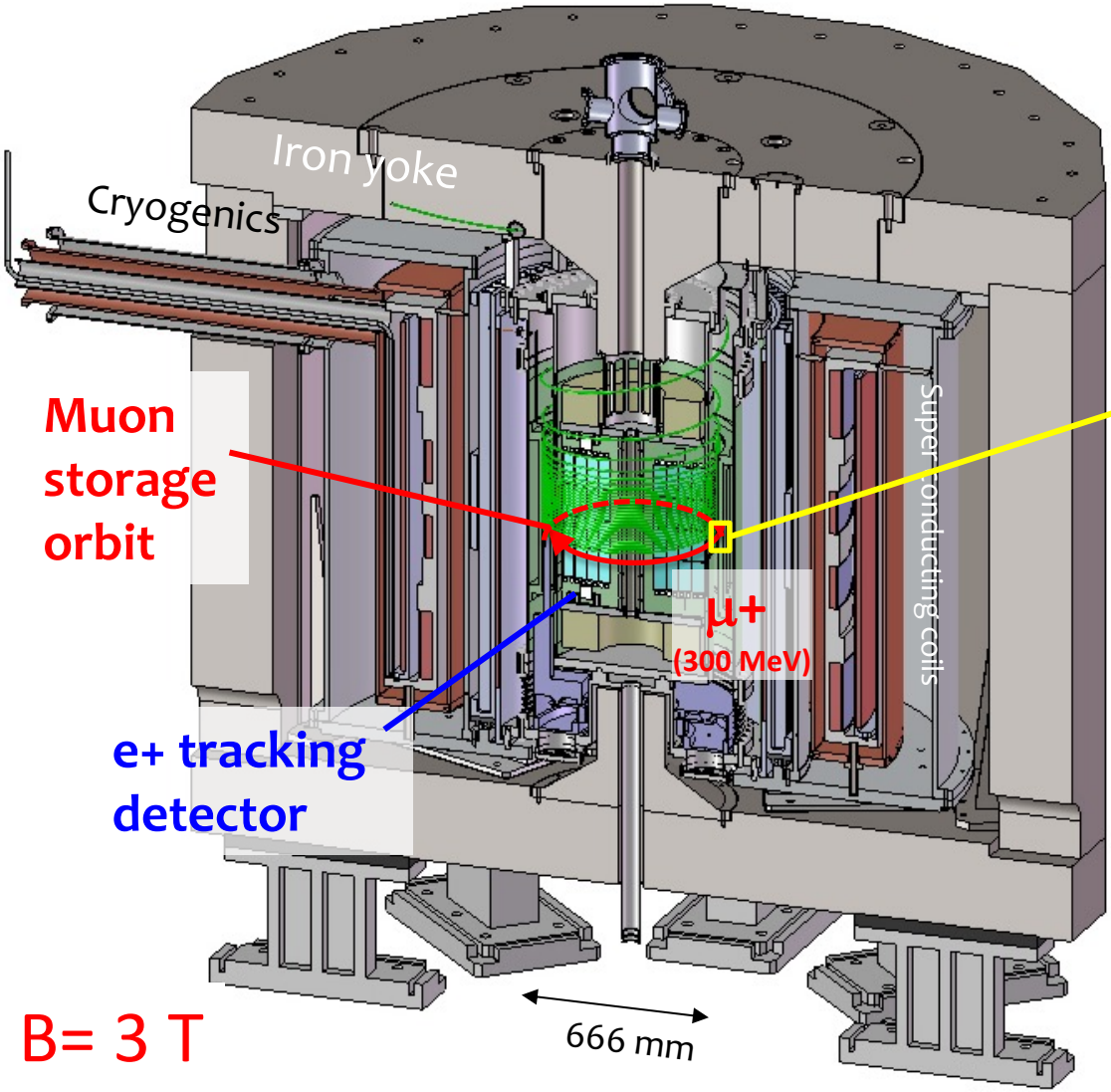


Goals:

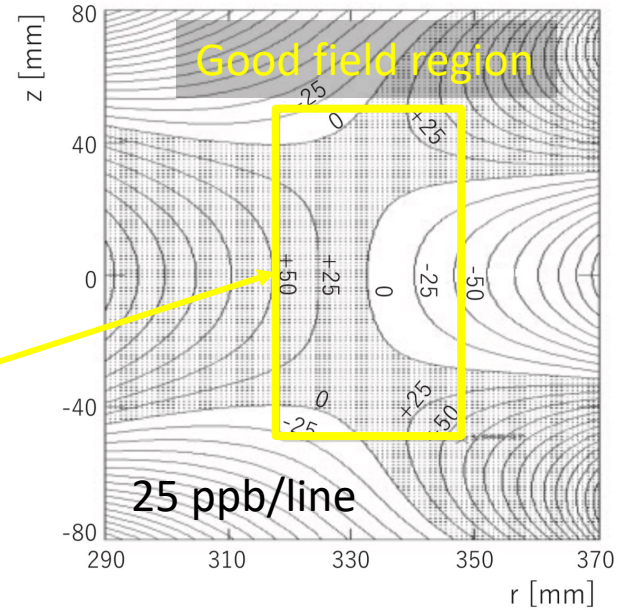
g-2 450 ppb (~ BNL/FNAL run 1)

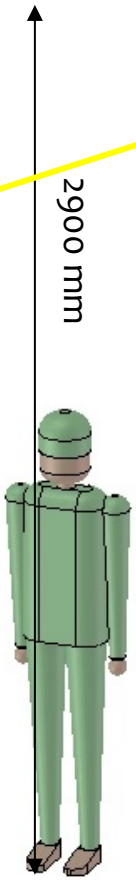
EDM 1.5×10^{-21} e・cm (x70 better)

Muon storage magnet and detector

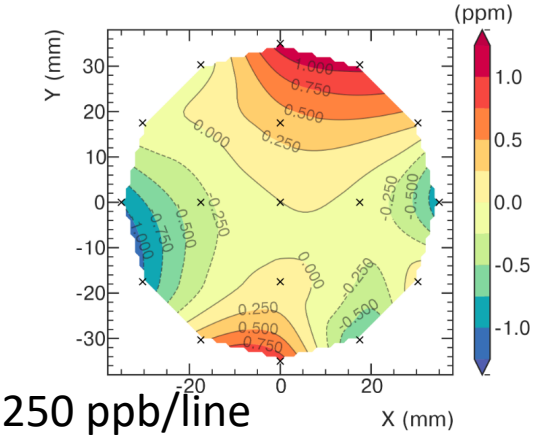


Calculated average field uniformity





FNAL Run 1 PRA 103, 042208 (2021)

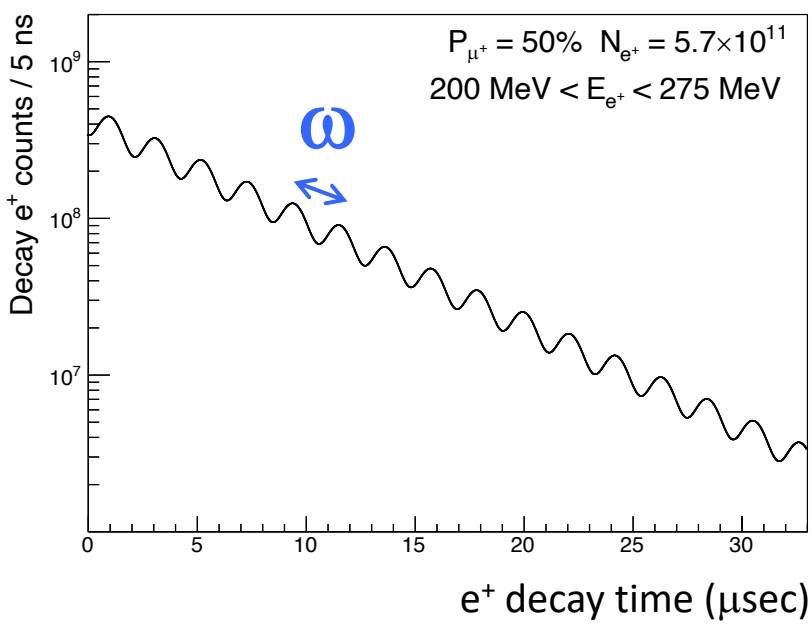


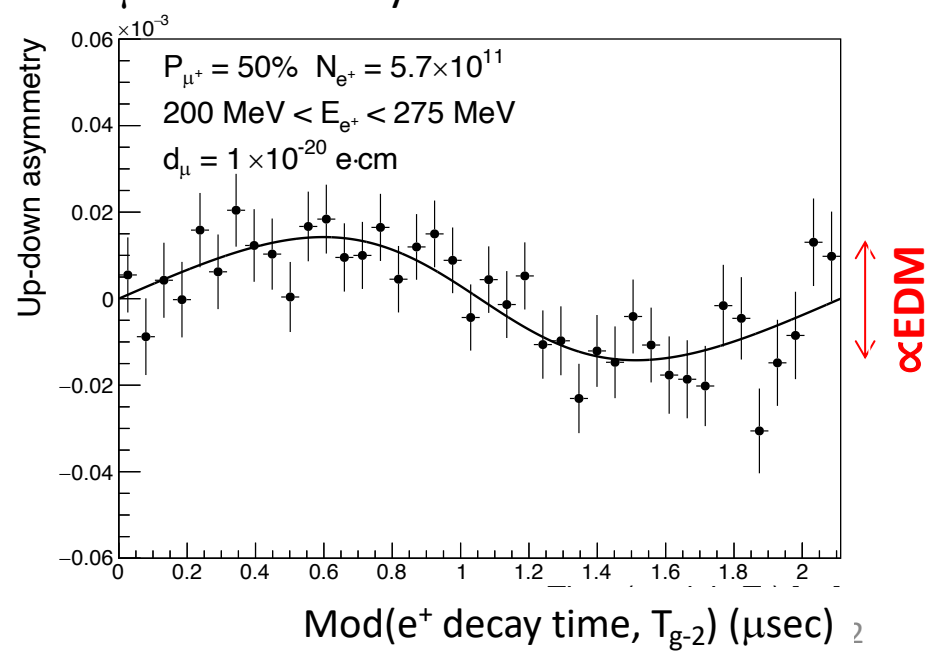
M. Abe et. al., NIM A 890, 51 (2018)

Simultaneous measurements: g-2, EDM

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

Expected time spectrum of e^+ in $\mu \rightarrow e^+\nu\nu$ decay





Comparison of g-2 experiments

Prog. Theor. Exp. Phys. **2019**, 053C02 (2019)

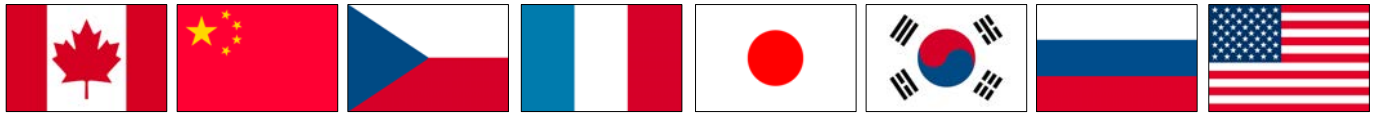
	BNL-E821	Fermilab-E989	Our experiment
Muon momentum	3.09 GeV/c		300 MeV/c
Lorentz γ	29.3		3
Polarization	100%		50%
Storage field	$B = 1.45$ T		$B = 3.0$ T
Focusing field	Electric quadrupole		Very weak magnetic
Cyclotron period	149 ns		7.4 ns
Spin precession period	4.37 μs		2.11 μs
Number of detected 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
	Completed	**Running**	**In preparation**

