Muon g-2/EDM Experiment at J-PARC

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20th Sep. 2016 @TAU2016

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TAU 2016

The 14th International Workshop on Tau Lepton Physics
Beijing, China, 19-23 September 2016

Dipole Moments

- Electromagnetic interaction Hamiltonian with magnetic and electric fields

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

$(\mu_0 = q/2m)$

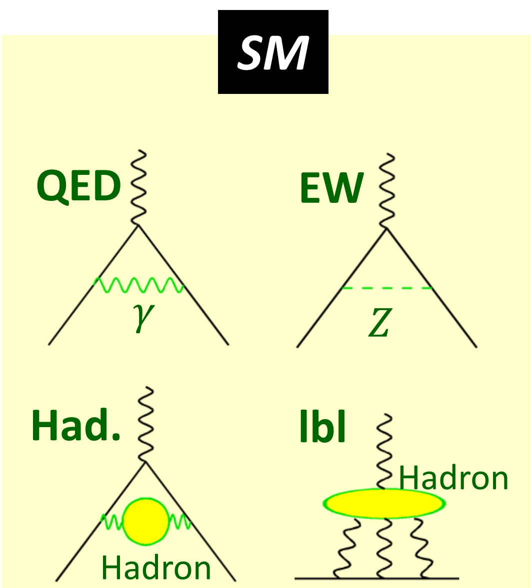
Magnetic dipole moment (MDM)

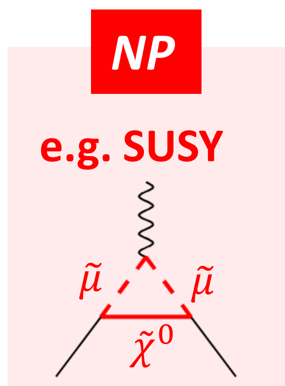
- $\vec{\mu} = g\mu_0\vec{s} = 2(a + 1)\,\mu_0\vec{s}$

Anomalous magnetic moment

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

- Induced by any interaction.

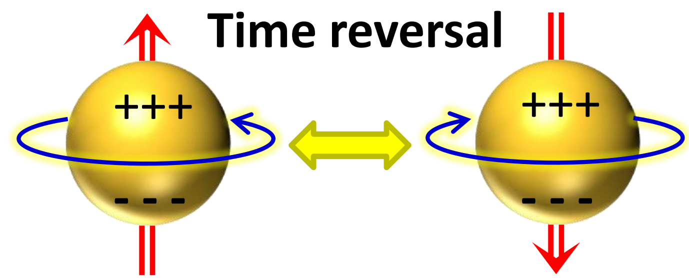




➢ **Precise test of the SM**

Electric dipole moment (EDM)

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

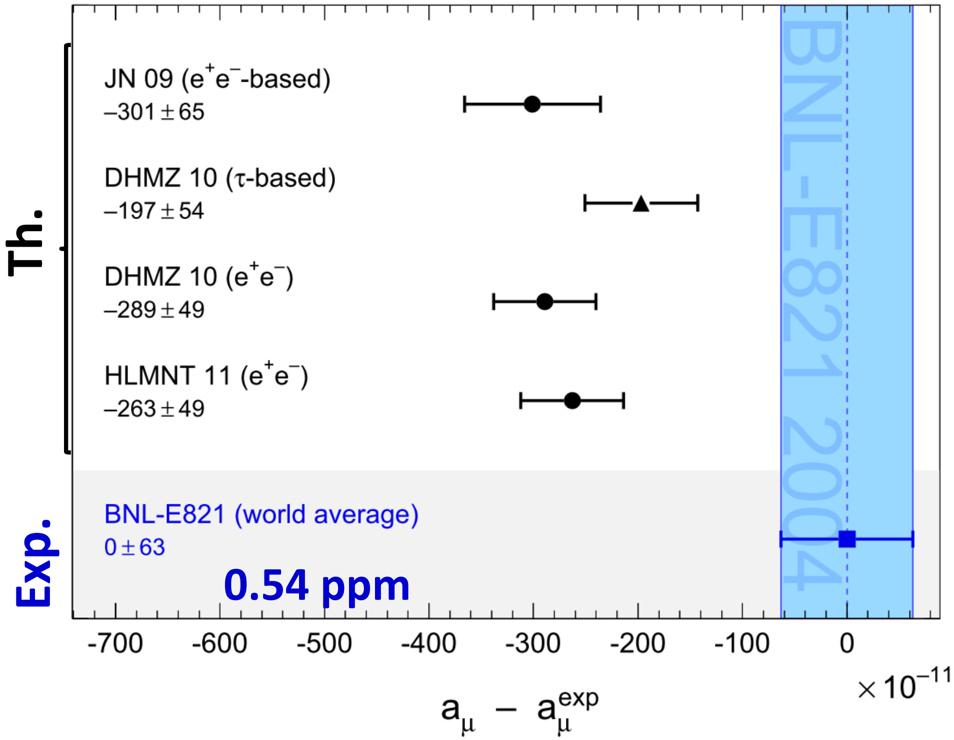


- Highly suppressed in the SM
  - $d^{\mathrm{SM}} \sim 10^{-38} e \cdot \mathrm{cm}$
  - Out of experimental reach.

➢ **Non-zero EDM is evidence for NP**

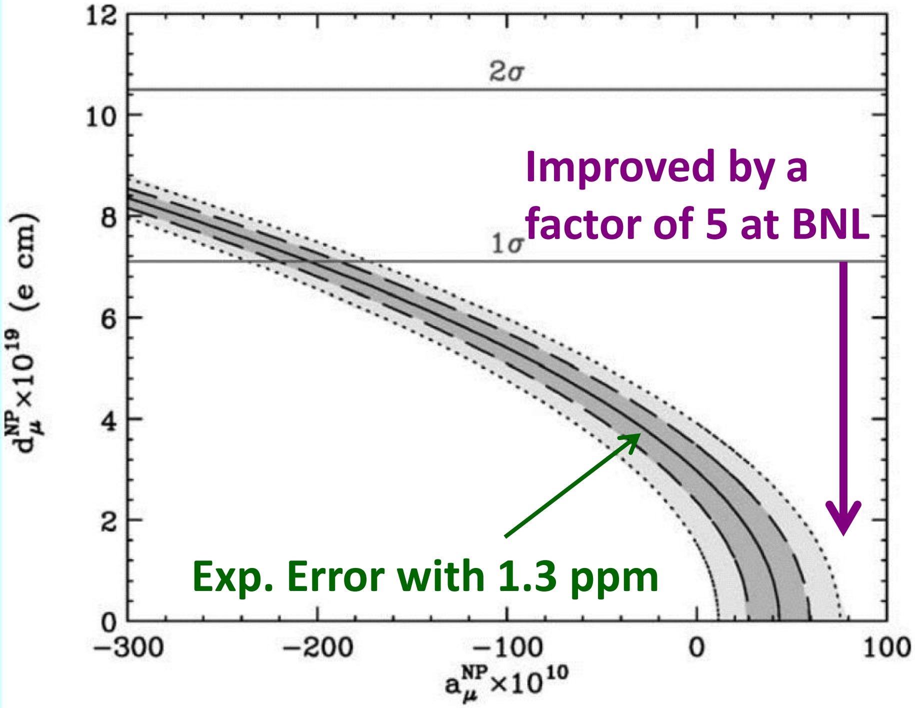
Muon g-2 and EDM Measurements

PDG



J.L. Feng et al. Nucl Phys B 613, 366 (2001)

(Constraints are not the latest in this plot.)



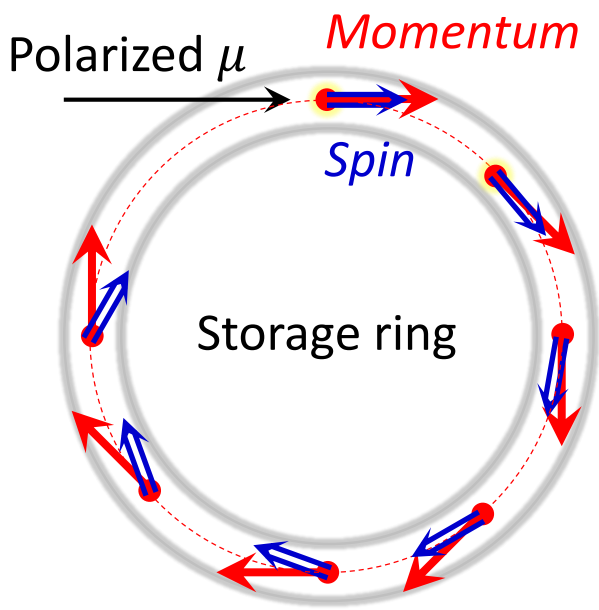
- ~3σ deviation from SM prediction.
- ➢ Need more precise/independent measurement.

- EDM also contributes spin precession.
  - $\vec{\omega} = \vec{\omega}_a + \vec{\omega}_\eta$
- ➢ EDM measurement is important.

Spin Precession

- In uniform B-field, muon spin rotates ahead of momentum due to $g-2 \neq 0$.

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



- Two approaches to cancel second term.

1. Magic momentum
"$\gamma = 29.3$"

2. Zero E-field
"$E = 0$" at any γ

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

→ **BNL E821 & FNAL E989**

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

→ **J-PARC E34**

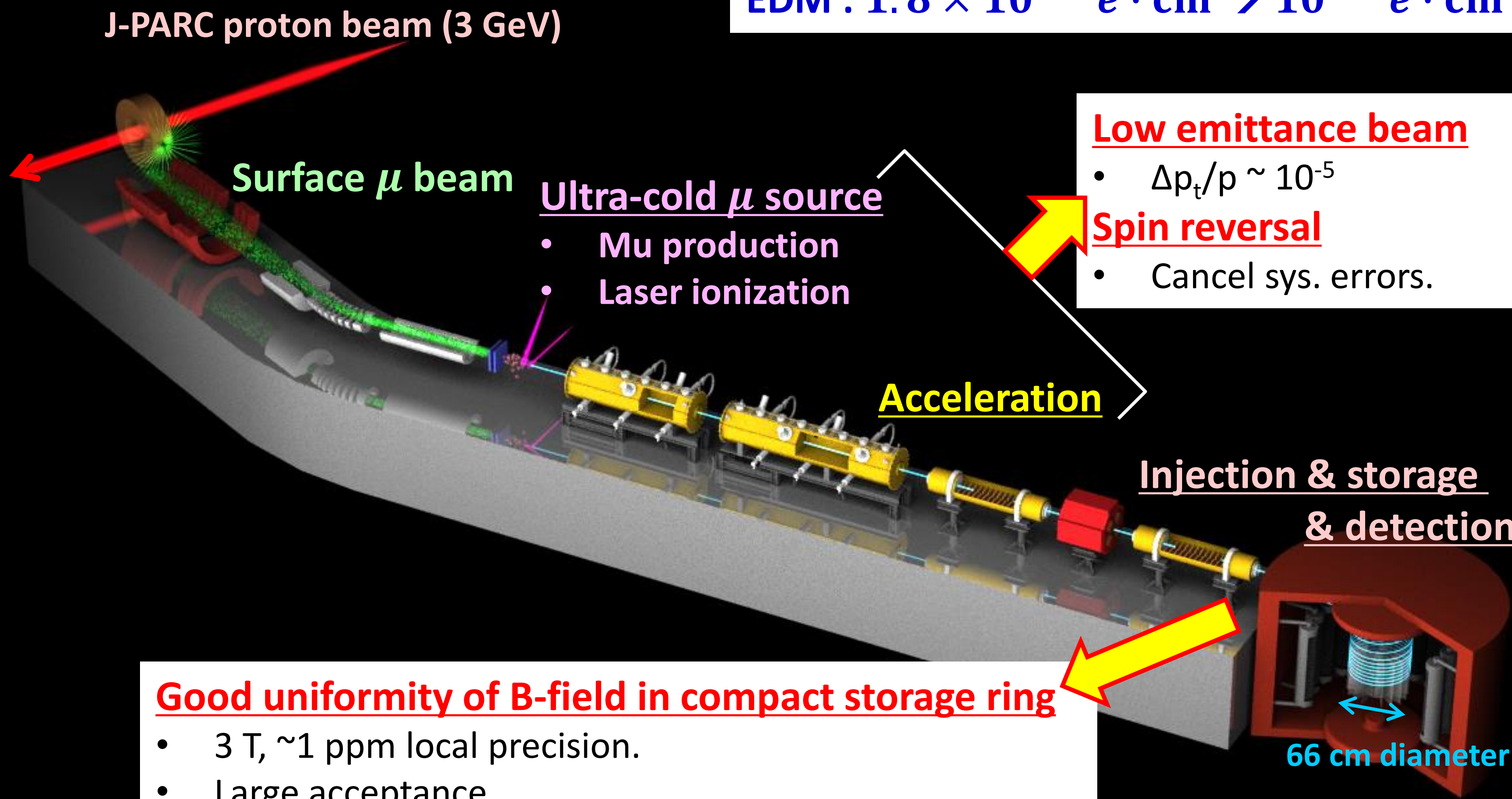
- Completely different techniques
  - Different systematic uncertainty.
- More simplified equation ($\vec{\omega}_a \perp \vec{\omega}_\eta$)
  - Clear separation of $\vec{\omega}_a$ and $\vec{\omega}_\eta$.

