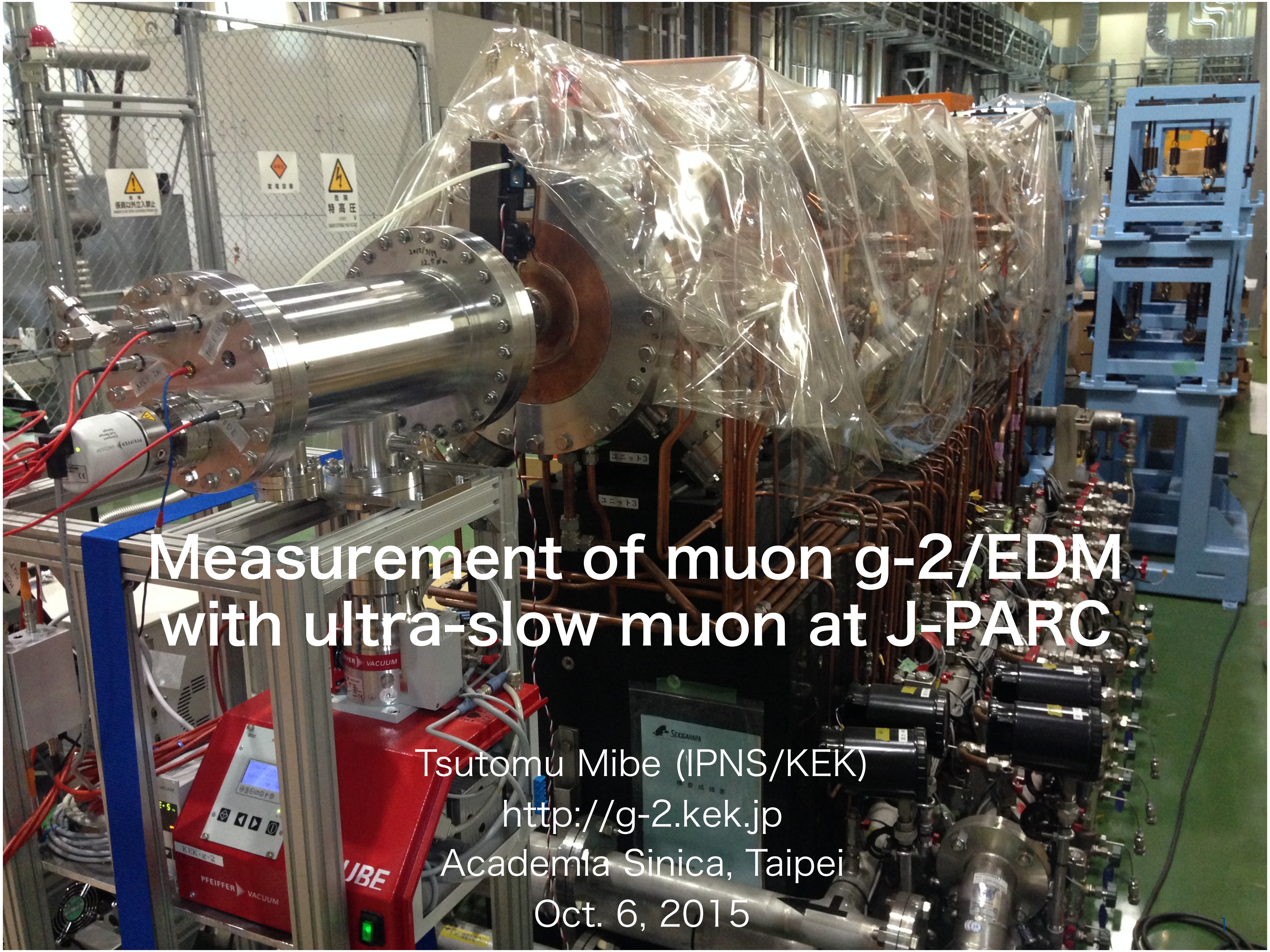


# Measurement of muon g-2/EDM with ultra-slow muon at J-PARC

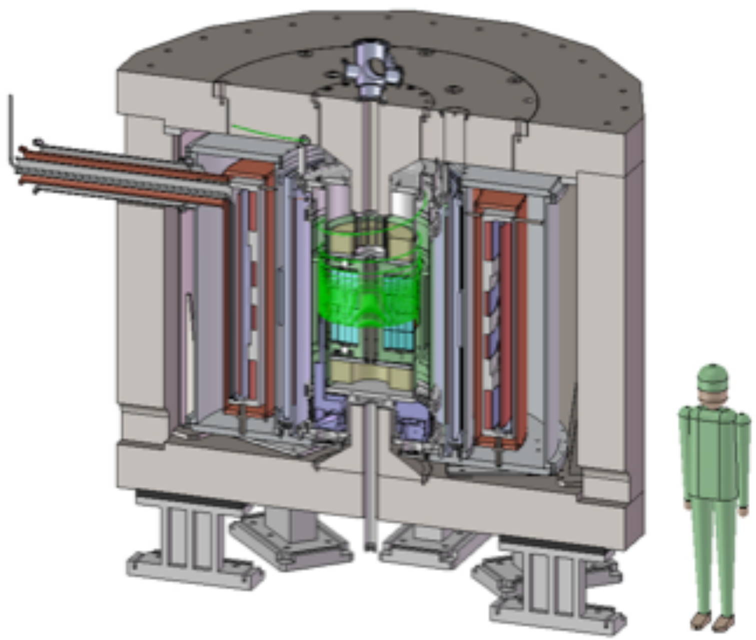
Tsutomu Mibe (IPNS/KEK)
http://g-2.kek.jp

Academia Sinica, Taipei

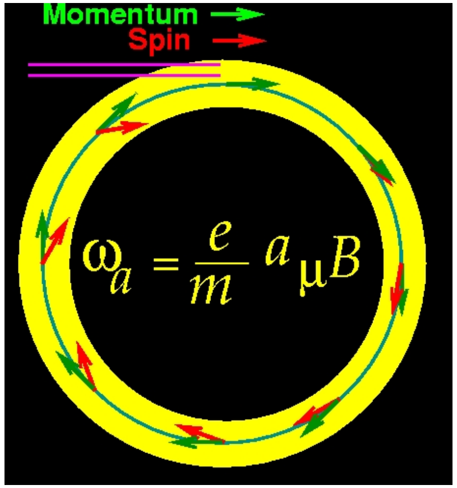
Oct. 6, 2015

# Why g-2 and EDM with new method?

- **BNL E821**
  - $a_\mu$ = 11 659 208.9 (6.3) x $10^{-10}$
    - – 0.46ppm (stat.) + 0.28ppm (syst.) = 0.54ppm →**Stat. dominant**
- **FNAL E989 (Dave's talk)**
- **J-PARC E34**
  - **Brand-new concept**
    - – **Ultra-cold muon beam**
    - – **Compact storage ring**



# 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)*

J-PARC approach
***E = 0 at any γ***

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

FNAL E989

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

J-PARC E34

# Major systematic uncertainties

- **BNL/FNAL major systematics (on $\omega_a$)**

| Source | BNL (ppm) | FNAL goal (ppm) |
|---|---|---|
| Gain changes | 0.12 | 0.02 |
| Lost muons | 0.09 | 0.02 |
| Pile up | 0.08 | 0.04 |
| CBO | 0.07 | 0.04 |
| E and pitch | 0.05 | 0.03 |
| **Total** | **0.18** | **0.07** |

All related with **beam quality and characteristics.**

Largely suppressed by using **"ulta-cold" muon**

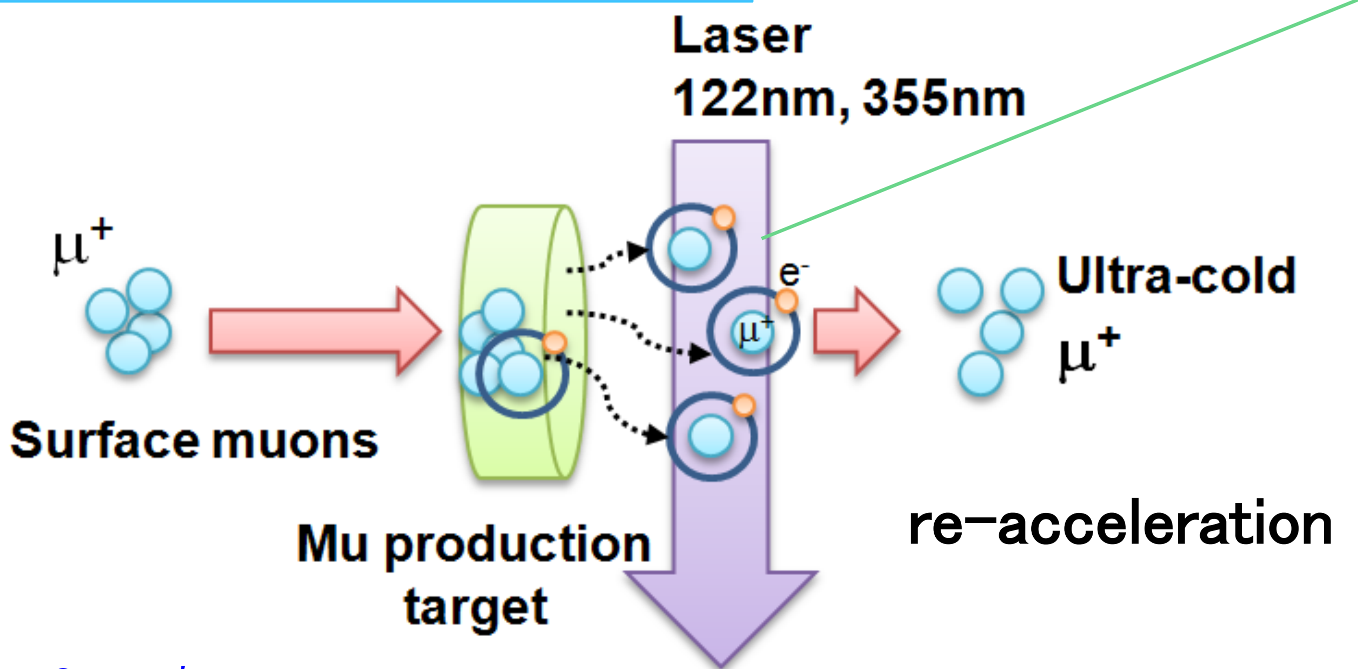
# Ultra-cold Muon

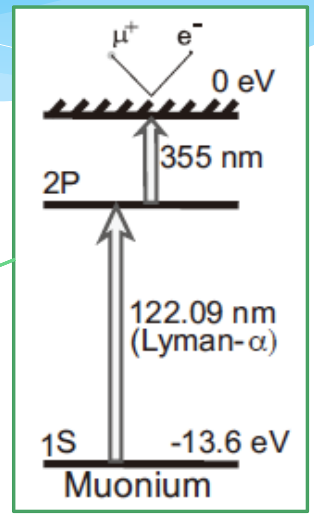
<u>Requirement for zero E-field:</u>

Muons should be kept stored without E-focusing

→ Beam with ultra-small transverse dispersion, i.e. $\Delta p_T/p \sim 0$

Laser resonant ionization of Mu ($\mu^+e^-$)



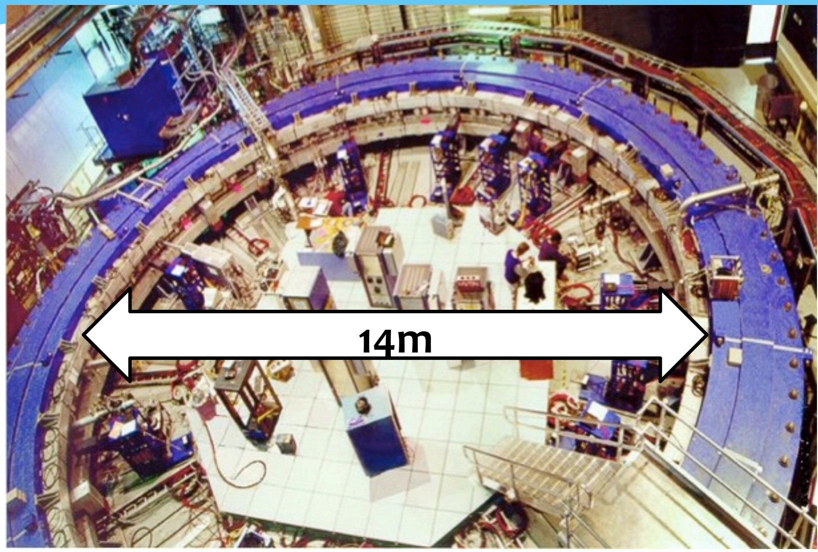




p = 28MeV/c | 3 keV/c | 300 MeV/c

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

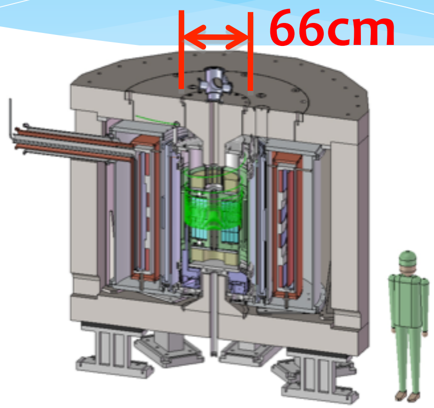
# A compact muon g-2/EDM experiment

*BNL E821 / FNAL E989*




**P= 3.1 GeV/c , B=1.45 T**

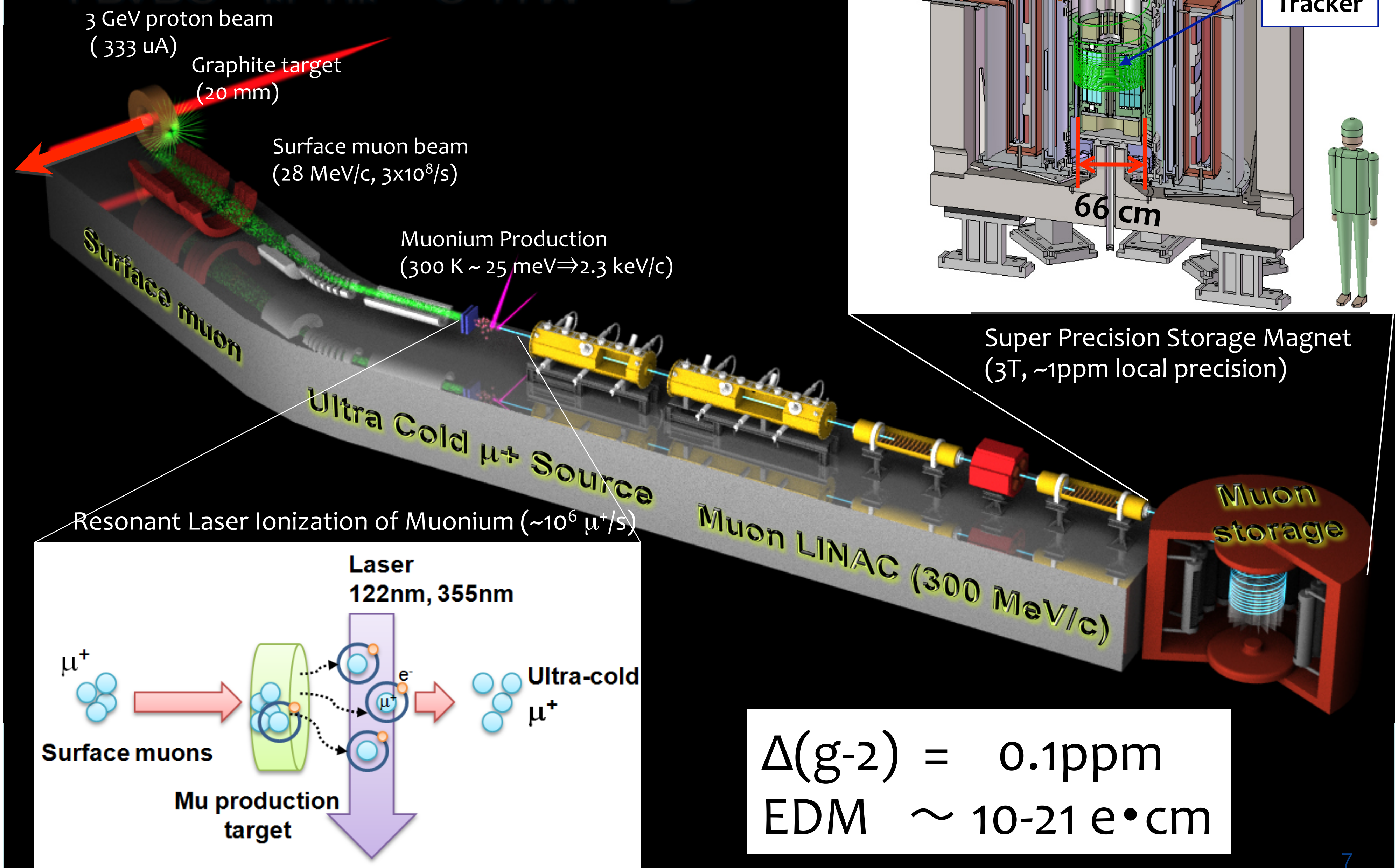
*J-PARC E34*




**P= 0.3 GeV/c , B=3.0 T**

- Advantages
  - **Suited for precision control of B-field**
    Example : MRI magnet , 1ppm local uniformity
  - **Possibility of spin manipulation**
    Effective to cancel various systematics
  - **Completely different systematics than the BNL E821 or FNAL**

# New Muon g-2/EDM Experiment at J-PARC with Ultra-Cold Muon Beam

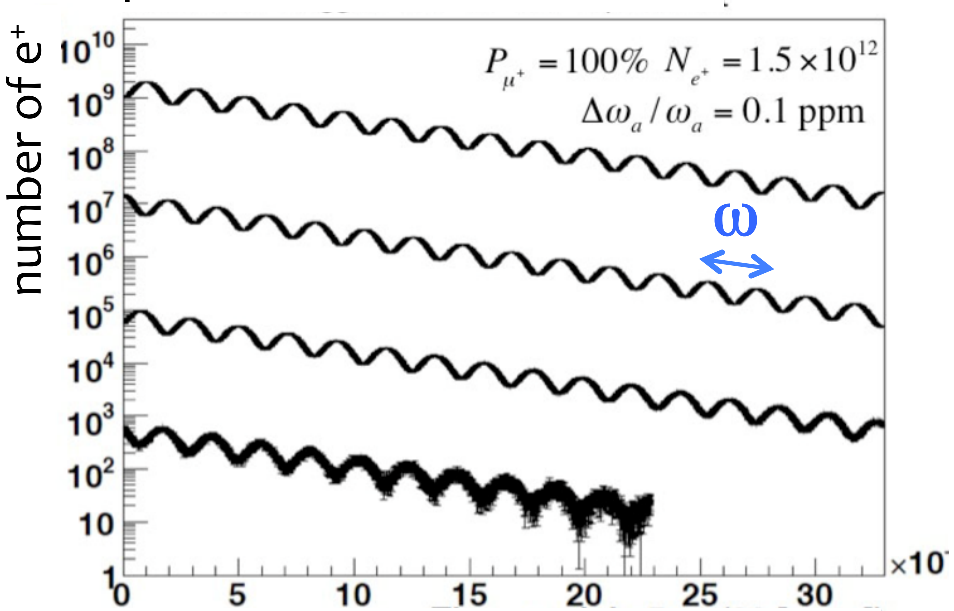


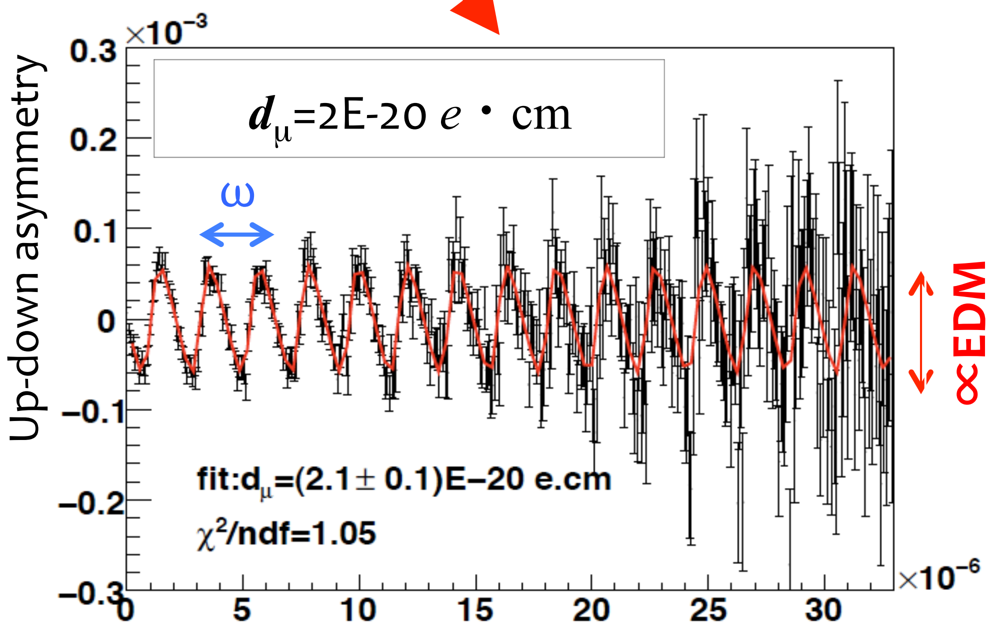

$$\Delta(g\text{-}2) = 0.1\text{ppm}$$
$$\text{EDM} \sim 10\text{-}21\ e\cdot\text{cm}$$

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

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

p>200 MeV/c



# Comparison of experiments

| | BNL-E821 | Fermilab | J-PARC |
|---|---|---|---|
| Muon momentum | 3.09 GeV/c | | **0.3 GeV/c** |
| gamma | 29.3 | | **3** |
| Storage field | B=1.45 T | | **3.0 T** |
| Focusing field | Electric quad | | **Very weak magnetic** |
| # of detected μ+ decays | 5.0E9 | 1.8E11 | **1.5E12** |
| # of detected μ- decays | 3.6E9 | - | **-** |
| Target Precision (stat) | 0.46 ppm | 0.1 ppm | **0.1 ppm** |