The collaboration

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

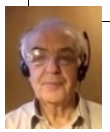


New

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

Committees

Speakers committee
chair: K.Ishida

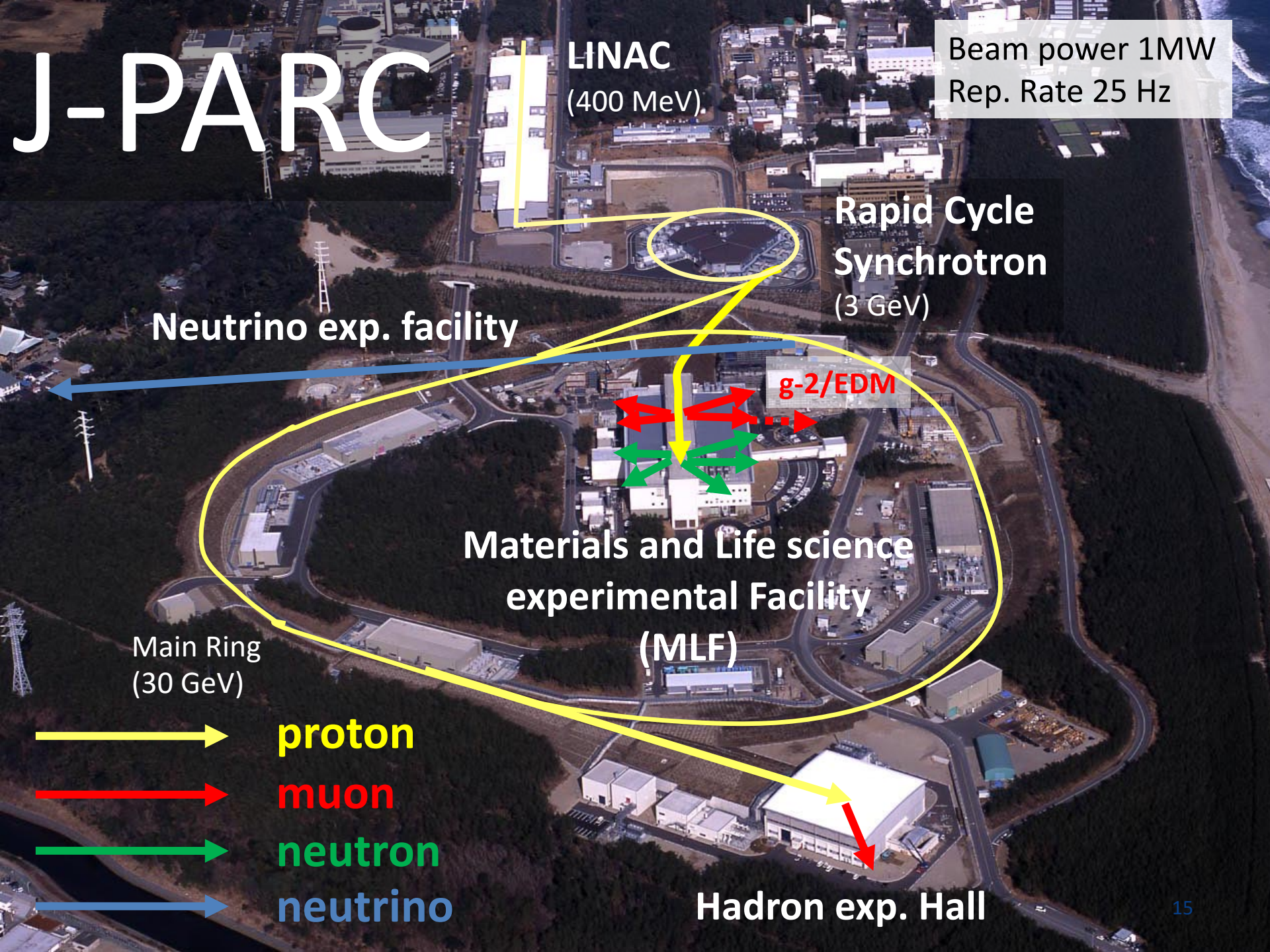


Publication committee
chair: B. Shwartz

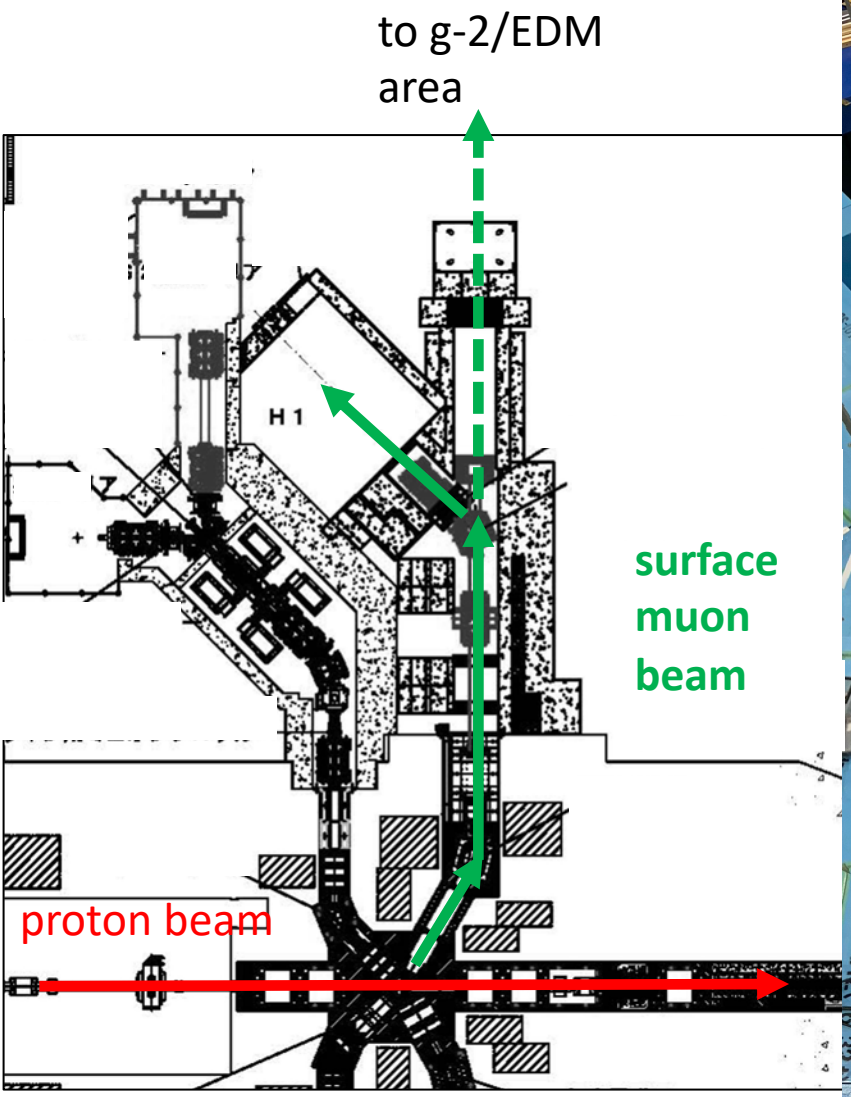
Domestic institutes :
Kyushu, Nagoya, Tohoku, Niigata, Tokyo, Ibaraki, RIKEN, JAEA, etc.

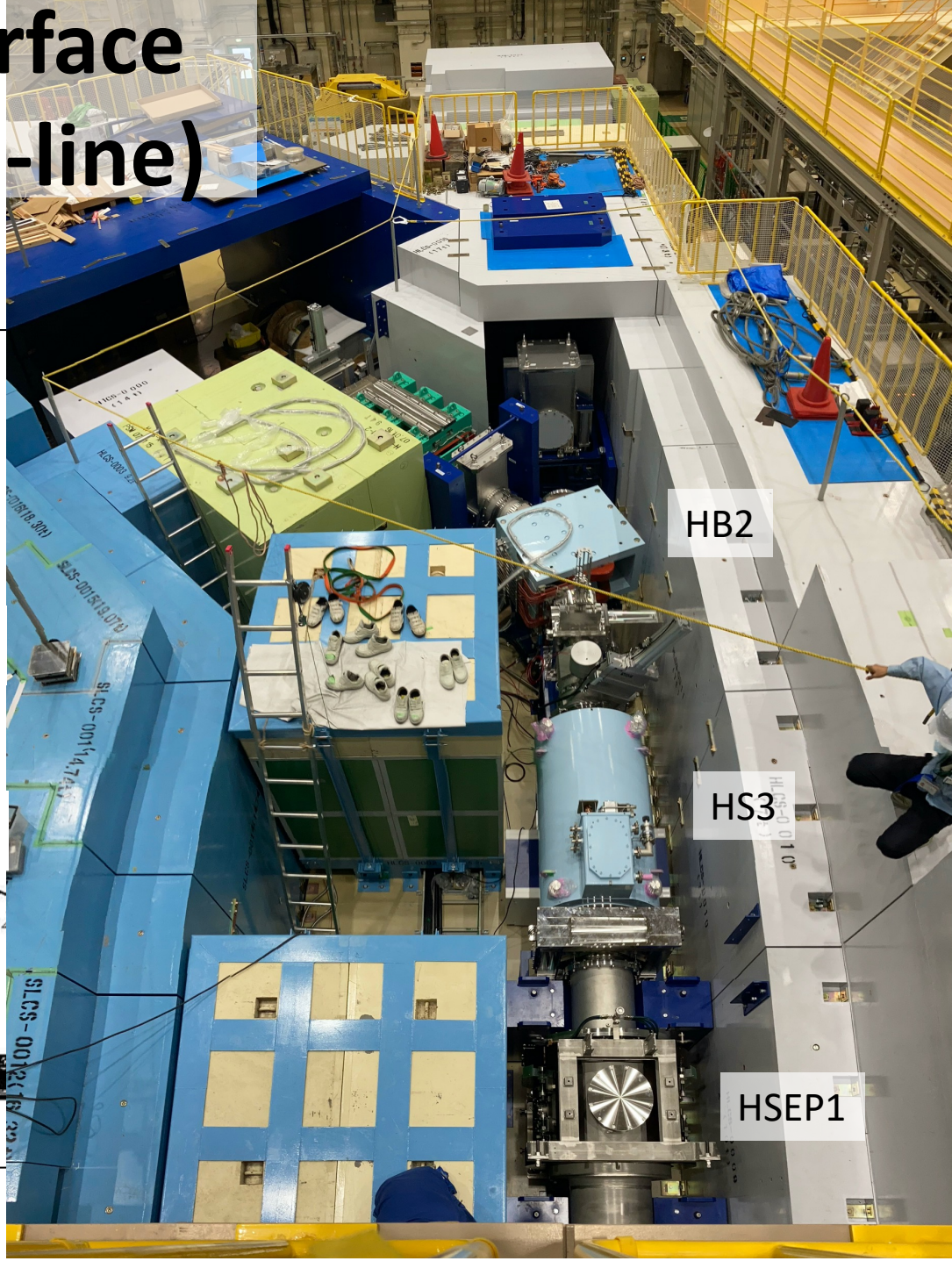
KEK: IPNS, IMSS, ACC, CRY, MEC, CRC

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


J-PARC
LINAC
(400 MeV)
Beam power 1MW
Rep. Rate 25 Hz
Rapid Cycle
Synchrotron
(3 GeV)
Neutrino exp. facility
g-2/EDM
Materials and Life science
experimental Facility
(MLF)
Main Ring
(30 GeV)
proton
muon
neutron
neutrino
Hadron exp. Hall

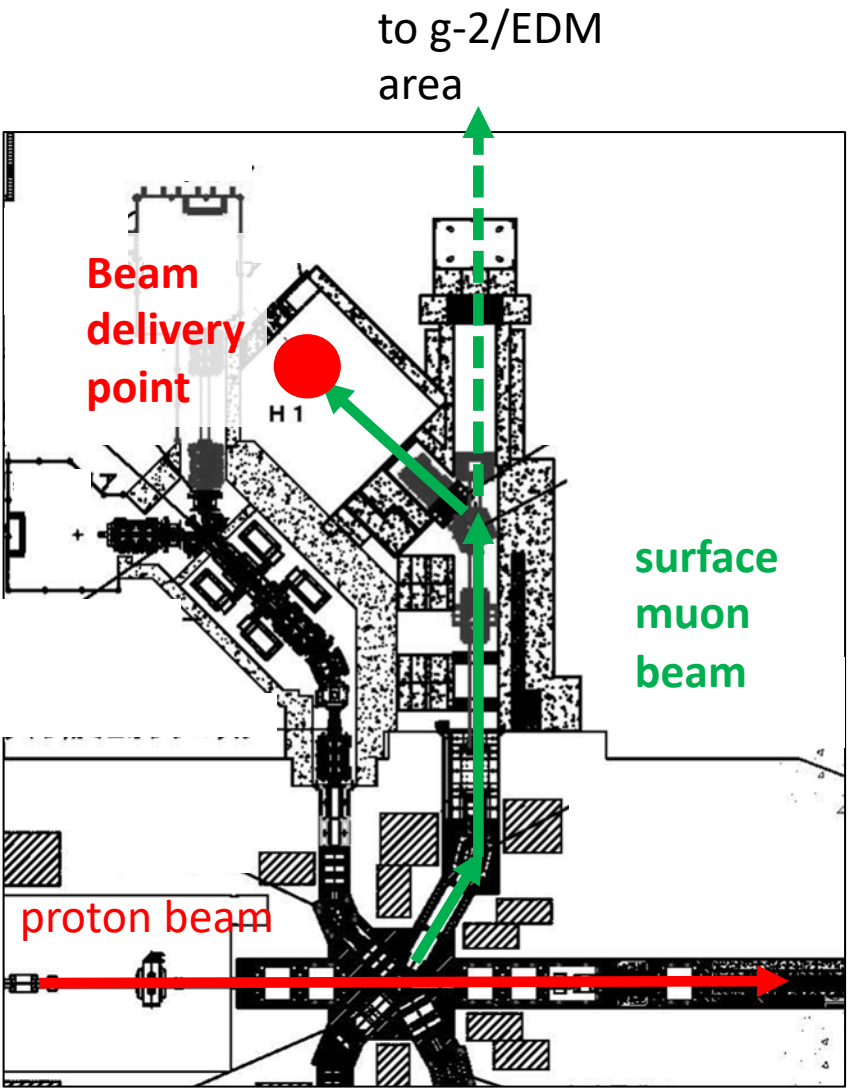
Construction of surface muon beamline (H-line)





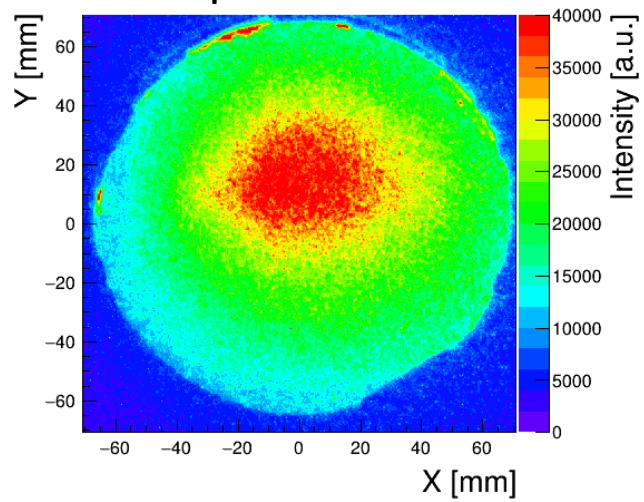
Prog. Theor. Exp. Phys. 2018, 113G01

First beam to H1 area (Jan 15, 2022)

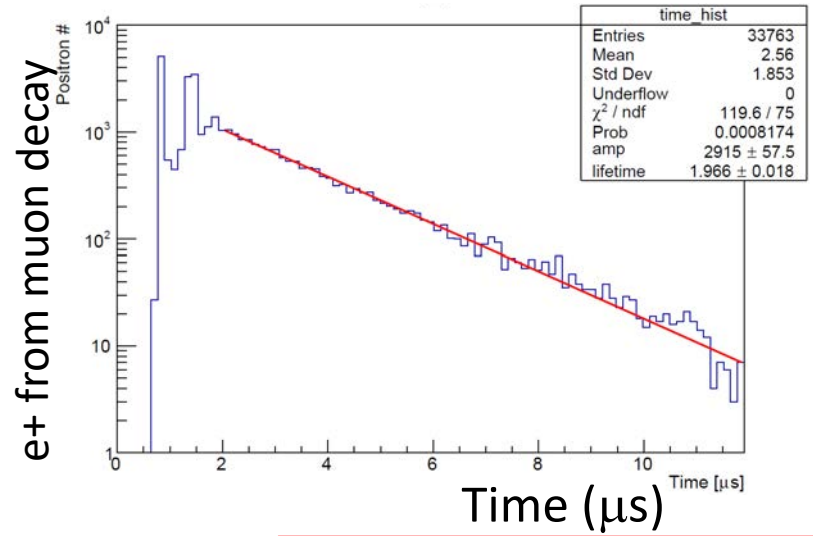


Prog. Theor. Exp. Phys. 2018, 113G01

Beam profile

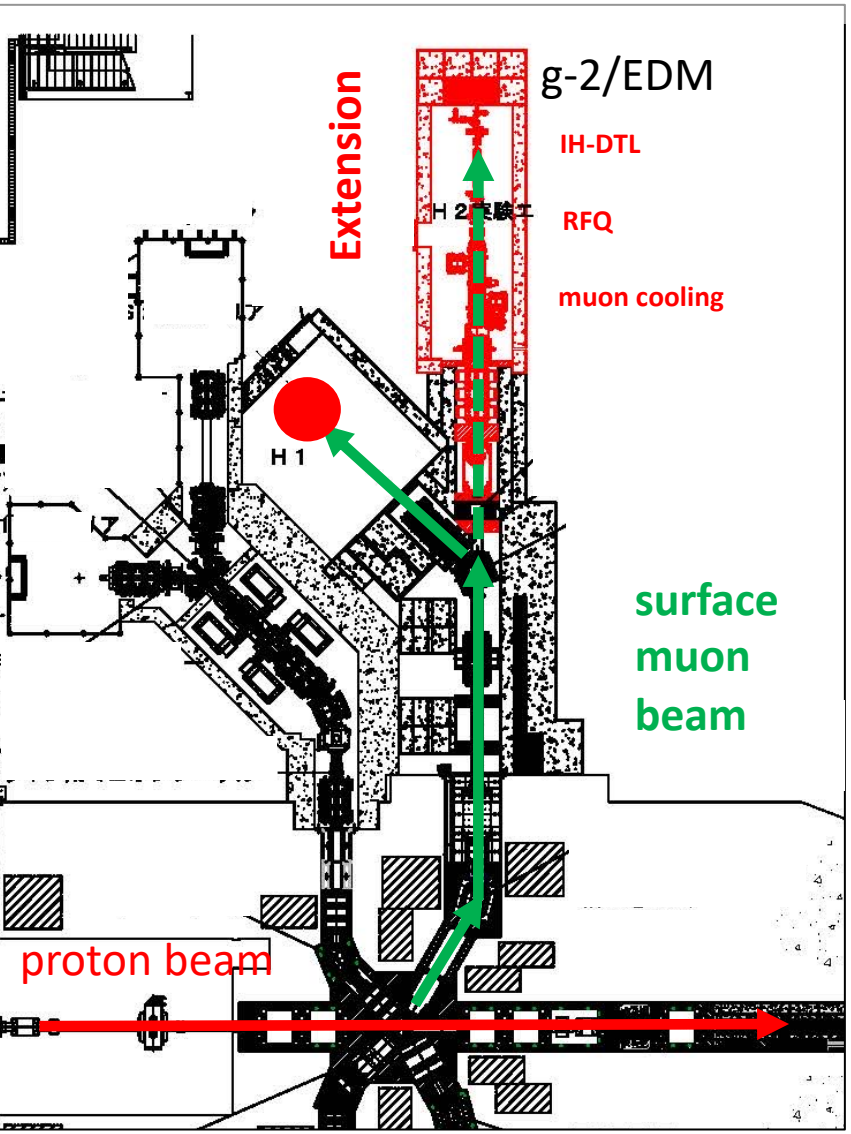


σ_x = 44 mm
σ_y = 24 mm



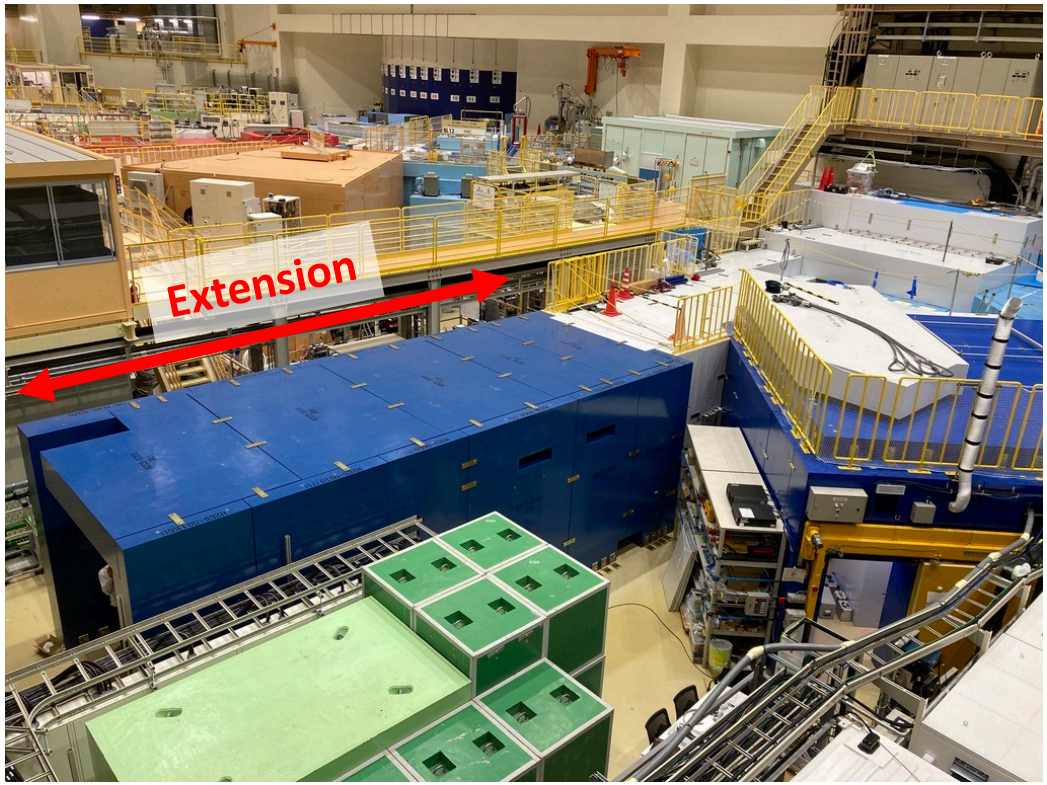
7 x 10^7/sec@p=28 MeV/c, 730kW
→ consistent with expectation