J-PARC E34 Experiment

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

g-2 : 0.54 ppm → 0.1 ppm

EDM : $1.8 \times 10^{-19} e \cdot \mathrm{cm} \rightarrow 10^{-21} e \cdot \mathrm{cm}$



Low emittance beam

- $\Delta p_t/p \sim 10^{-5}$

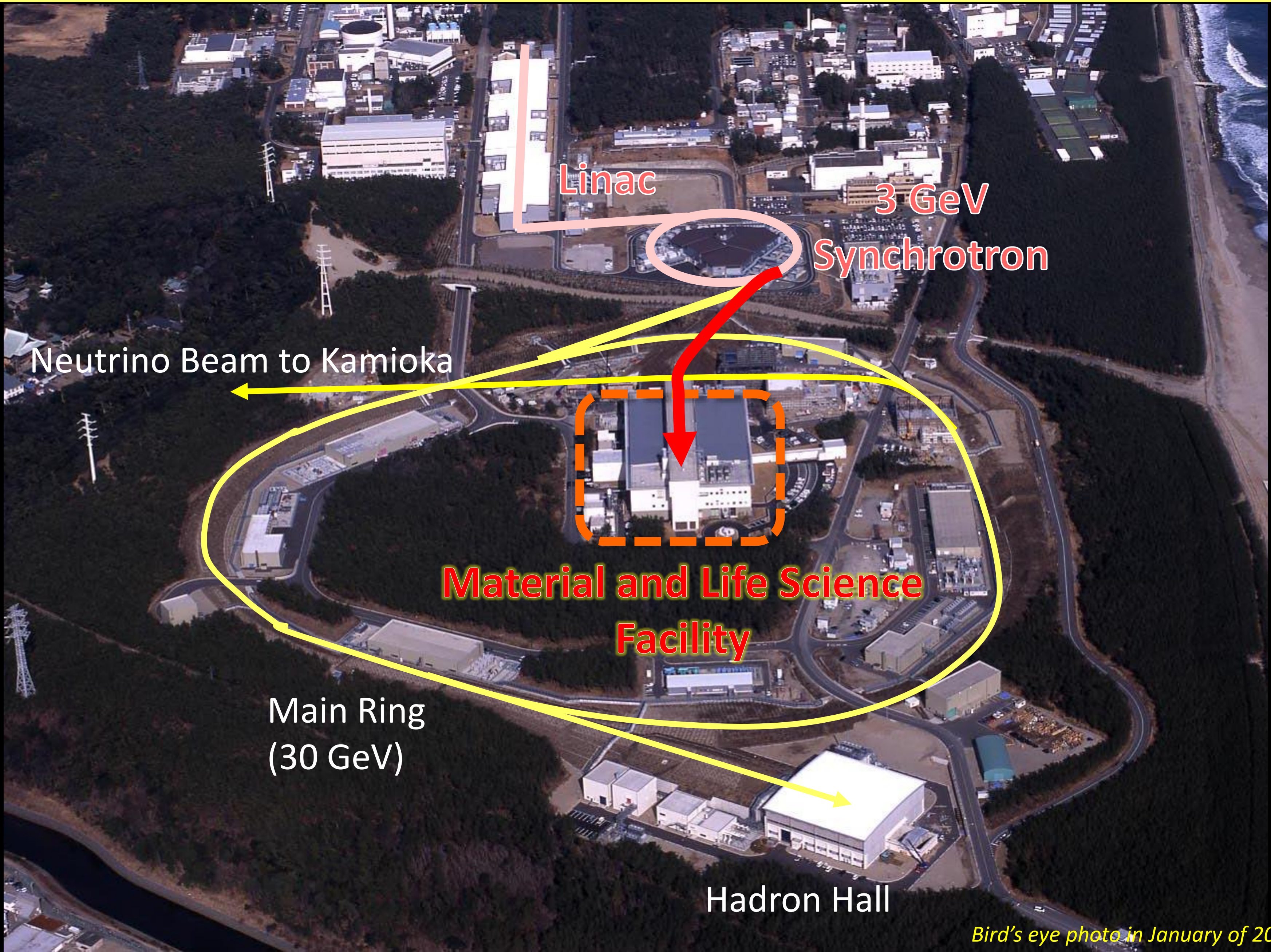
Spin reversal

- Cancel sys. errors.

Good uniformity of B-field in compact storage ring

- 3 T, ~1 ppm local precision.
- Large acceptance.

J-PARC Facility (KEK/JAEA)

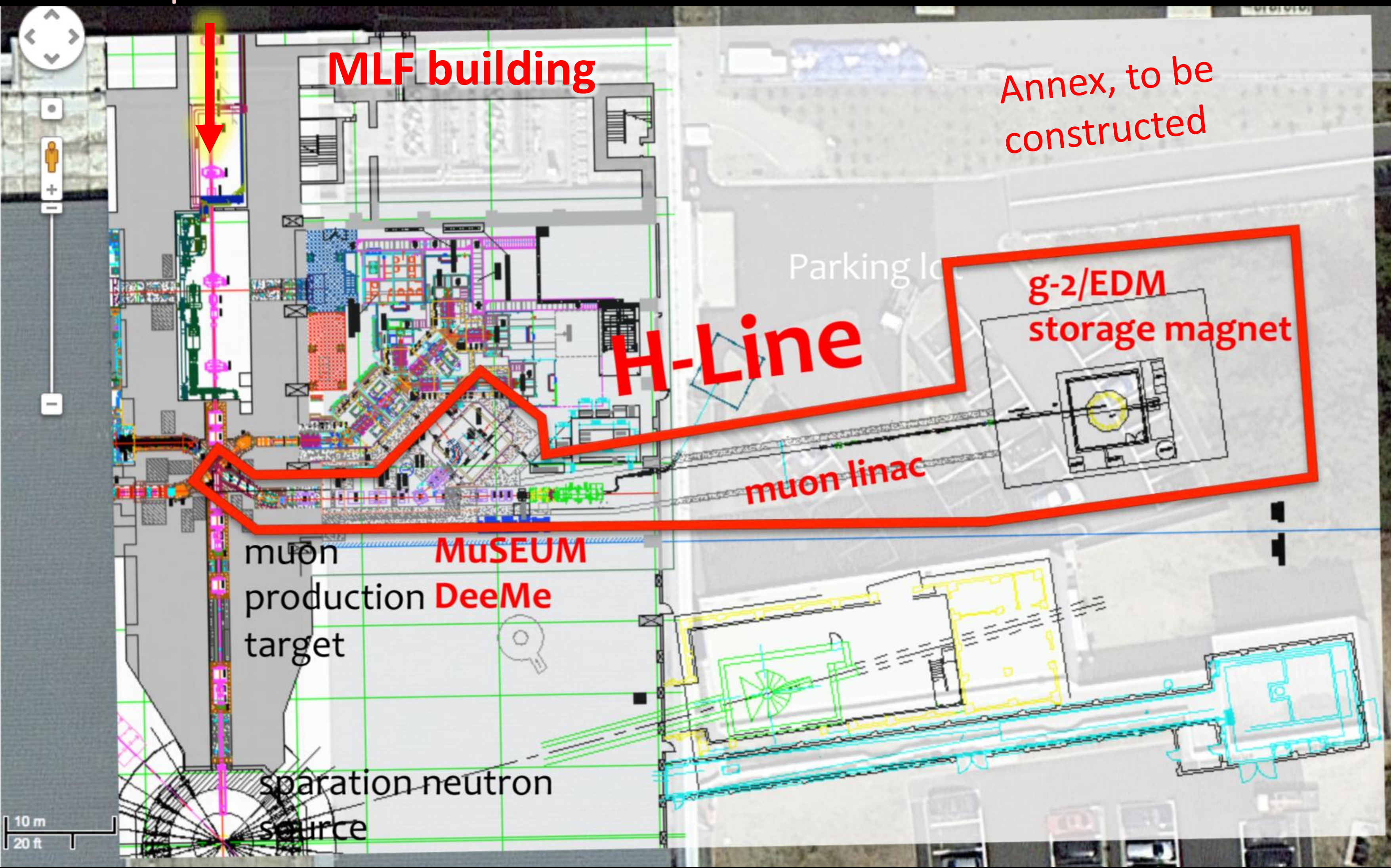


Bird's eye photo in January of 2008

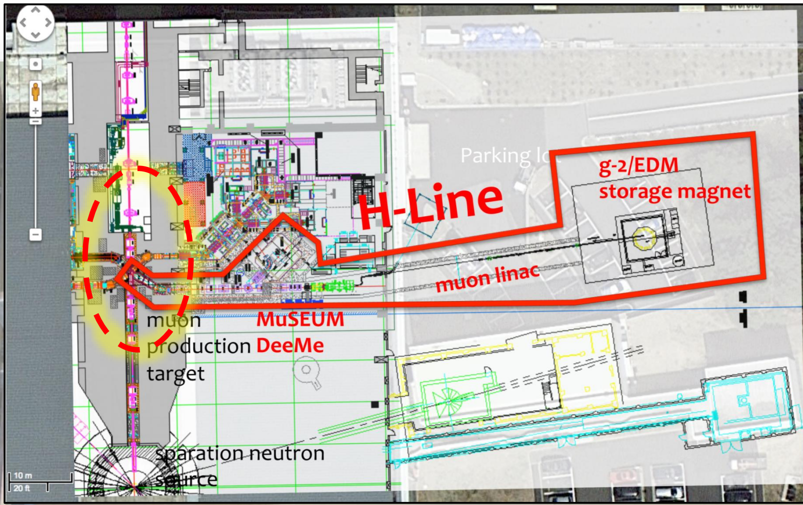
New Muon Beam Line ~H-Line~

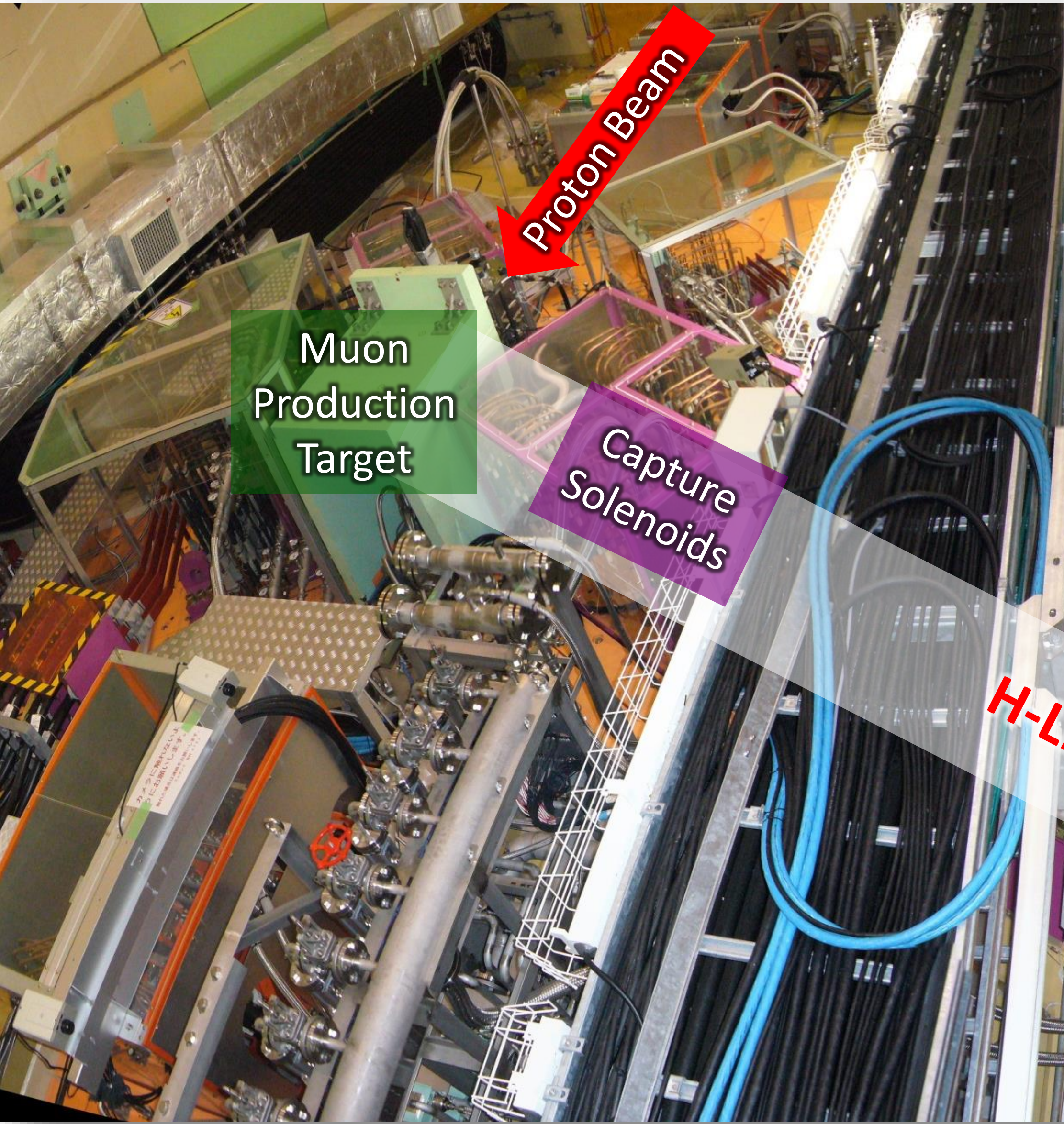
Three muon experiments
- g-2/EDM
- MuSEUM (Mu-HFS)
- DeeMe (muon cLFV)