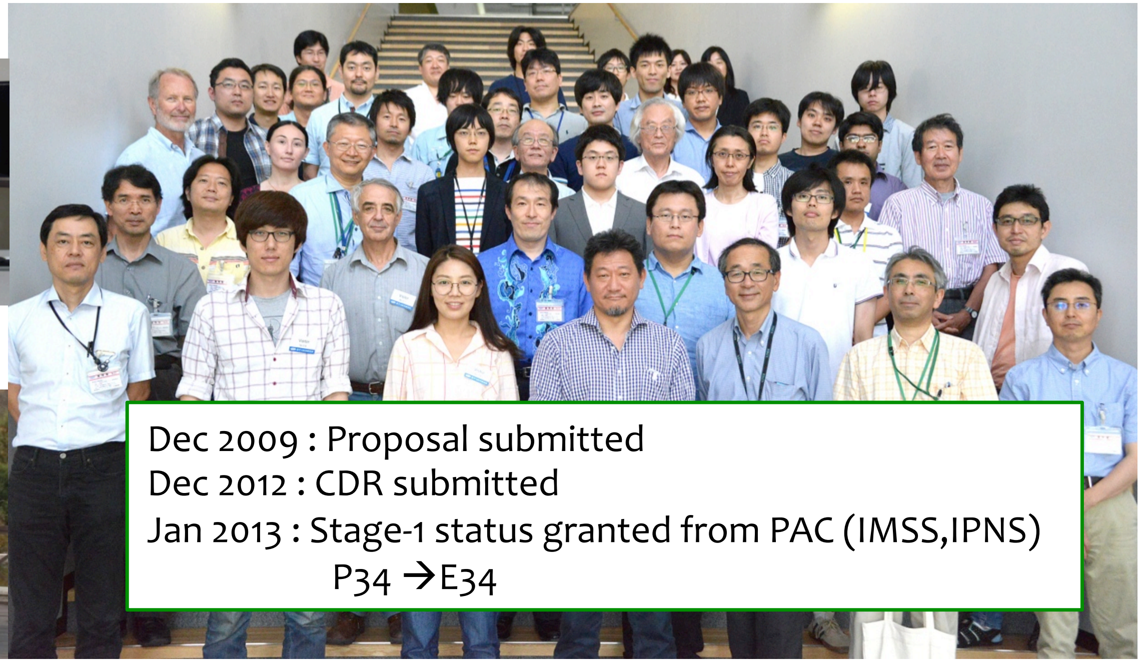
# E34 collaborators

- Collaborators
  - Proposal (2009) 72
  - Conceptual Design Report (2011) 92
  - Technical Design Report (2015) 136 (16 graduate students) (27 also in COMET)
- 9 countries, 49 institutions
  - Canada, China, Czech, France, Japan, Korea, Russia, UK, USA (in alphabetical order)

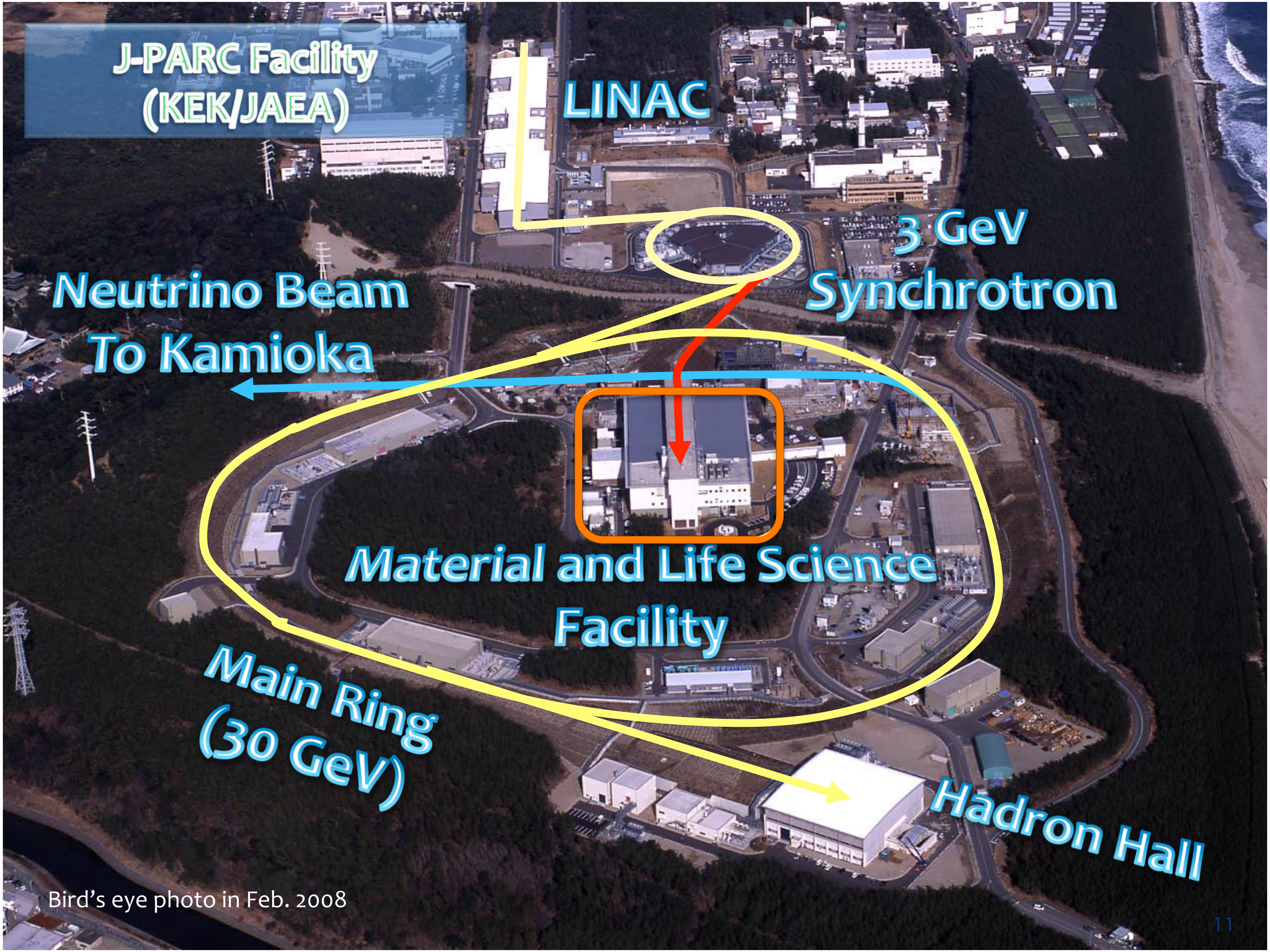
**J-PARC 2014.9**

**KAIST (Korea) 2014.11**


**J-PARC 2015.6**

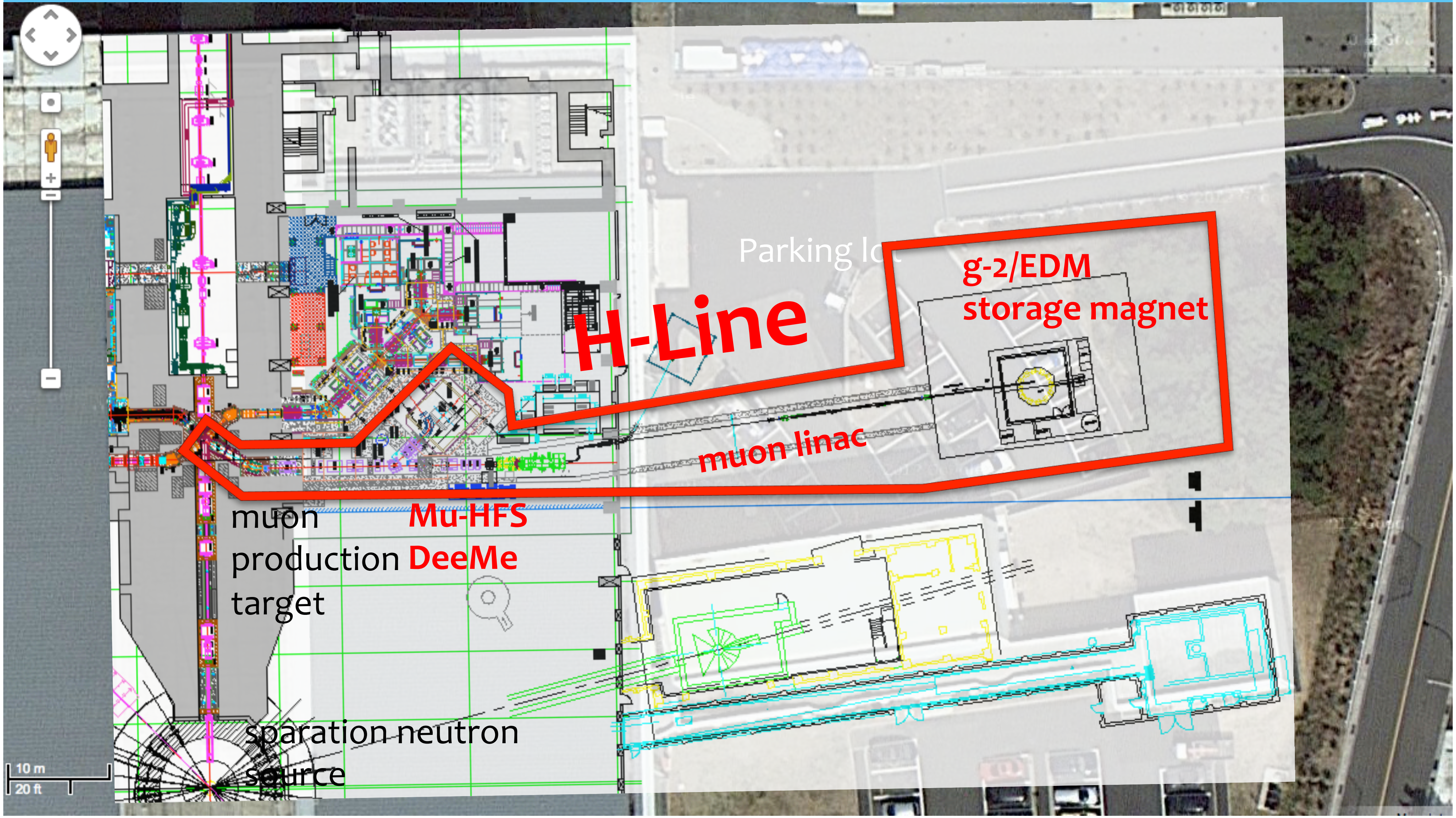


Dec 2009 : Proposal submitted
Dec 2012 : CDR submitted
Jan 2013 : Stage-1 status granted from PAC (IMSS,IPNS)
P34 → E34


J-PARC Facility
(KEK/JAEA)
LINAC
3 GeV
Synchrotron
Neutrino Beam
To Kamioka
Material and Life Science
Facility
Main Ring
(30 GeV)
Hadron Hall
Bird's eye photo in Feb. 2008

# Proposed experimental site

Material and Life science Facility in J-PARC



# TDR

**Technical Design Report**
**for**
**the Measurement of the Muon Anomalous Magnetic Moment $g-2$ and Electric Dipole Moment at J-PARC**

May 15, 2015

prepared by 136 authors

## Summary

In summary, this experiment intends to reach statistical uncertainties for muon $g-2$ of 0.37 ppm and for muon EDM of $1.3 \times 10^{-21} e \cdot \text{cm}$, during an acquisition time of $2 \times 10^{7}$ seconds of high-quality data, with a completely new experimental technique based on an ultra-cold muon beam and a compact storage ring. We will show in this document that our current understanding of the available beam power, the efficiency of the ultra-cold muon source, the muon acceleration, injection, and storage, and decay detection, all indicate that this is achievable. The statistical reach in the quoted running time is lower than we originally proposed. However, the $g-2$ sensitivity, even at this level, should exceed that of BNL E821 and provide an independent test of the three to four sigma discrepancy with the Standard Model prediction. Moreover, it would reduce the existing upper limit for the muon EDM by a factor of about 70. In the process of achieving these important goals, we would also be able to identify and understand any systematic uncertainties that may have to be reduced before attaining the final goal as originally proposed. In parallel, we will continue R&D, especially on the ultra-cold muon source intensity, to further improve the sensitivity to the final goal of 0.1 ppm for $g-2$.

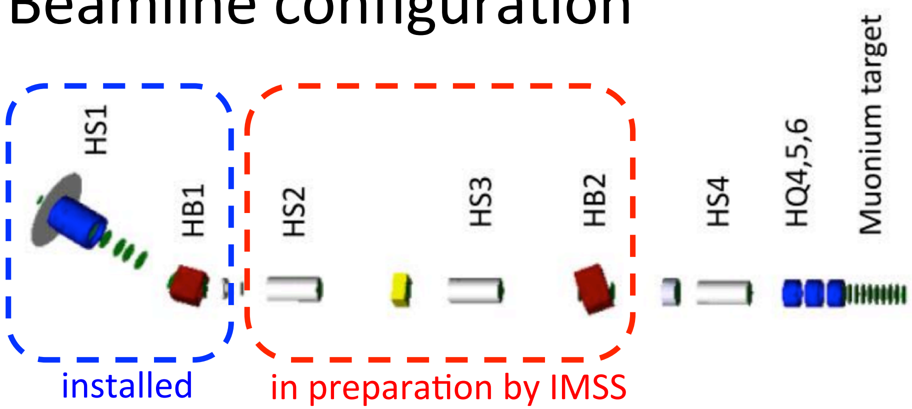
- TDR describes a technical design to achieve measurement of muon g-2 and EDM beyond BNL E821 precision.

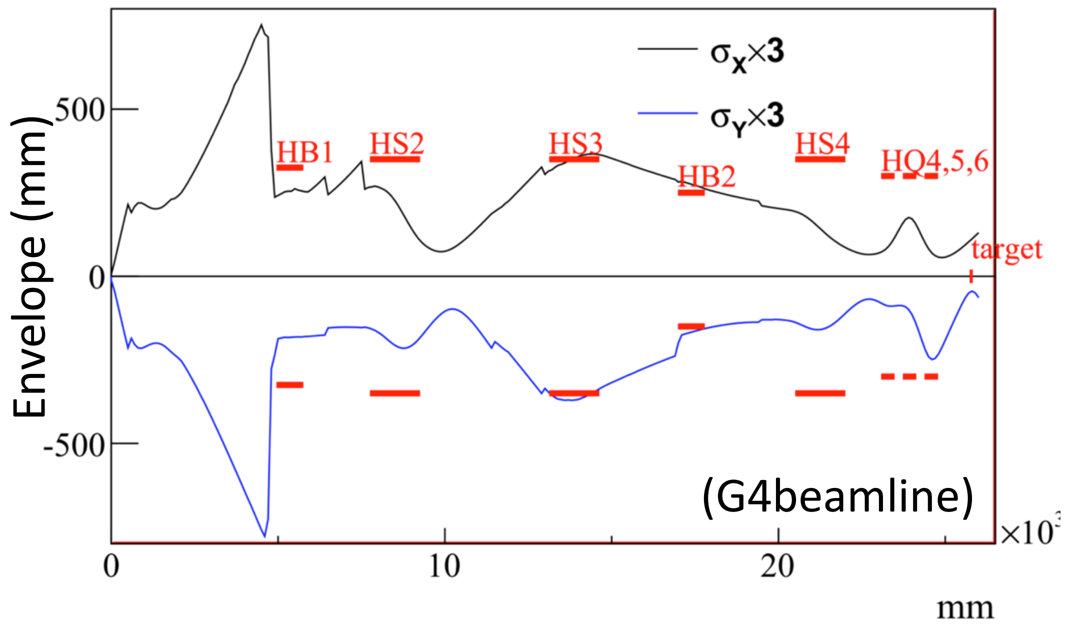
| | BNL E821 | | J-PARC E34 |
|---|---|---|---|
| g-2: | 0.46 ppm | → | 0.37 ppm (→0.1ppm) |
| EDM: | $0.9 \times 10^{-19}$ ecm | → | $1.3 \times 10^{-21}$ ecm |

# Surface muon beamline (H-line)

M. Otani, N. Kawamura

## Beamline configuration

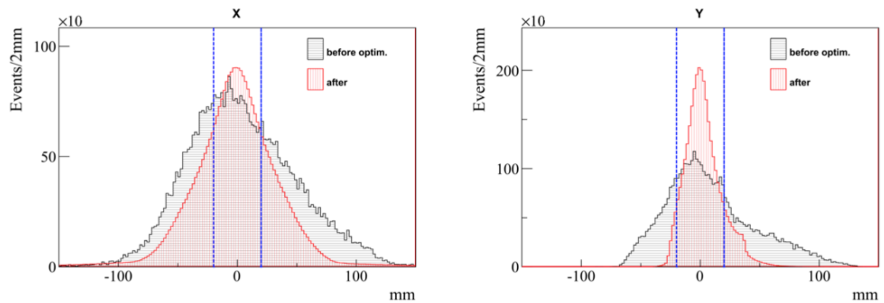



- Muon beam intensity was estimated by scaling from measured intensity at D-line (200kW) and simulated beam transport efficiency 16%:

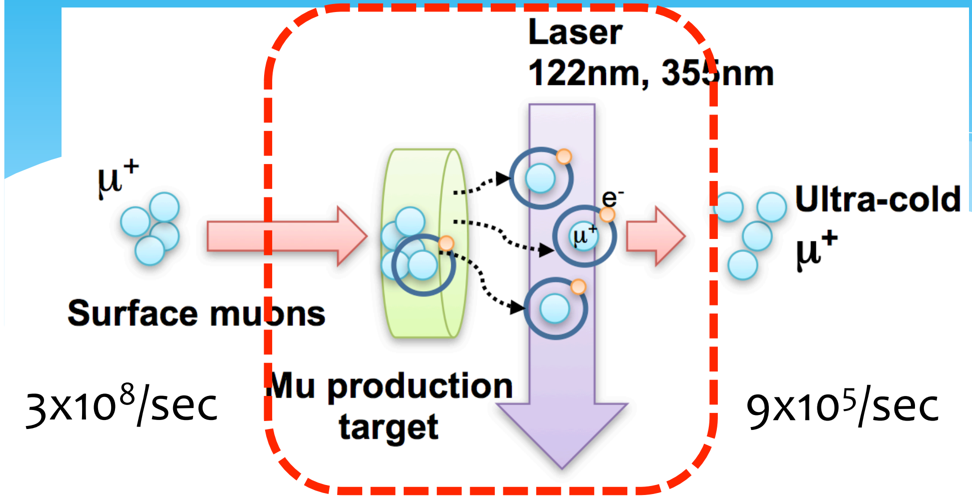
  3.2 E+8/sec (w/ SiC)

  on Mu production target at 1MW

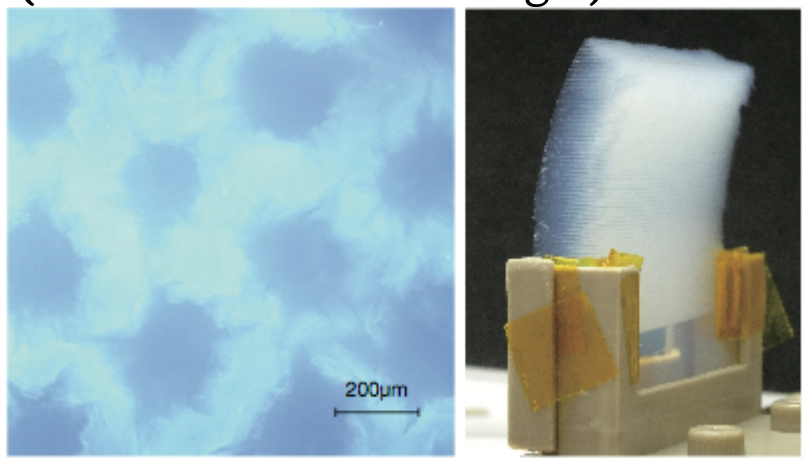


# Muonium production

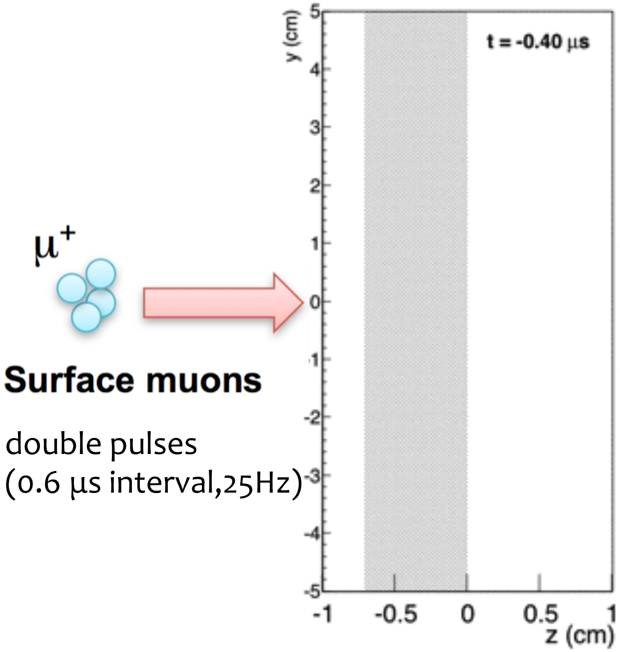
RIKEN, TRIUMF, UVic, Chiba, Korea U, KEK

