

Measurement of muon g-2 and EDM with ultra-cold muon beam at J-PARC

September 27, 2016

SPIN 2016

Tsutomu Mibe (KEK)

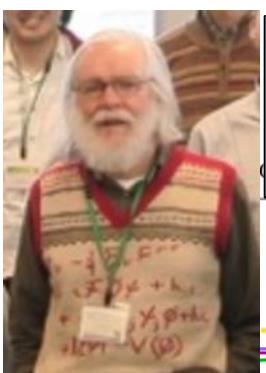
Beyond the standard model is dark.

Baryon asymmetry in the Universe

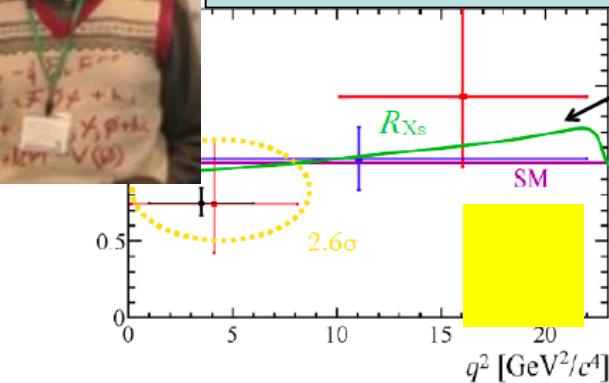
Dark matter

Hierarchy problem

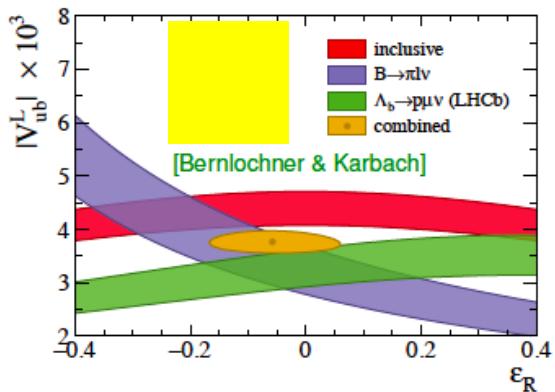
...



Flavour Anomalies



$h \rightarrow \tau\mu$
 $B \rightarrow K e^+ e^- / B \rightarrow K \mu^+ \mu^-$



$|V_{cb}|$ incl/excl

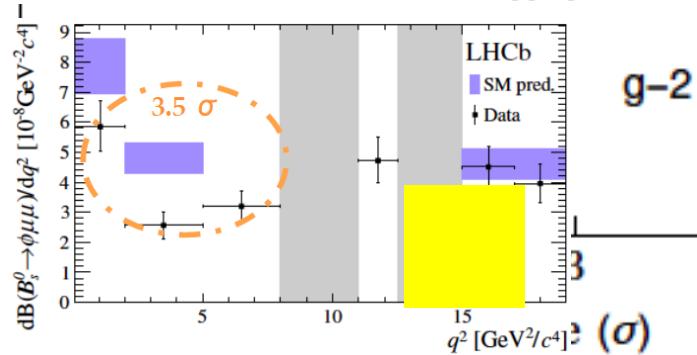
$|V_{ub}|$ incl/excl

$B_s \rightarrow \phi \mu^+ \mu^-$

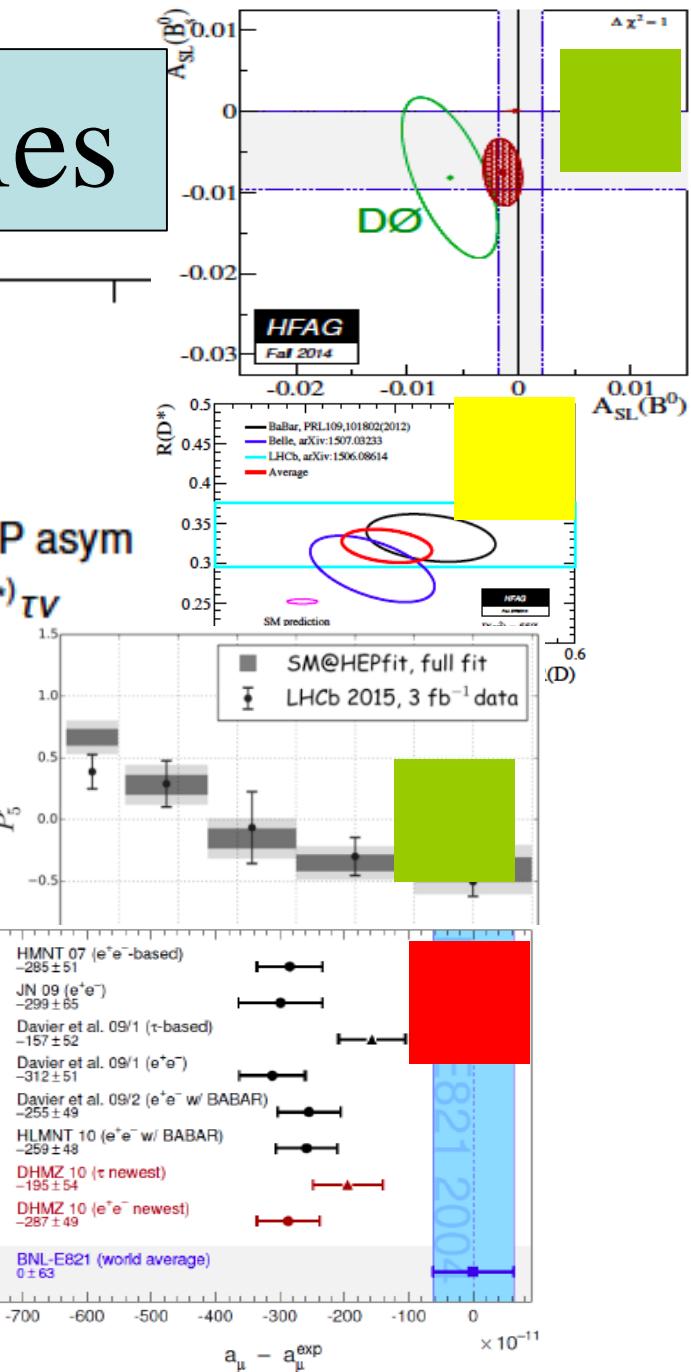
No worries

Wait & See

Serious?

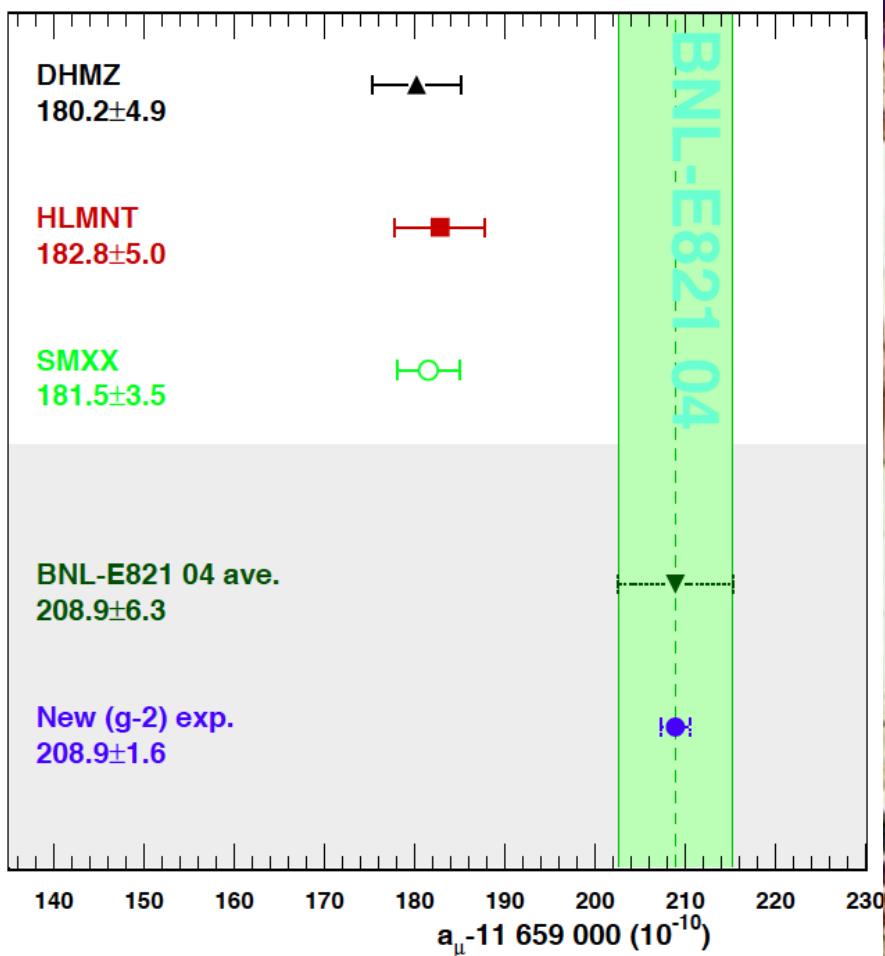


$g-2$



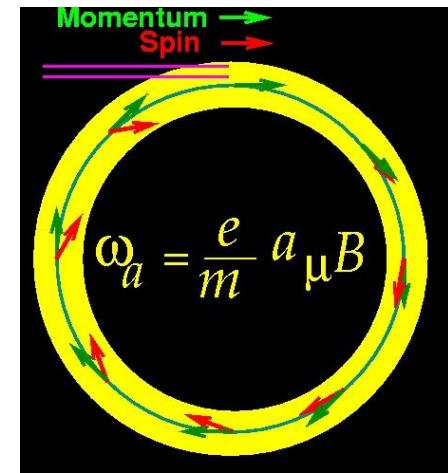
Muon anomalous magnetic moment ($g-2$)

Standard Model



muon g-2 and EDM measurements

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



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
 $\gamma=30$ ($P=3$ GeV/c)

$$\vec{W} = -\frac{e}{m} \hat{a}_m \vec{B} + \frac{\hbar \vec{a}_m}{2m} \vec{b} \cdot \vec{B} + \frac{\vec{E}}{c}$$