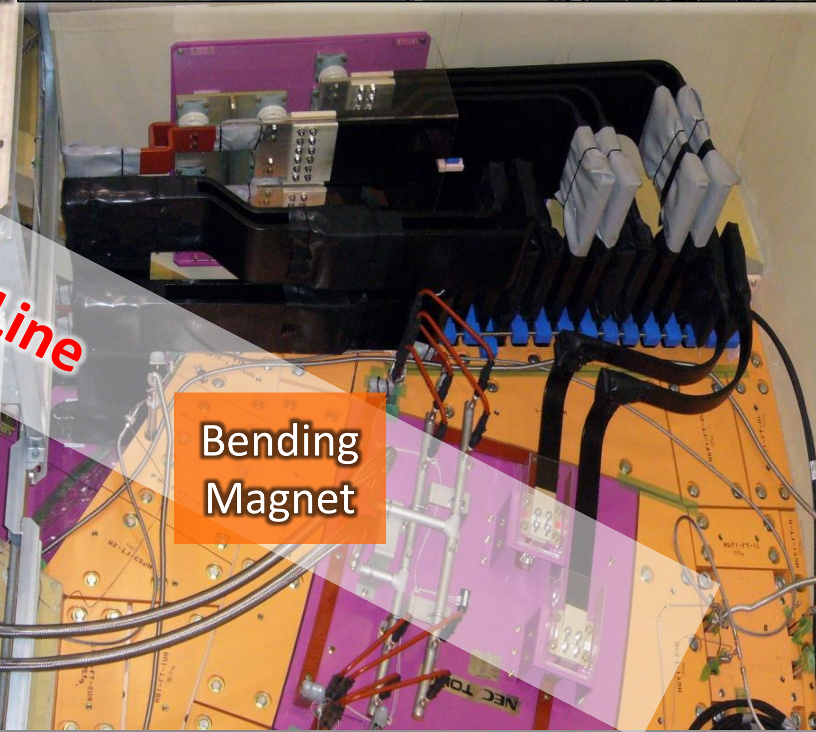
3 GeV proton beam



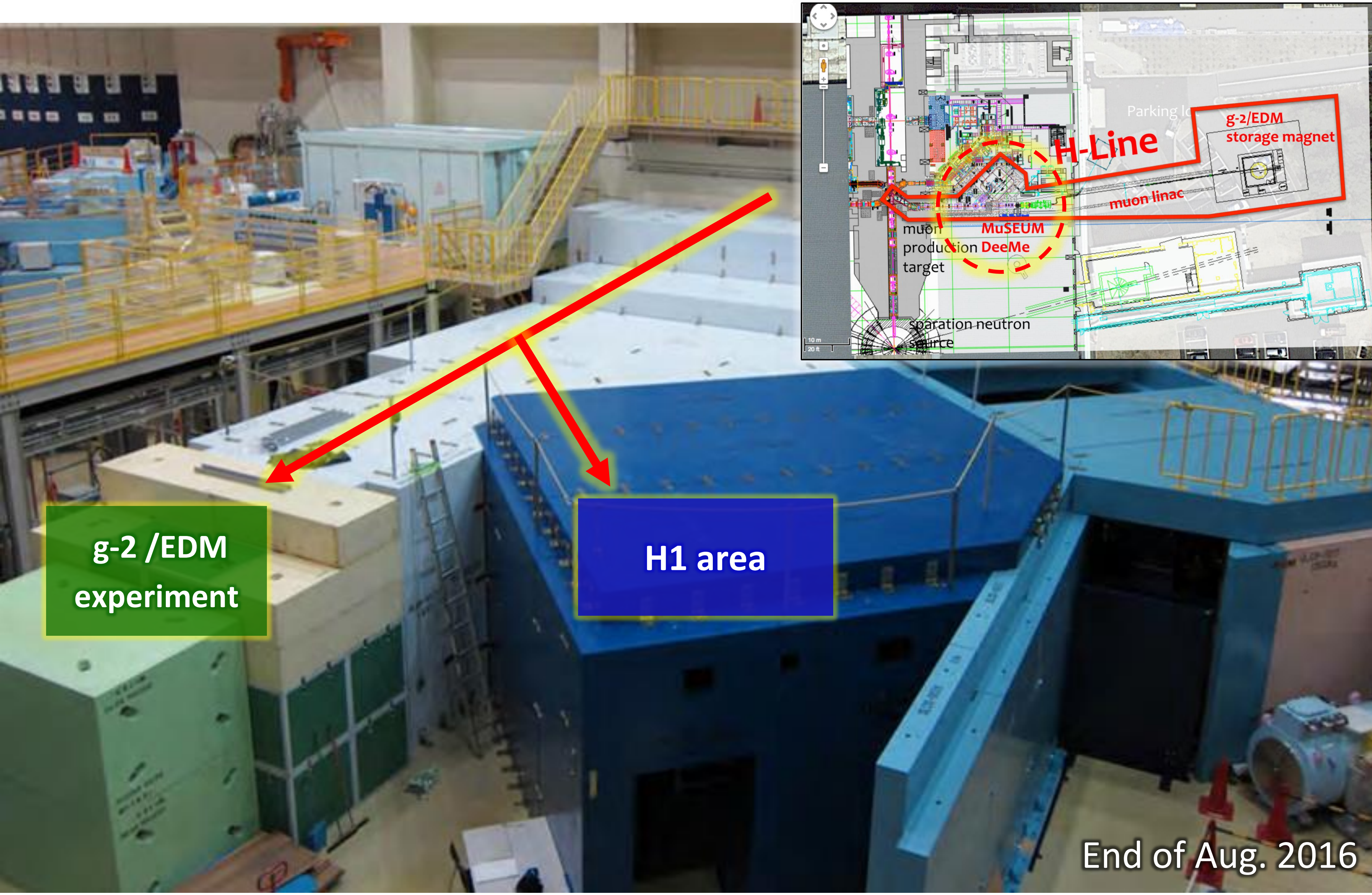
H-Line Construction ~Muon Production Target~





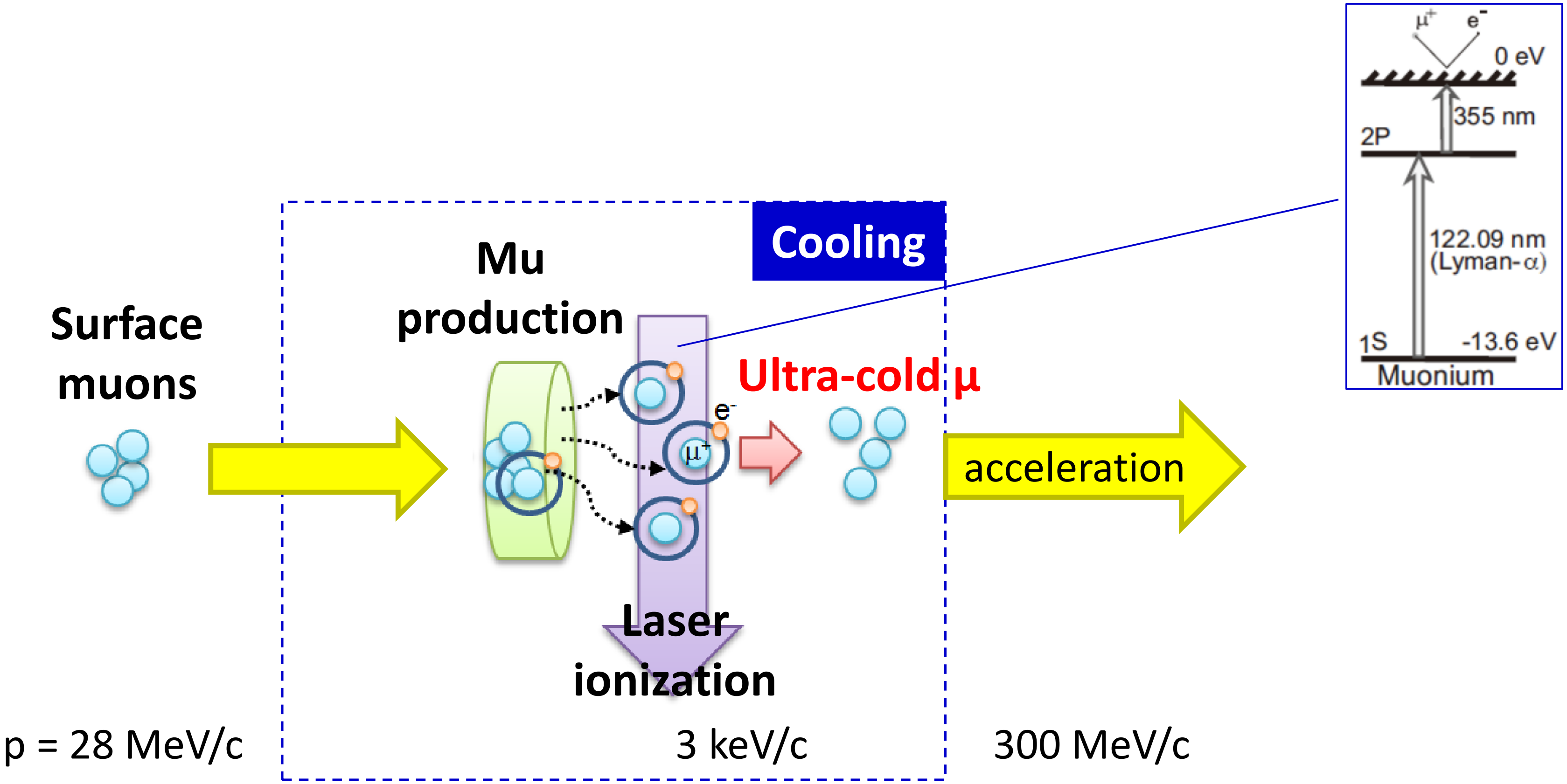


H-Line Construction ~Transportation Line~



Ultra-Cold Muon

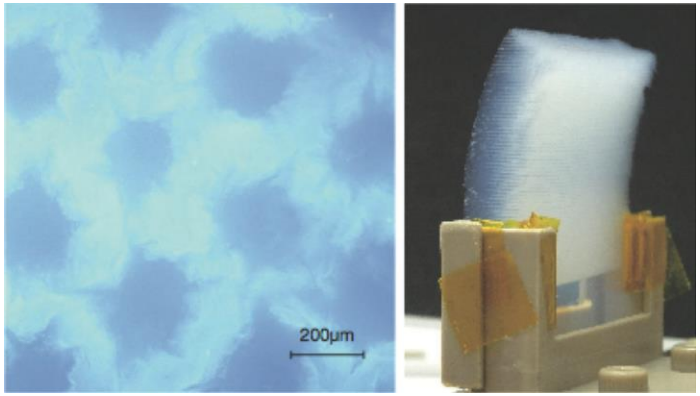
- Low emittance muon beam is necessary to storage muon without focusing.

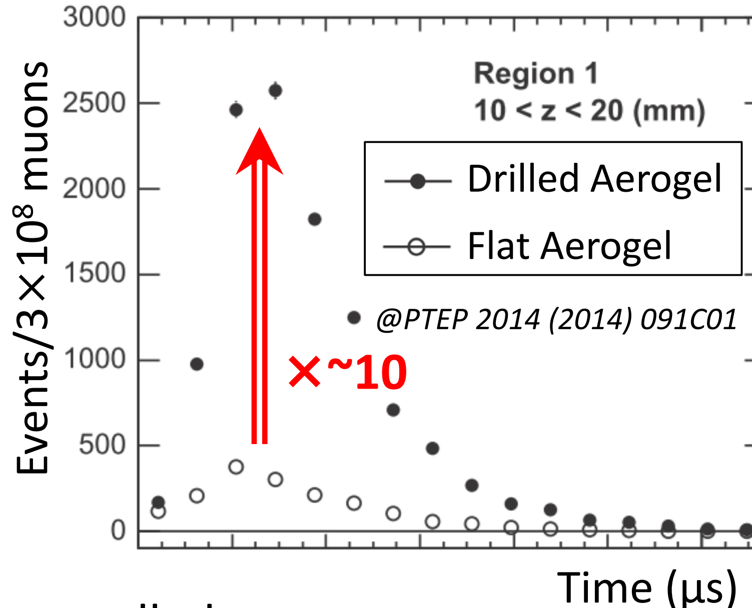


- **Low emittance muon beam**
  with $\Delta p_t/p \sim 3\text{keV}/300\ \text{MeV} \sim 10^{-5}$

