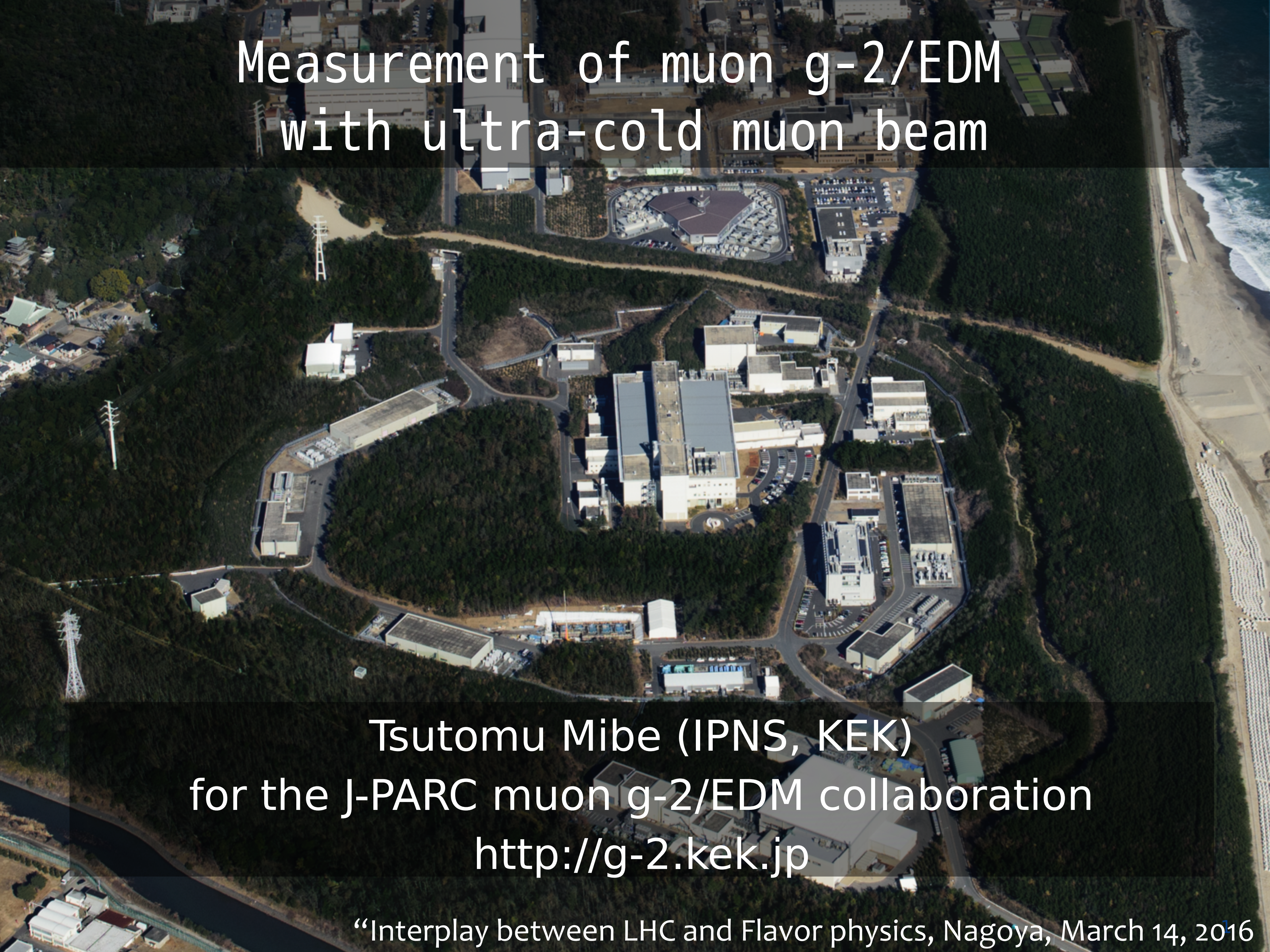
Towards a measurement of muon g-2/EDM at J-PARC

Frédéric Kapusta
LPNHE Paris

On behalf of Tsutomu Mibe



Measurement of muon g-2/EDM with ultra-cold muon beam

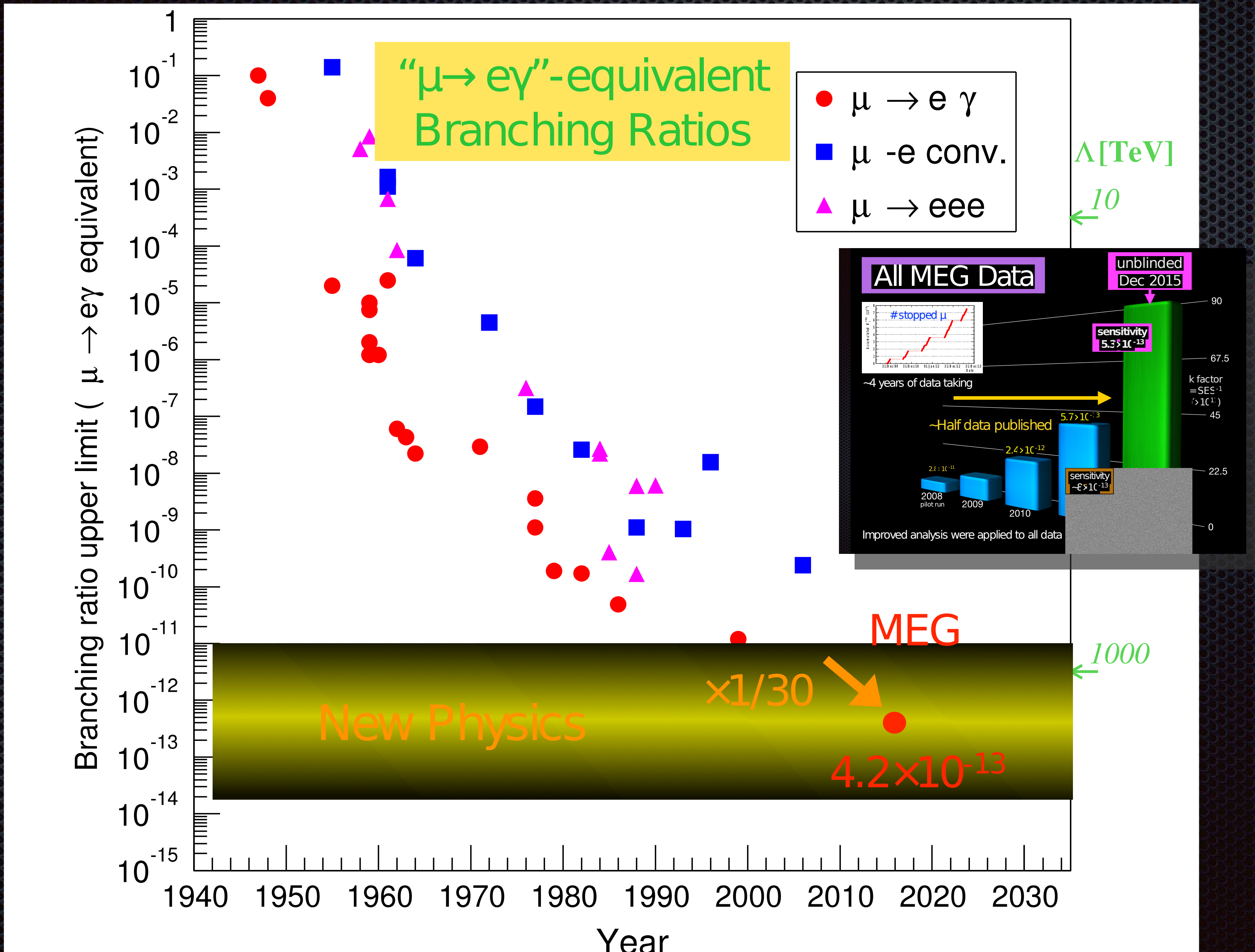
Tsutomu Mibe (IPNS, KEK)
for the J-PARC muon g-2/EDM collaboration

http://g-2.kek.jp

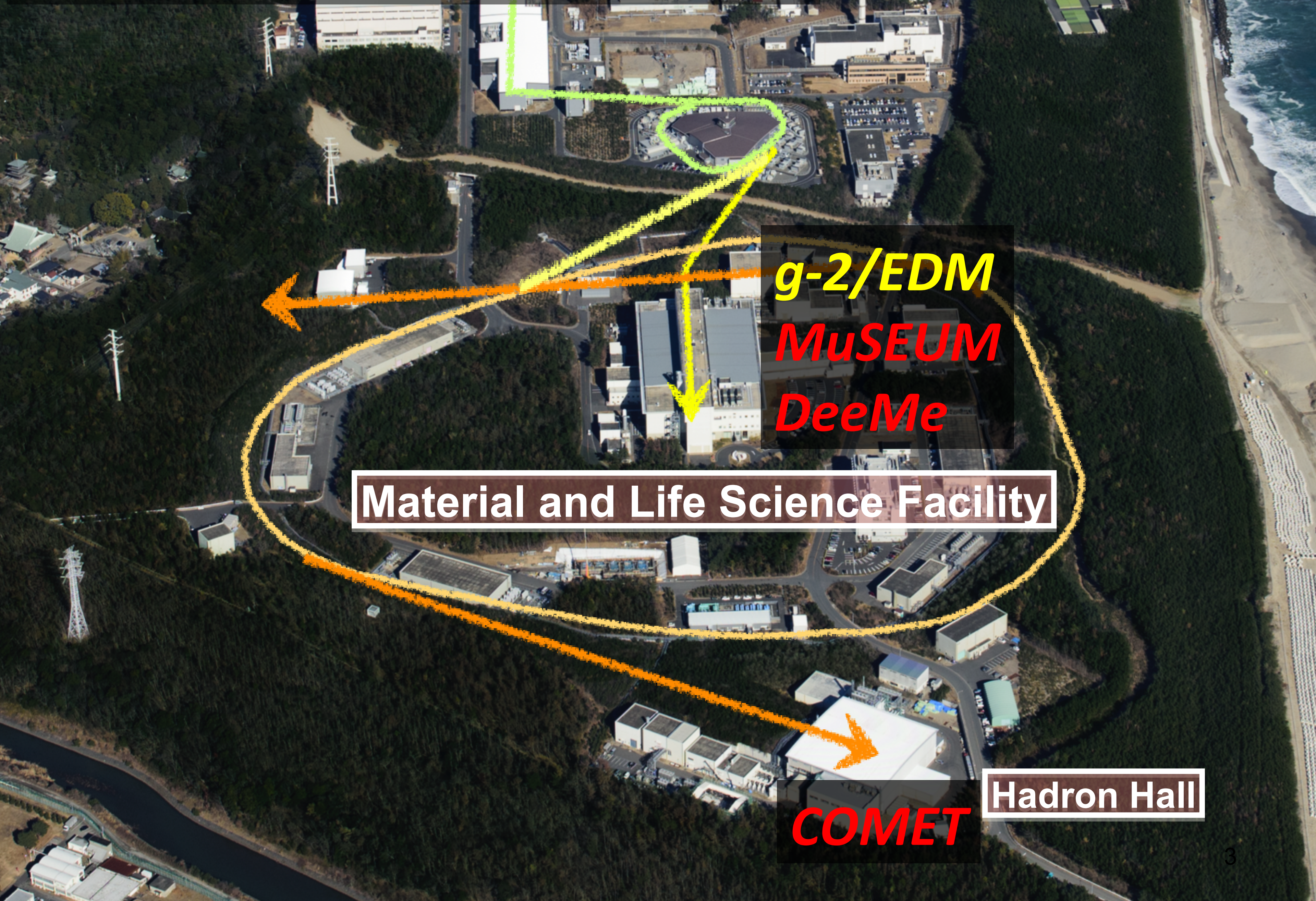
“Interplay between LHC and Flavor physics, Nagoya, March 14, 2016

Final MEG Result:

Slide by T. Mori
(La Thuile, Mar 8, 2016)

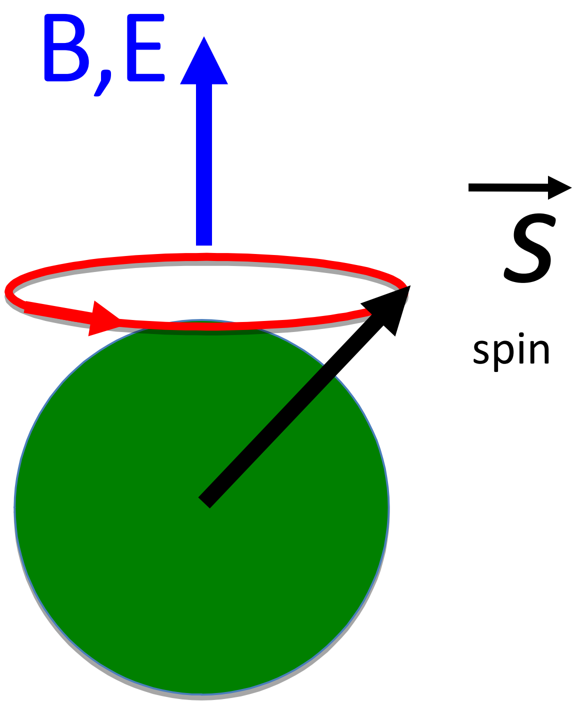


Muon experiments at J-PARC



Particle dipole moments

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



Magnetic Dipole Moment

$$\vec{\mu} = g \left(\frac{q}{2m} \right) \vec{s}$$

CP even

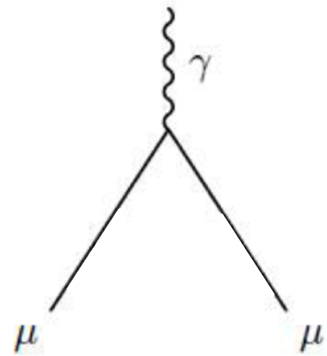
Electric Dipole Moment

$$\vec{d} = \eta \left(\frac{q}{2mc} \right) \vec{s}$$

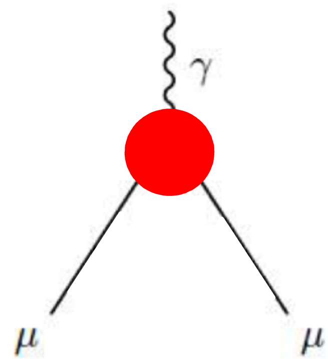
CP odd

Anomalous magnetic moment

- The Lande's *g* factor is 2 in tree level (Dirac equation)



