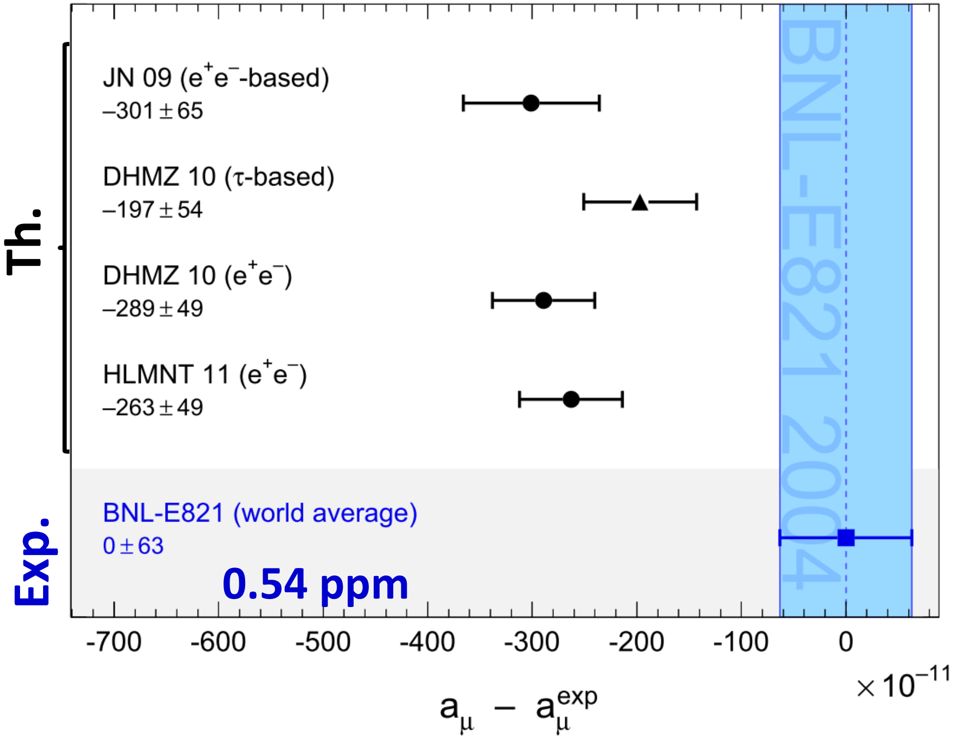
muon g-2/EDM experiment at J-PARC

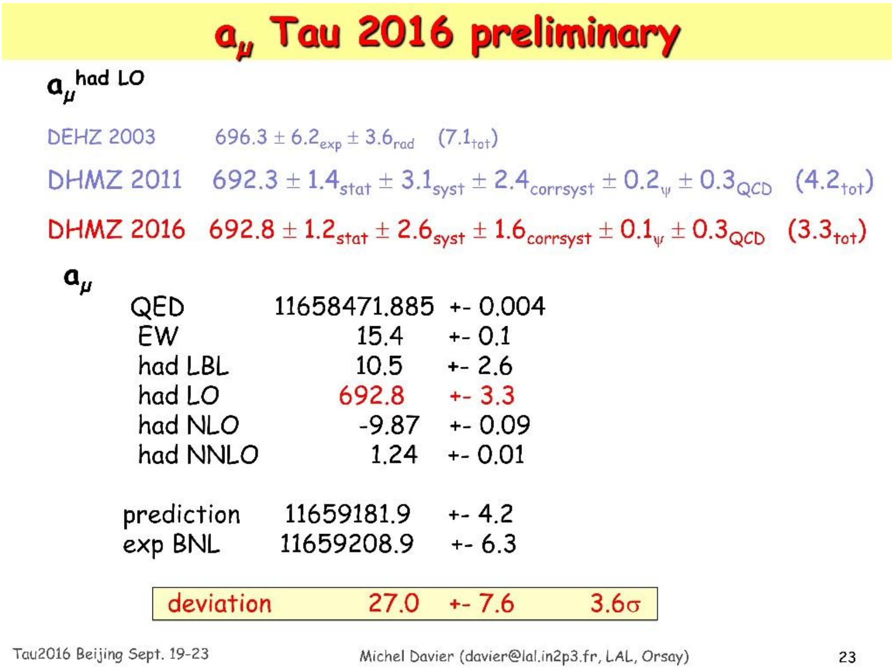
Y. Sato
KEK IPNS
On behalf of the E34 collaboration

5th Jan. 2017

The 3rd KMI International Symposium
on "Quest for the Origin of Particles and the Universe"
(KMI2017)

Muon g-2 Anomaly





a_μ Tau 2016 preliminary

$a_\mu^{\text{had LO}}$

DEHZ 2003	$696.3 \pm 6.2_{exp} \pm 3.6_{rad}$	(7.1_{tot})
DHMZ 2011	$692.3 \pm 1.4_{stat} \pm 3.1_{syst} \pm 2.4_{corrsyst} \pm 0.2_{\psi} \pm 0.3_{QCD}$	(4.2_{tot})
DHMZ 2016	$692.8 \pm 1.2_{stat} \pm 2.6_{syst} \pm 1.6_{corrsyst} \pm 0.1_{\psi} \pm 0.3_{QCD}$	(3.3_{tot})

a_μ

QED	11658471.885	+- 0.004
EW	15.4	+- 0.1
had LBL	10.5	+- 2.6
had LO	692.8	+- 3.3
had NLO	-9.87	+- 0.09
had NNLO	1.24	+- 0.01
prediction	11659181.9	+- 4.2
exp BNL	11659208.9	+- 6.3

deviation	27.0	+- 7.6	3.6σ

Tau2016 Beijing Sept. 19-23 Michel Davier (davier@lal.in2p3.fr, LAL, Orsay) 23

- >3σ deviation between muon g-2 measurement by BNL E821 and SM prediction for over 10 years.
- Theoretical prediction is being improved by continuous efforts.

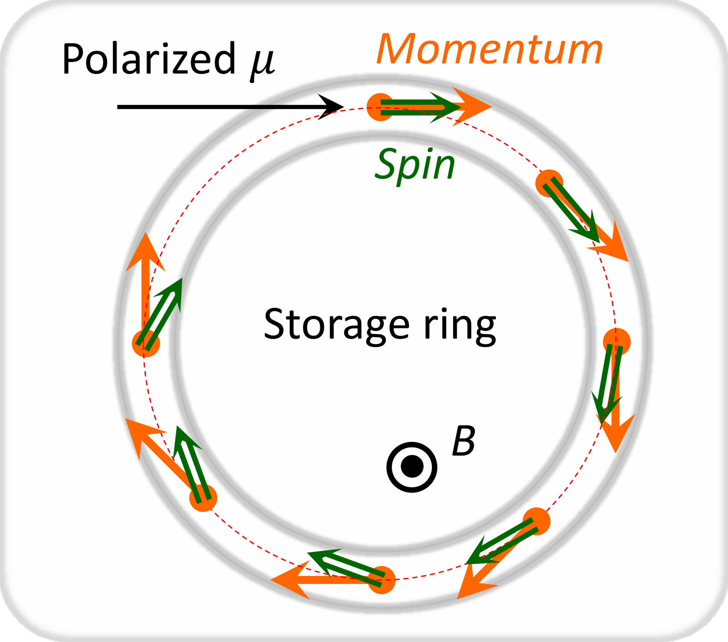
➢ Need more precise/independent measurement.

- Muon EDM is also important
  - Upper limit : $d < 1.8 \times 10^{-19} e \cdot \mathrm{cm} (95\%\ \mathrm{C.L.})$ by BNL E821

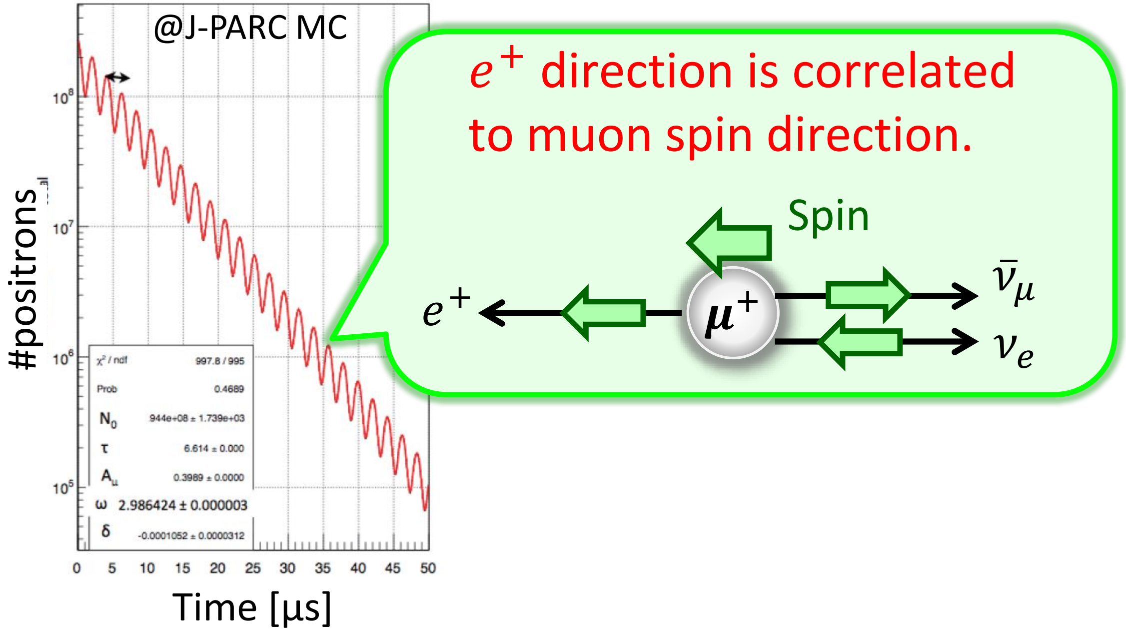
Principle of muon g-2 Measurement

1. Inject **polarized muons** to the storage ring.
   - $\pi^+ \rightarrow \mu^+ \nu_\mu$ decay
2. **Muon spin precession relative to momentum in cyclotron** is proportional to g-2 under "special" condition.

$$\vec{\boldsymbol{\omega}} = \vec{\omega}_{\mathrm{spin}} - \vec{\omega}_{\mathrm{cyclotron}} = \left(\frac{g-2}{2}\right)\frac{e\vec{B}}{m_\mu c} = a_\mu \frac{e\vec{B}}{m_\mu c}$$



3. Detect high energy e^+ from μ^+ decay

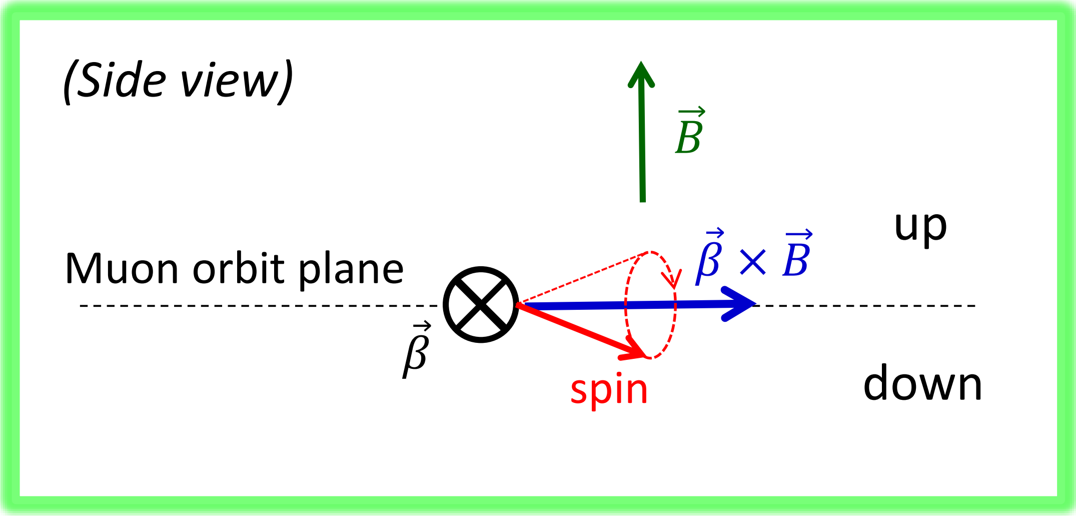


e^+ direction is correlated to muon spin direction.

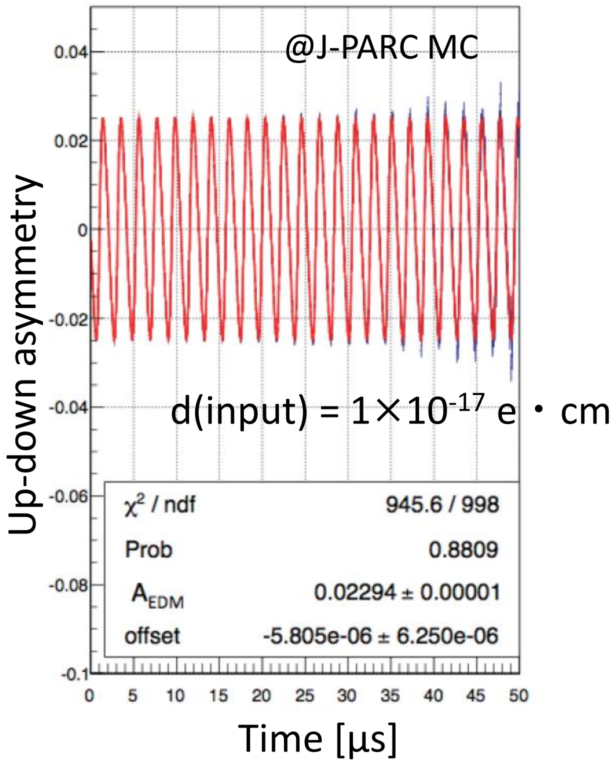
- ➢ Precise measurement of $g-2$ needs **precise determinations of ω and B.**
  - Muon-to-proton magnetic moment ratio is also used instead of e/m_μ.

Principle of muon EDM Measurement

- Non-zero EDM contributes to spin precession.
  - $\vec{\omega}_{\mathrm{EDM}} = -\frac{e}{m_\mu}\left[\frac{\boldsymbol{\eta}}{2}\left(\vec{\beta} \times \vec{B}\right)\right]$



- EDM can be measured from up-down asymmetry.
  - $\mathcal{A}_{UD} = \frac{N_{\mathrm{up}} - N_{\mathrm{down}}}{N_{\mathrm{up}} + N_{\mathrm{down}}}$



Experimental Approaches for g-2 and EDM

$$\vec{\omega} = -\frac{e}{m_\mu}\left[\overbrace{a_\mu \vec{B} - \underbrace{\left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}}_{}}^{\omega_{g-2}} + \overbrace{\frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \underbrace{\frac{\vec{E}}{c}}_{}\right)}^{\omega_{\mathrm{EDM}}}\right]$$

1. Magic momentum

$\gamma = 29.3$ ($P = 3.09$ GeV/c)

2. Zero E-field

$E = 0$ at any γ

BNL E821 (current best meas.) & FNAL E989 (upgrade)

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

- ➢ FNAL E989 will start from 2017.

J-PARC E34 (new methods)

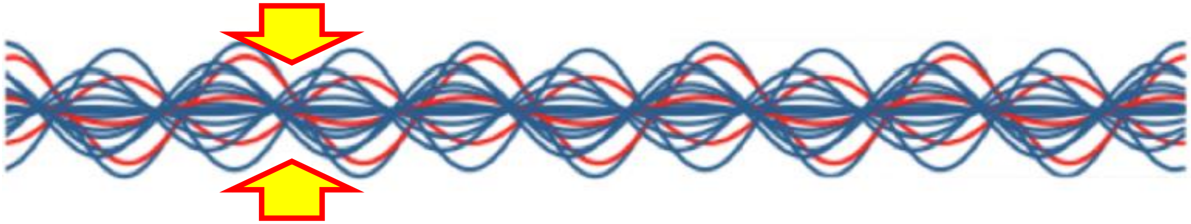
$$\vec{\omega} = -\frac{e}{m_\mu}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right]$$

- Completely different techniques
  - ➢ Different systematic uncertainty.
- More simplified equation ($\vec{\omega}_{g-2} \perp \vec{\omega}_{\mathrm{EDM}}$)
  - ➢ Clear separation of $\vec{\omega}_{g-2}$ and $\vec{\omega}_{\mathrm{EDM}}$.

Low Emittance Beam

Methods to storage muon beam

- **BNL & FNAL (magic momentum approach)**
  - Electric quadrupole field focusing



Electric focusing

- **J-PARC (zero E-field approach)**
  - Low-emittance “cold” muon beam.

  - $\frac{\sigma(p_T)}{p_T} < 10^{-5}$ → 10 cm spread over 10 km travel.

➢ Low emittance beam can avoid major syst. error at BNL.