Ultra-Cold Muon Source

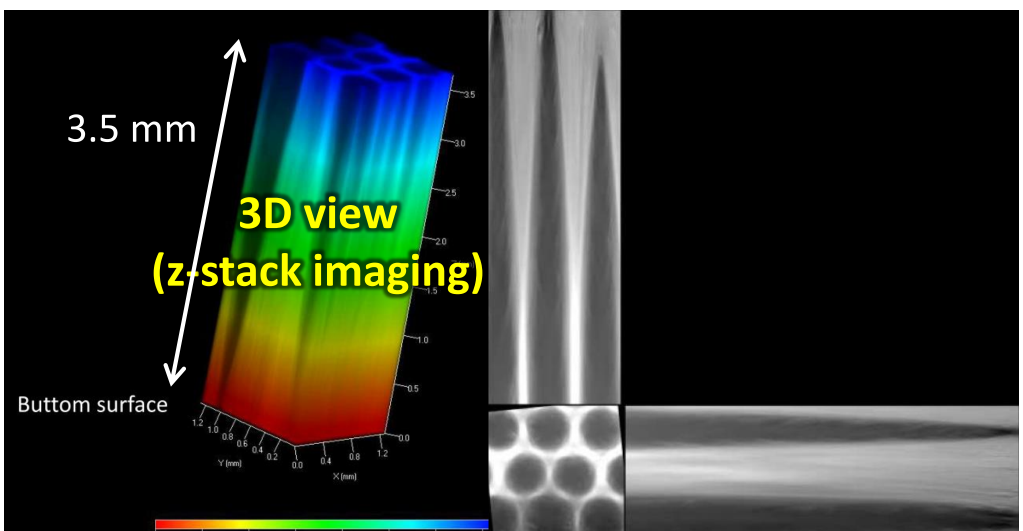
- Mu prod. target : **Laser ablated Silica Aerogel**

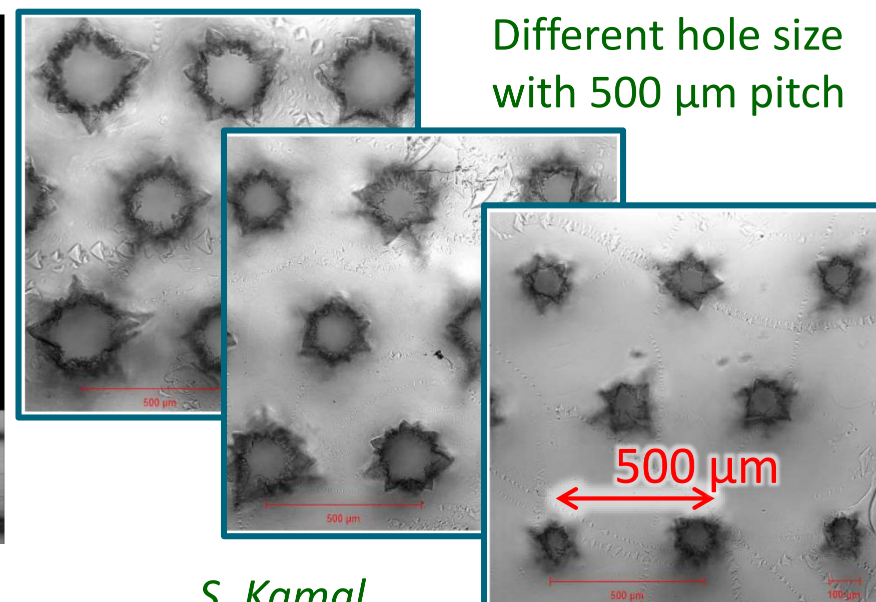




➢ Succeeded to enhance the Mu production rate.

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





Different hole size with 500 μm pitch

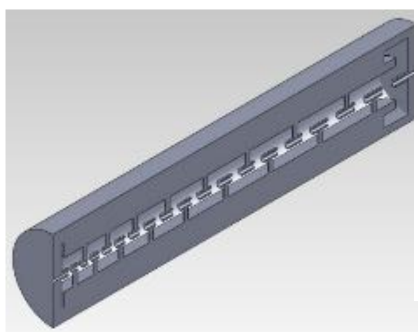
➢ Optimization is ongoing.

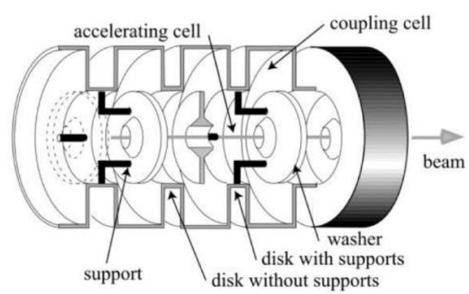
S. Kamal

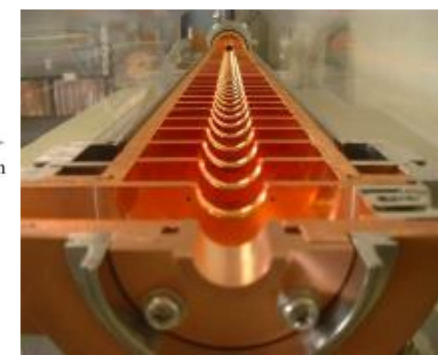
Muon Acceleration

- Ultra-cold muon beam must be reaccelerated to 300 MeV/c
  - in a sufficiently short period to avoid decay loss
  - without substantial emittance growth.
- Different design to realize fast re-acceleration through wide β region.

5.6 keV, $\beta = 0.01$ → **RFQ** → 0.3 MeV, $\beta = 0.08$ → **IH-DTL** → 4.5 MeV, $\beta = 0.3$ → **DAW** → 40 MeV, $\beta = 0.7$ → **Disk-loaded** → 212MeV, $\beta = 0.9$







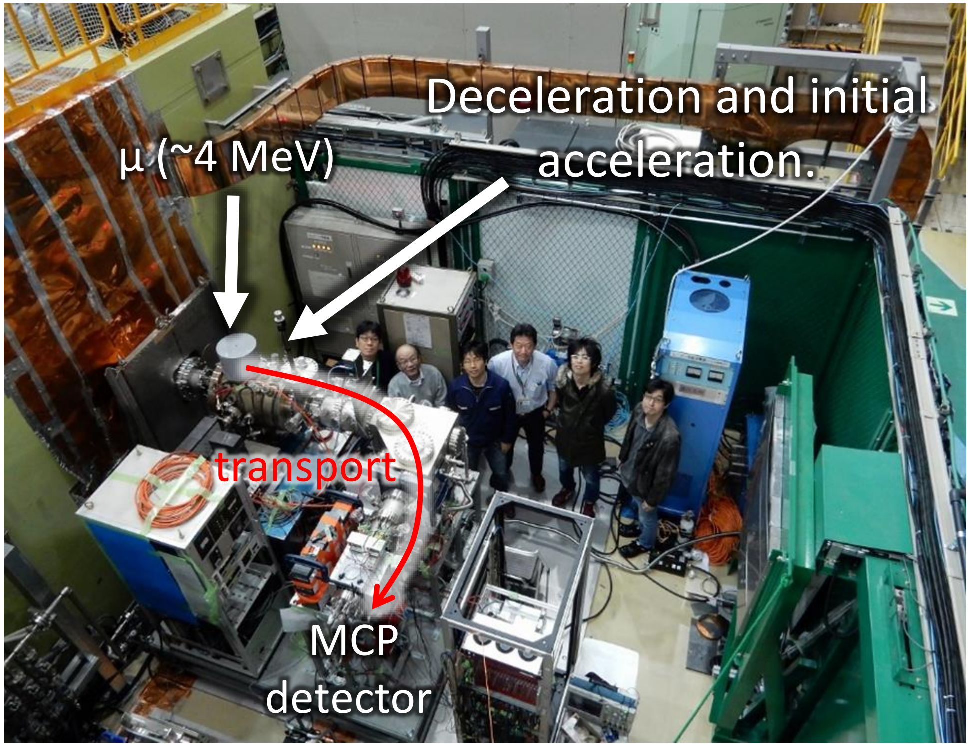
- Normalized emittance
  - 1000 π mm mrad (surface muon beam) → 1.5 π mm mrad (ultra-cold muon beam)

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

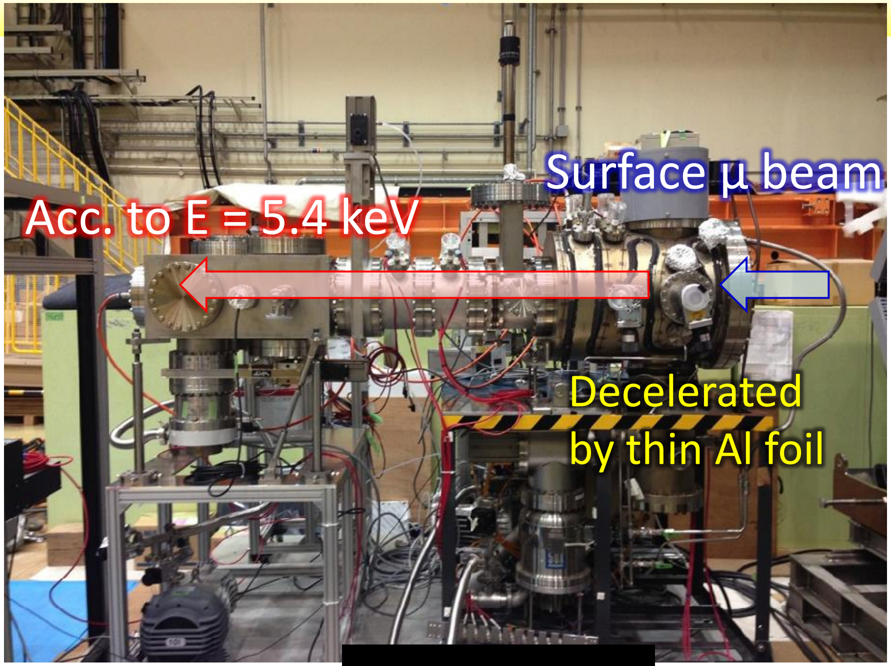
Demonstration of Deceleration and Initial Acc.

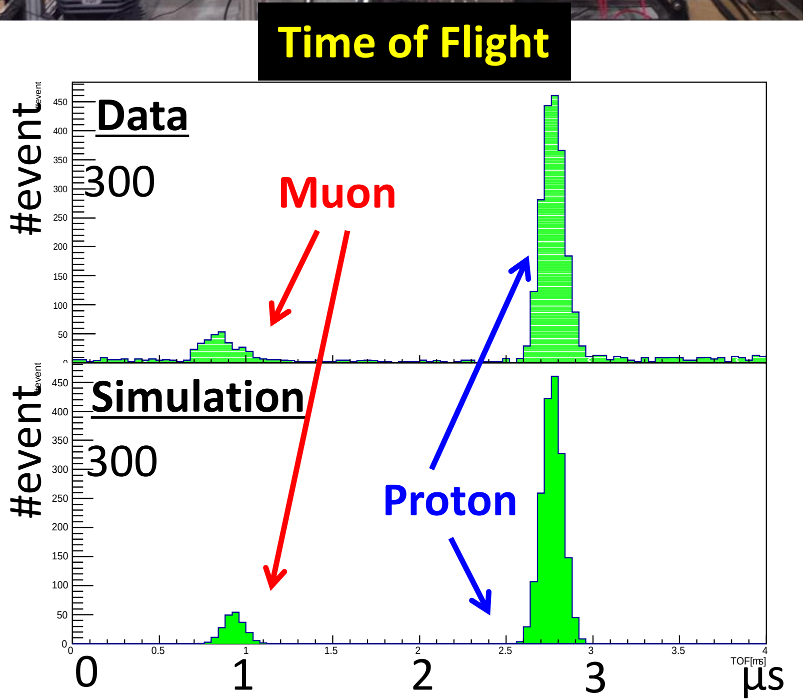
@ J-PARC MLF test muon beamline

(Feb. 2016)



