# Muon g-2/EDM experiment at J-PARC

Snowmass workshop on

dipole moments

Sep. 17, 2020

Tsutomu Mibe (KEK)

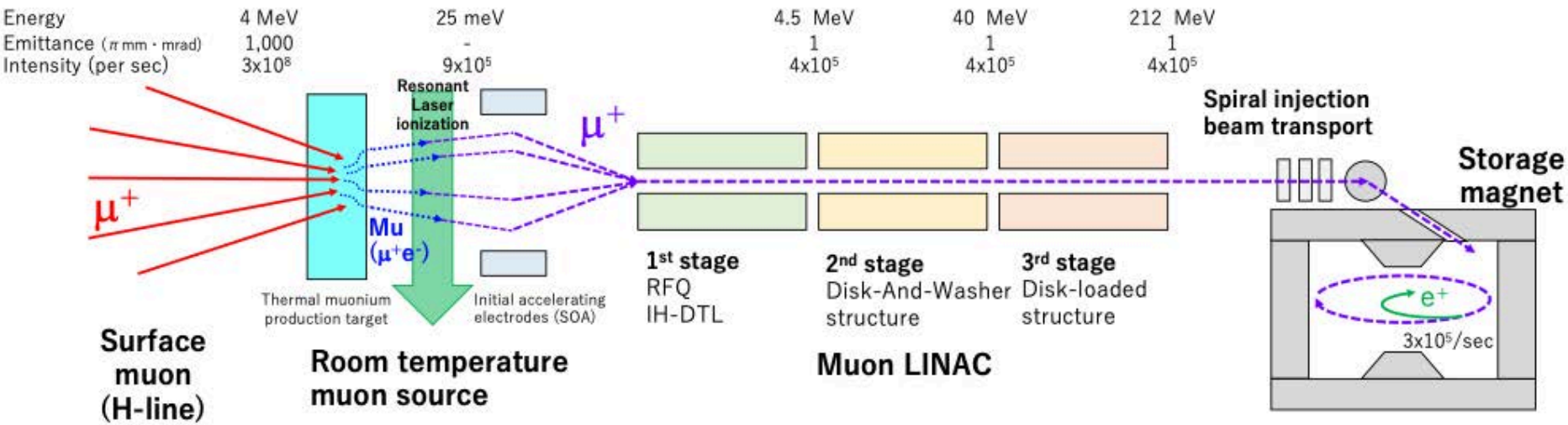
**Job opportunities:**

[1] Postdoc for J-PARC g-2/EDM experiment (https://www.kek.jp/en/Jobs/2020/08/25/2002/)

[2] Postdoc for KEK IPNS (https://www.kek.jp/en/jobs/ipns20-5e/)

# Muon g-2/EDM experiment at J-PARC

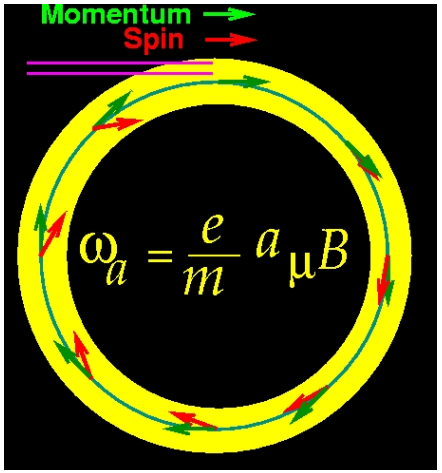
Prog. Theor. Exp. Phys. **2019**, 053C02




## 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 new method (different from BNL/FNAL)**

# muon g-2 and EDM measurements




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

general form of spin precession vector:

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

BNL E821 approach
***γ=30 (P=3 GeV/c)***

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

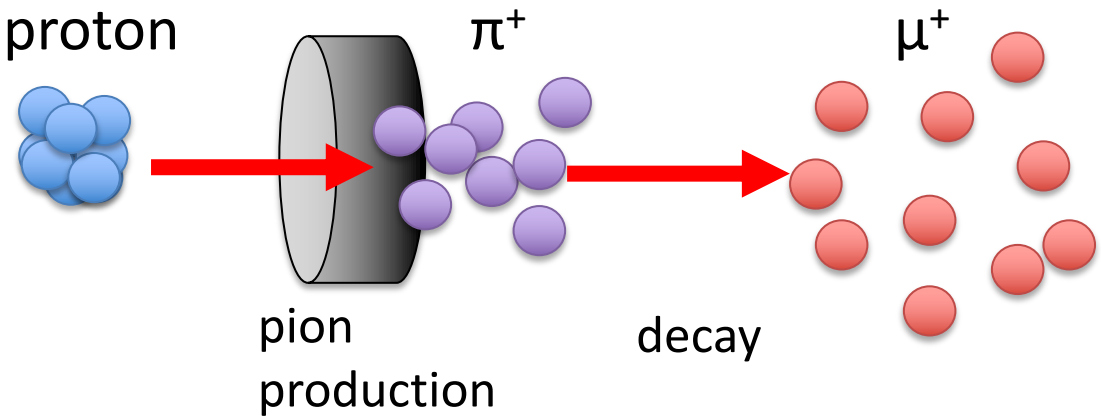
FNAL E989

J-PARC approach
***E = 0 at any γ***

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

J-PARC E34

# Conventional muon beam

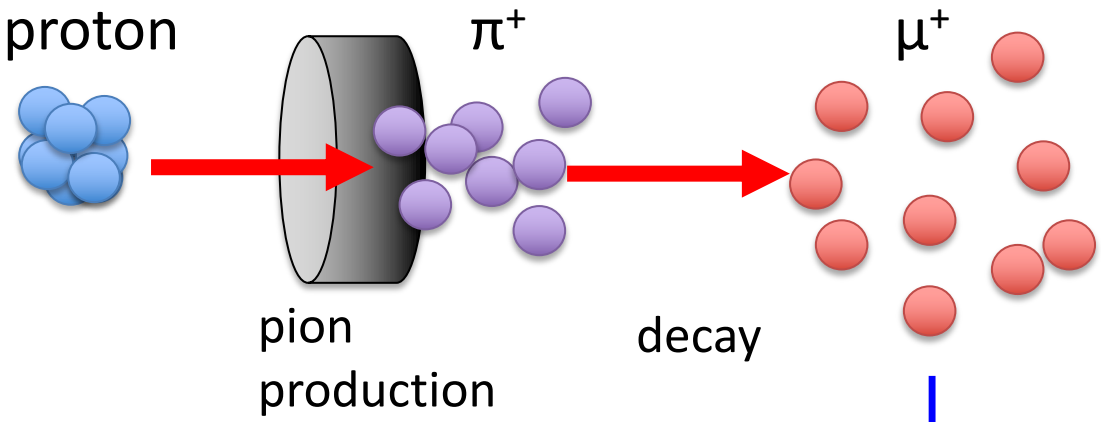



*emittance*

*~1000π mm ·mrad*

Strong focusing
Muon loss
BG π contamination

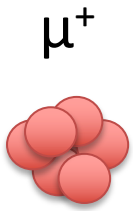
# Muon beam at J-PARC




*emittance*
*~1000π mm ･mrad*

Strong focusing
Muon loss
BG π contamination

cooling


*emittance*
*1π mm ･mrad*

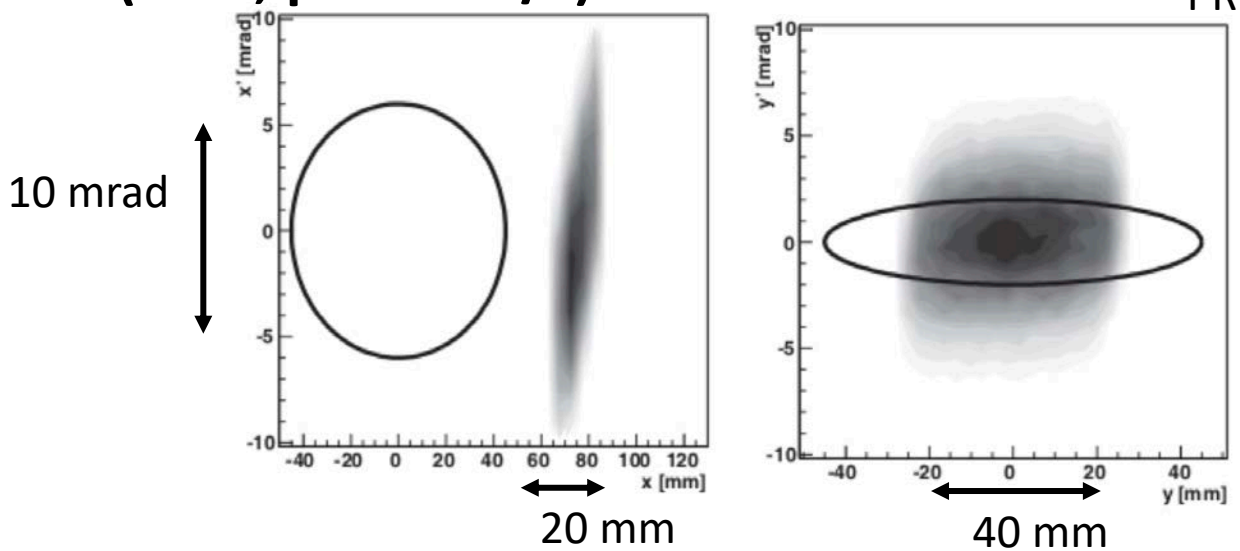
**Reaccelerated thermal muon**

Free from any of these

# Comparison of muon beam

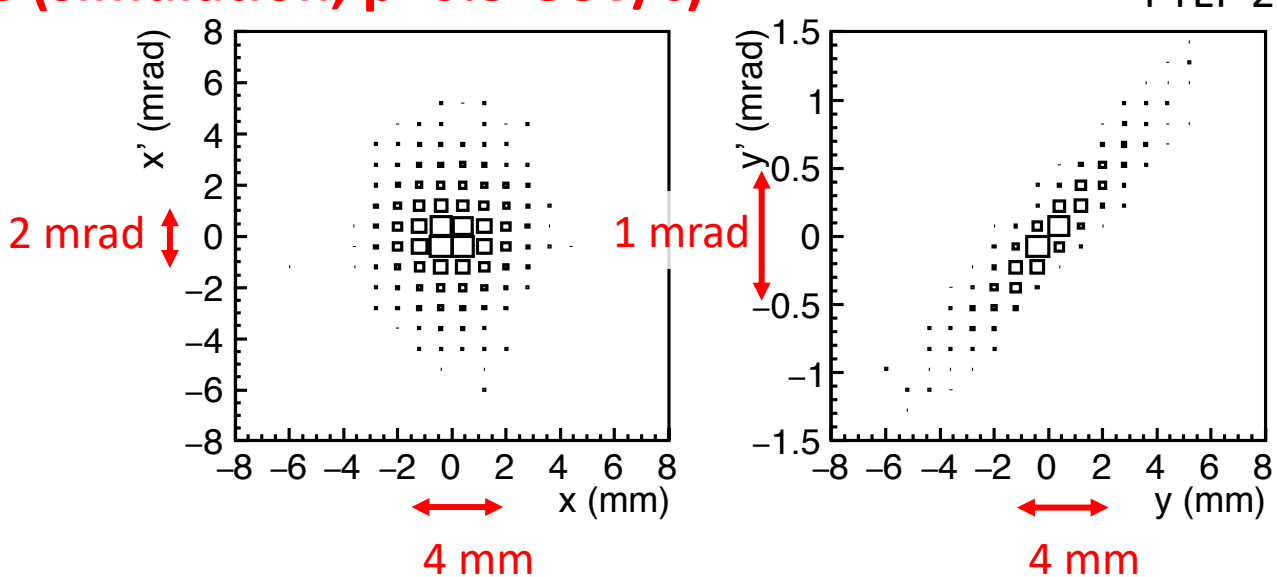
**BNL E821 (data, p= 3 GeV/c)**

PRD 73, 072003 (2006)

