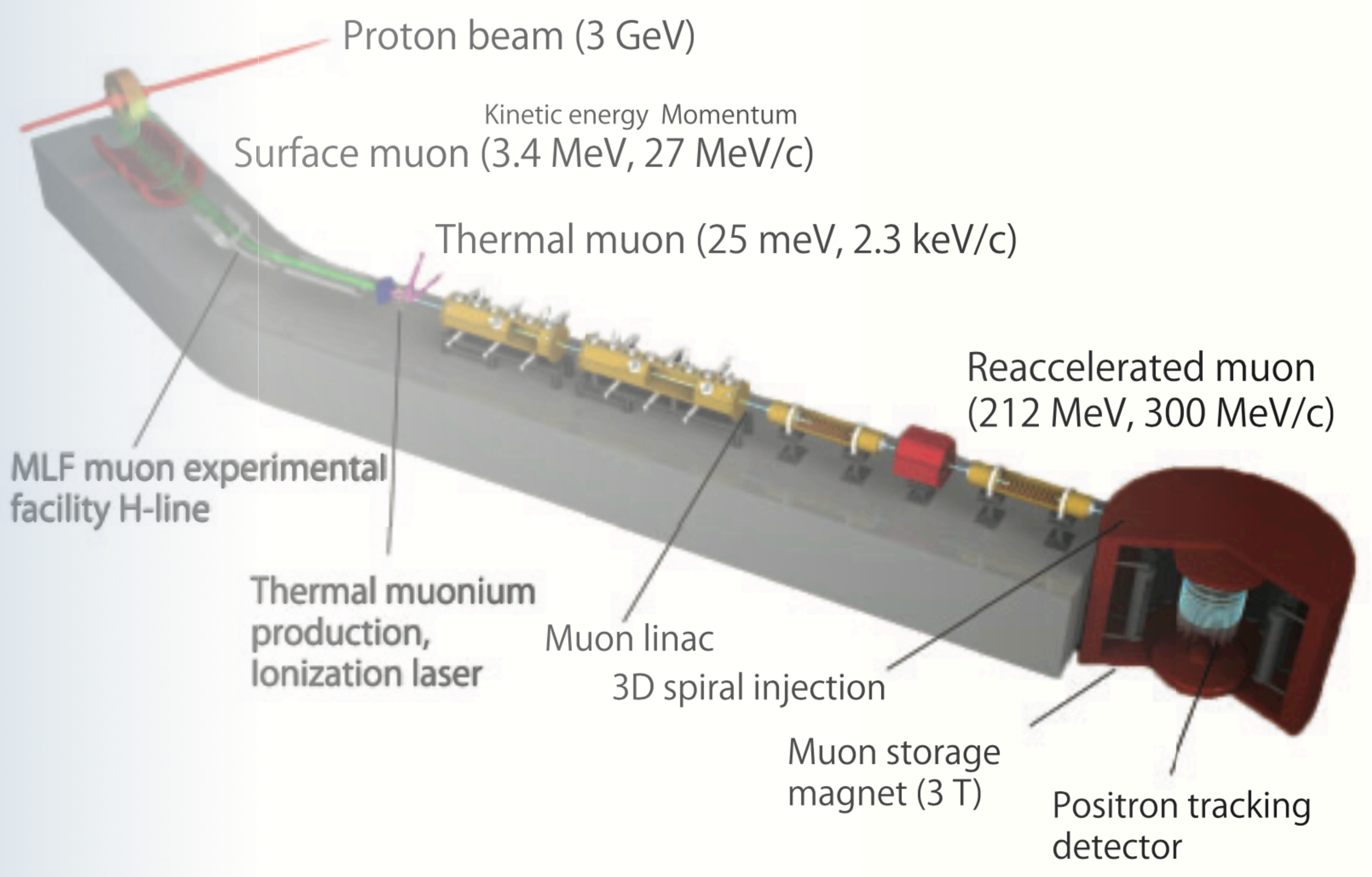
Muon $g-2$/EDM Experiment at J-PARC

Ce ZHANG (Cedric)

University of Liverpool

MITP 2024

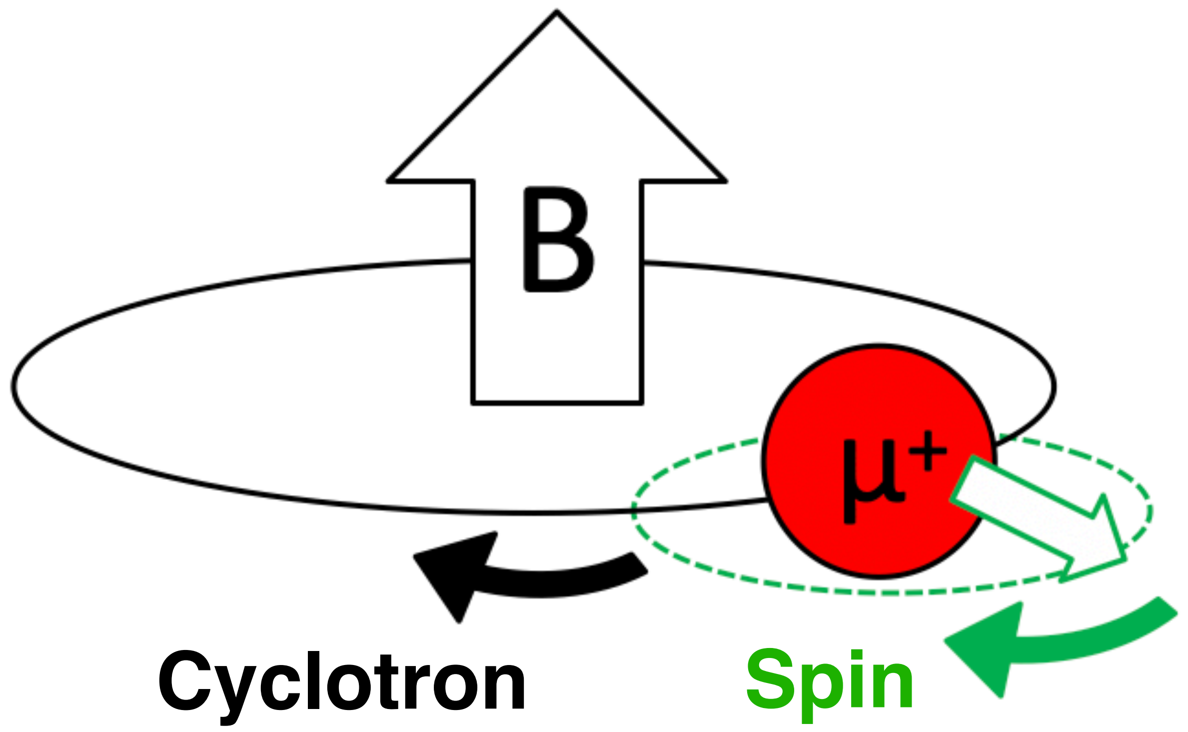


Muon $g-2$/EDM Experiment at J-PARC

- **Experimental principle**
- **Facilities**
  - Muon source
  - Muon accelerator
  - Magnet, storage and detector
- **Expected Sensitivity**
- **Status & Schedule**

Experimental Principle at J-PARC

Muon Precession in the Magnetic Field



$$\vec{\omega} = \vec{\omega_S} - \vec{\omega_C}$$

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

$g-2$ **terms**

EDM term

Experimental Principle at J-PARC

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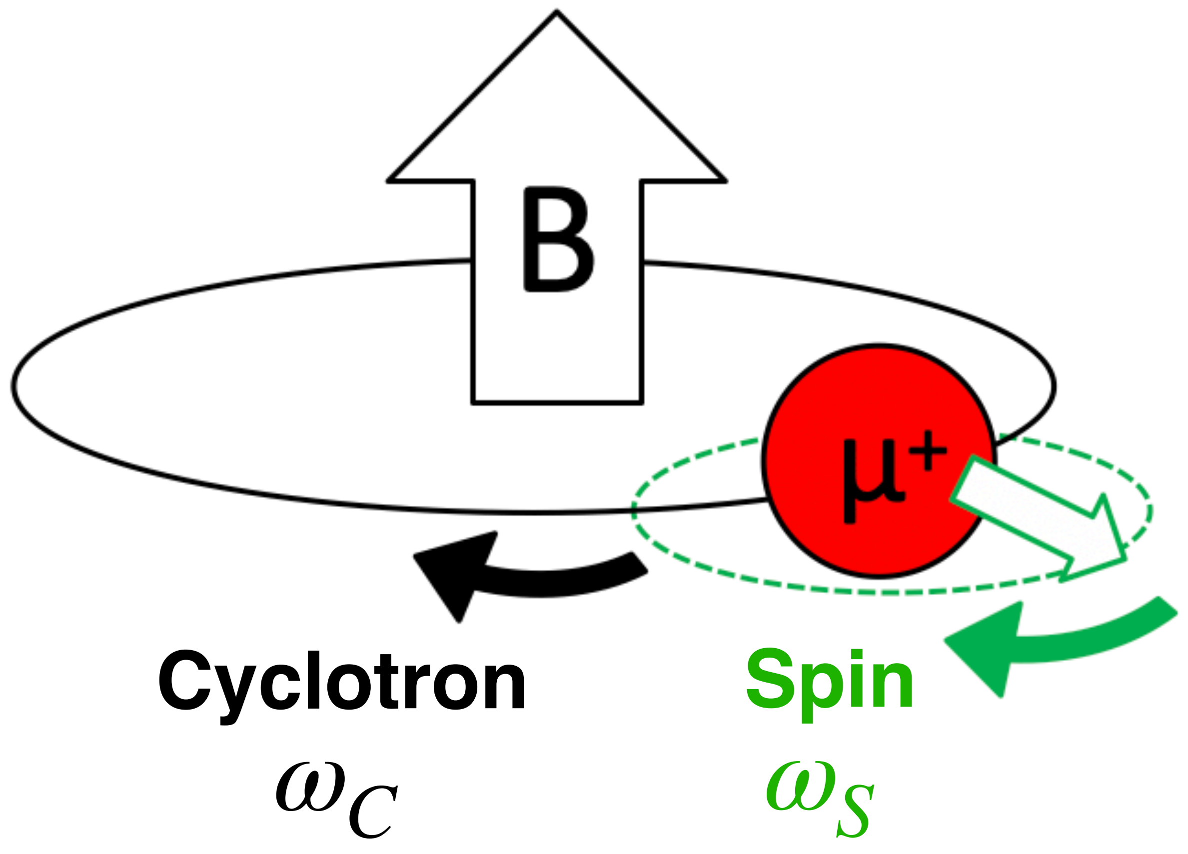

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Magic "γ": $a_\mu = \frac{1}{\gamma^2 - 1}$

BNL E821 approach

γ=30 (P=3 GeV/c)

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

FNAL E989

Experimental Principle at J-PARC

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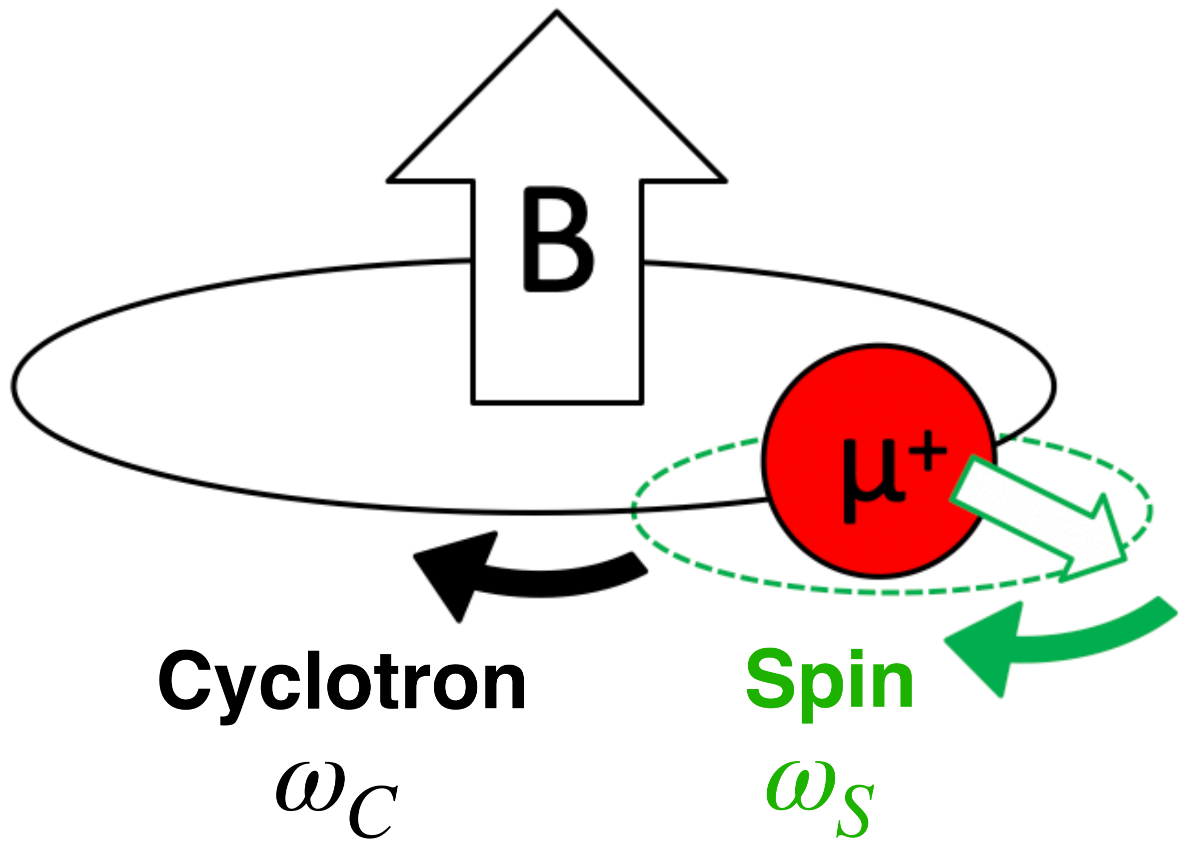

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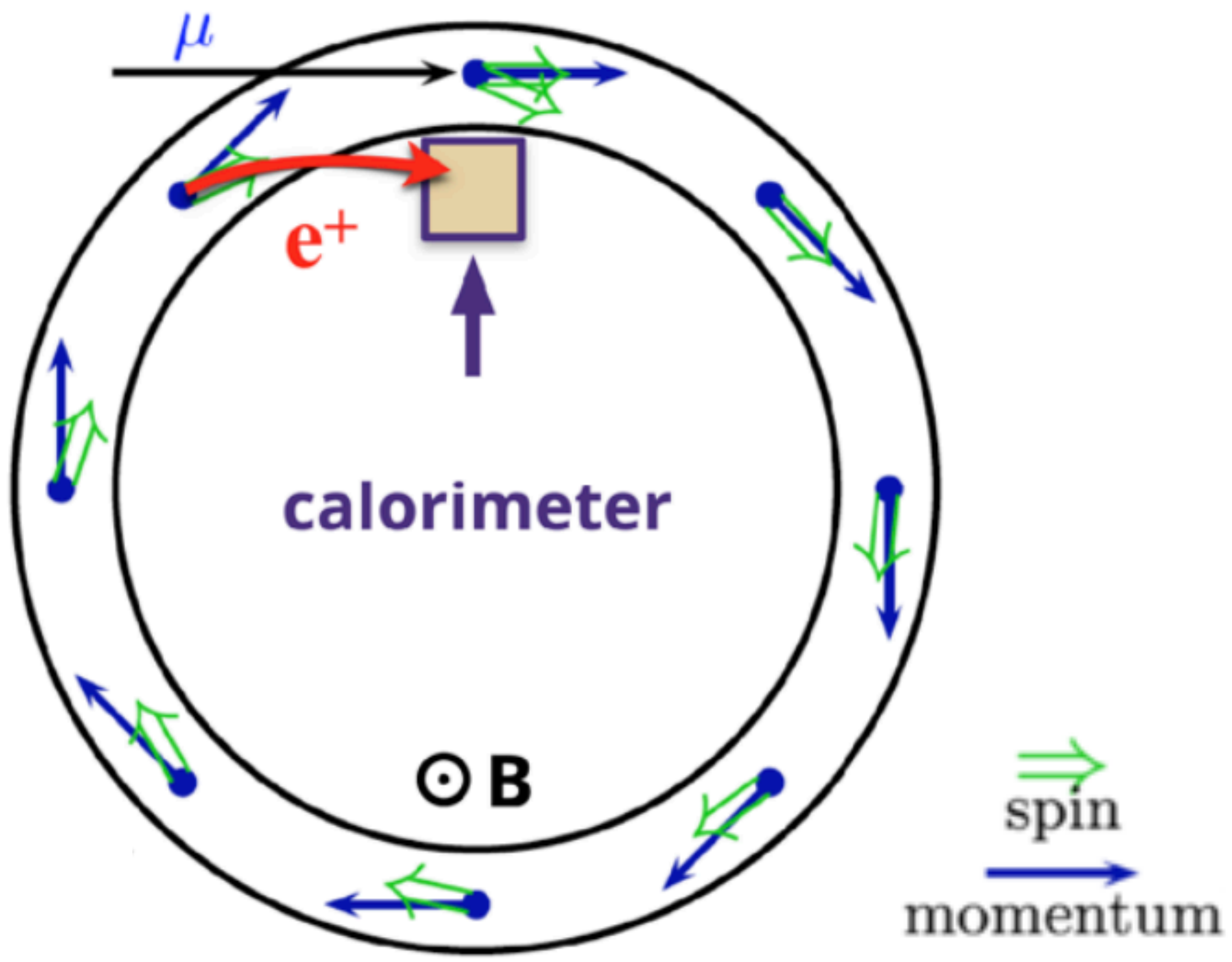
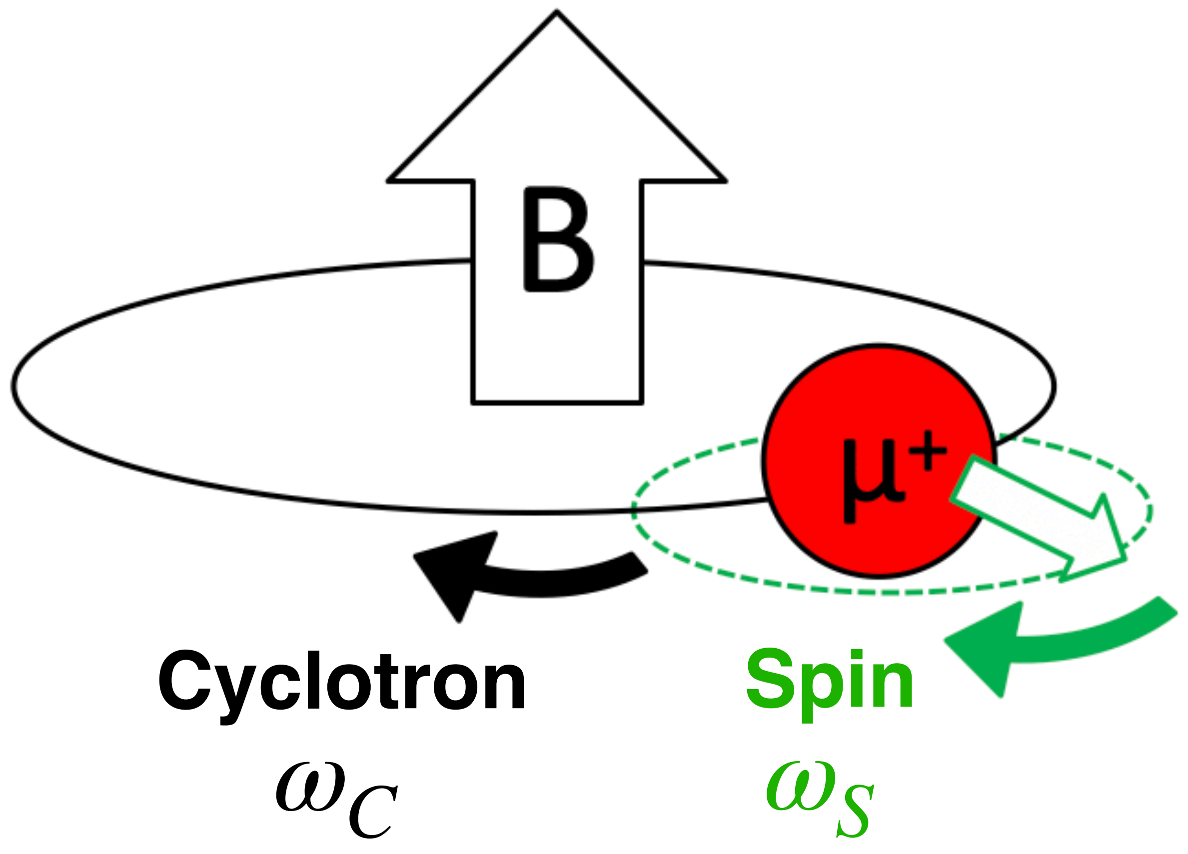


Experimental Principle at J-PARC

Muon Precession in the Magnetic Field



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FNAL E989

Experimental Principle at J-PARC

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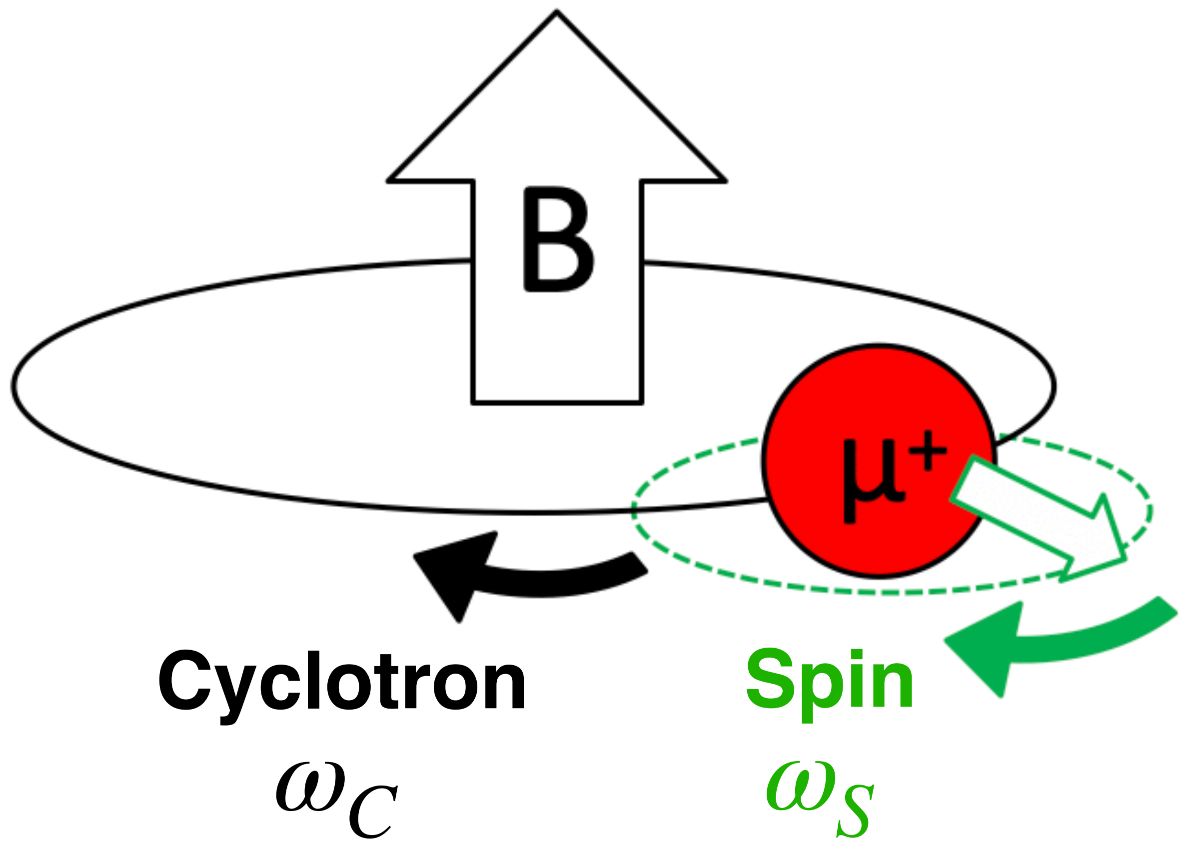

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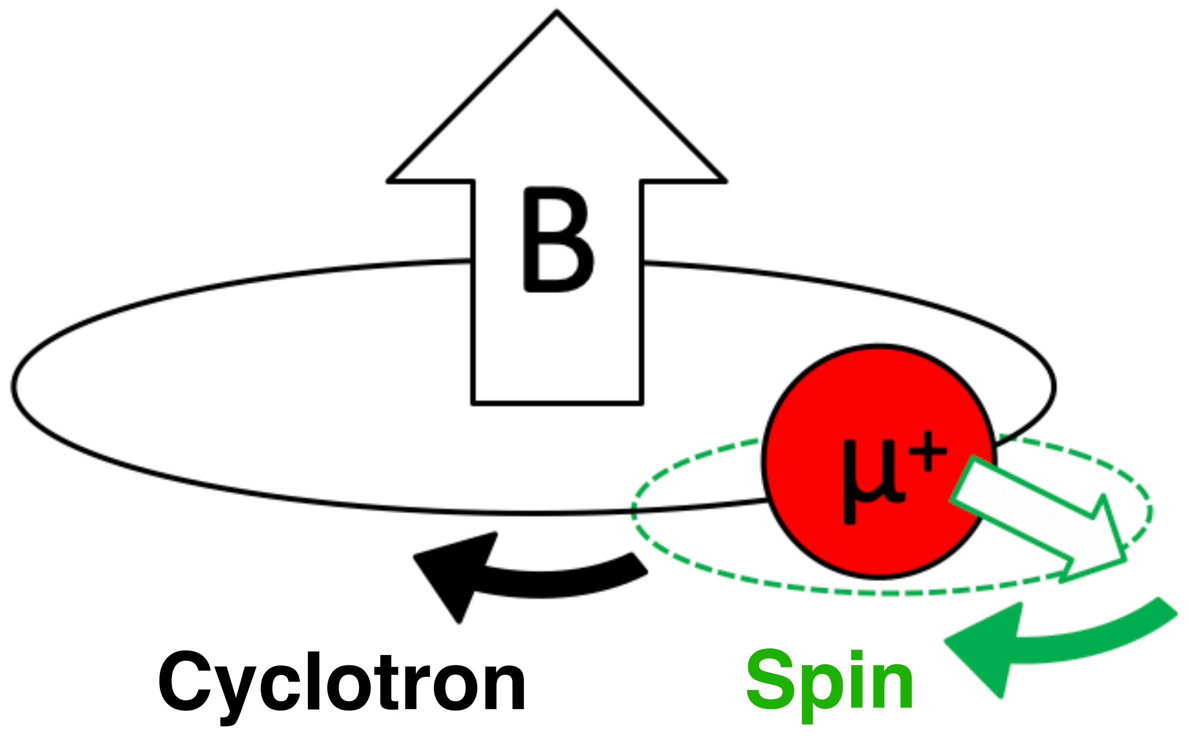
Experimental Principle at J-PARC

Muon Precession in the Magnetic Field



ω_C ω_S

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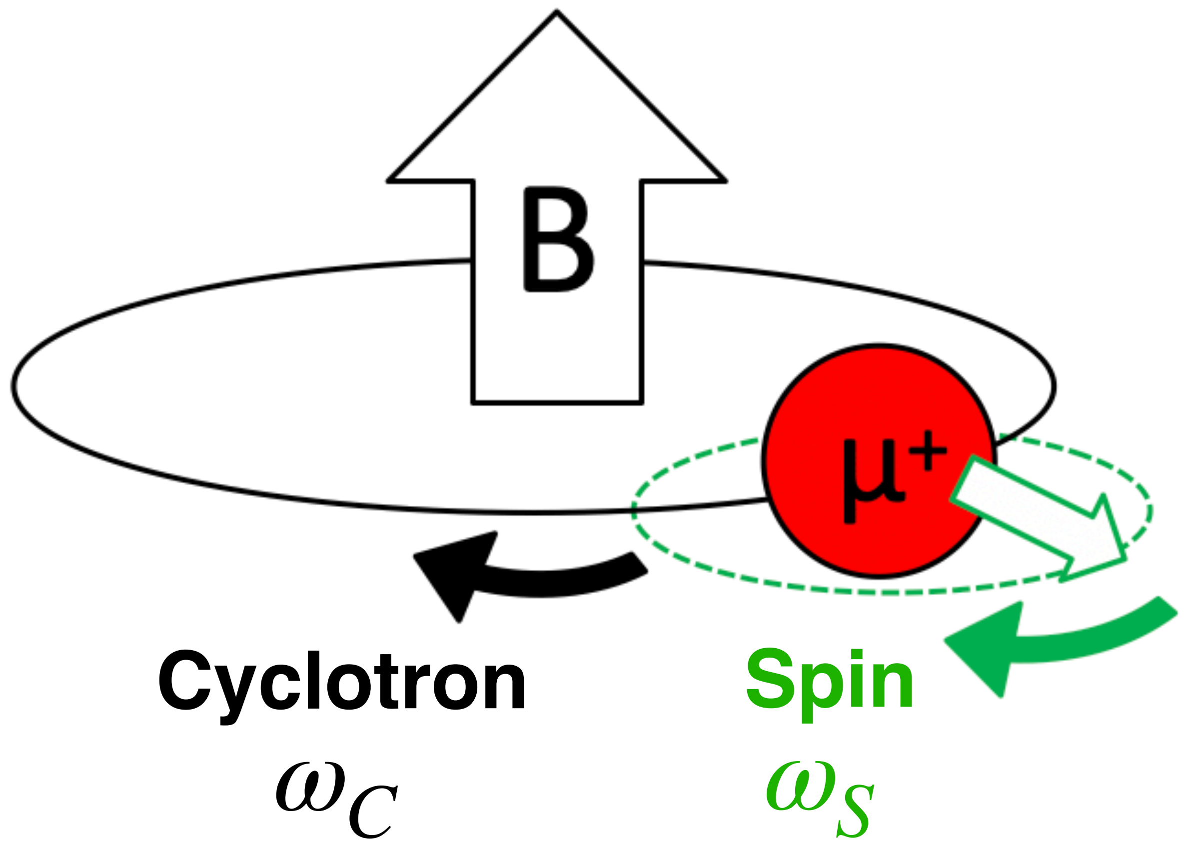
Experimental Principle at J-PARC

Muon Precession in the Magnetic Field



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Directly remove E field

J-PARC approach

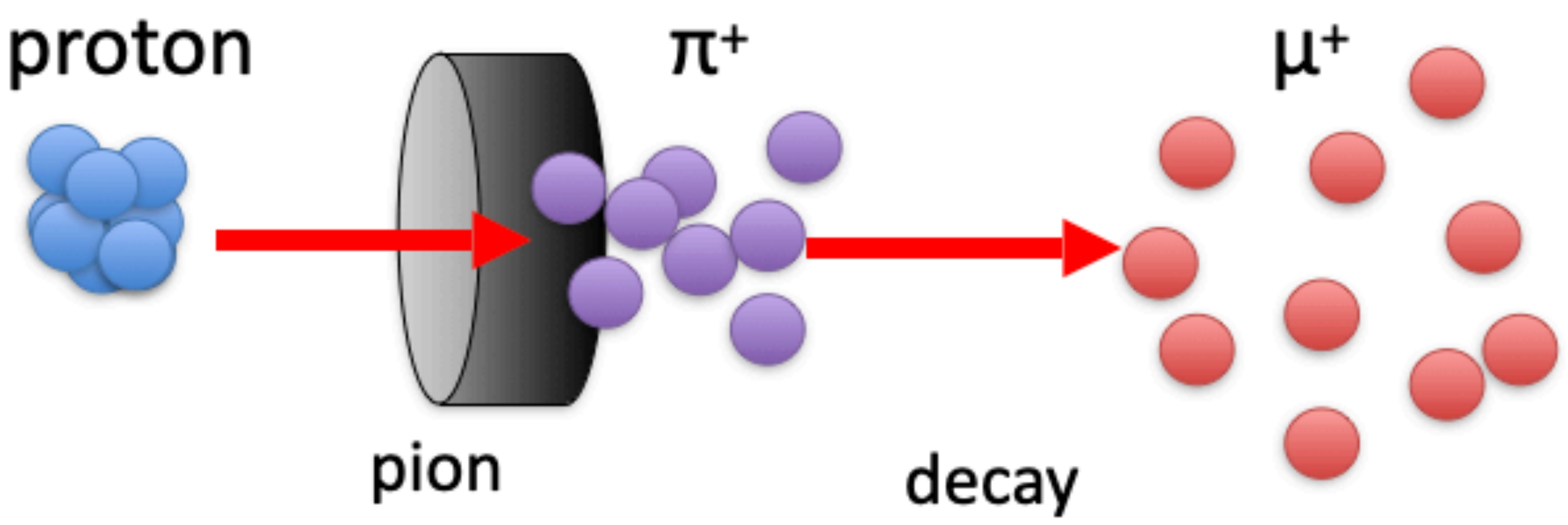
E = 0 at any γ

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

J-PARC E34

Experimental Principle at J-PARC

Low-emittance muons needed

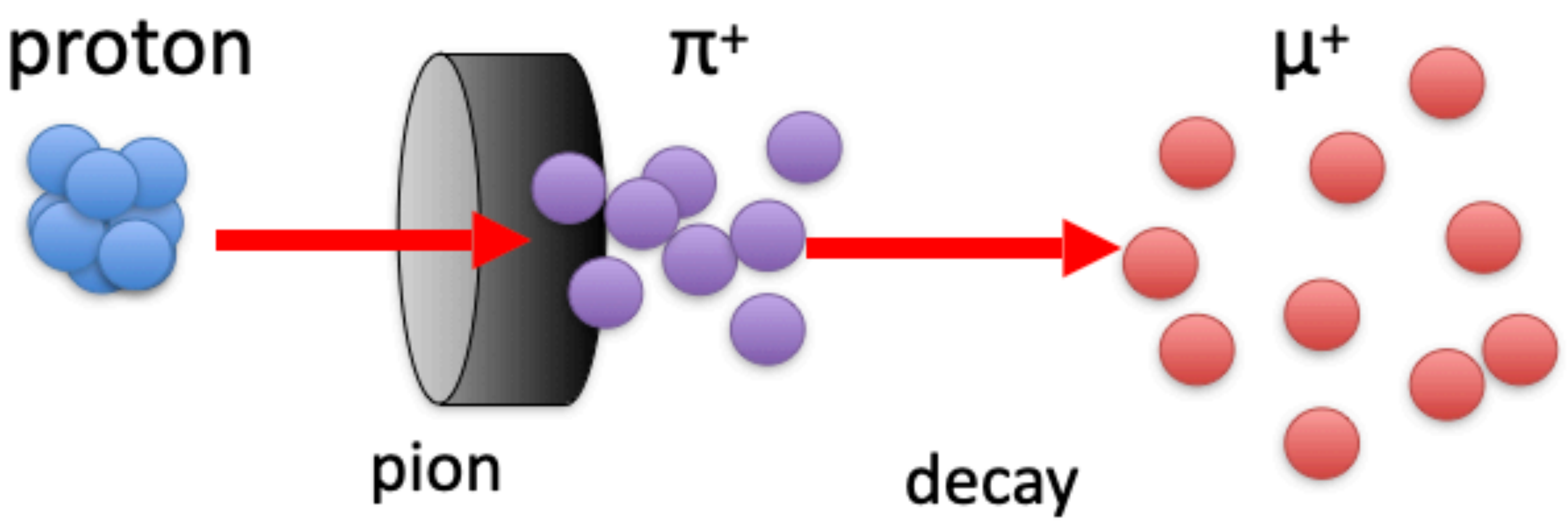


emittance

~1000π mm・mrad

Experimental Principle at J-PARC

Low-emittance muons needed



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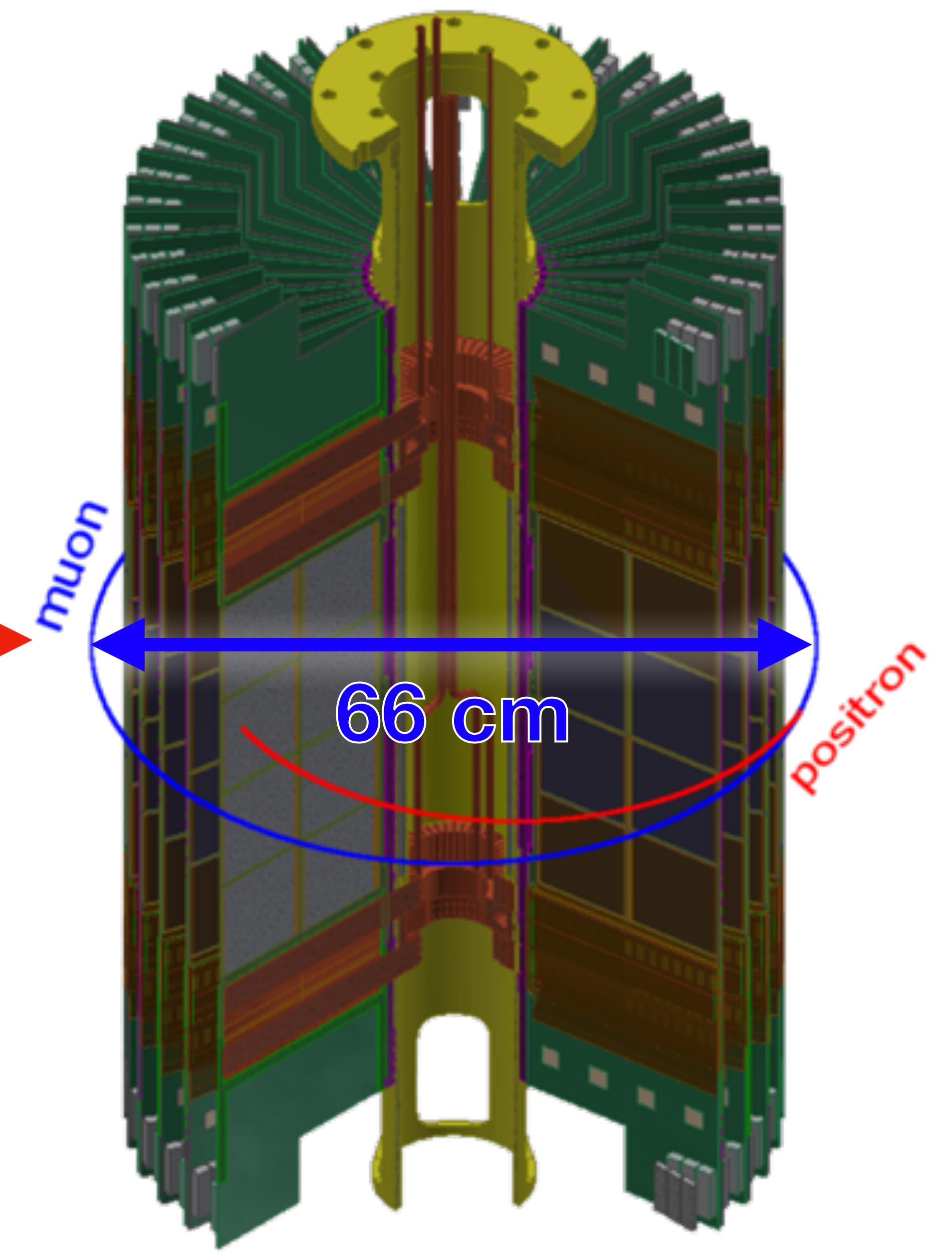