Extension of H-line

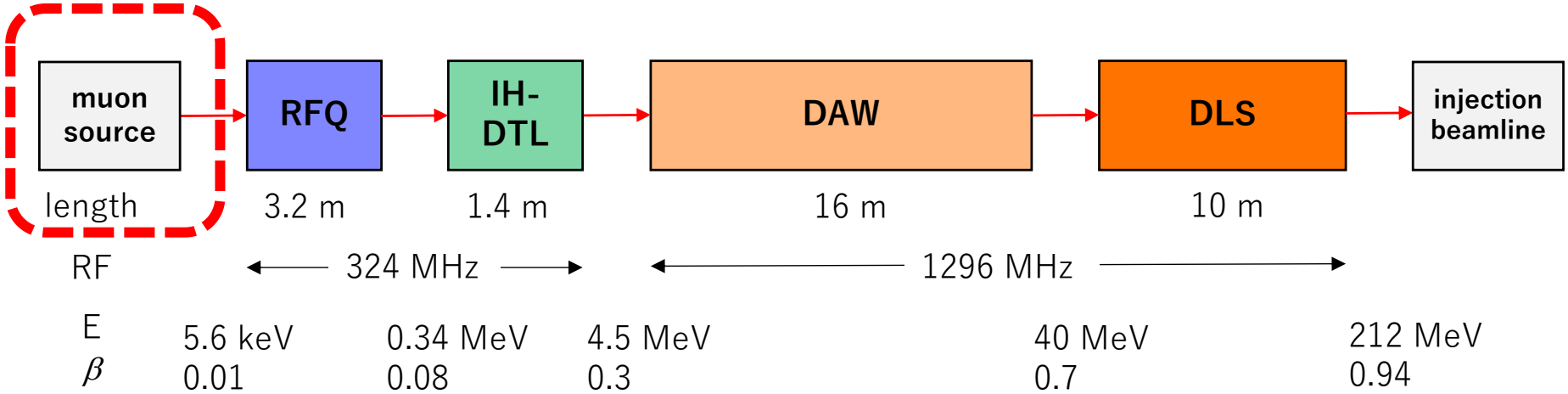


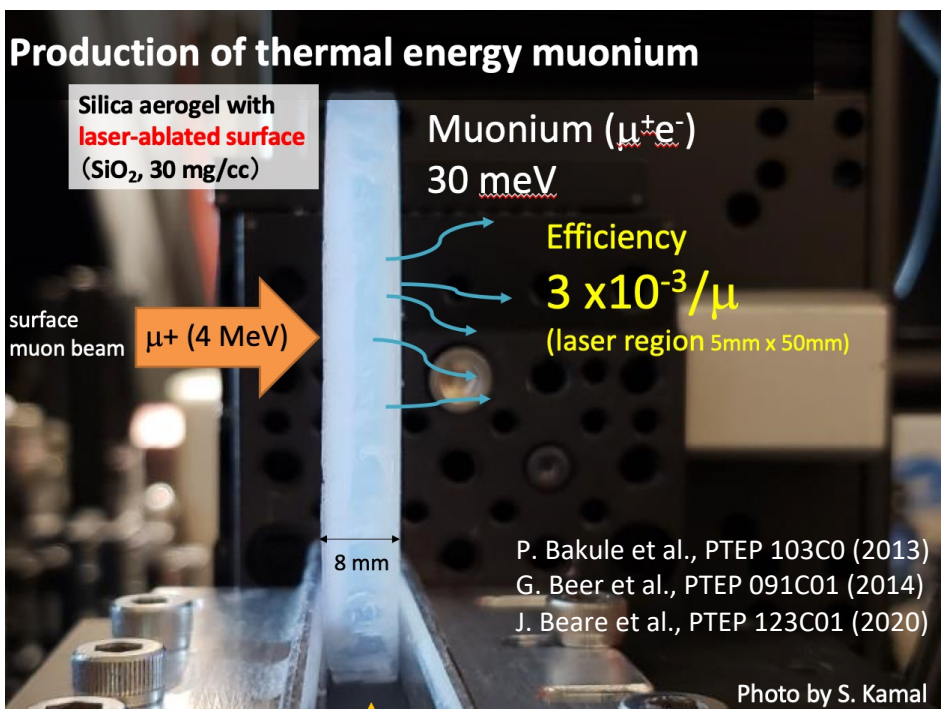
Prog. Theor. Exp. Phys. 2018, 113G01

Assembled radiation shields for extension (Oct 15, 2022)