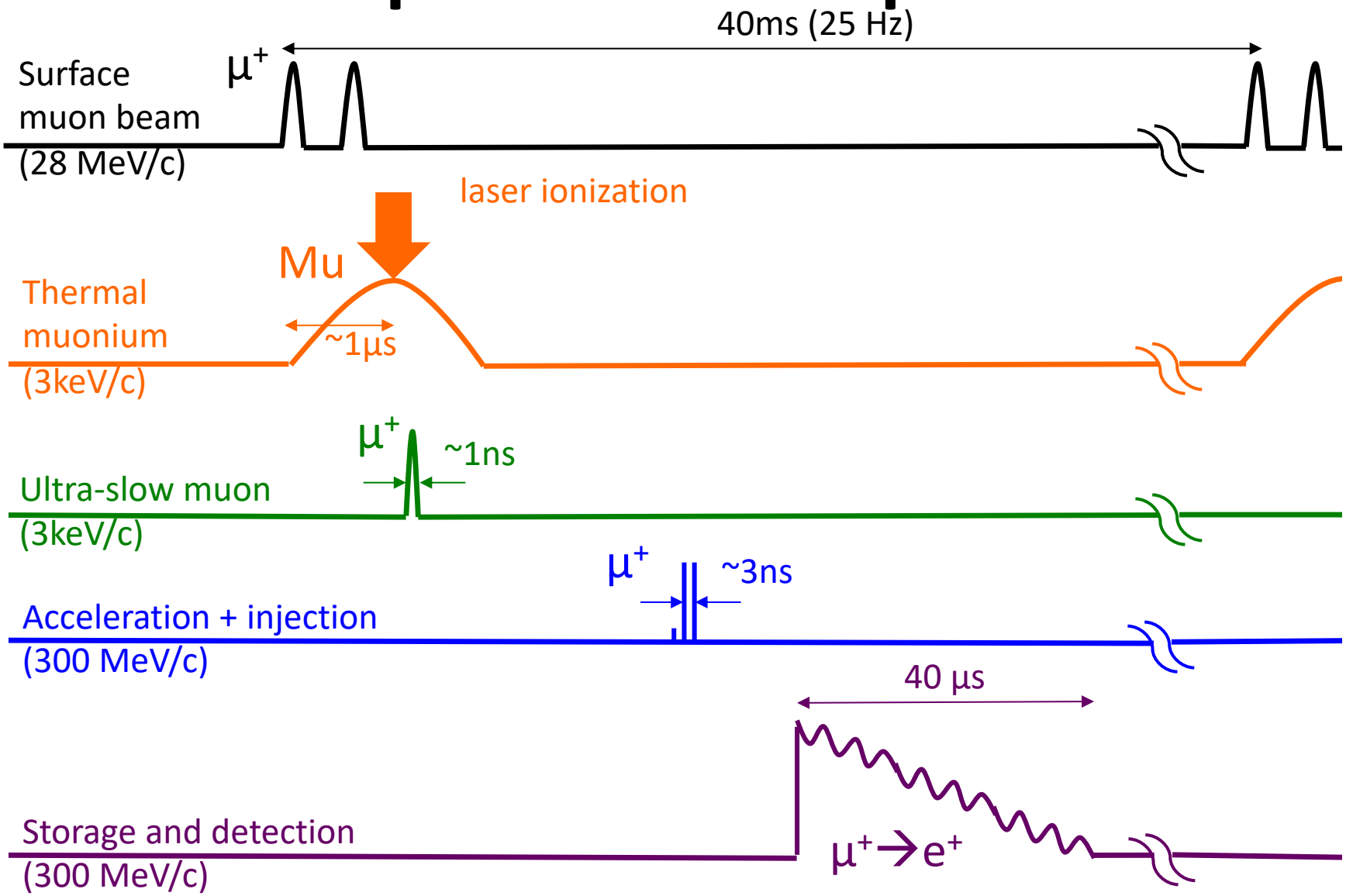



**J-PARC (simulation, p=0.3 GeV/c)**

PTEP 2019, 053C02 (2019)

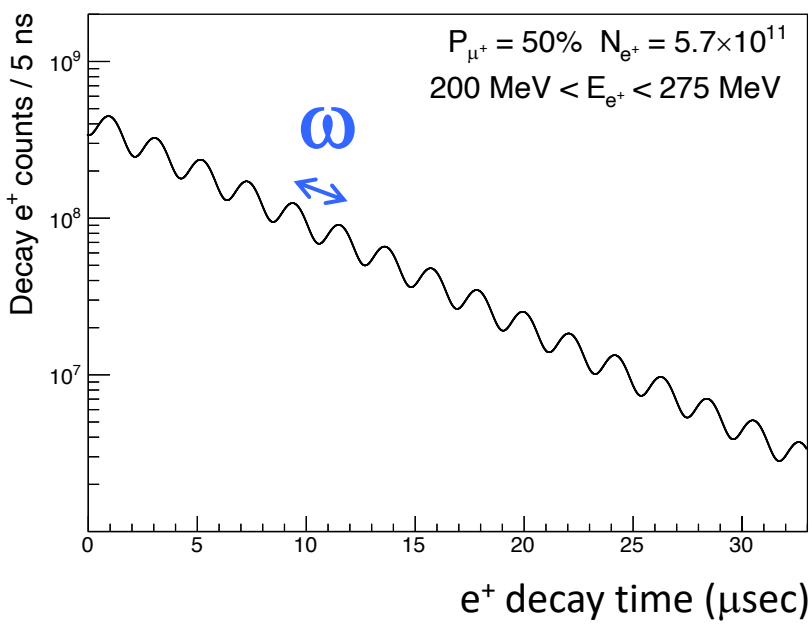


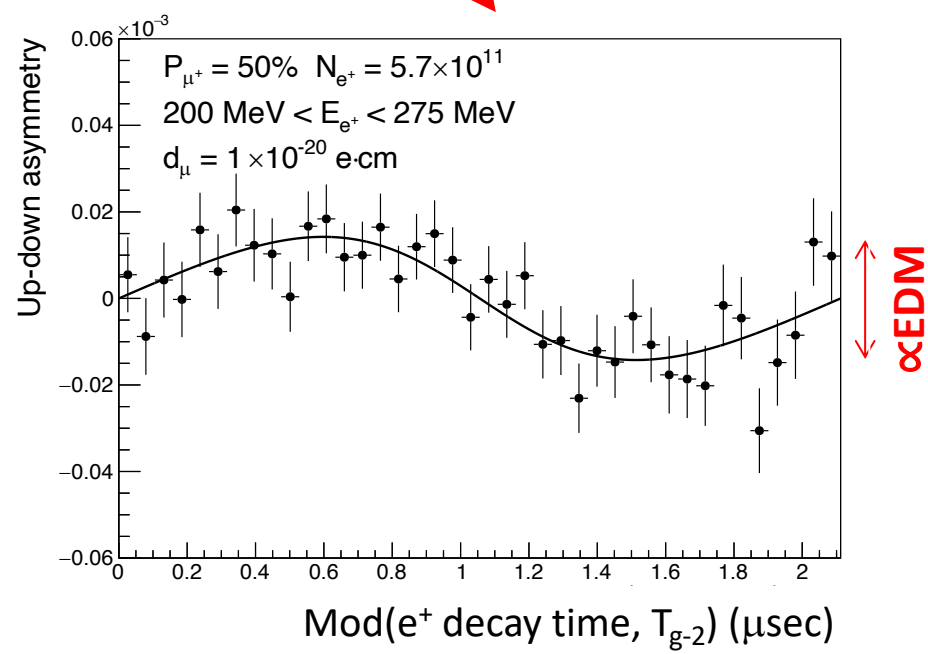
# Experimental sequence



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

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



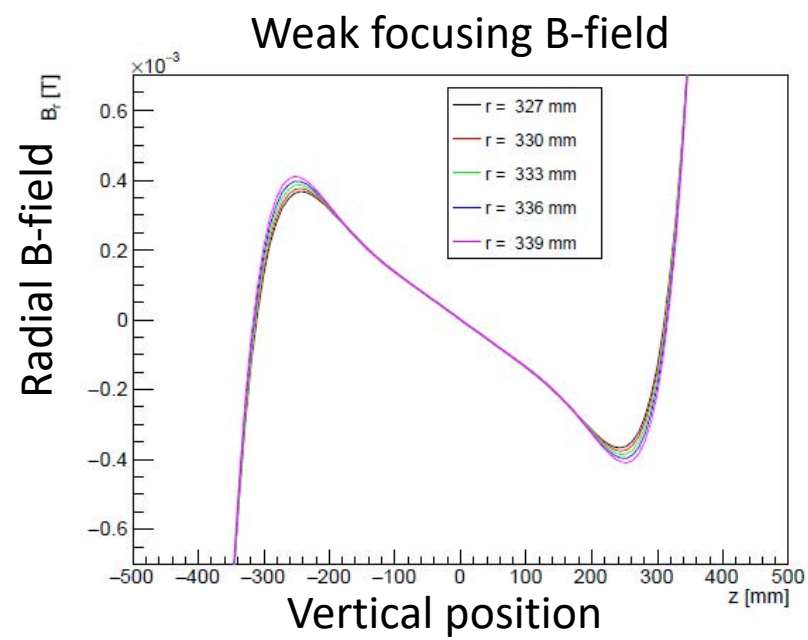

Prog. Theor. Exp. Phys. **2019**, 053C02 (2019)

# Very weak magnetic focusing

- **Radial magnetic field** can be a major source of systematics on EDM since the g-2 term mixes to the EDM term.