Experimental Principle at J-PARC

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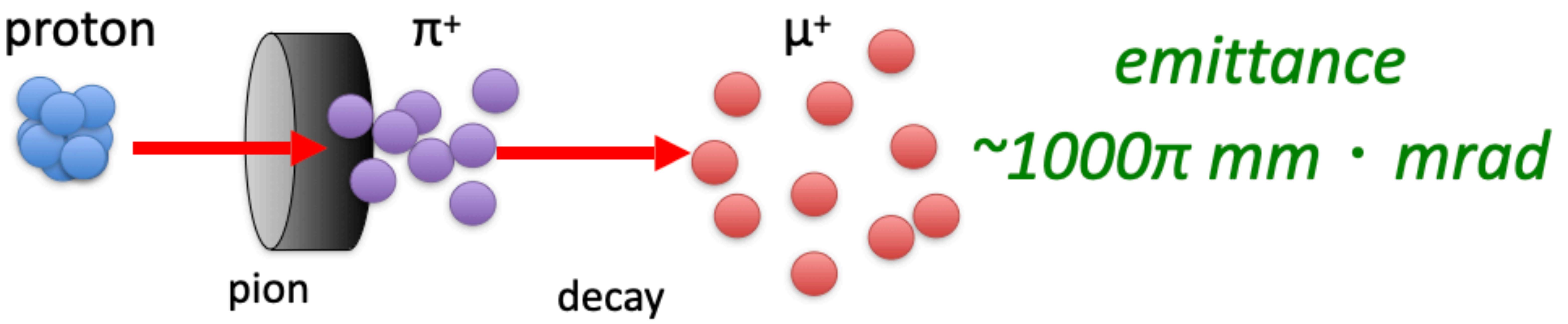
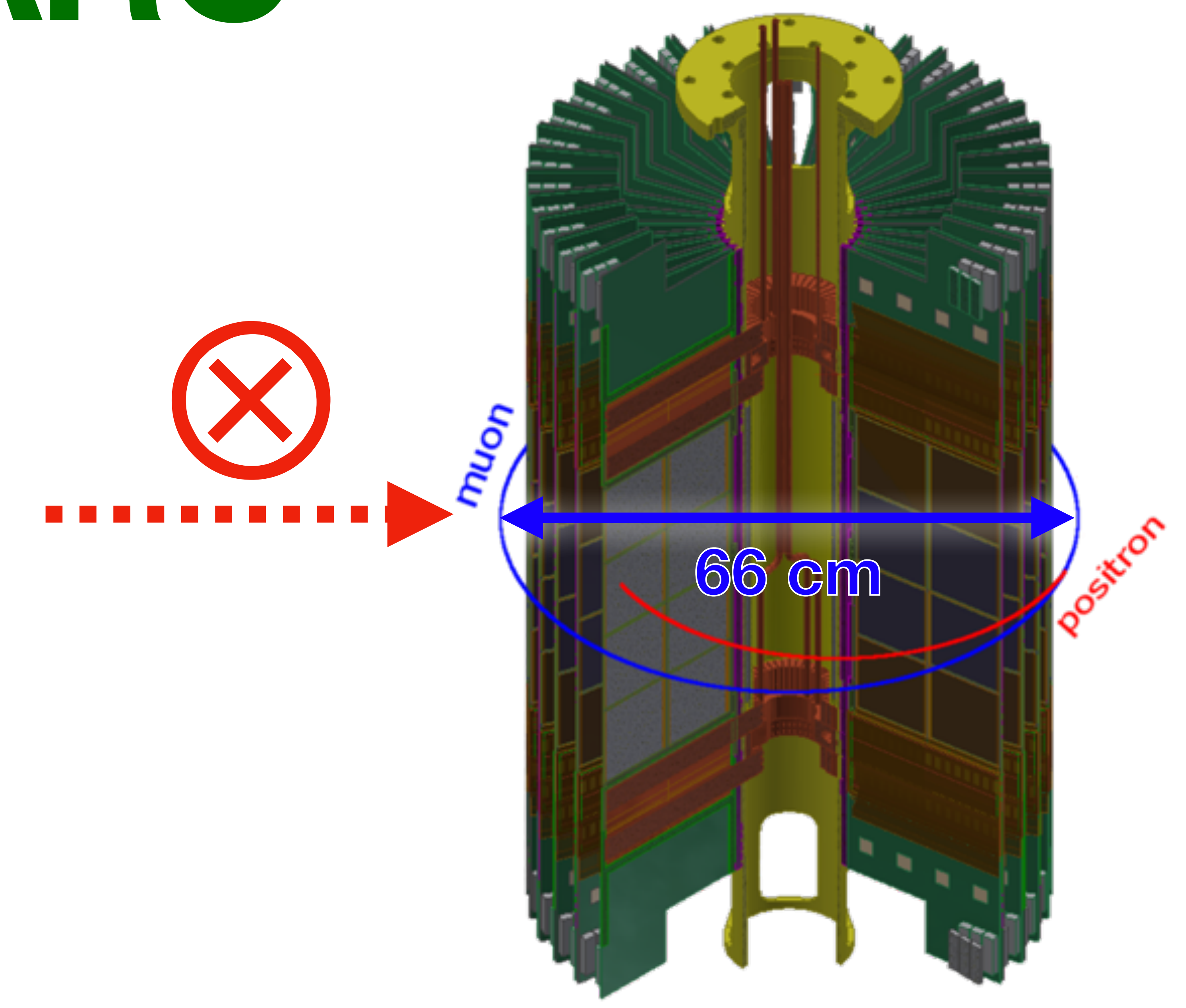
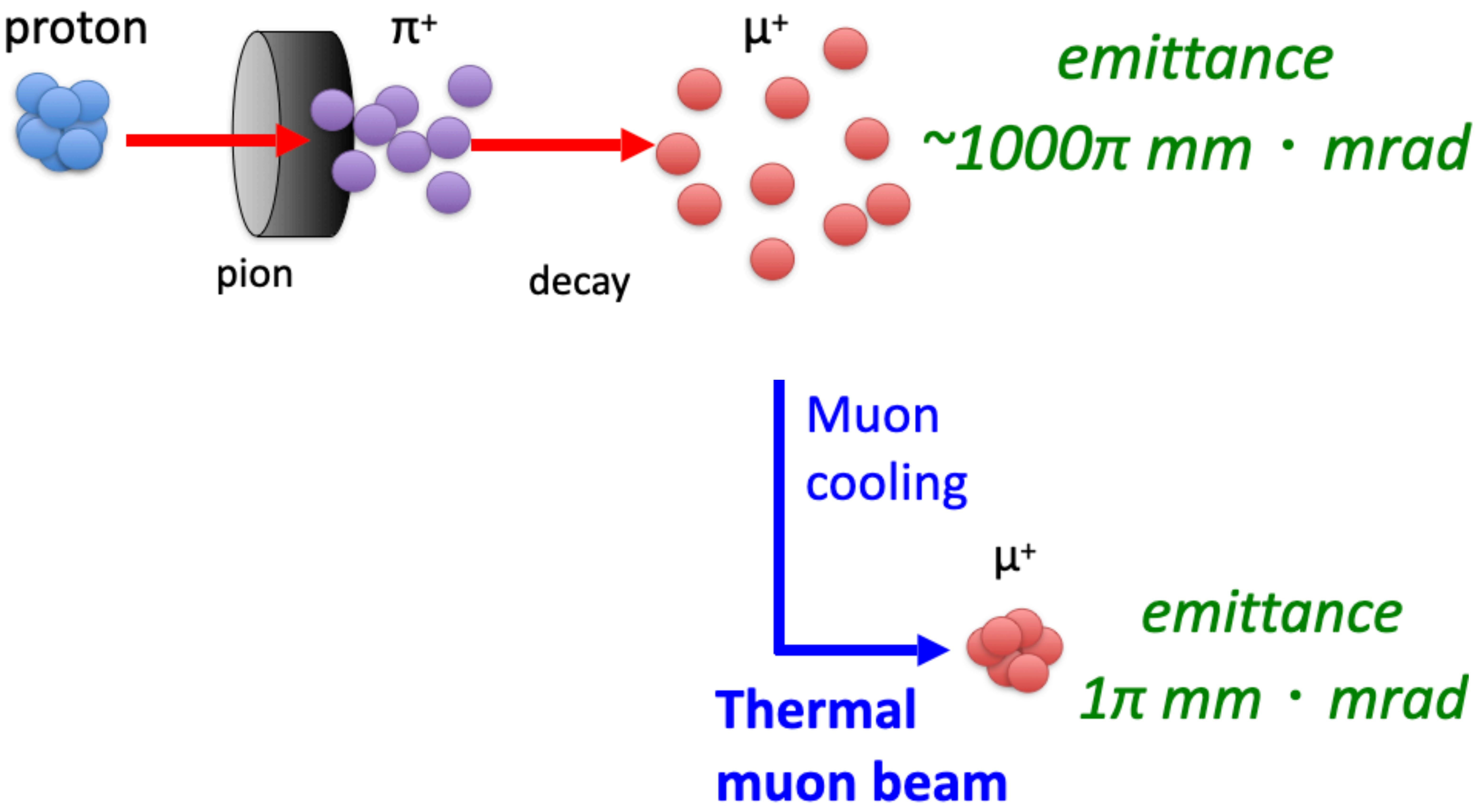




- The traditional surface muon beam without E focusing is not applicable for J-PARC E34
- A novel low-emittance thermal muon beam was proposed

Experimental Principle at J-PARC

Low-emittance muons needed



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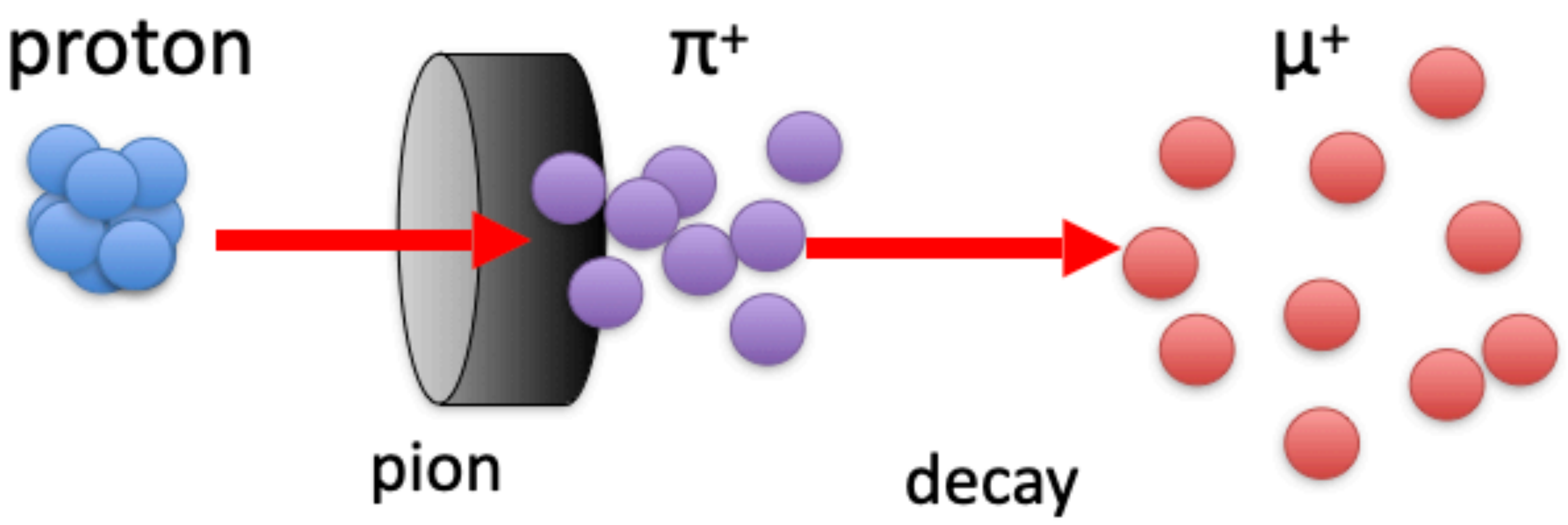
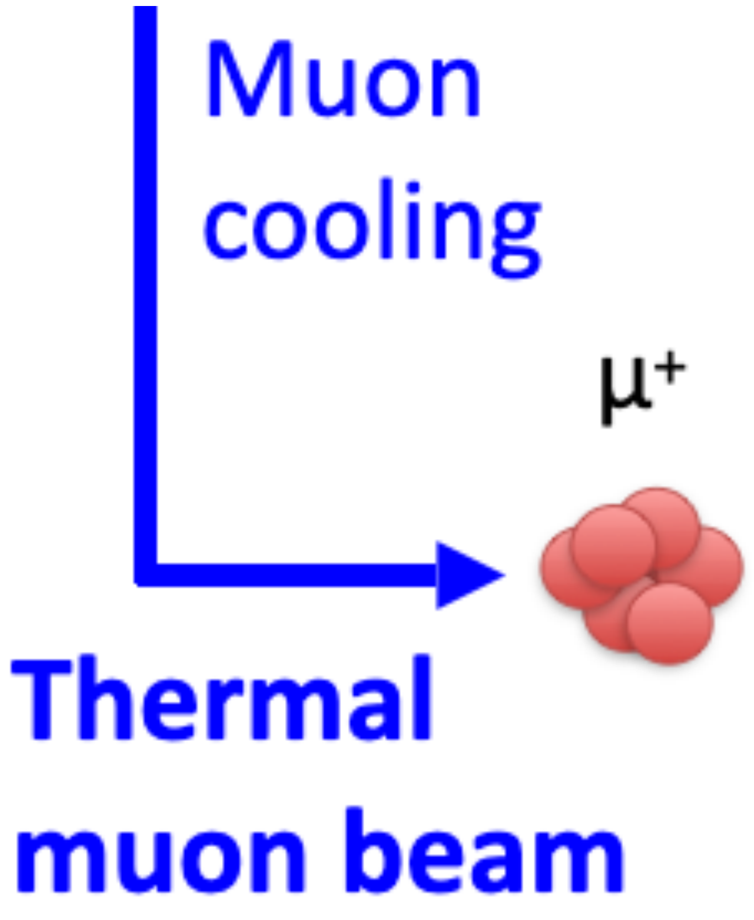


emittance

~1000π mm・mrad

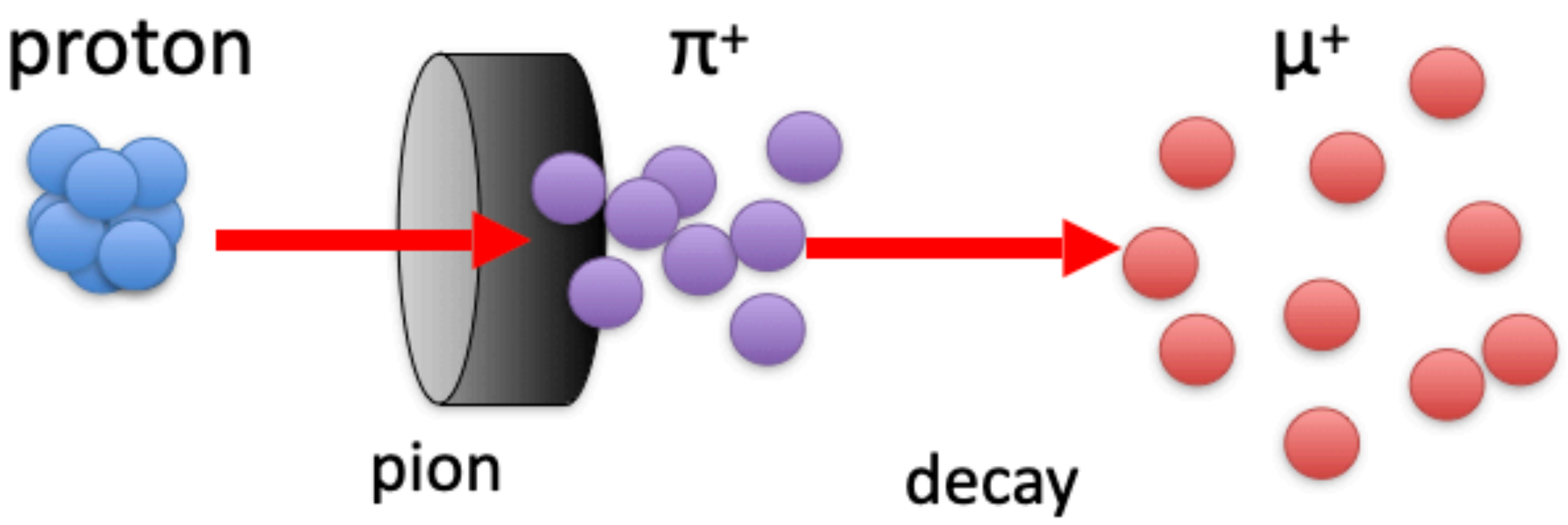


emittance

1π mm・mrad

Experimental Principle at J-PARC

Low-emittance muons needed

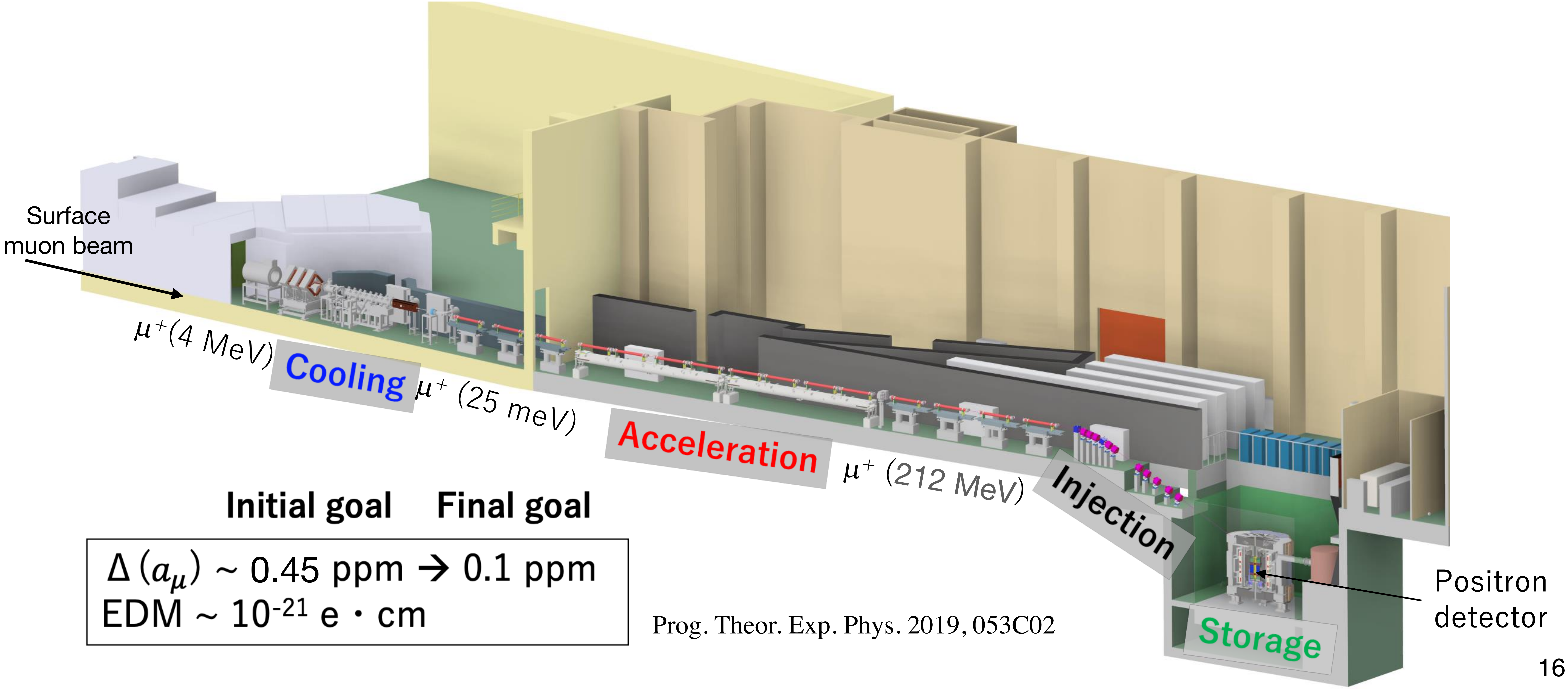


emittance

~1000π mm・mrad

	Fermilab Muon g-2	J-PARC Muon g-2/EDM
Focusing field	Electric quadrupole	E = 0, very weak magnetic
Muon momentum	3.09 GeV/c	300 MeV/c
Cyclotron period	149 ns	7.4 ns
Muon orbit diameter	14 m	66 cm
Storage Field	B = 1.45 T	B = 3 T (Solenoidal)
Polarization	100%	50%

J-PARC Muon $g - 2$/EDM experiment (E34)



Initial goal **Final goal**

$\Delta(a_\mu)$ ~ 0.45 ppm → 0.1 ppm
EDM ~ 10^{-21} e · cm

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

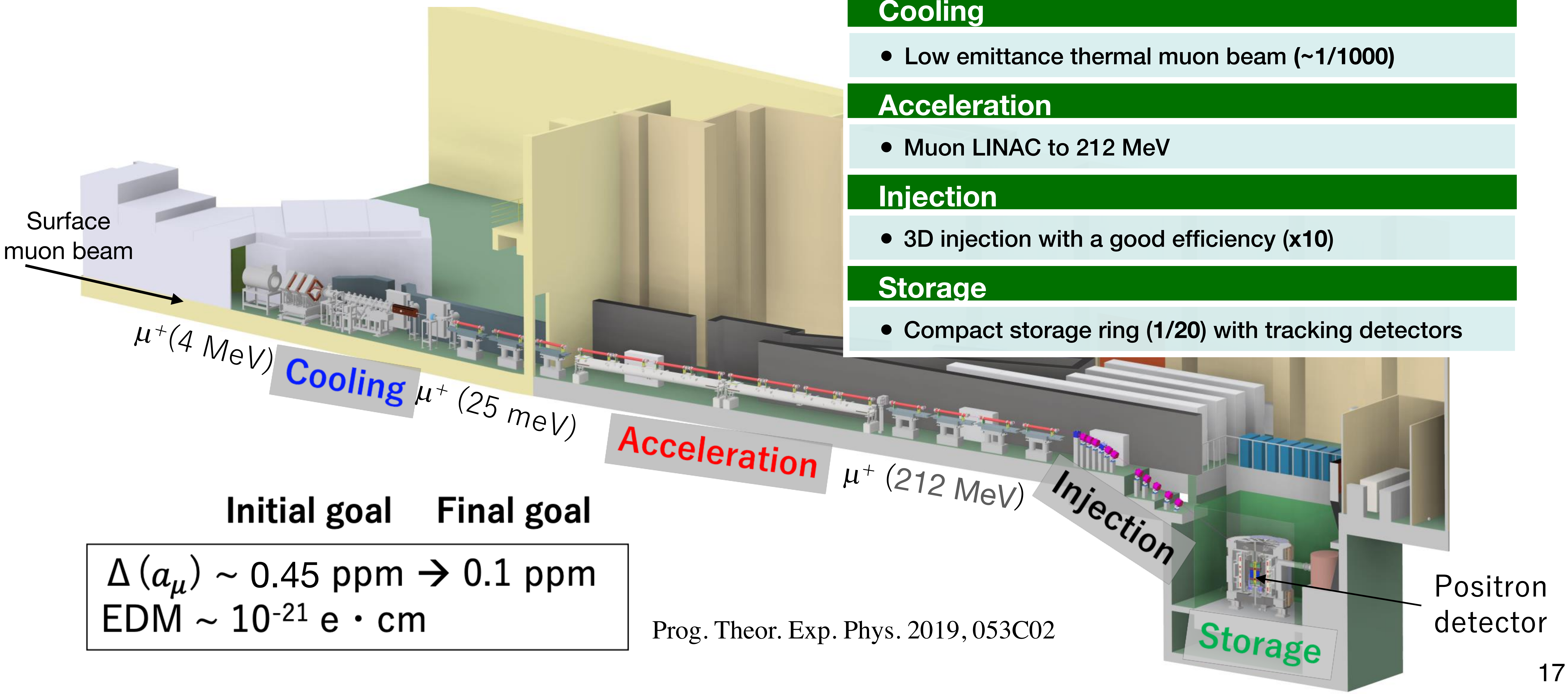
J-PARC Muon $g-2$/EDM experiment (E34)

Cooling
- Low emittance thermal muon beam **(~1/1000)**

Acceleration
- Muon LINAC to 212 MeV

Injection
- 3D injection with a good efficiency **(x10)**

Storage
- Compact storage ring **(1/20)** with tracking detectors



	Initial goal	Final goal
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J-PARC

Japan Proton Accelerator Research Complex

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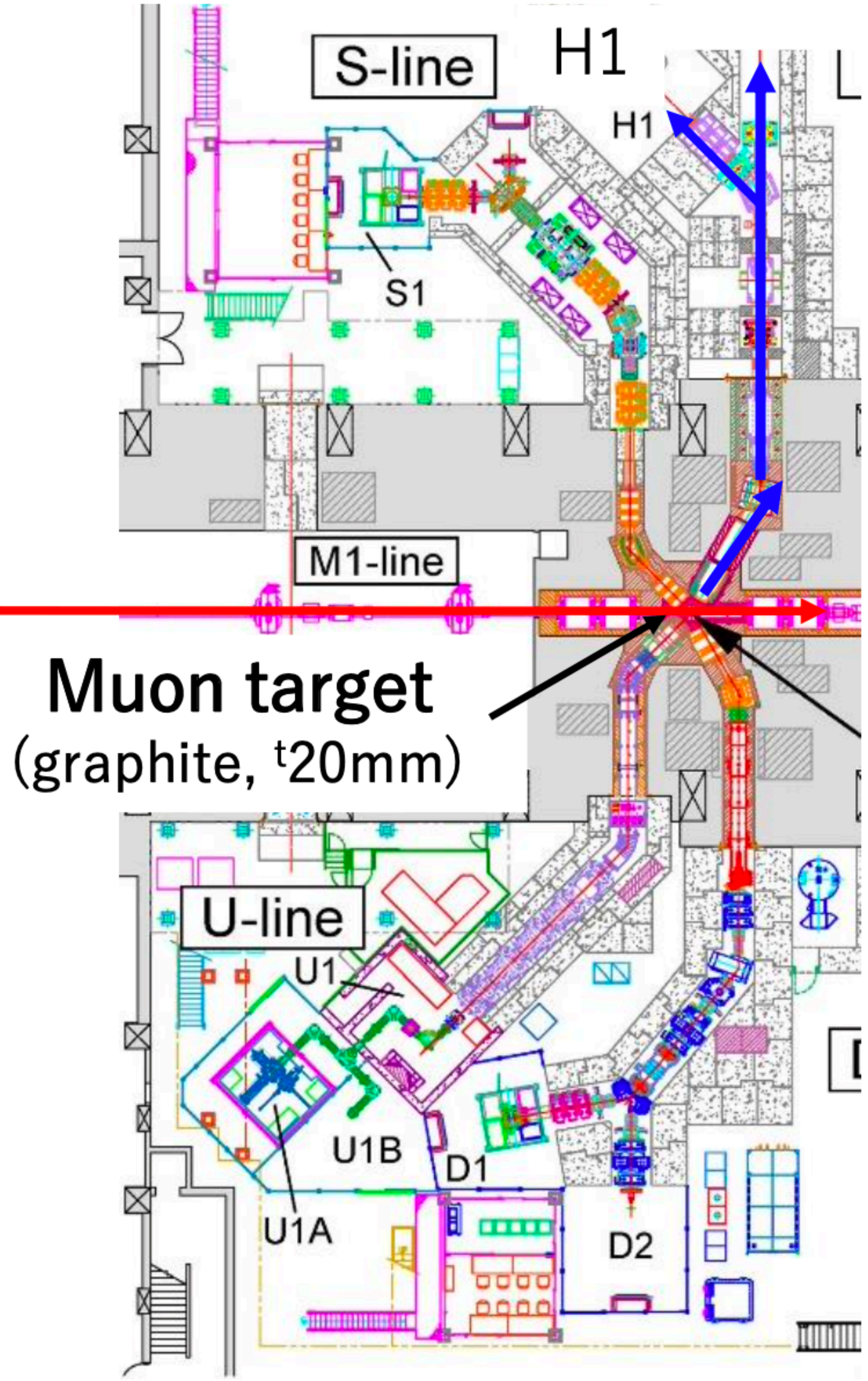
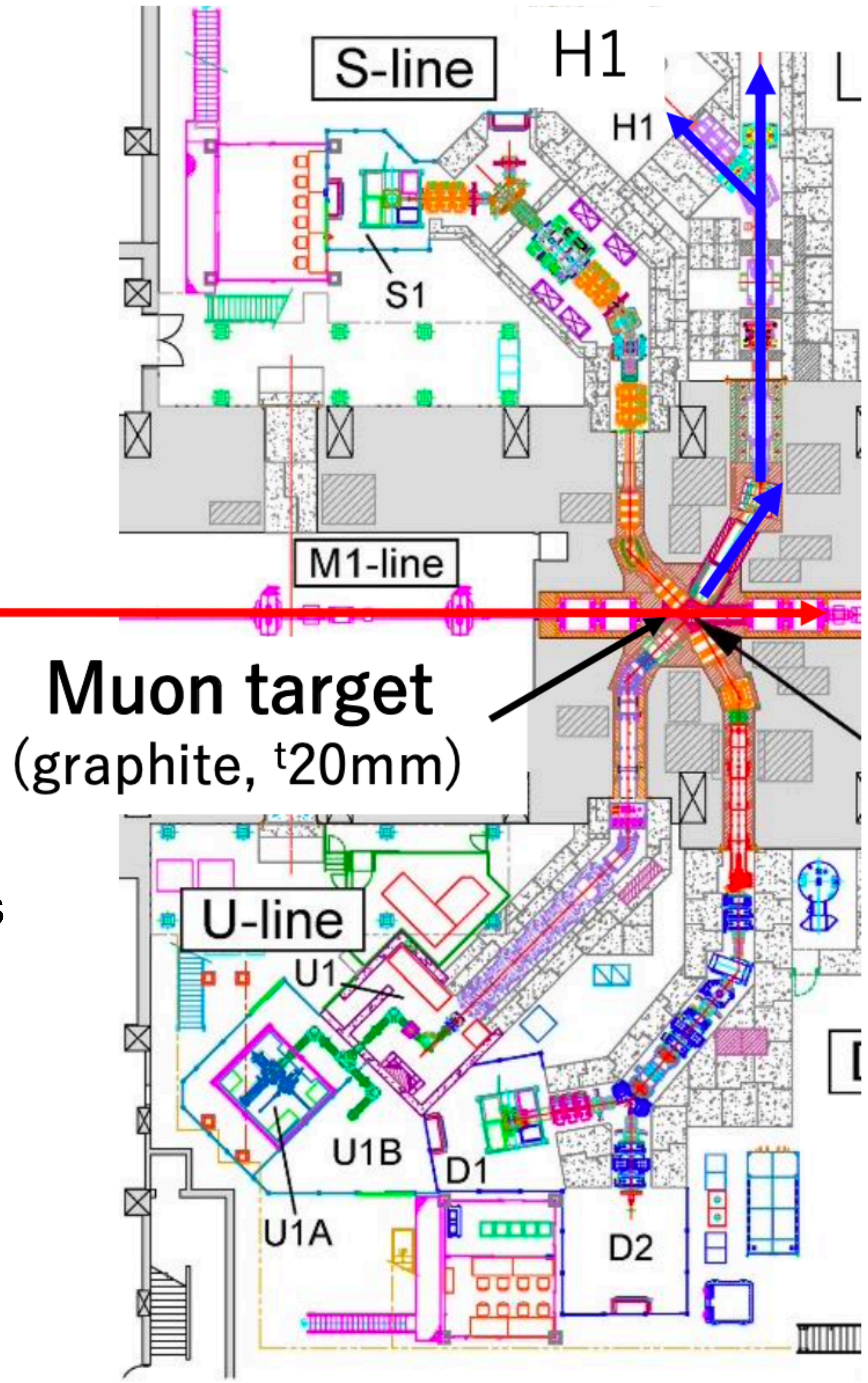
Muon Source at J-PARC MLF