- **Succeed to deceleration and initial acceleration.**

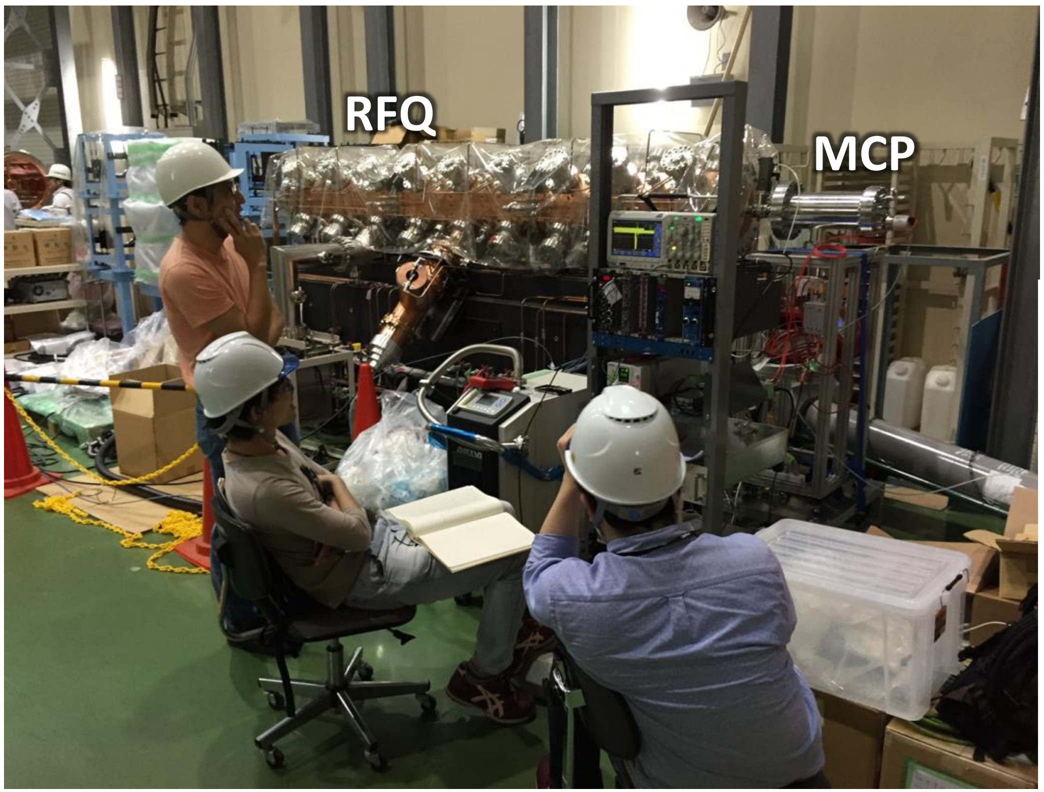


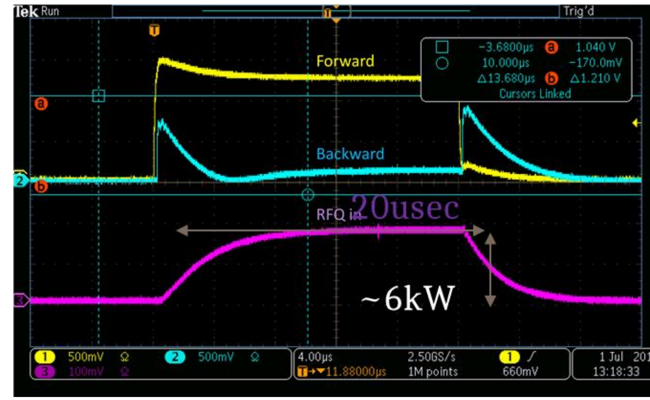


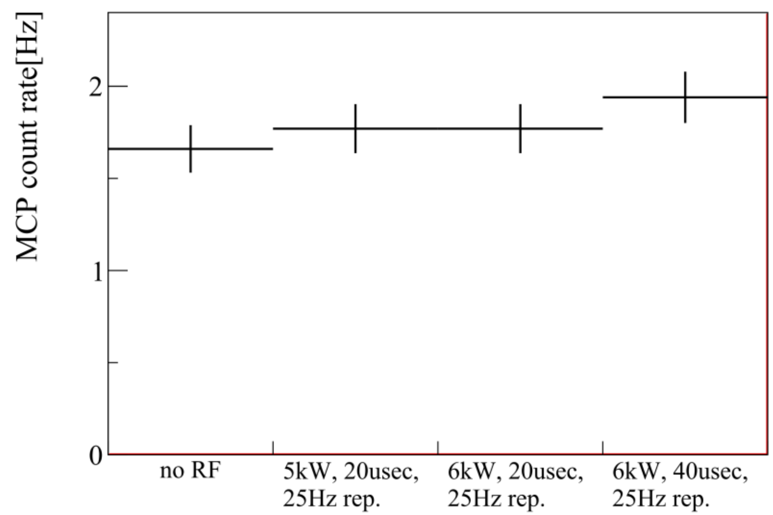
RFQ Commissioning

@ J-PARC LINAC facility, Jun. 2015.

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



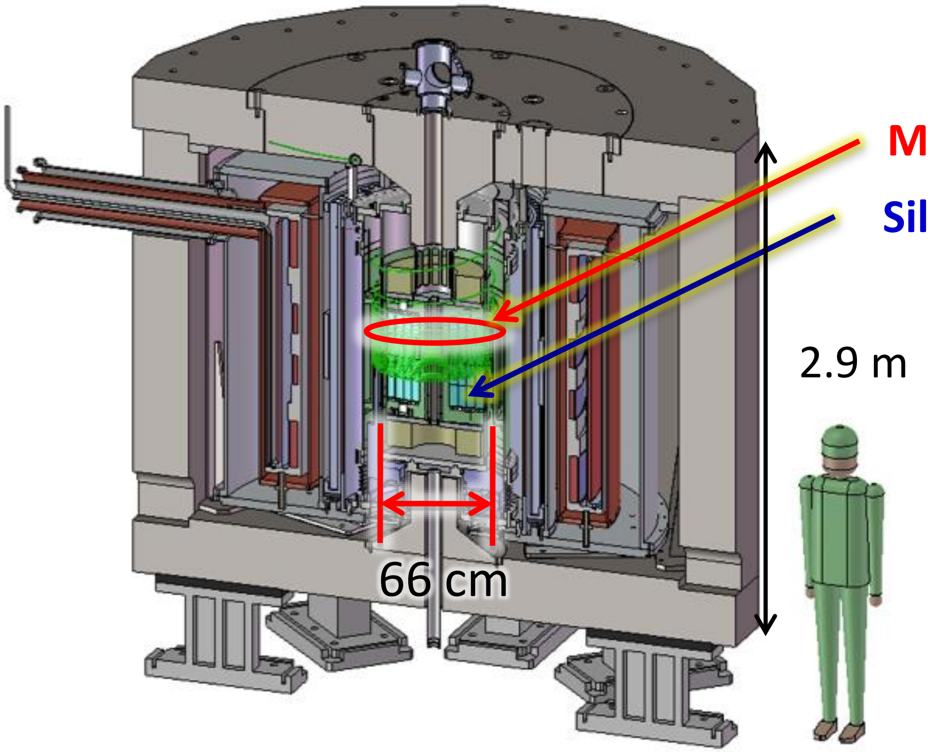


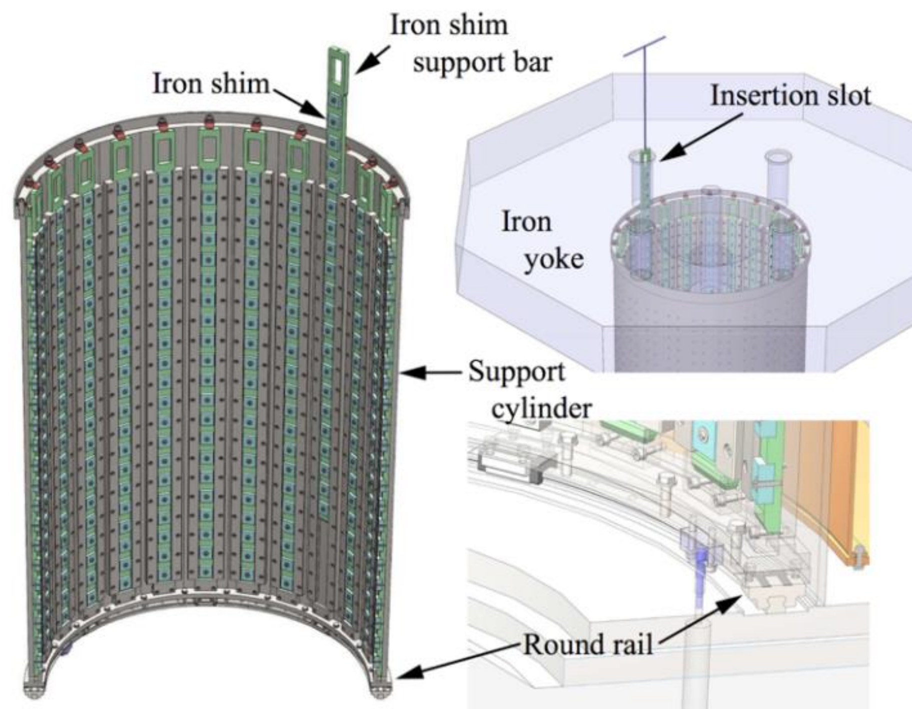


- ➢ **RFQ is ready.**
  - Muon acceleration with RFQ is planned.

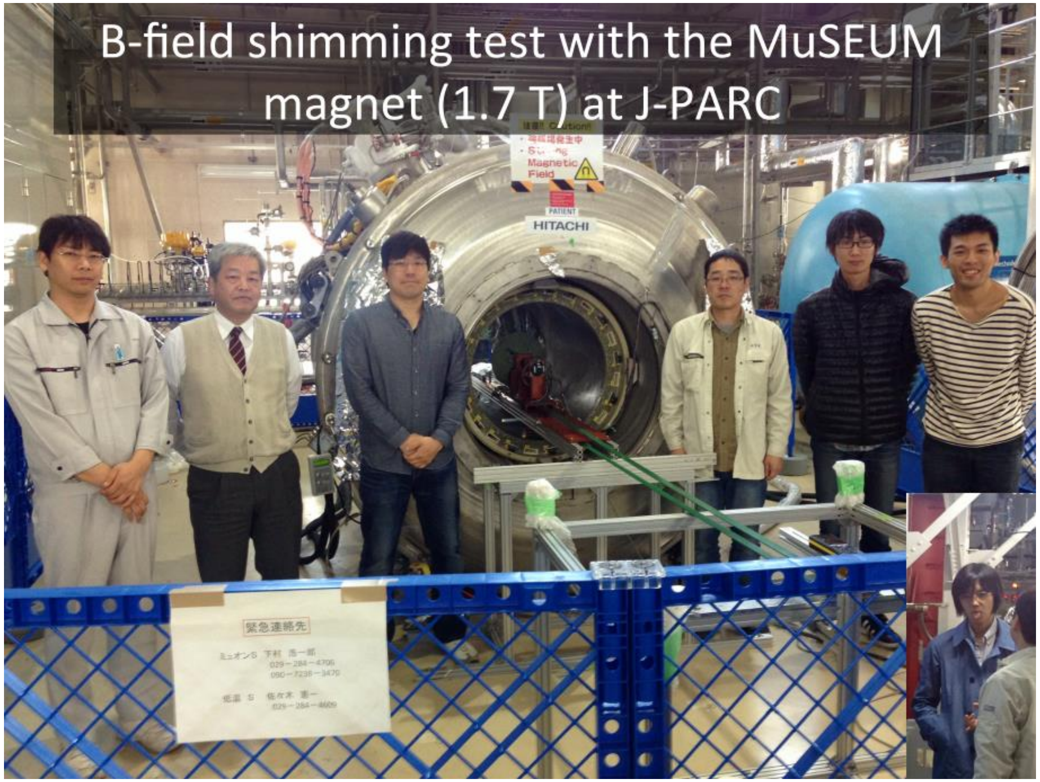
Storage Magnet

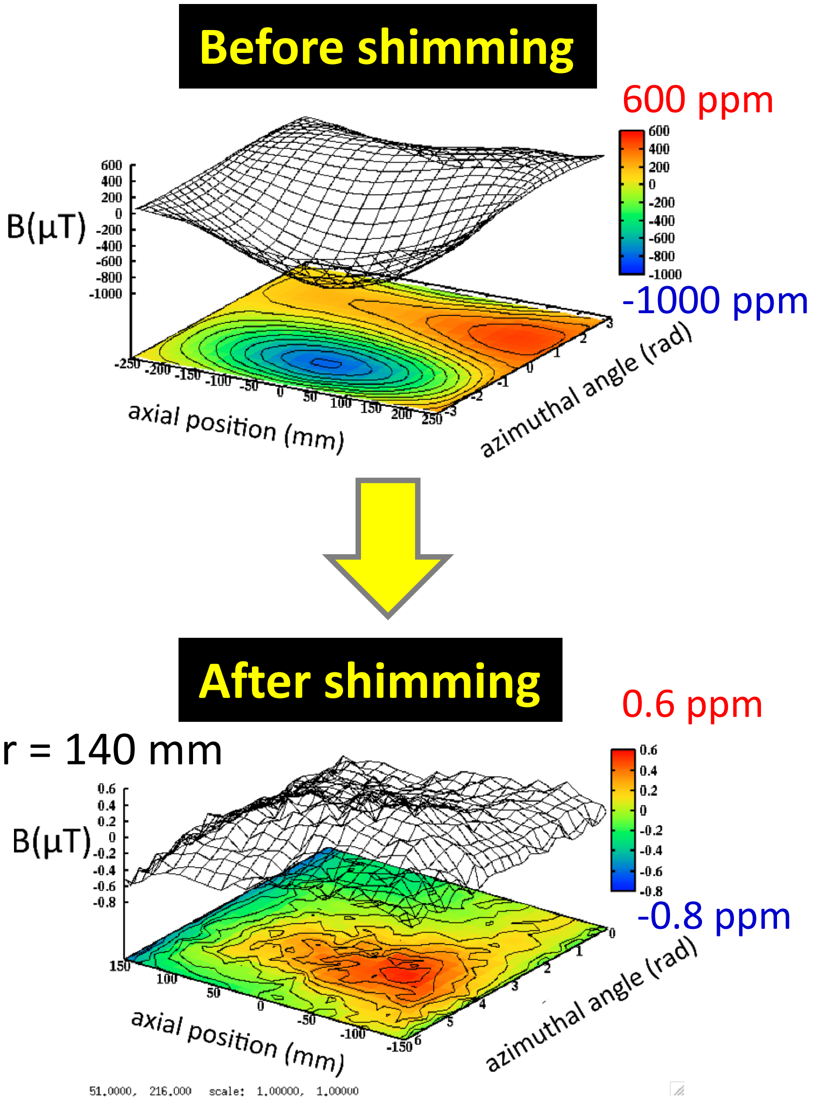
- Super Precision Storage Magnet
  - 3T with local uniformity of 1 ppm by iron shimming.