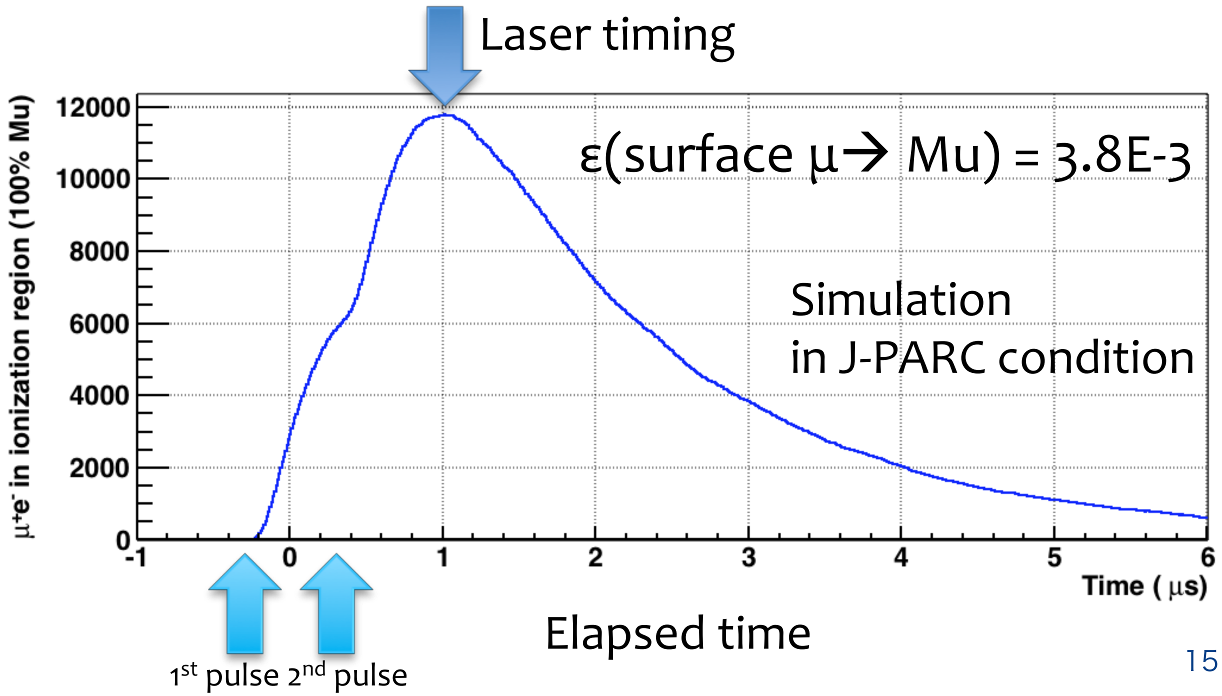



Mu production target
(laser-ablated silica aerogel)

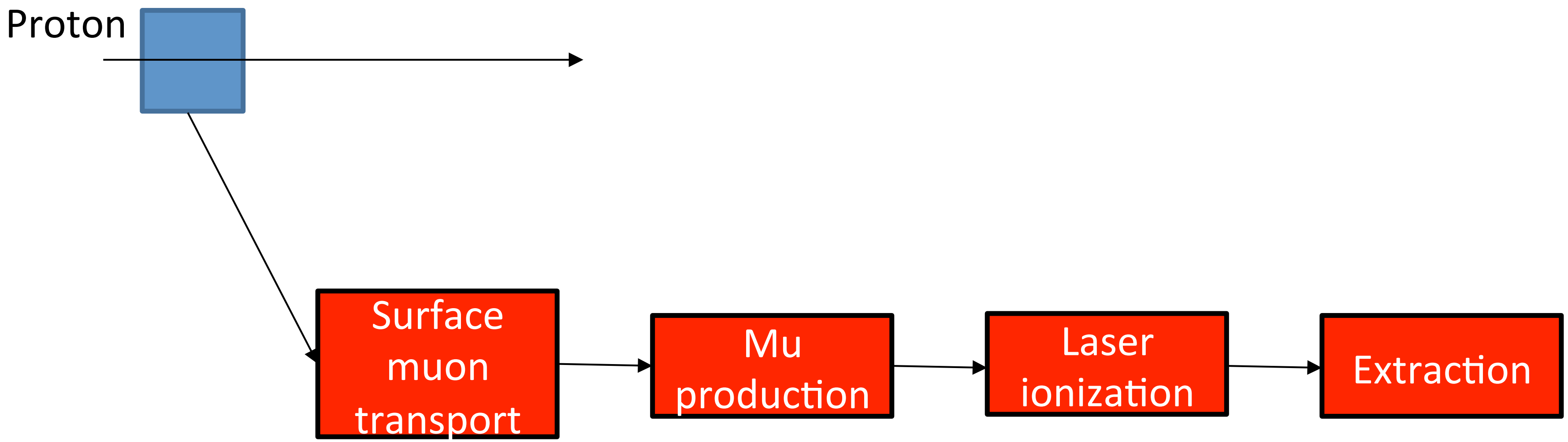



G. Beer et al., Prog.Theor.Exp.Phys. (2014)091C01



# Ultra slow muon source summary




| | | | | |
|---|---|---|---|---|
| energy | 4 MeV | 20 meV | 20 meV | ~100 eV |
| efficiency | 0.16 | 0.0038 | 0.73 | 0.76 |
| **status** | **to be ready** | **ready** | **evaluation** | **evaluation** |

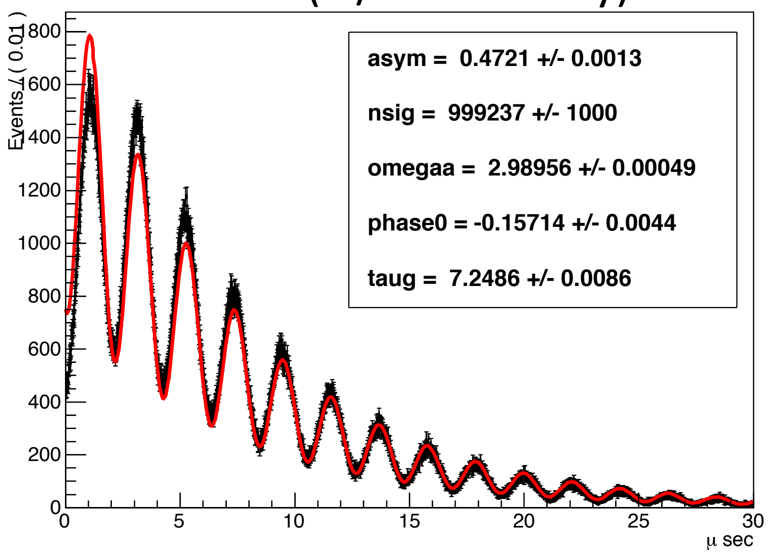
# Spin reversal
# (ONLY possible in J-PARC E34)

$$R(t, E_e) = \frac{N^{+}(t, E_e) - N^{-}(t, E_e)}{N^{+}(t, E) + N^{-}(t, E_e)}$$

$$R(t, E_e) = \cos(\omega_a t + \phi)$$

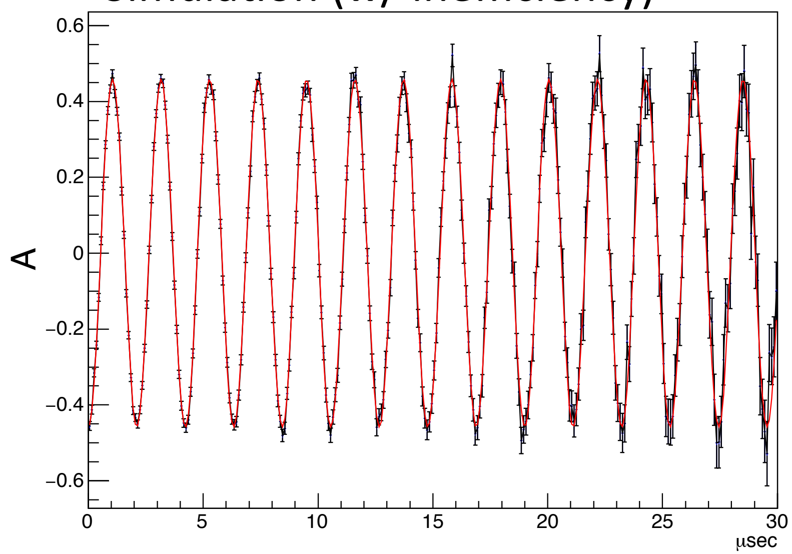
**Raw time distribution**

Simulation (w/ inefficiency)




**Asymmetry distribution**

Simulation (w/ inefficiency)




Plots by E. Won

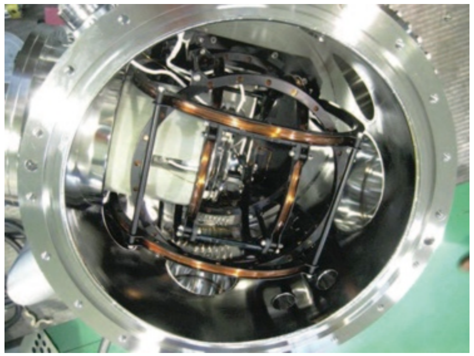
# Spin reversal
# (ONLY possible in J-PARC E34)

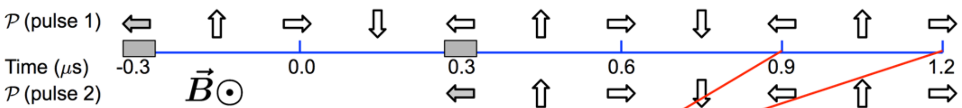
$$R(t, E_e) = \frac{N^+(t, E_e) - N^-(t, E_e)}{N^+(t, E) + N^-(t, E_e)}$$

$$R(t, E_e) = \cos(\omega_a t + \phi)$$

Two spin reversal apparatus are installed.

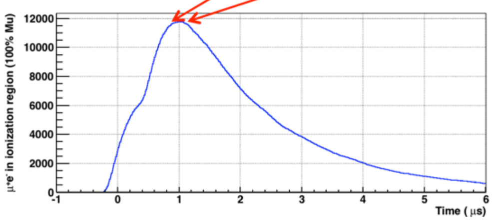
## Flip at rest (Muonium)





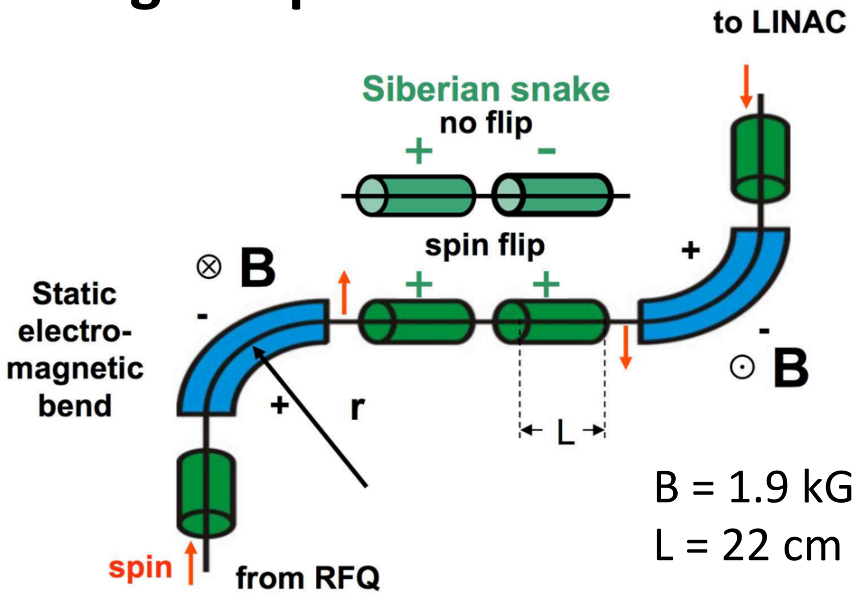

B=1.19 G

Simulation of Mu time distribution in vacuum ionization region for J-PARC beam.




Ishida, Okada, Marshall

## In-flight flip

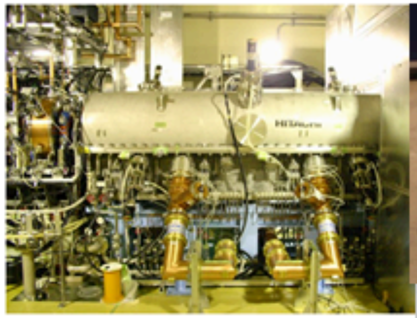
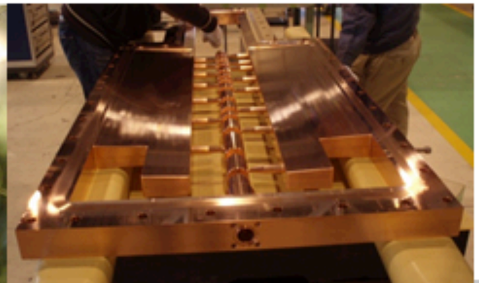
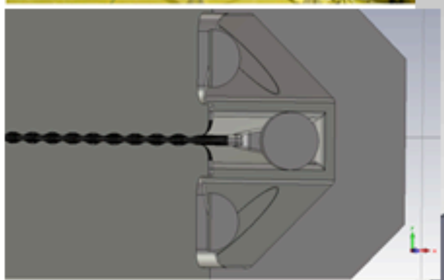
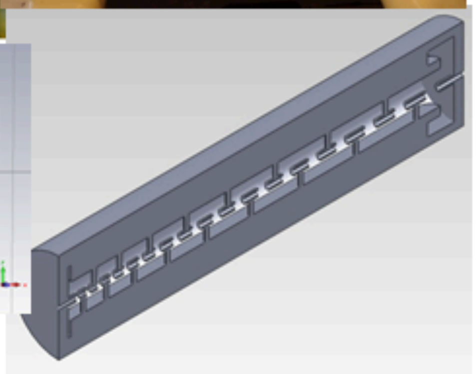
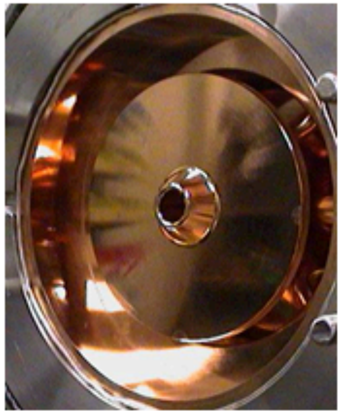
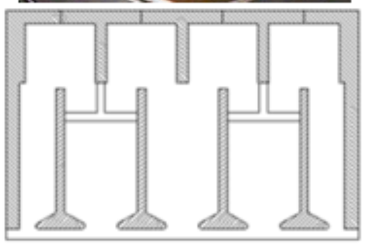
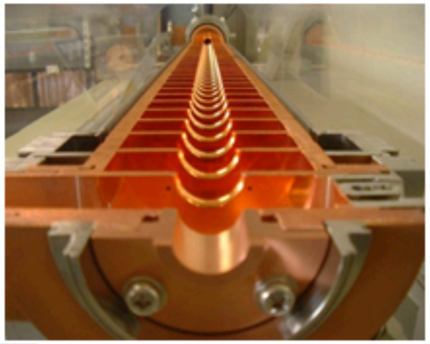
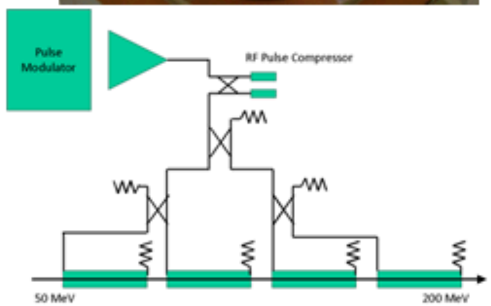



Satunov

# Adopted technology for muon acceleration

| 5.6 keV β≈0.01 | 0.34 MeV β≈0.08 | 5.1 MeV β≈0.3 | 42.3 MeV β≈0.7 | 200 MeV β≈0.94 |
|---|---|---|---|---|

| | Bunching Section | Low-β | Middle-β | High-β |
|---|---|---|---|---|
| $\mu e^-$ | RFQ (324 MHz) High capture efficiency | Interdigita-H (324 MHz) High shunt impedance | DAW (1300 MHz) External coupling structure for Middle-β | Disk loaded structure (1300 MHz) High gradient (4 structures) |

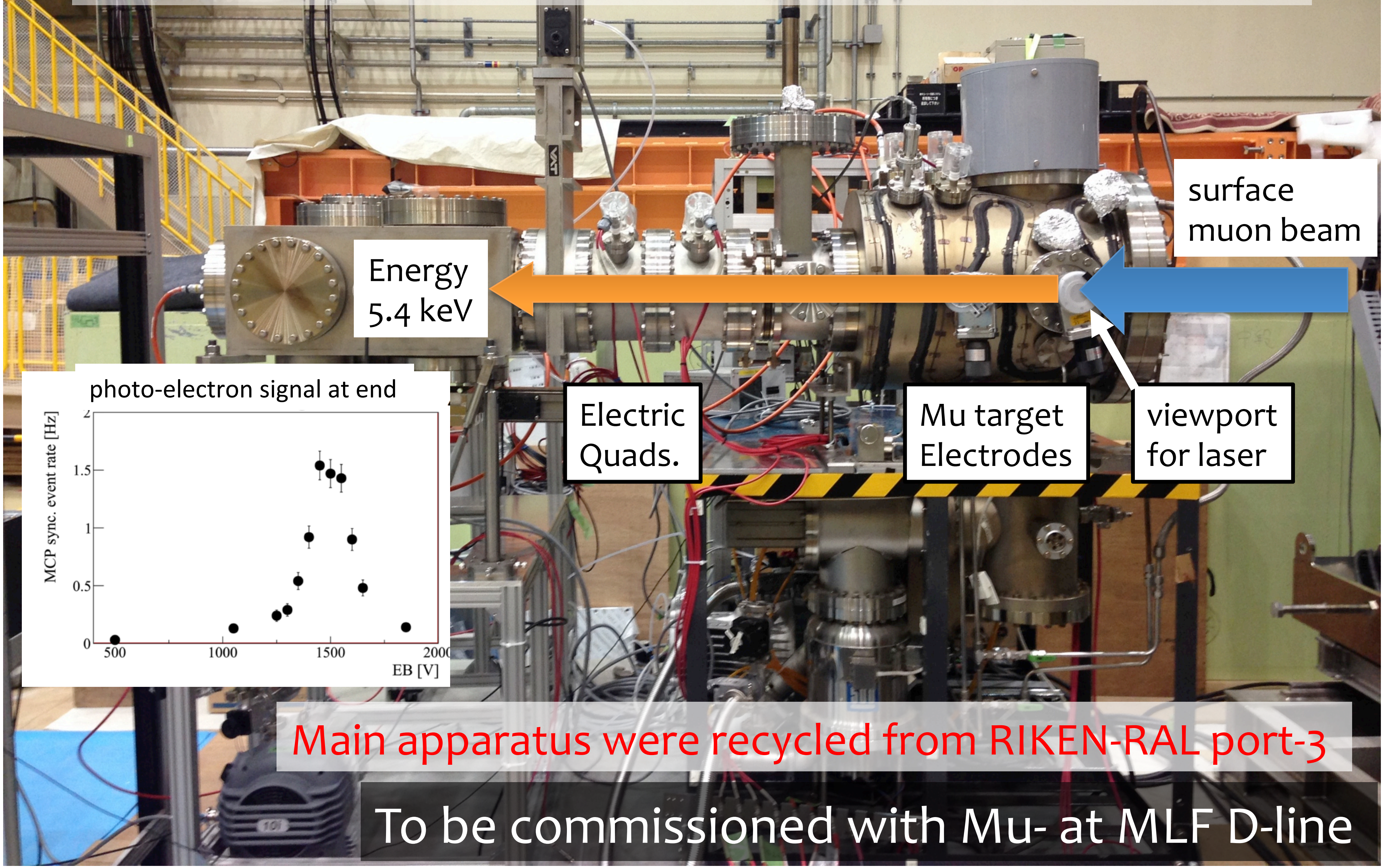

Bunching Section

High hunt impedance

External coupling structure for low-β

Similar to electron accelerator to obtain high gradient.