- In quantum field theory, *g* factor gets corrections:



Anomalous magnetic moment

$$g = 2\,(\,1 + a_{\mu})$$

Anomalous magnetic moment

$$a_\mu = a_\mu(QED) + a_\mu(had) + a_\mu(weak) + a_\mu(BSM)$$

All interactions, *including ones we don't know*, appear in quantum loops, and add up to contribute a_μ

Comparison with experiments

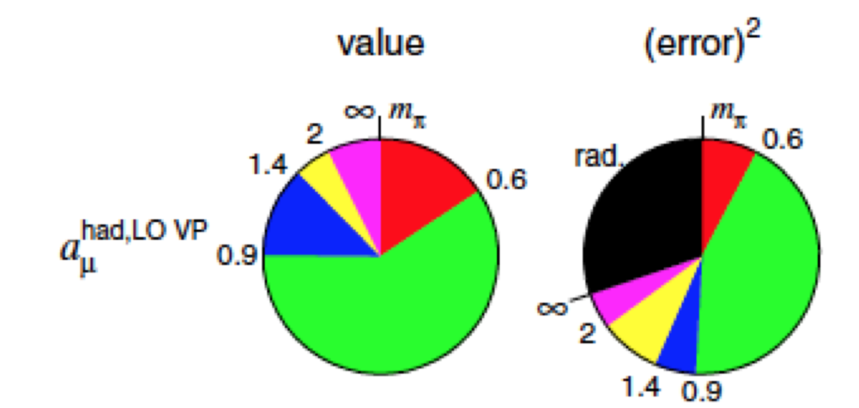
D. Nomura (tau2012)

QED contribution	$11\ 658\ 471.808\ (0.015) \times 10^{-10}$	Kinoshita & Nio, Aoyama et al
EW contribution	$15.4\ (0.2) \times 10^{-10}$	Czarnecki et al
Hadronic contribution		
LO hadronic	$\mathbf{694.9\ (4.3)} \times 10^{-10}$	HLMNT11
NLO hadronic	$-9.8\ (0.1) \times 10^{-10}$	HLMNT11
light-by-light	$10.5\ (2.6) \times 10^{-10}$	Prades, de Rafael & Vainshtein
Theory TOTAL	$\mathbf{11\ 659\ 182.8\ (4.9)} \times 10^{-10}$	
Experiment	$\mathbf{11\ 659\ 208.9\ (6.3)} \times 10^{-10}$	world avg ~ **BNL E821 (0.5ppm)**
Exp − Theory	$\mathbf{26.1\ (8.0)} \times 10^{-10}$	**3.3 σ discrepancy**

(HLMNT11 LO and NLO: in consistent with DHMZ10)

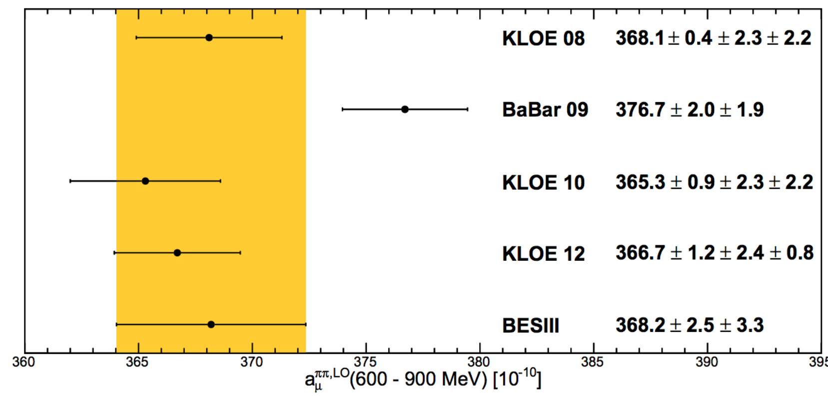
HLMNT11 : J.Phys.G38:085003,2011

Critical inputs : $e^+e^- \rightarrow \pi^+\pi^-$ cross section



Hagiwara et al., J. Phys. G: Nucl. Part. Phys. 38 (2011) 085003

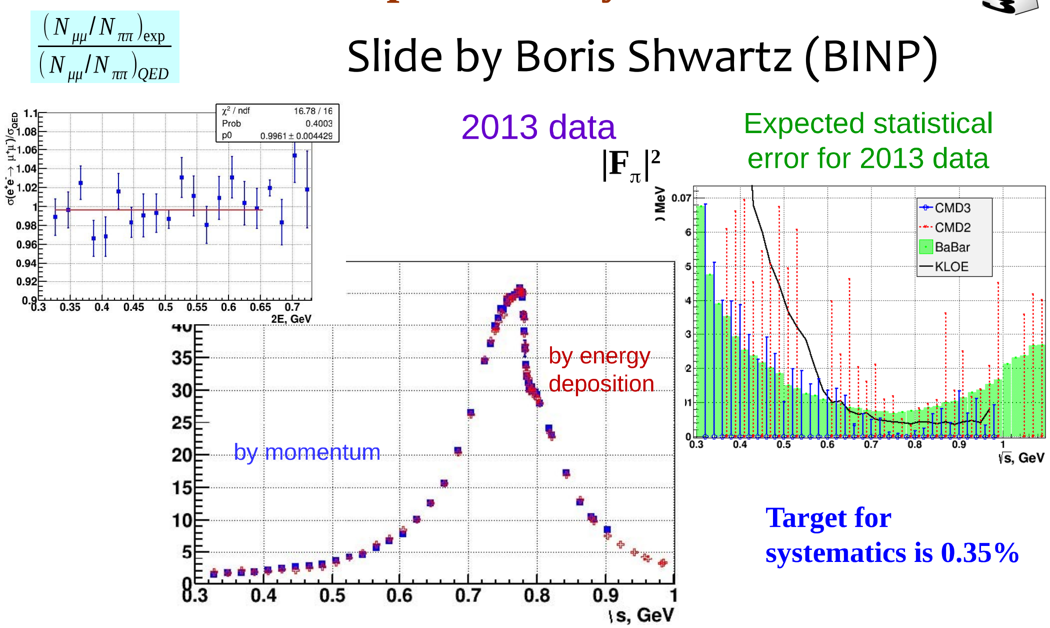
1507.08188v3



- Dominant uncertainty on a_μ (had,LO) comes from uncer tainty (inconsistency) on e+ e- data.
- Data from Belle-II in the fut ure is critical to improve th e situation.

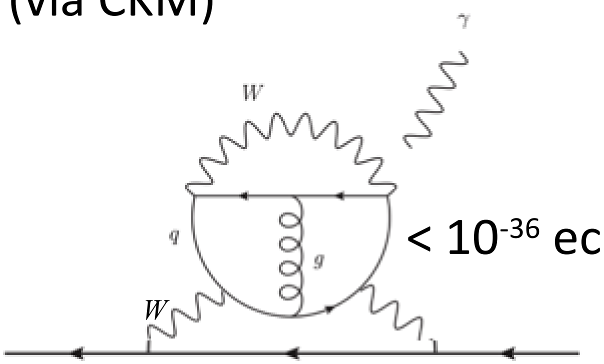
$e^+e^- \rightarrow \pi^+\pi^-$: preliminary results

Slide by Boris Shwartz (BINP)



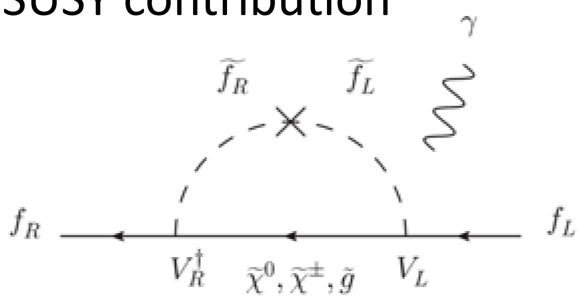
muon EDM

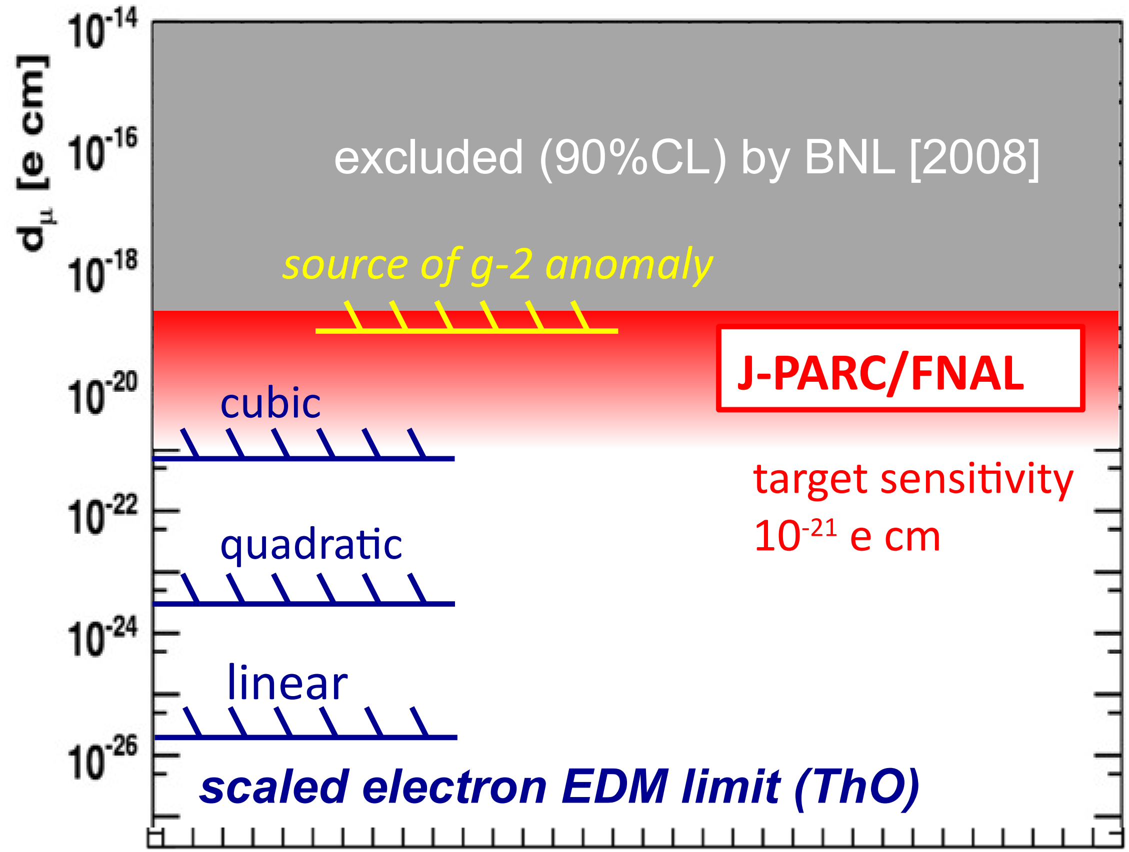
SM allowed diagram
(via CKM)



< 10^{-36} ecm

SUSY contribution



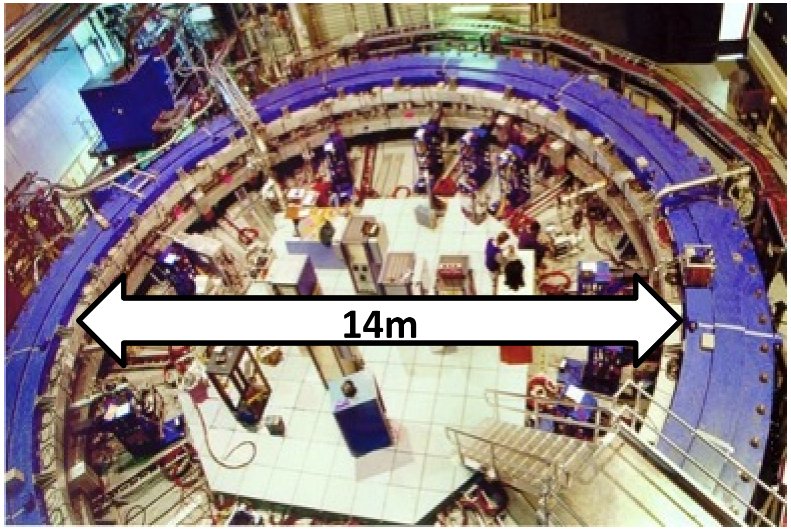


T. Fukuyama, Int.J.Mod.Phys. A27 (2012) 1230015

Why g-2 and EDM with new method?

