Next-generation measurement of Muon g-2 and EDM with Low-Emittance Muon Beam at J-PARC

Sep 9, 2019
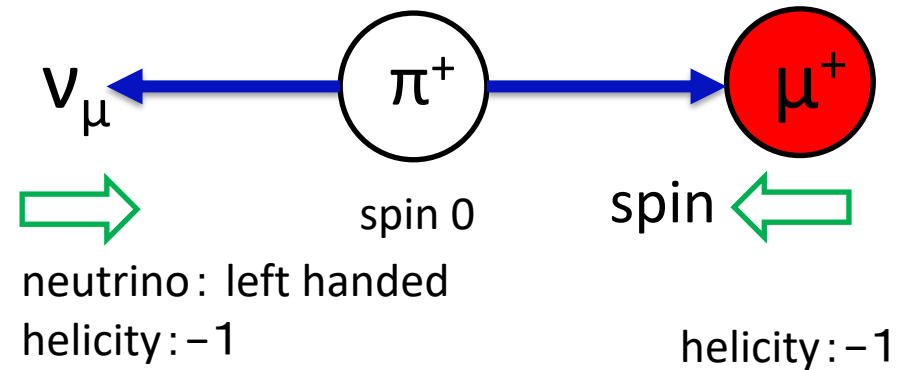
Tsutomu Mibe (KEK)

www.g-2.kek.jp
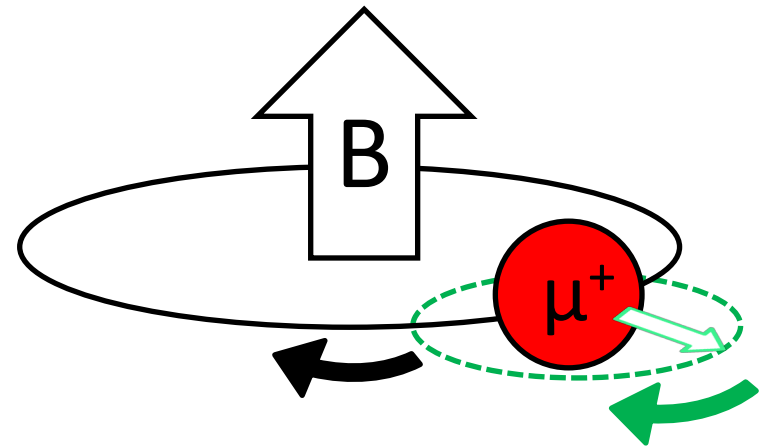
Three steps of g-2 measurement

1. Prepare a polarized muon beam.

ν_μ π^+ μ^+

spin 0

spin

neutrino : left handed
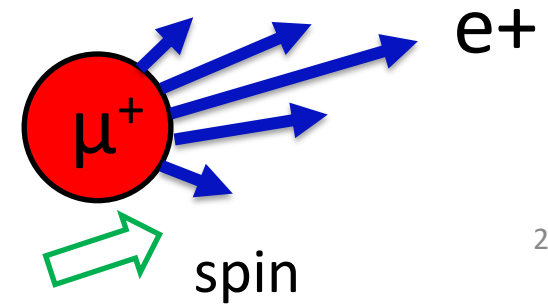helicity : -1

helicity : -1

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

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

B

μ^+

3. Measure decay positron

μ^+ e+

spin

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
$\Delta p/p$	0.05	0.4	4×10^{-4}

μ^+

Mu
$(\mu^+ e^-)$

μ^+

H-line

Mu production target

Electrodes(Soa)

LINAC

Ionization Laser
(122 nm, 355 nm)

Muon g-2/EDM experiment at J-PARC

Proton beam (3 GeV)

Surface muon (4 MeV)

Ultra-slow muon (25 meV)

Reaccelerated muon (212 MeV)

MLF muon experimental facility (H-line)

Thermal muonium production, Ionization laser

Muon LINAC

3D spiral injection

Muon storage magnet (3 T)

Positron tracking detector
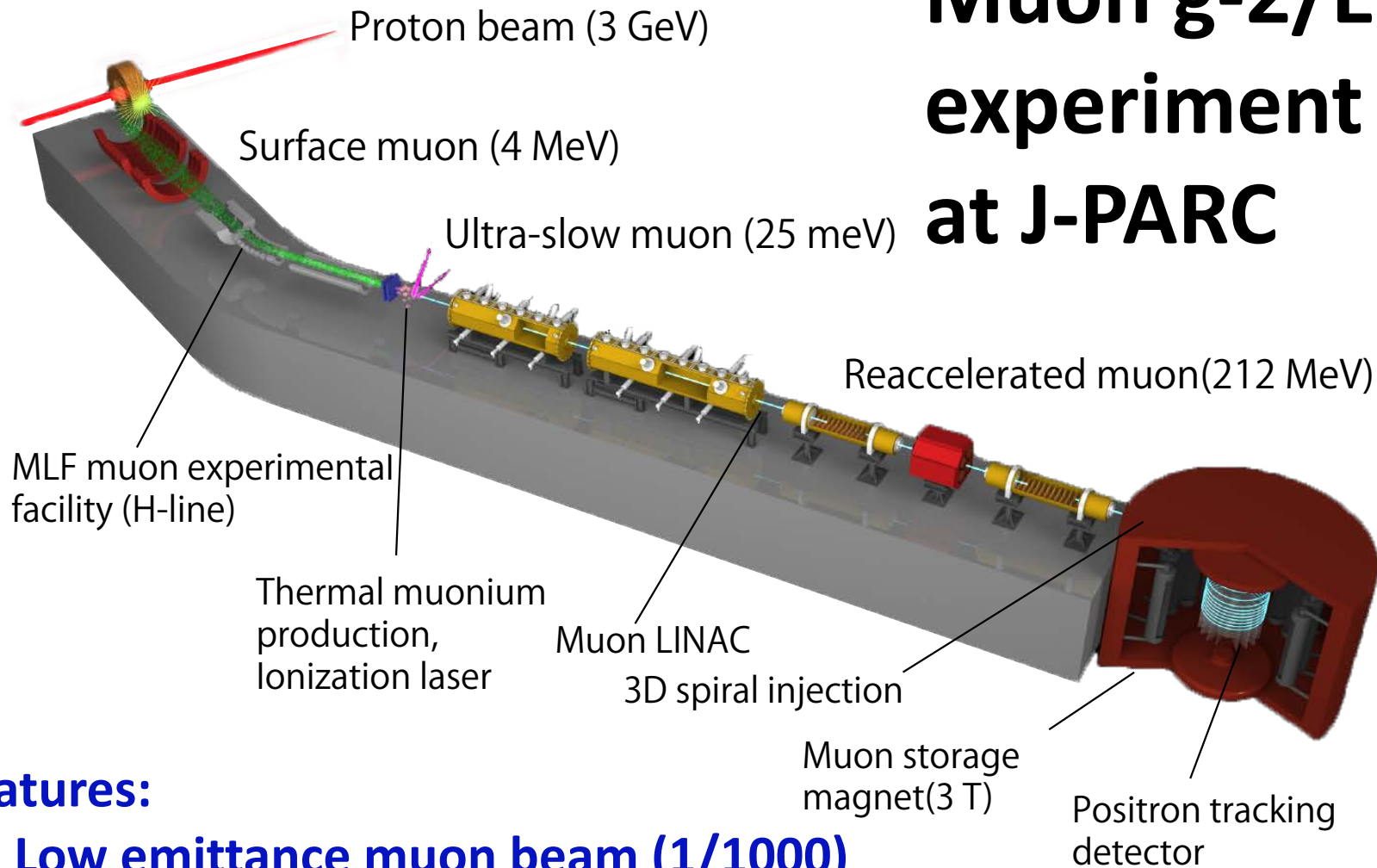
Features:

- **Low emittance muon beam (1/1000)**
- **No strong focusing (1/1000) & good injection eff. (x10)**
- **Compact storage ring (1/20)**
- **Tracking detector with large acceptance**
- **Completely different from BNL/FNAL method**

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muon g-2 and EDM measurements

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

$$\omega_a = \frac{e}{m} a_\mu B$$

general form of spin precession vector:

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} + \frac{\eta}{2} \left(\vec{\beta} \times \vec{B} + \frac{\vec{E}}{c} \right) \right]$$
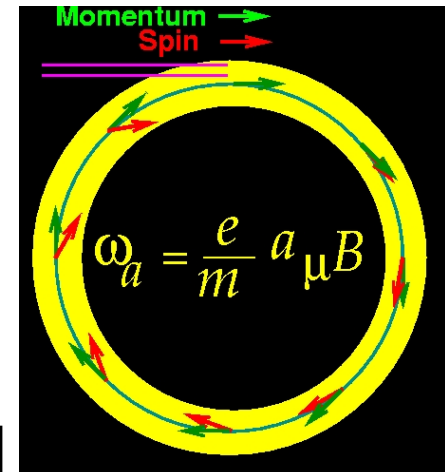
BNL E821 approach
γ=30 (P=3 GeV/c)

J-PARC approach
E = 0 at any γ

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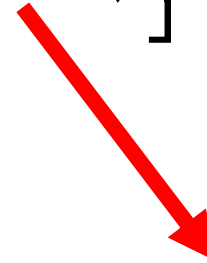
$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2} \left(\vec{\beta} \times \vec{B} \right) \right]$$