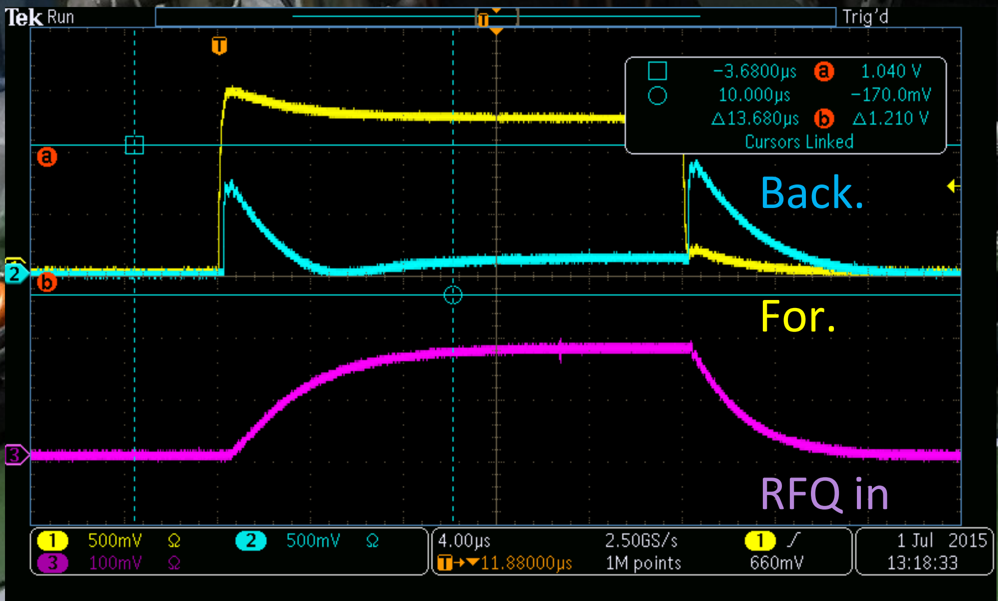
# Muon acceleration studies at J-PARC

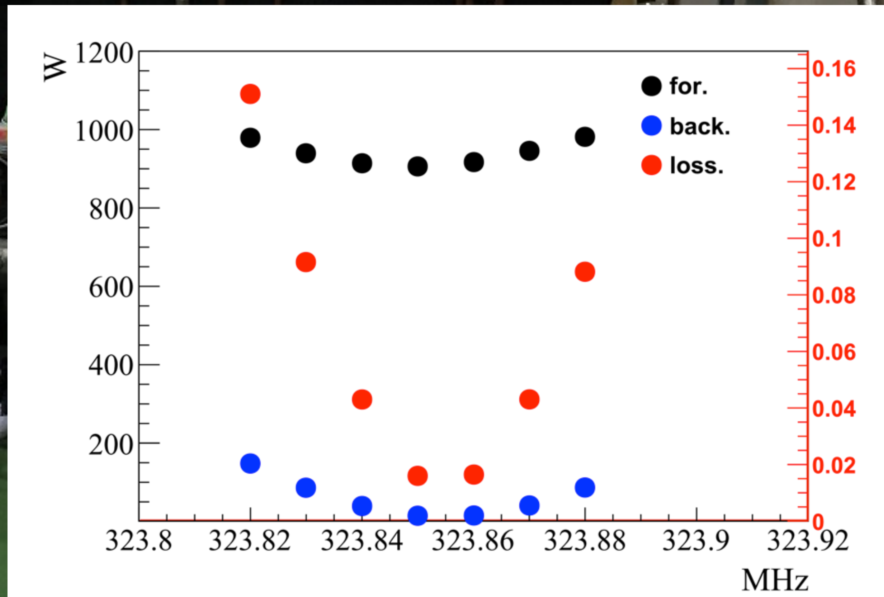


Y. Kondo, M. Otani

# RFQ offline test at J-PARC

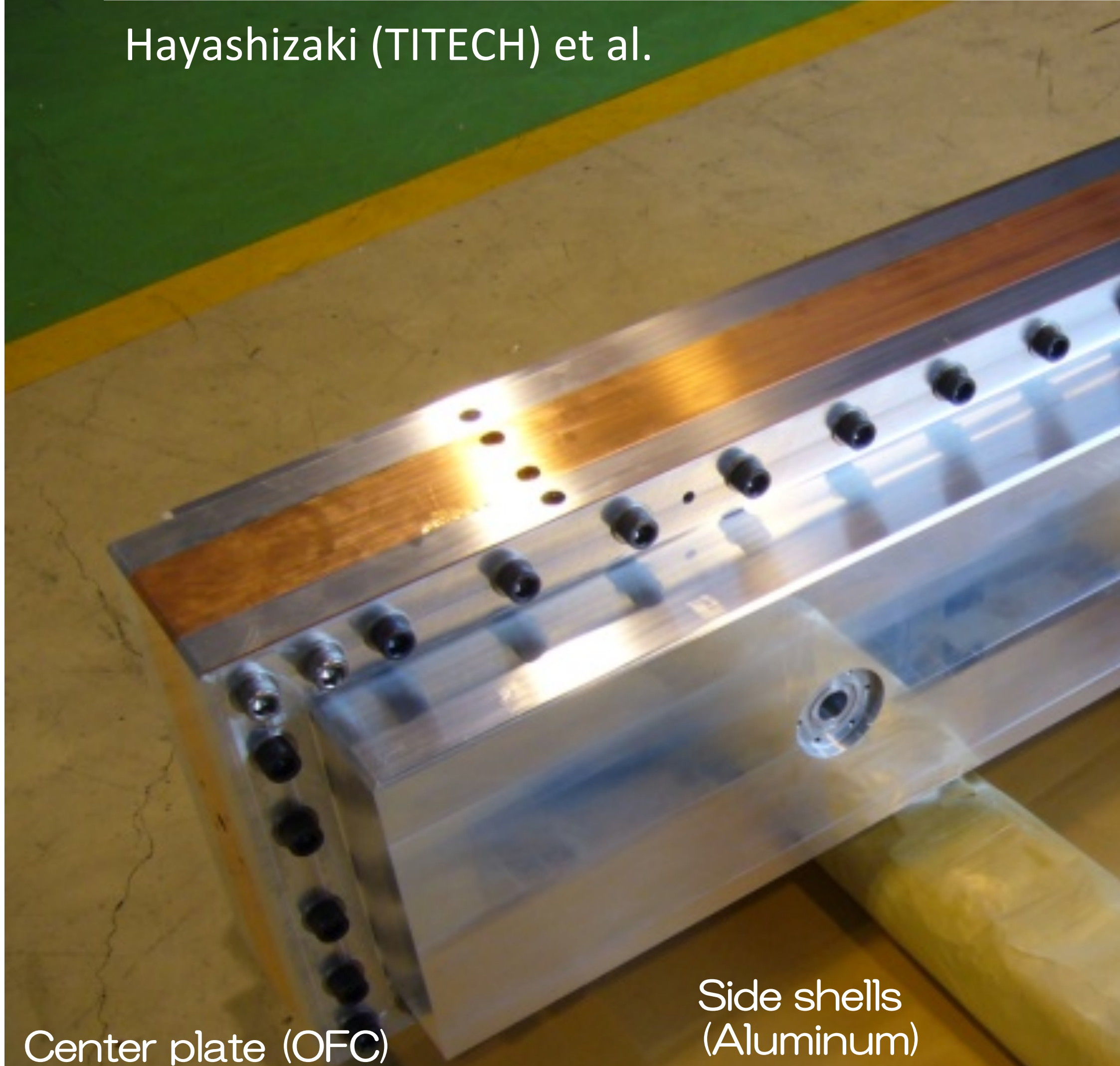
Data taken in July, 2015



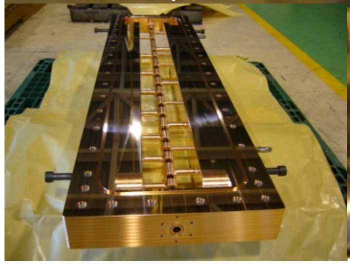



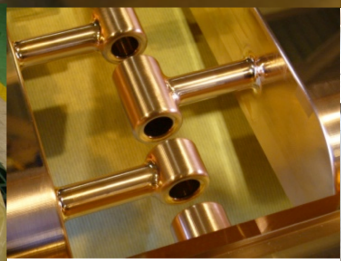
# Muon IH prototype

Hayashizaki (TITECH) et al.

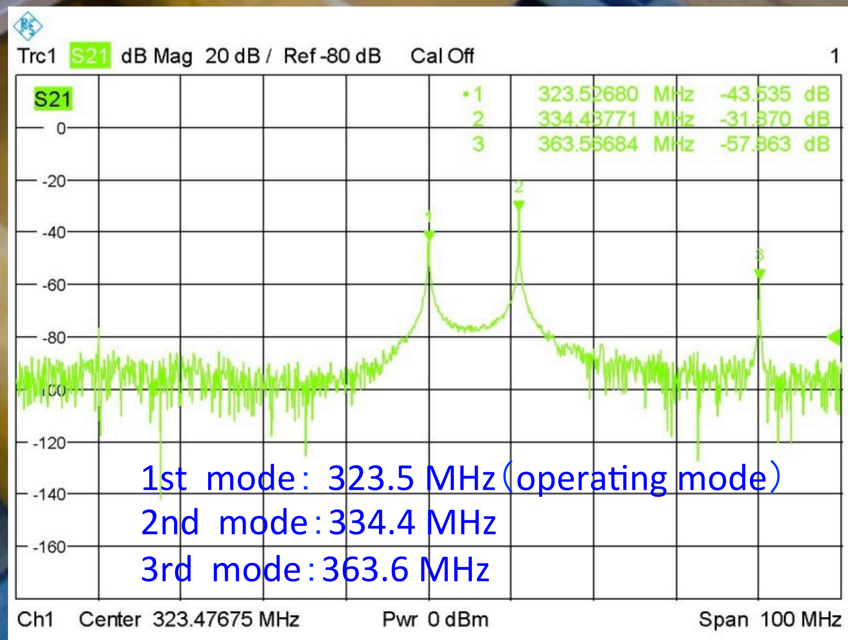


Center plate (OFC)



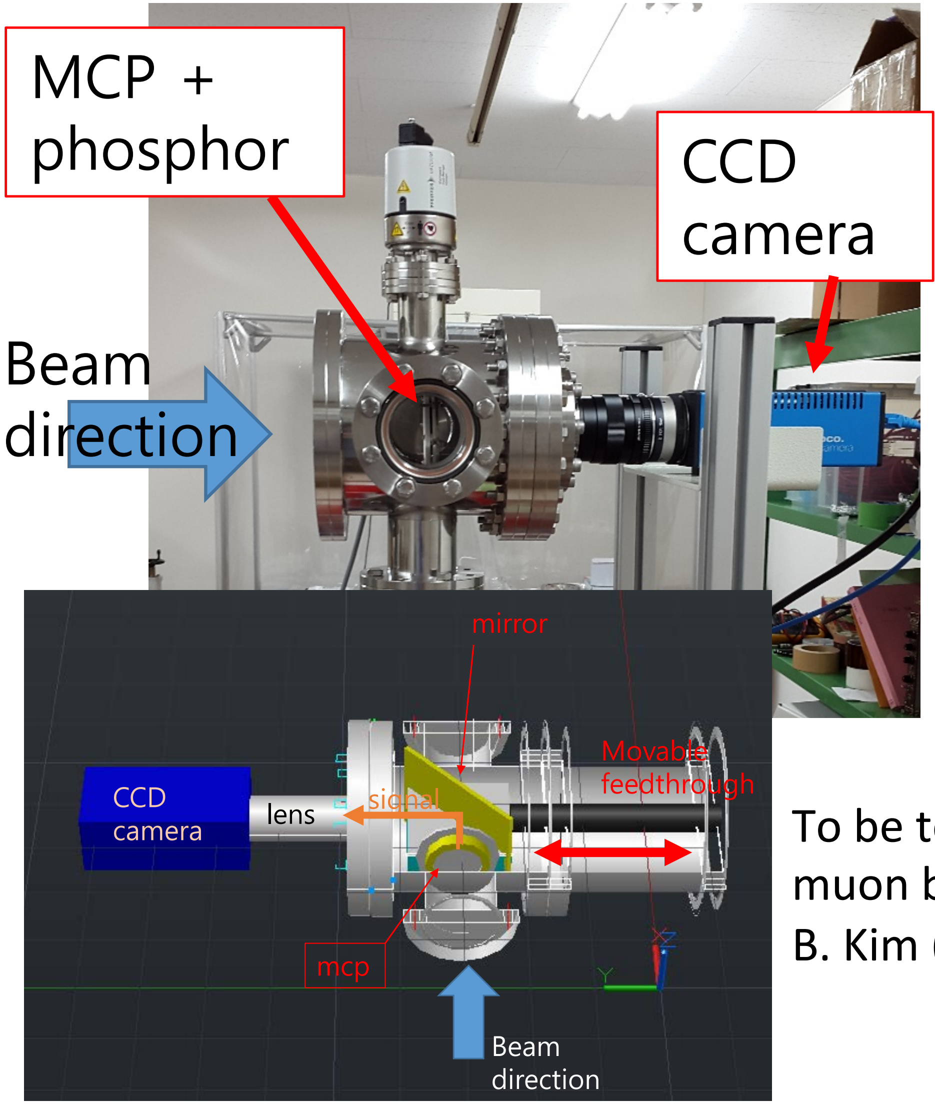


Side shells (Aluminum)



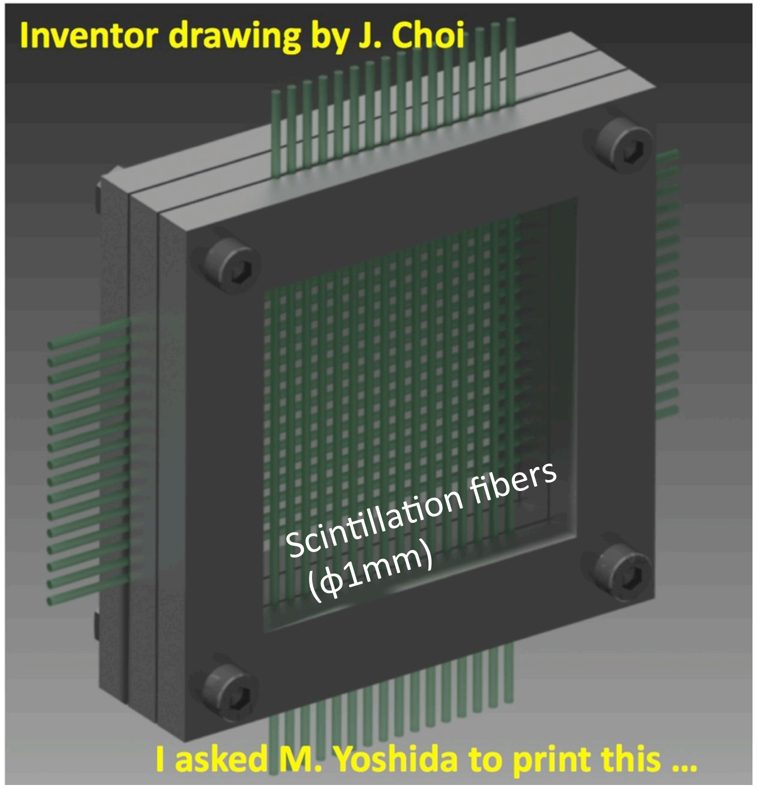
# Muon BPMs

**BPM for low energy muon (less than 1 MeV)**




To be tested with muon beam
B. Kim (SNU)

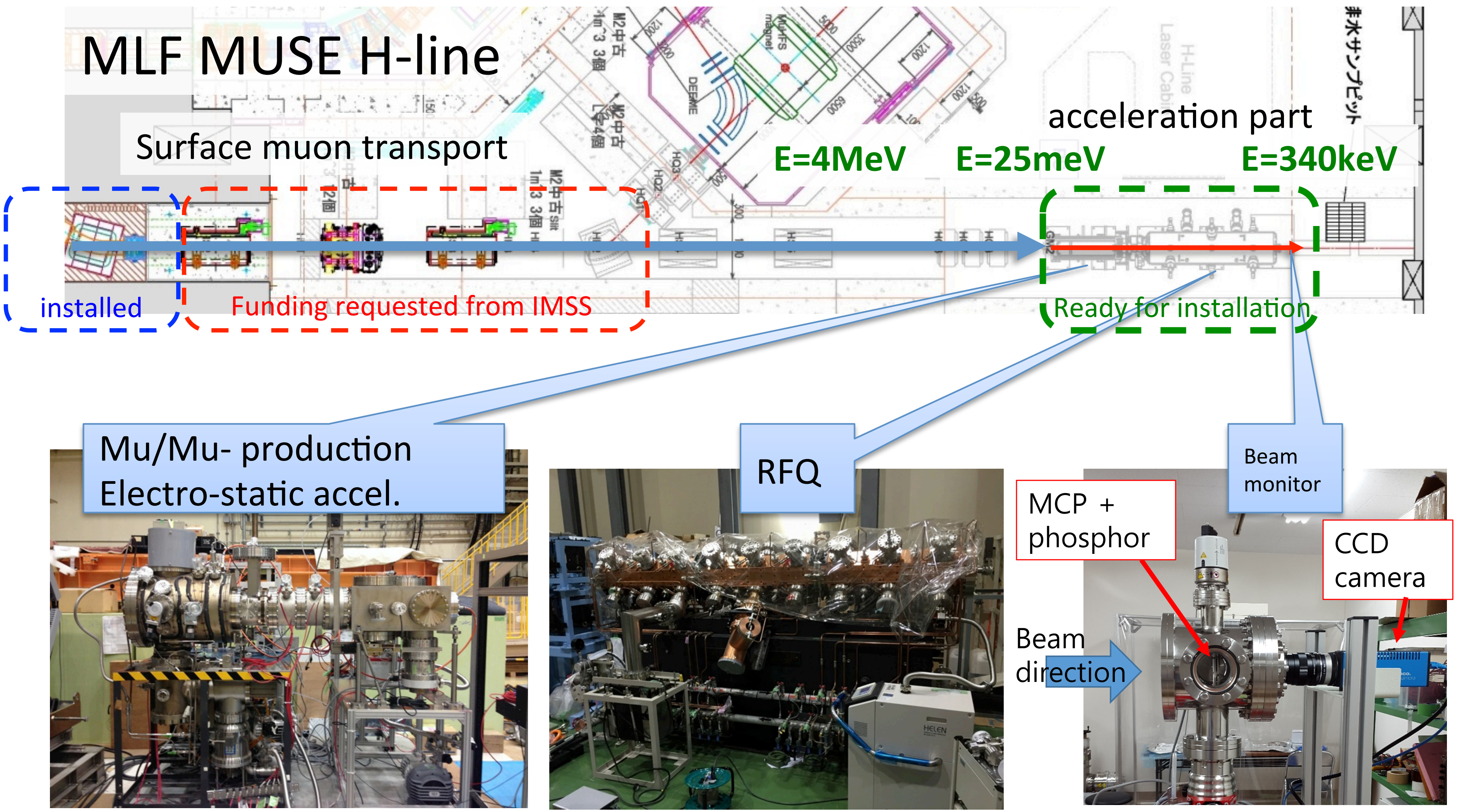
**BPM for higher energy muon (more than 1 MeV)**




E. Won, J. Choi (Korea U)

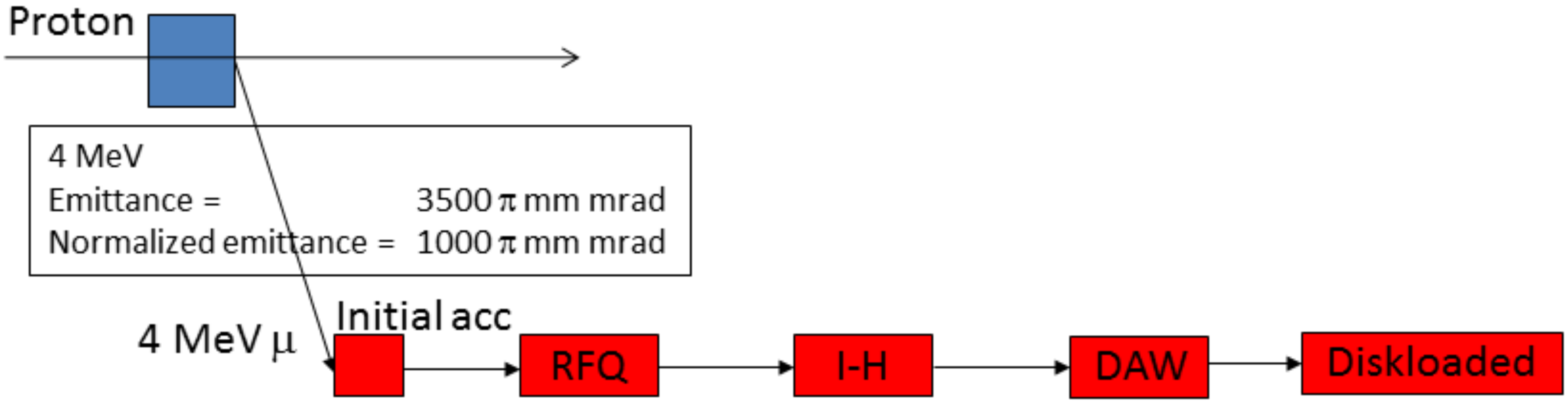
# Muon acceleration test

- World first muon accelerator!




A short extension of muon transport line + shield will make this possible.