3 GeV proton from RCS

2×10^{15} /s @1MW

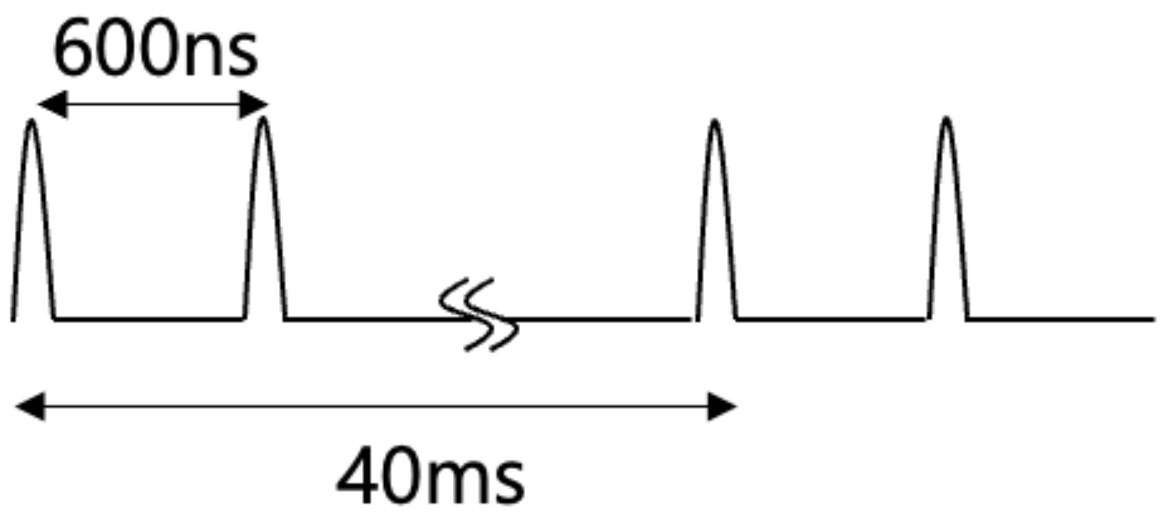
Muon Source at J-PARC MLF



3 GeV proton from RCS

2×10^{15} /s @1MW

Repetition rate 25 Hz, double bunches
Tandem target: 5% for μ, 95% for n



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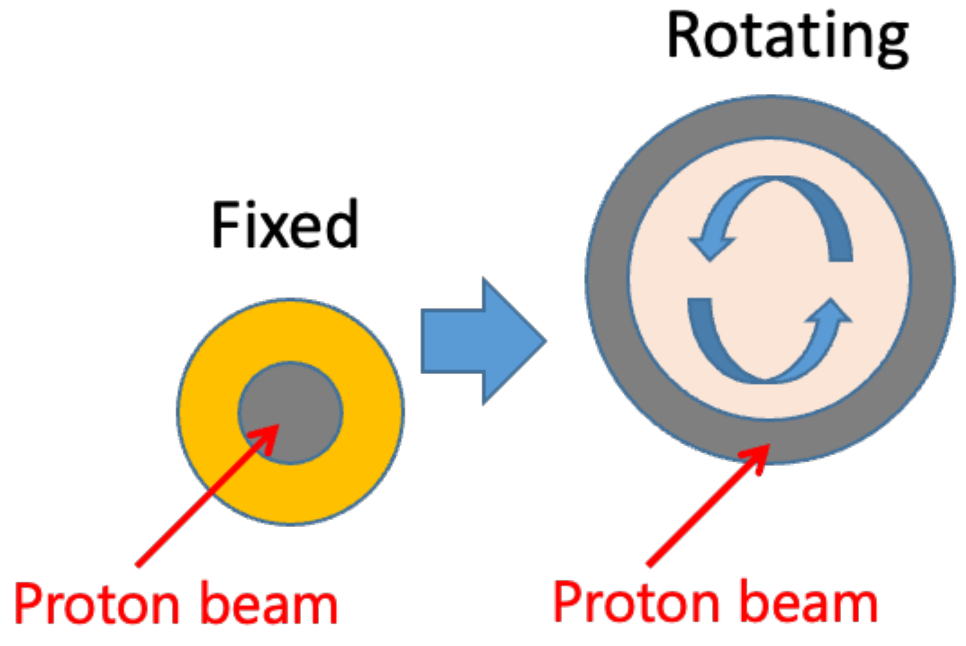
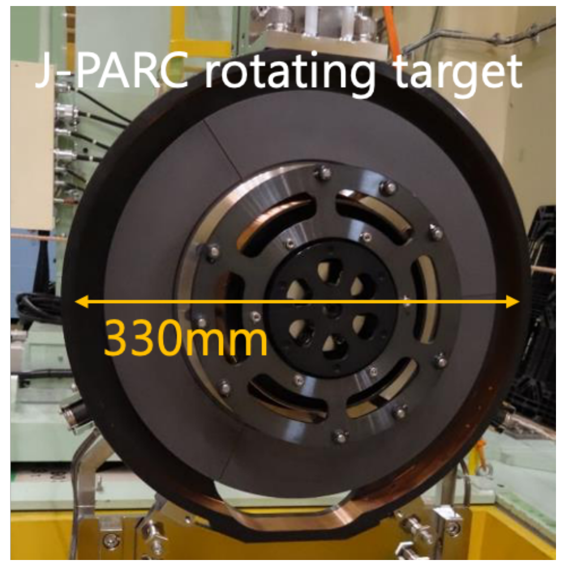
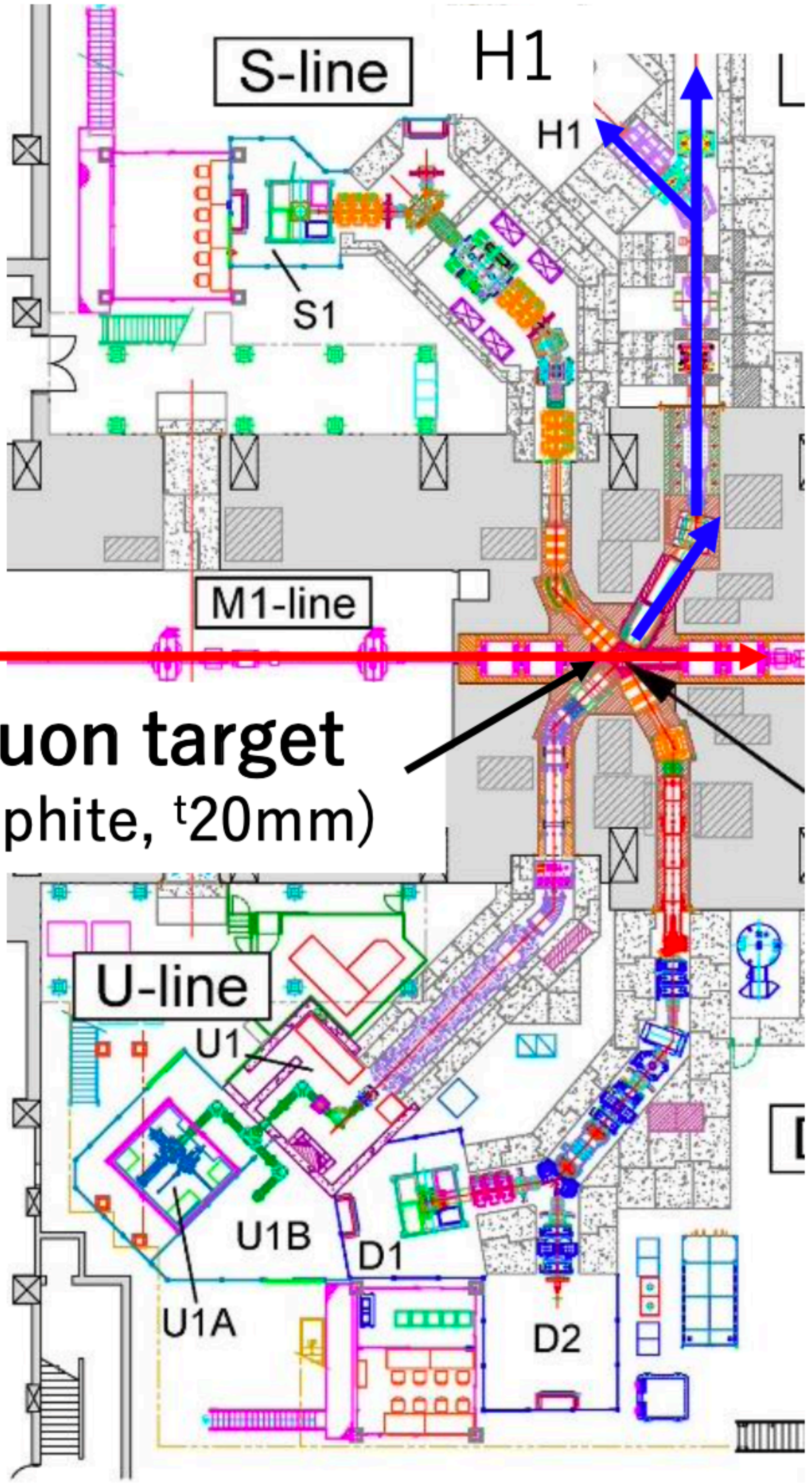






Muon Source at J-PARC MLF

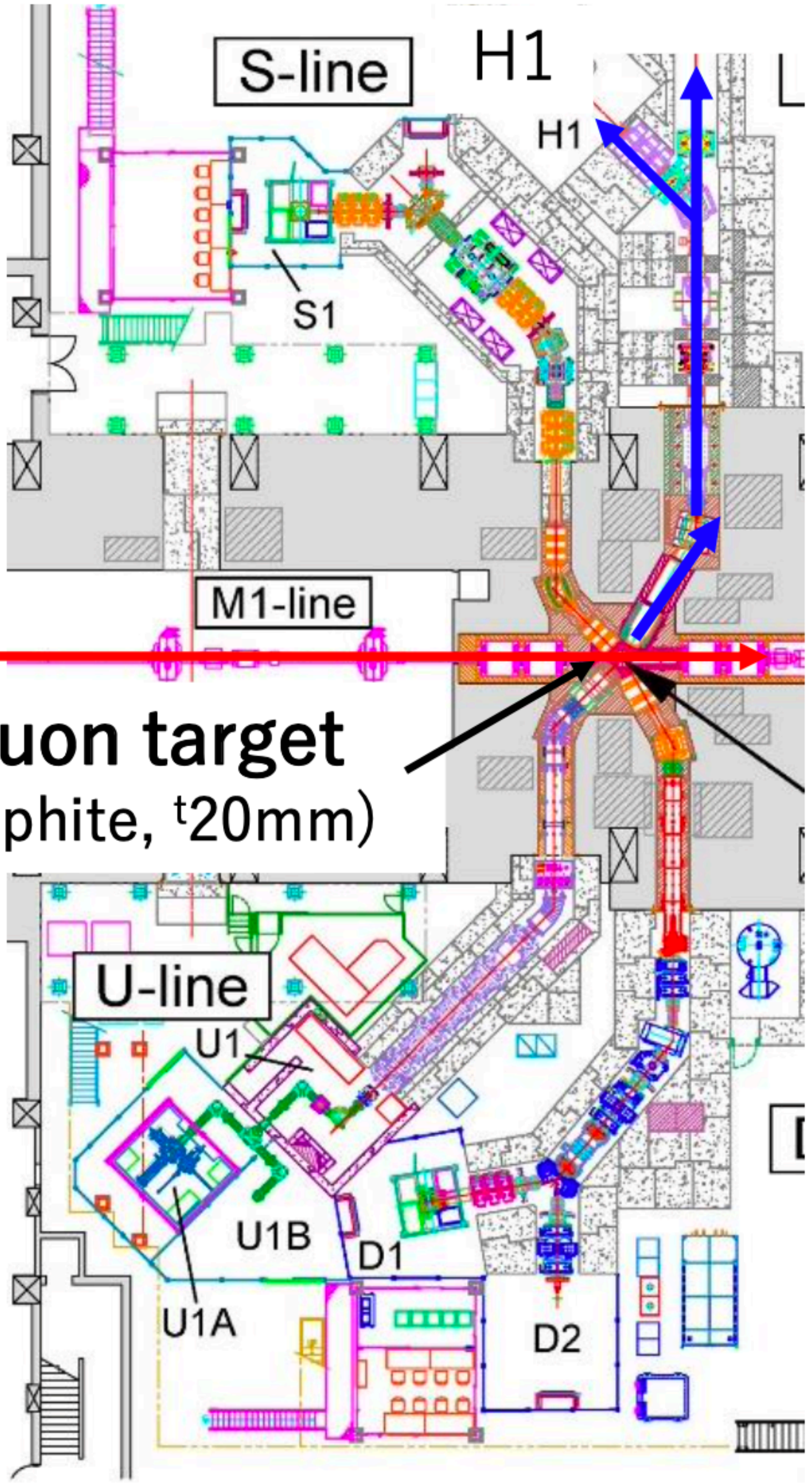
S line
- surface μ^+
- S1 for μSR
- S2 for Mu 1S-2S
- S3/S4 are planned

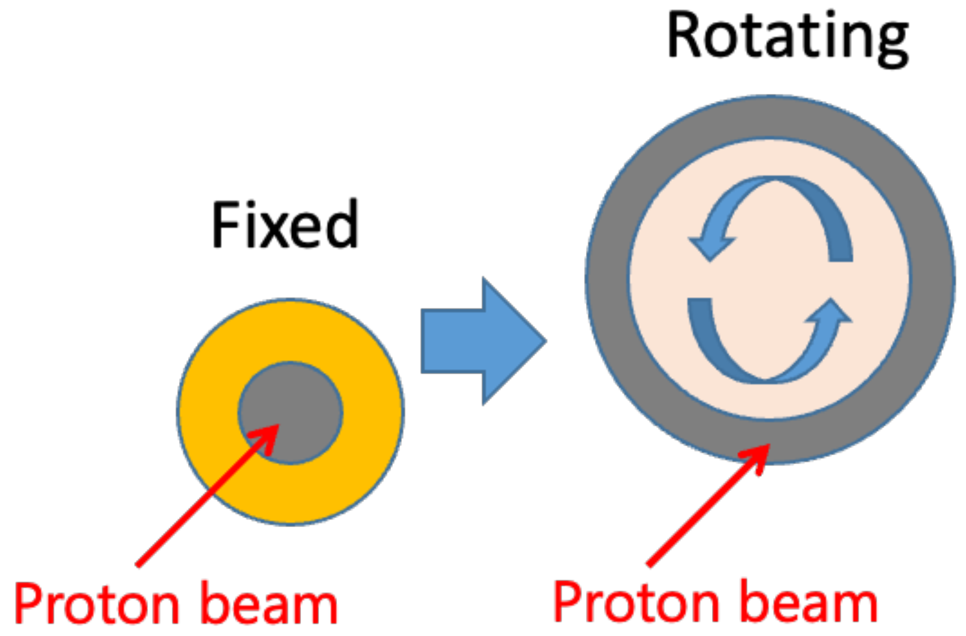
H line
- **surface μ^+ (>10^8 μ^+/s),** cloud μ^+/μ^-, e^-
- **for high intensity & long beamtime** experiments
- H1 for DeeMe & MuSEUM
- H2 for g-2/EDM & TμM

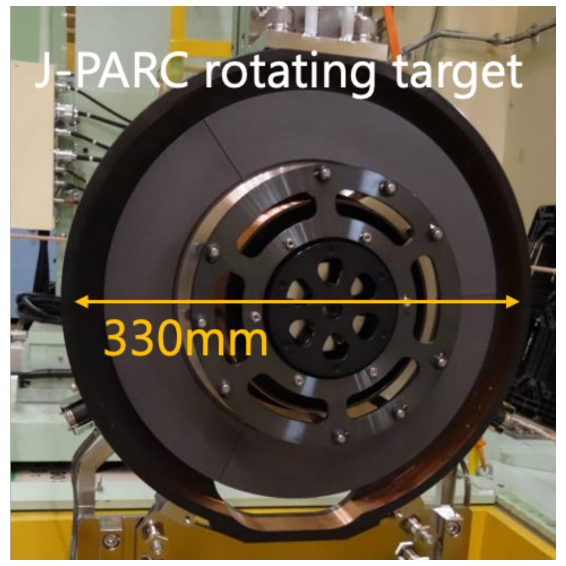
  Under construction

3 GeV proton from RCS

2×10^{15} /s @1MW



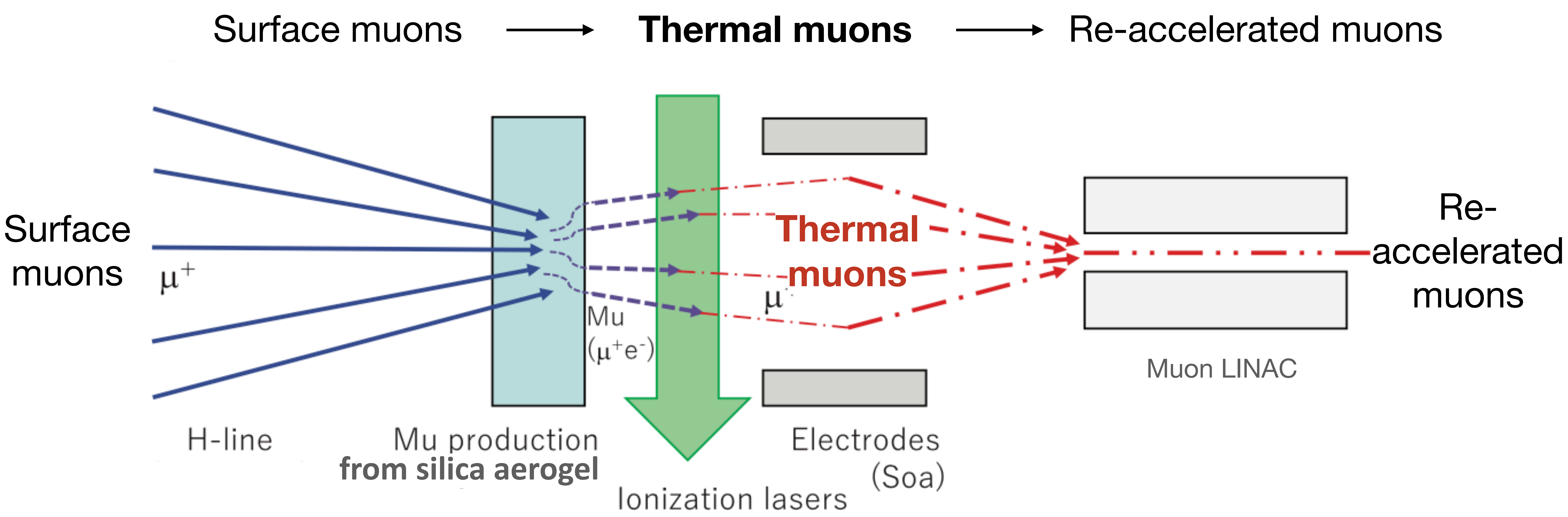




MLF H-line (as of Dec 2023)

Thermal Muon Source

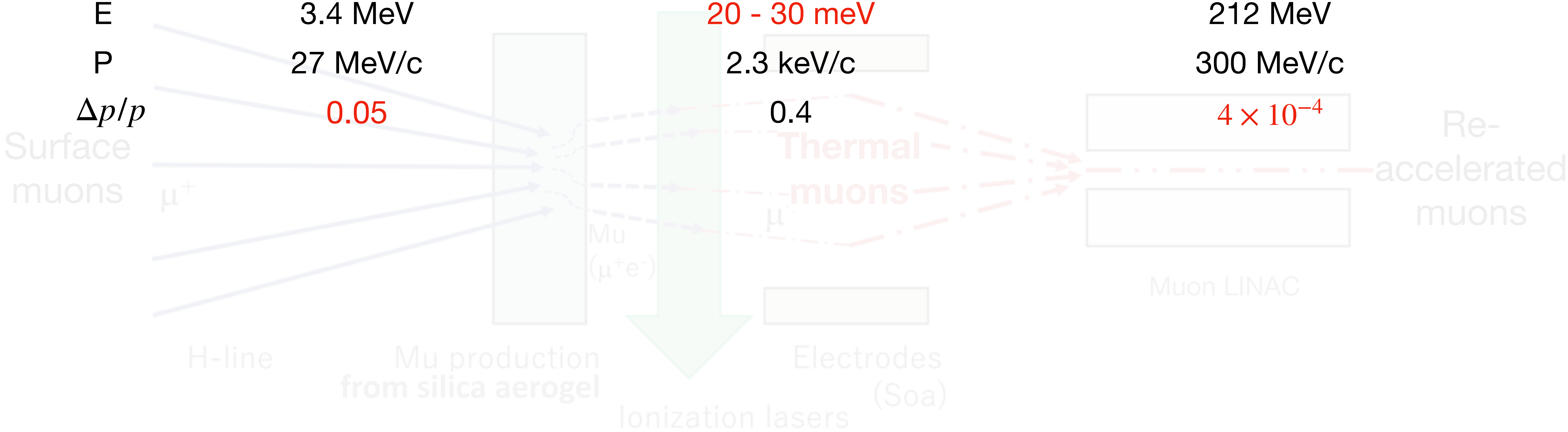
- Surface muon cooling by laser ionization of muonium (Mu) to thermal muon



Thermal Muon Source

- Surface muon cooling by laser ionization of muonium (Mu) to thermal muon

	Surface muons →	Thermal muons →	Re-accelerated muons
E	3.4 MeV	20 - 30 meV	212 MeV
P	27 MeV/c	2.3 keV/c	300 MeV/c
$\Delta p/p$	0.05	0.4	4×10^{-4}



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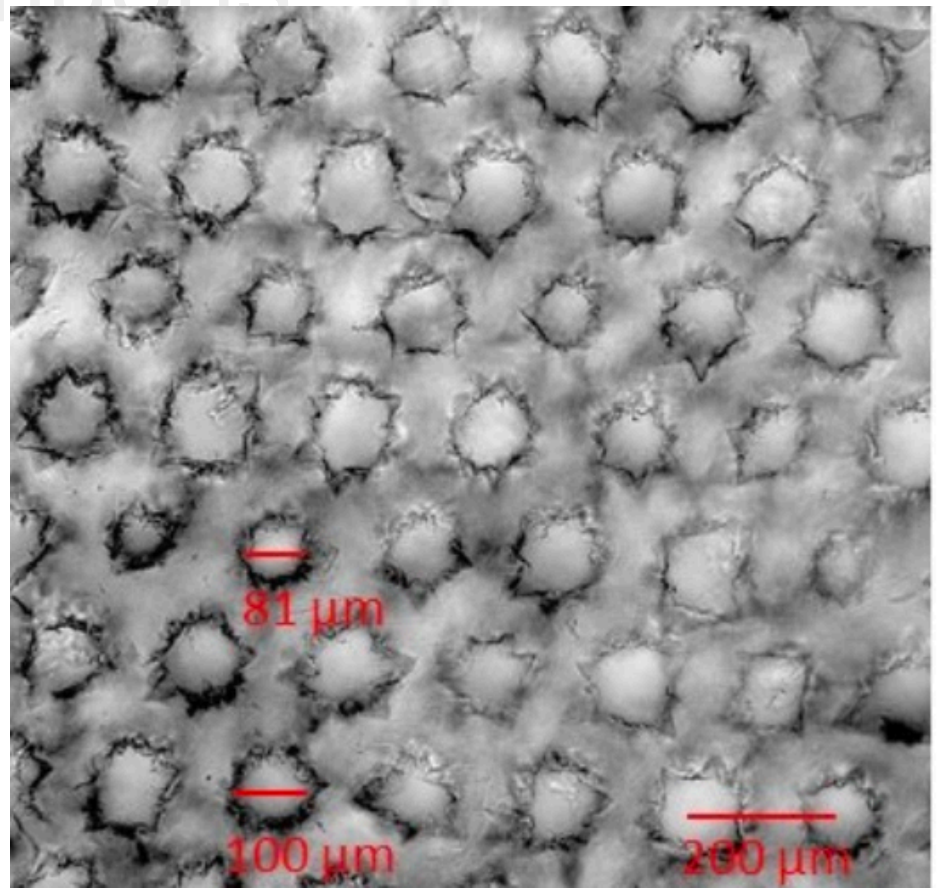
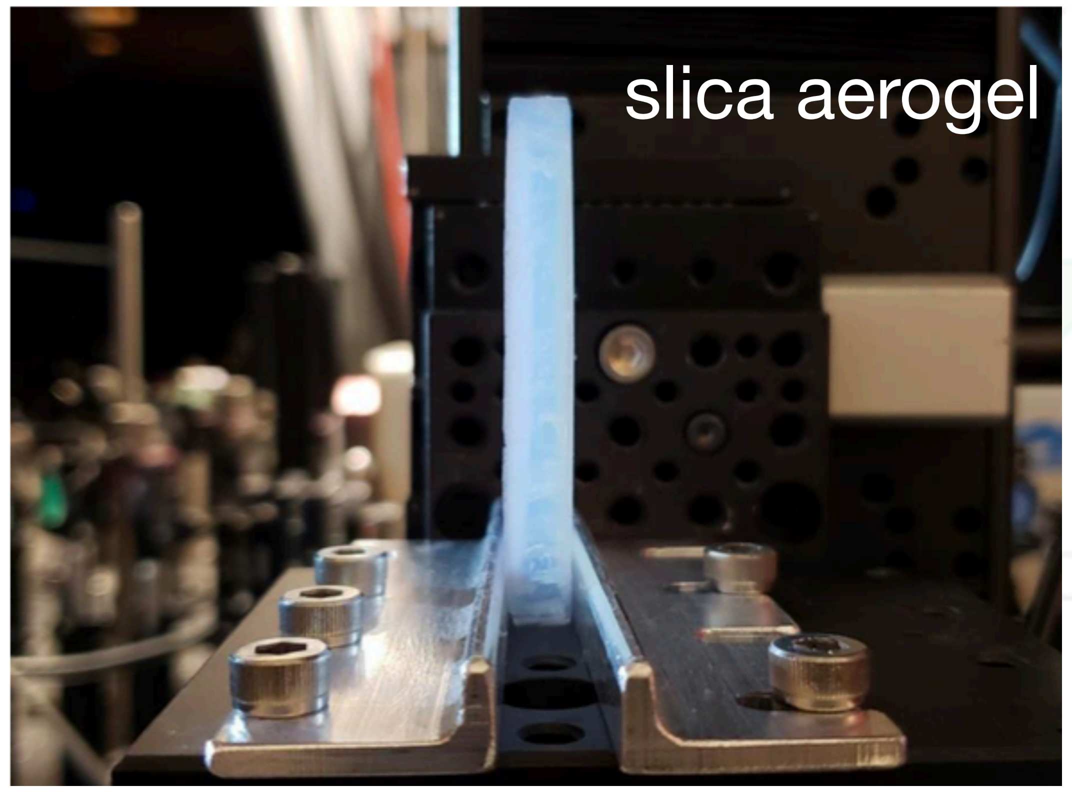
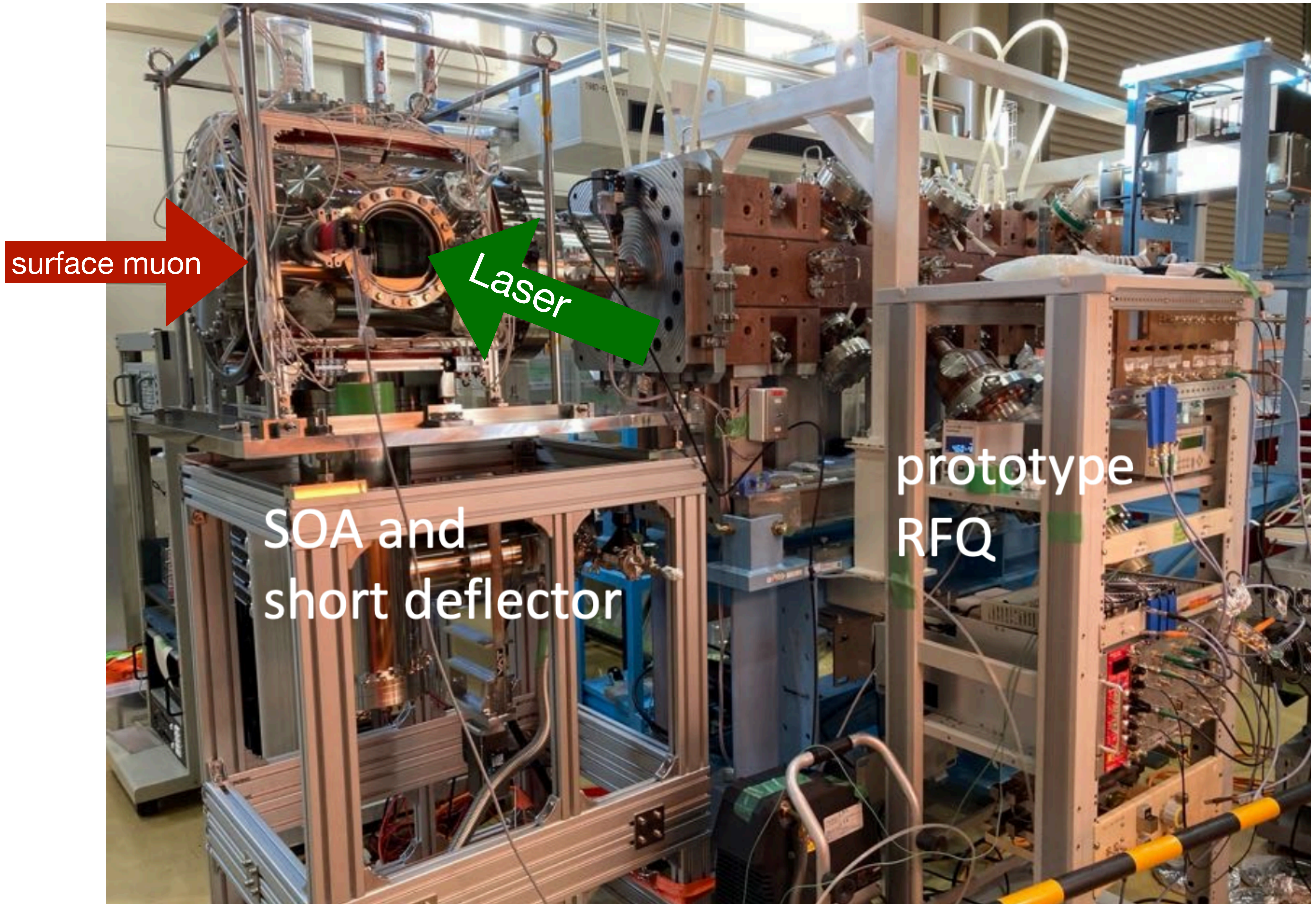




2013	• Muonium emission from silica aerogel [PTEP 103C0
2014	• Laser-ablation on aerogel surface [PTEP 091C01 (2014)]
2020	• Study of muonium emission from laser-ablated silica aerogel [PTEP 123C01 (2020)]

Thermal Muon Source



- Two laser options are under development:

122 nm laser

- Challenging
- High efficiency (73% efficiency at 100 μJ, now only 5 to 10 μJ achieved)

244 nm laser

- Easier for development
- Being used since 2021
- Efficiency under estimation (lower than 122 nm)

Key issues in the thermal muon source

- Thermal muon per injecting surface muon is low (10^{-3}) in the TDR estimation.
- What has been achieved now (10^{-5}) is even lower
- Muonium production and laser efficiency are two key weak points

Table 4. Breakdown of estimated efficiency.

