極冷ミューオンビームによる g-2/EDMの精密測定

素粒子物理学の進展２０１６
2016年9月5日
三部　勉 (KEK 素核研)

Beyond the standard model is dark.

Baryon asymmetry in the Universe

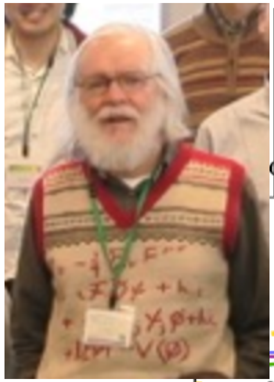
Dark matter

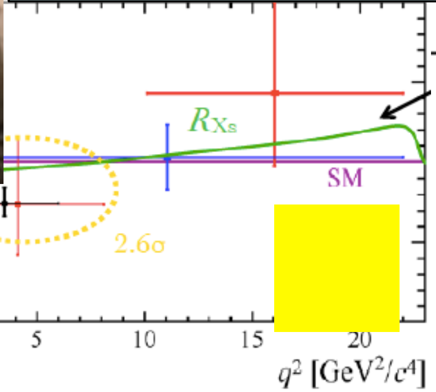
Hierarchy problem

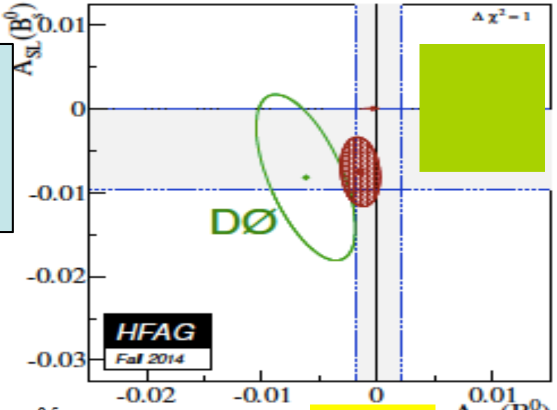
…

John Ellis, March 14, 2016 (Nagoya)

Flavour Anomalies





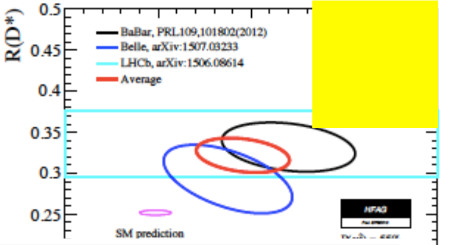


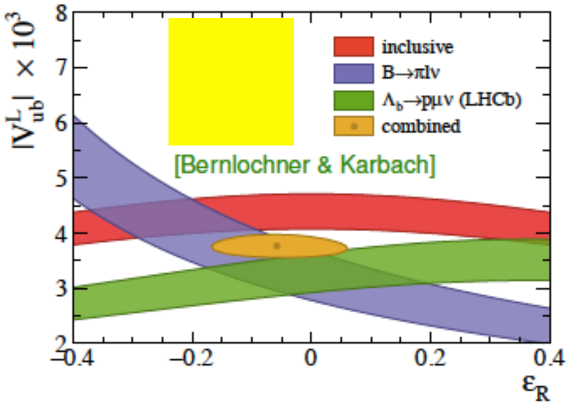
$h \to \tau\mu$

$B \to K e^+ e^- / B \to K \mu^+ \mu^-$

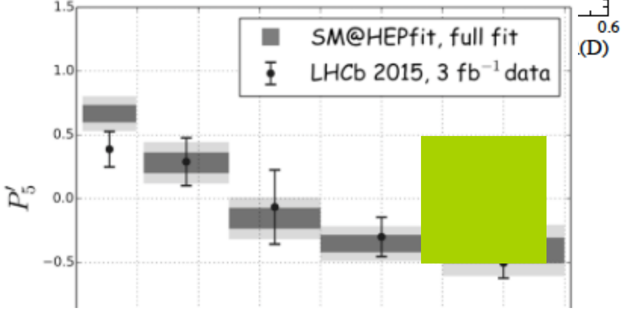
dimuon CP asym

$B \to D^{(*)} \tau\nu$





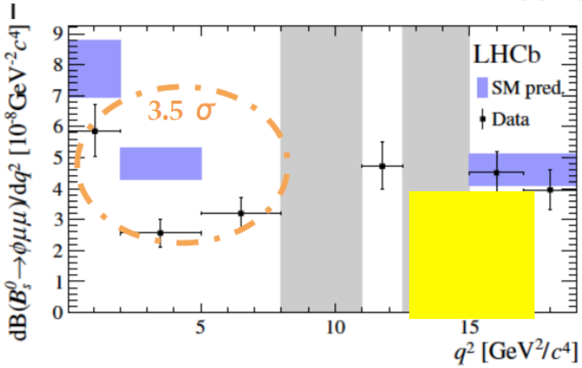
$B \to K^* \mu^+ \mu^-$ angular



$|V_{cb}|$ incl/excl

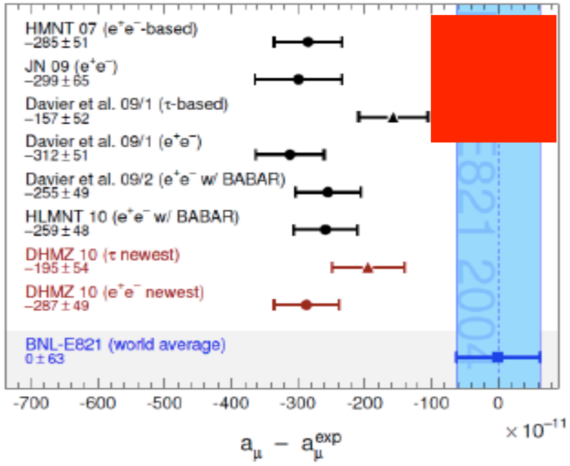
$|V_{ub}|$ incl/excl

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



g−2

(σ)



🟩 No worries

🟨 Wait & See

🟥 Serious?

Particle dipole moments

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

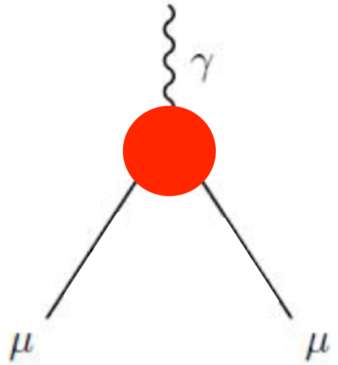
Magnetic Dipole Moment

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

Electric Dipole Moment

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

Anomalous magnetic moment



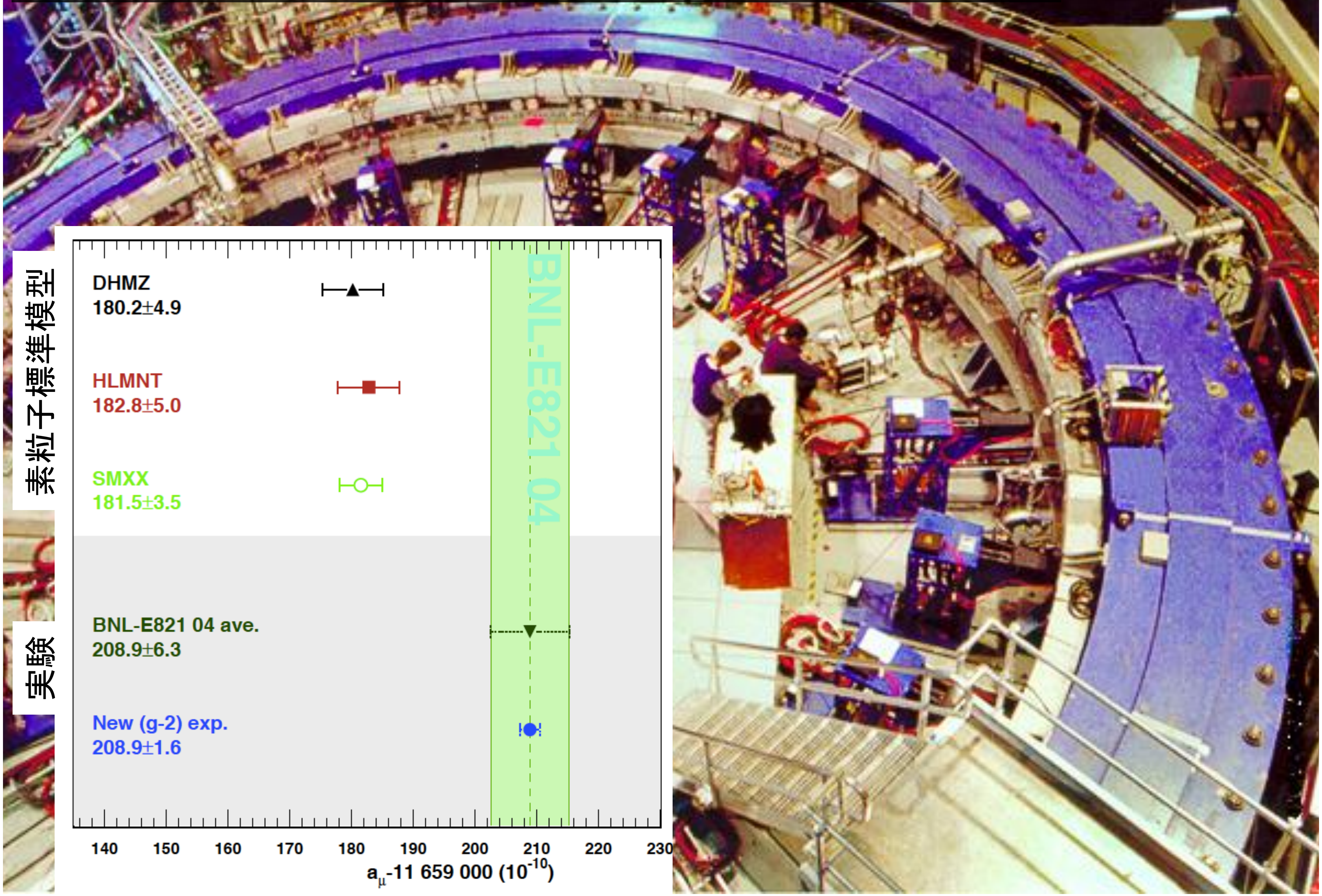
Anomalous magnetic moment

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

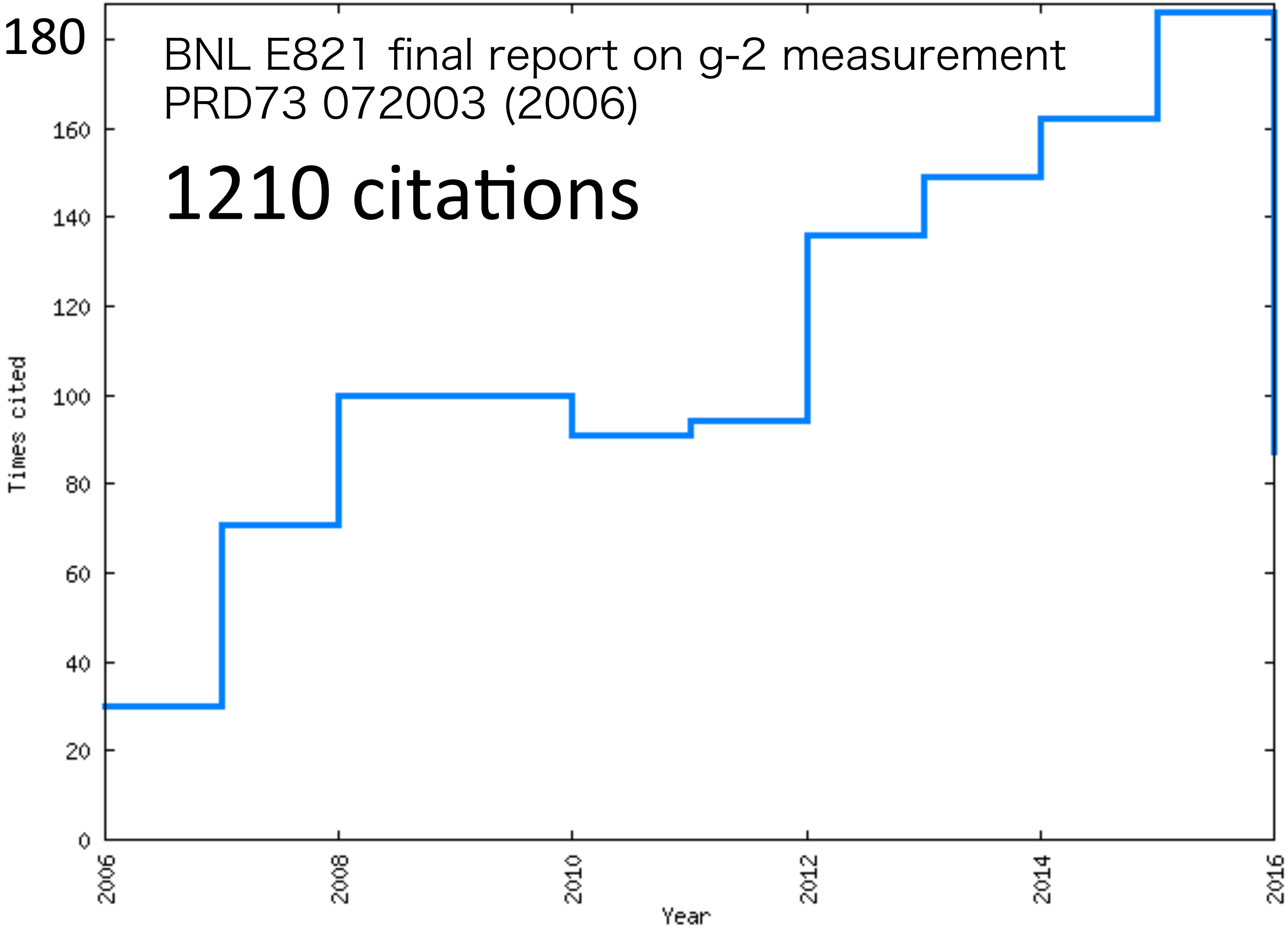
$$a_\mu = a_\mu(QED) + a_\mu(had) + a_\mu(weak) + a_\mu(BSM)$$

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

Muon anomalous magnetic moment (*g*-2)



Growing interests

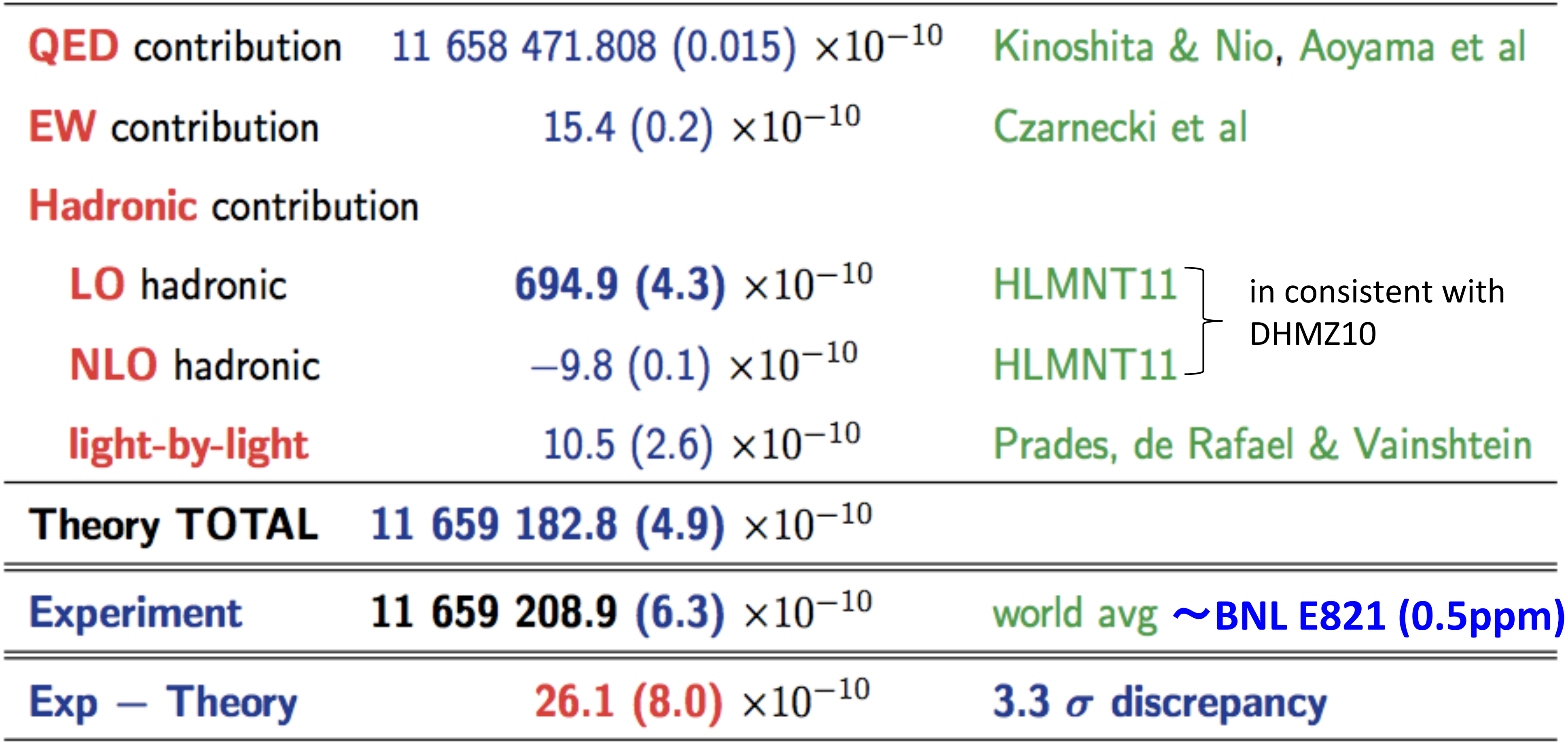


BNL E821 final report on g-2 measurement
PRD73 072003 (2006)

1210 citations

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	**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	**11 659 182.8 (4.9)** $\times 10^{-10}$	
Experiment	**11 659 208.9 (6.3)** $\times 10^{-10}$	world avg **～BNL E821 (0.5ppm)**
Exp − Theory	**26.1 (8.0)** $\times 10^{-10}$	**3.3 σ discrepancy**

in consistent with DHMZ10

HLMNT11 : J.Phys.G38:085003,2011

Contribution from new physics

Slide by M. Endo

$$\Delta a_\mu \sim \frac{g_{\mathrm{new}}^2}{16\pi^2}\frac{(\text{muon mass} \sim 0.1\,\mathrm{GeV})^2}{(\text{new particle mass})^2}$$

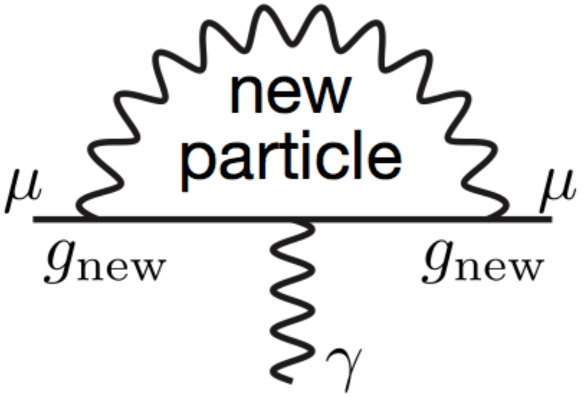
- weak interaction, small mass

  e.g. heavy photon model

  (dark photon)

- strong interaction, large mass

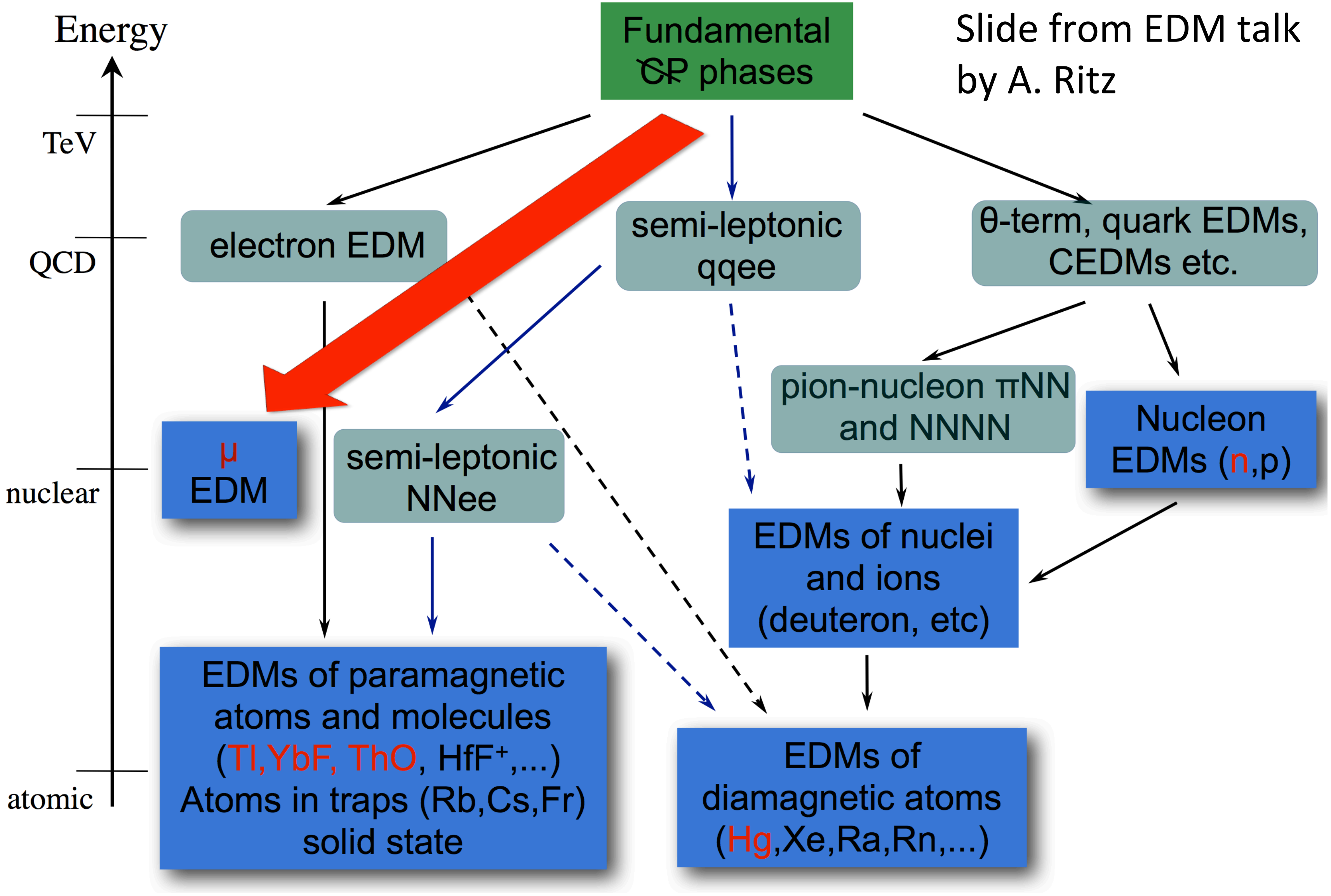
  e.g. supersymmetry



cf. NP signals may be hidden by SM background

Muon g-2 anomaly characterizes new physics.

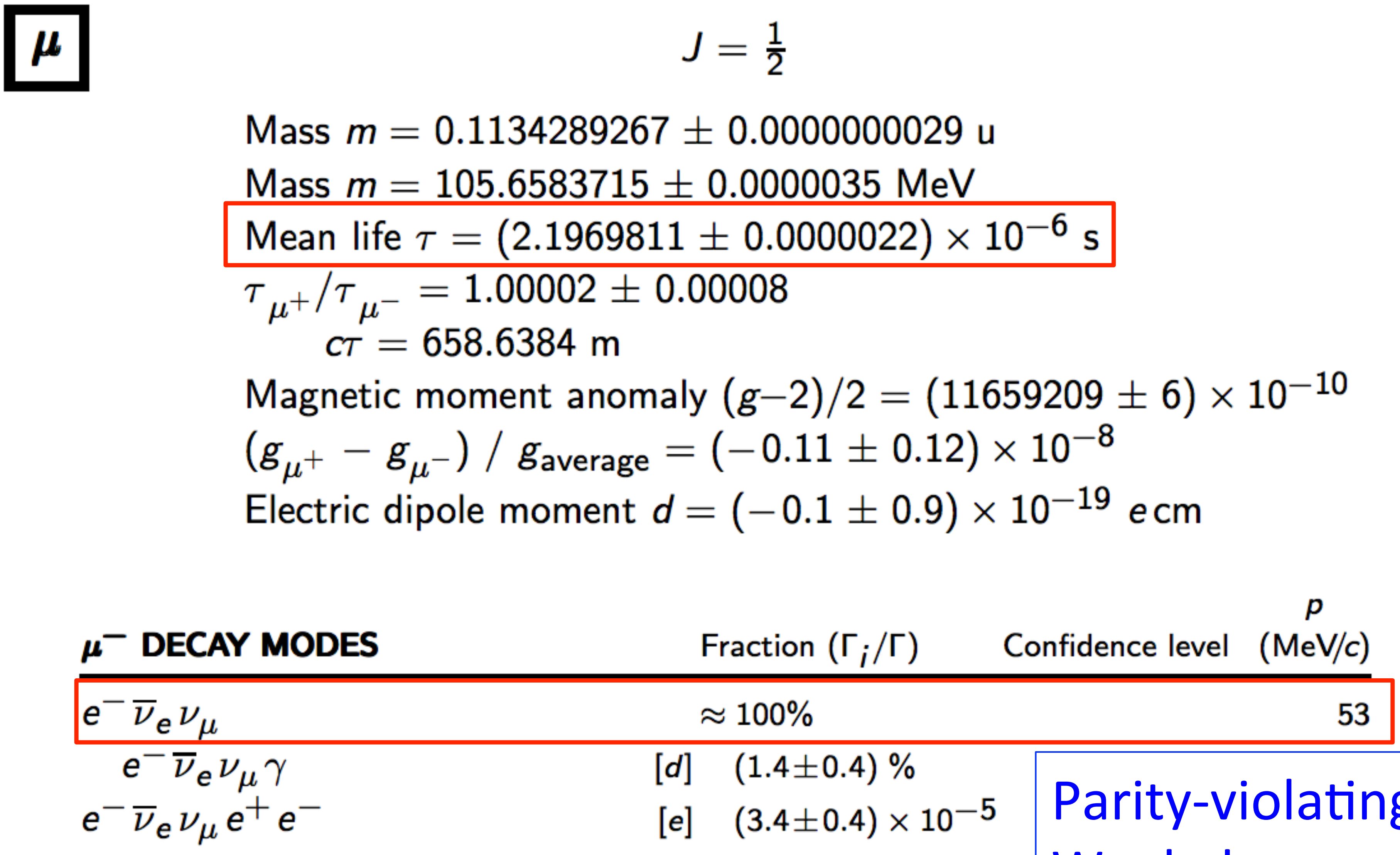
Scales of CPV sources and EDM



Slide from EDM talk
by A. Ritz

双極子能率の測定

ミューオン



μ

$$J = \tfrac{1}{2}$$

Mass $m = 0.1134289267 \pm 0.0000000029$ u

Mass $m = 105.6583715 \pm 0.0000035$ MeV

Mean life $\tau = (2.1969811 \pm 0.0000022) \times 10^{-6}$ s

$\tau_{\mu^+}/\tau_{\mu^-} = 1.00002 \pm 0.00008$

$c\tau = 658.6384$ m

Magnetic moment anomaly $(g{-}2)/2 = (11659209 \pm 6) \times 10^{-10}$

$(g_{\mu^+} - g_{\mu^-})\,/\,g_{\text{average}} = (-0.11 \pm 0.12) \times 10^{-8}$

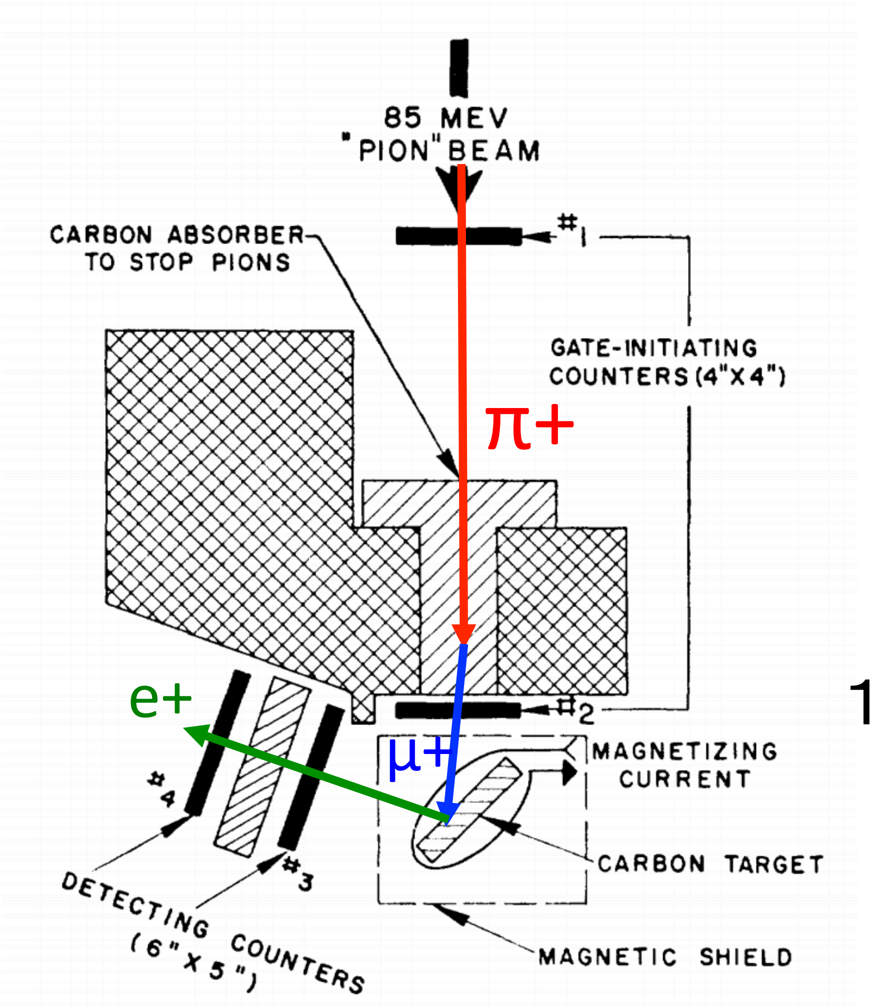
Electric dipole moment $d = (-0.1 \pm 0.9) \times 10^{-19}$ $e\,$cm