# Muon acceleration summary




| | | | | | |
|---|---|---|---|---|---|
| | 5.7keV | 340 keV | 4 MeV | 50MeV | 200 MeV |
| $\beta\gamma$ | 0.01 | 0.08 | 0.278 | 0.98 | 2.71 |
| Emittance(mm mrad) | 150 | 19 | 5.4 | 1.5 | 0.55 |
| Normalized emittance | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 |

| | | | | | |
|---|---|---|---|---|---|
| transmission | 0.72 | 0.95 | 1.00 | 1.00 | 0.98 |
| decay survived | ↑ | 0.81 | 0.98 | 0.99 | 0.99 |
| **status** | **ready** | **ready** | **evaluation** | **prototype** | **prototype** |

# Muon storage magnet and detector

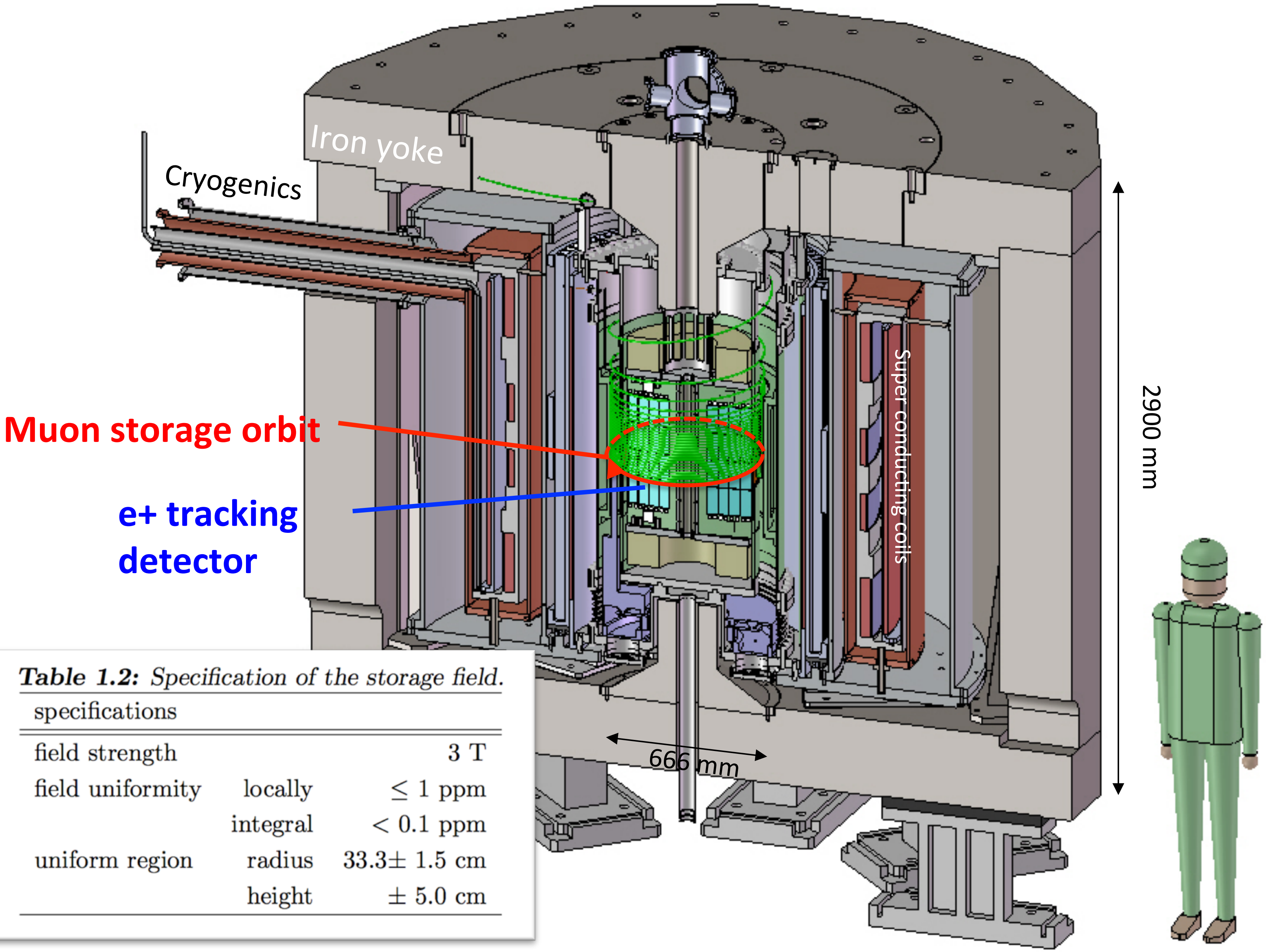
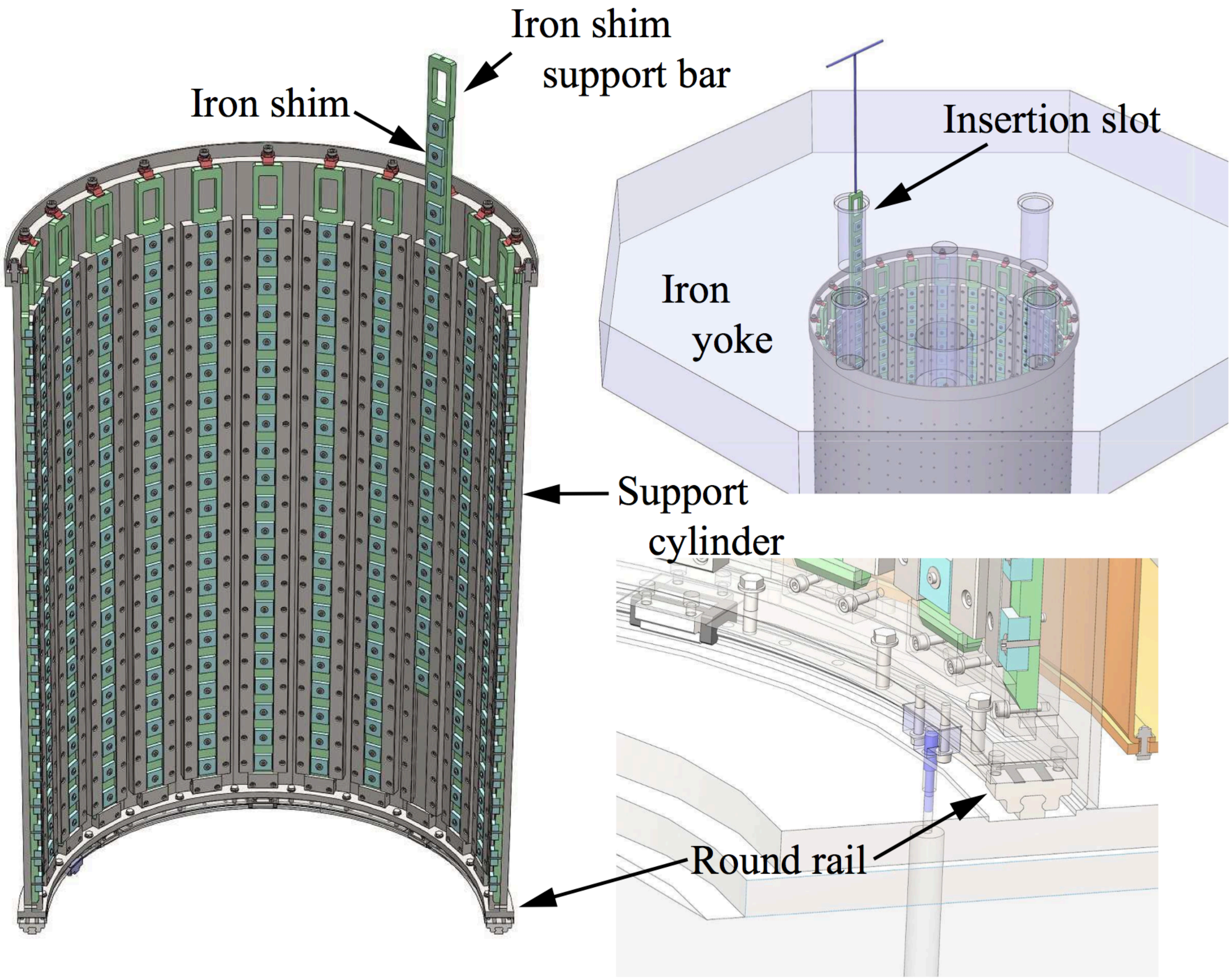



*Table 1.2: Specification of the storage field.*

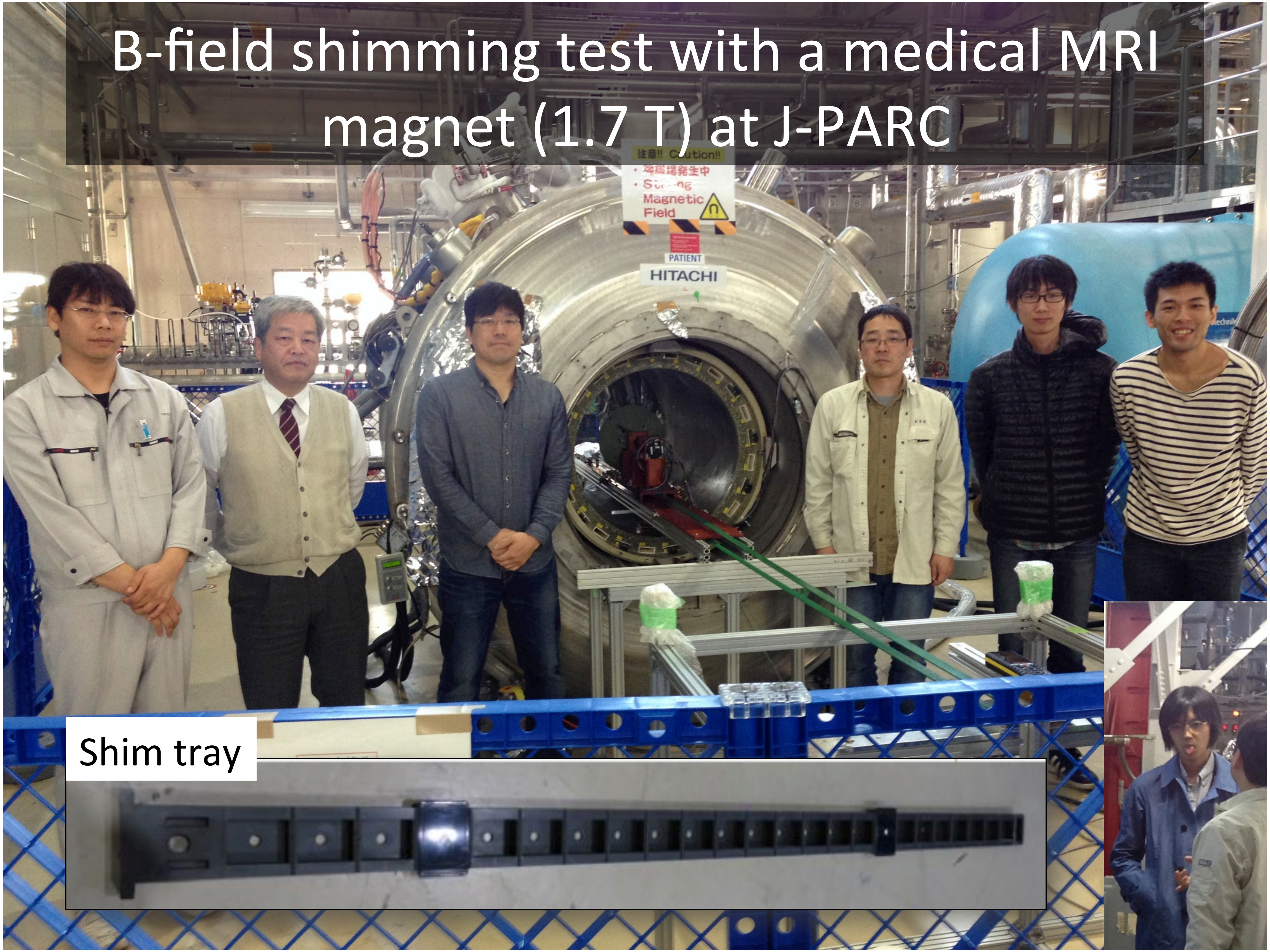
| specifications | | |
|---|---|---|
| field strength | | 3 T |
| field uniformity | locally | $\leq$ 1 ppm |
| | integral | $<$ 0.1 ppm |
| uniform region | radius | 33.3$\pm$ 1.5 cm |
| | height | $\pm$ 5.0 cm |


26

# Organization of iron shim arrays



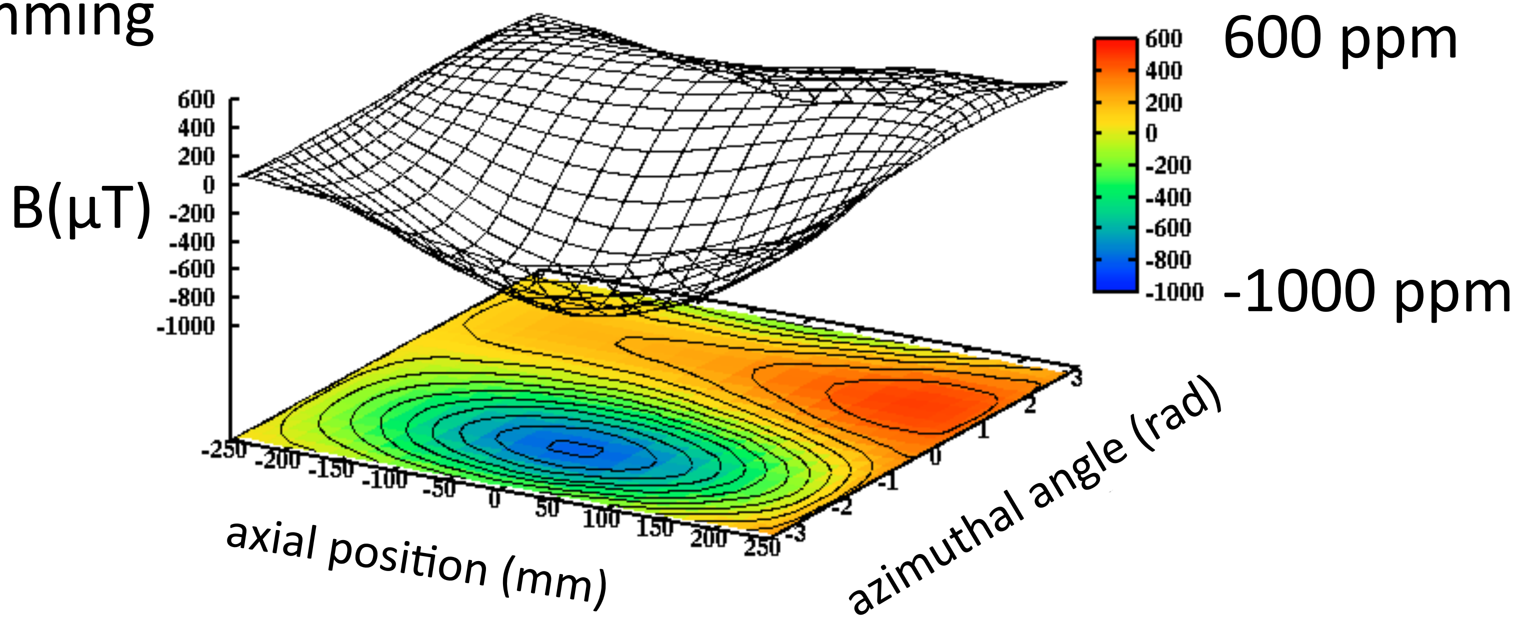
# B-field shimming test with a medical MRI magnet (1.7 T) at J-PARC



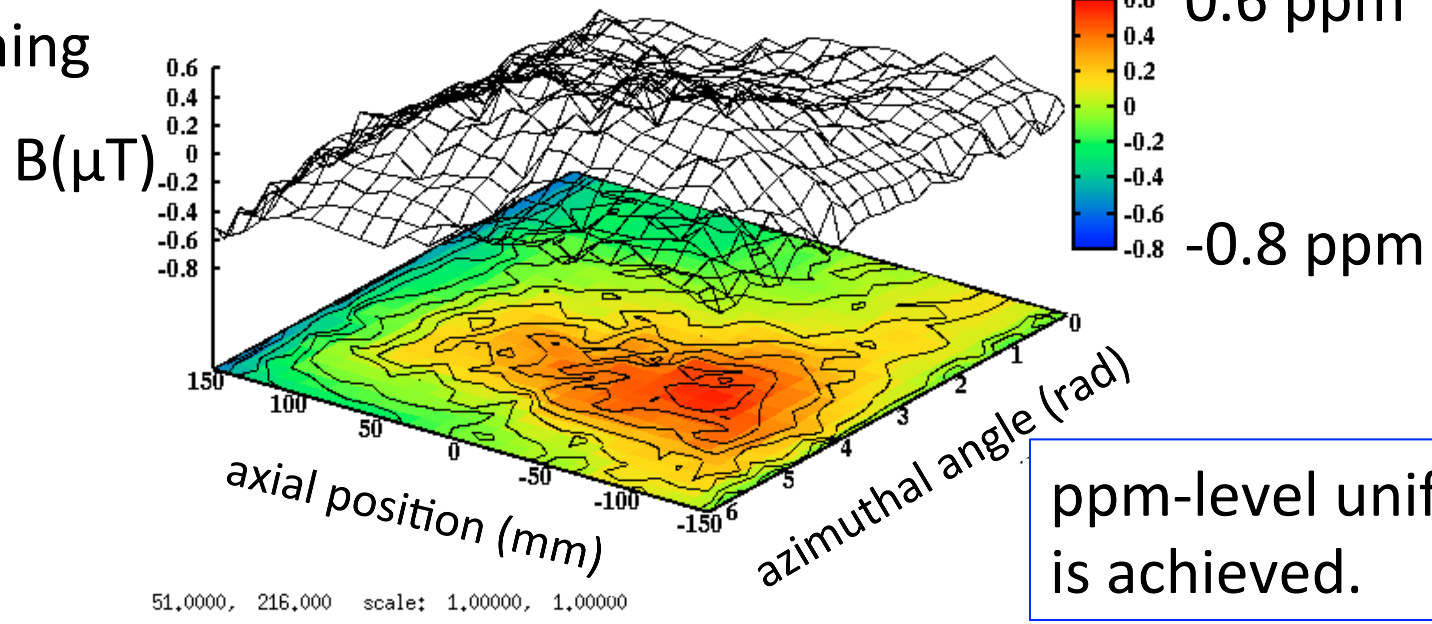
Plots by K. Sasaki

# Field shimming by iron arrays

Before shimming



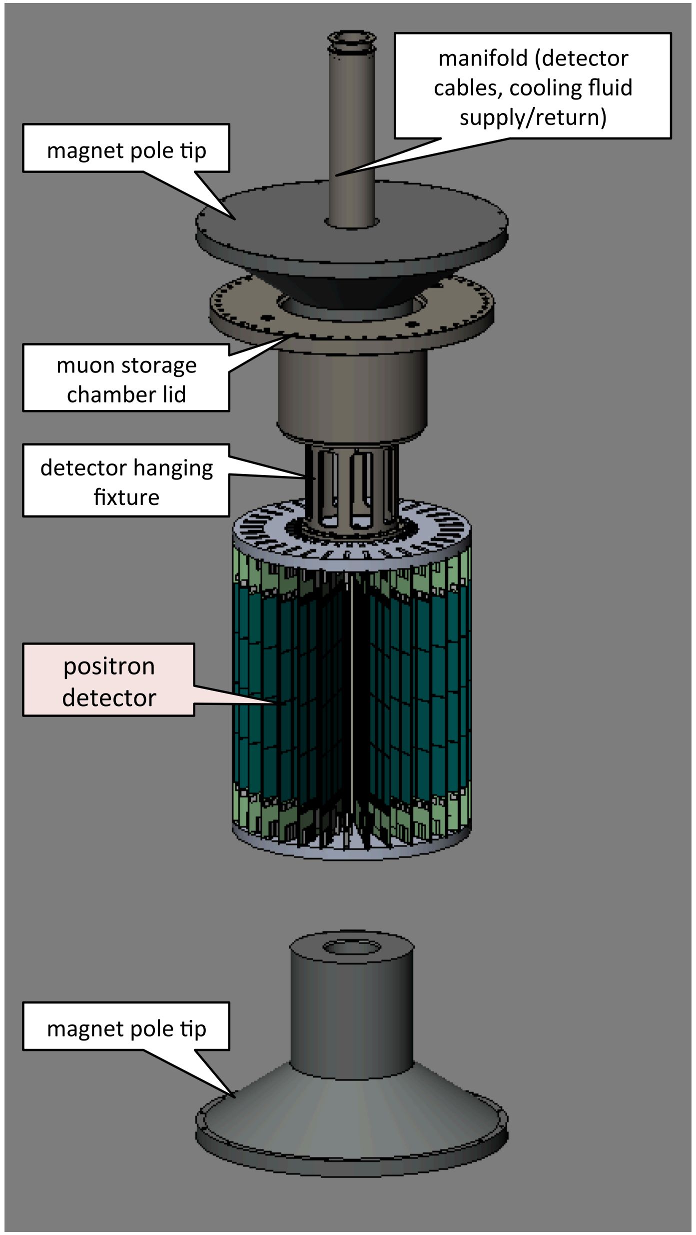

After shimming

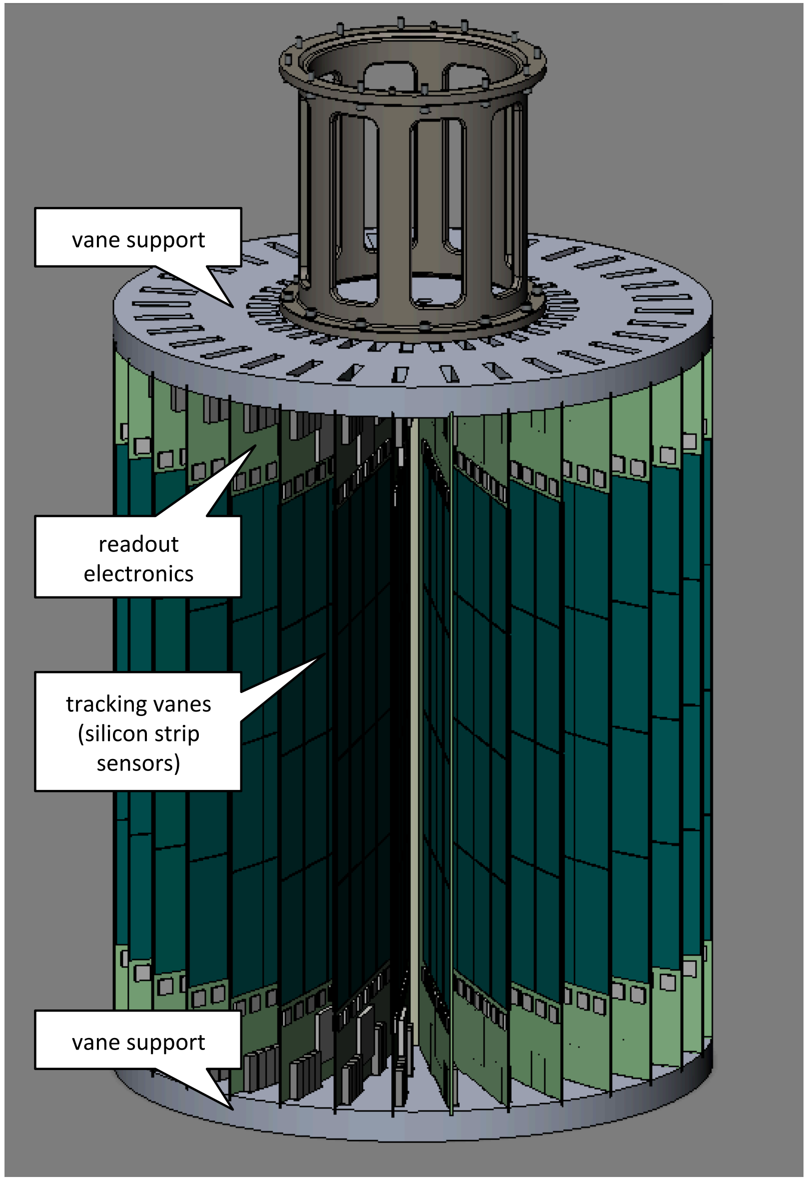



r = 140 mm

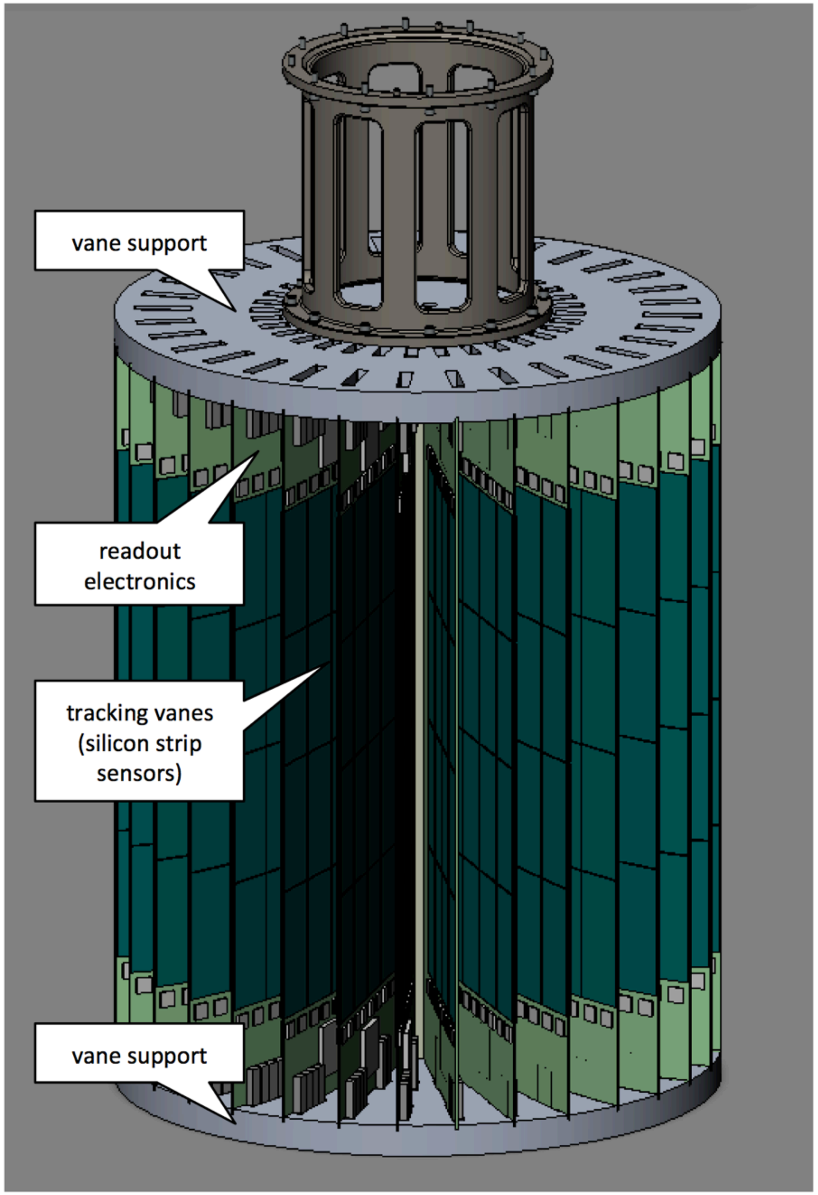
ppm-level uniformity is achieved.

