Muon g-2 and EDM

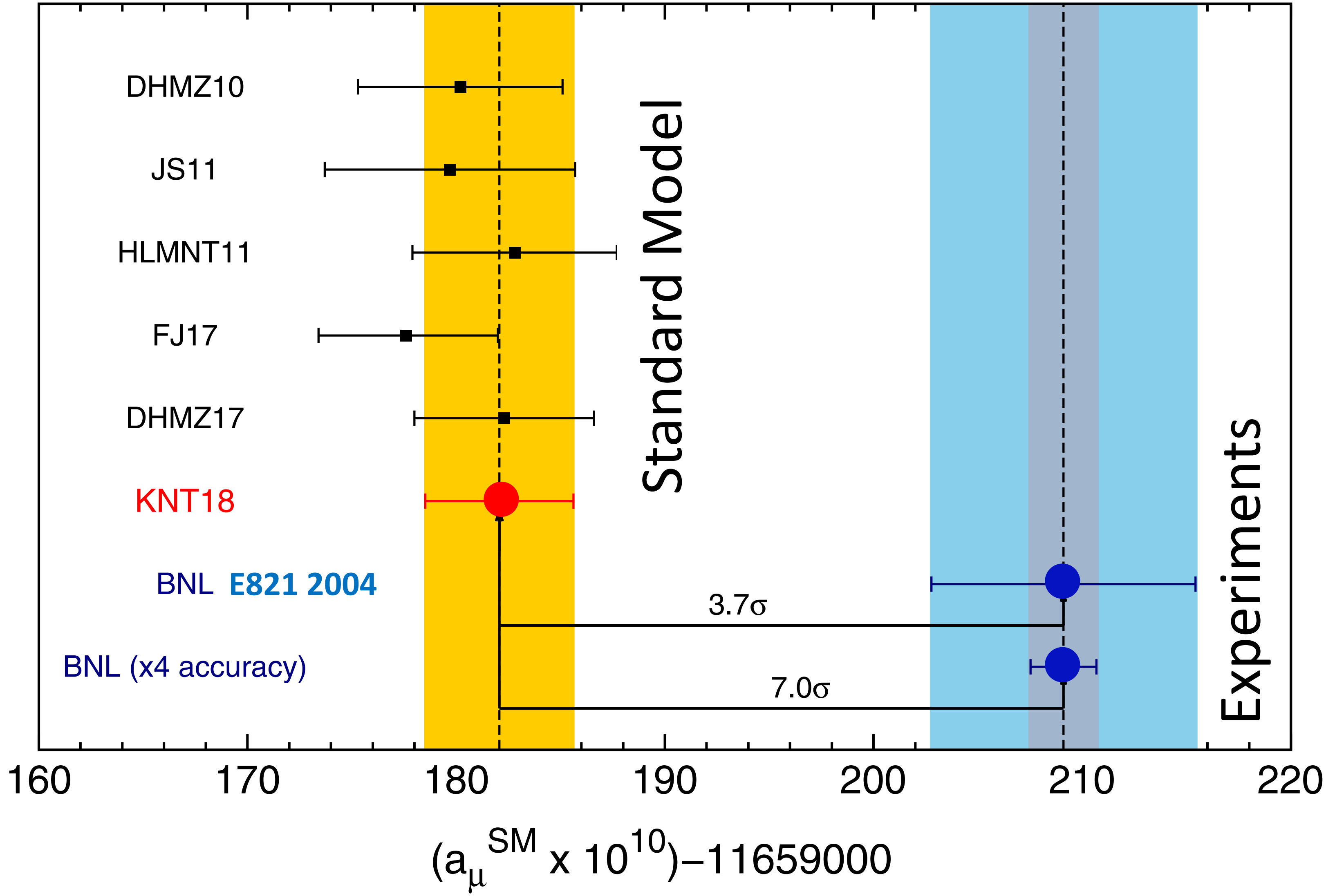
cLFV school

July 5-6, 2019

Tsutomu Mibe (IPNS, KEK)

Comparison between SM and a_μ

A. Keshavarzi, D. Nomura, T. Teubner, Phys. Rev. D 97, 114025 (2018)



Note that electron g-2 is consistent with the SM.

Comparison of experiments

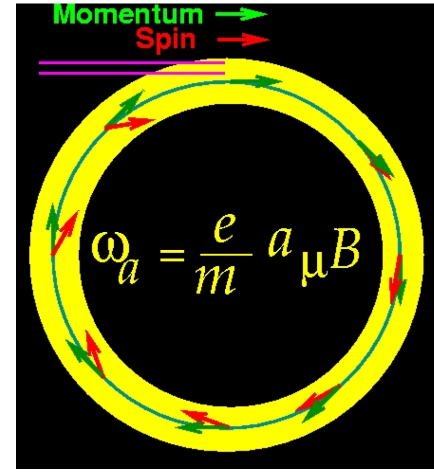
	BNL-E821	Fermilab-E989	Our experiment
Muon momentum	3.09 GeV/c		300 MeV/c
Lorentz γ	29.3		3
Polarization	100%		50%
Storage field	$B = 1.45$ T		$B = 3.0$ T
Focusing field	Electric quadrupole		Very weak magnetic
Cyclotron period	149 ns		7.4 ns
Spin precession period	4.37 μs		2.11 μs
Number of detected e^+	5.0×10^9	1.6×10^{11}	5.7×10^{11}
Number of detected e^-	3.6×10^9	–	–
a_μ precision (stat.)	460 ppb	100 ppb	450 ppb
(syst.)	280 ppb	100 ppb	<70 ppb
EDM precision (stat.)	$0.2 \times 10^{-19}\ e \cdot$ cm	–	$1.5 \times 10^{-21}\ e \cdot$ cm
(syst.)	$0.9 \times 10^{-19}\ e \cdot$ cm	–	$0.36 \times 10^{-21}\ e \cdot$ cm

Prog. Theor. Exp. Phys. **2019**, 053C02 (2019)

Contents

- Spin properties of muon
- Building a magnet from SM
- Measurement of g-2
- Searching for EDM
- Technical advances for higher precision
- Auxiliary measurements with muonium

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

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

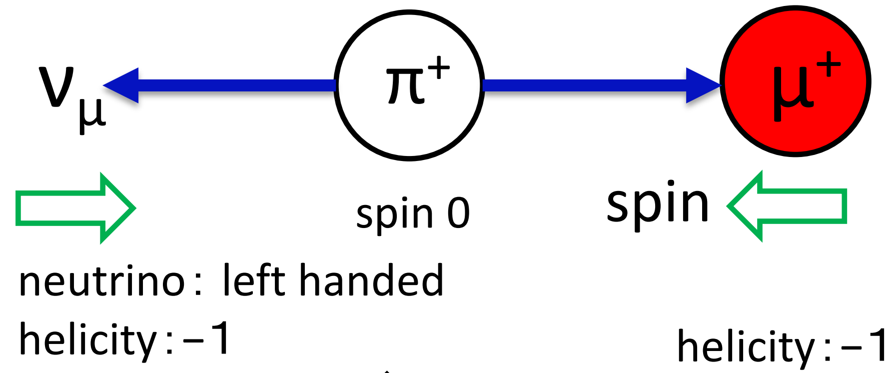
FNAL E989

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

J-PARC E34

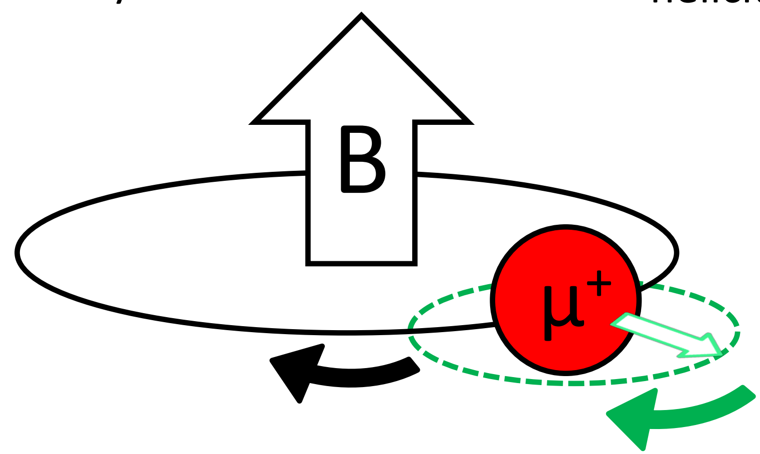
Three steps of g-2 measurement

1. Prepare a polarized muon beam.

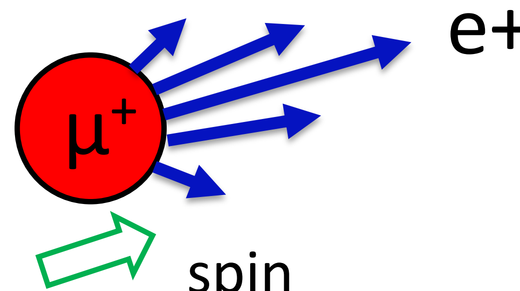


2. Store in a magnetic field (muon's spin precesses)

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



3. Measure decay positron



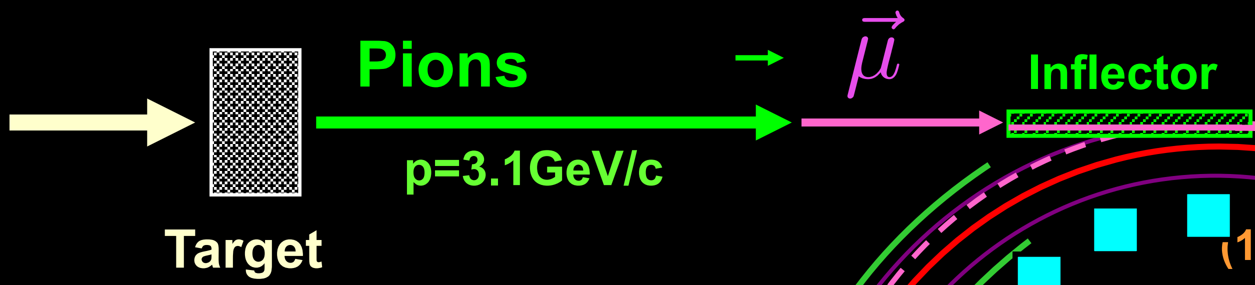
BNL & FNAL Experimental Technique

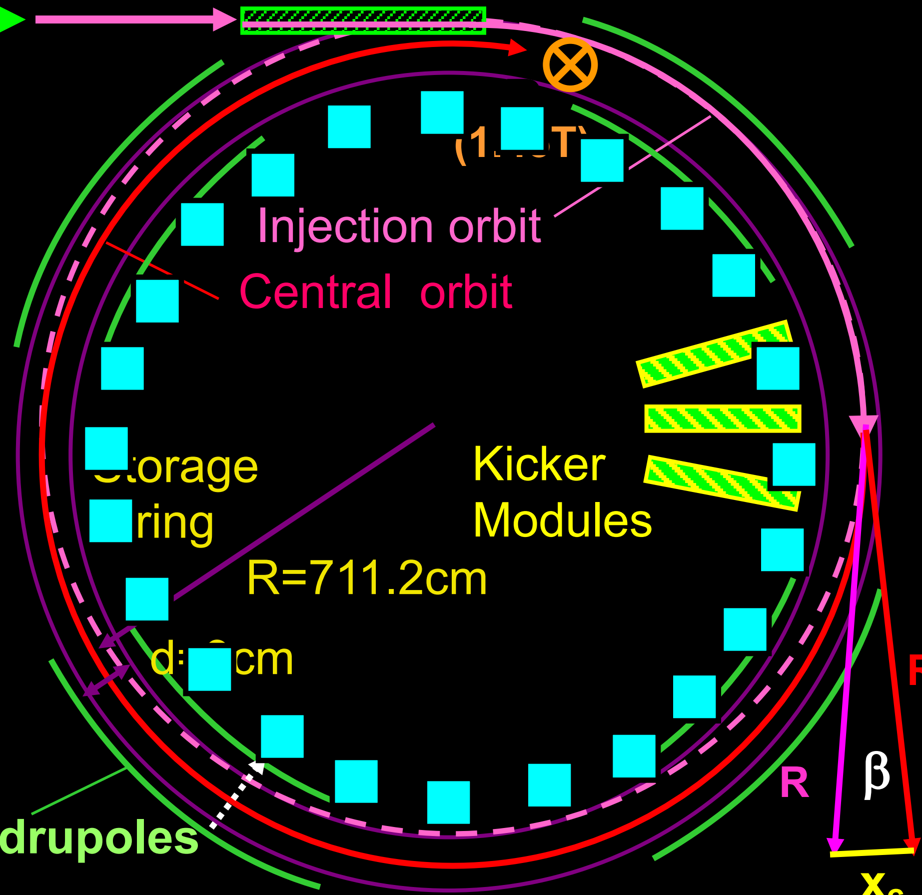
narrow bunch of protons

$x_c \approx 77$ mm

$\beta \approx 10$ mrad

$B \cdot dl \approx 0.1$ Tm





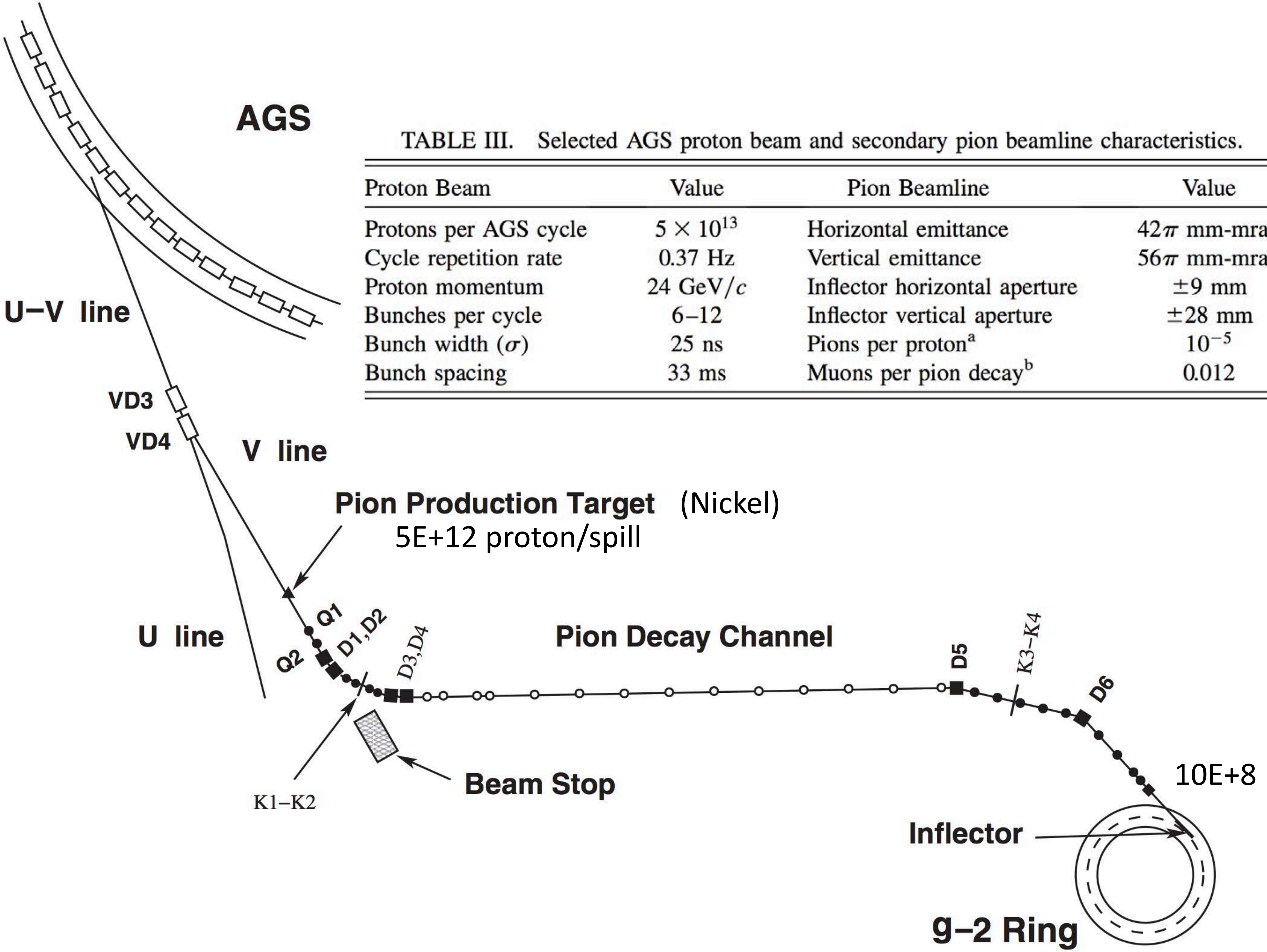
- Muon polarization
- Muon storage ring
- injection & kicking
- focus with Electric Quadrupoles
- 24 electron calorimeters

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

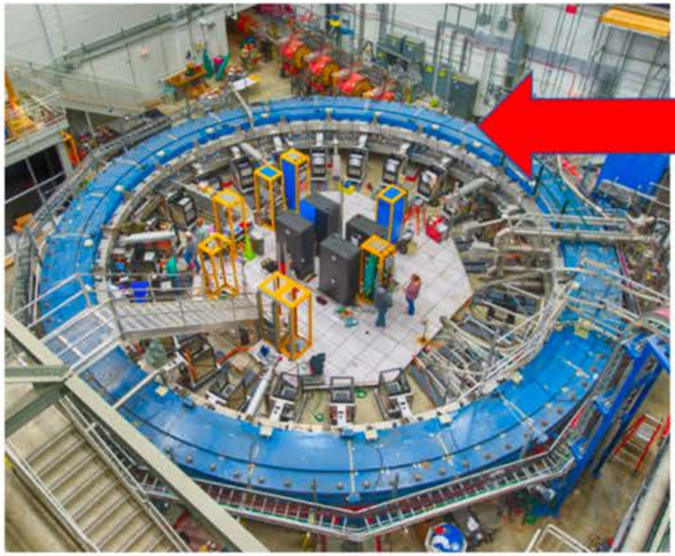
Slide by Lee Roberts

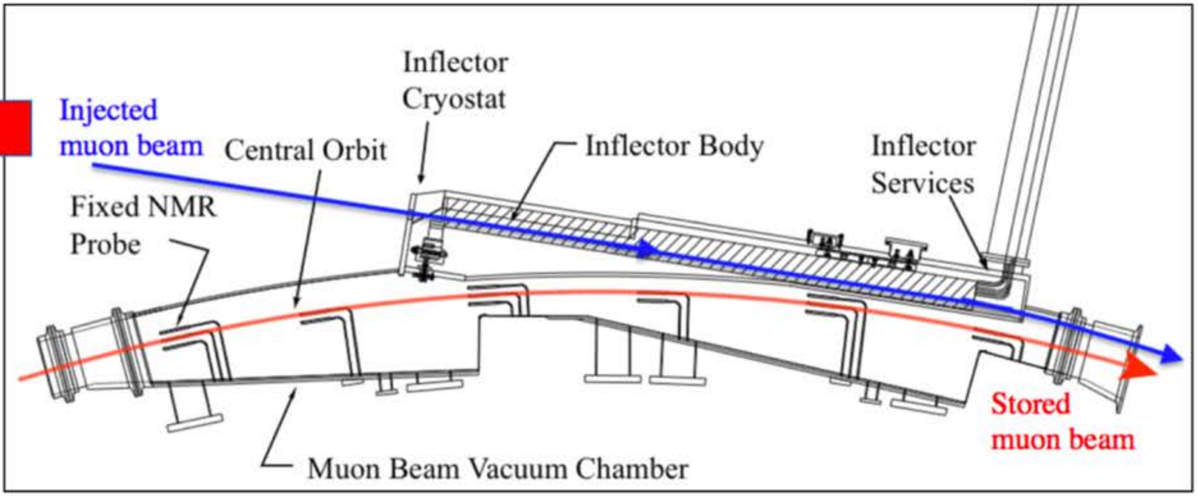
TABLE III. Selected AGS proton beam and secondary pion beamline characteristics.

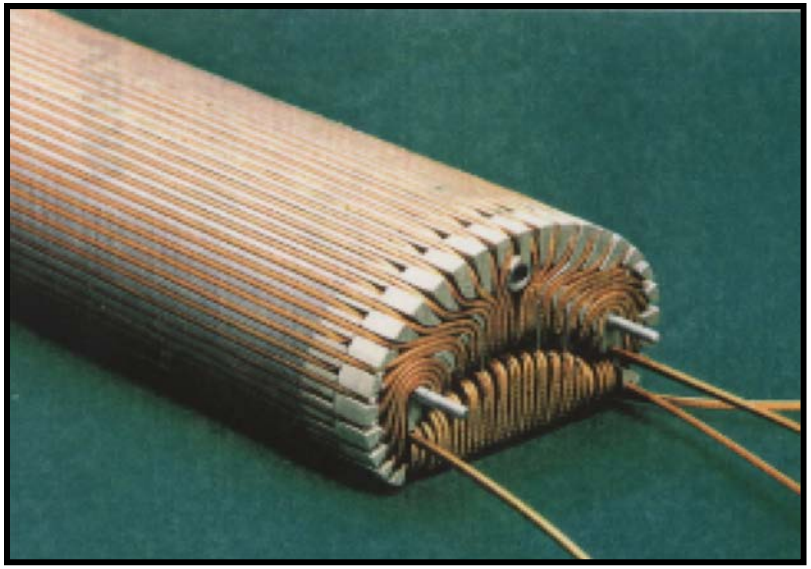
Proton Beam	Value	Pion Beamline	Value
Protons per AGS cycle	5×10^{13}	Horizontal emittance	42π mm-mrad
Cycle repetition rate	0.37 Hz	Vertical emittance	56π mm-mrad
Proton momentum	24 GeV/c	Inflector horizontal aperture	± 9 mm
Bunches per cycle	6–12	Inflector vertical aperture	± 28 mm
Bunch width (σ)	25 ns	Pions per proton[a]	10^{-5}
Bunch spacing	33 ms	Muons per pion decay[b]	0.012

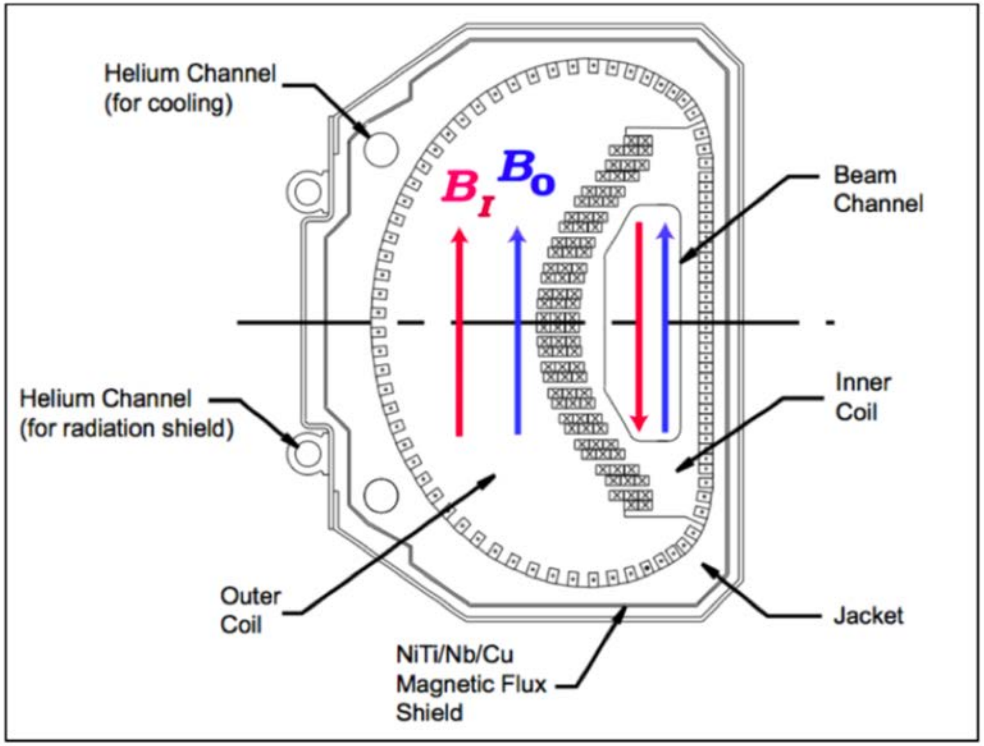


Injection

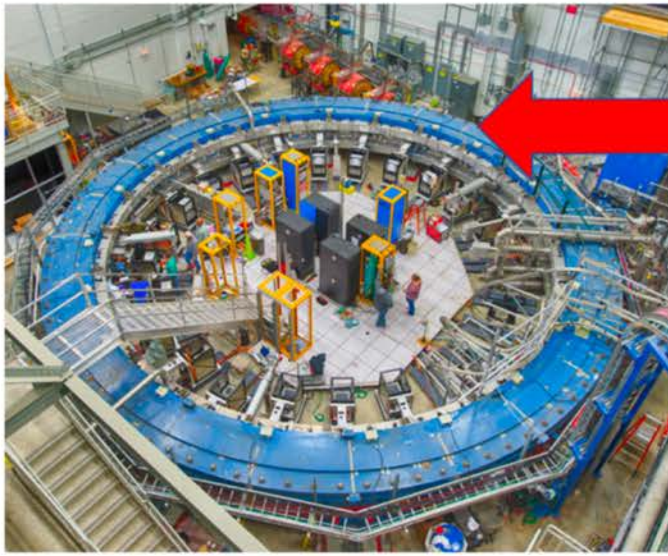


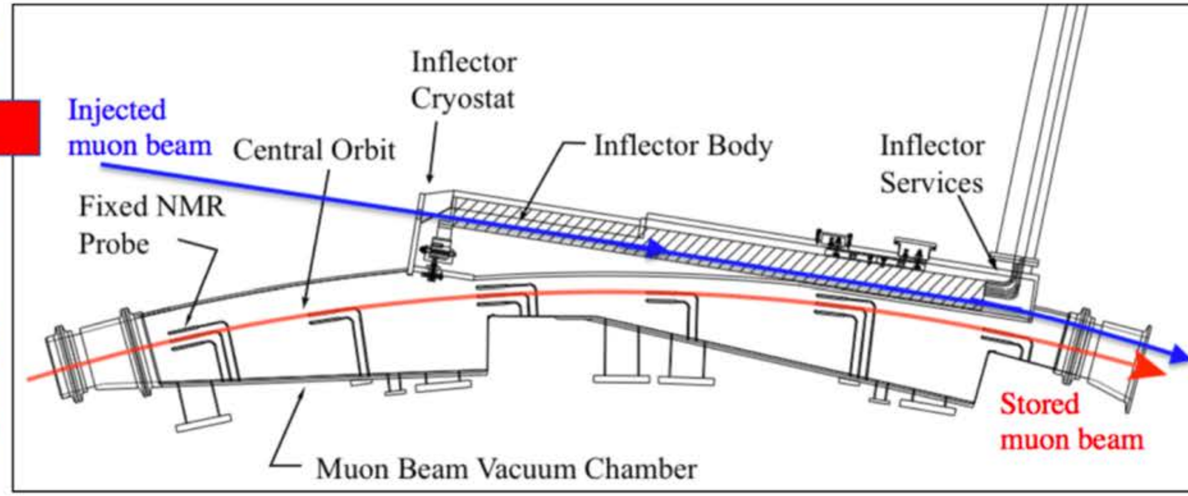

Injected
muon beam
Central Orbit
Inflector
Cryostat
Inflector Body
Inflector
Services
Fixed NMR
Probe
Stored
muon beam
Muon Beam Vacuum Chamber

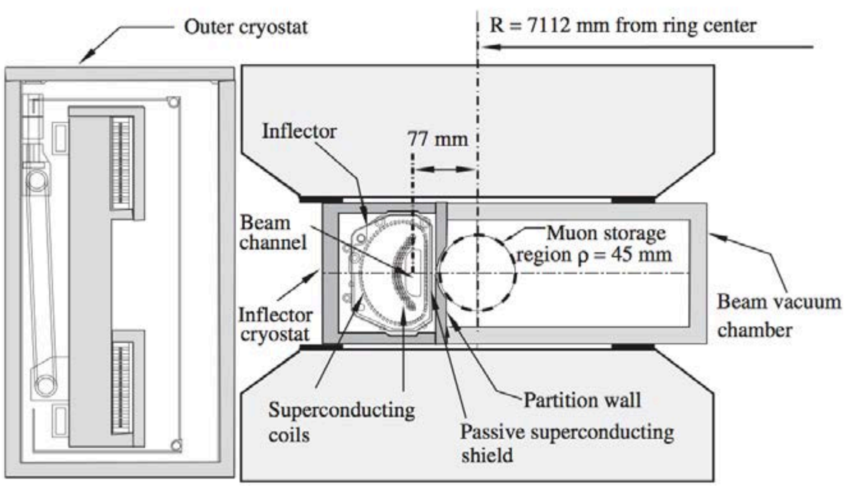


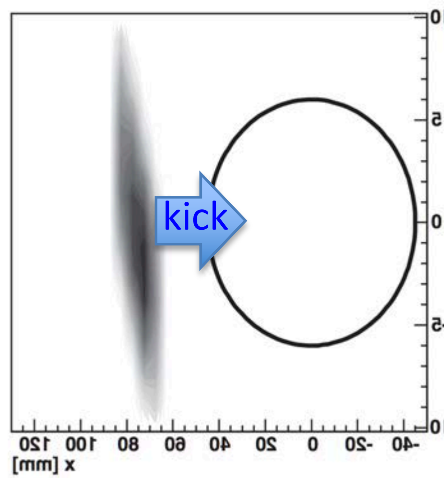

Helium Channel
(for cooling)
B_I
B_0
Beam
Channel
Helium Channel
(for radiation shield)
Inner
Coil
Outer
Coil
Jacket
NiTi/Nb/Cu
Magnetic Flux
Shield

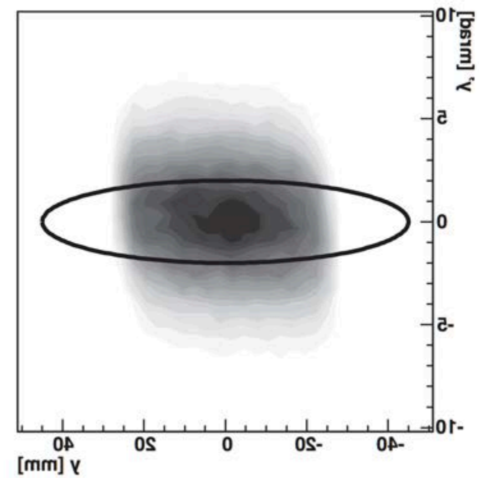
Injection







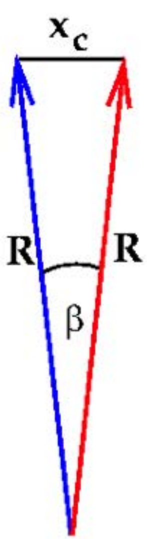


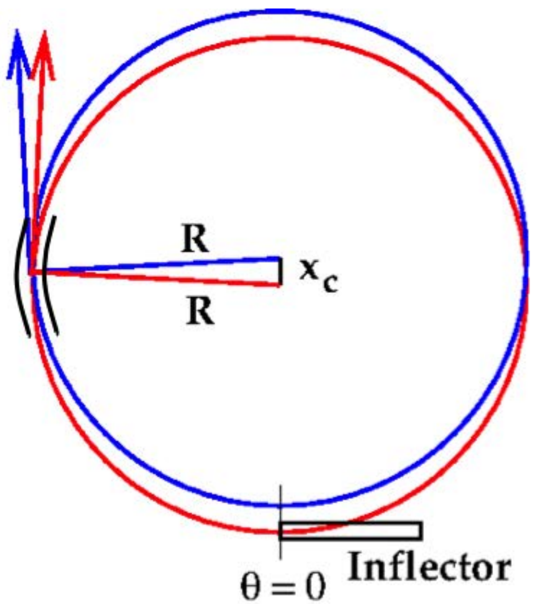


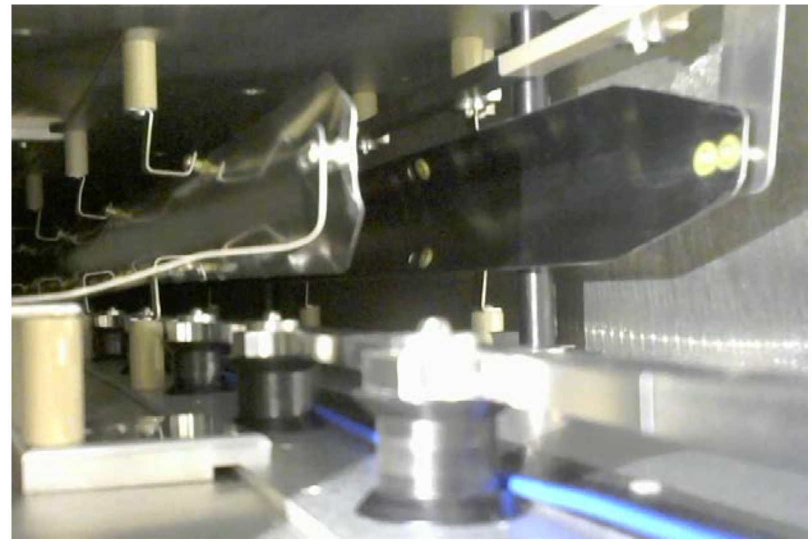
Injection efficiency 3-5%

Kicker

Slide by D. Kawall







- Muons enter 77 mm outside ideal closed orbit with radius 7112 mm
- Muons cross ideal orbit at 90°, angle off by 77 mm/7112 mm $\approx$ 11 mrads

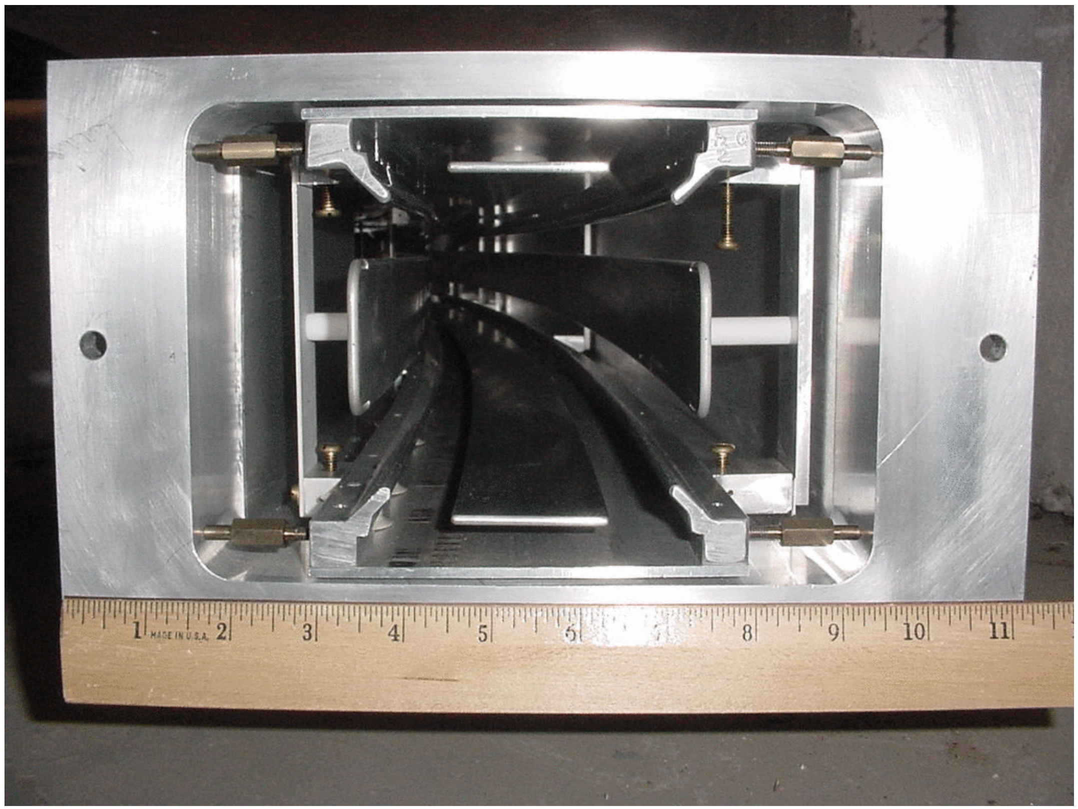
$\Rightarrow$ Reduce $\mathbf{B}$ by $\approx$ 300 Gauss over 4 metres for 149 ns at 100 Hz, 10% homogeneity