FNAL E989

J-PARC E34

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Expected results

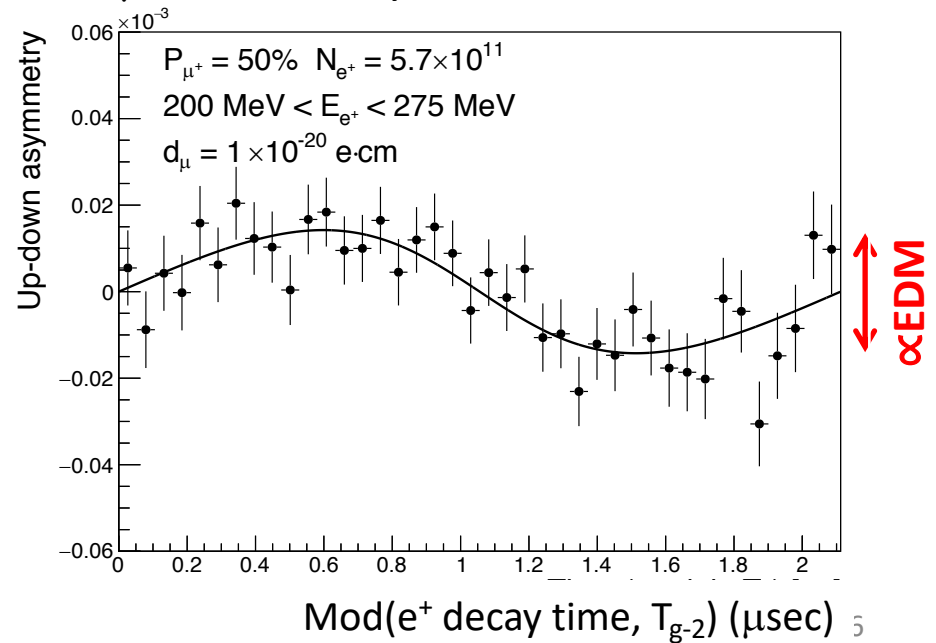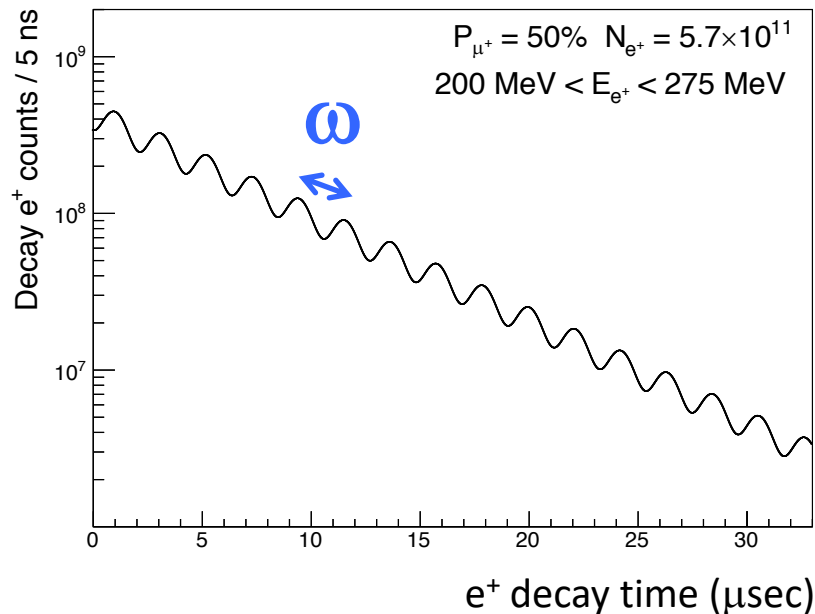$$\vec{\omega} = -\frac{e}{m}\left[a_{\mu}\vec{B} + \frac{\eta}{2}\left(\vec{\beta} \times \vec{B}\right)\right]$$
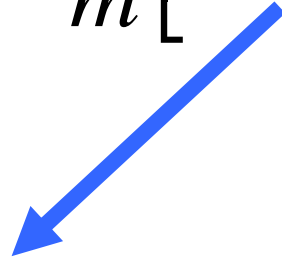
Expected time spectrum of e^+ in $\mu \rightarrow e^+\nu\nu$ decay

The first collaboration paper on experimental design

A new approach for measuring the muon anomalous magnetic moment and electric dipole moment

M. Abe[1], S. Bae[2,3], G. Beer[4], G. Bunce[5], H. Choi[2,3], S. Choi[2,3], M. Chung[6], W. da Silva[7], S. Eidelman[8,9,10], M. Finger[11], Y. Fukao[1], T. Fukuyama[12], S. Haciomeroglu[13], K. Hasegawa[14], K. Hayasaka[15], N. Hayashizaki[16], H. Hisamatsu[1], T. Iijima[17], H. Iinuma[18], H. Ikeda[19], M. Ikeno[1], K. Inami[17], K. Ishida[20], T. Itahashi[21], M. Iwasaki[20], Y. Iwashita[22], Y. Iwata[23], R. Kadono[1], S. Kamal[24], T. Kamitani[1], S. Kanda[20], F. Kapusta[7], K. Kawagoe[25], N. Kawamura[1], B. Kim[2,3], Y. Kim[26], T. Kishishita[1], R. Kitamura[14], H. Ko[2,3], T. Kohriki[1], Y. Kondo[14], T. Kume[1], M. J. Lee[13], S. Lee[13], W. Lee[27], G. M. Marshall[28], Y. Matsuda[29], T. Mibe[1,30], Y. Miyake[1], T. Murakami[1], K. Nagamine[1], H. Nakayama[1], S. Nishimura[1], D. Nomura[1], T. Ogitsu[1], S. Ohsawa[1], K. Oide[1], Y. Oishi[1], S. Okada[20], A. Olin[4,28], Z. Omarov[26], M. Otani[1], G. Razuvaev[8,9], A. Rehman[30], N. Saito[1,31], N. F. Saito[20], K. Sasaki[1], O. Sasaki[1], N. Sato[1], Y. Sato[1], Y. K. Semertzidis[26], H. Sendai[1], Y. Shatunov[32], K. Shimomura[1], M. Shoji[1], B. Shwartz[9,32], P. Strasser[1], Y. Sue[17], T. Suehara[25], C. Sung[6], K. Suzuki[17], T. Takatomi[1], M. Tanaka[1], J. Tojo[25], Y. Tsutsumi[25], T. Uchida[1], K. Ueno[1], S. Wada[20], E. Won[27], H. Yamaguchi[1], T. Yamanaka[25], A. Yamamoto[1], T. Yamazaki[1], H. Yasuda[33], M. Yoshida[1], and T. Yoshioka[25,*]

7

Comparison of g-2 experiments

	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 J-PARC g-2/EDM collaboration

116 members (Canada , China, Czech,
France, Japan, Korea, Russia, USA)

Collaboration Meeting on J–PARC Muon g–2/EDM

Seoul National University, June 24-27, 2019
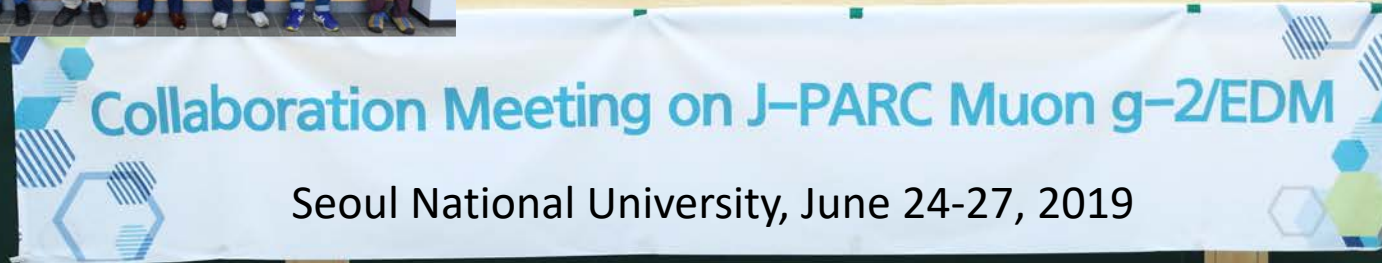
History

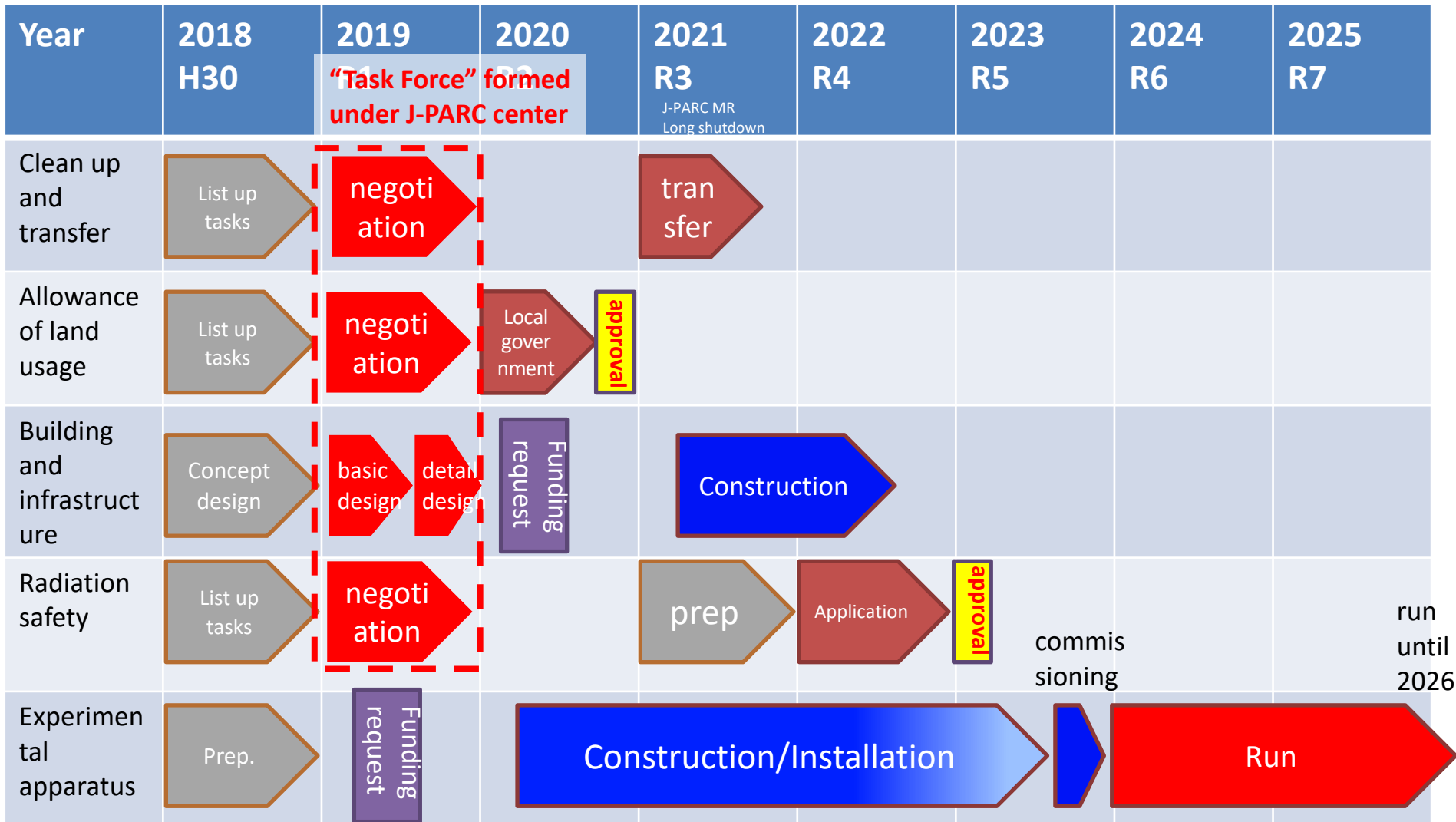| Date	Events
July, 2009	LOI submitted to PAC8
Jan, 2010	Proposal submitted to PAC9
Jan, 2012	CDR submitted to PAC13, Milestones defined.
July, 2012	Stage-1 status recommended by PAC15 Stage-1 status granted by the IPNS director
May, 2015	TDR submitted to PAC
Oct, 2016	Revised TDR submitted to PAC and FRC
June, 2016	**Selected as a KEK-PIP priority project**
Nov, 2016	Focused review on technical design
Dec, 2017	Responses and Revised TDR submitted to PAC
July, 2018 **Nov, 2018**	Stage-2 status recommended by IPNS-PAC **Stage-2 status granted by the IPNS director**
Jan, 2019 **Mar, 2019**	Stage-2 status recommended by IMSS-PAC **Stage-2 status granted by the IMSS director** **KEK-SAC endorsed the E34 for the near-term priority**
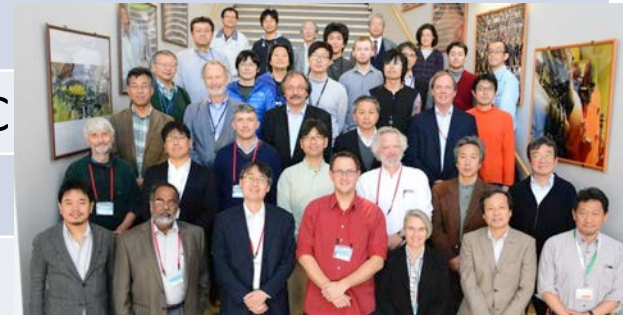
KEK Science Advisory Committee
(Mar 23-24, 2019)

The SAC strongly endorses KEK's decision on near-term priorities (the muon g-2/EDM experiment, the upgrade of the J-PARC Hadron Hall, and the upgrade of the Photon Factory), and the updated KEK roadmap. The KEK leadership should be congratulated for establishing outstanding near- and longer-term strategies and for producing the implementation plan. Specific comments and/or recommendations are discussed in Chapters 3 and 4.