Subsystem	Efficiency	Subsystem	Efficiency
H-line acceptance and transmission	0.16	DAW decay	0.96
Mu emission	0.0034	DLS transmission	1.00
Laser ionization	0.73	DLS decay	0.99
Metal mesh	0.78	Injection transmission	0.85
Initial acceleration transmission and decay	0.72	Injection decay	0.99
RFQ transmission	0.95	Kicker decay	0.93
RFQ decay	0.81	e^+ energy window	0.12
IH transmission	0.99	Detector acceptance of e^+	1.00
IH decay	0.99	Reconstruction efficiency	0.90
DAW transmission	1.00		

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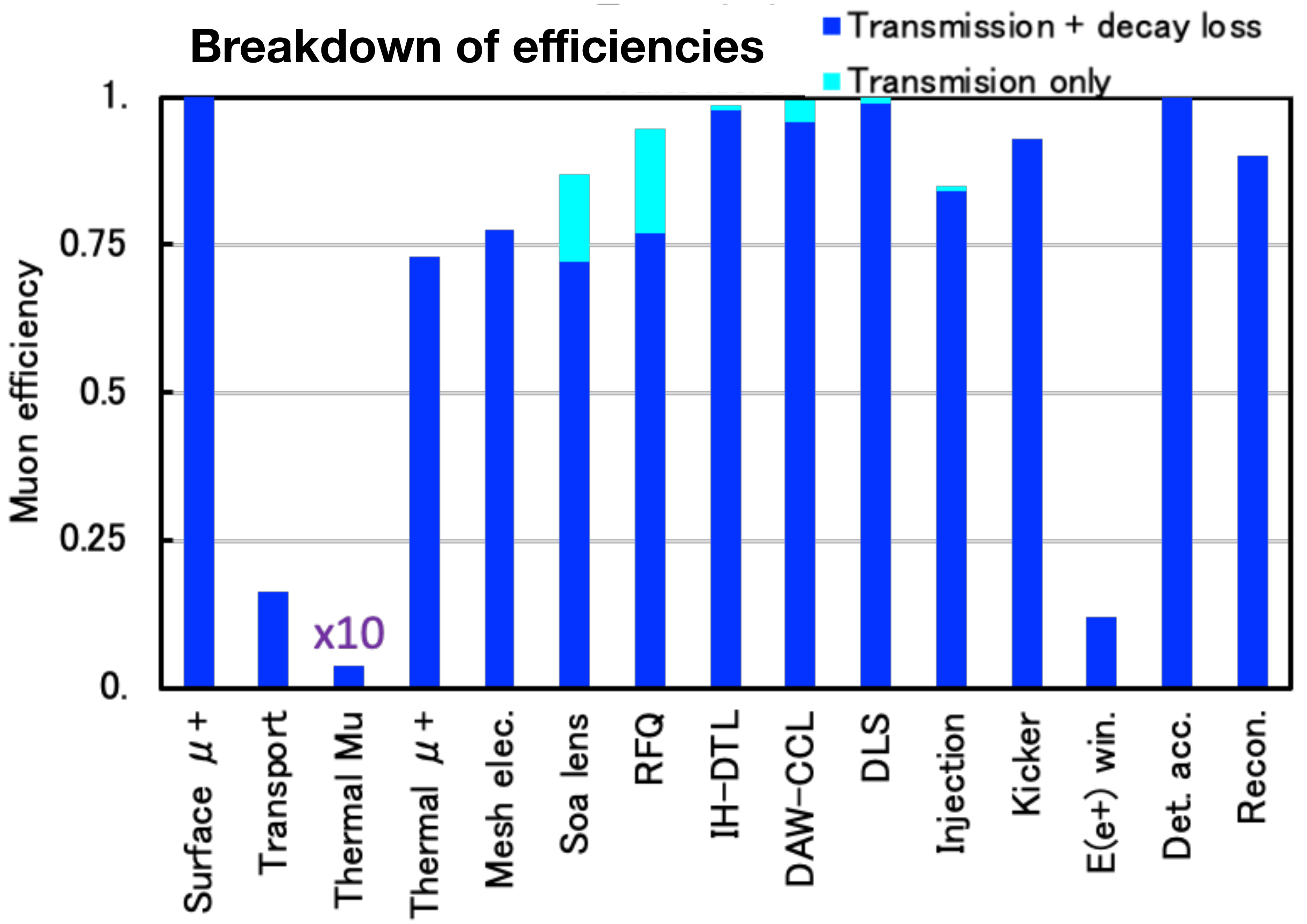
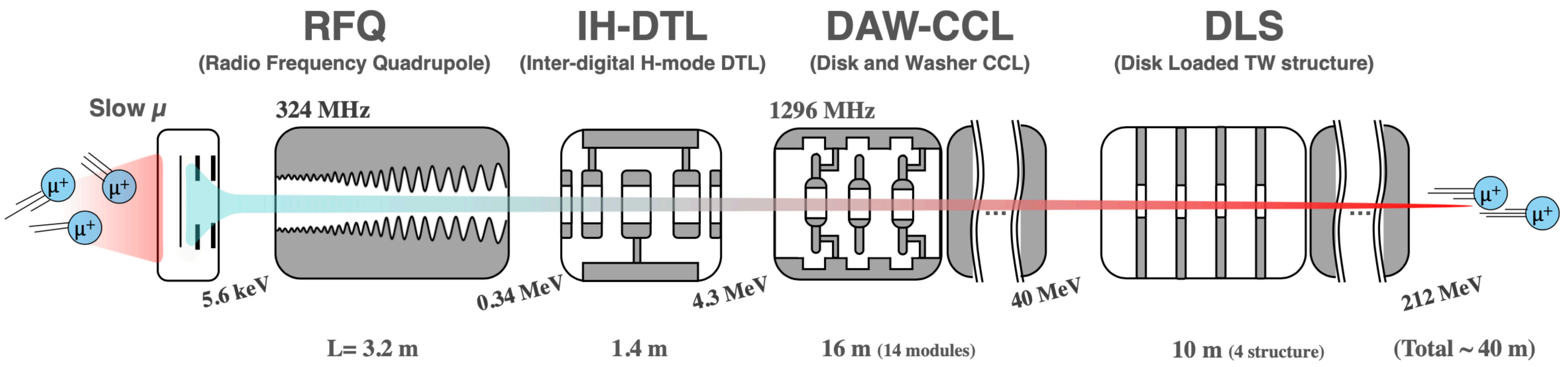


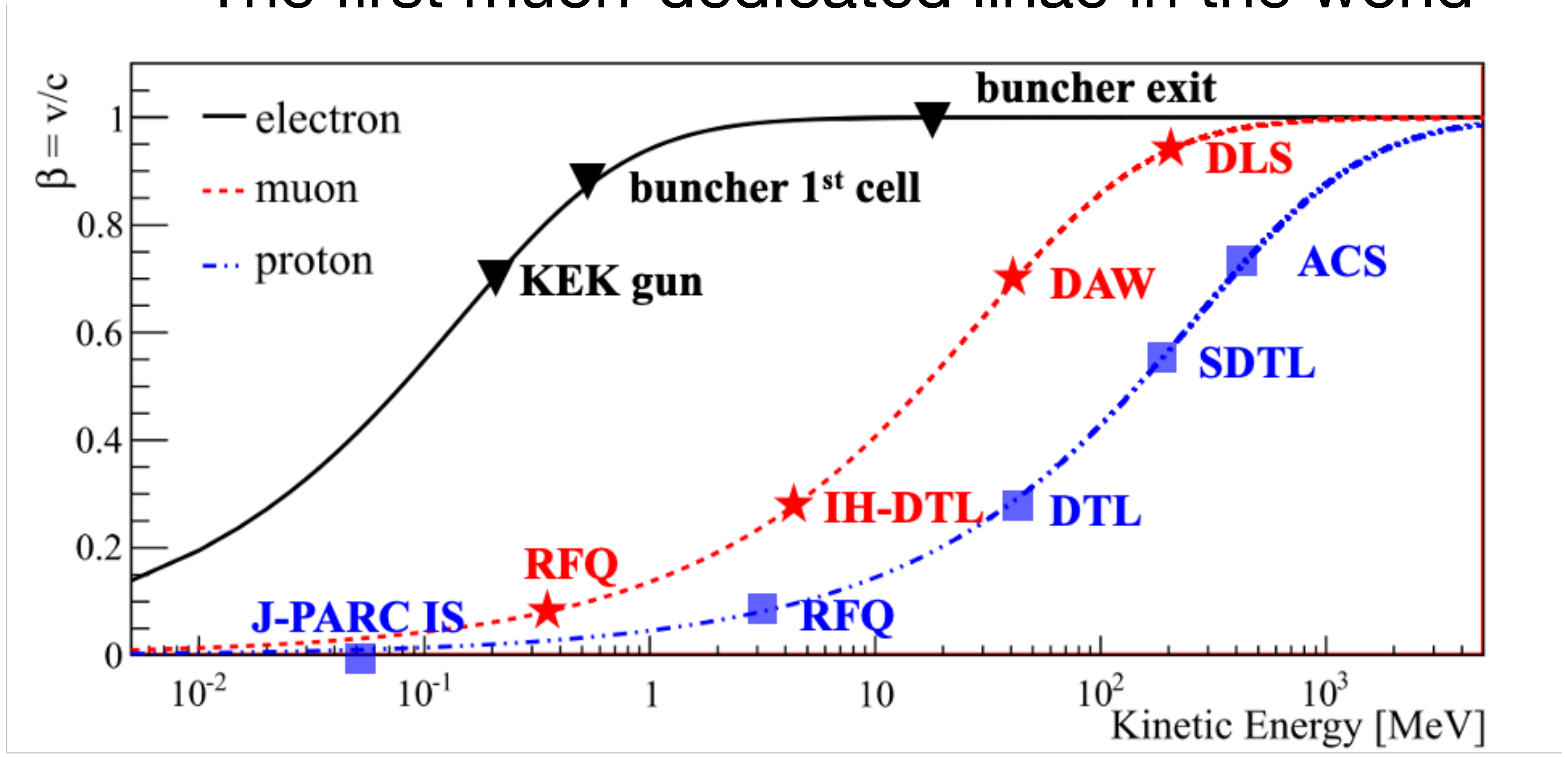
Muon Acceleration



Muon LINAC parameters

Frequency (2-stage)	324MHz, 1296MHz
Intensity	1×10^6 /s
Rep rate	25 Hz
Pulse width	10 ns
Norm. rms emittance	1.5 π mm mrad
Momentum spread	0.1 %

- The first muon-dedicated linac in the world



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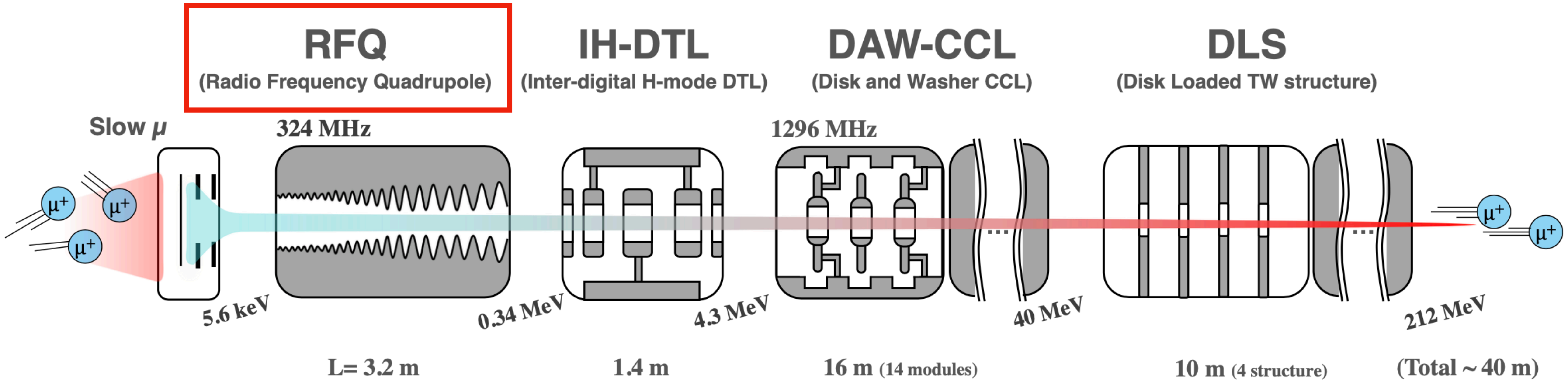

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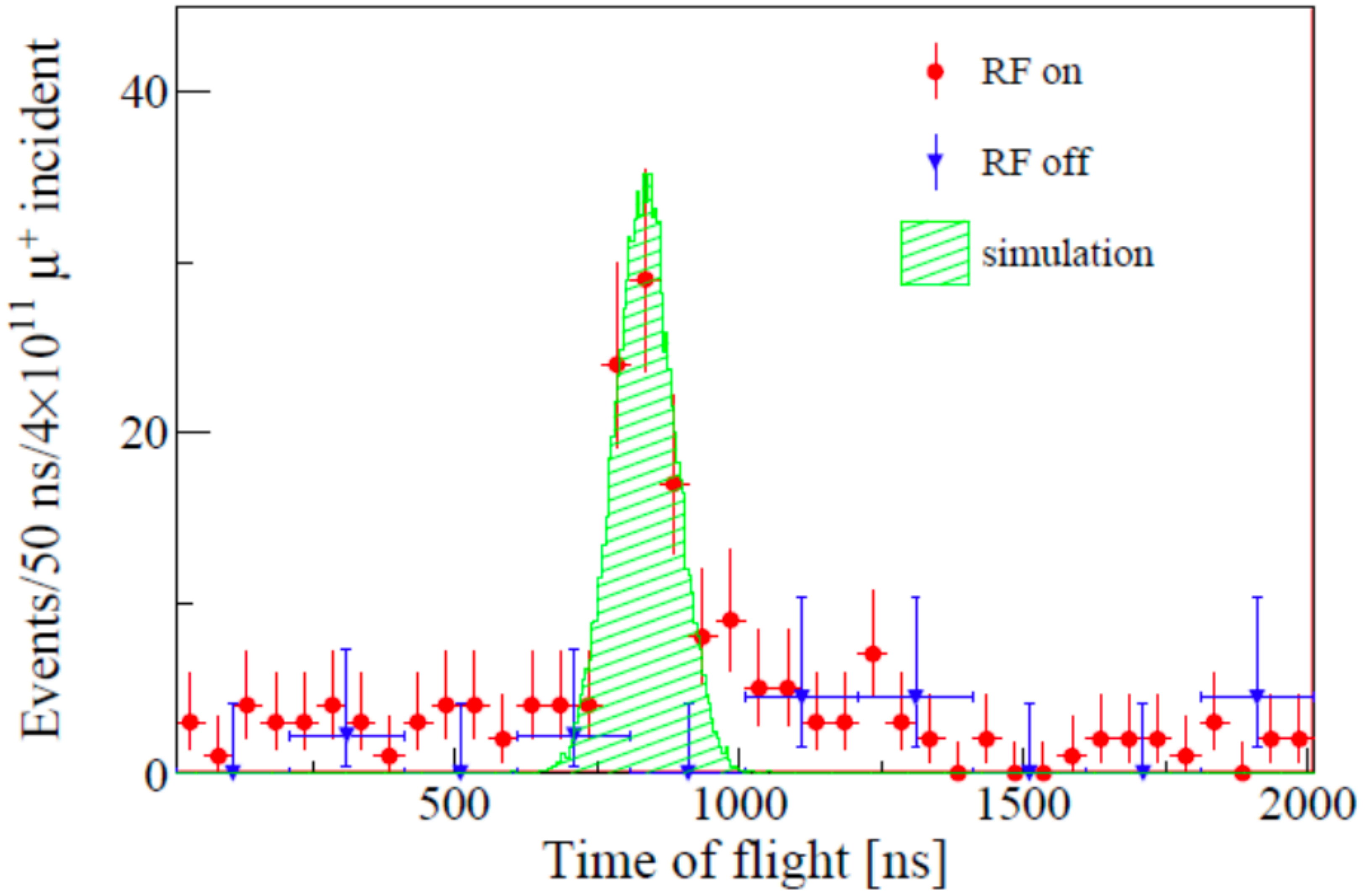
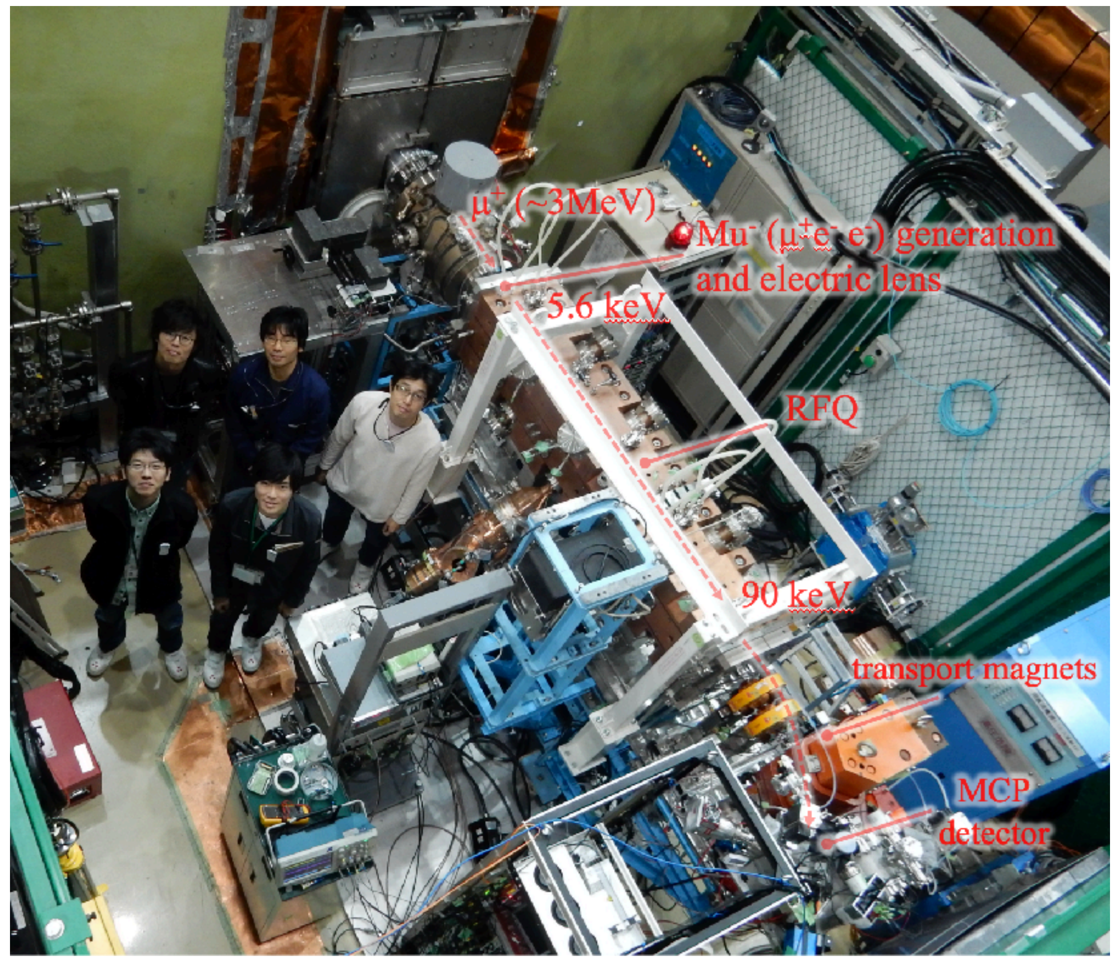
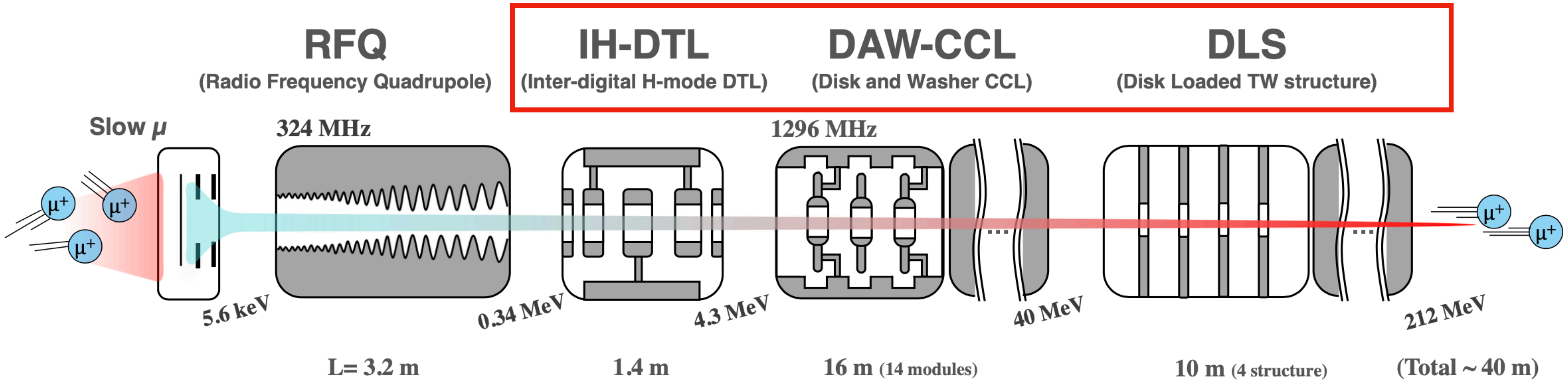
- **Muonium- acceleration using RF linac**
- Phys. Rev. Accel. Beams 21, 050101 (2018)





Muon Acceleration



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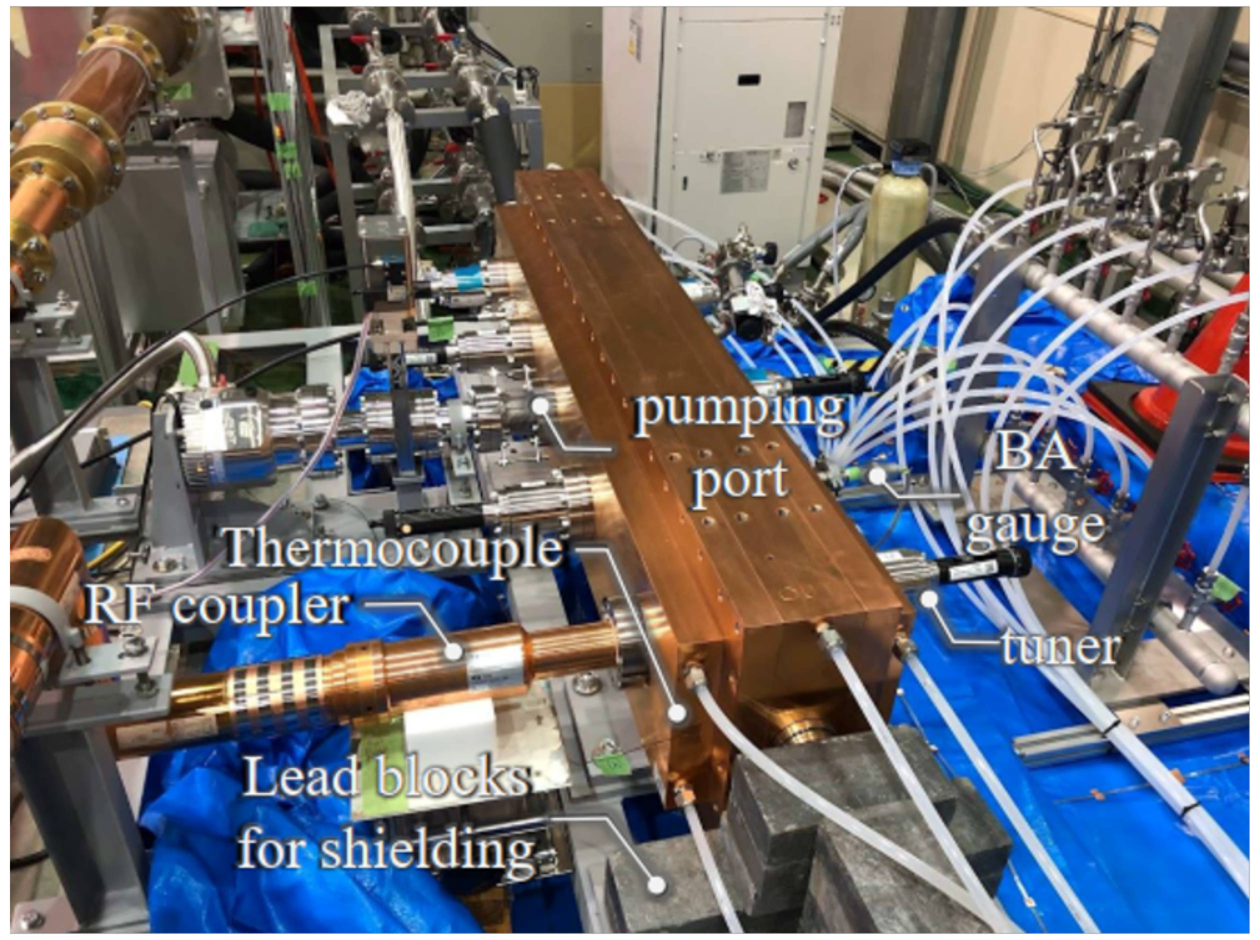
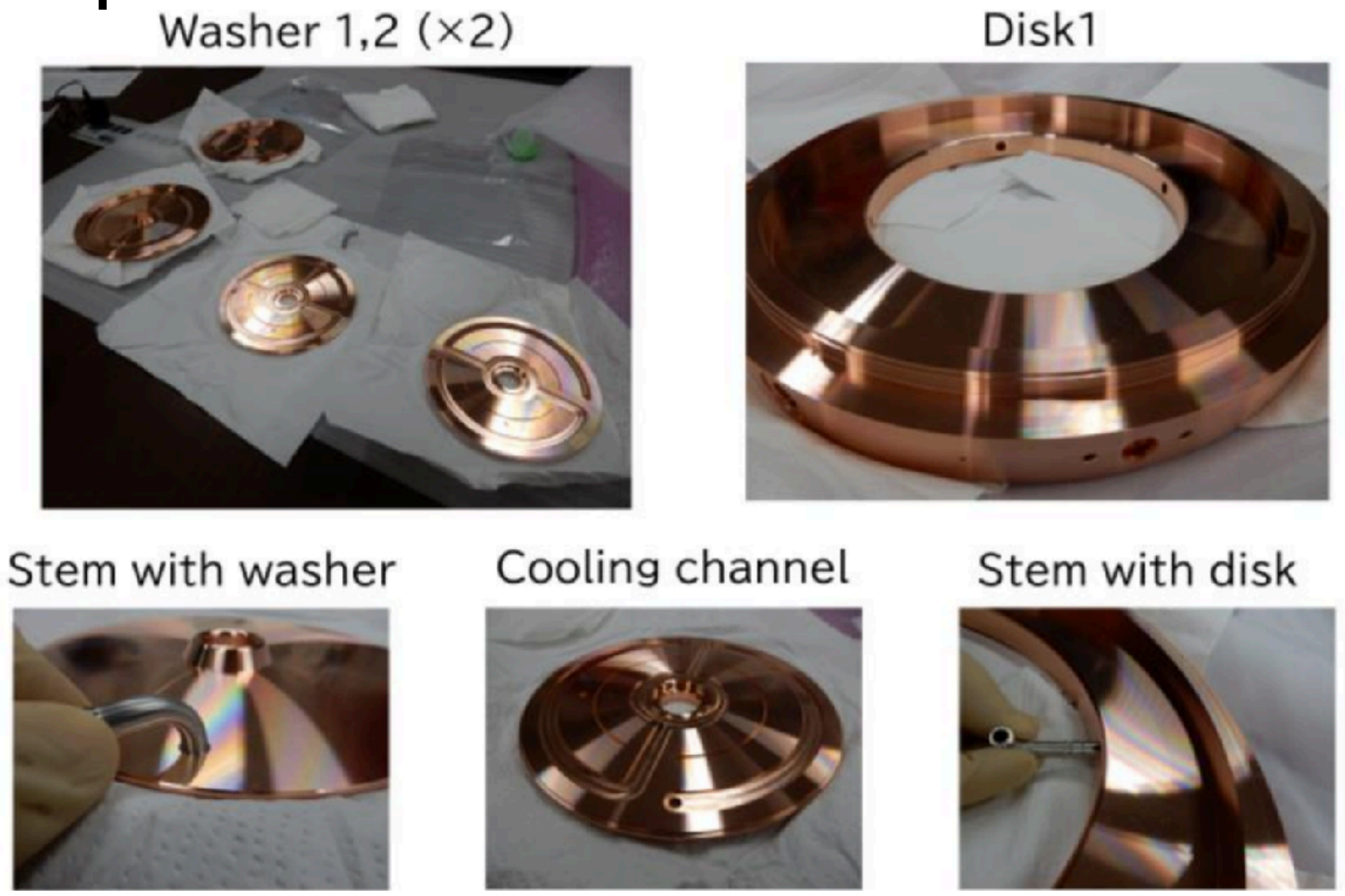
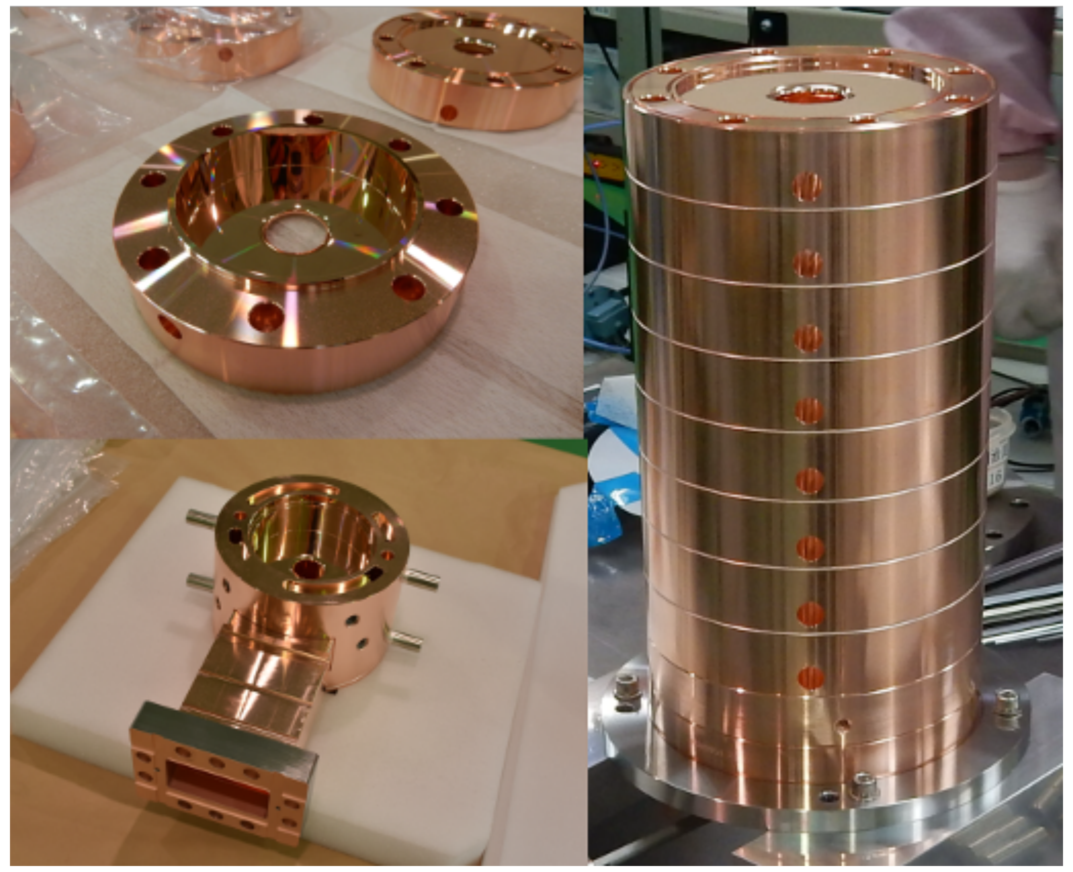
- Fabrication of the real IH-DTL completed
- Fabricating the 1st DAW tank & proton-DLS.



Real IH-DTL with high-power test



DAW ready for production

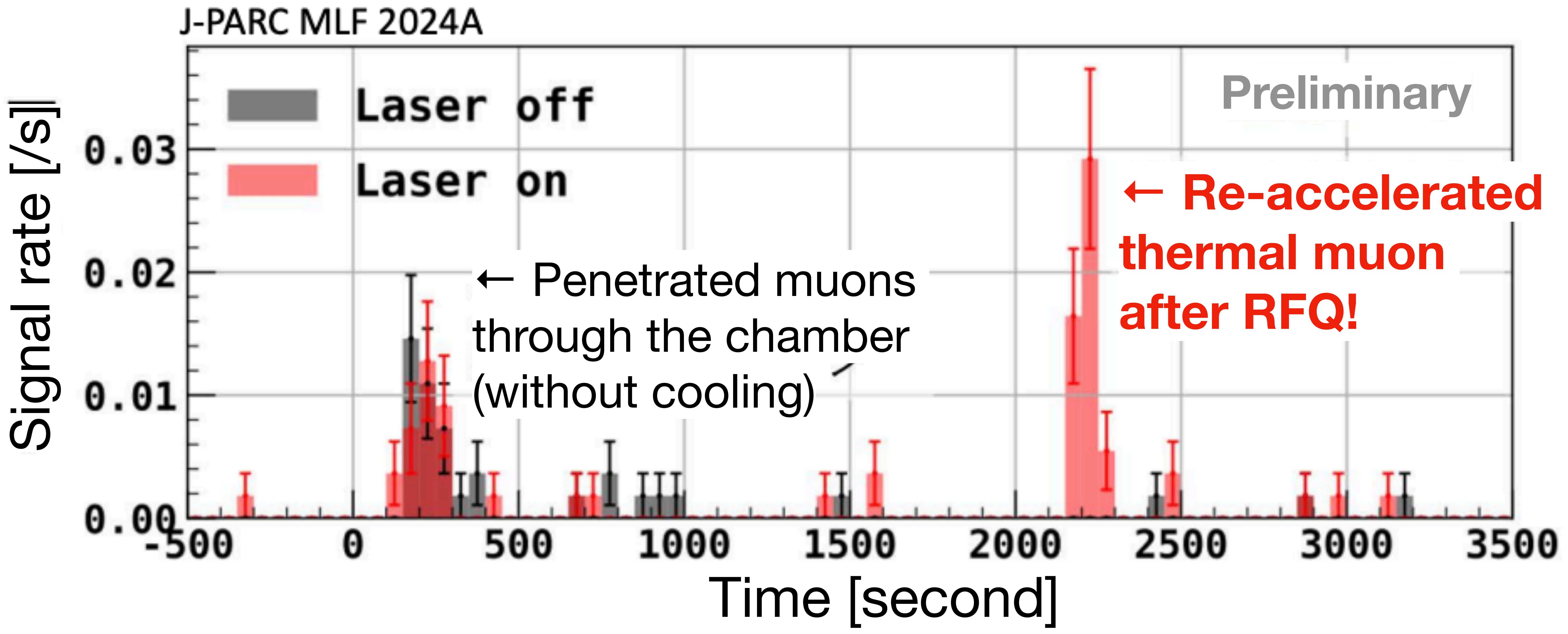


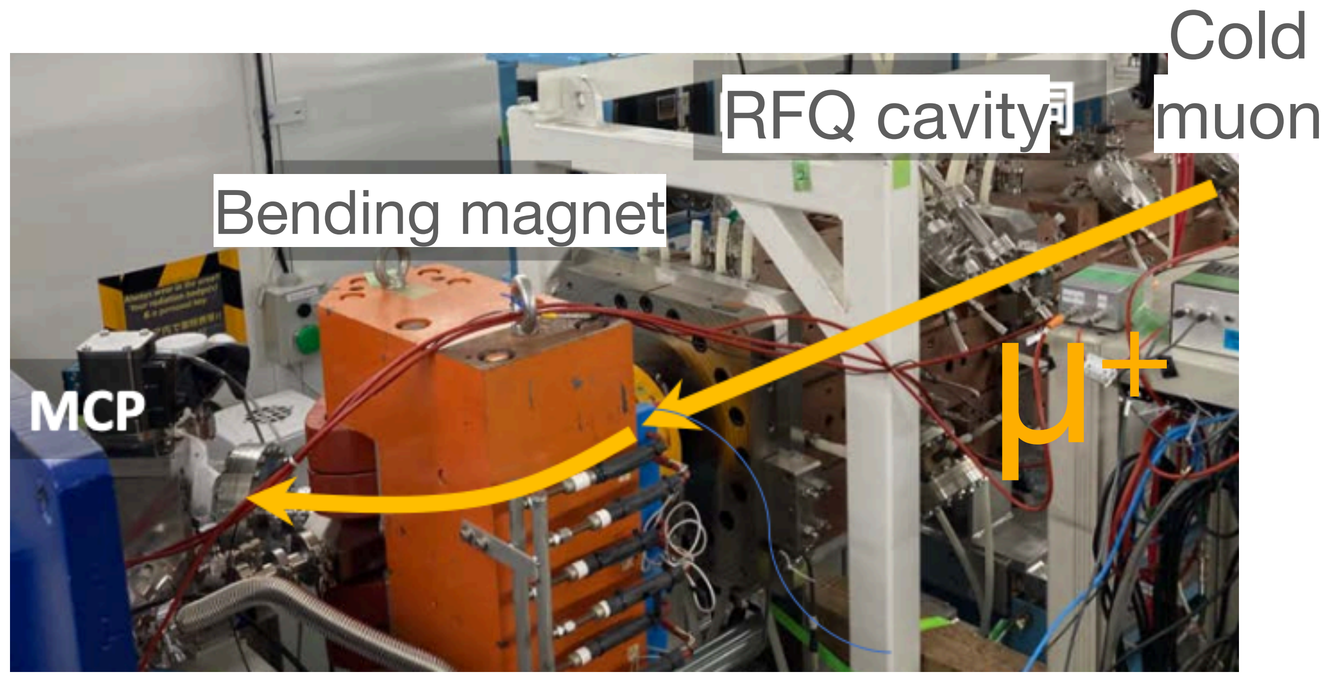
DLS prototype
(ready for production soon)

Muon Acceleration

The latest exciting result on April 2024

- The first-ever positive thermal muon RF re-acceleration to 90 keV was demonstrated at the J-PARC MLF S2 area on April 2024.