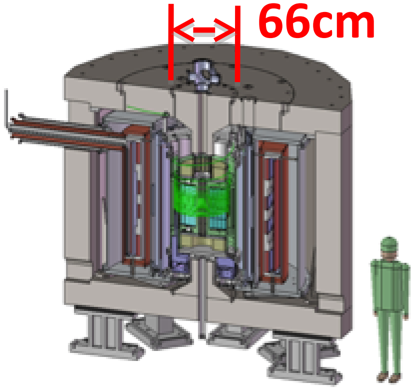
- **BNL E821**
  - a_μ = 11 659 208.9 (6.3) x 10^{-10}
    - 0.46ppm (stat.) + 0.28ppm (syst.) = 0.54ppm
    - **3σ deviation from SM**
    - **→Stat. dominant**
- **FNAL E989**
  - Recycle major parts of the muon storage rin g.
  - **Will become online in 2017-**
- **J-PARC E34 (new method)**
  - **Ultra-cold muon beam + Compact storage rin g + Spin flip**
  - **An independent measurement of muon g-2**

BNL E821 / FNAL E989



P= 3.1 GeV/c , B=1.45 T

J-PARC E34



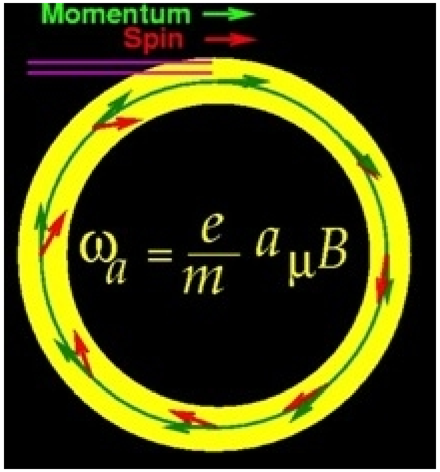
P= 0.3 GeV/c , B=3.0 T

Major systematic uncertainties

Source		**BNL (ppm)**	**FNAL goal (ppm)**
Gain changes	π contamination in beam	0.12	0.02
Lost muons	Beam spread> ring acceptance	0.09	0.02
Pile up	Detector pile up	0.08	0.04
CBO	Beam betatron frequency ~ spin precession frequency	0.07	0.04
E and pitch	Vertical Beam angular dist.	0.05	0.03
Total		**0.18**	**0.07**

Next-generation experiment must improve **beam quality.**
→ulta-cold muon beam

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:

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

BNL E821 approach
γ=30 (P=3 GeV/c)

J-PARC approach
E = 0 at any γ

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

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

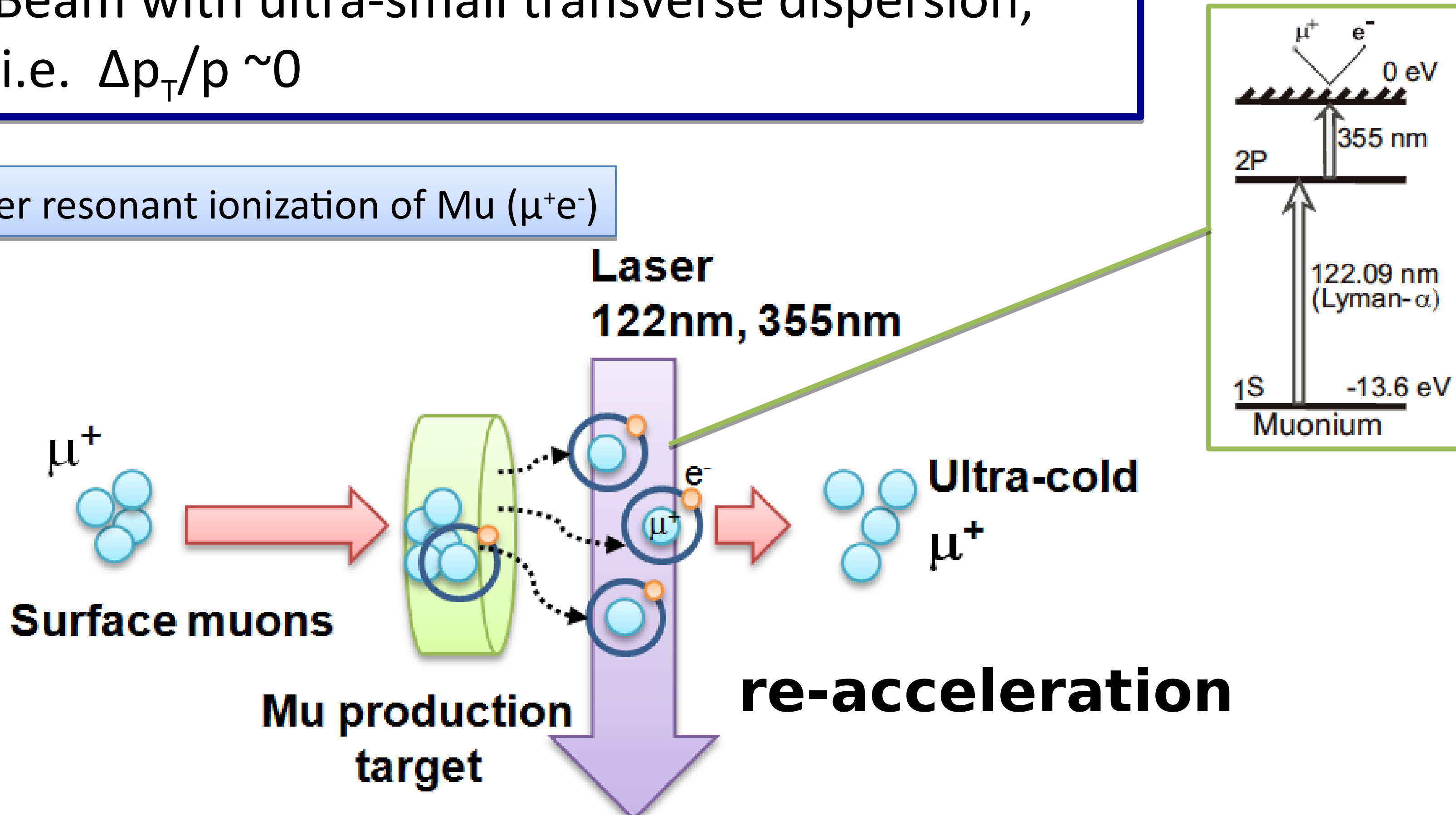
Ultra-cold Muon

<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 (μ^+e^-)



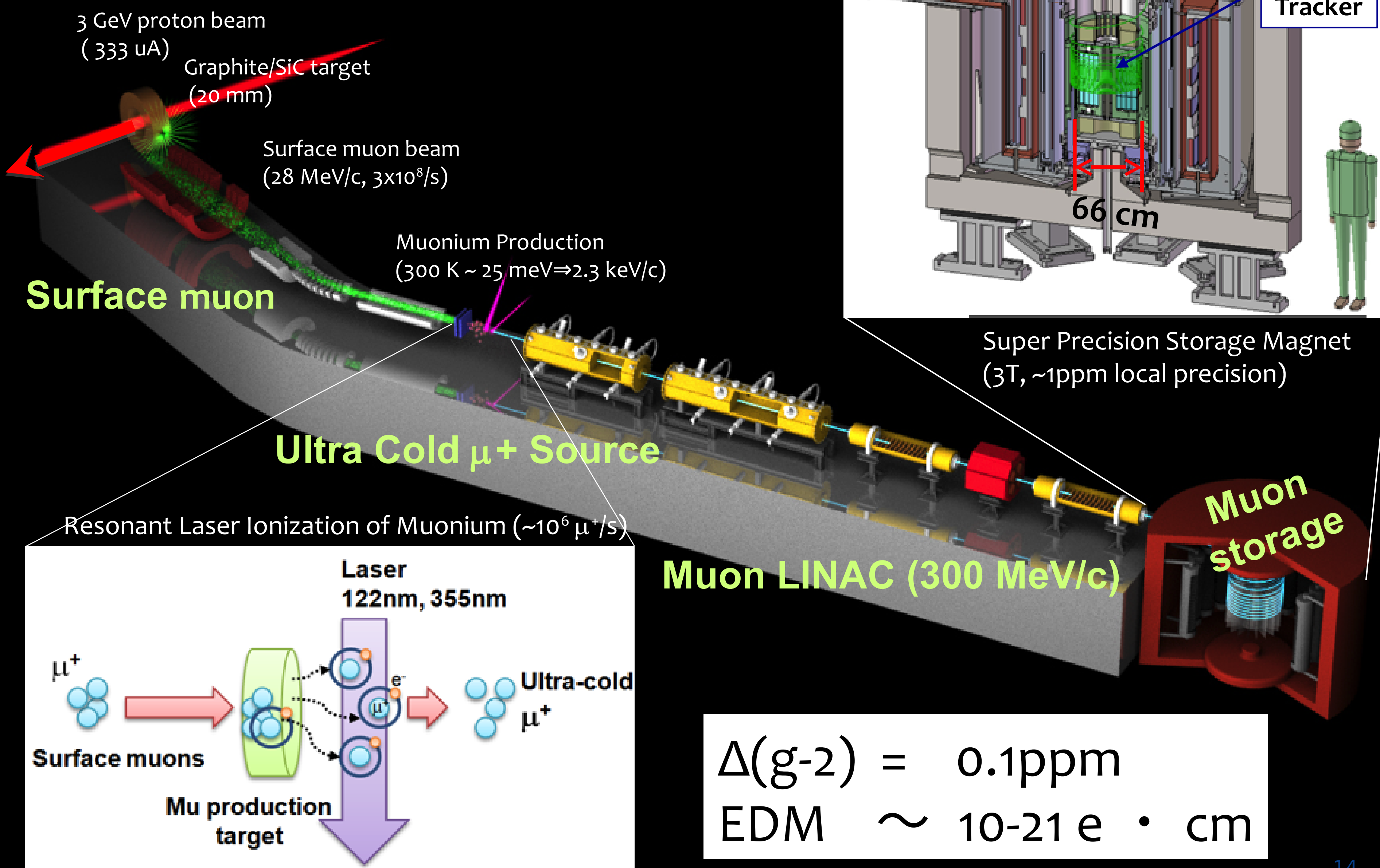
p = 28MeV/c

3 keV/c

300 MeV/c

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

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



Δ(g-2) = 0.1ppm

EDM ～ 10-21 e · cm

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 $1.3 \times 10^{-21} e \cdot \mathrm{cm}$, during an acquisition time of 2×10^7 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 x 10^{-19} ecm	→	1.3 x 10^{-21} ecm

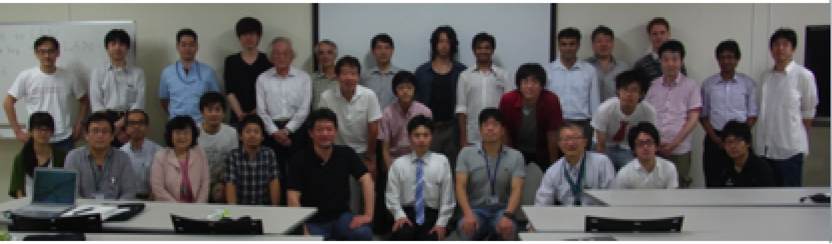
Comparison of experiments

	BNL E821	J-Parc E34
	-----------	----------
muon momentum	3.09 GeV/c	0.3 GeV/c
storage ring radius	7 m	33 cm
storage field	1.5 T	3 T
local field uniformity	50-200 ppm	1 ppm
injection	inflector/kick	spiral/kick
injection efficiency	3-5%	90%
storage focus	E (magic γ)	very weak B
muon spin reversals	not possible	pulse-to-pulse
positron measurement	calorimeters	tracking (p)
positron acceptance	65%	100%
muon polarization	100%	50%
events to 0.14 ppm	2 x 10^11	2 x 10^12 (P=1)
events to 0.46 ppm	9 x 10^9	5 x 10^11

E34 collaborators

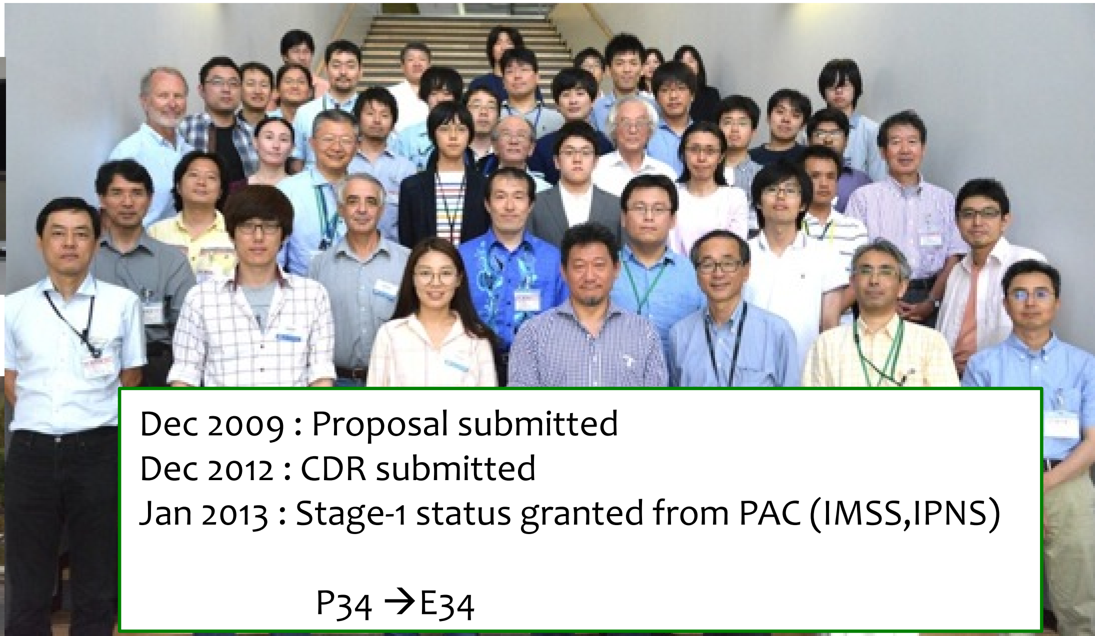
* **Collaborators**
  * Proposal (2009) 72
  * Conceptual Design Report (2011) 92
  * Technical Design Report (2015) 136 (16 graduate students) (27 also in COMET)
* **9 countries, 49 institutions**
  * Canada, China, Czech, France, Japan, Korea, Russia, UK, USA (in alphabetical order)