Intended global schedule

Year	2018 H30	2019	2020	2021 R3	2022 R4	2023 R5	2024 R6	2025 R7
		"Task Force" formed under J-PARC center		J-PARC MR Long shutdown				
Clean up and transfer	List up tasks	negotiation		transfer				
Allowance of land usage	List up tasks	negotiation	Local government → approval					
Building and infrastructure	Concept design	basic design / detail design	Funding request	Construction				
Radiation safety	List up tasks	negotiation		prep / Application → approval		commissioning		run until 2026
Experimental apparatus	Prep.	Funding request	Construction/Installation				Run	

Start taking data

J-PARC Facility

LINAC

3 GeV Synchrotron

Neutrino Beam To Kamioka

Material and Life Science Facility

Main Ring (30 GeV)

Bird's eye photo in Feb. 2008

Beam energy: 3 GeV
Beam power : 1 MW (500 kW as of Jun 2018)
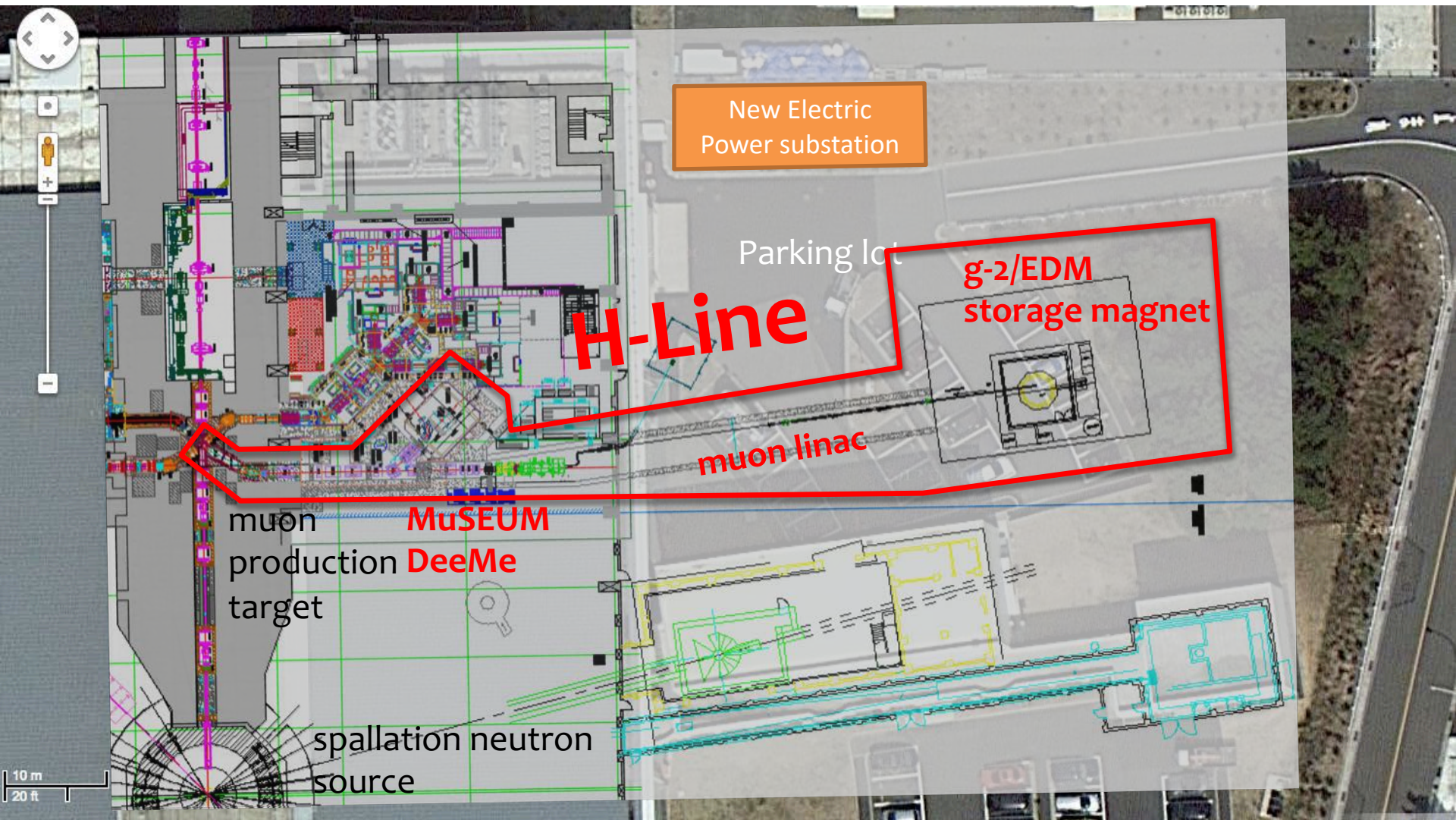Intensity: 2E15 protons/sec
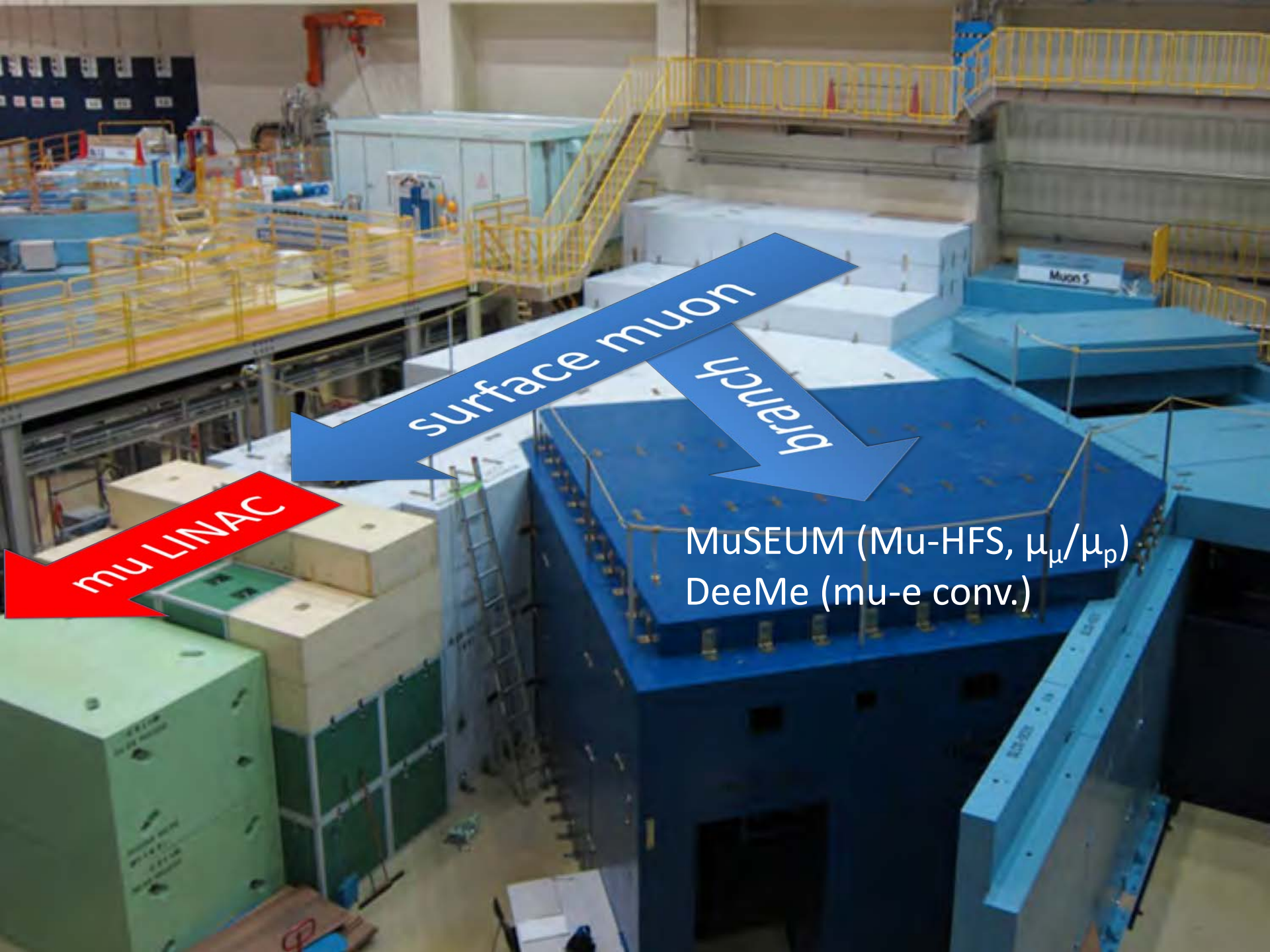Repetition rate: 25 Hz (double bunches)