FNAL E989

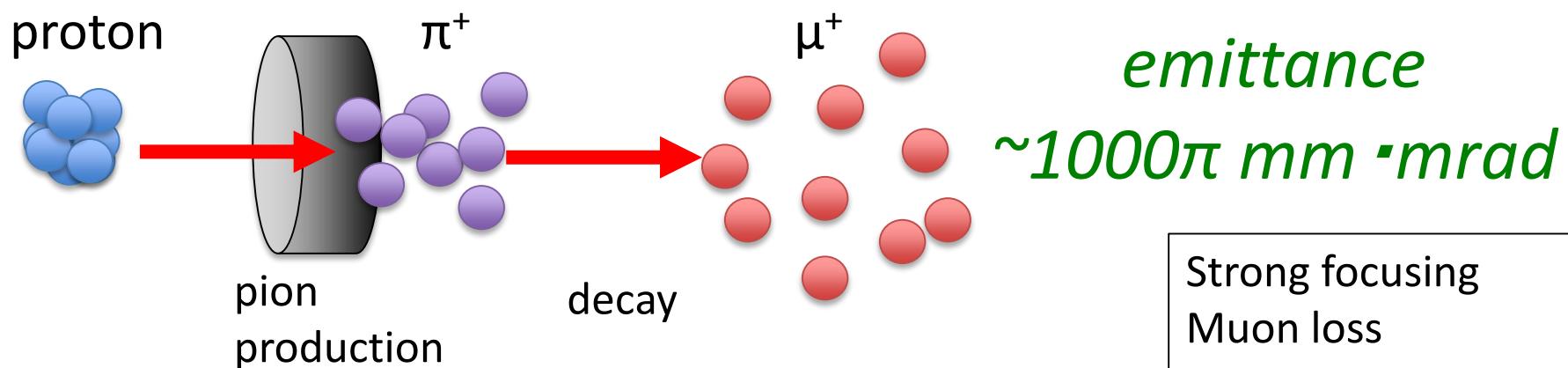
J-PARC approach
 $E = 0$ at any γ

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

J-PARC E34

Muon beam

Conventional muon beam

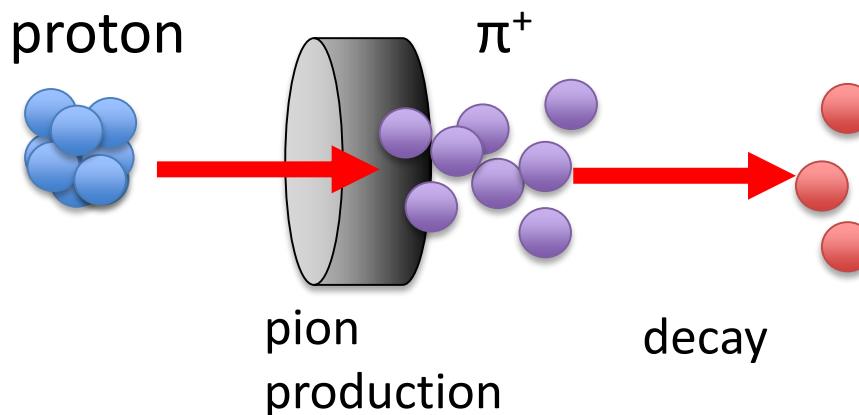


Strong focusing
Muon loss
BG π contamination



Muon beam

Conventional muon beam

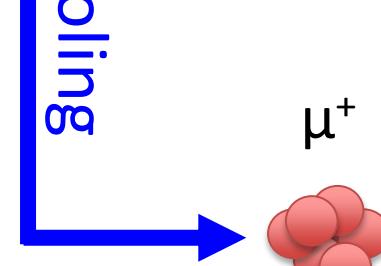


emittance
 $\sim 1000\pi \text{ mm} \cdot \text{mrad}$

Strong focusing
Muon loss
BG π contamination



**Ultra-cold
muon beam**



emittance
 $1\pi \text{ mm} \cdot \text{mrad}$

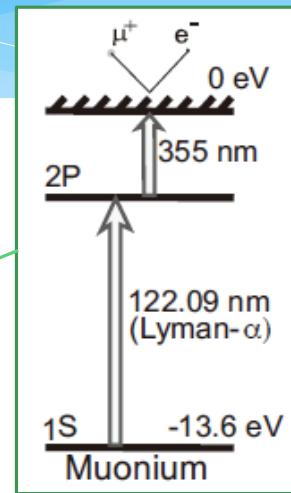
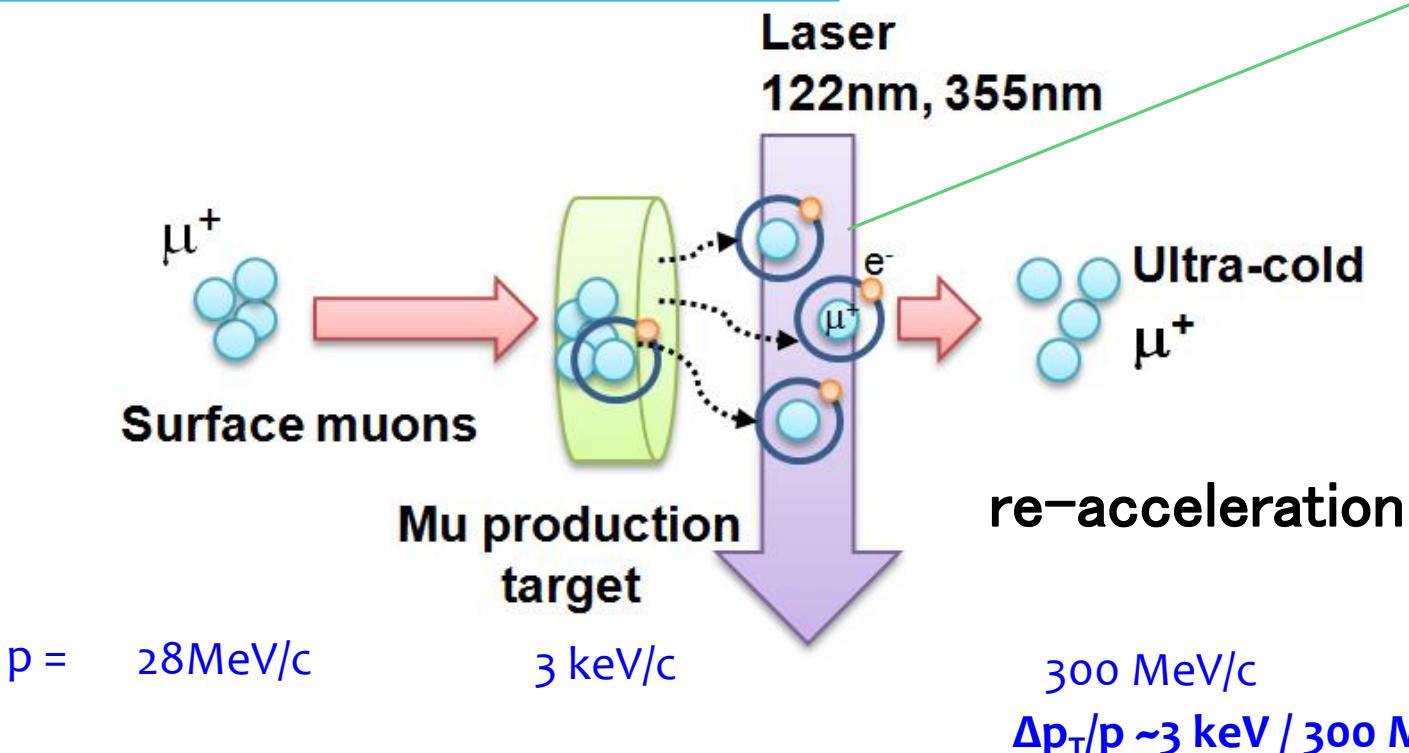
Free from any of these

Ultra-cold Muon

Requirement for zero E-field:

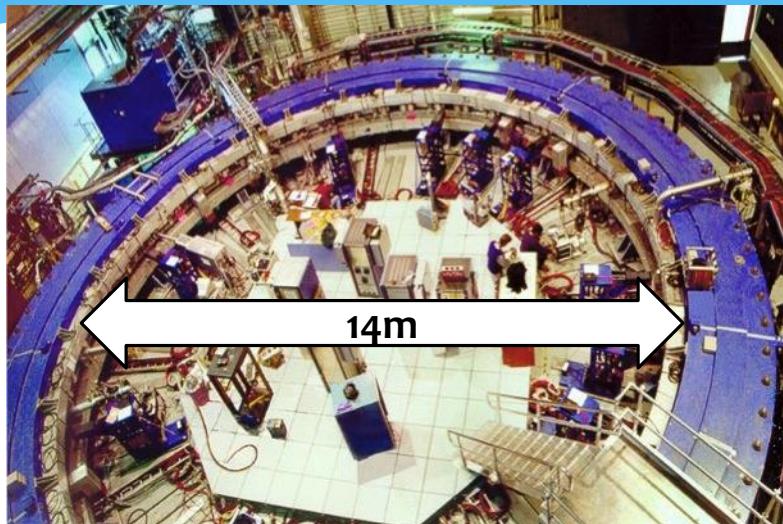
Muons should be kept stored without E-focusing
→ Beam with ultra-small transverse dispersion,
i.e. $\Delta p_T/p \sim 0$

Laser resonant ionization of Mu (μ^+e^-)



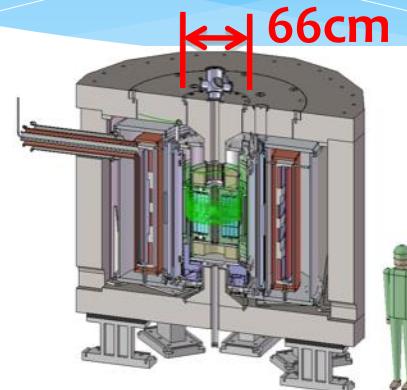
A compact muon g-2/EDM experiment

BNL E821 / FNAL E989



$P = 3.1 \text{ GeV}/c$, $B = 1.45 \text{ T}$

J-PARC E34



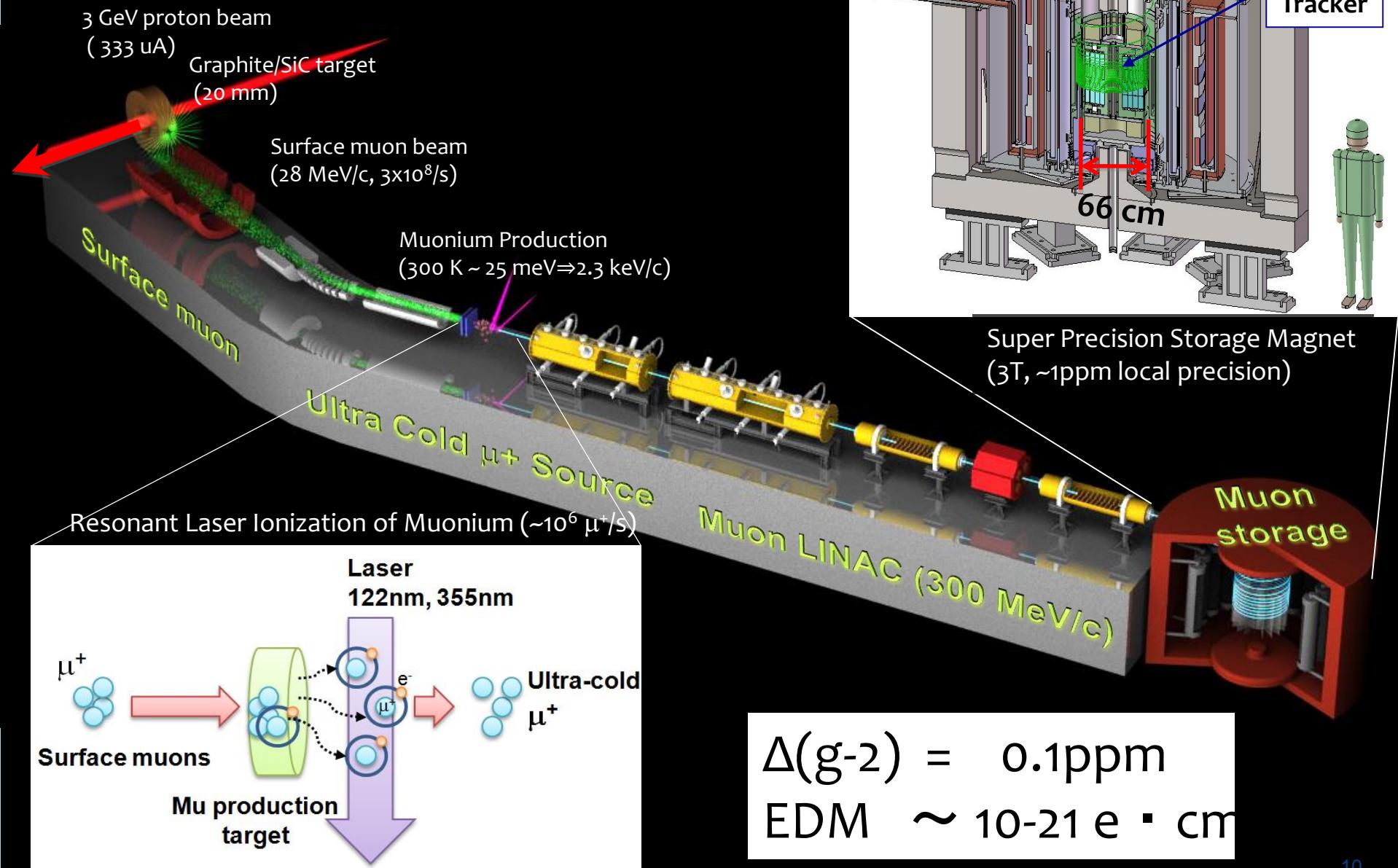
$P = 0.3 \text{ GeV}/c$, $B = 3.0 \text{ T}$

* 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



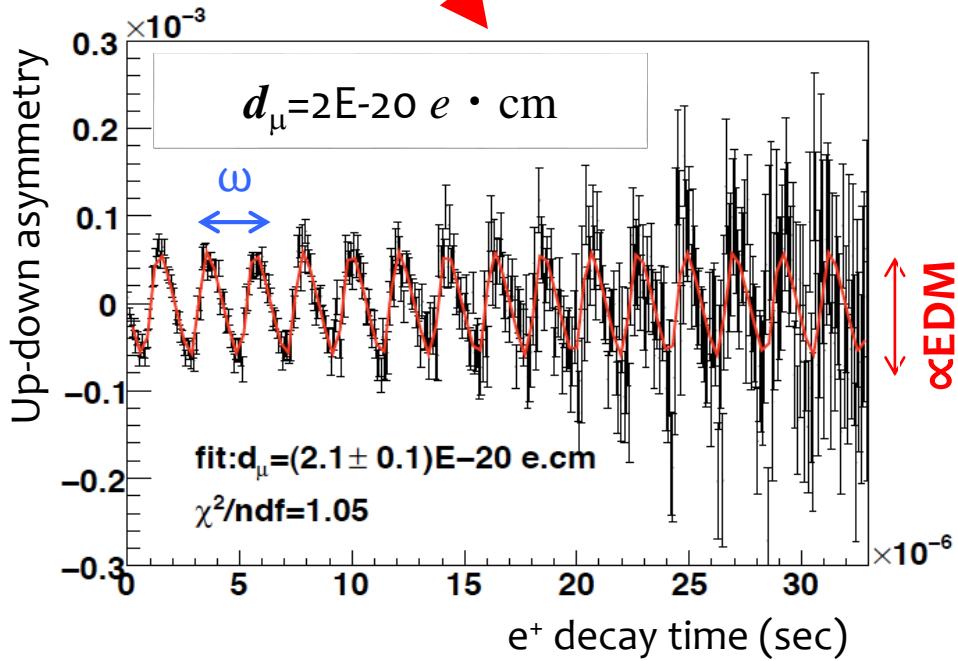
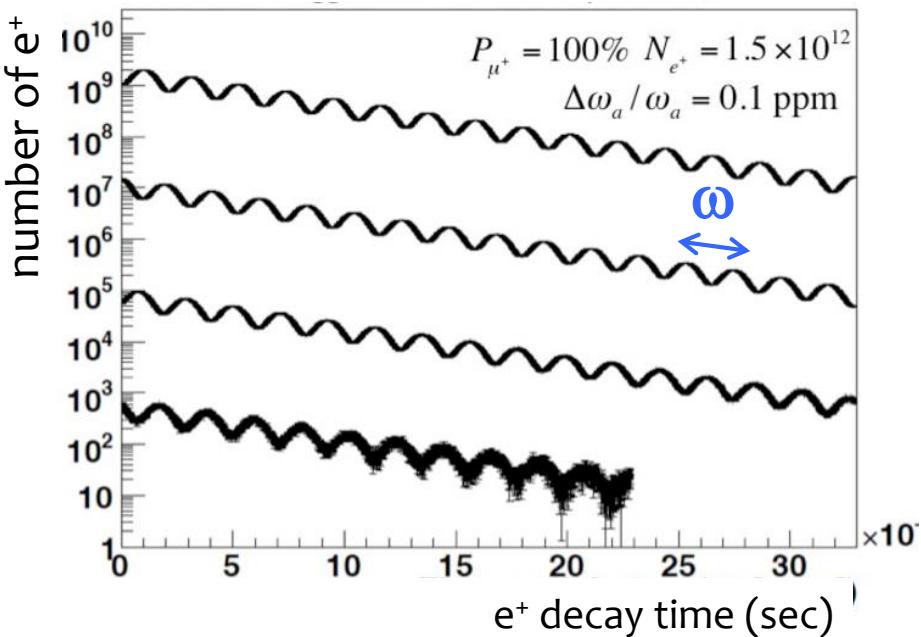
New Muon g-2/EDM Experiment at J-PARC with Ultra-Cold Muon Beam



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

$$\vec{W} = -\frac{e}{m} \hat{\vec{a}}_m \vec{B} + \frac{\hbar}{2} (\vec{b} \cdot \vec{B}) \hat{\vec{u}}$$

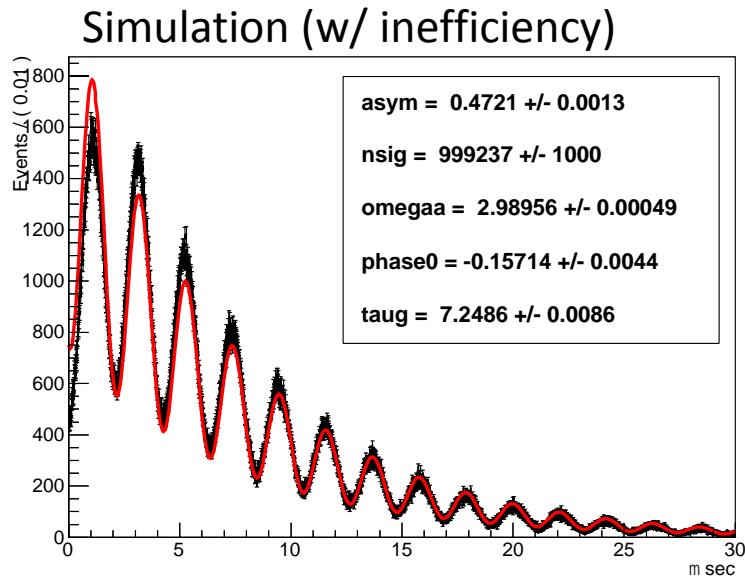
$p > 200 \text{ MeV}/c$



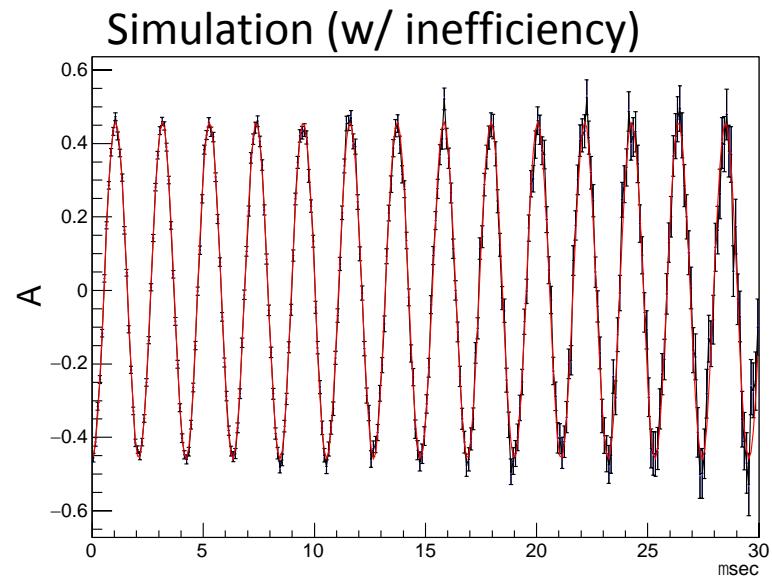
Spin reversal (ONLY possible in E34)