Syst. Err. @BNL

Sources	ppm
Gain changes	0.12
Pile up	0.08
Lost muons	0.09
CBO	0.07
E and pitch	0.05
Total for ω	0.18

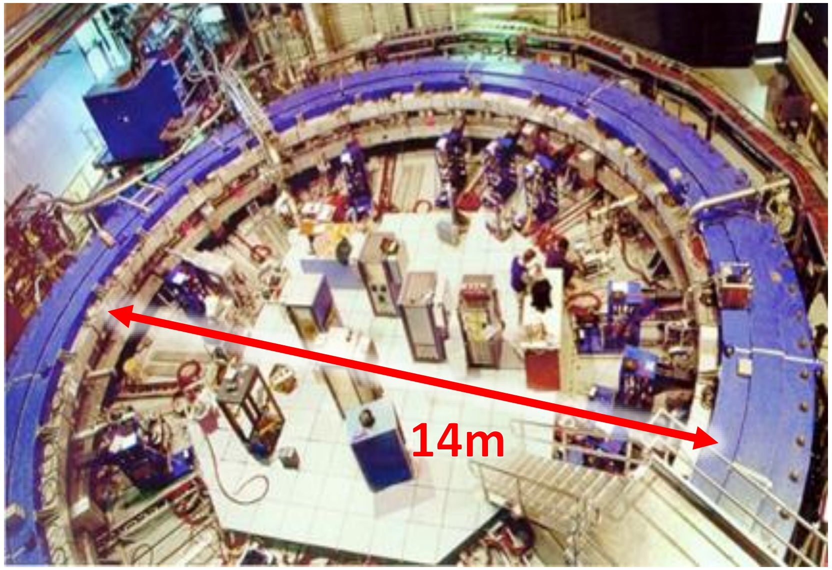
Off-magic momentum

- Off magic momentum at **300 MeV/c**
  - Compact storage ring provides **precise control of B-field**.
    - 3 T, ~1 ppm local precision.
  - **Spin manipulation of μ beam** cancel various systematics.

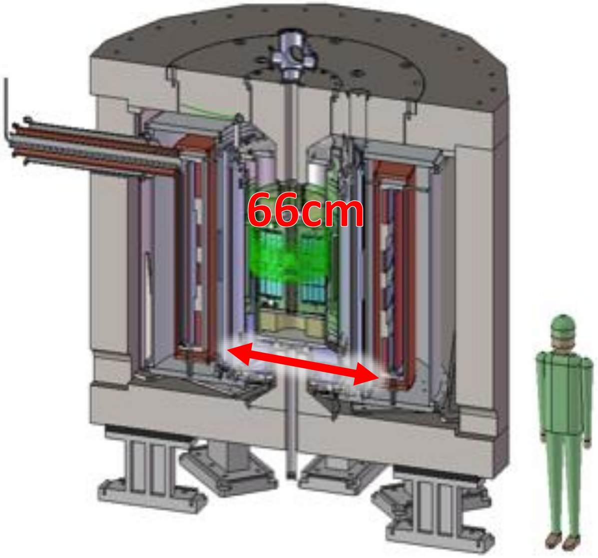
Syst. Err. @BNL

Sources	**ppm**
Total for ω	0.18
Total for B	0.17

BNL & FNAL (P = 3 GeV/c, 1.45T)



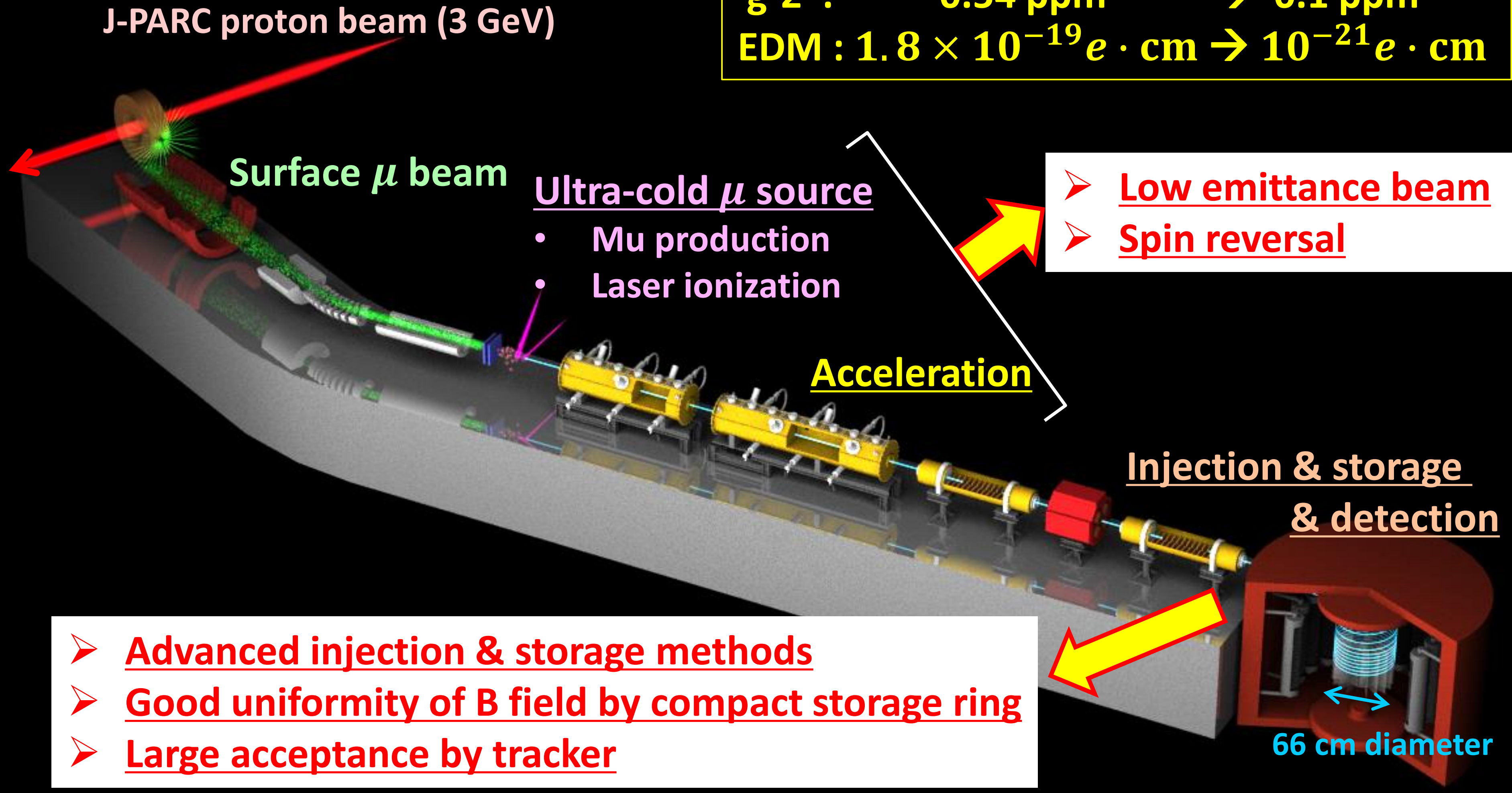
J-PARC (P = 300 MeV/c, 3T)



J-PARC E34 Experiment

- New muon g-2/EDM experiment at J-PARC MLF with a newly developed method, off-magic momentum with **ultra-cold muon beam**.

	BNL	**Our goal**
g-2 :	**0.54 ppm**	**→ 0.1 ppm**
EDM :	$1.8 \times 10^{-19} e \cdot \mathrm{cm}$	**→** $10^{-21} e \cdot \mathrm{cm}$



J-PARC proton beam (3 GeV)

Surface μ beam

Ultra-cold μ source
- Mu production
- Laser ionization

Acceleration

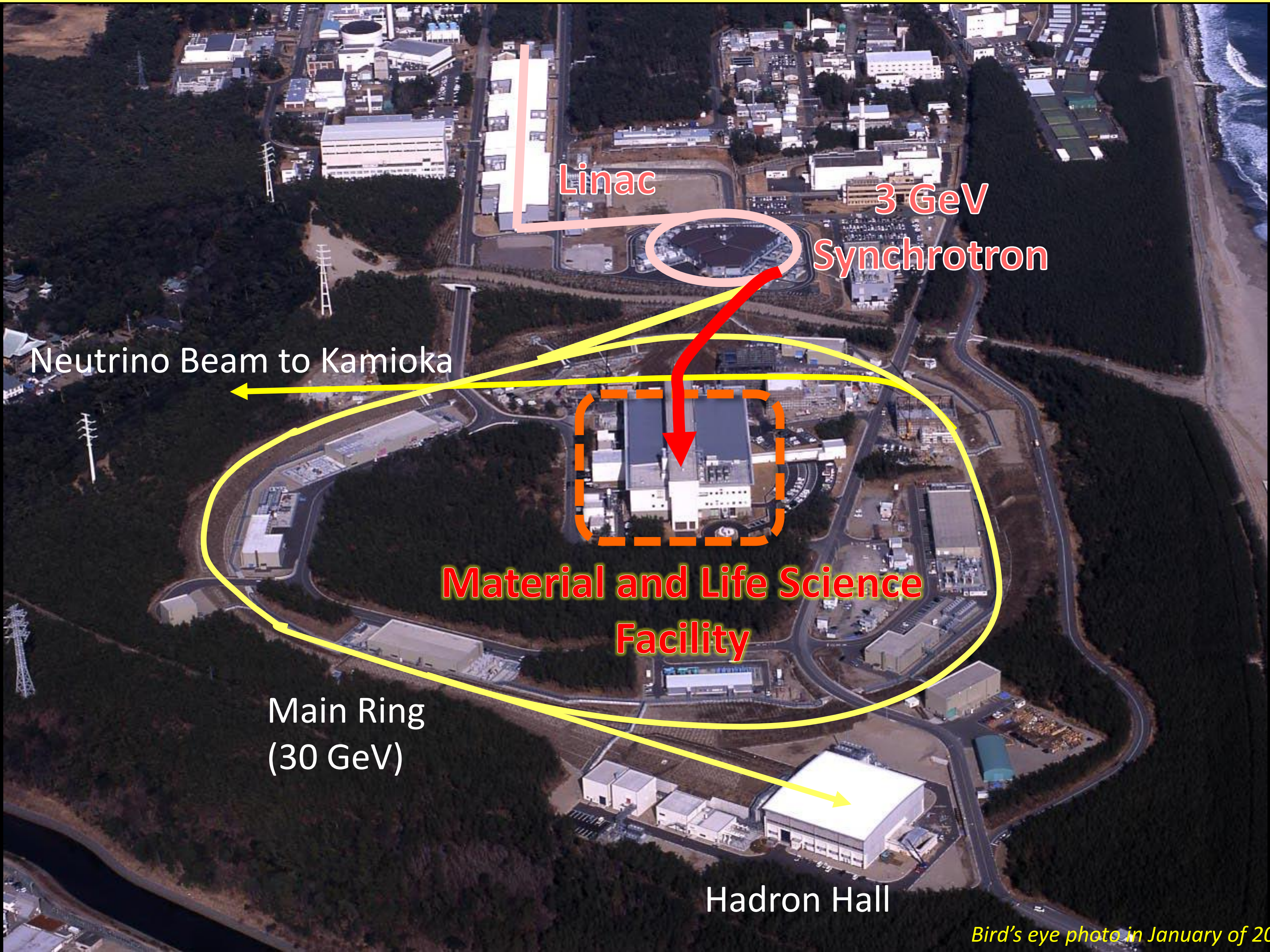
- ➢ **Low emittance beam**
- ➢ **Spin reversal**

Injection & storage & detection

66 cm diameter

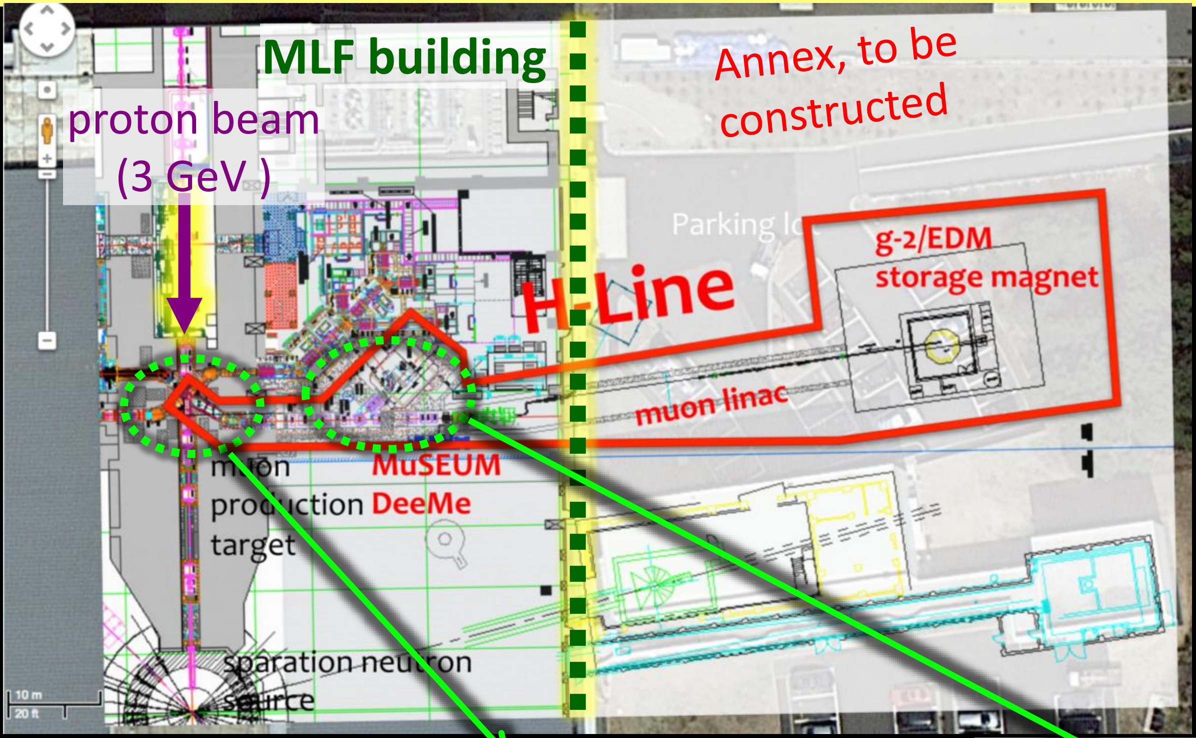
- ➢ **Advanced injection & storage methods**
- ➢ **Good uniformity of B field by compact storage ring**
- ➢ **Large acceptance by tracker**

J-PARC Facility (KEK/JAEA)