# Positron tracking detector



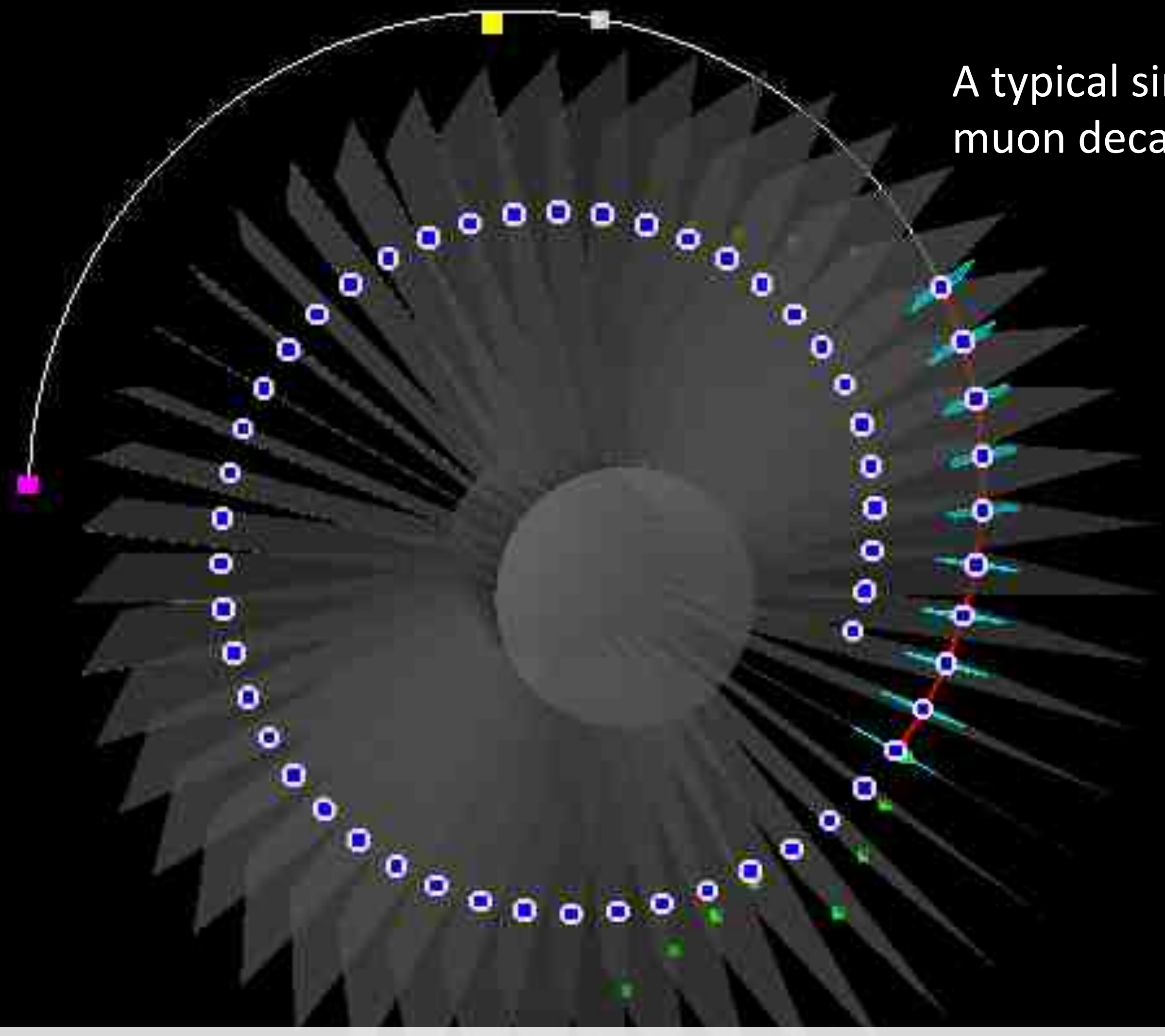
# Positron tracking detector





**Detector construction fund (~1.5M USD) was approved.**
**Postdoc opportunities : http://inspirehep.net/record/1394918**

# Track reconstruction



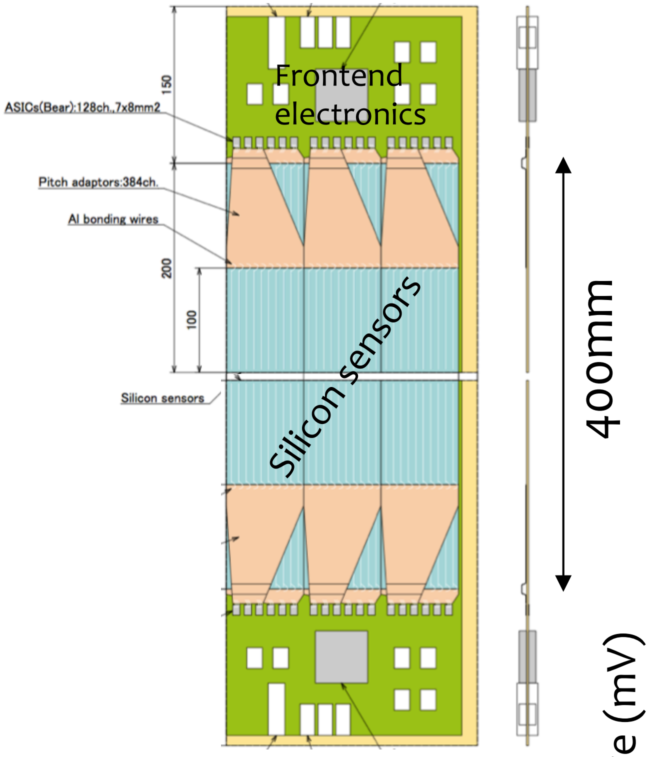
A typical simulated event of muon decay (p = 200 MeV/c)

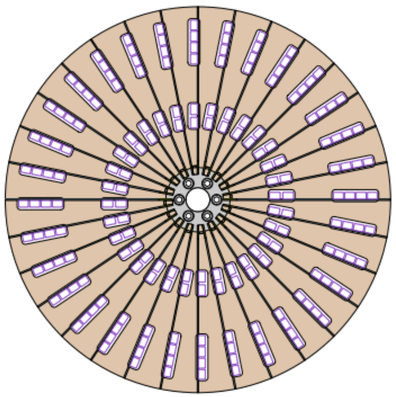
Full acceptance coverage

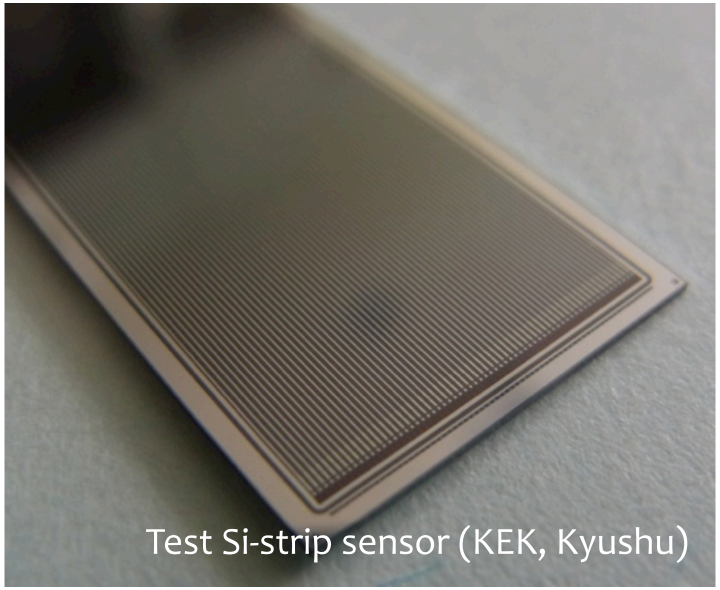
Track angle information → Sensitivity to muon EDM

# Silicon strip tracker

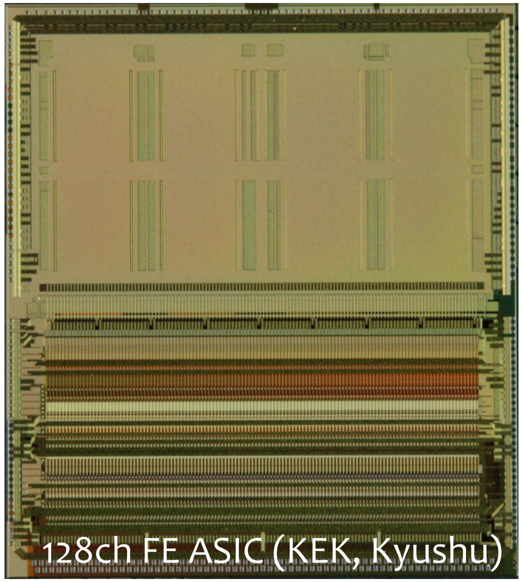
Detector module



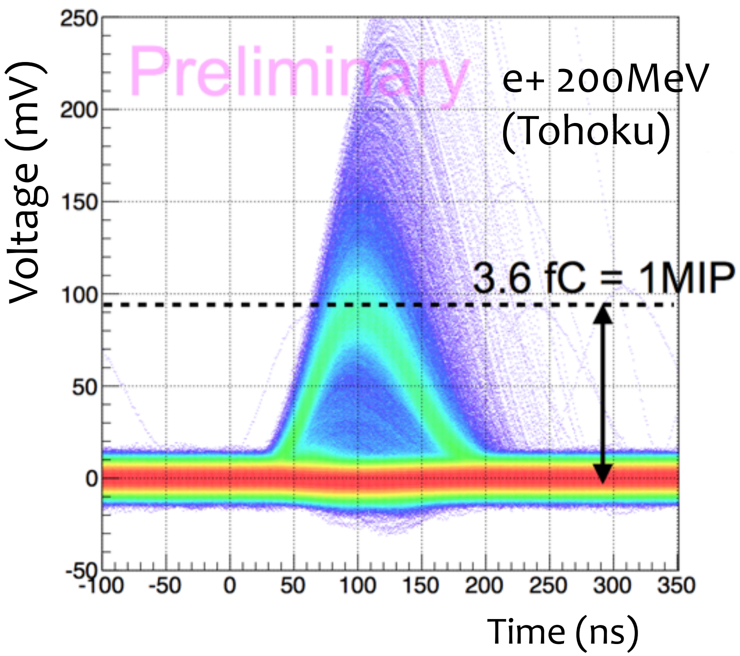



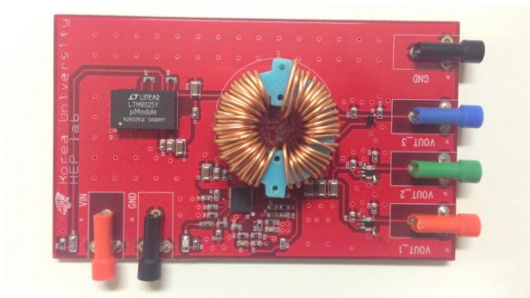


Test Si-strip sensor (KEK, Kyushu)



128ch FE ASIC (KEK, Kyushu)



DC-DC convertor (Korea U)

**Construction budget (~1.5 Oku yen, Kakenhi-S) was approved.**

# Projected statistical sensitivity

- With presently established design, one expects
  - Ultra-cold muon intensity : 3.3E+5/sec — design [1.0E+6/sec]
  - Statistical uncertainty on $a_\mu$: 0.37ppm — E821 0.46ppm
  - Statistical uncertainty on $d_\mu$: 1.3E-21 e・cm — 9E-20 e・cm
    - Running time = 2E+7 sec, polarization = 50%

Already good enough to test BNL E821 results.

# Summary

- J-PARC E34 aims to measure muon g-2 and EDM with ultra-cold muon beam.
- Progress
  - Technical design report
  - A part of construction budget was approved.
    - **Postdoc opportunities**
- Intended to start data taking from 2019.
- New technologies
  - Polarized thermal Muonium atoms
  - Polarized muon acceleration

# Summary of experimental conditions

| Quantities | Description | Value |
|---|---|---|
| $m$ | Muon mass [MeV/$c^2$] | 105.658 371 5 (35) |
| $\tau$ | Muon lifetime [$\mu s$] | 2.196 981 1(22) |
| $p$ | Muon momentum [MeV/$c$] | 300 |
| $E$ | Muon energy [MeV] | 318 |
| $K$ | Muon kinetic energy [MeV] | 212 |
| $\beta$ | Muon velocity | 0.94321 |
| $\gamma$ | Lorentz gamma factor, $1/\sqrt{1-\beta^2}$ | 3.0103 |
| $B$ | Magnetic field | 3 T |
| $r$ | Radius of Cyclotron motion | 333 mm |
| $\lambda$ | Magnetic moment ratio $(\mu_\mu/\mu_p)$ | 3.18334539(10) |
| $a_\mu$ | Anomalous magnetic moment | 0.001 165 920 89(63) |
| $\omega_a$ | Anomalous spin precession angular frequency, $\frac{e}{m}a_\mu B$ | 2.9752 $\mu$sec$^{-1}$ |
| $T_{cyclotron}$ | Cyclotron period $2\pi/\omega_c$ | 7.387 ns |
| $T_{anomalous}$ | Anomalous spin precession period $2\pi/\omega_a$ | 2112 ns |
| | | 286 turns |
| $d_\mu$ | Electric dipole moment, $\frac{e\hbar}{4mc}\eta$ | $0.467 \times 10^{-13}\eta$ $e$·cm |
| $\eta$ | Coefficient for EDM | $2.14 \times 10^{13} d_\mu (e \cdot \mathrm{cm})$ |
| $P$ | Muon beam polarization | 0.5 |
| $A_\mu$ | Momentum-averaged muon decay asymmetry ($p > 200$ MeV/$c$) | 0.44 |
| $A_{EDM}$ | Oscillation amplitude of EDM decay asymmetry w.r.t the muon storage plane, $\frac{A_\mu P \beta}{\pi a_\mu}\eta$ | $1.21 \times 10^{15} d_\mu (e \cdot \mathrm{cm})$ |
| $T$ | Running time | $2 \times 10^7$ sec |
| $\frac{dN_\mu}{dt}$ | Average muon rate in the storage magnet | $0.334 \times 10^6$/sec |
| $N_{e^+}$ | Total number of positrons $(N_\mu \epsilon_{acc} \epsilon_{trk})$ | $0.80 \times 10^{12}$ |
| $\frac{\Delta\omega_a}{\omega_a}$ | Uncertainty on anomalous spin precession frequency | 0.36 ppm |
| $\frac{\Delta a_\mu}{a_\mu}$ | Uncertainty on anomalous magnetic moment | 0.37 ppm |
| $\Delta d_\mu$ | Uncertainty on EDM | $1.3 \times 10^{-21} e \cdot \mathrm{cm}$ |

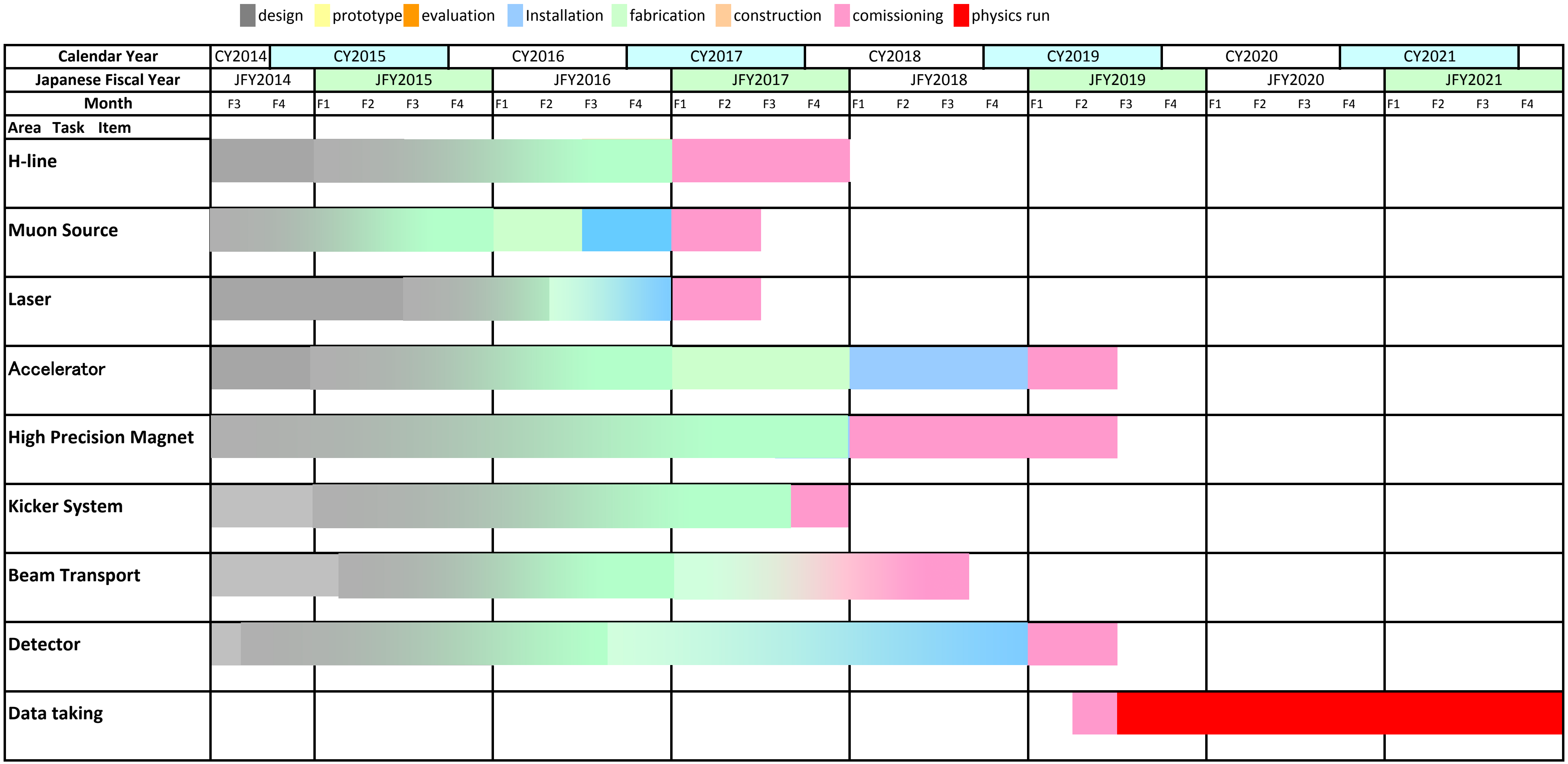
# Muon beam intensity

1MW, SiC target are assumed.