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

- **Very weak magnetic focusing**
  - Bill Morse, Yannis Semertizdis (2010)
  - Field index n = 1E-4 (1ppm/cm)
  - Vertical position of muon beam will be **self-adjusted to find $B_r$ = 0**.
  - Also very powerful to **suppress the "pitch effect" on g-2** (~10 ppb).

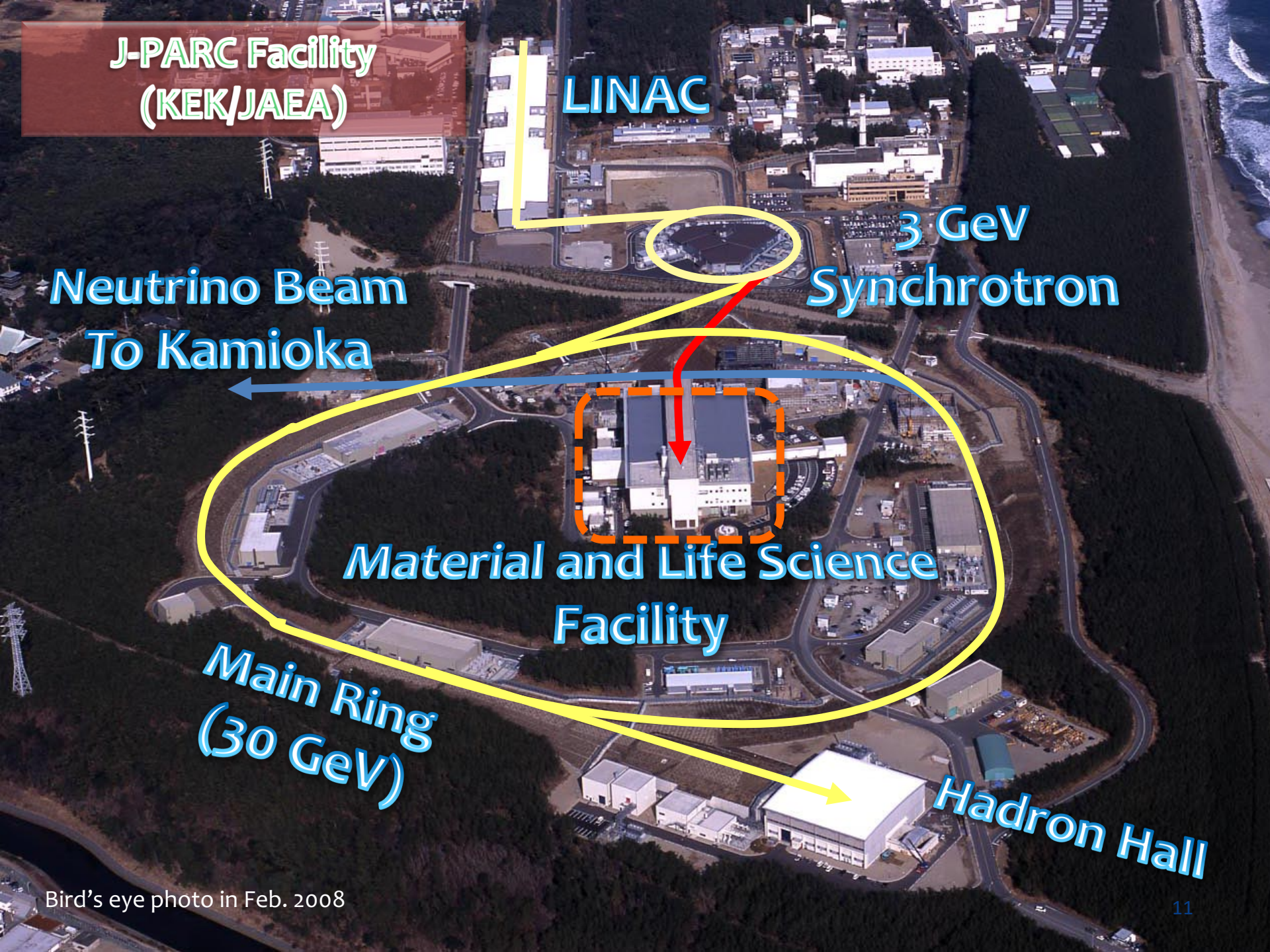


# Comparison of experiments

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

| | BNL-E821 | Fermilab-E989 | Our experiment |
|---|---|---|---|
| Muon momentum | 3.09 GeV/$c$ | | 300 MeV/$c$ |
| Lorentz $\gamma$ | 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 $\mu$s | | 2.11 $\mu$s |
| Number of detected $e^+$ | $5.0\times10^9$ | $1.6\times10^{11}$ | $5.7 \times 10^{11}$ |
| Number of detected $e^-$ | $3.6\times10^9$ | – | – |
| $a_\mu$ precision (stat.) | 460 ppb | 100 ppb | 450 ppb * |
| (syst.) | 280 ppb | 100 ppb | <70 ppb |
| EDM precision (stat.) | $0.2 \times 10^{-19}$ $e \cdot$ cm | – | $1.5 \times 10^{-21}$ $e \cdot$ cm |
| (syst.) | $0.9 \times 10^{-19}$ $e \cdot$ cm | – | $0.36 \times 10^{-21}$ $e \cdot$ cm |
| | **Completed** | **Running** | **In preparation** |