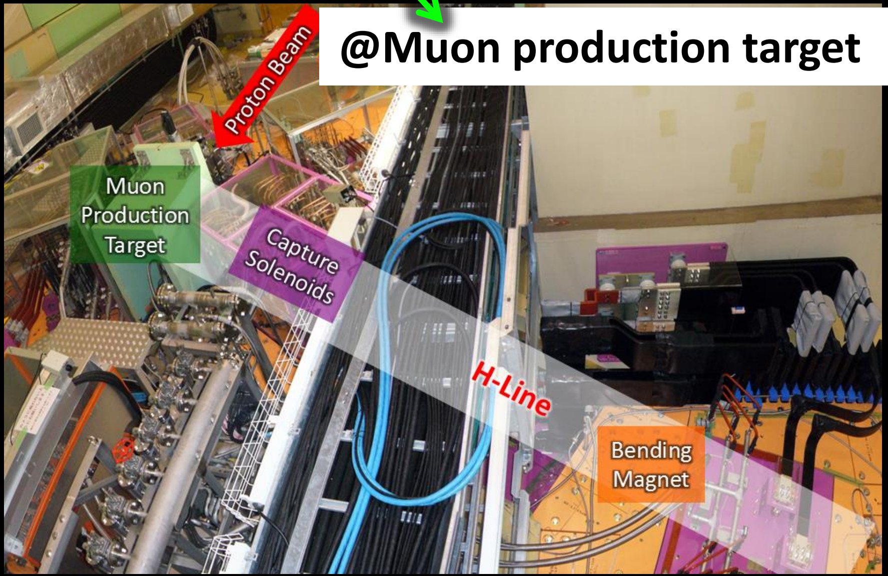
Bird's eye photo in January of 2008

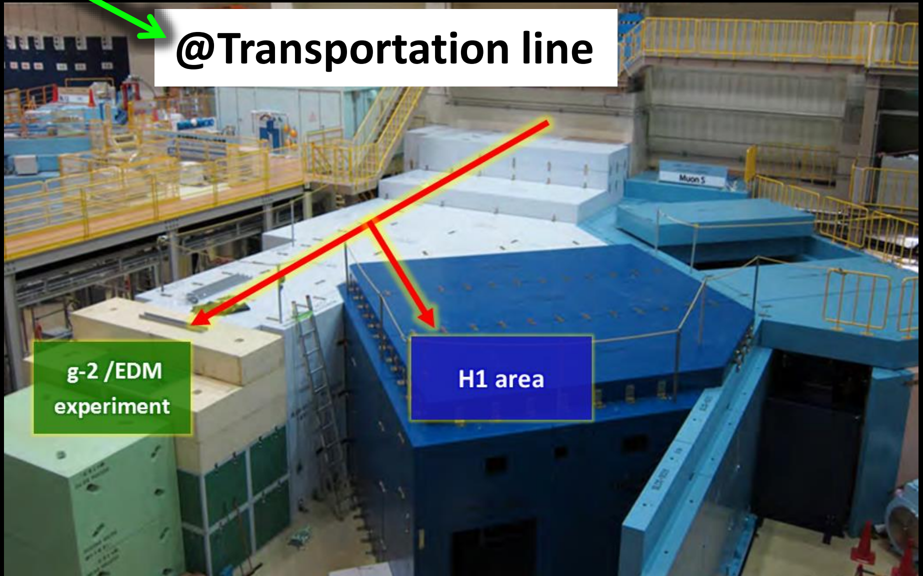
New Muon Beam Line ~H-Line~



Three muon experiments

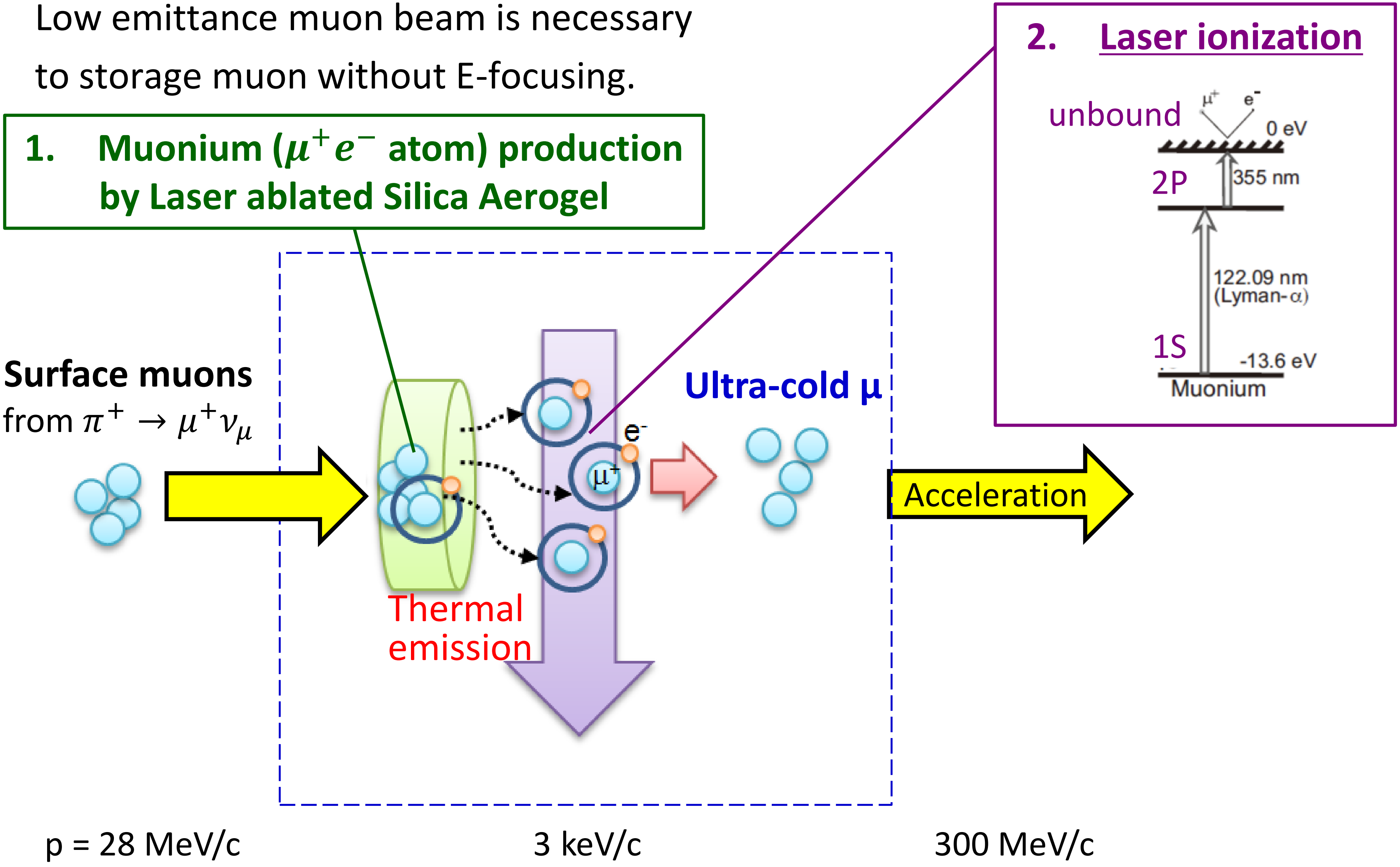
- **g-2/EDM**
- MuSEUM (Mu-HFS)
- DeeMe (muon cLFV)





Ultra-Cold Muon Source

- Low emittance muon beam is necessary to storage muon without E-focusing.



1. Muonium ($\mu^+ e^-$ atom) production by Laser ablated Silica Aerogel

2. Laser ionization

Surface muons
from $\pi^+ \to \mu^+ \nu_\mu$

Thermal emission

Ultra-cold μ

Acceleration

p = 28 MeV/c

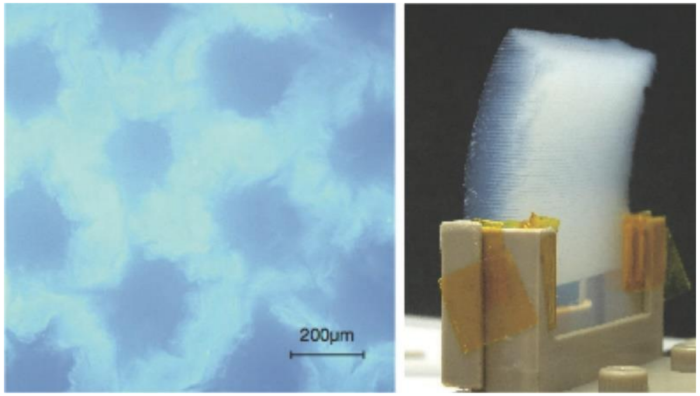
3 keV/c

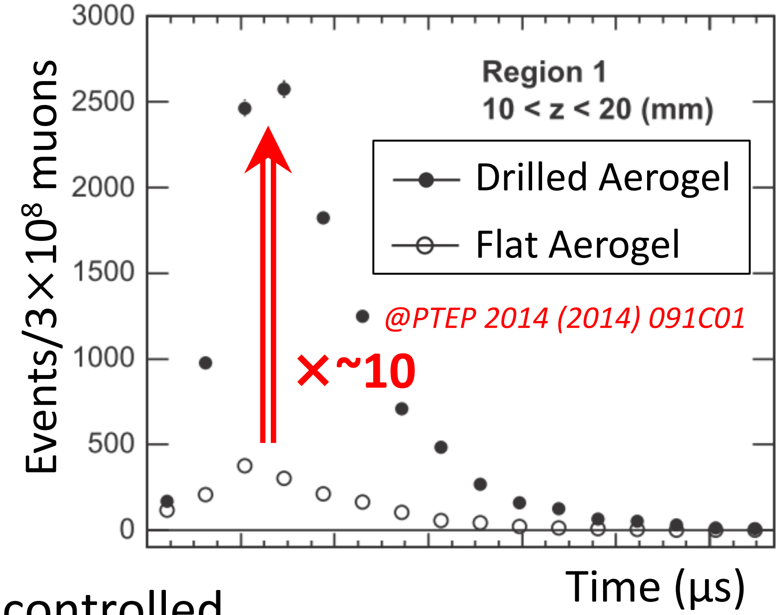
300 MeV/c

➢ **Low emittance muon beam** with $\Delta p_t/p$ ~ 3keV/300 MeV ~ 10^{-5}

Muonium Production Target

- Mu prod. target : **Laser ablated Silica Aerogel**

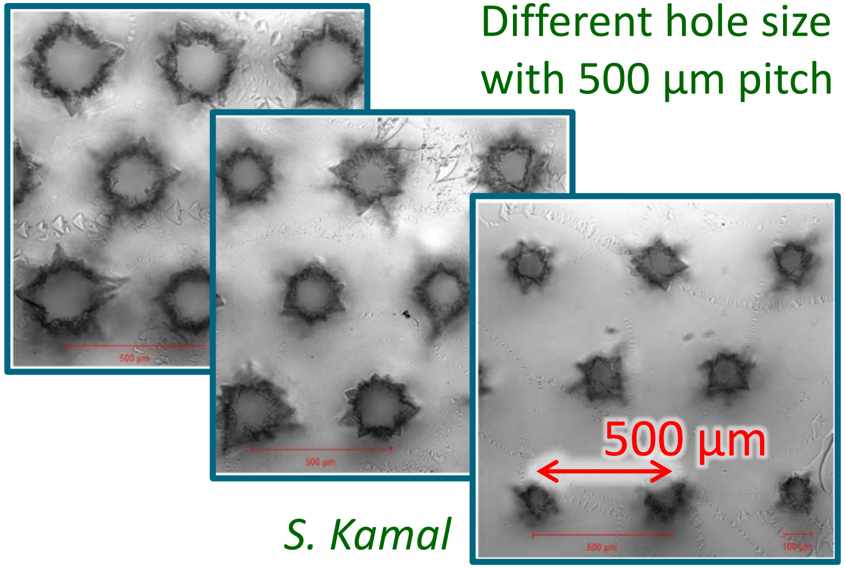




@PTEP 2014 (2014) 091C01

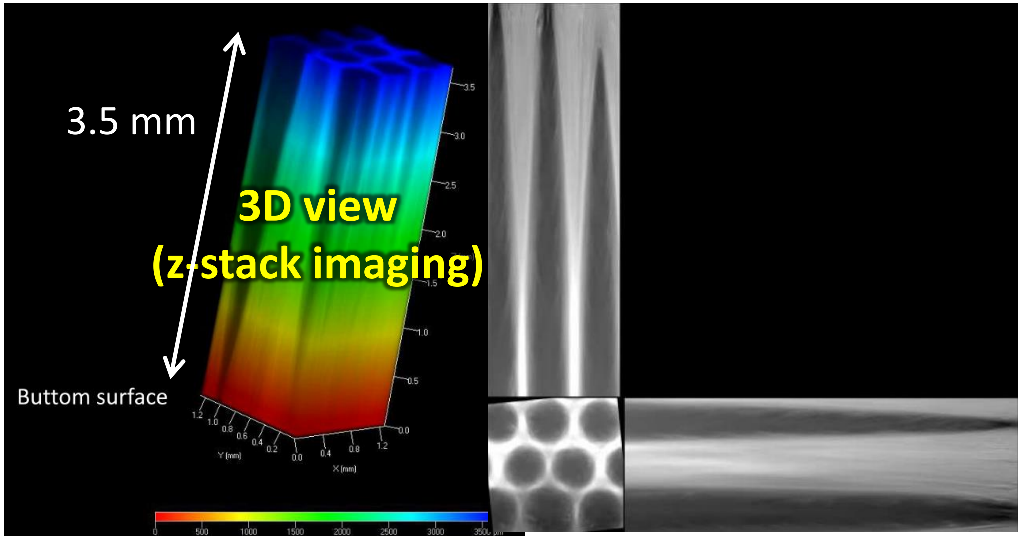
➢ Succeeded to enhance the Mu production rate.

- The width, pitch, and depth of the holes can be controlled.



Different hole size with 500 μm pitch

S. Kamal



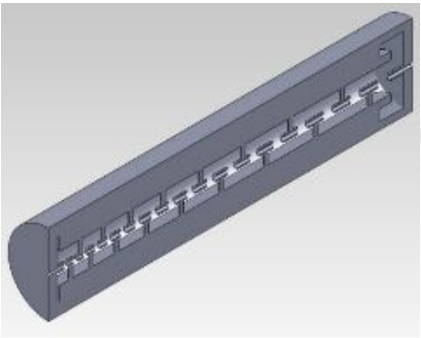
➢ Beam test for Mu production is planned in this month at J-PARC.

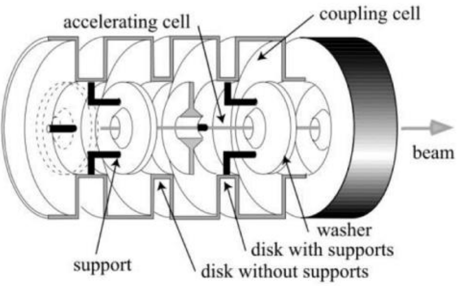
Muon Acceleration

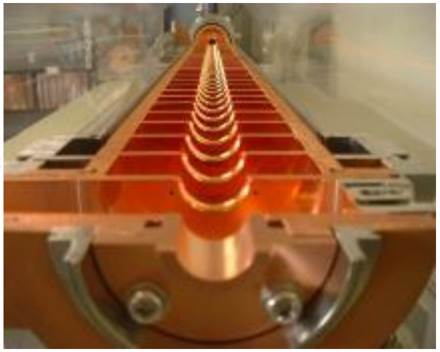
- Ultra-cold muon beam is transported to **linac (linear accelerator)** with initial acceleration and must be **reaccelerated to 300 MeV/c** by linac
  - in a sufficiently short period to avoid decay loss
  - without substantial emittance growth.
- Different design to realize fast re-acceleration through wide β region.

Initial Acc.	5.6 keV β = 0.01	0.3 MeV β = 0.08	4.5 MeV β = 0.3	40 MeV β = 0.7	(P = 300 MeV/c) 212MeV β = 0.9

$\mu \rightarrow$ **RFQ** → **IH-DTL** → **DAW** → **Disk-loaded**





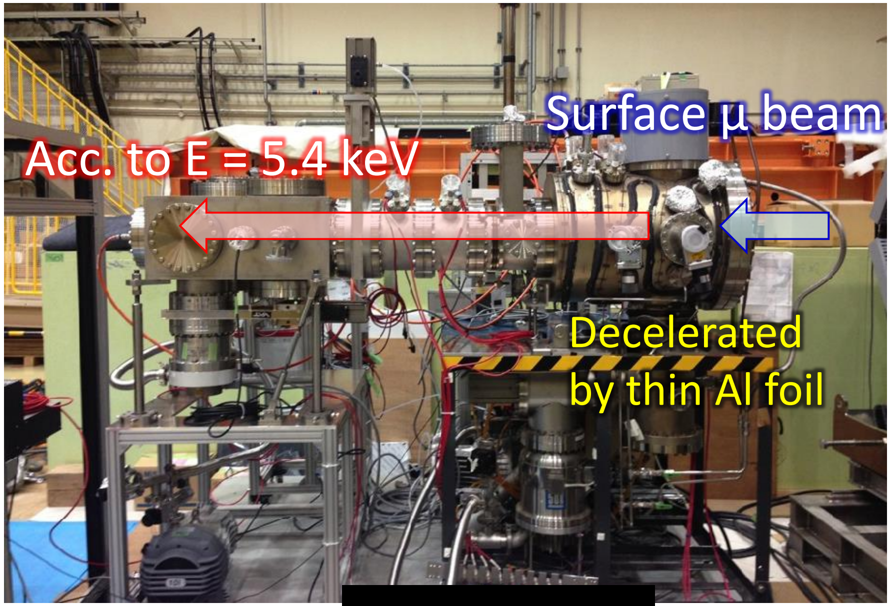


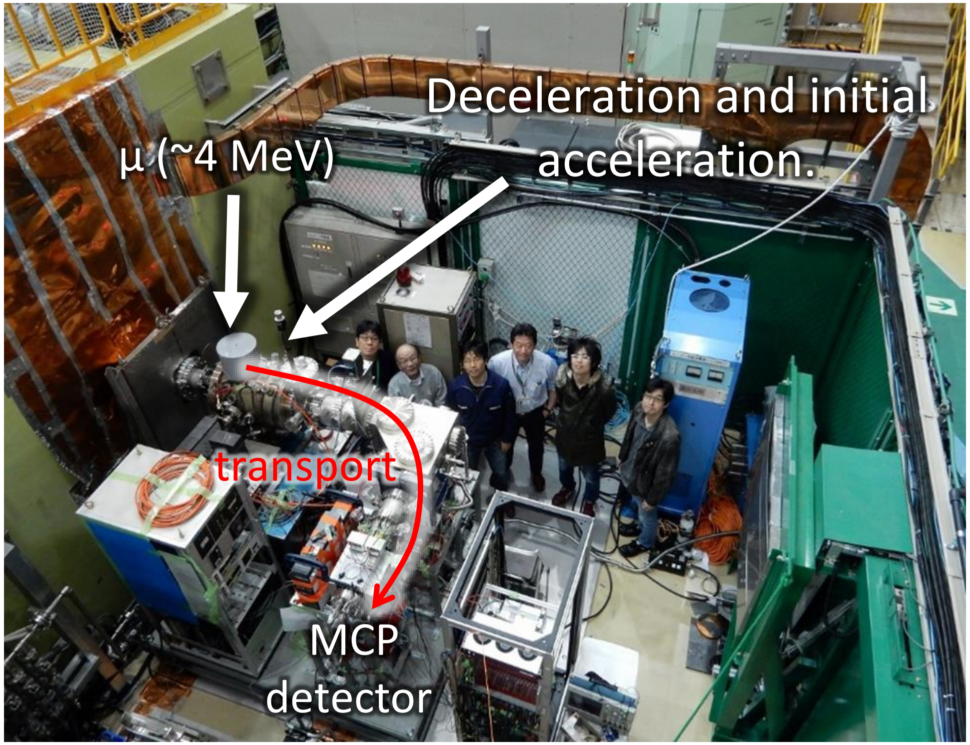
➢ Basic reference design for linac has been completed.
  - Recently IH-DTL paper has been published ***@M. Otani et al., PRAB19, 040101, 2016.***

Demonstration of Deceleration and Initial Acc.