μ^- **DECAY MODES**		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$e^- \overline{\nu}_e \nu_\mu$		$\approx 100\%$		53
$e^- \overline{\nu}_e \nu_\mu \gamma$	[d]	(1.4 ± 0.4) %		
$e^- \overline{\nu}_e \nu_\mu e^+ e^-$	[e]	$(3.4\pm0.4) \times 10^{-5}$		

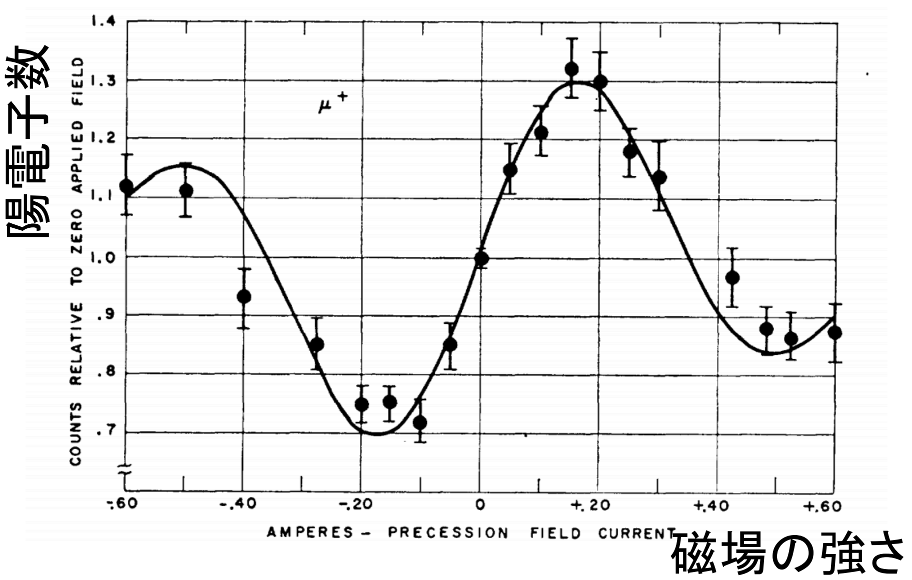
Parity-violating
Weak decay

Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: The Magnetic Moment of the Free Muon

R. Garwin, L. Lederman, M. Weinrich, Phys.Rev. 105 (1957) 1415–1417.



$$g = 2.00 \pm 0.10$$



１つの実験で3つの重要な発見をした。

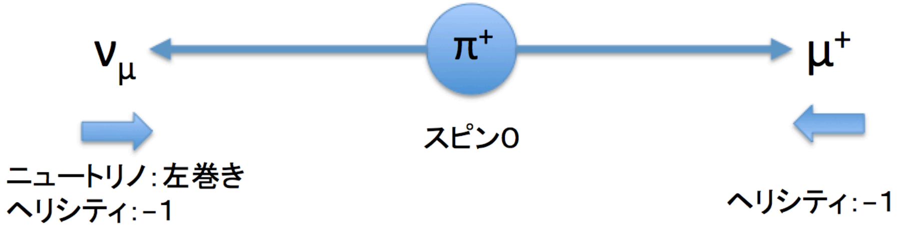
1）パイオン崩壊のパリティ非保存

2）ミューオン崩壊のパリティ非保存

3）ミューオン磁気能率の決定

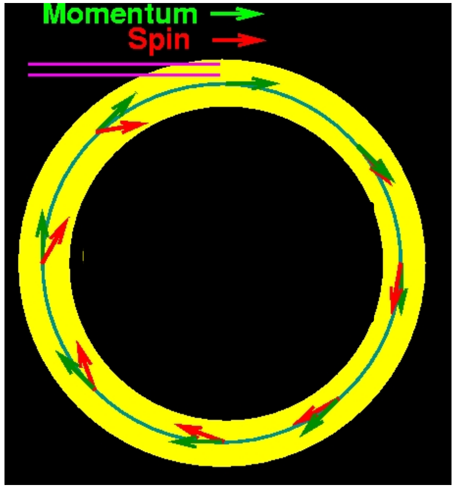
双極子能率の測定ステップ

1. 偏極したミューオンビームを作る。

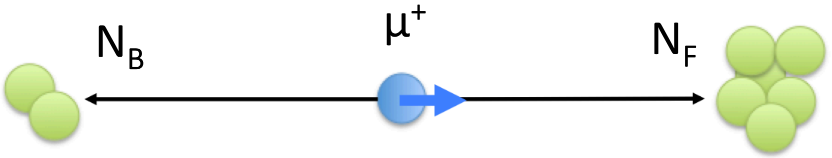


2. 磁場中に蓄積する(スピンは歳差運動する)。

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

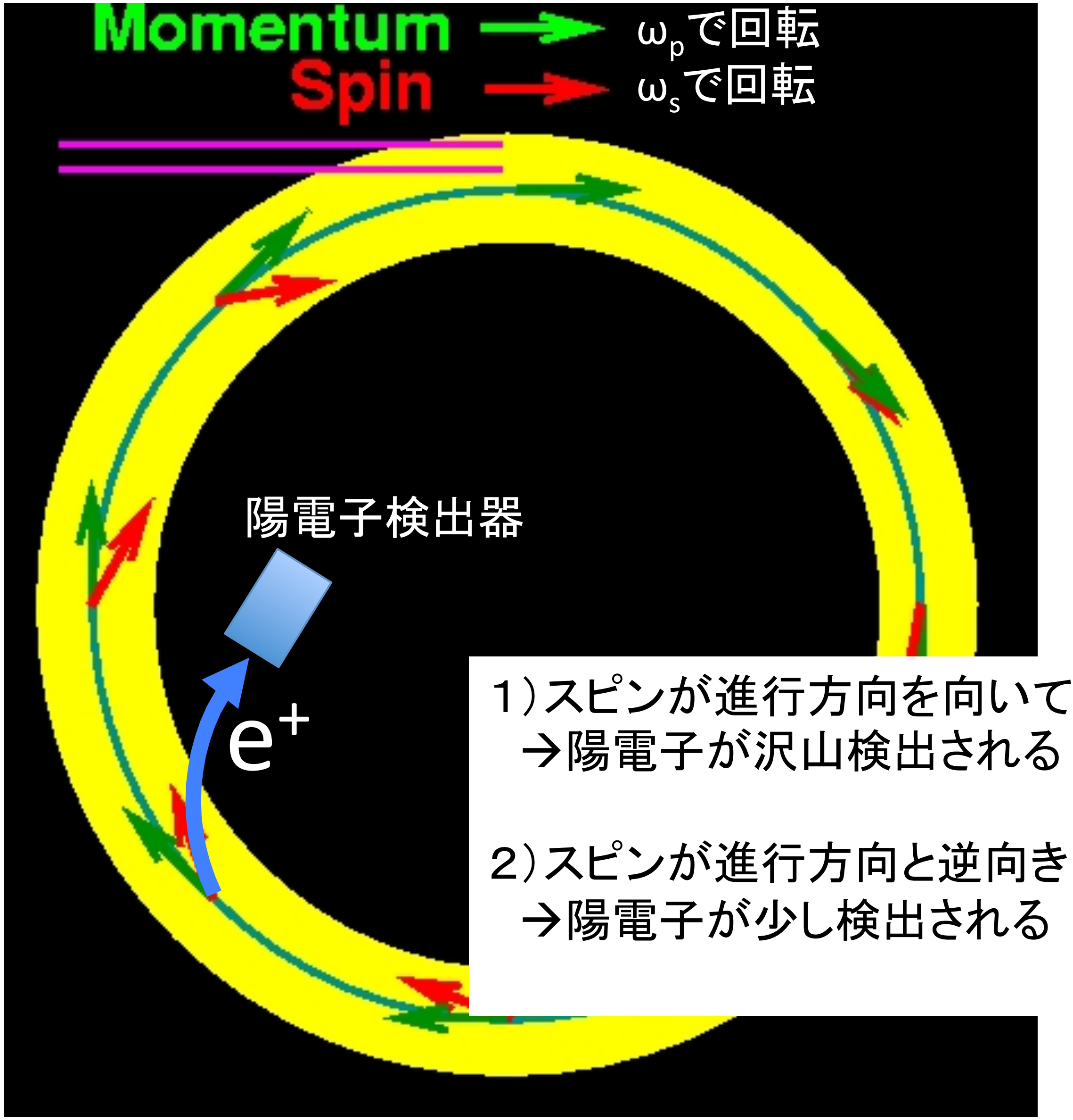


3. 崩壊陽電子を測定する。



崩壊陽電子の測定

一様磁場
（スクリーンに垂直）

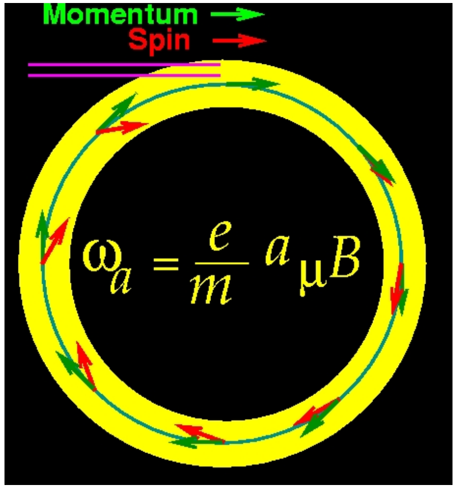


1）スピンが進行方向を向いているとき：
→陽電子が沢山検出される

2）スピンが進行方向と逆向きのとき：
→陽電子が少し検出される

muon g-2 and EDM measurements

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



general form of spin precession vector:

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

BNL E821 approach

γ=30 (P=3 GeV/c)

J-PARC approach

E = 0 at any γ

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

FNAL E989

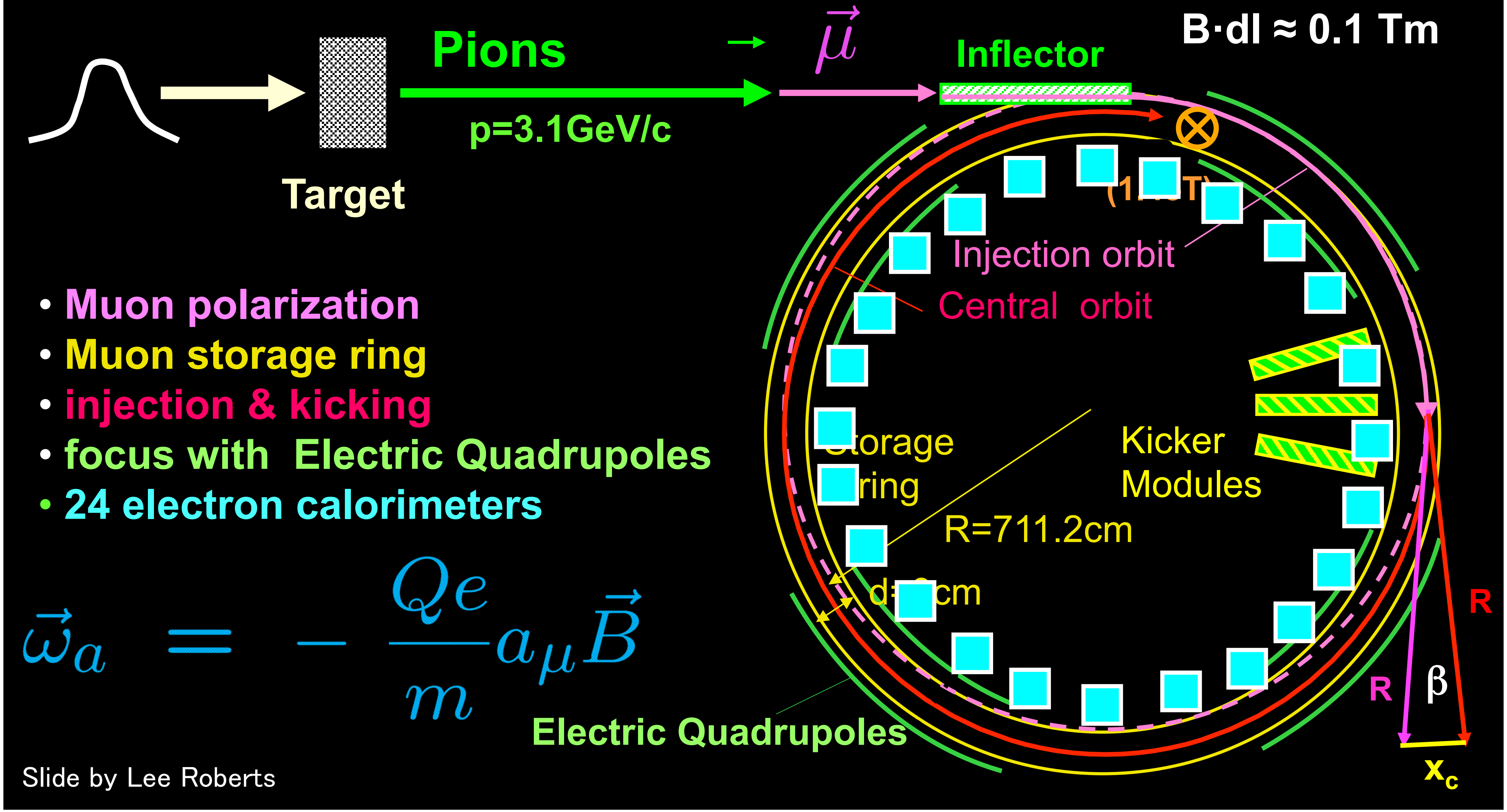
$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right]$$

J-PARC E34

BNL & FNAL

Experimental Technique

narrow bunch of protons



$x_c \approx 77$ mm

$\beta \approx 10$ mrad

B·dl ≈ 0.1 Tm

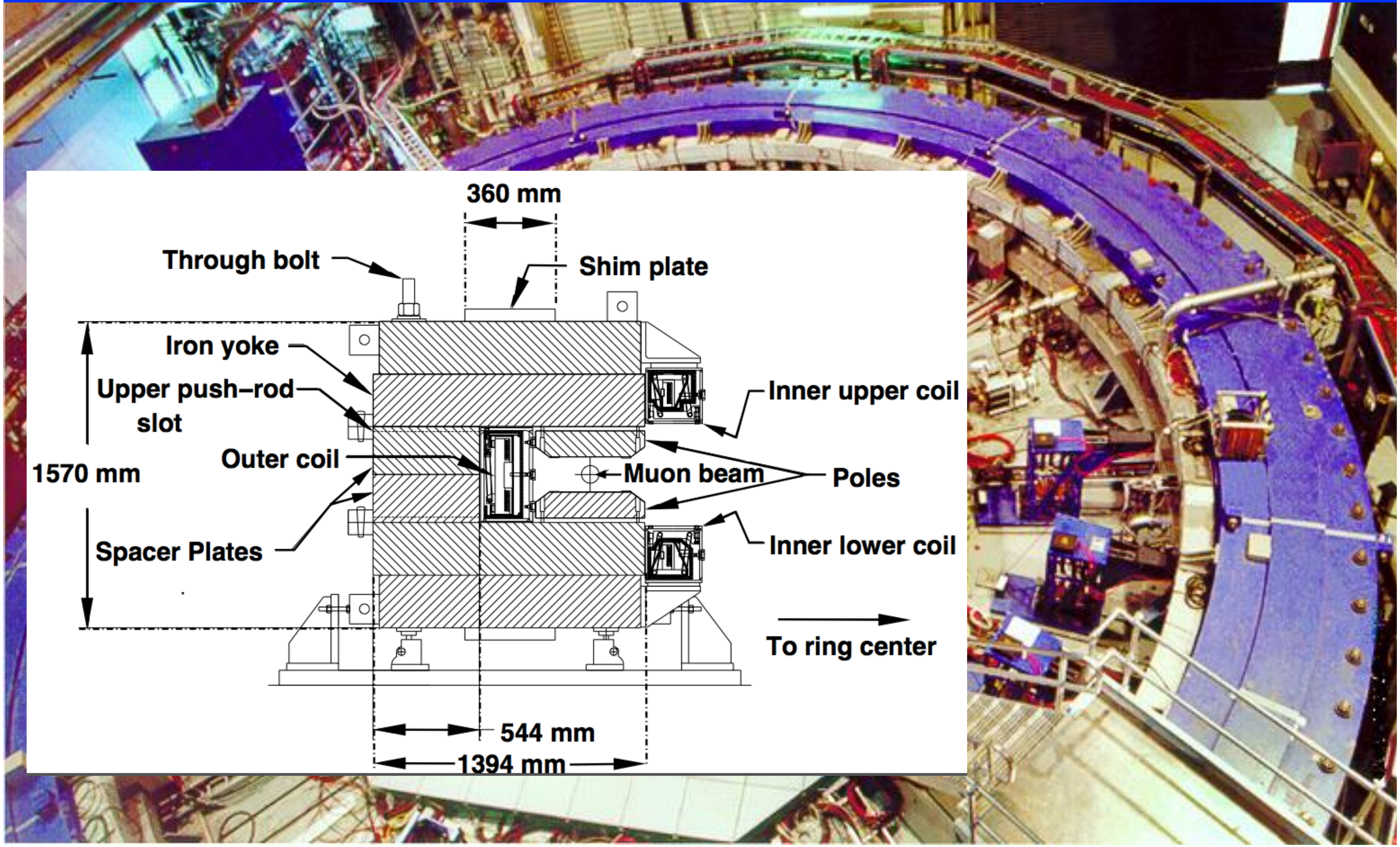
- Muon polarization
- Muon storage ring
- injection & kicking
- focus with Electric Quadrupoles
- 24 electron calorimeters

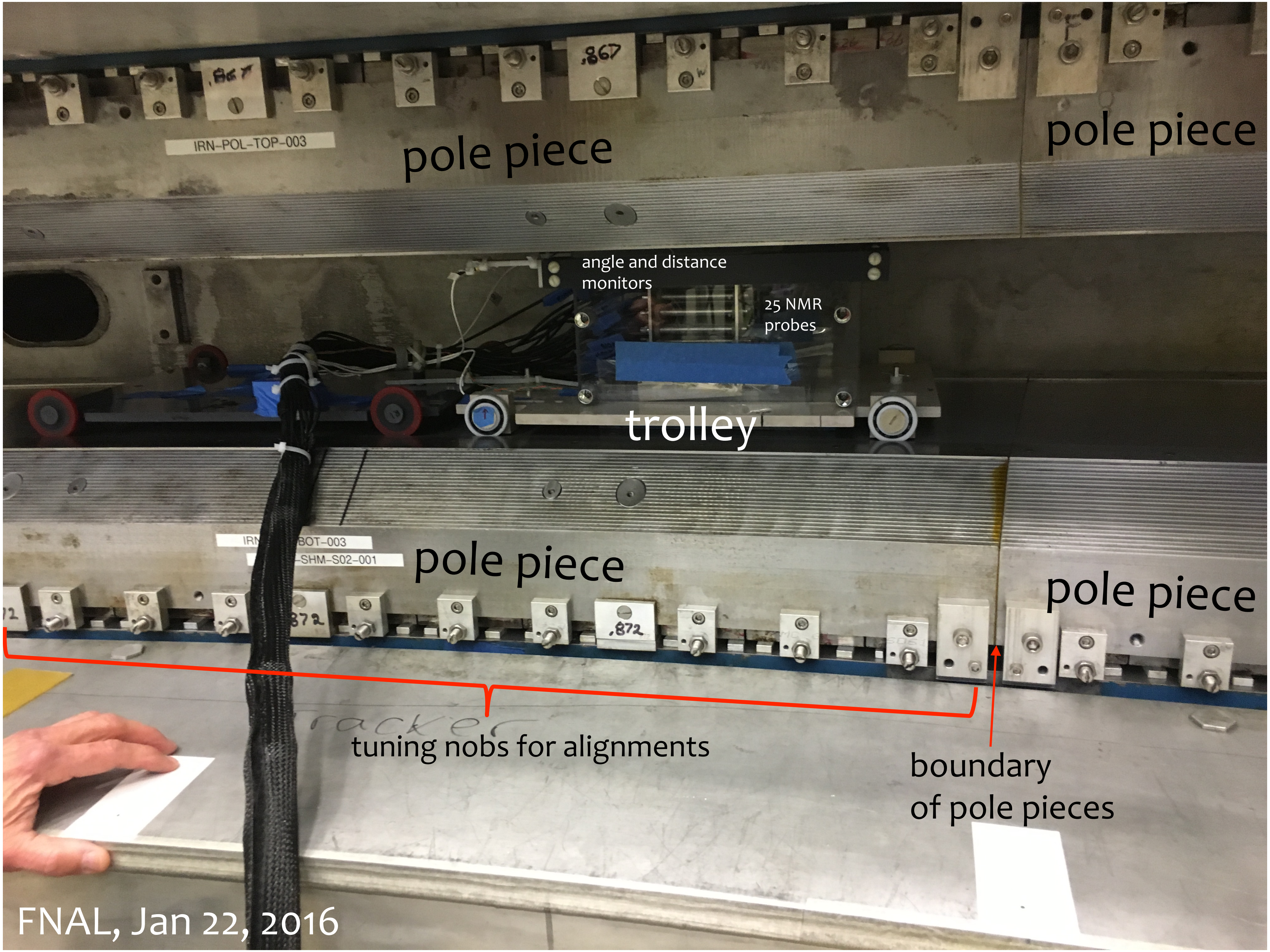
$$\vec{\omega}_a = -\frac{Qe}{m} a_\mu \vec{B}$$

Slide by Lee Roberts

Slide by Lee Roberts

The Magnet

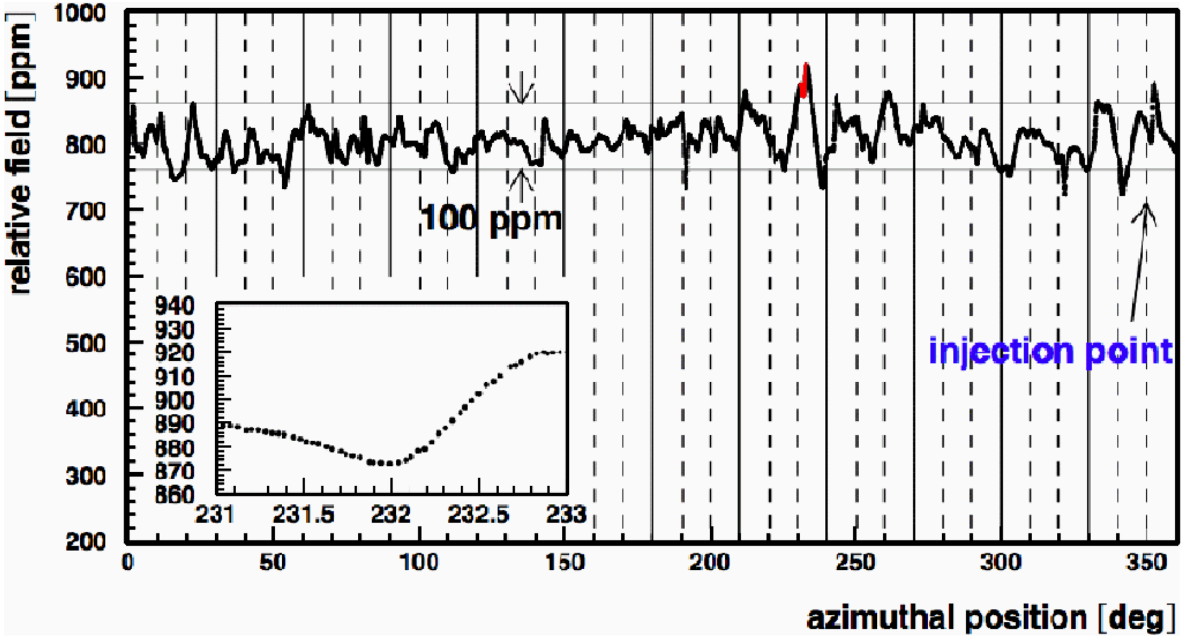




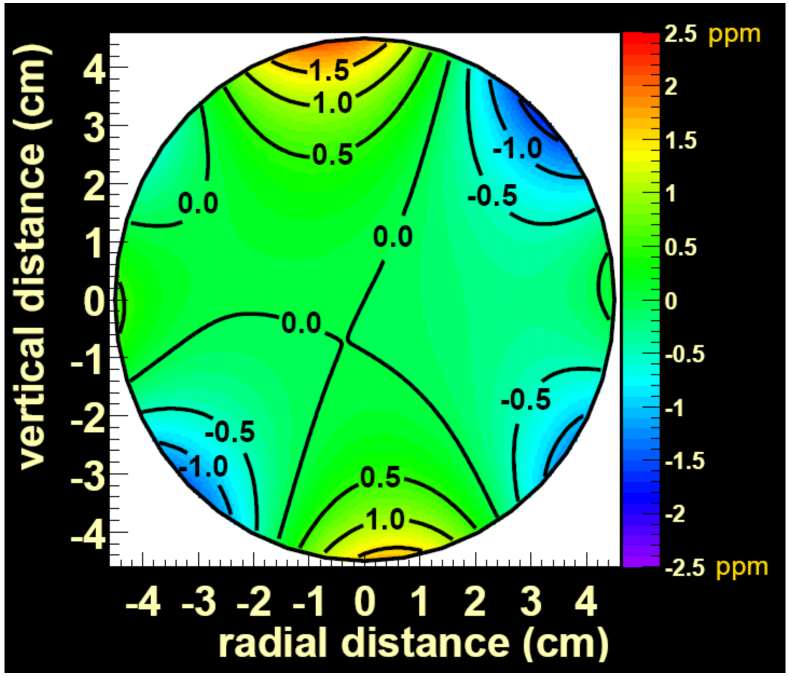
FNAL, Jan 22, 2016

BNL E821 : magnetic field map

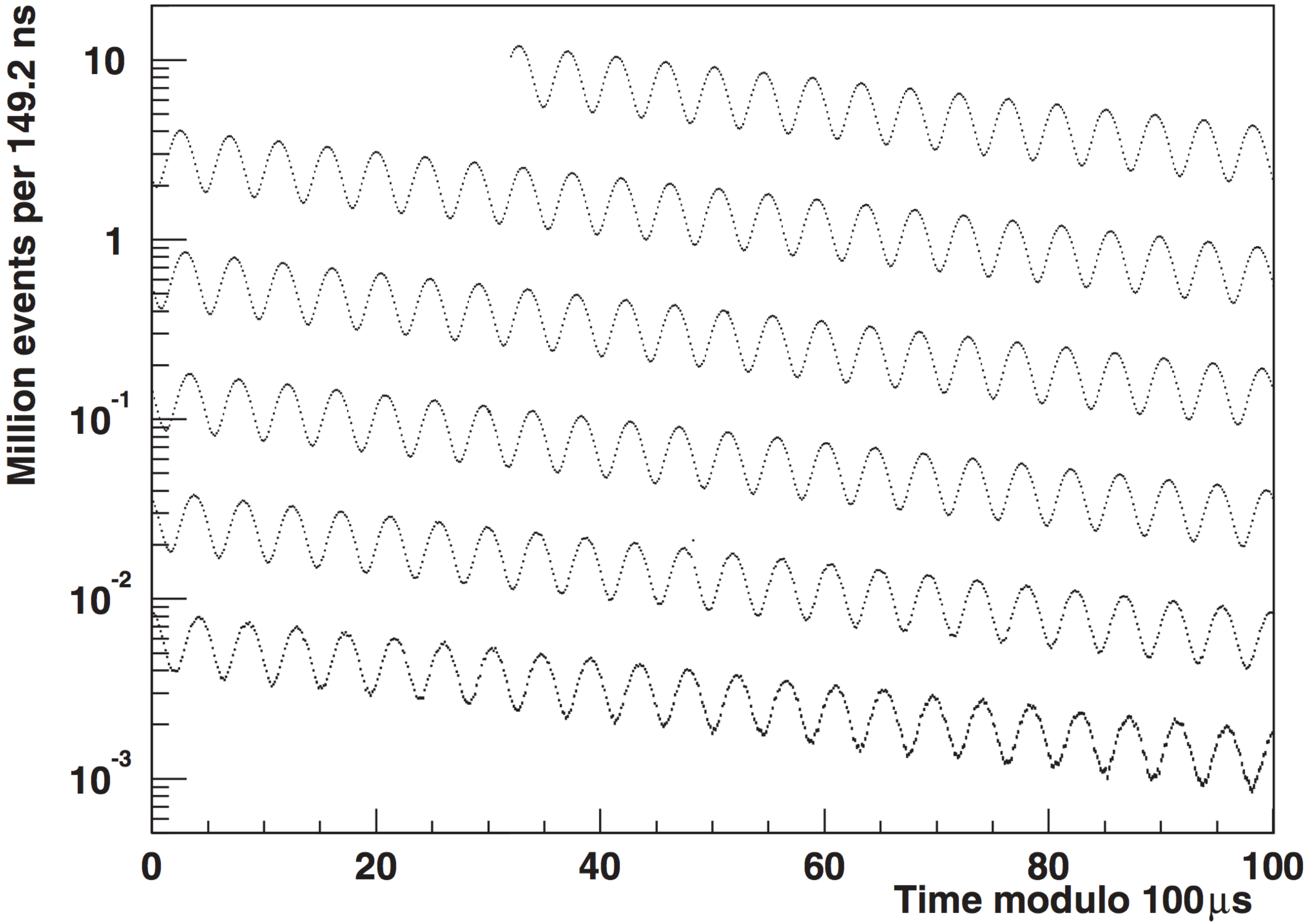
Local field map



Averaged field map



Positron time spectrum in BNL E821

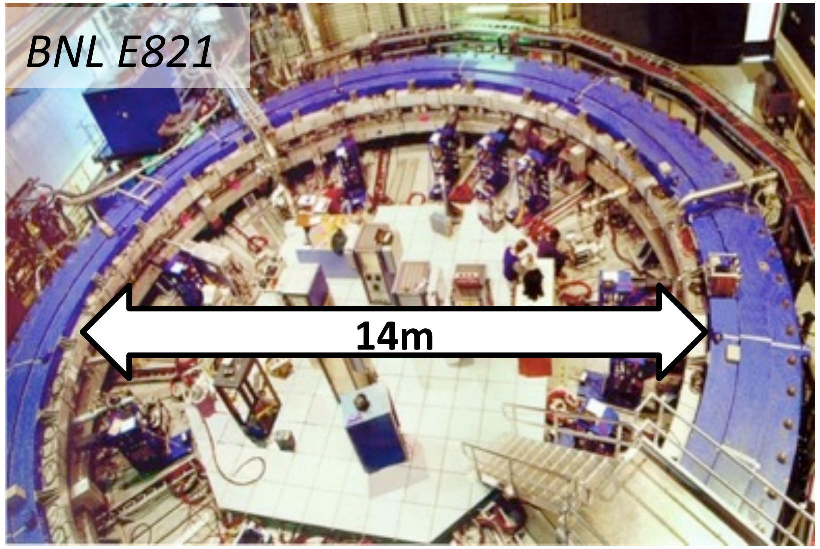


a_μ = 11 659 208.9 (6.3) x 10^{-10}

0.46ppm (stat.) + 0.28ppm (syst.) = 0.54ppm

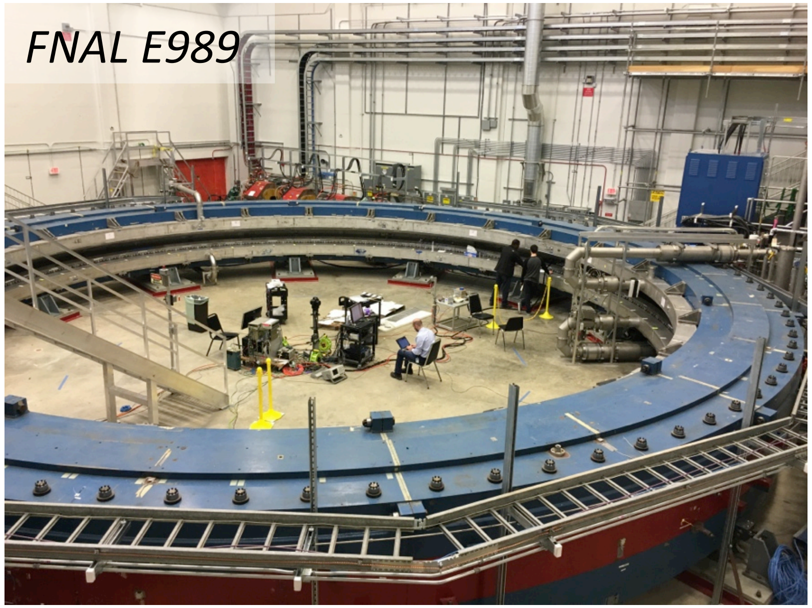
BNL E821 and FNAL E989

- **BNL E821 (completed)**
  - A “text book” experiment
  - reached precision of muon g-2 down to 0.54 ppm (stat. limited).