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

Raw time distribution



Asymmetry distribution



Comparison of experiments

	BNL E821 / FNAL E989	J-PARC E34
muon momentum	3.09 GeV/c	0.3 GeV/c
storage ring radius	7 m	0.33 m
storage field	1.5 T	3.0 T
average field uniformity	1 ppm	<< 1ppm
(local uniformity)	100 ppm → 50ppm	1ppm
Injection	inflector + kick	spiral + kick
Injection efficiency	3-5%	90%
muon spin reversal	no possible	pulse-to-pulse
positron measurement	calorimeters	tracking
positron acceptance	65%	100%
muon polarization	100%	50%
events to 0.46 ppm	9×10^9	5×10^{11}

J-PARC Facility
(KEK/JAEA)

LINAC

Neutrino Beam
To Kamioka

3 GeV
Synchrotron

Material and Life Science
Facility

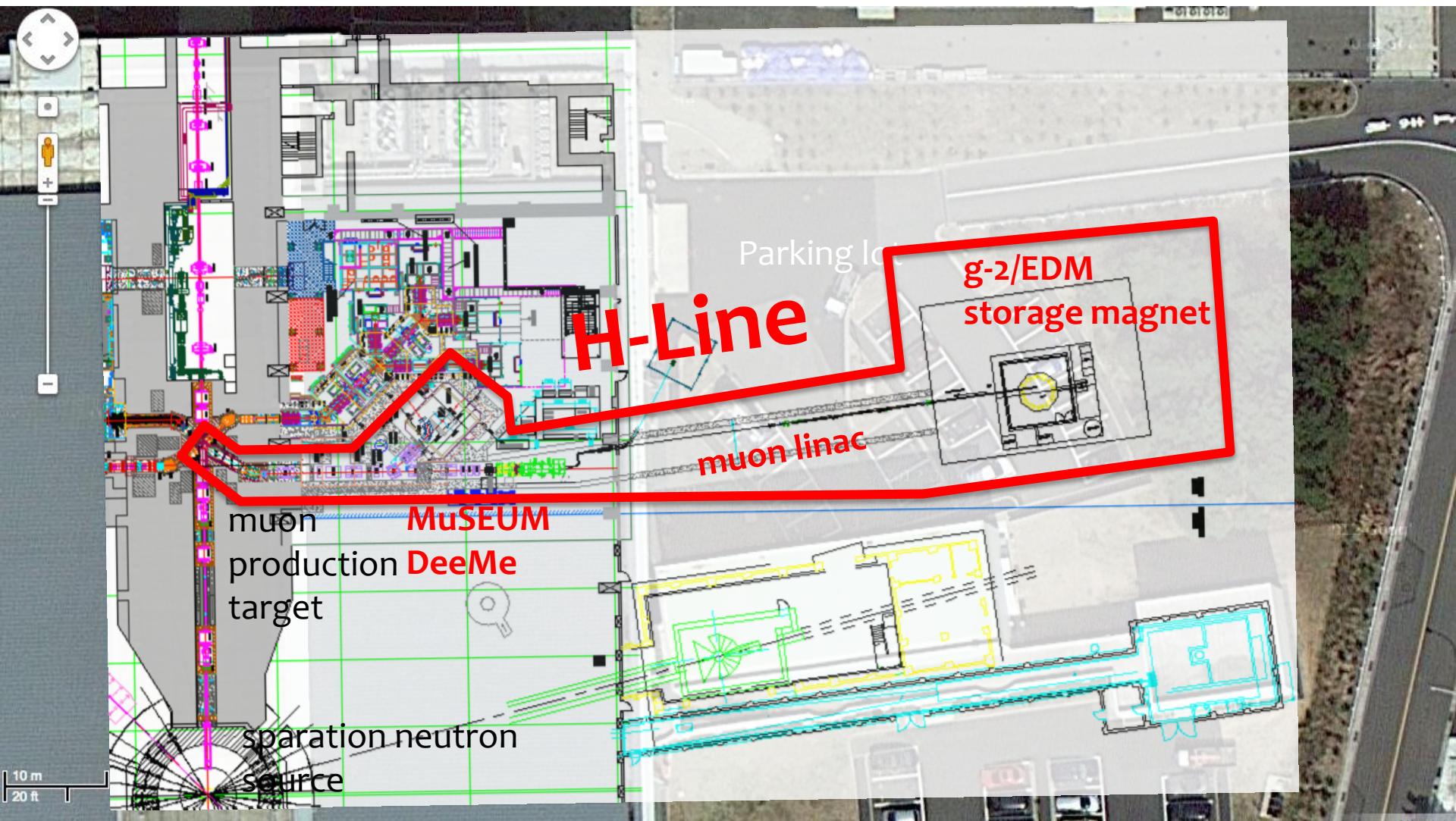
Main Ring
(30 GeV)

Hadron Hall

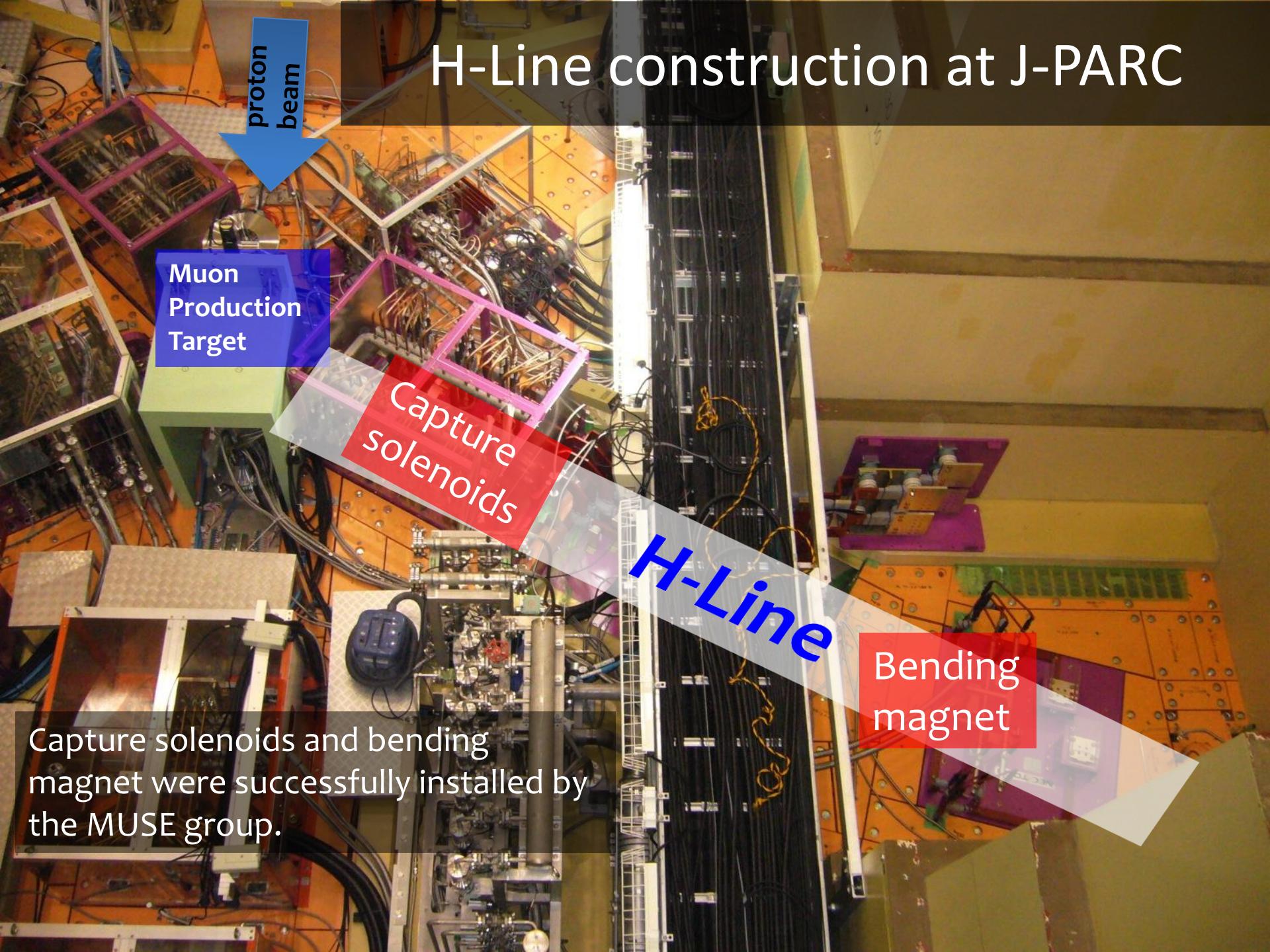
Bird's eye photo in Feb. 2008

Proposed experimental site

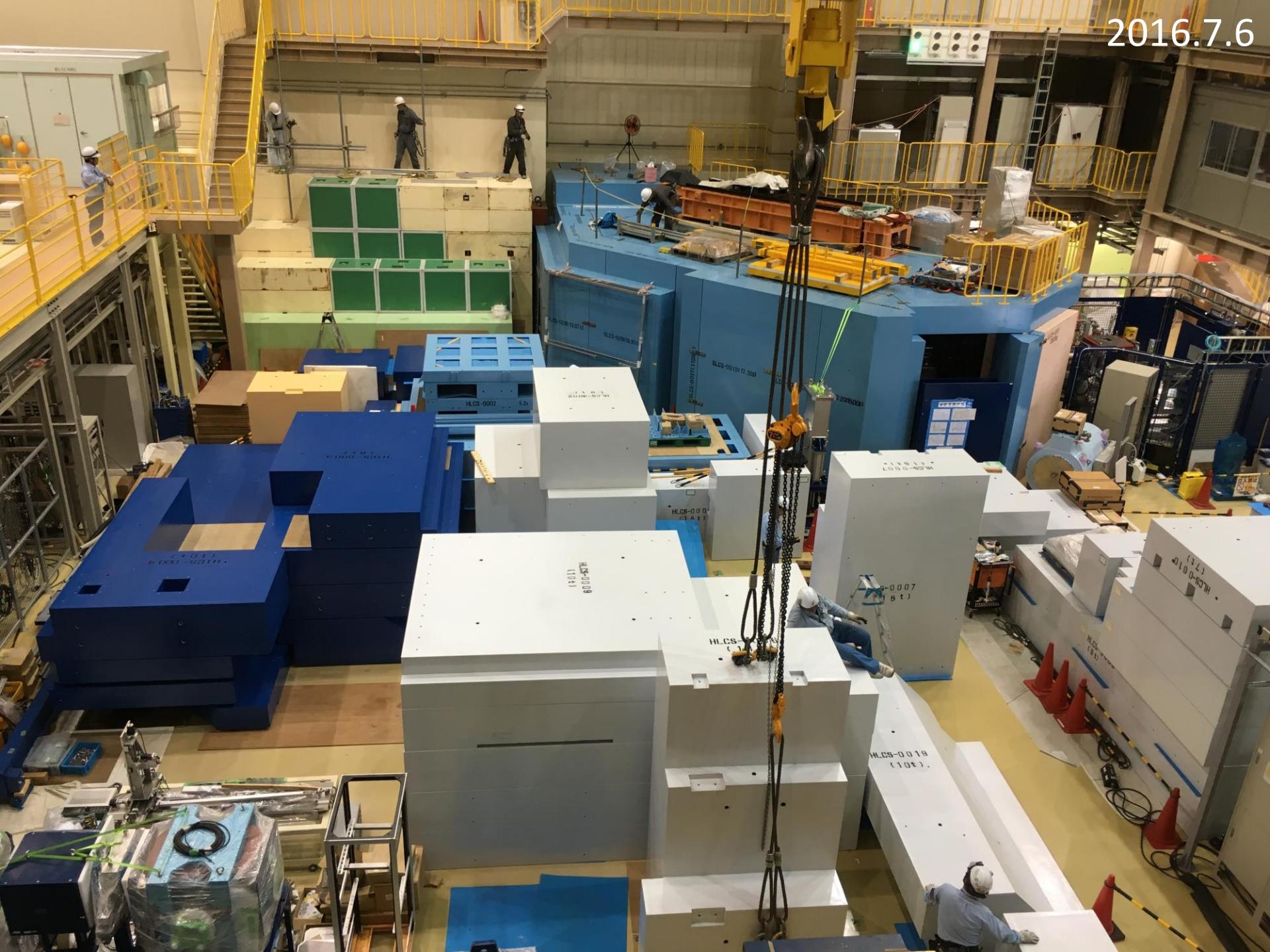
Material and Life science Facility in J-PARC