J-PARC 2014.9



KAIST (Korea) 2014.11

J-PARC 2015.6

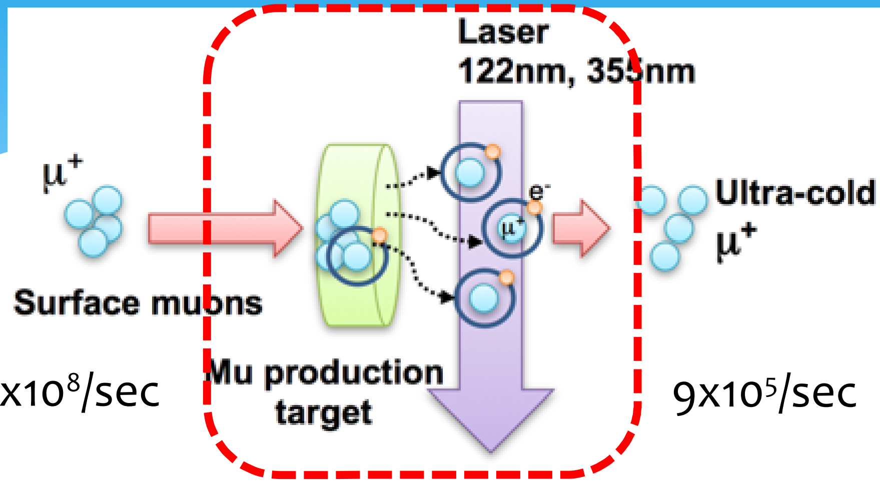


Dec 2009 : Proposal submitted
Dec 2012 : CDR submitted
Jan 2013 : Stage-1 status granted from PAC (IMSS,IPNS)

P34 → E34

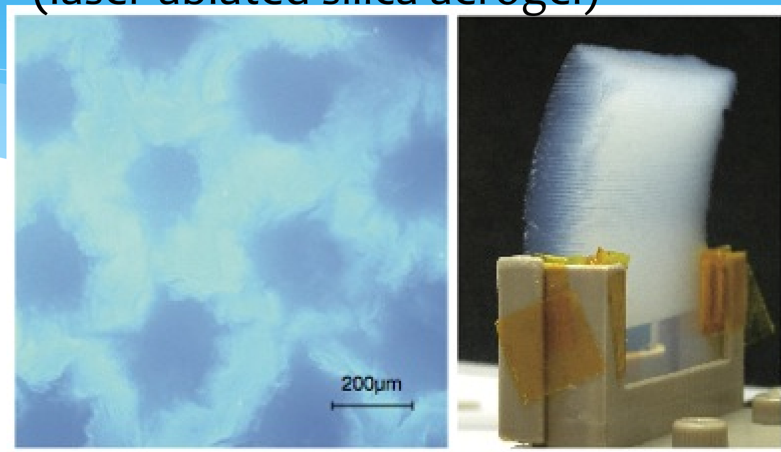
Muonium production

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

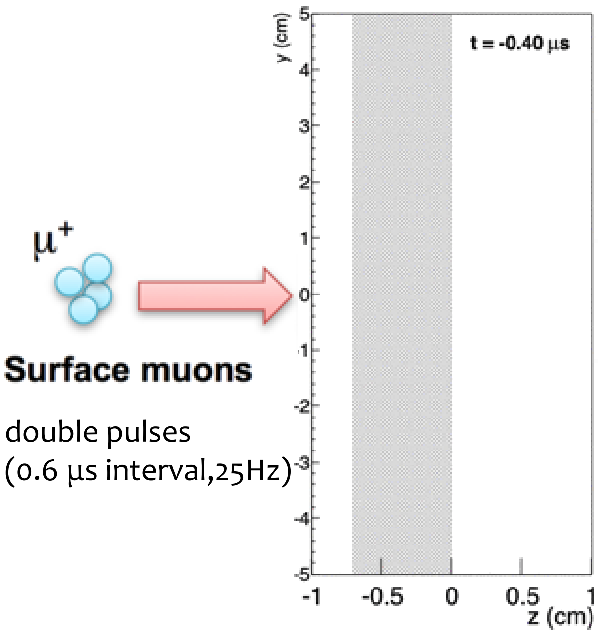


3x10^8/sec   9x10^5/sec

Mu production target
(laser-ablated silica aerogel)

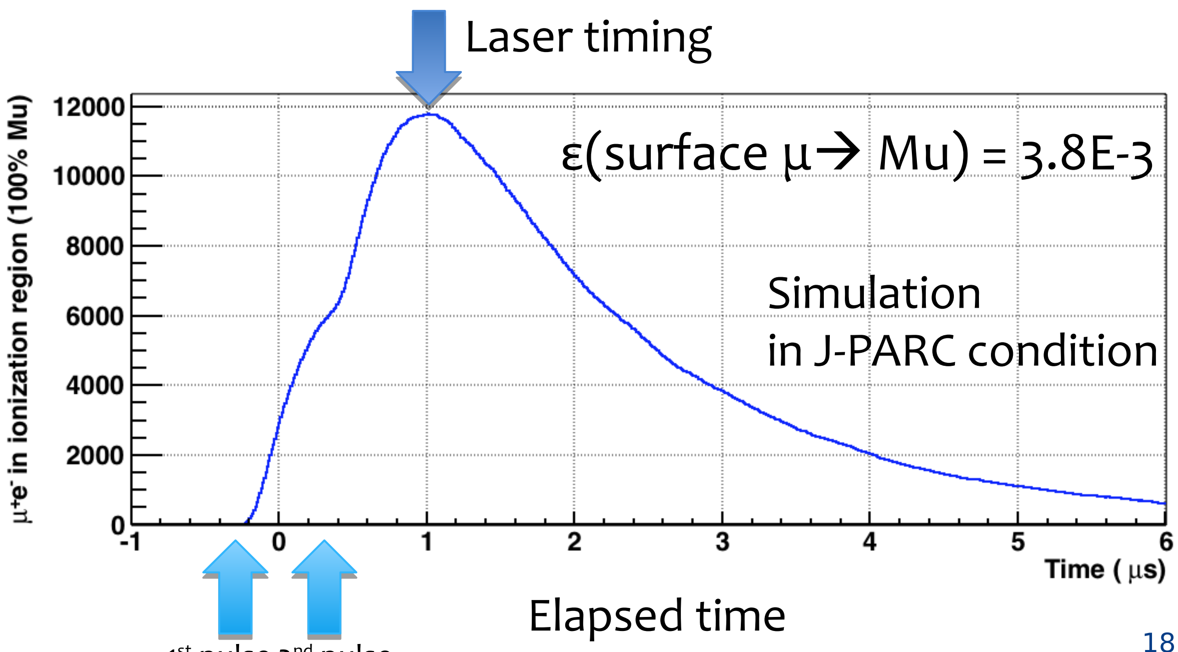


G. Beer et al., Prog.Theor.Exp.Phys. (2014)091C01



double pulses
(0.6 μs interval,25Hz)

G. Marshall

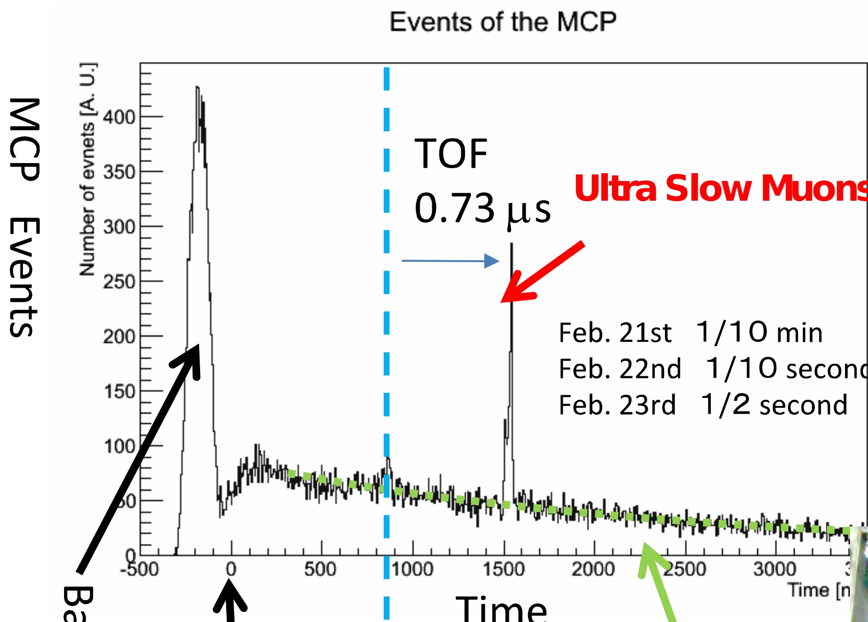


Elapsed time

Slide by M. Miyake

The fist observation of ultra slow muons at U-Line

At the commissioning on Feb. 21st right after MLF recovery!

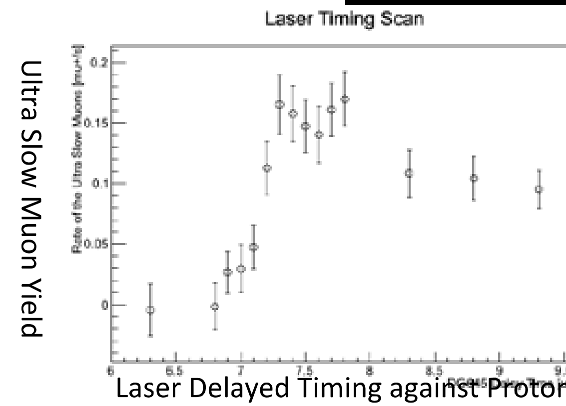


Background by decay positron

Arrival timing of Surface Muons

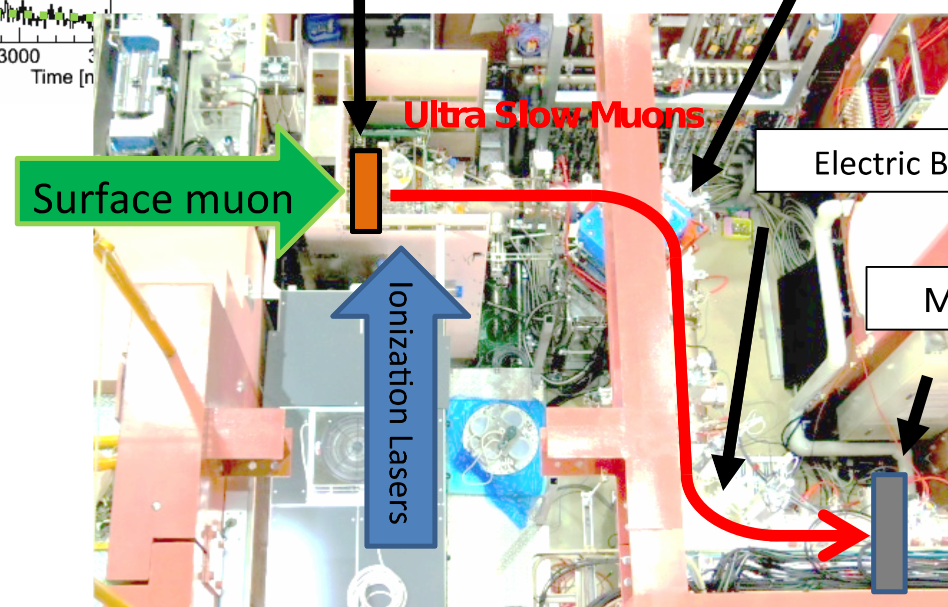
Laser Timing

Background



Mu Target (W)

Magnetic Bend (Mass Separation)