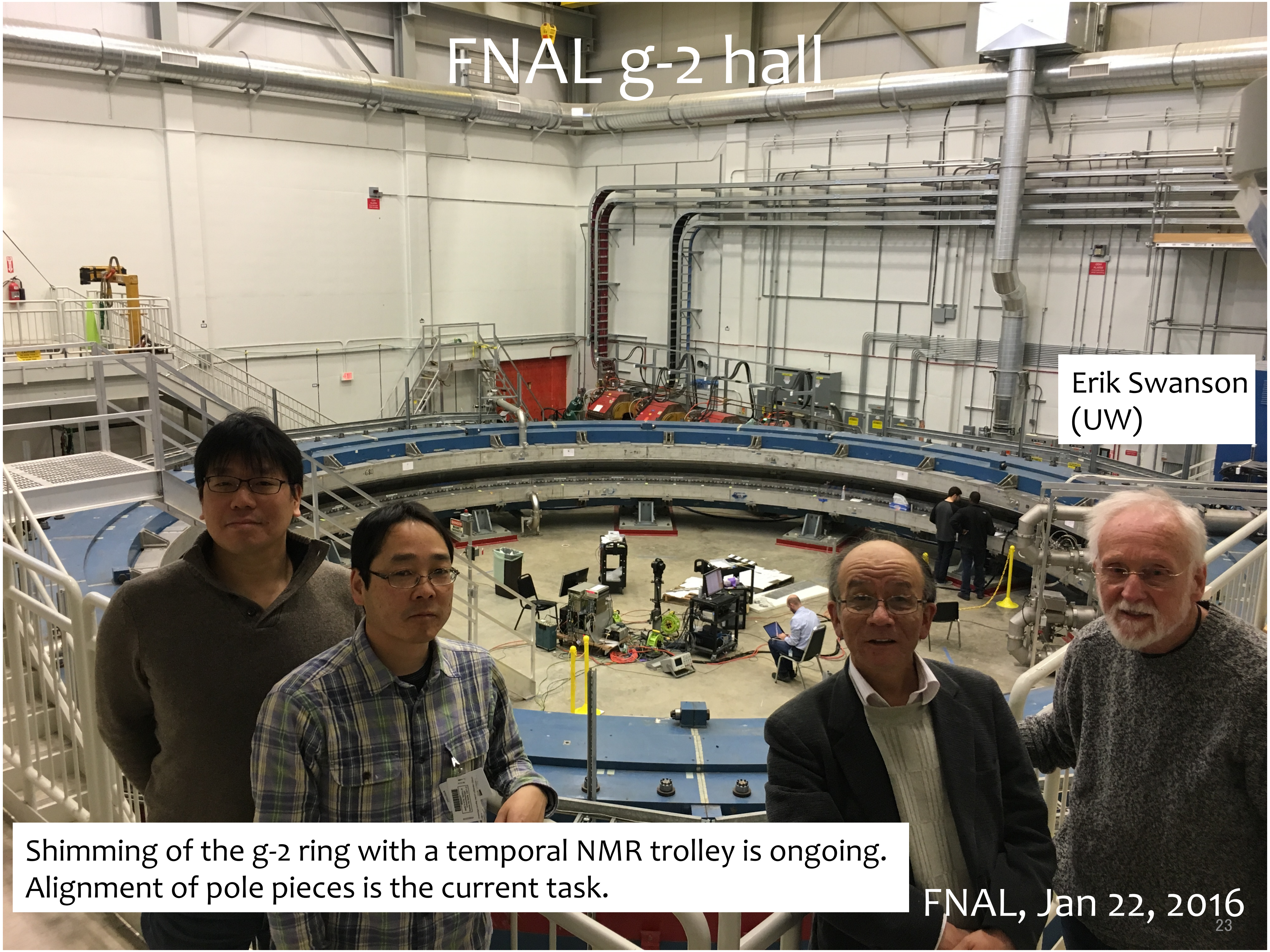


P= 3.1 GeV/c , B=1.45 T

- **FNAL E989 (in preparation)**
  - aims to reach 0.14 ppm by using the same experimental method and storage ring.
  - intends to start data taking from 2017



FNAL g-2 hall



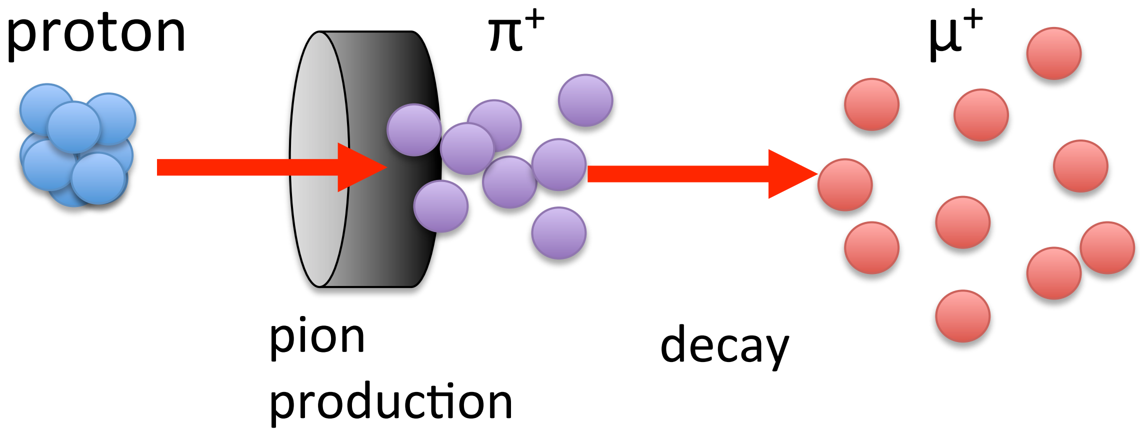
Erik Swanson
(UW)

Shimming of the g-2 ring with a temporal NMR trolley is ongoing.
Alignment of pole pieces is the current task.

FNAL, Jan 22, 2016

Muon beam

Conventional muon beam

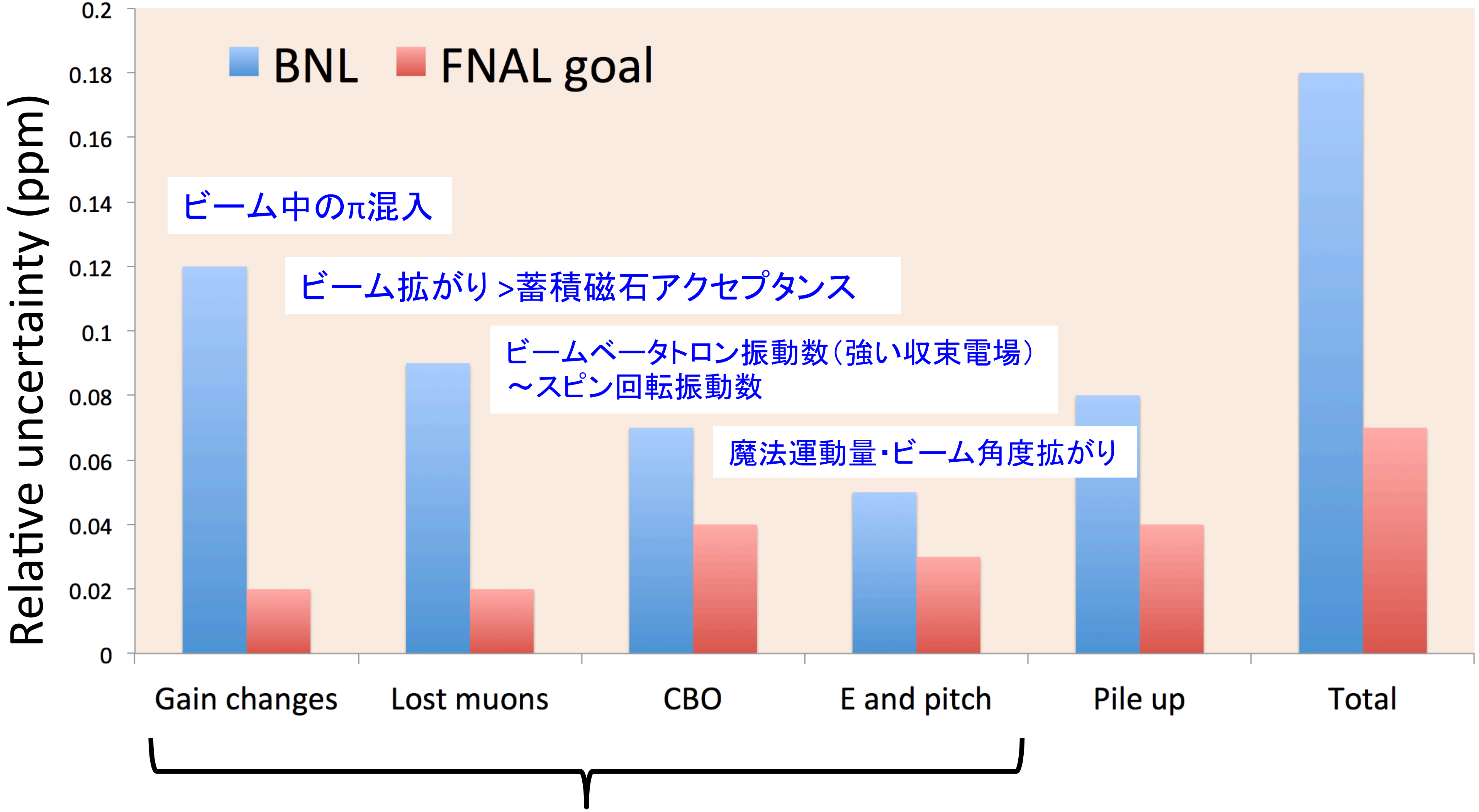


emittance

~1000π mm ·mrad

Strong focusing
Muon loss
BG π contamination

BNL/FNAL systematic uncertainties



ビーム中のπ混入

ビーム拡がり >蓄積磁石アクセプタンス

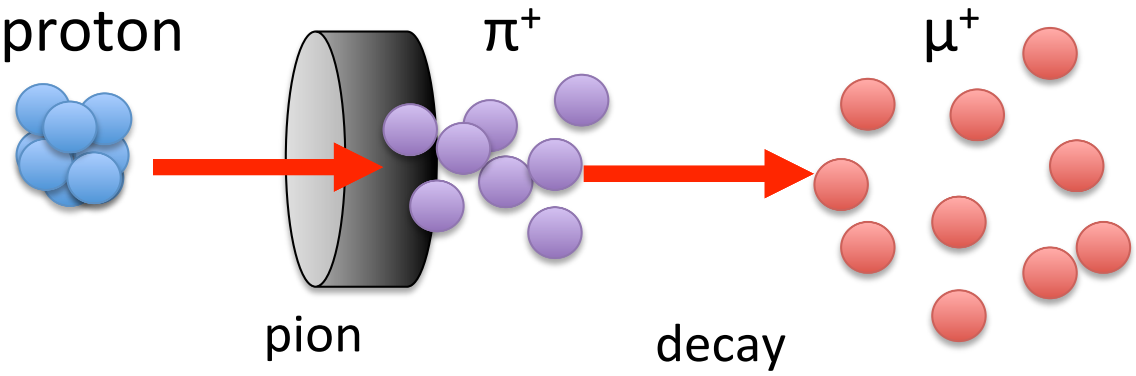
ビームベータトロン振動数（強い収束電場）
～スピン回転振動数

魔法運動量・ビーム角度拡がり

All attributed to **quality of muon beam**

Muon beam

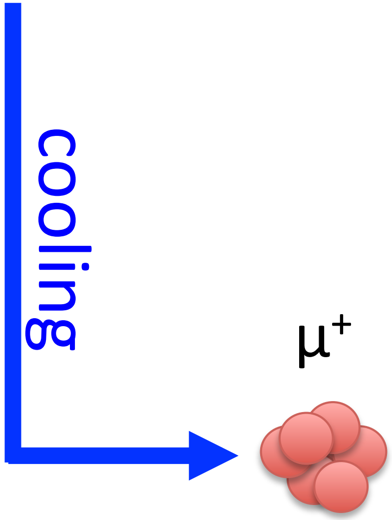
Conventional muon beam



emittance

$\sim 1000\pi$ mm·mrad

Strong focusing
Muon loss
BG π contamination



emittance

1π mm·mrad

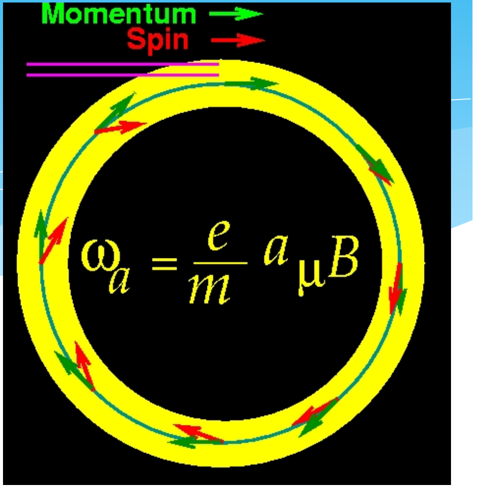
レーザーガイド補償光学用レーザー照射実験@理化学研究所(5/31)

Ultra-cold muon beam

Free from any of these

muon g-2 and EDM measurements

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



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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

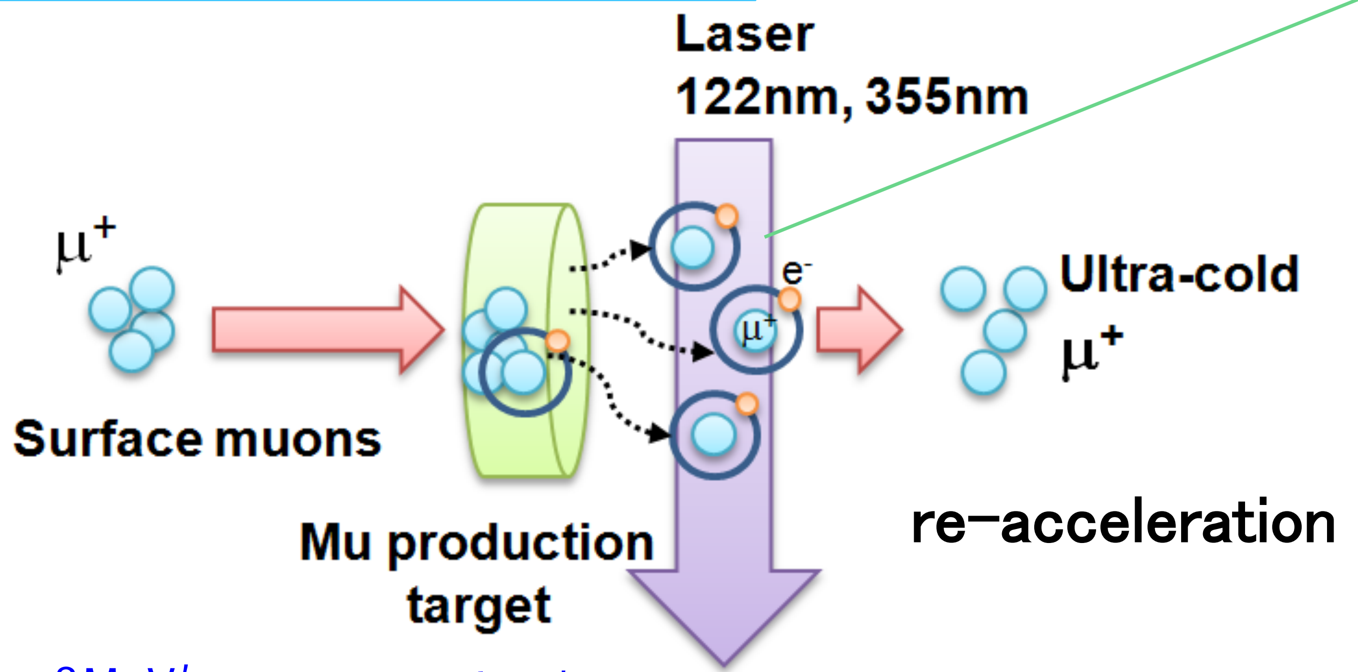
Requirement for zero E-field:

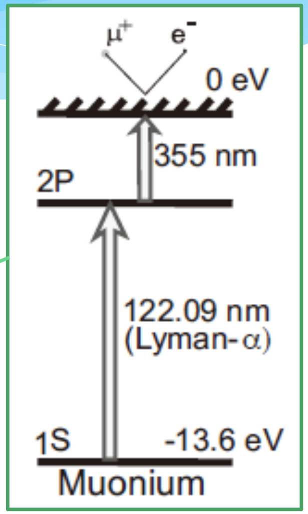
Muons should be kept stored without E-focusing

→ Beam with ultra-small transverse dispersion,

i.e. $\Delta p_T/p \sim 0$

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





p = 28MeV/c

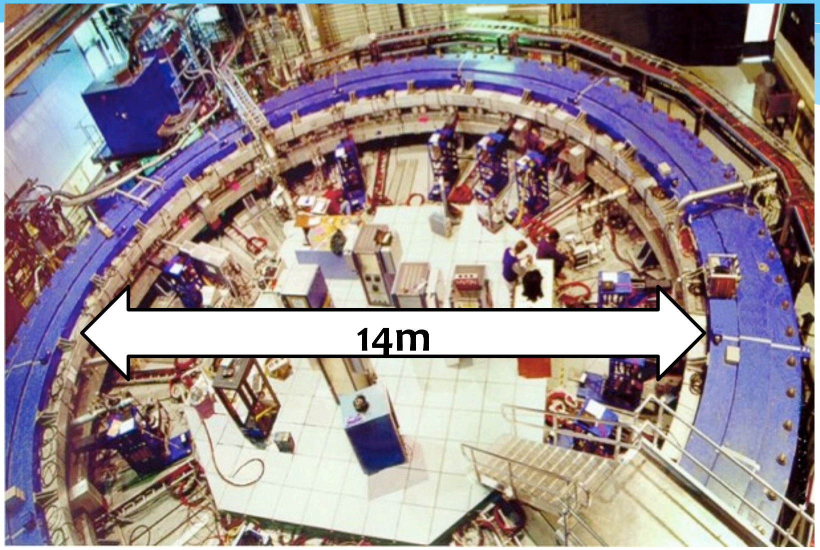
3 keV/c

300 MeV/c

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

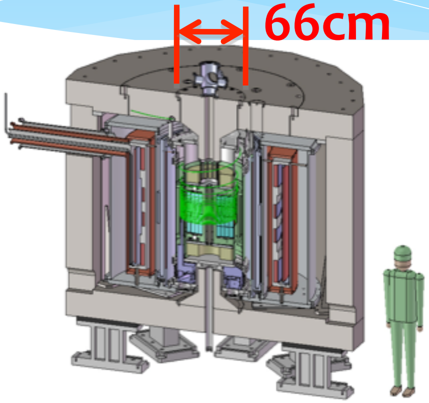
A compact muon g-2/EDM experiment

BNL E821 / FNAL E989



P= 3.1 GeV/c , B=1.45 T

J-PARC E34



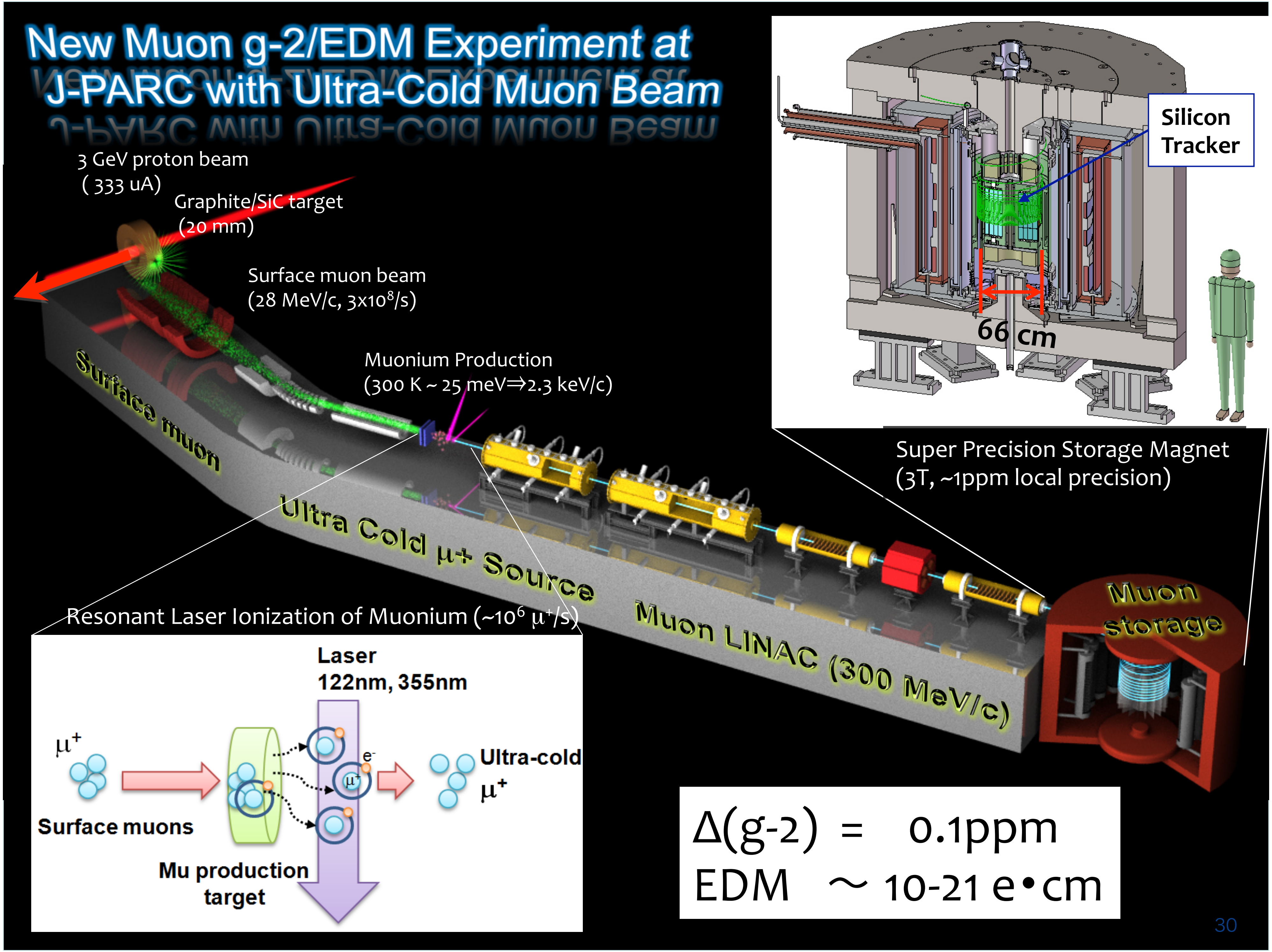
P= 0.3 GeV/c , B=3.0 T

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


図１：オープンMRI装置の概観図

Hitachi co.

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


3 GeV proton beam
(333 uA)

Graphite/SiC target
(20 mm)

Surface muon beam
(28 MeV/c, $3\mathrm{x}10^8$/s)

Muonium Production
(300 K ~ 25 meV⇒2.3 keV/c)

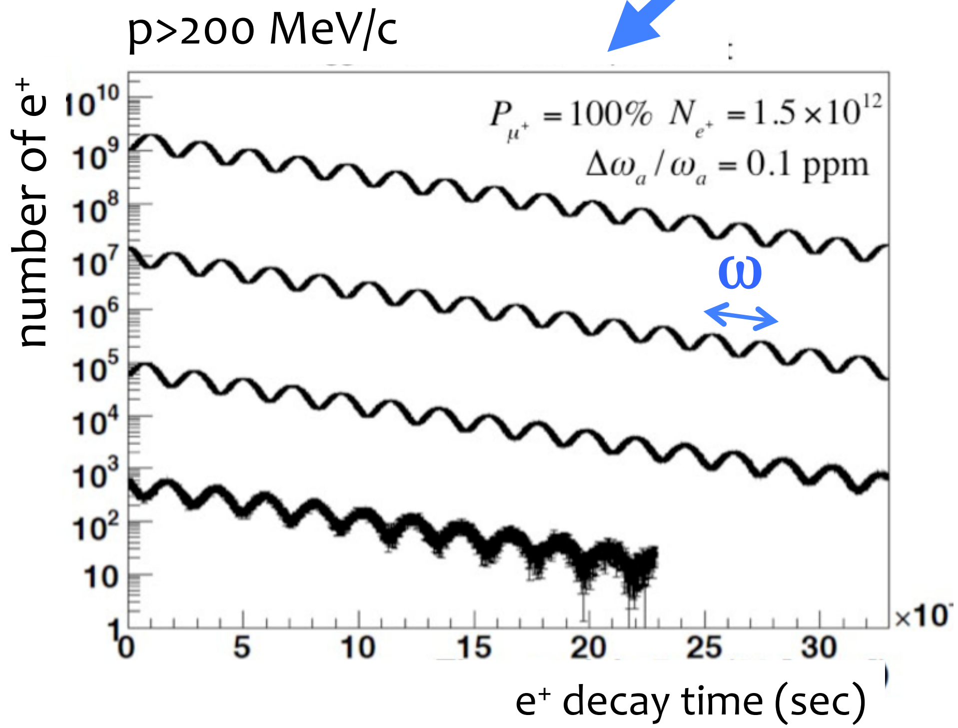
Super Precision Storage Magnet
(3T, ~1ppm local precision)

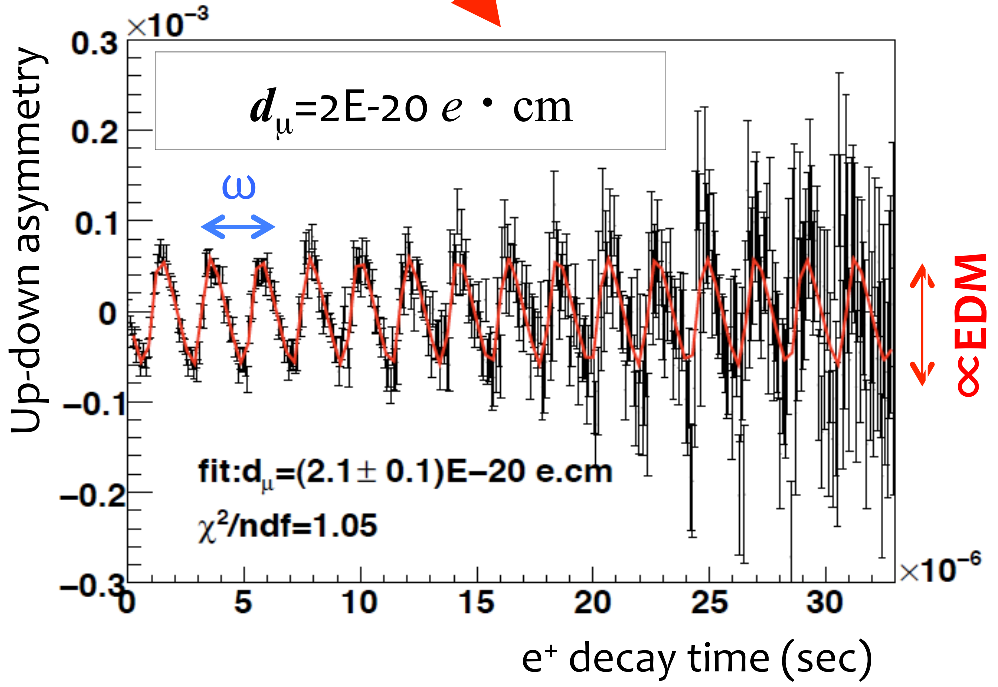
Resonant Laser Ionization of Muonium (~10^6 μ^+/s)