- Kicker steers muons onto stored orbit with $\approx$ 50 kV, 5000 Amp pulse

Electric quadrupoles

Slide by D. Kawall

- Use electric quadrupoles for linear restoring force in vertical
- Uniform quadrupole field leads to simple harmonic motion about closed orbit

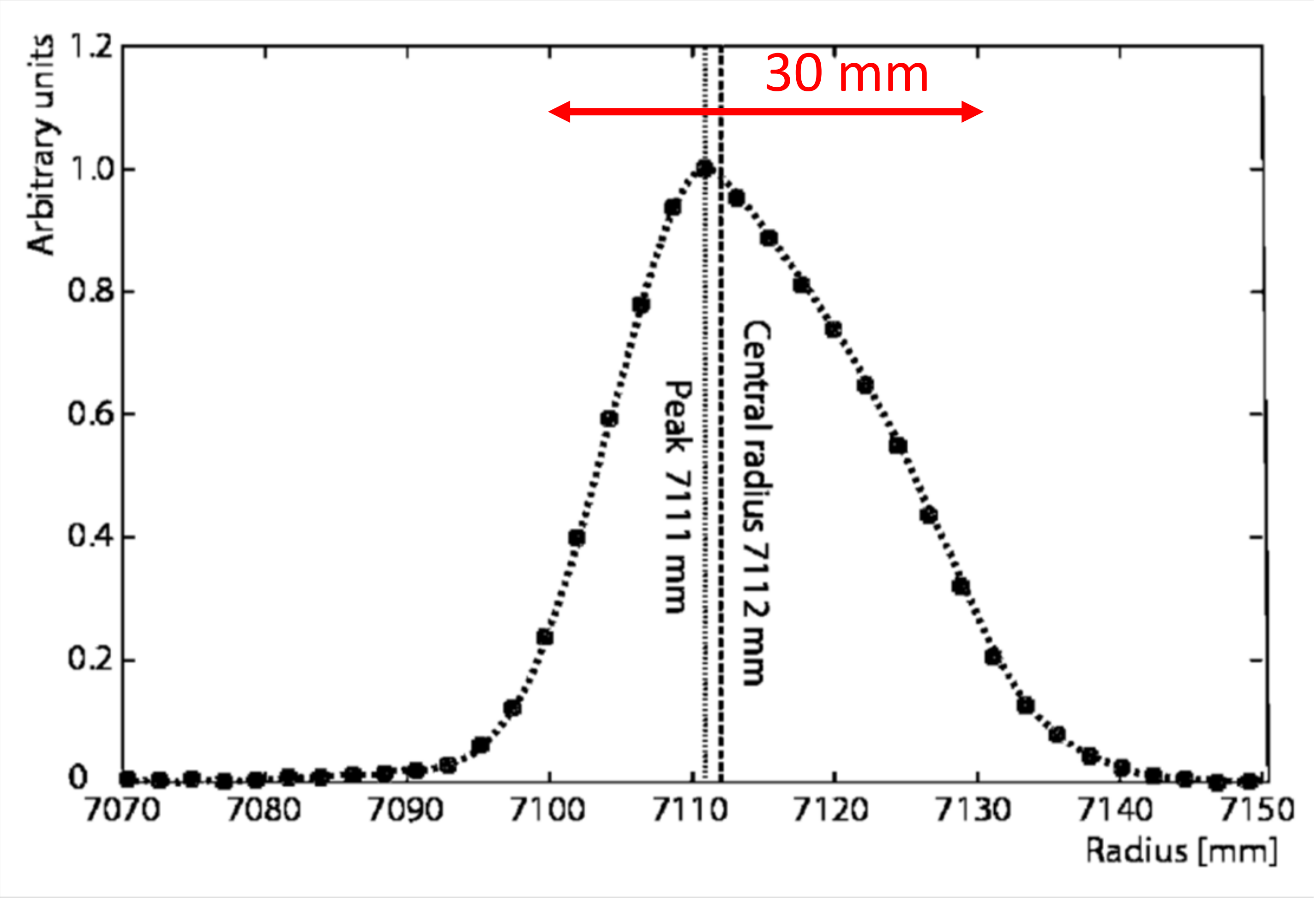


V=~24 kV

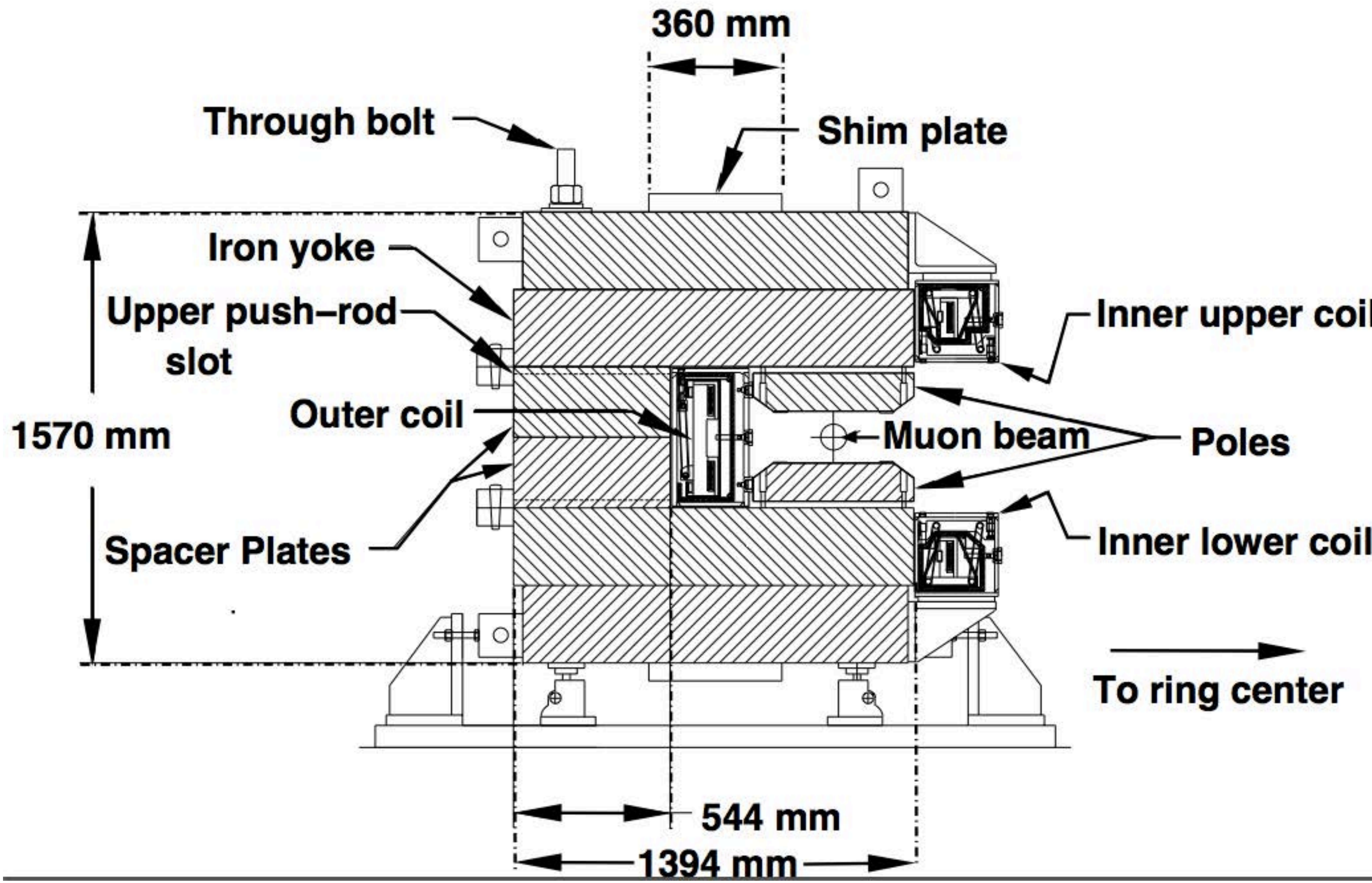
n =~0.14

$$x = x_e + A_x \cos\left(\nu_x \frac{s}{R_0} + \delta_x\right),\ y = A_y \cos\left(\nu_y \frac{s}{R_0} + \delta_y\right)$$

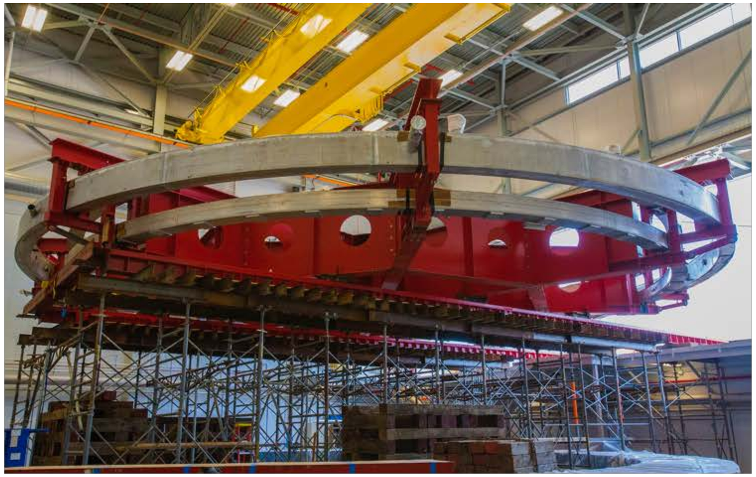
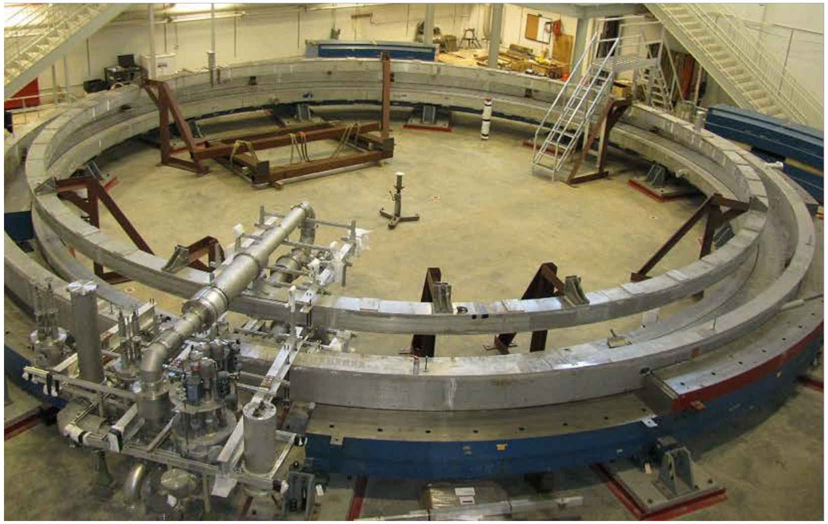
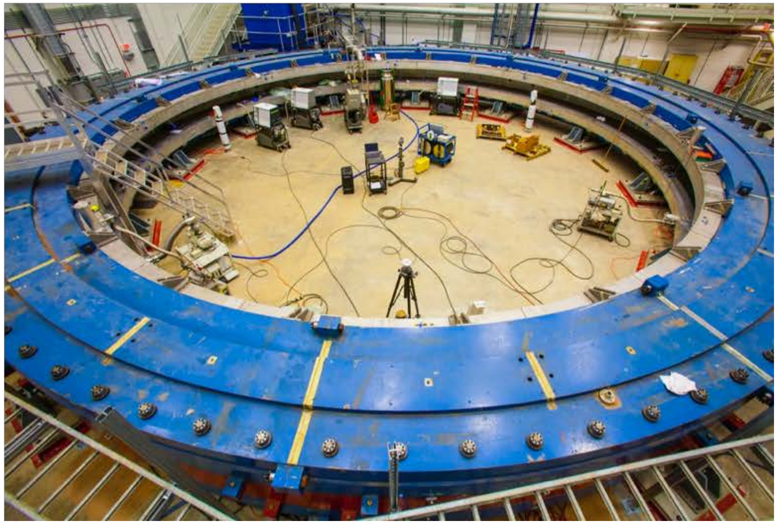
Beam distribution at storage



Storage magnet

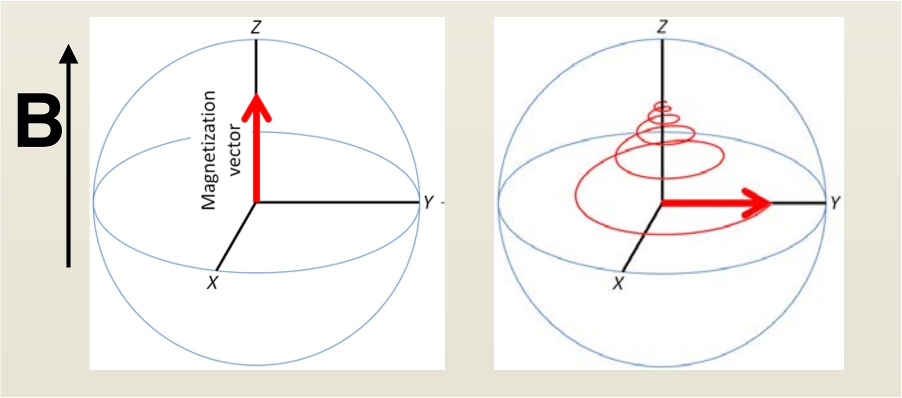


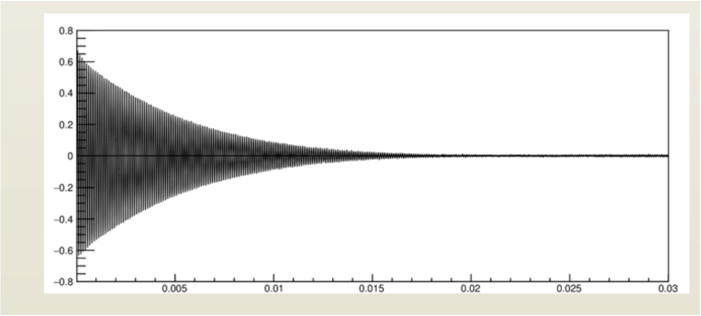
Magnet Reassembly at Fermilab June 2014 - June 2015

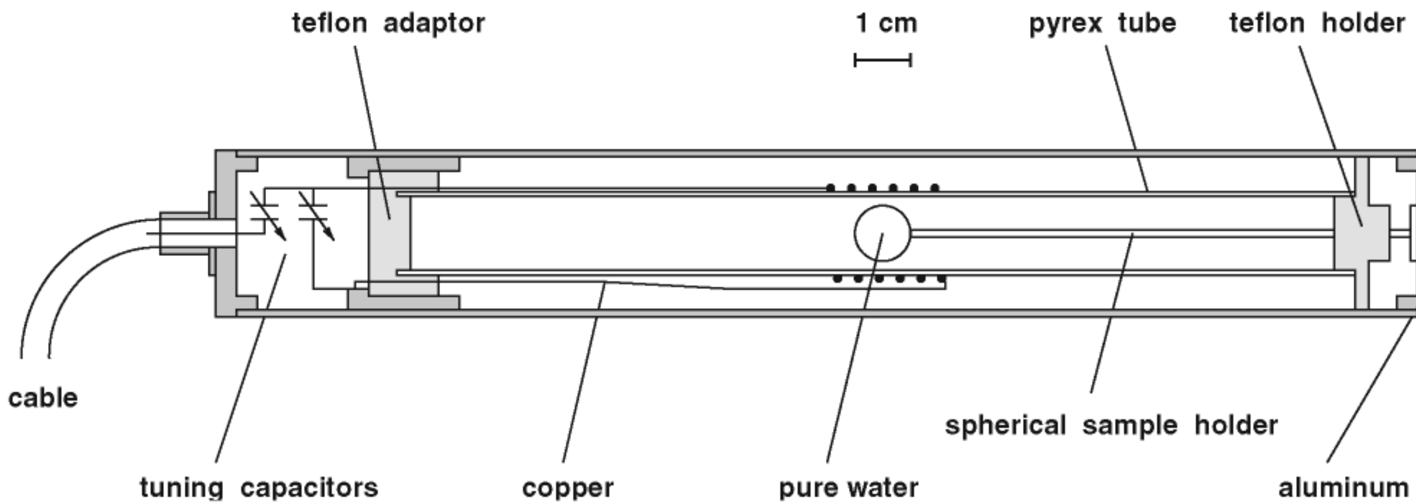





Measurement of magnetic field

NMR (Nuclear Magnetic Resonance) $\omega_p = \mu_p B$

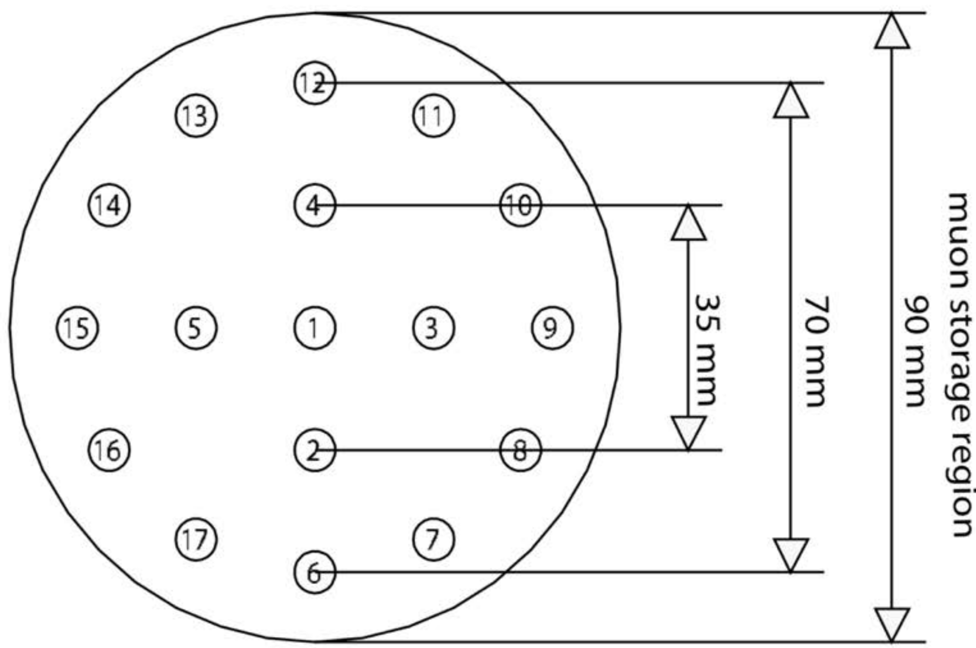






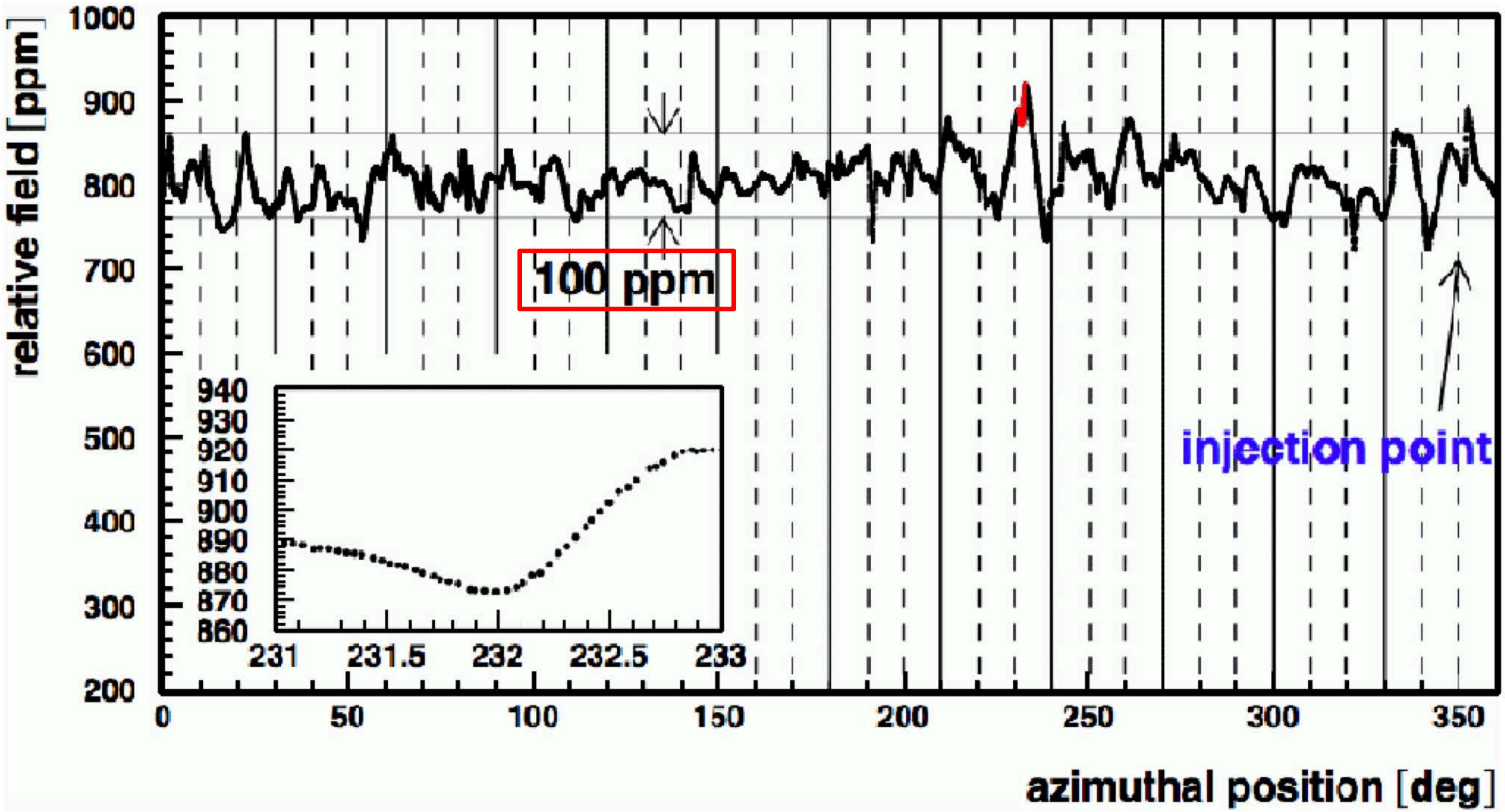
Field mapping trolley

(a) NMR Trolley



(b) Distribution of NMR probes over a cross section of the trolley

Magnetic field distribution along the muon beam orbit



Phys. Rev. D 73 072003 (2006)

The ± 1 ppm uniformity in the average field is obtained with special shimming tools.

$\langle B \rangle_{\text{azimuth}}$

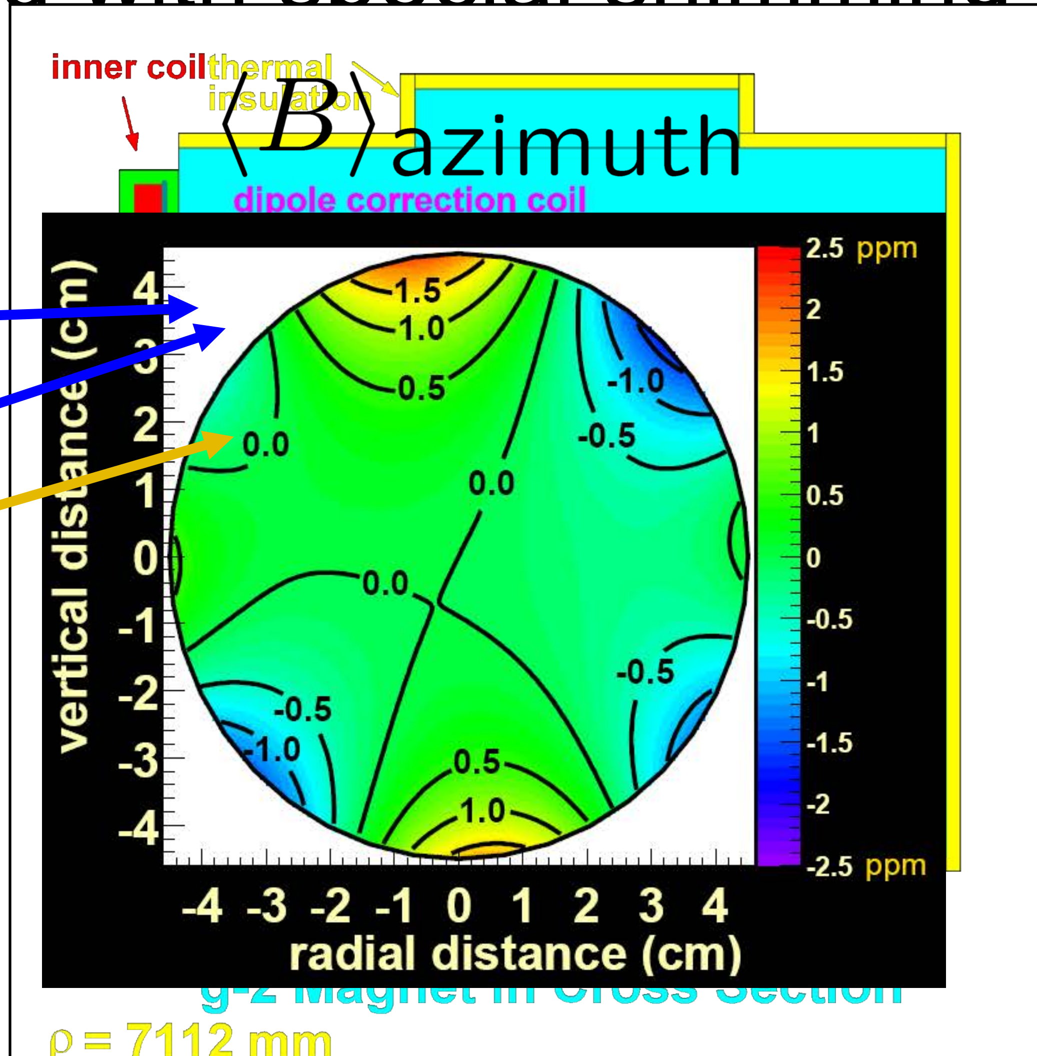
We can shim the

dipole,

quadrupole

sextupole

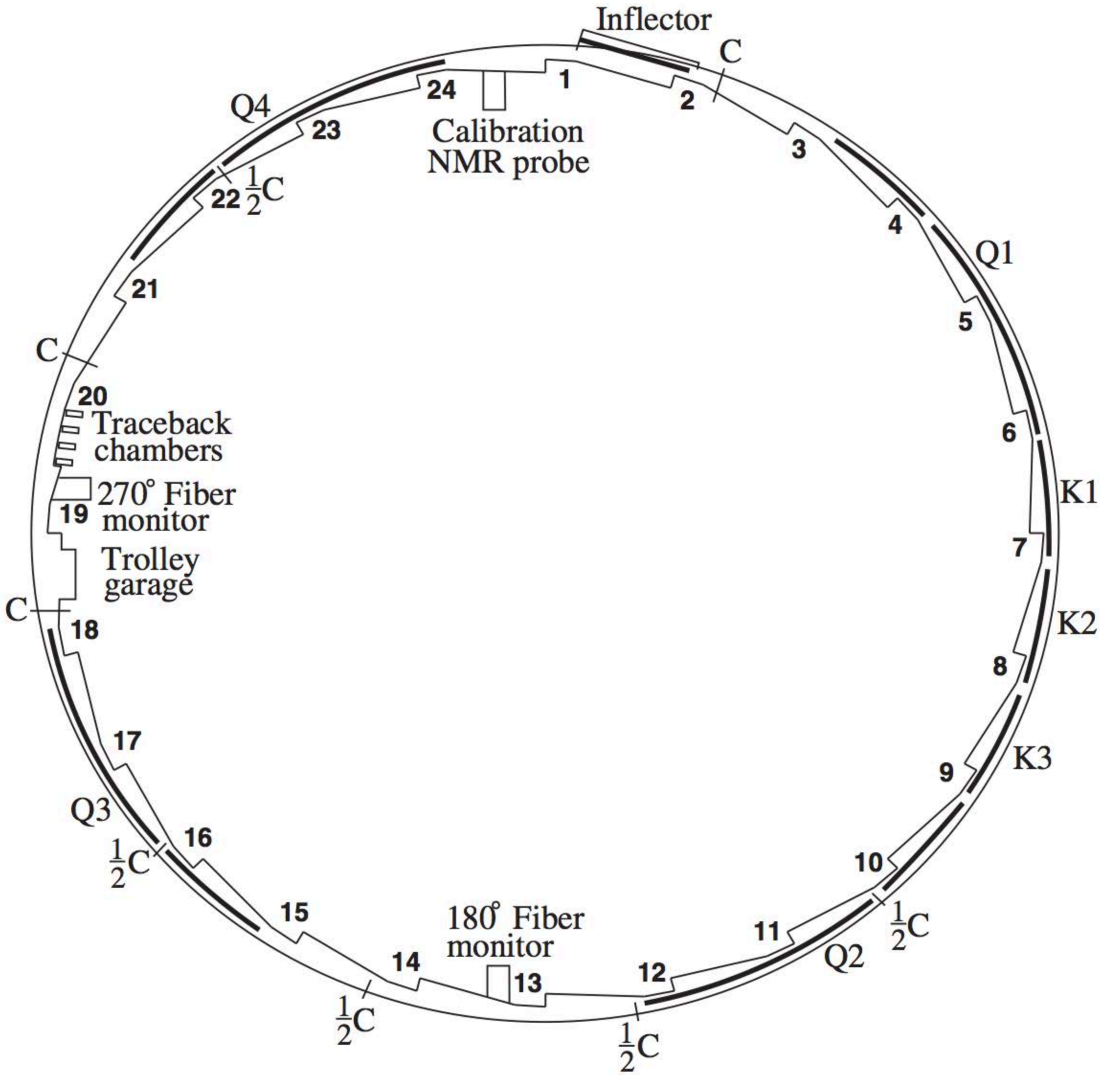
independently

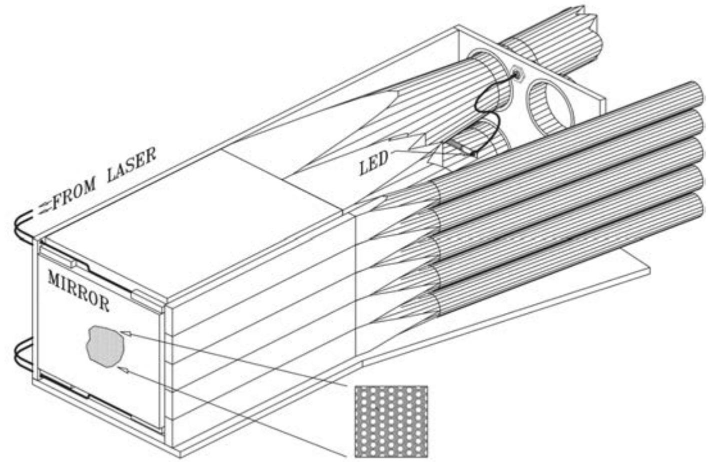


0.5 ppm contours

$$\sigma_{\text{syst}} \text{ on } \langle B \rangle_{\mu-\text{dist}} = \pm 0.03 \text{ ppm}$$

Positron detectors

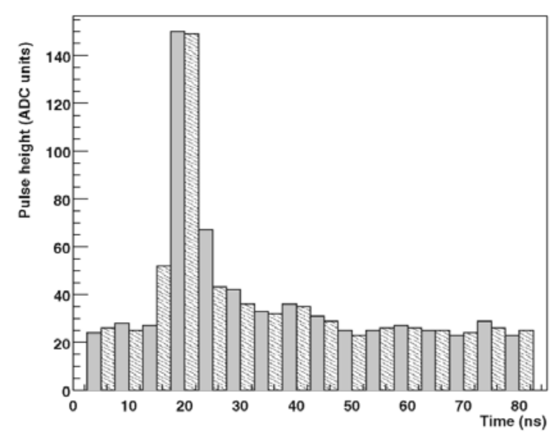




Pb/SciFi calorimeter

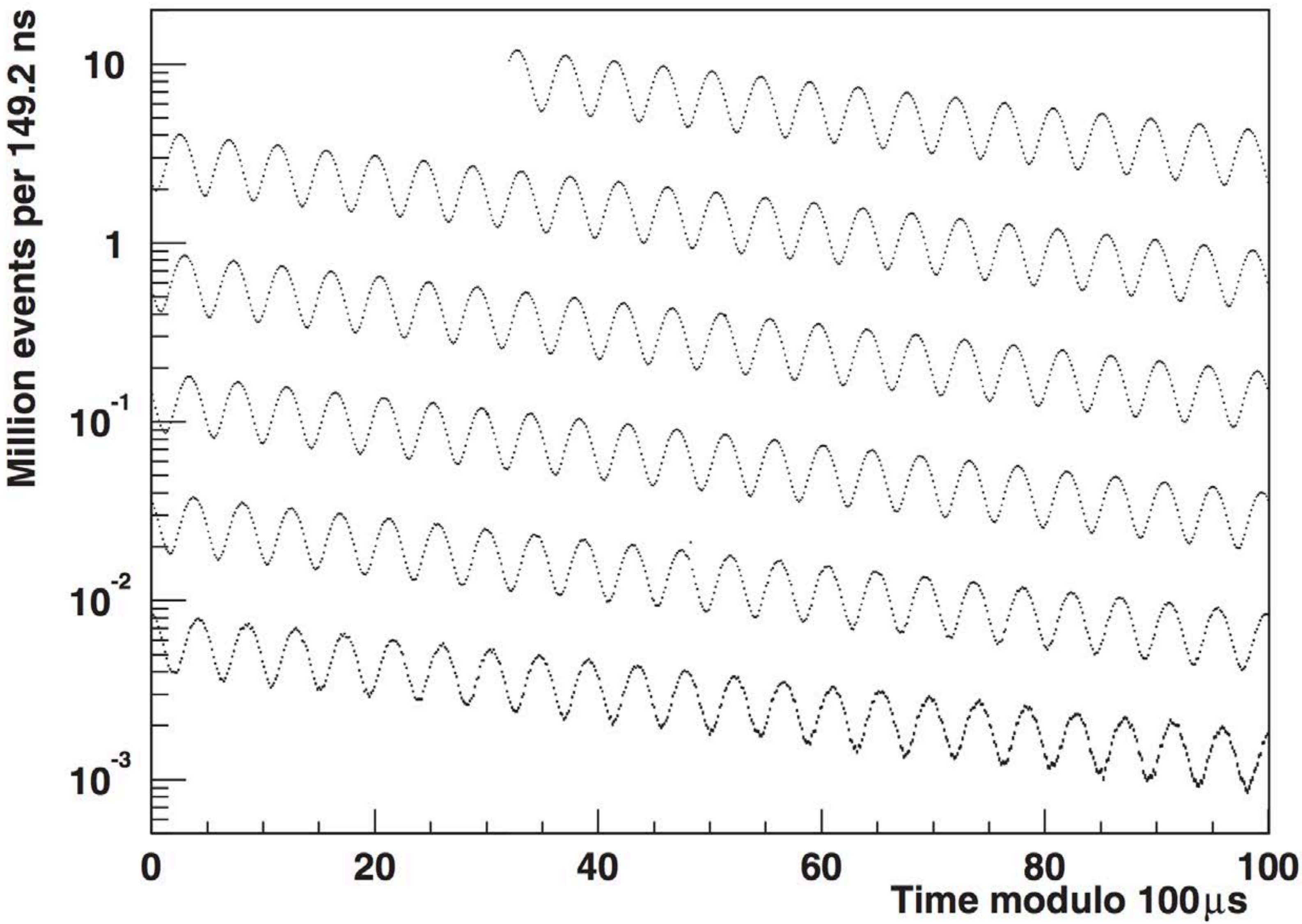
- Lead alloy (52%)
- Scintillation fiber (38%)
- Epoxy (10%)

Energy resolution 7% at 1.9 GeV



Time distribution of e+ (BNL E821)

Number of e+



Pitch and E-field corrections

- Corrections to ω_a determined by calorimeter required because:

(1) Not all muons at magic momentum $\Rightarrow$ not on center orbit $\Rightarrow$ see net electric field

(2) Vertical betatron motion: muons pitching up/down out of horizontal plane

$$\vec{\omega}_a \approx \vec{\omega}_S - \vec{\omega}_C = \underbrace{-\frac{e}{m}\left[a_\mu \vec{B}\right.}_{\textbf{What we want}} \underbrace{- a_\mu \left(\frac{\gamma}{\gamma+1}\right)\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta}}_{\textbf{Pitch Correction}} \underbrace{- \left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\left.\right]}_{\textbf{E-Field Correction}}$$

+0.27 ± 0.04 ppm   +0.47 ± 0.05 ppm

Relating measurements to g-2

- muon spin precession $$\omega_a = \frac{e}{m_\mu} a_\mu B$$
- proton spin precession $$\omega_p = \mu_p B$$
- muon magnetic moment $$\mu_\mu = g \frac{e}{2m_\mu} = (1 + a_\mu) \frac{e}{m_\mu}$$

$$a_\mu = \frac{\frac{\omega_a}{\omega_p}}{\frac{\omega_a}{\omega_p} - \frac{\mu_\mu}{\mu_p}}$$

540 ppb (BNL)
140 ppb
(Fermilab/J-PARC)

Magnetic moment ratio

LAMPF(1999)

$$\Delta\left(\frac{\mu_\mu}{\mu_p}\right) = 120\ ppb\ (30\ ppb)$$

direct

using Δν
+ theory

Systematic uncertainties ω_a

TABLE XIV. Systematic errors for ω_a in the R99, R00 and R01 data periods.