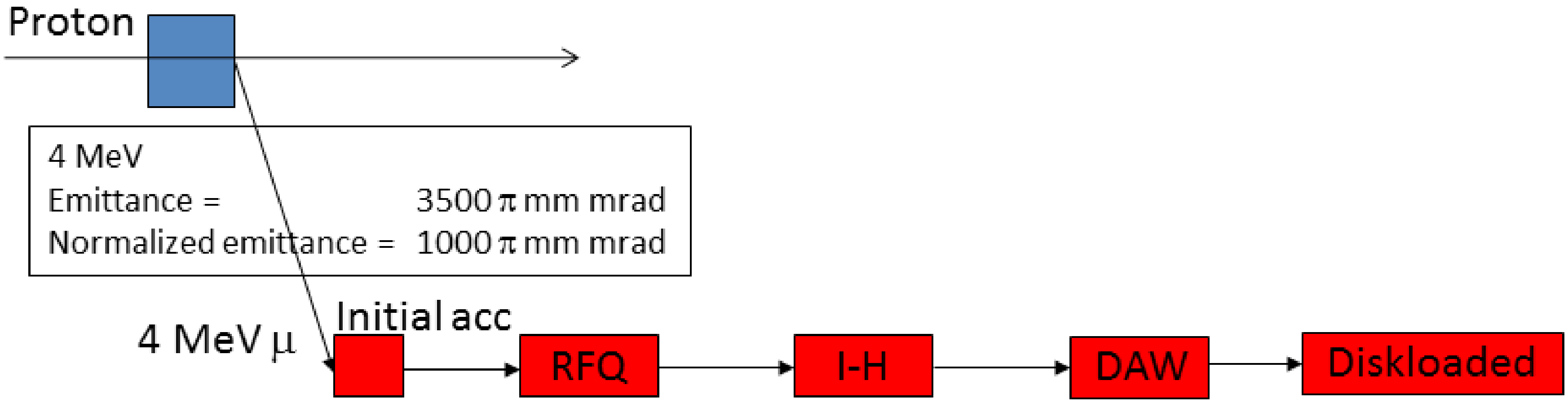


Electric Bend

MCP

Top view of the U－Line

Muon accelerator development

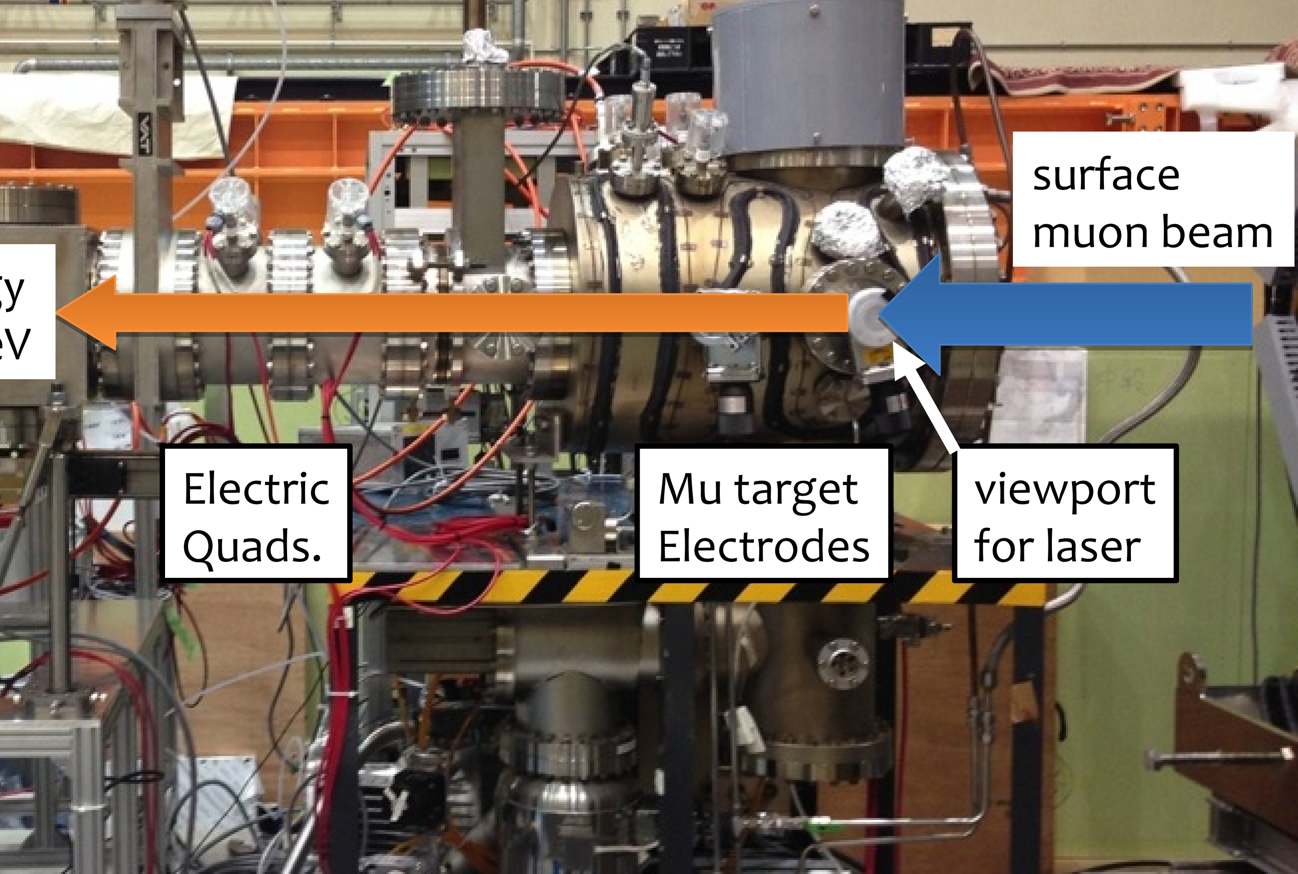


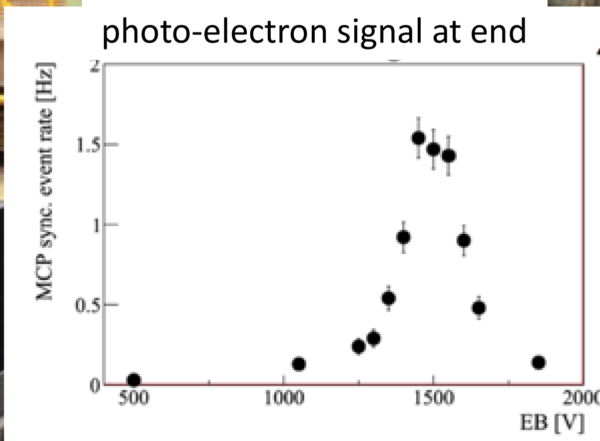
	5.7keV	340 keV	4 MeV	50MeV	200 MeV
$\beta\gamma$	0.01	0.08	0.278	0.98	2.71
Emittance(mm mrad)	150	19	5.4	1.5	0.55
Normalized emittance	1.5	1.5	1.5	1.5	1.5

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**	**design**

Electro-static acceleration

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





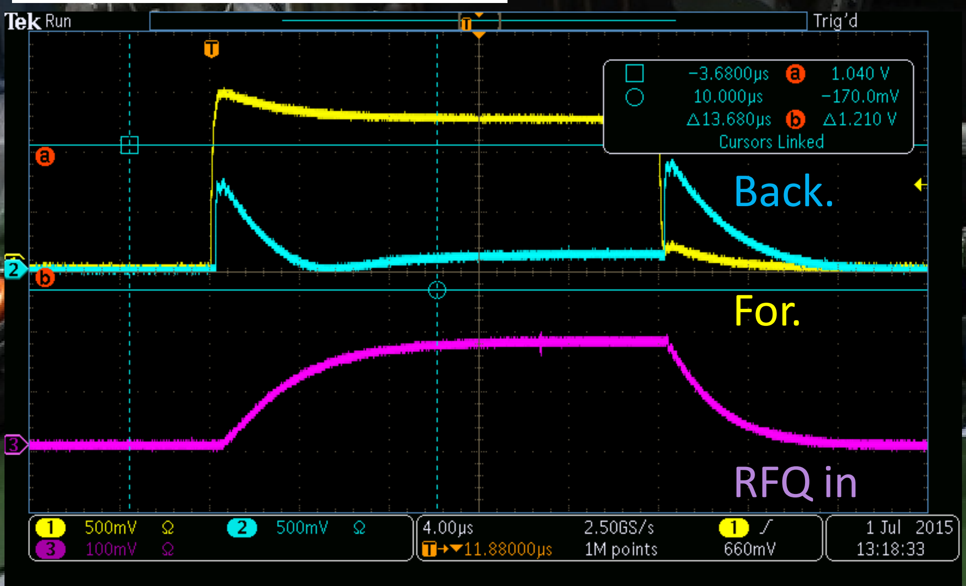
Main apparatus were recycled from RIKEN-RAL port-3

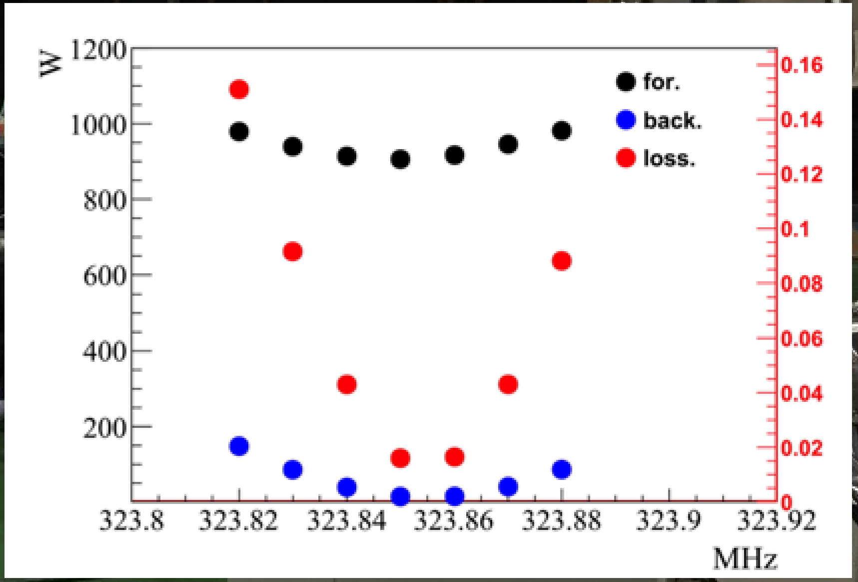
Commissioned with muon beam in Feb, 2016

Y. Kondo, M. Otani

RFQ offline test at J-PARC

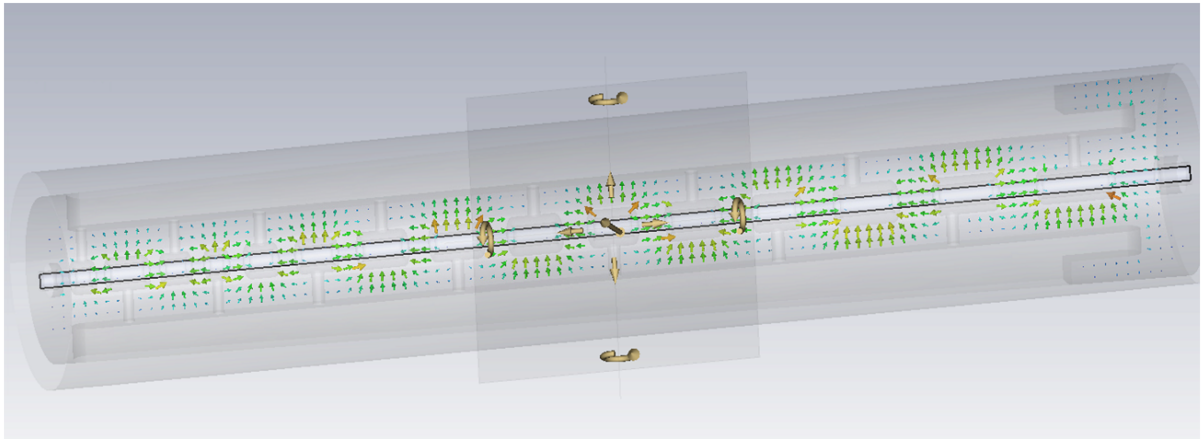
Data taken in July, 2015





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
βin	0.0797	
Output energy	4.50	MeV
βout	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

$\Delta\varepsilon_x \sim 0.015\pi$

$\Delta\varepsilon_y \sim 0.013\pi$

- After optimization, IH LINAC satisfies requirements for E34.
- To be submitted to Phys. Rev. STAB soon by M. Otani et al.

mid-β section (DAW)

by M. Otani

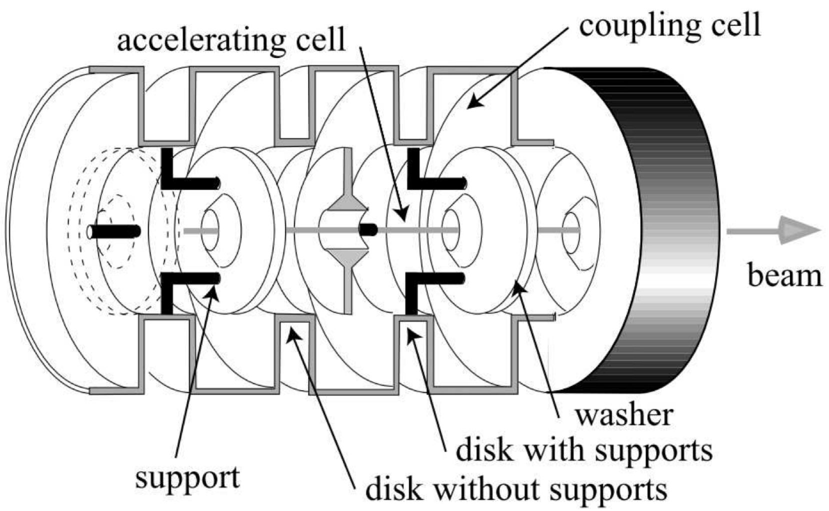
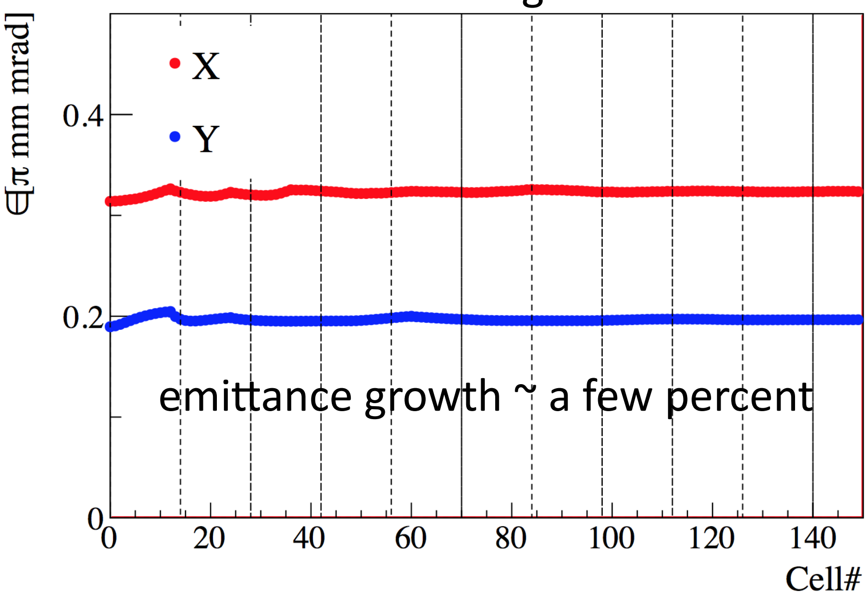


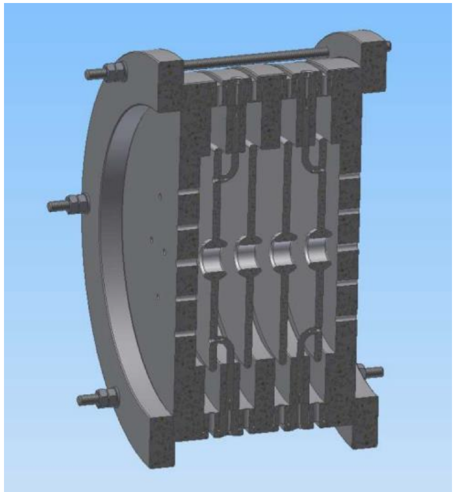
Table 6.1. DAW Main parameters

Parameter	Value	Unit	Comment
Length *1		m	
Input energy	4.5	MeV	MeV/c
Output energy	42.7	MeV	MeV/c
Operation frequency	1296	MHz	
Accelerator cavity type	DAW		Disk and Washer
Number of DAW modules	13		
Number of quadrupoles	24		