H-Line construction at J-PARC

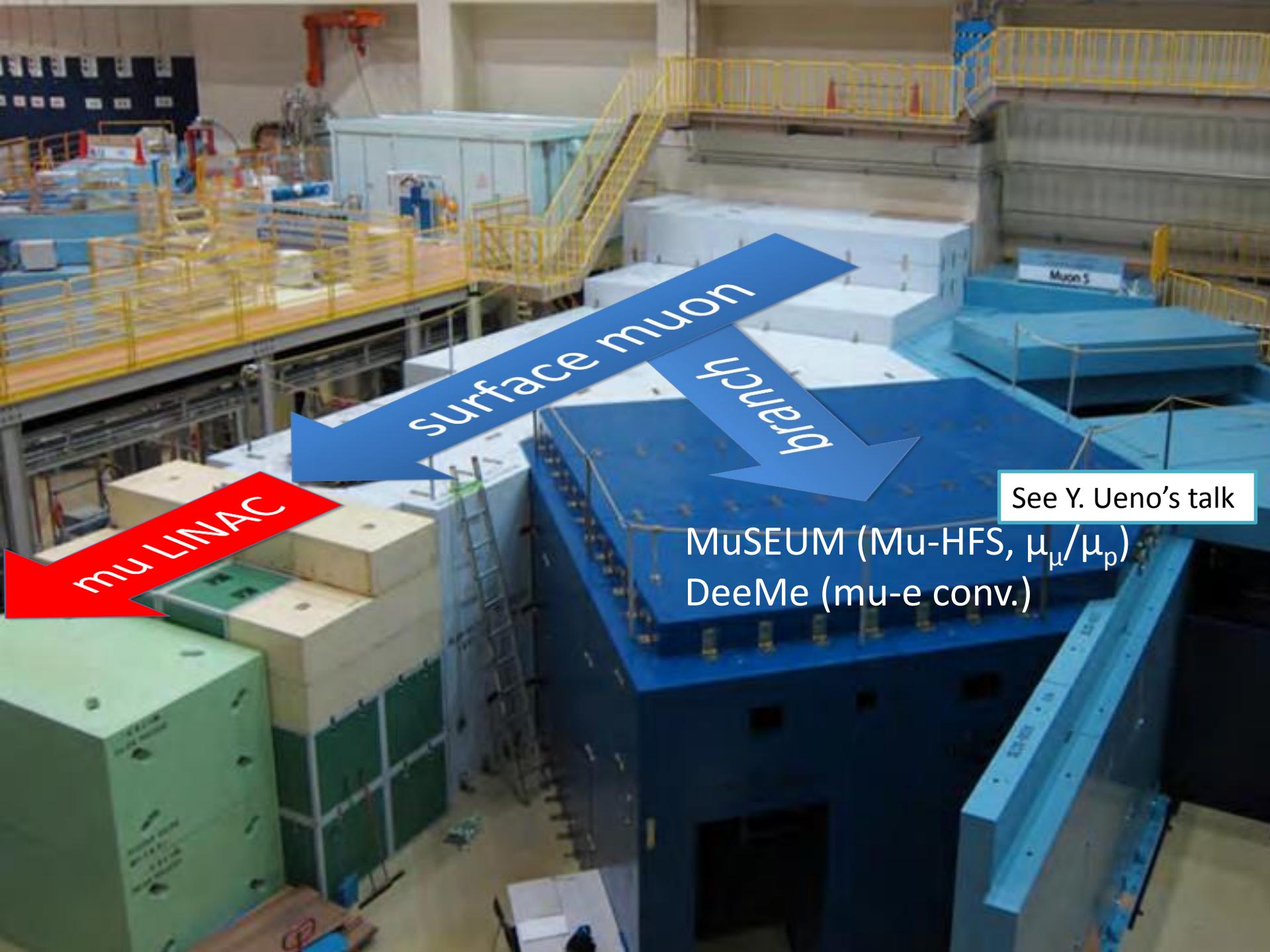


2016.7.6



2016.8.17





mu LINAC

Surface muon
branch

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

See Y. Ueno's talk

g-2/EDM collaborators

- **Collaborators**

- Proposal (2009) 7 2
- Conceptual Design Report (2011) 9 2
- Technical Design Report (2015) 1 3 7 (16 graduate students)
– (27 also in COMET)

- **9 countries, 49 institutions**

- Canada, Japan, Korea, UK, USA, France, Russia, Czech, China

CM10@J-PARC 2015.6 (50 participants)

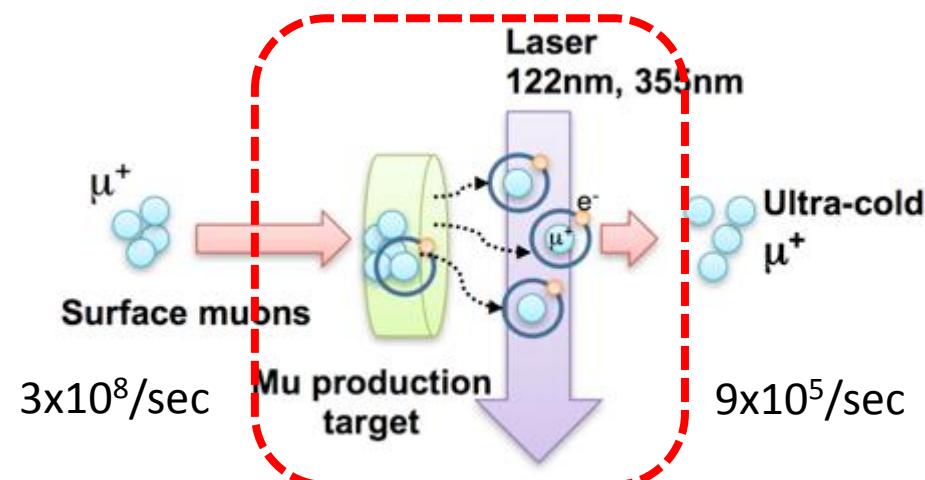


CM12@J-PARC 2016.6 (65 participants)

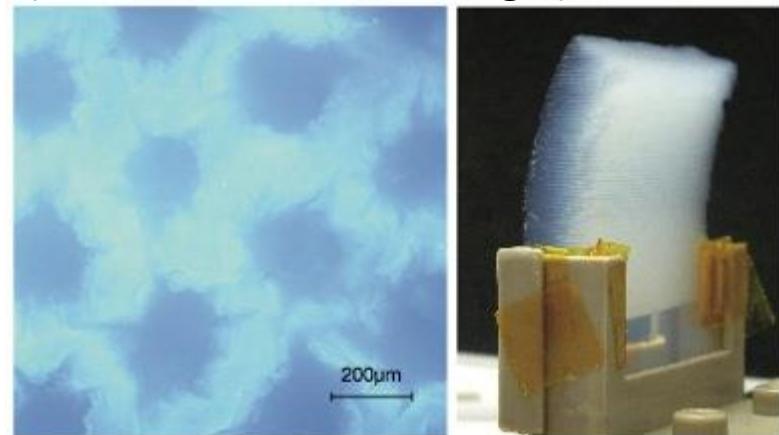


Muonium production

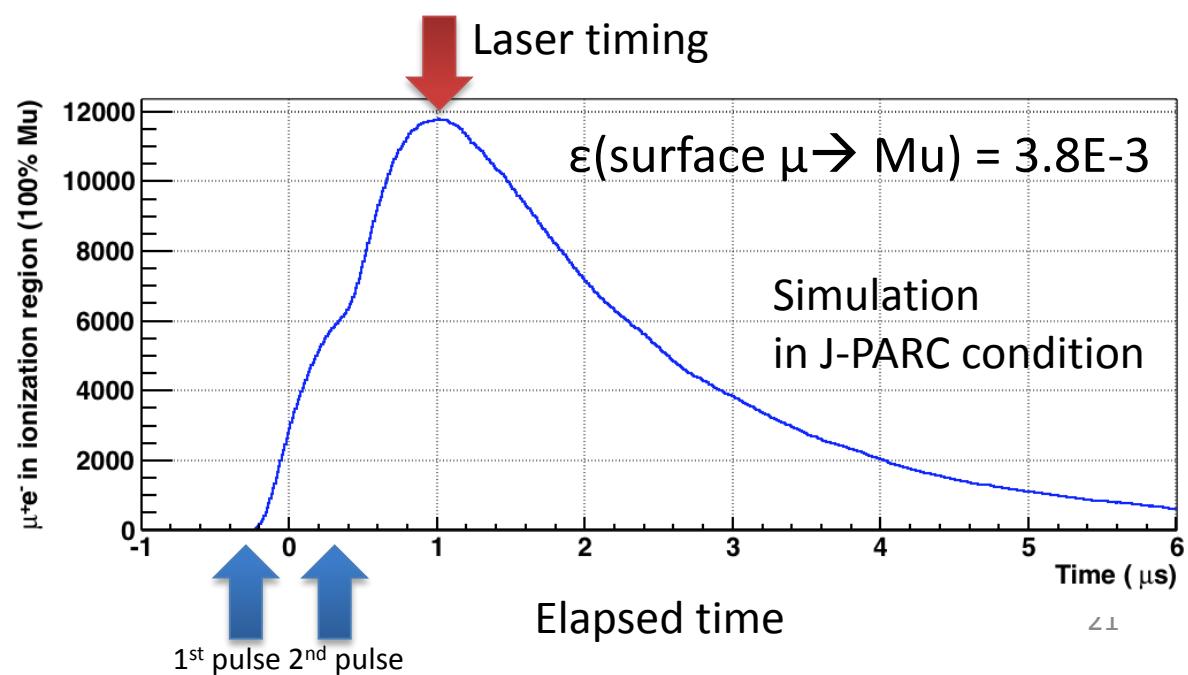
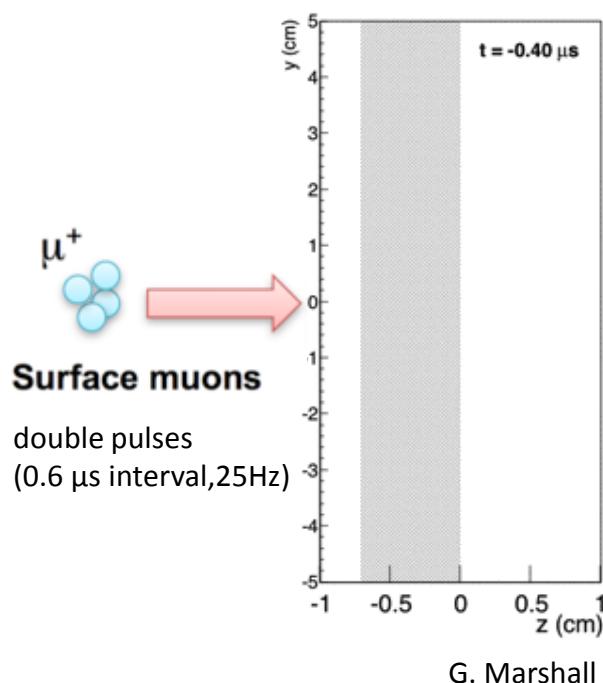
RIKEN, TRIUMF, UVic,
Chiba, Korea U, KEK



Mu production target
(laser-ablated silica aerogel)

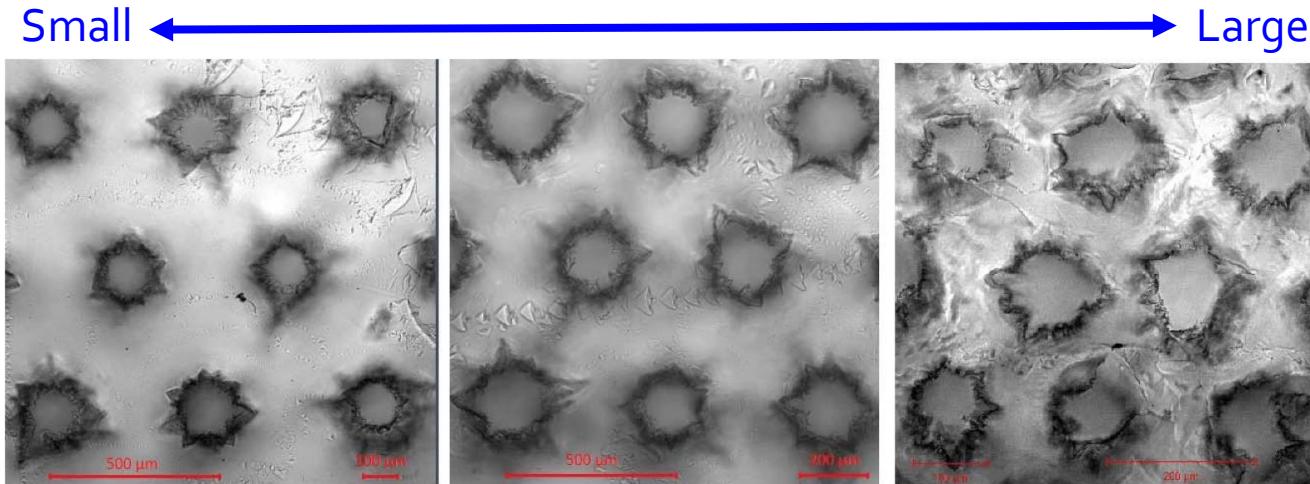


G. Beer et al., Prog.Theor.Exp.Phys. (2014)091C01



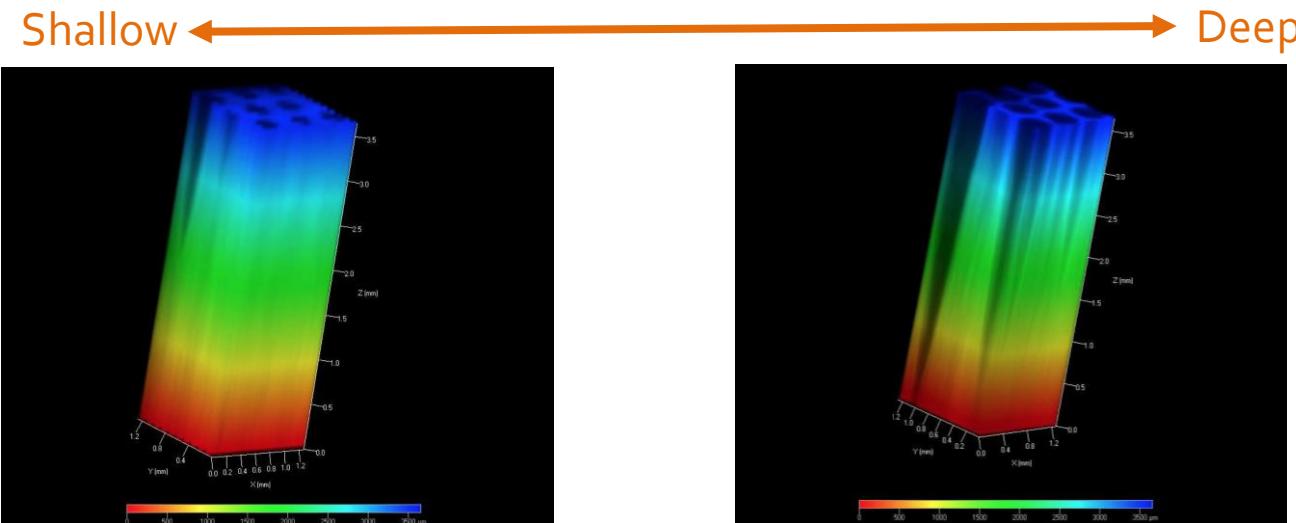
New laser-ablated samples in preparation