Beam Power History at MLF
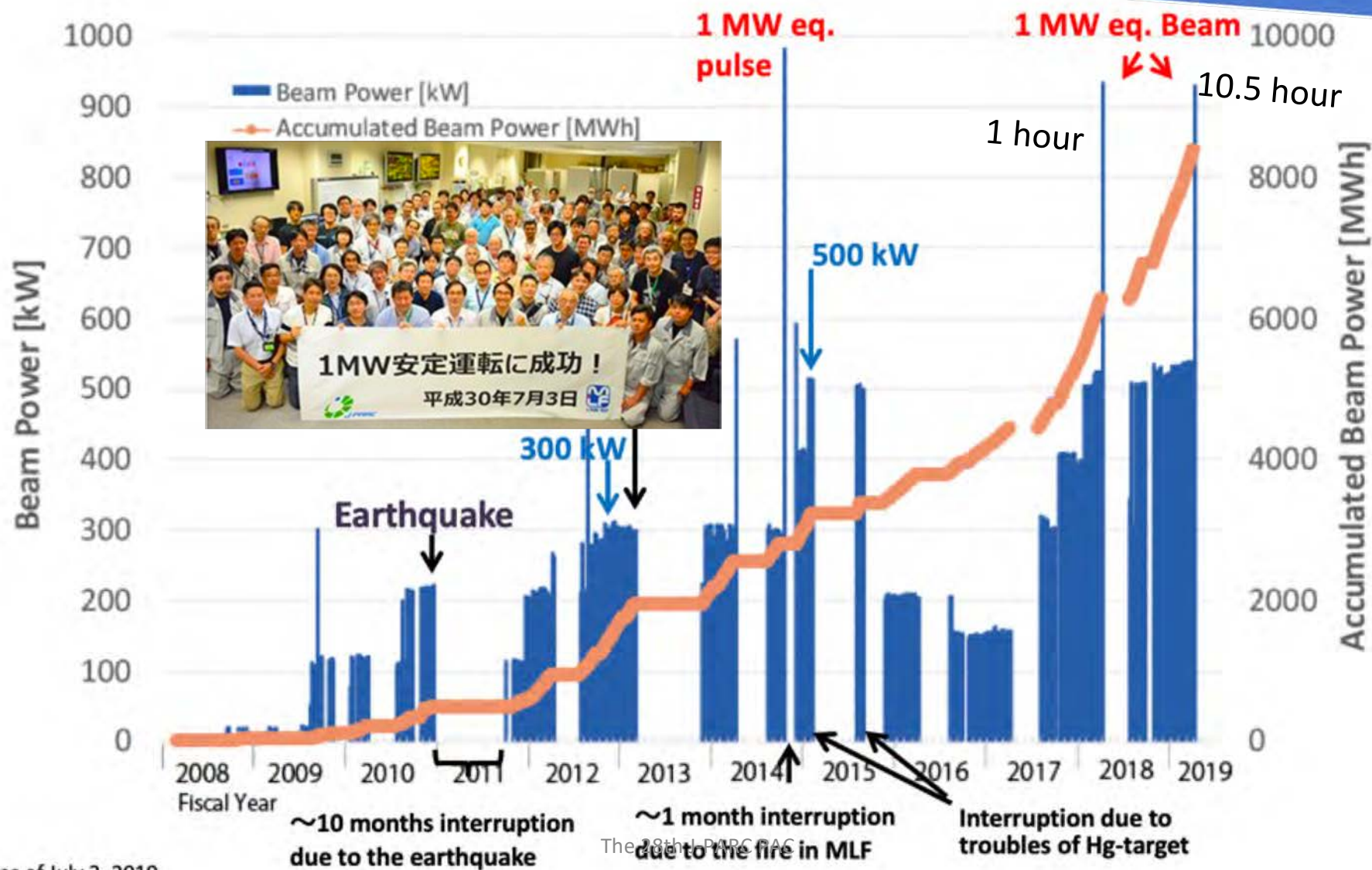
Proposed experimental site (H-line)

Material and Life science Facility in J-PARC

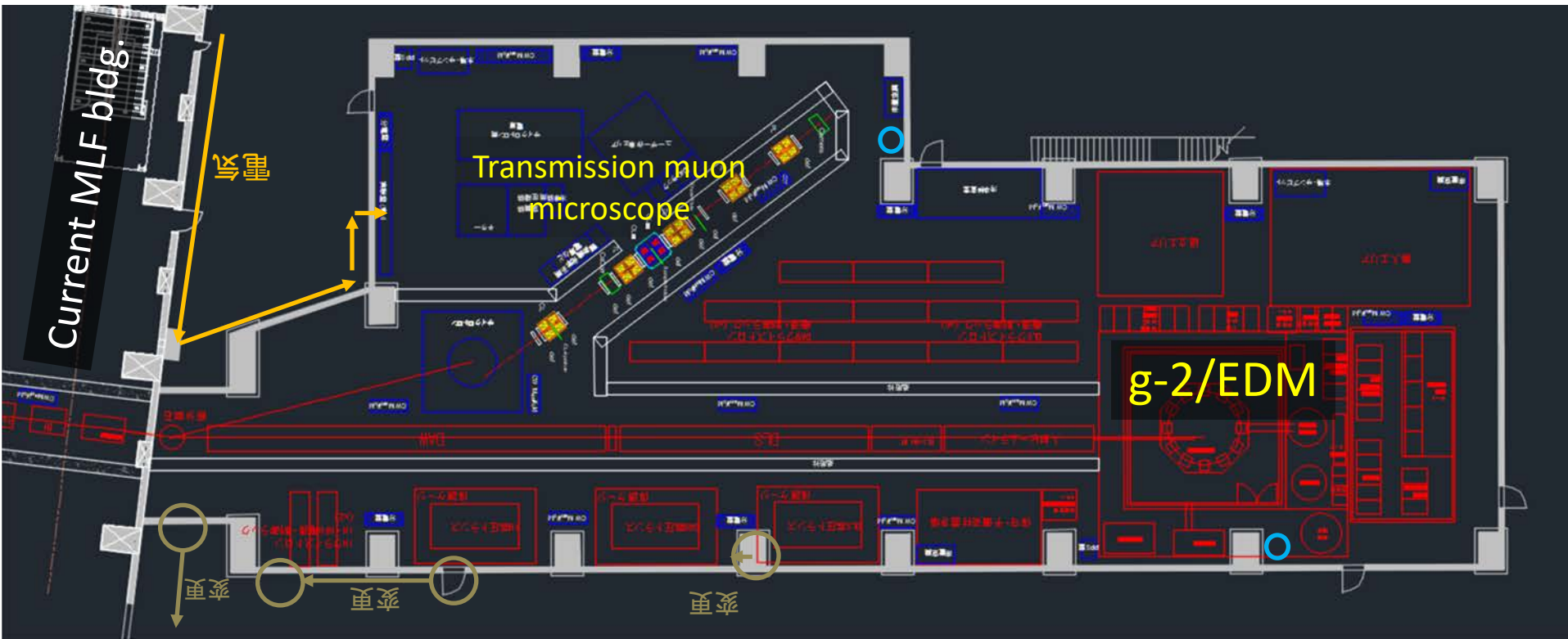**N. Kawamura et al., PTEP 2018, 113G01 (2018)**

surface muon

branch

mu LINAC

MuSEUM (Mu-HFS, μ_μ/μ_p)
DeeMe (mu-e conv.)

New electric power station for H-line under construction

MLF bldg.

Bedding for new power station

Parking lot
(location of the H-line extension bldg. for the g-2/EDM)

Mar 21, 2019

Conceptual design of
the H-line extension building

Work in progress

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
$\Delta p/p$	0.05	0.4	4×10^{-4}

μ^+

Mu
($\mu^+ e^-$)

μ^+

H-line

Mu production
target

Electrodes(Soa)

LINAC

Ionization Laser
(122 nm, 355 nm)
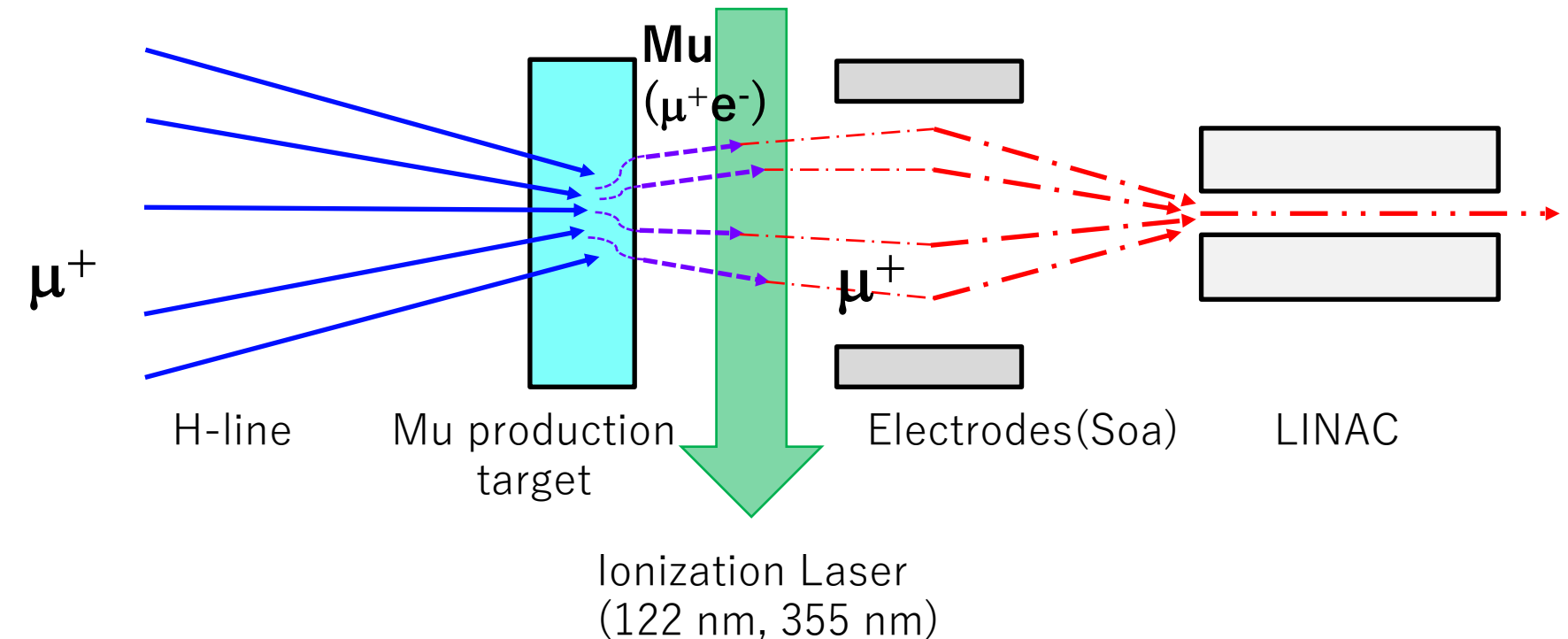
Production of thermal energy muonium

Laser-ablated holes

Silica aerogel
(SiO$_2$, 30 mg/cc)

Muonium
(μ^+e^-)

surface
muon beam

Efficiency (measured)

3 x10^{-3}/μ

(laser region 5mm x 50mm)

Data taken at TRIUMF

8 mm

Region 1
**10 < z < 20 (mm)**

○ no hole
● w/ holes

x 10

陽電子数(∝Muの数)

Time (μs)
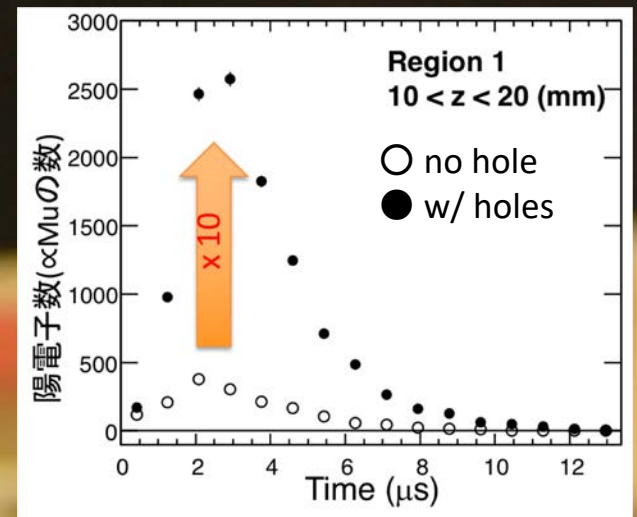
P. Bakule et al., PTEP 103C0 (2013)
G. Beer et al., PTEP 091C01 (2014)

Demonstration of Mu ionization

UBC, RIKEN, KEK, Peking U

- Laser-ablated silica aerogel for the Mu production were prepared. Ablation patterns are same as those studied at TRIUMF in 2017.