Simulated emittance along the beam line

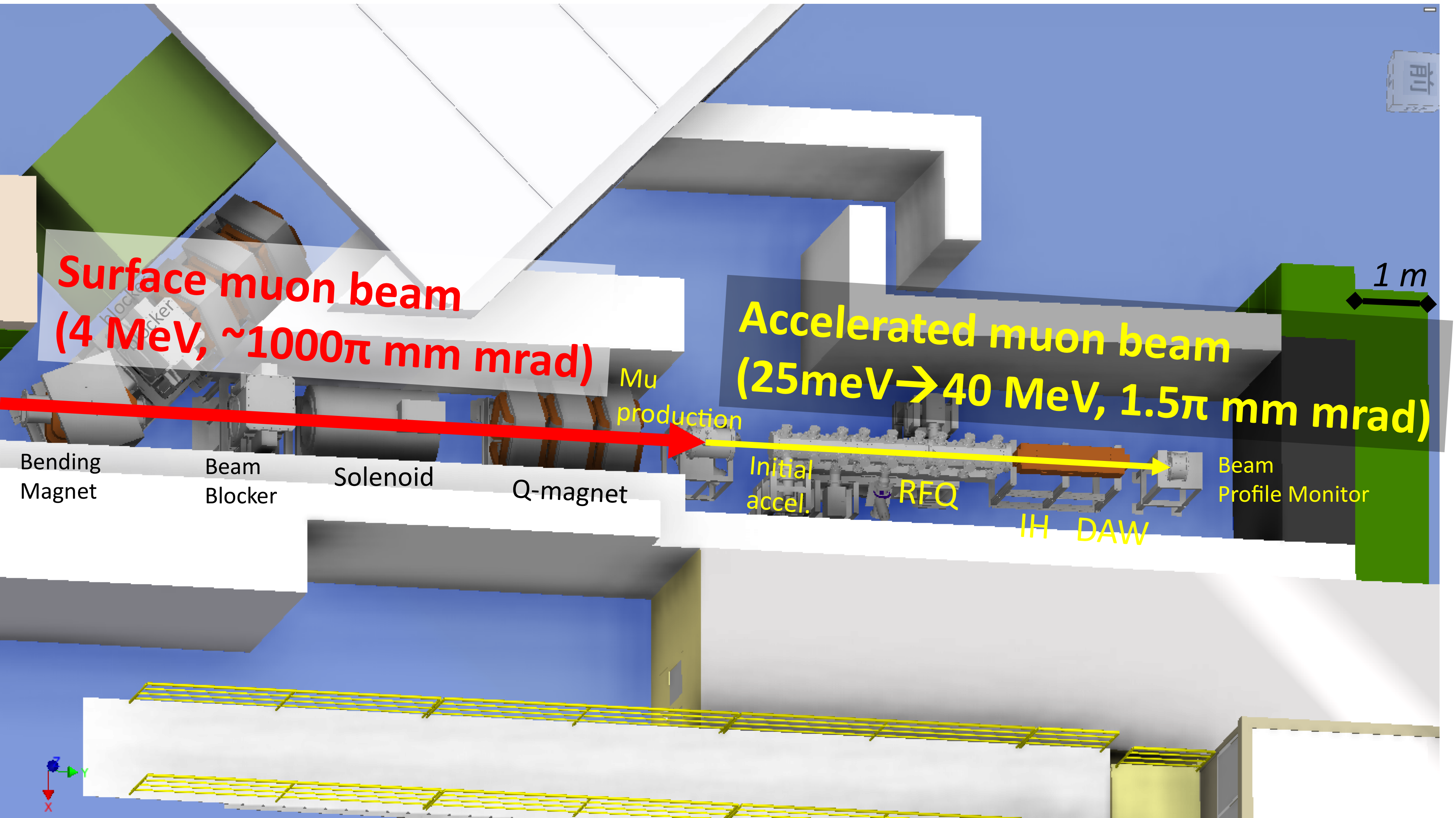


3D mechanical model

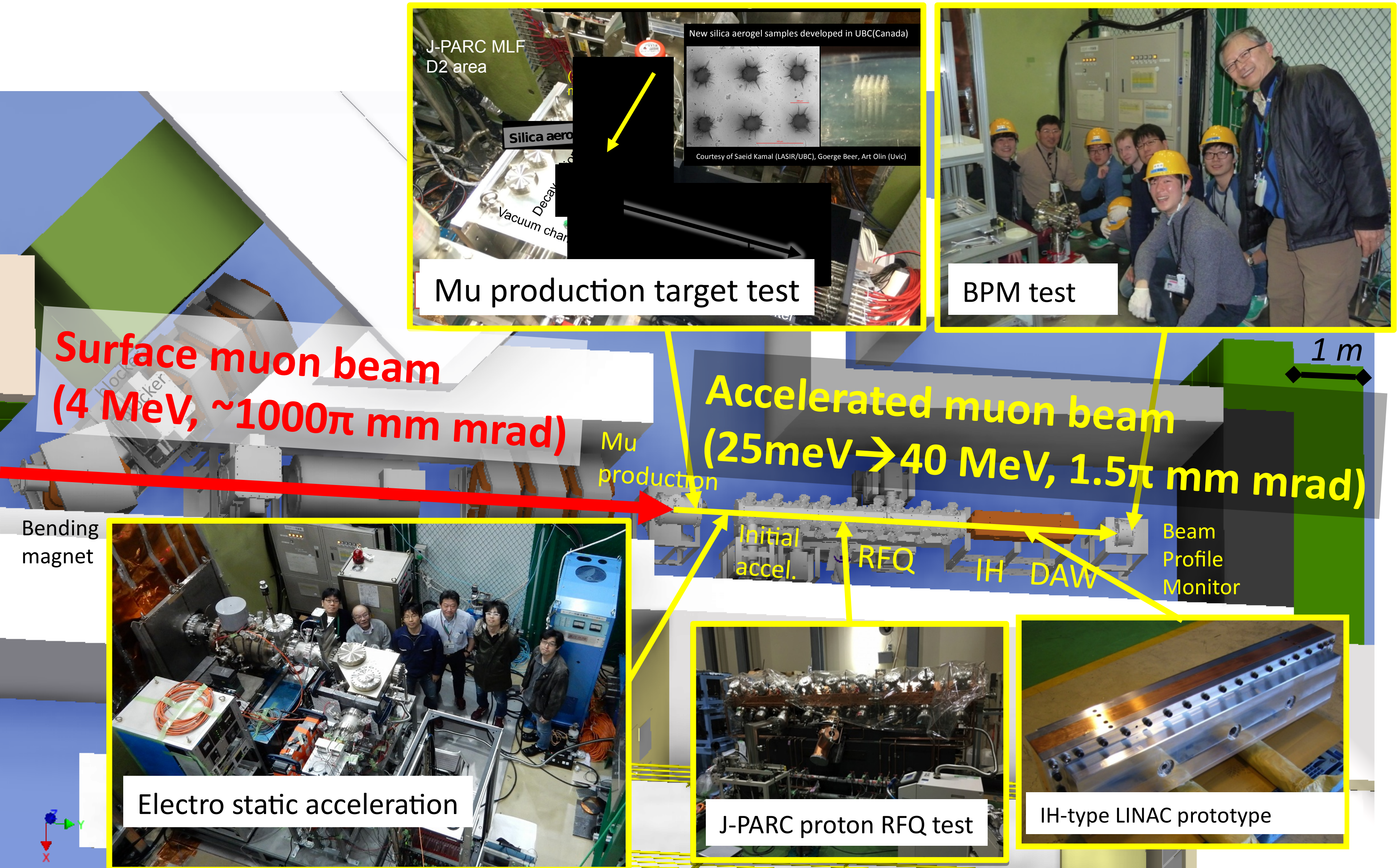


- R&D supported by Kakenhi-B (Otani).
- After optimization, DAW LINAC satisfies requirements for E34.
- The first prototype will be manufactured by March, 2016.
- Simulated outputs will be used to design high-β LINAC.

Muon acceleration at H-line

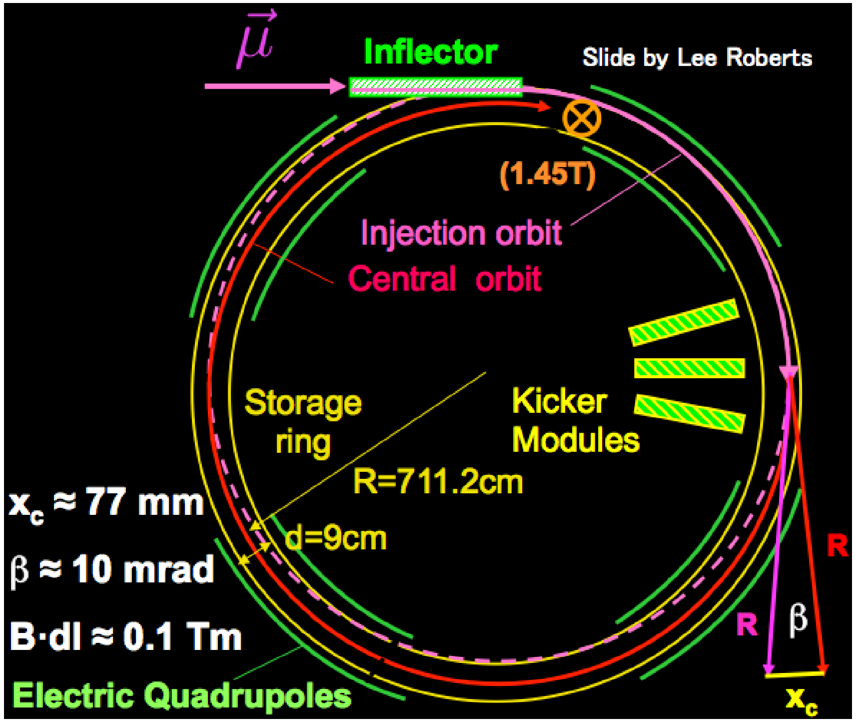


Muon acceleration at H-line



Muon beam injection and storage

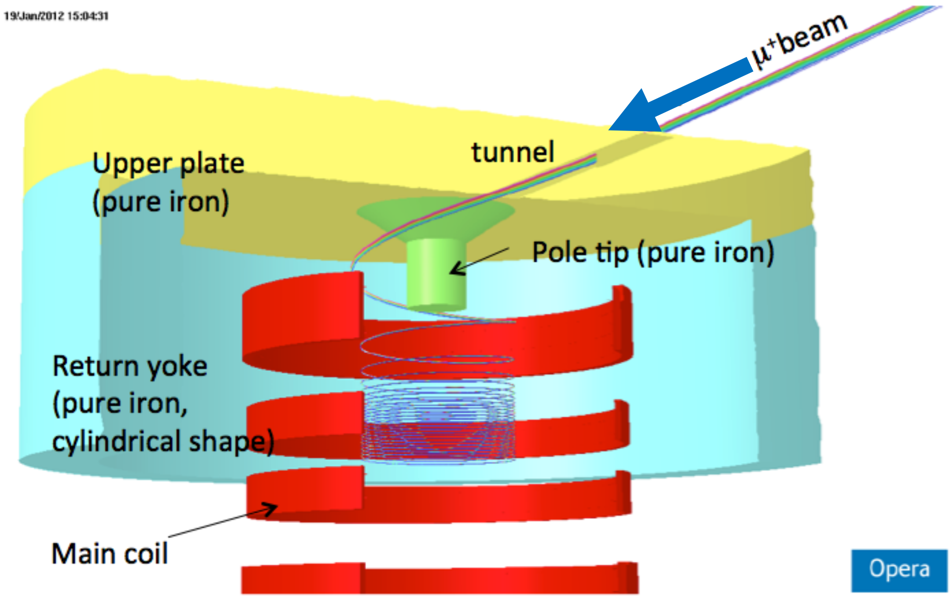
Horizontal injection + kicker (BNL E821, FNAL E989)



Injection efficiency : 3-5%(*)

(*) PRD73,072003 (2006)