B-Field Shimming



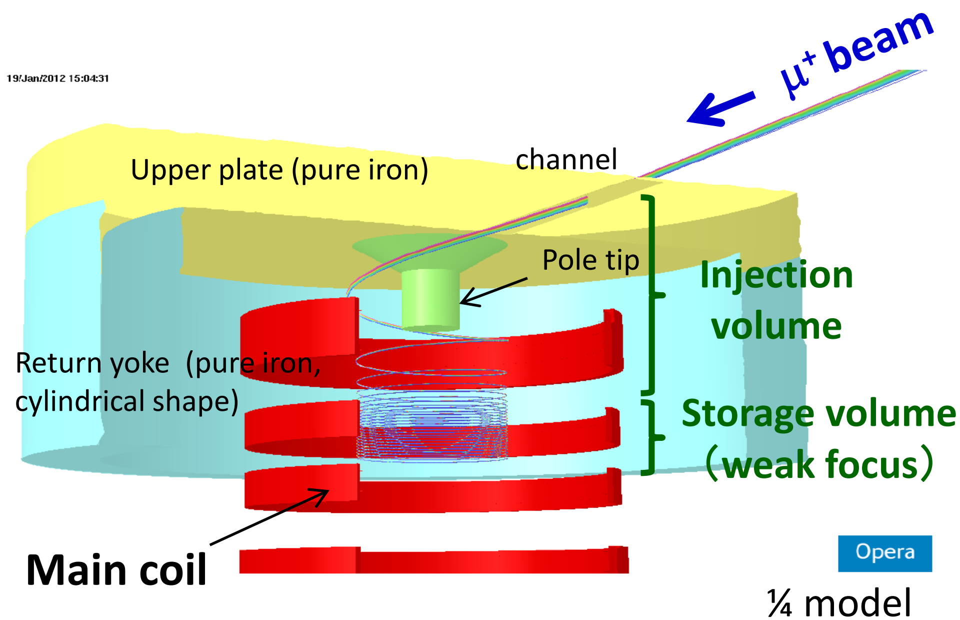


- ppm level uniformity is achieved.
- ➢ Shimming method is established.

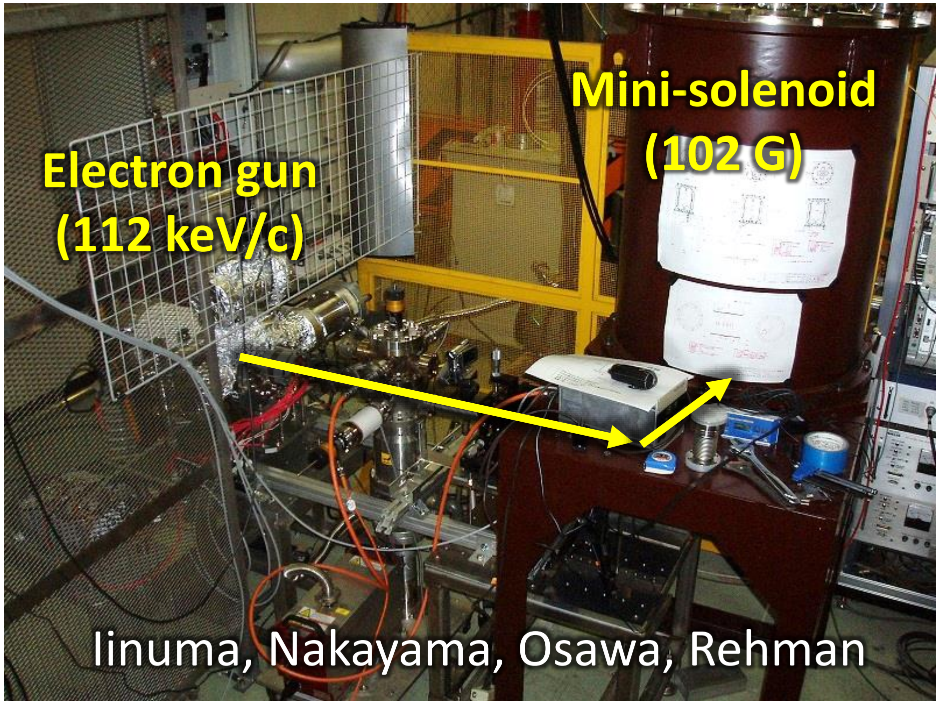
Muon Injection

3D-spiral injection scheme

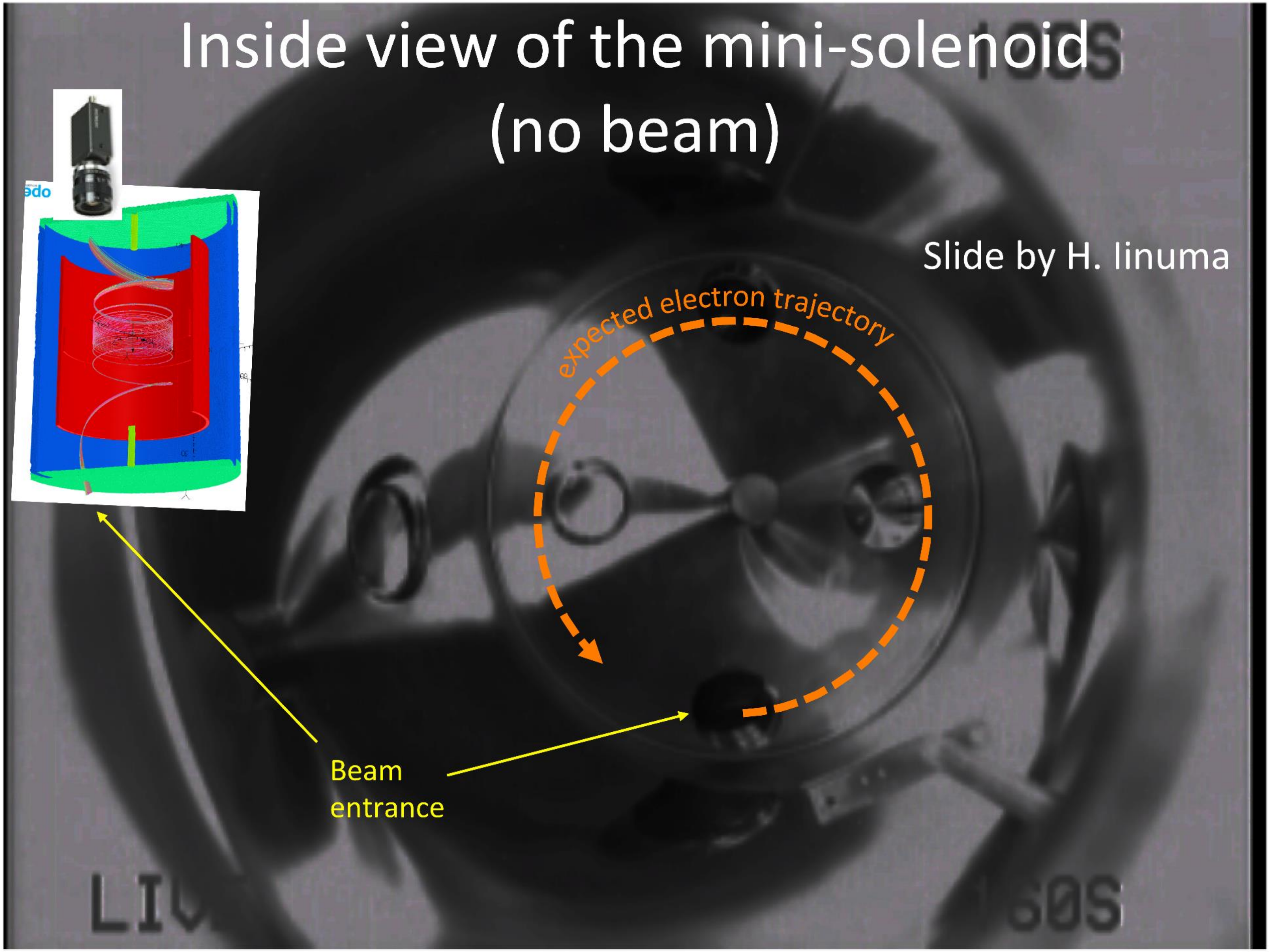
- Difficult to use horizontal injection in our compact storage ring with 3T field.
- ➢ 3D-spiral injection scheme has been designed. H. Iinum et al. NIMA 832 (2016) 51
  - – Smooth connection between injection and storage sections without any sources of error field.
- ➢ Demonstration of spiral injection is ongoing.



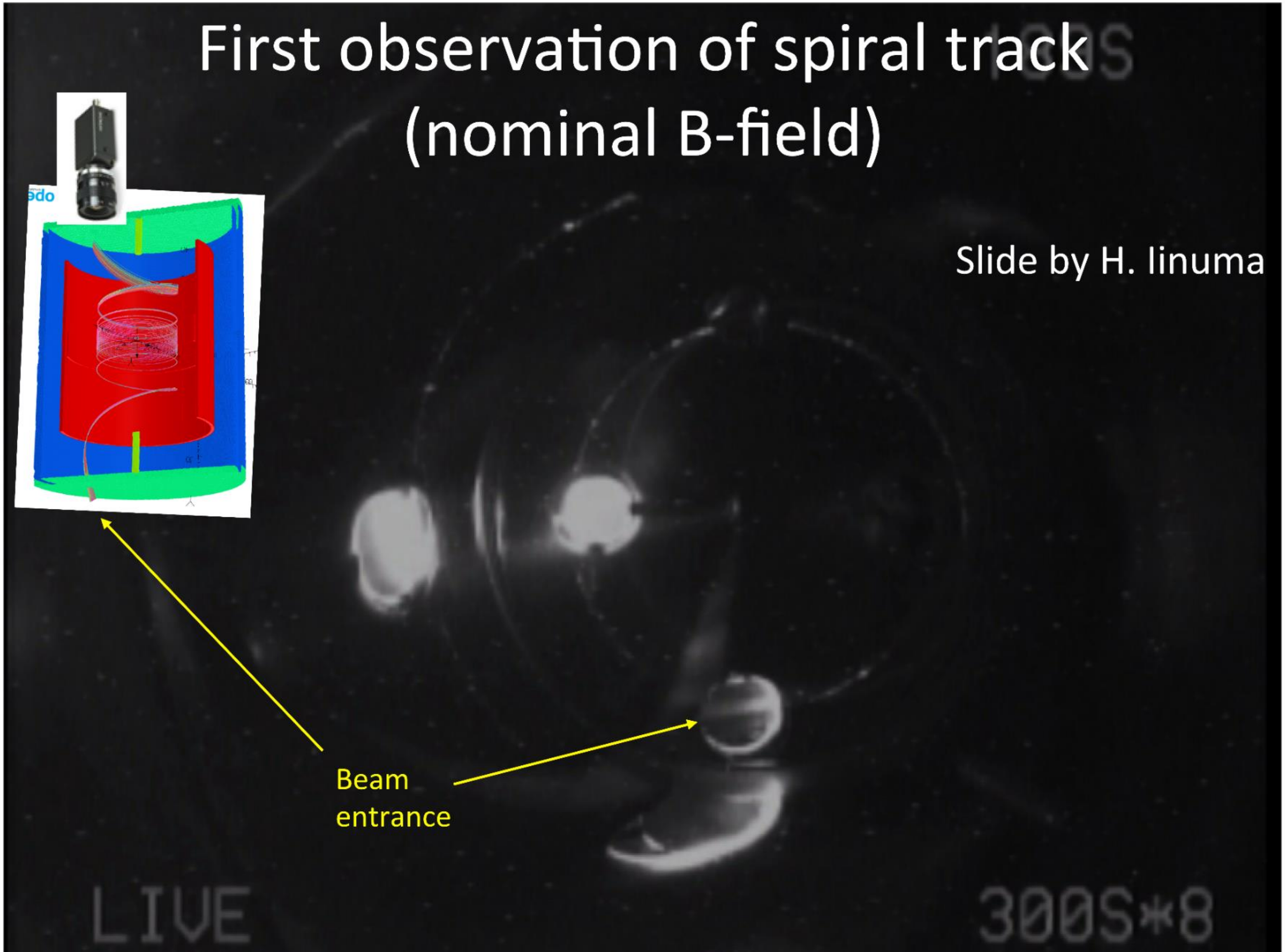
Demonstration of spiral injection with low-E electron beam



Demonstration of Spiral Injection

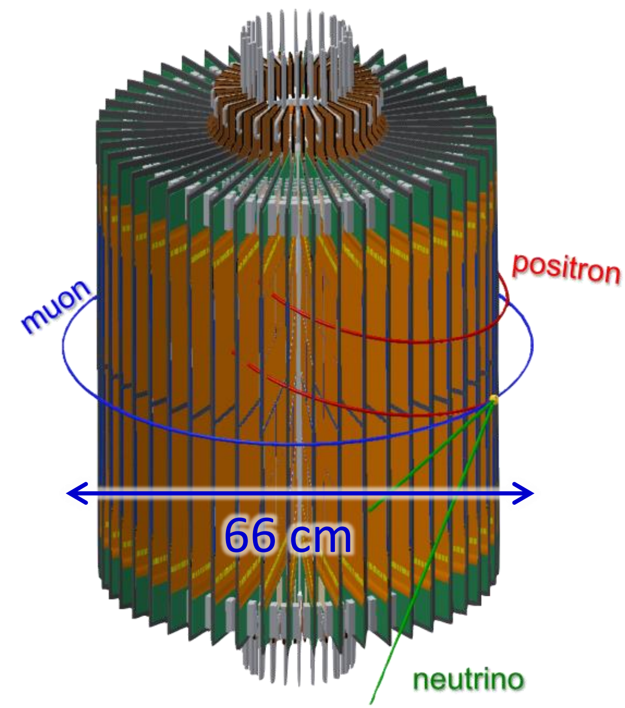


Demonstration of Spiral Injection



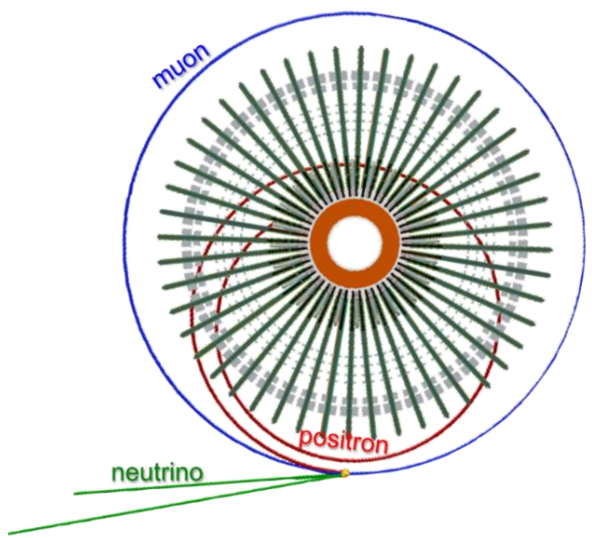
Requirement for Detector

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



Requirements

- **High hit rate capability** with 30 track/5ns (max).
  - 40k muons/spill with 25 Hz @final beam intensity goal
- **Early-to-late stability**
  - Rate changes by a factor of ~1/150 during 5 times dilated lifetime.
- **No contamination of electromagnetic field in the muon storage region.**
  - B-field (<1 ppm) and E-field (< 10 mV/cm)
- **Compact detector** inside compact storage ring.