Hole size



S. Kamal

Hole depth

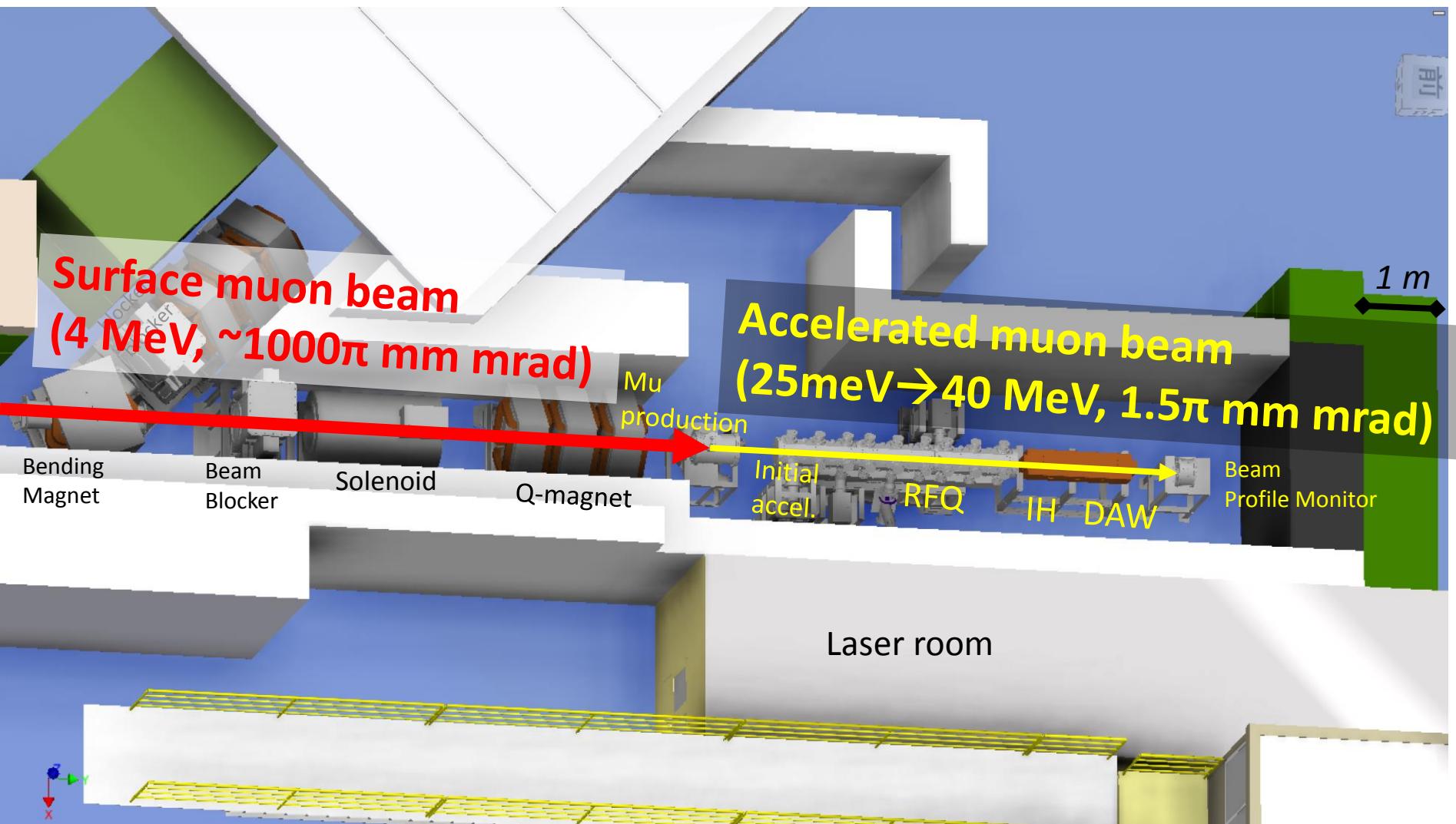


S. Kamal

To be evaluated at TRIUMF (28 shifts approved)

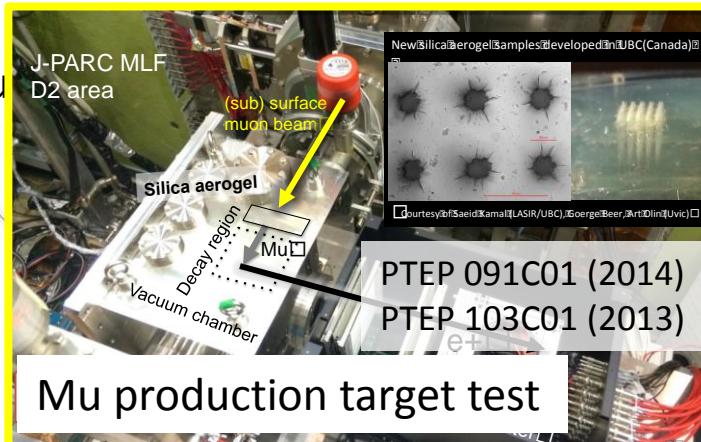
Ultra-cold muon beam at H-line

Design of H-line and the muon acceleration test



Ultra-cold muon beam at H-line

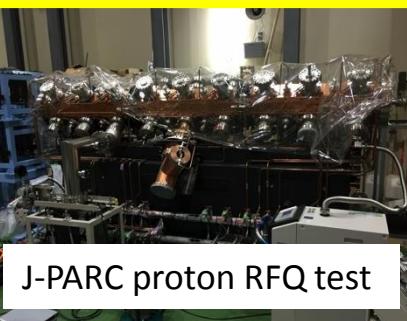
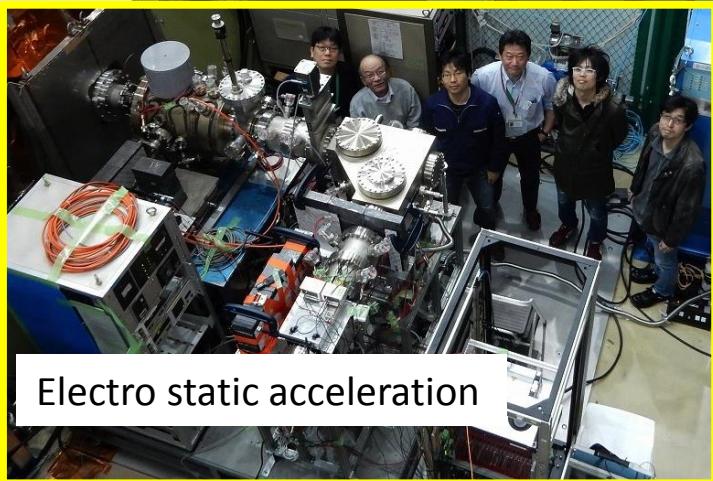
Design of H-line and the mu



Surface muon beam
(4 MeV, $\sim 1000\pi$ mm mrad)

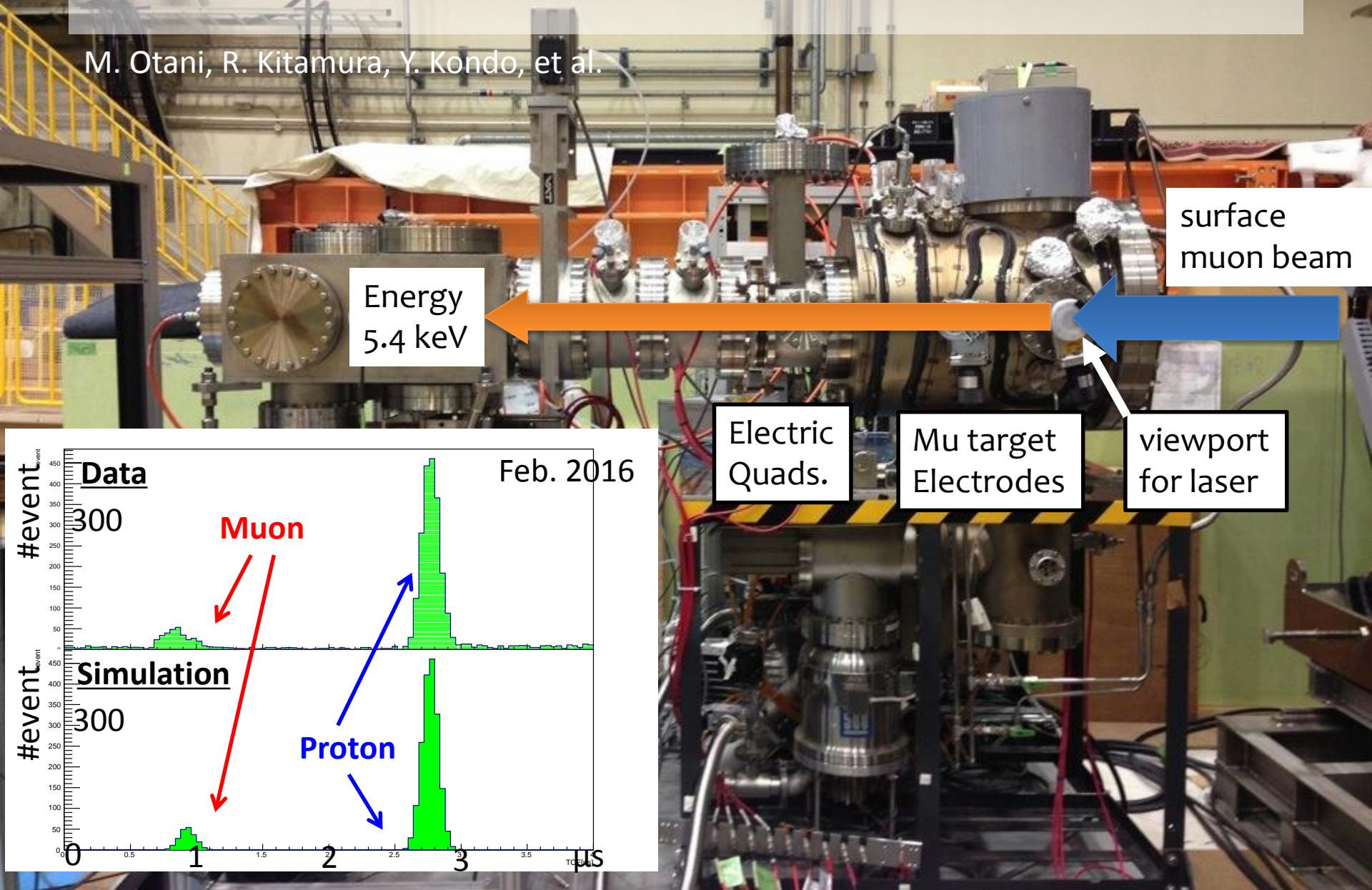
Accelerated muon beam
(25 meV \rightarrow 40 MeV, 1.5π mm mrad)

Bending magnet



Electro-static acceleration

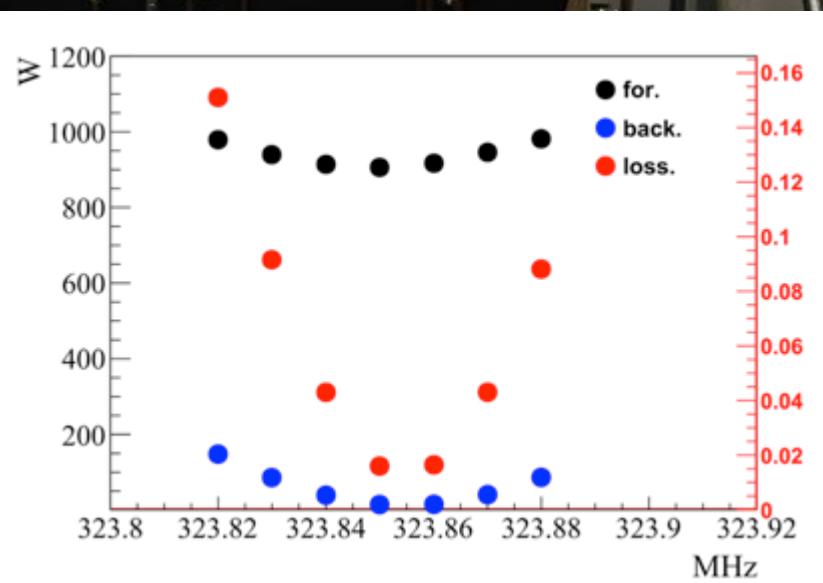
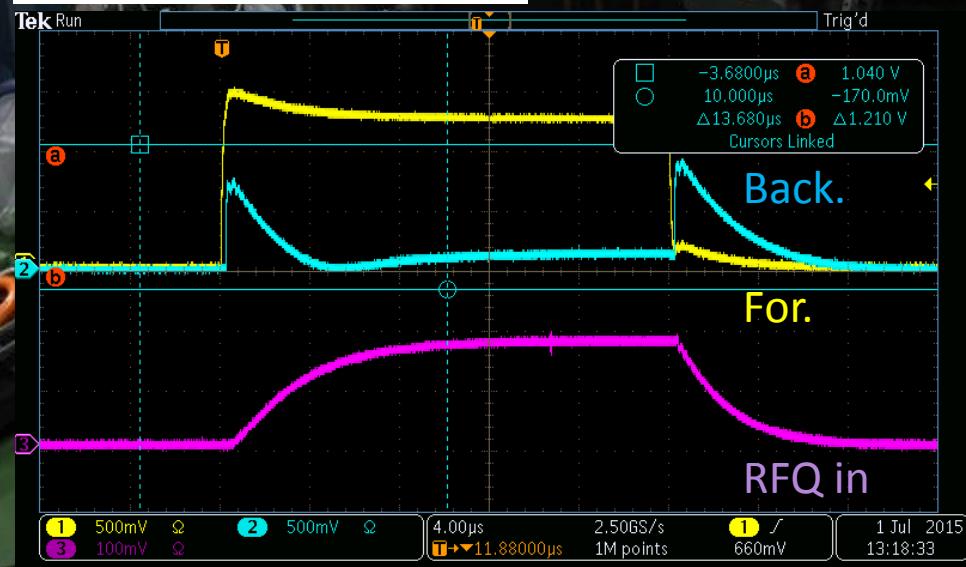
M. Otani, R. Kitamura, Y. Kondo, et al.