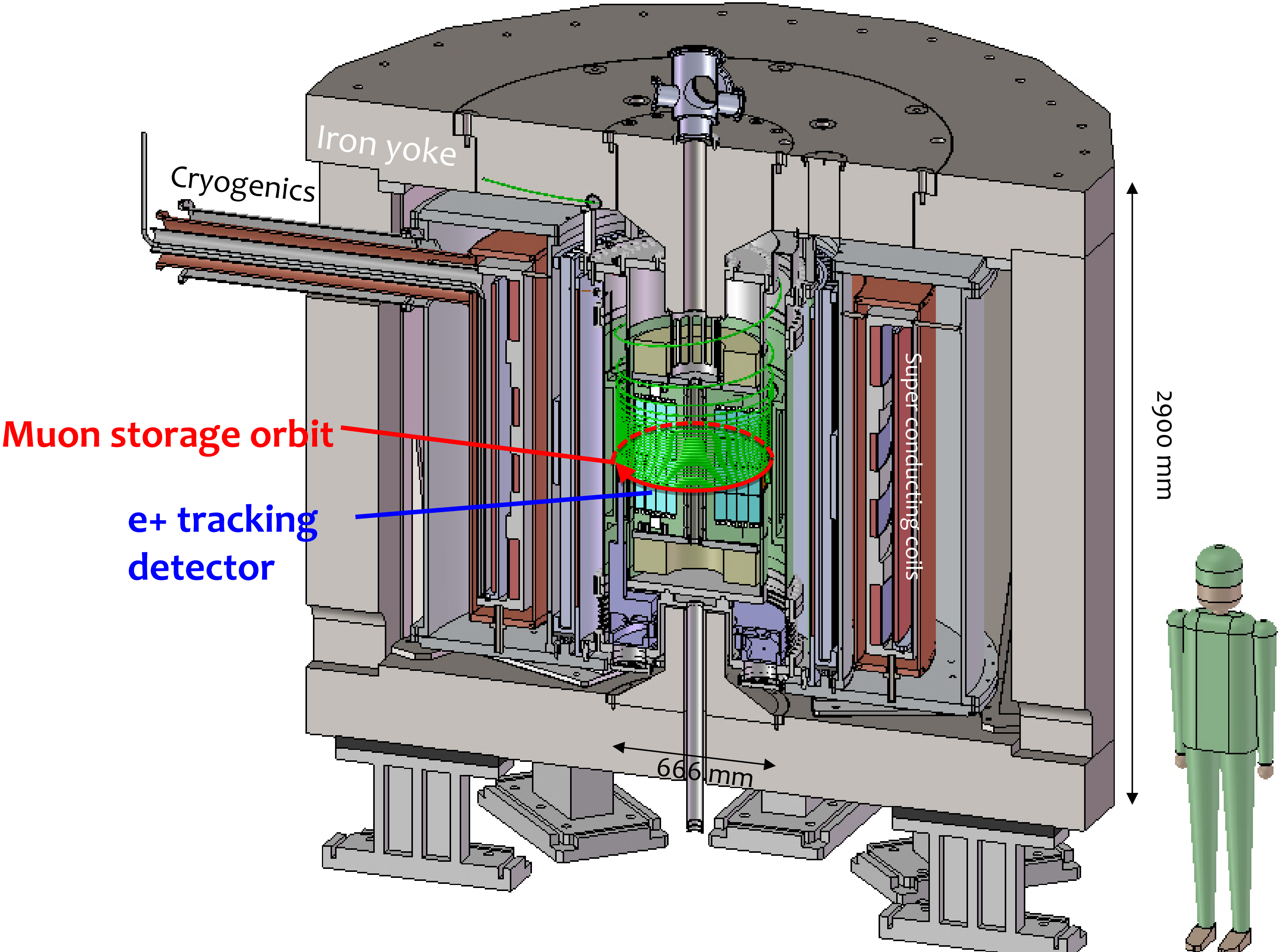
3D spiral injection + kicker (J-PARC E34)



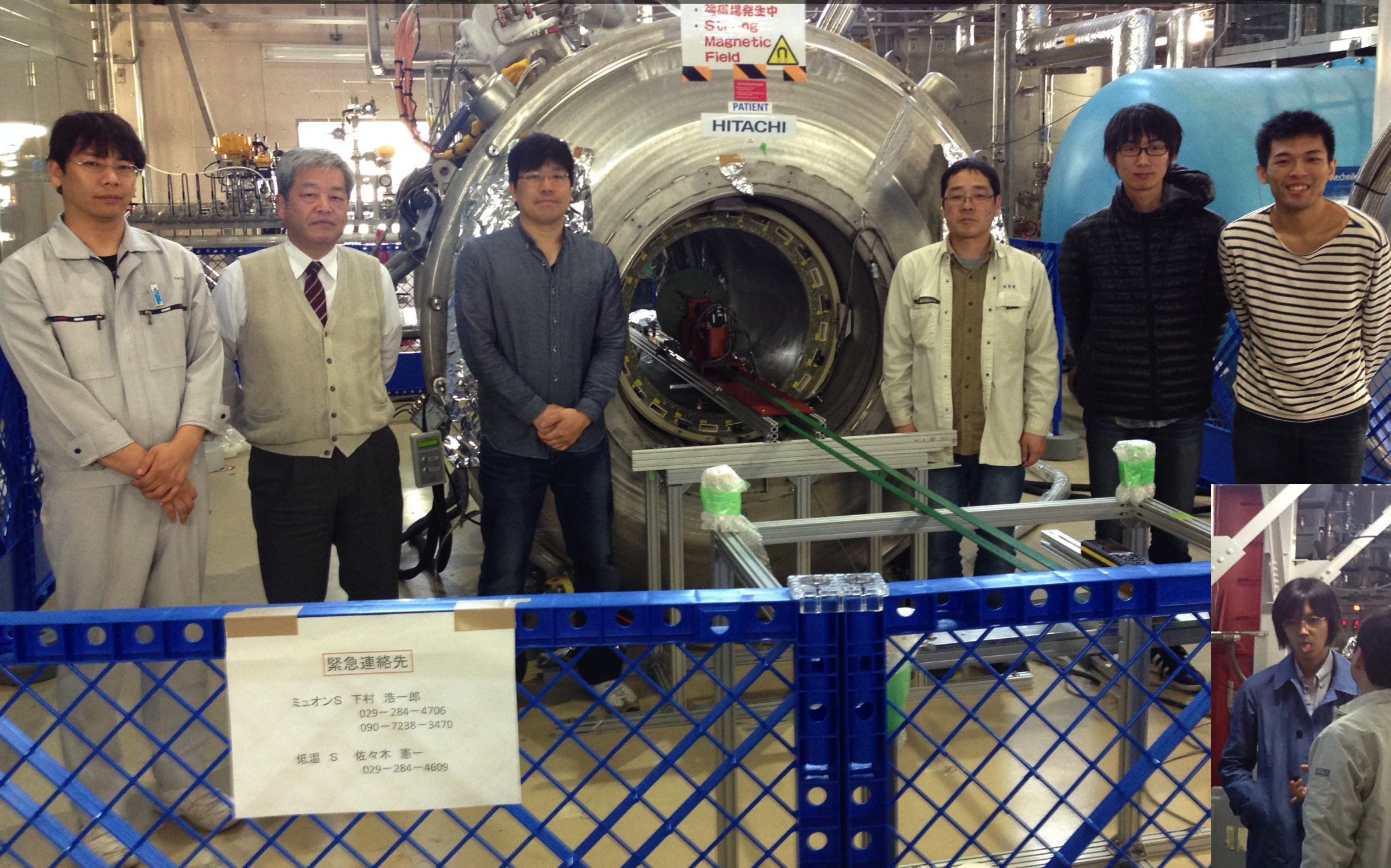
Injection efficiency : ~90%

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

Muon storage magnet and detector



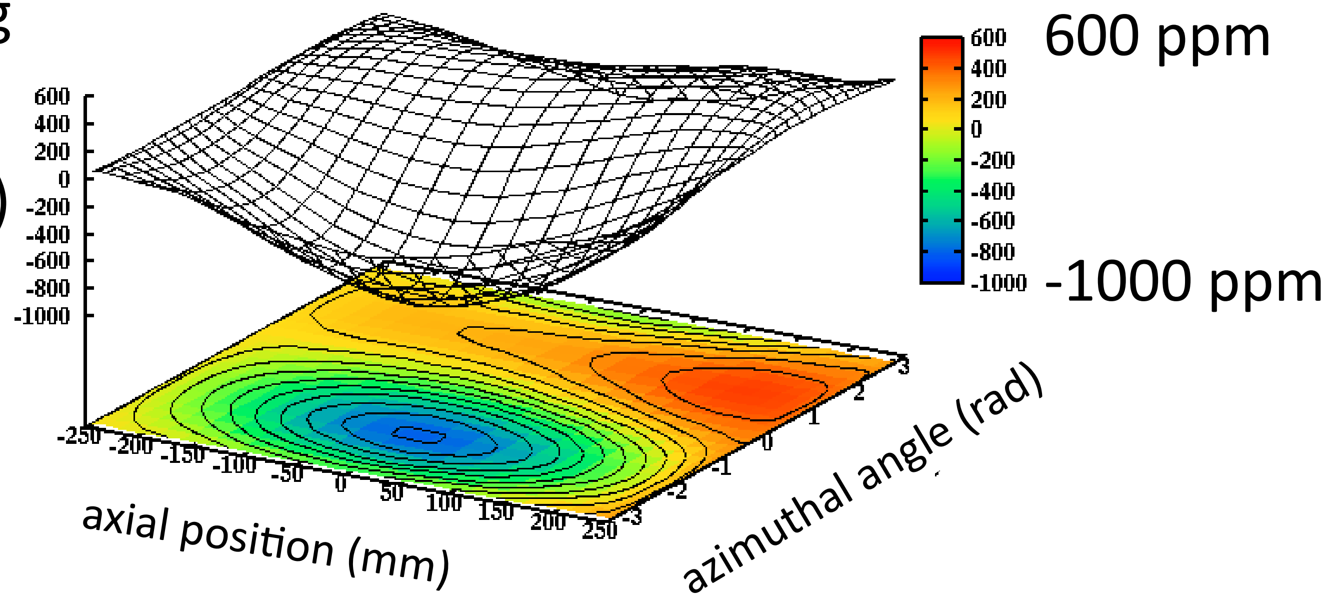
B-field shimming test with the MuSEUM magnet (1.7 T) at J-PARC