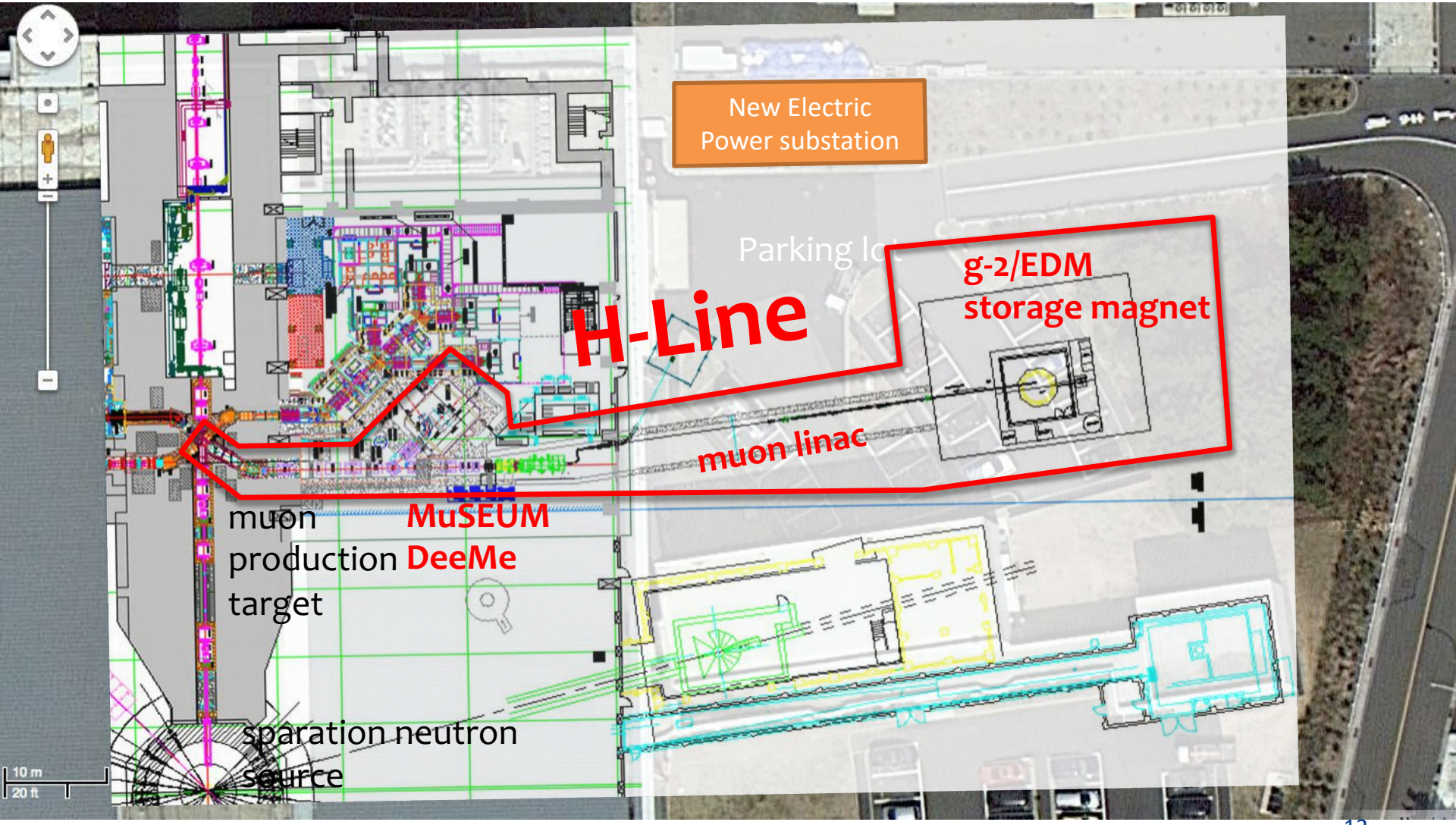
* w/o muon source upgrade




Bird's eye photo in Feb. 2008

# Proposed experimental site

Material and Life science Facility in J-PARC



# H-line being constructed!

Photo by T. Yamazaki

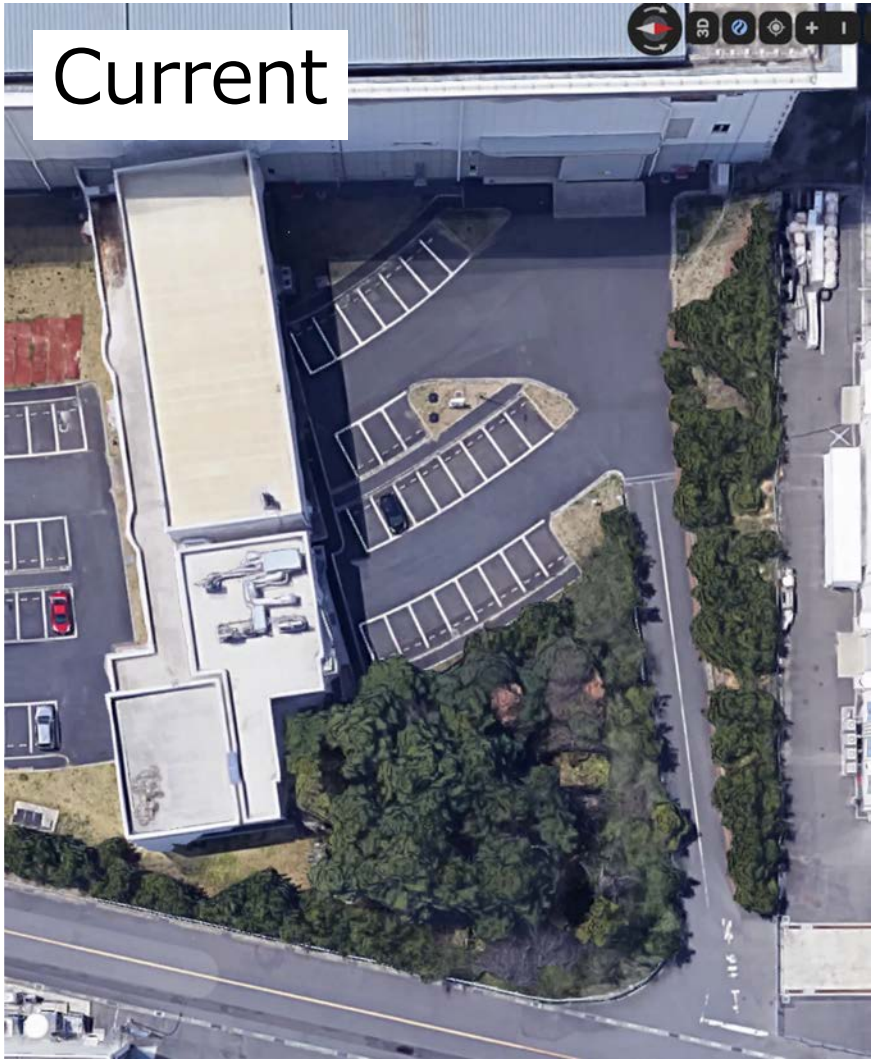
Photo by T. Yamazaki

# H-line being constructed!

# H-line extension



The J-PARC center taskforce endorsed the plan and construction procedure (Jan 2020).

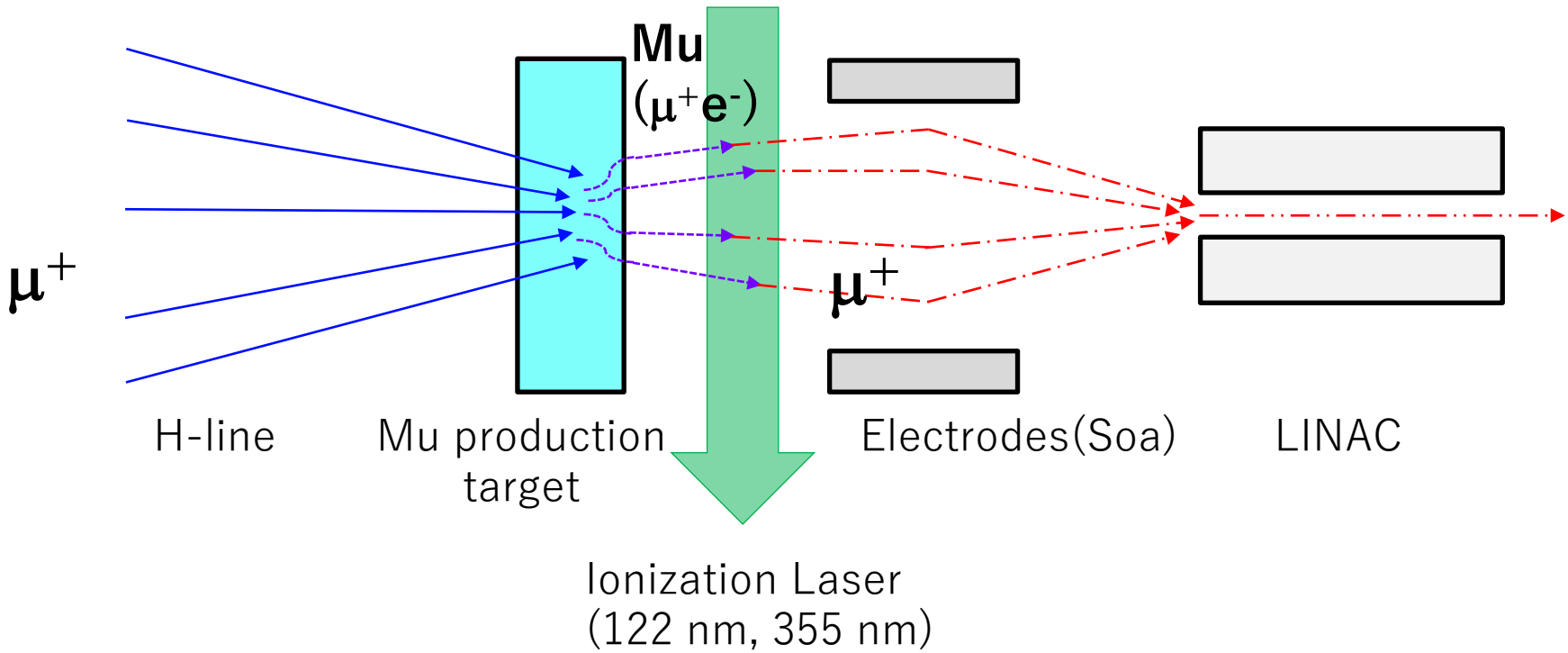



# Ground survey in progress this week

Photo taken by T. Yamazaki

# 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 | $4\times10^{-4}$ |



# Production of thermal energy muon

Photo by S. Kamal

**Silica aerogel with**
**laser-ablated surface**
**($SiO_2$, 30 mg/cc)**

Muonium ($\mu^+e^-$)
30 meV

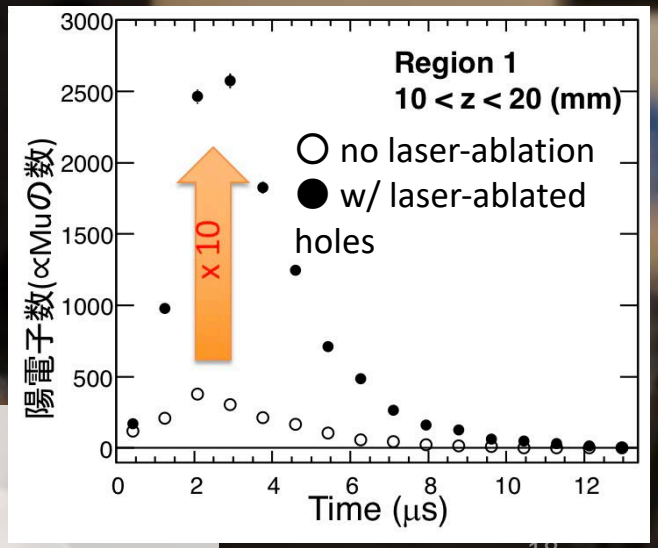
Efficiency
$3 \times 10^{-3}/\mu$
(laser region 5mm x 50mm)

surface
muon beam

$\mu$+ (4 MeV)

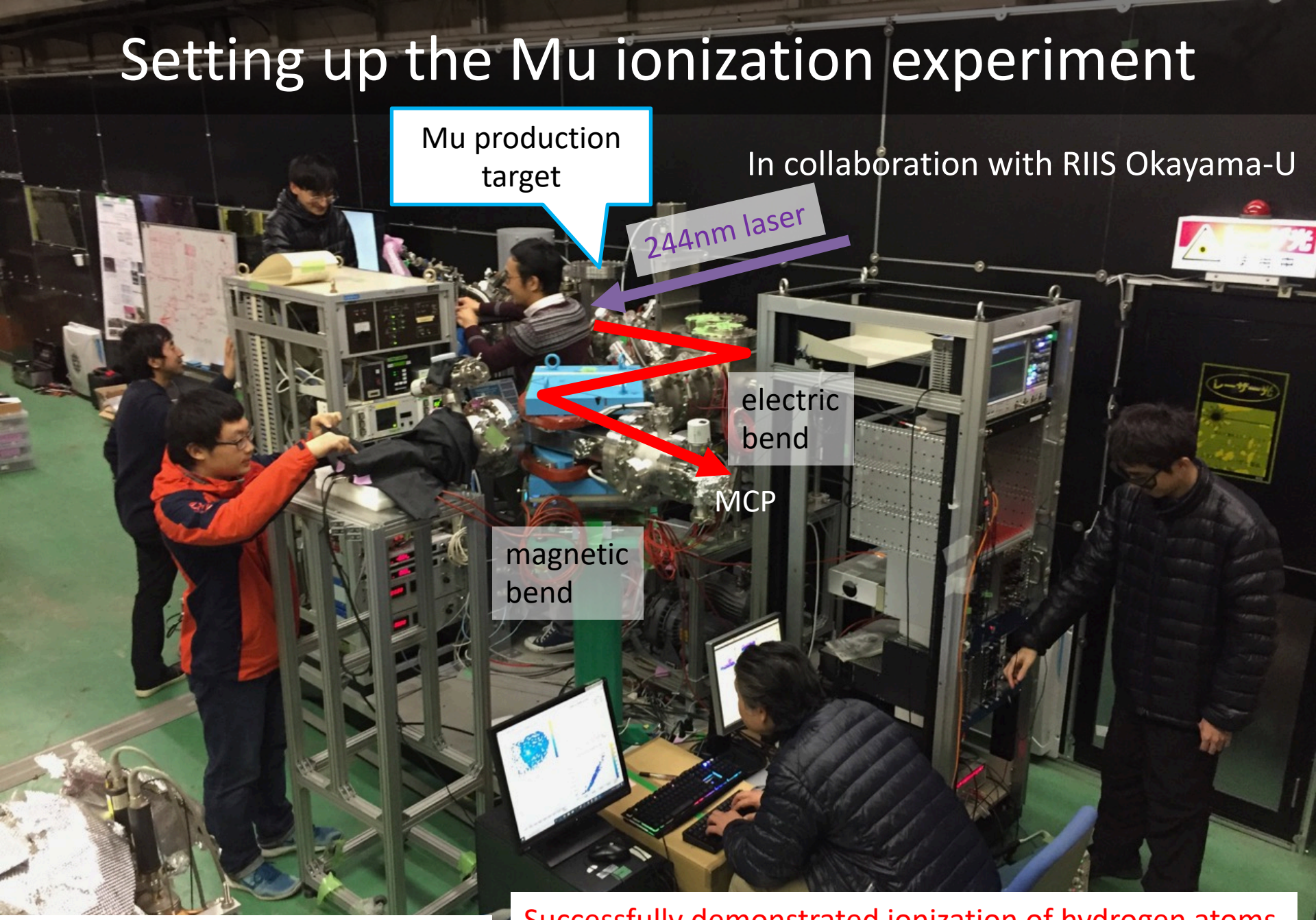
8 mm

Data taken at TRIUMF




P. Bakule et al., PTEP 103C0 (2013)
G. Beer et al., PTEP 091C01 (2014)
J. Beare et al., arXiv:2006.01947 (2020) (to be published in PTEP)