RFQ offline test at J-PARC



Data taken in July, 2015

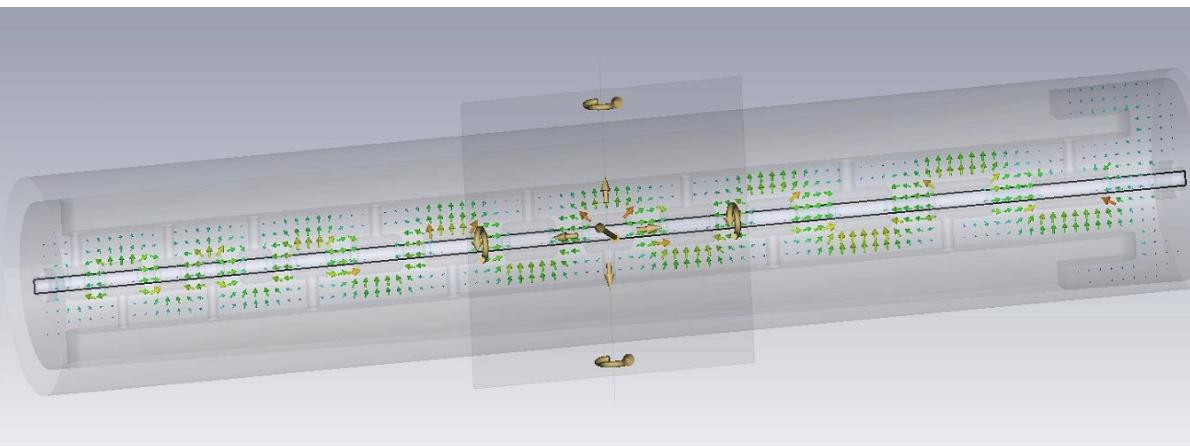


low- β section (IH)

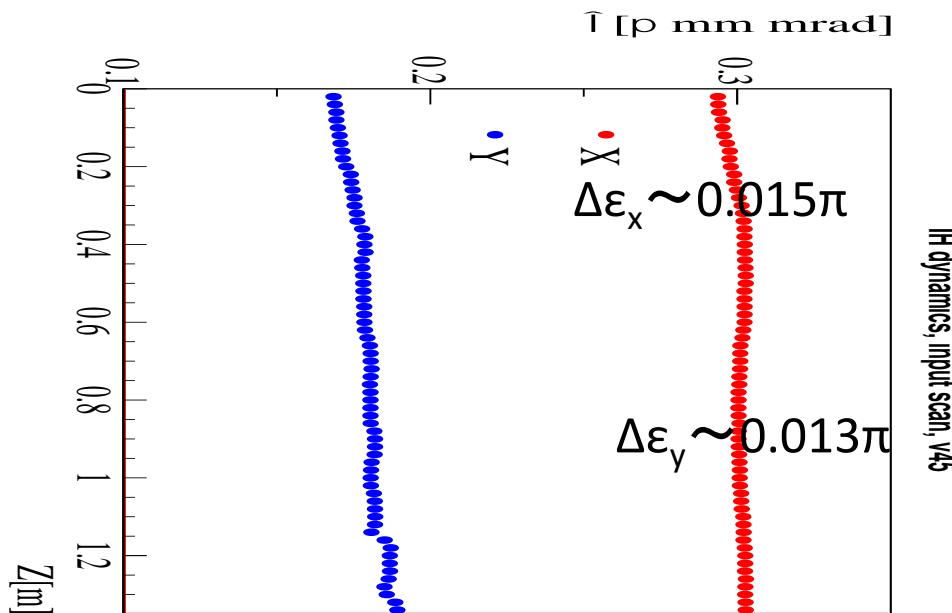
by M. Otani

Design and output parameters

Parameter	Value	Unit
Structure length*1	1.44	m
Input energy	0.34	MeV
β_{in}	0.0797	
Output energy	4.50	MeV
β_{out}	0.283	
Operation frequency	324	MHz
Accelerator cavity type	IH DTL	
Number of tanks	1	
Number of cells	16	



Simulated phase space distributions at the exit of IH



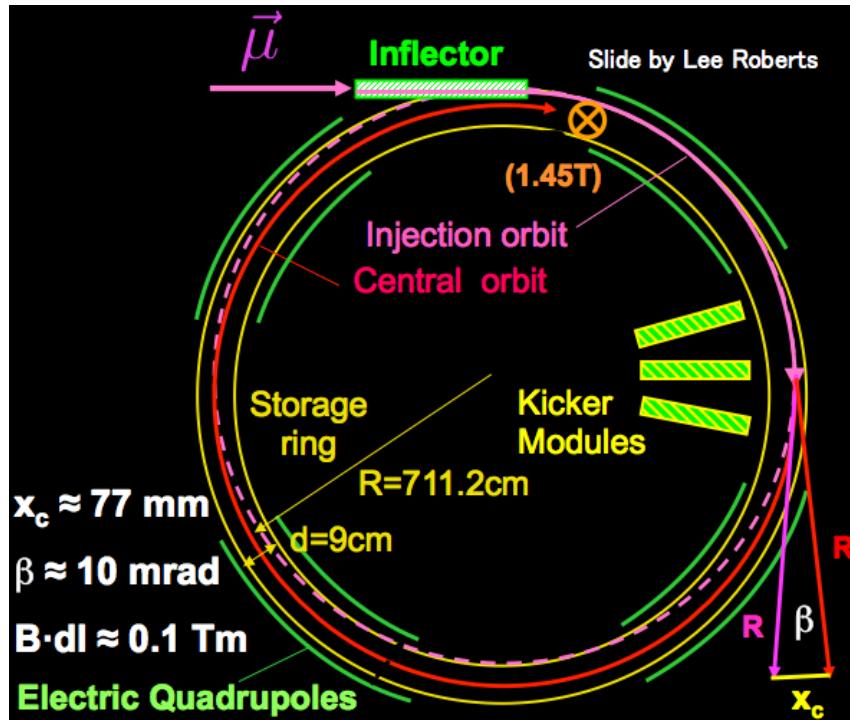
- After optimization, IH LINAC satisfies requirements for E34.
- Published in Phys. Rev. Accel. Beams 19, 040101 (2016) by M. Otani et al.



Muon beam injection and storage

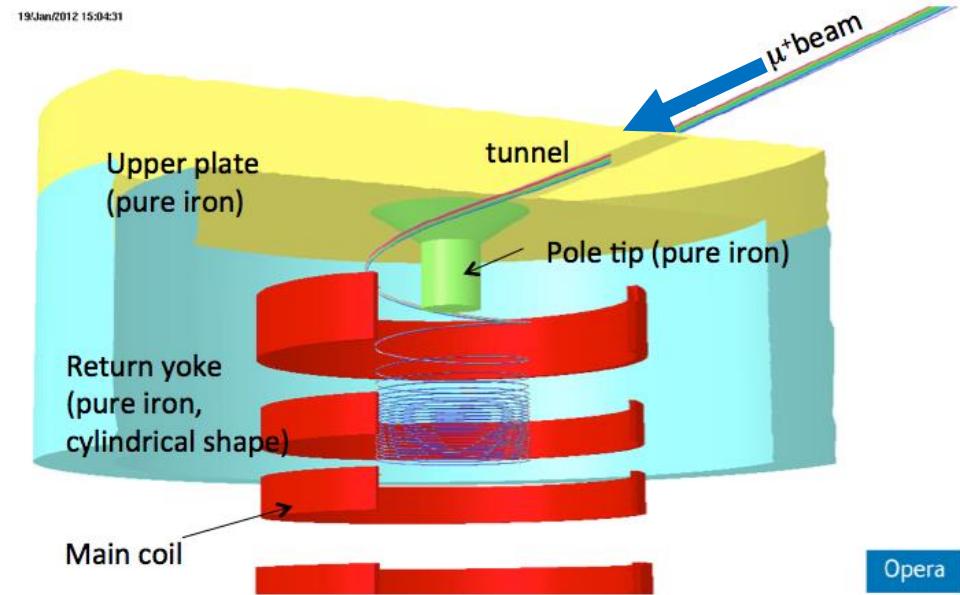
Horizontal injection + kicker
(BNL E821, FNAL E989)

3D spiral injection + kicker
(J-PARC E34)



Injection efficiency : 3-5%^(*)

(*) PRD73,072003 (2006)



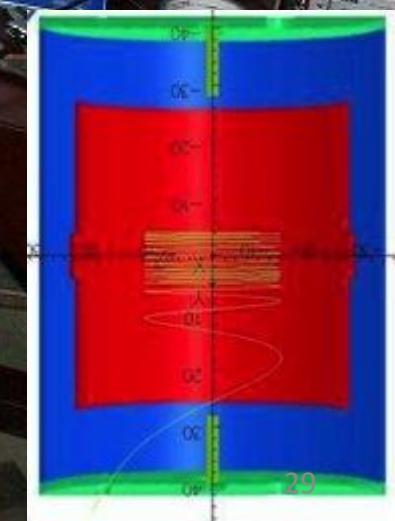
Injection efficiency : ~90%

A paper was submitted to NIMA in Oct 2015
by H. Iinuma et al.
28

Demonstration of spiral injection with low-E electron beam in Tsukuba

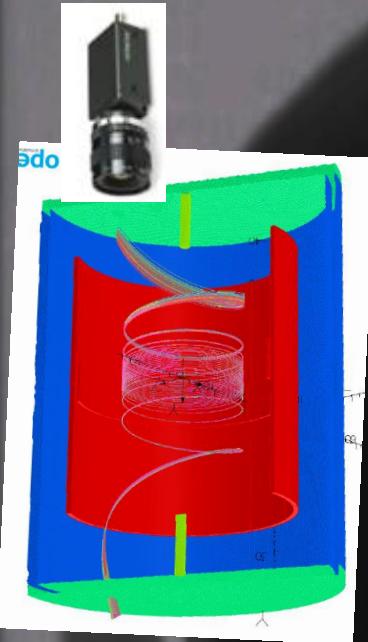
Electron gun
(112 keV/c)

Mini-solenoid
(102 G)

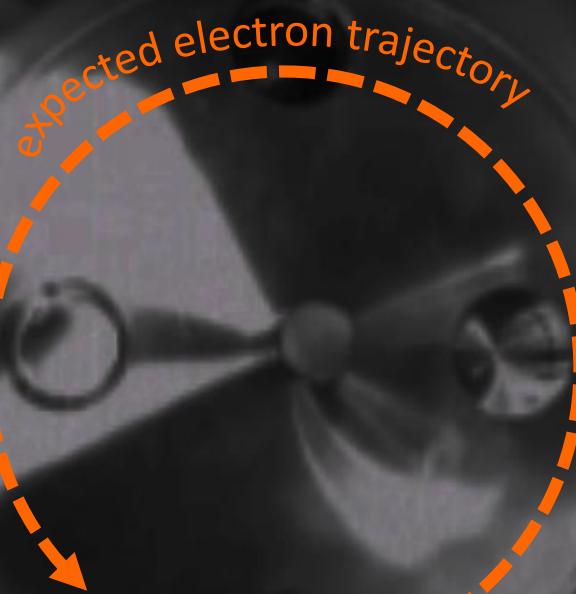


Inside view of the mini-solenoid (no beam)

Slide by H. Iinuma

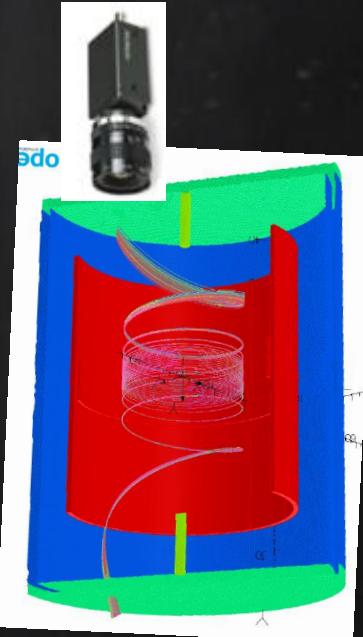


Beam
entrance



First observation of spiral track (nominal B-field)