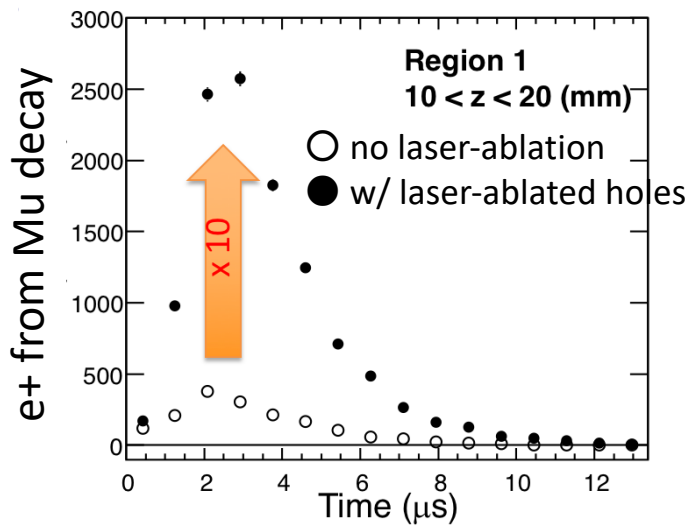


Muon source developments



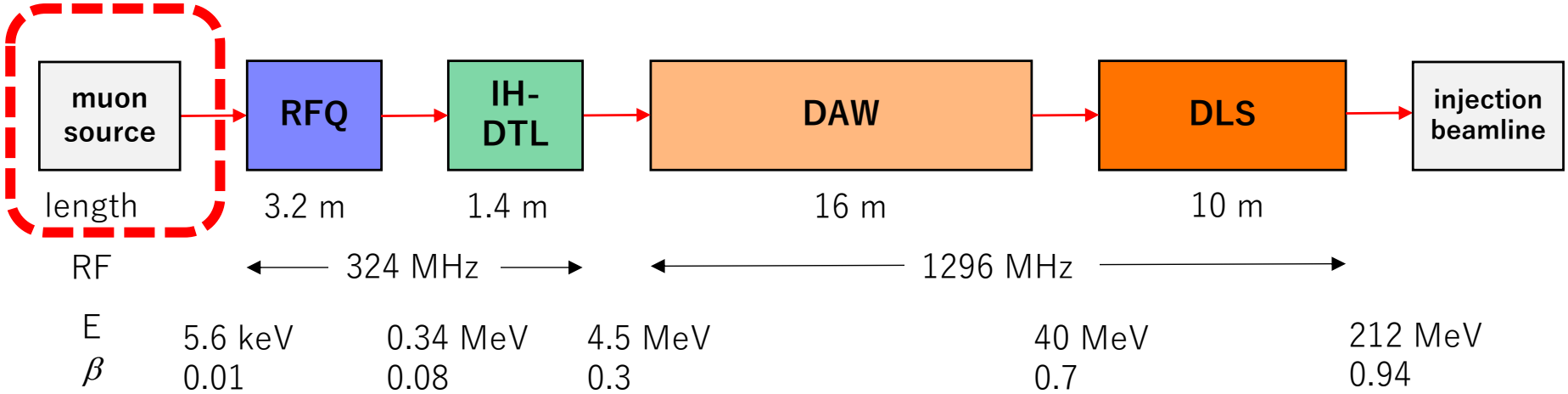


Muonium yield measured at TRIUMF

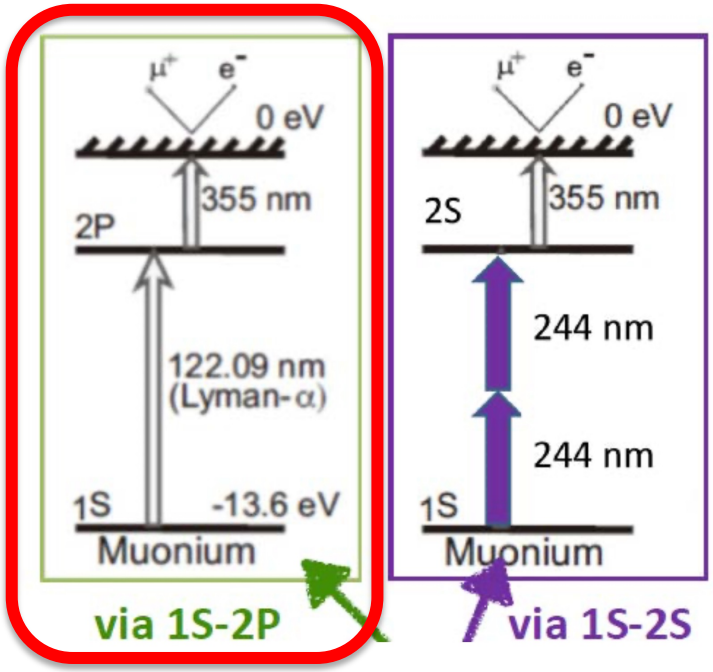


Sufficient efficiency to achieve Δa_μ~450ppb

Muon source developments

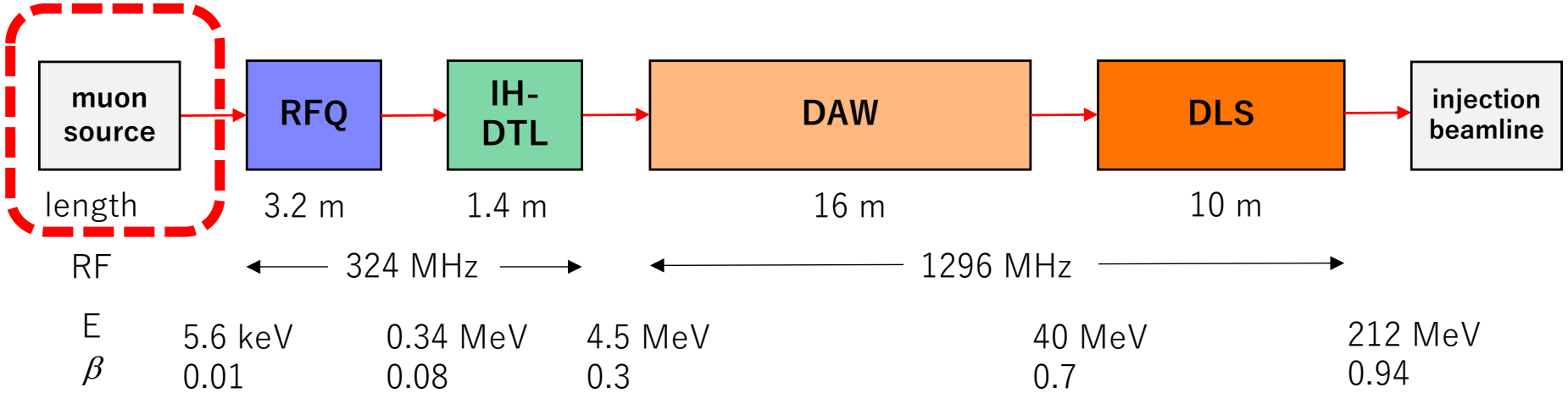


Schemes of ionization

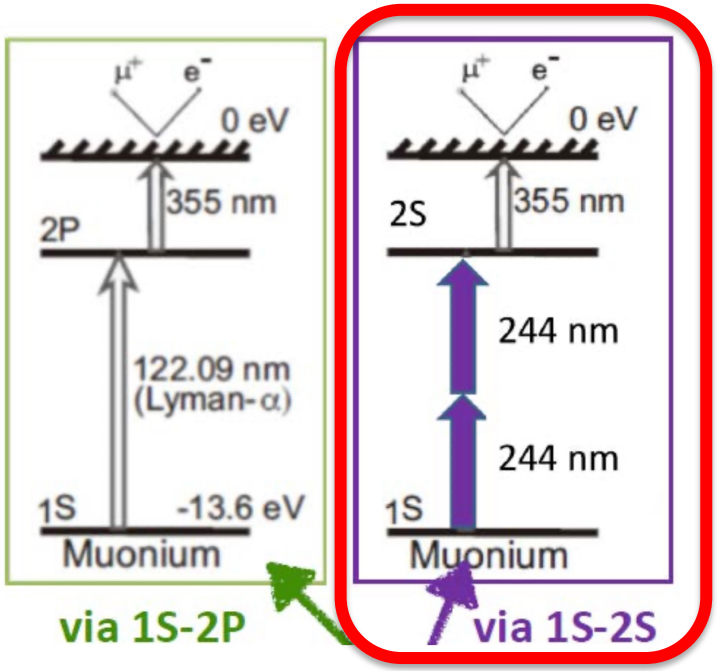


First-ever demonstration of Mu ionization via 1S-2P from Silica aerogel

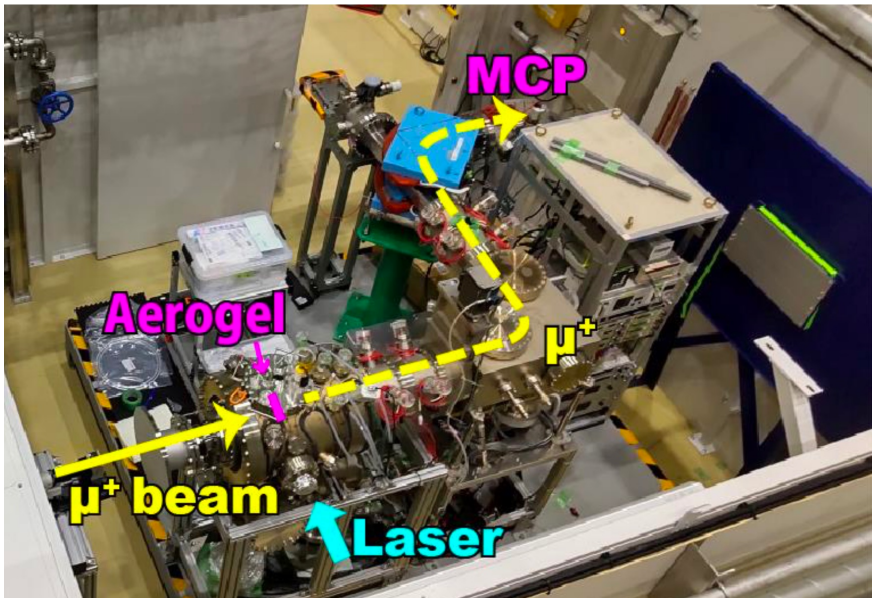
Muon source developments



Schemes of ionization

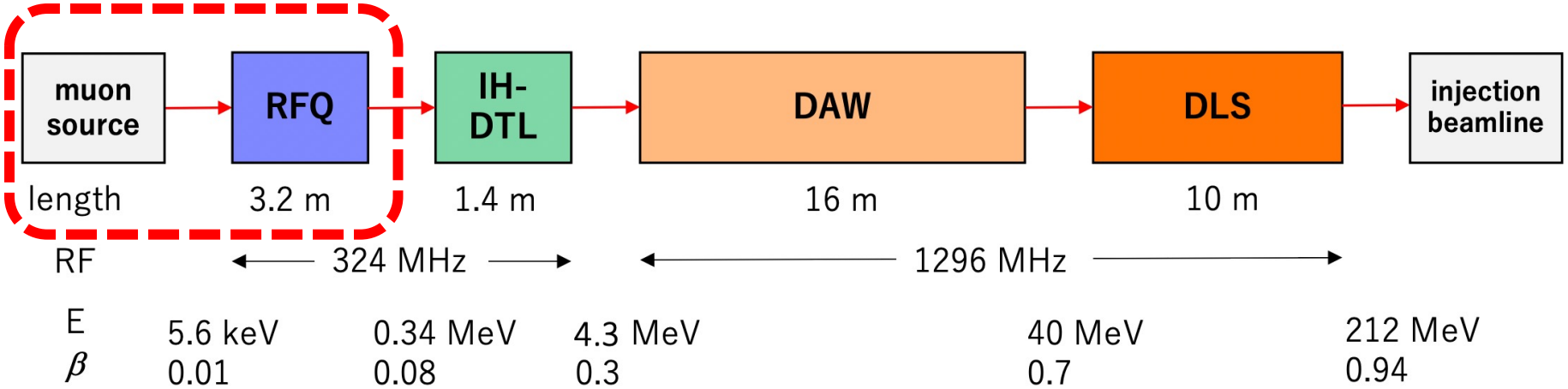


Ionization test via 1S-2S at S-line

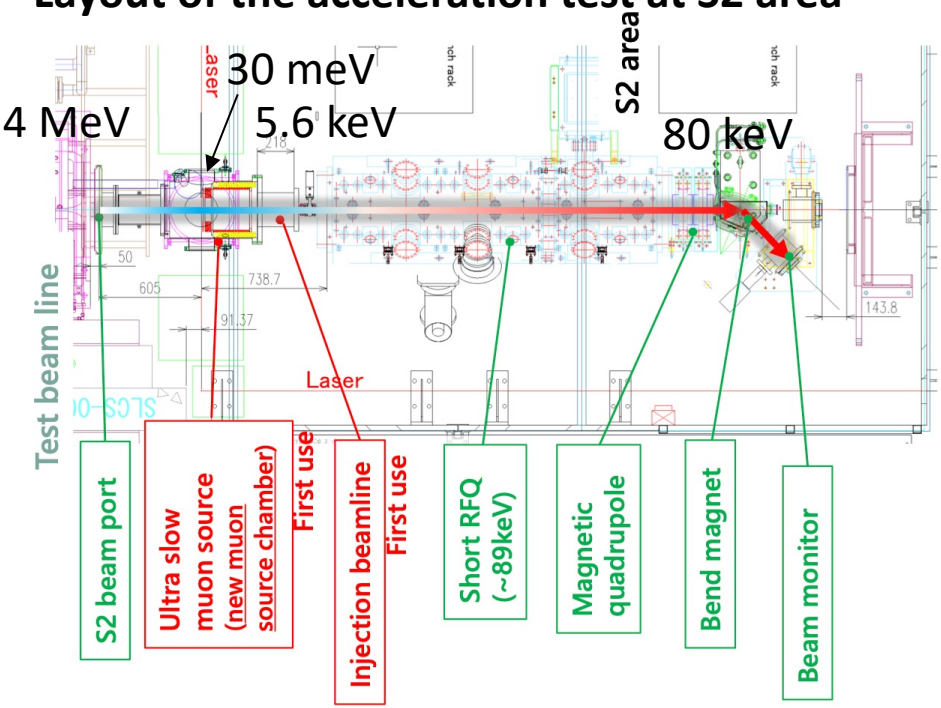


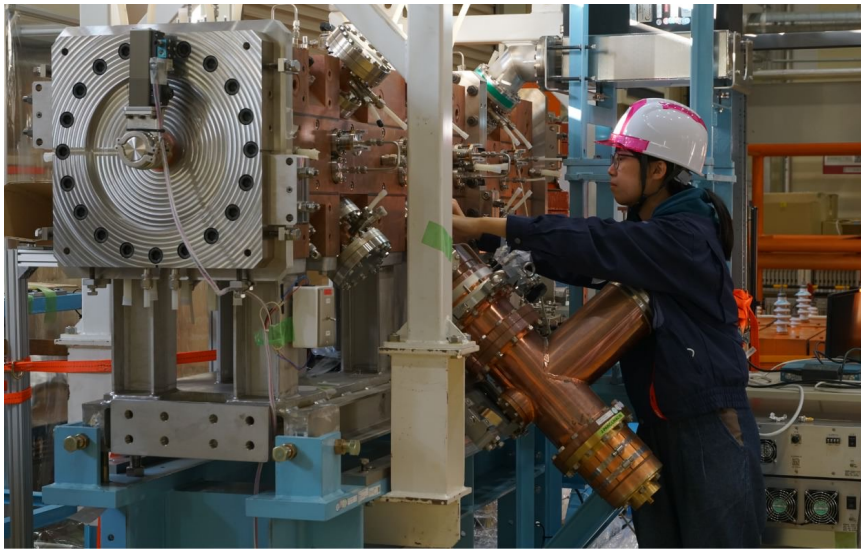
in collaboration with the Mu 1S-2S spectroscopy group

Muon source + LINAC



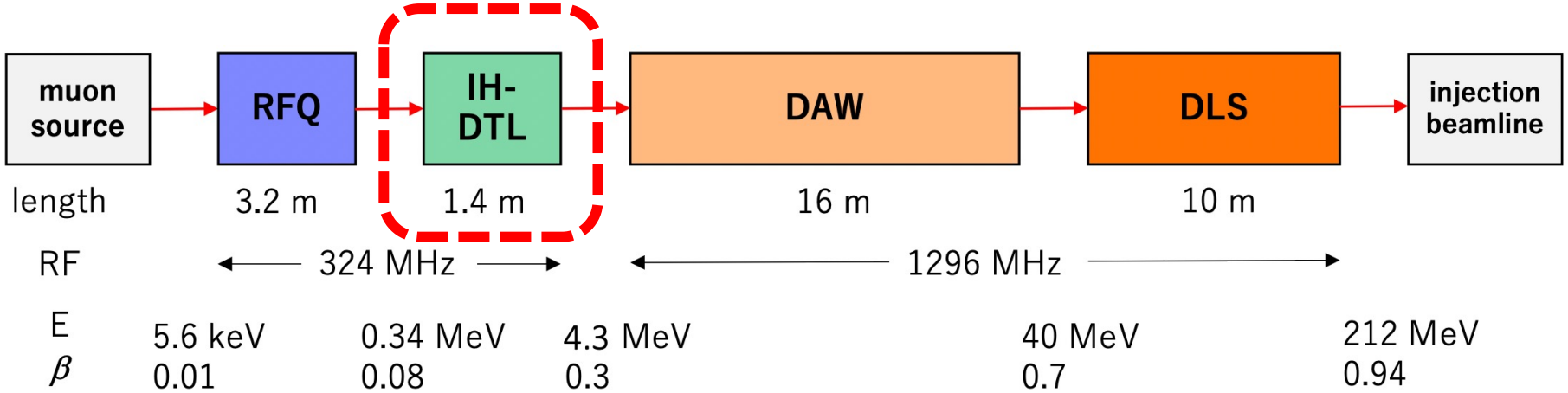
Layout of the acceleration test at S2 area

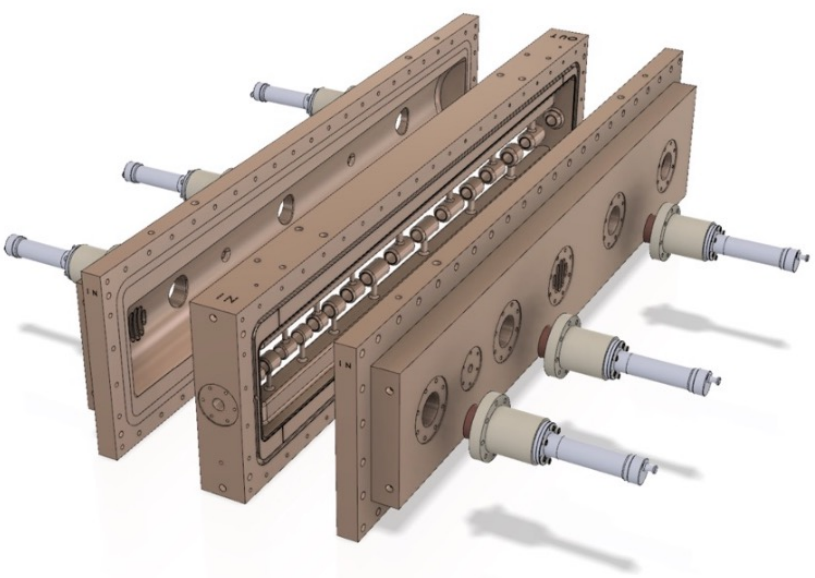


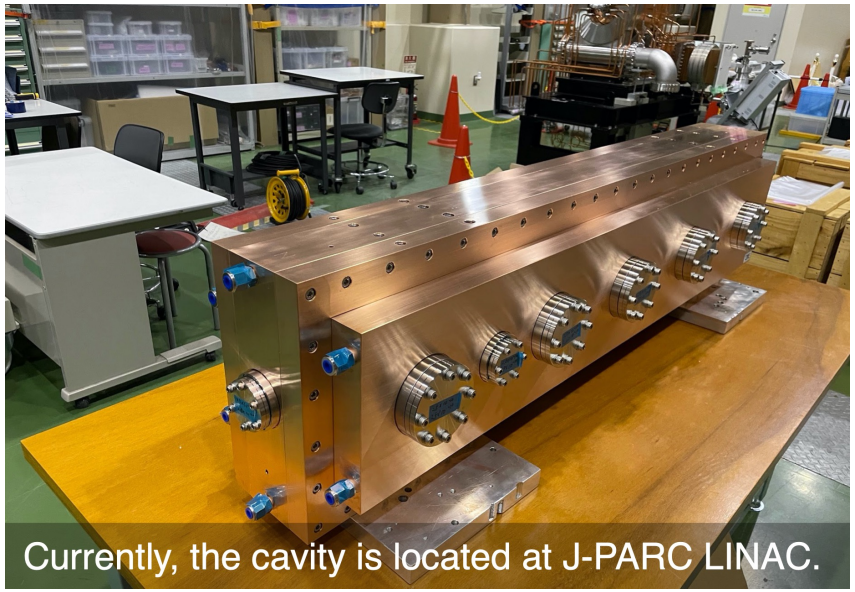


First-ever demonstration of thermal muon acceleration is in preparation
Next: beam time approved in 2023

Muon LINAC developments



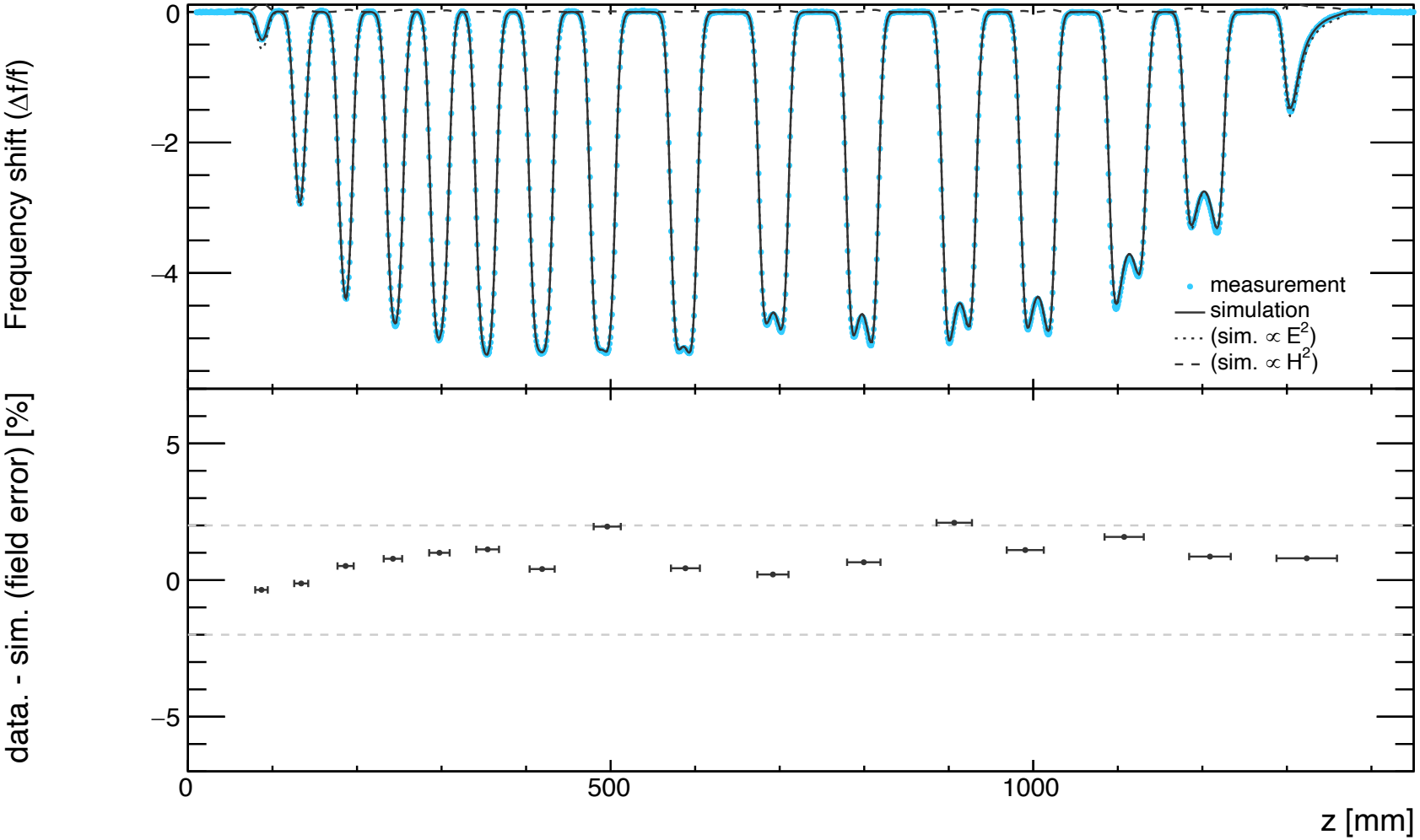




The cavity was manufactured in March 2022

Muon LINAC developments

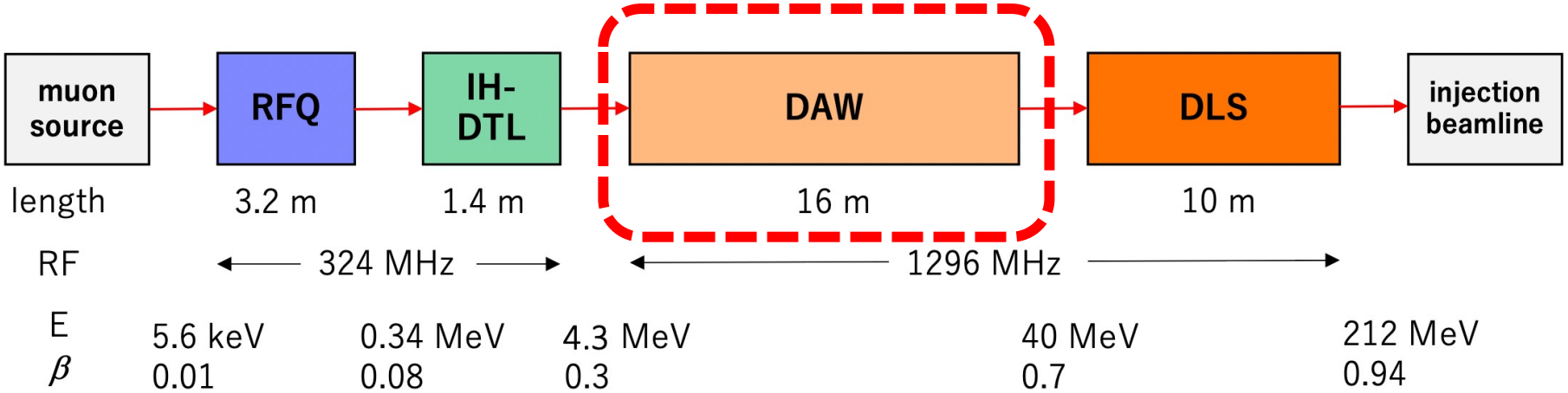
Bead-pull measurement of the IH-DTL cavity