# Setting up the Mu ionization experiment

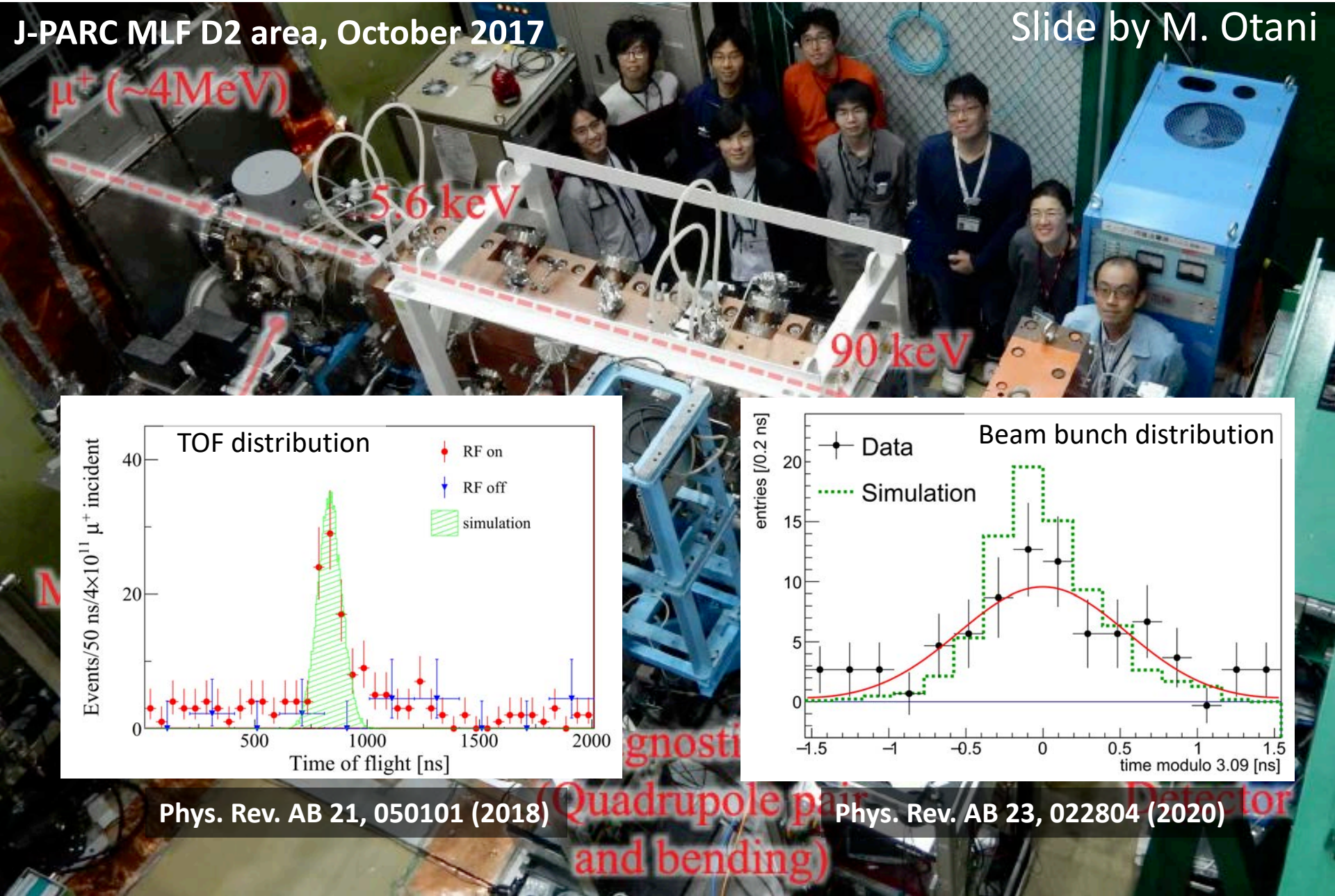



**KEK, Tsukuba Campus**

Successfully demonstrated ionization of hydrogen atoms
To be transported to J-PARC MLF S-line in winter 2020

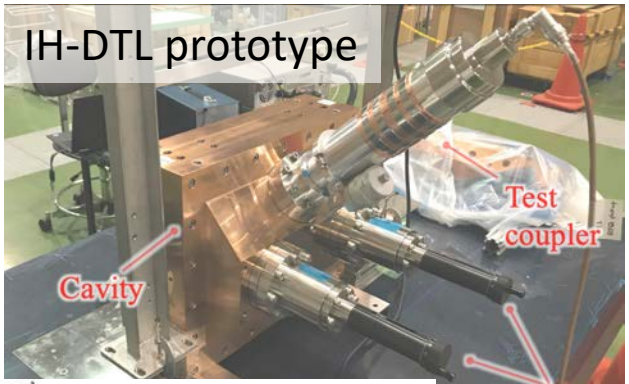
# Demonstration of muon RF acceleration

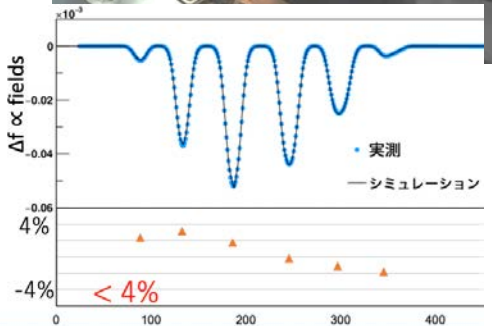
# Demonstration of muon RF acceleration

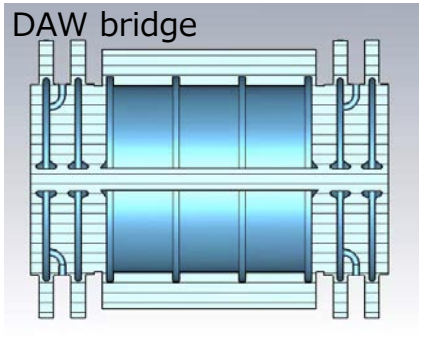


# Muon LINAC

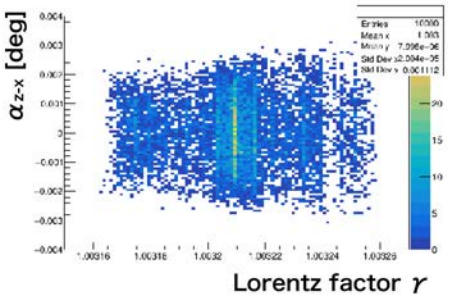

| | | | | | |
|---|---|---|---|---|---|
| length | 3.2 m | 1.4 m | 16 m | 10 m | |
| RF | ← 324 MHz → | | ← 1296 MHz → | | |
| E | 5.6 keV | 0.34 MeV | 4.5 MeV | 40 MeV | 212 MeV |
| $\beta$ | 0.01 | 0.08 | 0.3 | 0.7 | 0.94 |