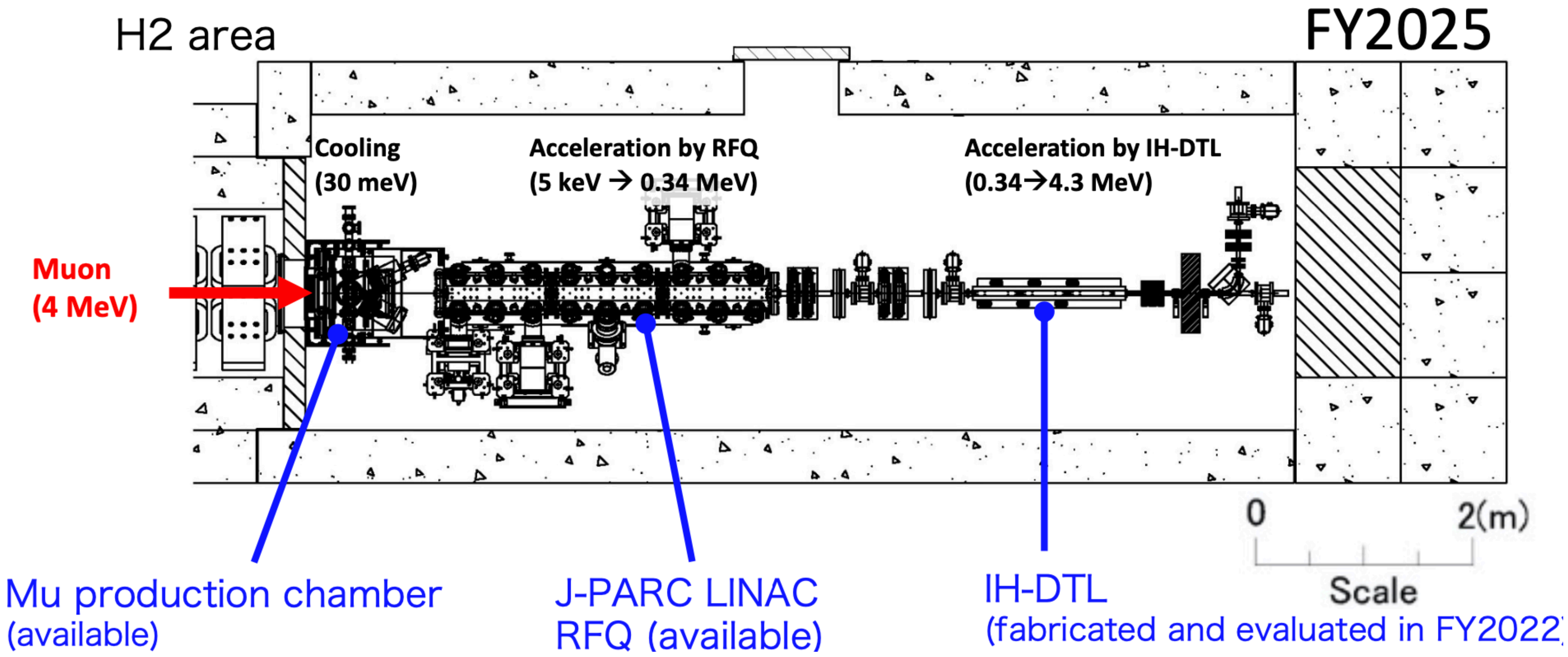
A big milestone for the experiment

Press release in English: https://j-parc.jp/c/en/press-release/2024/05/23001341.html

Muon Acceleration

Next milestone: acceleration to 4 MeV

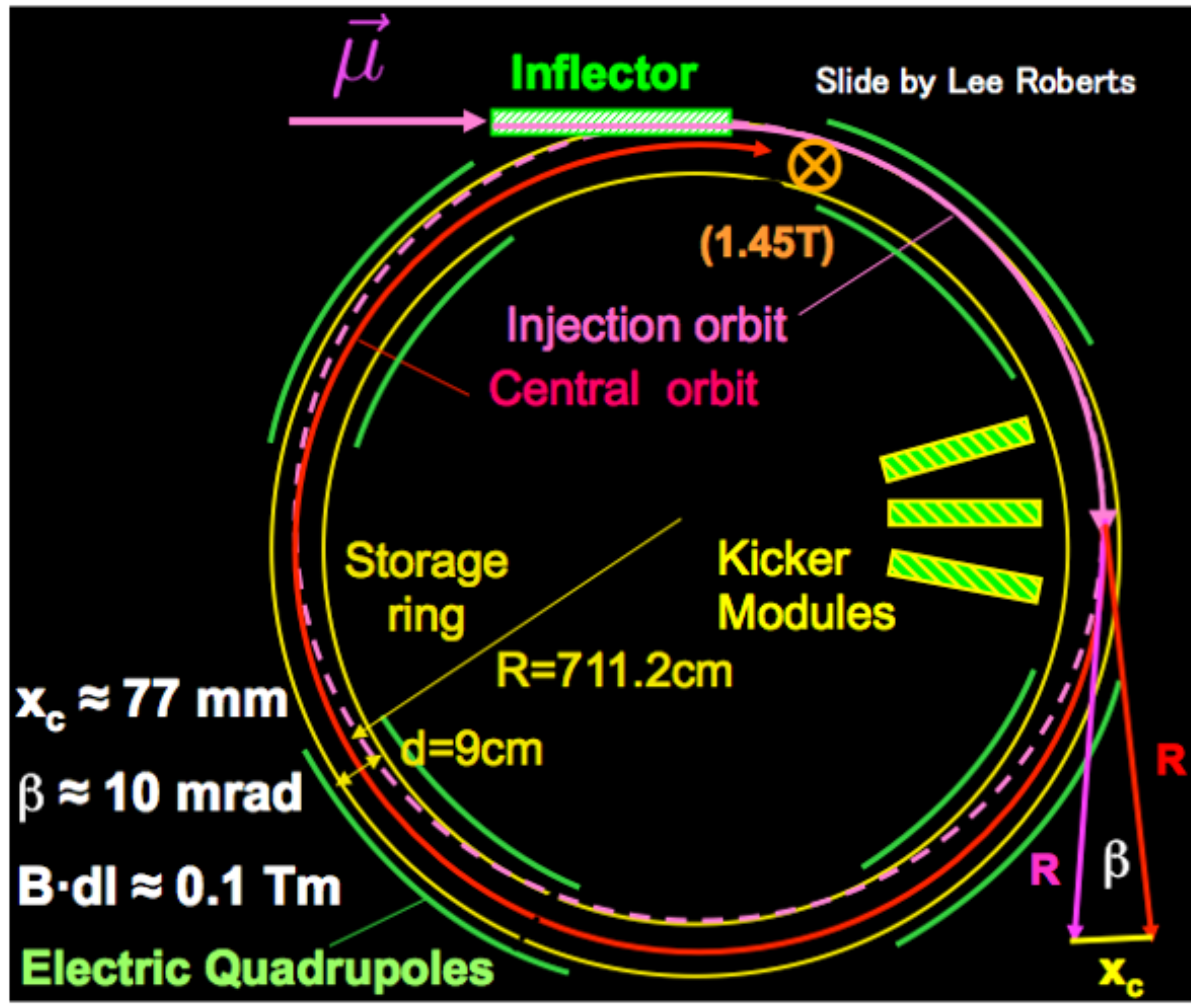
- the next step is to add IH-DTL to do further acceleration to 4 MeV at H2 area (the final experimental site)



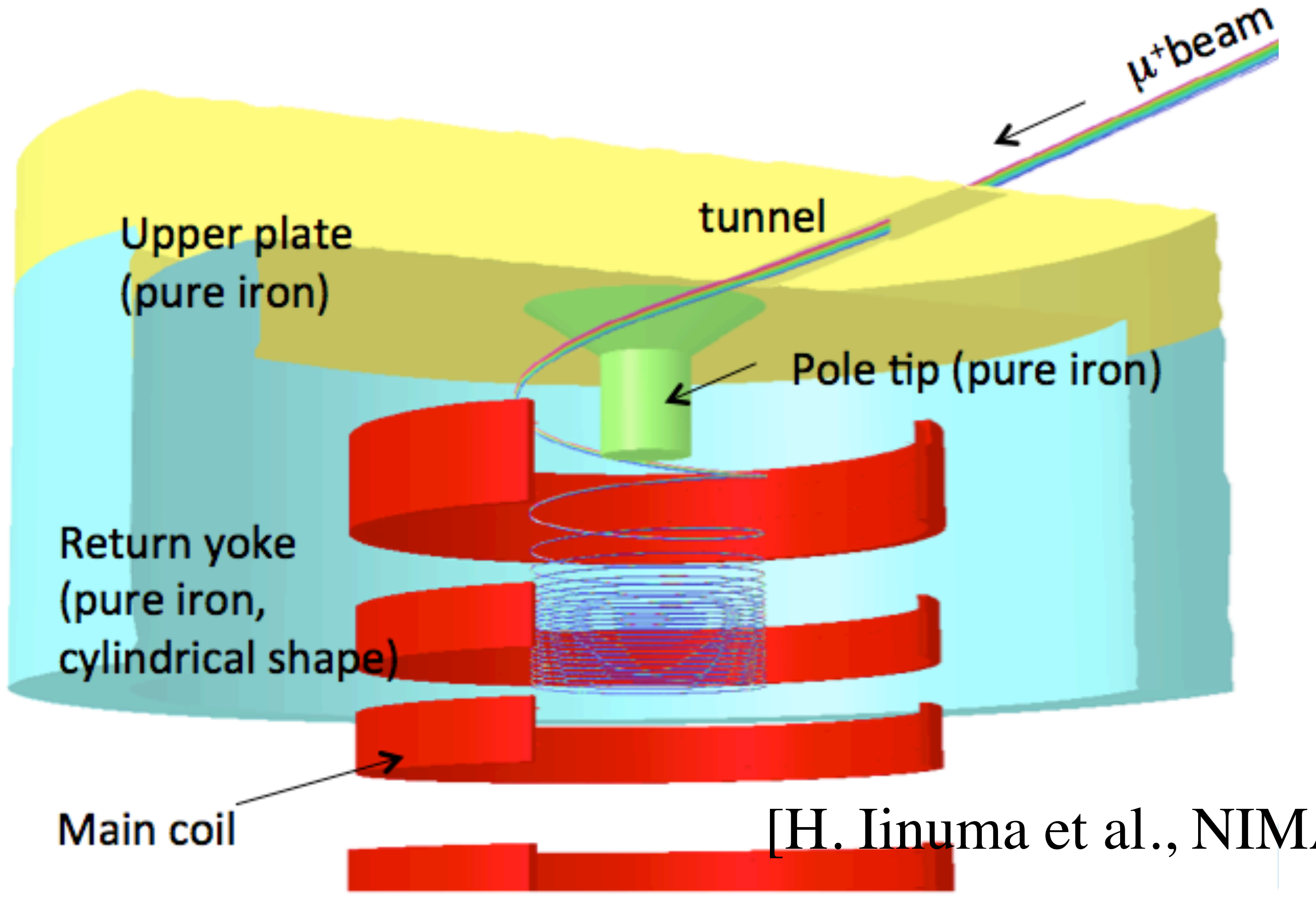
3D Spiral Injection

Why to inject the beam 3D spirally?

- The 3D spiral injection scheme has been invented for **small muon orbit**



[PRD73, 072003, 2006]



[H. Iinuma et al., NIMA 832, 51, 2016]

Conventional 2D injection @BNL and FNAL

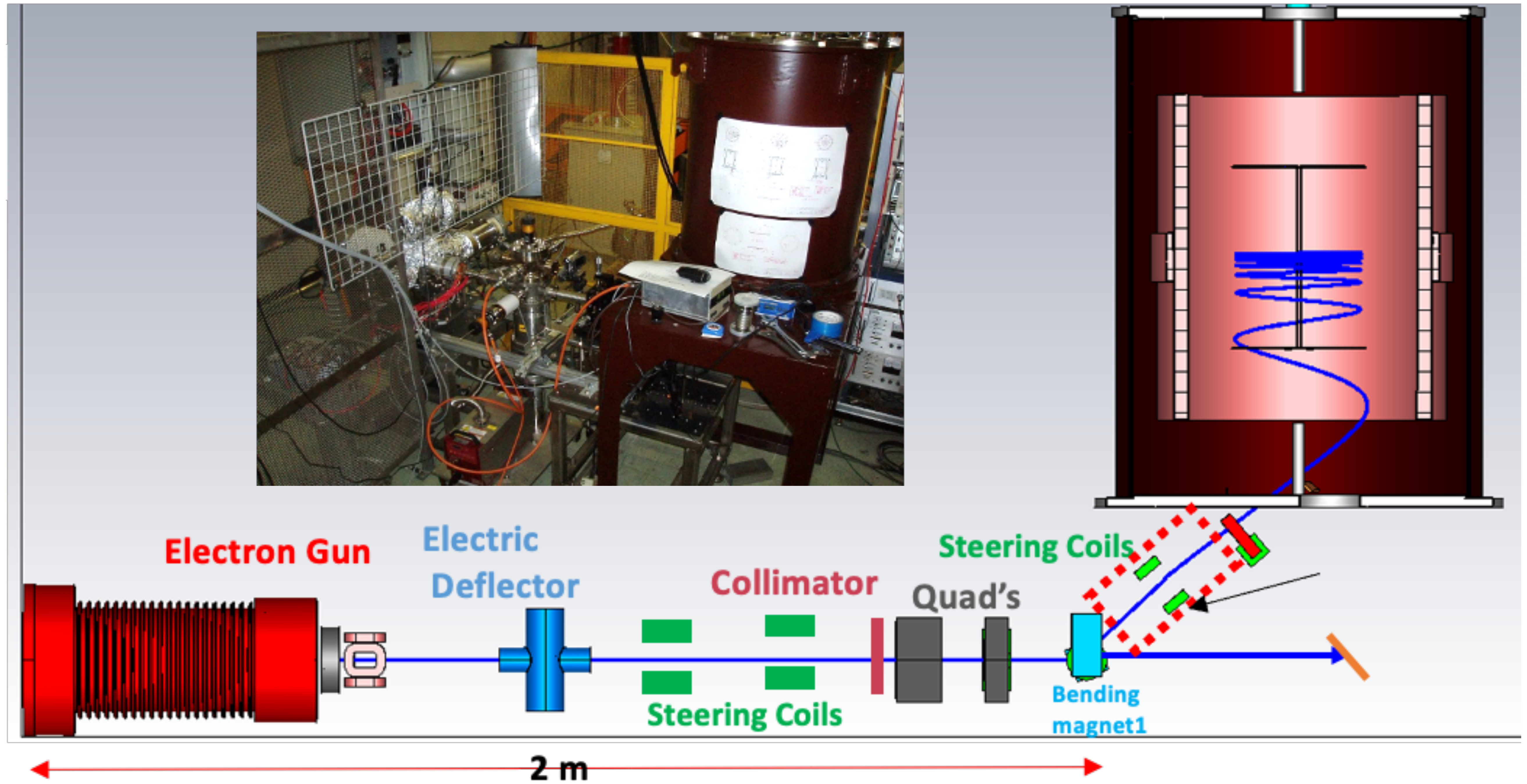
- Inflector + horizontal kicker
- Efficiency ~3-5%

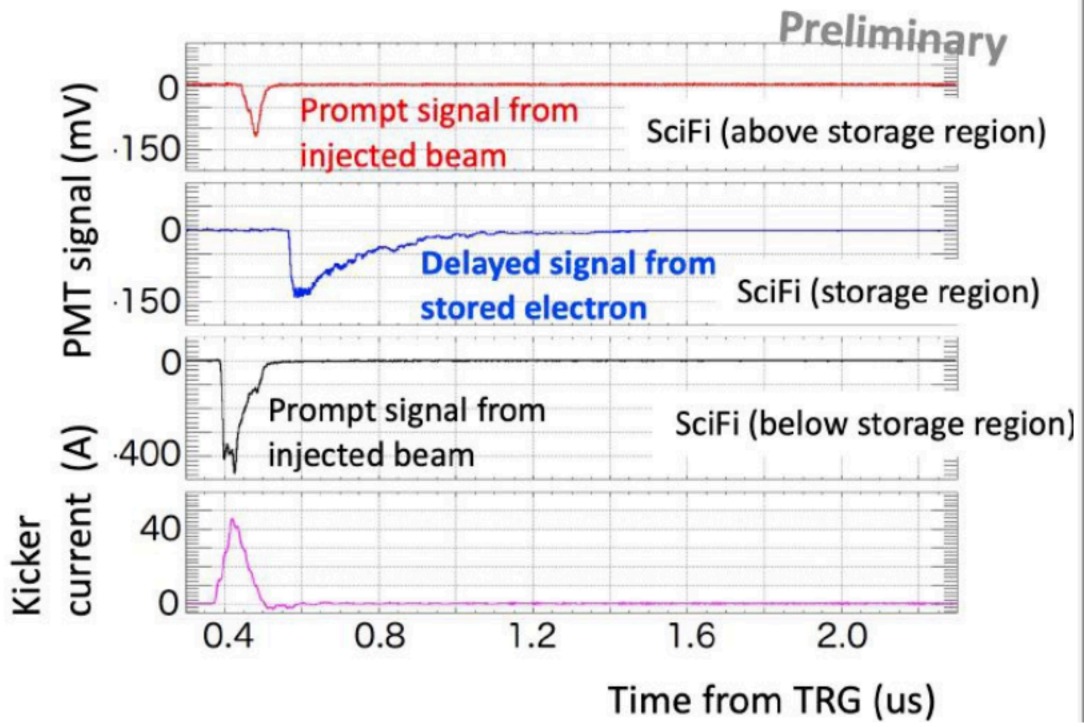
Novel injection @J-PARC

- 3D spiral injection + vertical kicker
- Efficiency > 80%
- to be adopted for the EDM @ PSI too

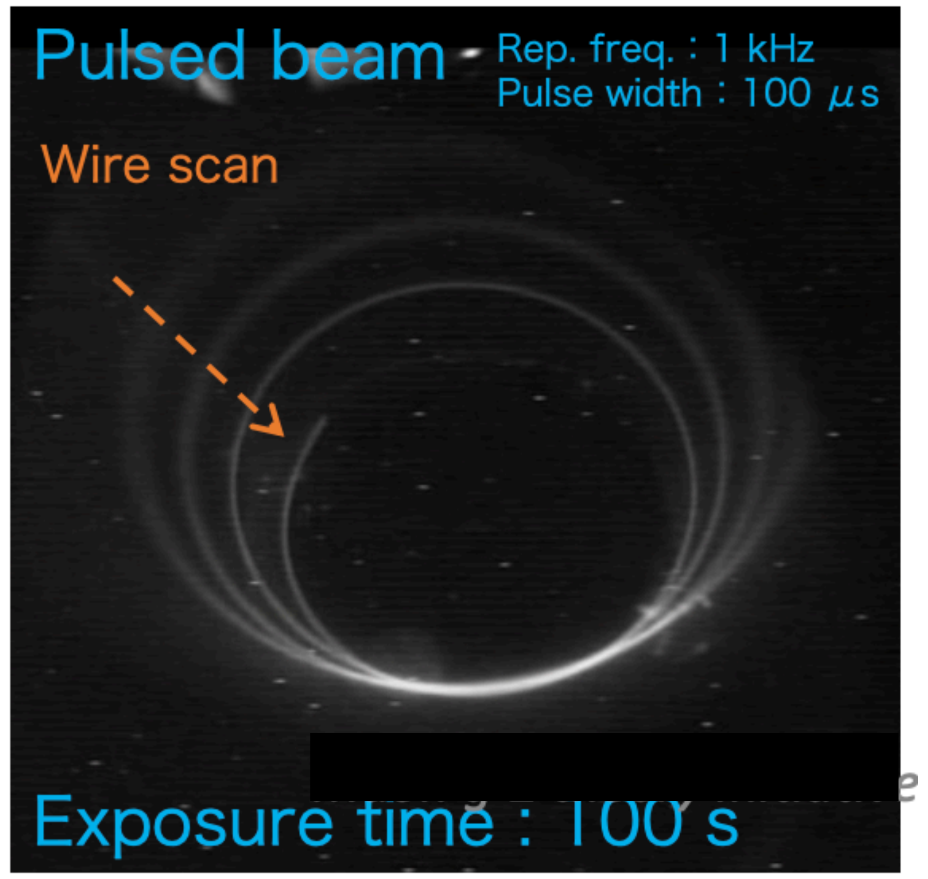
3D Spiral Injection

- Prototypes of the kicker were fabricated, and the 3D injection scheme is validated using a low momentum pulsed electron beam at KEK
- Simulation is still ongoing before finalising the design





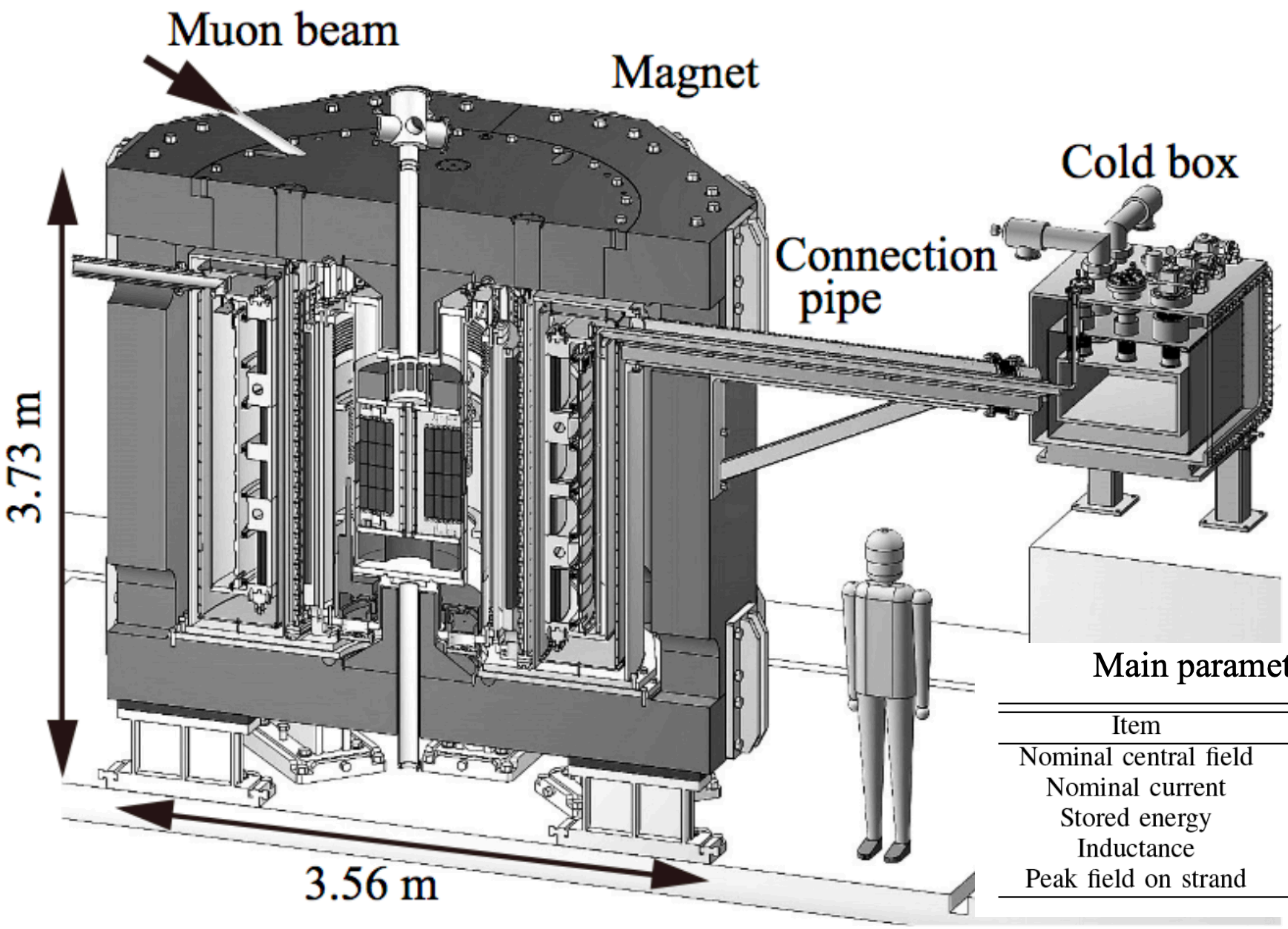
- First signal from stored electron beam was successfully observed



- Visualisation of 3D spiral geometry with a CCD camera

Storage Magnet

- **3 Tesla** MRI-type superconducting solenoid magnet is under design

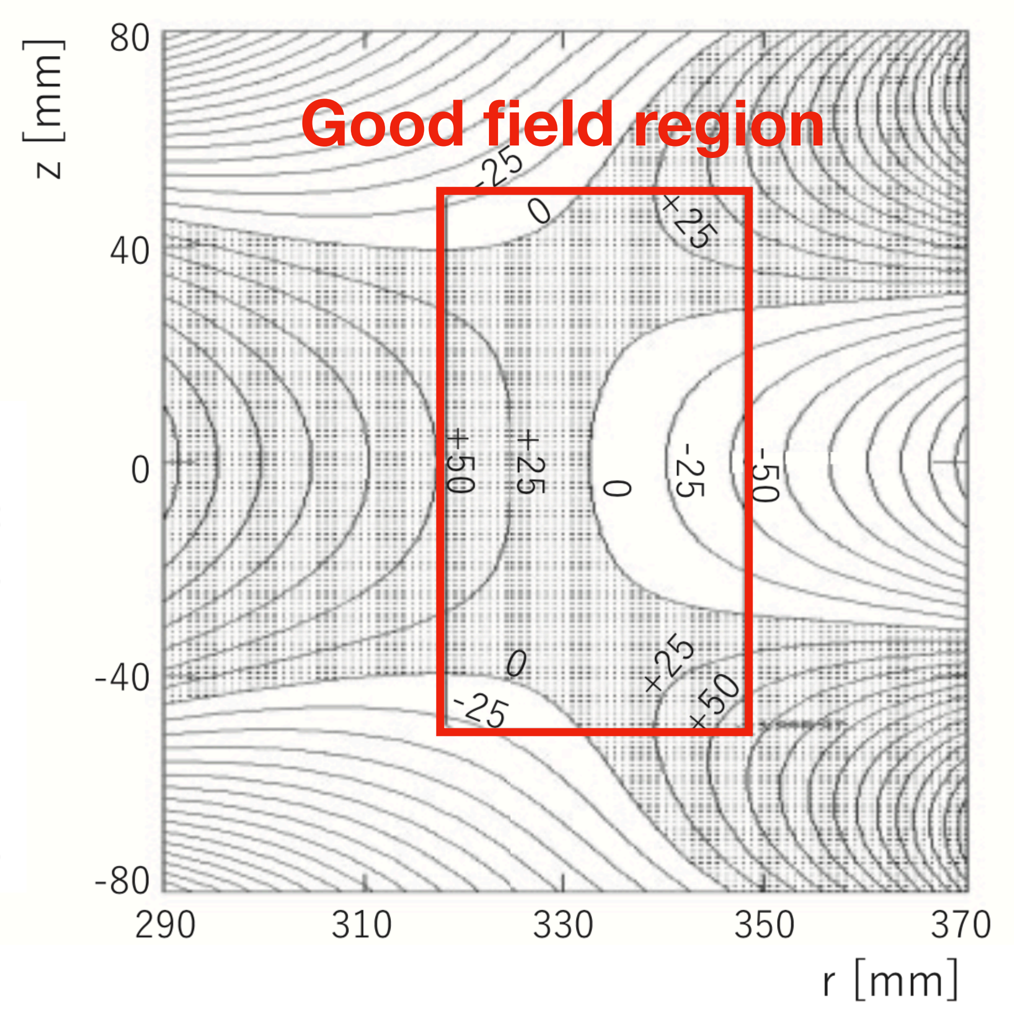


Main parameters

Item	Unit	Value
Nominal central field	T	3.0
Nominal current	A	417.5
Stored energy	MJ	14.6
Inductance	H	166.9
Peak field on strand	T	5.4

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

- Muon storage region:
  - radius : 33.3±1.5 cm
  - height : ±5 cm
  - Field strength : 3T
  - Uniformity : 0.1 ppm (Azimuthal integral)
- Injection region :
  - Smooth field for beam injection
- Weak focus field: -5e-4 T/m of Br at maximum



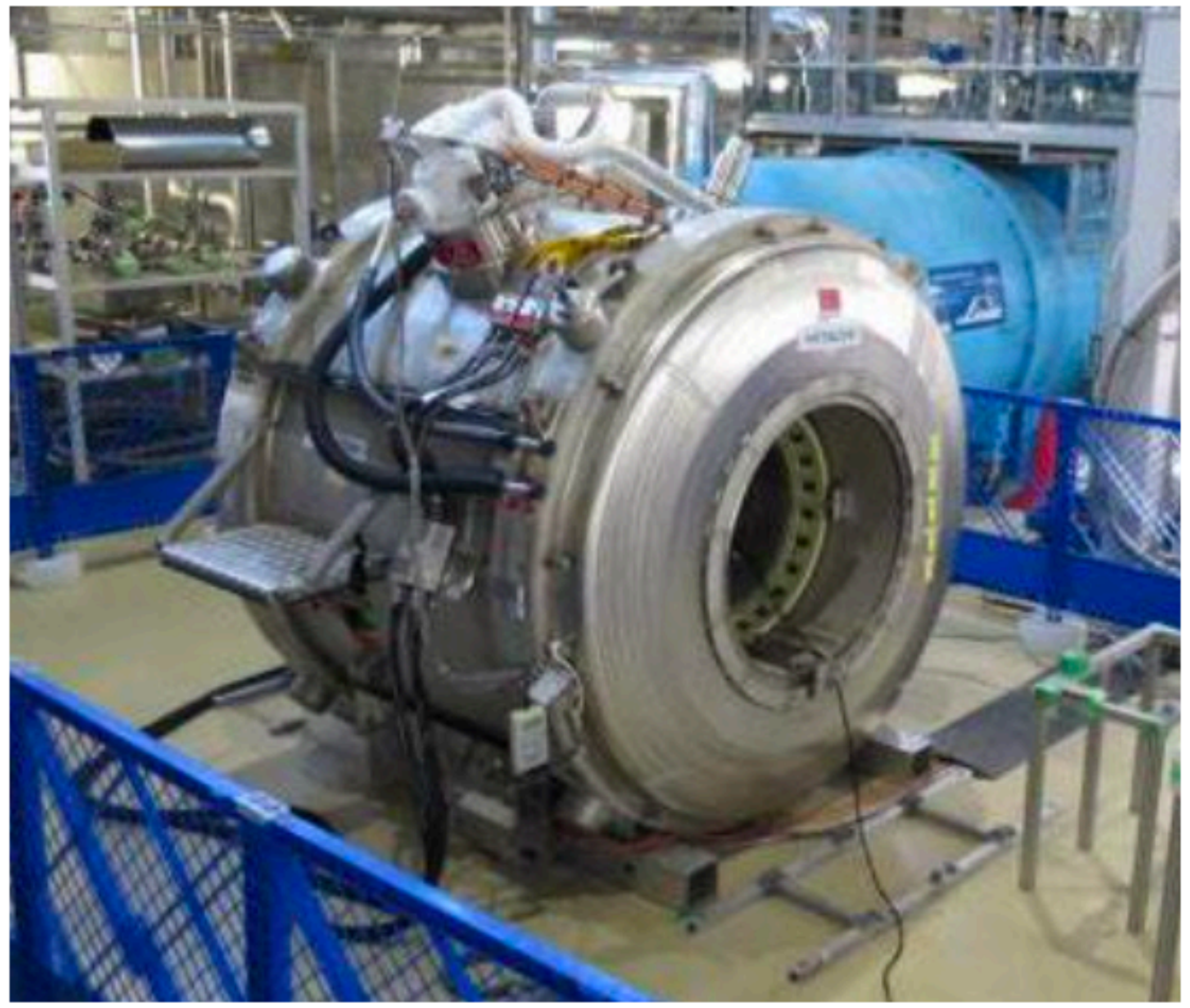
Average magnetic field uniformity is better than 0.1 ppm

25 ppb/line

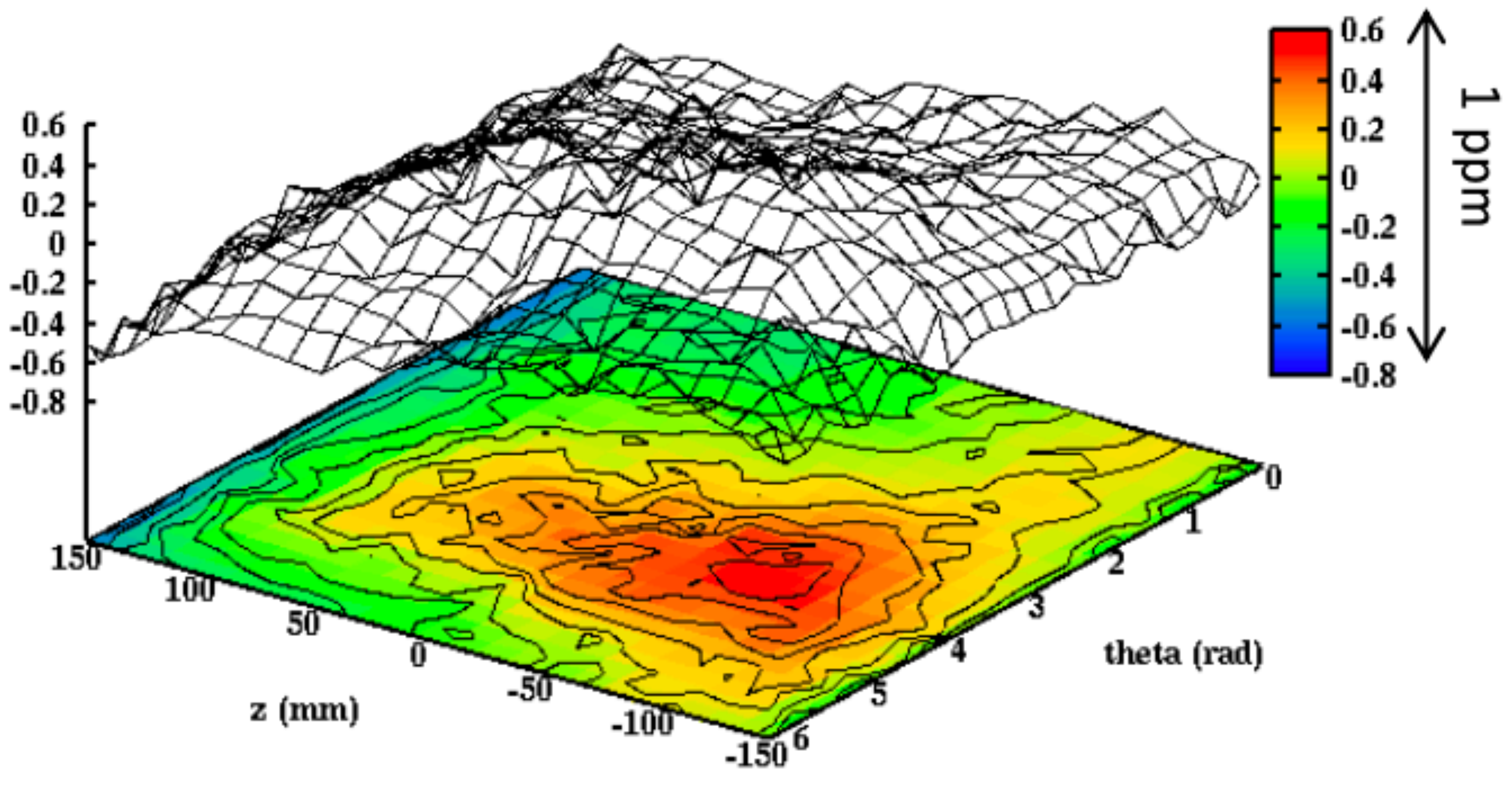
Storage Magnet

Magnetic Field Calibration

- Local uniformity of 1 ppm was demonstrated by the MUSEUM experiment magnet at **1.2 T**; further tests will be carried out at **3 T.**
- In the **cross-calibration of FNAL and J-PARC** field probes at ANL, ~7 ppb agreement was obtained with 15 ppb uncertainties.