$\sigma_{\text{syst}}\ \omega_a$	R99 (ppm)	R00 (ppm)	R01 (ppm)
Pileup	0.13	0.13	0.08
AGS background	0.10	0.01	[a]
Lost muons	0.10	0.10	0.09
Timing shifts	0.10	0.02	[a]
E-field and pitch	0.08	0.03	[a]
Fitting/binning	0.07	0.06	[a]
CBO	0.05	0.21	0.07
Gain changes	0.02	0.13	0.12
Total for ω_a	0.3	0.31	0.21

[a]In R01, the AGS background, timing shifts, E field and vertical oscillations, beam debunching/randomization, binning and fitting procedure together equaled 0.11 ppm.

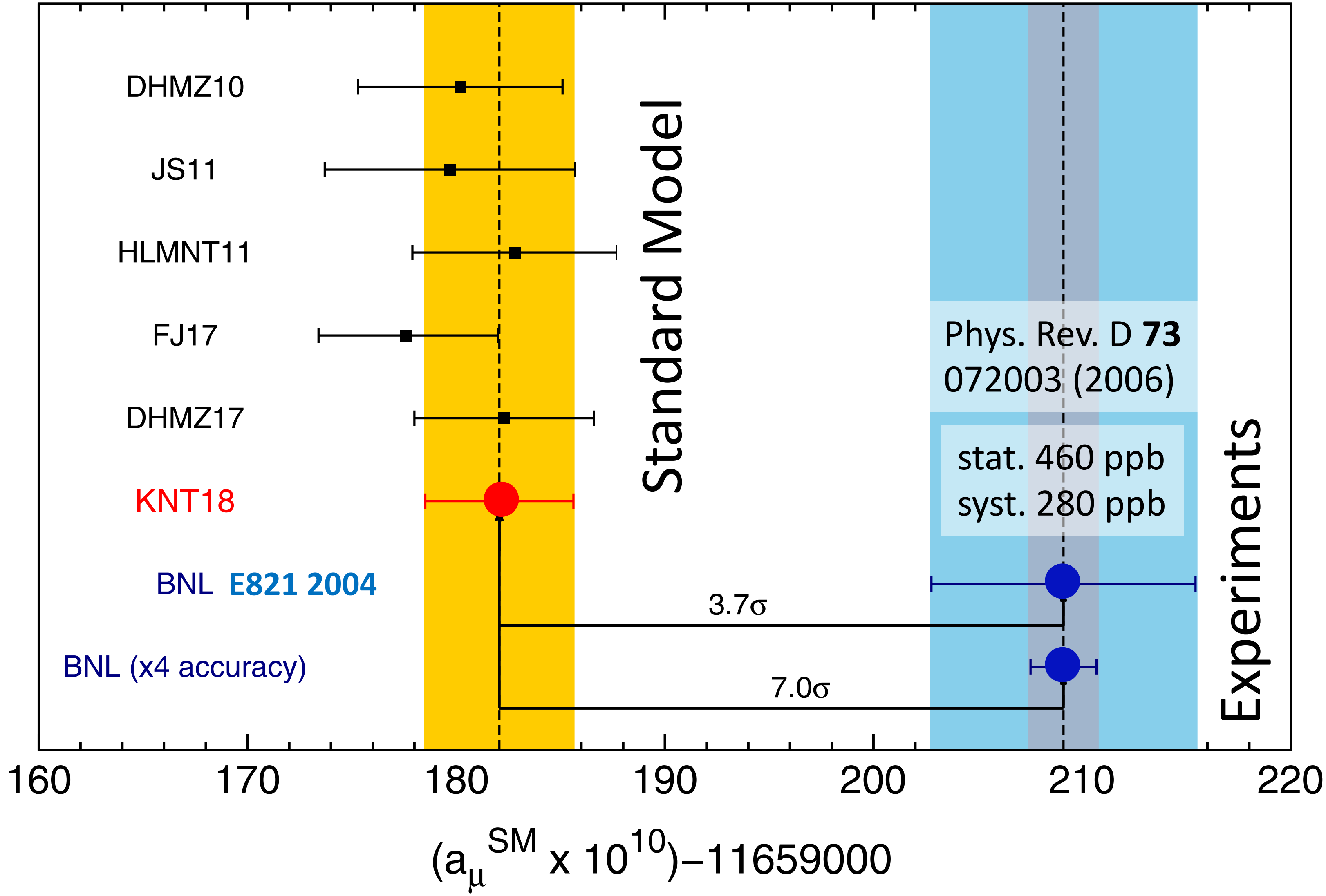
Systematic uncertainties ω_p

TABLE XI. Systematic errors for the magnetic field for the different run periods.

Source of errors	R99 [ppm]	R00 [ppm]	R01 [ppm]
Absolute calibration of standard probe	0.05	0.05	0.05
Calibration of trolley probes	0.20	0.15	0.09
Trolley measurements of B_0	0.10	0.10	0.05
Interpolation with fixed probes	0.15	0.10	0.07
Uncertainty from muon distribution	0.12	0.03	0.03
Inflector fringe field uncertainty	0.20	—	—
Others[a]	0.15	0.10	0.10
Total systematic error on ω_p	0.4	0.24	0.17
Muon-averaged field [Hz]: $\tilde{\omega}_p/2\pi$	61791256	61791595	61791400

[a]Higher multipoles, trolley temperature and its power supply voltage response, and eddy currents from the kicker.

Result of BNL E821 experiment



A. Keshavarzi, D. Nomura, T. Teubner, Phys. Rev. D 97, 114025 (2018)

Why Fermilab? Statistics!

⇒ Brookhaven statistics limited:
$a_\mu^{\mathrm{BNL}} = 0.001\,165\,920\,89\,(54)_{\mathrm{stat}}\,(33)_{\mathrm{sys}}$

- BNL ± 540 ppb uncertainty on a_μ, 9×10^9 events

⇒ Fermilab goal 2×10^{11}, factor 21

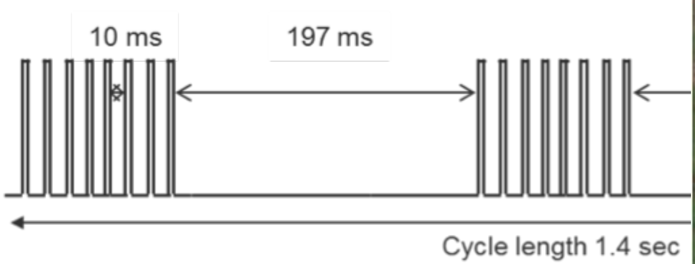
Fermilab Advantages:

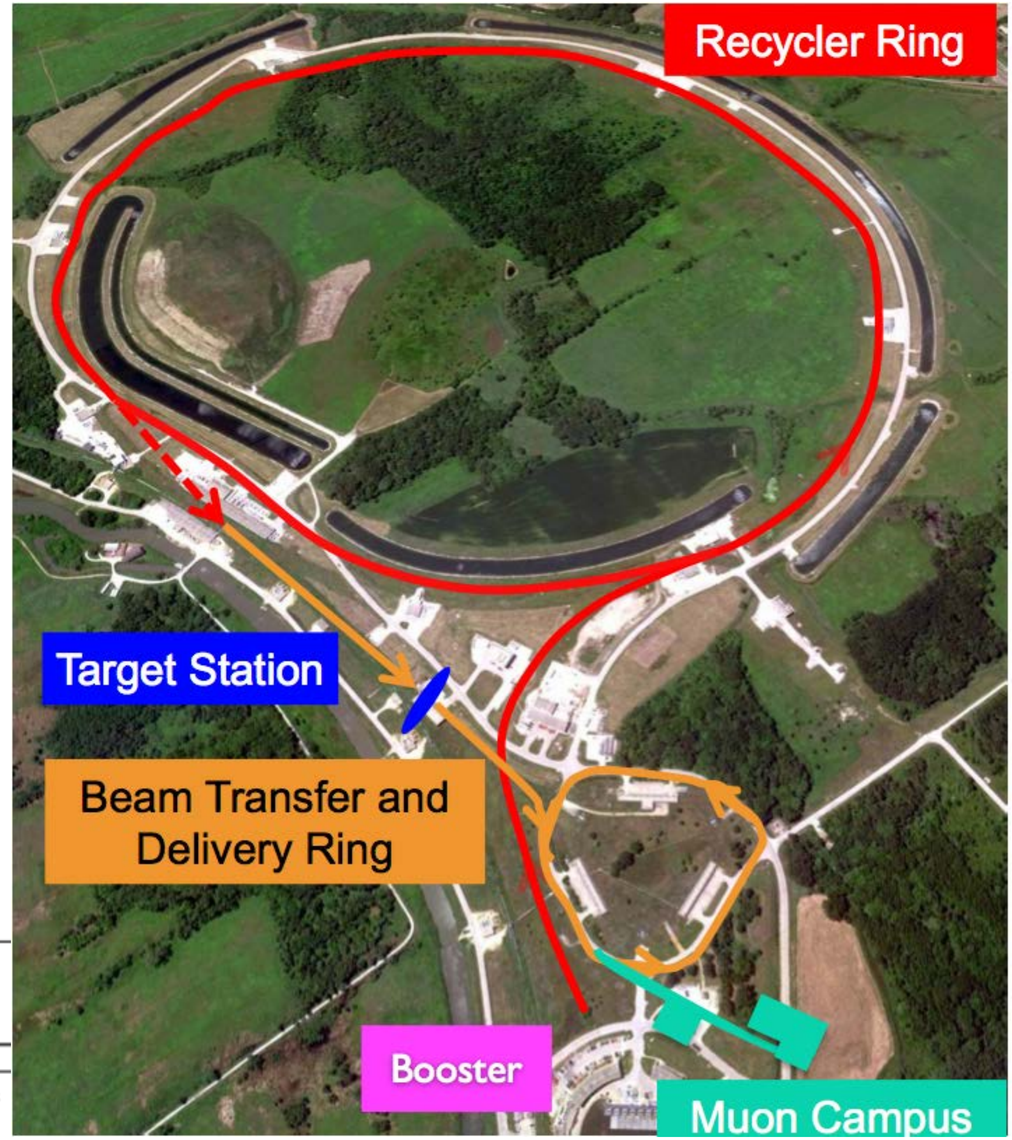
- Long decay channel for $\pi \Rightarrow \mu$
- Reduced π and p in ring
- Factor 20 reduction in hadronic flash

⇒ $4\times$ higher fill frequency than BNL

- Muons per fill about the same

⇒ 21 times more detected e^+, 2×10^{11}





21 times more detected e^+

Estimated systematic uncertainties ω_a

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

Estimated systematic uncertainties ω_p

Source of uncertainty	1999	2000	2001		E989
Systematics of calibration probes	50	50	50	→	35
Calibration of trolley probes	200	150	90	→	30
Trolley measurements of B_0	100	100	50	→	30
Interpolation with fixed probes	150	100	70	→	30
Uncertainty from muon distribution	120	30	30	→	10
Inflector fringe field uncertainty	200	–	–		–
Time dependent external B fields	–	–	–	→	5
Others †	150	100	100	→	30
Total systematic error on ω_p	400	240	170	→	70
Muon-averaged field [Hz]: $\omega_p/2\pi$	61 791 256	61 791 595	61 791 400		–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CERNCOURIER
VOLUME 54 NUMBER 9 NOVEMBER 2014
Muon g-2 moves on to a new life
EMMERT
OVERSIZE LOAD
Driving Discovery in Particle Physics
CERN60
Celebrations of 60 years of science for peace p28
CP VIOLATION
Meeting honours 50 years of a major discovery p32
NEW RESULTS FROM AMS
Evidence for a new source of positrons p6

Fermilab E989 experiment

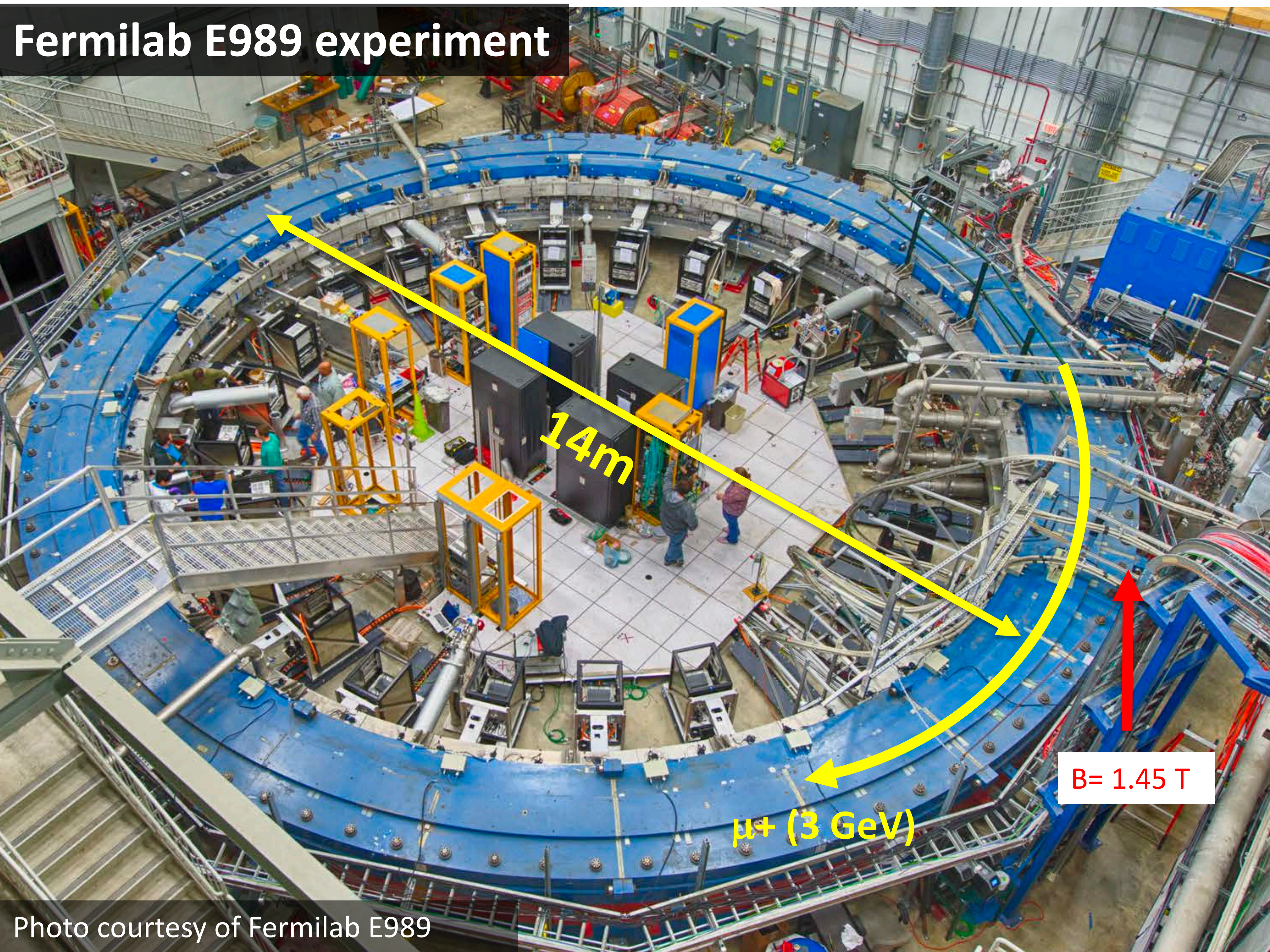


Photo courtesy of Fermilab E989

Muon beam line

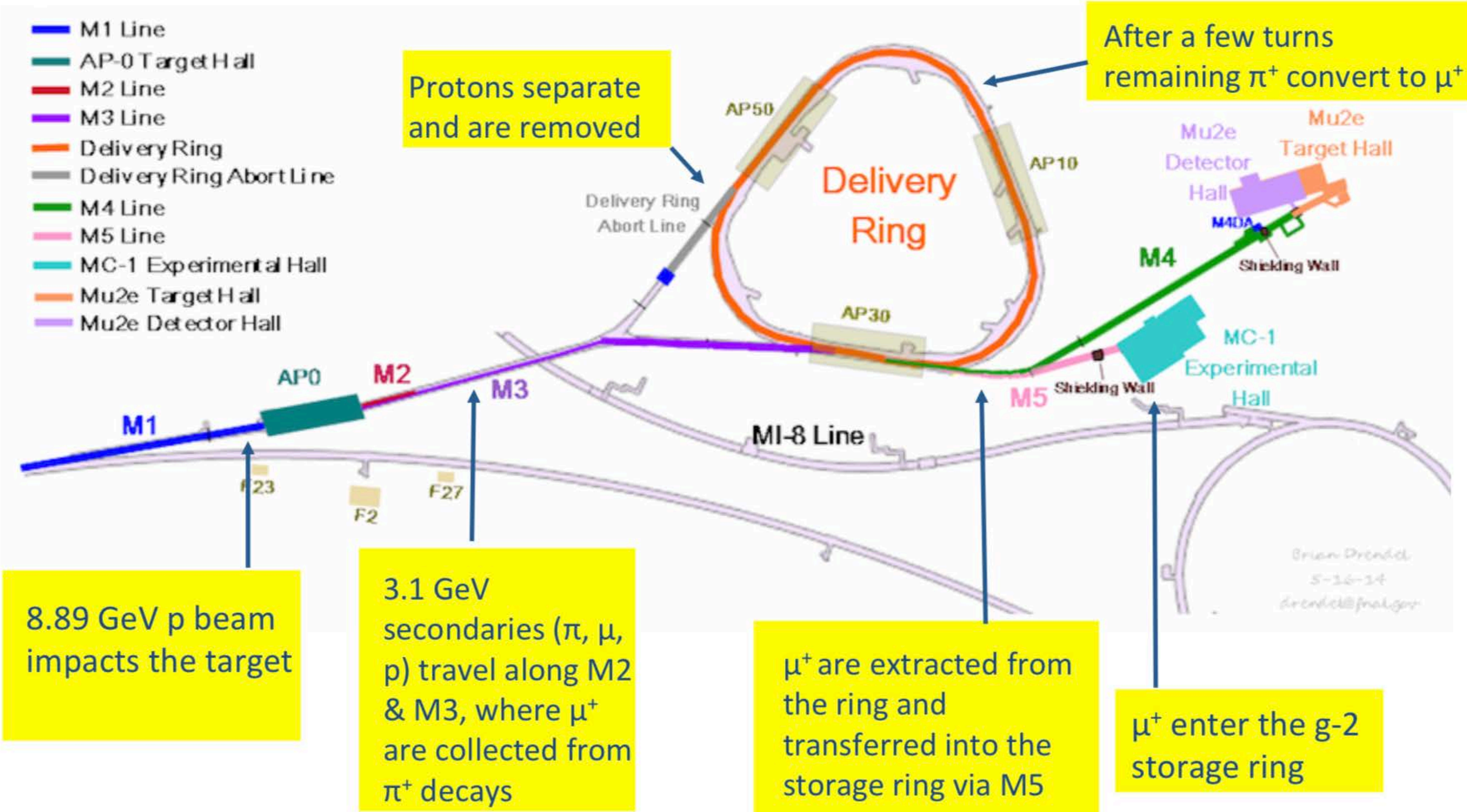
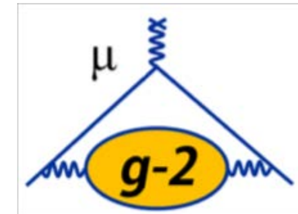


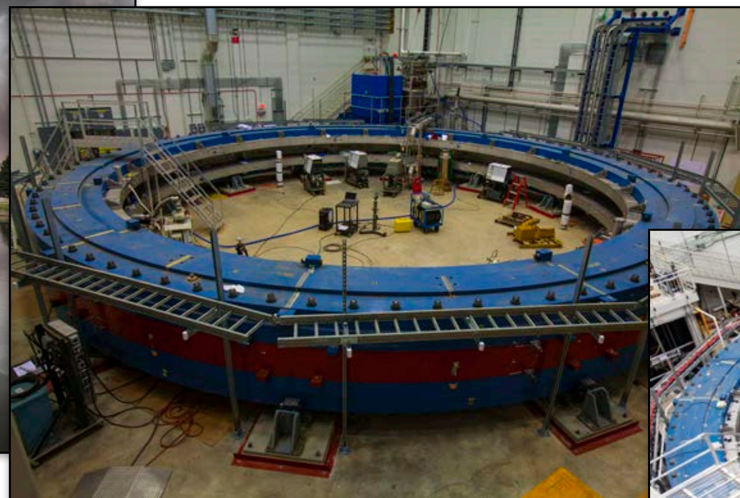
Image from D. Stratakis

History of Fermilab muon g-2 (2009-present)

Courtesy of Kim Siang Khaw

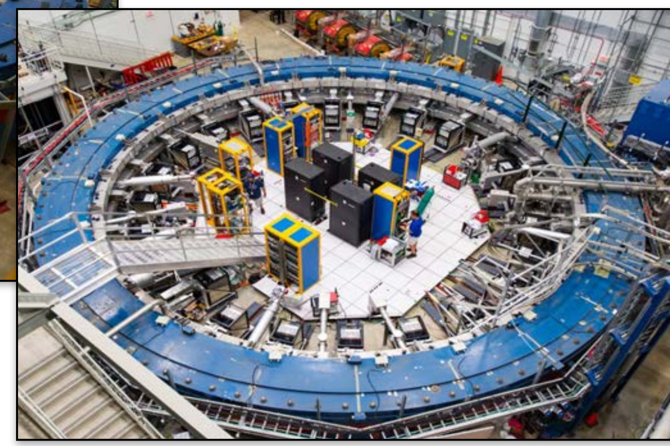


Transportation of magnet to FNAL (2013)

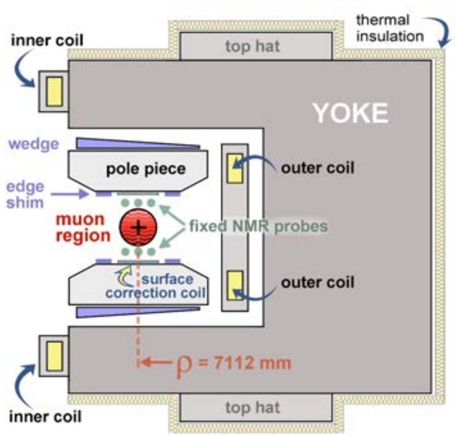


Assembly of the magnet (2014-2015)

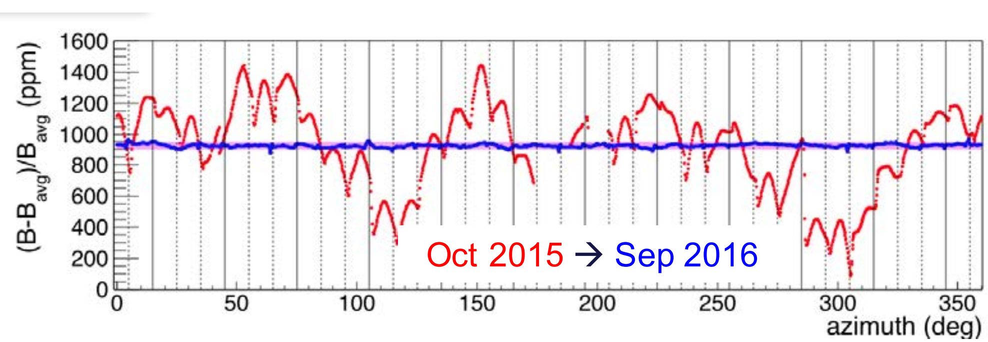
Passive shimming (2015-2016)



Full installation (2017)



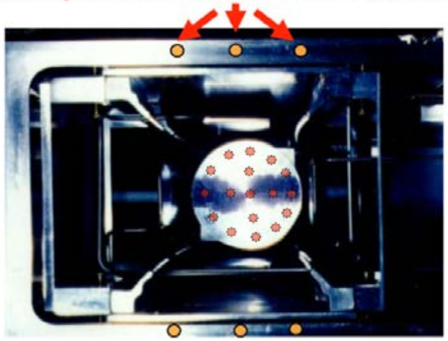
g-2 Magnet in Cross Section



Mapping the magnetic field

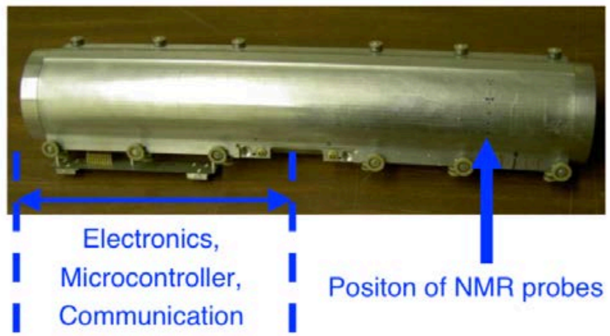
- Map the magnetic field inside the ring every 3 days
- Fixed probes for continuously monitoring

Fixed probes on vacuum chambers



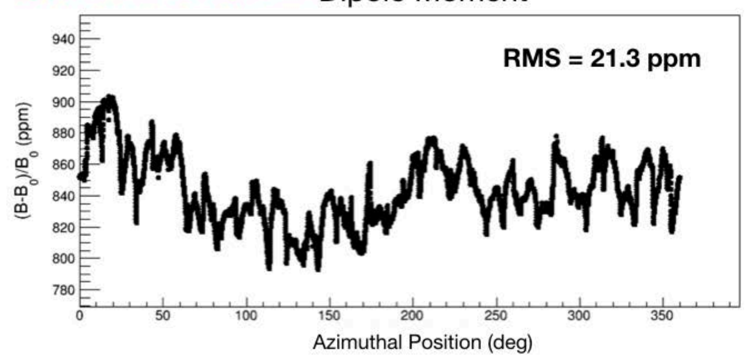
- Measure field while muons are in ring
  – 378 probes **outside** storage region

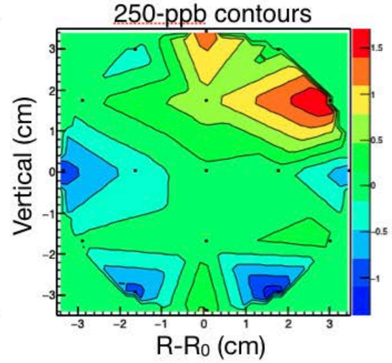
Trolley matrix of 17 NMR probes



- Measure field in storage region during **specialized runs** when **muons are not being stored**

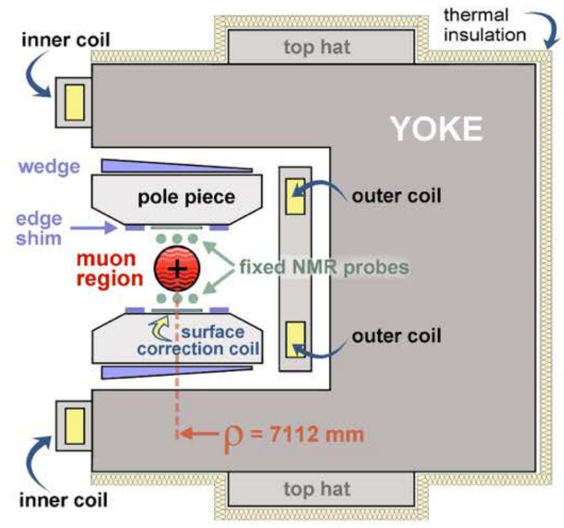
Typical trolley run





BOSTON UNIVERSITY

Storage Ring Magnet: Centerpiece of the Experiment

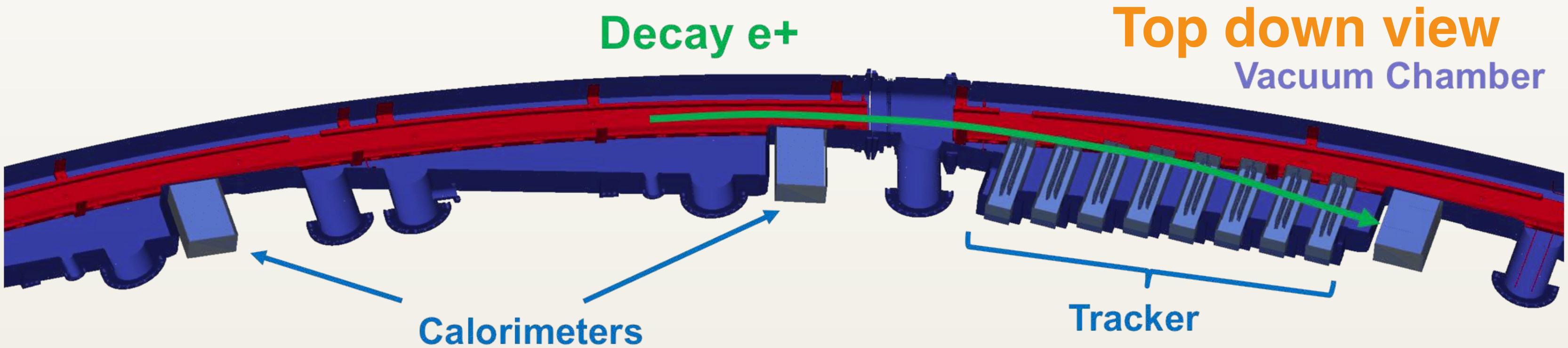


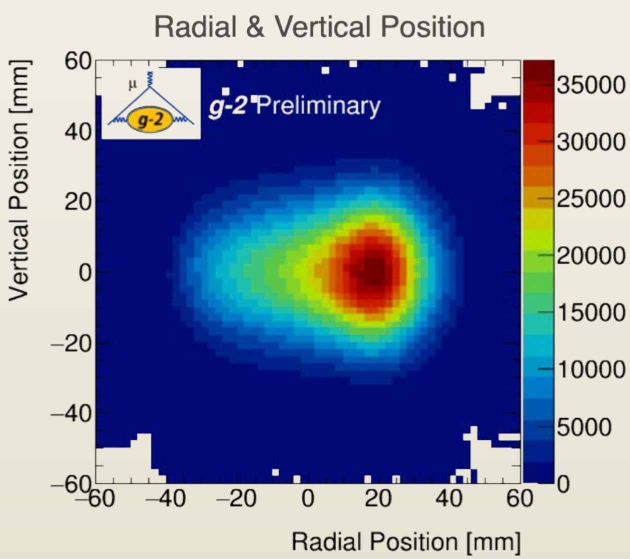
g-2 Magnet in Cross Section

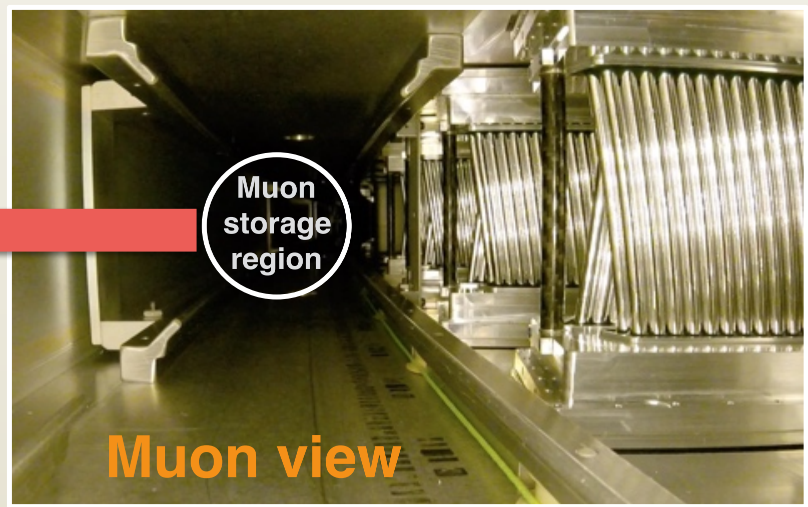
- 682 tons, 4 coils×24 windings×5200 Amps/winding, 72 poles, B=1.4513 T
- B×gap ≈ $\mu_0 I$ ⇒ 1.45 T× 0.2 m ≈ $4\pi \times 10^{-7} \times 48 \times 5200$ Amps, $\frac{\Delta B}{B} \approx -\frac{\Delta \text{gap}}{\text{gap}}$
- Oct 2015-Aug 2016: adjustments of pole gaps, tilts, 8000+ fine iron laminations
- B uniformity at ± 20 ppm level (RMS) ⇔ gap uniform at 4 micron level over 45 m