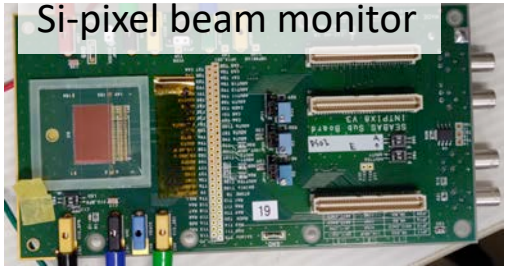


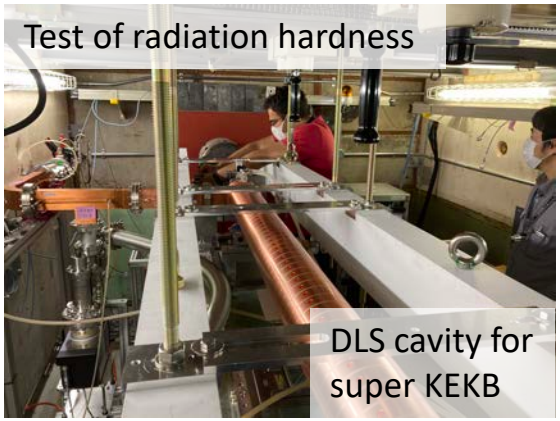




Simulated spin direction and momentum



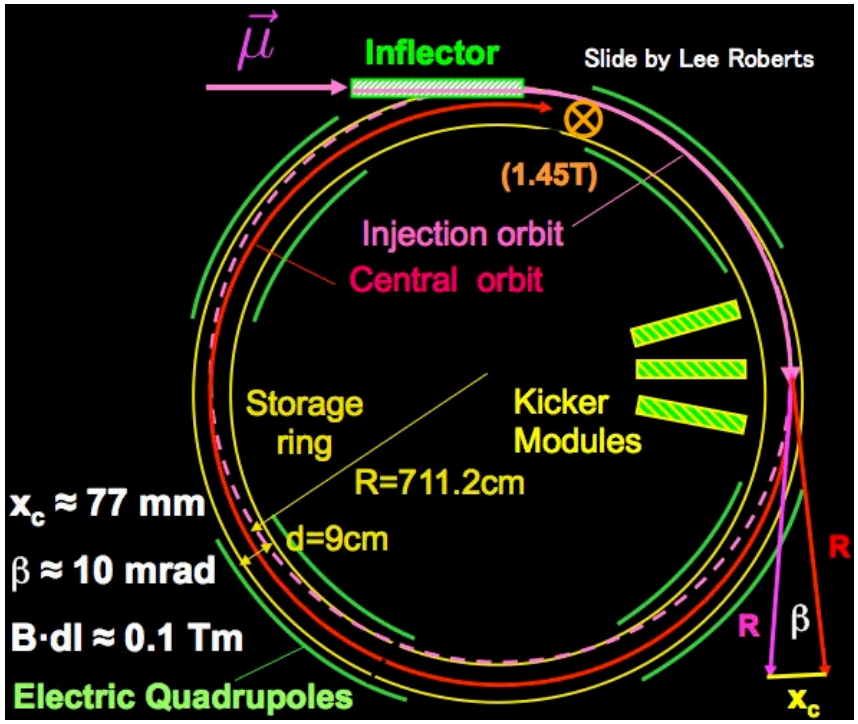



# Muon beam injection and storage

**Horizontal injection + kicker**

**(BNL E821, FNAL E989)**

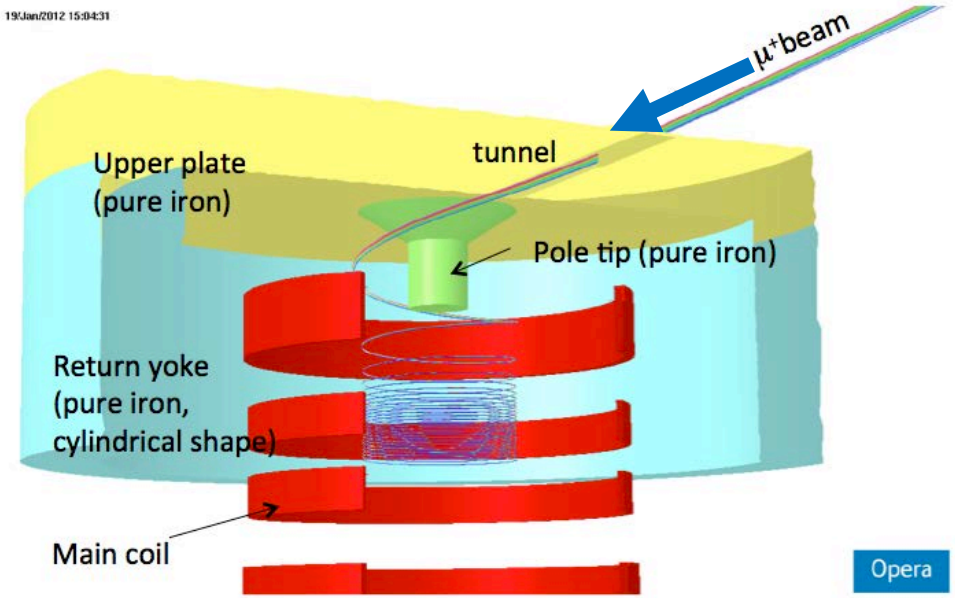



**Injection efficiency : 3-5%(*)**

(*) PRD73,072003 (2006)

**3D spiral injection + kicker**

**(J-PARC E34)**




**Injection efficiency : ~85%**

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

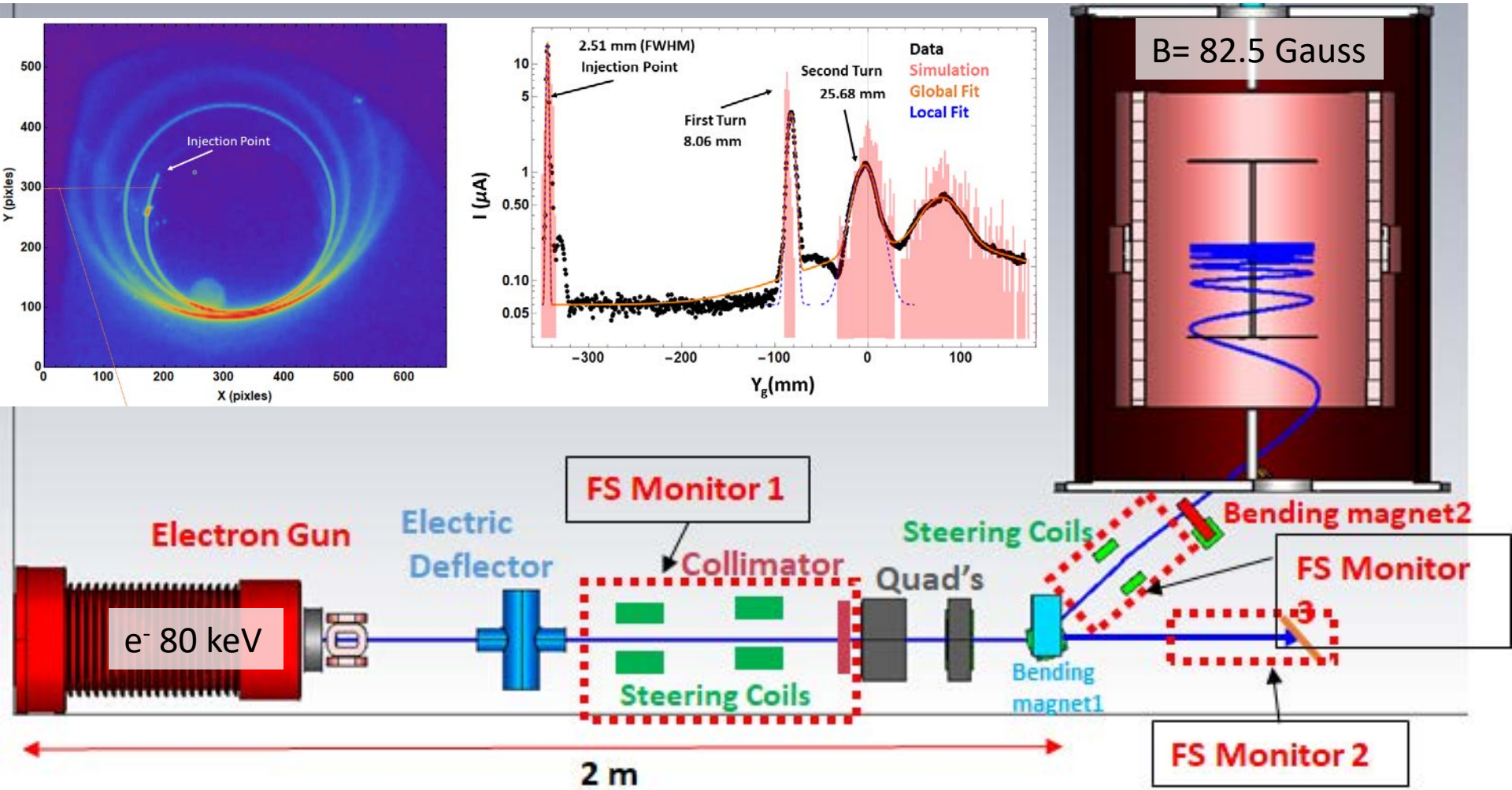
# Spiral Injection Test Experiment with low-energy electron beam