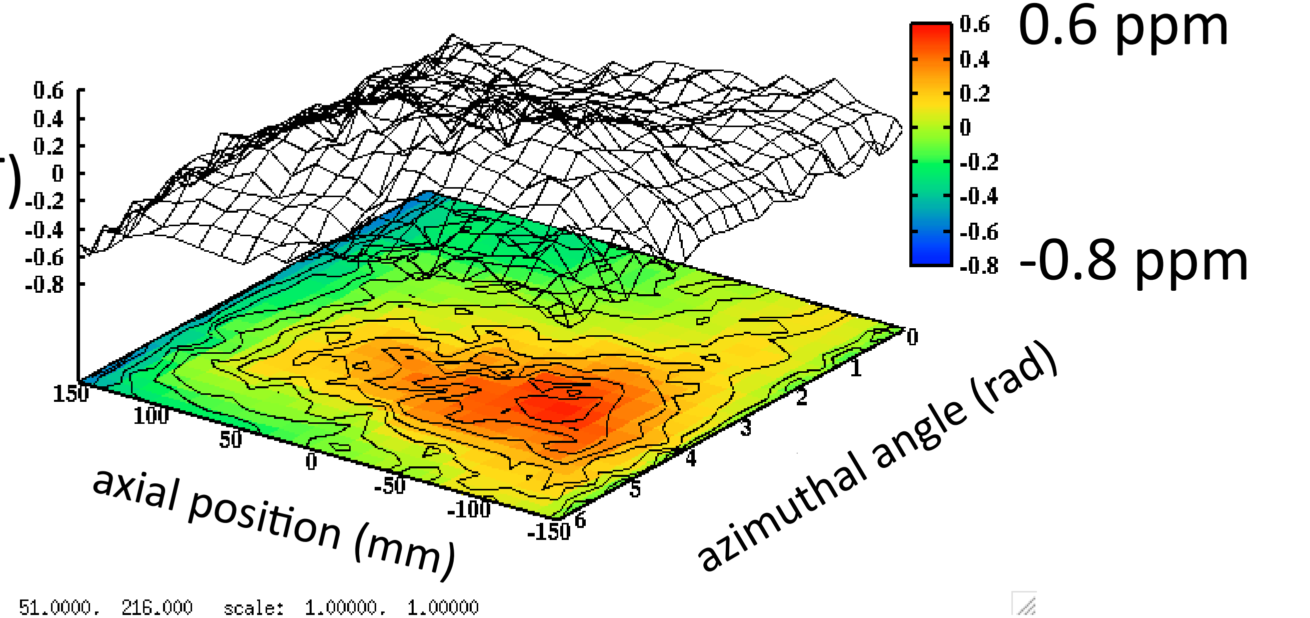
Field shimming by iron arrays

Plots by K. Sasaki

Before shimming



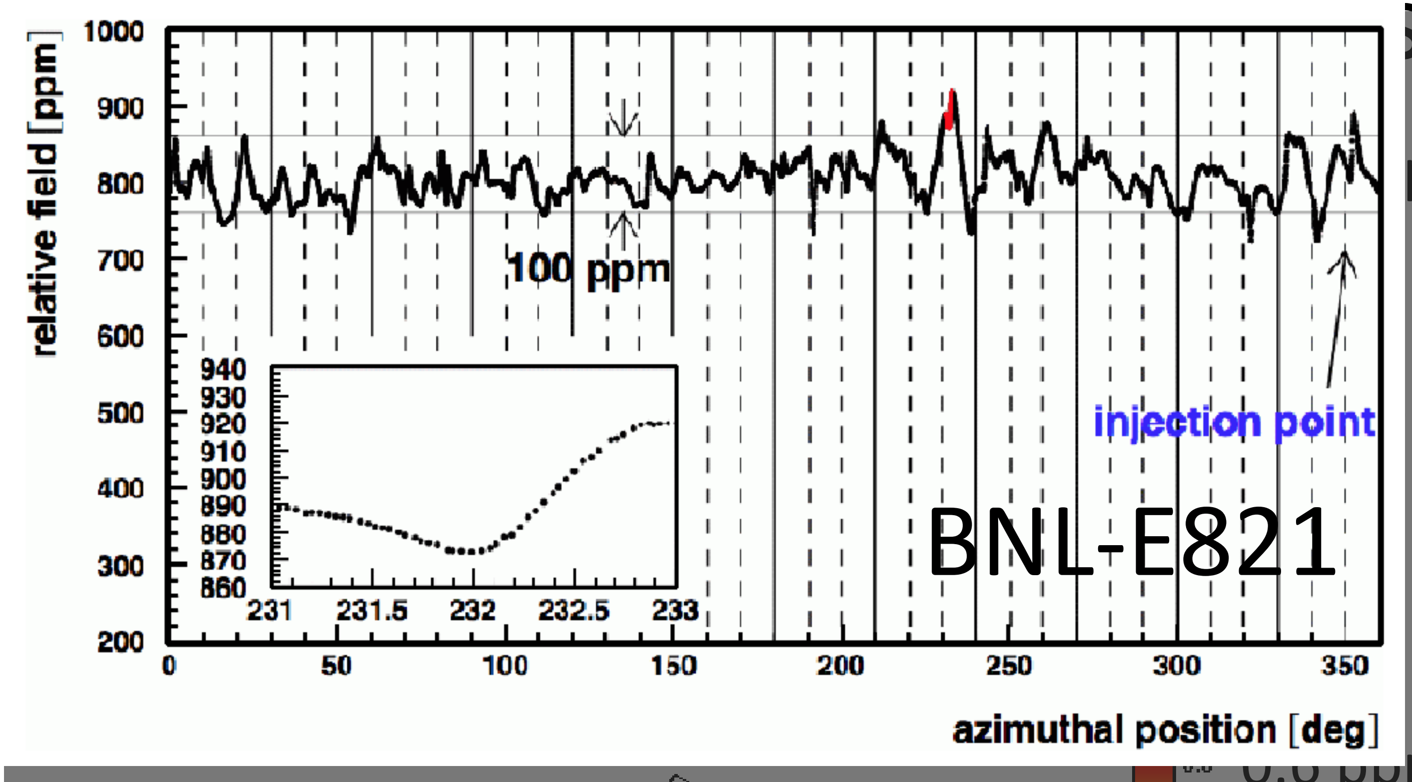
After shimming



r = 140 mm

Plots by K. Sasaki

Before s

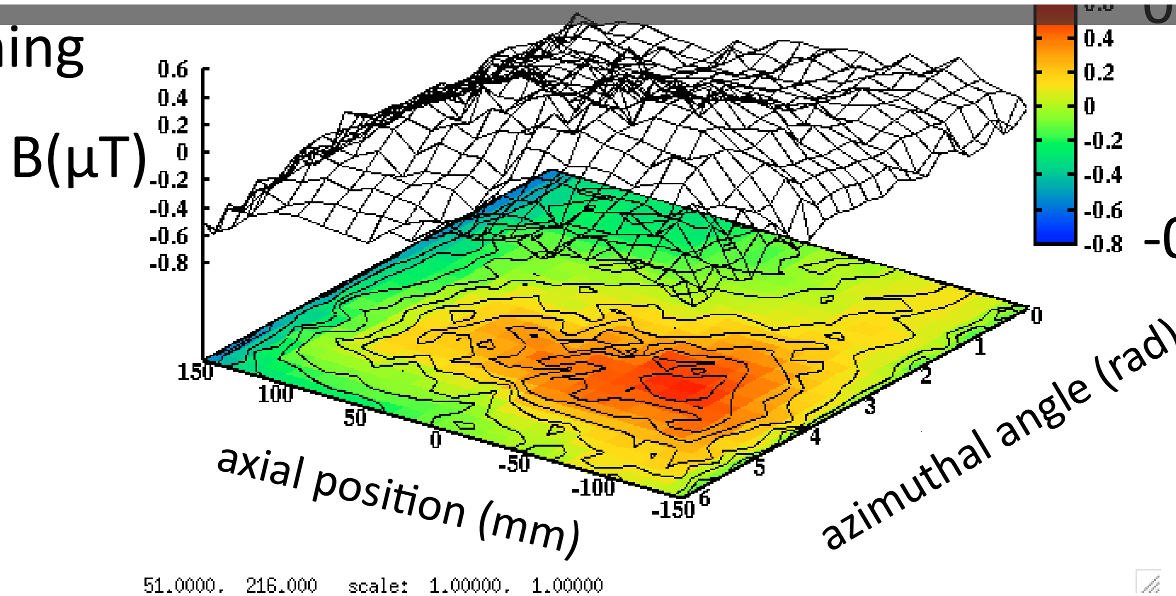


pm

ppm

0.6 ppm

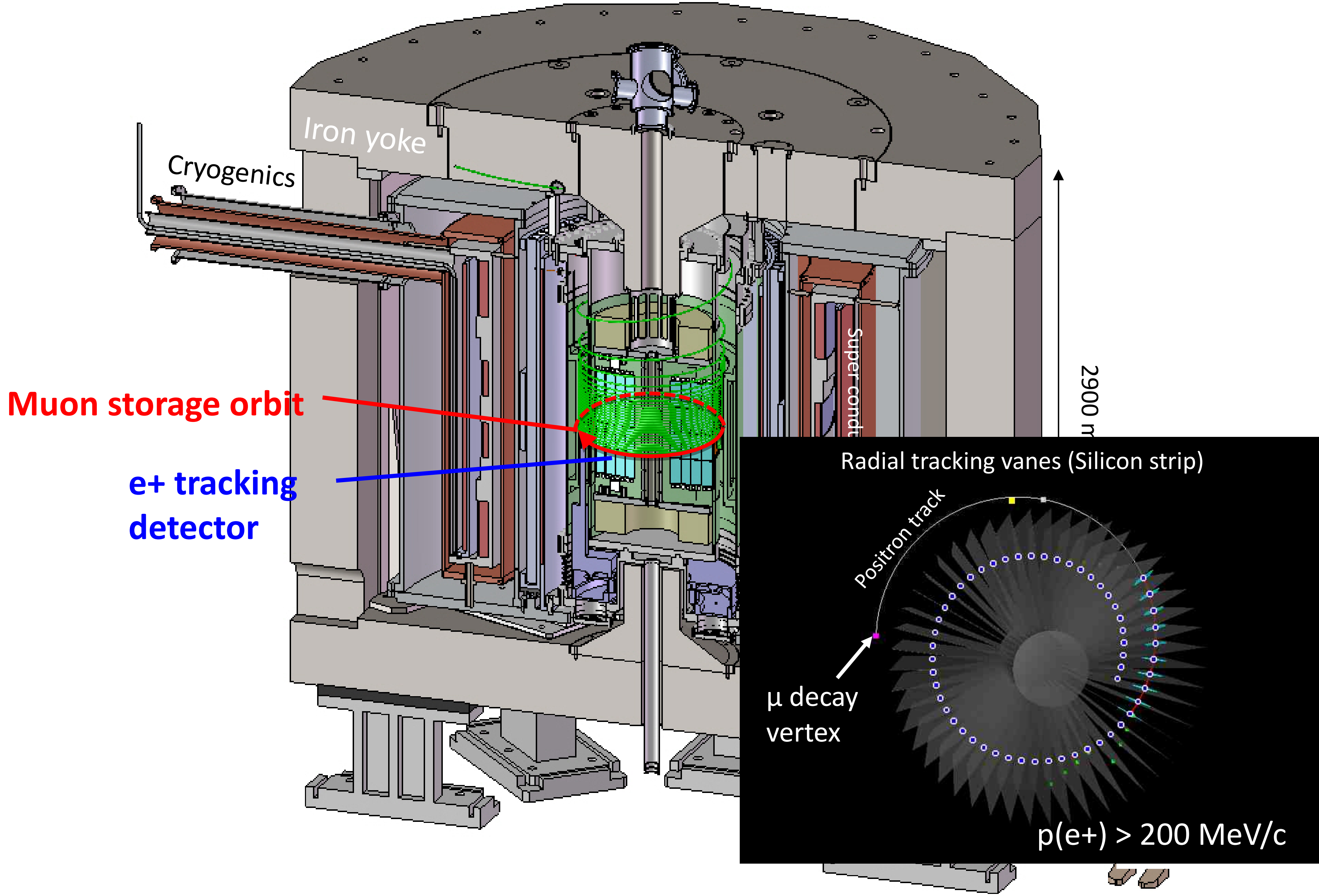
After shimming



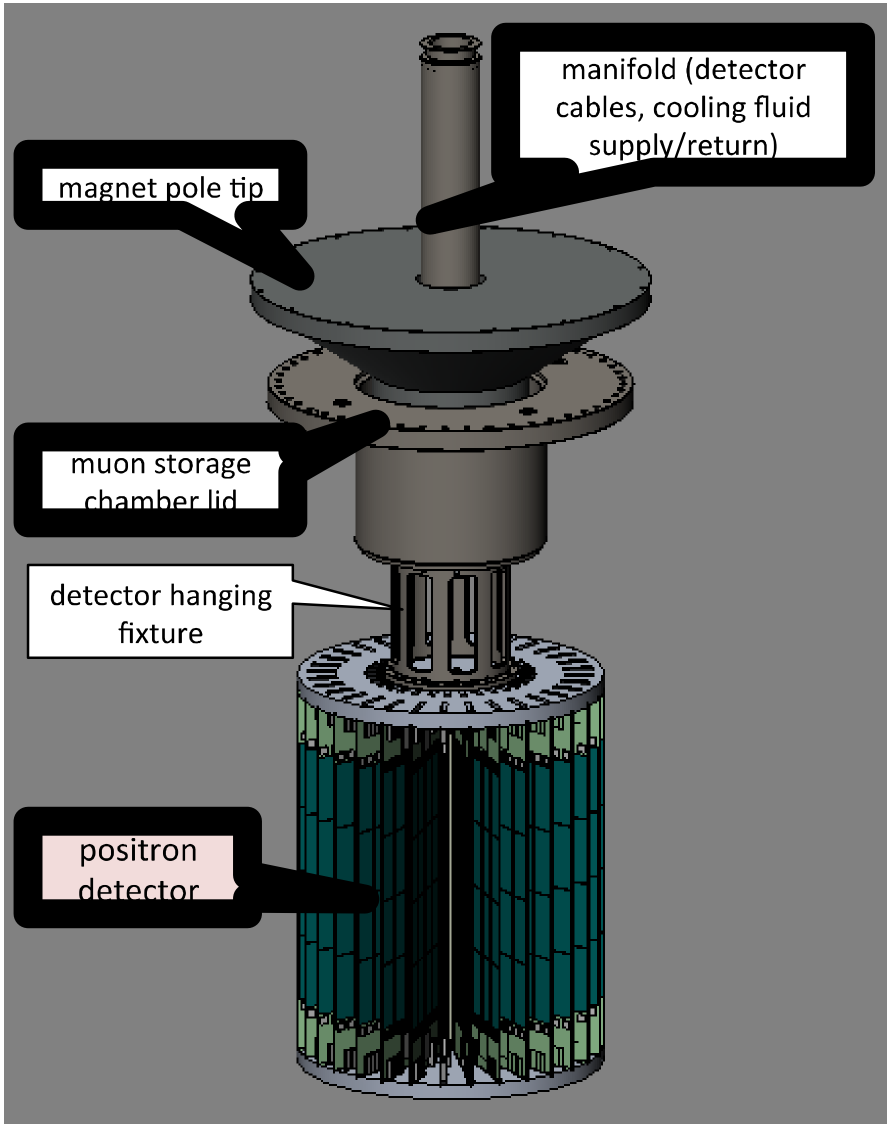
-0.8 ppm

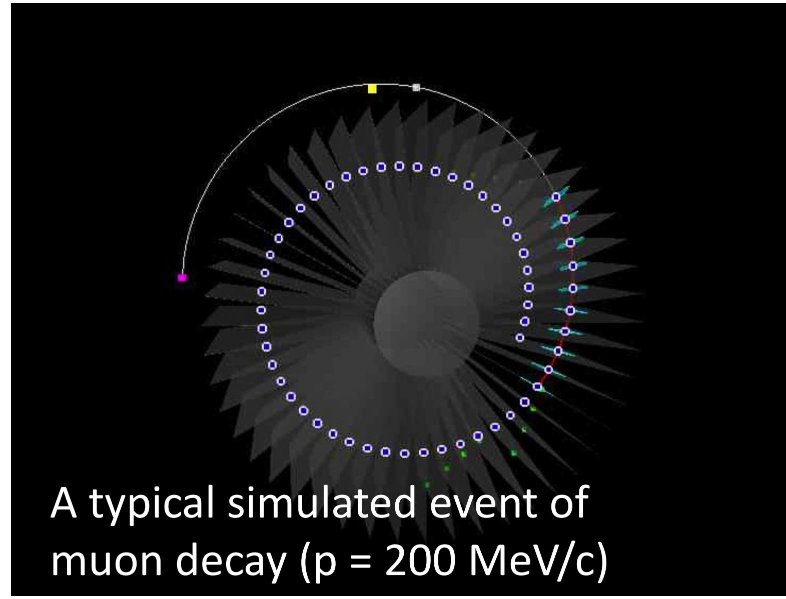
r = 140 mm

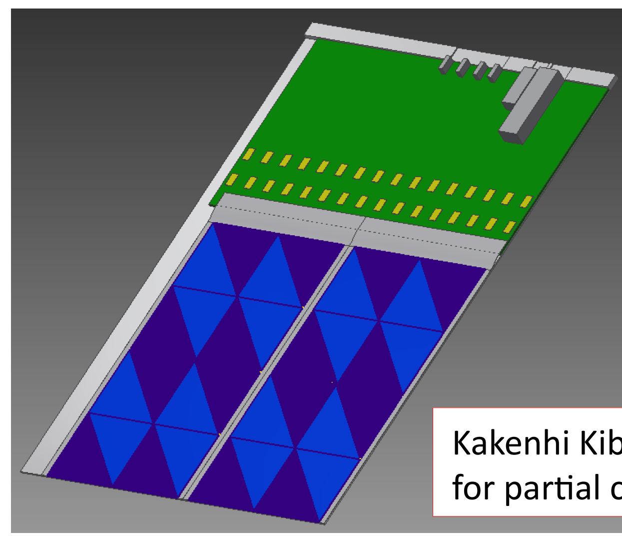
Muon storage magnet and detector



Positron tracking detector







Kakenhi Kiban-S (2015-2019) for partial construction

Full acceptance coverage

Track angle information → Sensitivity to muon EDM

Summary

- A new independent measurement of muon g-2 and E DM with **ultra-cold muon beam** is being prepared at J-PARC.
- **R&D is in the final stage** to meet remaining mileston es including muon acceleration test.
- We are moving to a construction phase. Partial const ruction fund is approved (detector).