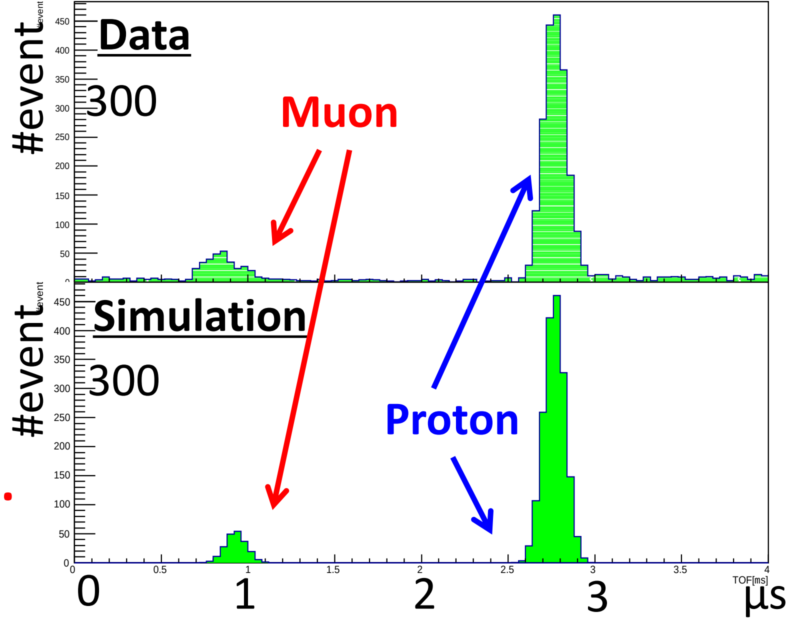
@ J-PARC MLF test muon beamline

(Feb. 2016)





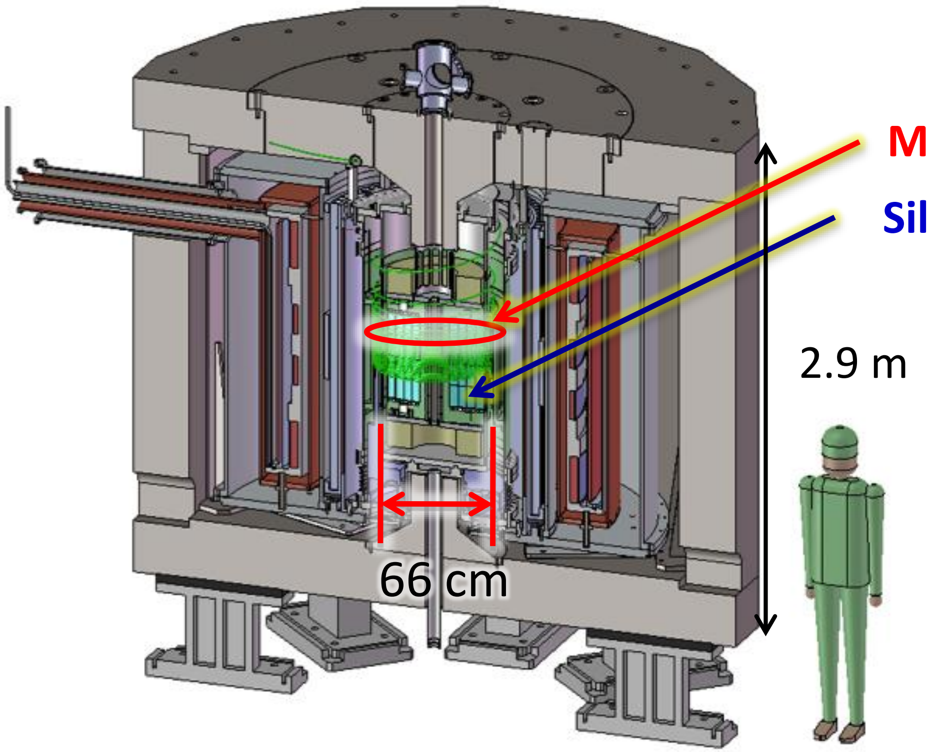
Time of Flight

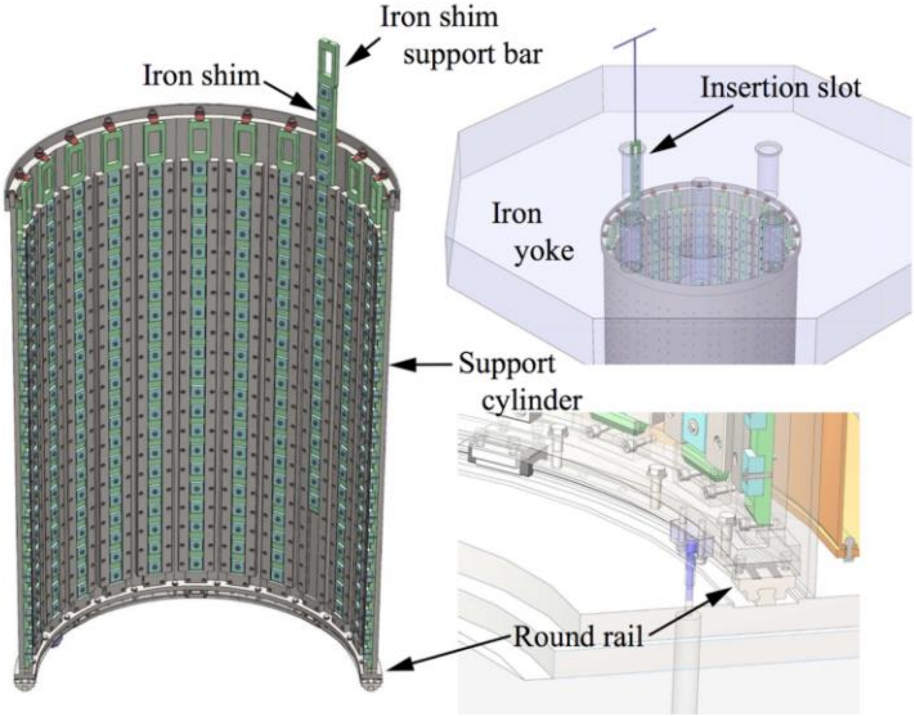


- ➢ **Succeed to deceleration & initial acceleration.**
  - Next step is muon acceleration with RFQ

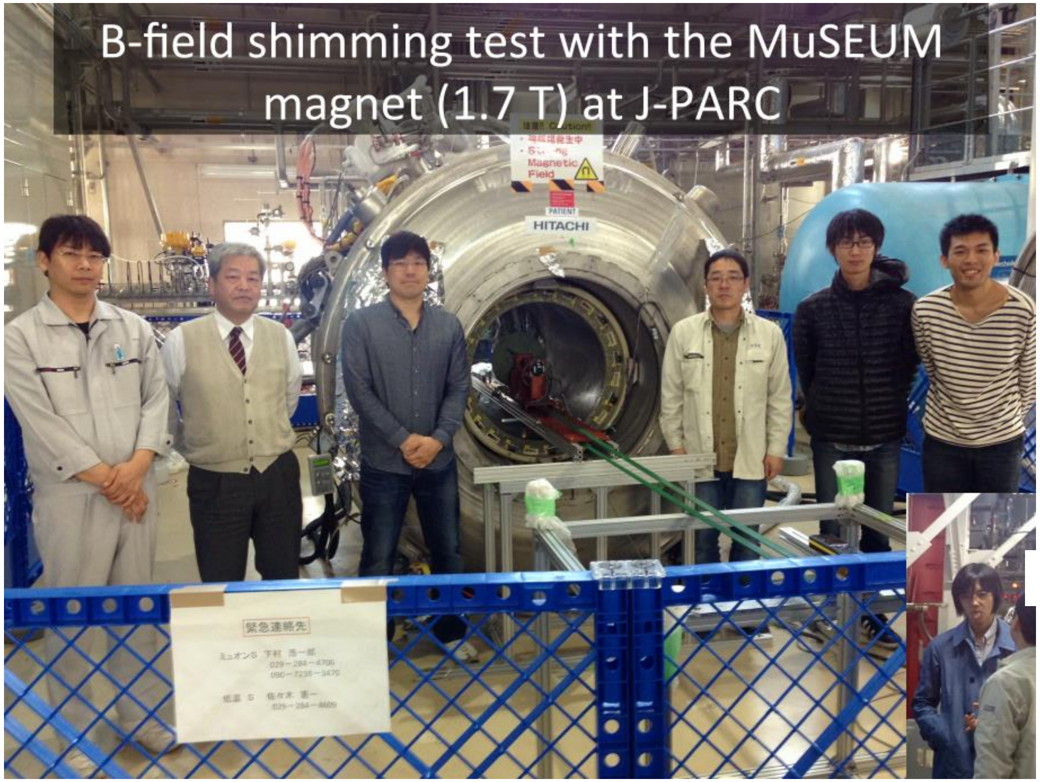
Storage Magnet

- Super Precision Storage Magnet
  - 3T with local uniformity of 1 ppm by iron shimming.





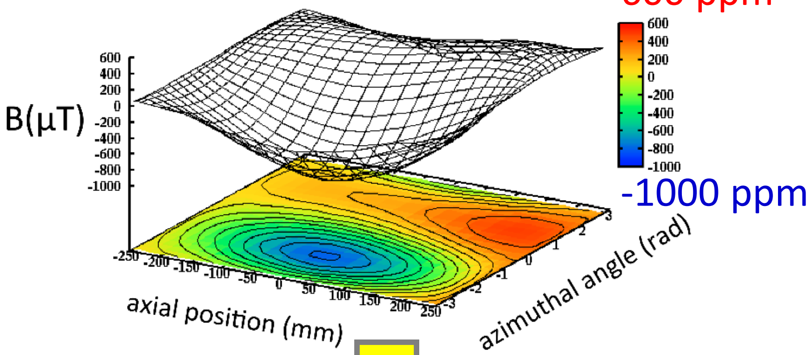
B-Field Shimming


B-field shimming test with the MuSEUM magnet (1.7 T) at J-PARC

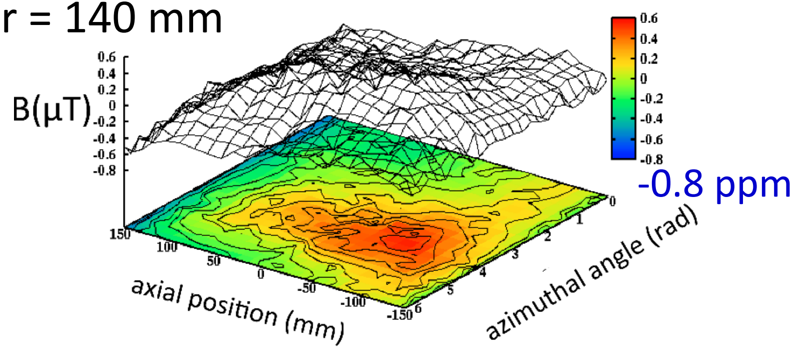
- ppm level uniformity is achieved.

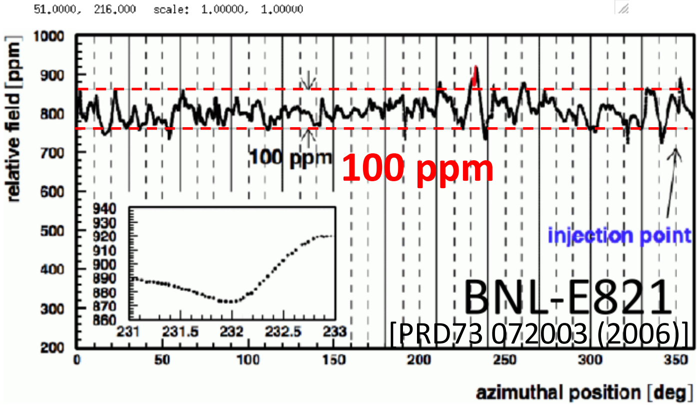
➢ Shimming method is established.

Before shimming



After shimming



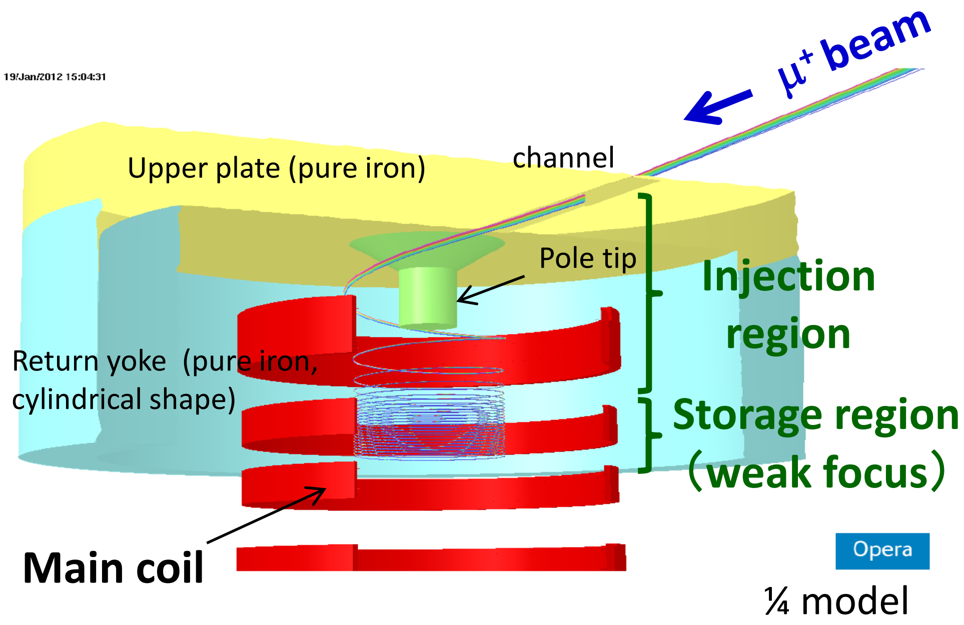


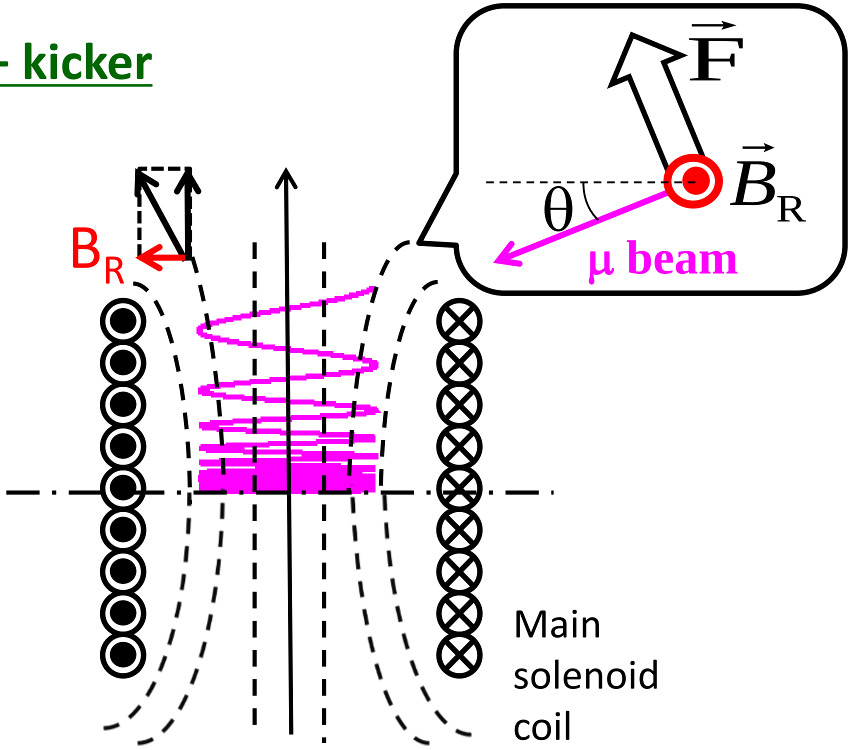
BNL-E821 [PRD73 072003 (2006)]

Muon Injection Scheme @J-PARC

- Injection method used at BNL (Horizontal injection + kicker) can not be applied to our experiment due to compact storage ring and strong B field.
- **3D-spiral injection scheme** has been designed. *H. Iinum et al. NIMA 832 (2016) 51*
  - Smooth connection btw **injection** and **storage regions** w/o any sources of error field.
  - Vertical motion is controlled by radial field (Br).
    - **Pulsed magnetic kicker** to guide muon beam into stable orbit.
    - **Weak-focusing magnetic field** to hold muon beam in stable orbit.