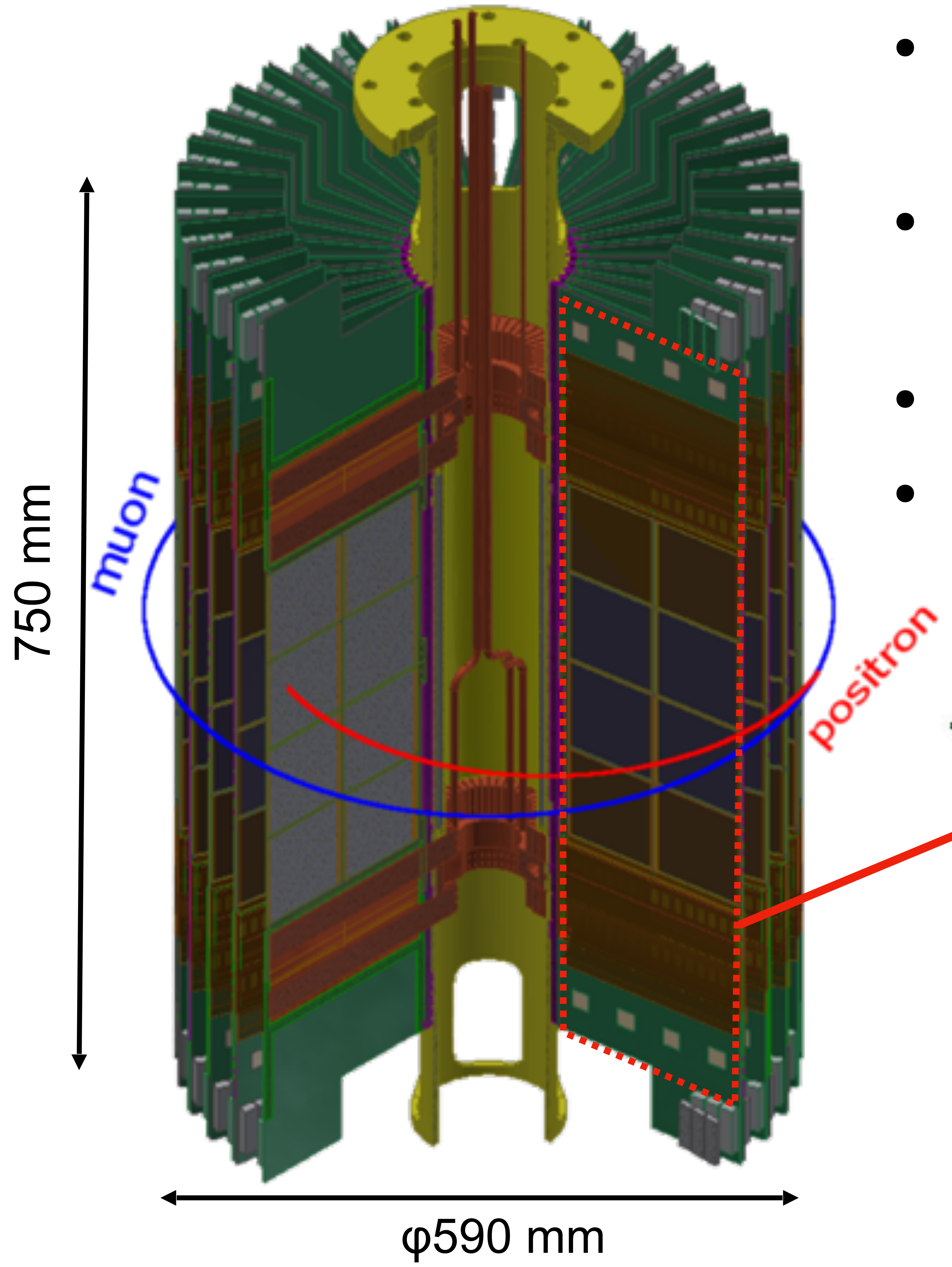
MRI magnet for MuSEUM experiment



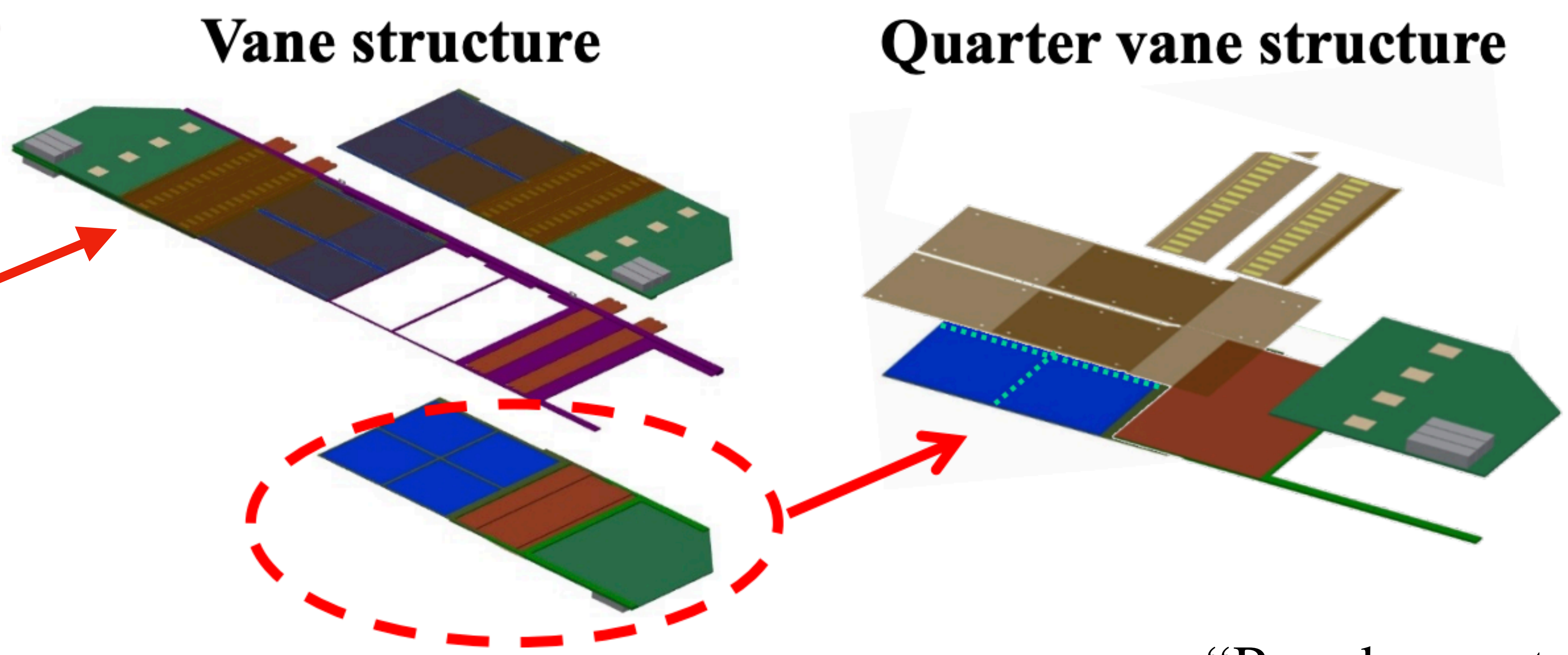
Magnetic field after shimming

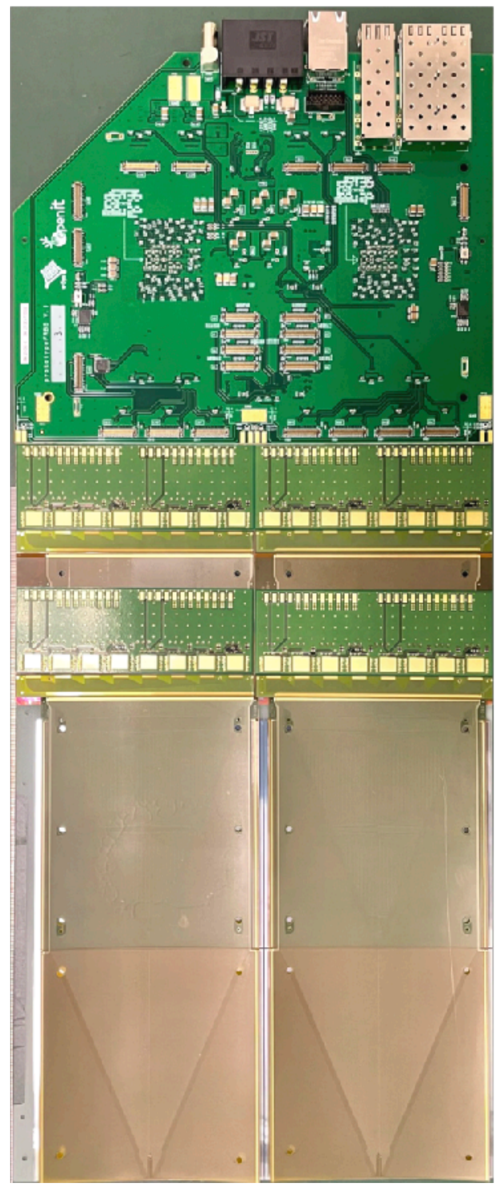
Cross calibration at ANL in January 2019

Positron Tracking Detector



- Positrons tracks are reconstructed from hits in radially arranged detector modules (Vane).
- Consists of **40** radial rectangle modules. A quarter vane consists of **4 silicon sensors + 32 readouts ASICs.**
- Mass production is ongoing.
- Operation test in a high magnetic field in 2023.

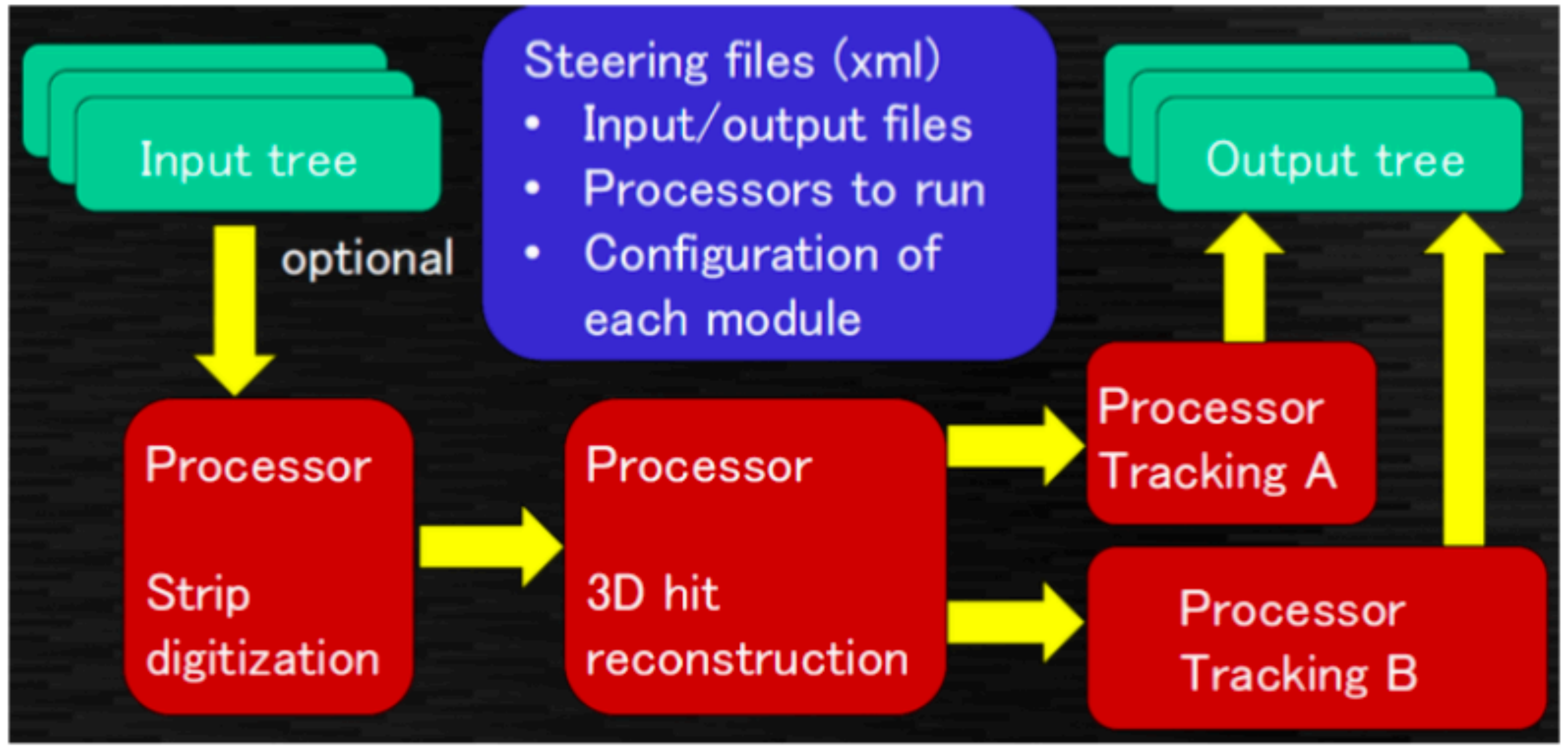




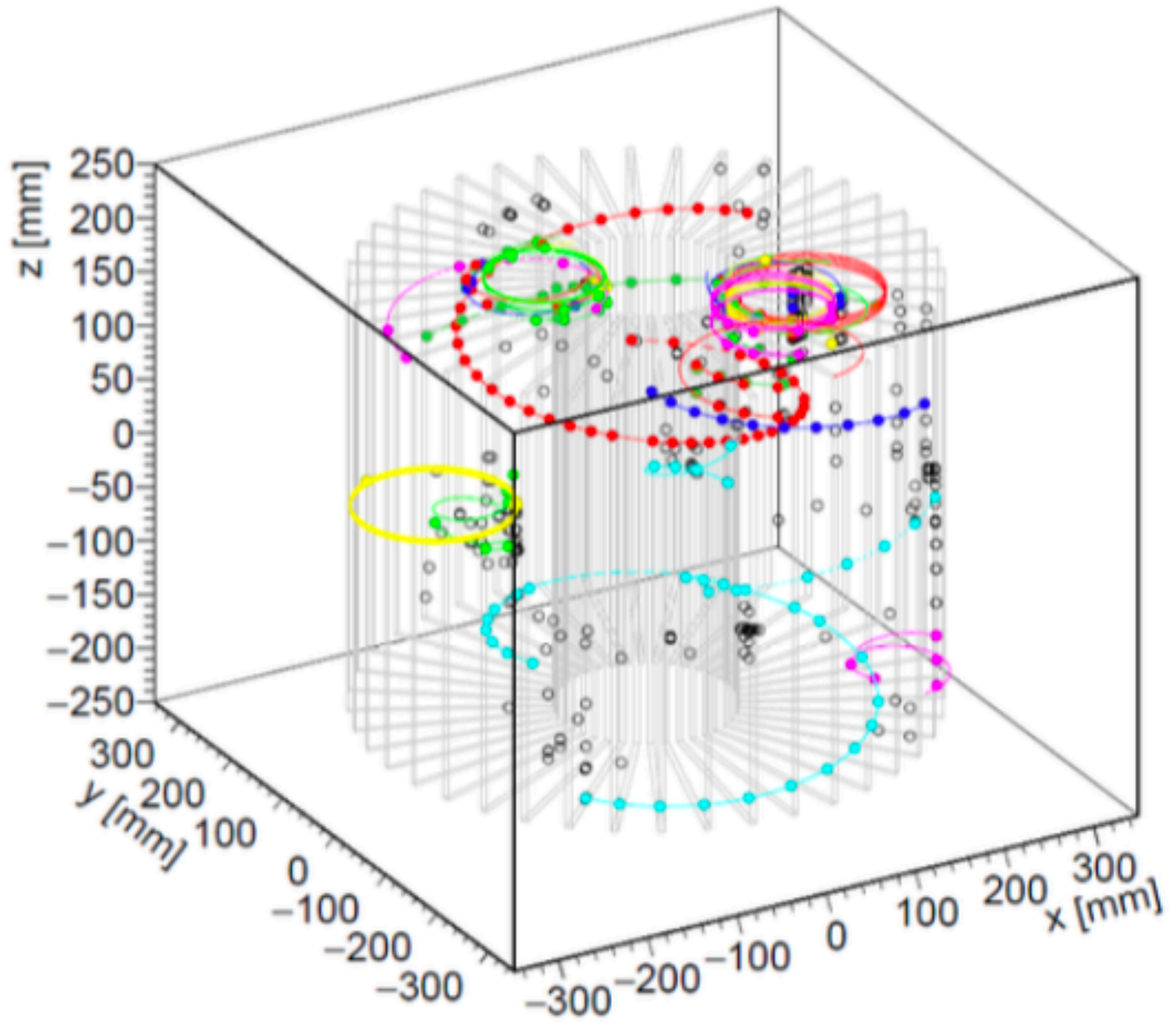
"Pseudo-quarter vane"

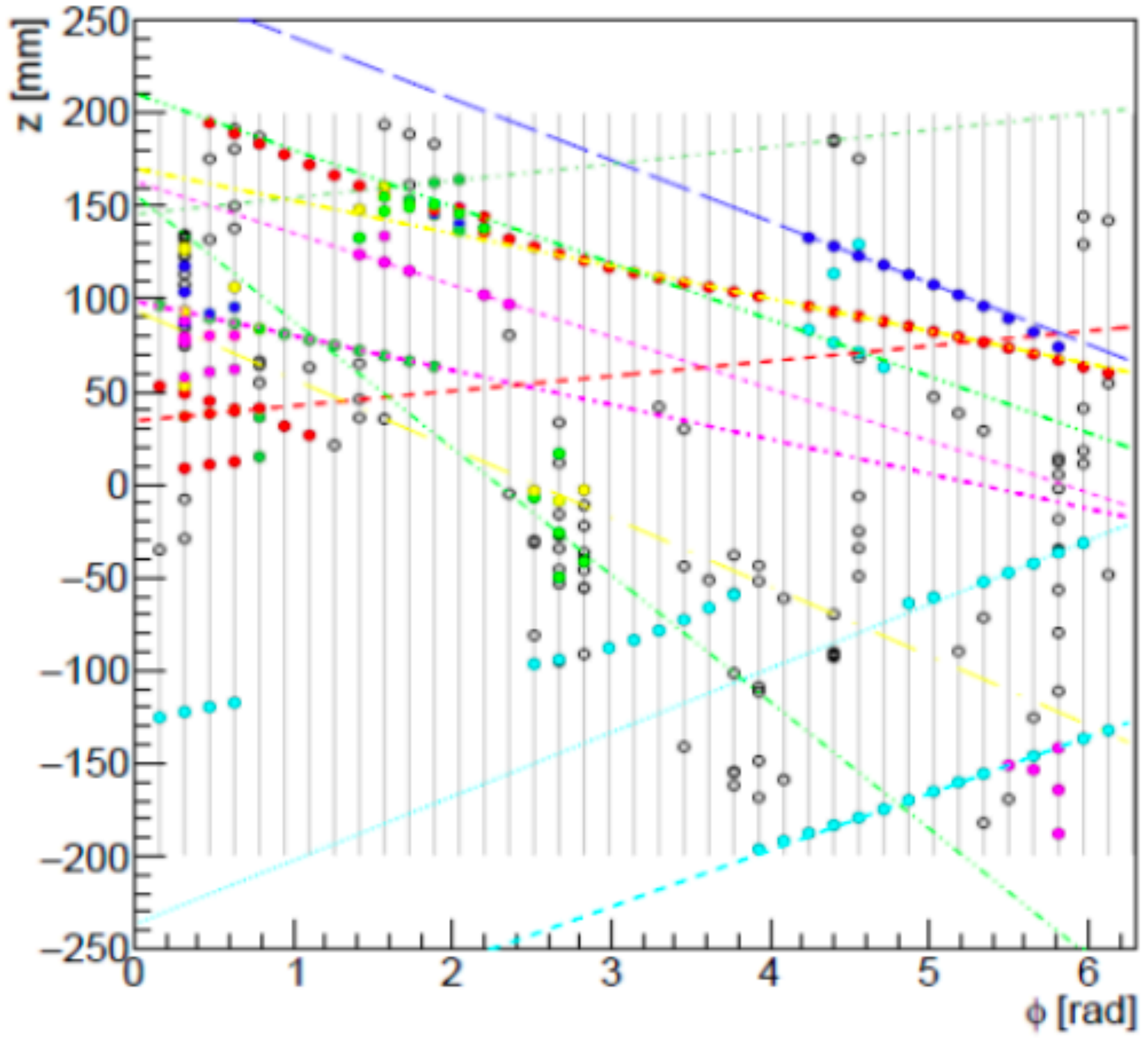
Software Development

- To manage detector simulation and track reconstruction, a new software framework was developed (named “g2esoft”).
- A reconstruction algorithm in high track density is being implemented. Application of Graph Neural Networks (GNN), etc., is ongoing.



Concept of g2esoft





Simulated positron hits and reconstructed tracks with 25 positrons

Expected Sensitivity

- Initially, a **3.2×10^{8}μ/sec** is expected at the entrance of the H2 area at 1 MW proton power.
- The expected intensity of stored muon is **1.3×10^{5} μ/sec.** Cumulative efficiency from thermal muon generation to reconstructed positron is 4.0×10^{-4}.
- **2-year data taking** (2×10^{7} seconds, ~230 days) will give a total positron **5.7×10^{11}**, achieving the BNL precision of **0.45 ppm** on a_μ.

Table 5. Summary of statistics and 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.)

Expected Sensitivity

- Systematic uncertainties are estimated to be less than **70 ppb** - smaller than the statistical ones.

Table 6. Estimated systmatic 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

$\delta a_{\mu\,(\text{syst.})} < 70$ ppb

→ the experiment is still statistically limited

Expected Sensitivity

TABLE II. Values and uncertainties of the $\mathcal{R}'_\mu$ correction terms in Eq. (4), and uncertainties due to the constants in Eq. (2) for a_μ. Positive C_i increase a_μ and positive B_i decrease a_μ.

Quantity	Correction terms (ppb)	Uncertainty (ppb)		
ω_a^m (statistical)	⋯	434		
ω_a^m (systematic)	⋯	56	↦ <36	: Pileup, (gain, CBO)
C_e	~~489~~	53	↦ 10	: residual E-fields (no Quads)
C_p	~~180~~	13	↦ 13	: pitch correction
C_{ml}	~~−11~~	5	↦ 2	: differential decay & (muon losses)
C_{pa}	~~−158~~	75	↦ 0	: transverse muon distribution
$f_{\text{calib}}\langle\omega_p(x,y,\phi) \times M(x,y,\phi)\rangle$	⋯	56	↦ 49	: probe positioning & calibration
B_k	~~−27~~	37	↦ <10	: kicker transients
B_q	~~−17~~	92		
$\mu'_p(34.7°)/\mu_e$	⋯	10		
m_μ/m_e	⋯	22		
$g_e/2$	⋯	0		
Total systematic	⋯	157	↦ <64	
Total fundamental factors	⋯	25		
Totals	~~544~~	462		

$\delta a_{\mu\,(\text{syst.})} < 70$ ppb

Abe *et al.*, DOI: 10.1093/ptep/ptz030 (2019)
Abi *et al.*, DOI: 10.1103/PhysRevLett.126.141801 (2021)

Schedule & Funding Status

JFY	2022	2023	2024	2025	2026	2027	2028 and beyond
KEK Budget							
Surface muon	✓Beam at H1 area		Funding Secured!	★ Beam at H2 area			Commissioning / Data taking
Bldg. and facility		Final design ★	Funding Requested to KEK			★ Completion	
Muon source	✓ Ionization test @S2			★ Ionization test at H2			
LINAC			★ 90keV acceleration@S2	★ 4.3 MeV@ H2		★ fabrication complete	★ 210 MeV
Injection and storage			★ Completion of electron injection test				★ muon injection
Storage magnet				★ B-field probe ready		★ Install ★ Shimming done	
Detector		✓ Quoter vane prototype		★ Mass production ready		★ Installation	
DAQ and computing		✓ grid service open ★ common computing resource usage start		★ small DAQ system operation test	★ Ready		
Analysis				★ Tracking software ready	★ Analysis software ready		

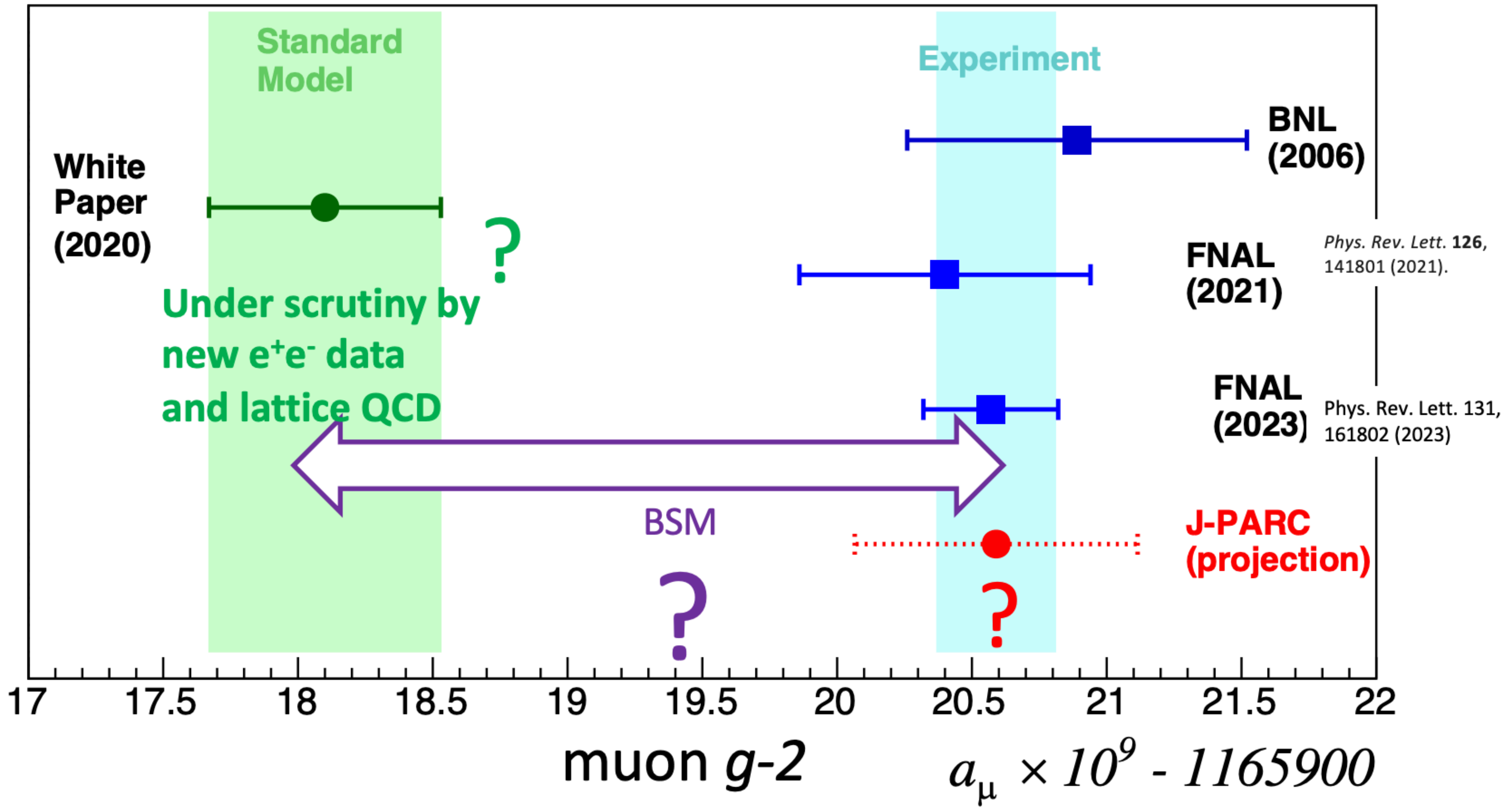
- Fundings secured for most critical facilities. Construction is ongoing.
- Data-taking from 2028 and beyond

Funding 15

- **FY2023**
  - MEXT provided a funding for the H-line extension. (procurement of magnet components) and H2 area including the laser room and the PS platform.
  - KEK provided additional funding to carry out the engineering design of the H-line extension building.
- **FY2024**
  - KEK requested funding to complete the H-line extension.
  - KEK submitted a funding proposal to JST for subsidiary use of accelerated muon.
  - Decisions will be announced by the end of December.

Summary

- J-PARC muon $g-2$/EDM experiment will take a different approach than FNAL.
  - A thermal muon beam enables a high-quality muon beam.
  - Muon LINAC re-accelerates muon beam, which is 3D injected into the compact storage region.
  - The tracking detector reduces pile-up and measures positron direction in a highly uniform B-field.
- **Expecting 0.45 ppm** of a_μ with **2 years** of data taking starting possibly from 2028



Backup

Towards the ultimate muon anomaly test

Slides by T. Mibe, inspired by K. Jungmann's slide

Fermilab Muon g-2 (E989)

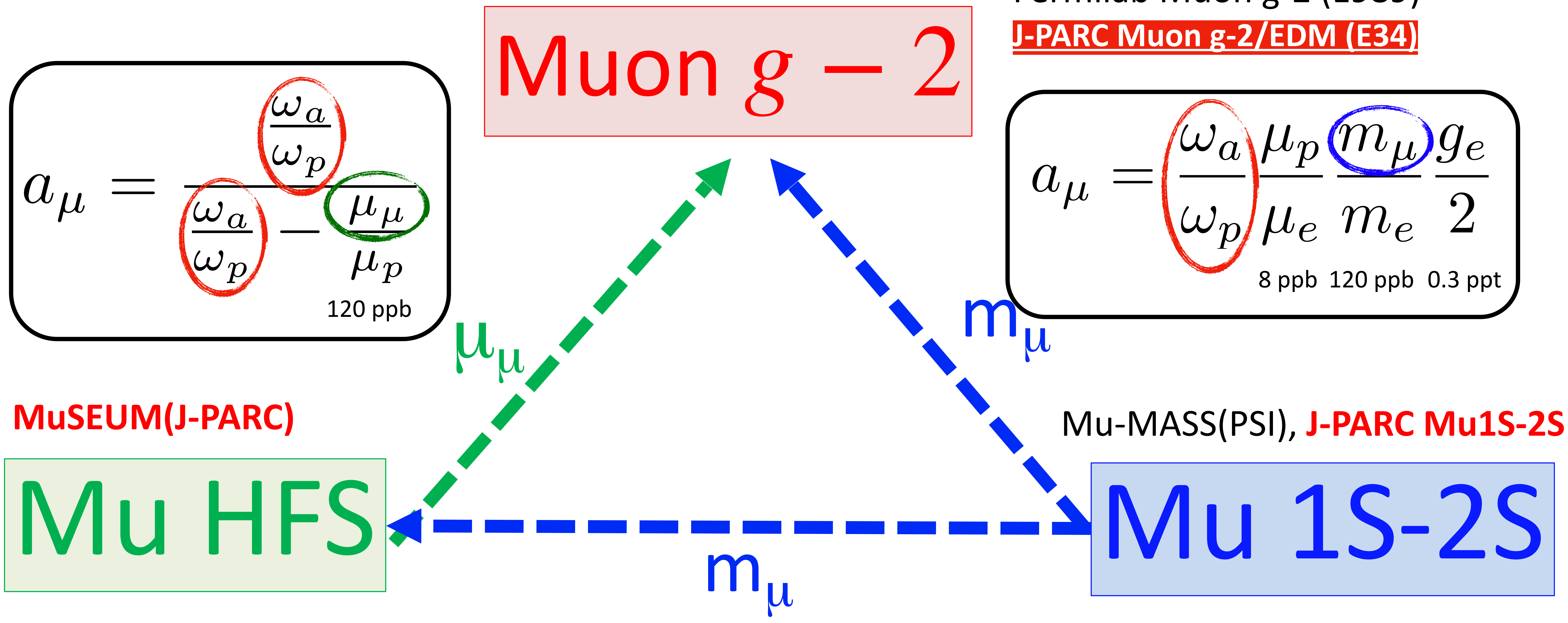
J-PARC Muon g-2/EDM (E34)

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

120 ppb

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

8 ppb 120 ppb 0.3 ppt



MuSEUM(J-PARC)

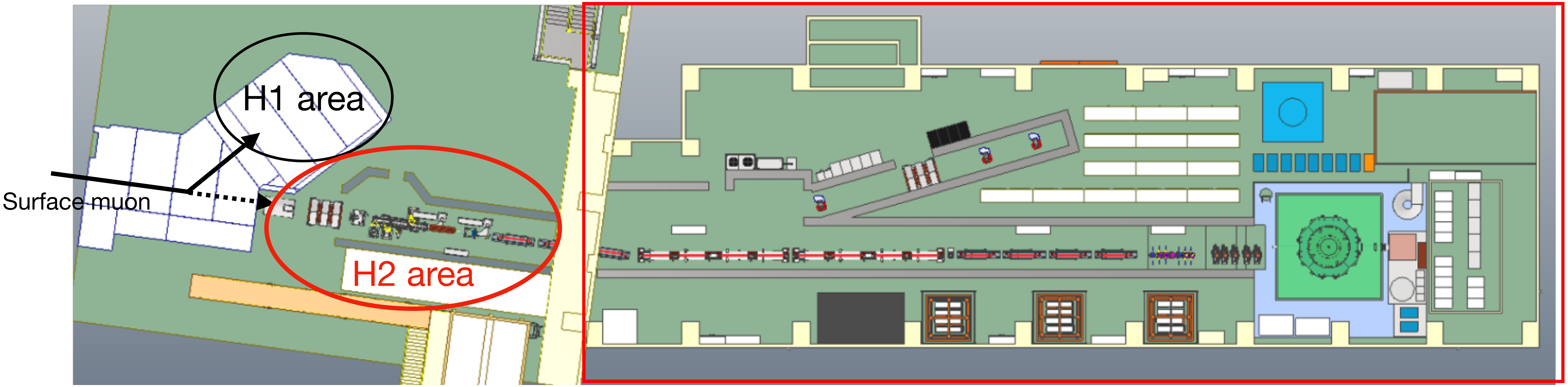
Mu-MASS(PSI), J-PARC Mu1S-2S exp.