M. A. Rehman (PhD thesis, Sokendai 2020)

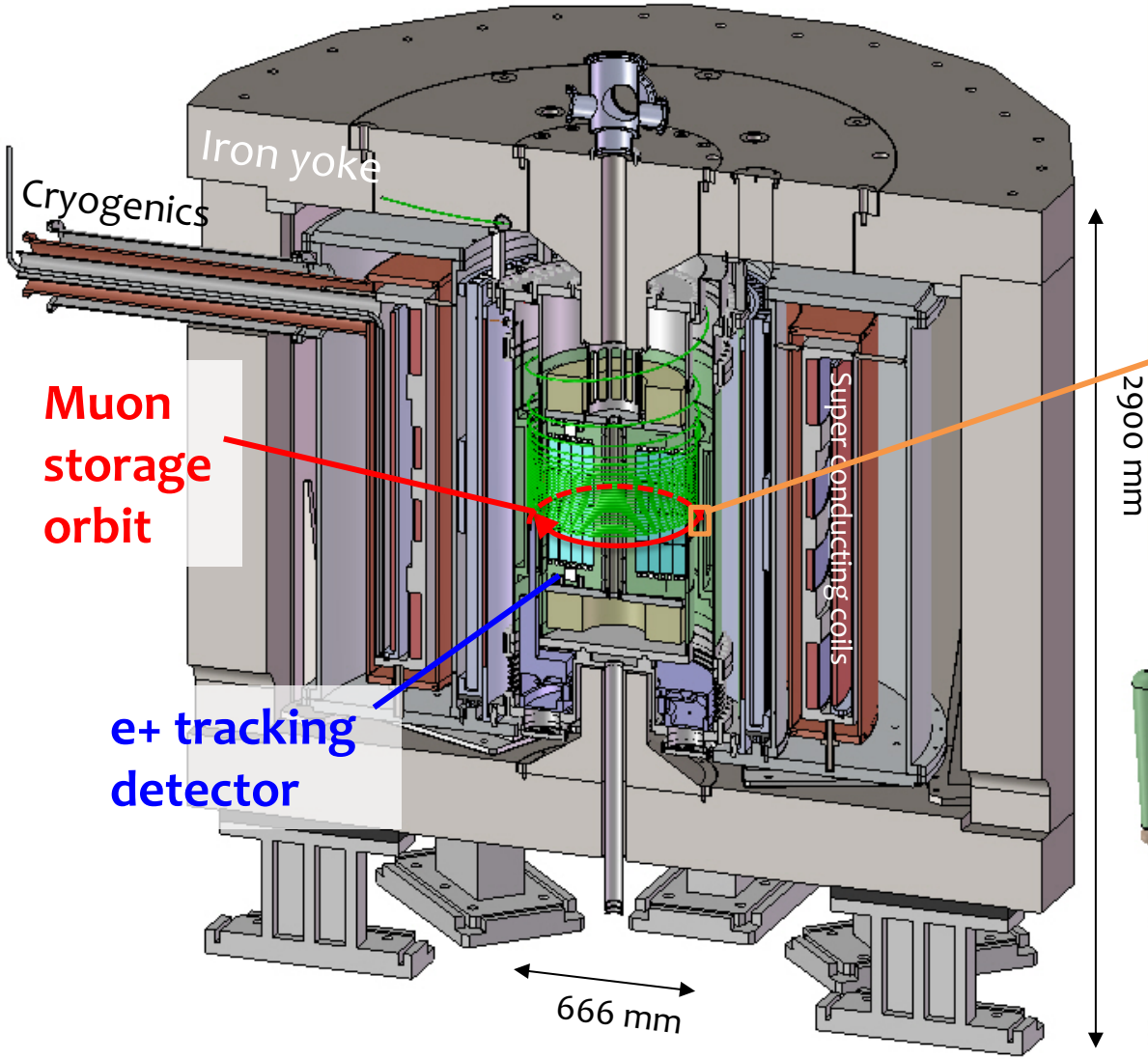




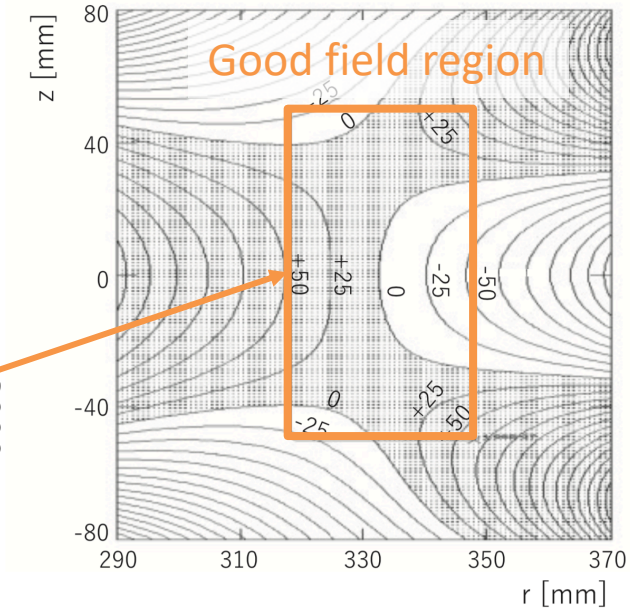




# Muon storage magnet and detector




Calculated average field uniformity

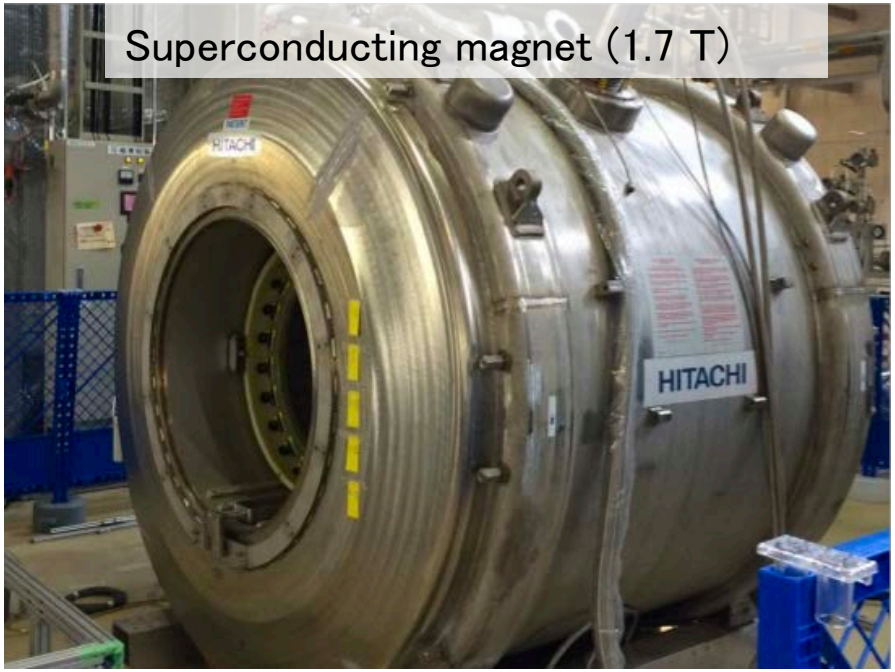


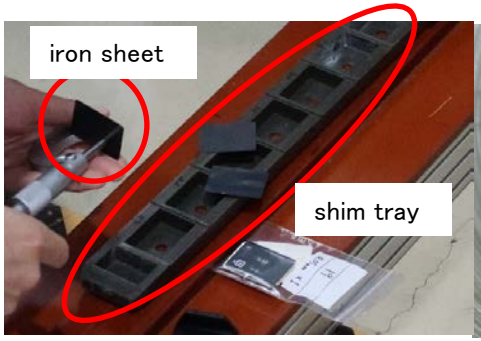

25 ppb/line

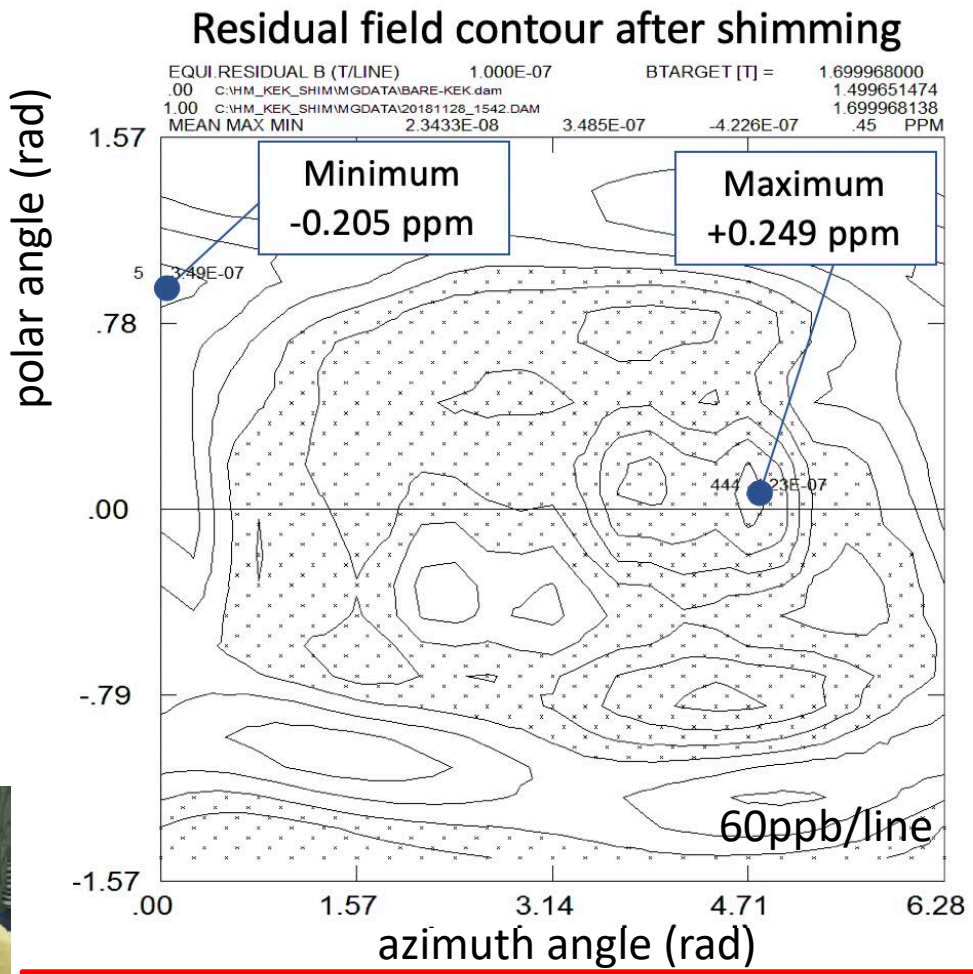
M. Abe et. al., Nuclear Inst. and Methods in Physics Research A 890, 51 (2018)