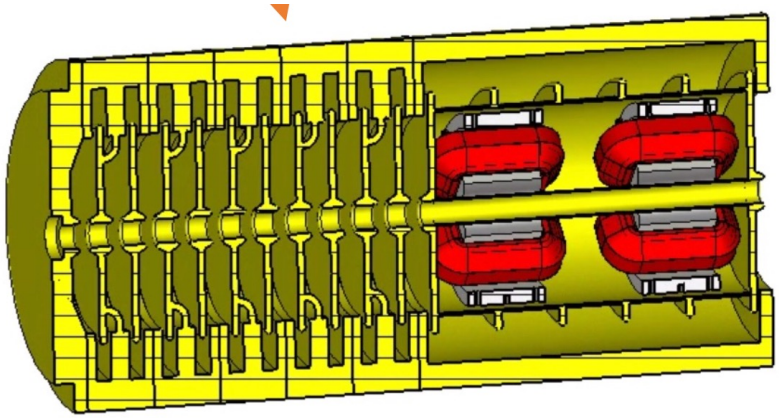
A paper was submitted to PRAB

EM fields are consistent with simulation within a few percent
To be used in the acceleration to 4.3 MeV in 2024

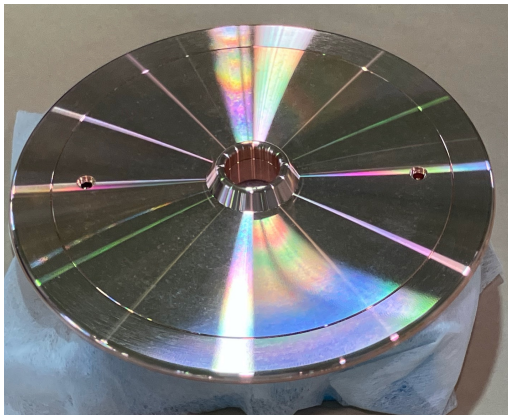
Muon LINAC developments



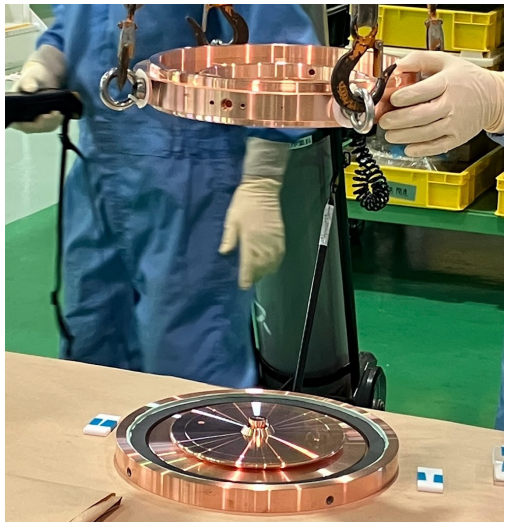
Disk-And-Washer (DAW) type cavity



Washer

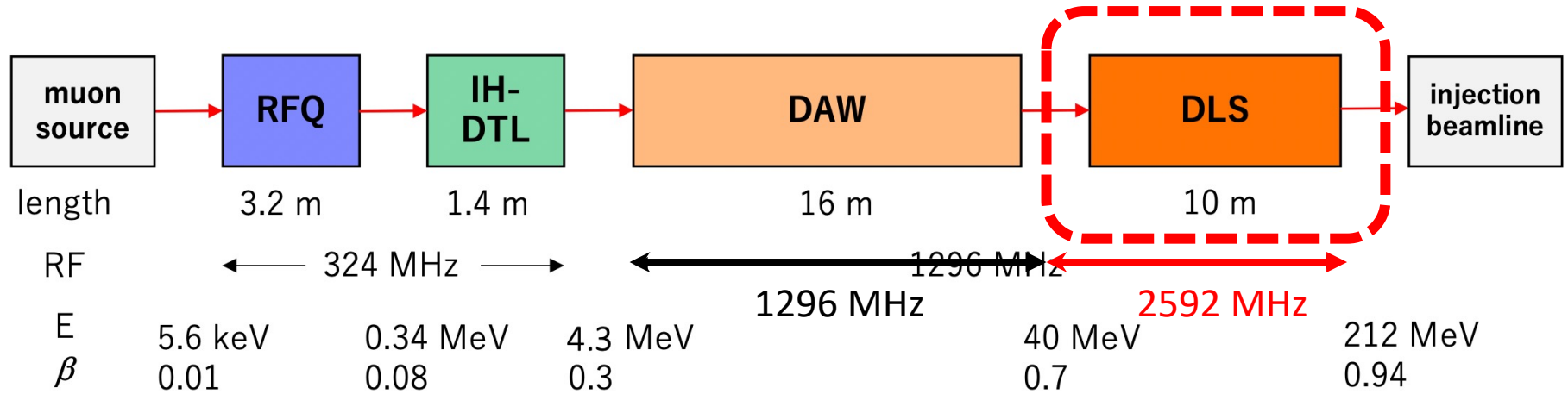


Assembly with brazing

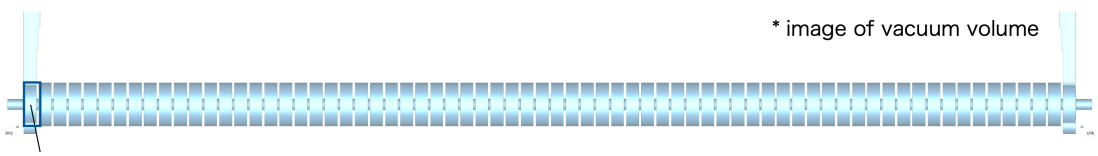


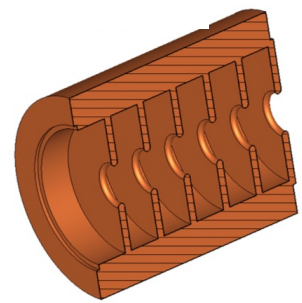
The cavity design completed. Fabrication started.
Next: build a complete module and test

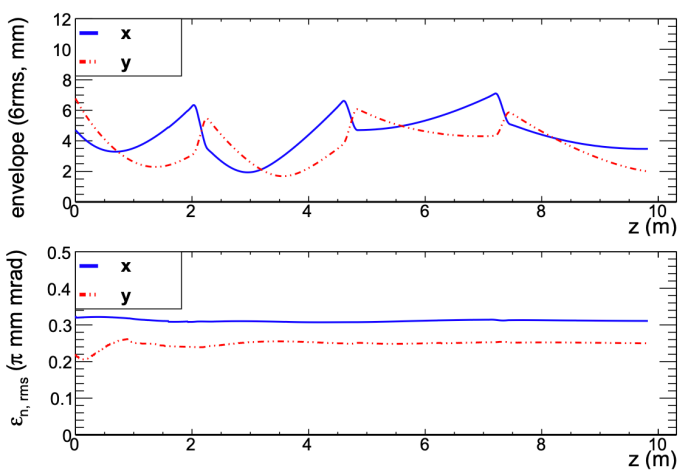
Muon LINAC developments



The Disk-Loaded-Structure (DLS) cavity module







Updated design to use higher RF frequency.

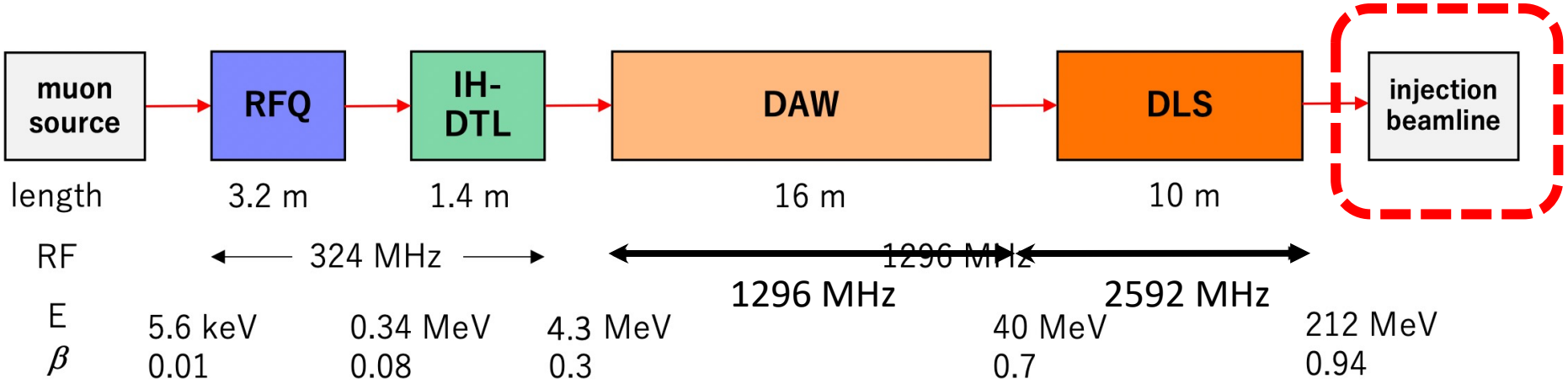
1296 MHz (L-band) → 2592 MHz (S-band)

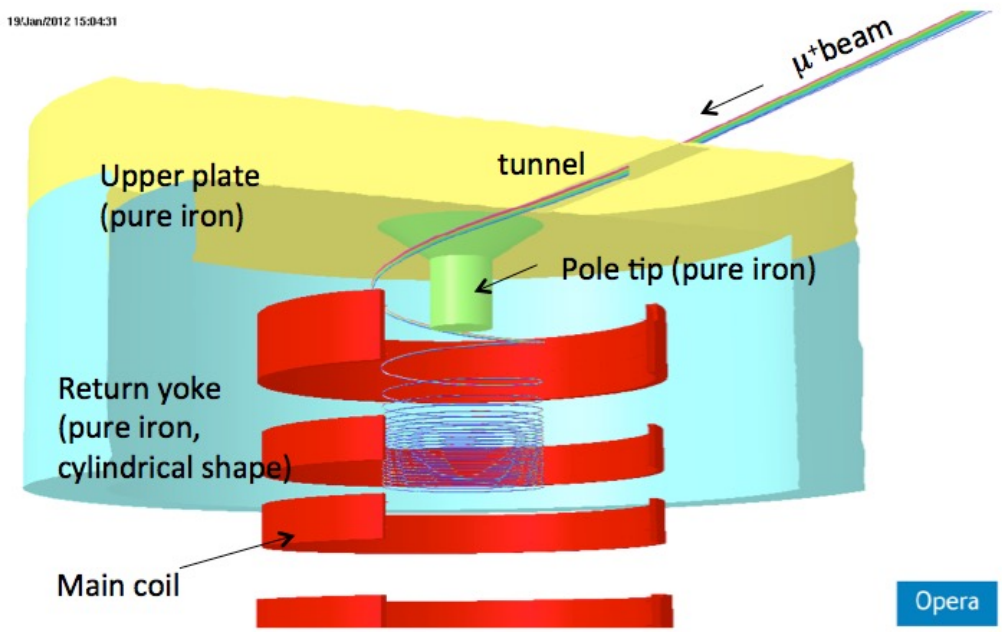
The acceleration gradient increases from