- The sample was installed at U-line in May for demonstration of ionizing Mu from silica aerogel.

- Initial tests successfully confirmed ionization of Mu. Detail tuning and systematic studies are planned in forthcoming beamtime at U-line.
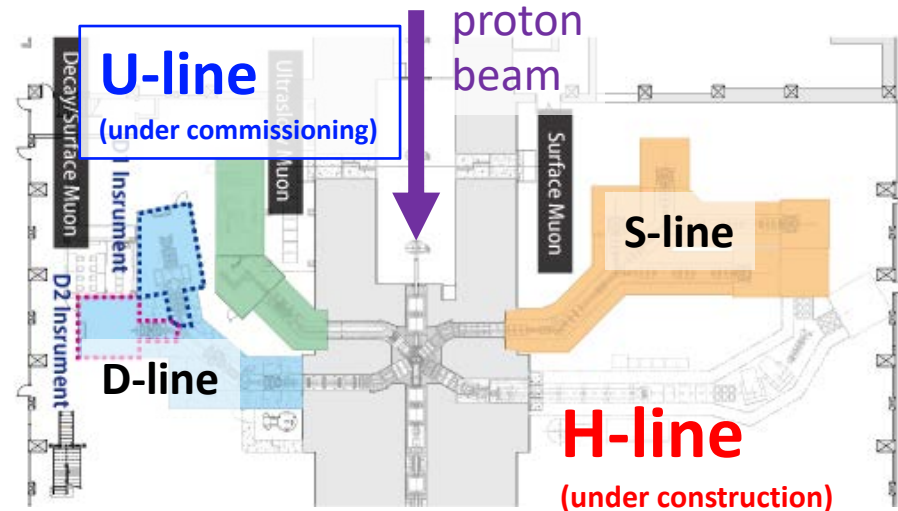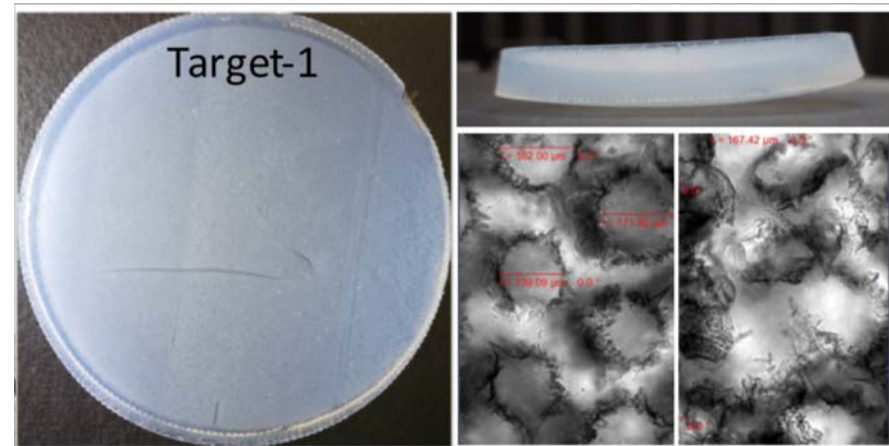
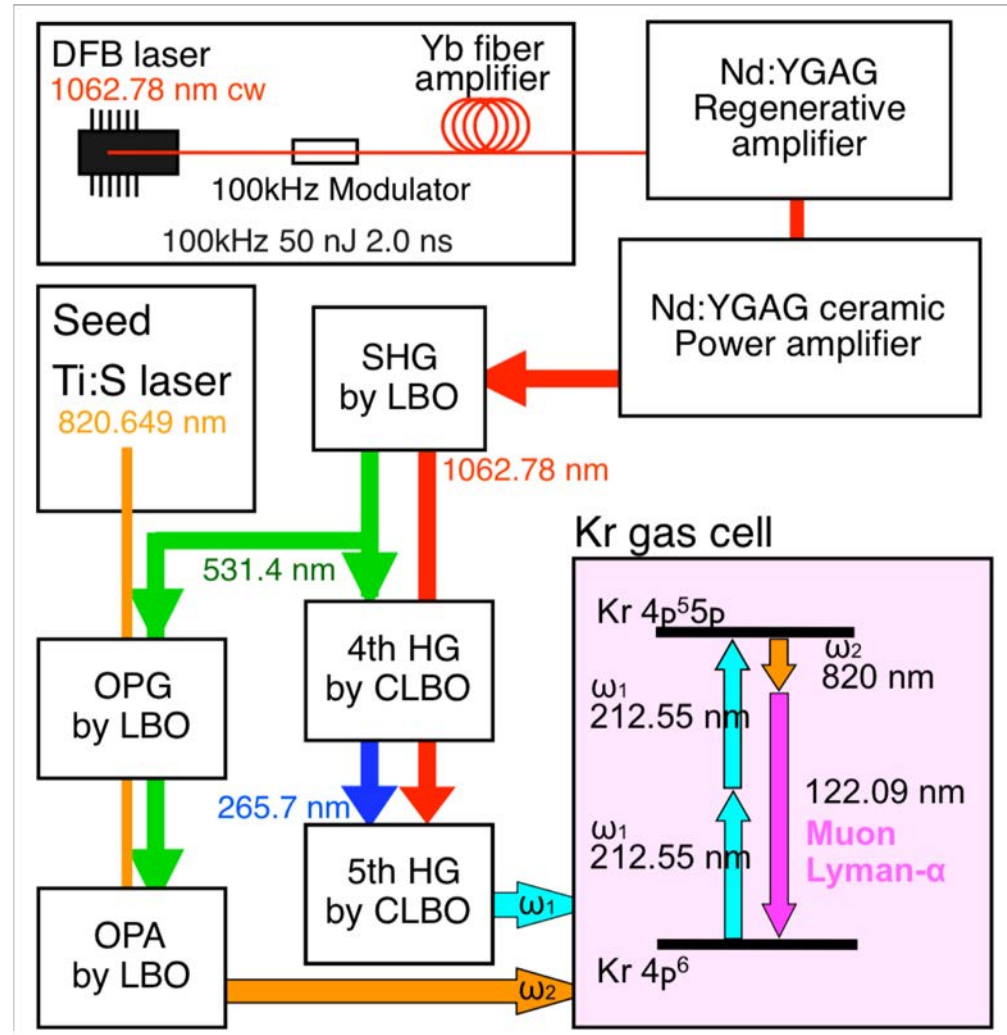# Laser ionization of muonium

1S→2P→unbound
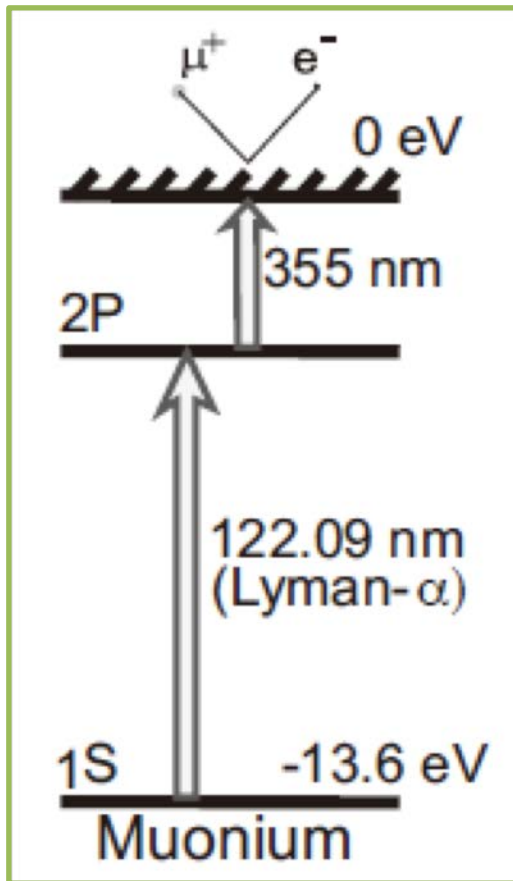
J-PARC MLF U-line laser system（RIKEN+KEK）