Δ(g-2) = 0.1ppm
EDM ～ 10-21 e•cm

Expected time spectrum of e⁺ in μ→e⁺νν̄ decay

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

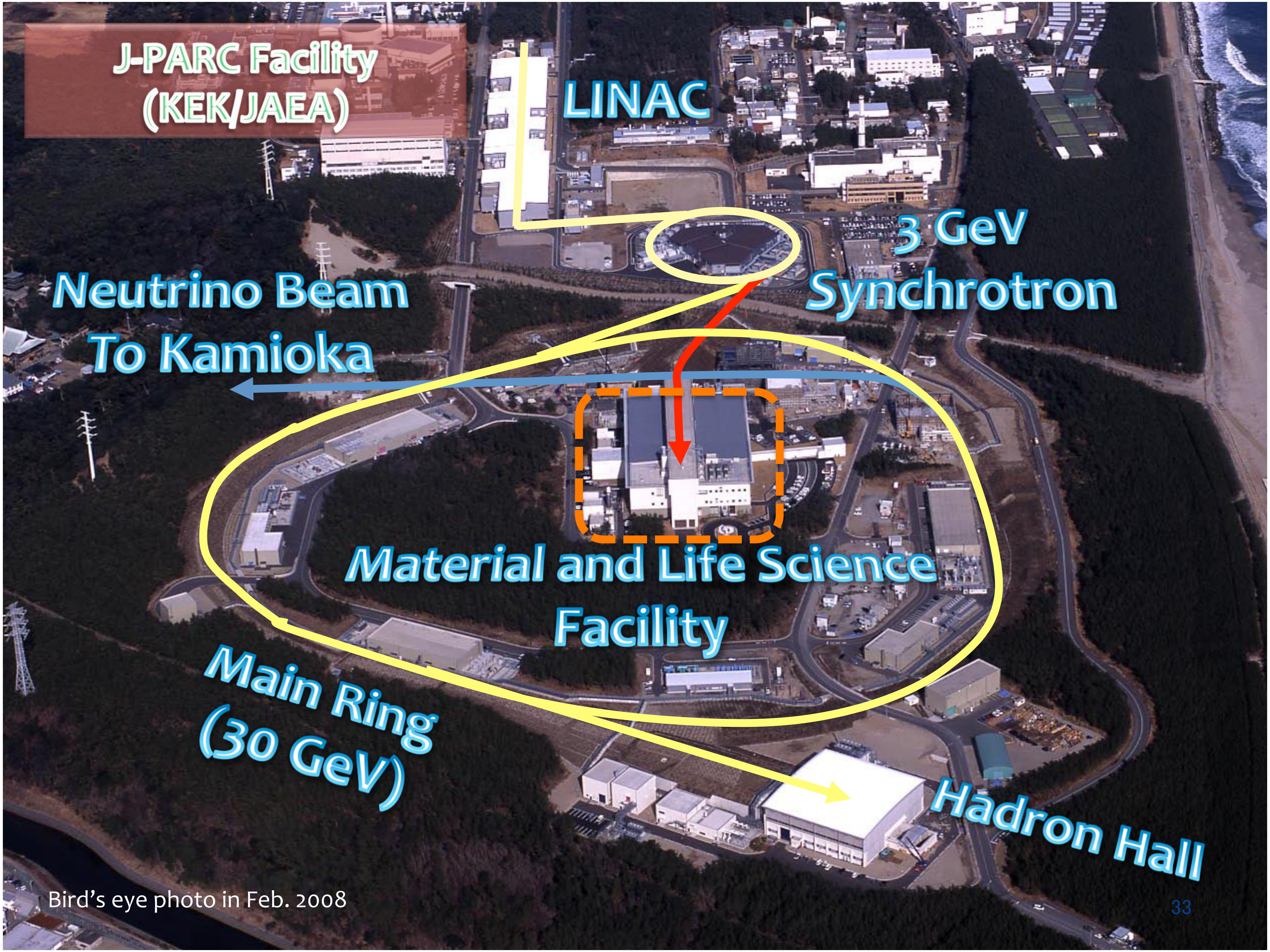




Comparison of experiments

	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}

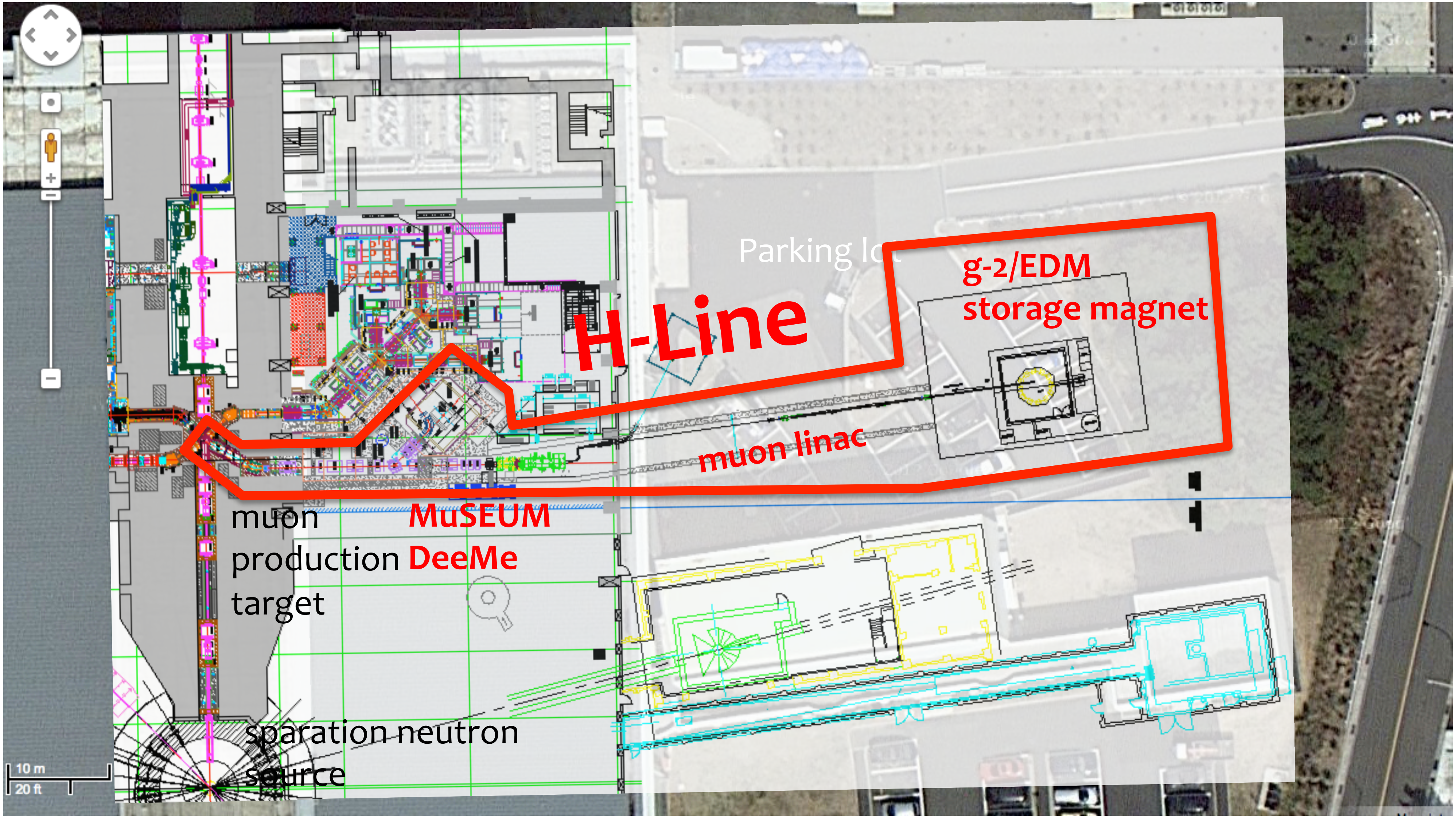
J-PARC Facility (KEK/JAEA)



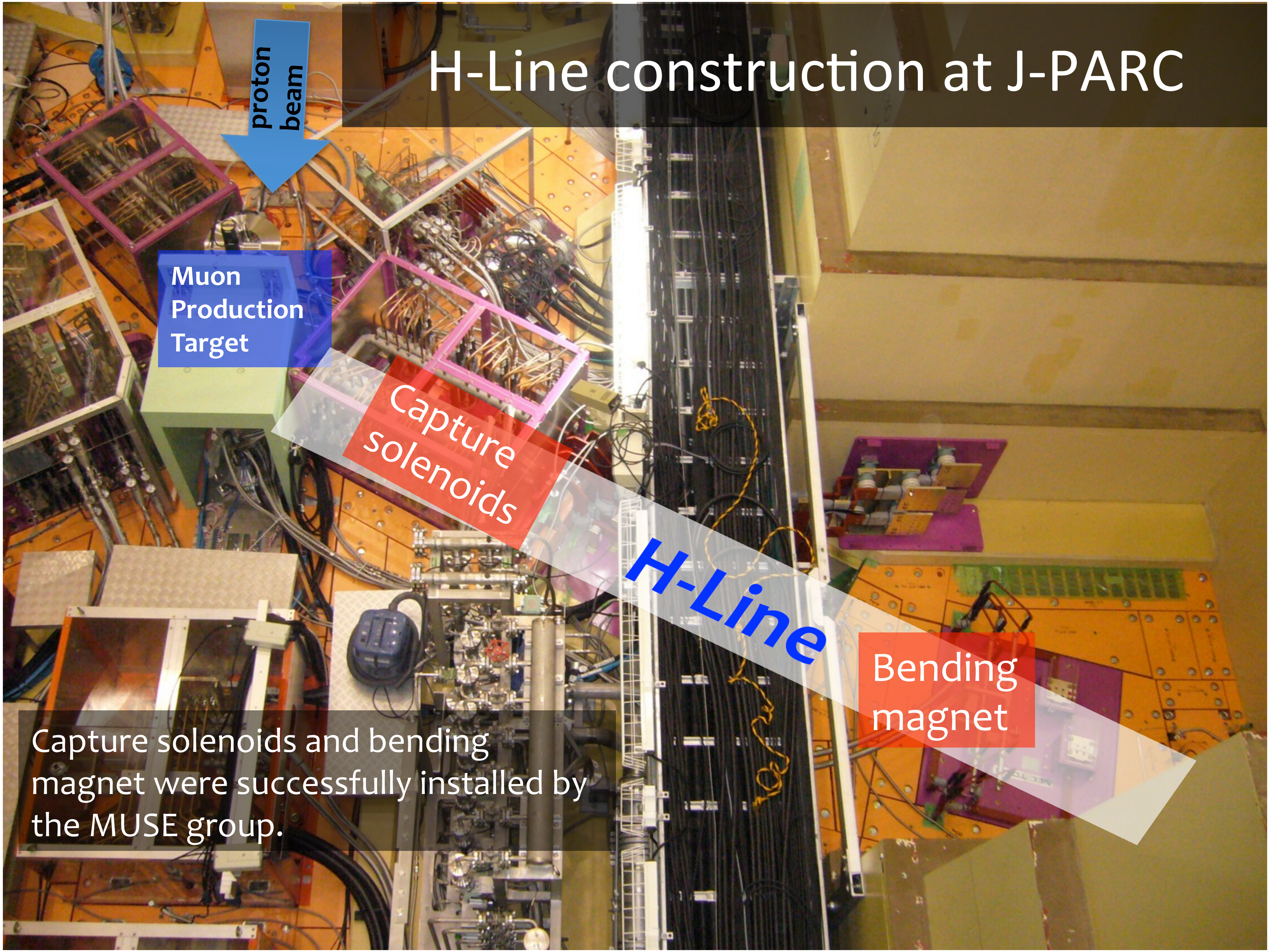
Bird's eye photo in Feb. 2008

Proposed experimental site

Material and Life science Facility in J-PARC



H-Line construction at J-PARC



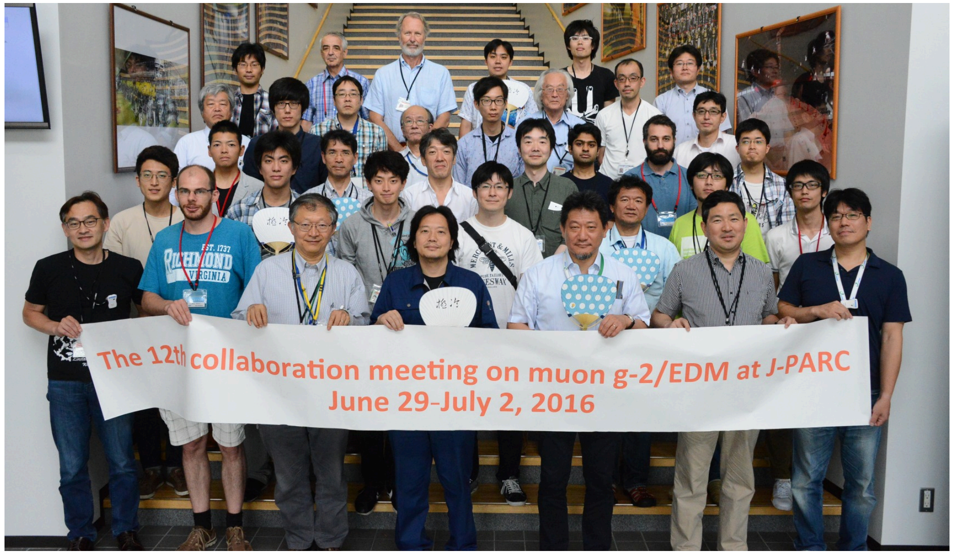
Capture solenoids and bending magnet were successfully installed by the MUSE group.

g-2/EDM collaborators

- Collaborators
  - Proposal (2009) 72
  - Conceptual Design Report (2011) 92
  - Technical Design Report (2015) 137 (16 graduate students)
  - (27 also in COMET)
- 9 countries, 49 institutions
  - Canda, Japan, Korea, UK, USA, France, Russia, Czech, China

CM10@J-PARC 2015.6 (50 participants)

CM12@J-PARC 2016.6 (65 participants)



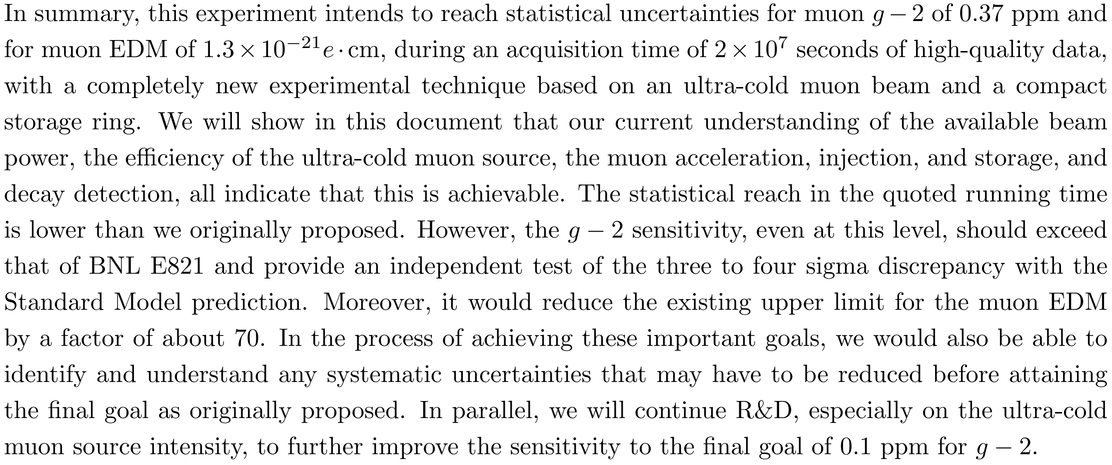
TDR

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

ミュオンg-2/EDMと極冷ミュオンビーム

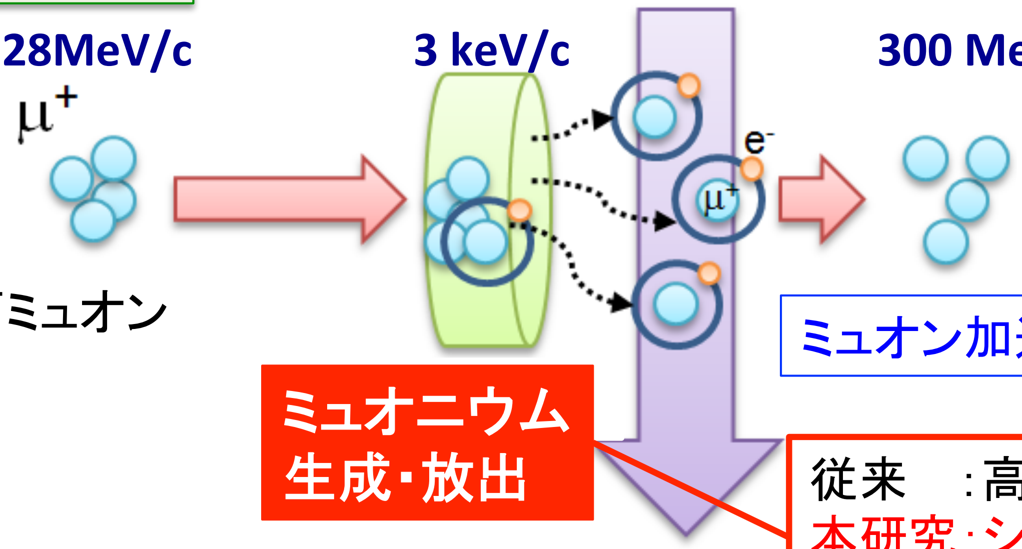
J-PARCで行う新しいミュオンg-2/EDM精密測定 www.g-2.kek.jp

- BNLが報告した標準模型からのズレ(3σ)の検証(0.1ppm)
- 全く新しいコンセプトで主要系統誤差要因を払拭
  - ゼロ電場
  - コンパクトな蓄積磁石(0.7 m << 14 m)
- 通常に比べてエミッタンスが1/1000程度小さいミュオンビーム（**極冷ミュオンビーム**）が必須

ミュオニウムMu (μ^+e^-)のレーザー共鳴イオン化

Nagamine et al. PRL 74 (1995)
P. Bakule et al. INM B266(2008)

Laser
122nm, 355nm



表面ミュオン

ミュオニウム生成・放出

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

極冷ミュオンビーム

ミュオン加速（世界初）

従来　：高温金属（タングステン箔）
本研究：シリカエアロゲルを用いて
　　　　室温で高効率生成に成功

ミューオニウム生成標的

- 様々な条件で**シリカエアロゲルからのMu生成を評価**

P. Bakule, et al., PTEP 103C0 (2013)
G. Beer, et al., PTEP 091C01 (2014)
修士論文：廣田誠子(2010)・北村遼(2013)

- シリカエアロゲルにレーザー穴加工を施すことで、**Mu生成量を10倍増加することに成功**

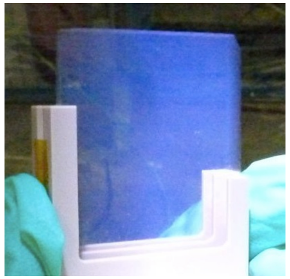
RIKEN-KEK-TRIUMFプレスリリース(2015)

  - J-PARCのミュオンビームで結果の再現
  - 穴構造の最適化によりさらに向上する可能性を探求 (J-PARCで試験予定)

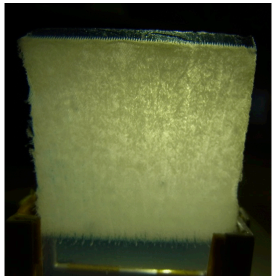
- この結果に基づき、レーザーイオン化試験を準備中(RIKEN-RAL)（岡田（理研）他）

- **先行実験BNL-E821を上回る感度で測定可能なレベルに達成。→TDRの提出(2015)**

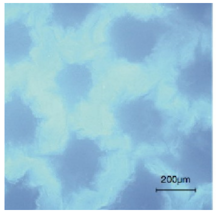
通常のエアロゲル
（○）

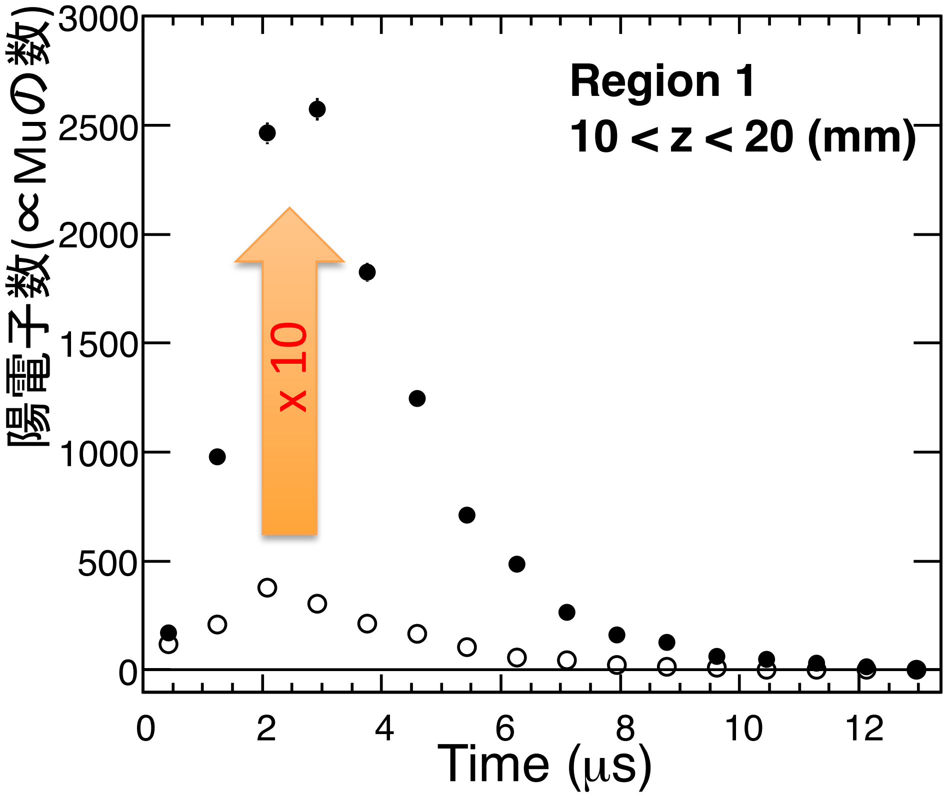


穴加工を施した
エアロゲル（●）



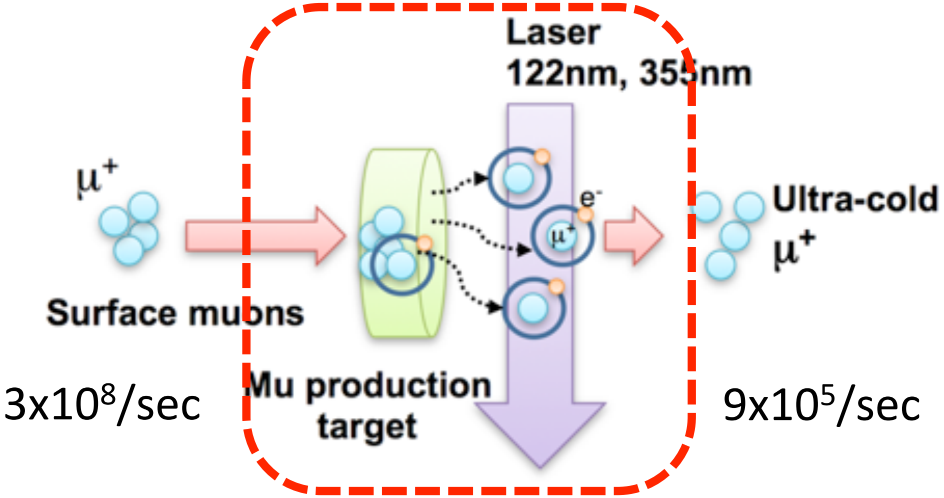
エアロゲル：
田端（千葉大）
穴加工：
大石（理研（当時））



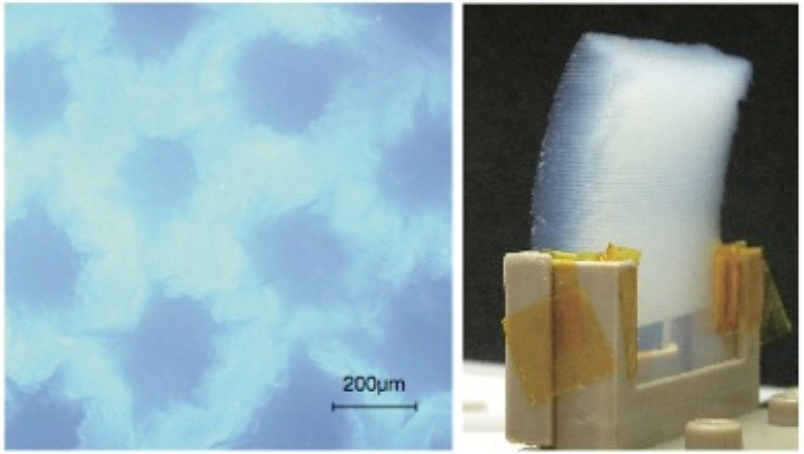


Muonium production

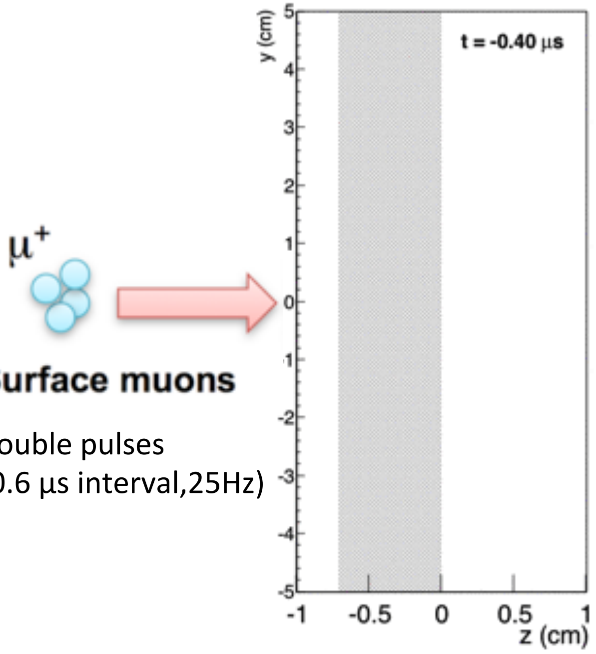
RIKEN, TRIUMF, UVic,
Chiba, Korea U, KEK



Mu production target
(laser-ablated silica aerogel)

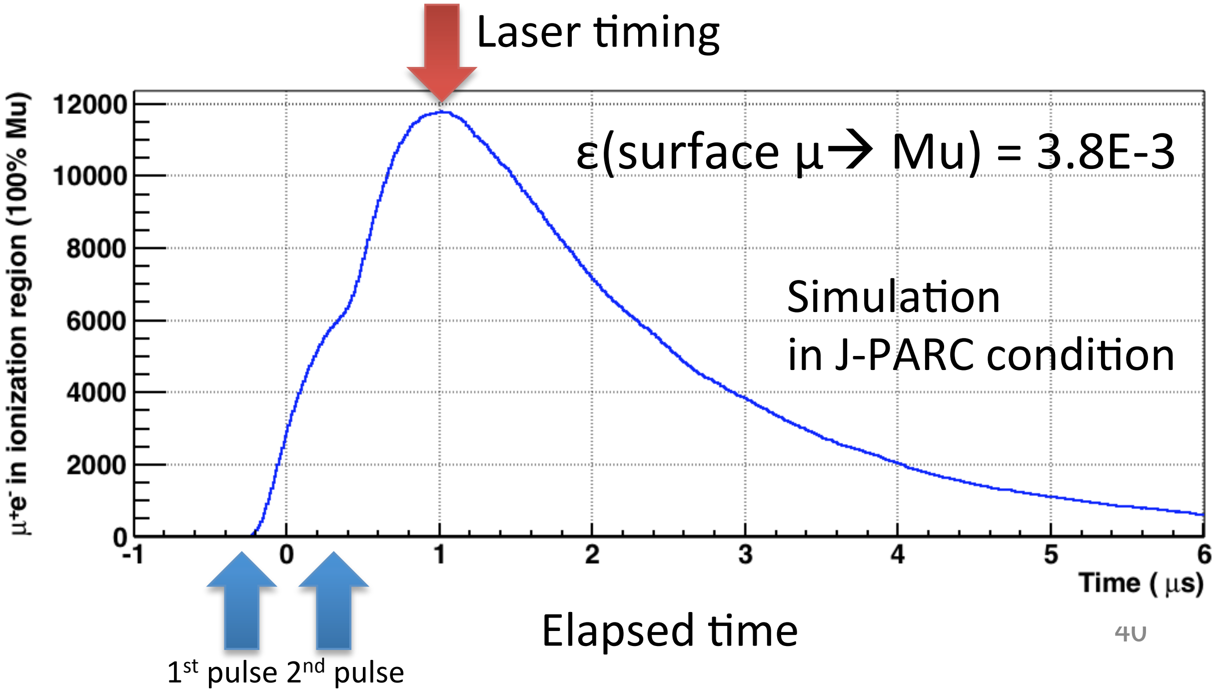


G. Beer et al., Prog.Theor.Exp.Phys. (2014)091C01



double pulses
(0.6 μs interval,25Hz)