12 MeV/m → 20 MeV/m (at 40 MW)

The cavity parameters were optimized.
Next: fabrication of a prototype

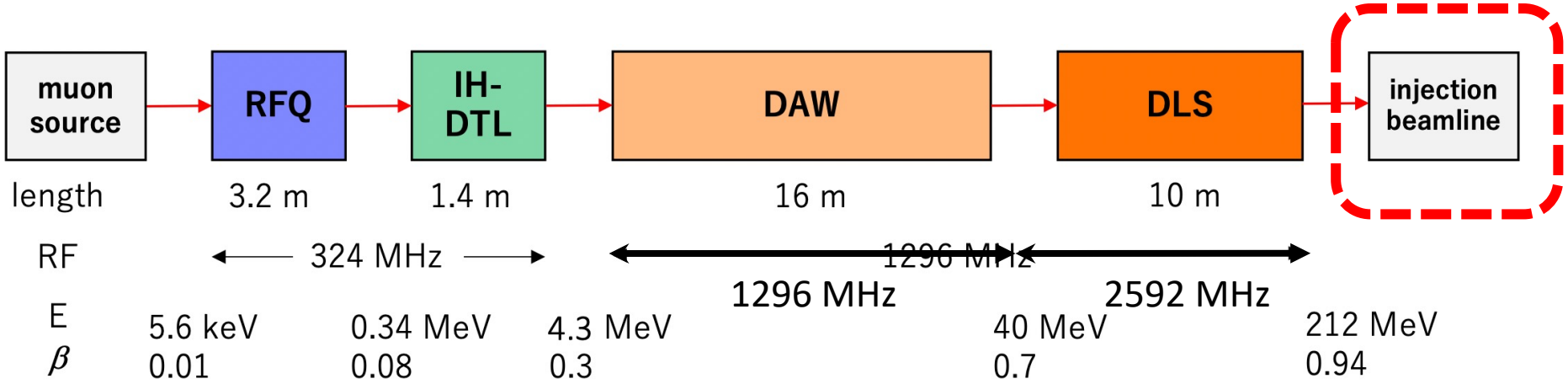
Muon beam injection



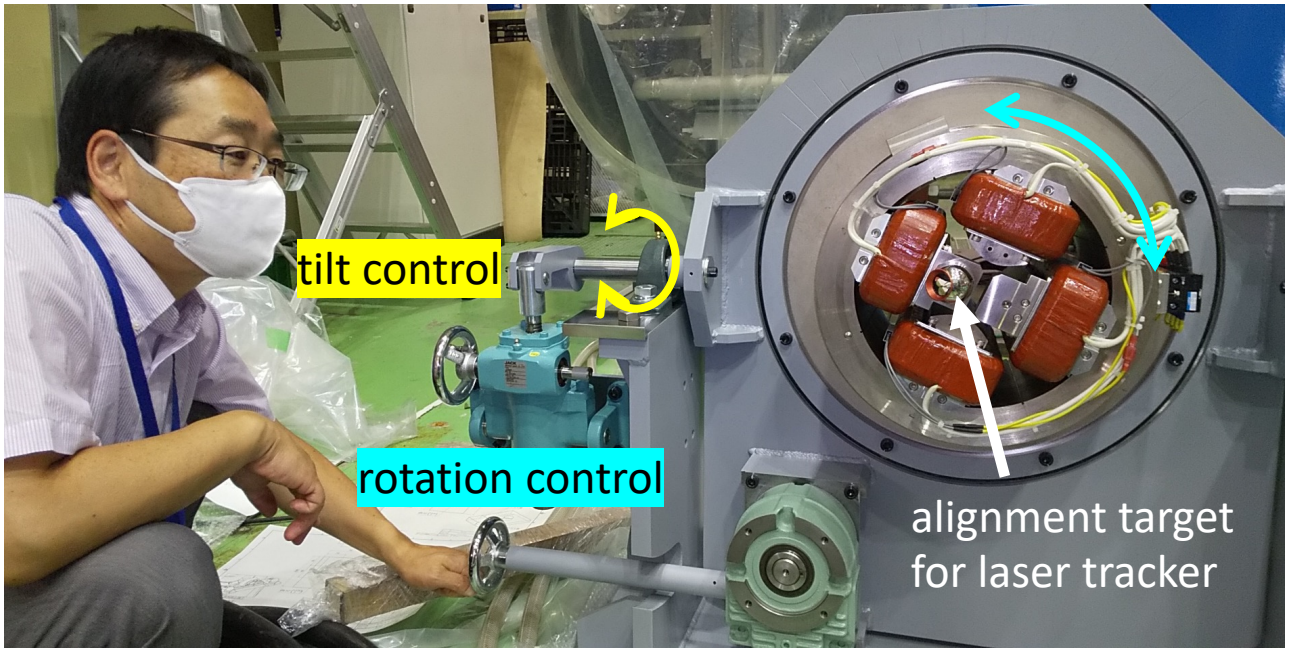


H. Iinuma et al., Nucl. Instr. And Methods. A 832, 51 (2016)

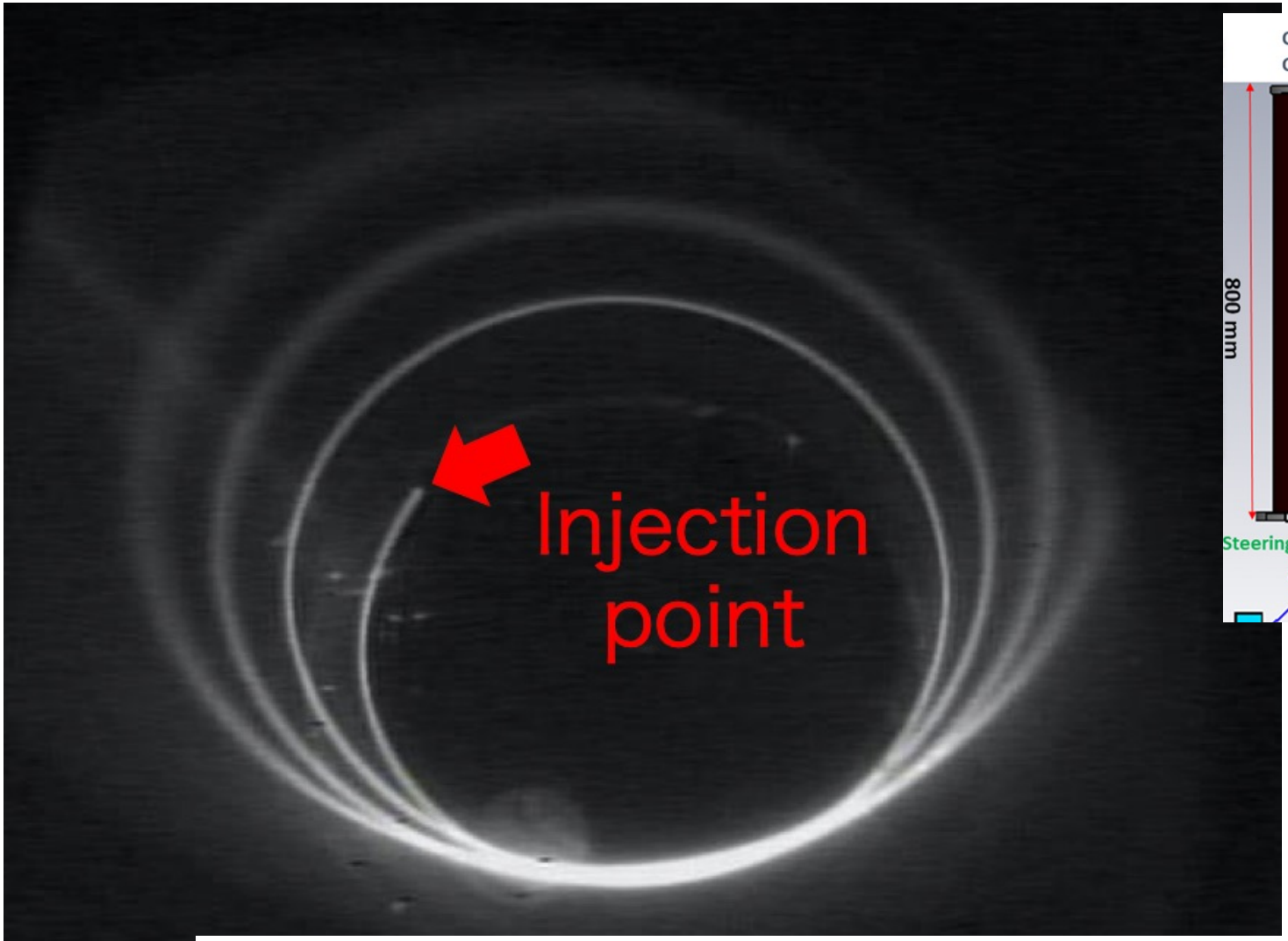
Muon beam injection

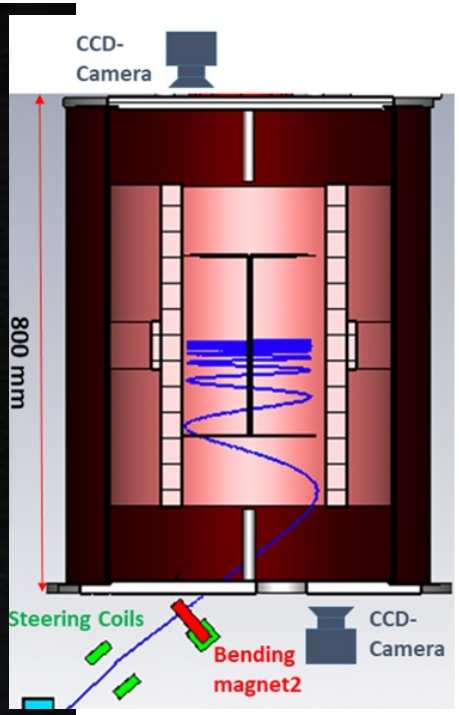


Rotating quadrupole magnet for injection beamline



Spiral Injection Test Experiment with electron beam

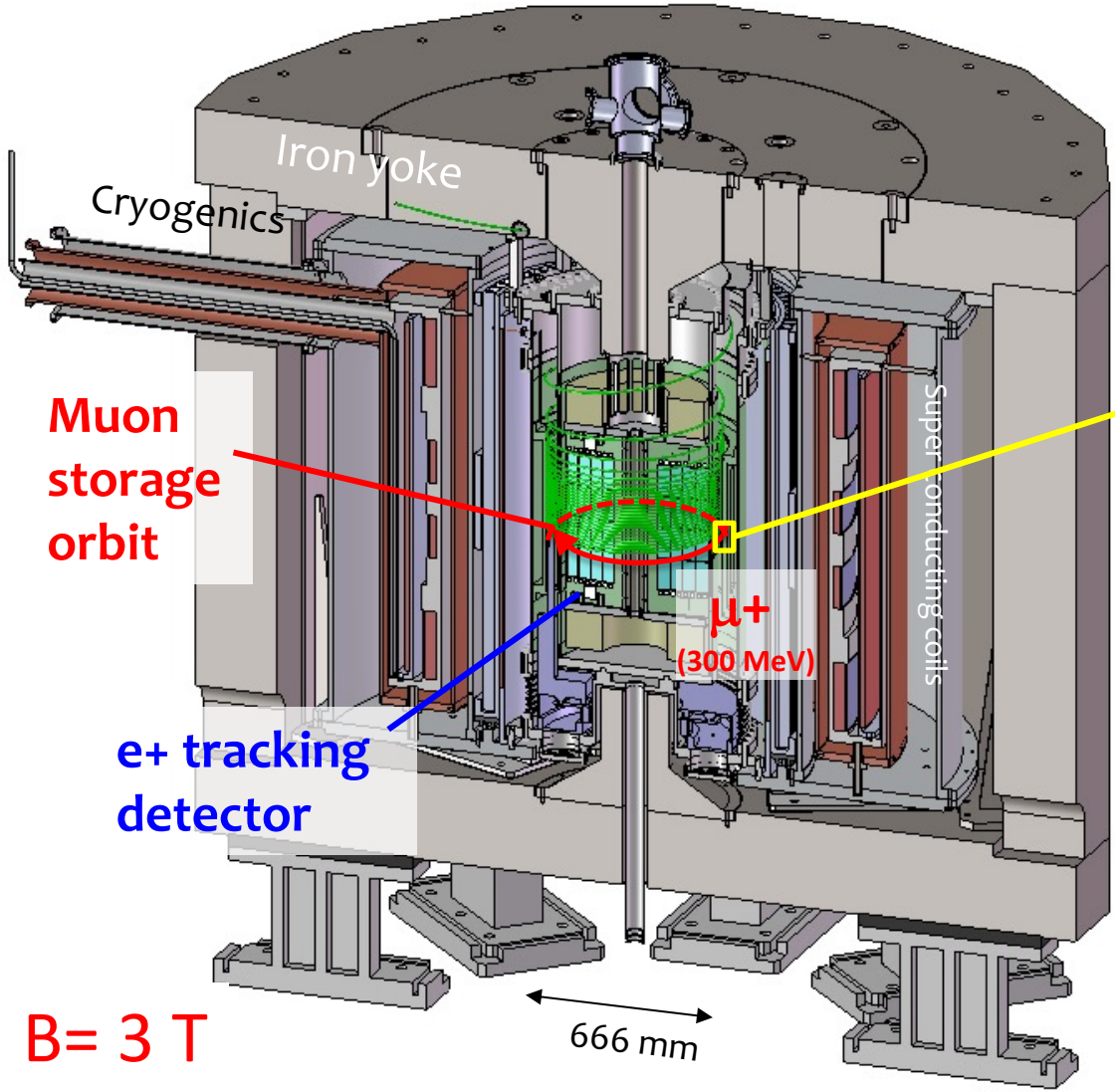




Electrons successfully injected.

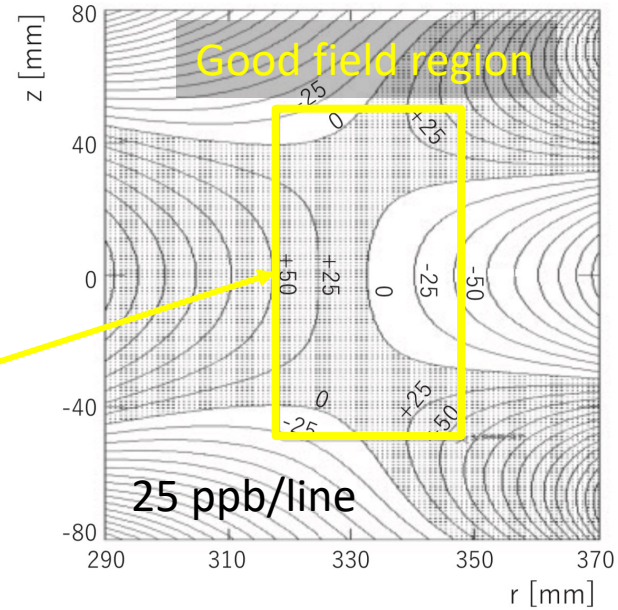
Next step: demonstration of storage by a pulsed kicker

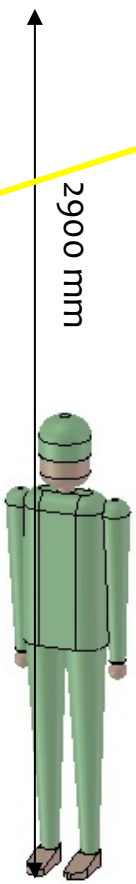
Muon storage magnet and detector



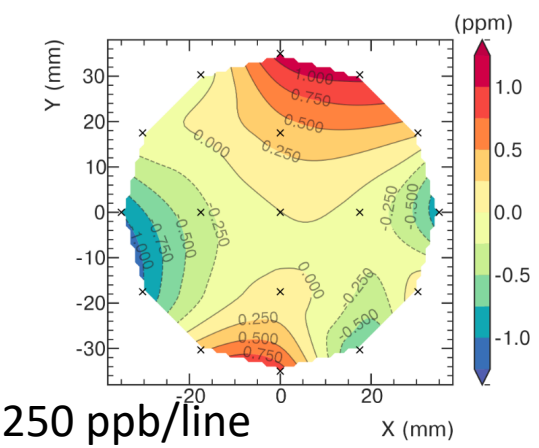
B= 3 T

Calculated average field uniformity



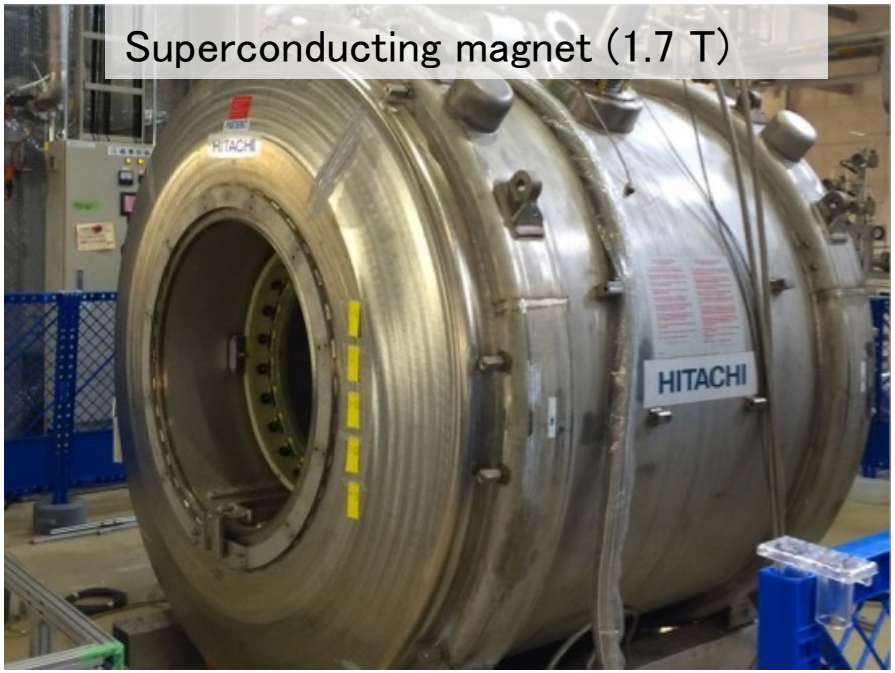


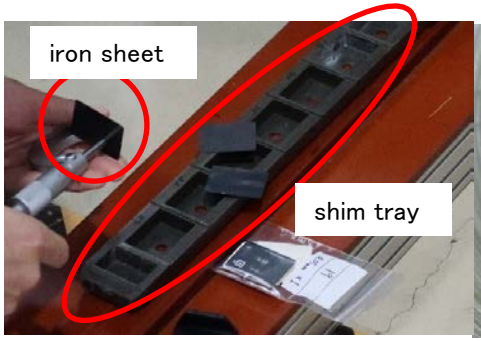
FNAL Run 1 PRA 103, 042208 (2021)