3D spiral injection + kicker

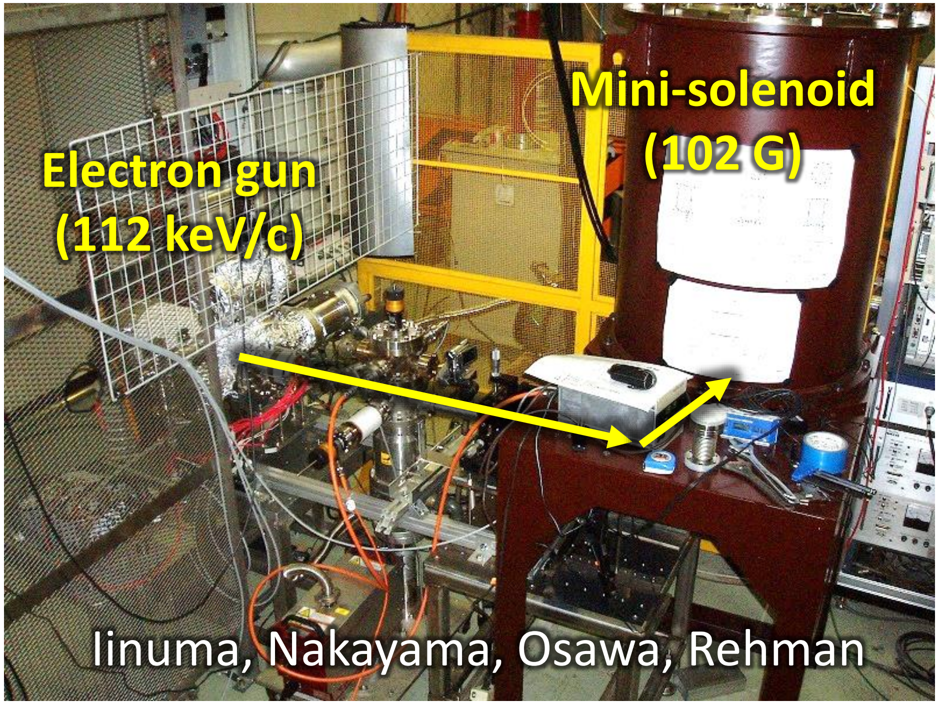


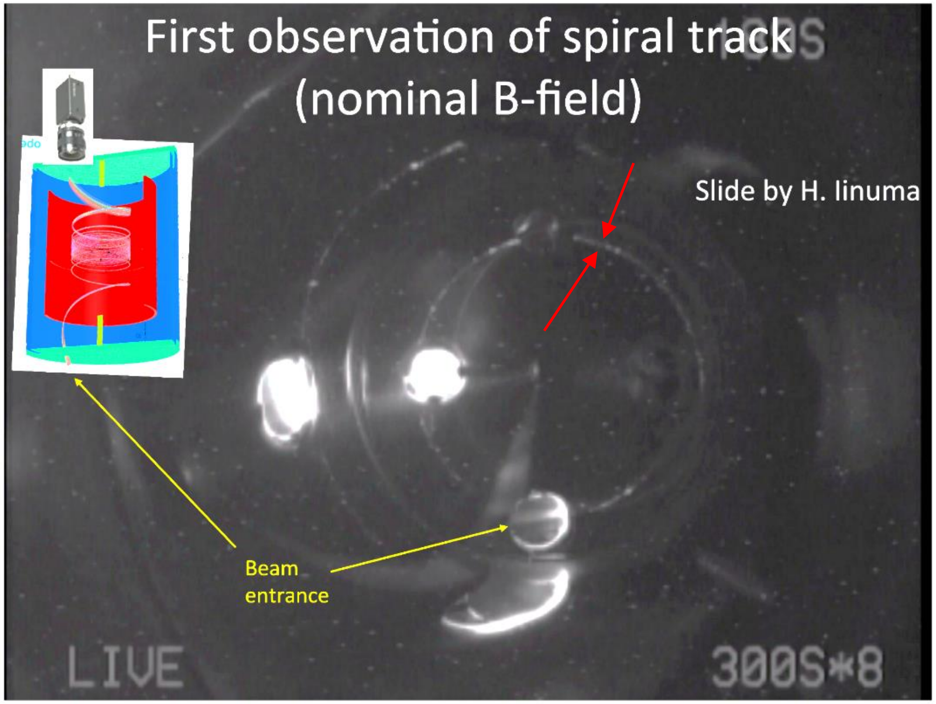


➢ **Higher injection efficiency : ~80%** ⇔ 3-5% @BNL E821 [PRD73 072003 (2006)]

Demonstration of Spiral Injection

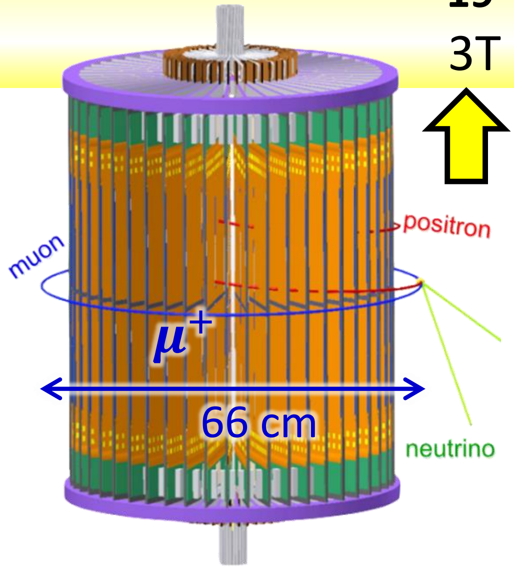
- Demonstration of spiral injection is ongoing.





➢ Succeeded in observation of first spiral track.

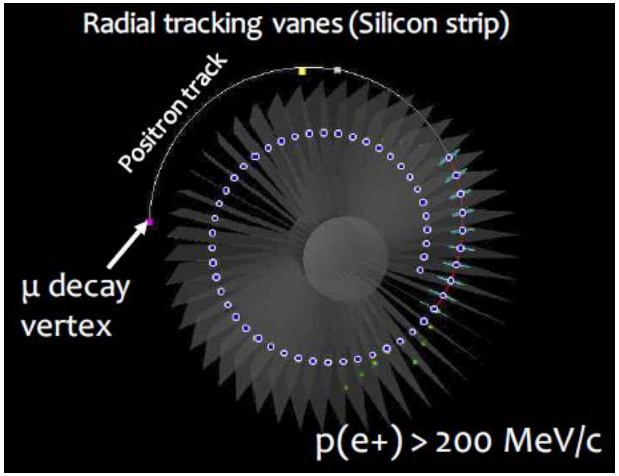
Positron Tracking Detector

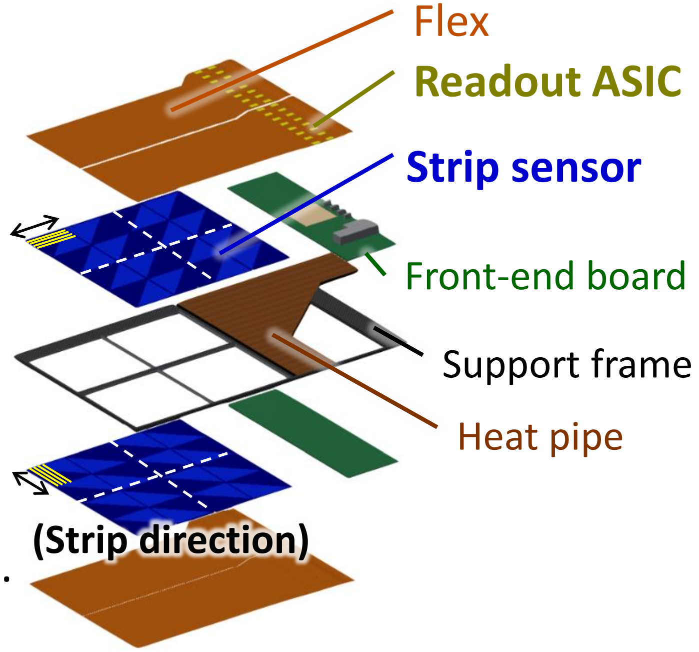


- Compact storage ring gives good uniformity of B-field, but lead to dense muon decay.

Silicon strip tracking detector (not calorimeter)

- **High position resolution and tracking efficiency**
- **High hit rate capability and early-to-late stability**
  - 40k muons/spill with 25 Hz @final goal
  - Rate changes by a factor of ~1/150 during 5 times dilated lifetime.
- **No contamination of electromagnetic field in the muon storage region.**
  - $\Delta B/B < 1$ ppm and E-field << 10 mV/cm

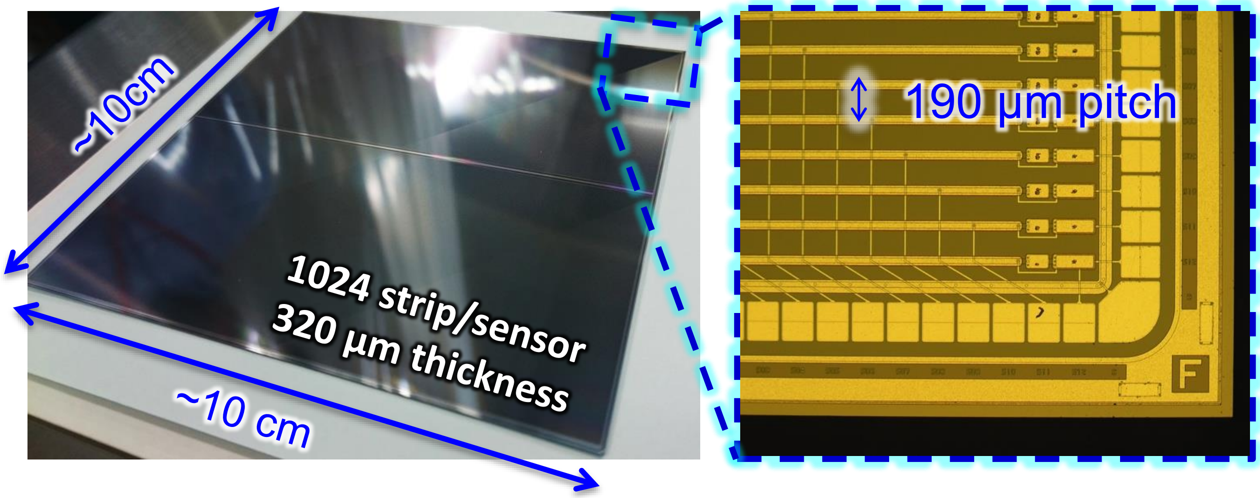




- Detector construction fund is partially covered by Kiban-S.

➢ **Move to detector construction phase.**

Silicon Strip Sensor and Front-end ASIC



Full-size sensor production

- Basic properties of sensors have been confirmed.

➢ **Mass production will start in this JFY.**

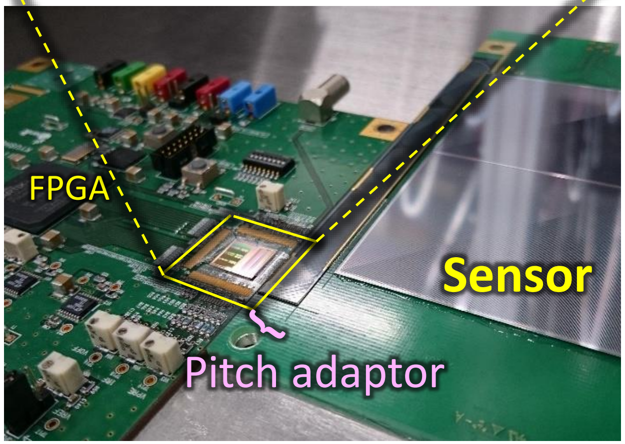
Front-end ASIC "SliT128A" (3rd prototype)

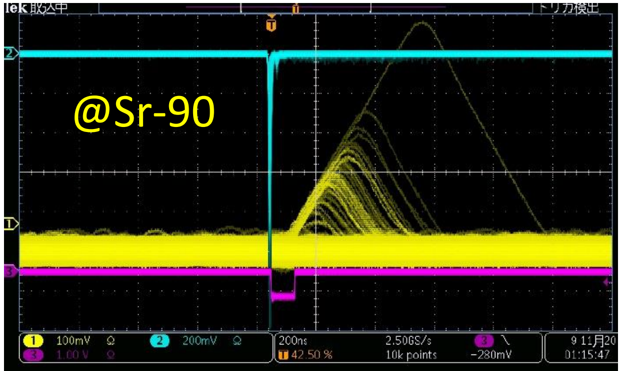
- Confirmed to satisfy almost all requirements for ASIC.

➢ **Final version of ASIC will be fabricated in next JFY.**

Full-size sensor & 3rd prototype ASIC

- Signal from radiation source is observed as expected.
- Application for muonimun HFS experiment "MuSEUM"



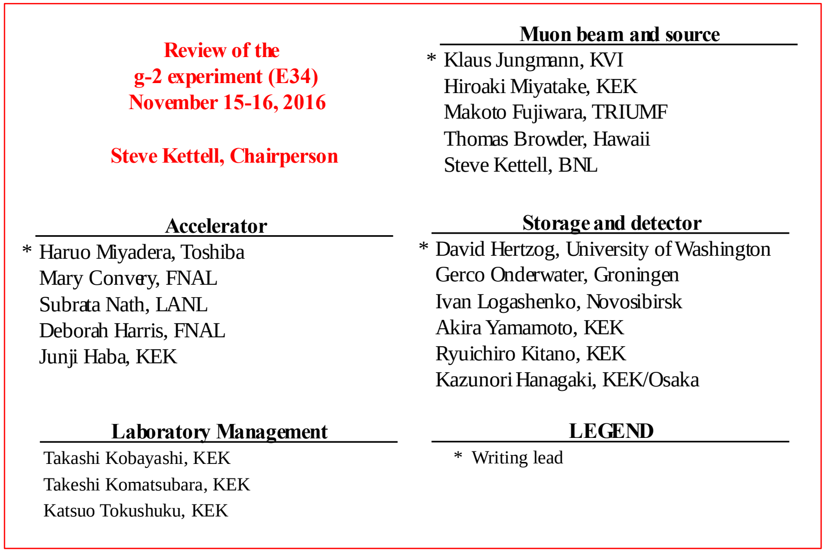


Status of J-PARC E34 Collaboration

- 144 members from 9 countries, 49 institutions (Still evolving).
- Submitted **technical design report (TDR)**.
  - Aim 0.4 ppm as stage 1.

	BNL E821	**J-PARC E34**
g-2	0.46 ppm	**0.37 ppm** **(→ 0.1 ppm)**
EDM	0.9×10^{-19} e・cm	**1.3×10^{-21} e・cm**

- Approved as **one of priority projects in the future by KEK**.
- **Focused review** to move construction stage was held (Nov.15-16, 2016)



Review of the
g-2 experiment (E34)
November 15-16, 2016

Steve Kettell, Chairperson

Muon beam and source
* Klaus Jungmann, KVI
Hiroaki Miyatake, KEK
Makoto Fujiwara, TRIUMF
Thomas Browder, Hawaii
Steve Kettell, BNL

Accelerator
* Haruo Miyadera, Toshiba
Mary Convery, FNAL
Subrata Nath, LANL
Deborah Harris, FNAL
Junji Haba, KEK

Storage and detector
* David Hertzog, University of Washington
Gerco Onderwater, Groningen
Ivan Logashenko, Novosibirsk
Akira Yamamoto, KEK
Ryuichiro Kitano, KEK
Kazunori Hanagaki, KEK/Osaka

Laboratory Management
Takashi Kobayashi, KEK
Takeshi Komatsubara, KEK
Katsuo Tokushuku, KEK

LEGEND
* Writing lead

CM12@J-PARC 2016.6

Focused Review @J-PARC 2016.11

Summary

- **J-PARC E34 experiment** measures muon g-2 and EDM by completely different approach : **"off-magic momentum with ultra-cold muon beam".**
- A lot of interesting techniques are being developed.
  - **No focusing E-field to storage muon beam**
    - **Low emittance muon beam**
      - Efficient muonium production and laser ionization & muon re-acceleration
  - **3D-spiral injection scheme**
  - **Compact storage ring**
    - Good uniformity of B-field & large acceptance by tracking detector.
- TDR was submitted.
  - g-2 : 0.37 ppm (final goal is 0.1 ppm)
  - EDM : 1.3×10^{-21} e・cm
  - ➢ Statistical precision exceeds BNL E821.
- Moving to construction phase.
  - Partial construction fund (detector) is approved.
- Job opening for the H-Line construction@hecforum:06663
  - http://www.kek.jp/en/Jobs/

Backup

Dipole Moments

- Electromagnetic interaction Hamiltonian with magnetic and electric fields

$$\mathcal{H} = -\vec{\mu}\cdot\vec{B} - \vec{d}\cdot\vec{E}$$

$(\mu_0 = q/2m)$

Magnetic dipole moment (MDM)

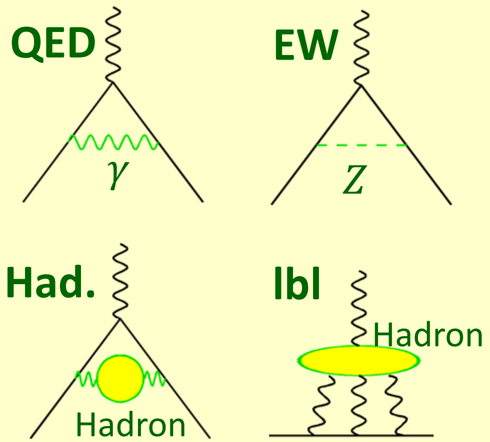
- $\vec{\mu} = g\mu_0\vec{s} = 2(a+1)\,\mu_0\vec{s}$

Anomalous magnetic moment

- $a = (g-2)/2$

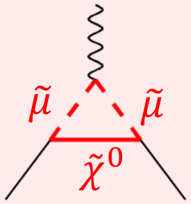
- Induced by any interaction.