Beam profile measurement

- Two tracker stations for monitoring

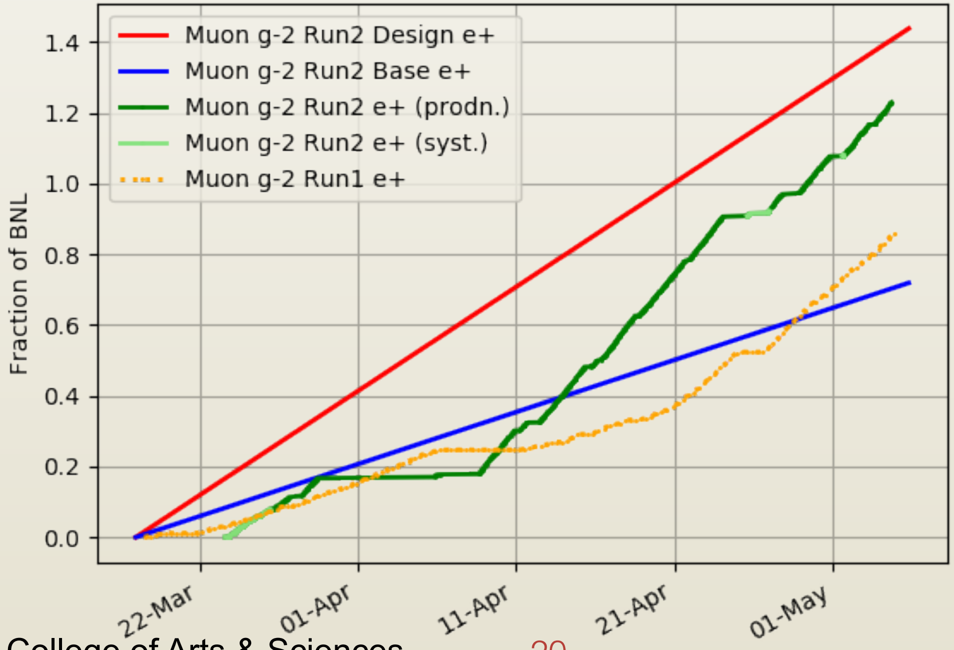






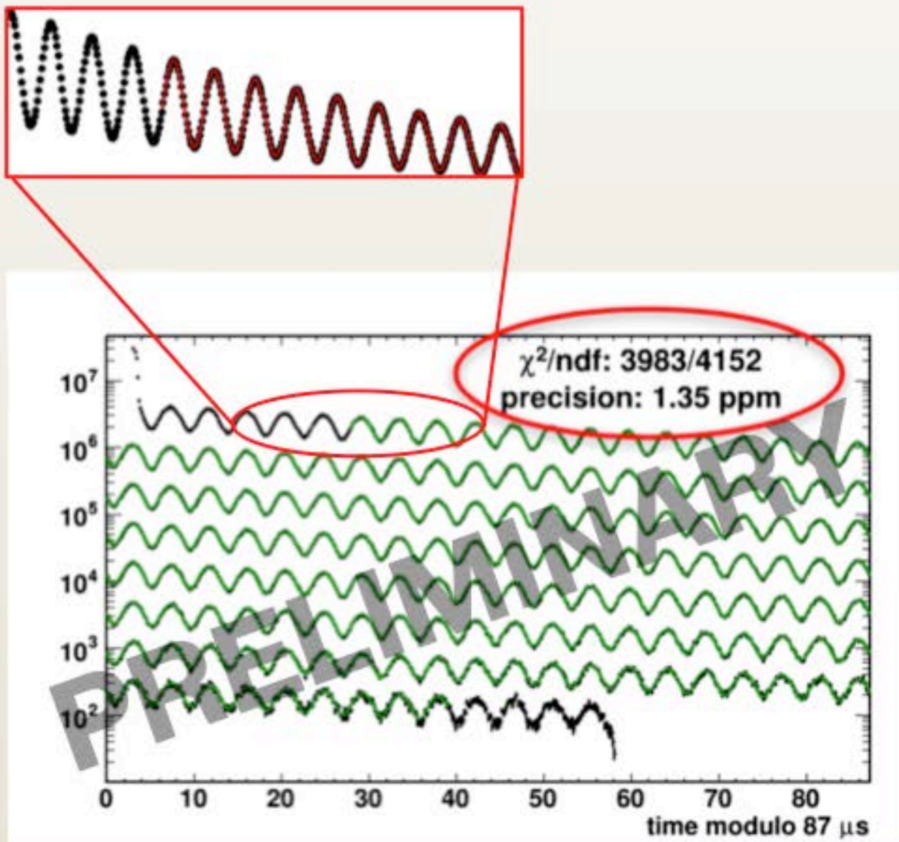
Data taking progress

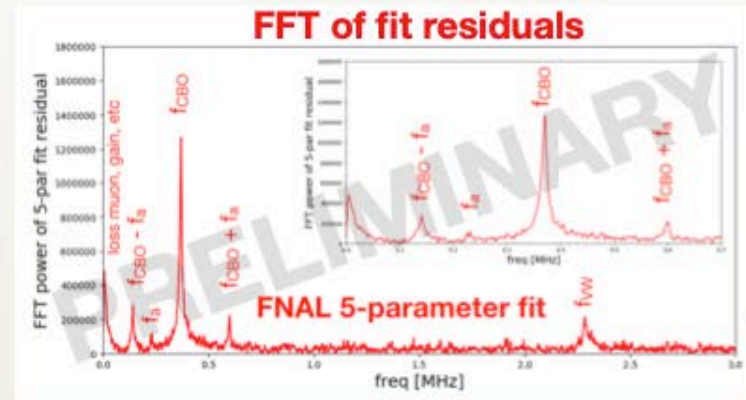
- Finished first physics run, Run 1, in July 2018
  - Field uniformity 2x better than BNL
  - 1.75×10^{10} positrons collected, ~ 2x BNL stats
    - 1.4x BNL after data quality cut, $\delta\omega_a$(stat) ~ 350 ppb
    - analysis in progress
- Half way through the Run 2
  - Improvements: muon flux, kicker strength, overall stability, …



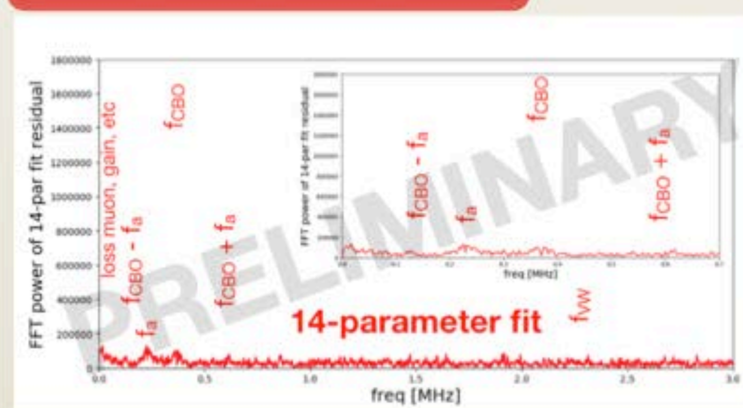
ω_a in Run 1

$$N(t) = N_0 e^{-t/\tau}\left[1 - A\cos\left(\omega_a t + \phi\right)\right]$$





Big improvements when accounting for CBO, lost muons,...



Systematic uncertainties

- **BNL/FNAL major systematics (on ω_a)**

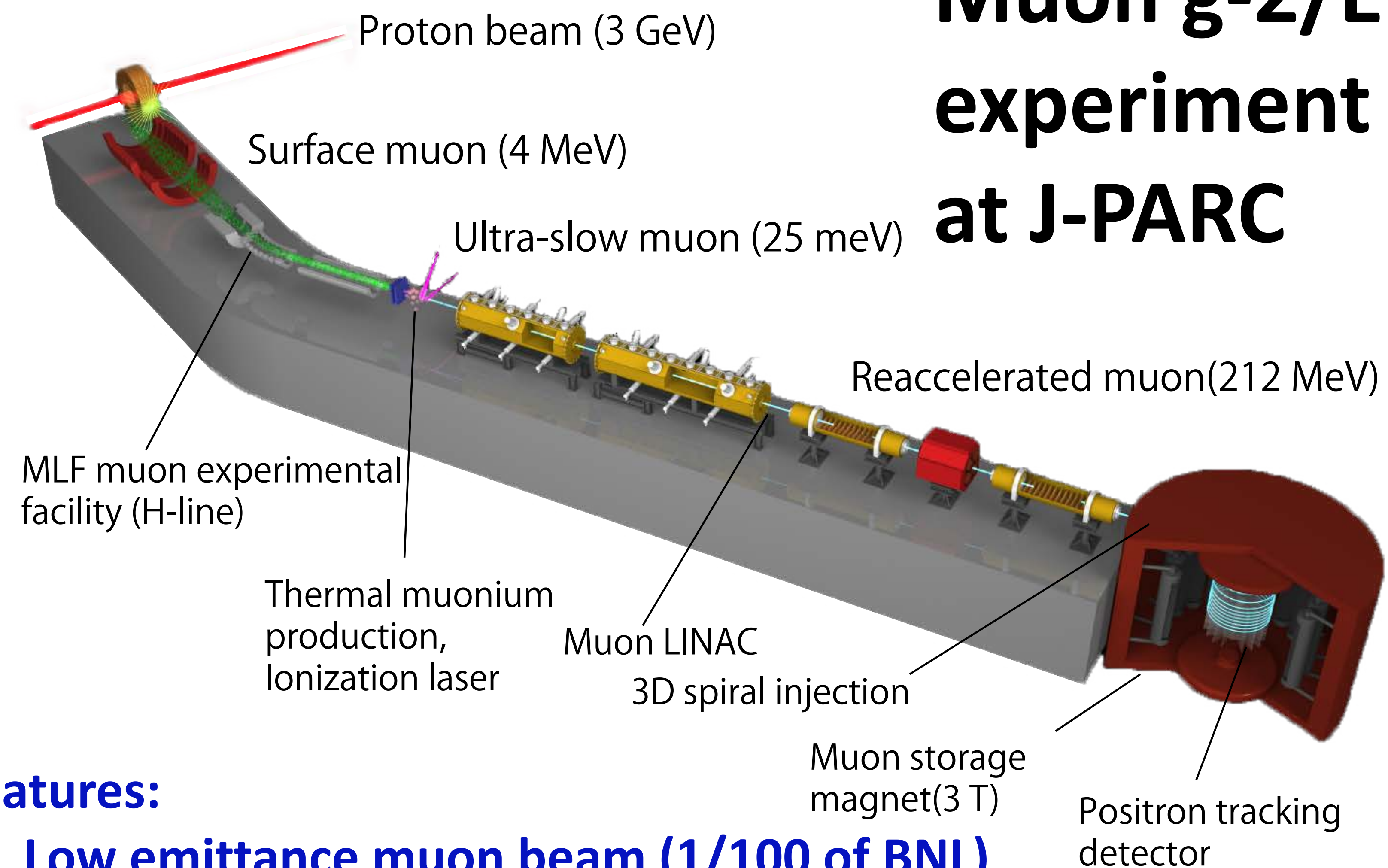
Source	BNL (ppm)	FNAL goal (ppm)
Gain changes	0.12	0.02
Lost muons	0.09	0.02
Pile up	0.08	0.04
CBO	0.07	0.04
E and pitch	0.05	0.03
Total	**0.18**	**0.07**

All related with **beam quality and characteristics.**

↓

Largely suppressed if **emittance of muon beam is small.**

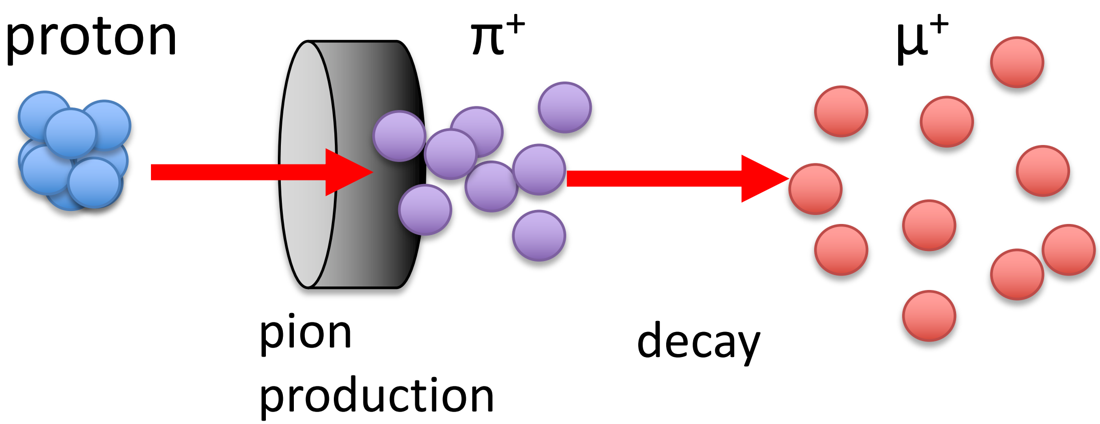
Muon g-2/EDM experiment at J-PARC



Features:

- **Low emittance muon beam (1/100 of BNL)**
- **No strong focusing (1/1000) & good injection eff. (x10)**
- **Compact storage ring (1/20)**
- **Tracking detector with large acceptance**
- **Completely different from BNL/FNAL method**

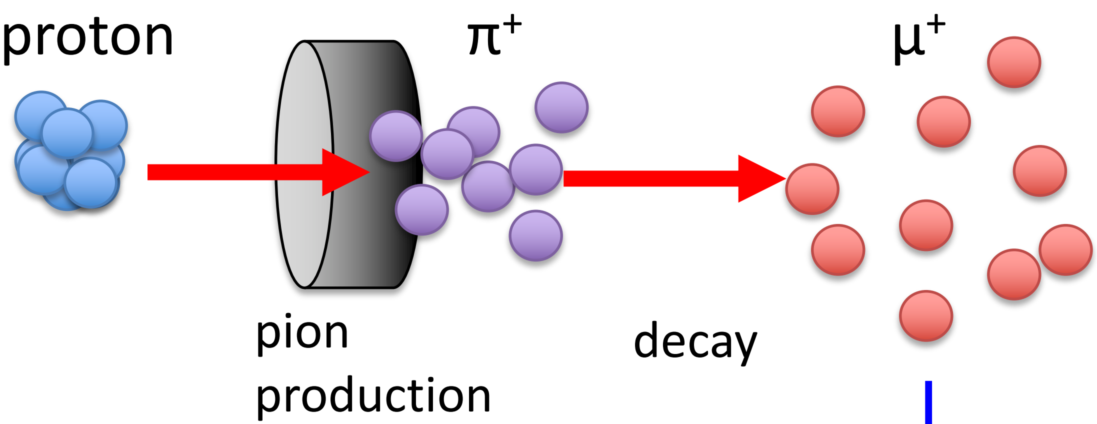
Conventional muon beam



emittance
~1000π mm·mrad

Strong collimation
Strong focusing
Muon loss
BG π contamination

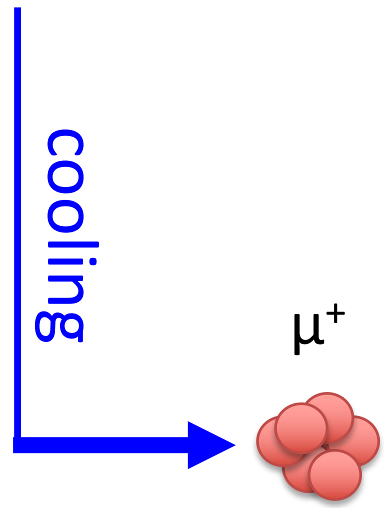
Muon beam at J-PARC



emittance

~1000π mm ･mrad

Strong collimation
Strong focusing
Muon loss
BG π contamination



emittance

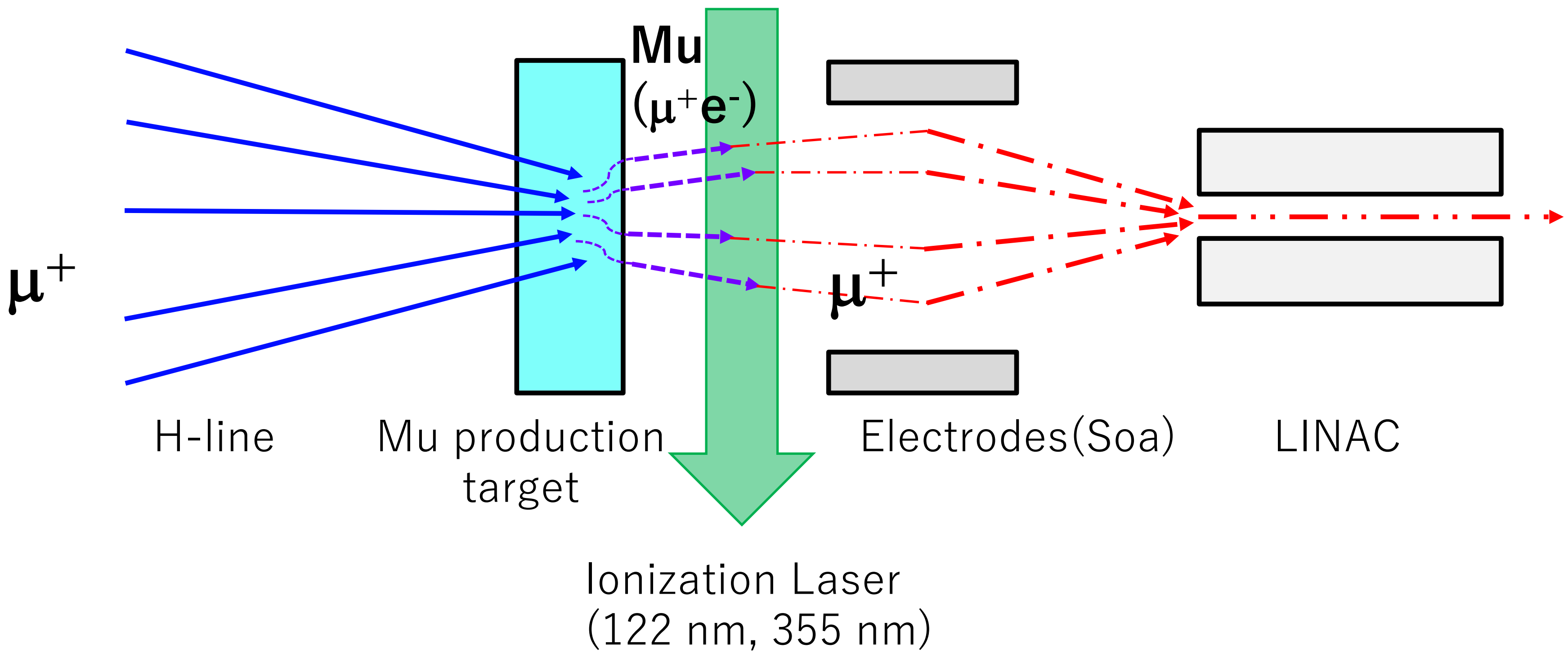
1π mm ･mrad

Free from any of these

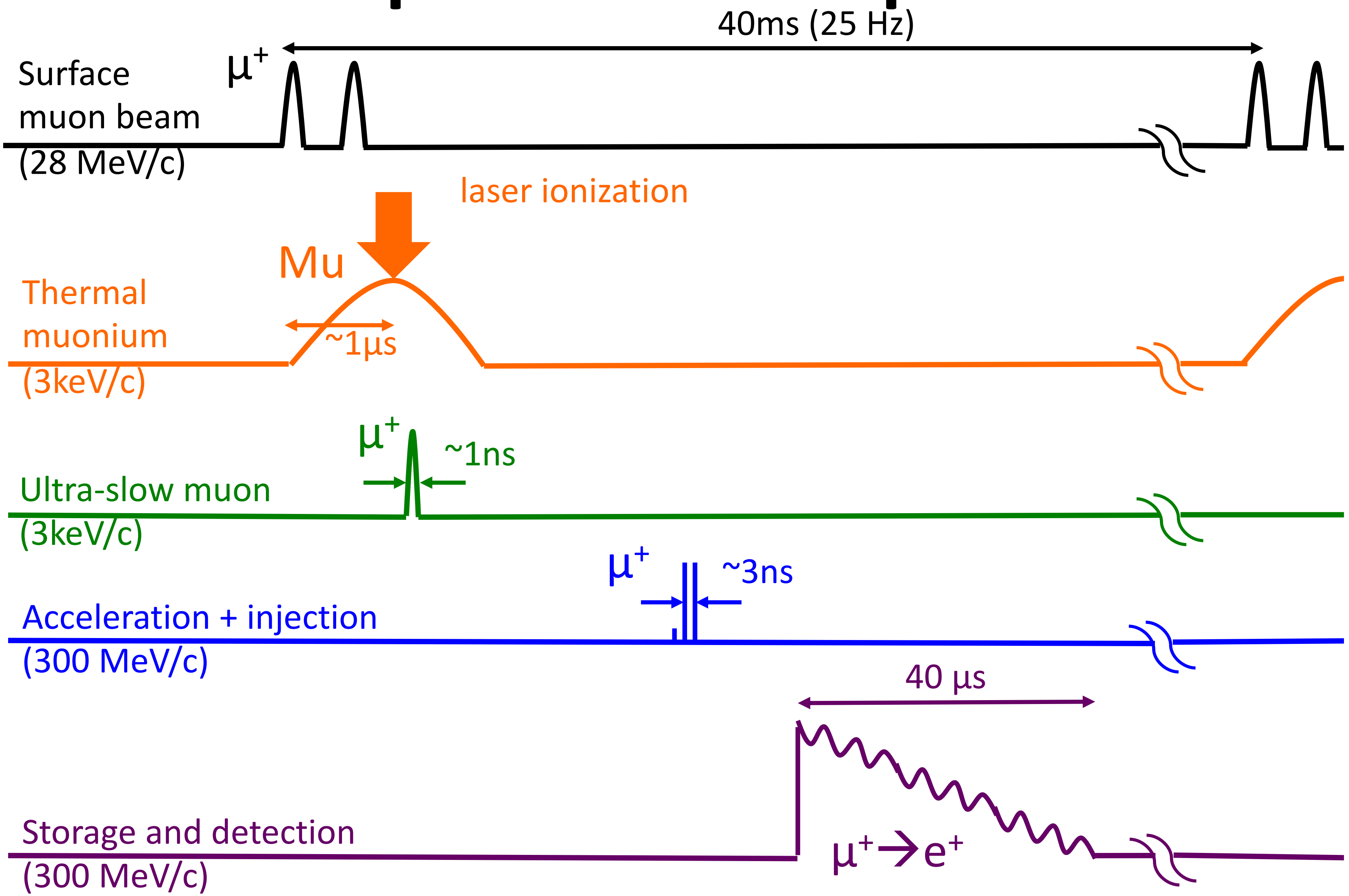
Reaccelerated thermal muon

Re-accelerated thermal muon

	surface muon	thermal muon	accelerated muon
E	3.4 MeV	30 meV	212 MeV
p	27 MeV/c	2.3 keV/c	300 MeV/c
Δp/p	0.05	0.4	4×10^{-4}

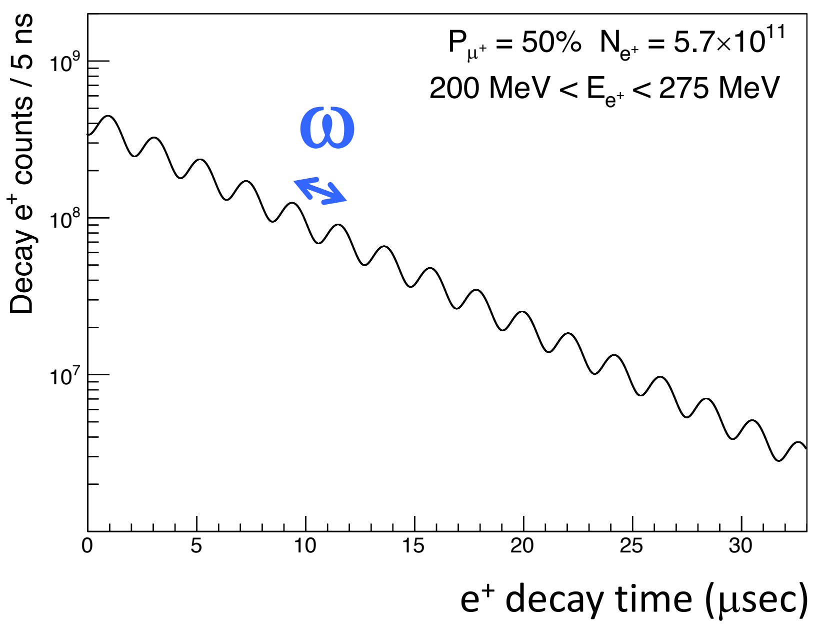


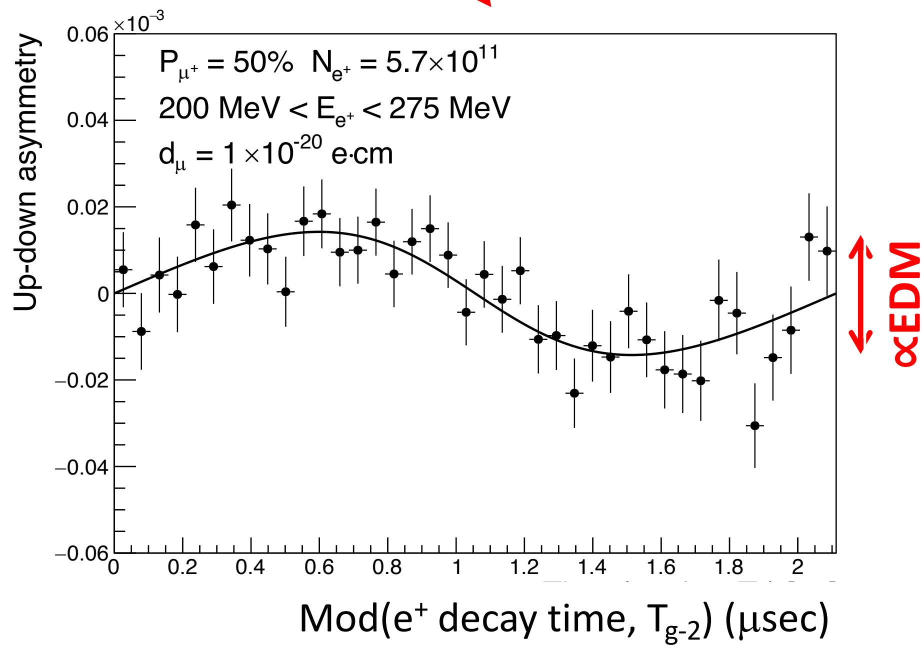
Experimental sequence



Expected time spectrum of e^+ in $\mu \rightarrow e^+\nu\nu$ 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	Fermilab-E989	Our experiment
Muon momentum	3.09 GeV/c		300 MeV/c
Lorentz γ	29.3		3
Polarization	100%		50%
Storage field	$B = 1.45$ T		$B = 3.0$ T
Focusing field	Electric quadrupole		Very weak magnetic
Cyclotron period	149 ns		7.4 ns
Spin precession period	4.37 μs		2.11 μs
Number of detected e^+	5.0×10^9	1.6×10^{11}	5.7×10^{11}
Number of detected e^-	3.6×10^9	–	–
a_μ precision (stat.)	460 ppb	100 ppb	450 ppb
(syst.)	280 ppb	100 ppb	$<$70 ppb
EDM precision (stat.)	$0.2 \times 10^{-19}\ e \cdot$ cm	–	$1.5 \times 10^{-21}\ e \cdot$ cm
(syst.)	$0.9 \times 10^{-19}\ e \cdot$ cm	–	$0.36 \times 10^{-21}\ e \cdot$ cm

Prog. Theor. Exp. Phys. **2019**, 053C02 (2019)

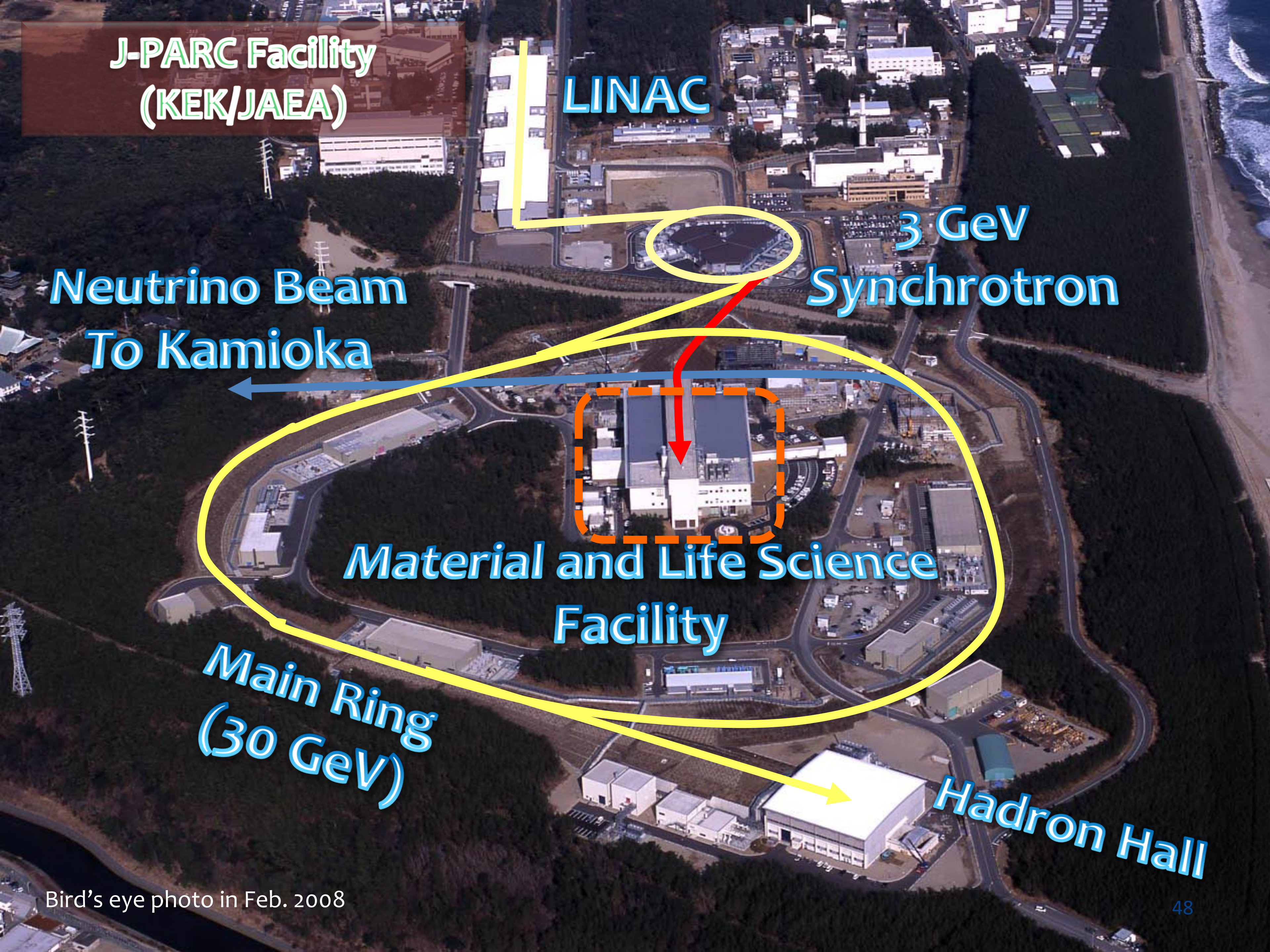
Expected uncertainties

Table 5. Summary of statistics and uncertainties.

	Estimation
Total number of muons in the storage magnet	5.2×10^{12}
Total number of reconstructed e^+ in the energy window [200, 275 MeV]	5.7×10^{11}
Effective analyzing power	0.42
Statistical uncertainty on ω_a [ppb]	450
Uncertainties on a_μ [ppb]	450 (stat.)
	$<$ 70 (syst.)
Uncertainties on EDM [10^{-21} $e\cdot$cm]	1.5 (stat.)
	0.36 (syst.)

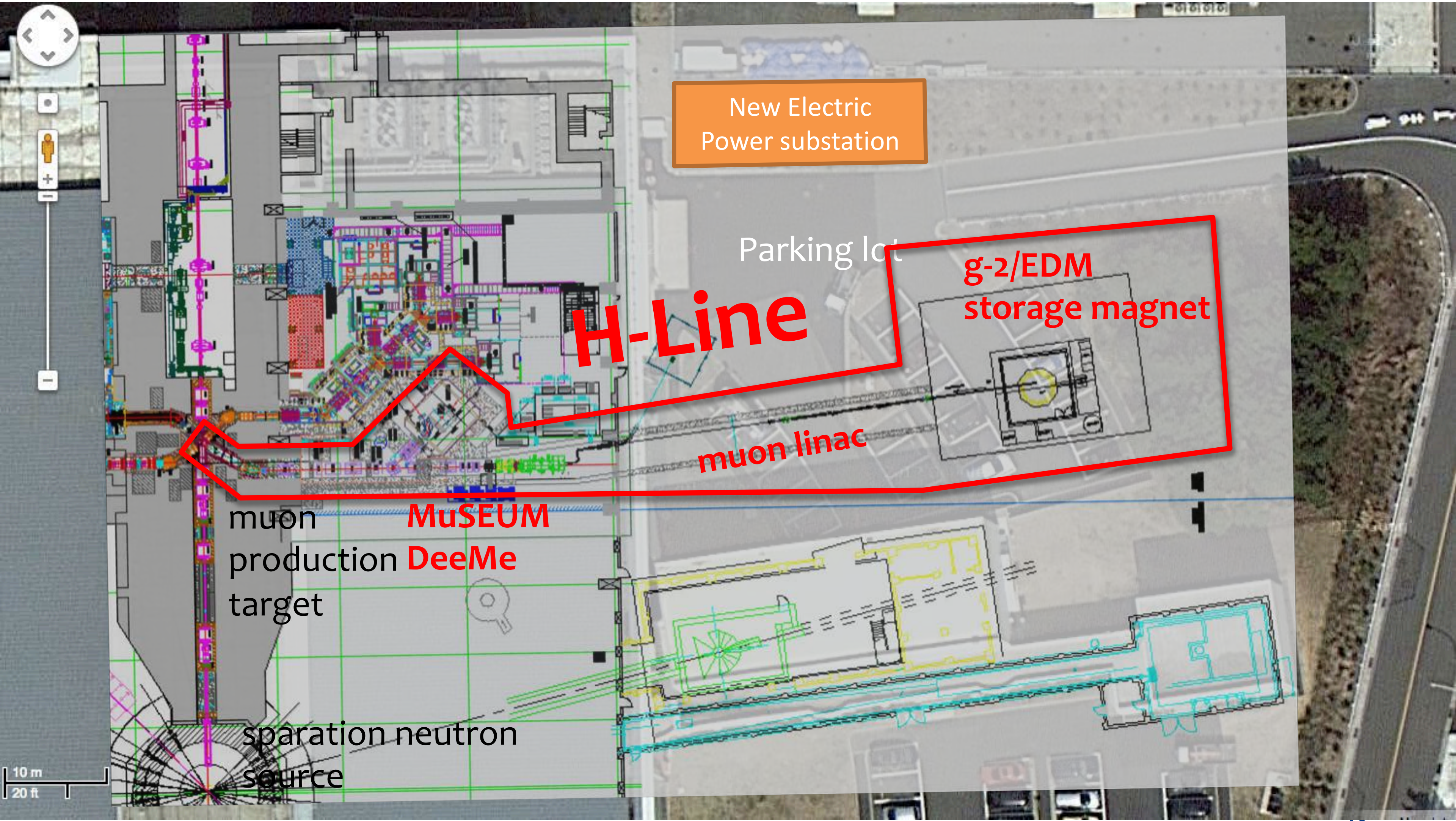
Table 6. Estimated systmatic uncertainties on a_μ.