efficiency (calculated) 73% @100uJ

Muon LINAC

First step

muon source	RFQ	IH-DTL	DAW	DLS	injection beamline

length		3.2 m	1.4 m	16 m	10 m	
RF		← 324 MHz →		← 1296 MHz →		
E	5.6 keV	0.34 MeV	4.5 MeV	40 MeV	212 MeV	
β	0.01	0.08	0.3	0.7	0.94	
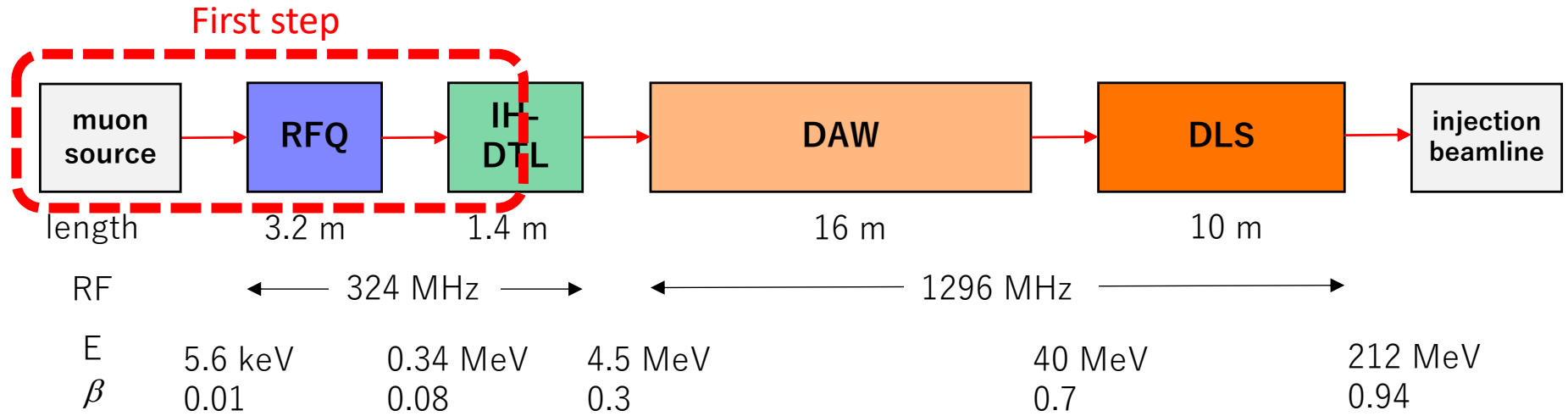
Phase space distributions after muon LINAC (simulation)
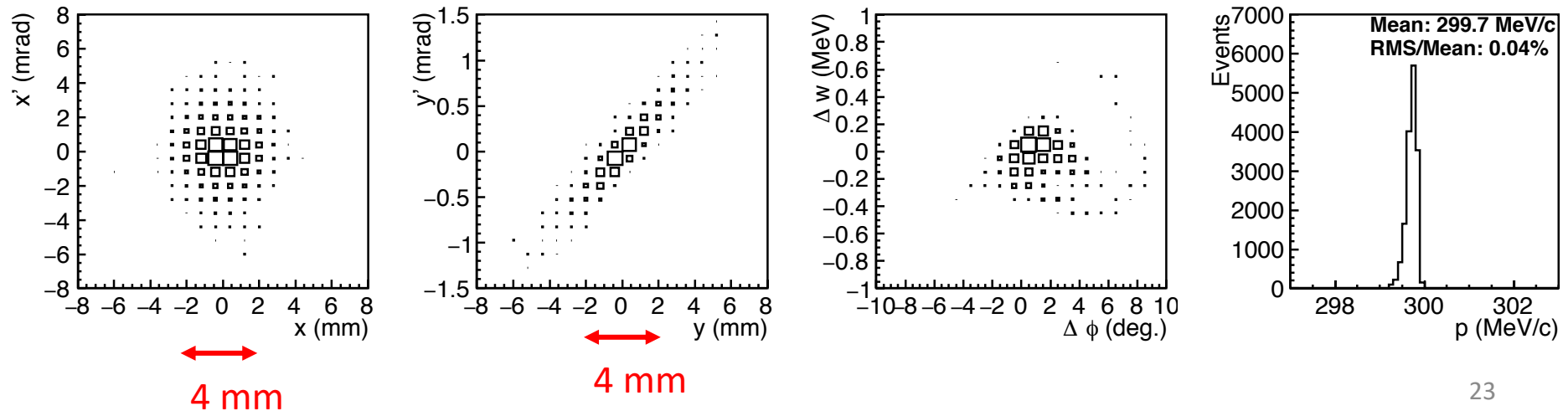
4 mm   4 mm

Mean: 299.7 MeV/c
RMS/Mean: 0.04%

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RF acceleration of Mu⁻ for the first time!

J-PARC MLF D2 area, October 2017

Slide by M. Otani

μ⁺ (~4MeV)

5.6 keV

90 keV

Mu⁻ production

RFQ

Diagnostic line
(Quadrupole pair
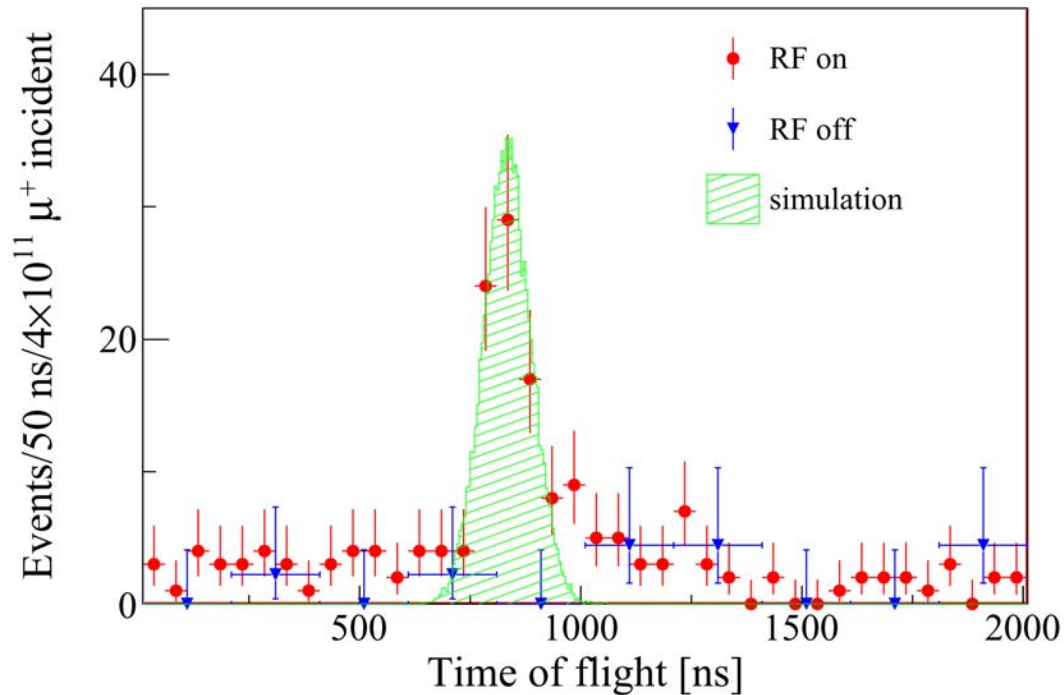and bending)

Detector

RF acceleration of Mu⁻ for the first time!

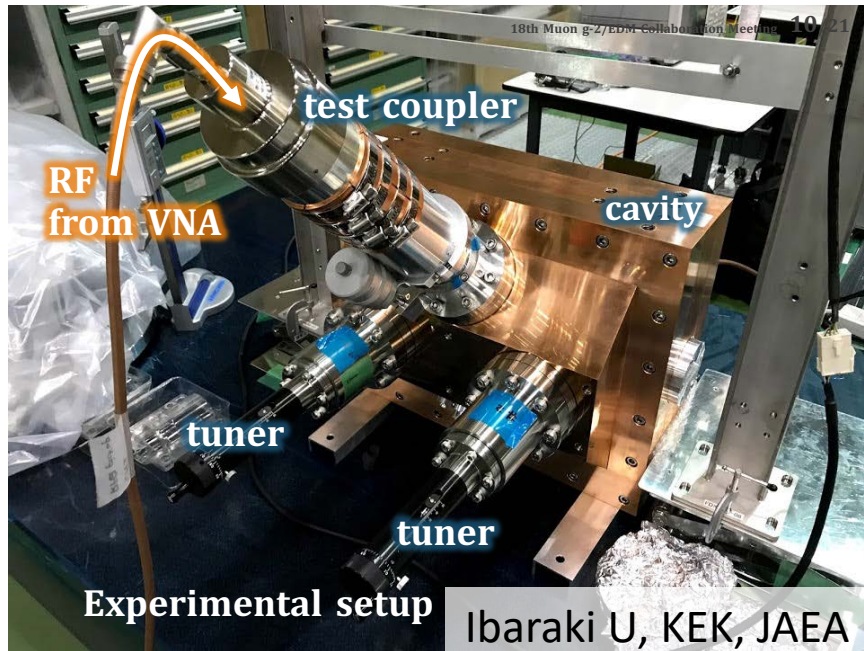J-PARC MLF D2 area, October 2017

Slide by M. Otani

μ⁺ (~4MeV)

5.6 keV

90 keV

Detector

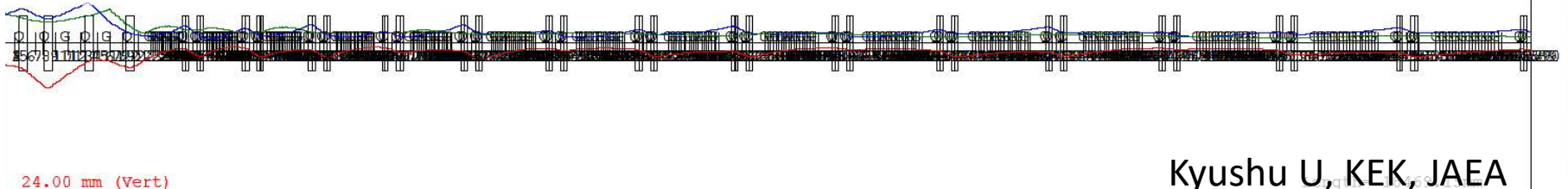S. Bae et al.,Phys. Rev. AB 21, 050101 (2018).

Muon LINAC and beam diagnostics

Development of RF input coupler for IH-type cavity (low β)

RF from VNA

test coupler

cavity

tuner

tuner

Experimental setup Ibaraki U, KEK, JAEA

Non-destructive beam profile monitor

4 stripline electrodes

76 mm

UNIST, KAIST **Stripline length in 230 mm**

Studies on effects on beam dynamics
due to manufacturing/alignment errors (middle β)

24.00 mm (Horiz)   40.0 Deg (Long.)

24.00 mm (Vert)