Silicon strip detector

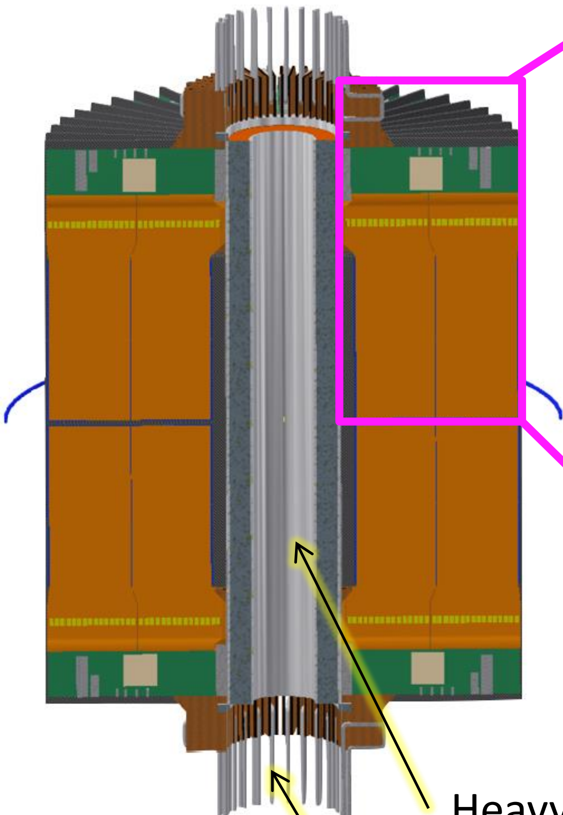
- Almost full-coverage by tracking device
  - p = 200-300 MeV/c

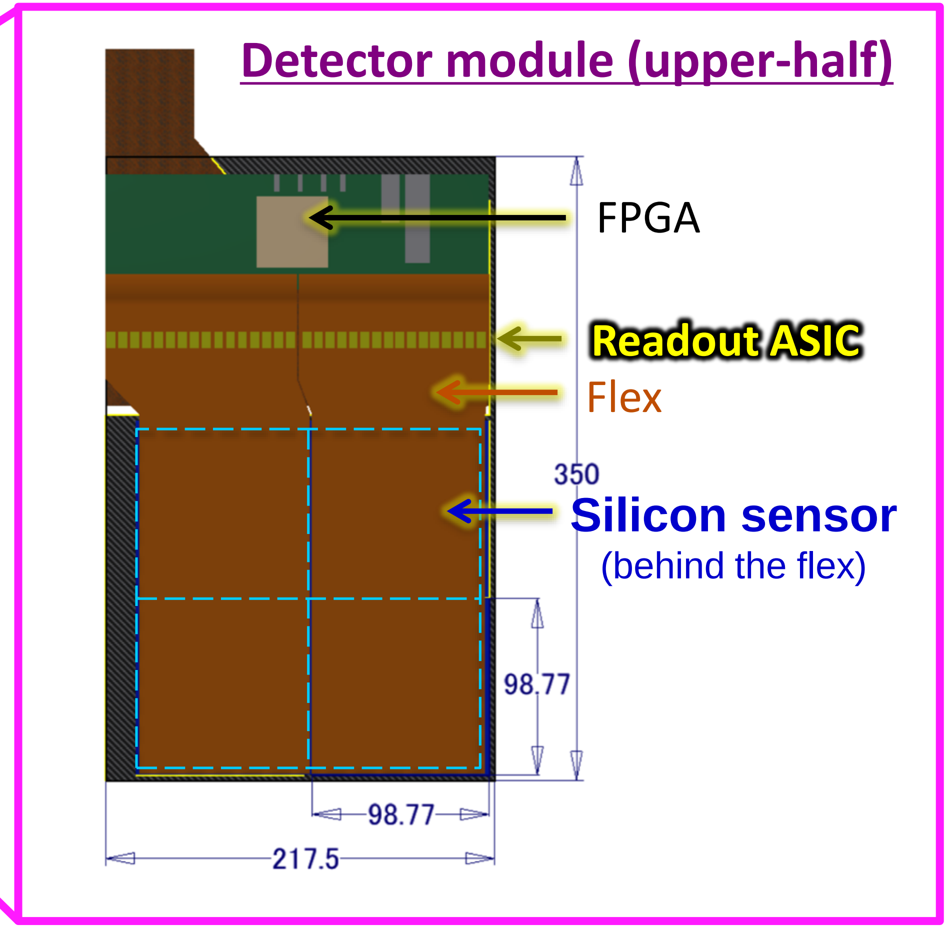
➢ Advantage to EDM measurement

Silicon Strip Detector

<u>Cross section of detector</u>

48 detector “vanes”





Heavy material to absorb low energy e+.

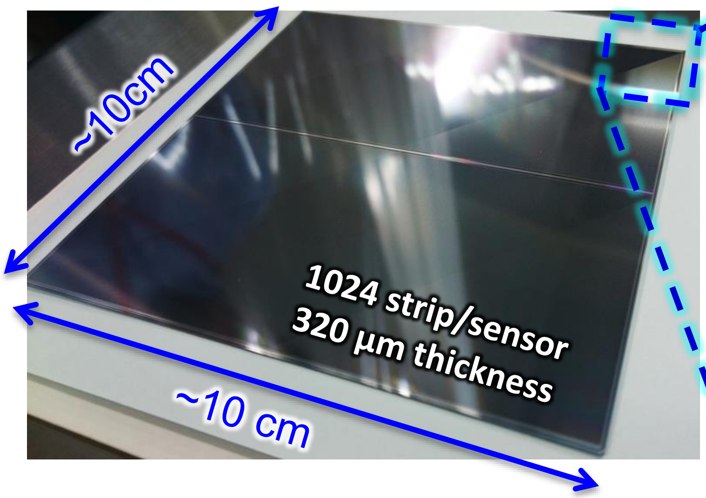
Water pipe to cool ASIC

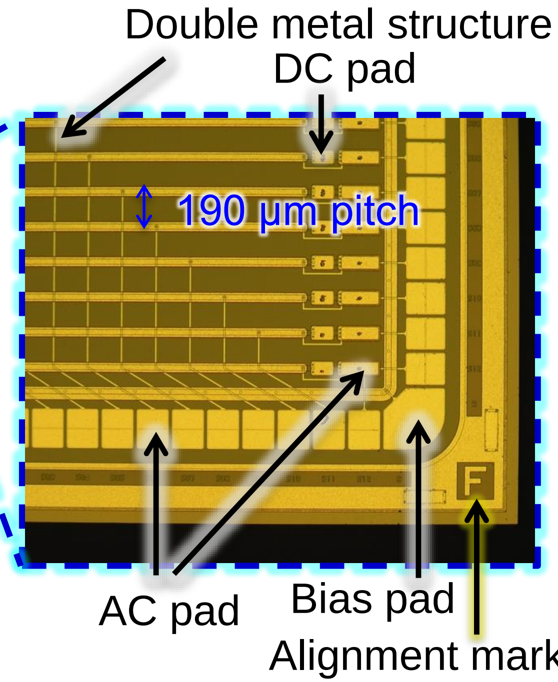
- Detector construction fund is partially covered with Kiban-S.

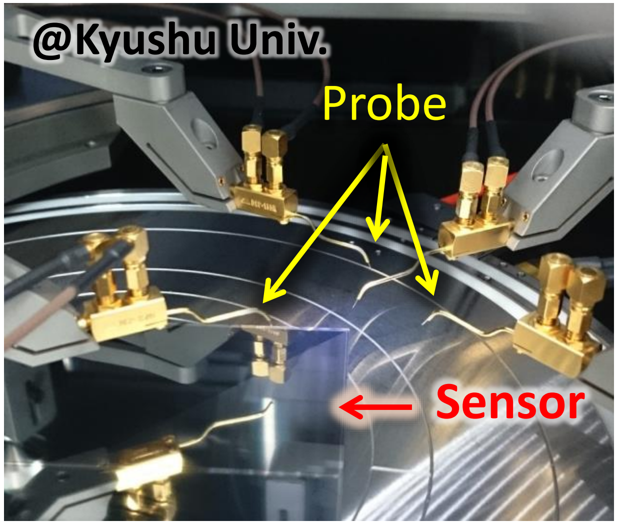
➢ **Start the detector construction.**

Silicon Strip Sensor

Full-size sensor production







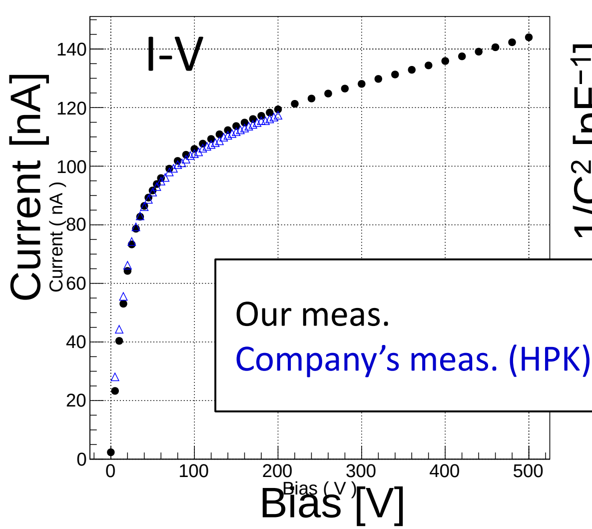
- Basic characterization has been confirmed.

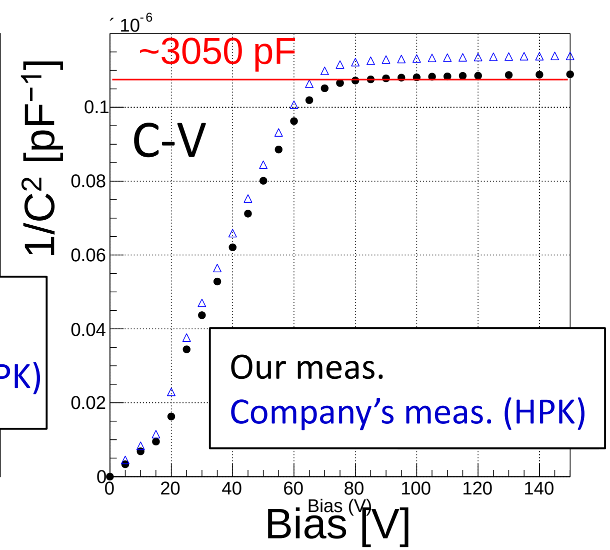
➢ **Mass production will start in JFY.**

  – Total# sensor : 768

  – Total# strip : 786,432

  – Total# area : 7.49 m^2





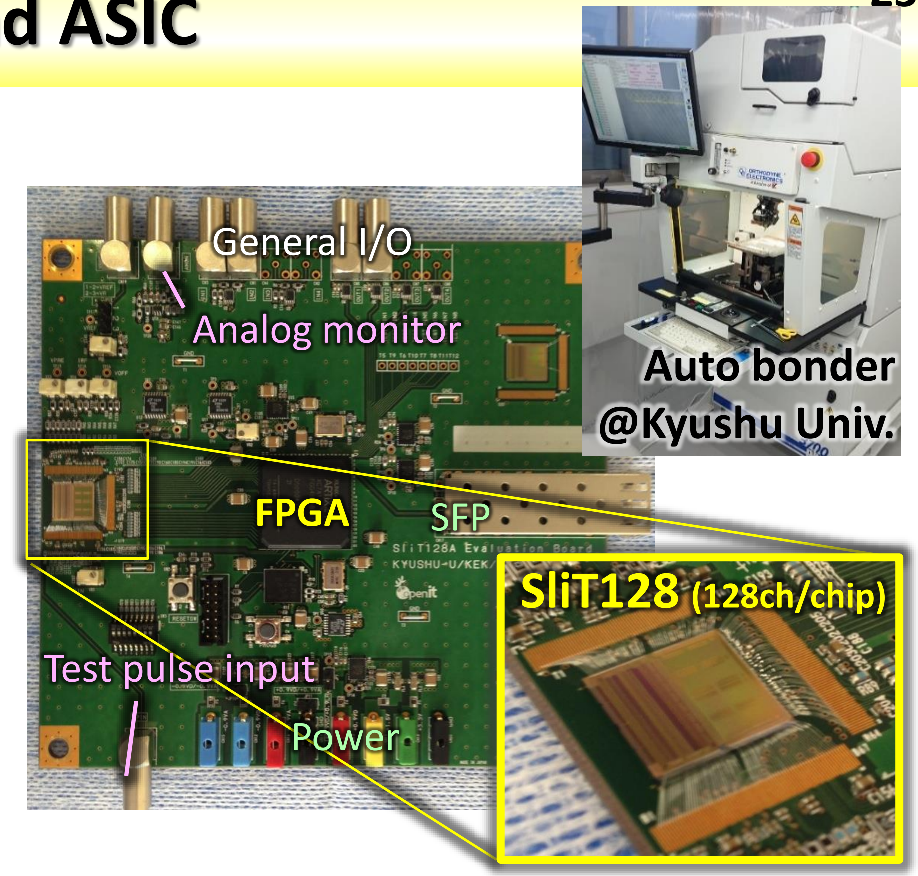
Frontend ASIC

“SliT128A” (3rd prototype)

- Binary signal sampled with 5 ns interval
- Connected with evaluation board by wire-bonding.