Anomalous spin precession (ω_a)		Magnetic field (ω_p)	
Source	Estimation (ppb)	Source	Estimation (ppb)
Timing shift	< 36	Absolute calibration	25
Pitch effect	13	Calibration of mapping probe	20
Electric field	10	Position of mapping probe	45
Delayed positrons	0.8	Field decay	< 10
Diffential decay	1.5	Eddy current from kicker	0.1
Quadratic sum	< 40	Quadratic sum	56


J-PARC Facility
(KEK/JAEA)
LINAC
3 GeV
Synchrotron
Neutrino Beam
To Kamioka
Material and Life Science
Facility
Main Ring
(30 GeV)
Hadron Hall
Bird's eye photo in Feb. 2008

Proposed experimental site

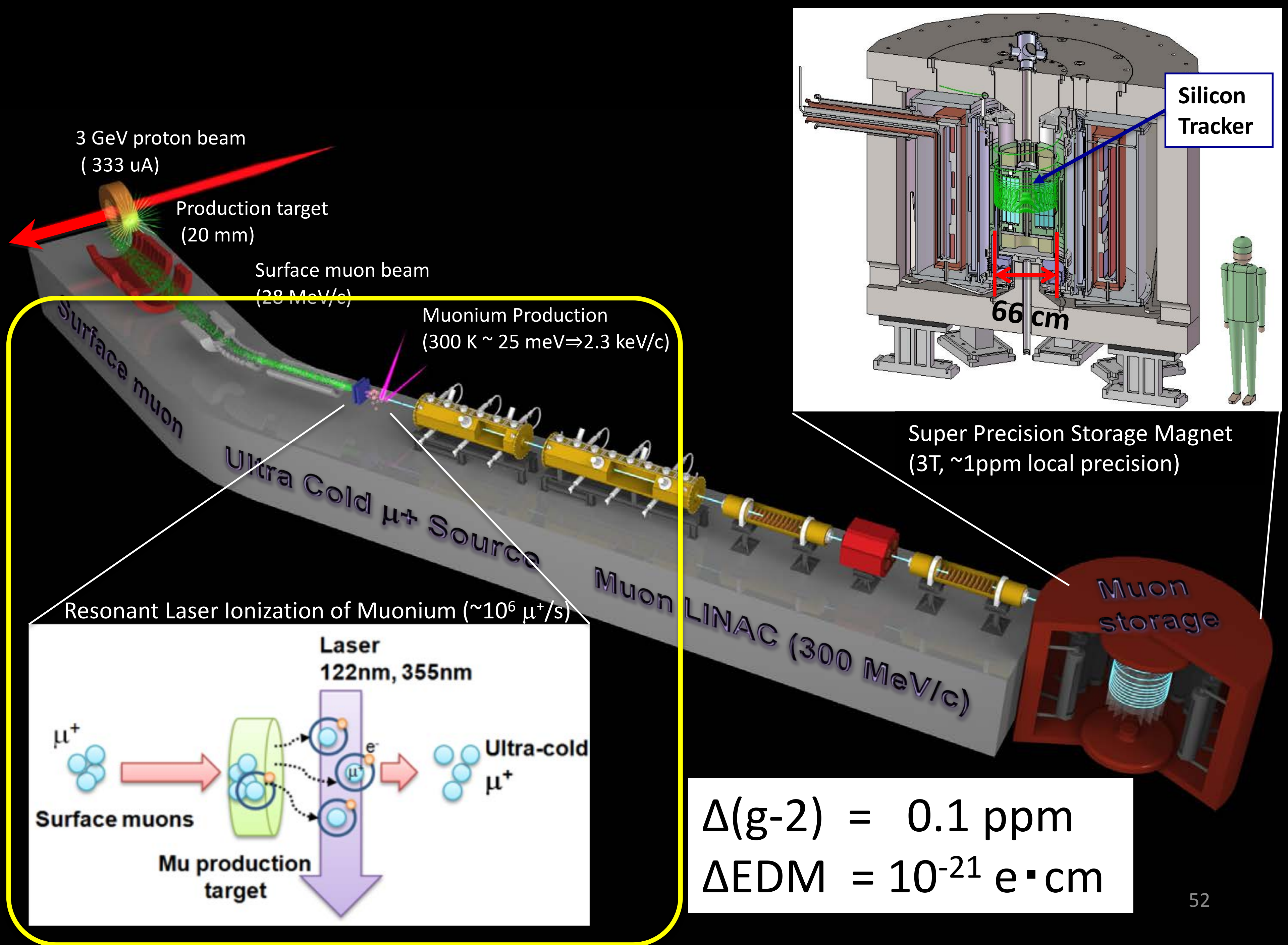
Material and Life science Facility in J-PARC



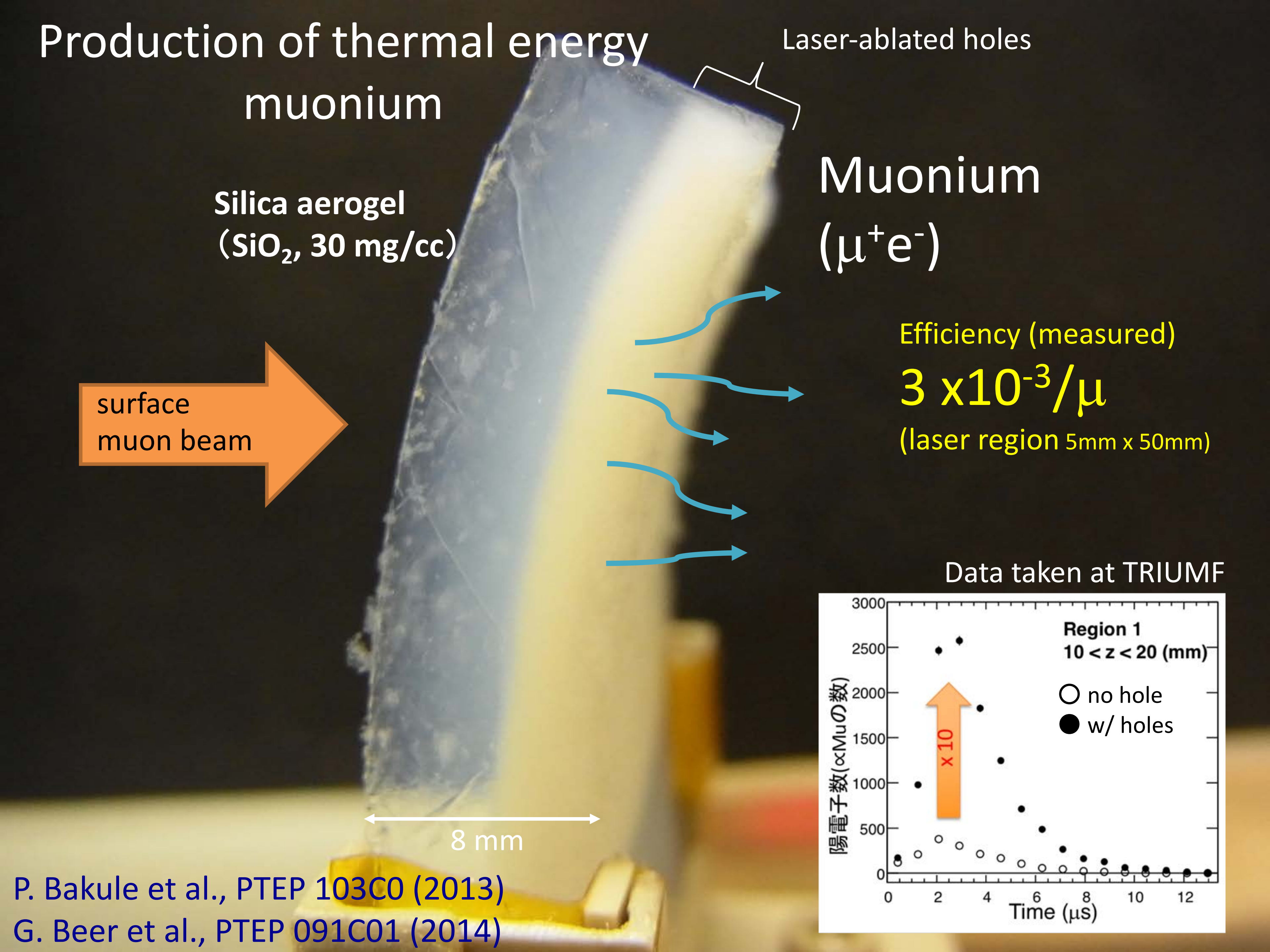
H-line being constructed!

Photo by T. Yamazaki

H-line being constructed!

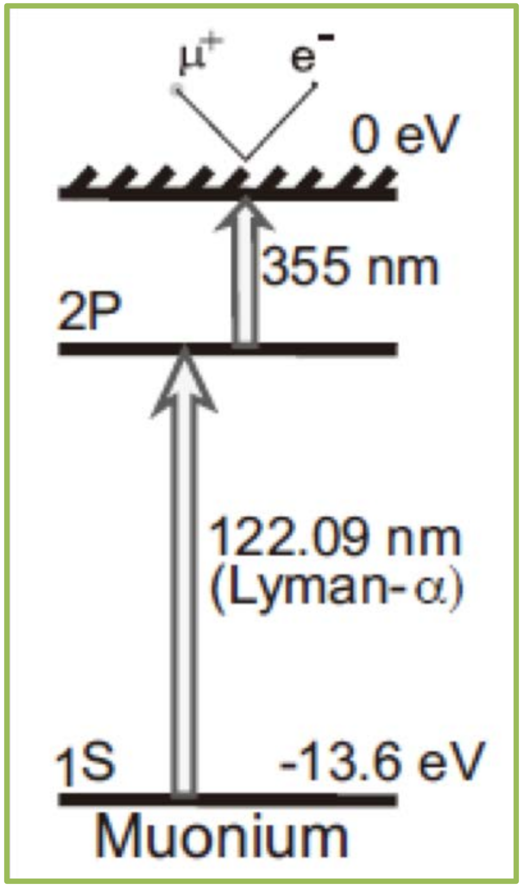


$$\Delta(g\text{-}2) = 0.1\ \text{ppm}$$
$$\Delta EDM = 10^{-21}\ e\cdot cm$$

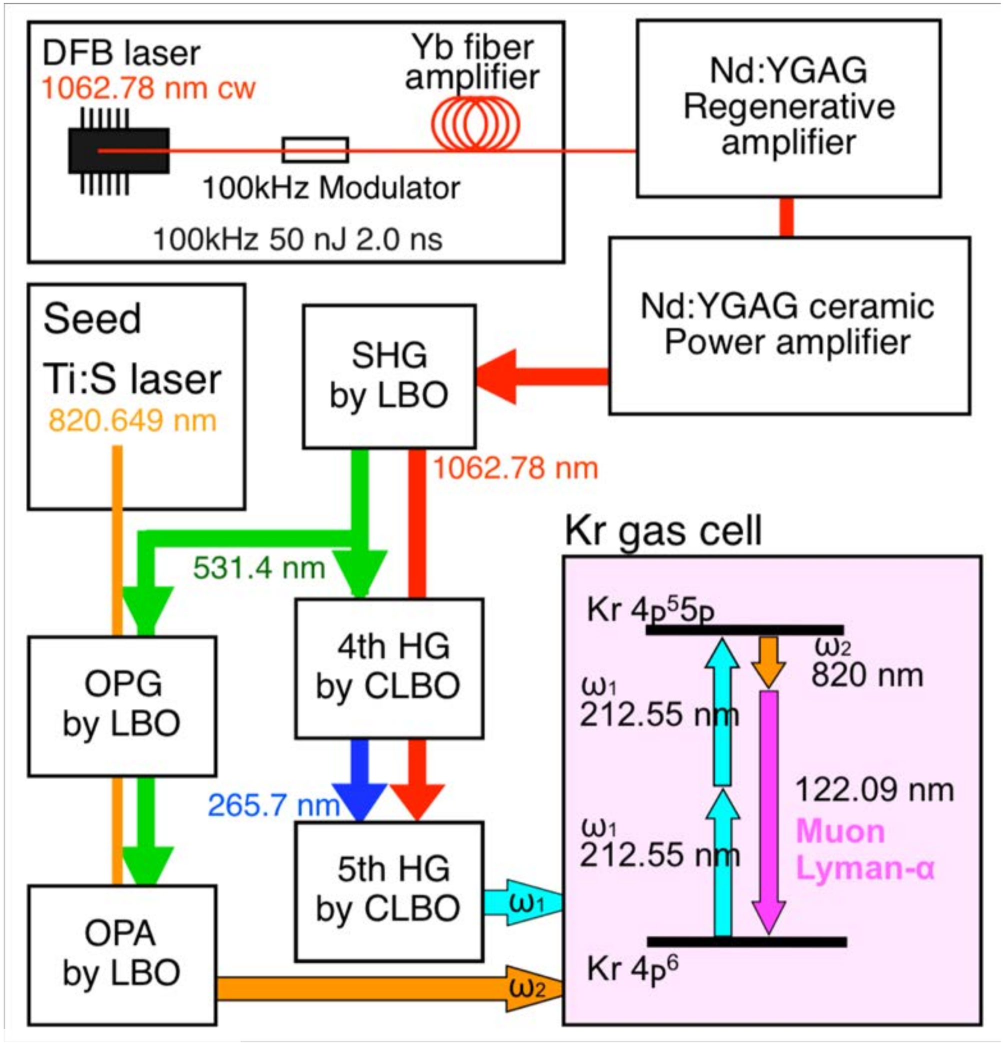

Production of thermal energy muonium
Laser-ablated holes
Muonium
(μ+e-)
Silica aerogel
(SiO2, 30 mg/cc)
surface muon beam
Efficiency (measured)
3 x10-3/μ
(laser region 5mm x 50mm)
Data taken at TRIUMF
Region 1
10 < z < 20 (mm)
no hole
w/ holes
x 10
陽電子数(∝Muの数)
Time (μs)
0
500
1000
1500
2000
2500
3000
2
4
6
8
10
12
8 mm
P. Bakule et al., PTEP 103C0 (2013)
G. Beer et al., PTEP 091C01 (2014)

Laser ionization of muonium

1S→2P→unbound



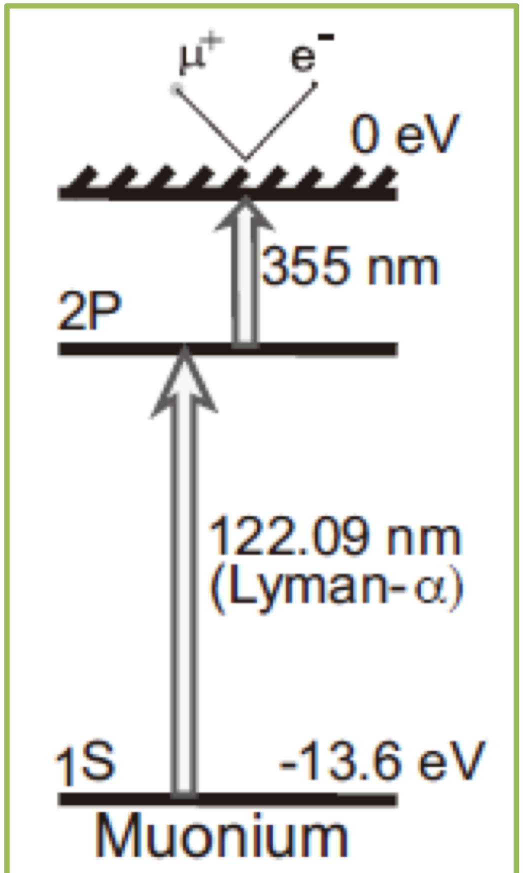
J-PARC MLF U-line laser system（RIKEN+KEK）



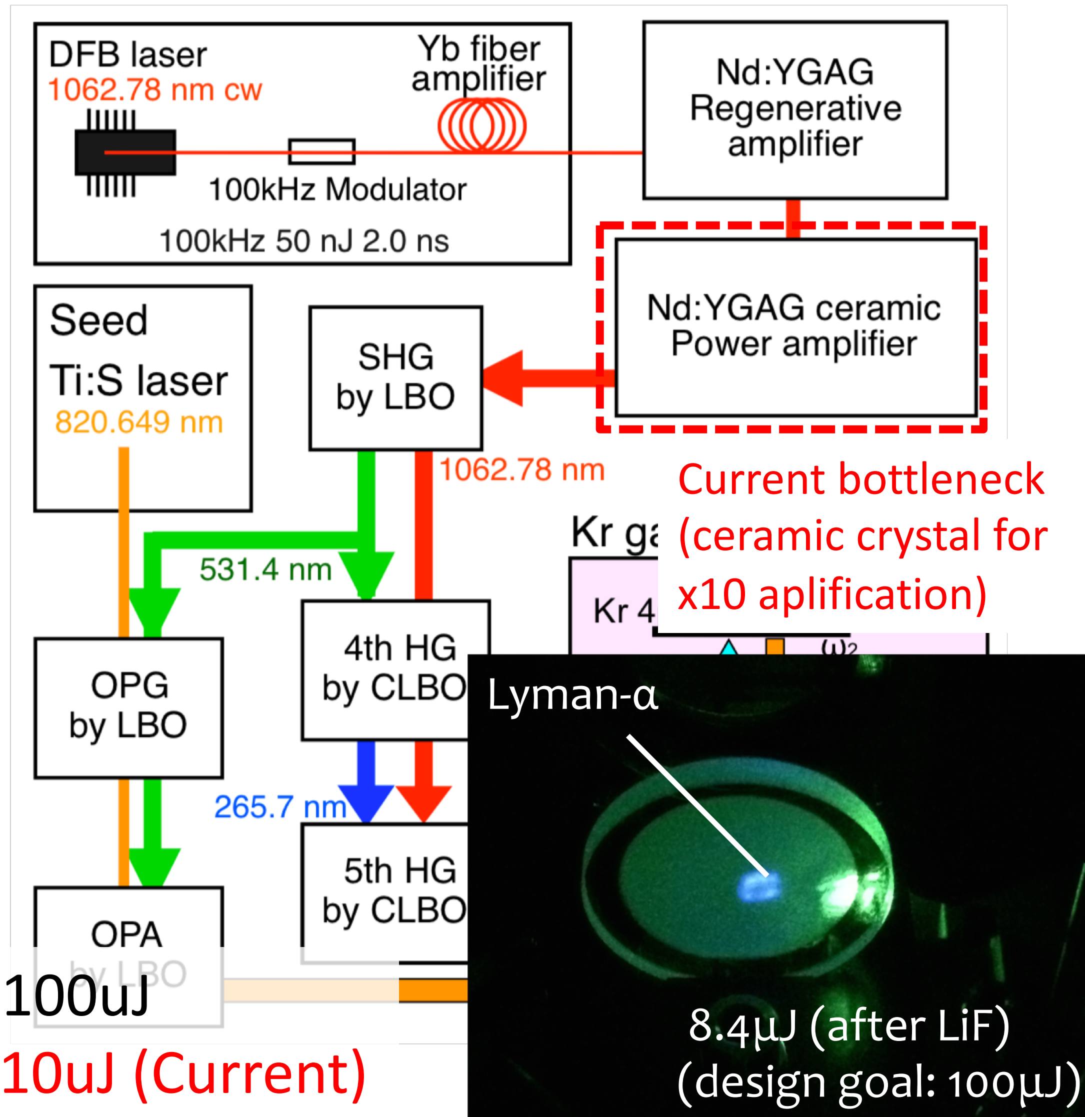
efficiency (calculated) 73% @100uJ

Laser ionization of muonium

1S→2P→unbound



J-PARC MLF U-line laser system（RIKEN+KEK）



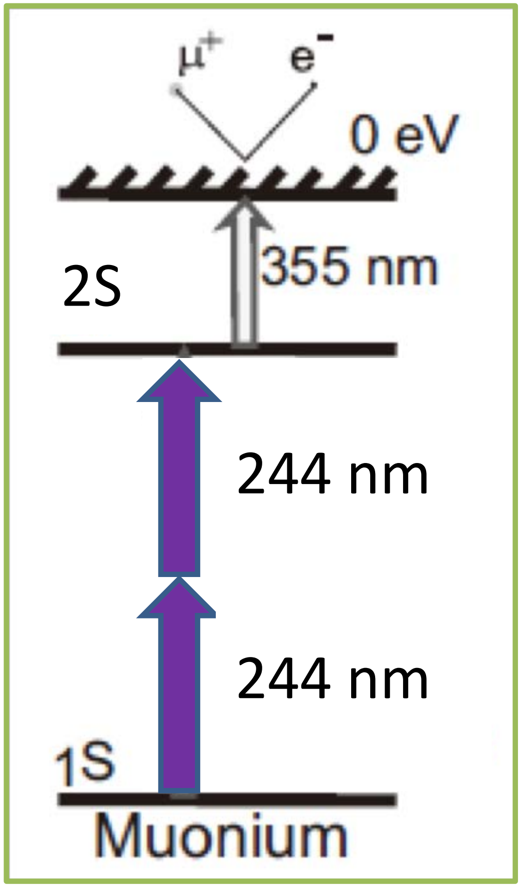
Current bottleneck (ceramic crystal for x10 aplification)

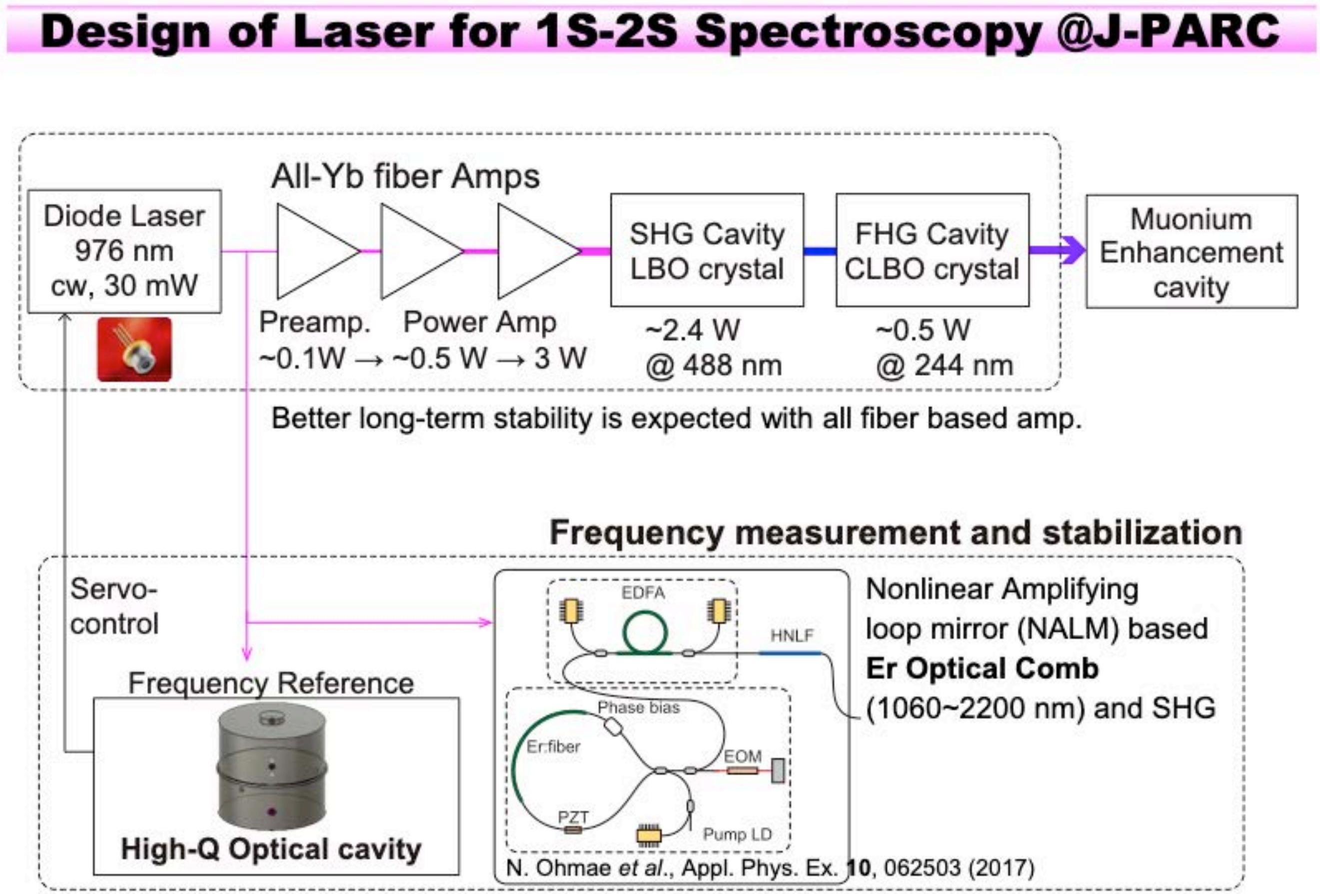
efficiency (calculated) 73% @100uJ

~20% @10uJ (Current)

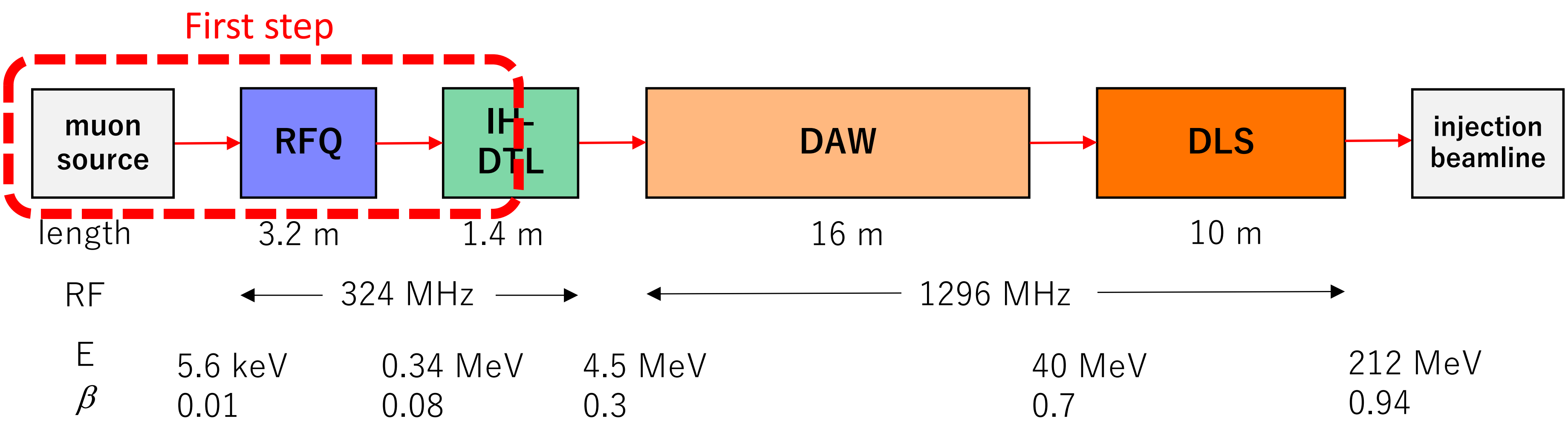
Laser ionization of muonium (Plan B)

Slide by S. Uetake (Muonium WS in Osaka, Dec. 2018)

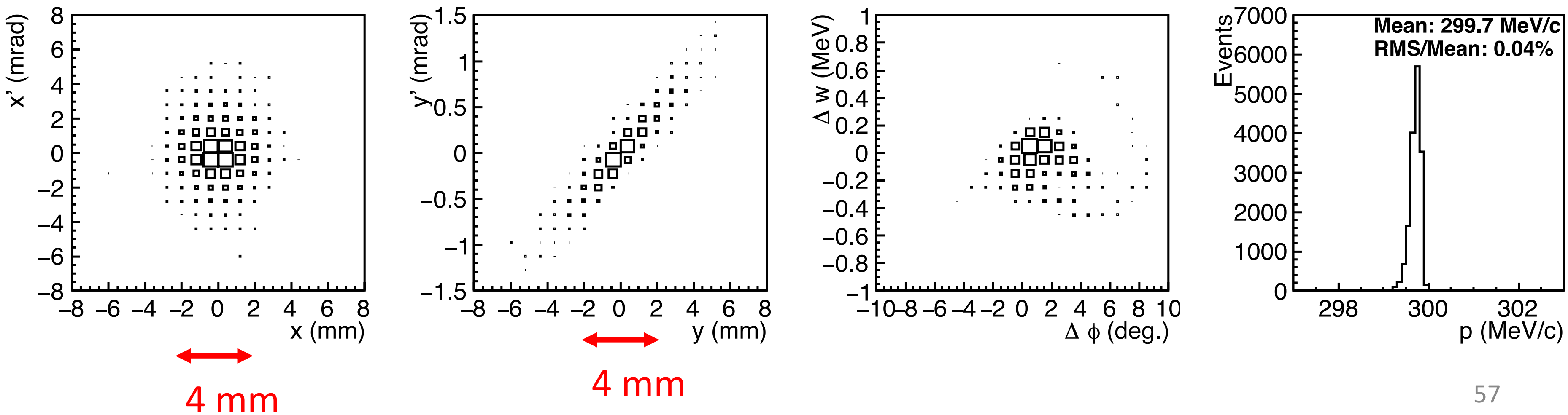




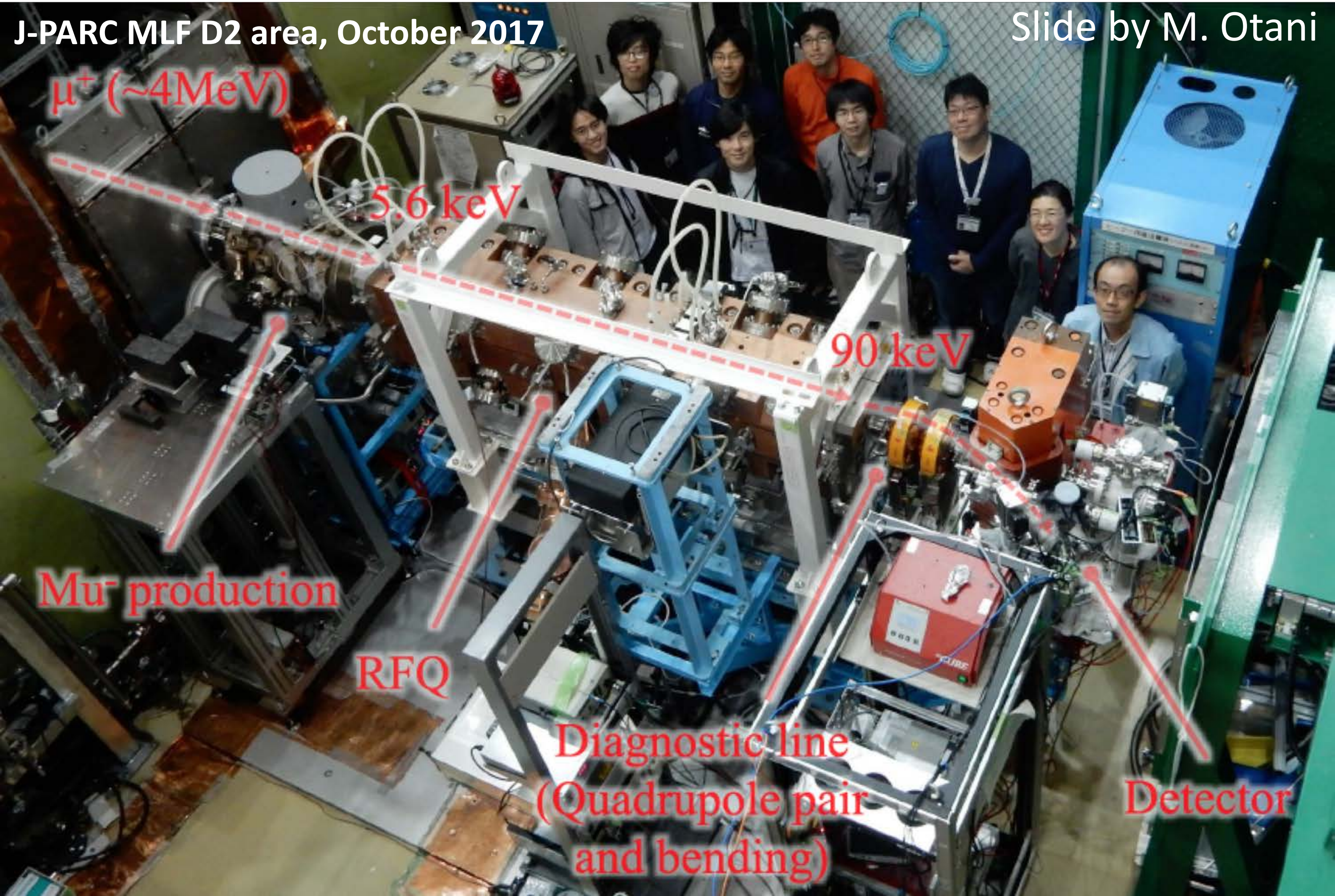
Muon LINAC



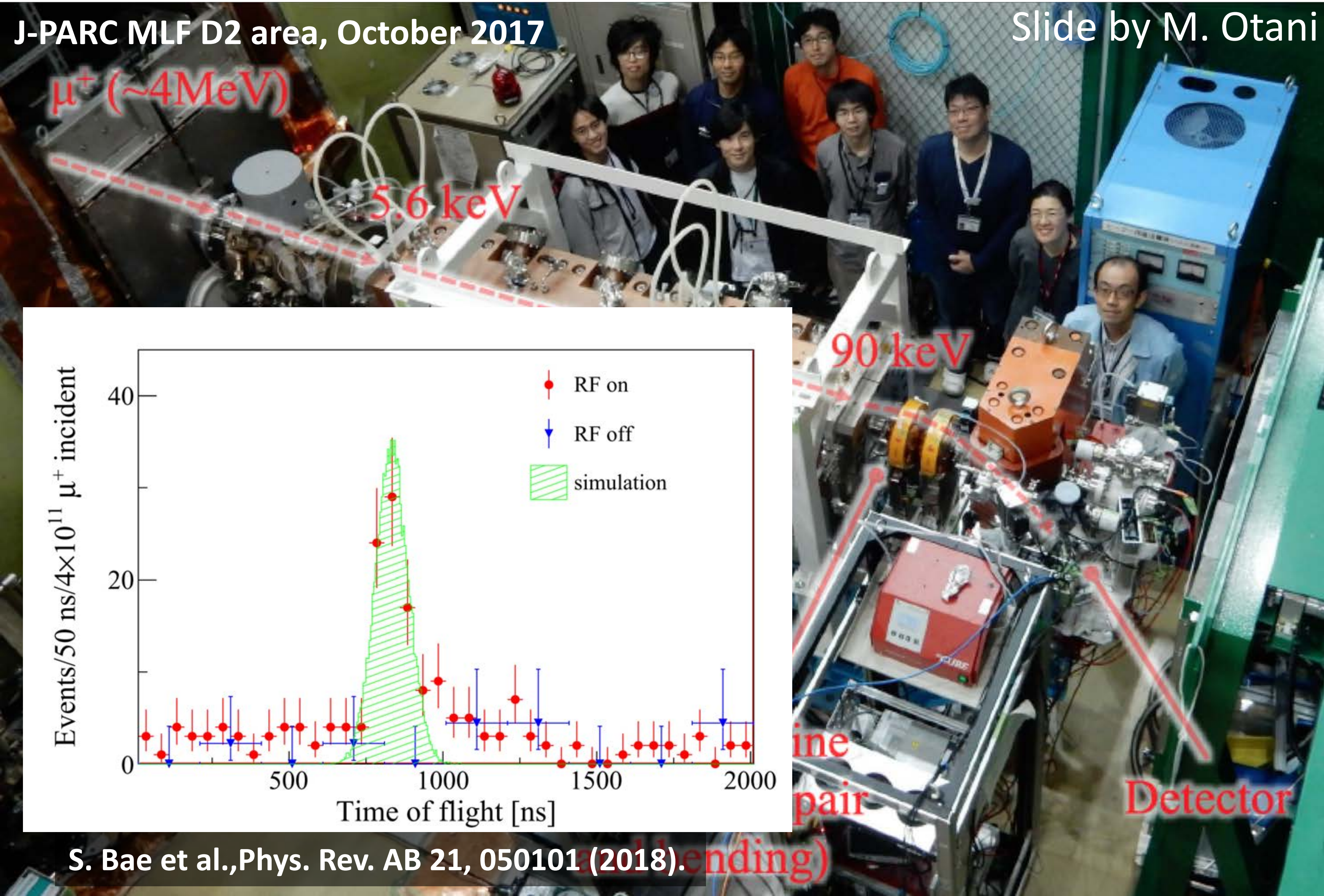
Phase space distributions after muon LINAC (simulation)



RF acceleration of Mu⁻ for the first time!