G. Marshall

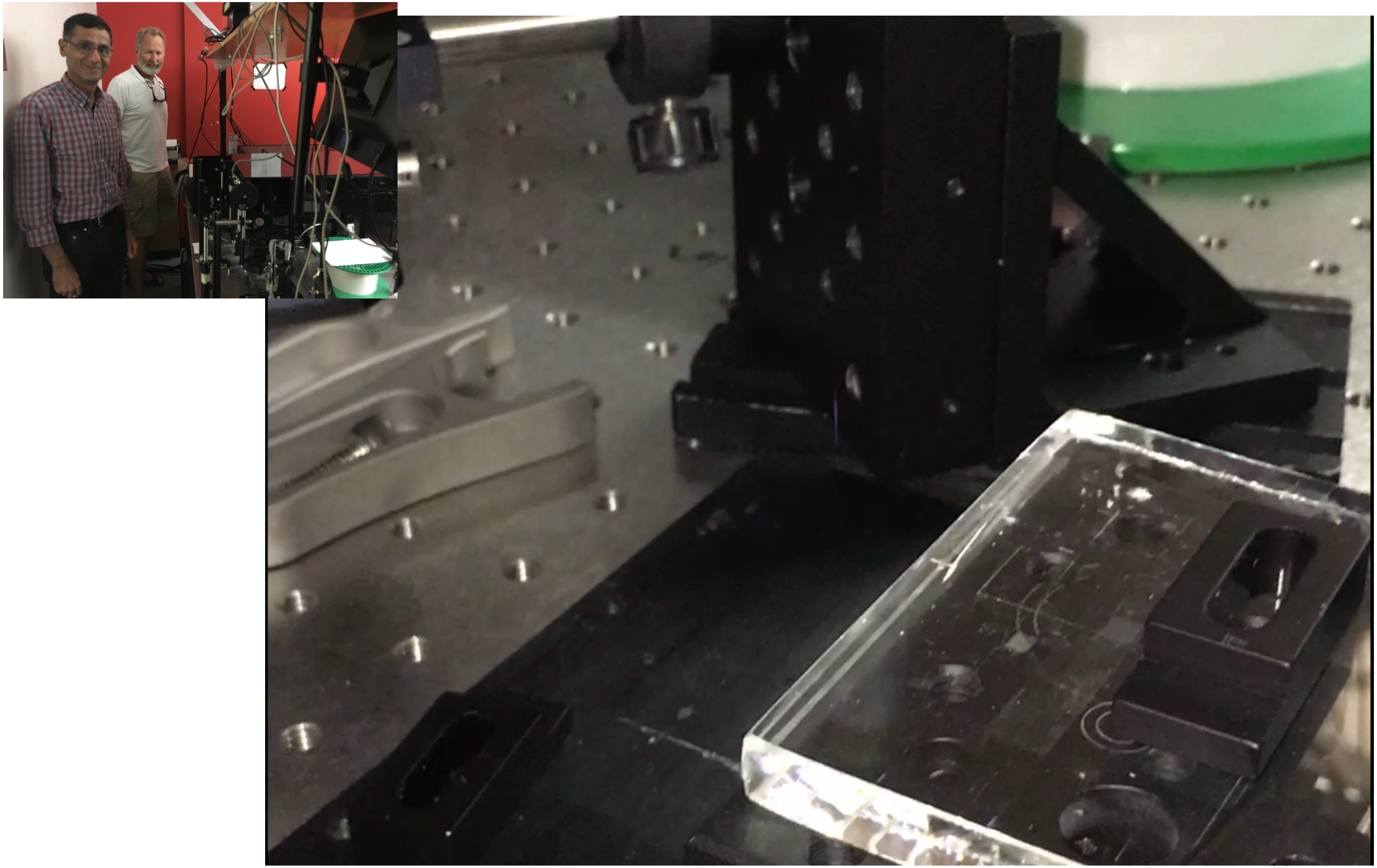


ε(surface μ→ Mu) = 3.8E-3

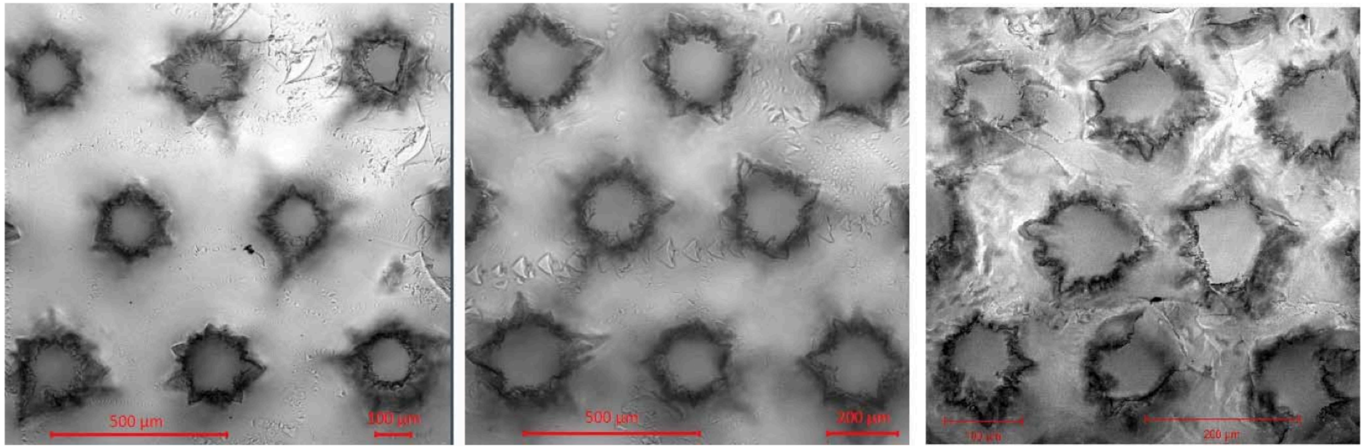
Simulation
in J-PARC condition

Elapsed time

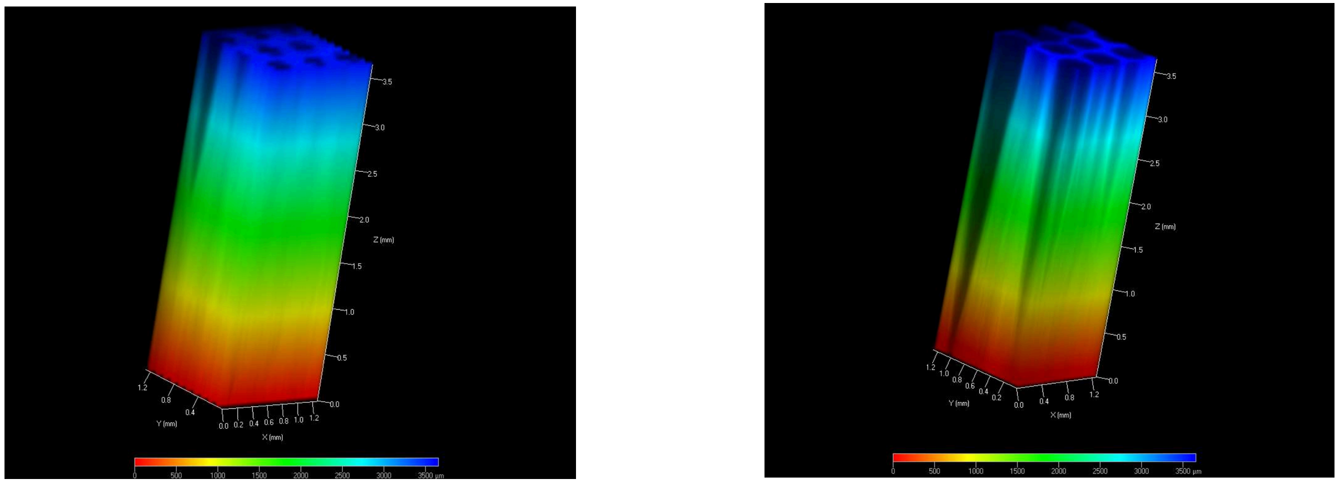
Laser set up at UBC (S. Kamal)



New laser-ablated samples in preparation



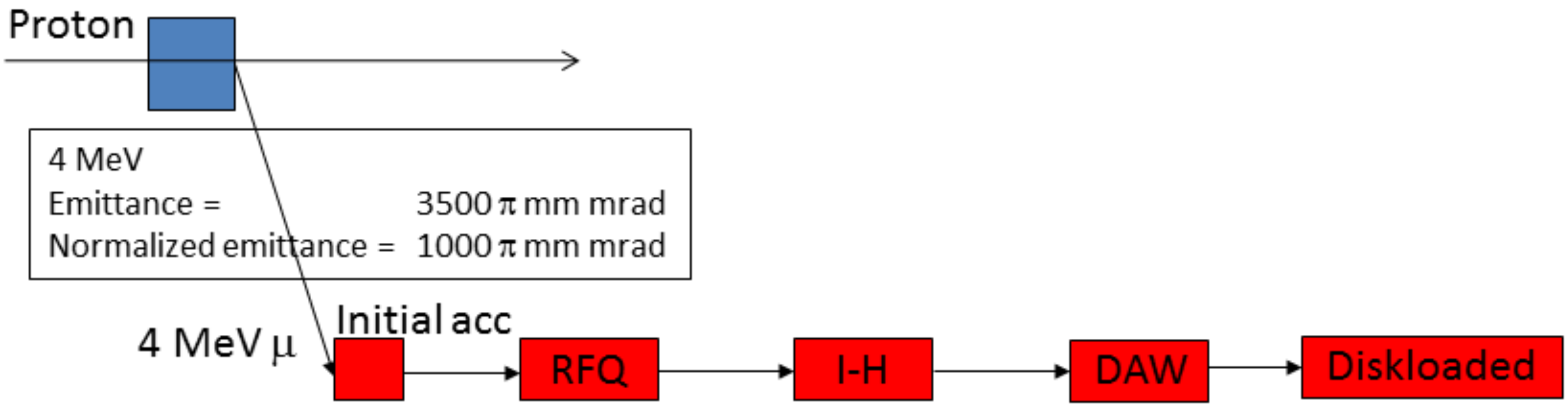
S. Kamal



S. Kamal

To be evaluated at TRIUMF in this November

Status of muon accelerator development

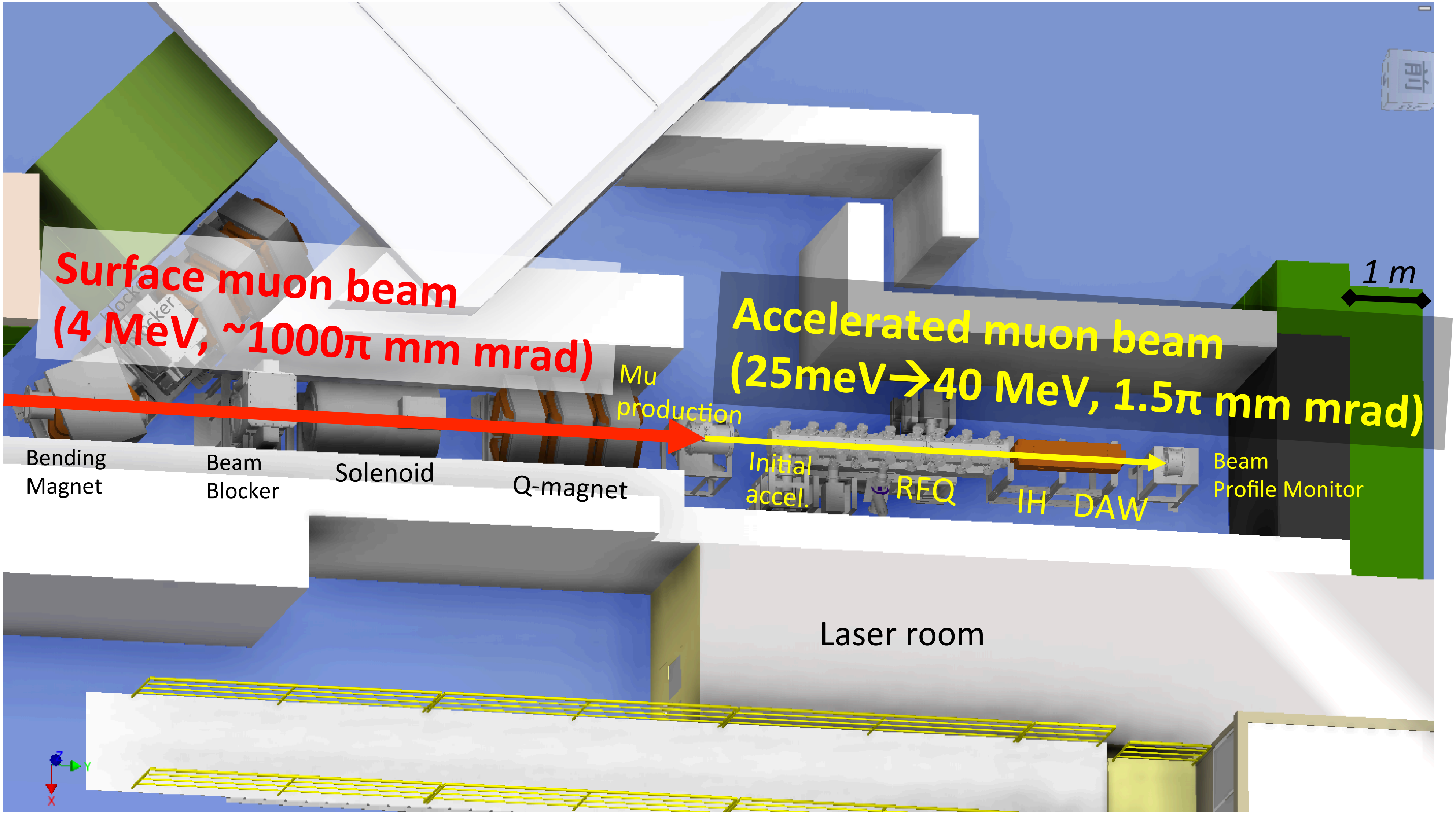


	5.7keV	340 keV	4 MeV	50MeV	200 MeV
βγ	0.01	0.08	0.278	0.98	2.71
Emittance(mm mrad)	150	19	5.4	1.5	0.55
Normalized emittance	1.5	1.5	1.5	1.5	1.5

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**

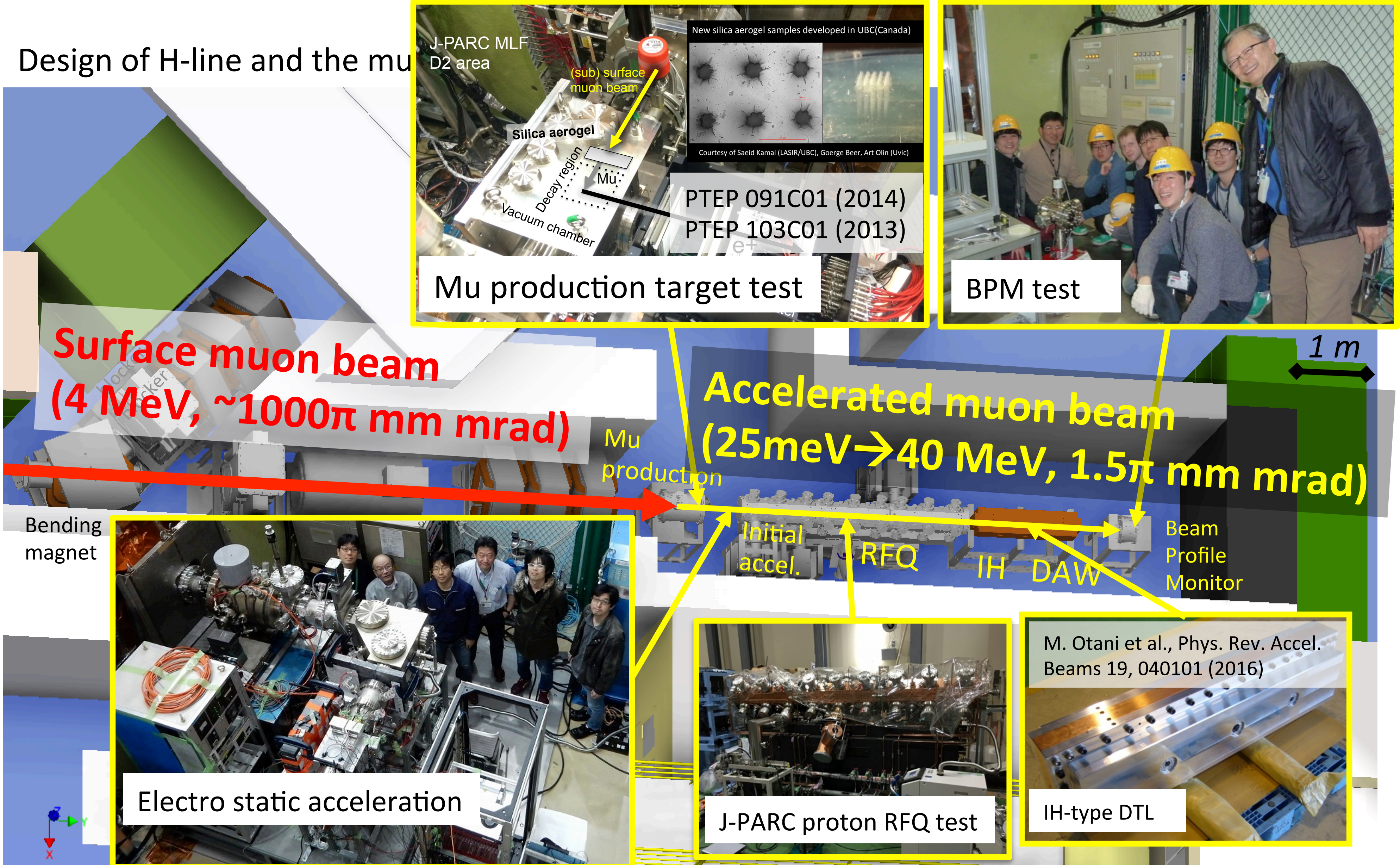
Ultra-cold muon beam at H-line

Design of H-line and the muon acceleration test



Ultra-cold muon beam at H-line

Design of H-line and the mu



New silica aerogel samples developed in UBC(Canada)

Courtesy of Saeid Kamal (LASIR/UBC), Goerge Beer, Art Olin (Uvic)

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

Mu production target test

BPM test

Surface muon beam
(4 MeV, ~1000π mm mrad)

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

Electro static acceleration

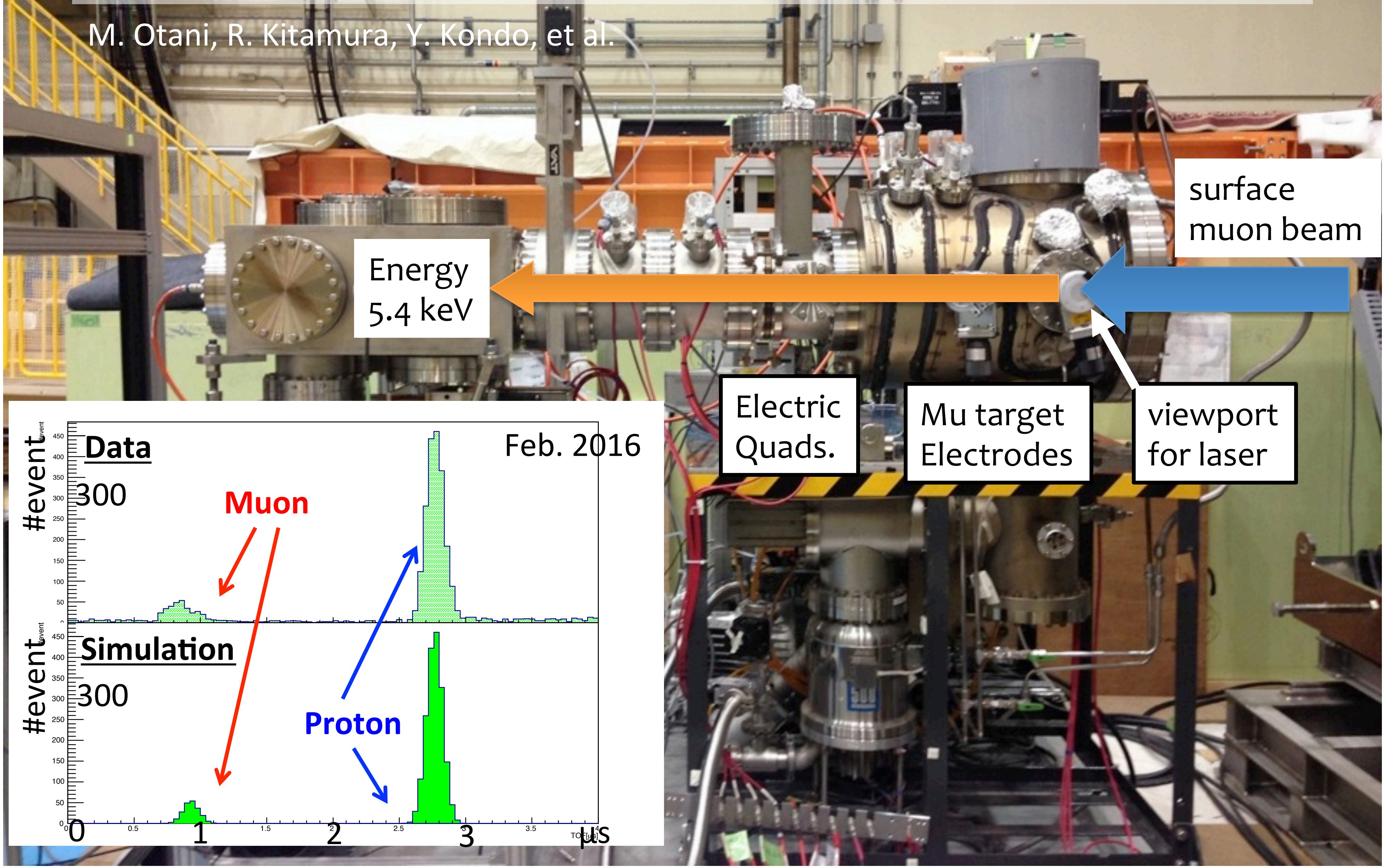
J-PARC proton RFQ test

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

IH-type DTL

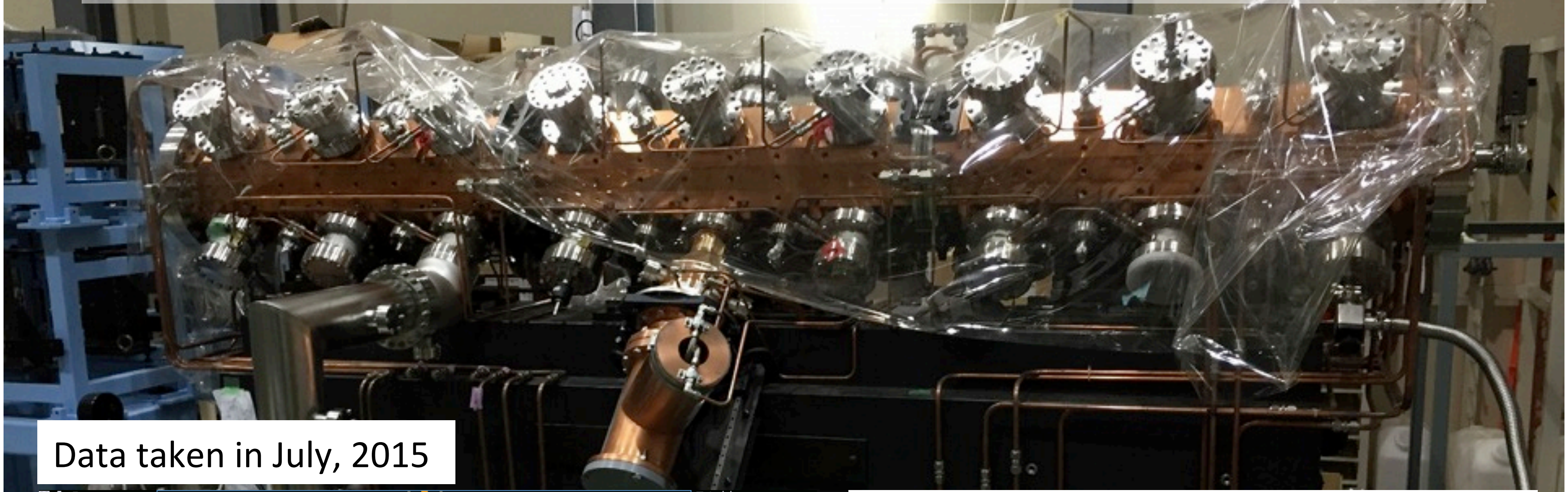
Electro-static acceleration

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

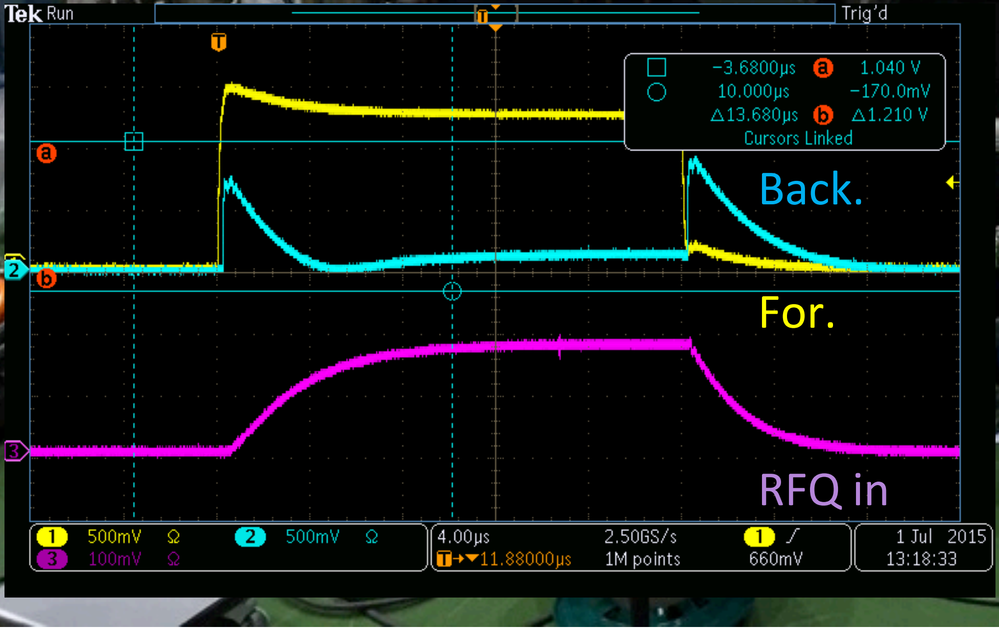


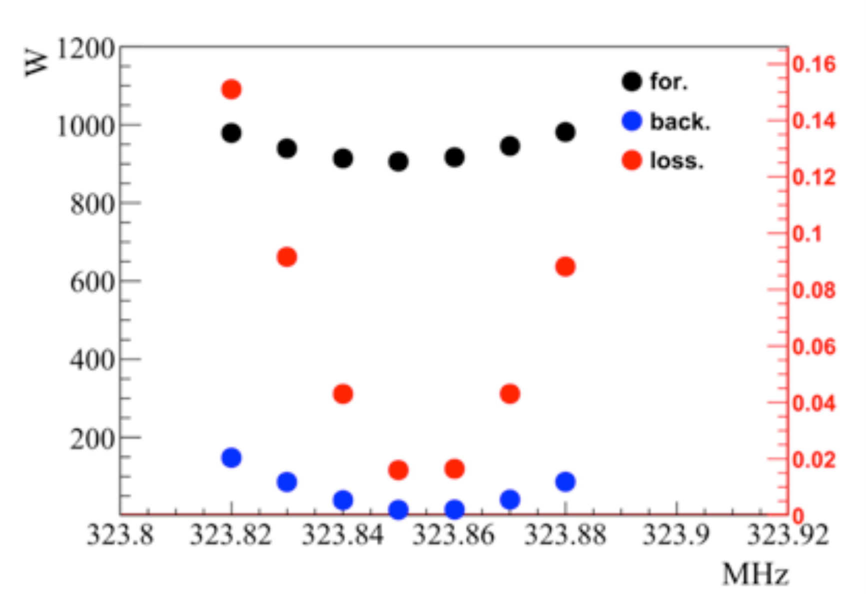
Y. Kondo, M. Otani

RFQ offline test at J-PARC



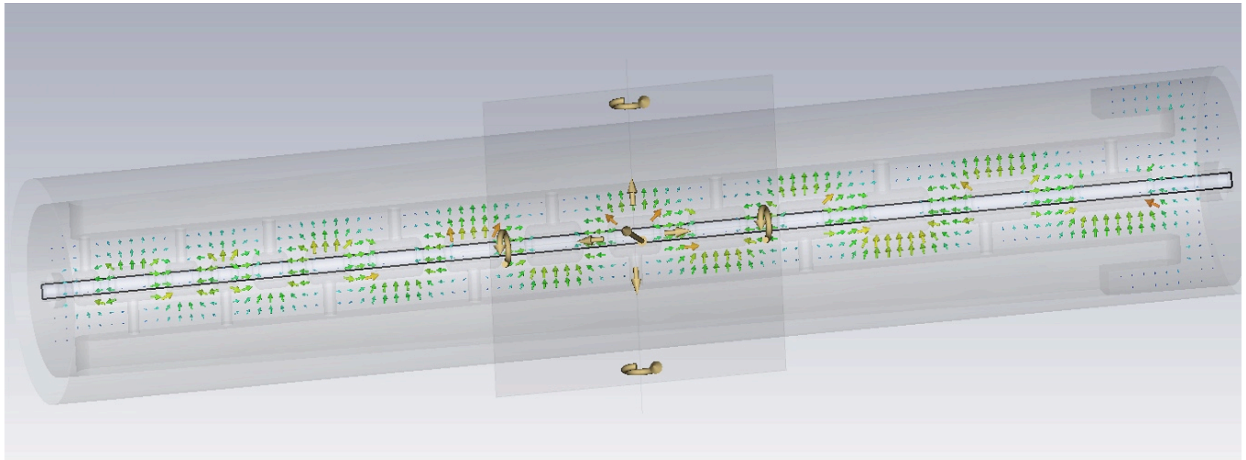
Data taken in July, 2015





low-β section (IH)

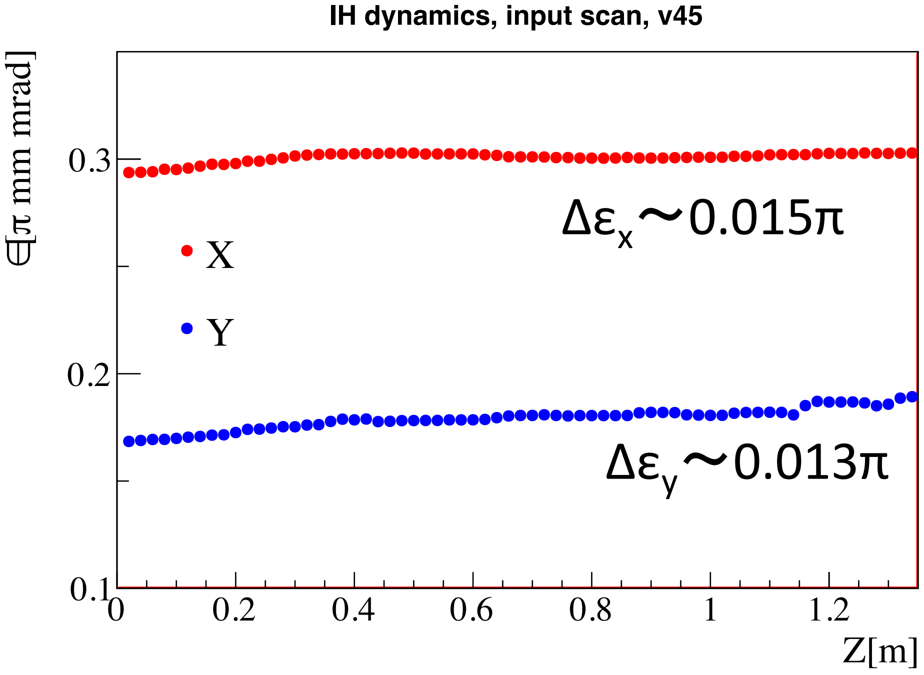
by M. Otani



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	

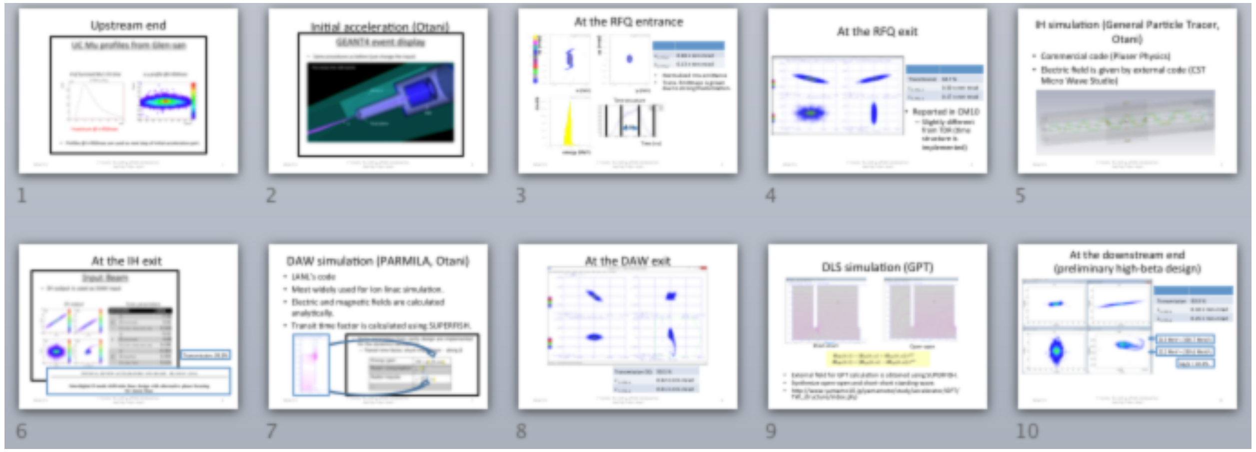
Simulated phase space distributions at the exit of IH



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

End-to-end simulation

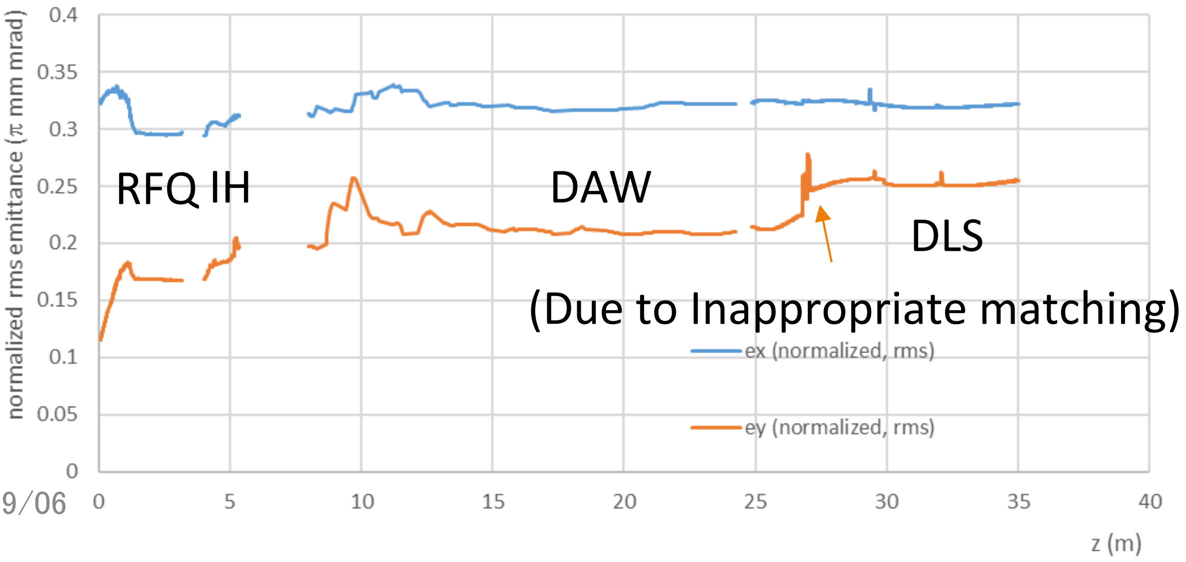
- Beam acceleration and transport were simulated from ultra-slow muon source to the exit of muon LINAC.