***Table 13.1:*** *Efficiency and beam intensity*

| Quantity | Reference | Efficiency | Cumulative | Intensity (Hz) |
|---|---|---|---|---|
| Muon intensity at production target | [2] | | | 1.99E+09 |
| H-line transmission | [2] | 1.62E-01 | 1.62E-01 | 3.22E+08 |
| Mu emission | [3] | 3.82E-03 | 6.17E-04 | 1.23E+06 |
| Laser ionization | [4] | 7.30E-01 | 4.50E-04 | 8.97E+05 |
| Metal mesh | [5] | 7.76E-01 | 3.49E-04 | 6.96E+05 |
| Init.Acc.trans.+decay | [5] | 7.18E-01 | 2.51E-04 | 5.00E+05 |
| RFQ transmission | [6] | 9.45E-01 | 2.37E-04 | 4.72E+05 |
| RFQ decay | [6] | 8.13E-01 | 1.93E-04 | 3.84E+05 |
| IH transmission | design goal | 1.00E+00 | 1.93E-04 | 3.84E+05 |
| IH decay | [7] | 9.84E-01 | 1.90E-04 | 3.78E+05 |
| DAW transmission | design goal | 1.00E+00 | 1.90E-04 | 3.78E+05 |
| DAW decay | [8] | 9.94E-01 | 1.88E-04 | 3.76E+05 |
| High beta transmission | design goal | 9.80E-01 | 1.85E-04 | 3.68E+05 |
| High beta decay | [9] | 9.88E-01 | 1.83E-04 | 3.64E+05 |
| Injection transmission | design goal | 1.00E+00 | 1.83E-04 | 3.64E+05 |
| Injection decay | [10] | 9.90E-01 | 1.81E-04 | 3.60E+05 |
| Detector start time | [10] | 9.27E-01 | 1.67E-04 | 3.34E+05 |
| Muon at storage | | | | 3.34E+05 |

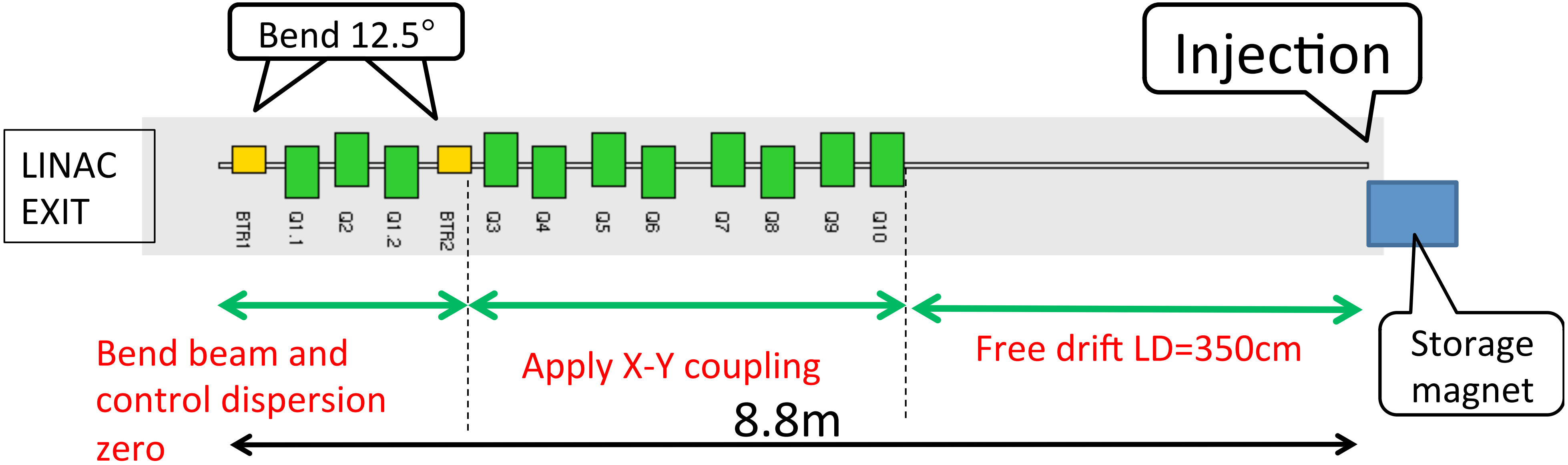
# Technically driven schedule

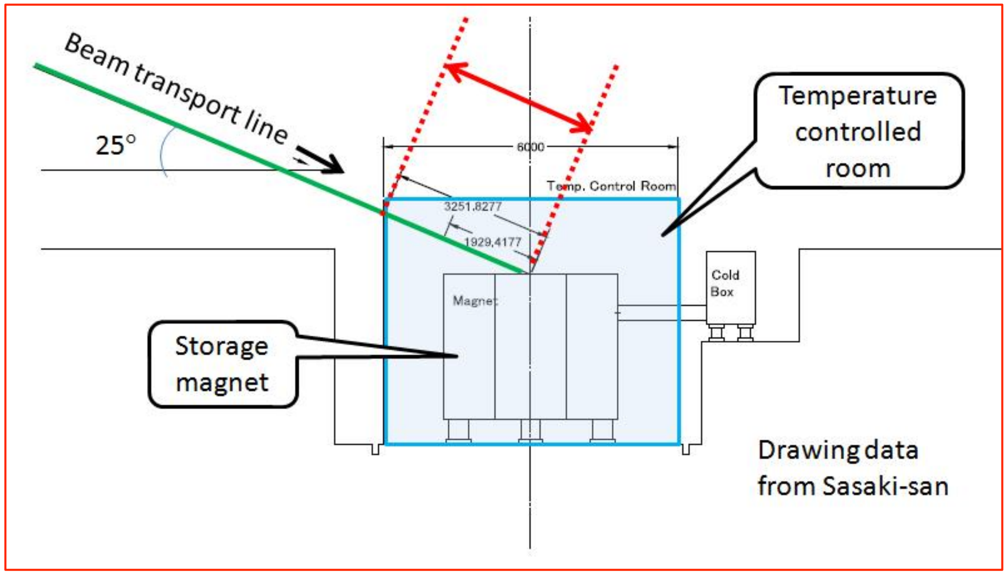


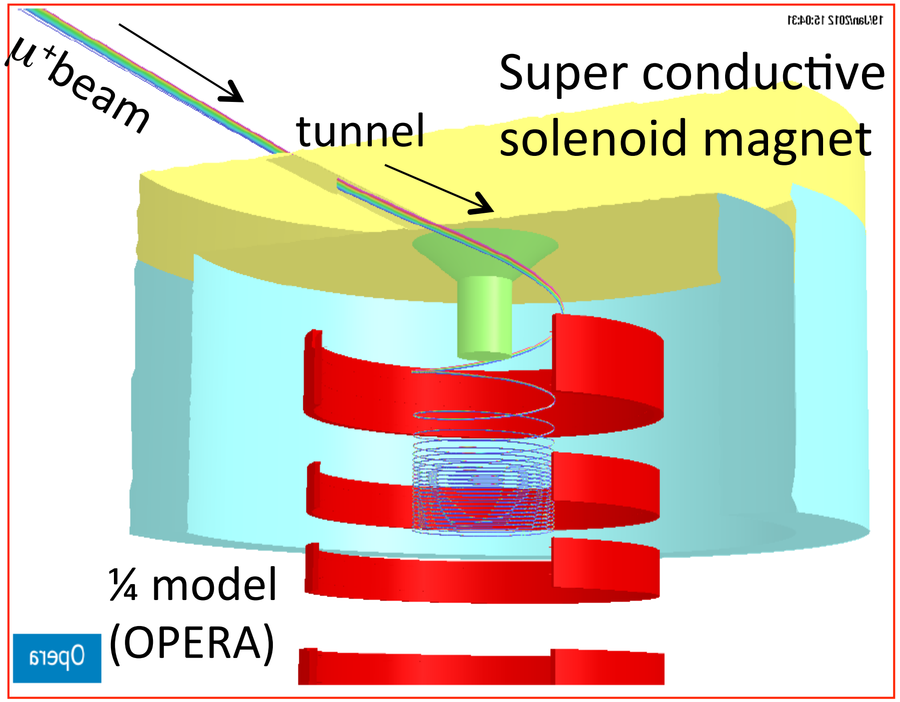

Assumption : Major construction fund become available in JFY2016

Note : Detector construction fund (Kakenhi-S) is available.

# Transport beam line and injection

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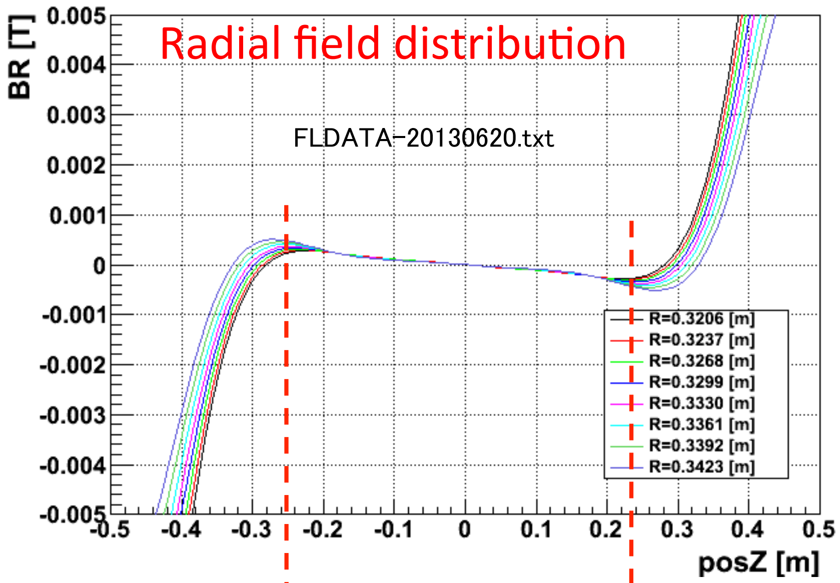
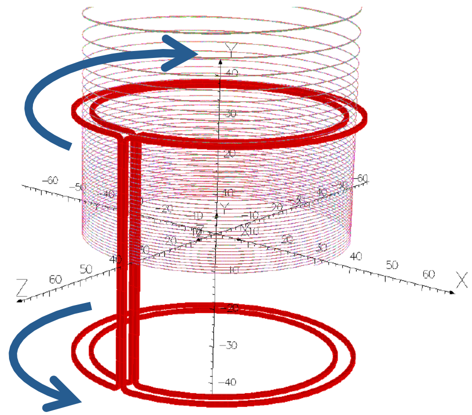
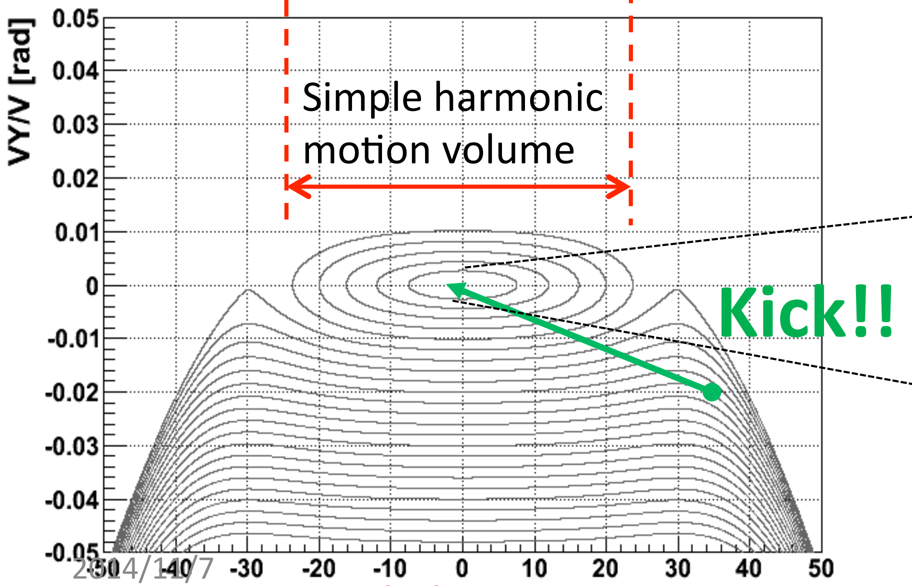
# Kicker and weak focusing field

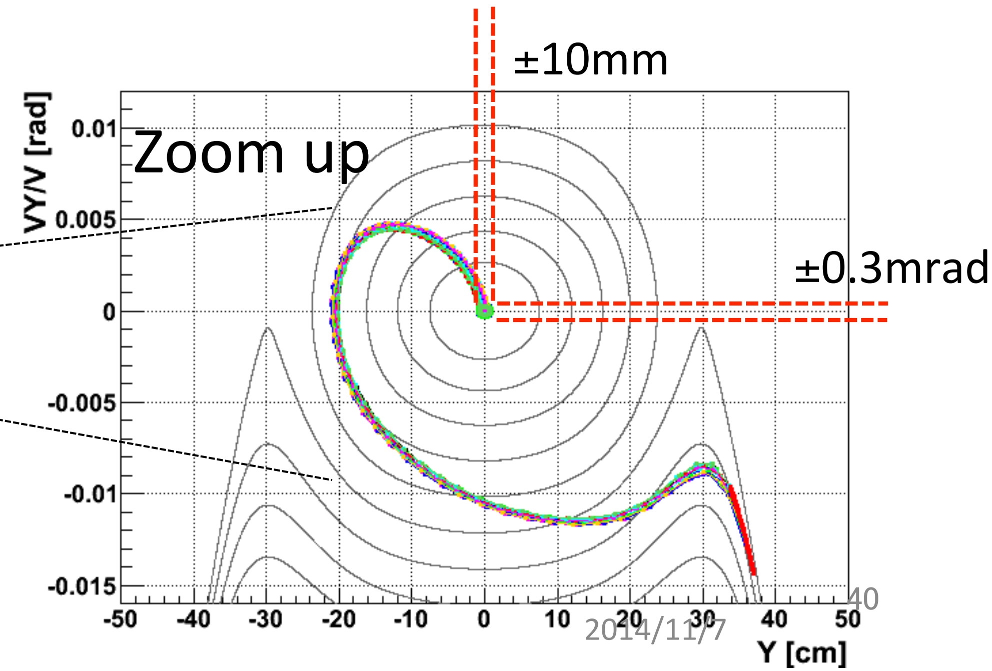


- Pulsed Radial field ;
  $B_{kick}(t)=B_{peak} \times \sin(\omega t) \times \exp(-t/\tau)$
  $\omega=\pi/T_{kick}$
  - $T_{kick}$~500nsec
  - Peak field $B_0$~2 gauss
- 2pairs of coil, pulsed high current
  $I(t)=I_{peak} \times \sin(\omega t)$
  $I_{peak}$ ~100A/coil
- Decay loss ~ 1%
- Weak magnetic focus n = 1.5E-4




Vertical phase space

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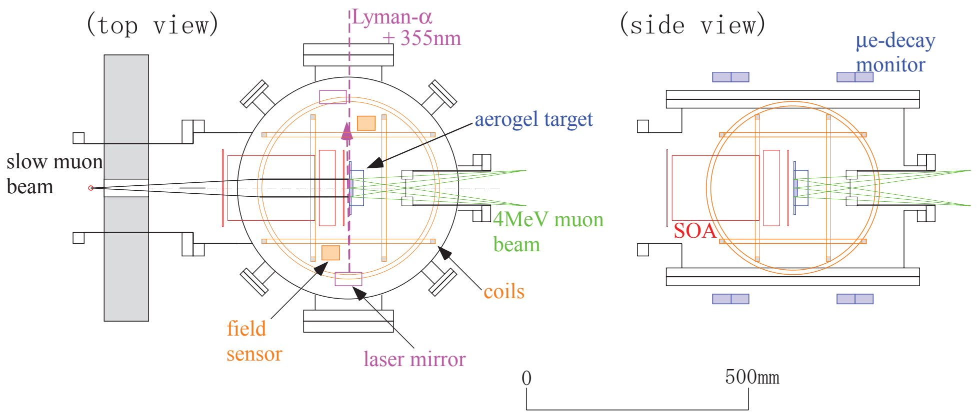
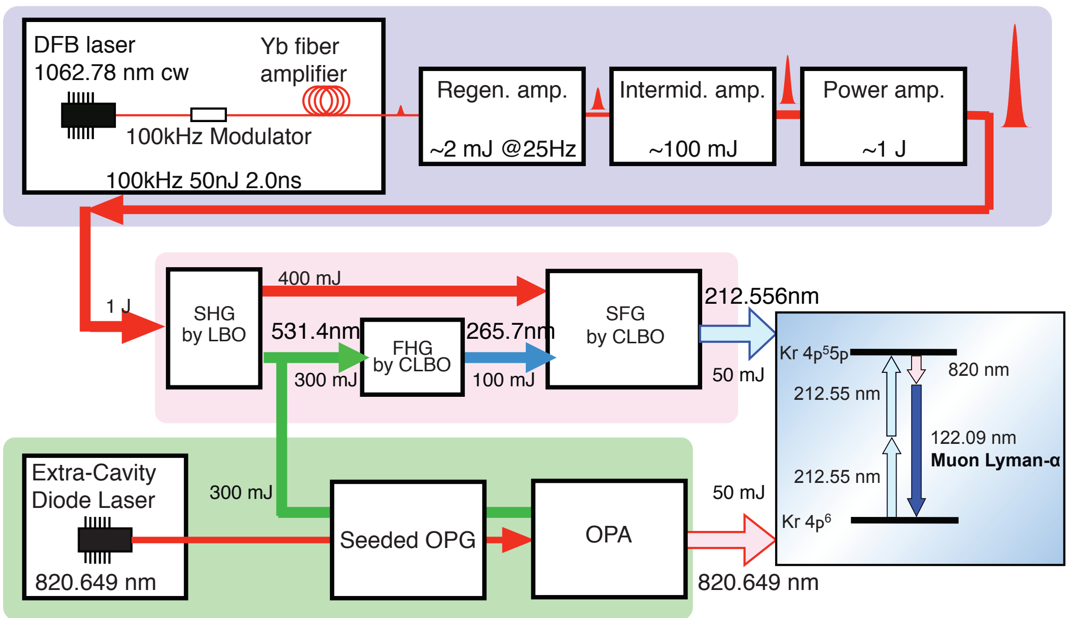
# Specifications: USM source




| Item | Specifications |
|---|---|
| Mu production target | laser-ablated silica aerogel (30 mg/cc, ϕ50 mm, 8 mm thick) |
| Laser ionization region | 1-6mm from the target surface |
| Target electrode voltate | 5 kV |
| Mesh | 88% opening |
| SOA voltages | 4.8 kV → GND |
| SOA aperture | 240 mm |




| Property | Target |
|---|---|
| ***OMEGA 1*** | |
| ***Wavelength (nm)*** | ***212.556*** |
| ***Pulse width (ns)*** | ***2*** |
| ***Output energy in Laser Cabin (mJ)*** | ***50*** |
| *Output energy in U-1 area (mJ)* | |
| ***OMEGA 2*** | |
| ***Wavelength (nm)*** | ***820.649*** |
| ***Pulse width (ns)*** | ***2*** |
| ***Output energy in Laser Cabin (mJ)*** | ***50*** |
| ***Output energy in U-1 area (mJ)*** | |
| ***Spectral linewidth (GHz)*** | ***230*** |
| ***Delay $\Delta t = t_{212} - t_{820}$ (s)*** | ***0*** |

# Specifications: surface muon transport


***Table 3.1:*** *Design parameters of HS1 coil 1*

| | |
|---|---|
| design magnet field | 72 T |
| design current | 3000 A |
| inner coil radius | 282 mm |
| # of turns | 72 |
| coil length | 196 mm |
| voltage | 74.5 V |

***Table 3.2:*** *Design parameters of HS1 coil 2*

| | |
|---|---|
| design magnet field | 64 T |
| design current | 2980 A |
| inner coil radius | 336 mm |
| # of turns | 64 |
| coil length | 196 mm |
| voltage | 72 V |

***Table 3.3:*** *Design parameters of HS1 other coils*

| | |
|---|---|
| design magnet field | 36 T |
| design current | 3150 A |
| inner coil radius | 390 mm |
| # of turns | 36 |
| coil length | 144 mm |
| voltage | 42 V |

***Table 3.4:*** *Design parameters of HB1*

| | |
|---|---|
| design magnet field | 0.26 T |
| design current | 500 A |
| aperture width | 700 mm |
| aperture height | 300 mm |
| aperture length | 791 mm |
| curvature radius | 1528 mm |
| # of turns | 132 |
| voltage | 42 V |

# Specifications: LINAC

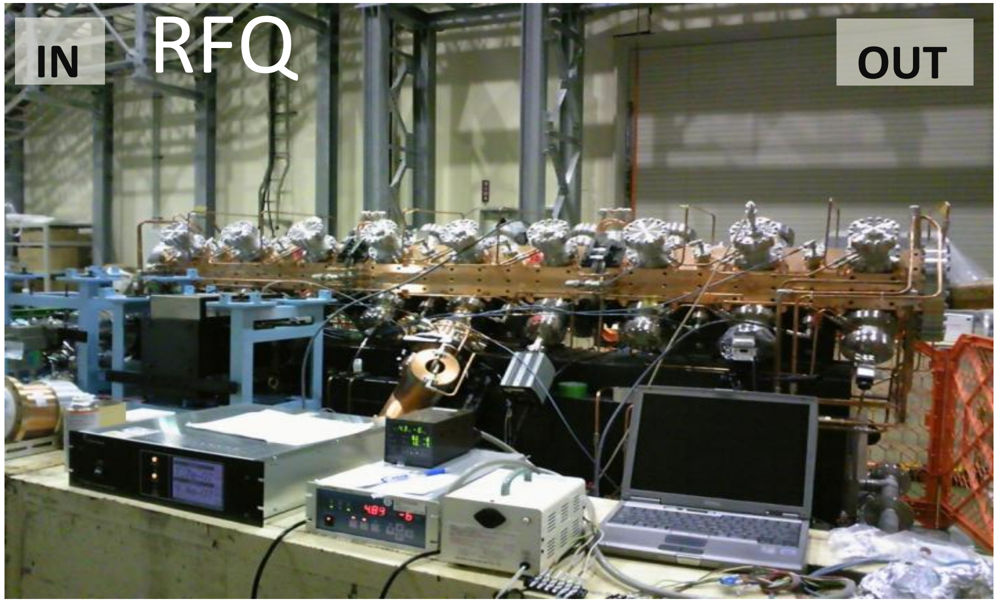
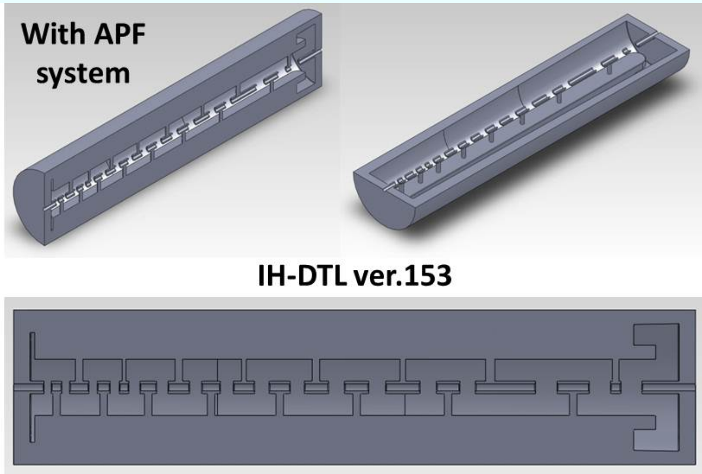