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

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

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

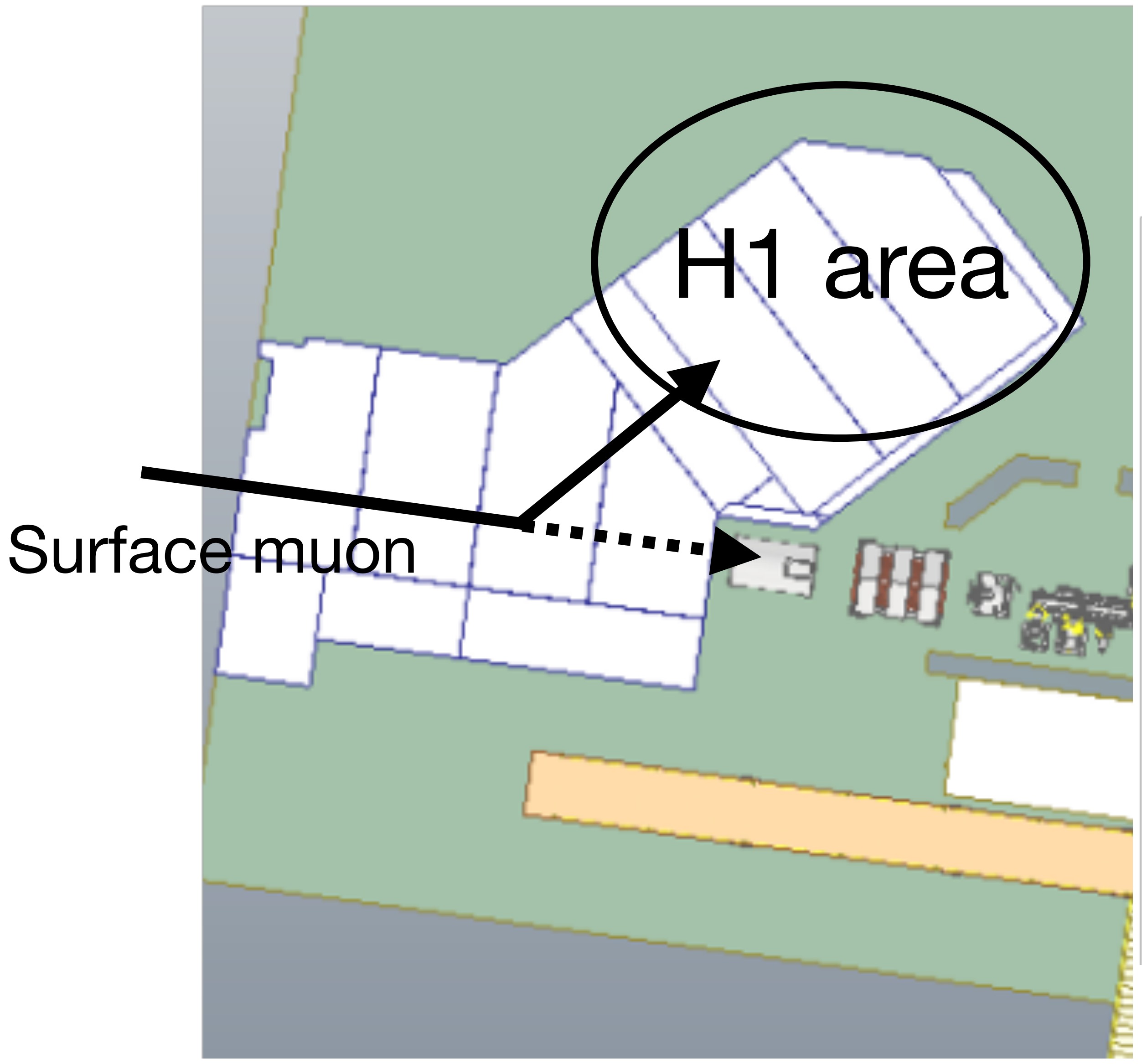
H-line construction



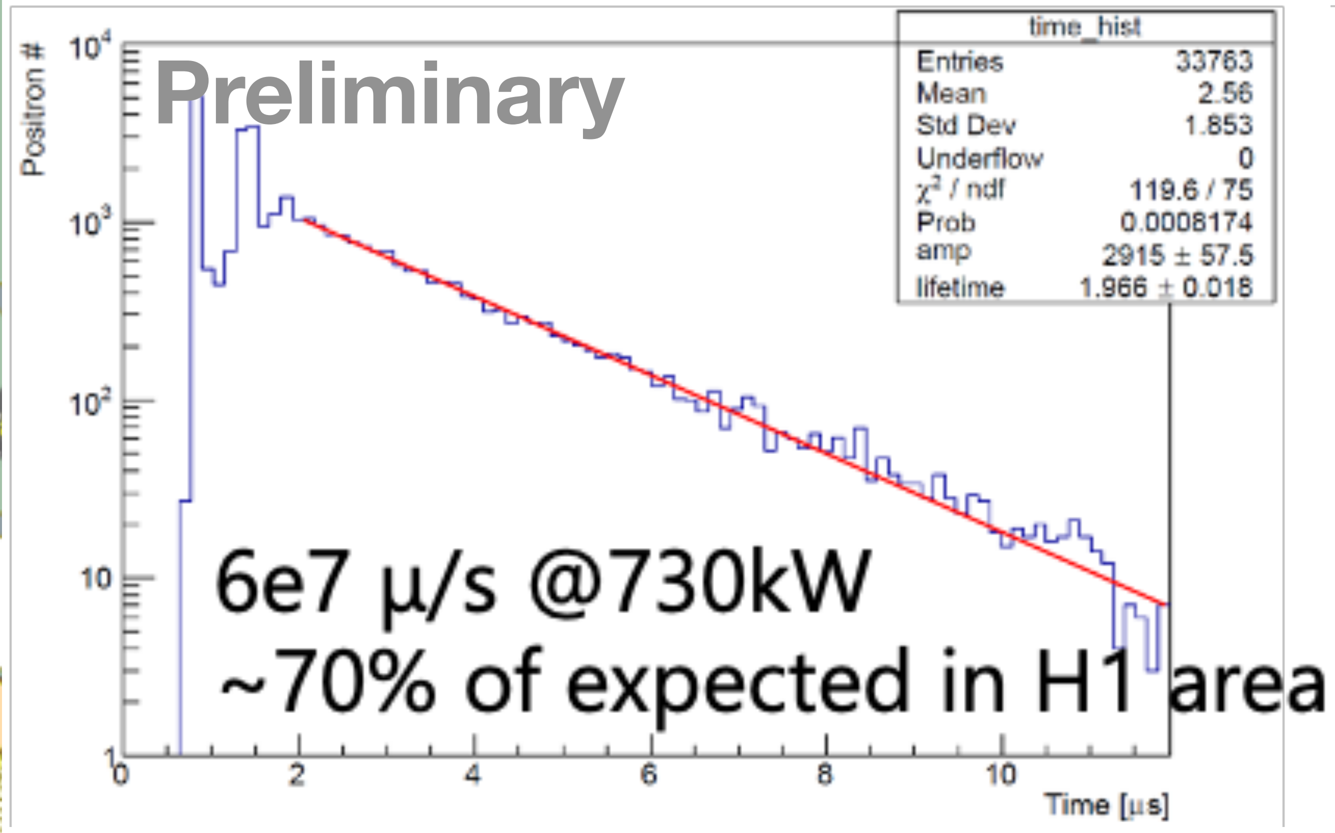
Extension building for muon LINAC, kicker and storage ring

- Beam commissioning is ongoing at the **H1 area.**
- Construction of the **H2 area** is in progress.
- **The extension building** design is ready to start construction.

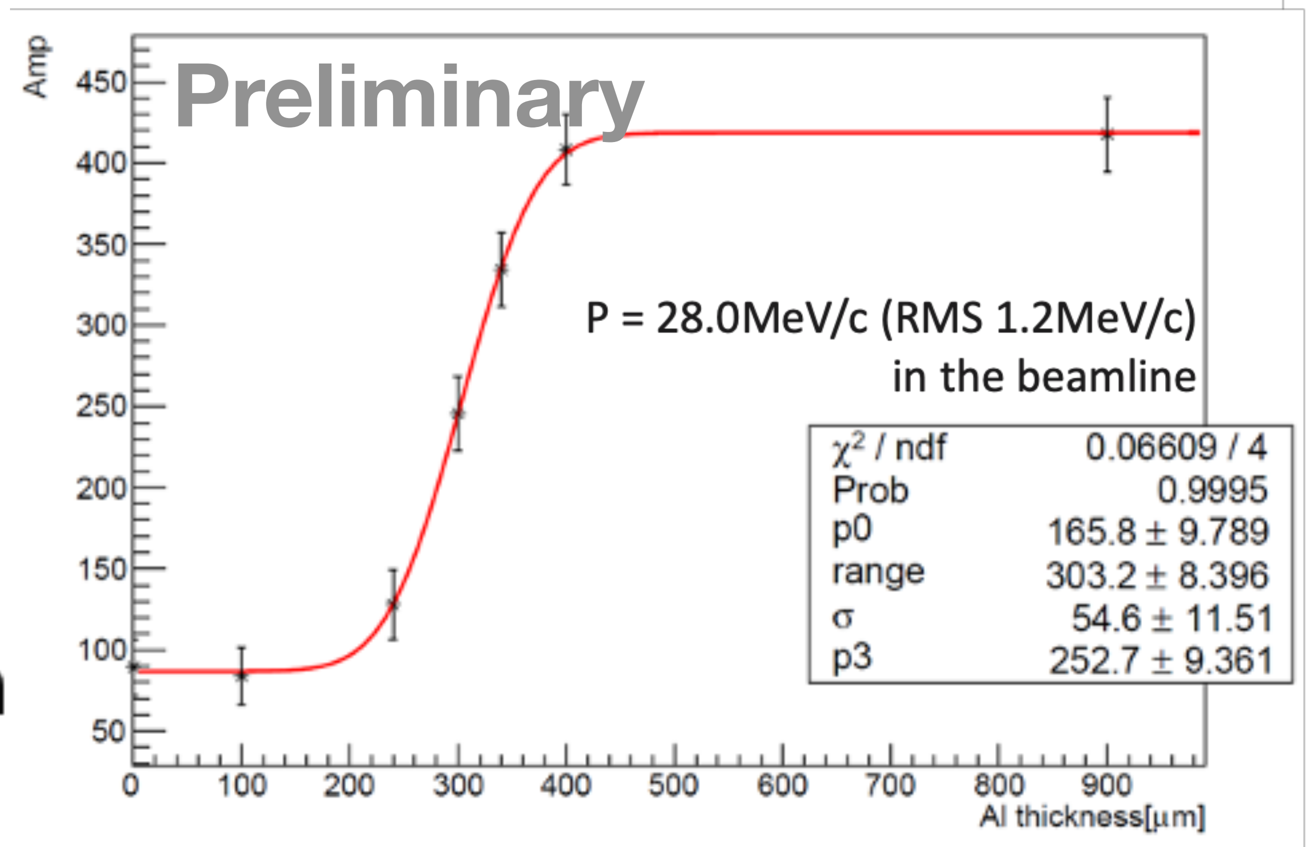
H-line construction



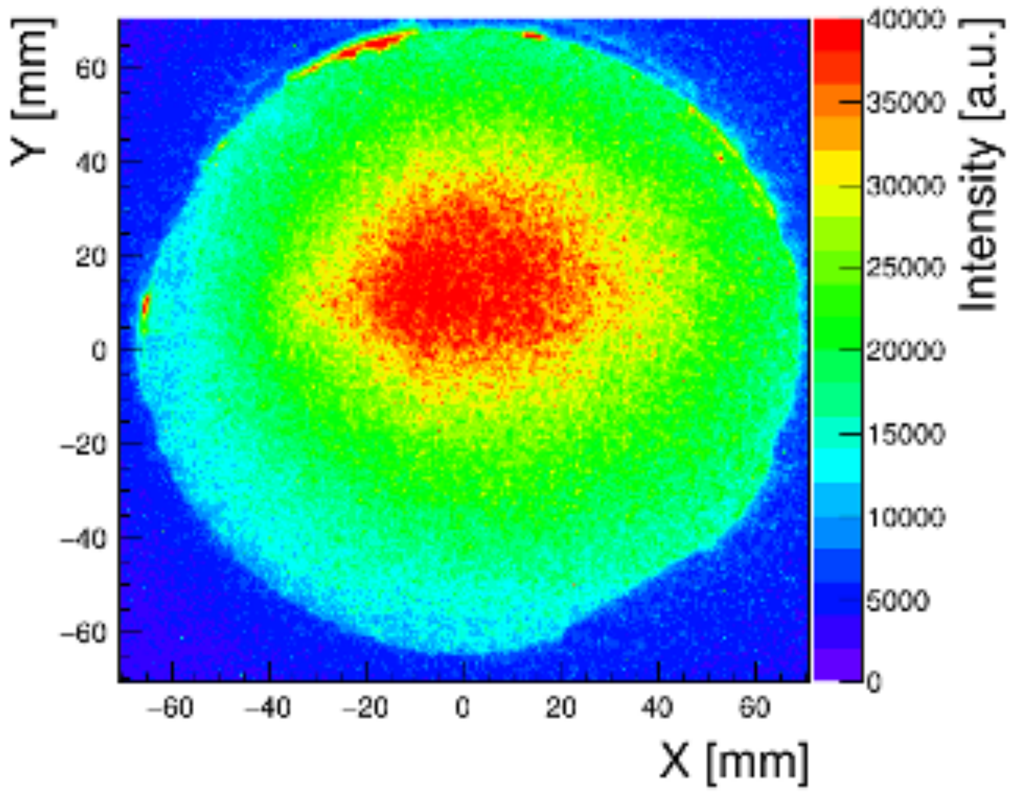
- The first beam was delivered to the **H1 area** on Jan. 15th, 2022



① Beam intensity measurement



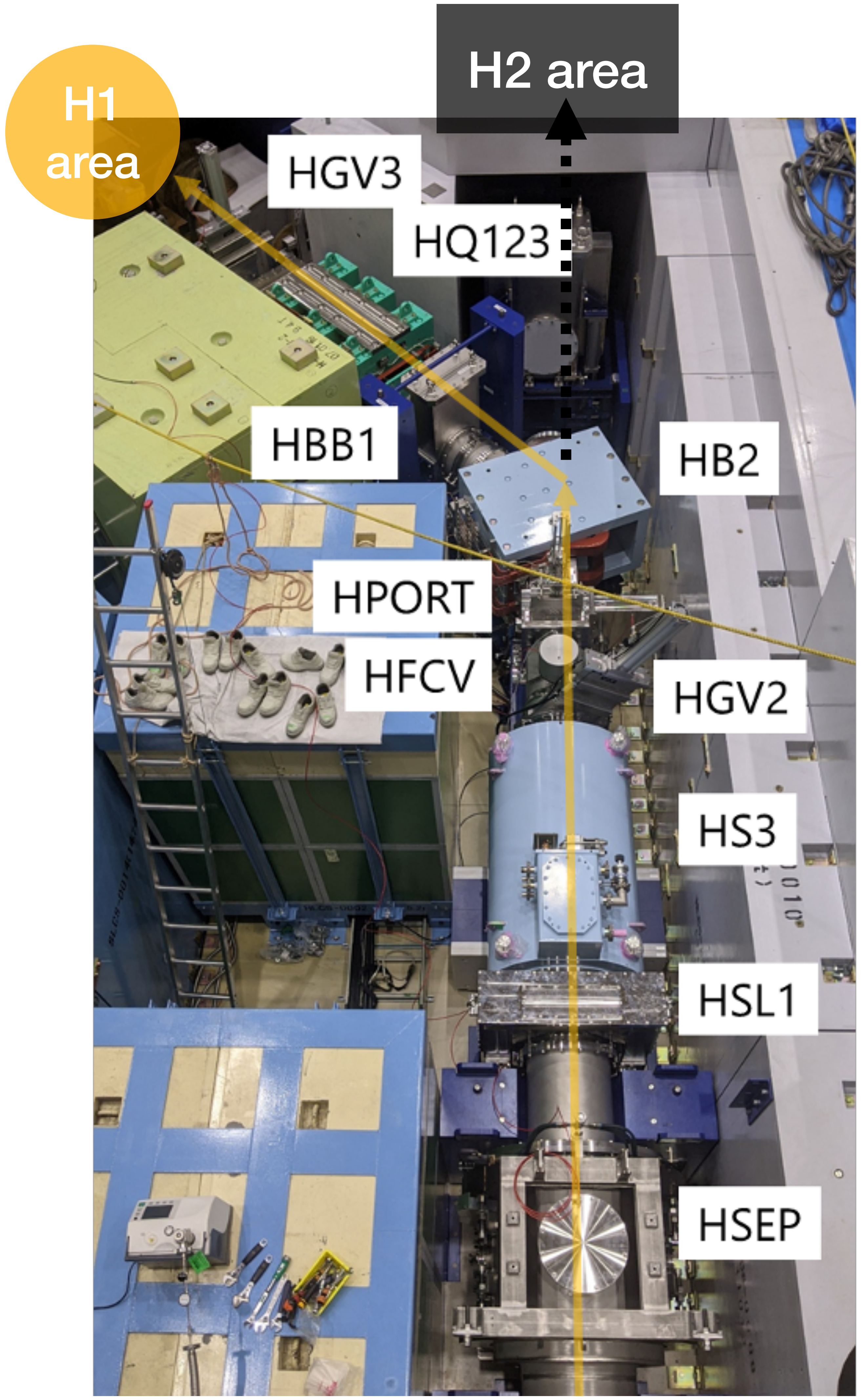
② Momentum estimation

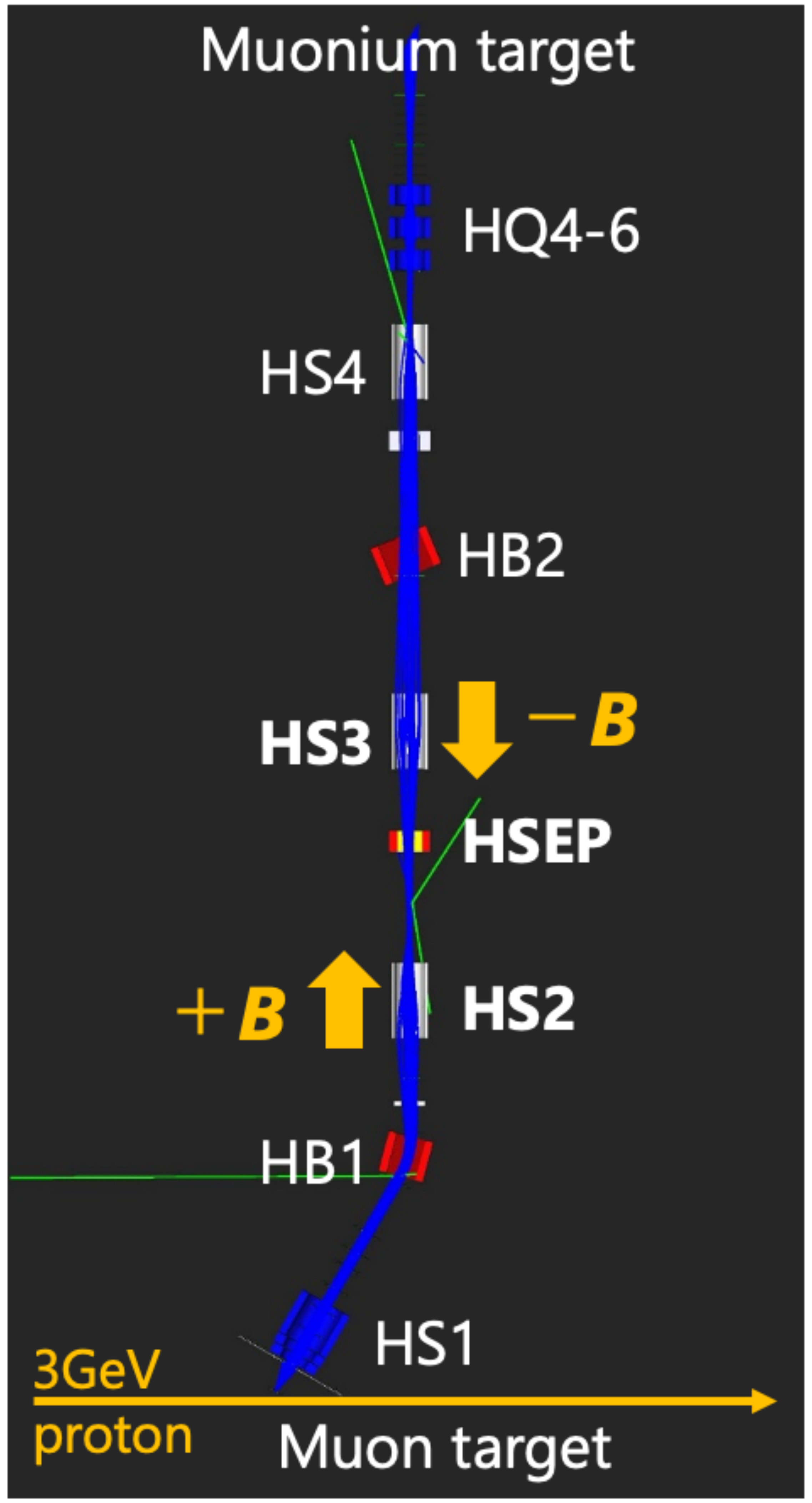


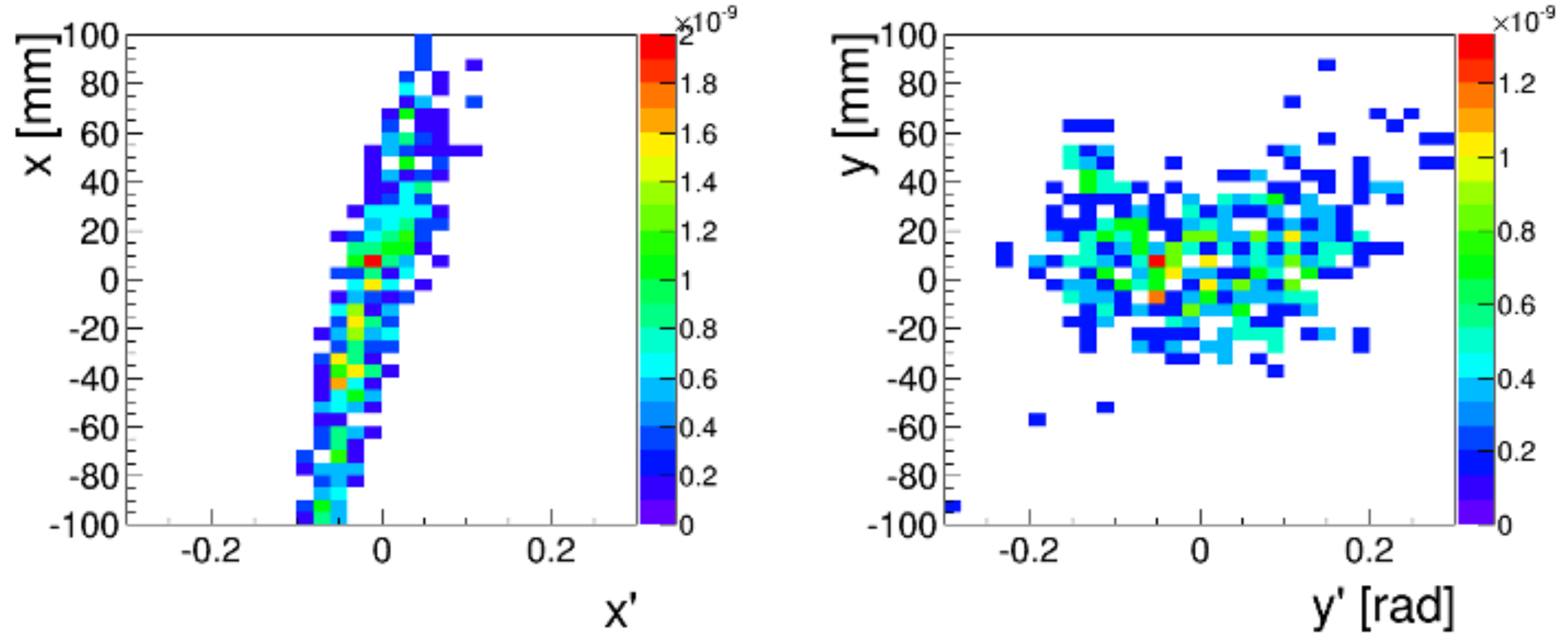
③ Beam profile measurement

- Beam commissioning is ongoing at the **H1 area.**
- Construction of the **H2 area** is in progress.
- **The extension building** design is ready to start construction.

H-line surface muon optics







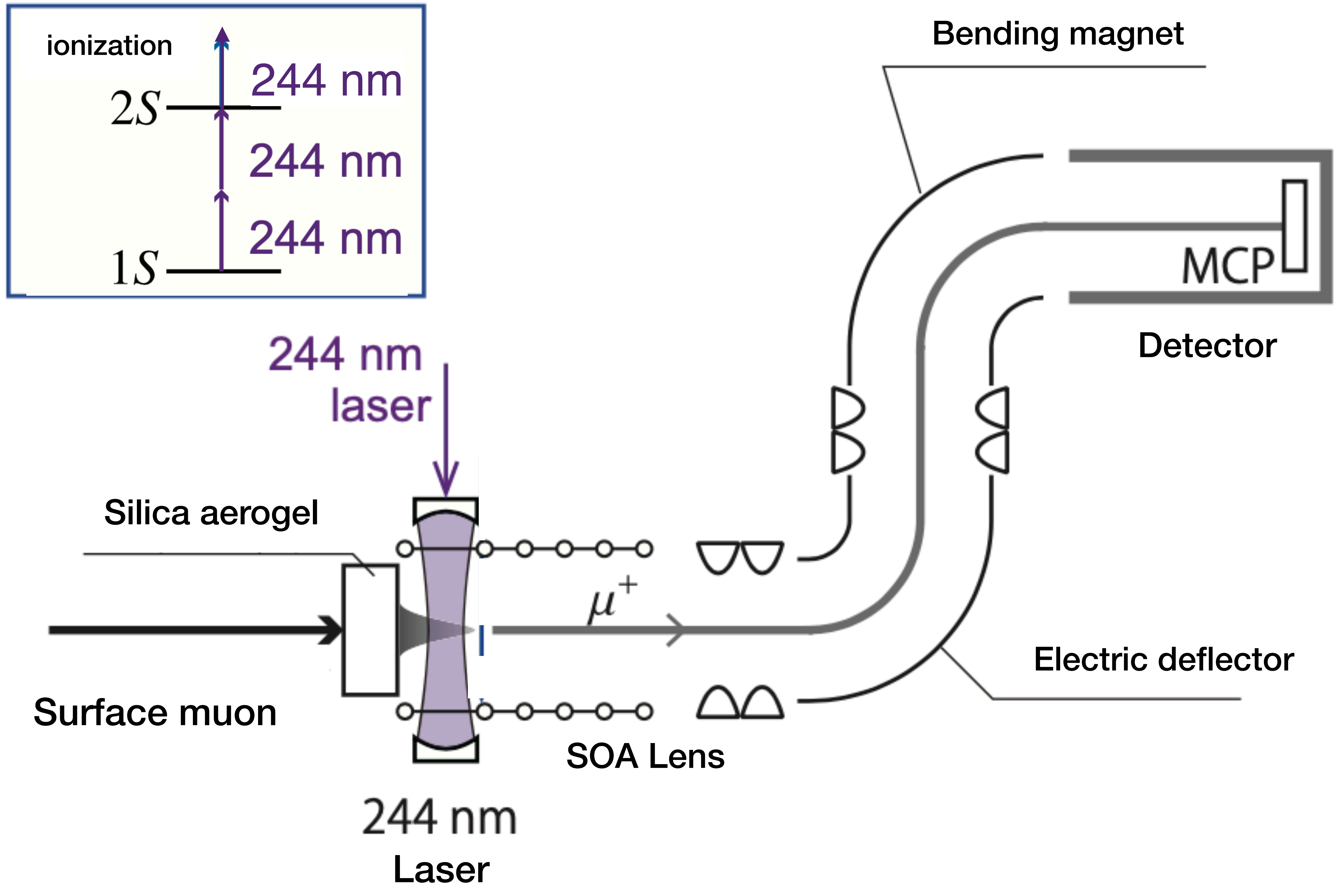
Simulated beam profile at H2 area entrance

- The beam-line consist of solenoids ("HS"), bending magnets ("HB"), DC separator ("HSEP"), quadruples ("HQ"), etc.
- Beam-line optics was tuned to deliver 1.6×10^8 surface μ/s at the muonium production target under a 1MW proton beam power.

Thermal muon source

Muonium (Mu) laser ionization test

- The quick demonstration of thermal muon generation via laser ionization of muonium from silica aerogel at the J-PARC MLF S2 area



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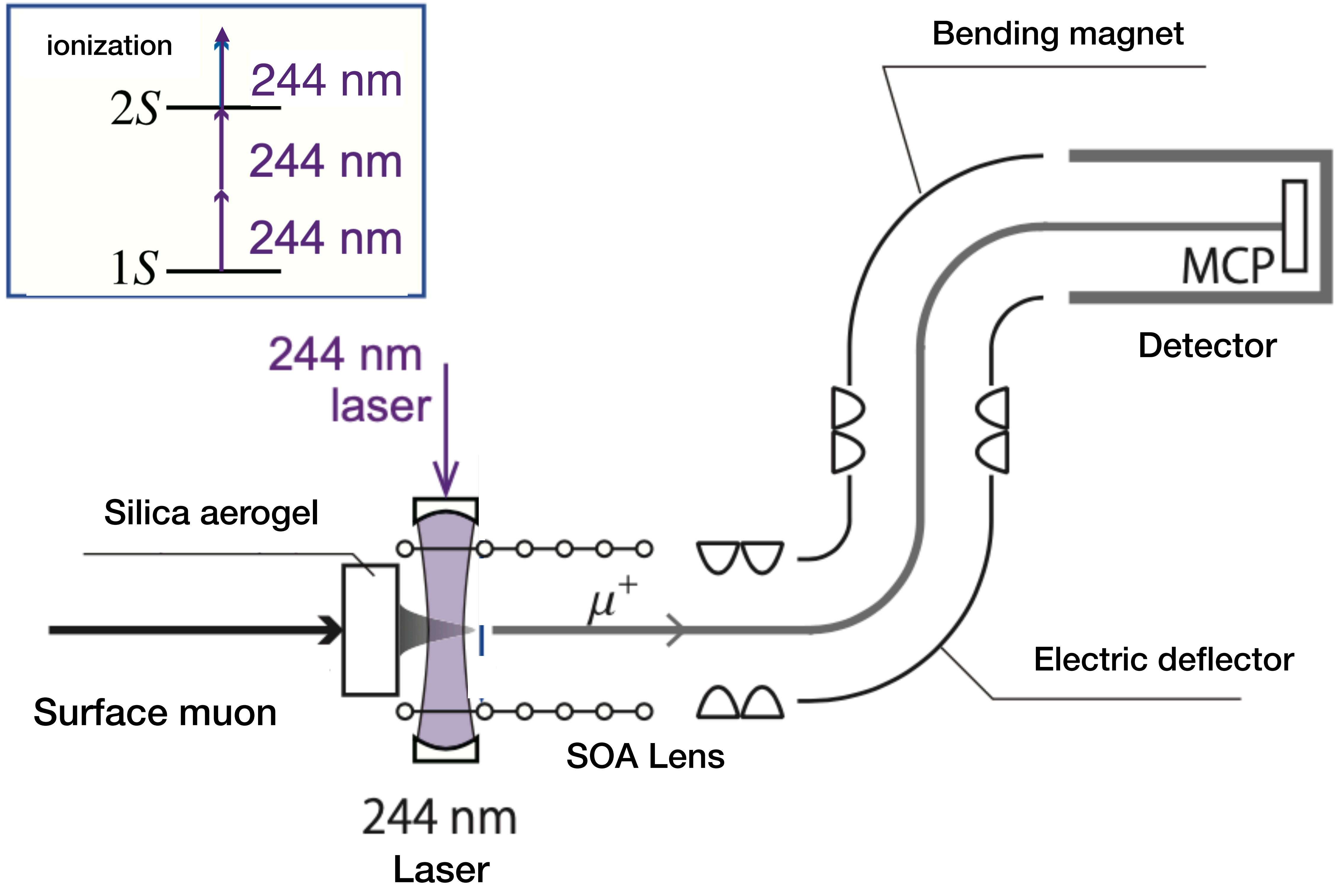


$$\Delta\nu_{1S2S} \simeq \frac{3\alpha^2}{8h} m_e c^2 (1 + \frac{m_e}{m_\mu})^{-1}$$

- With the 244 nm laser, It is also a direct measurement of Mu 1S-2S interval → **determination of muon mass**

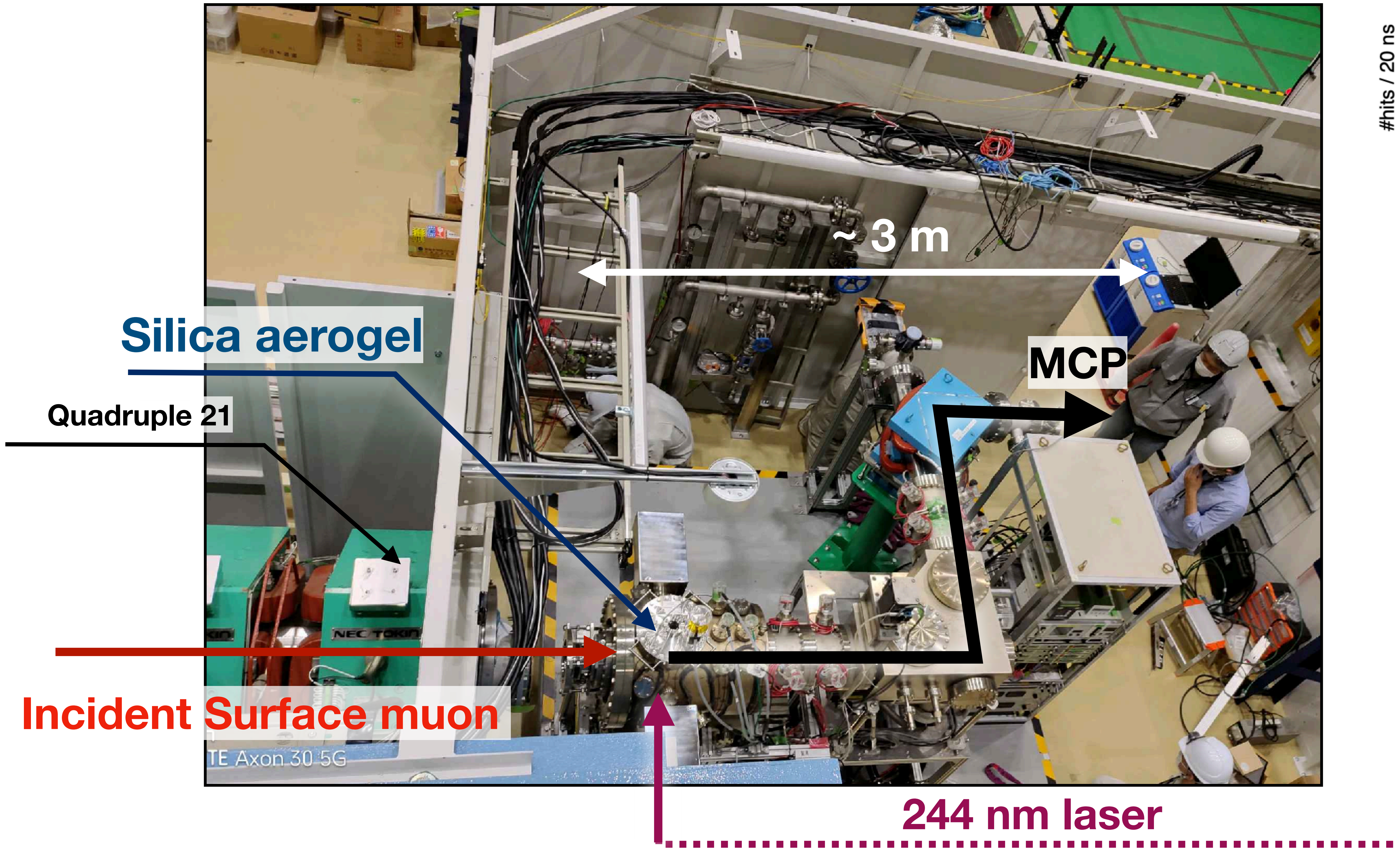
  (Similar to Mu-MASS at PSI)