Sasaki, Abe, Yamaguchi, Ibaraki U

# Magnet shimming test



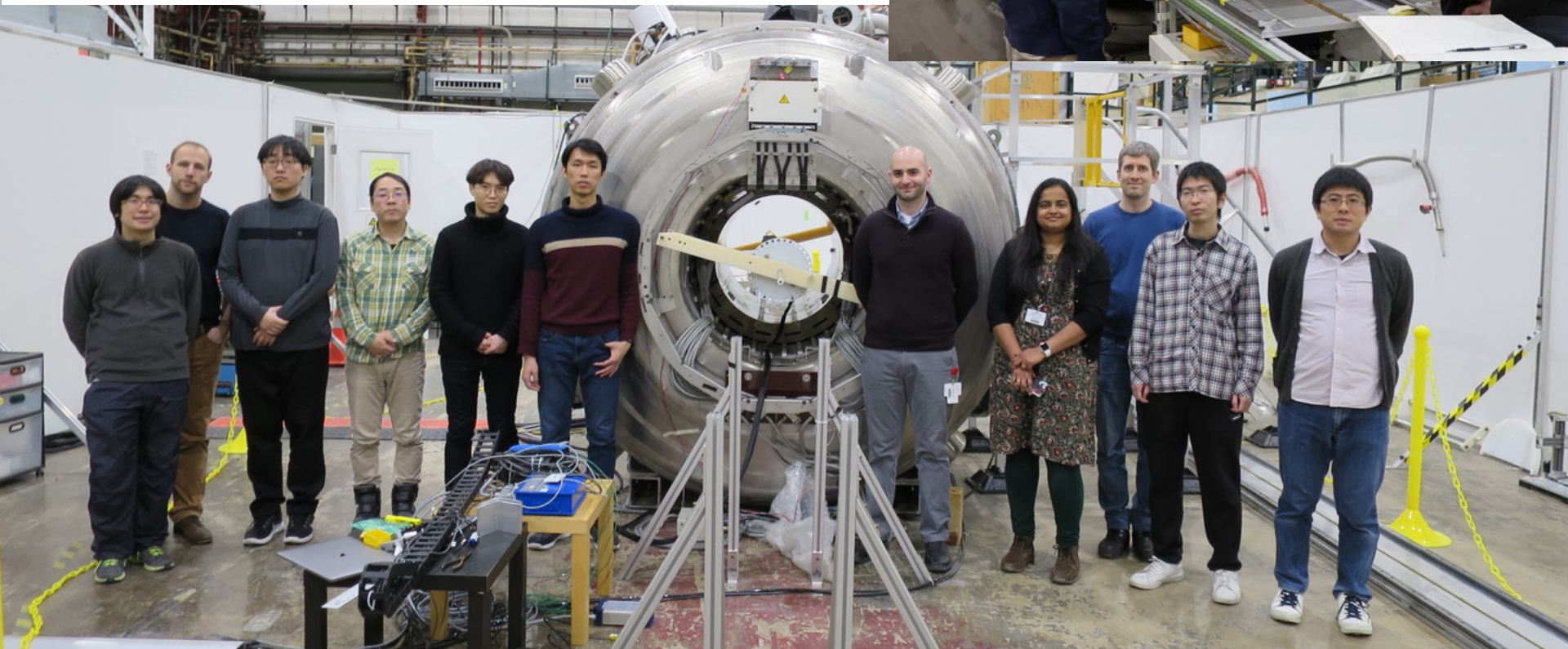



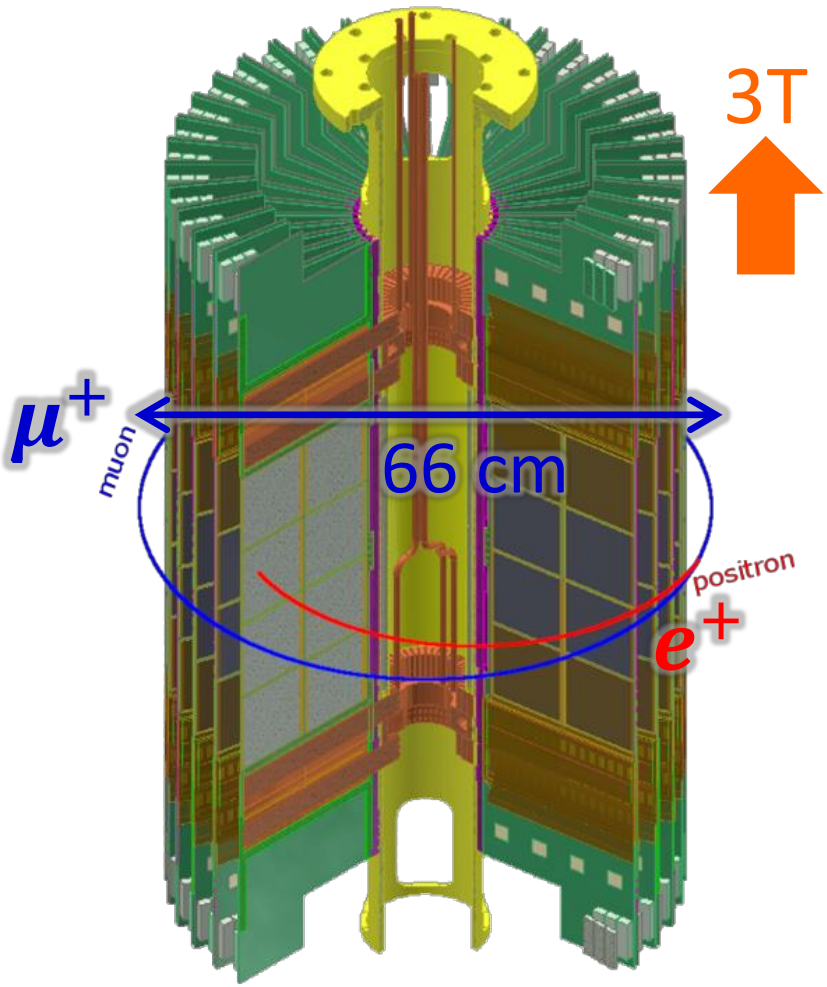

Field uniformity: **0.454 ppm** (peak-to-peak)
on the surface of sphere r=15 cm

# Cross-calibration of absolute probe

- Absolute probes from **Fermilab g-2** and **J-PARC** are compared in the magnet at ANL for cross calibration.
- Data taking completed at **B=1.45 T (Fermilab)** and **1.7 T (MuSEUM)**. Planned another data taking at **3.0 T (J-PARC)**.
- Supported by the US-Japan cooperative program (2017-2020), P. Winter (US-PI), K. Sasaki (JP-PI)

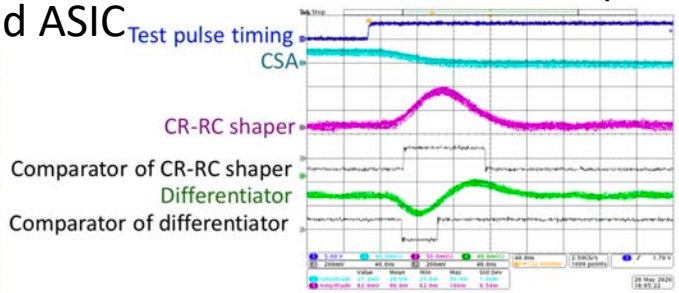



# Positron tracking detector



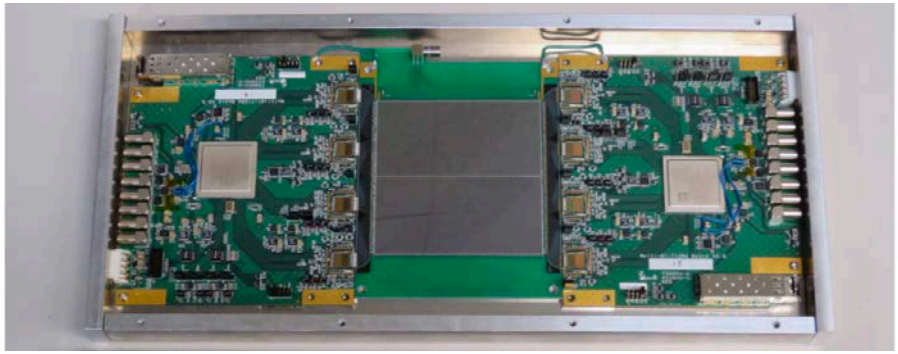

IEEE, TNS 67, 2089 (2020)

New frontend ASIC

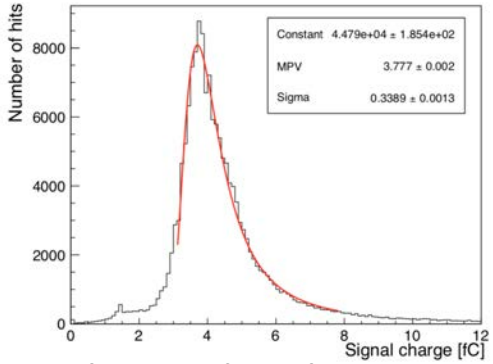




Test module

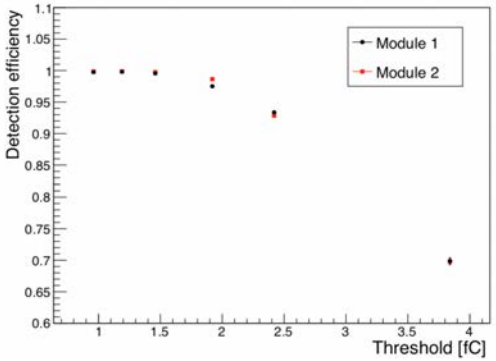
JINST 15 P04027 (2020)



Test results with positron beam at Tohoku U



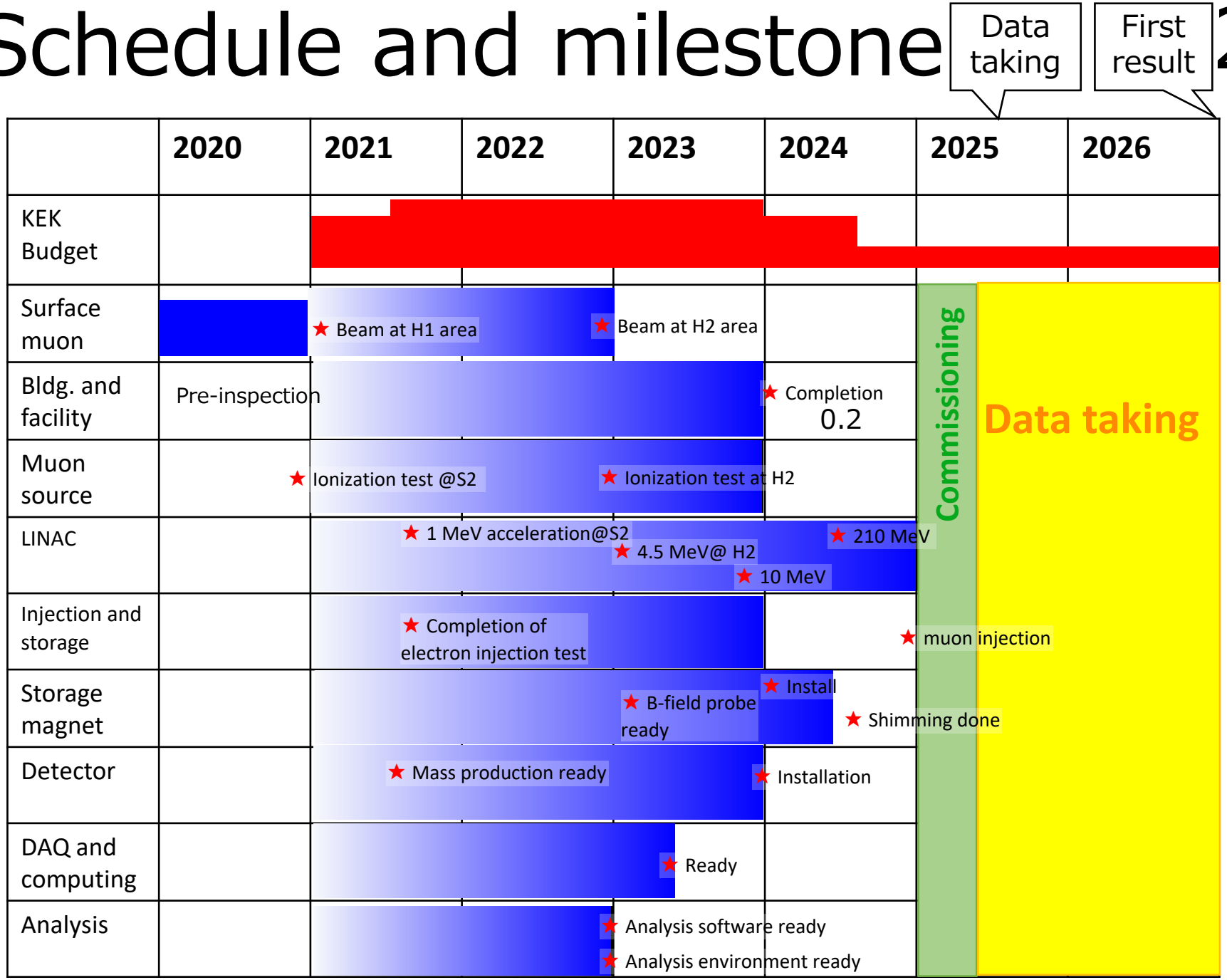

Charge distribution




Efficiency

# Schedule and milestone





# 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, granted by the IPNS |
| 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<br>Nov, 2018 | Stage-2 status recommended by IPNS-PAC<br>Stage-2 status granted by the IPNS director |
| Jan, 2019<br><br>Mar, 2019 | Stage-2 status recommended by IMSS-PAC<br>Stage-2 status granted by the IMSS director<br>KEK-SAC endorsed the E34 for the near-term priority |
| June, 2020<br>July, 2020 | KEK prepares for a funding request to MEXT<br>Collaboration received a grant-in-aid funding for detector + field monitor + injection BT + a part of acc. cavities |

# The collaboration

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

**Collaboration board (CB)**
Chair: Seonho Choi

**Executive board (EB)**
Spokesperson: T. Mibe

**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

**DAQ and computing**
leader: Y. Sato, S. Lee

T. Suehara

**Analysis**
leader: T. Yamanaka (K. Hayasaka)

T. Yamanaka

**Committees**

**Speakers committee**
chair: K.Ishida, E. Won

**Publication committee**
chair: S. Eidelman

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

KEK: IPNS, IMSS, ACC, CRY, MEC

# Summary and outlook



- **The J-PARC experiment** aims to measure muon g-2 and EDM with the reaccelerated thermal muon beam with compact storage ring.
  - **New method (complementary to magic gamma experiments)**
  - **EDM sensitivity ~1E-21 e・cm**
    - All-tracking detector set up
    - Very weak magnetic focusing

- **Important contributions and supports** from the US physicists in the past.
    - Experimental design (initial design, technical review)
    - Cross calibrations

- The experiment is under preparation aiming for data taking from 2025.