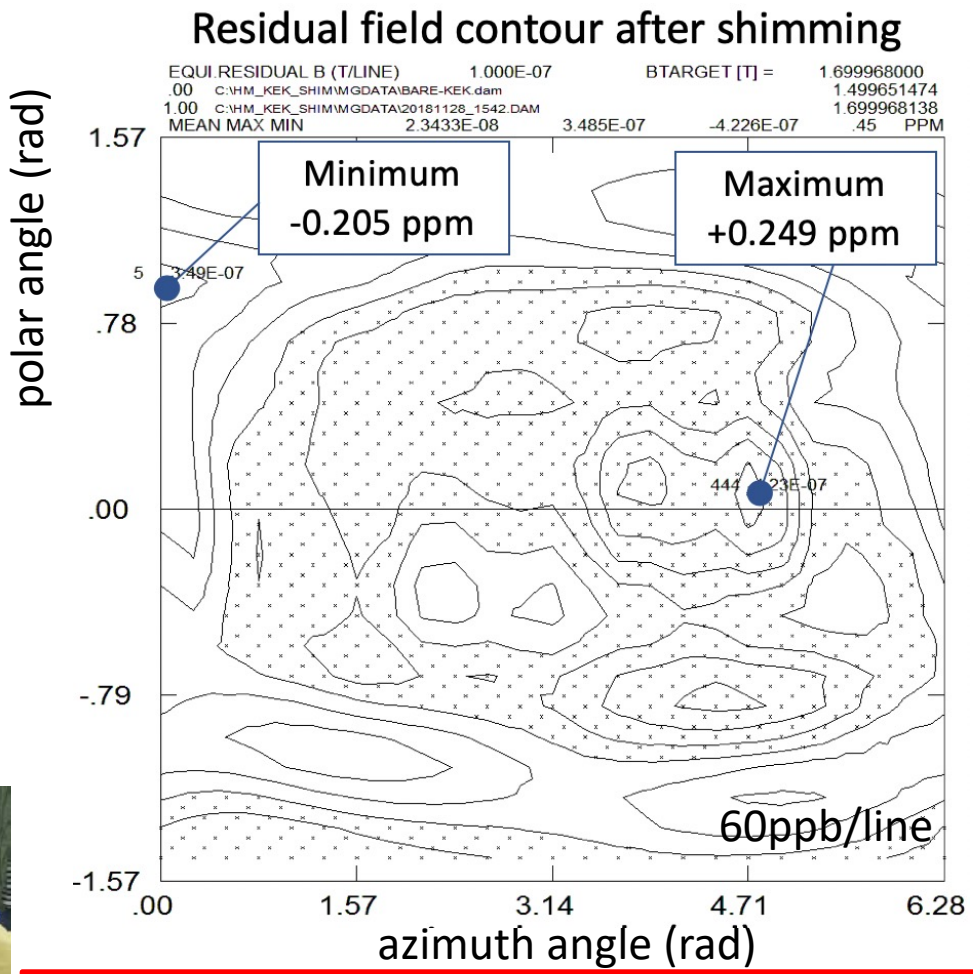


M. Abe et. al., NIM A 890, 51 (2018)

Magnet shimming test

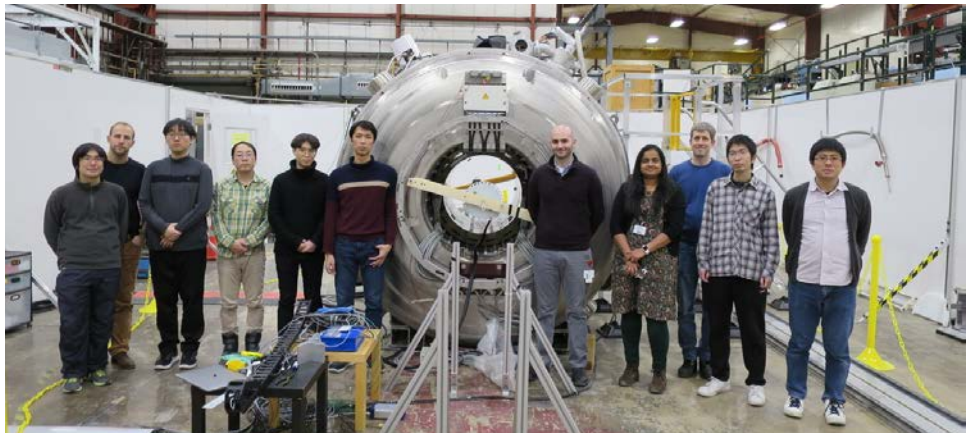






Field uniformity: **0.454 ppm** (peak-to-peak)
on the surface of sphere r=15 cm

US-Japan cross calibration campaign



PRECISION CROSS-CALIBRATION OF THE NMR CALIBRATION PROBES FOR THE J-PARC MUON G-2/EDM, J-PARC MUSEUM, AND FNAL MUON G-2 EXPERIMENTS AT THE ANL 4T MAGNET FACILITY

Physics of fundamental Symmetries and Interactions - PSI 2022, 10/16/2022 - 10/21/2022, Villigen, Switzerland.
S. Corrodi[1], D. Flay[2], R. Hong[1], D. Kawall[2], S. Oyama[3], S. Ramachandran[2], K. Sasaki[3], K. Shimomura[3], T. Tanaka[3], P. Winter[1], H. Yamaguchi[3]
[1]Argonne National Laboratory, [2]University of Massachusetts, [3]High Energy Accelerator Research Organization - KEK

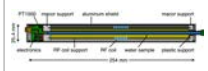
Motivation

- The measurement of the muon anomalous magnetic moment a_μ is a precision test of the Standard Model and an indirect search for New Physics.
- The Muon g-2 (E989) collaboration at Fermilab has published the most precise measurement of the muon anomalous magnetic moment with an uncertainty of 460 ppb in 2021, leading to a world average that deviates by 4.2 standard deviations from the Standard Model prediction provided by the Muon g-2 Theory Initiative.
- The complementary Muon g−2/EDM experiment (E34) at Japan Proton Accelerator Research Complex (J-PARC) is under construction.

$$a_\mu = \frac{\omega_a}{\boxed{\tilde{\omega}'_p(T_r)}} \frac{\mu'_p(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

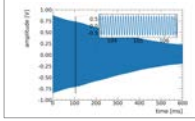
- Both experiments use nuclear magnetic resonance (NMR) probes to measure the magnetic field in terms of the precession frequency of the protons.
- **Goal: cross-calibration of the NMR calibration probes on the 30 ppb level at 1.45T, 1.7T, and 3.0T**

Fermilab Calibration Probe



Pulsed NMR

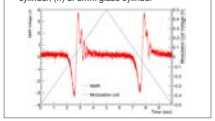
Schematic drawing of the calibration probe used to calibrate the trolley probe measurements.



J-PARC Calibration Probe

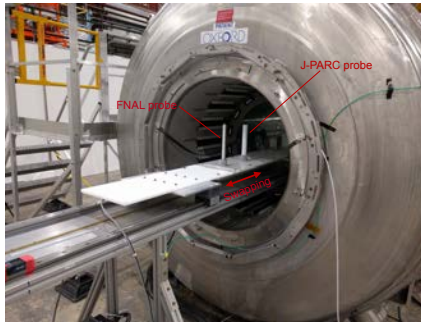
Continuous Wave NMR

(a) Teflon pipe, (b) Modulation coil, (c) Aluminum pipe, (d) RF coil, (e) Readout board, (f) Board holder, (g) d: 14mm glass cylinder, (h) d: 5mm glass cylinder

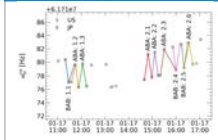


Facility

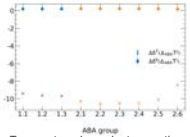
- 4-Tesla magnet facility at Argonne National Laboratory (Oxford OR66)
- Very stable and highlight uniform field due to passive and active shimming, local gradients below 2 ppb/mm
- Passive shimming based on single-value decomposition from field maps on a 50-cm diameter sphere obtained with Metrolab cameras



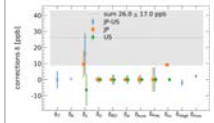
Measurement (1.45T)



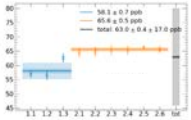
Raw difference measured at the same position from swapping the probes back and forth inside the magnet at 1.45T.



Temperature dependent corrections from diamagnetic shielding δ^T and bulk magnetic susceptibility δ^b



Correction terms from material effects (δ_s, δ_{cc}, δ_{stage}), water sample (δ_p), radiation damping (δ_{RD}), probe tune and frequency extraction (δ_{tune}, δ_{freq}), and misalignment (δ_{miss}).



Difference of the shielded proton precession frequency ω_p between the FNAL and the J-PARC calibration probes at 1.45T.

Status

- Cross-calibration at 1.45T and 1.7T with uncertainties of ~17ppb
- The 3T calibration was delayed because of COVID
- The cross-calibration campaigns at 1.45T and at 1.7T yield a ~60ppb difference between the two probes (after unblinding)
- Thorough investigations and correction reevaluations have not led to any indication of the source of the discrepancy yet
- Next Step: Cross-calibration at 3T in October 2022

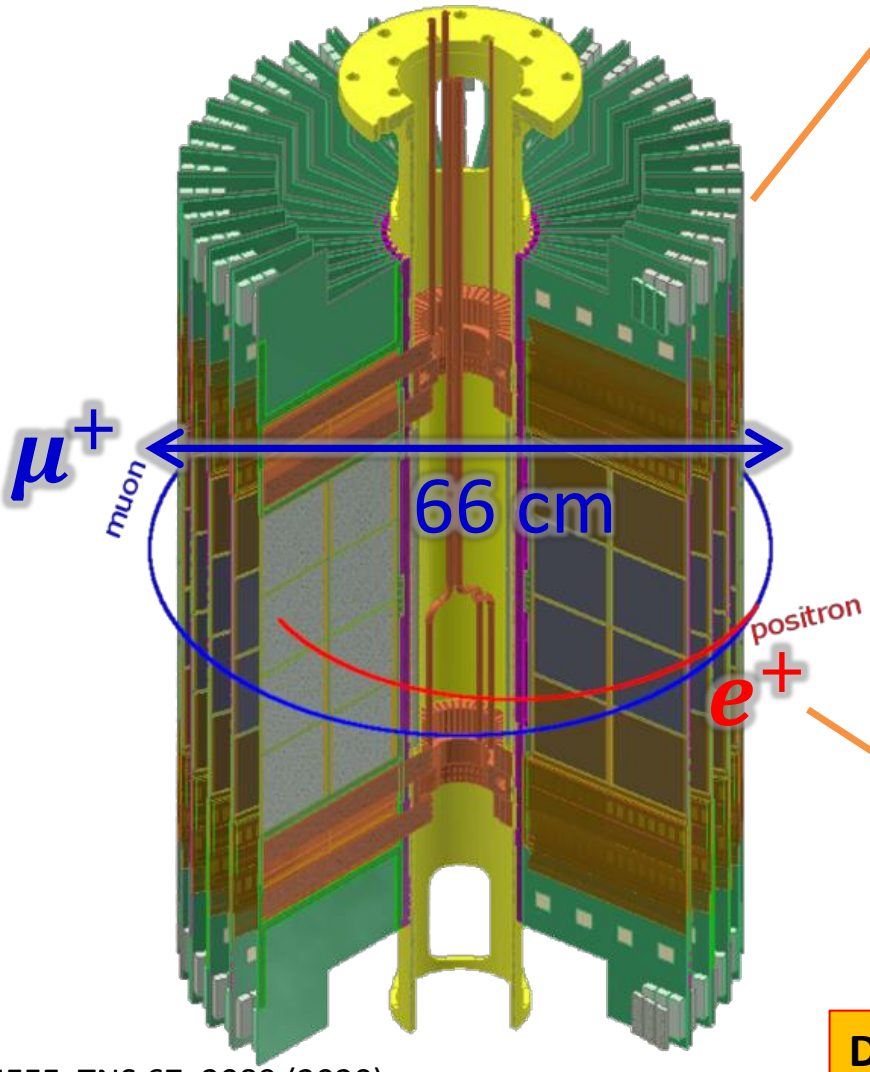
Additional Measurements

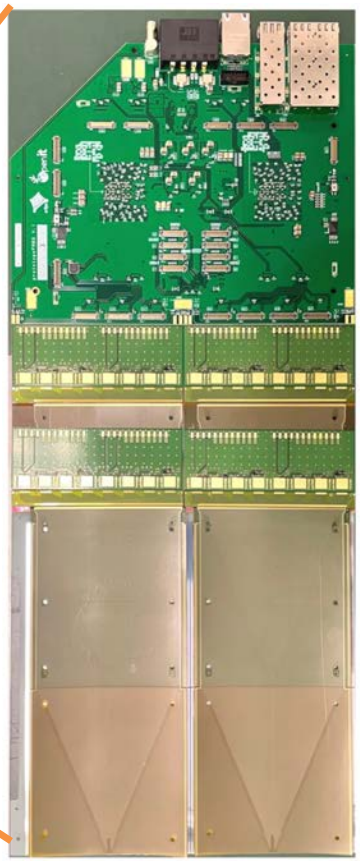
- The cross-calibration at 1.7T is motivated by the J-PARC Muonium Spectroscopy Experiment Using Microwave (MuSEUM). It yield a consistent difference of ~60ppb.
- The same facility is used to cross-calibrate the FNAL calibration probe with ^{3}He NMR probe developed by the University of Michigan

References

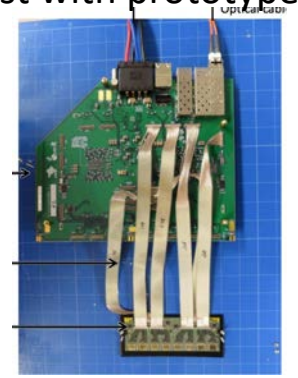
- H. Yamaguchi *et al.*, "Development of a CW-NMR Probe for Precise Measurement of Absolute Magnetic Field" in *IEEE Transactions on Applied Superconductivity*, vol. 29, no. 5, pp. 1-4, Aug. 2019, Art no. 9000904, doi: 10.1109/TASC.2019.2895360.
- D. Flay *et al.*, "High-accuracy absolute magnetometry with application to the Fermilab Muon g-2 experiment", *JINST* **16** P12041, 2021.
- M. Farooq *et al.*, "Absolute Magnetometry with ^{3}He", Phys. Rev. Lett. **124**, 223001, 2020.

Positron tracking detector

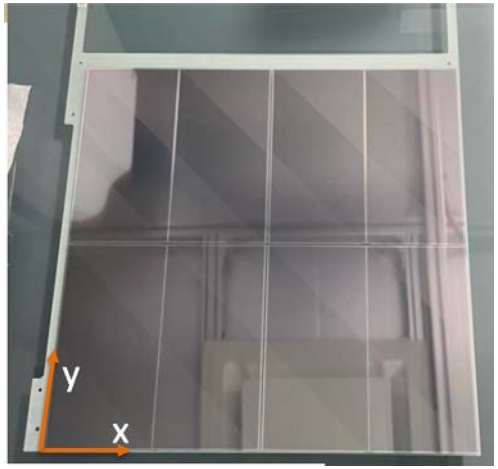




Test with prototype boards



Si strip sensors



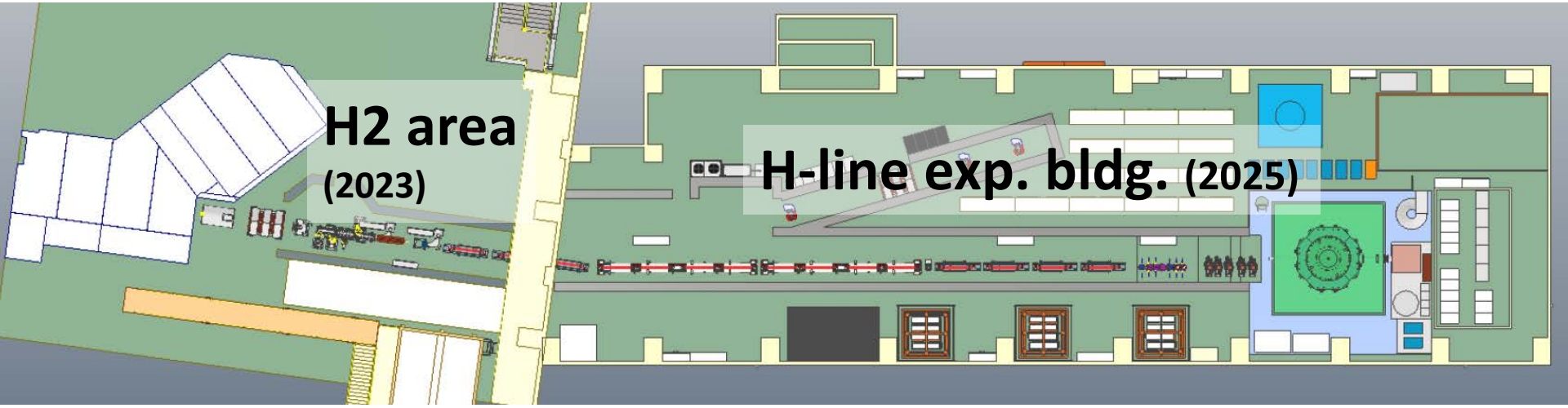
~200 mm

IEEE, TNS 67, 2089 (2020)
JINST 15 P04027 (2020)

Development of the detector system is in progress.
Mechanical & electrical prototypes in production.