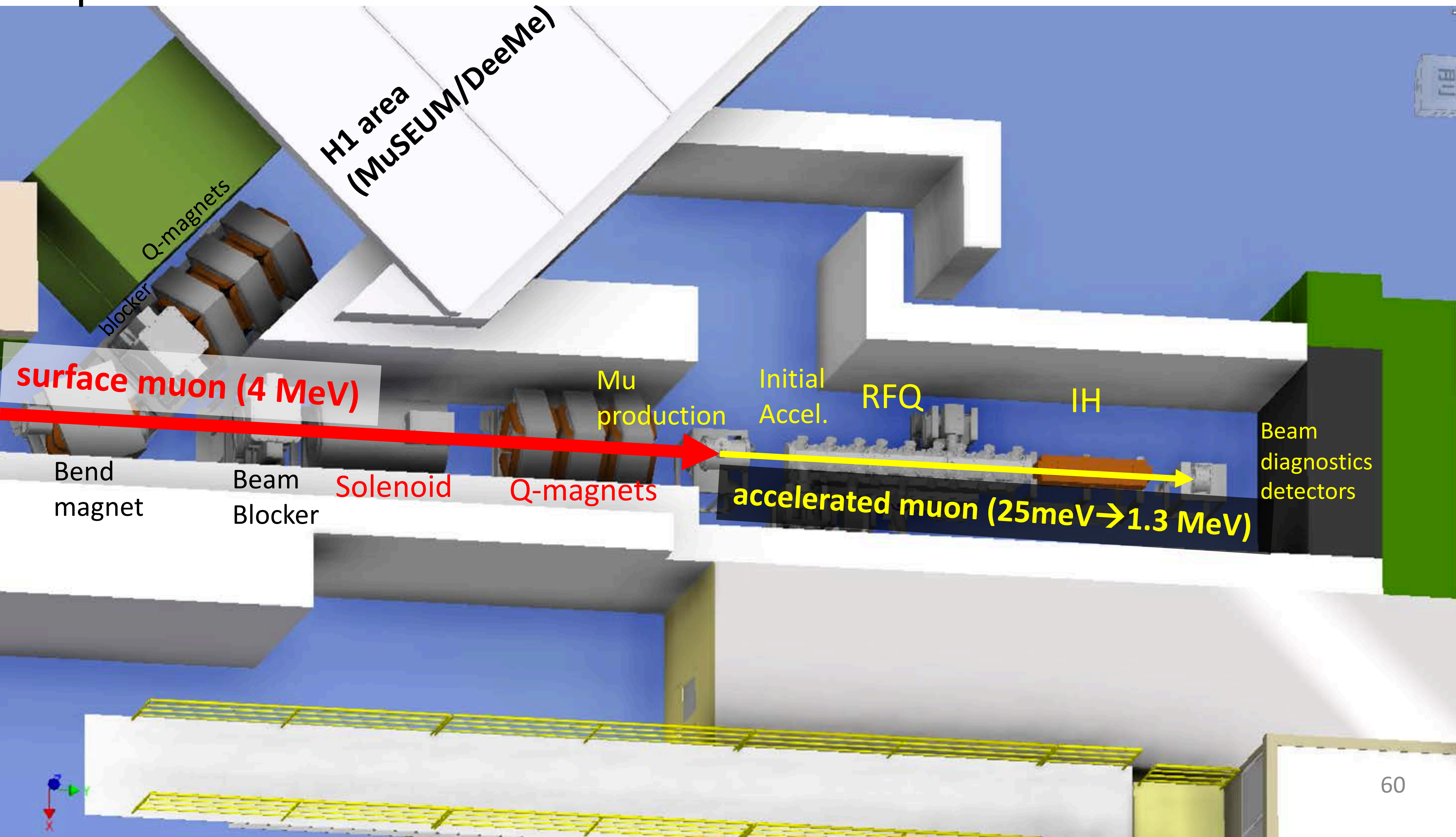
RF acceleration of Mu$^-$ for the first time!



S. Bae et al.,Phys. Rev. AB 21, 050101 (2018).

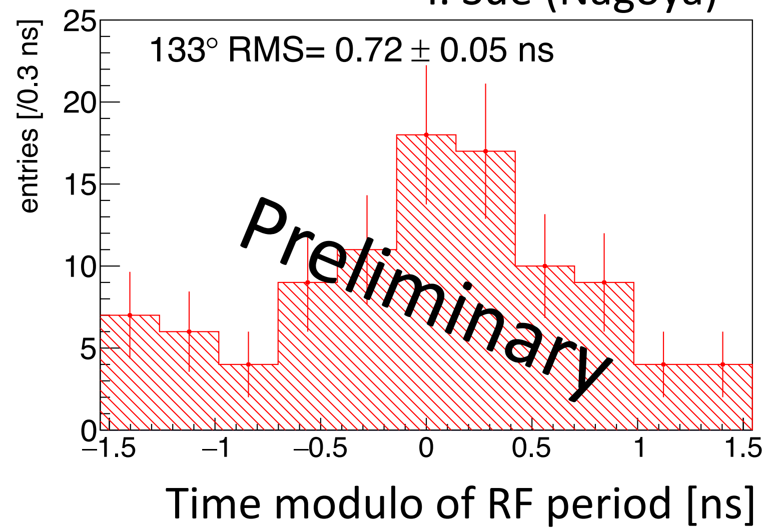
Next step: re-acceleration to 1 MeV

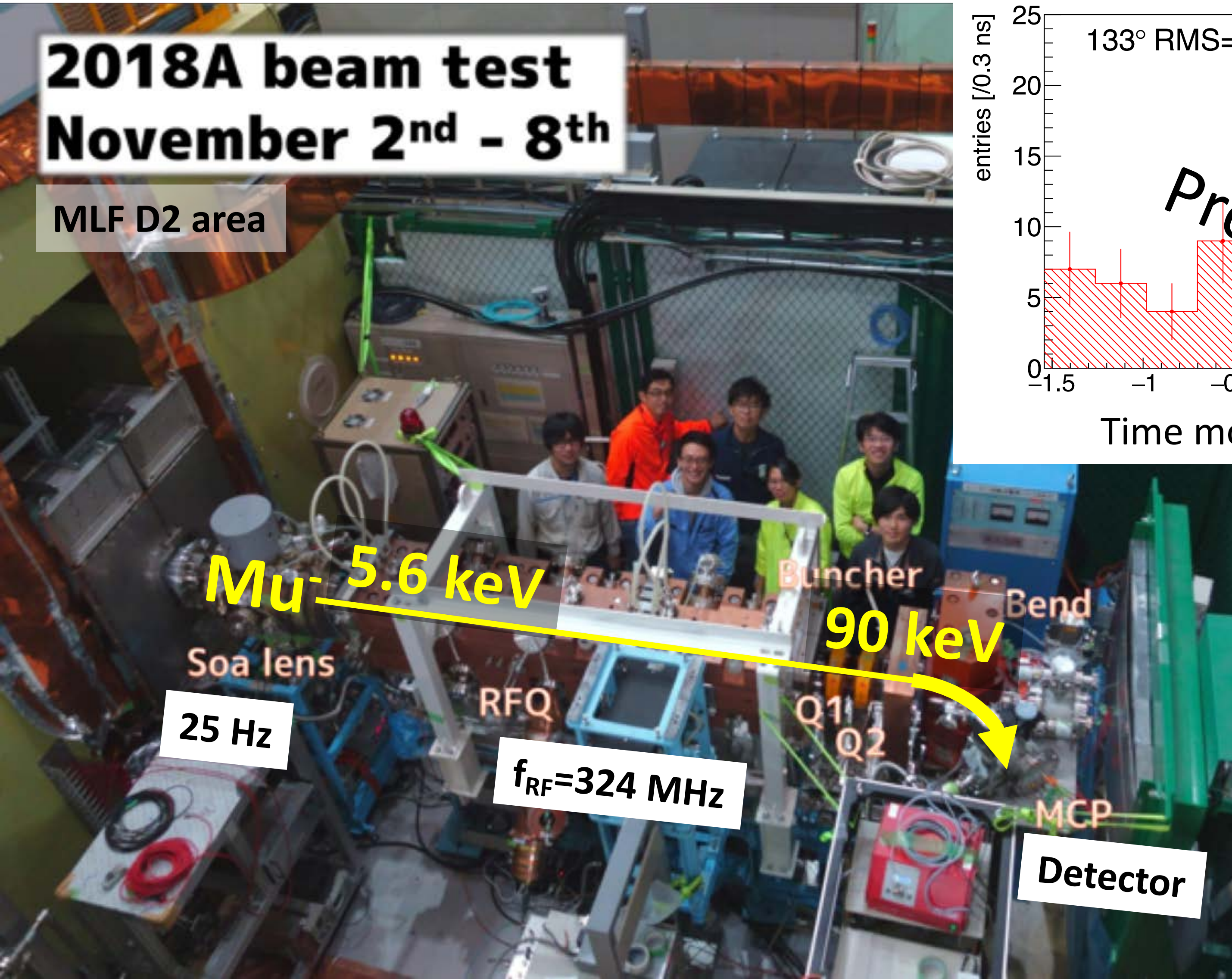
J-PARC MLF
Experimental Hall



First measurement of beam bunch structure of accelerated Mu-

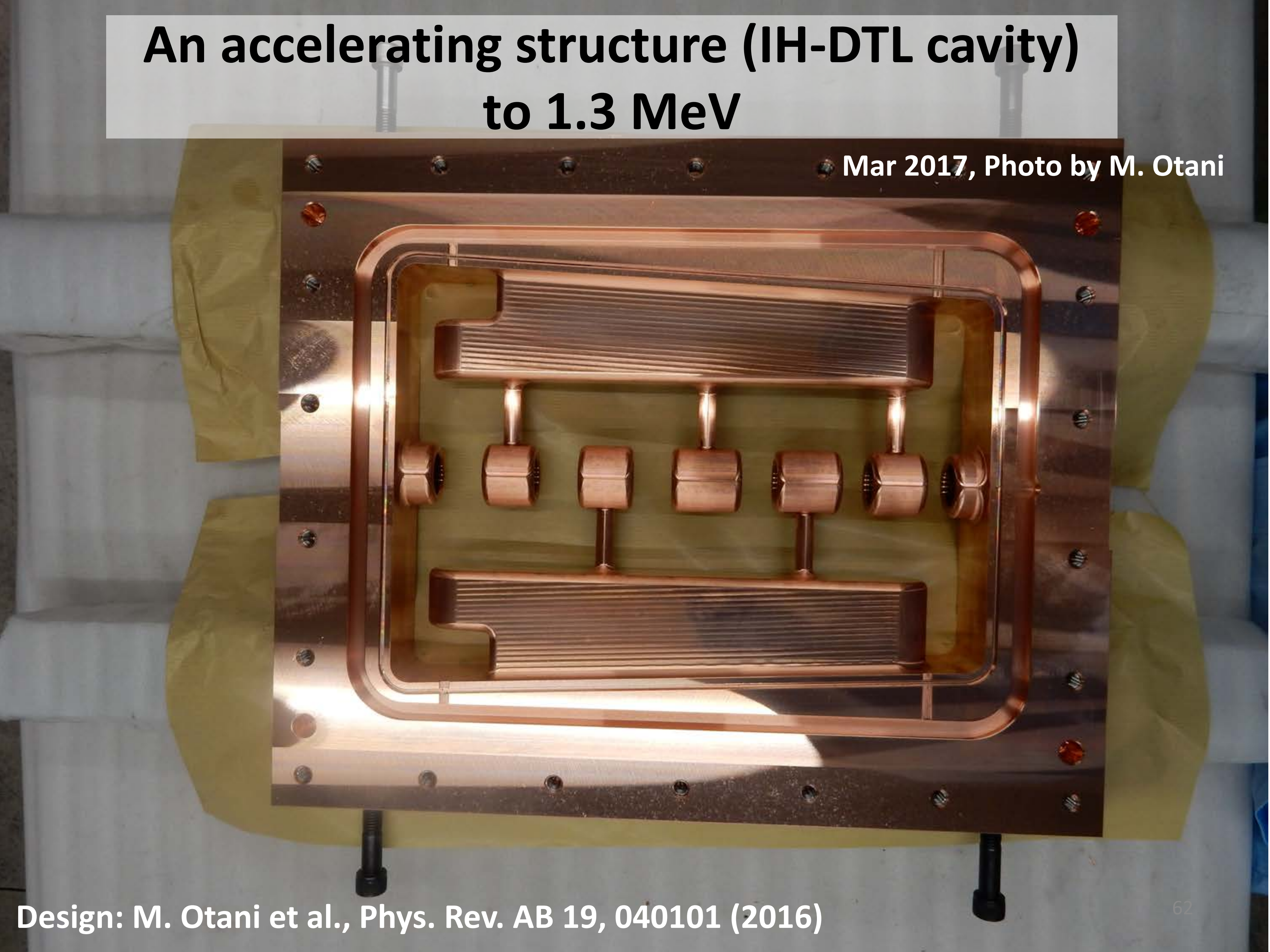
Y. Sue (Nagoya)





Nagoya, KEK, JAEA, Ibaraki, Tokyo

An accelerating structure (IH-DTL cavity) to 1.3 MeV

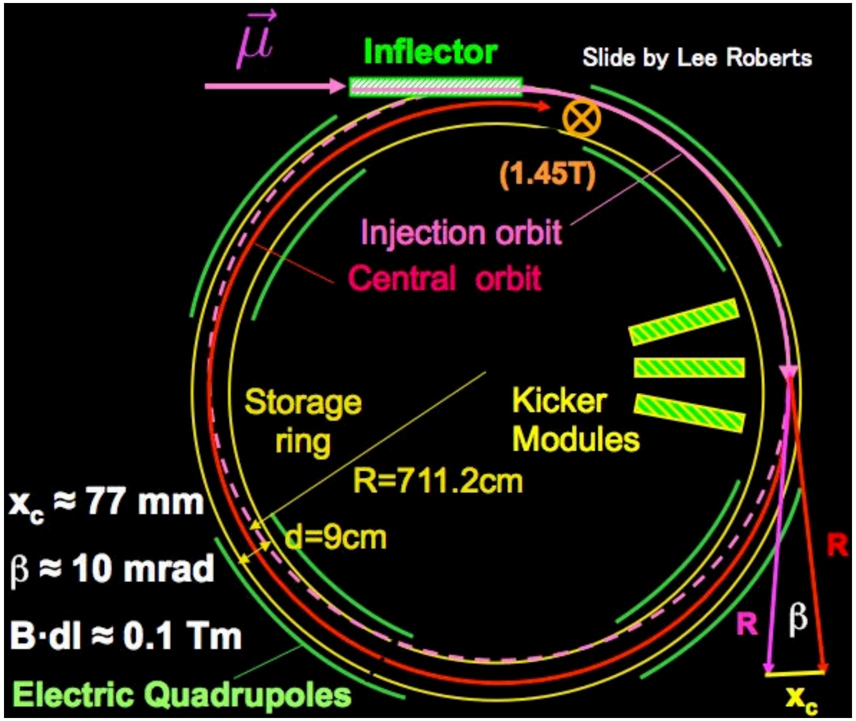


Mar 2017, Photo by M. Otani

Design: M. Otani et al., Phys. Rev. AB 19, 040101 (2016)

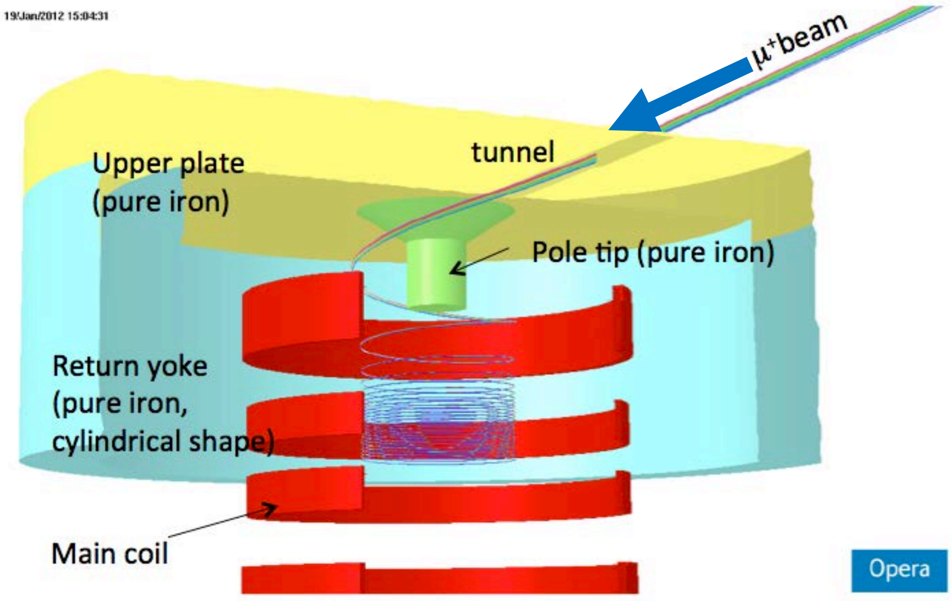
Muon beam injection and storage

Horizontal injection + kicker (BNL E821, FNAL E989)



Injection efficiency : 3-5%(*)

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



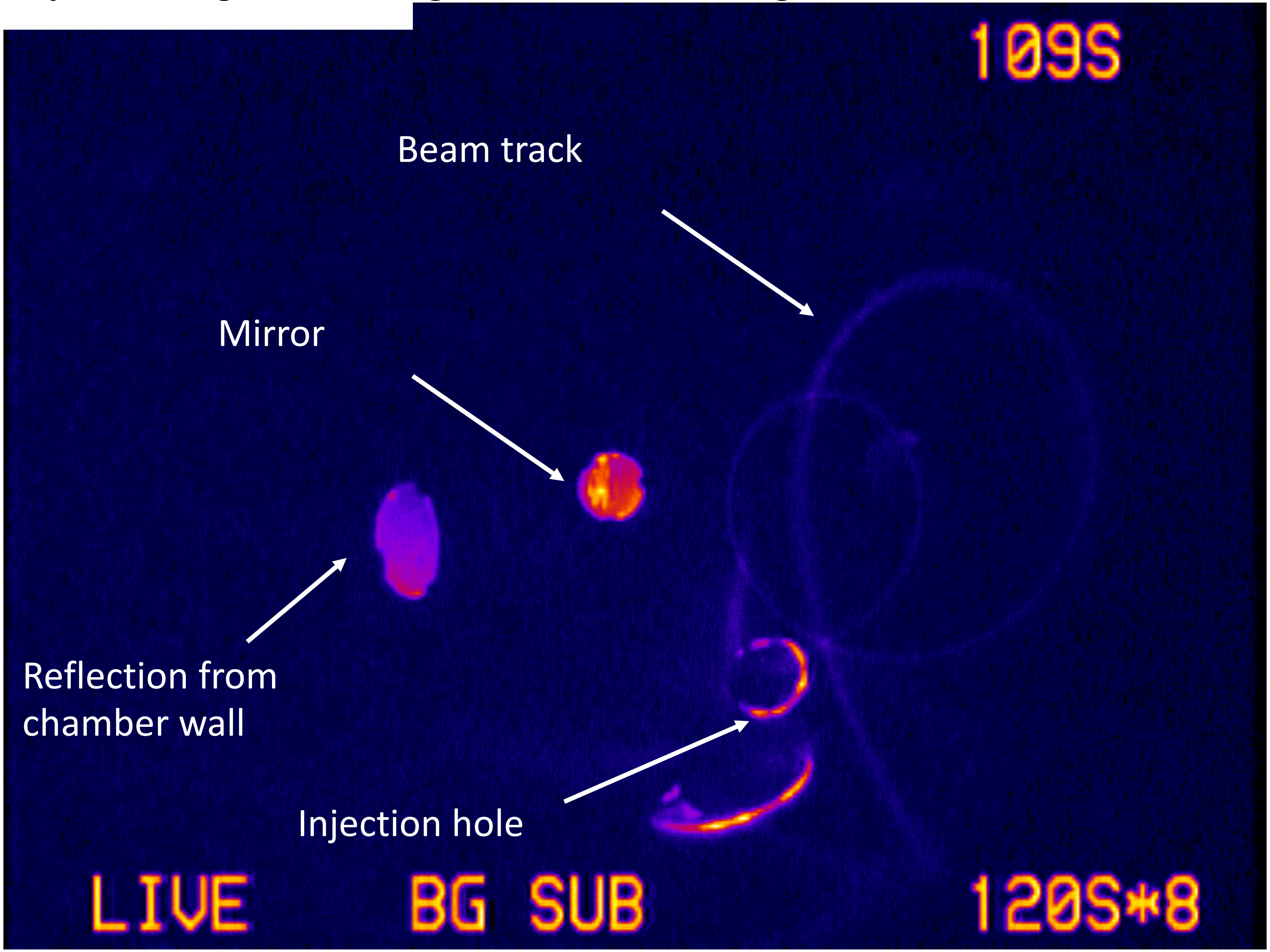
Injection efficiency : ~85%

(*) PRD73,072003 (2006)

H. Iinuma et al., Nucl. Instr. And Methods. A 832, 51 (2016)

Testing spiral injection with electron beam

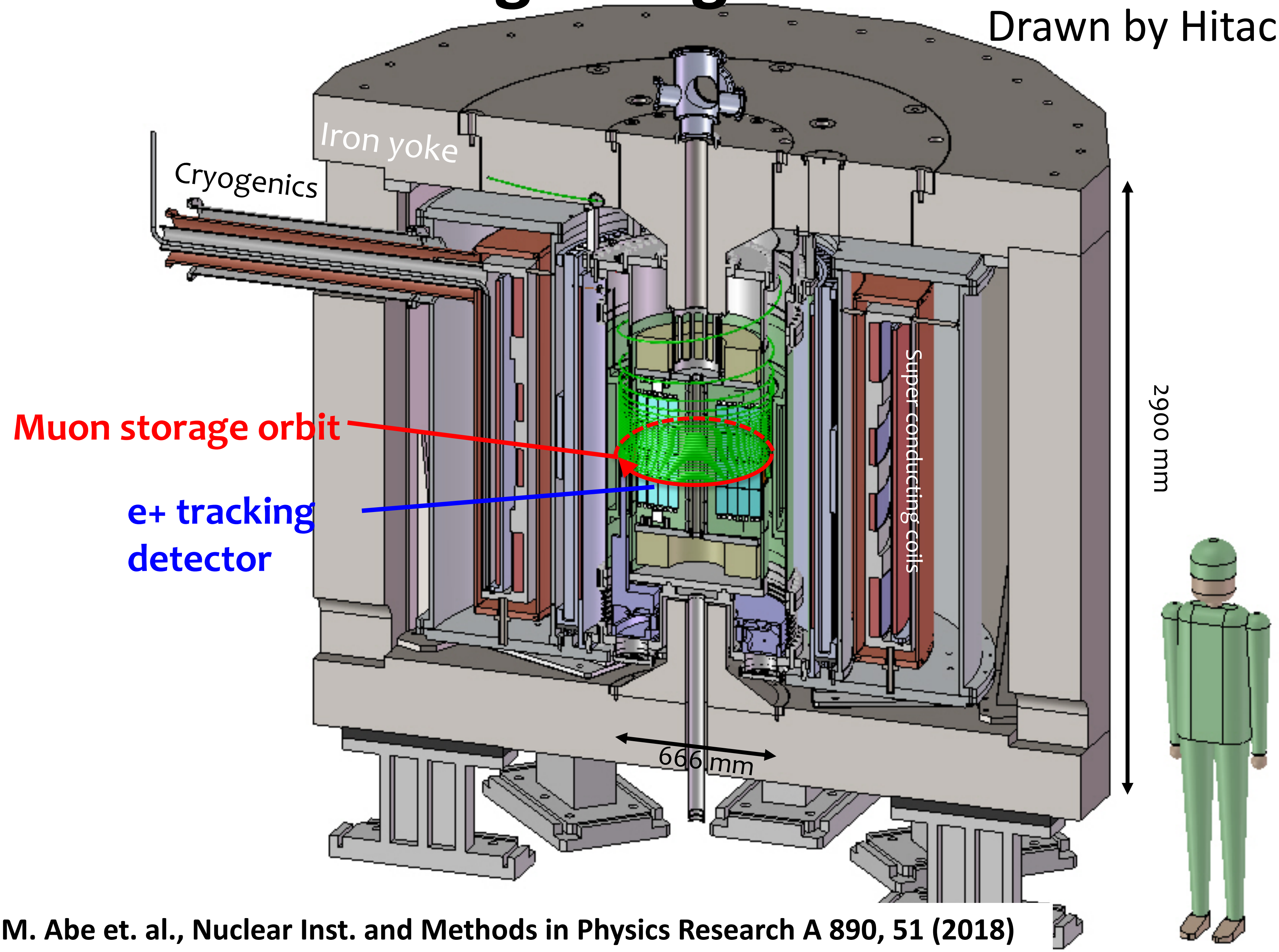
Injection angle was changed from 47 to 44 deg.



Master thesis, M. A. Rehman (2017)

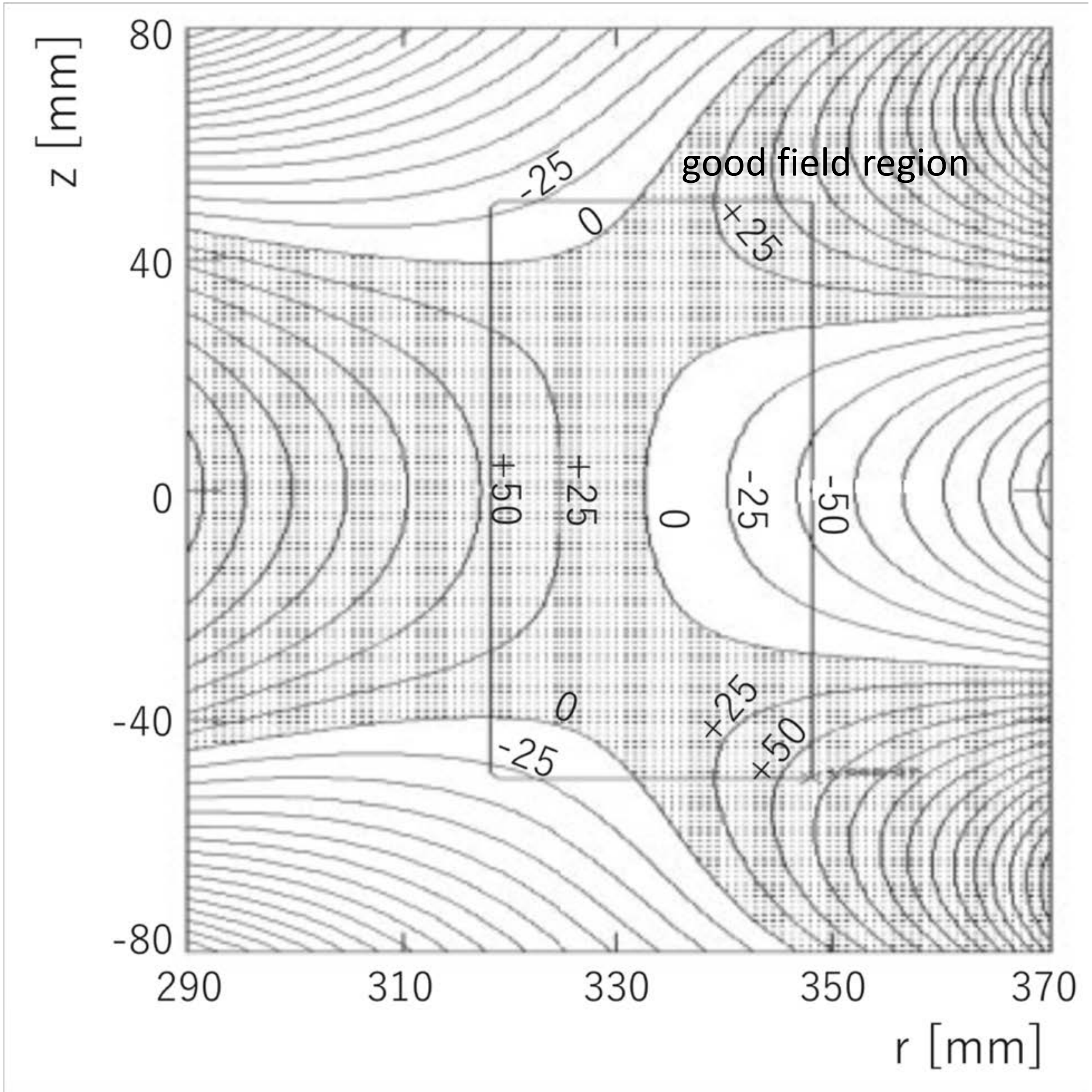
Muon storage magnet and detector

Drawn by Hitachi Co.