Kyushu U, KEK, JAEA

Muon storage magnet and detector

Iron yoke

Cryogenics

Super conducting coils

Muon storage orbit

e+ tracking detector

2900 mm

666 mm

M. Abe et. al., Nuclear Inst. and Methods in Physics Research A 890, 51 (2018)
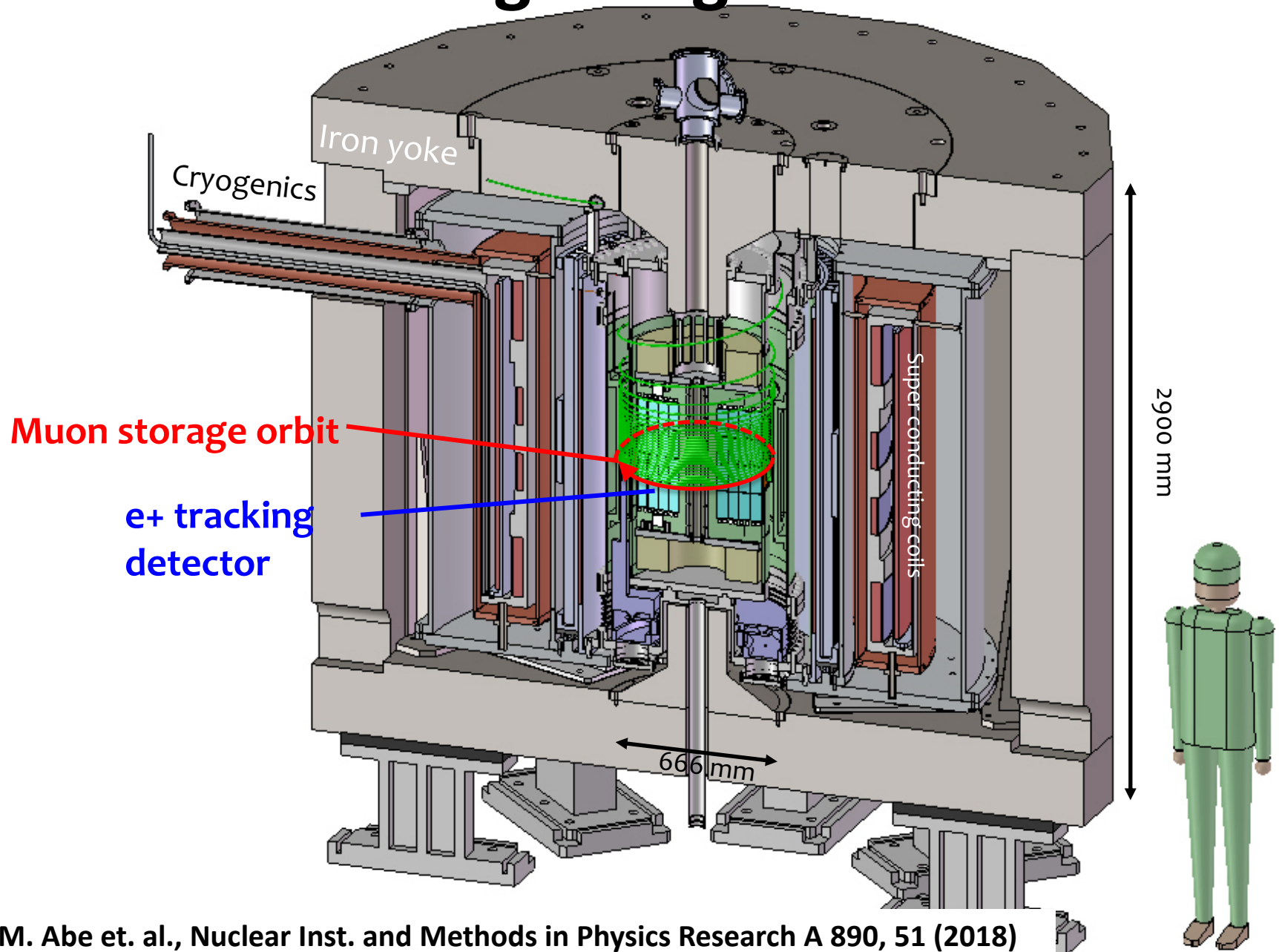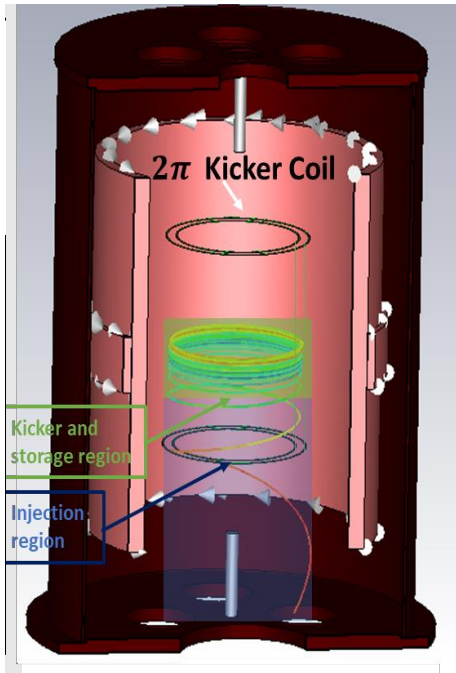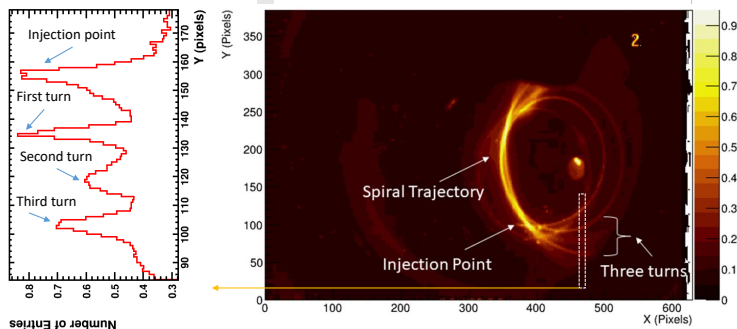
Average magnetic field

25 ppb/line
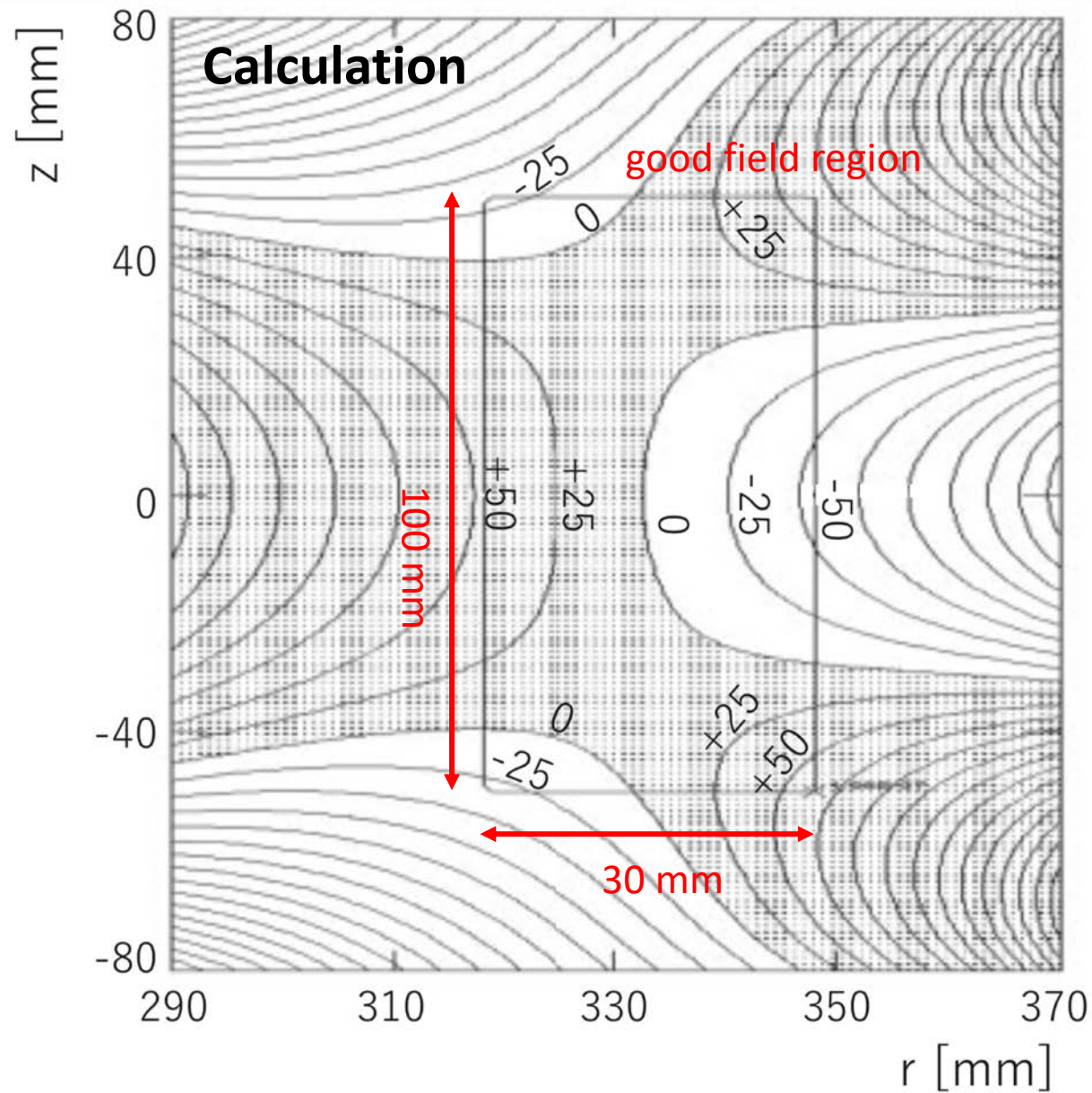
Beam injection and storage magnet

Spiral Injection Test Experiment (SITE) with low energy electron beam
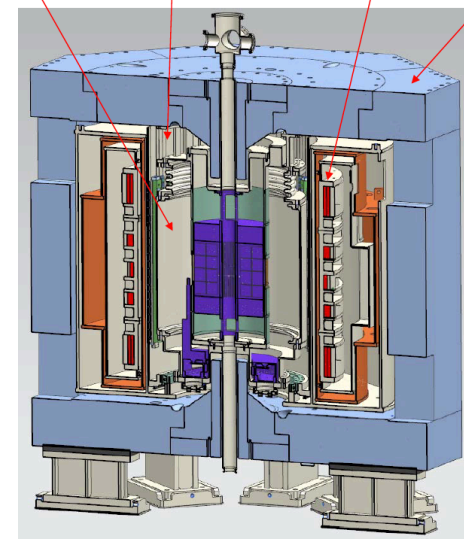

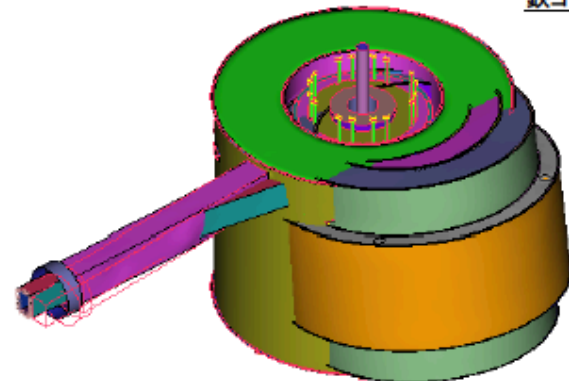Ibaraki U, KEK

Refined design of the storage magnet

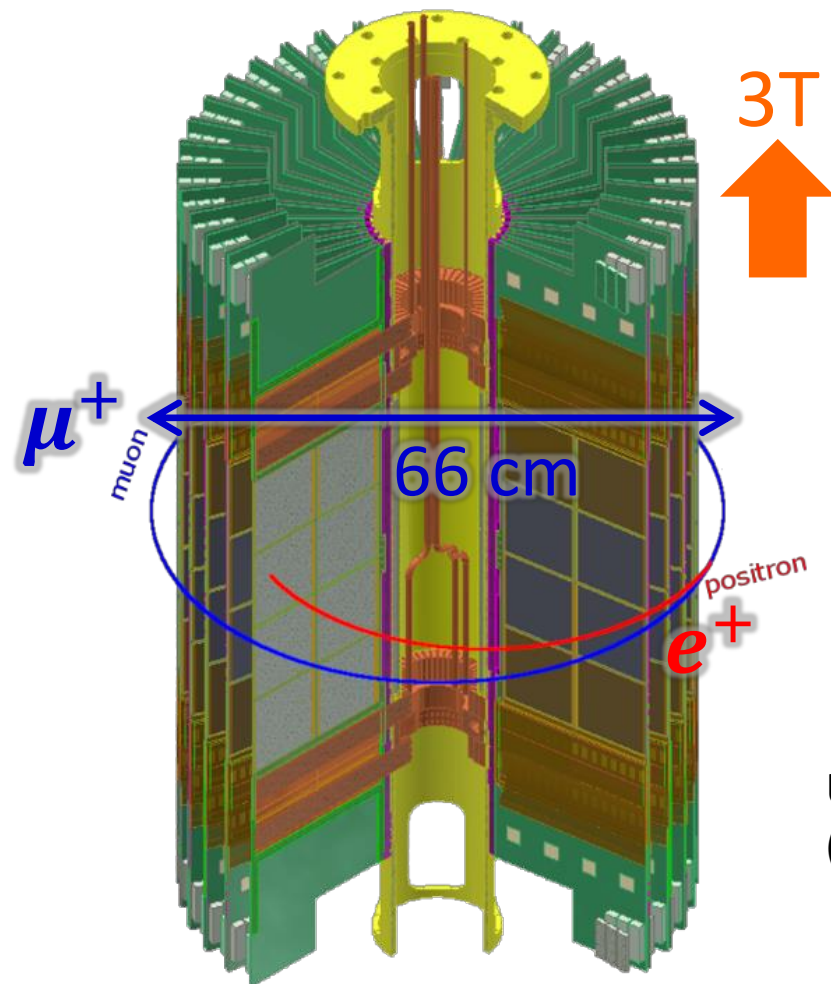Muon chamber   Shim tray   Main coil   Iron yoke