1 Upstream end
2 Initial acceleration (Otani)
3 At the RFQ entrance
4 At the RFQ exit
5 IH simulation (General Particle Tracer, Otani)
6 At the IH exit
7 DAW simulation (PARMILA, Otani)
8 At the DAW exit
9 DLS simulation (GPT)
10 At the downstream end (preliminary high-beta design)

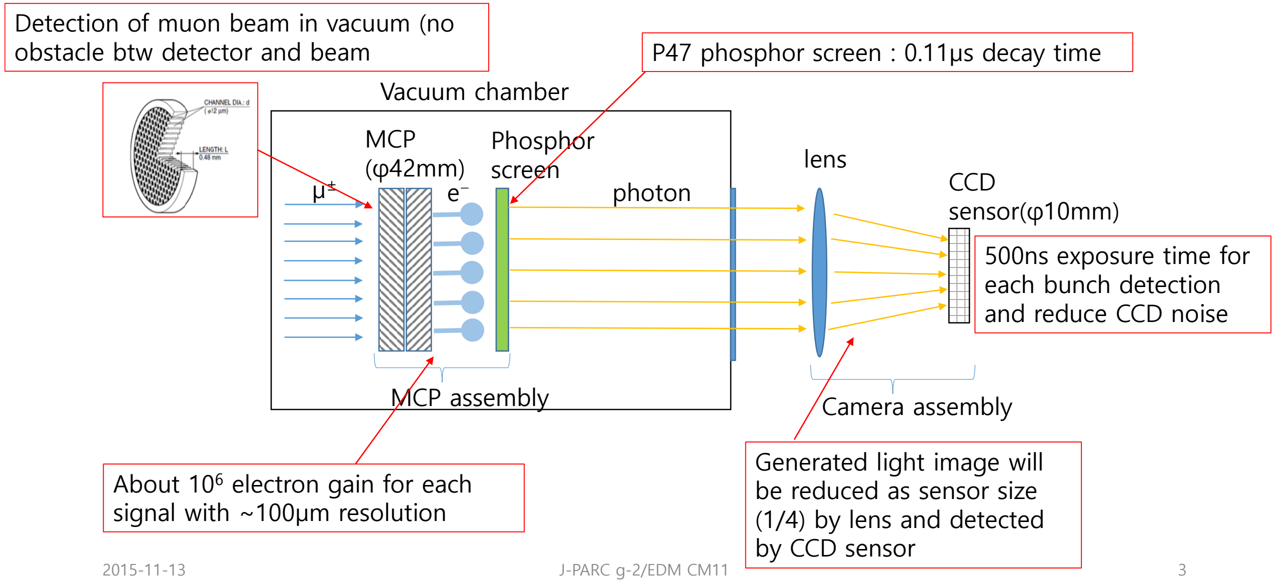
Y. Kondo

- Emittance evolution



- Emittance growth was not significant.
- Meets the requirements for muon injection.

Beam profile monitor



Detection of muon beam in vacuum (no obstacle btw detector and beam

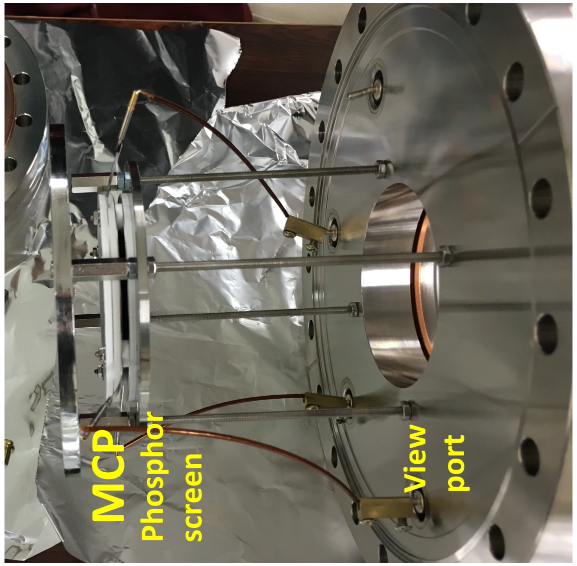
P47 phosphor screen : 0.11μs decay time

500ns exposure time for each bunch detection and reduce CCD noise

About 10^6 electron gain for each signal with ~100μm resolution

Generated light image will be reduced as sensor size (1/4) by lens and detected by CCD sensor

2015-11-13 J-PARC g-2/EDM CM11 3

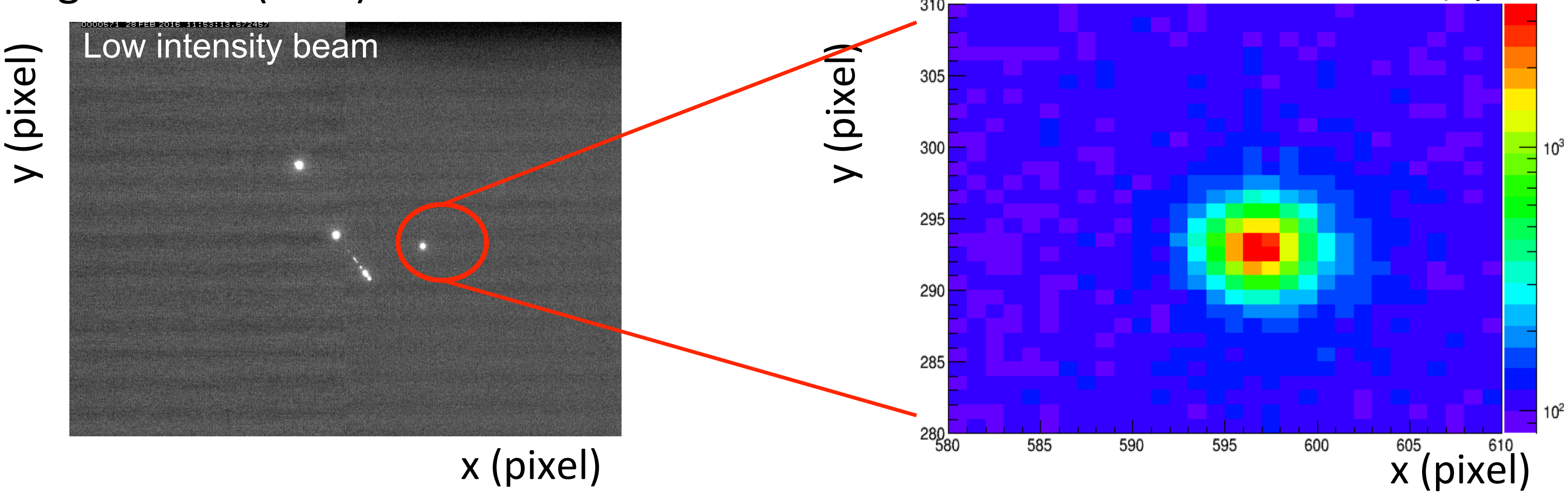


- Developed by SNU group
- Tested with surface muon beam at D2 area in Feb. 2016
- Basic performance (single muon response, linearlity) is evaluated.

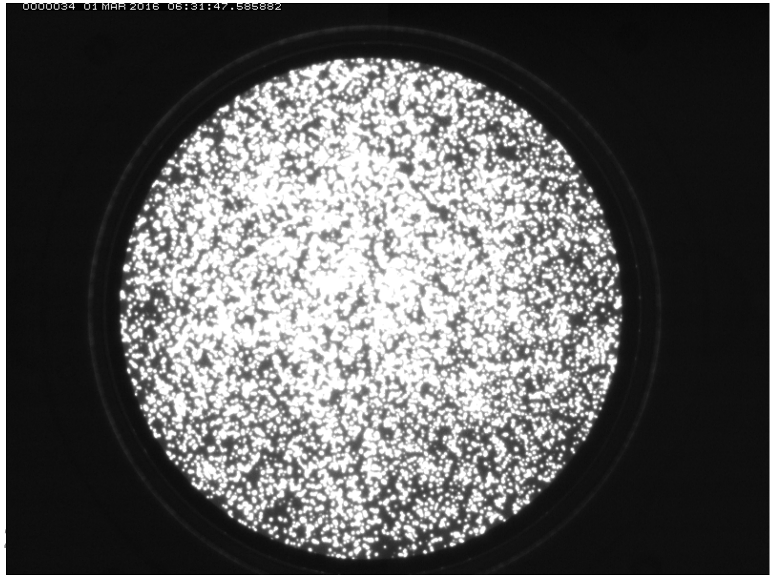
Test of beam profile monitor

Sunghan Bae (SNU)

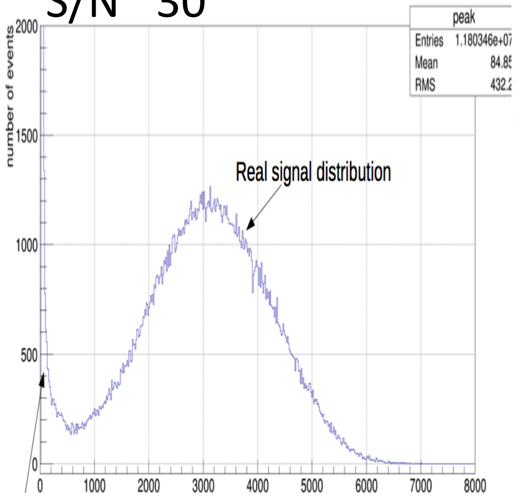
(1px = 77um)



High intensity beam

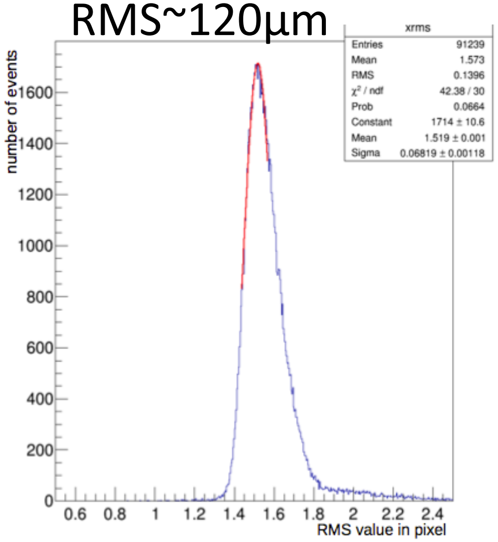


S/N ~30



cluster brightness (ADC)

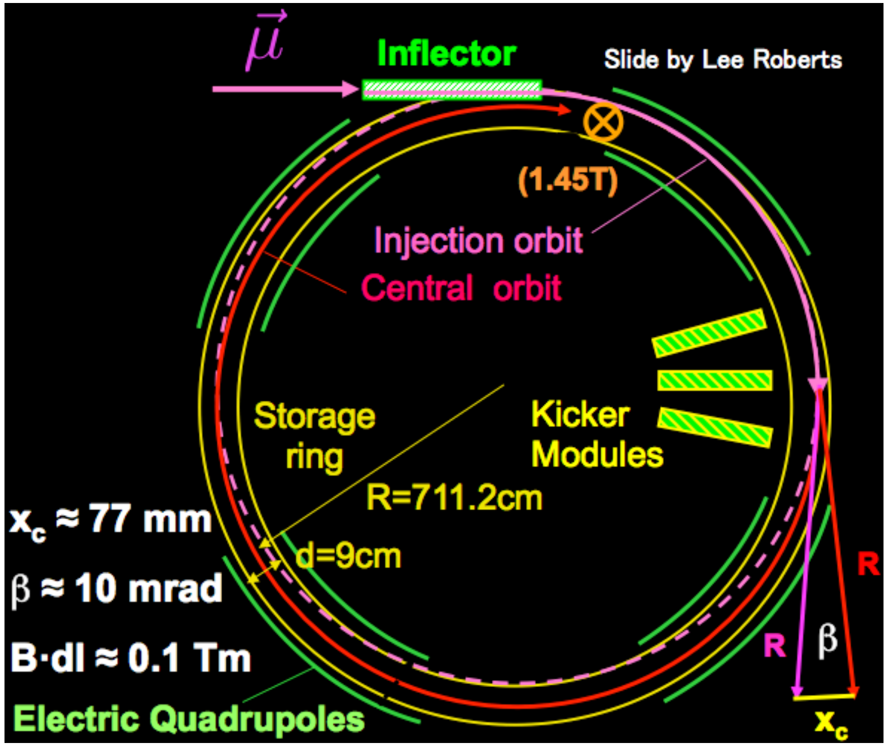
RMS~120μm



cluster RMS (pixel)

Muon beam injection and storage

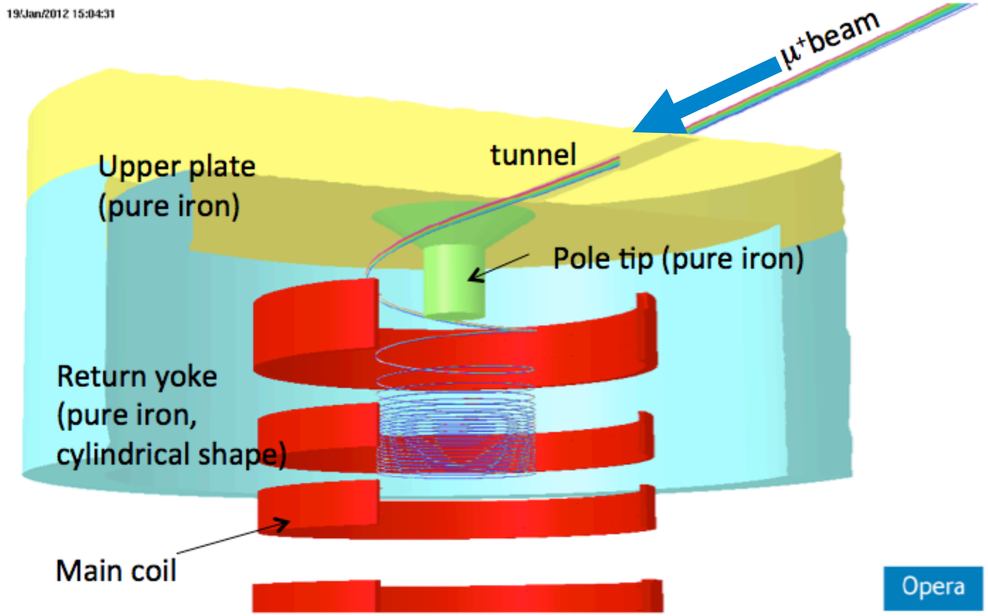
Horizontal injection + kicker
(BNL E821, FNAL E989)



Injection efficiency : 3-5%(*)

(*) PRD73,072003 (2006)

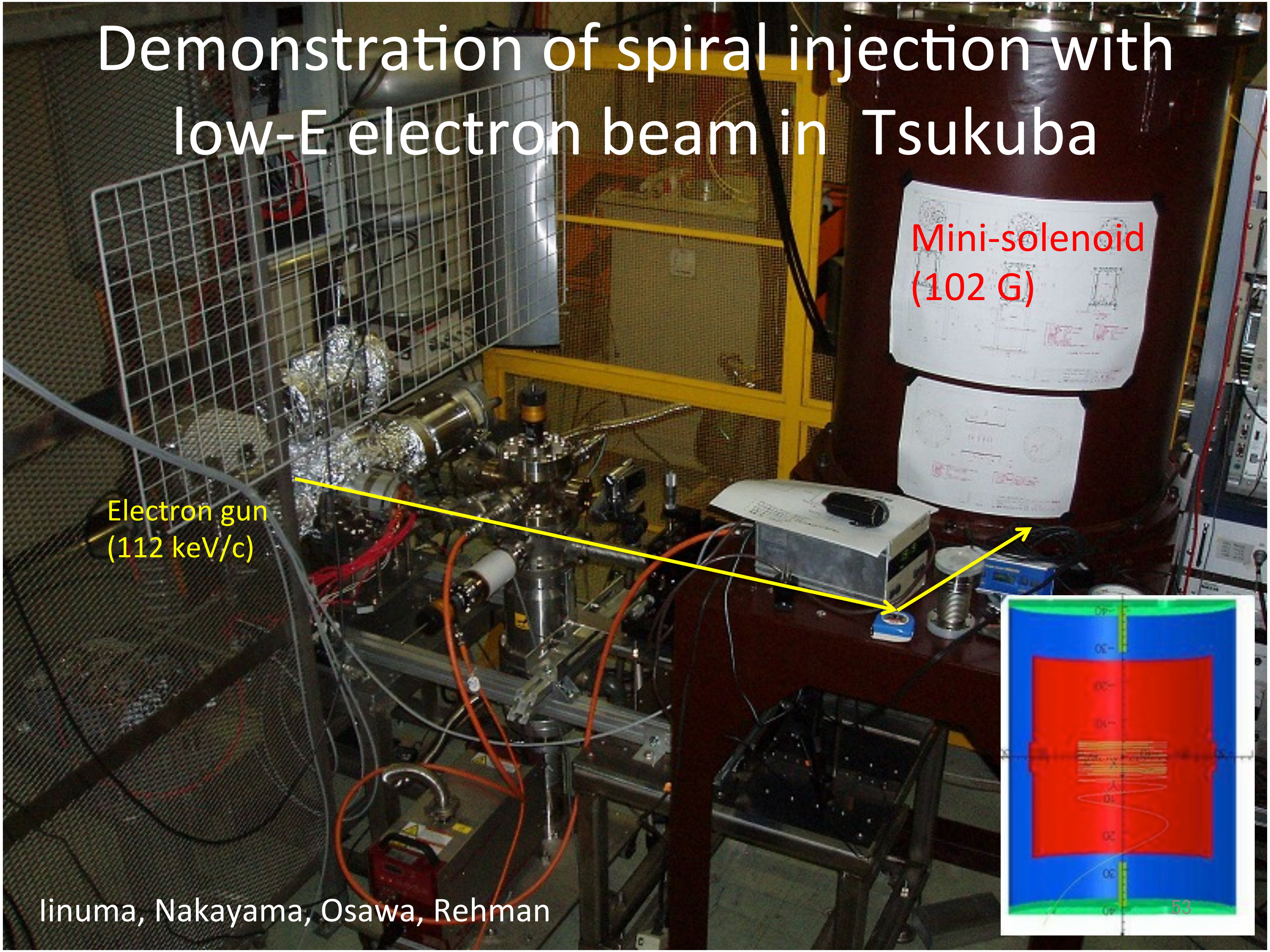
3D spiral injection + kicker
(J-PARC E34)



Injection efficiency : ~90%

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

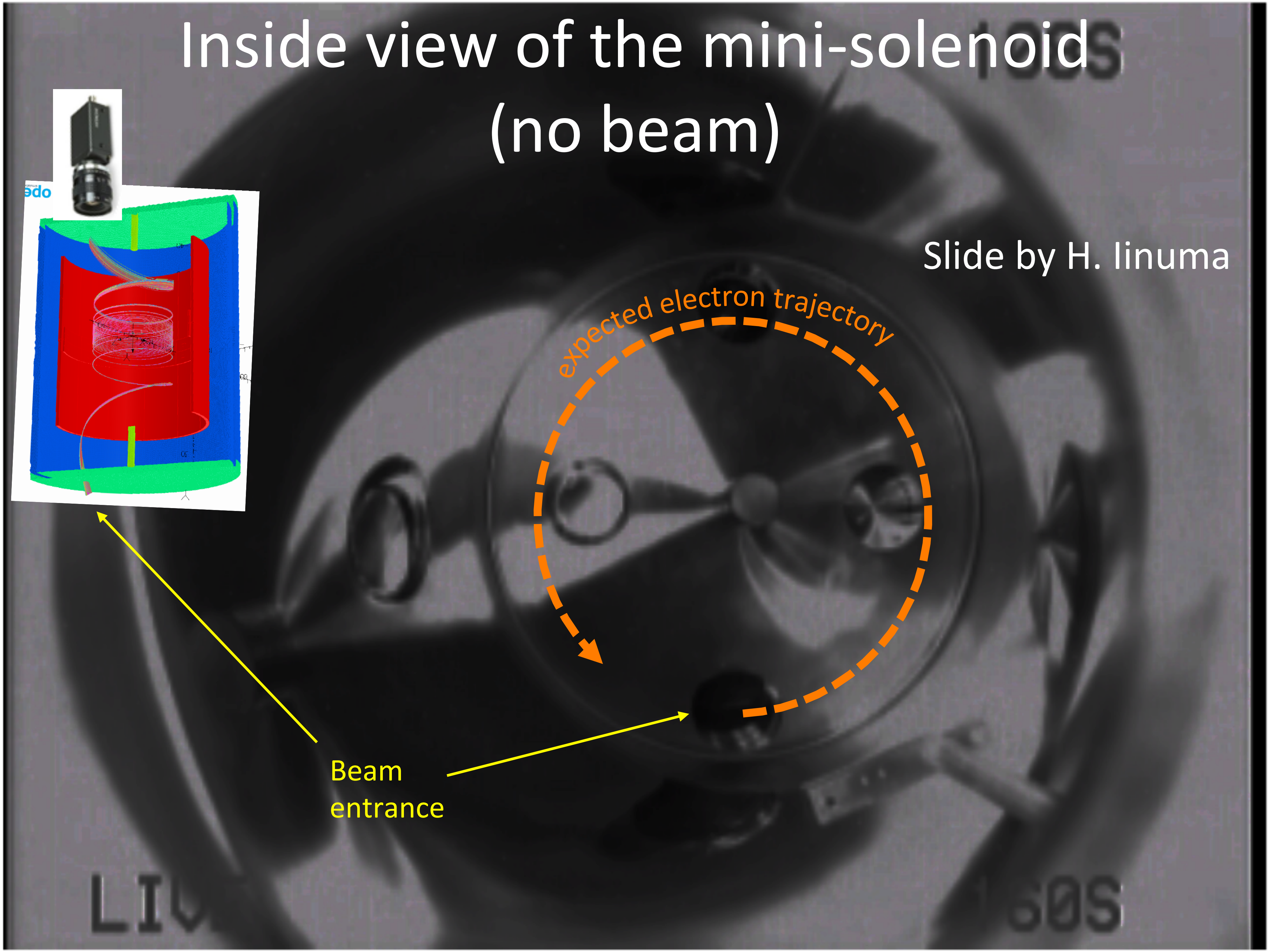
Demonstration of spiral injection with low-E electron beam in Tsukuba



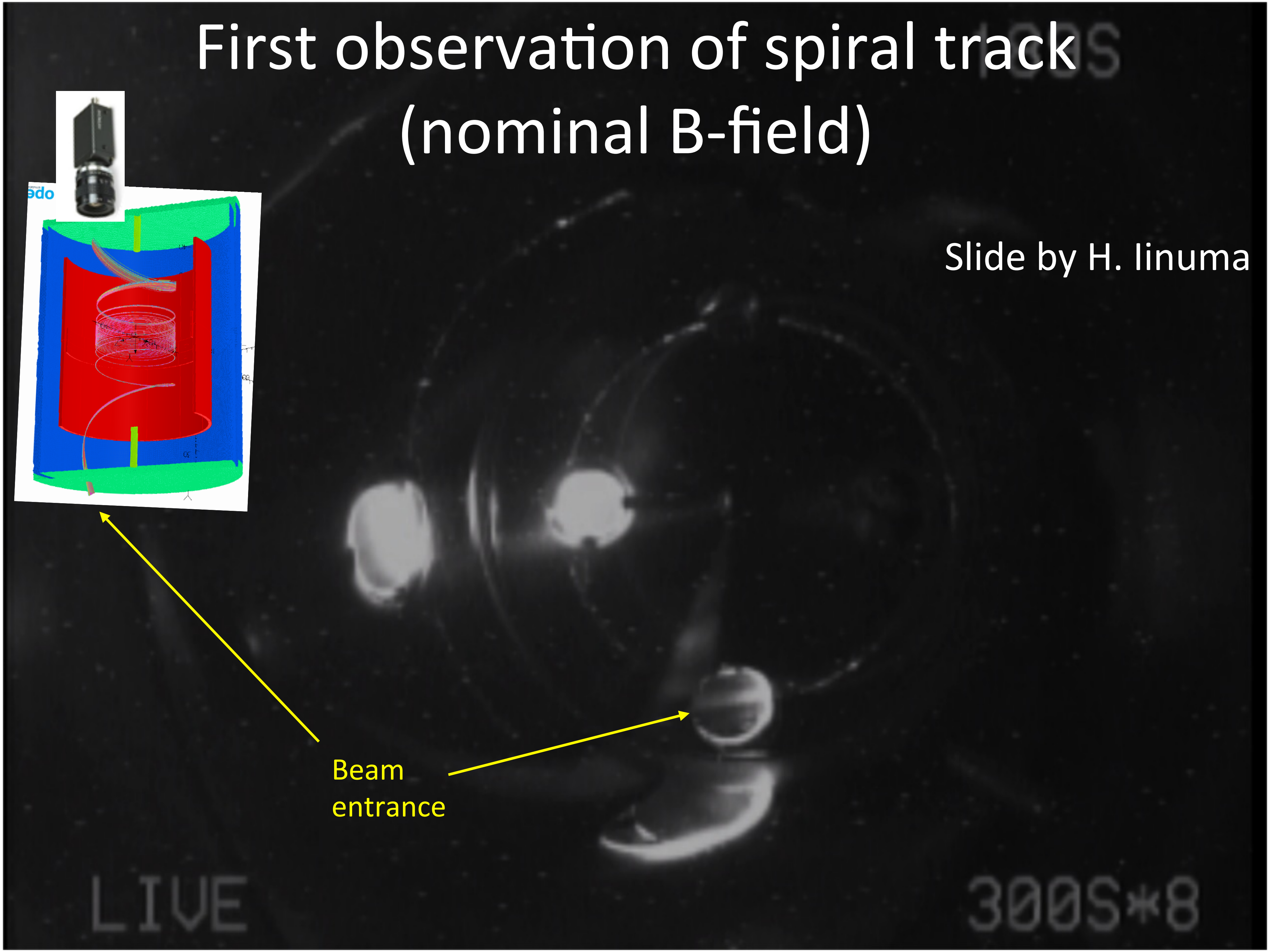
Iinuma, Nakayama, Osawa, Rehman

Inside view of the mini-solenoid (no beam)