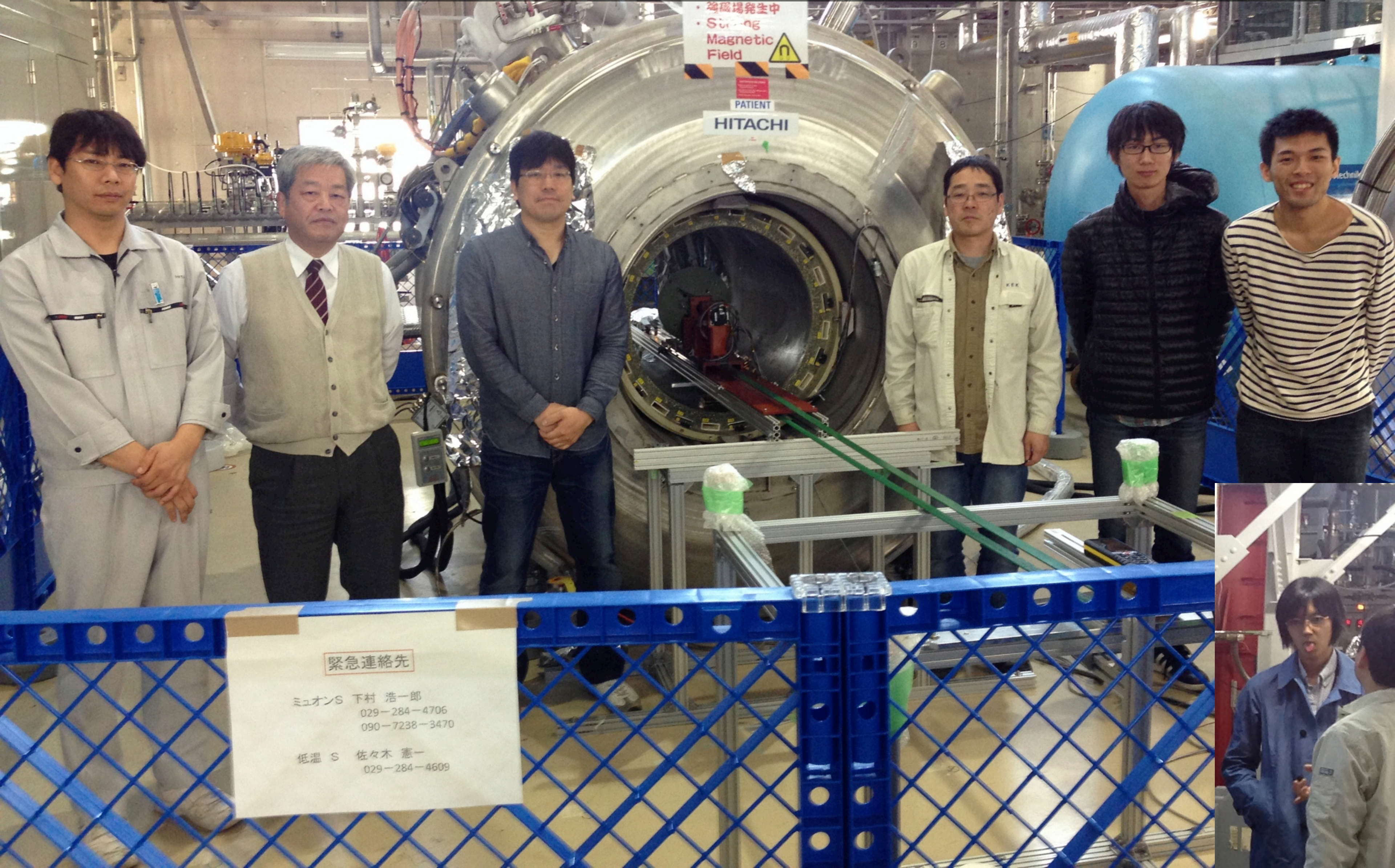
M. Abe et. al., Nuclear Inst. and Methods in Physics Research A 890, 51 (2018)

Average magnetic field



25 ppb/line

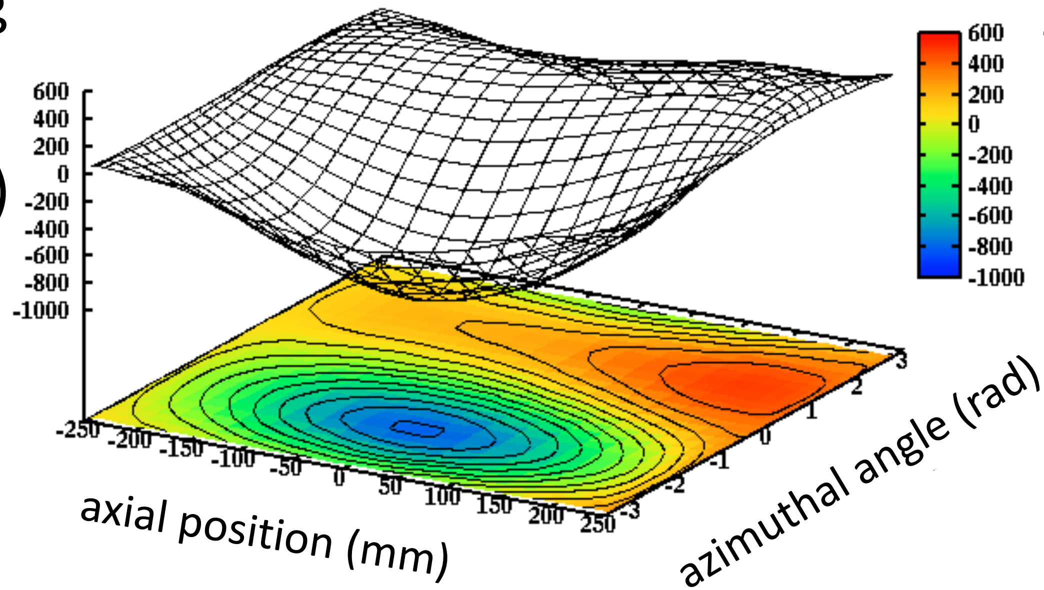
B-field shimming test with the MuSEUM magnet (1.7 T) at J-PARC



Field shimming by iron arrays

Plots by K. Sasaki

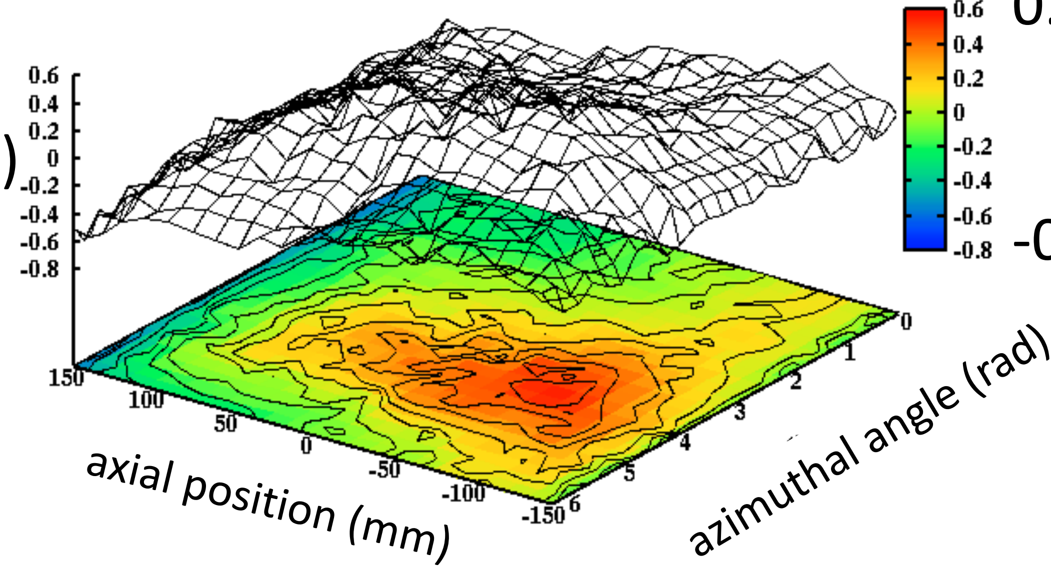
Before shimming



400 ppm

-600 ppm

After shimming



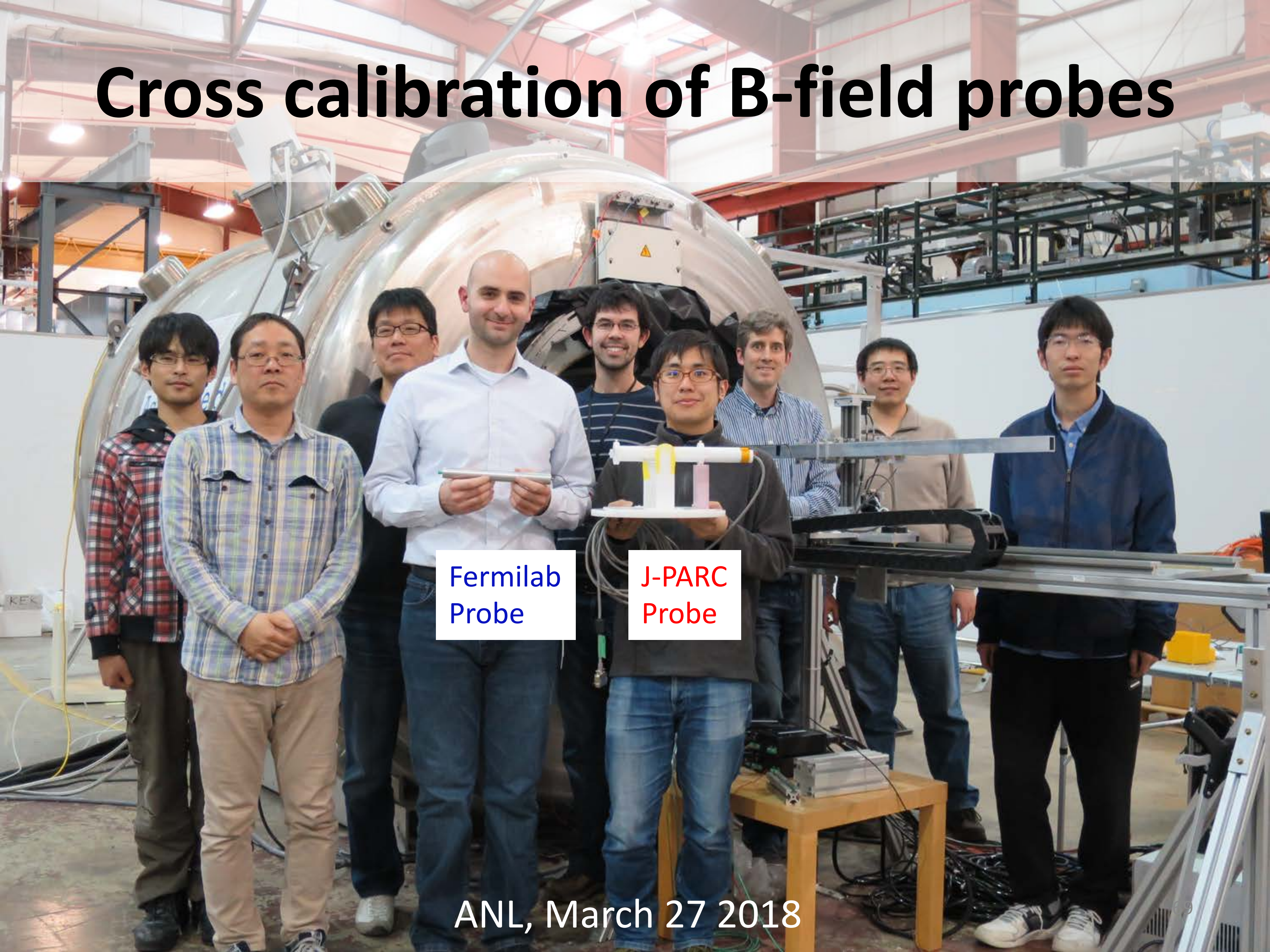
0.4 ppm

-0.5 ppm

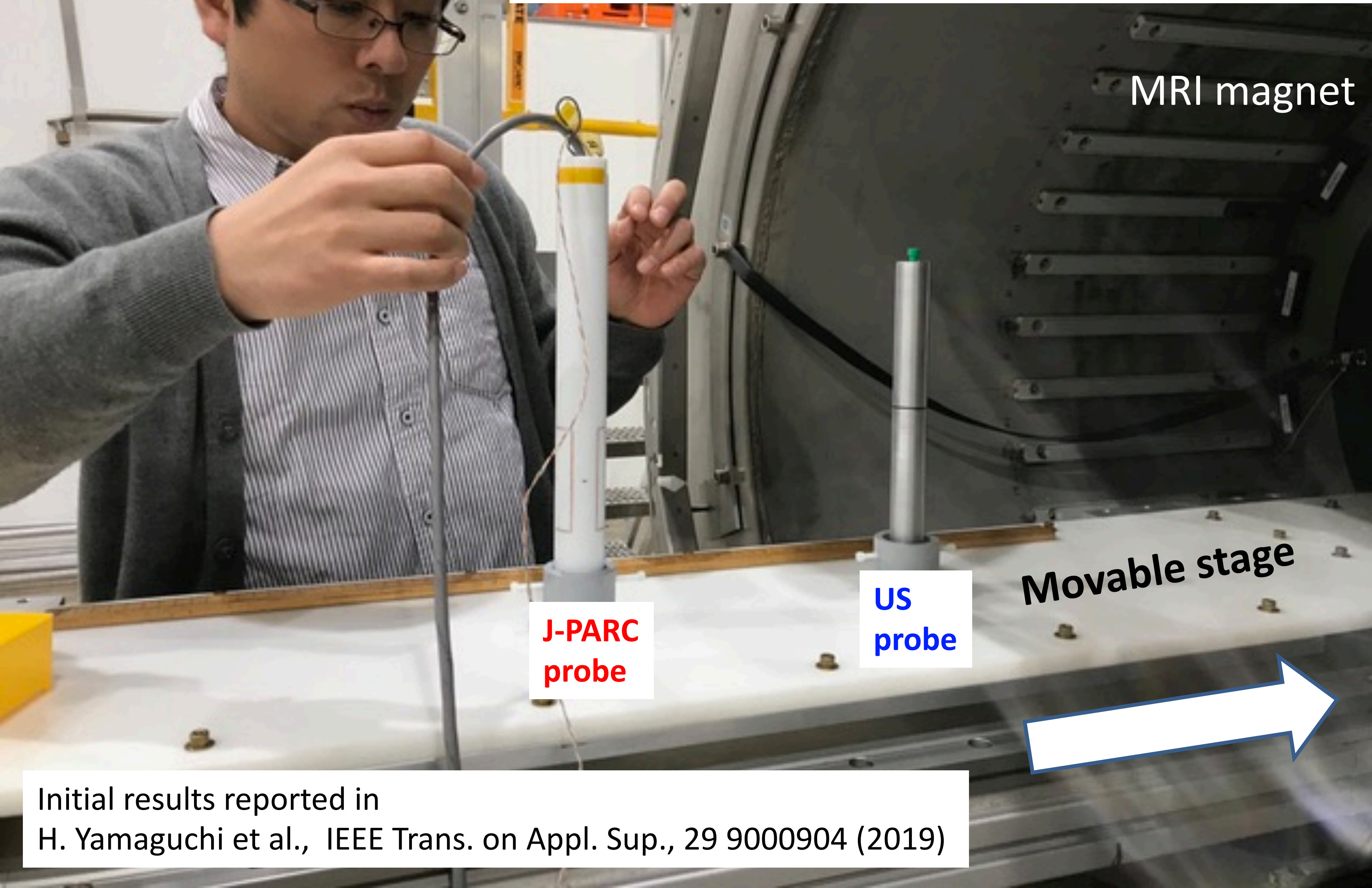
r = 140 mm

51.0000, 216.000 scale: 1.00000, 1.00000

Cross calibration of B-field probes



Cross calibration between J-PARC and US NMR probes at ANL (Jan 14- 2019)

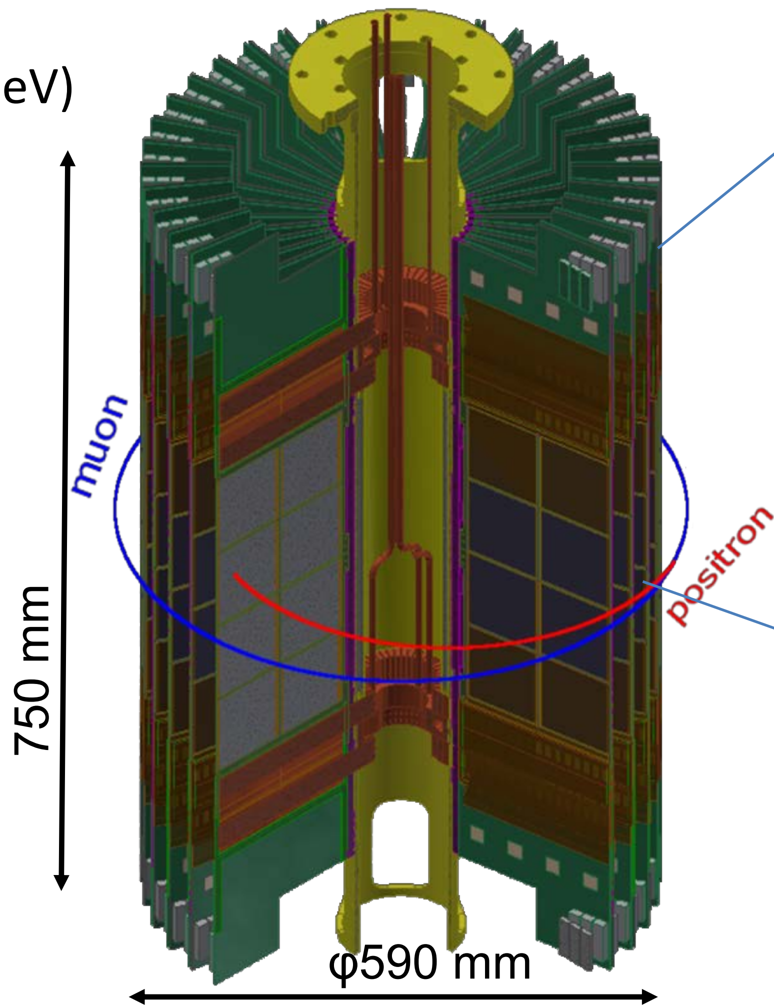


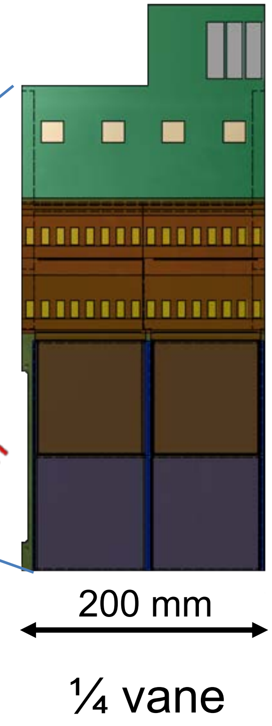
Initial results reported in
H. Yamaguchi et al., IEEE Trans. on Appl. Sup., 29 9000904 (2019)

Positron tracking detector

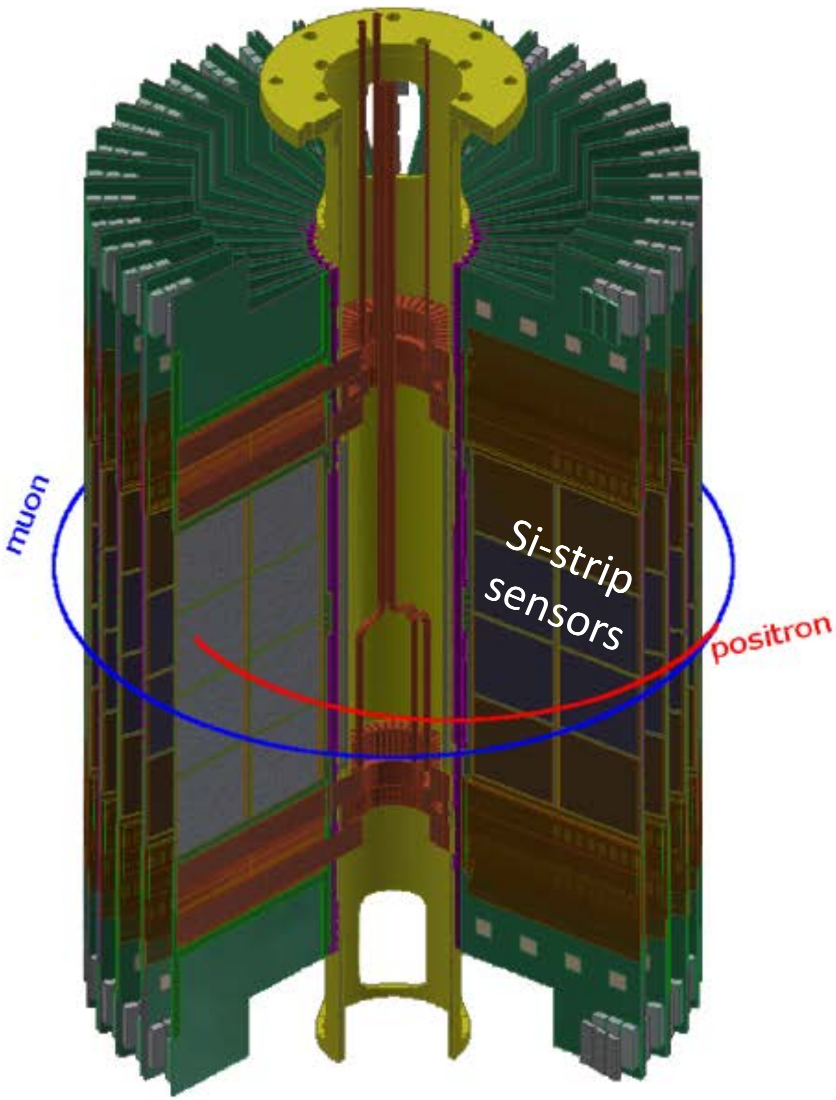
- Requirements
  - Detection of e+ (100<E<300 MeV)
  - Reconstruction of momentum vector
  - Stability over rate changes (1.4 MHz → 14 kHz)

- Specifications
  - Sensor: p-on-n single-sided strip
  - Number of vanes: 40
  - Number of sensors : 640
  - Number of strips : 655,360
  - Area of sensors : 6.24 m^2

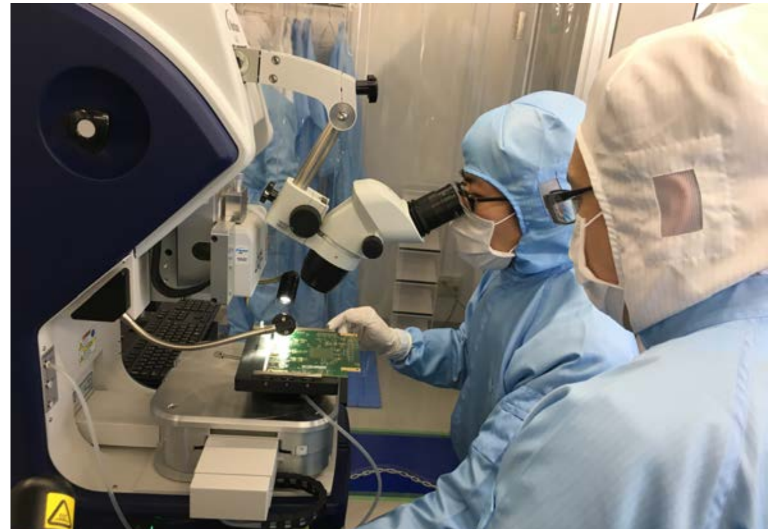




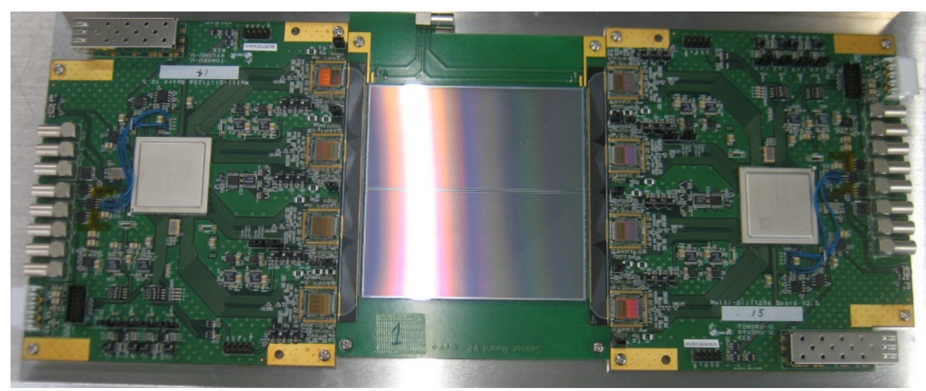
Positron tracking detector



Assembly (Kyushu + KEK)

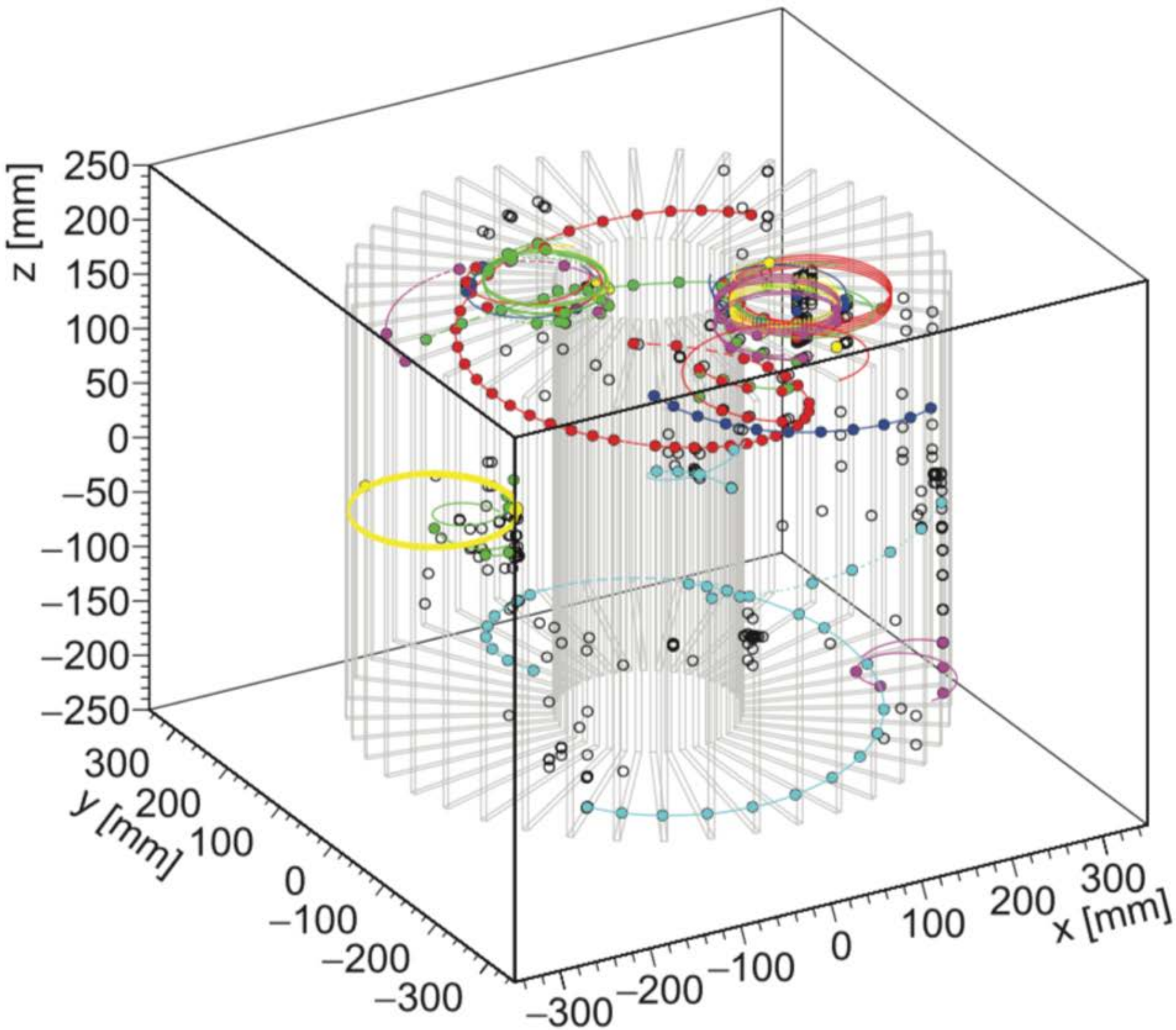


Test module (Kyushu + KEK)

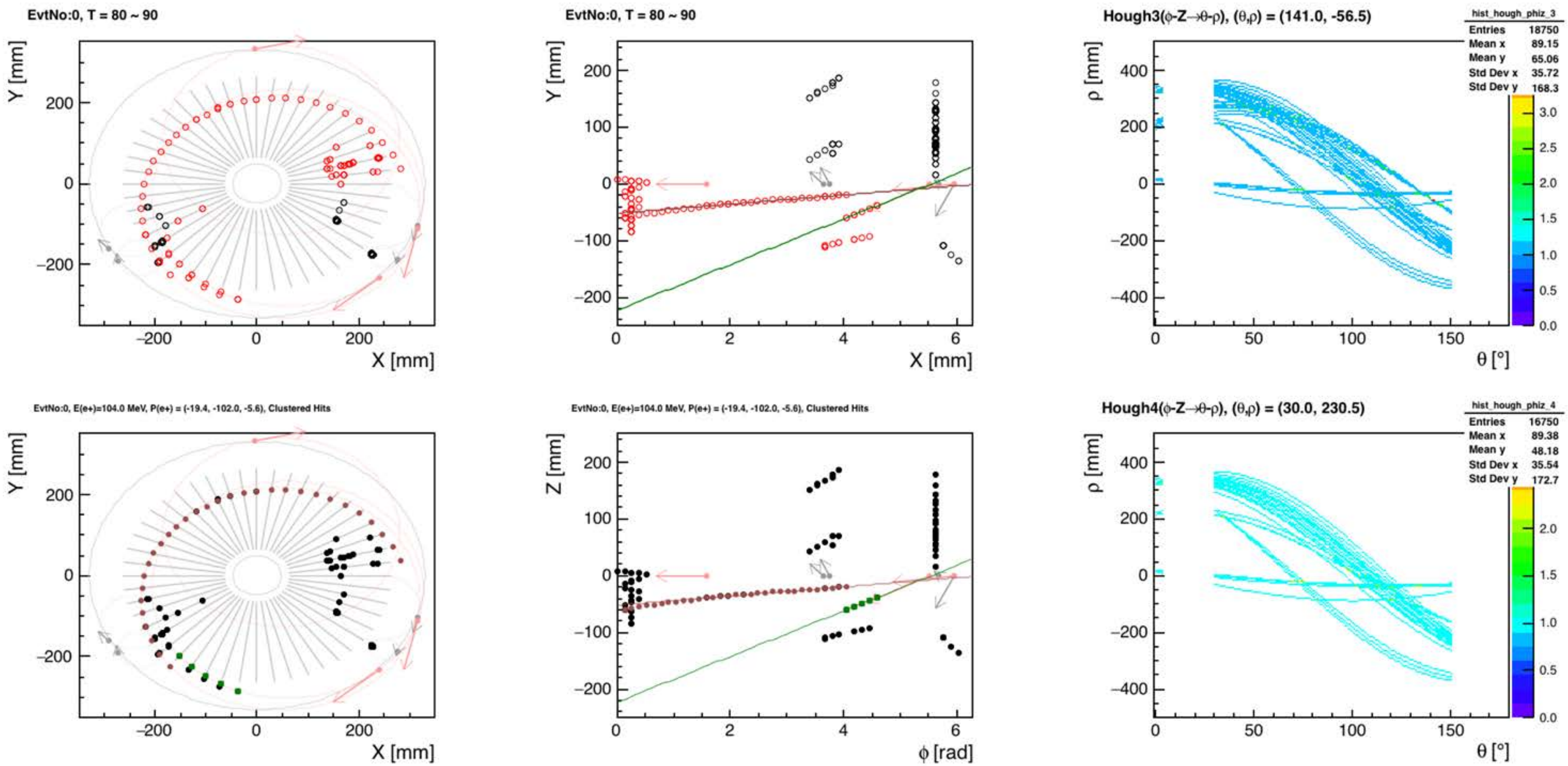


Great help from ATLAS and Belle II group at KEK

Typical event positron track in a 5 ns time window

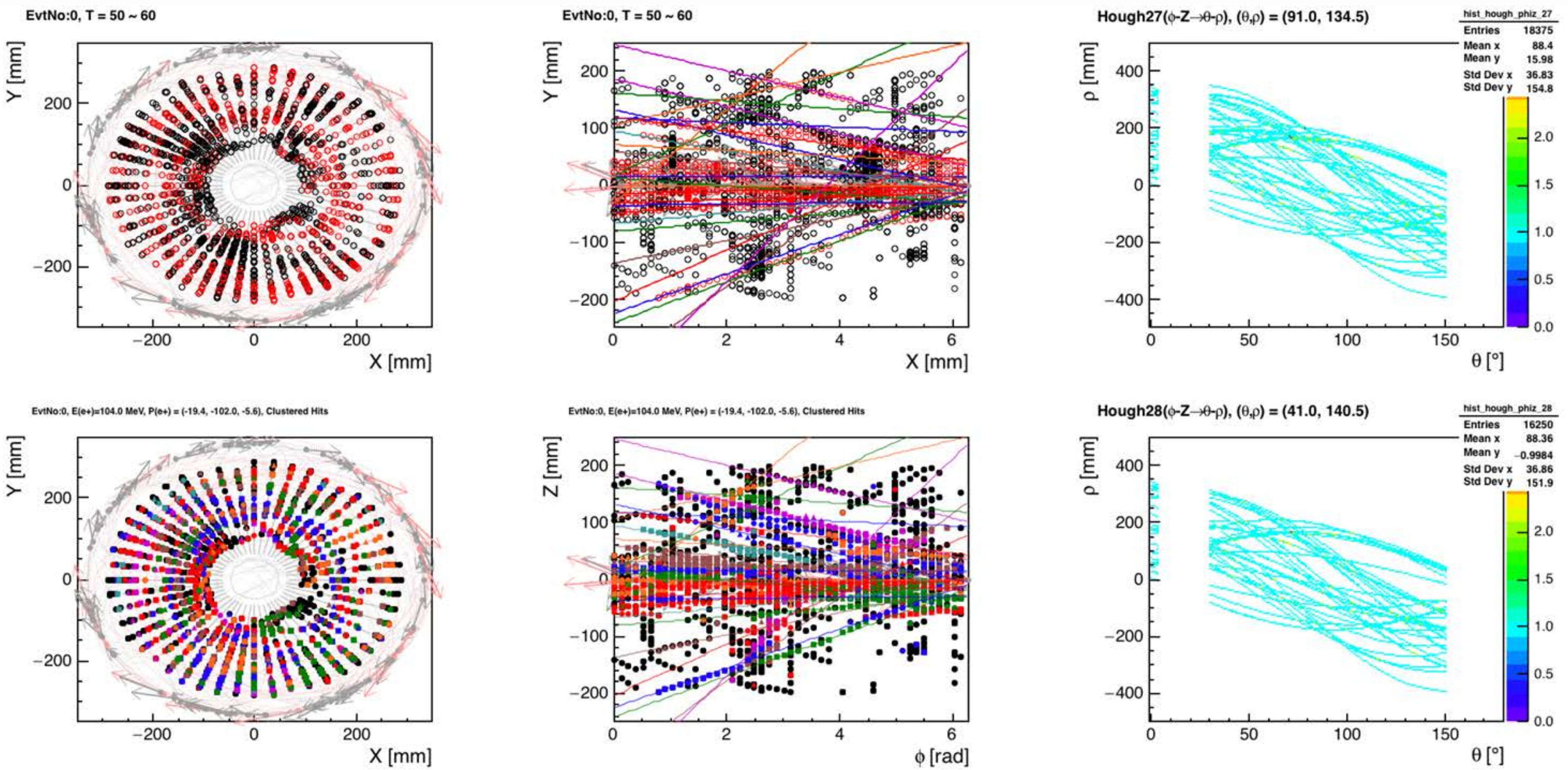


Track finding at low rate (0.6 track/ns)