SM



NP

e.g. SUSY

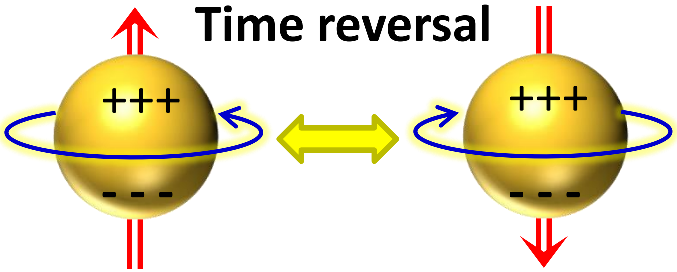


➢ **Precise test of the SM**

Electric dipole moment (EDM)

- $\vec{d} = \eta\mu_0\vec{s}$
- Induced by T&P-violating interaction.

Time reversal

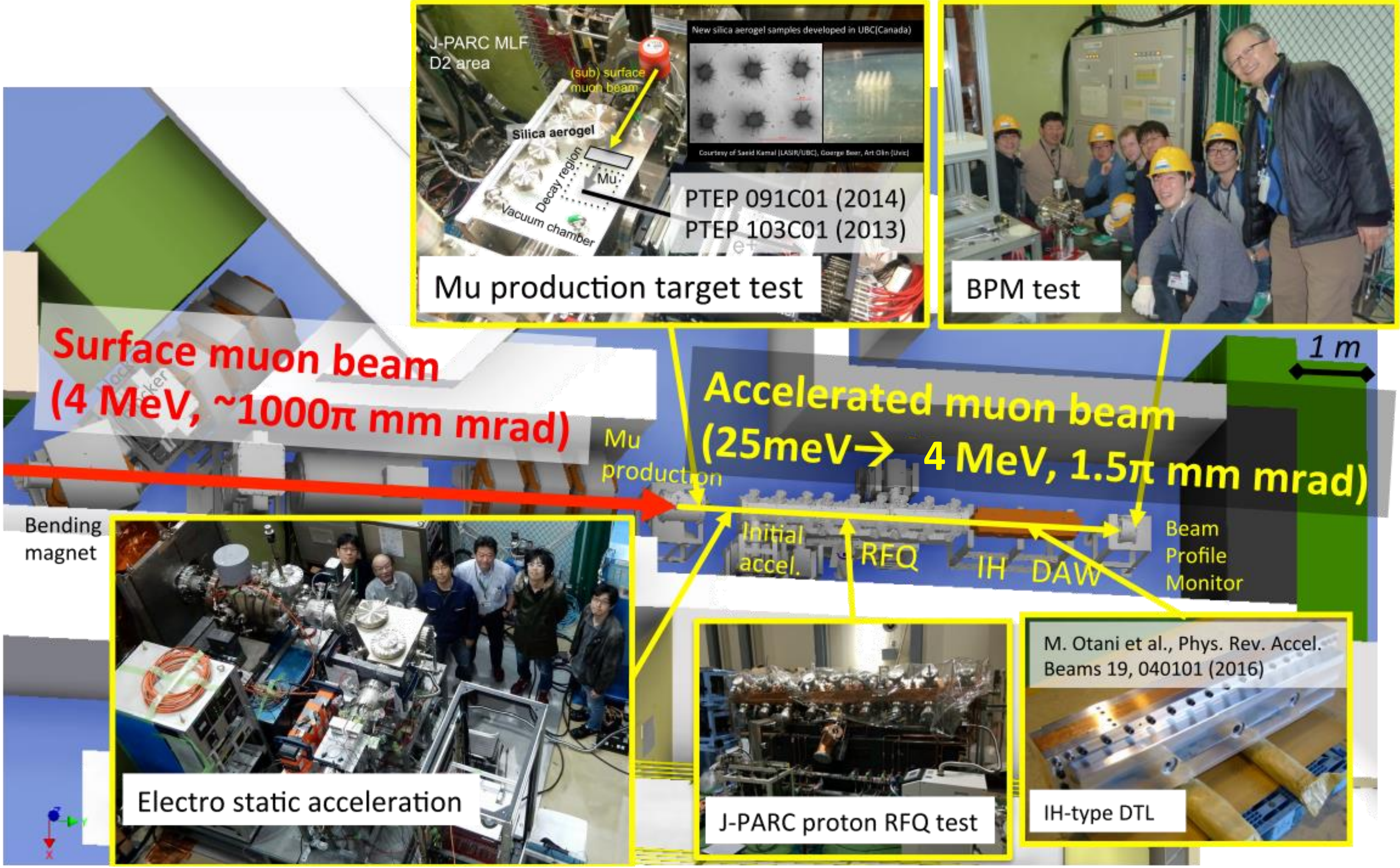


- Highly suppressed in the SM
  - $d^{\mathrm{SM}} \sim 10^{-38} e\cdot\mathrm{cm}$
  - Out of experimental reach.

➢ **Non-zero EDM is evidence for NP**

Ultra-cold Muon Beam at H-line

- Design of H-line and the muon acceleration test.



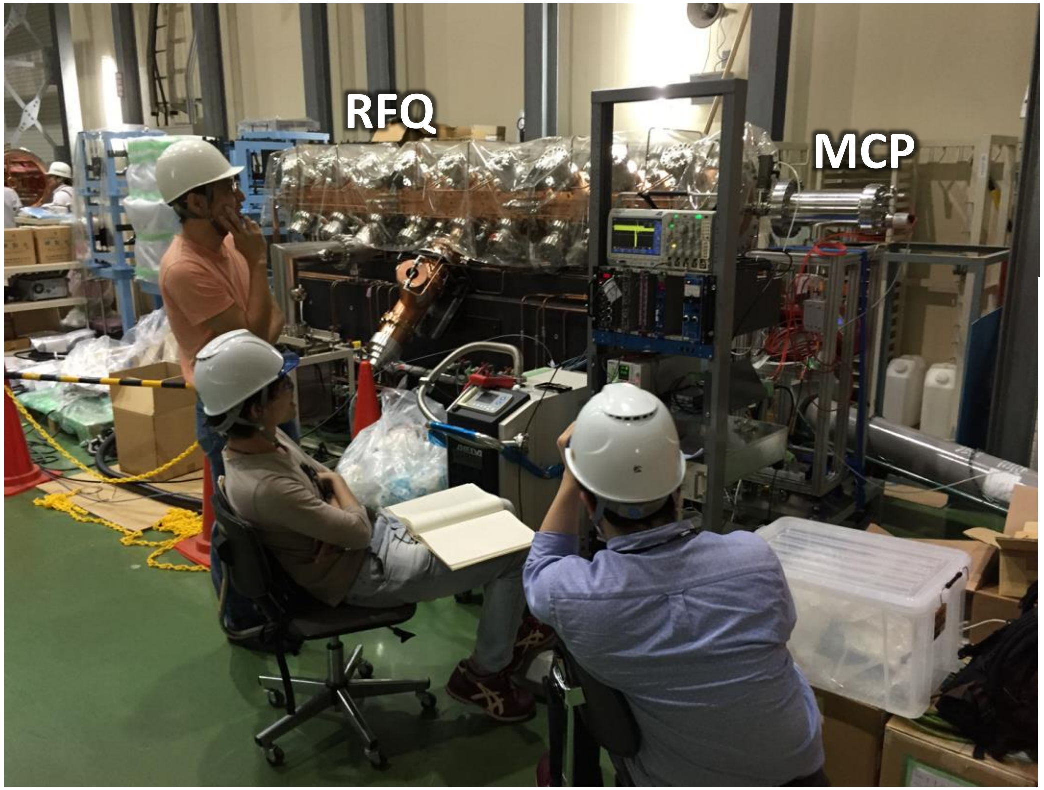
PTEP 091C01 (2014)
PTEP 103C01 (2013)

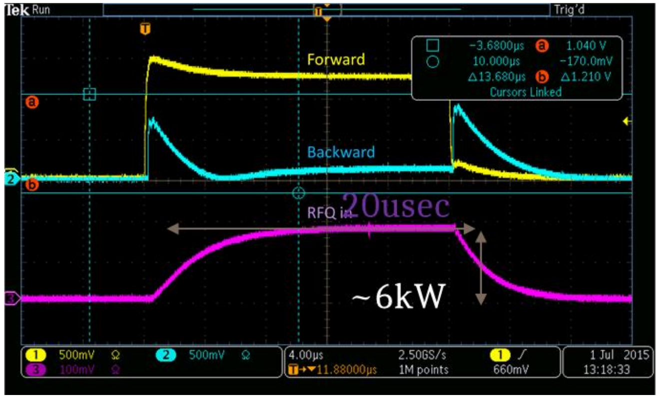
M. Otani et al., Phys. Rev. Accel. Beams 19, 040101 (2016)

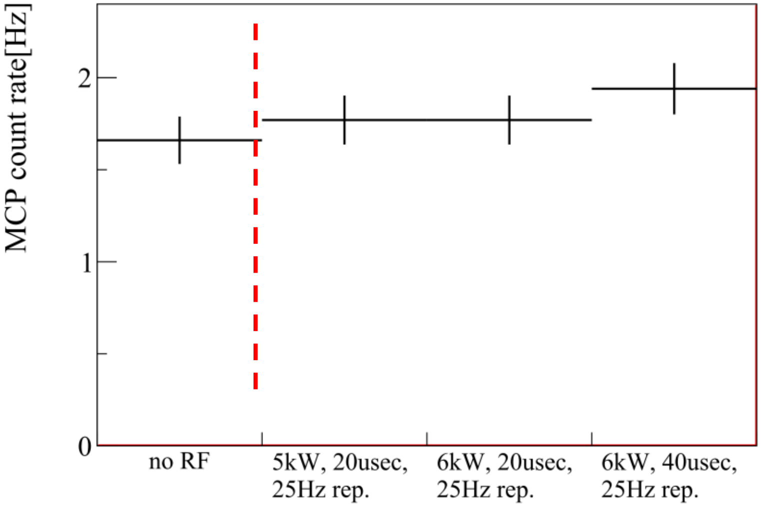
RFQ Commissioning

@ J-PARC LINAC facility, Jun. 2015.

- Nominal power (4.6 kW) and duty operation.
- No RF-related background with MCP.

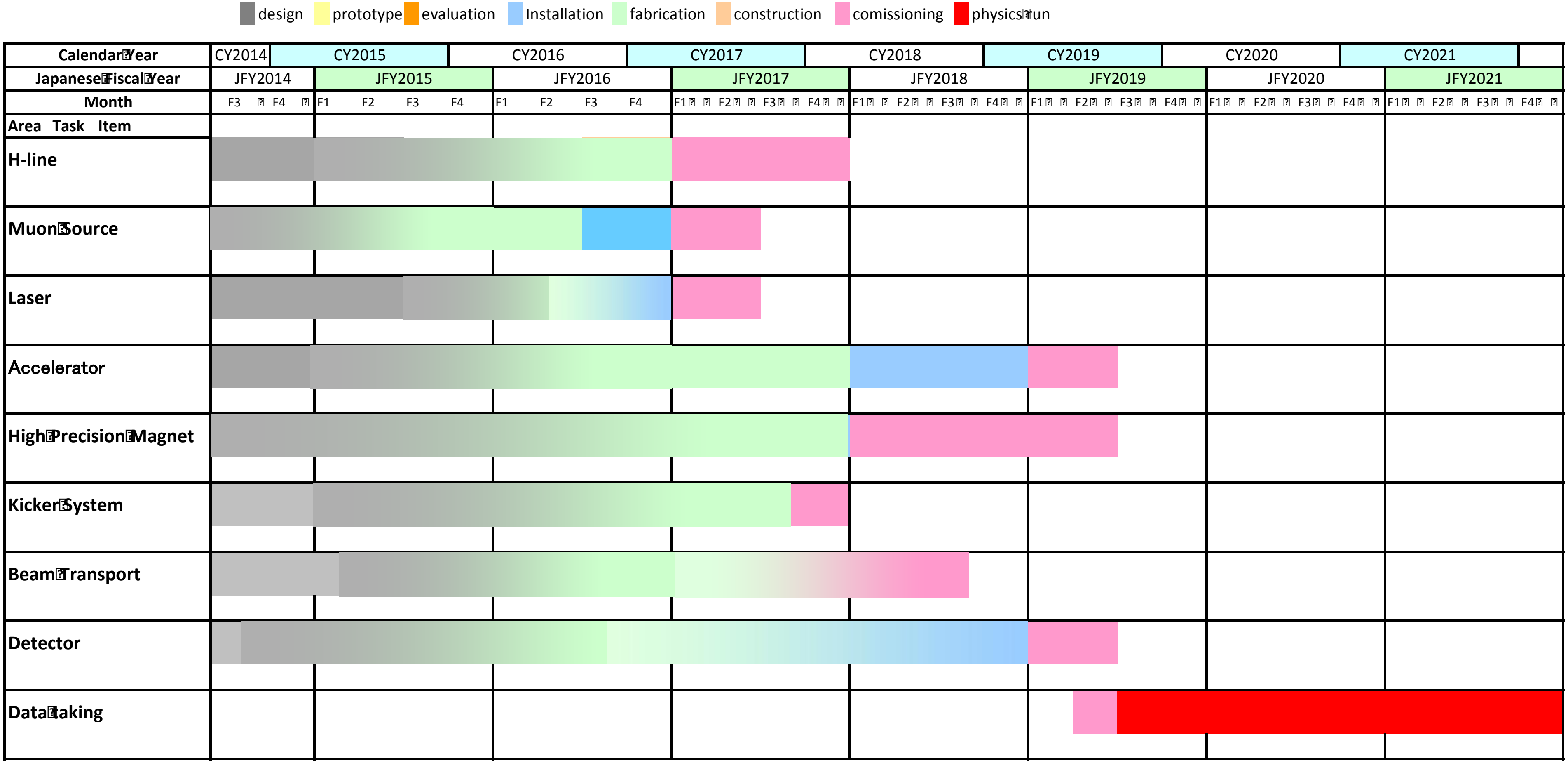






- ➢ **RFQ is ready.**
  - Muon acceleration with RFQ is planned.

Technically driven schedule



Assumption : Major construction fund become available in JFY2016

Comparison of Experiments

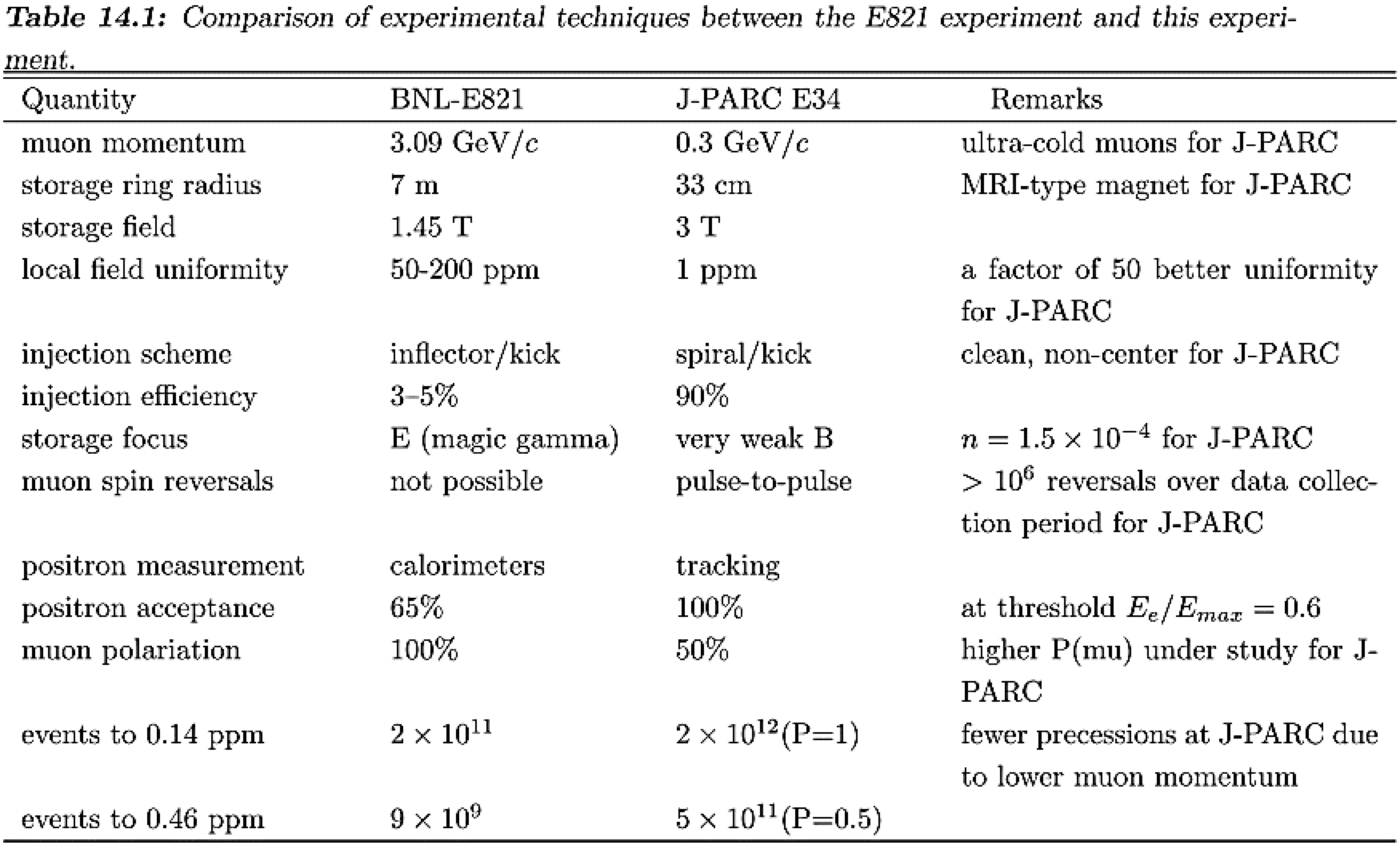


Table 14.1: Comparison of experimental techniques between the E821 experiment and this experiment.