Slide by H. Iinuma



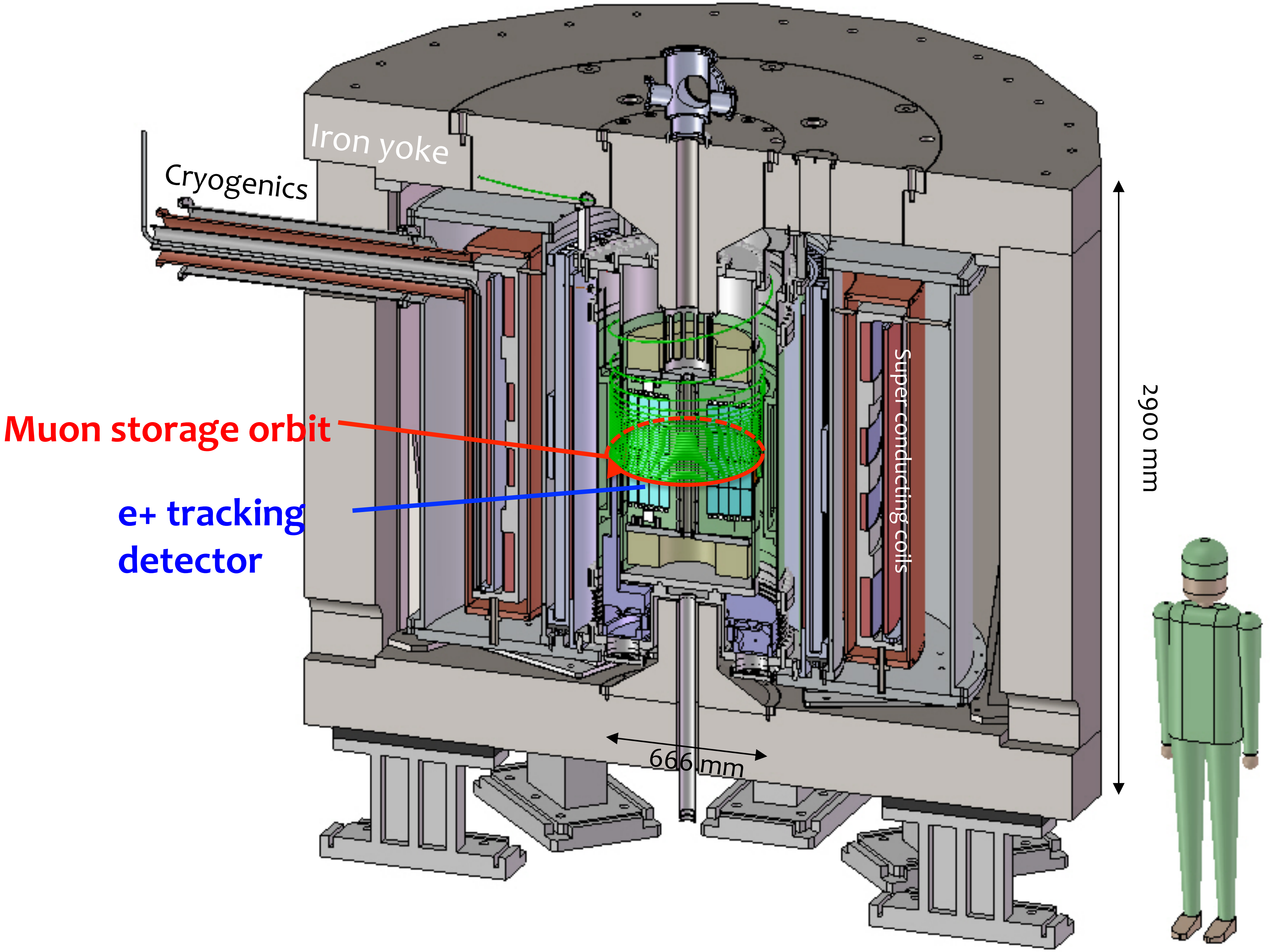
First observation of spiral track (nominal B-field)



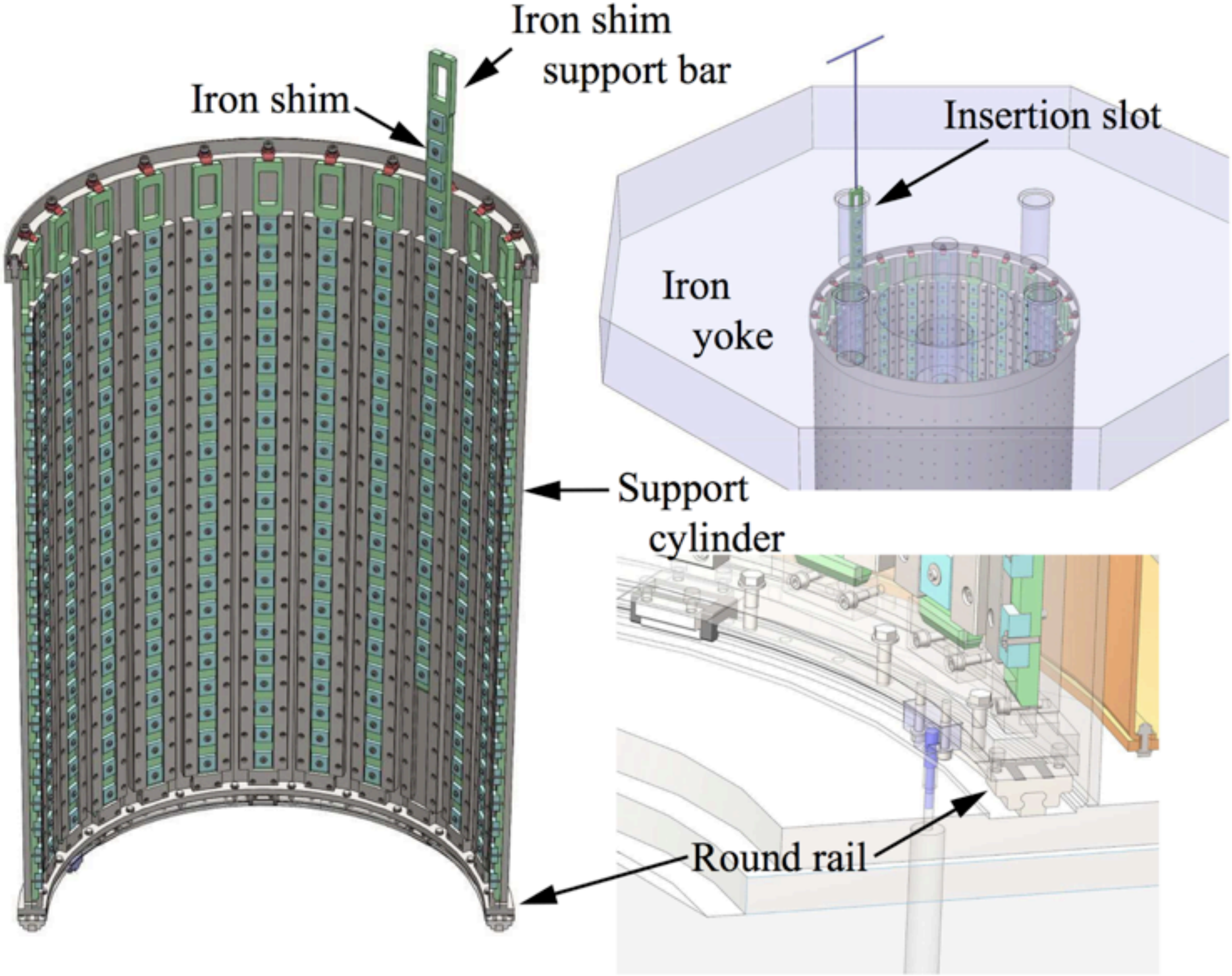
Slide by H. Iinuma

Beam entrance

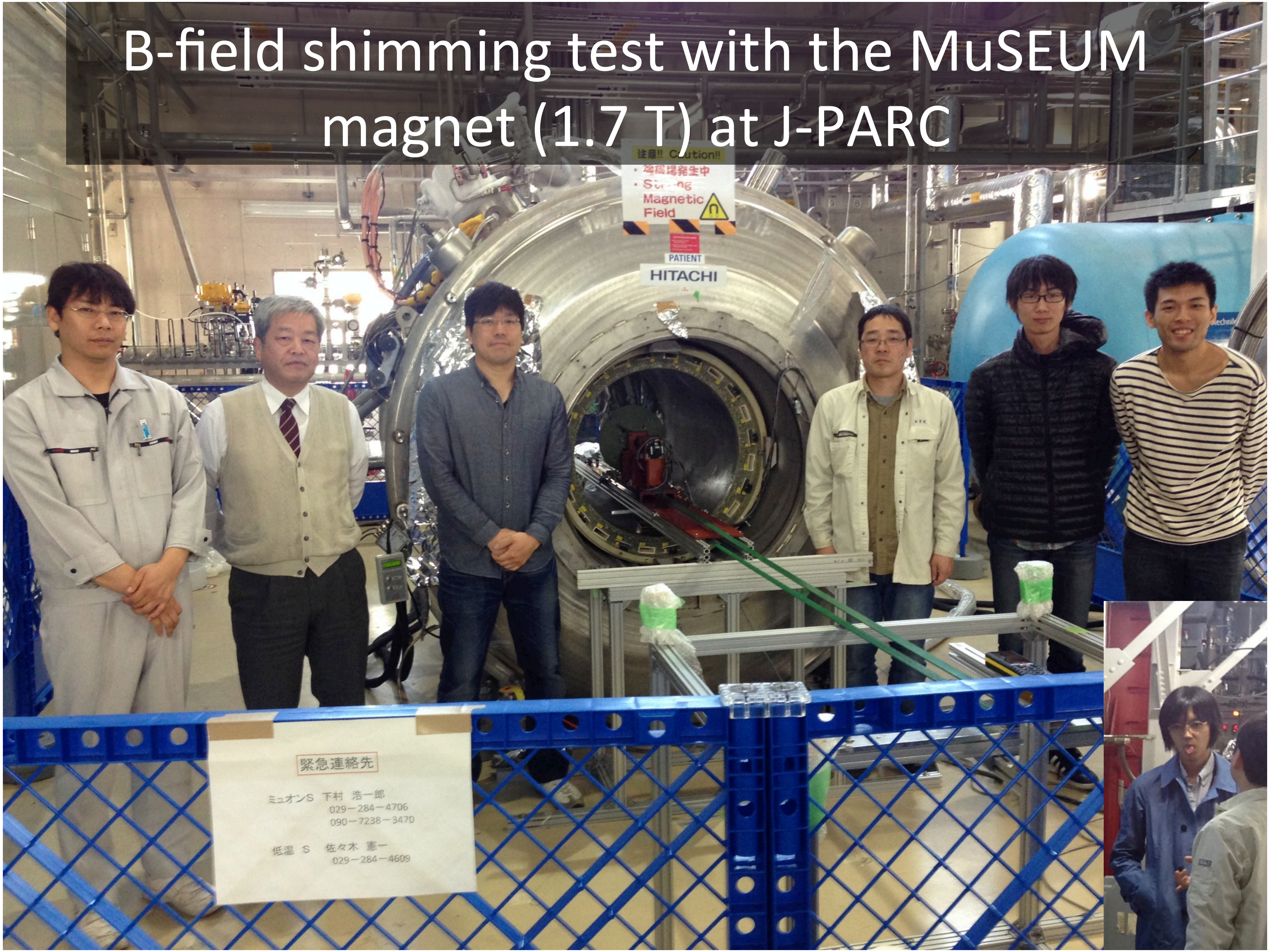
Muon storage magnet and detector



Organization of iron shim arrays



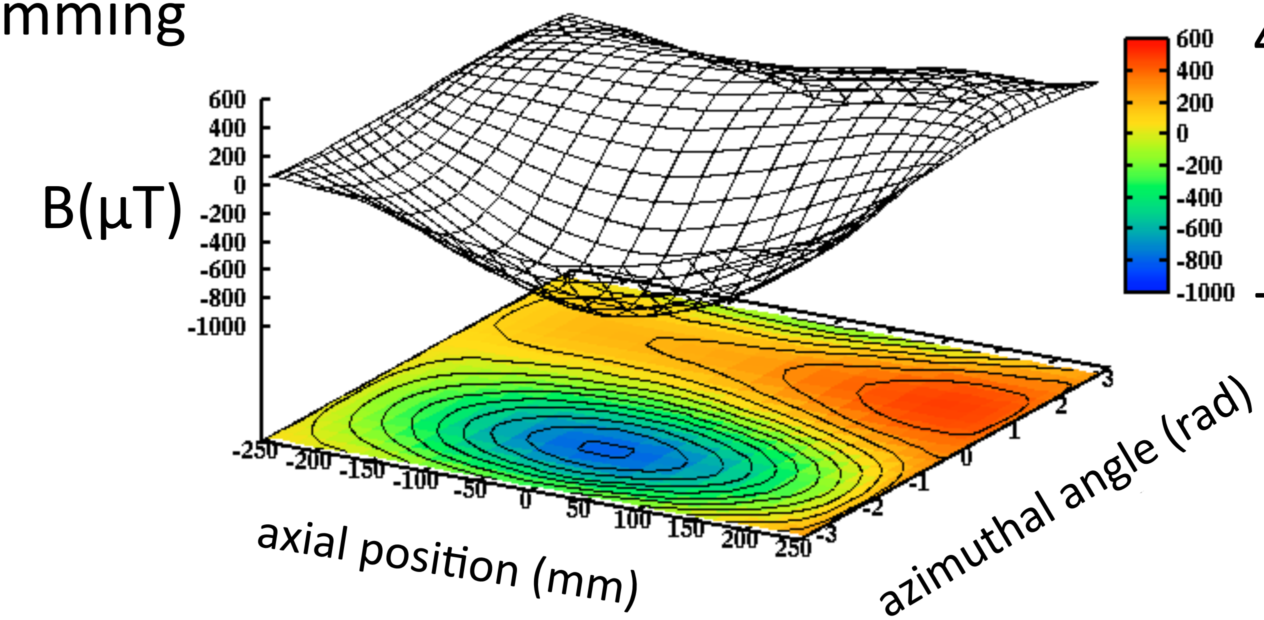
B-field shimming test with the MuSEUM magnet (1.7 T) at J-PARC



Plots by K. Sasaki

Field shimming by iron arrays

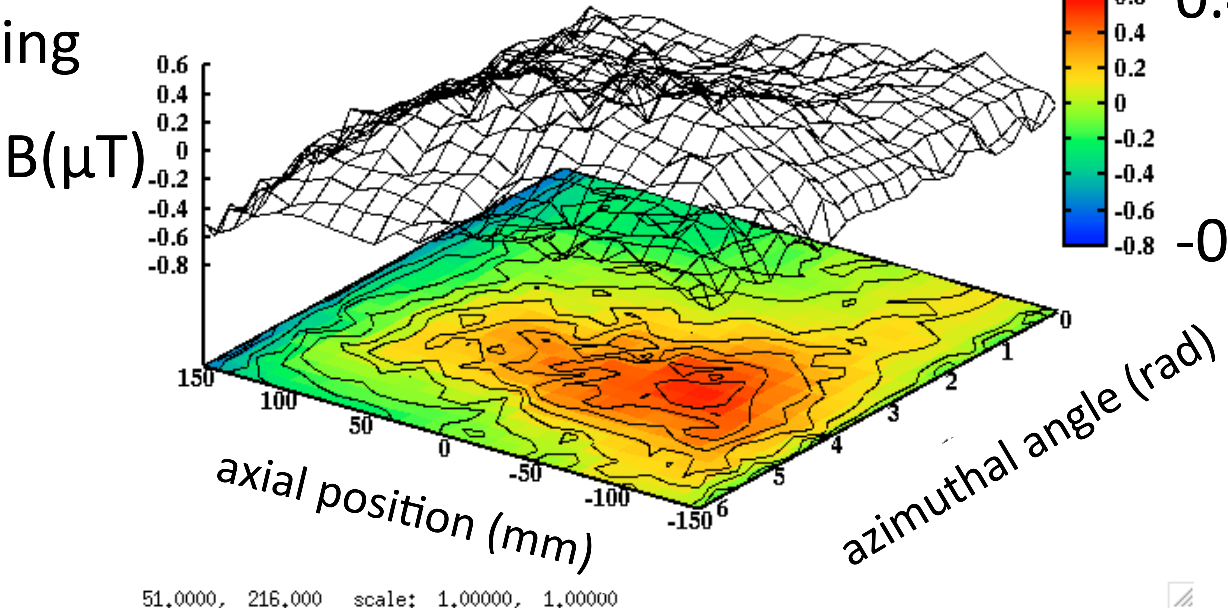
Before shimming



400 ppm

-600 ppm

After shimming



0.4 ppm

-0.5 ppm

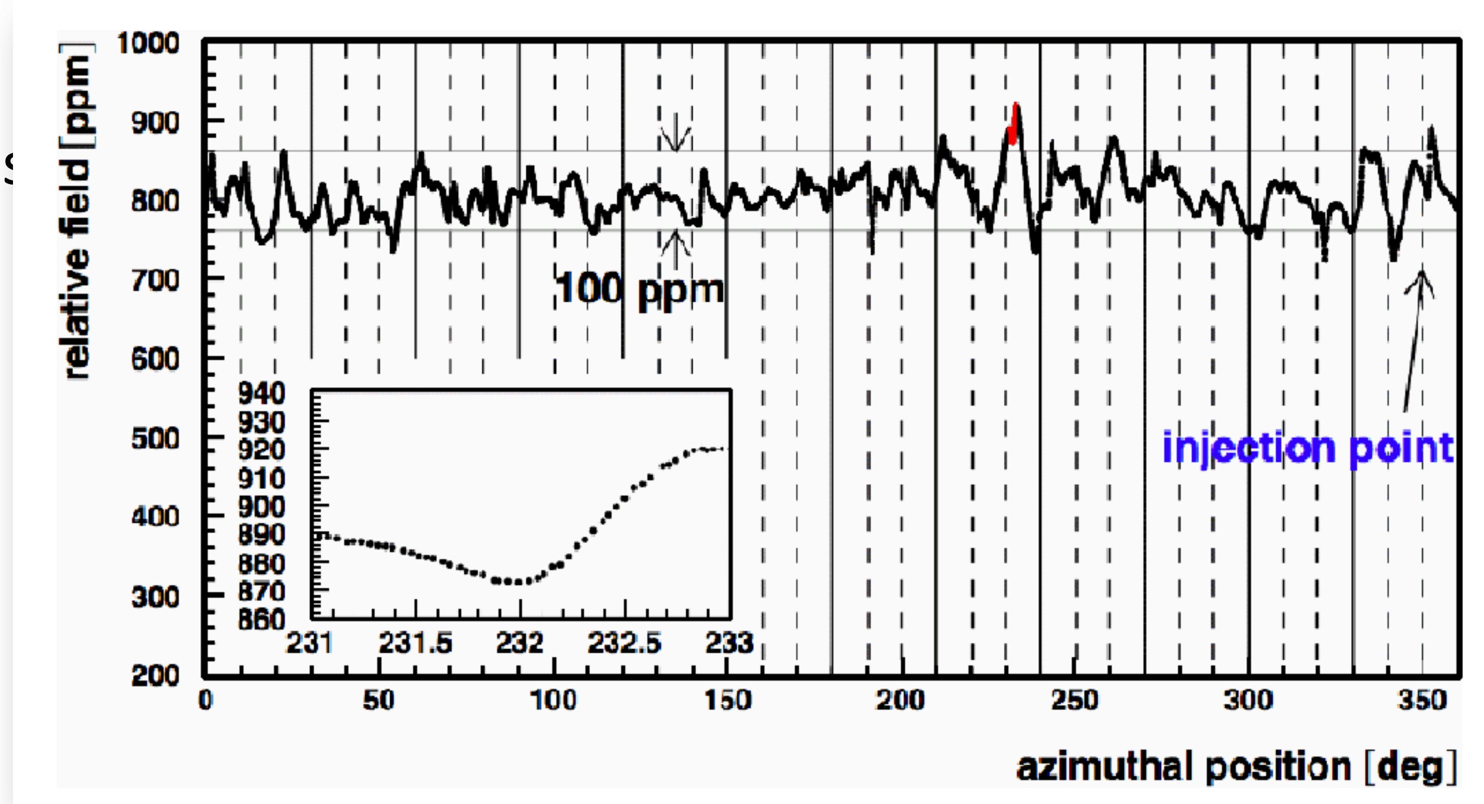
r = 140 mm

Plots by K. Sasaki

Before s

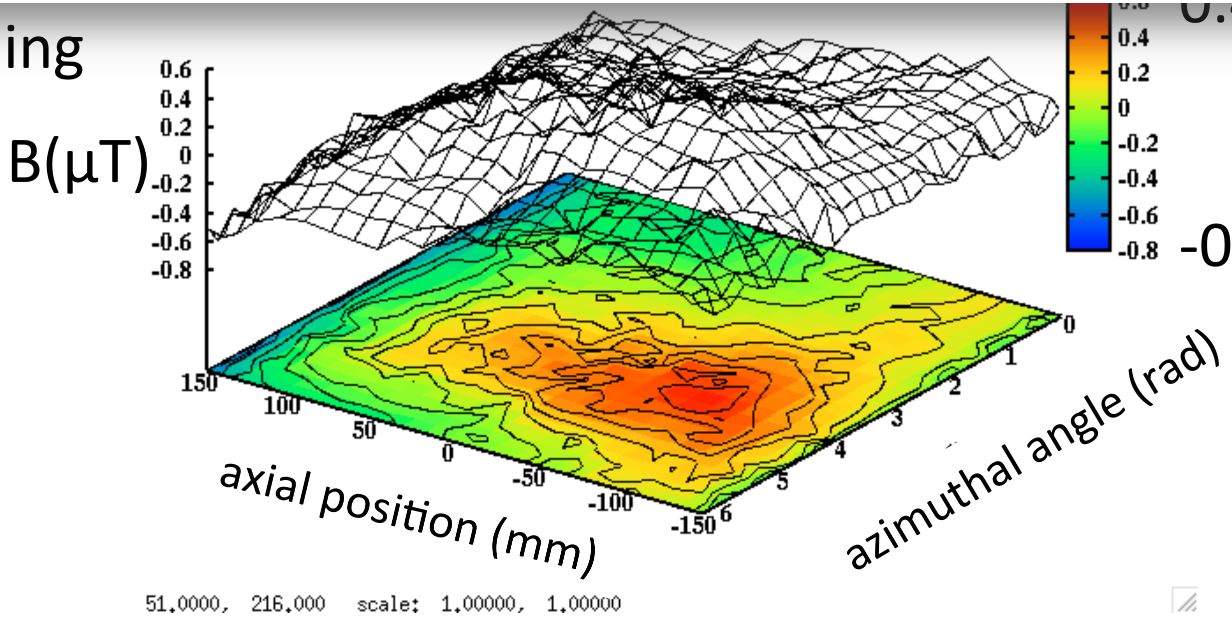
pm

ppm



0.4 ppm

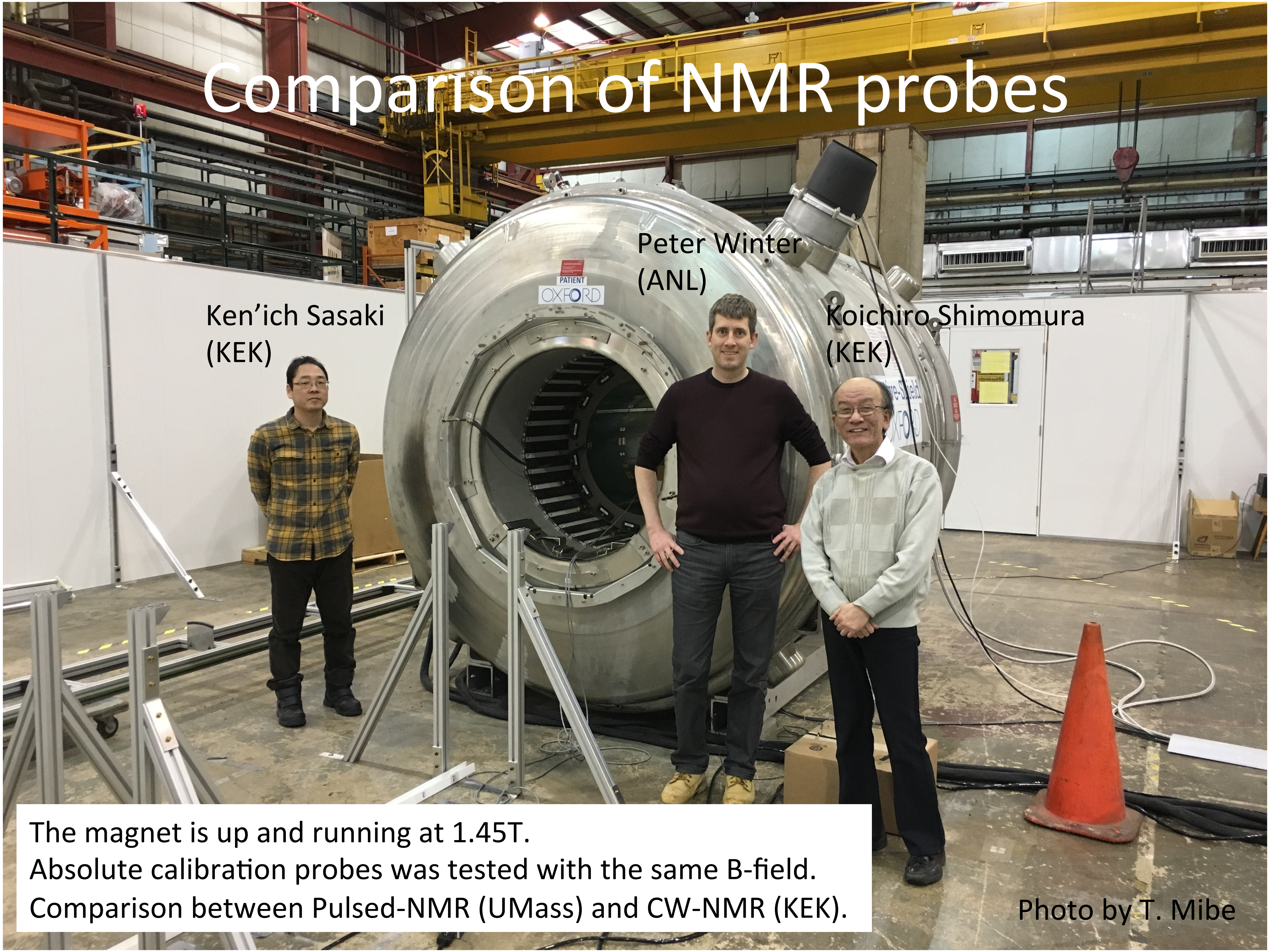
After shimming



-0.5 ppm

r = 140 mm

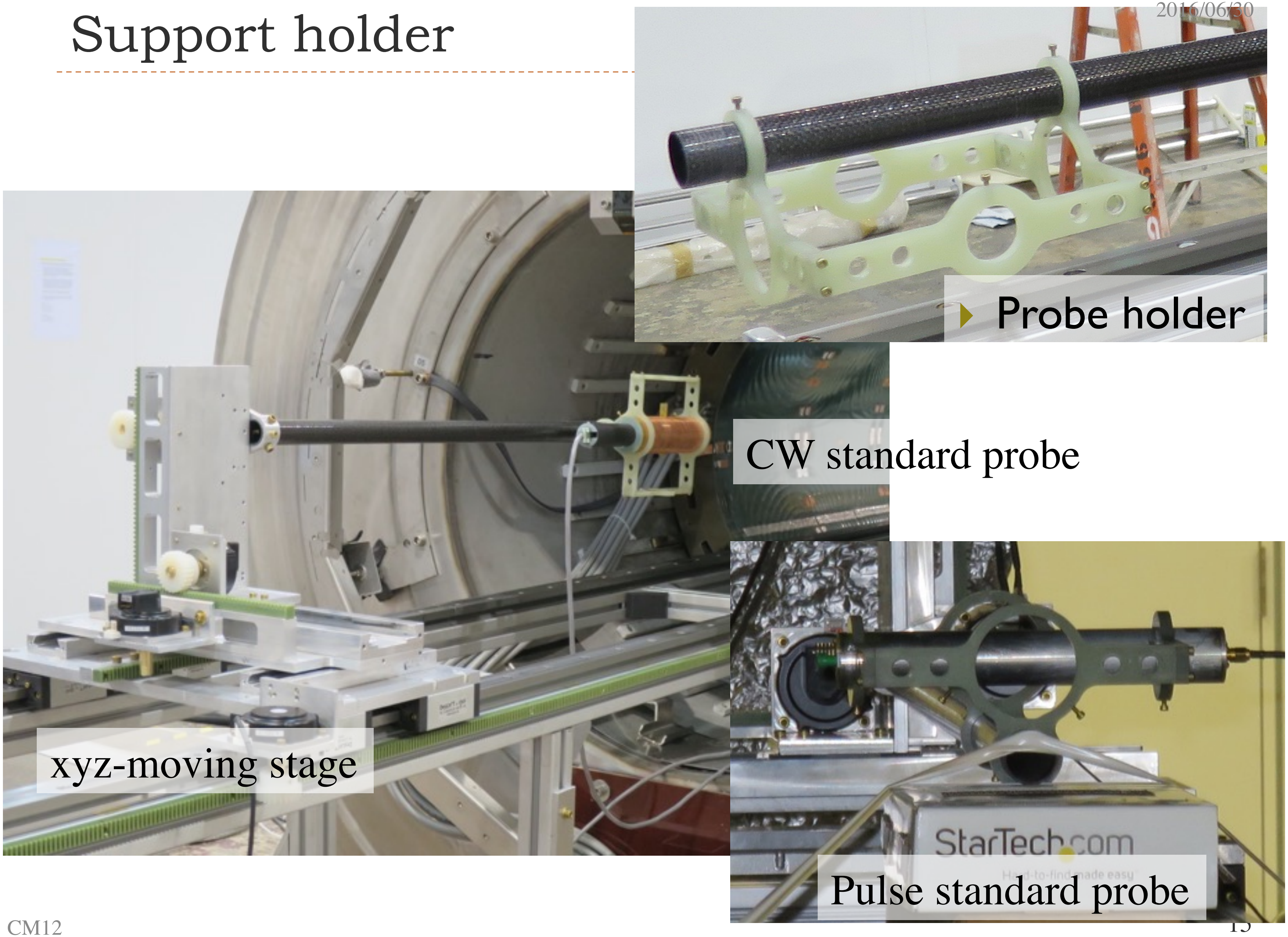
Comparison of NMR probes



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

Support holder



- Probe holder

CW standard probe

Pulse standard probe

xyz-moving stage

Crosscheck btw CW and Pulse

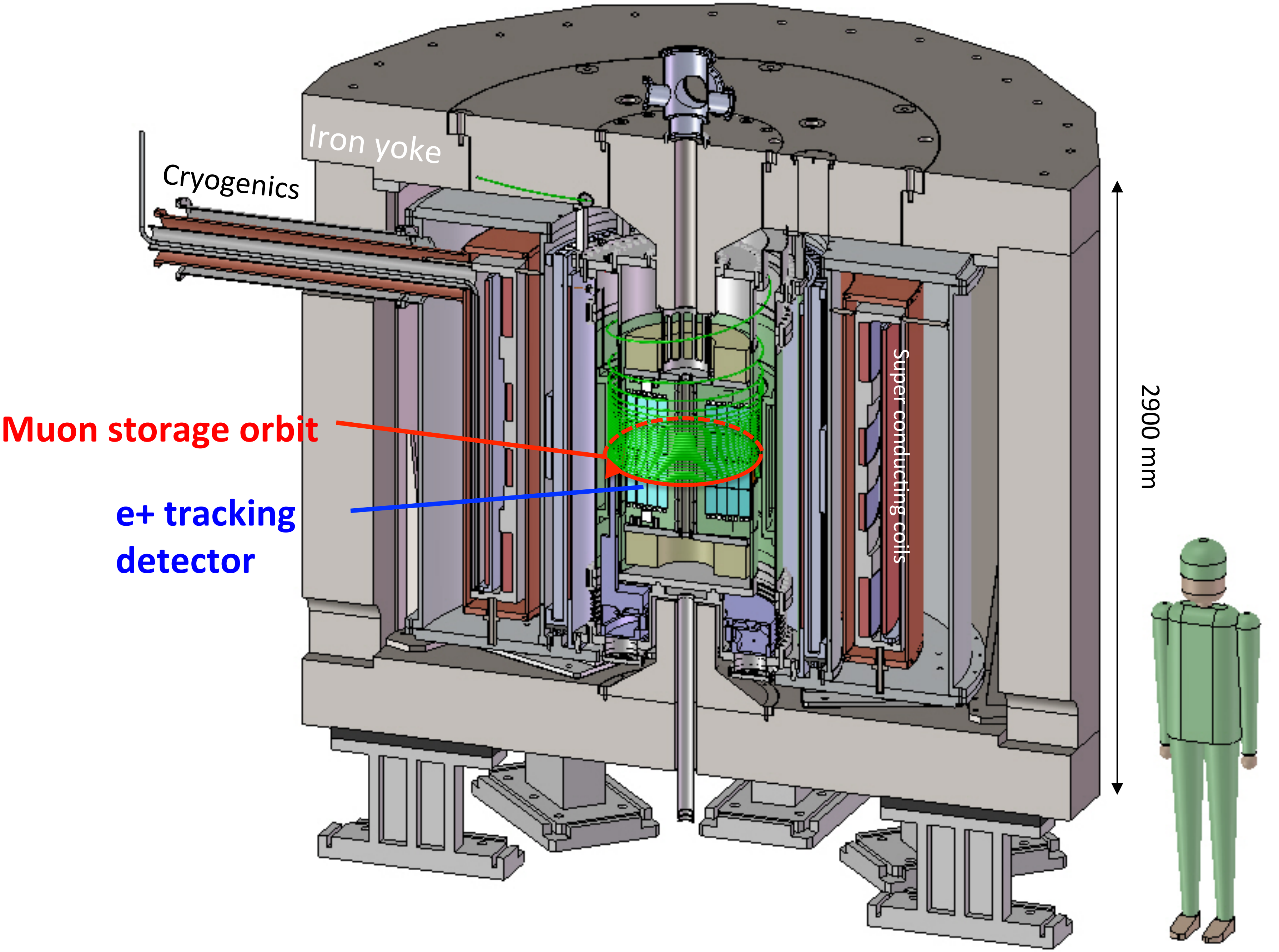
Slide by K. Sasaki

	CW-NMR	Pulse-NMR
Measured value	61732818.34 Hz	61732806.93 Hz
Temperature	24.6 ℃	not measured, assume 24.6 ℃
Internal diamagnetic shielding (Hz) (- 25.680(±0.0025) ppm @ 25 ℃)	~ -1585.298 Hz	
Temperature dependence (-0.01036(30) ppm/℃)	~ +0.256Hz	→ ~ +0.256Hz
Shape effect (Long cylinder) (χ : Water susceptibility)	χ: not measured. Assume pure water: -93.093 [1,2]	→ -93.093
Paramagnetic impurities in the water sample	~0	~0
Material effect	+5.685 Hz (by Copper shell) -0.845 Hz (by Glass tube for water)	-2.645 Hz (by Al cover etc.) -0.194 Hz (by Al shell)
Total	61734490.630 Hz	61734487.904 Hz
Difference	+2.73 Hz (+44.16 ppb)	