Slide by H. Iinuma

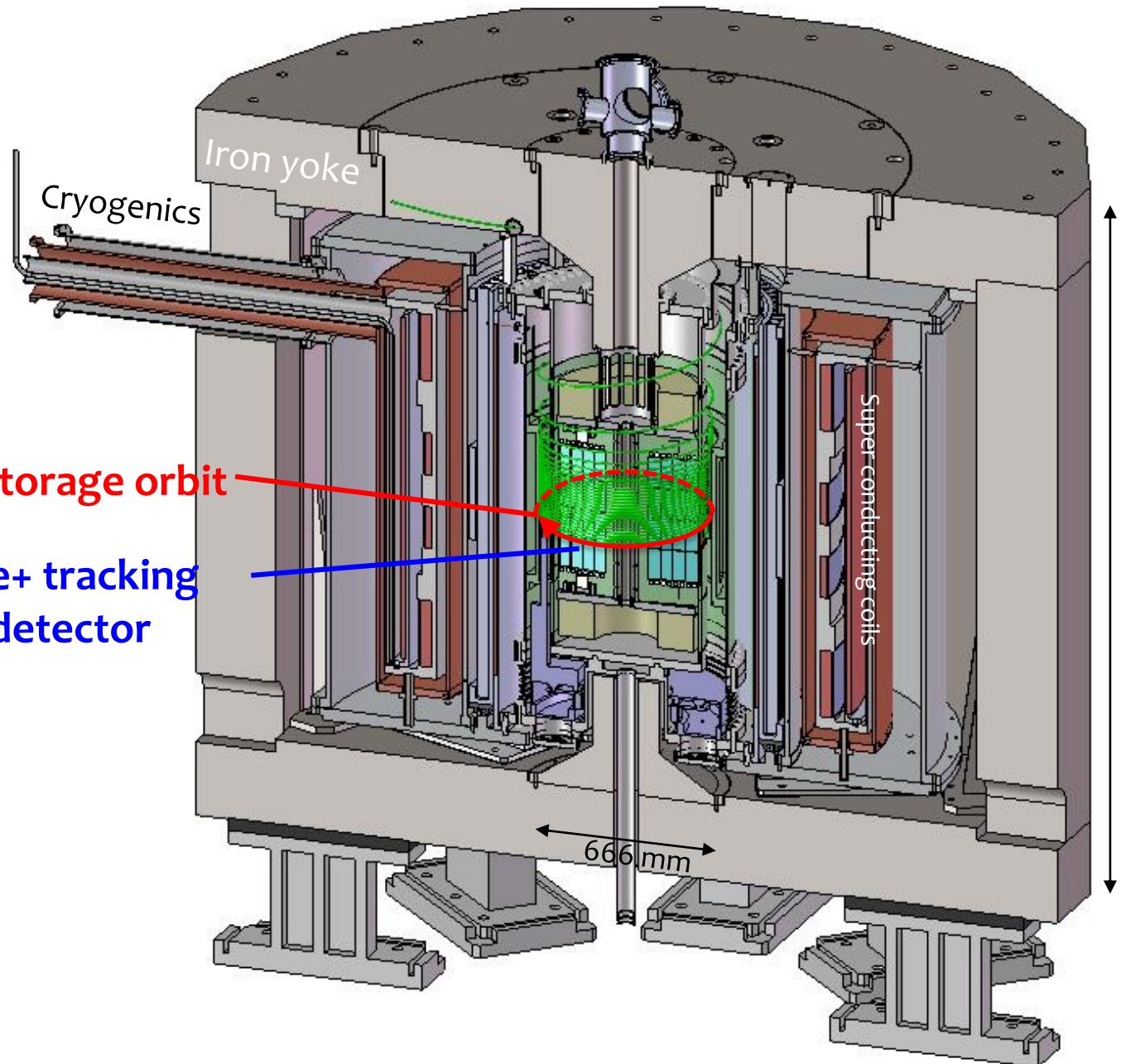


Beam
entrance

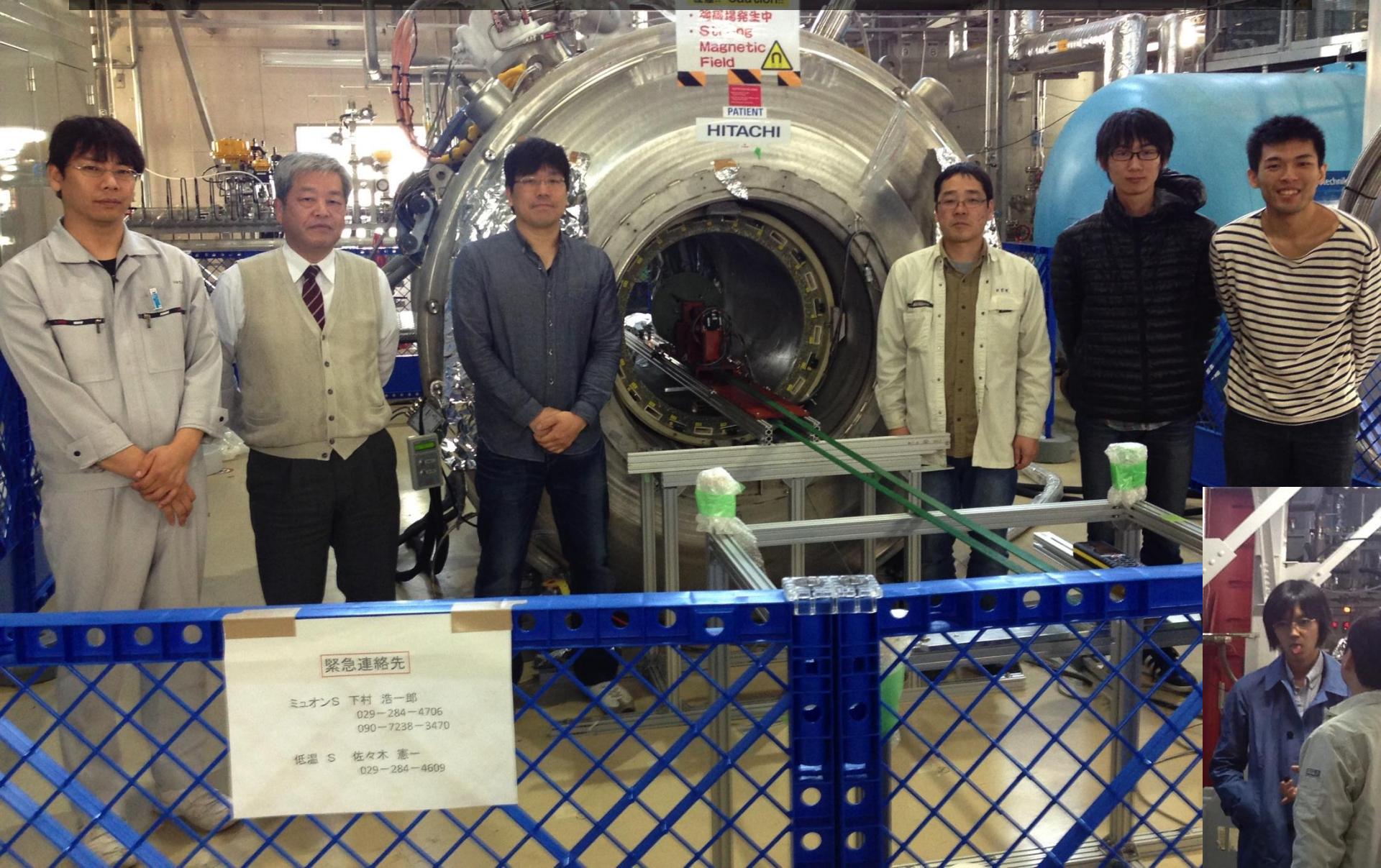
LIVE

300S*8

Muon storage magnet and detector

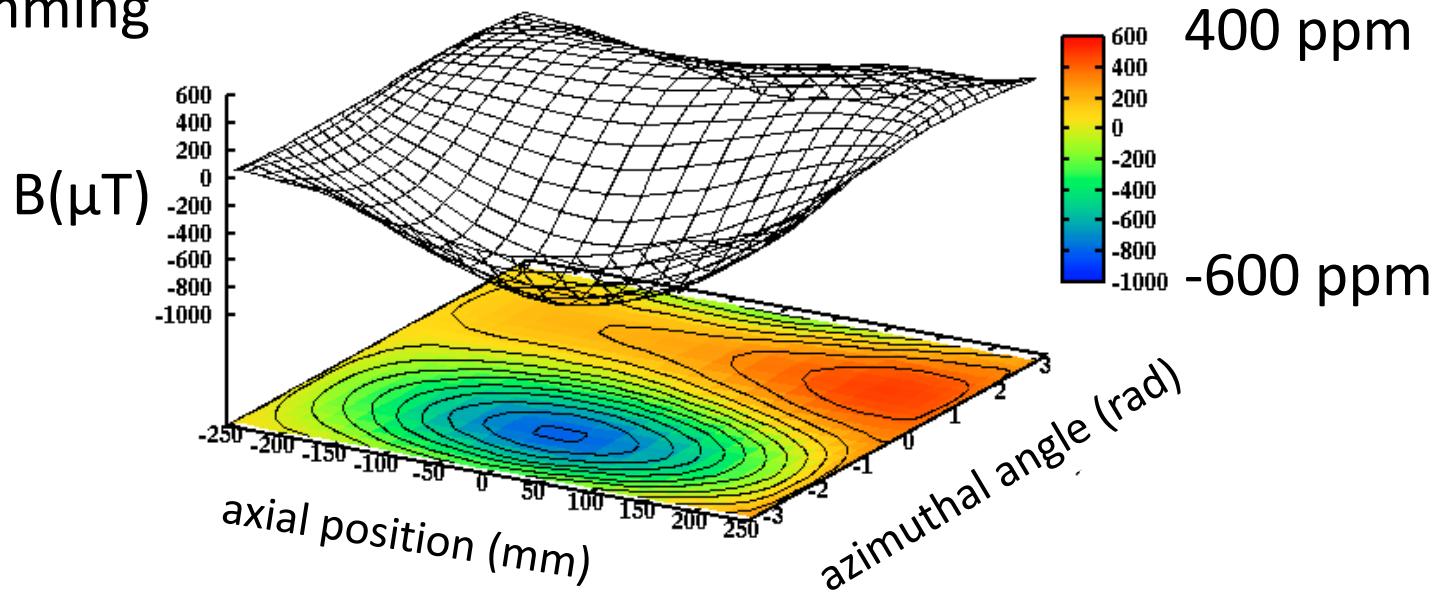


B-field shimming test with the MuSEUM magnet (1.7 T) at J-PARC

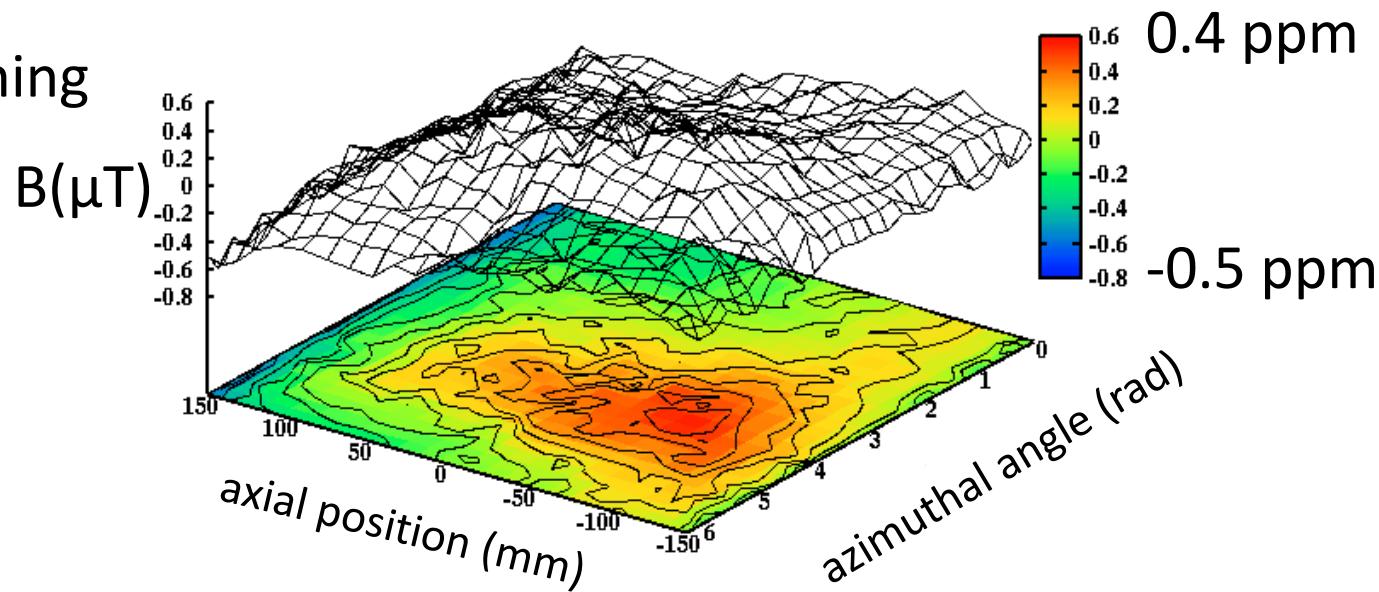


Field shimming by iron arrays

Before shimming

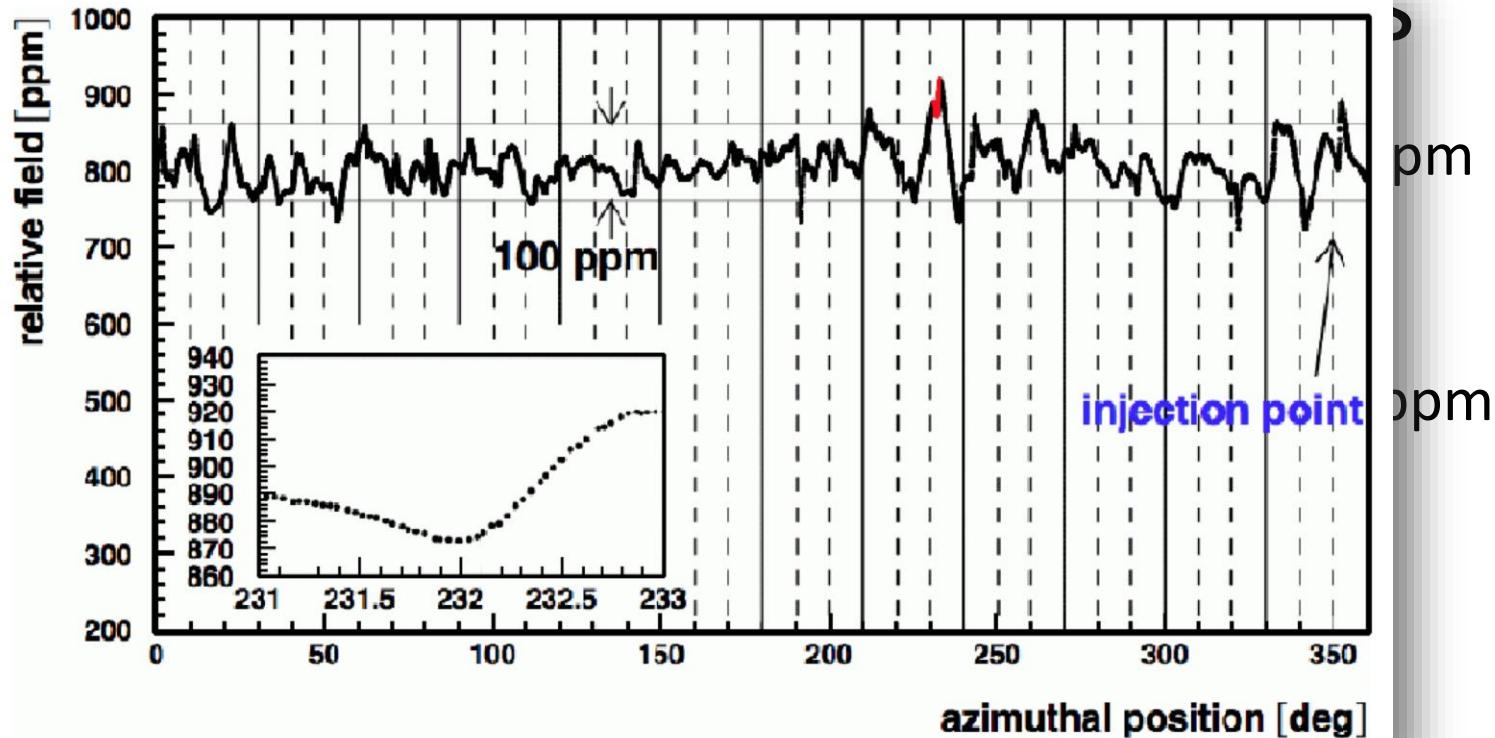


After shimming

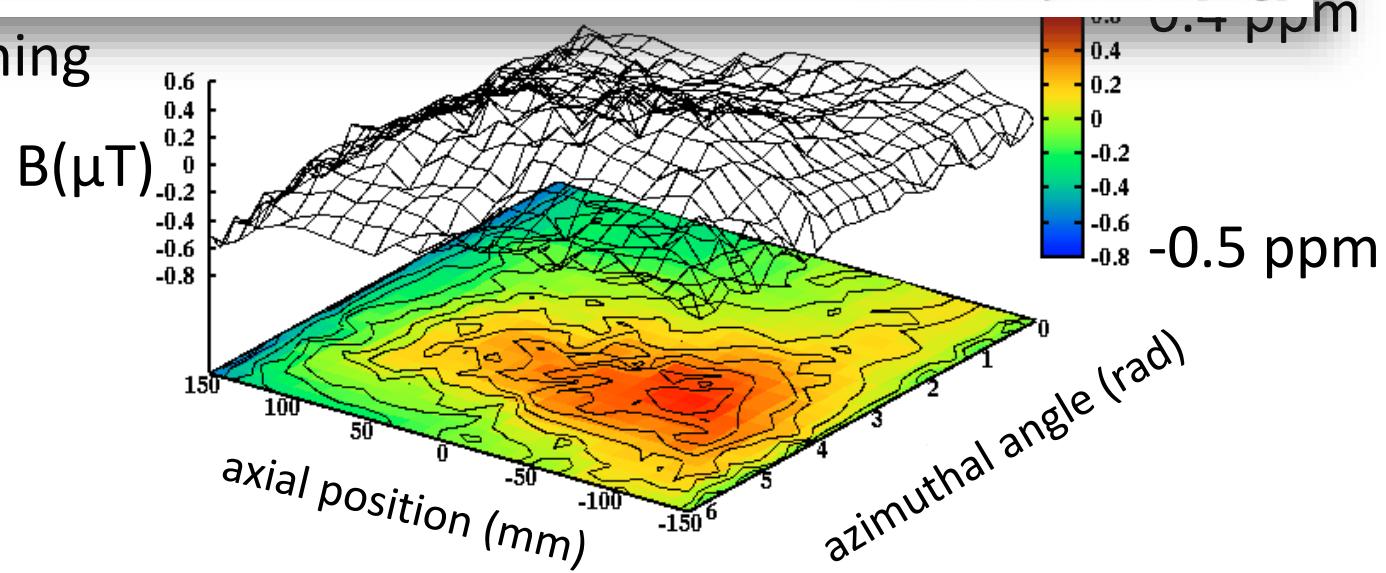


$r = 140 \text{ mm}$

Before shimming



After shimming

 $r = 140 \text{ mm}$

Comparison of NMR probes

See D. Flay's talk

Ken'ich Sasaki
(KEK)



Peter Winter
(ANL)