Quantity	BNL-E821	J-PARC E34	Remarks
muon momentum	3.09 GeV/c	0.3 GeV/c	ultra-cold muons for J-PARC
storage ring radius	7 m	33 cm	MRI-type magnet for J-PARC
storage field	1.45 T	3 T	
local field uniformity	50-200 ppm	1 ppm	a factor of 50 better uniformity for J-PARC
injection scheme	inflector/kick	spiral/kick	clean, non-center for J-PARC
injection efficiency	3–5%	90%	
storage focus	E (magic gamma)	very weak B	$n = 1.5 \times 10^{-4}$ for J-PARC
muon spin reversals	not possible	pulse-to-pulse	$> 10^6$ reversals over data collection period for J-PARC
positron measurement	calorimeters	tracking	
positron acceptance	65%	100%	at threshold $E_e/E_{max} = 0.6$
muon polariation	100%	50%	higher P(mu) under study for J-PARC
events to 0.14 ppm	2×10^{11}	2×10^{12}(P=1)	fewer precessions at J-PARC due to lower muon momentum
events to 0.46 ppm	9×10^9	5×10^{11}(P=0.5)	

Efficiency

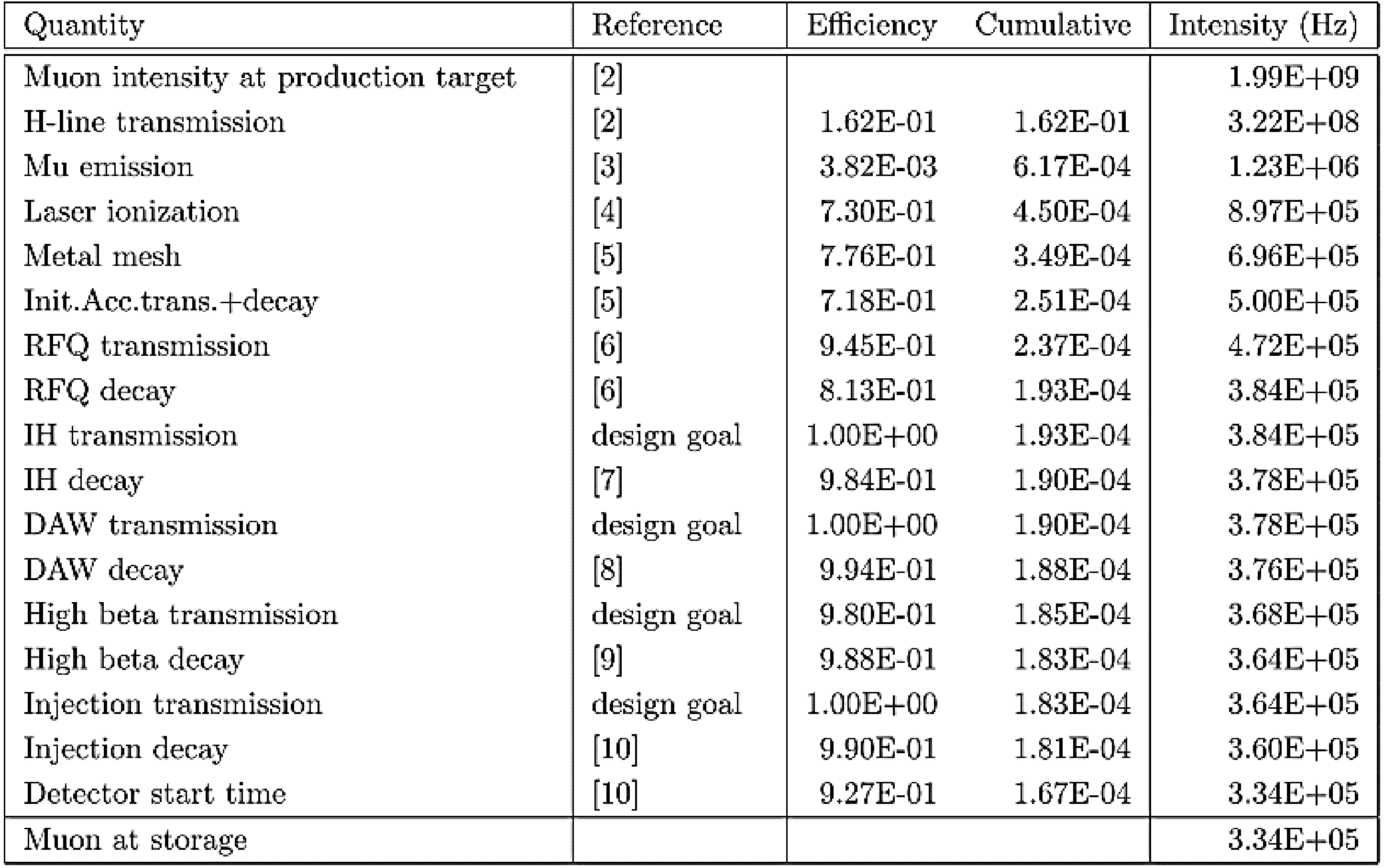


Table 13.1: Efficiency and beam intensity

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

Laser Timing

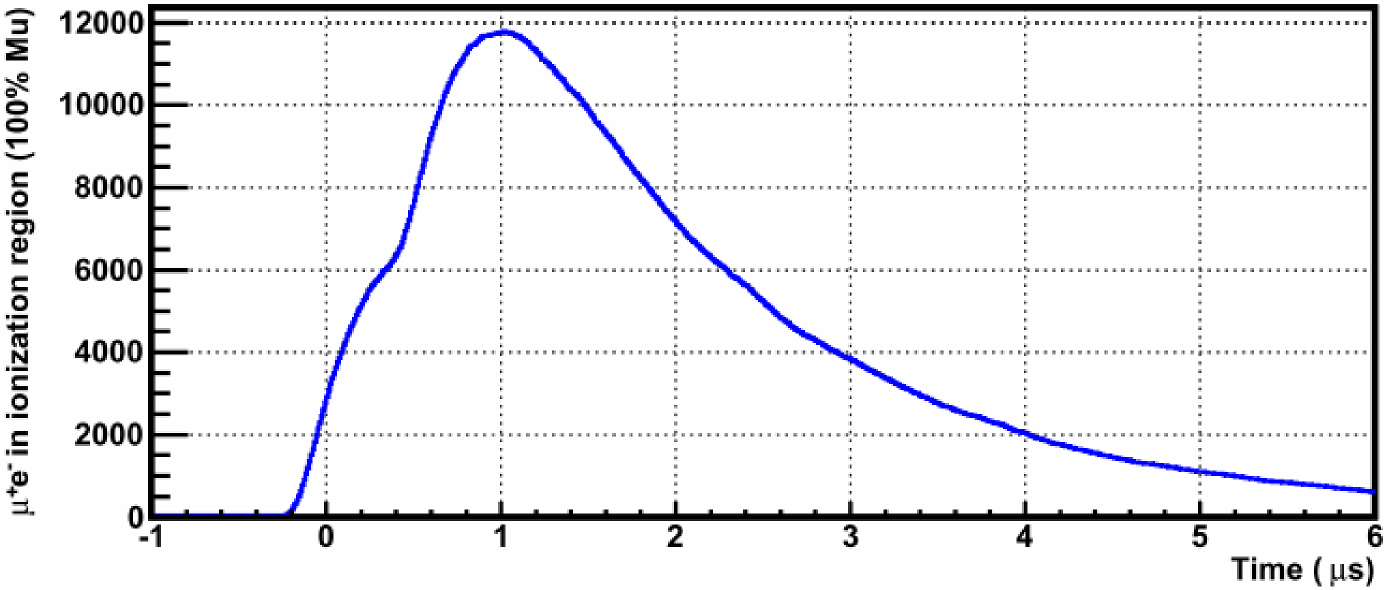
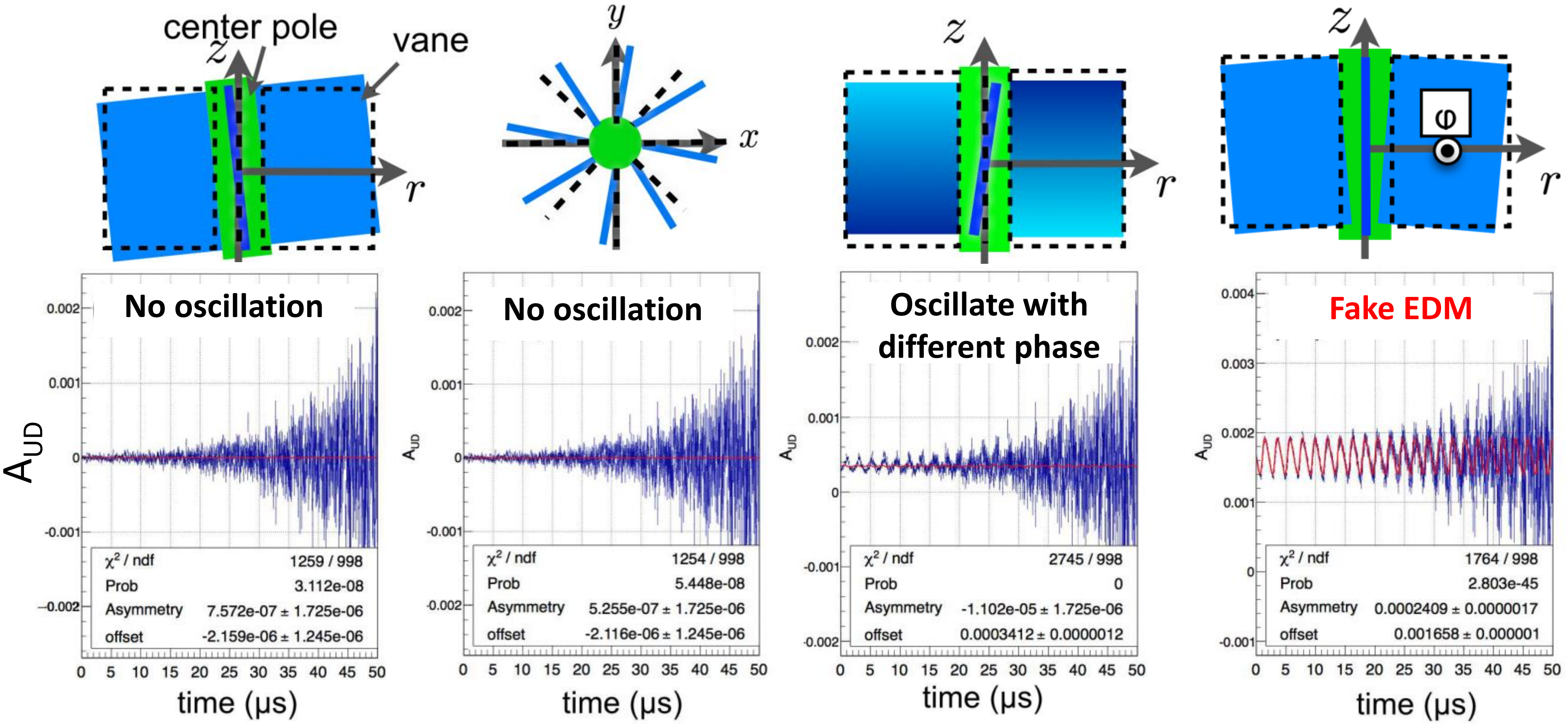


Figure 5.8: *Evolution of muonium into a laser ionization region following diffusion and emission from a laser-ablated aerogel production target. This is the result of a diffusion simulation with parameters that fit the results of TRIUMF S1249 as shown in Fig. 5.7, after changing the muon stopping distribution to match that produced from the G4beamline J-PARC H-line simulation and G4 beam energy loss simulation in the aerogel target. The double pulse of the beam causes the time structure at the leading edge.*

Fake EDM Signal by Misalignment

- EDM is measured from up-down asymmetry “A_{UD}”.

Simulation with 1 mrad misalignment and null EDM signal



No oscillation

No oscillation

Oscillate with different phase

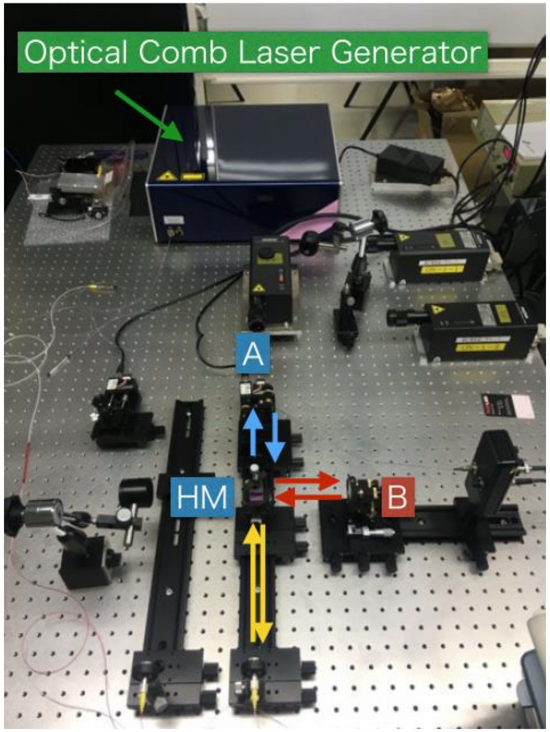
Fake EDM

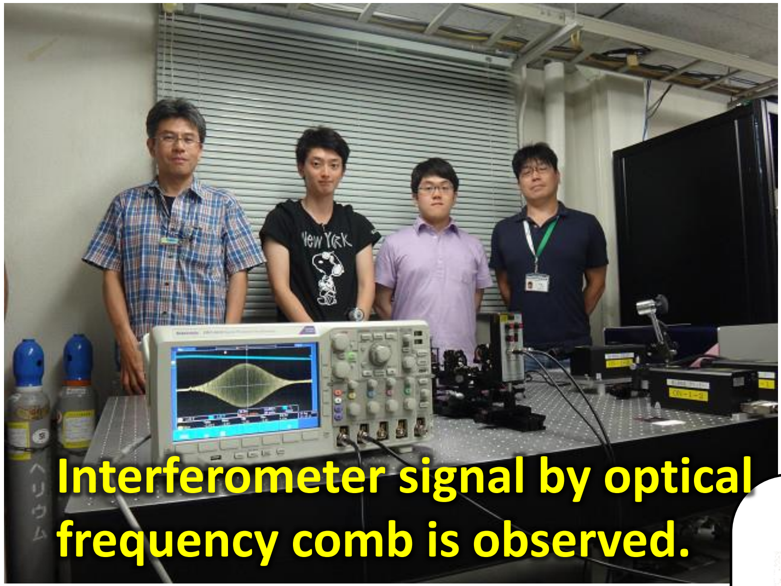
➢ The alignment must be controlled with 10 μrad accuracy to measure EDM with $10^{-21} e \cdot \mathrm{cm}$.