[1] Volumetric susceptibility of water at 37°C : -9.053e-6(SI), -0.720(2)e-6 (CGI)
John F. Schenck, Med. Phys. 23 (6), 815-850, June 1996

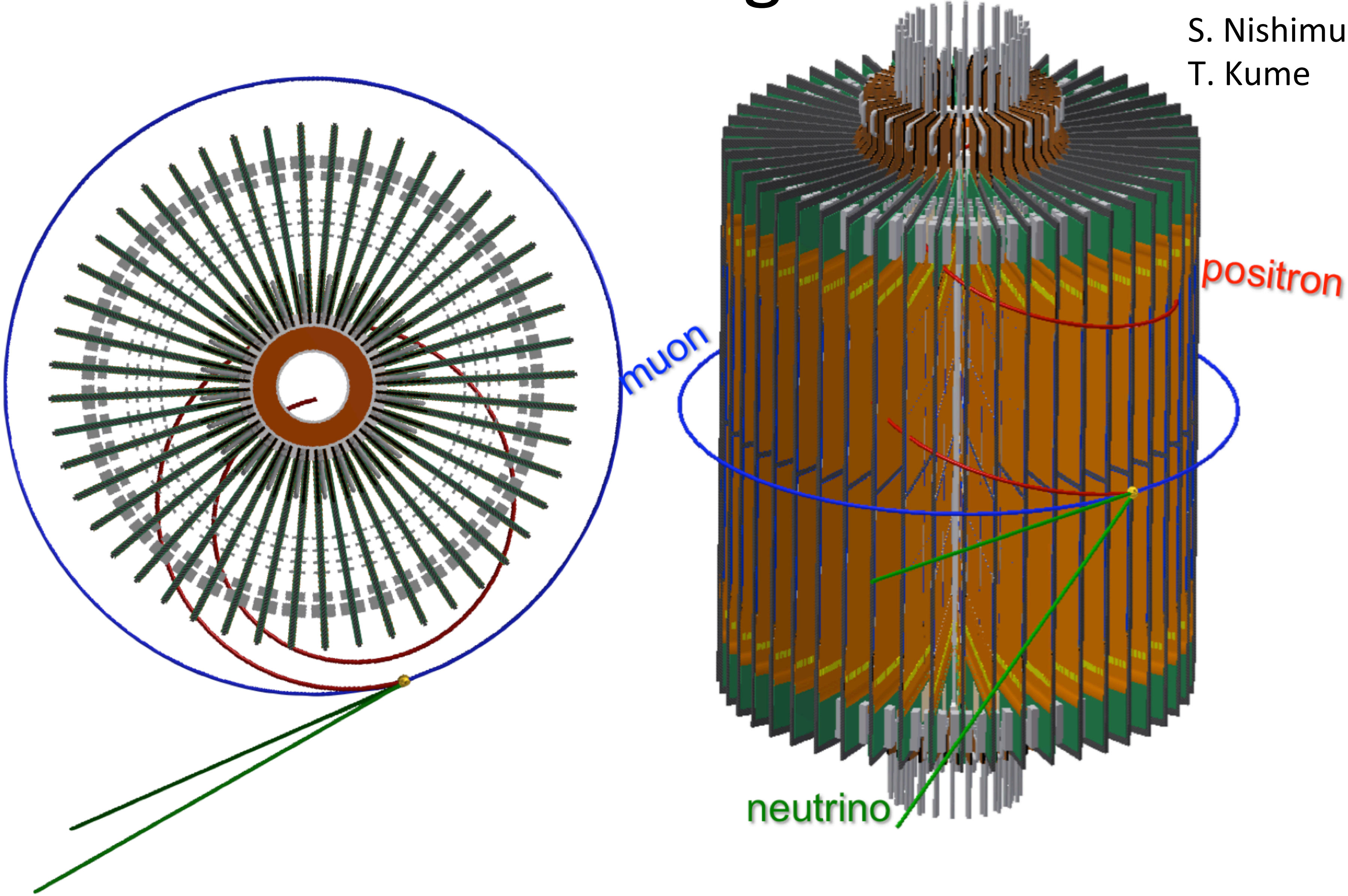
[2] Temp. dependence of χ of water :
R. Cini and M. Torrini, J. Chem. Phys 49, 2826-2830, 1968

Muon storage magnet and detector



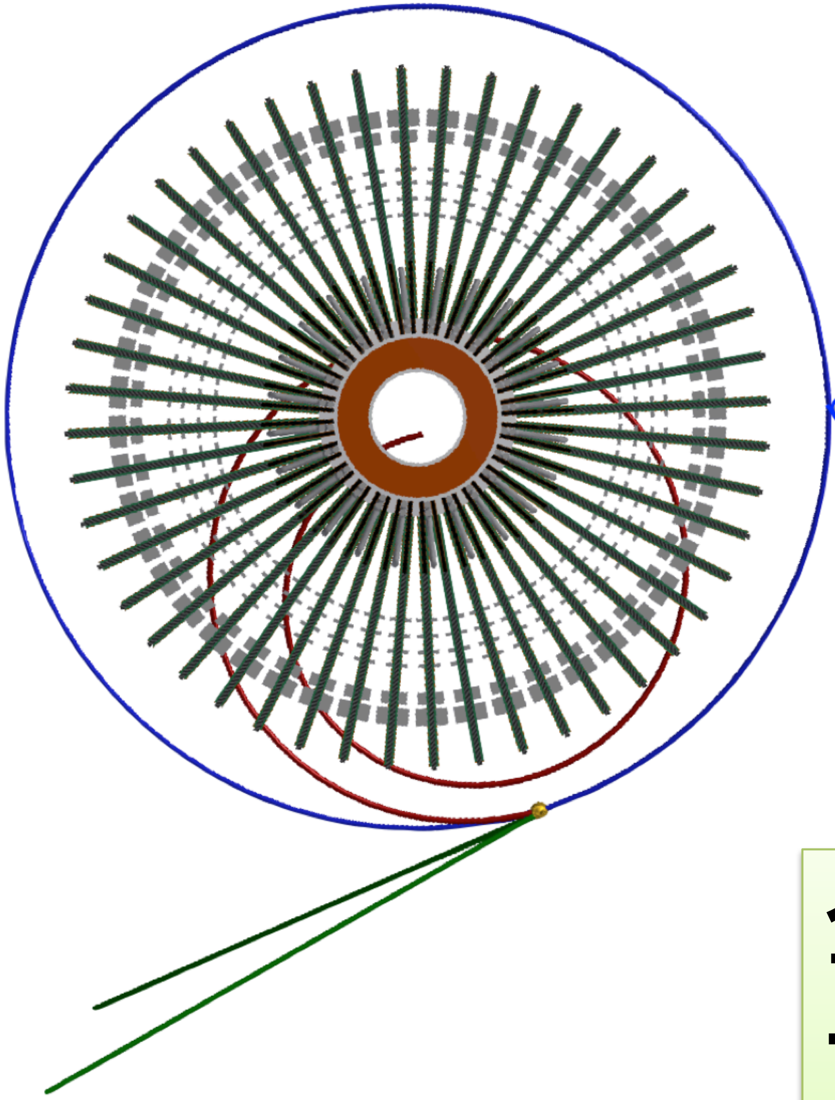
Positron tracking detector

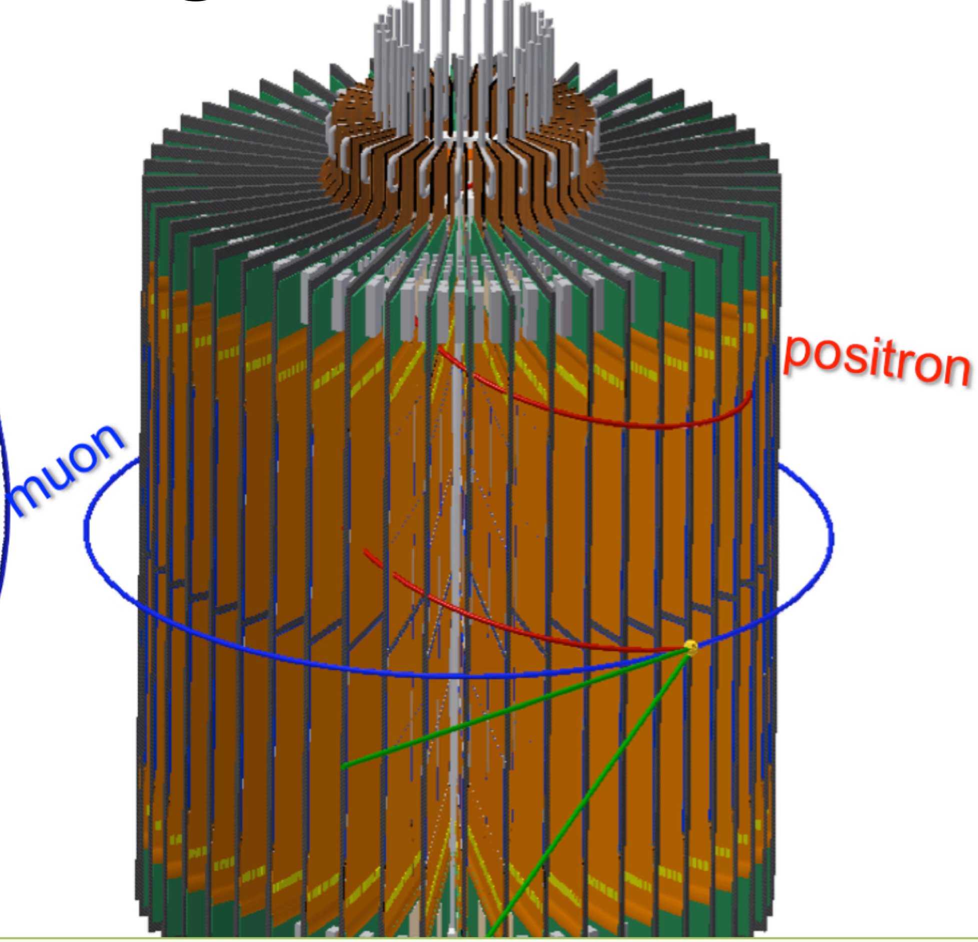
S. Nishimura
T. Kume



A typical simulated event of muon decay

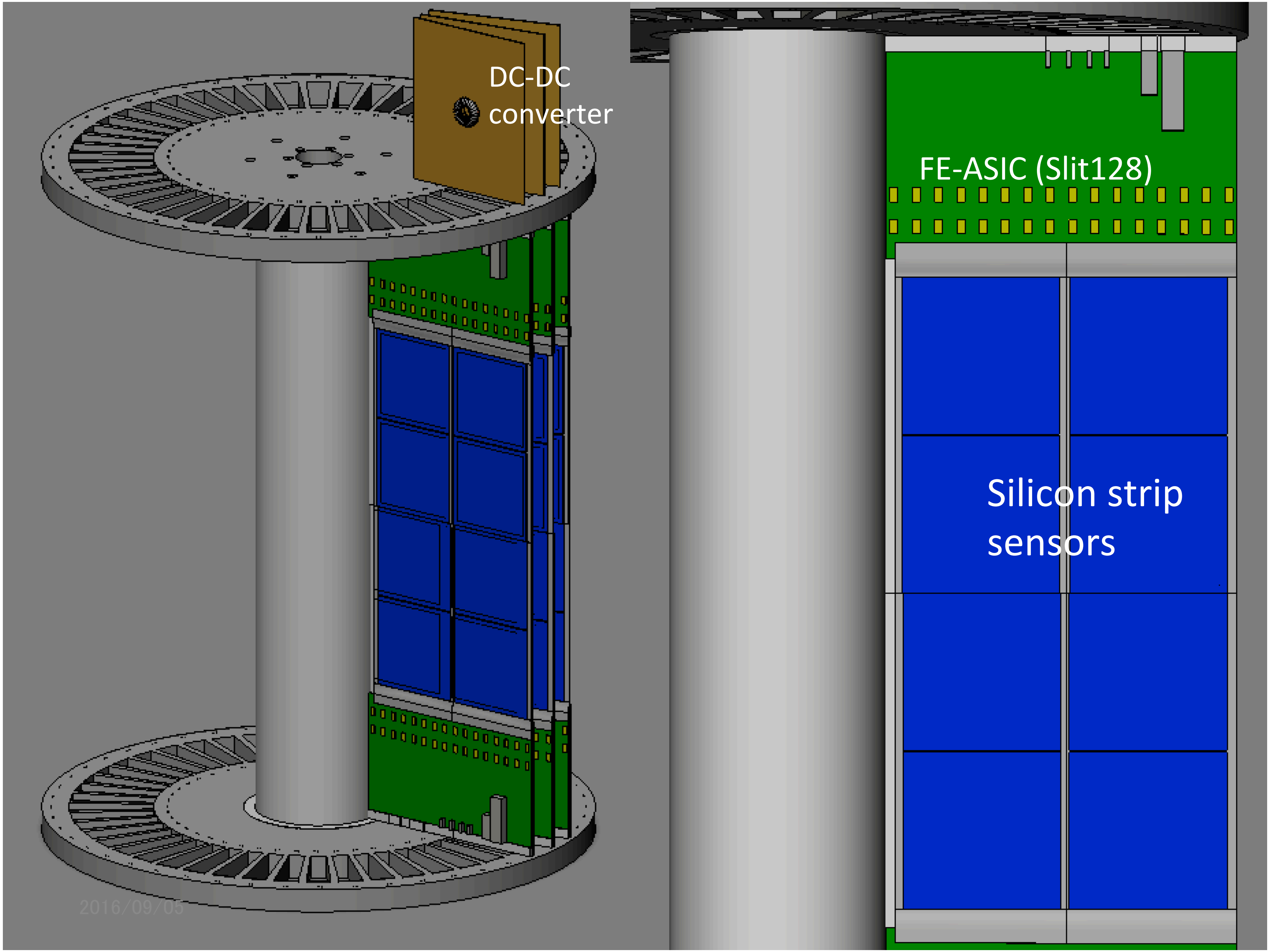
Positron tracking detector





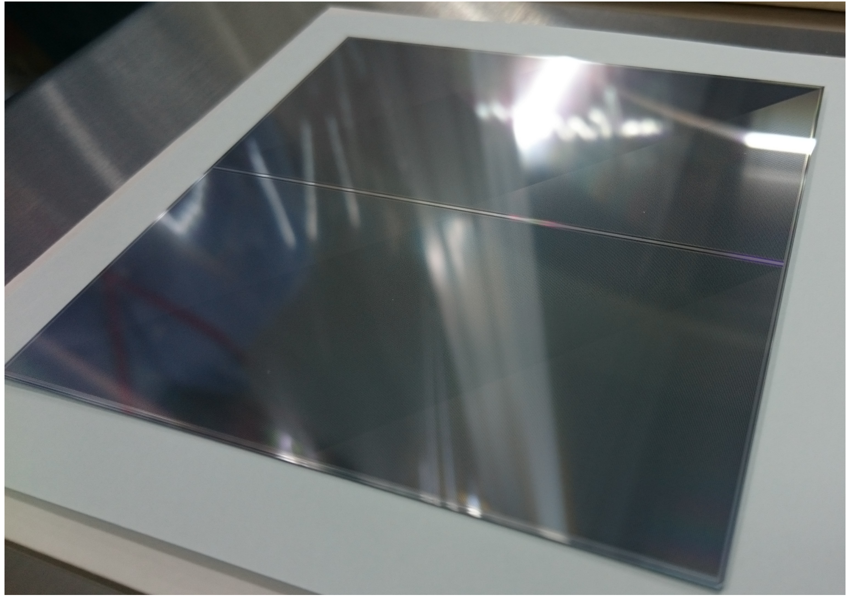
A typical simulated even

全て飛跡検出器で構成
一様なアクセプタンス
→EDM 測定に最適

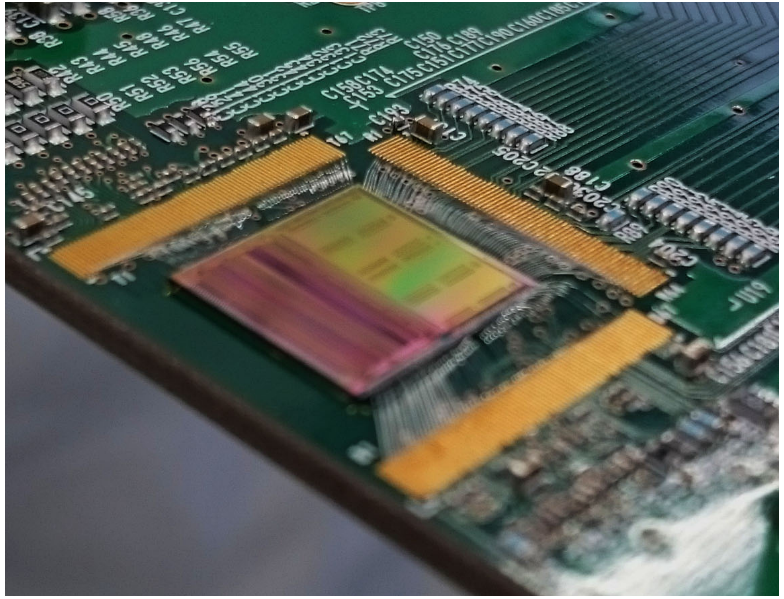

DC-DC converter
FE-ASIC (Slit128)
Silicon strip sensors
2016/09/05

Detector components

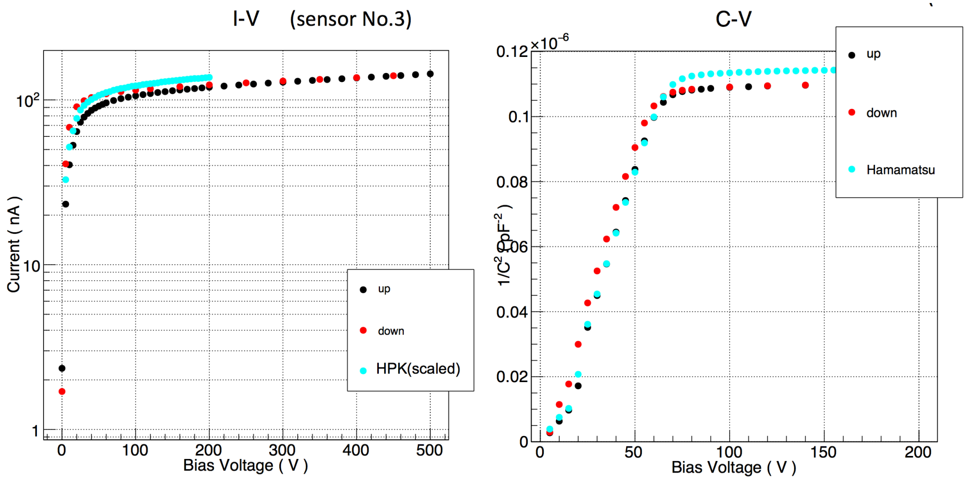
Silicon strip sensor
(100 x 100 mm^2, 190um pitch, 1024ch)



Front end ASIC
(Slit128A, Silterra CMOS 0.18um)



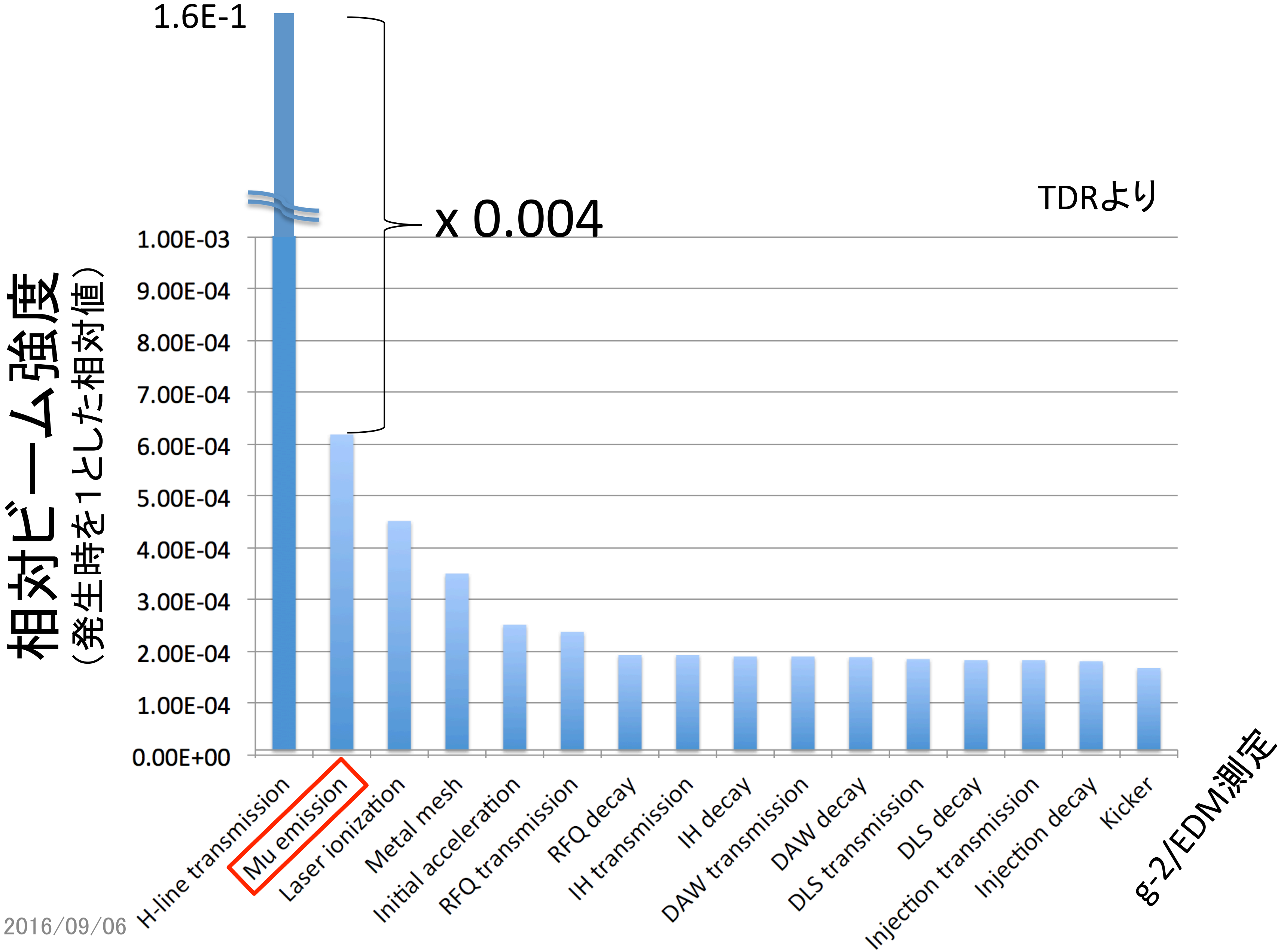
Evaluated by S. Nishimura



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

ミューオンビーム強度

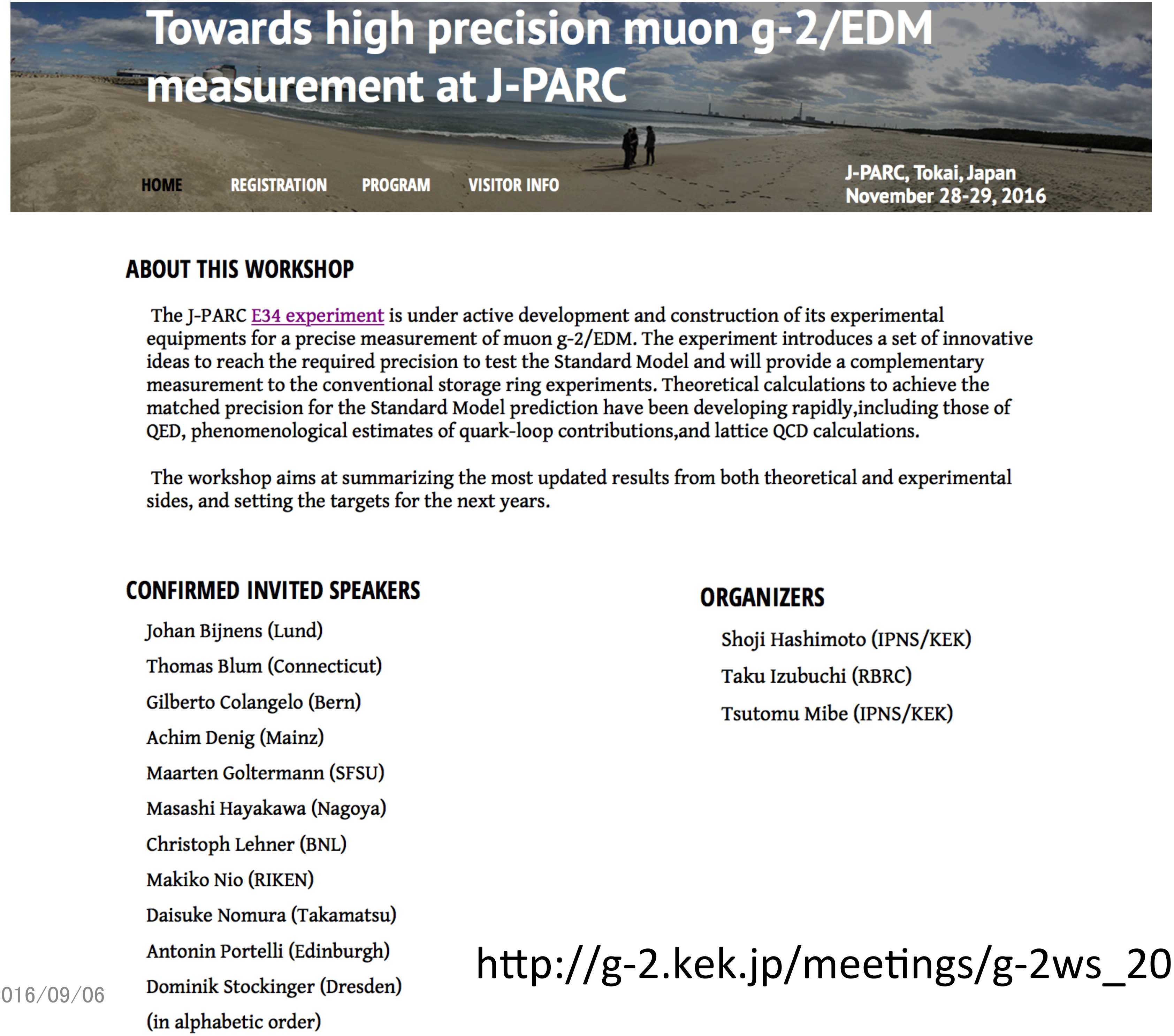


1.6E-1
x 0.004
TDRより
1.00E-03
9.00E-04
8.00E-04
7.00E-04
6.00E-04
5.00E-04
4.00E-04
3.00E-04
2.00E-04
1.00E-04
0.00E+00
相対ビーム強度
（発生時を1とした相対値）
H-line transmission
Mu emission
Laser ionization
Metal mesh
Initial acceleration
RFQ transmission
RFQ decay
IH transmission
IH decay
DAW transmission
DAW decay
DLS transmission
DLS decay
Injection transmission
Injection decay
Kicker
g-2/EDM測定

Projected statistical sensitivity

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

Already good enough to test BNL E821 results.



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

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)

http://g-2.kek.jp/meetings/g-2ws_2016

まとめ

- ミューオンの異常磁気能率(g-2)
  - 先行実験(BNL-E821)で標準模型の予想より3σ大きい値を持つと報告。独立な検証が待たれている。
- ミューオン電気双極子能率
  - 未知のCP非保存現象の探索
- J-PARCで計画中のミューオンg-2/EDMの測定手法では、極冷ミューオンビームを用いることによる、次世代の実験。
- TDRの完成を経て、建設フェーズへ。
- 2019年頃よりデータ収集開始を目指して準備中。