MLF
muon target
neutron target

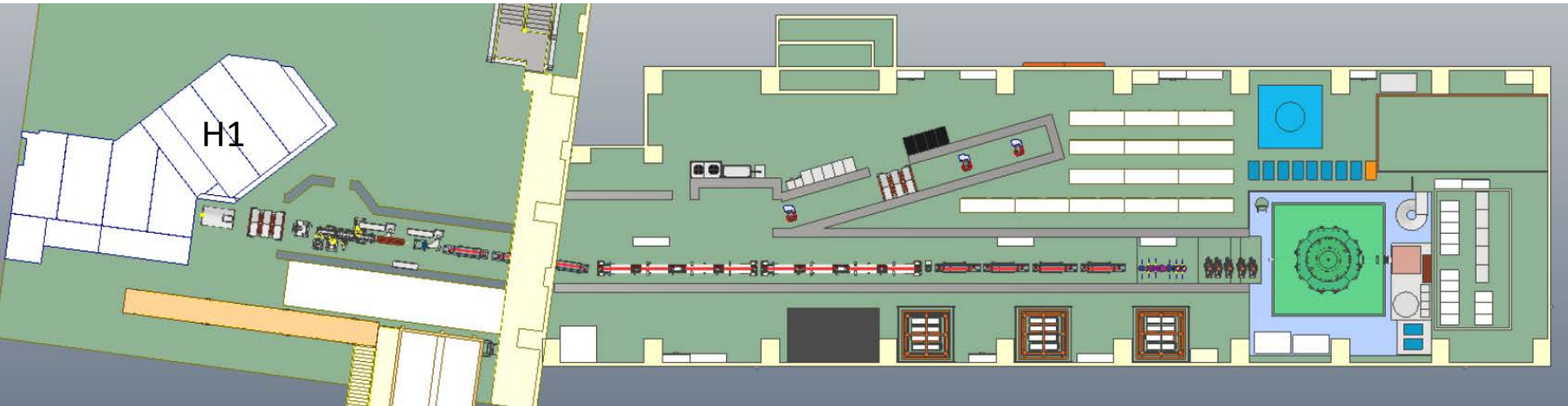
Intended schedule and milestone



	2021	2022	2023	2024	2025	2026	2027 and beyond
H2 area		Shields Approval ★	Magnets				Commissioning Data taking
H line exp. bldg		Re-location	Eng. design of bldg. Exterior construction	bldg. construction			
Components	construction					Installation	

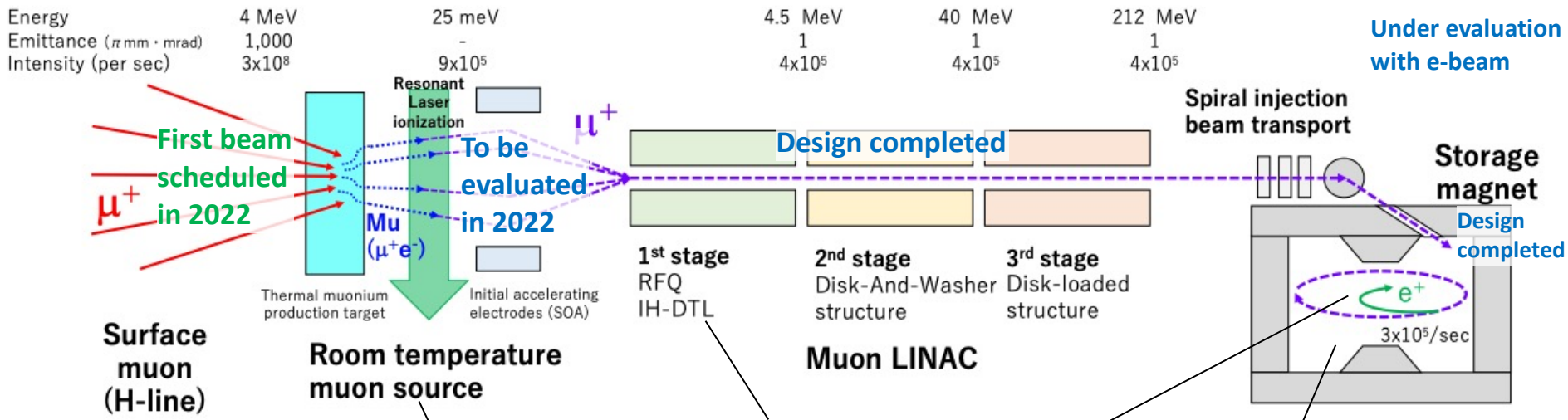
Summary

- **J-PARC g-2/EDM experiment uses new method**
  - **Cooling + acceleration of positive muons**
  - **Storage in a compact ring**
  - **Complementary to magic gamma experiments**
- **Surface muon beam delivered on Jan. 2022.**
- **Expected date of data taking from 2027.**

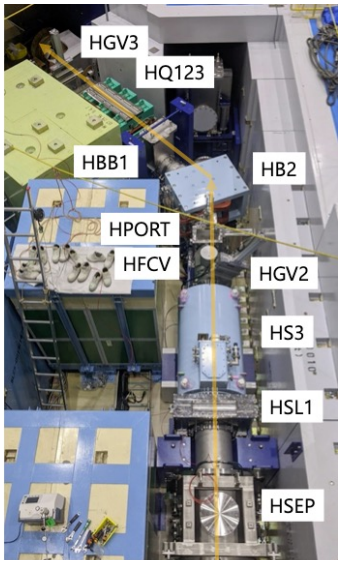


Achievements in the past

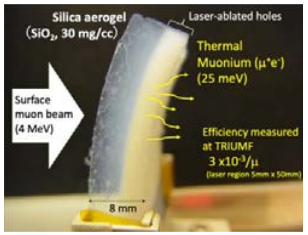
Prog. Theor. Exp. Phys. **2019**, 053C02

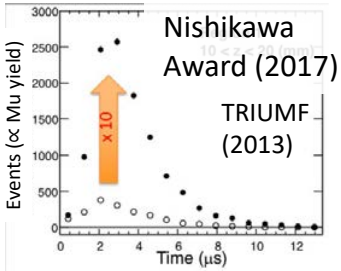


Beamline construction (2020)



(a) Muonium production target



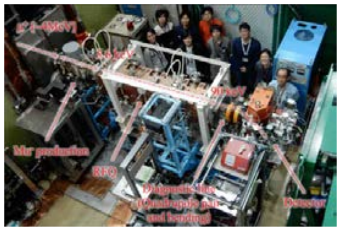


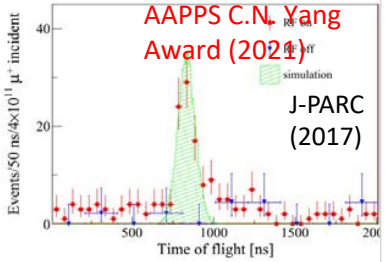
Nishikawa Award (2017)

TRIUMF (2013)

PTEP 2013,103C01
PTEP 2014,091C01
PTEP 2020,123C01

(b) Muon acceleration to 80 keV



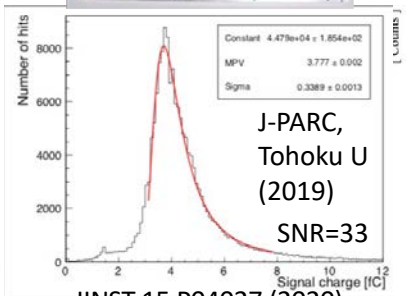


AAPPS C.N. Yang Award (2021)

J-PARC (2017)

PRAB 19, 040101 (2016)
PRAB 21, 050101 (2018)
PRAB 23, 022804 (2020)
PRAB 24, 033403 (2021)

(c) Unit module of positron detector

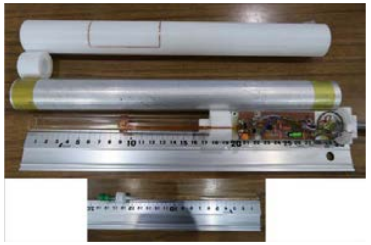


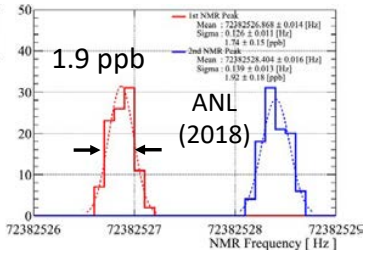
J-PARC, Tohoku U (2019)

SNR=33

JINST 15 P04027 (2020)
IEEE TNS 67, 2089, 2020

(d) Magnetic field probe (NMR)





ANL (2018)

NIMA 890, 51 (2018)
IEEE TAS, 29, 9000904 (2019)

The collaboration received **a new Grant-in-Aids for 6 years (2020-2025)** for construction of detector system and other key components.

g-2 and muonium experiments 38

Inspired by K. Jungmann

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

120 ppb

g-2

Fermilab E989

J-PARC g-2/EDM (preparation)

$$a_\mu = \frac{\omega_a}{\omega_p}\frac{\mu_p}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2}$$

8 ppb 120 ppb 0.3 ppt

μ_μ

m_μ

MuSEUM(J-PARC) **Ongoing**

Mu-MASS(PSI), **new exp.(J-PARC)**

Mu HFS

Mu 1S-2S

m_μ

muonium

$$\Delta\nu_{\text{1S-HFS}} \simeq \frac{16}{3}\alpha^2 R_\infty \frac{\mu_\mu}{\mu_B}\left(1+\frac{m_e}{m_\mu}\right)^{-3}$$

muonium

$$\Delta\nu_{\text{1S2S}} \simeq \frac{3\alpha^2}{8h} m_e c^2 \left(1+\frac{m_e}{m_\mu}\right)^{-1}$$

$$\nu_{34} - \nu_{12} \propto \frac{\mu_\mu}{\mu_p}$$

Three quantities are mutually correlated.
Closing a triangle with new experiments will establish ultimate precision.

g-2 and muonium experiments at J-PARC

Inspired by K. Jungmann

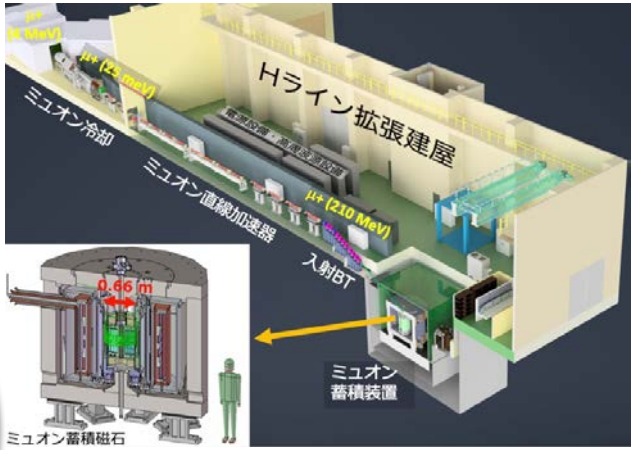
Lead by K. Shimomura (IMSS/KEK)

MuSEUM(J-PARC) **Ongoing**

g-2

Fermilab E989

J-PARC g-2/EDM (preparation)



Mu-MASS(PSI), **new exp.(J-PARC)**

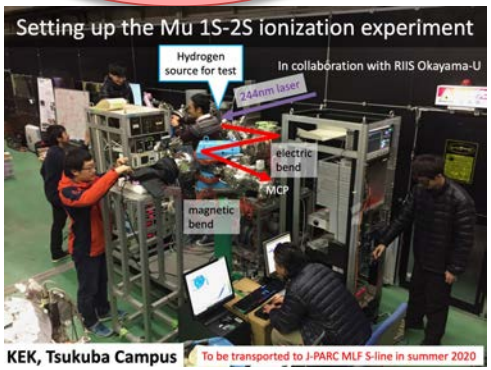
Positron detector
NMR probes

Muonium production
and ionization

Technical synergies

Mu HFS

Mu 1S-2S

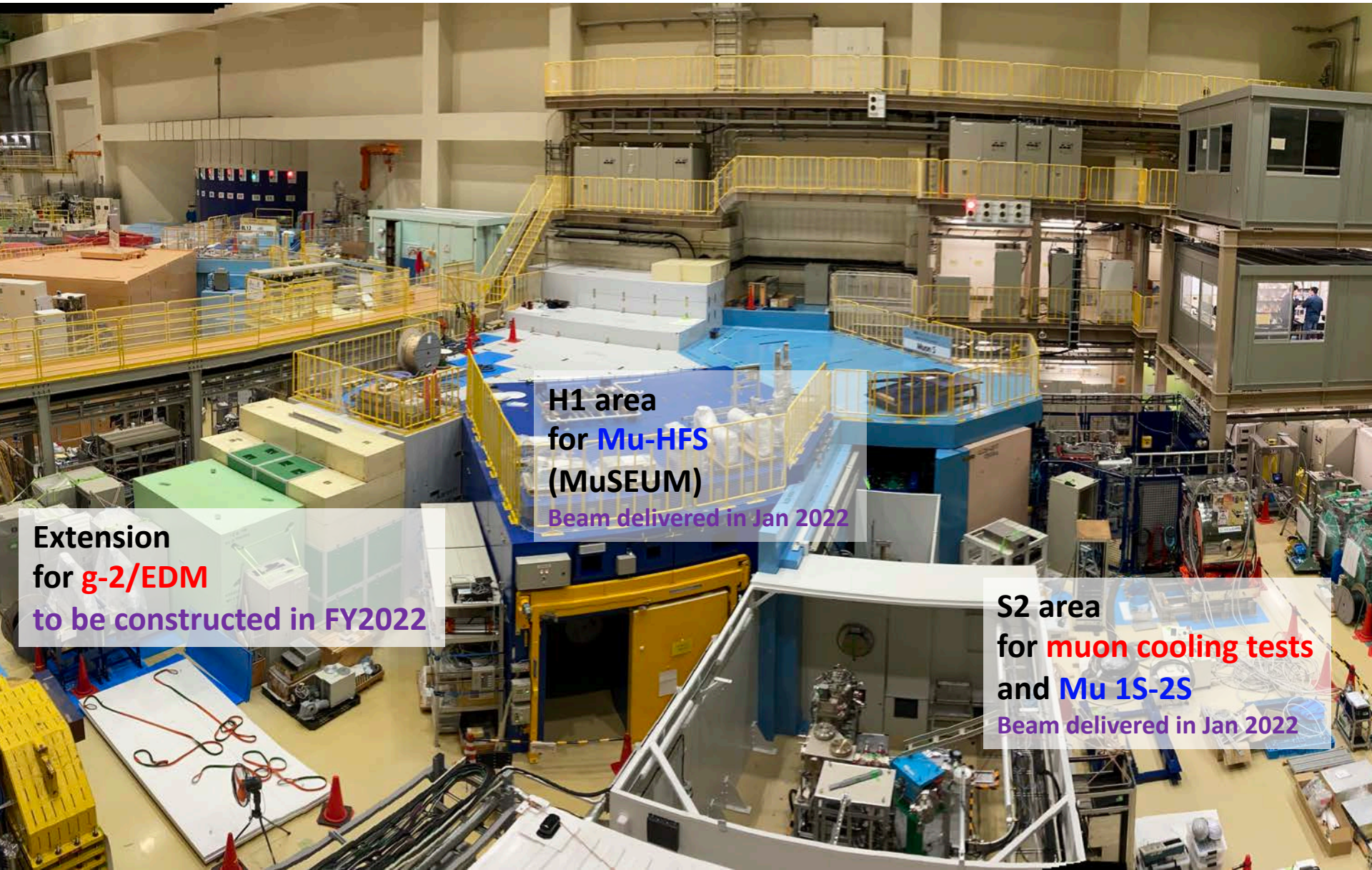


In preparation

Lead by S. Uetake (Okayama)

Three independent experiments have launched at J-PARC for improved measurements.

Experimental areas for experiments



Statistical and systematic uncertainties

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·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

J-PARC Muon Science Facility (MUSE)