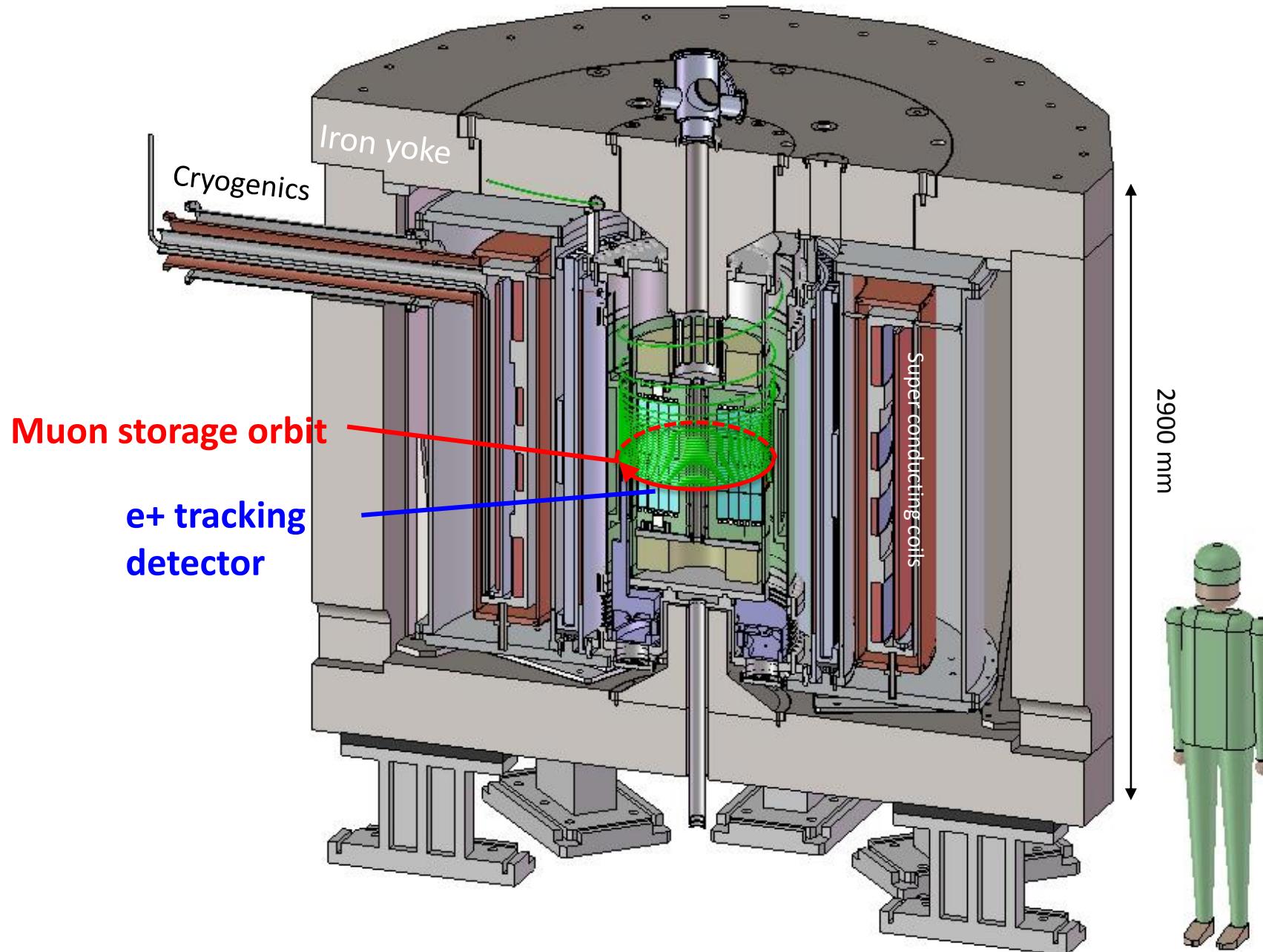
Koichiro Shimomura
(KEK)



The magnet is up and running at 1.45T.
Absolute calibration probes was tested with the same B-field.
Comparison between Pulsed-NMR (UMass) and CW-NMR (KEK).

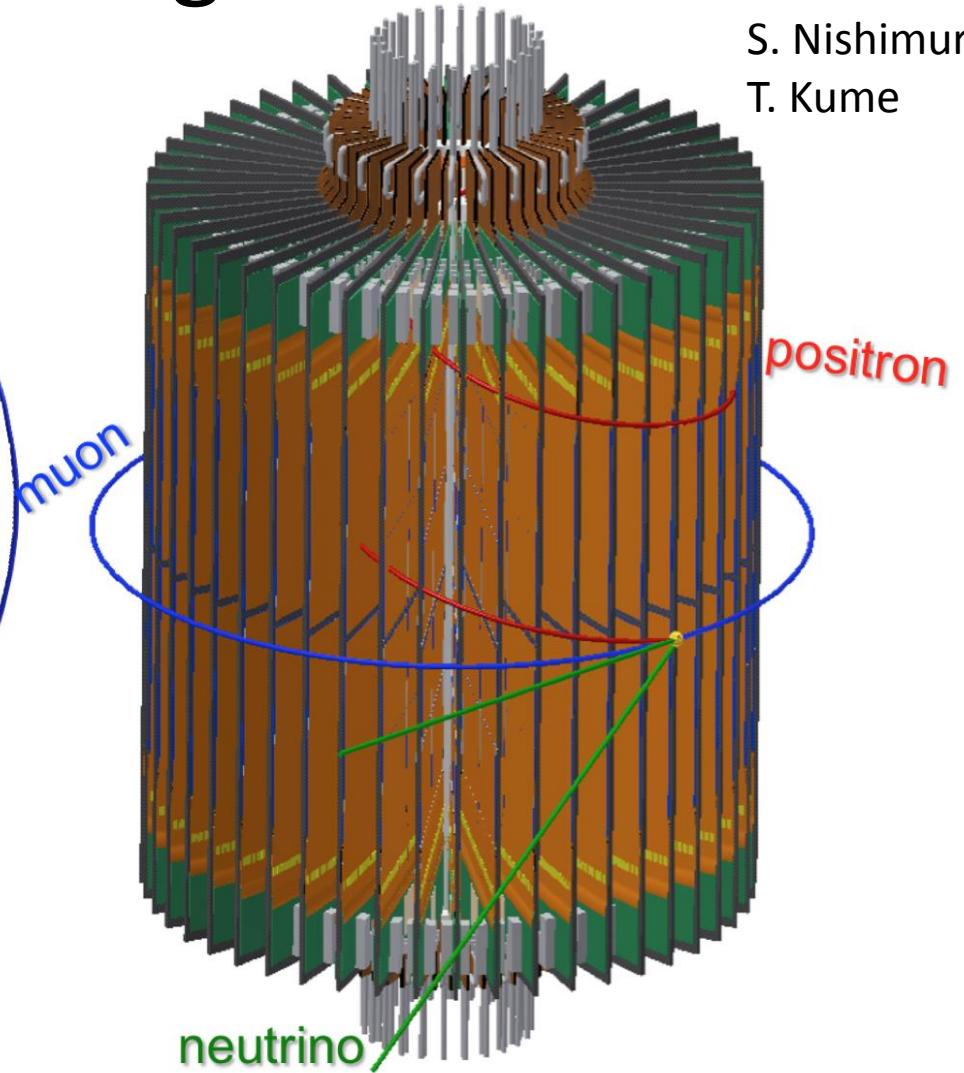
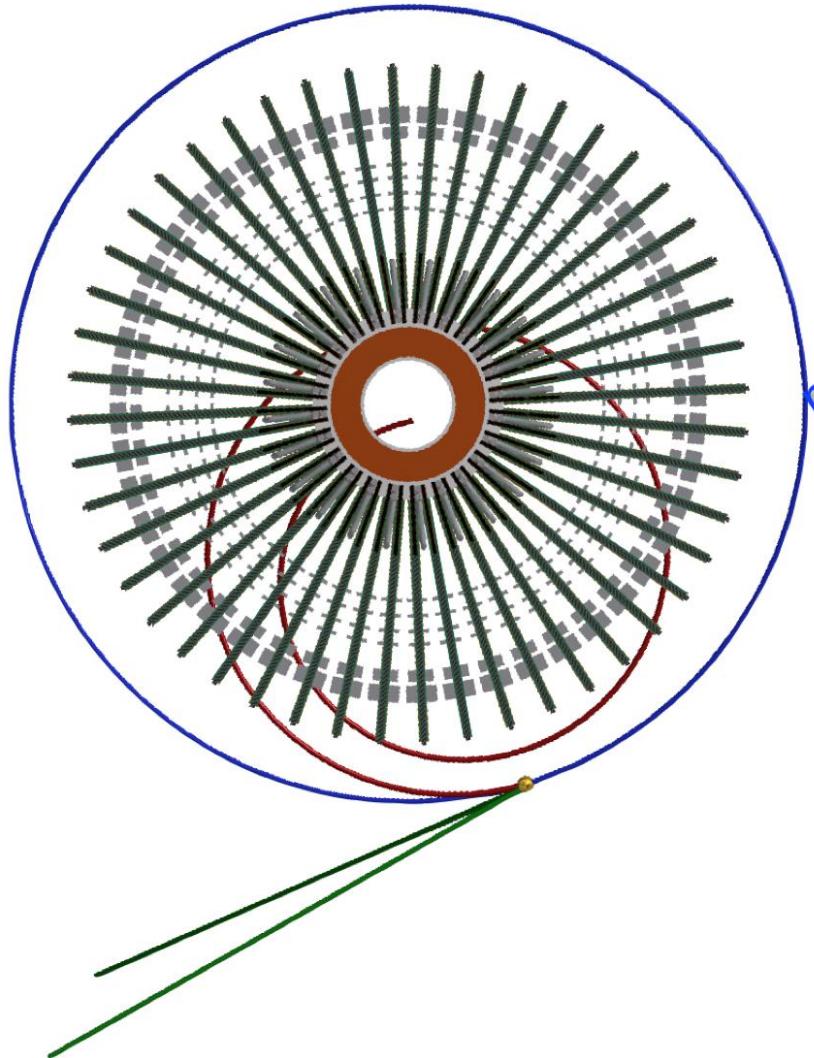
Photo by T. Mibe

Muon storage magnet and detector



Positron tracking detector

S. Nishimura
T. Kume



A typical simulated event of muon decay

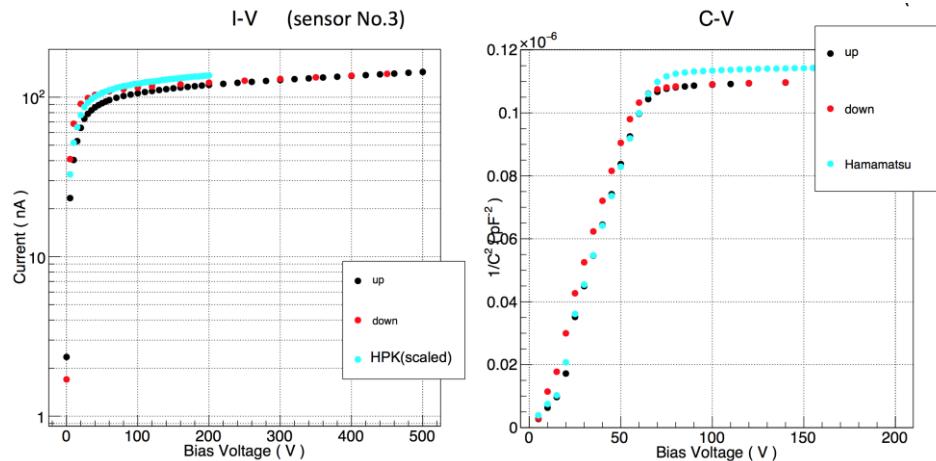
Detector components

Silicon strip sensor

(100 x 100 mm², 190um pitch, 1024ch)

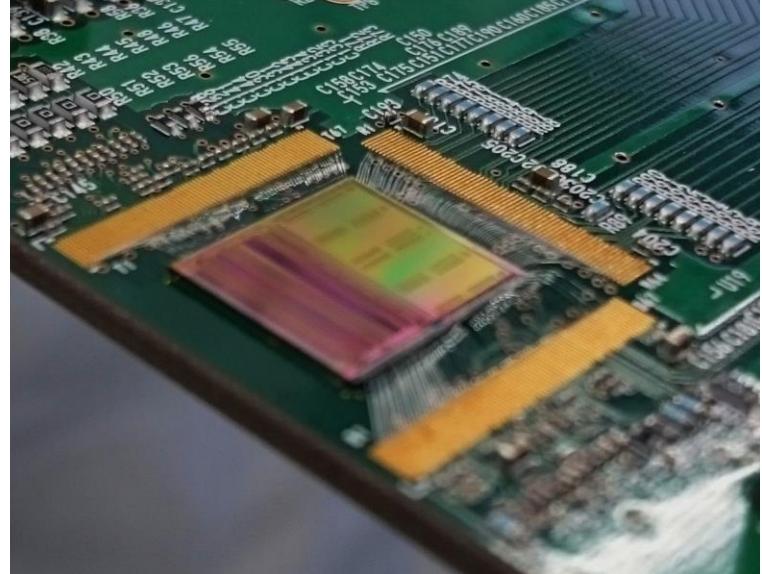


Evaluated by S. Nishimura



Front end ASIC

(Slit128A, Silterra CMOS 0.18um)



Evaluated by Y. Sato, M. Matama

Parameter	Requirement	Slit128A
		Result
S/N	>15	56
Gain	> 19 mV/fC	49.5 mV/fC
ENC	< 1600 e	n.a.
Dynamic range	~ 3MIP	~5 MIP
Pulse width (1 MIP)	< 100 ns	155 ns
Time walk (0.5 MIP → 3MIP)	< 5 ns	11.5 ns
Power consumption	0.64 W/chip	0.44 W/chip

Projected statistical sensitivity

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

Already good enough to test BNL E821 results.

Towards high precision muon g-2/EDM measurement at J-PARC

HOME

REGISTRATION

PROGRAM

VISITOR INFO

J-PARC, Tokai, Japan
November 28-29, 2016

ABOUT THIS WORKSHOP

The J-PARC [E34 experiment](#) is under active development and construction of its experimental equipments for a precise measurement of muon g-2/EDM. The experiment introduces a set of innovative ideas to reach the required precision to test the Standard Model and will provide a complementary measurement to the conventional storage ring experiments. Theoretical calculations to achieve the matched precision for the Standard Model prediction have been developing rapidly, including those of QED, phenomenological estimates of quark-loop contributions, and lattice QCD calculations.

The workshop aims at summarizing the most updated results from both theoretical and experimental sides, and setting the targets for the next years.

CONFIRMED INVITED SPEAKERS

- Johan Bijnens (Lund)
 - Thomas Blum (Connecticut)
 - Gilberto Colangelo (Bern)
 - Achim Denig (Mainz)
 - Maarten Goltermann (SFSU)
 - Masashi Hayakawa (Nagoya)
 - Christoph Lehner (BNL)
 - Makiko Nio (RIKEN)
 - Daisuke Nomura (Takamatsu)
 - Antonin Portelli (Edinburgh)
 - Dominik Stockinger (Dresden)
- (in alphabetic order)

ORGANIZERS

- Shoji Hashimoto (IPNS/KEK)
- Taku Izubuchi (RBRC)
- Tsutomu Mibe (IPNS/KEK)

Summary

- We aim to measure muon g-2 and EDM with **ultra-cold muon beam** at J-PARC.
 - Complementary approach
- A **technical design report** has developed.
 - Beyond BNL precision on both g-2 and EDM
- Approved as **one of priority projects in the future** by KEK.
- **R&D → Construction**
 - Construction funding is partially available.
- **Further information**
 - collaboration web page: g-2.kek.jp