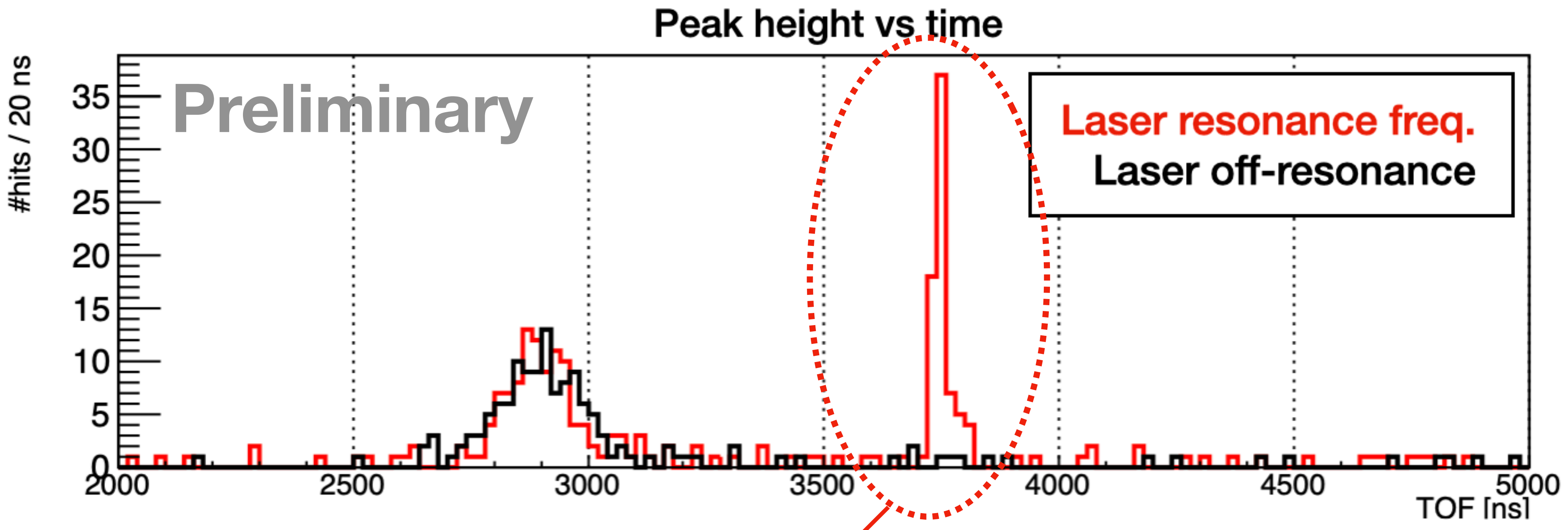
- **Final goal:**
  - Muon mass: 1 ppb
  - (1S-2S: 10 kHz, 4 ppt)

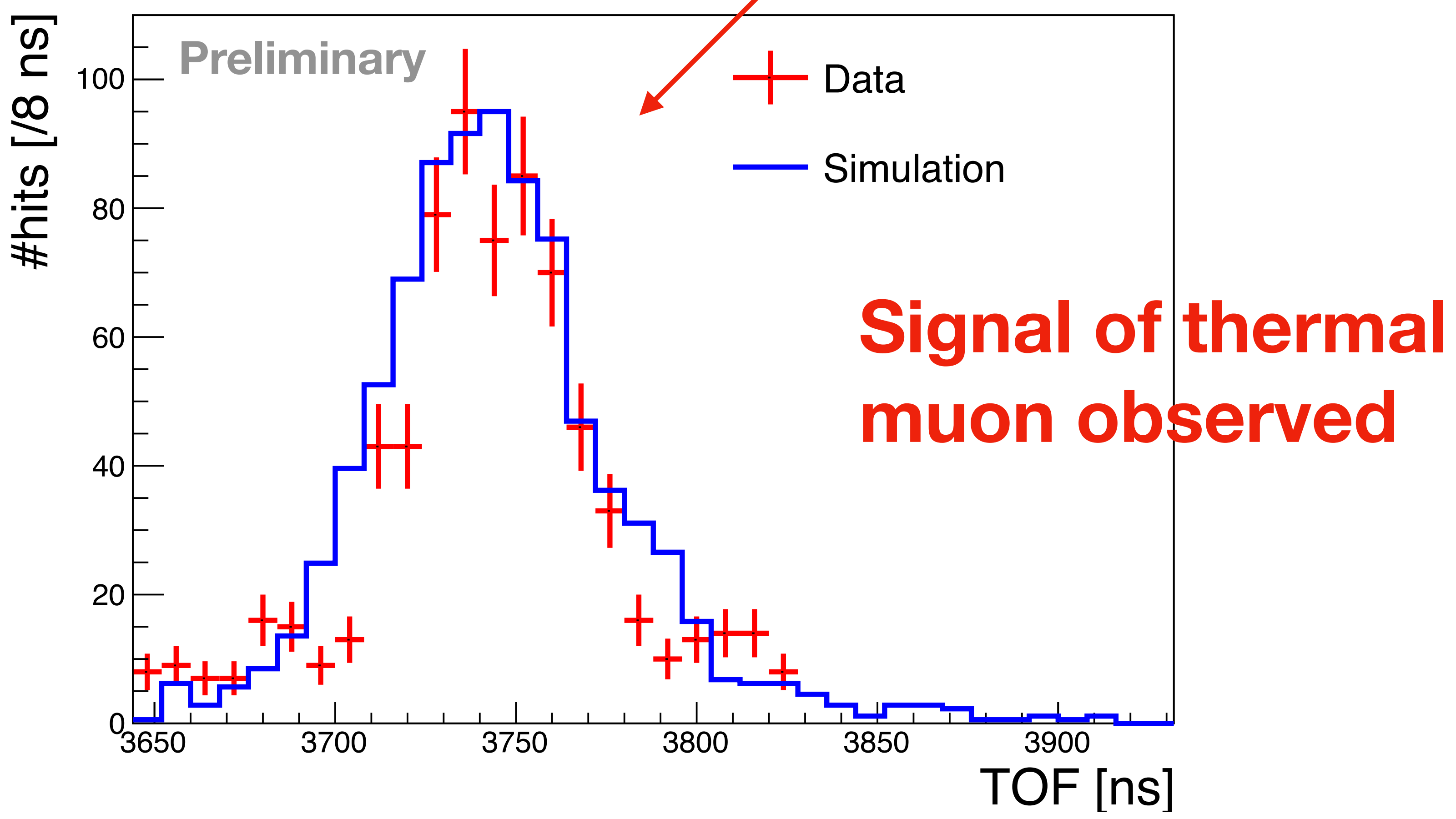
Thermal muon source

Muonium (Mu) laser ionization test

- The quick demonstration of thermal muon generation via laser ionization of muonium from silica aerogel at the J-PARC MLF S2 area



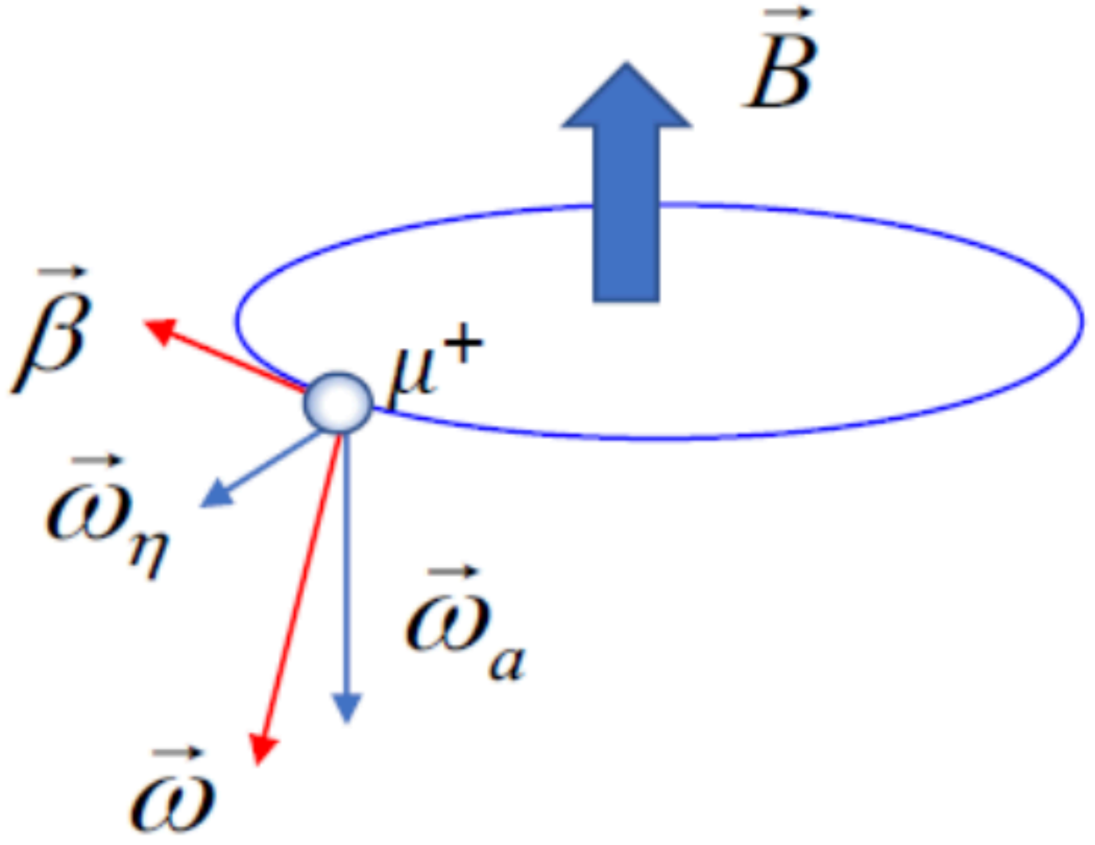


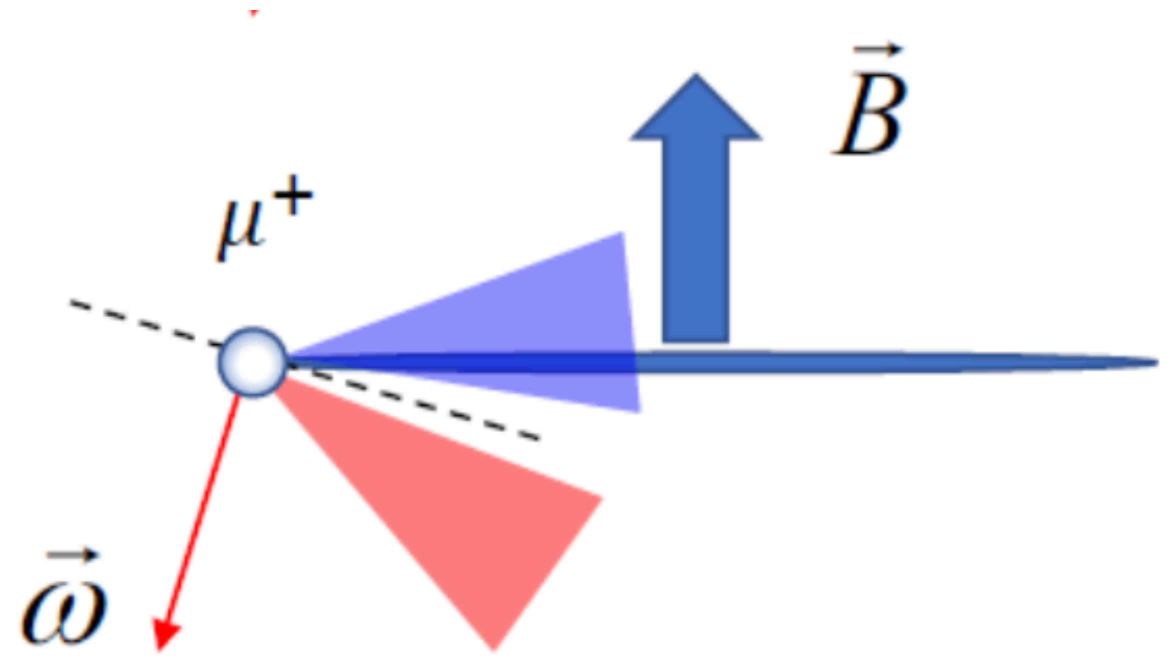


Signal of thermal muon observed

EDM measurement

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





- No E-field simplifies the measurement for J-PARC.

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

FNAL E989

(at magic γ)

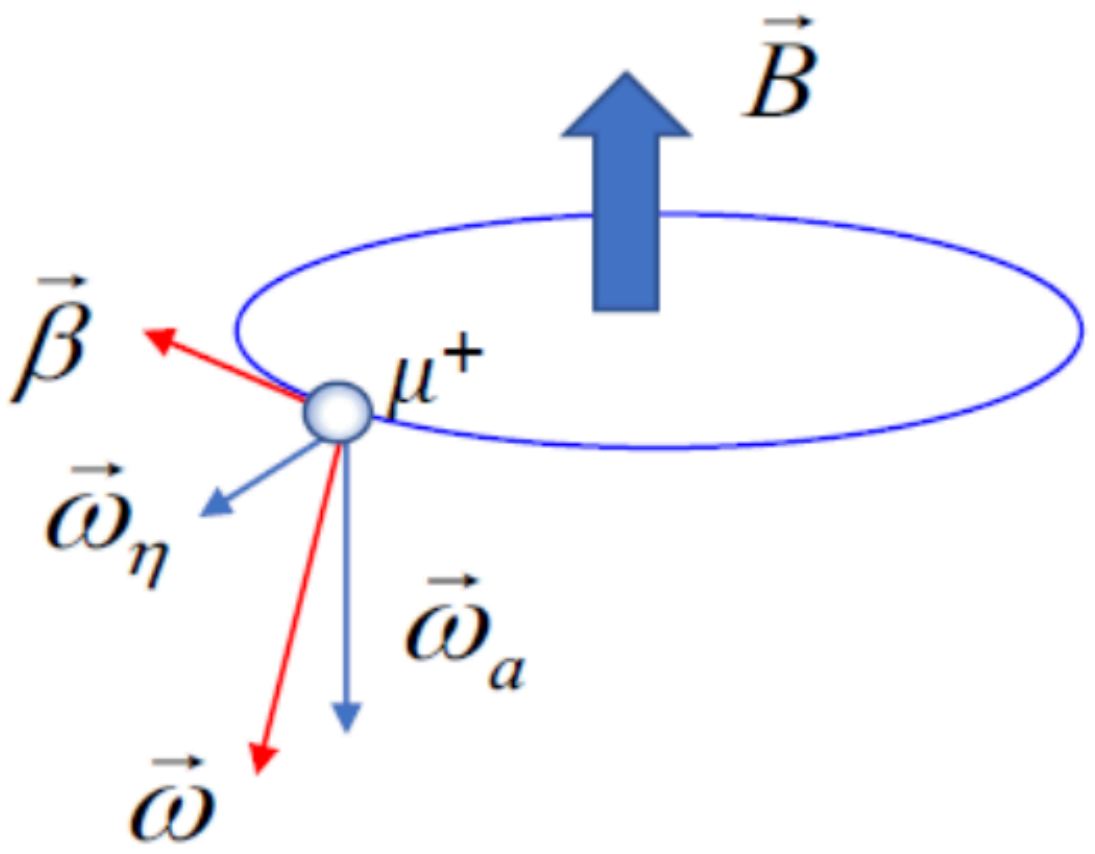
$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right]$$

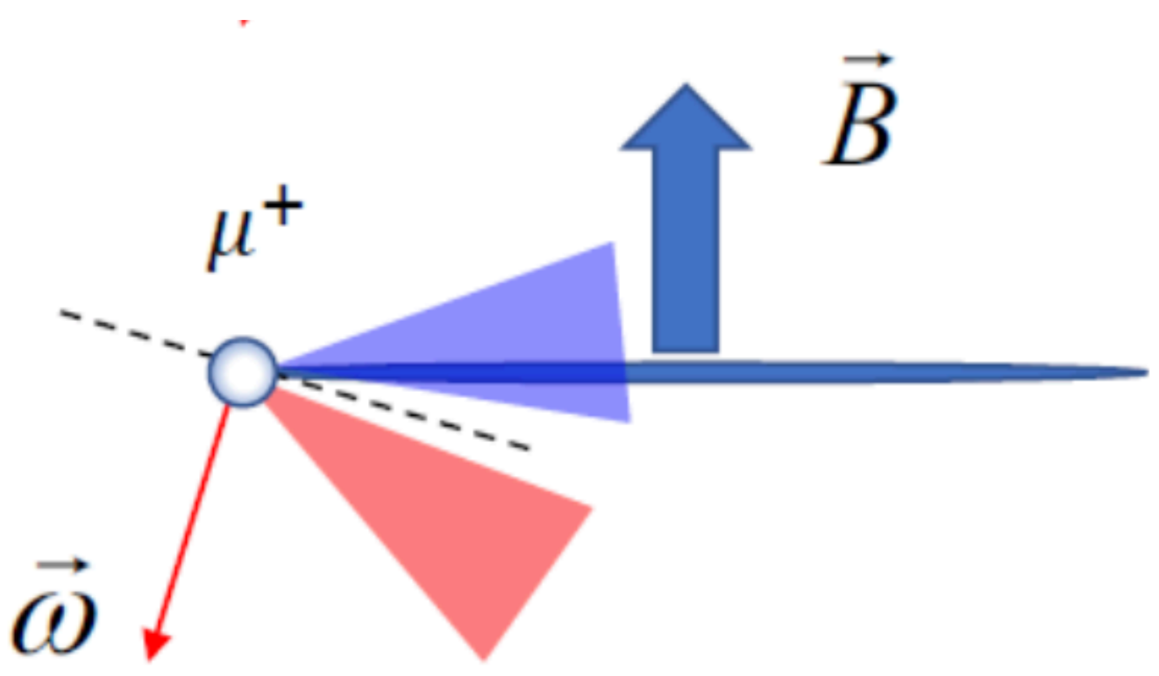
J-PARC E34

(E = 0 at any γ)

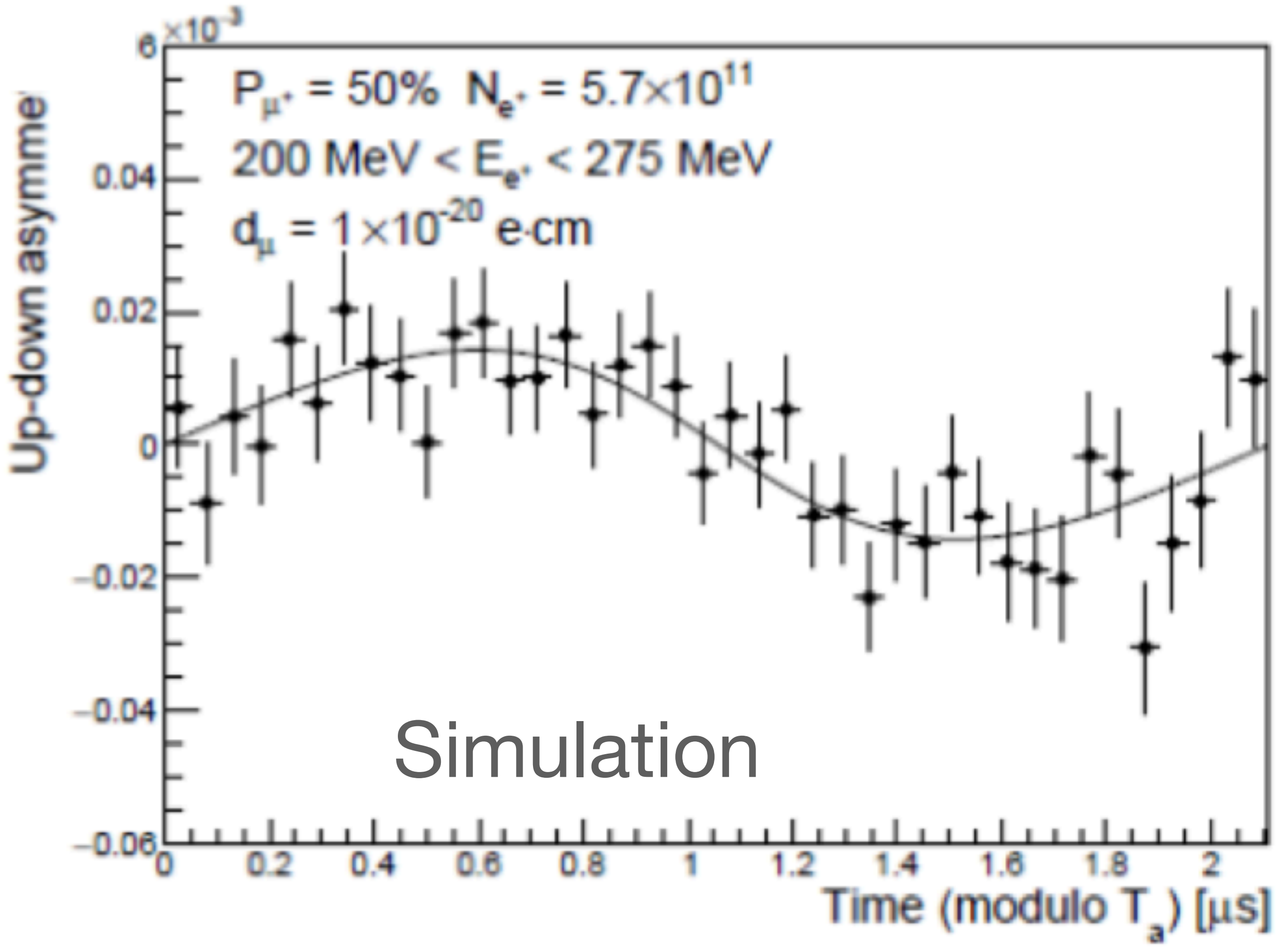
EDM measurement

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



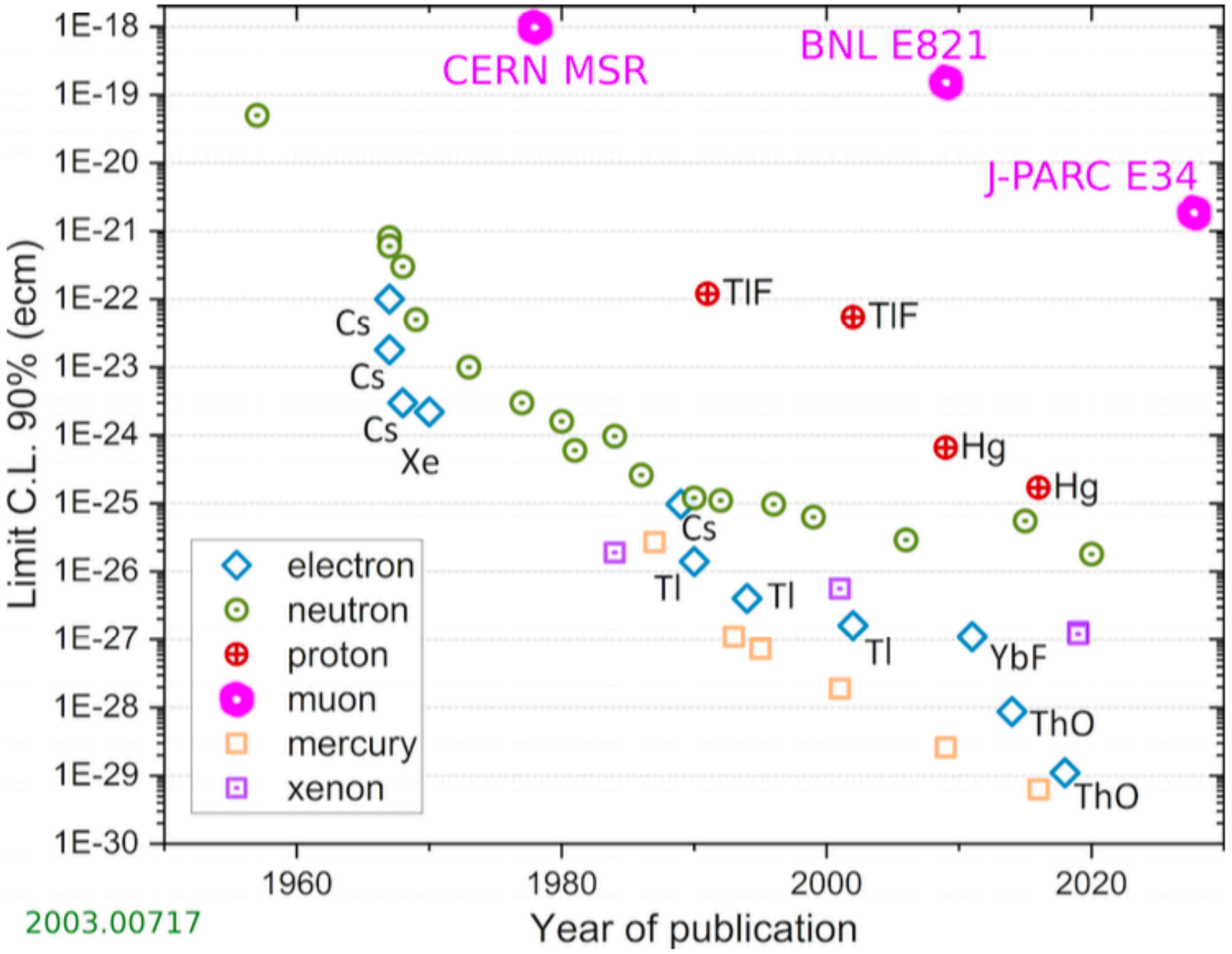


- Observed in up-down asymmetry
- $\omega_\eta/\omega_a \sim(\eta\beta/2a_\mu)$
- Good detector alignment precision is essential
- aim at 10^{-21} e cm sensitivity (10^{-5} rad)
- 1 μm detector alignment measurement is developed



EDM measurement

- The muon EDM SM expectation is ~ 2×10^{-38} e cm
- The current experimental limit is 1.8×10^{-19} e cm by the BNL E821.

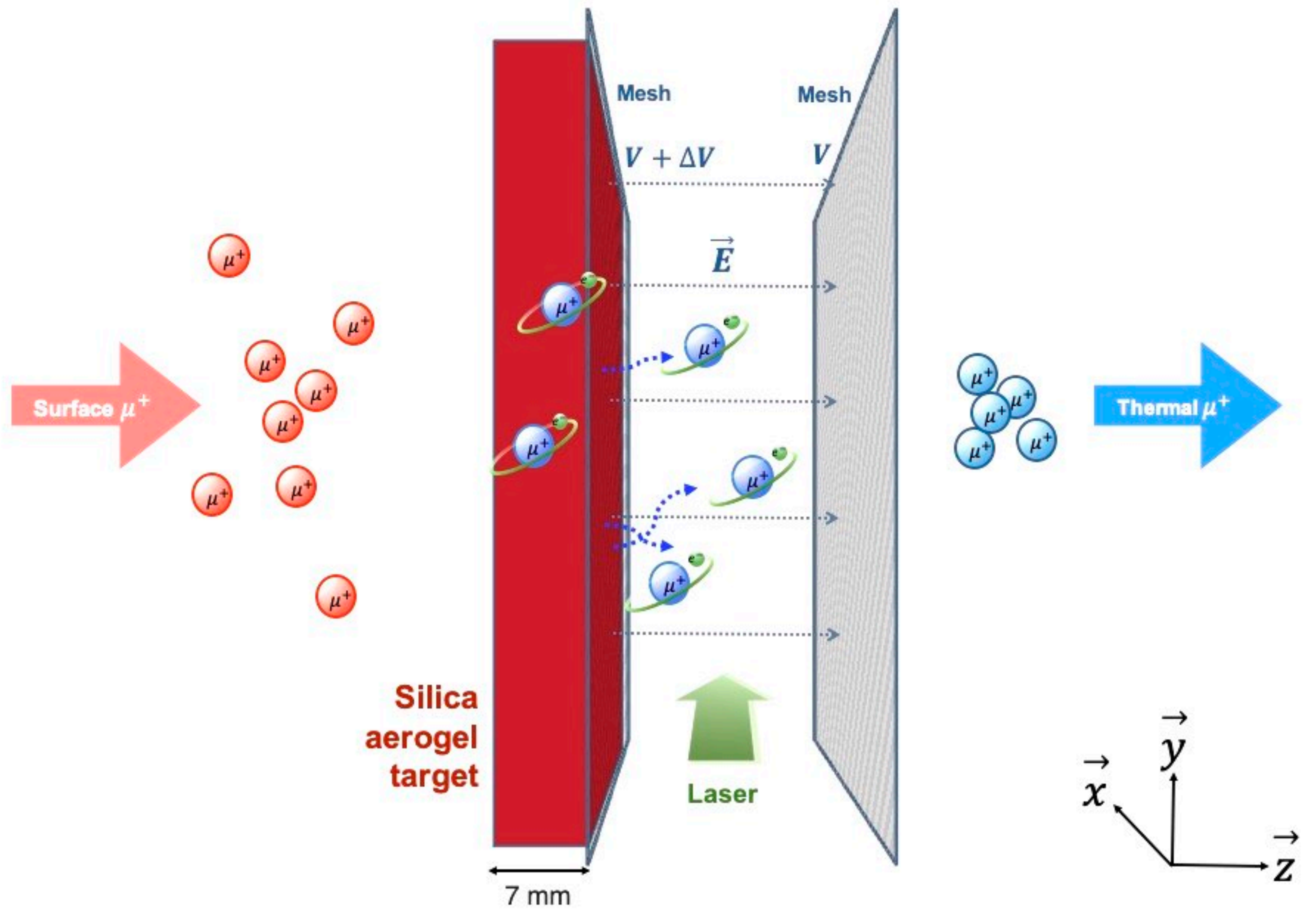


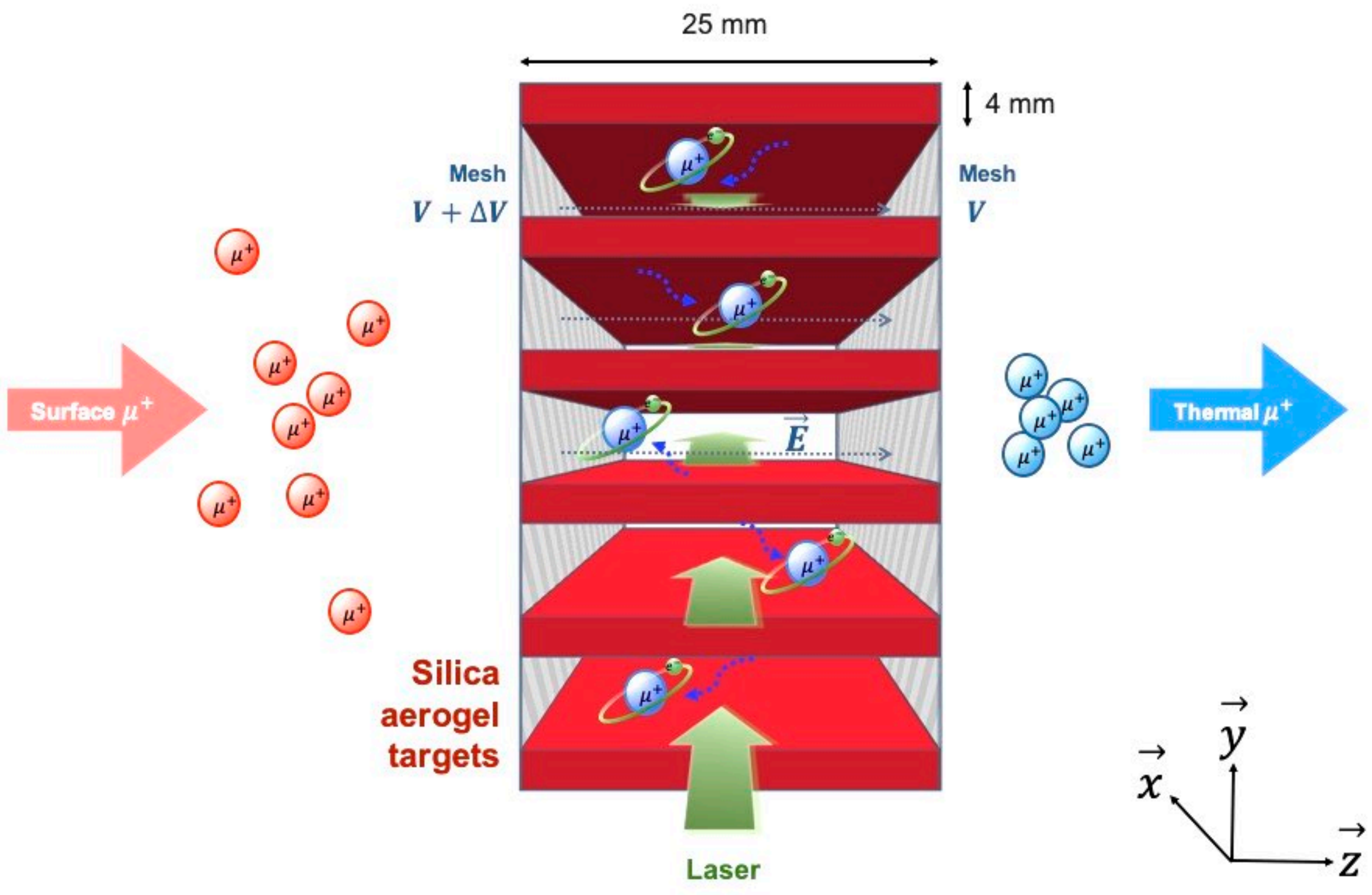
Precision comparison

J-PARC E34

	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 (Phase-1)
(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

Novel design of multi-layer target





Current design (single-layer)

- **Mu emission efficiency (0.0034):**
  - Muon stopping (0.418)
  - Mu formation (0.52)
  - Vacuum emission (0.060)
  - Laser spatial constraint (0.269)

Novel multi-layer target design

- Multi-layer targets stop incident muon
- Mu emits from upper and lower surfaces
- Mu confined between targets
- The extraction direction is the same as the incident beam