**Table 6.4:** *Simulation inputs and results of RFQ II and muon RFQ.*

| | RFQ II | muRFQ |
|---|---|---|
| Resonant frequency (MHz) | 324 | |
| Injection energy (keV) | 5.625 | 30 |
| Extraction energy (MeV) | 0.34 | |
| Inter vane voltage (kV) | 9.3 | 138 |
| Power (kW) | 4.2 | 200 |
| Number of cells | 295 | 72 |
| Length (m) | 3.17 | 1.10 |
| Transmission (%) | 99.9 | 96.2 |
| Input emittance ($\pi$ mm mrad, normalized, rms) | 0.17 | |
| Output emittance x ($\pi$ mm mrad, normalized, rms) | 0.17 | 0.20 |
| Output emittance z ($\pi$ MeV deg, rms) | 0.021 | 0.25 |

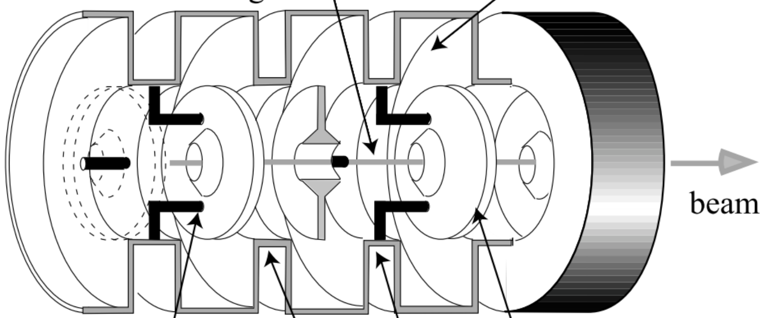
## 324MHz APF IH-DTL



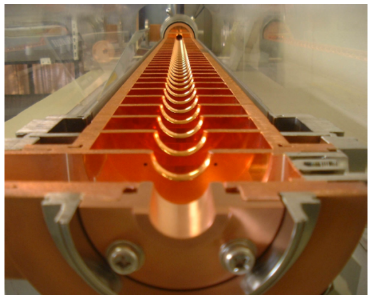

| Operation parameters (IH-DTL ver.153) | |
|---|---|
| Frequency [MHz] | 324 |
| Length of IH-DTL [mm] | 1440 |
| Number of Gaps [gaps] | 17 |
| Electric field on the axis [MV/m] | 9.00 |
| Average bohr radius [mm] | 7.5 |
| RF Power [kW] | 168 |
| Q value | 11822 |
| Shunt impedance [MΩ/m] | 56.6 |
| Input energy [keV] | 340 |
| Output energy [MeV] | 3.75 |
| Acceptance [$\pi$ mm-mrad] | 1.8 |

# Specifications: LINAC

DAW




Disc-loaded structure



| | |
|---|---|
| Operation frequency | 1300 MHz |
| Input beam energy | 42 MeV |
| Output beam energy | 200 MeV |
| Field gradient | ~20 MV/m |
| RF power | 40 MW |
| Total length | ~10 m |

***Table 6.5:*** *Design parameters of the DAW part*

| | |
|---|---|
| Operation frequency | 1300 MHz |
| Input beam energy | 4.1 MeV |
| Output beam energy | 42 MeV |
| RF power | 10 MW |
| Total length | 821 mm |

Power source

***Table 6.6:*** *Power source for the entire LINAC.*

| | | Power for device | AC plug power |
|---|---|---|---|
| RF | RFQ | 5 kW | - |
| | I-H | 100 kW x 10$\mu$s | |
| | DAW | 20 MW x 10$\mu$s | 20 kW |
| | Disk loaded | 40 MW x 10$\mu$s | 30 kW |
| Magnet | Quadrupole | 1 kW $\times$ 10 doublets = 20kW | |
| | Bends for injection | 1 kW | |

# Specifications: Injection line & kicker

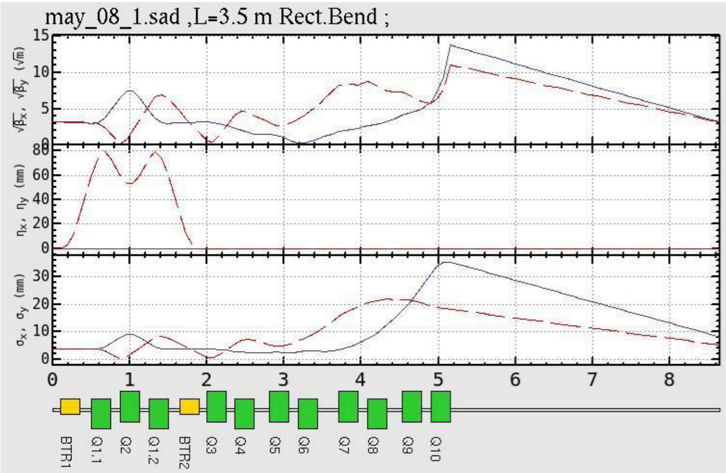
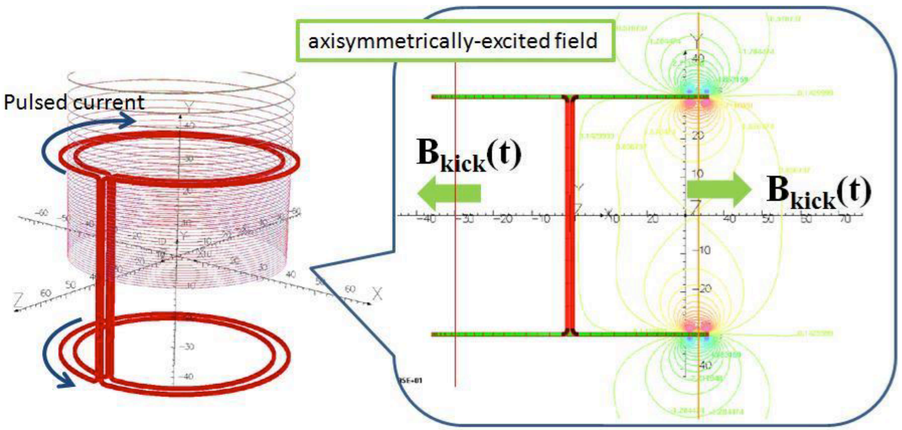



***Table 7.3:*** *Parameters of vertical dipole magnet*

| parameters | values |
|---|---|
| full gap | 80 mm |
| Length | 250 mm |
| bend angle | 12.5° |
| flux density | 0.87 T |
| NI (AT) | 3000 AT |
| | (300A  turns) |

***Table 7.4:*** *Parameters of vertical quadrupole magnets*

| Q-mag id | rotation angle | $K1$ | Length | Bore radius | NI/pole (AT/pole) |
|---|---|---|---|---|---|
| Q1 | 0.0 | −18.17 | | | 3000AT/pole |
| Q2 | 0.0 | 17.13 | 250 mm | 40 mm | (500A ×6 turn) |
| Q3 | 31.25° | −11.80 | | | |
| Q4 | 12.88° | −5.92 | | | |
| Q5 | 7.41° | 14.10 | | | |
| Q6 | 17.92° | −6.71 | 250 mm | 40 mm | 1800AT/pole |
| Q7 | 17.13° | −2.42 | | | (300A ×6 turn) |
| Q8 | 11.96° | −2.70 | | | |
| Q9 | 8.12° | −2.20 | | | |
| Q10 | 12.70° | 5.113 | | | |




| Item | Specifications |
|---|---|
| Inner radius | 300 mm |
| Outer radius | 360 mm |
| Coil separation | 350 mm |
| Pulse shape | Sine or half-sine |
| Kick time | 390 - 655 ns |
| Peak B-field | 2 Gauss |

# Specifications: storage magnet

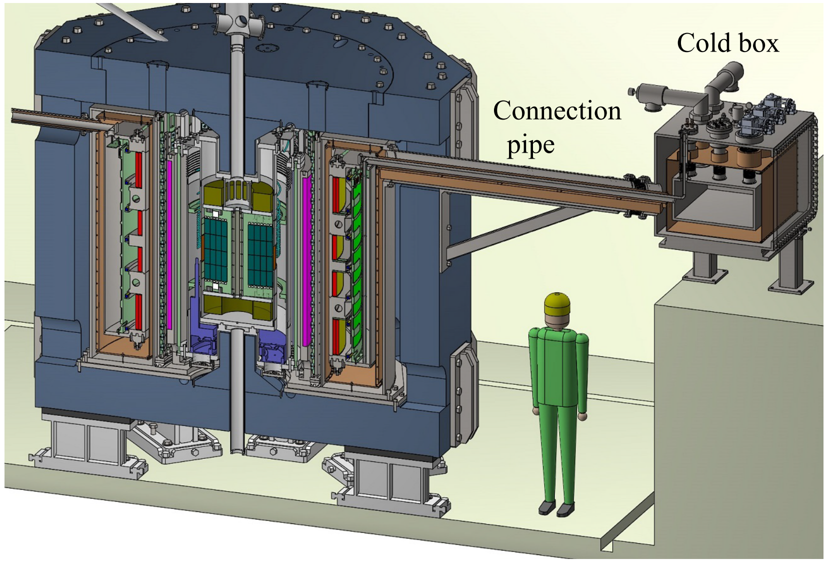



*Table 8.1: Magnet main characteristics*

| Item | Unit | Value |
|---|---|---|
| Nominal current | A | 423.4 |
| Stored energy | MJ | 17.2 |
| Magnet inductance | H | 198 |
| Peak field on SC coil | T | 4.9 |

*Table 8.2: Parameters of main coils*

| Item | MC10 (MC11) | MC20 (MC21) | MC30 (MC31) |
|---|---|---|---|
| Coil inner radius | 0.8275 m | 0.8504 m | 0.8191 m |
| Coil outer radius | 0.8504 m | 0.8733 m | 0.848 |
| Coil length | 0.2884 m | 0.2884 m | 0.2139 m |
| Z position of coil center | 0.60065 m | 0.60065 m | 0.15835 m |
| Number of turns | 2105 | 2105 | 1888 |

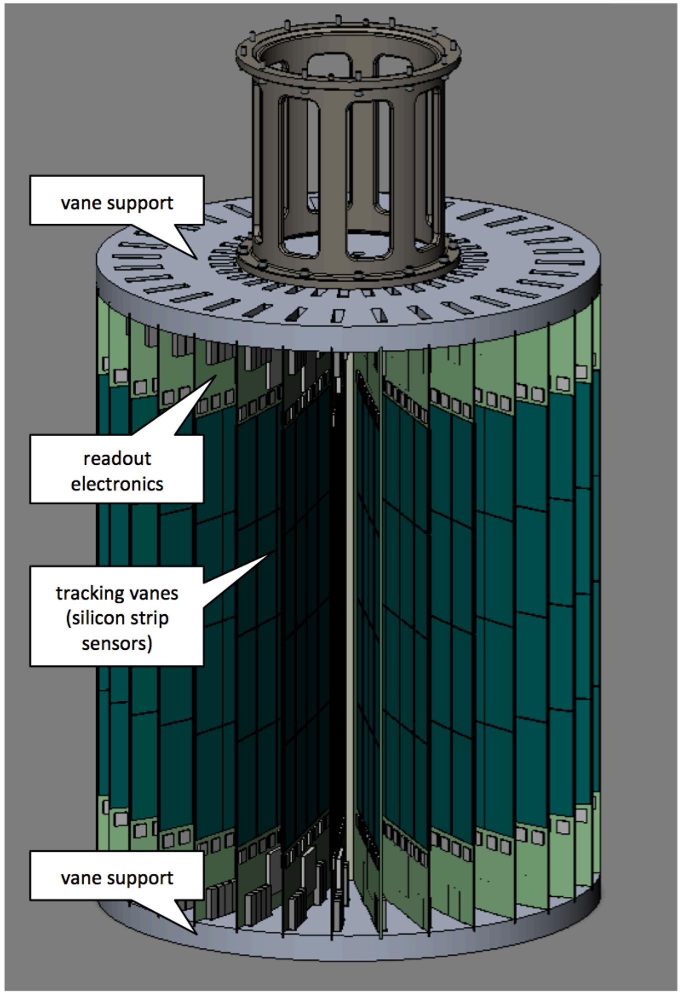
*Table 8.6: Parameters for main coil conductor*

| | Unit | Value |
|---|---|---|
| Superconductor | NbTi | |
| Stabilizer | Copper | |
| Cross section | | Rectangular |
| Size with Insulation | mm | $2.2 \times 1.5$ |
| Size w/o Insulation | mm | $2.1 \times 1.4$ |
| Corner R | mm | 0.3 |
| Cu/Sc Ratio | | 4 |
| Insulation Material | PVF | |
| Insulation Thickness | mm | 0.05 |
| No. of Filaments | | 336 |
| Filament Diameter | mm | 46.5 |
| Ic at the Peak Field of 5 T | A | 1290 |

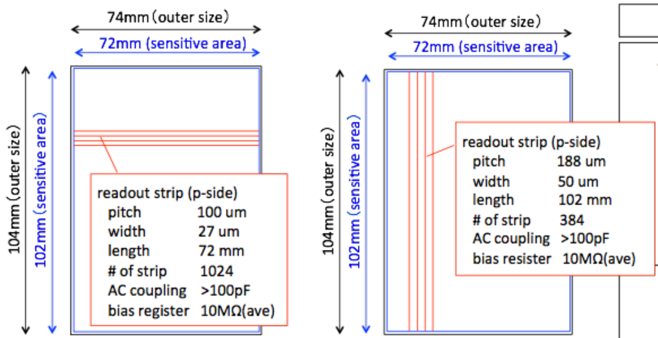
*Table 8.7: Parameters for shim and weak focus coil conductor*

| | Unit | Value |
|---|---|---|
| Cross section | | Round |
| Diameter with Insulation | (mm) | 0.78 |
| Diameter w/o Insulation | (mm) | 0.88 |
| Cu/Sc Ratio | | $> 4$ |
| Insulation Thickness | (mm) | 0.05 |
| No. of Filaments | | 54 |
| Filament Diameter | (mm) | 46.5 |
| Ic at 3 T | (A) | 404 |
| Ic at 5 T | (A) | 275 |

# Specifications: Silicon strip tracker




| Item | Requirement |
|---|---|
| Spill repetition rate | 25 Hz |
| Track rate | 30 track / 5 ns |
| Fiducial volume | $-200 < z < 200$ mm, $50 < r < 300$ mm |
| Magnetic field immunity | operational under 3 T |
| Distortion of Magnetic field in the muon storage region | $<$ 10ppm |
| Electric field in the muon storage region | $<$ 10 mV/cm |
| Time resolution | $<<\sim$ 5 ns |
| Accuracy of time stamp | $< 5 \times 10^9$ |
| Energy resolution | $<\sim$ 10% |
| Eearly to late stability of reconstructed track time | $<<$ 8 ps |
| Tracking plane alignment | $< 10^{-5}$ rad for $\phi$ rotation |
| | $< 10^{-4}$ rad for r rotation |
| | $< 10^{-1}$ rad for global rotation |

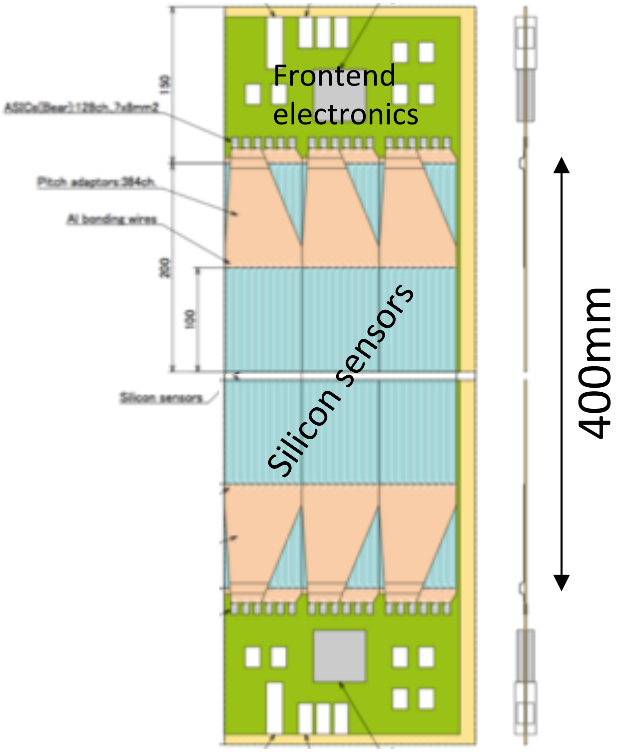


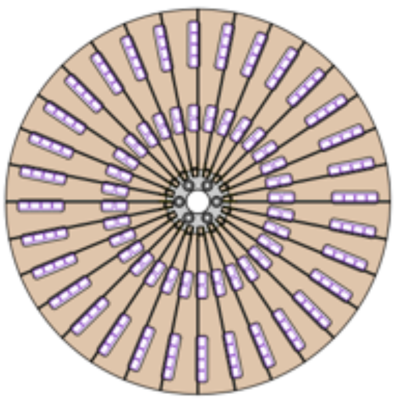

| Block | Parameter | Value |
|---|---|---|
| Analog | conversion gain | 90 mV/fC |
| | dynamic range | 4 MIP |
| | pulse width | 80 ns |
| | peaking time | 25 ns |
| | time walk | <5 ns |
| | noise | $< 1600\ e^-$ |
| | number of channel | 128 |
| Digital | reference clock | 200 MHz |
| | sampling period | 5 ns |
| | event buffer length | 8k (40.96 $\mu s$) |
| | serial outputs rate | 100 Mbps |
| Mechanical | chip size | <9 mm× 5 mm |
| | thickness | ~300 $\mu m$ |
| | pad pitch | 60 $\mu m$ |
| Electronical | supply voltages | ±0.9 V, 2.4 V, GND |
| | power consumption | <5 mW/ch |

***Table 10.3:*** *Specifications of the Slit128A*

# Specifications : Silicon strip tracker

Detector module



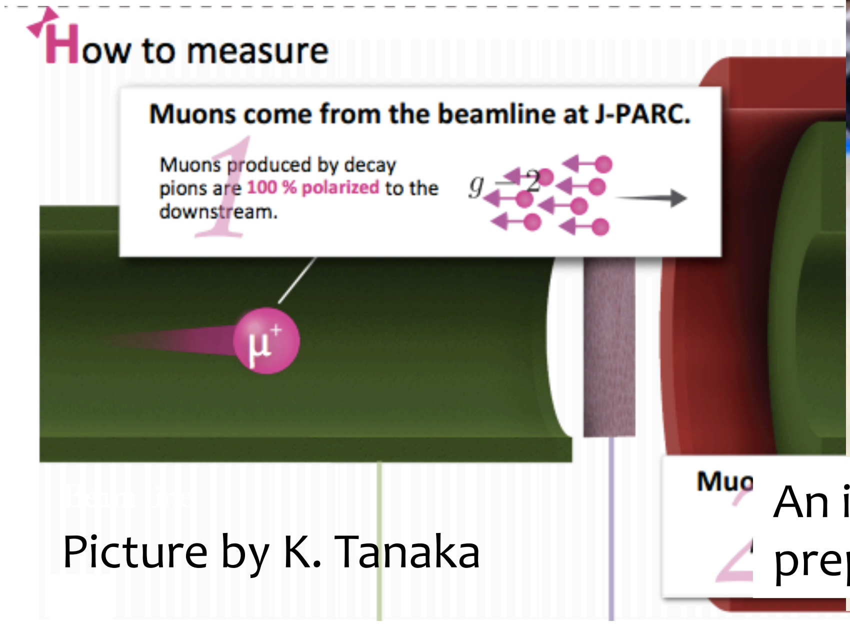



| Item | Specifications |
|---|---|
| Fiducial volume | 240mm (radial) x 400 mm (axial) |
| Number of vane | 48 |
| Sensor technology | Single-sided Silicon strip sensor (p-on-n) |
| Strip | axial-strip : 100mm pitch, 72mm long , 1024 ch<br>radial-strip: 188mm pitch, 98mm long, 384 ch |
| Sensor dimension | 74 mm x 98 mm x 0.32mm |
| Number of sensor | 1152 ( 12 sensors per vane) |
| Number of channel | 811,008ch |
| Time measurement | Period : 33ms, Sampling time : 5ns |

# Muonium HFS and $\mu_\mu/\mu_p$ ratio

- Future g-2 experiments (~0.1ppm) require more precise determination of magnetic moment ratio $\mu_\mu/\mu_p$ (current uncertainty : 0.12ppm)

$$a_\mu = \frac{R}{\lambda - R}$$




Picture by K. Tanaka


An improved measurement of Mu-HFS and $\mu_\mu/\mu_p$ is in preparation at J-PARC (KEK IMSS K. Shimomura et al.)