Alignment Monitor

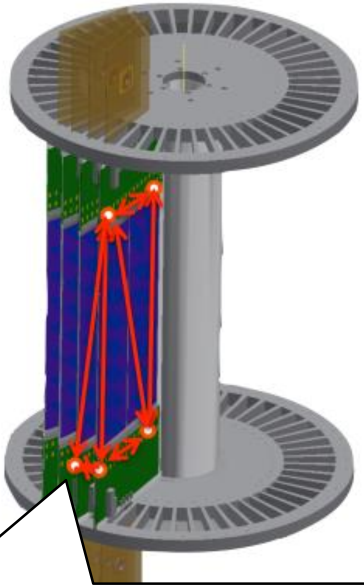
Interferometer by optical frequency comb with a ball-lens target

- Absolute length can be measured with µm level up to 10 m.
  - W. Sudatham, H. Matsumoto, S. Takahashi, K. Takamasu Precis Eng 43, 486 (2016)

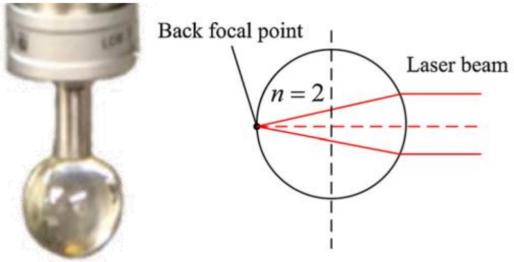




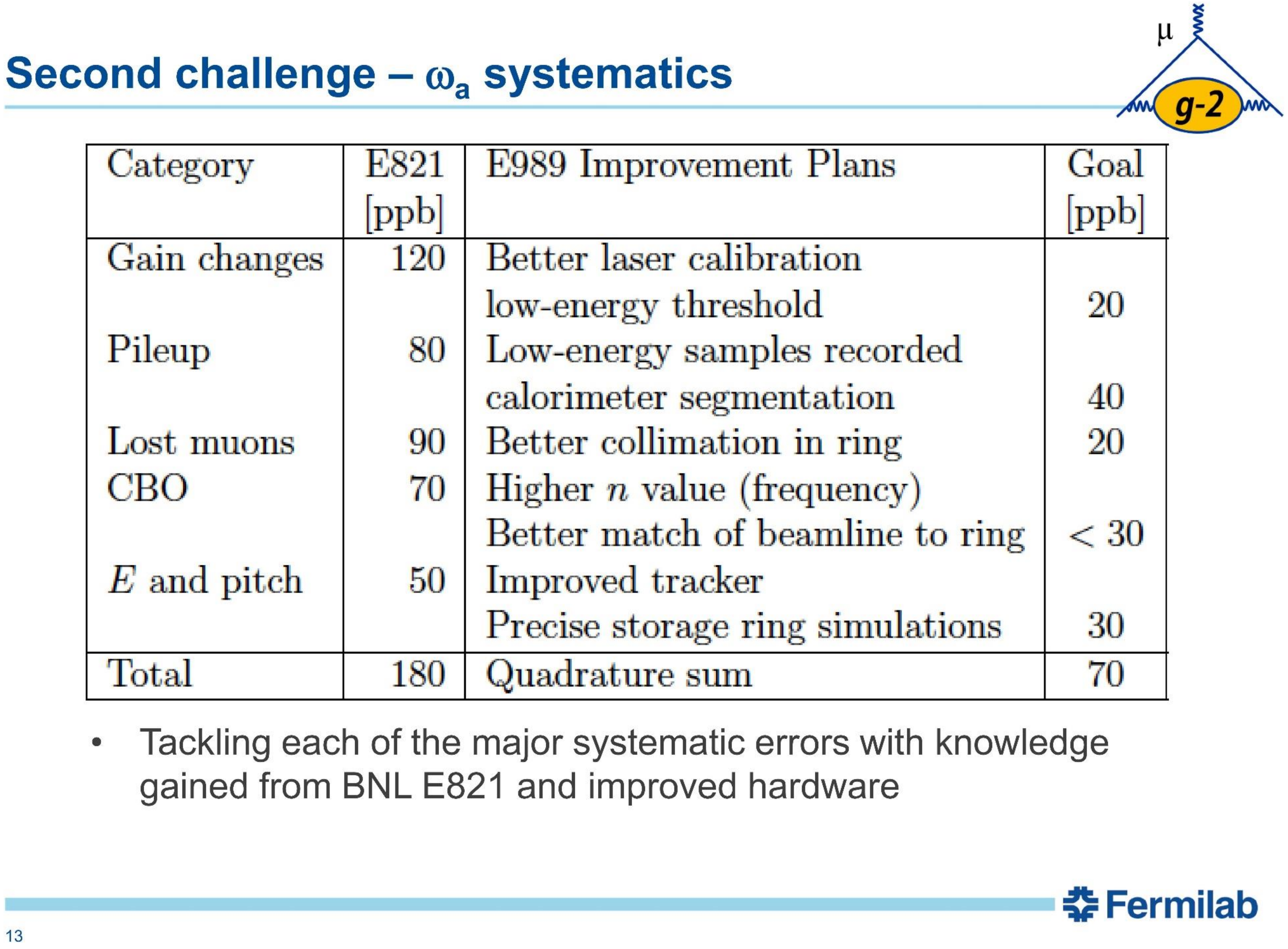
Interferometer signal by optical frequency comb is observed.



Ball-lens



- Try to measure absolute length by ourselves and apply it in our detector system.
- "Ball-lens" will be located on the detector as a target to measure the position of detector.
  - Incoming beam with any direction will focus at the ball-lens end surface.
  - The reflected beam retraces its incoming path in the opposite direction.

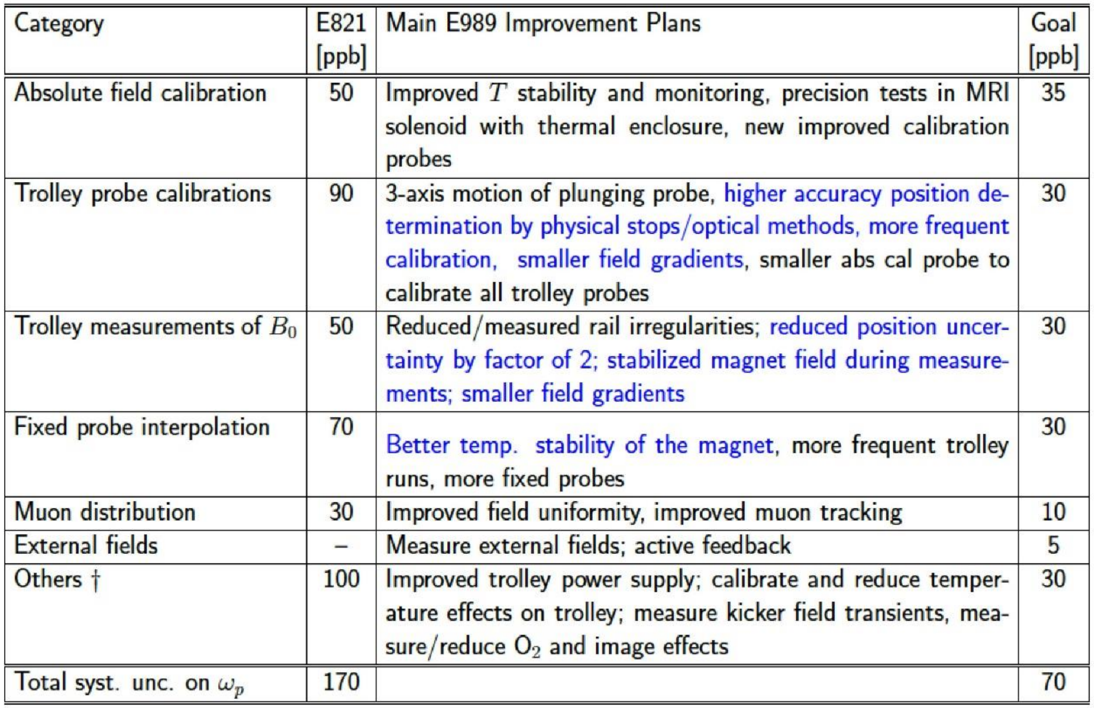


Second challenge – ω_a systematics

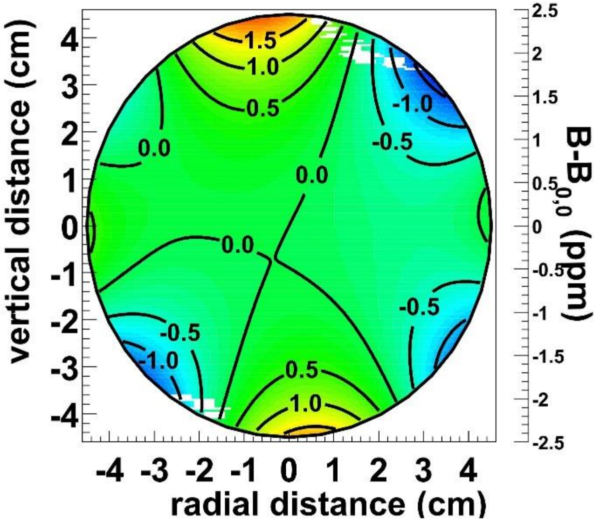
Category	E821 [ppb]	E989 Improvement Plans	Goal [ppb]
Gain changes	120	Better laser calibration	
		low-energy threshold	20
Pileup	80	Low-energy samples recorded	
		calorimeter segmentation	40
Lost muons	90	Better collimation in ring	20
CBO	70	Higher n value (frequency)	
		Better match of beamline to ring	< 30
E and pitch	50	Improved tracker	
		Precise storage ring simulations	30
Total	180	Quadrature sum	70

- Tackling each of the major systematic errors with knowledge gained from BNL E821 and improved hardware

Third challenge – ω_p systematics

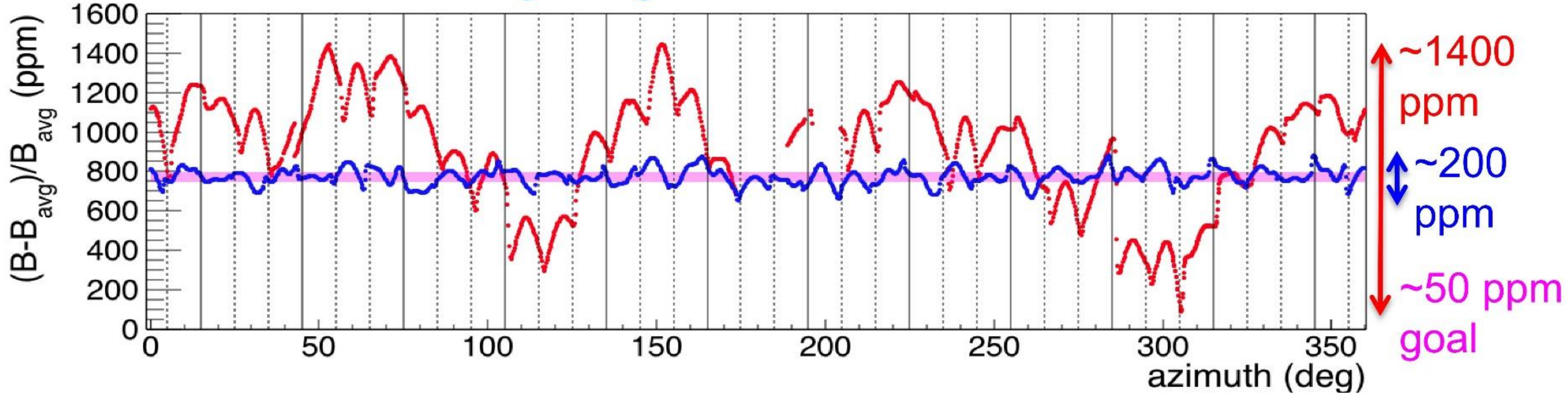


Category	E821 [ppb]	Main E989 Improvement Plans	Goal [ppb]
Absolute field calibration	50	Improved T stability and monitoring, precision tests in MRI solenoid with thermal enclosure, new improved calibration probes	35
Trolley probe calibrations	90	3-axis motion of plunging probe, higher accuracy position determination by physical stops/optical methods, more frequent calibration, smaller field gradients, smaller abs cal probe to calibrate all trolley probes	30
Trolley measurements of B_0	50	Reduced/measured rail irregularities; reduced position uncertainty by factor of 2; stabilized magnet field during measurements; smaller field gradients	30
Fixed probe interpolation	70	Better temp. stability of the magnet, more frequent trolley runs, more fixed probes	30
Muon distribution	30	Improved field uniformity, improved muon tracking	10
External fields	–	Measure external fields; active feedback	5
Others †	100	Improved trolley power supply; calibrate and reduce temperature effects on trolley; measure kicker field transients, measure/reduce O_2 and image effects	30
Total syst. unc. on ω_p	170		70



- Need to know the average field observed by a muon in the storage ring absolutely to better than 70 ppb, many hardware improvements
- Very challenging…first major step is making the field as uniform as possible
  - Has been our main thrust over the last 9 months

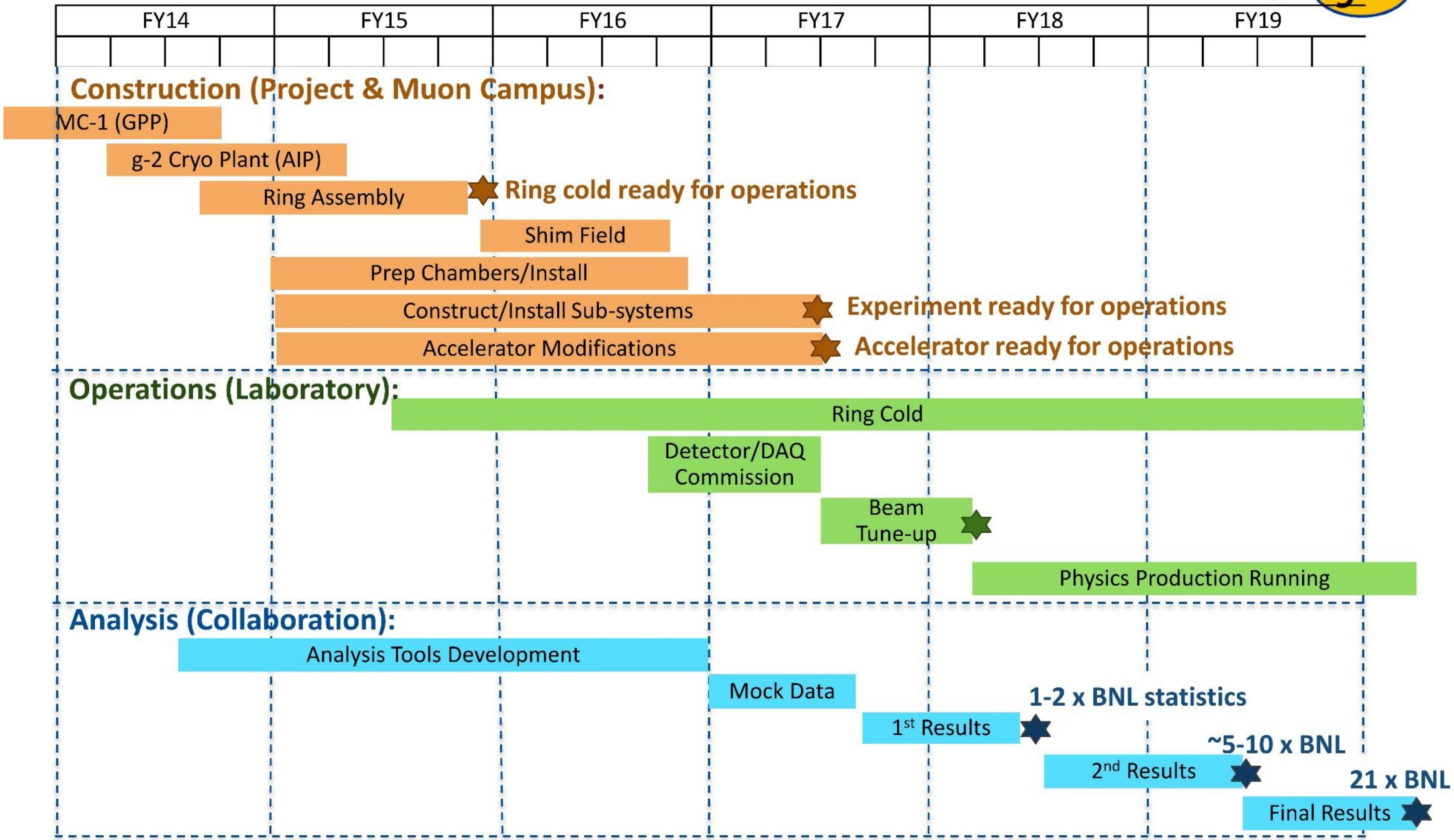
Making the Precision Field



Average magnetic field vs. azimuth

- Magnet achieved full power September 21, 2015
- Field started out with a peak variation of 1400 ppm
- June 2016 peak to peak variation was reduced to 200 ppm
- The goal of shimming is 50 ppm with a muon weighted systematic uncertainty of 70 ppb
- BNL achieved 100 ppm with an RMS value about 30 ppm
- They estimated their systematic uncertainty at 140 ppb

Project Timeline



FY14 | FY15 | FY16 | FY17 | FY18 | FY19

Construction (Project & Muon Campus):

- MC-1 (GPP)
- g-2 Cryo Plant (AIP)
- Ring Assembly
- **Ring cold ready for operations**
- Shim Field
- Prep Chambers/Install
- Construct/Install Sub-systems
- **Experiment ready for operations**
- Accelerator Modifications
- **Accelerator ready for operations**

Operations (Laboratory):

- Ring Cold
- Detector/DAQ Commission
- Beam Tune-up
- Physics Production Running

Analysis (Collaboration):

- Analysis Tools Development
- Mock Data
- 1st Results
- **1-2 x BNL statistics**
- 2nd Results
- **~5-10 x BNL**
- Final Results
- **21 x BNL**

FNAL@TAU2016

Take-home messages

- The Muon g-2 experiment will reduce error by a factor of 4 compared to the previous Muon g-2 (BNL E821)
- The storage ring magnet has been operational for a year and our rough shimming targets have been achieved
- Beamline commissioning begins in April 2017, with real data collection starting Autumn 2017
- We anticipate a result with the same precision as E821 by mid-2018
- We expect to report three results with 100%, 50% and 25% of the E821 uncertainty