KEK

Studies on seismic ground vibration
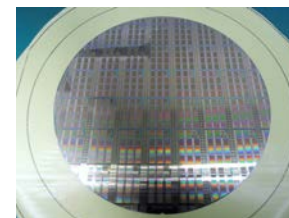
鉄ヨーク非表示

Positron tracking detector

Development of components

3T

66 cm

μ^+

muon

positron

e^+

Specification

2024 ch/piece	Design fixed
Line/space ~ 30/50 μm	Mass production

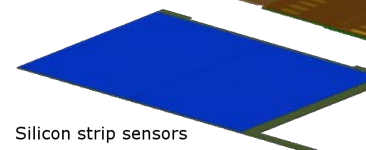Quarter Vane

Flexible Printed Circuits

ASICs

FPGA-based Readout Board

Production version has been delivered. Evaluation is on-going.

Requirement
> 4MIP range
1600e ENC@30 pF
128 ch/chip
5 nsec sampling

Silicon strip sensors
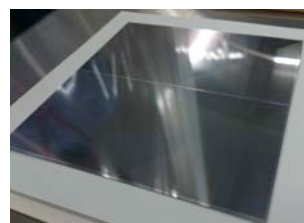
Design fixed. Mass production.

Specification
98.77 mm × 98.77 mm
190 μm pitch
512 ch × 2 block

Test modules production/operation

→Mechanical moc. this JFY.

Used as a working detector in MuSEUM experiment (Mu-HFS)

Data collected in Mar and June 2019

Very priliminary

Signal [(Non-Noff)/Noff]

frequency - 4,463,302 (kHz)

resonance with Kr 20% gas at 1.0 atm

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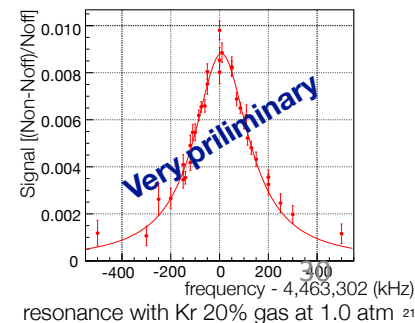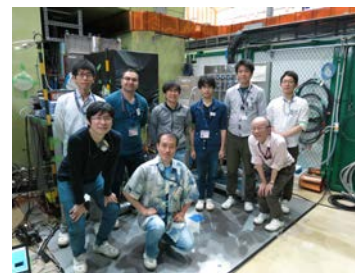
Cross calibration between J-PARC and US NMR probes at ANL (Jan 14- 2019)
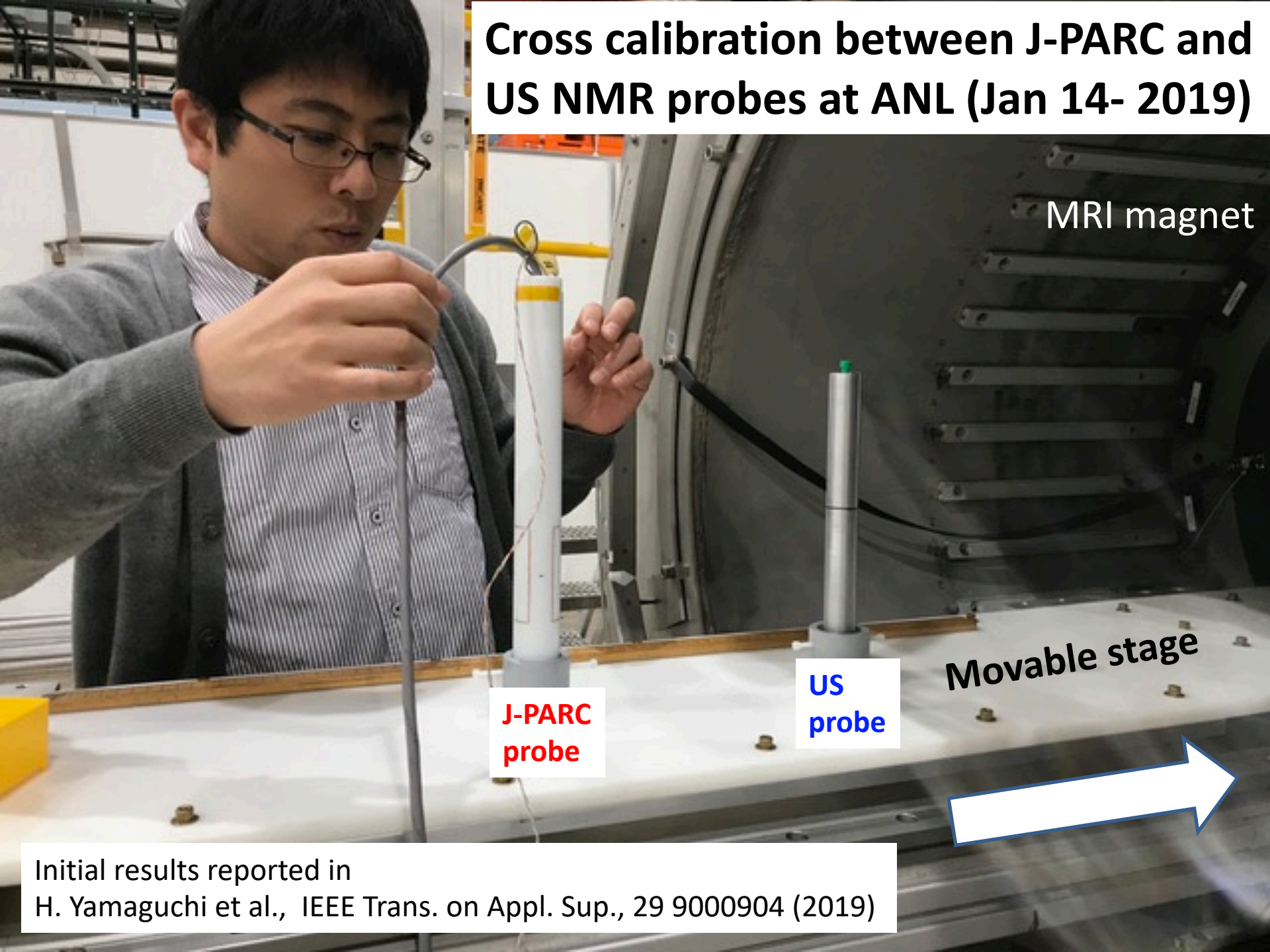
MRI magnet

Movable stage

J-PARC probe

US probe

Initial results reported in
H. Yamaguchi et al., IEEE Trans. on Appl. Sup., 29 9000904 (2019)

US-Japan collaboration on B-field cross calibration

Ken'ichi Sasaki (PI)

Peter Winter (PI)

Collaboration meeting at J-PARC
(Sep 2-4, 2019)

Summary

- The J-PARC **muon g-2/EDM experiment** will independently measure g-2 and EDM with completely different method.

- Construction was partially started.

- Requesting funding for full construction.

- **In coming years,**
  - Construction of muon beamline (H-line)
  - Demonstration of "muon cooling" by ionization of Mu
  - Re-acceleration to 1 MeV

Conventional muon beam

proton π^+ μ^+

emittance
~1000π mm·mrad

pion
production
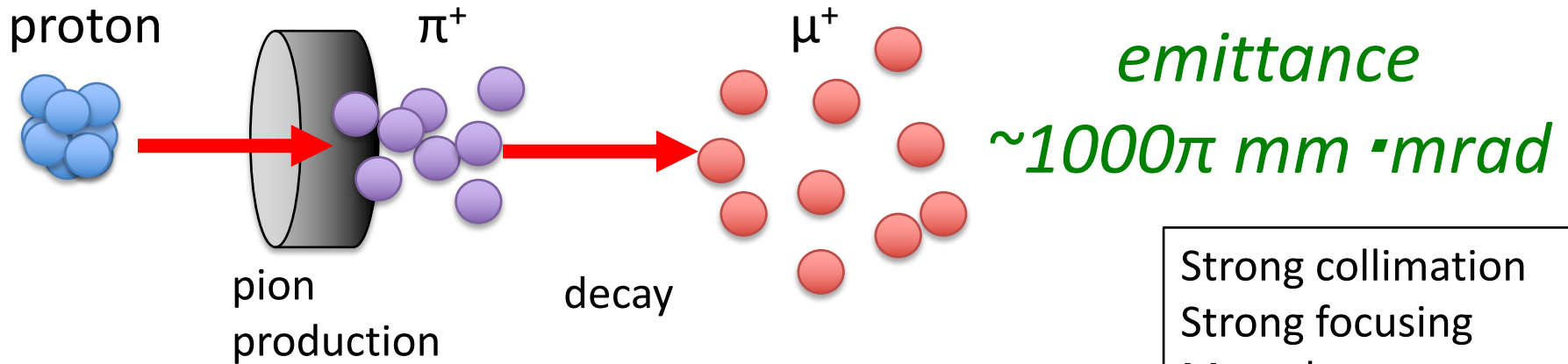
decay

Strong collimation
Strong focusing
Muon loss
BG π contamination

Muon beam at J-PARC

proton

π⁺

μ⁺

emittance
~1000π mm·mrad

pion
production

decay

Strong collimation
Strong focusing
Muon loss
BG π contamination

cooling

μ⁺

emittance
1π mm·mrad

**Reaccelerated
thermal muon**

Free from any of these

レーザーガイド補償光学用レーザー
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Experimental sequence

40ms (25 Hz)

Surface muon beam (28 MeV/c)

μ⁺

laser ionization

Thermal muonium (3keV/c)

Mu

~1μs

Ultra-slow muon (3keV/c)

μ⁺

~1ns

Acceleration + injection (300 MeV/c)

μ⁺

~3ns

Storage and detection (300 MeV/c)

40 μs

μ⁺→e⁺

Breakdown of efficiencies

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		

Statistical and systematic uncertainties

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} $e\cdot$cm]	1.5 (stat.)
	0.36 (syst.)

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