➢ Confirmed to satisfy almost all requirement for ASIC.

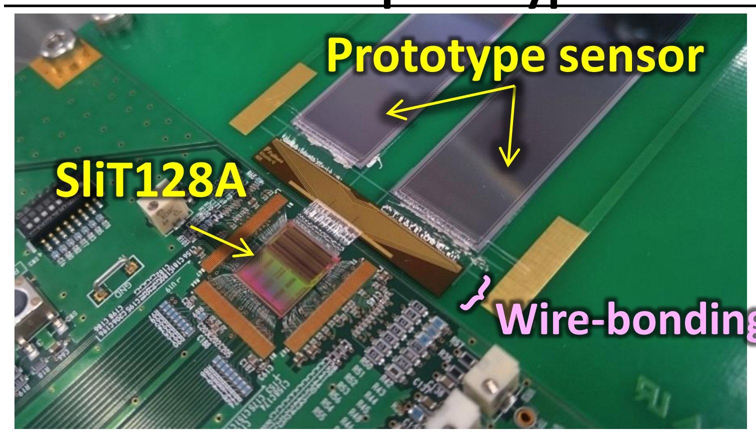
Parameter	Requirement	SliT128A TEG		SliT128A
		Simulation	Result	Result
S/N	>15	19.7	22.4	56 *
Gain	> 19 mV/fC	46.2 mV/fC	49.0 mV/fC	49.5 mV/fC
ENC	< 1600 e	1210 e	1070 e	n.a.
Dynamic range	~ 3MIP	~ 4 MIP	~3 MIP	~5 MIP
Pulse width (1 MIP)	< 100 ns	53.5 ns	96.0 ns	155 ns
Time walk (0.5 MIP→3MIP)	< 5 ns	6.5 ns	14.6 ns	11.5 ns
Power consumption	0.64 W/chip		n.a.	0.44 W/chip



- Performance study of “detector” (sensor + ASIC) is ongoing.

➢ Next ASIC (probably “final” version) will be fabricated in next JFY.

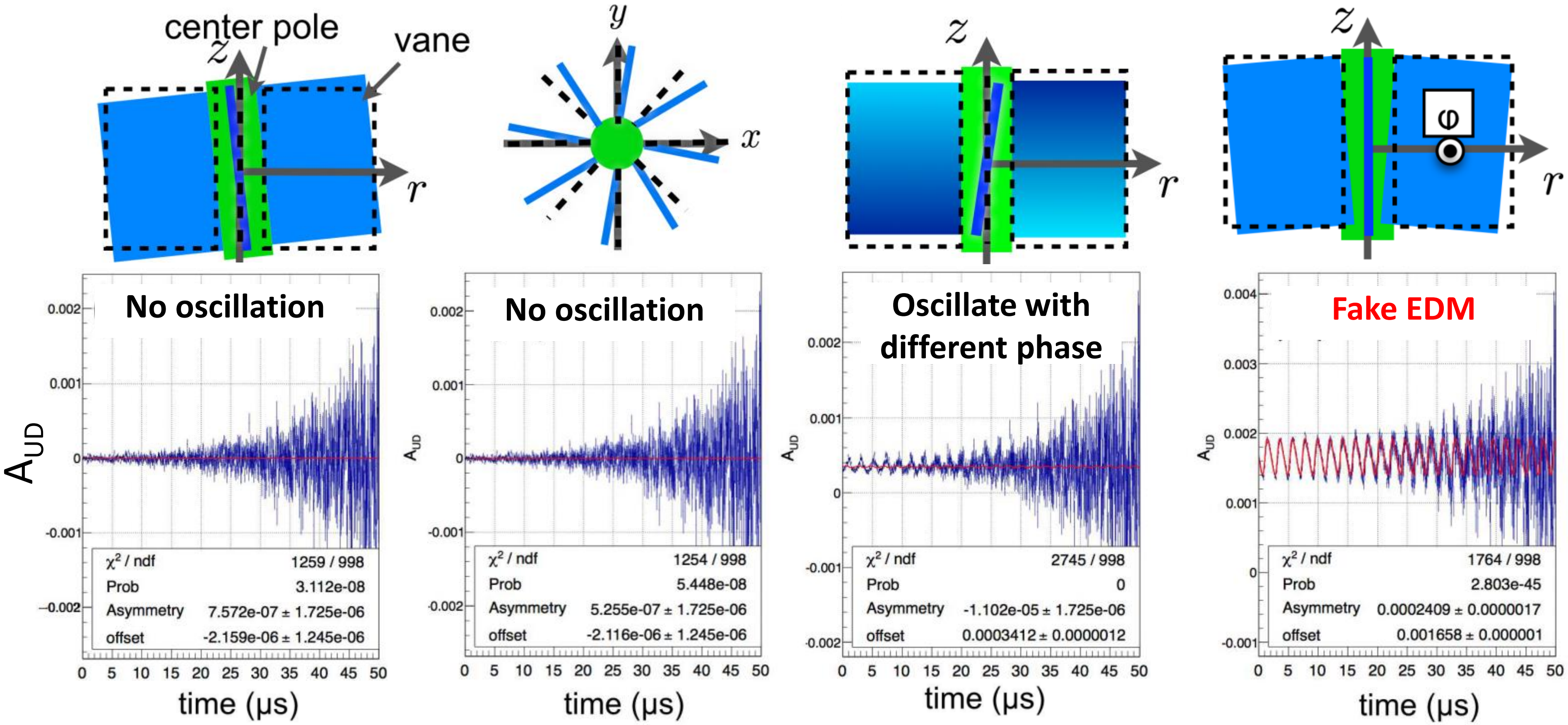
Connection with prototype sensor



Fake EDM Signal by Misalignment

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

Simulation with 1 mrad misalignment and null EDM signal

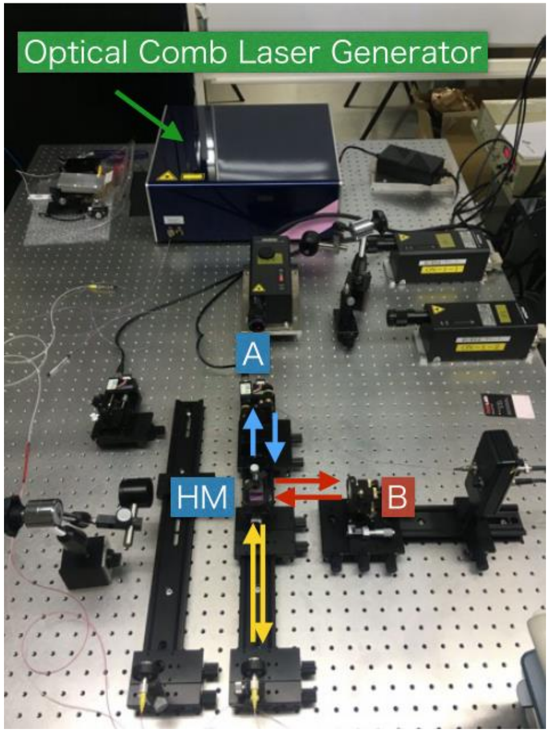


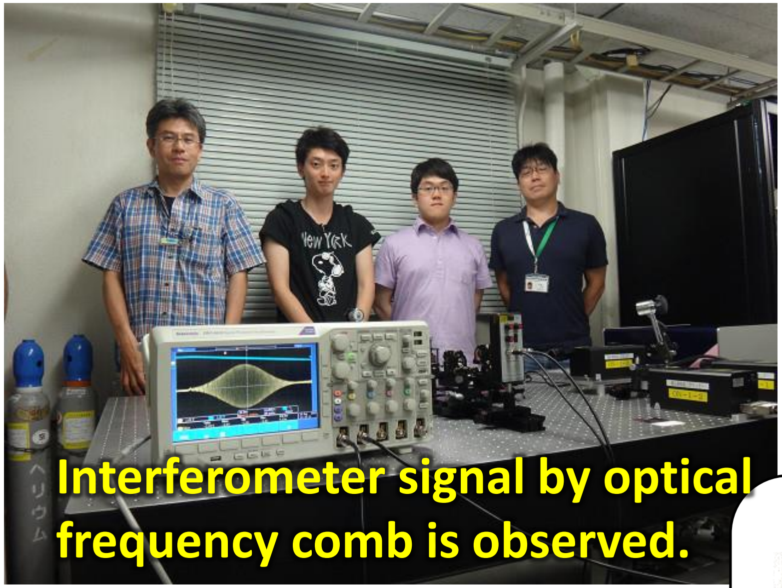
- The alignment must be controlled with 10 μrad accuracy to measure EDM with $10^{-21} e \cdot \mathrm{cm}$.

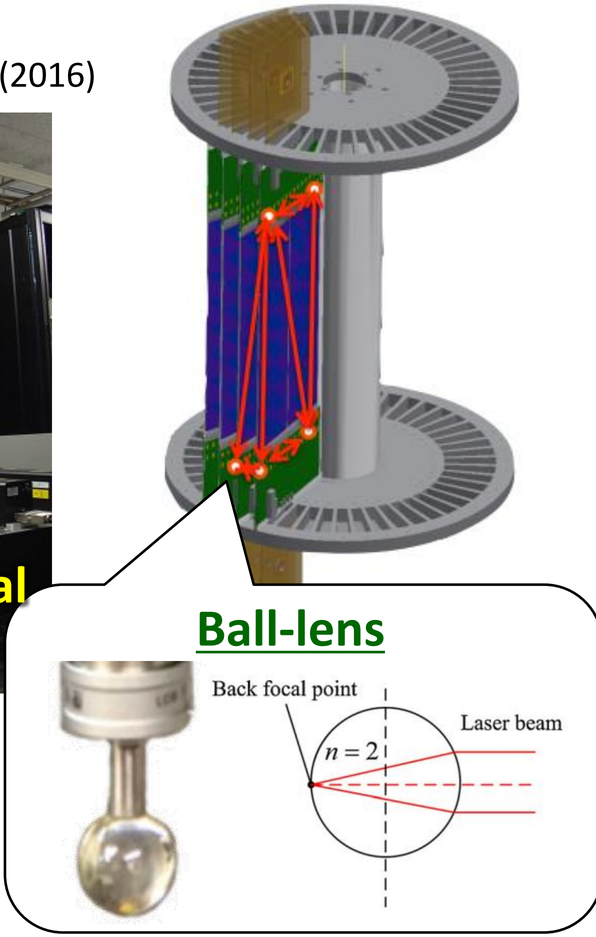
Alignment Monitor

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)







- 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.

J-PARC E34 Collaboration

- 137 members from 9 countries, 49 institutions.
  - Still evolving

J-PARC 2014.9

KAIST (Korea) 2014.11

- Submitted technical design report (TDR).
  - Aim measurement beyond BNL E821 precision 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

- High priority in KEK Project Implementation plan.

J-PARC 2015.6

J-PARC 2016.7

Summary

- **J-PARC E34 experiment** measures muon g-2 and EDM by completely different approach.
- A lot of interesting techniques are being developed.
  - **No focusing E-field to storage muon beam**
    - Efficient Mu production
    - Muon re-acceleration
    - ➢ Low emittance muon beam
  - **3D-spiral injection scheme**
  - **Compact storage ring**
    - Good uniformity of B-field.
    - Almost full-coverage by tracking detector.
- TDR was submitted.
  - g-2 : 0.37 ppm (→ 0.1 ppm)
  - EDM : 1.3×10^{-21} e・cm
- High priority in KEK Project Implementation plan.
- Moving to construction stage.

Backup