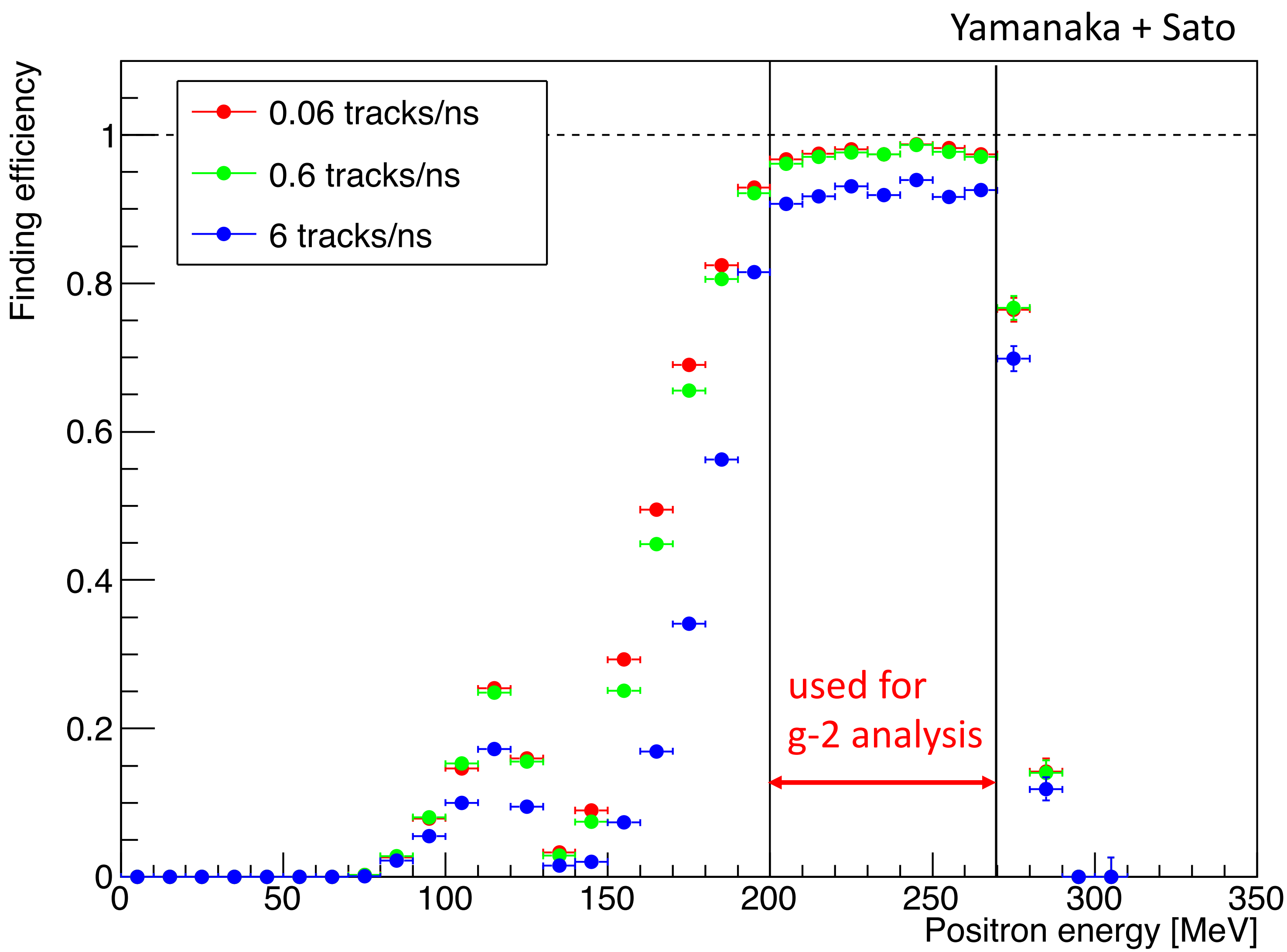
Y. Sato

Track finding at high rate (6 track/ns）

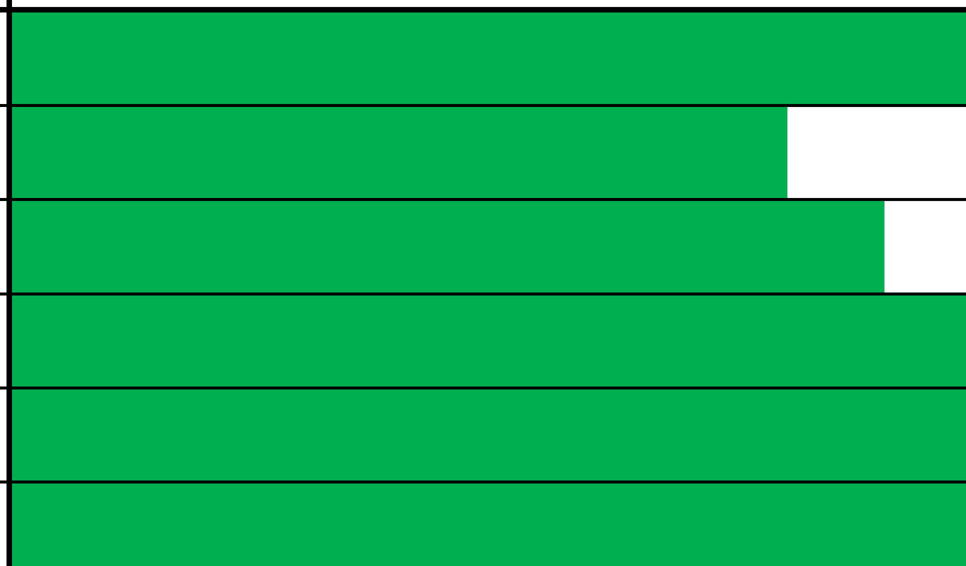


Y. Sato

Reconstruction efficiency

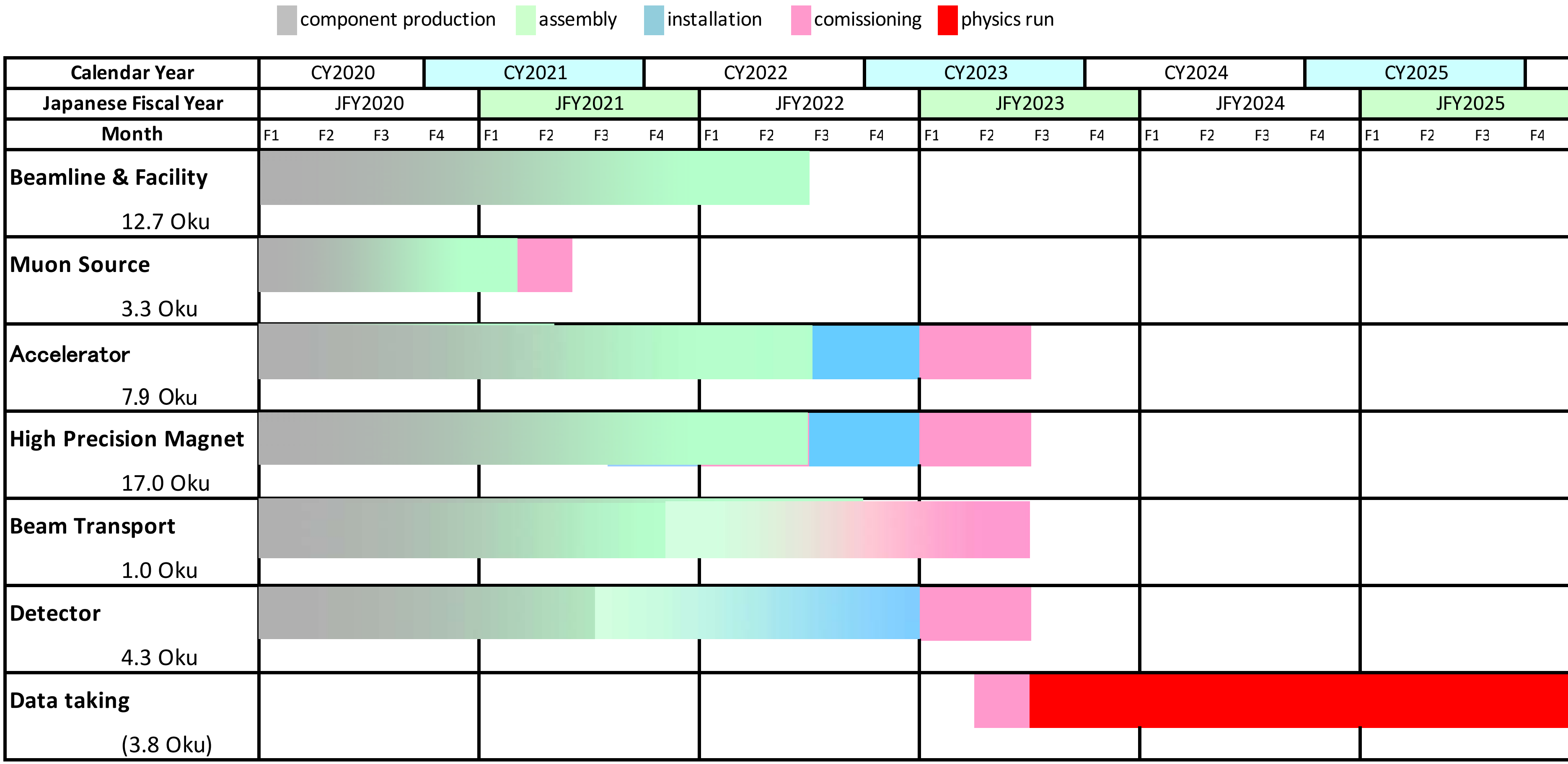


Status of R&D and remaining milestones

Level of R&D achievements (%)	0 10 20 30 40 50 60 70 80 90 100 	Status Remaining milestones
Beamline & Facility		Done Under construction
Muon Source		(1) Hi-power laser (2) ionization test
Accelerator		(3) Demonstration of low emittance acceleration
High Precision Magnet		Done
Beam Transport		Done
Detector		Done Under construction

Technically-driven schedule and cost

Assumption : Major construction fund becomes available in JFY201X



Relating measurements to g-2

- **muon spin precession** $\omega_a = \frac{e}{m_\mu} a_\mu B$
- **proton spin precession** $\omega_p = \mu_p B$
- muon magnetic moment $\mu_\mu = g\frac{e}{2m_\mu} = (1 + a_\mu)\frac{e}{m_\mu}$

$$a_\mu = \frac{\frac{\omega_a}{\omega_p}}{\frac{\omega_a}{\omega_p} - \frac{\mu_\mu}{\mu_p}}$$

540 ppb (BNL)
140 ppb
(Fermilab/J-PARC)

Magnetic moment ratio

LAMPF(1999)

$$\Delta\left(\frac{\mu_\mu}{\mu_p}\right) = 120\ ppb\ (30\ ppb)$$

direct

using Δν
+ theory

Relating **measurements** to g-2

- **muon spin precession** $\omega_a = \frac{e}{m_\mu} a_\mu B$
- **proton spin precession** $\omega_p = \mu_p B$
- muon magnetic moment $\mu_e = g_e \frac{e}{2m_e}$

$$a_\mu = \frac{\omega_a}{\omega_p} \frac{\mu_p}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

540 ppb (BNL)
140 ppb
(Fermilab/J-PARC)

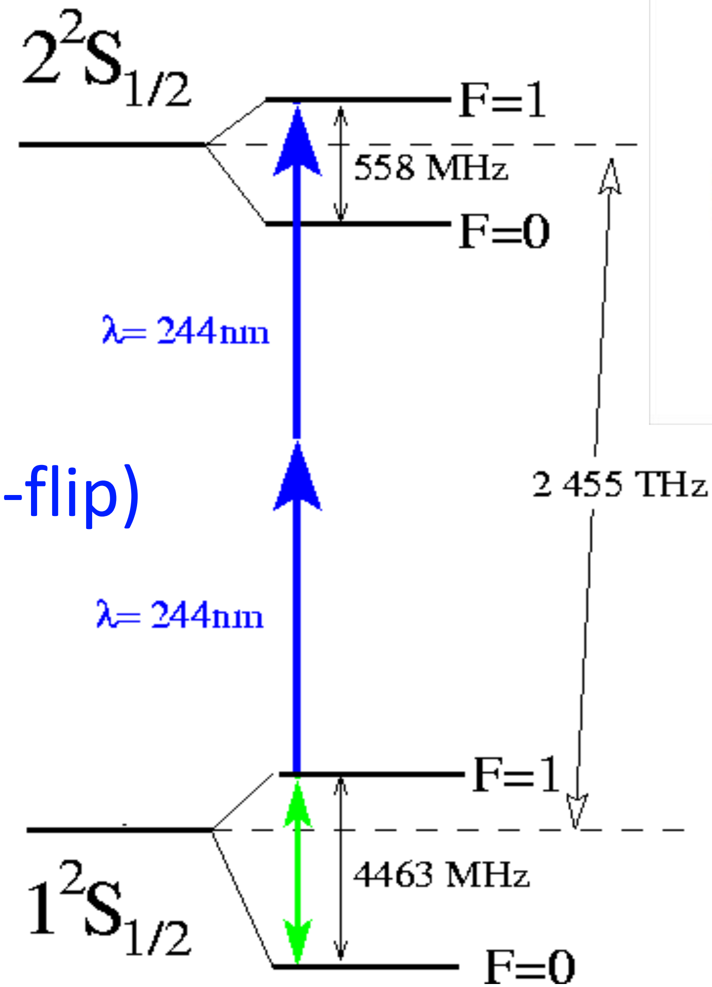
8 ppb

120 ppb (using μ_μ/μ_p)
22 ppb (using $\Delta\nu$ + theory)

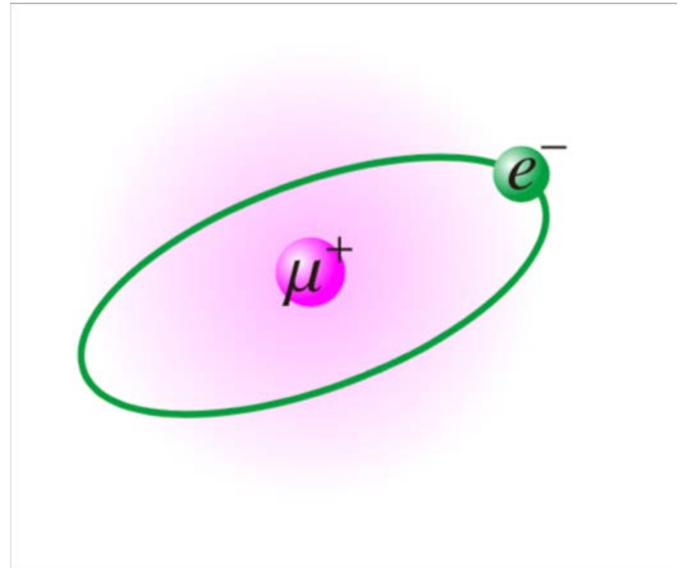
0.3 ppt

Energy spectrum of muonium

From K. Jungmann



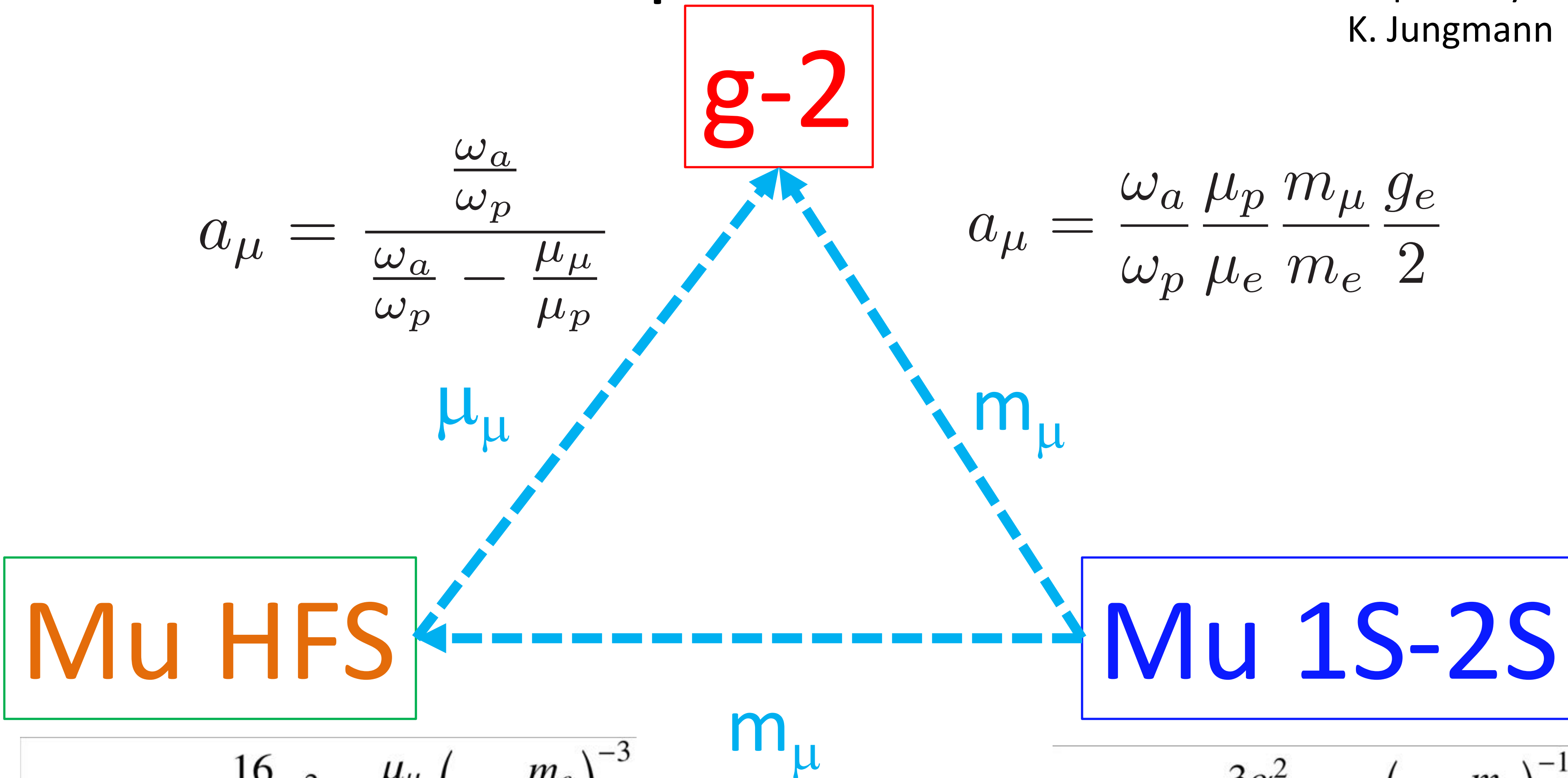
1S-2S
(spin non-flip)



HFS (spin flip transition)

Muon g-2 and muonium spectroscopy experiments

inspired by
K. Jungmann



$$a_\mu = \frac{\frac{\omega_a}{\omega_p}}{\frac{\omega_a}{\omega_p} - \frac{\mu_\mu}{\mu_p}}$$

$$a_\mu = \frac{\omega_a}{\omega_p}\frac{\mu_p}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2}$$

$$\Delta\nu_{\text{1S-HFS}} \simeq \frac{16}{3}\alpha^2 R_\infty \frac{\mu_\mu}{\mu_B}\left(1+\frac{m_e}{m_\mu}\right)^{-3}$$

$$\nu_{34} - \nu_{12} \propto \frac{\mu_\mu}{\mu_p}$$

$$\Delta\nu_{\text{1S2S}} \simeq \frac{3\alpha^2}{8h} m_e c^2 \left(1+\frac{m_e}{m_\mu}\right)^{-1}$$

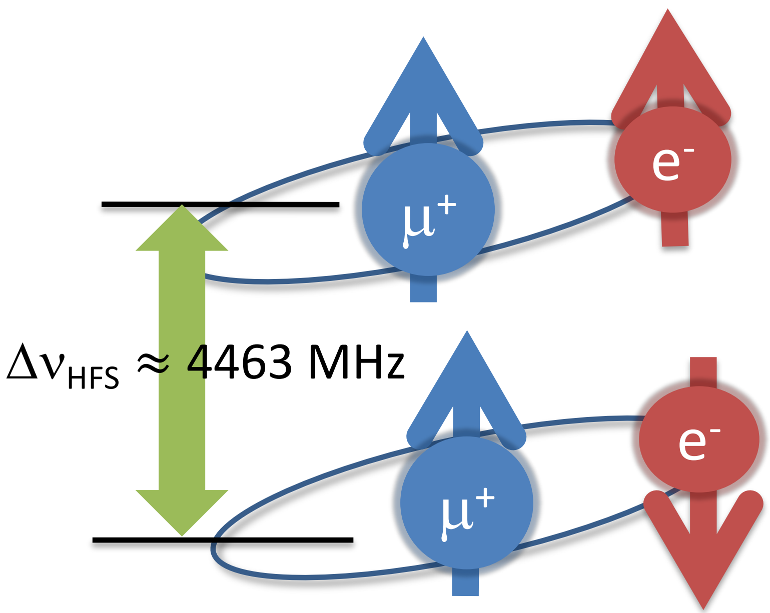
Muonium Hyperfine Structure

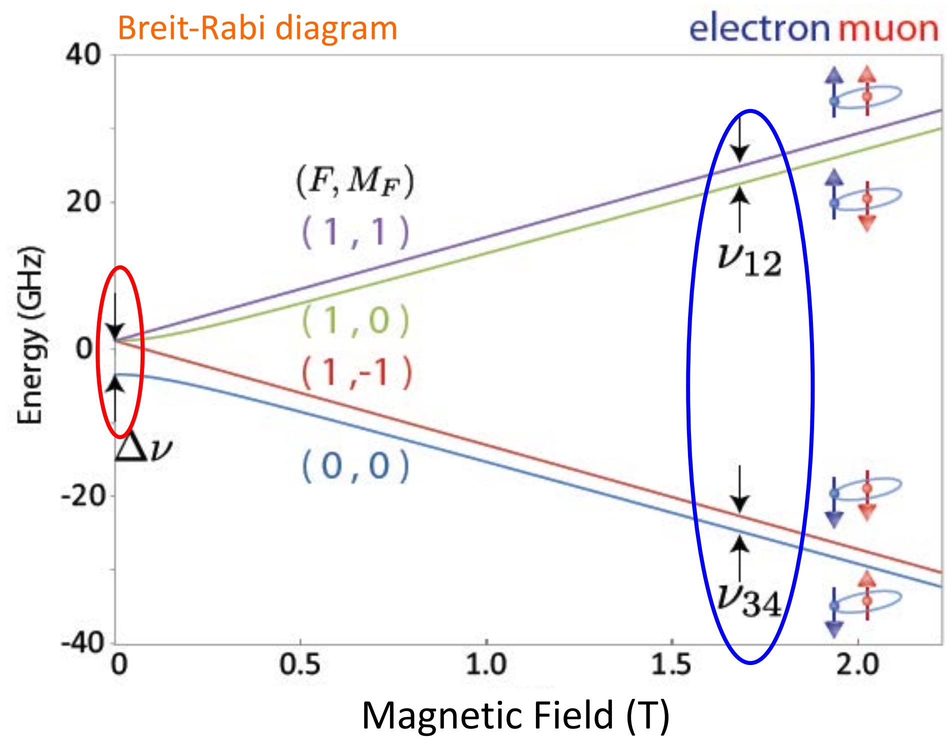
K. Shimomura

$$\mathcal{H} = h\Delta\nu \mathbf{I}_\mu \cdot \mathbf{J} - \mu_B^\mu g'_\mu \mathbf{I}_\mu \cdot \mathbf{H} + \mu_B^e g_J \mathbf{J} \cdot \mathbf{H}$$

$\Delta\nu_{HFS}$: Mu Hyperfine Structure

Zeeman Splitting





$\nu_{12}+\nu_{34} = \Delta\nu_{HFS}$

$\nu_{12}-\nu_{34} \propto \mu_\mu/\mu_p \propto m_\mu/m_p$

Most Precise Test of Bound State QED

Experiment:

LAMPF Experiment (1999)

ν_{HFS}(exp) 4463.302 765 (53) MHz [12 ppb]

μ_μ/μ_p = 3.18334524(37) [120ppb]

m_μ/m_e = 206.768277(24) [120ppb]

Theory:

ν_{HFS}(theory) 4463.302 868 (271) MHz [61 ppb]

ν_{HFS}(QED) 4463.302 720 (253) (98) (3) MHz

(m_μ/m_e) (QED) (α)

ν_{HFS}(weak) -65 Hz

ν_{HFS}(had. v.p.) 232 (1) Hz

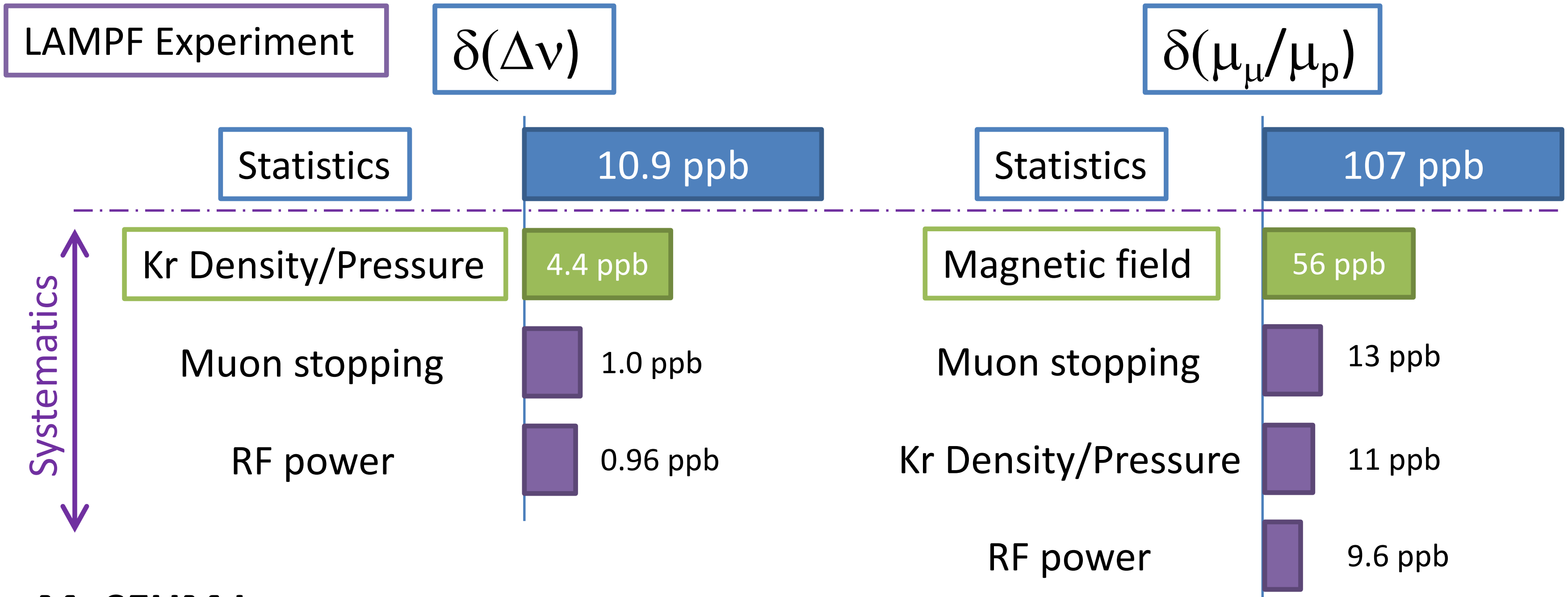
ν_{HFS}(had. h.o.) 5 (2) Hz

QED calculation: Effort for 10 Hz accuracy in progress (by Eides et al.)

Progress: PRA 86 (2012) 024501, PRL 112 (2014) 173004, PRD 89 (2014) 014034

K. Shimomura

Improvement of statistics at J-PARC



MuSEUM Improvements:

Statistics:

LAMPF: DC 10^7/s
total 10^{13}

x200 →

J-PARC/MUSE: **Pulsed 1x10^8**/s
H-Line total 2x10^{15}

Systematics:

- magnetic field accuracy & uniformity
- pressure dependence (longer cavity lower pressure)
- muon stopping distribution measurement
- RF power stability

K. Shimomura

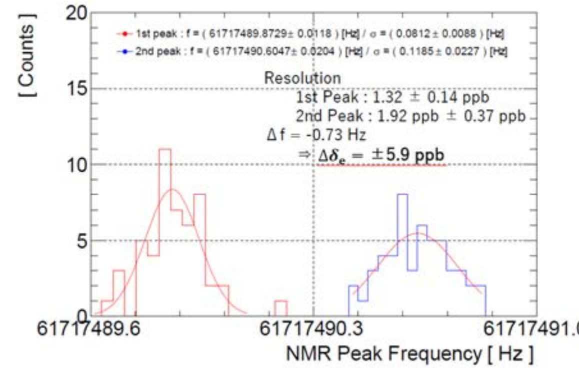
MRI Magnet for High-Field Experiment

Sasaki, Yamaguchi , T. Tanaka

Second-hand 2.9 T MRI magnet

CW-NMR Field Monitoring System

18 ppb→5.9 ppb (2017→2018)

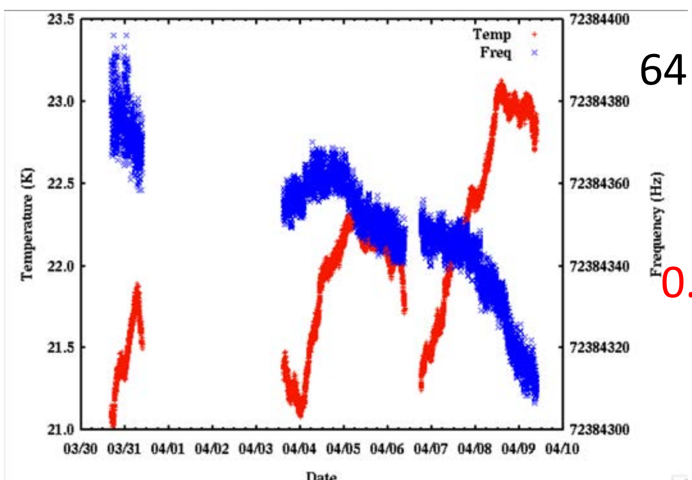


Field Homogeneity (after shimming)

Spheroid : r=100 mm, z=300 mm

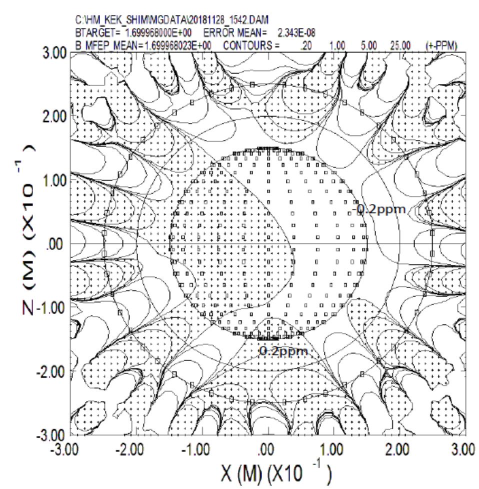
1.4 ppm p-p→0.27 ppm p-p (2017→2018)

Long Term Stability



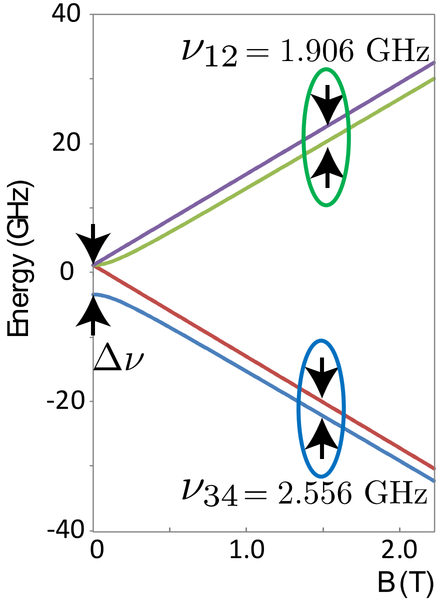
64 Hz / 9.7 days

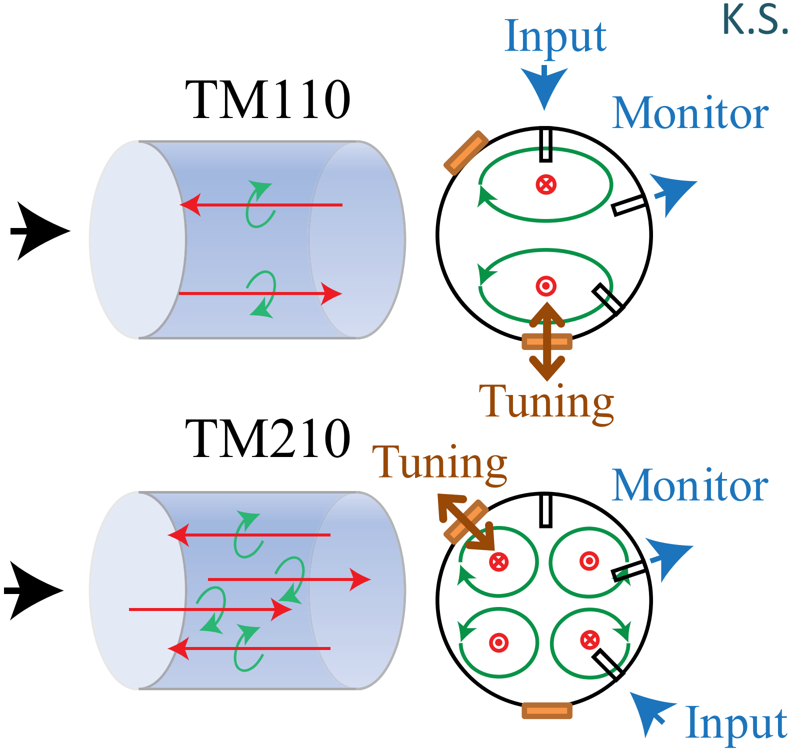
0.003 ppm /h



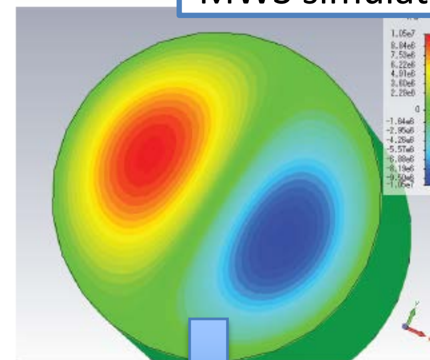
RF Cavity for High Field Experiment

K.S. Tanaka, Seo

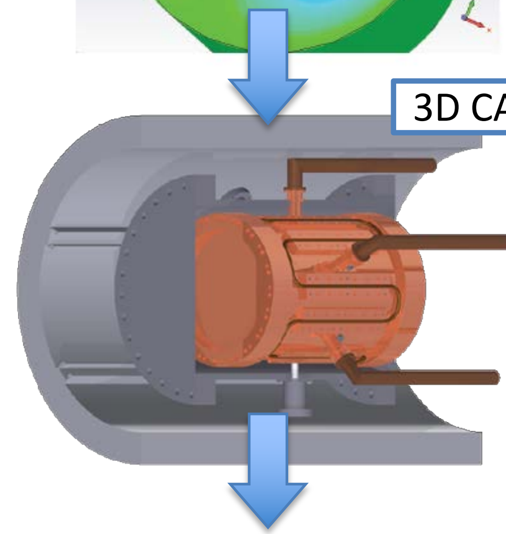




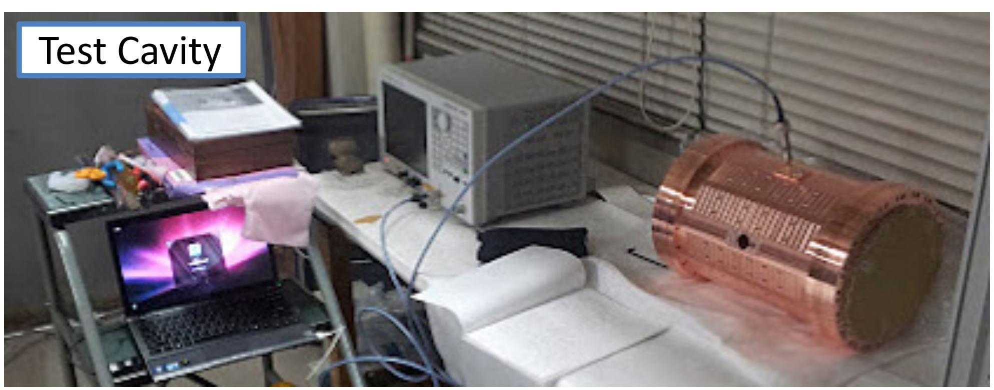
MWS simulation



3D CAD



Test Cavity



Q Value

Modes	Q (measured)	Q (simulation)
TM110	11,300	29,700
TM210	8,050	28,900

Mu 1S-2S (Mu-MASS@PSI)

Mu-MASS vs RAL(1999) - New essential developments

	RAL (1999)	Mu-MASS Phase1	Mu-MASS Phase2
μ^+ beam intensity	3500×50 Hz	5000 s^{-1}	$>$ 9000 s^{-1}
μ^+ beam energy	4 MeV	5 keV	5 keV
Temperature M atoms	300 K	100 K	100 K
Total number of 2S events	99	1900 (10 d)	$>$ 7000 (40 d)
Spectroscopy	Pulsed laser	CW (25 W)	CW (50 W)
Experimental linewidth	20 MHz	750 kHz	300 kHz
Laser chirping	10 MHz	0 kHz	0 kHz
Residual Doppler shift uncert.	3.4 MHz	0 kHz	0 kHz
2nd-order Doppler shift uncert.	44 kHz	15 kHz	1 kHz (corrected)
Frequency calibration uncert.	0.8 MHz	$<$ 1 kHz	$<$ 1 kHz
Background events	2.8 events/day	1.6 events/day	1.6 events/day
Statistical uncertainty	9.1 MHz	$<$100 kHz	10 kHz
Total uncertainty	9.8 MHz	$<$100 kHz (linewidth/10)	10 kHz (linewidth/30)

Improved muonium source (higher yield + lower temperature)

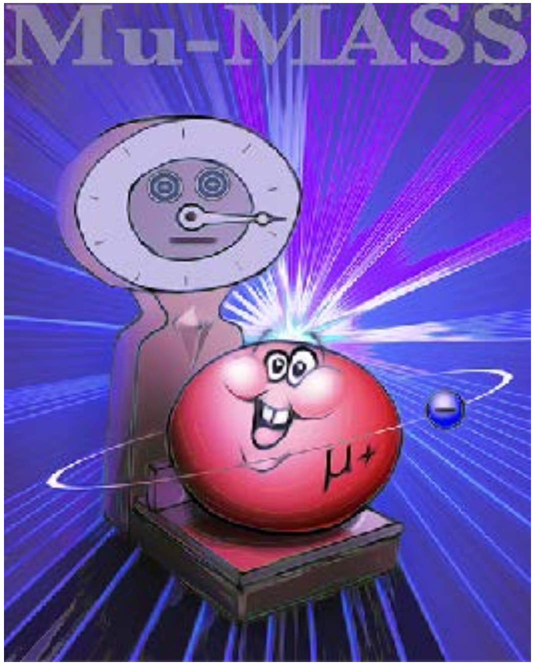
Continuous wave laser spectroscopy vs pulsed

Mu-Mass

Mu 1S-2S (Mu-MASS@PSI)

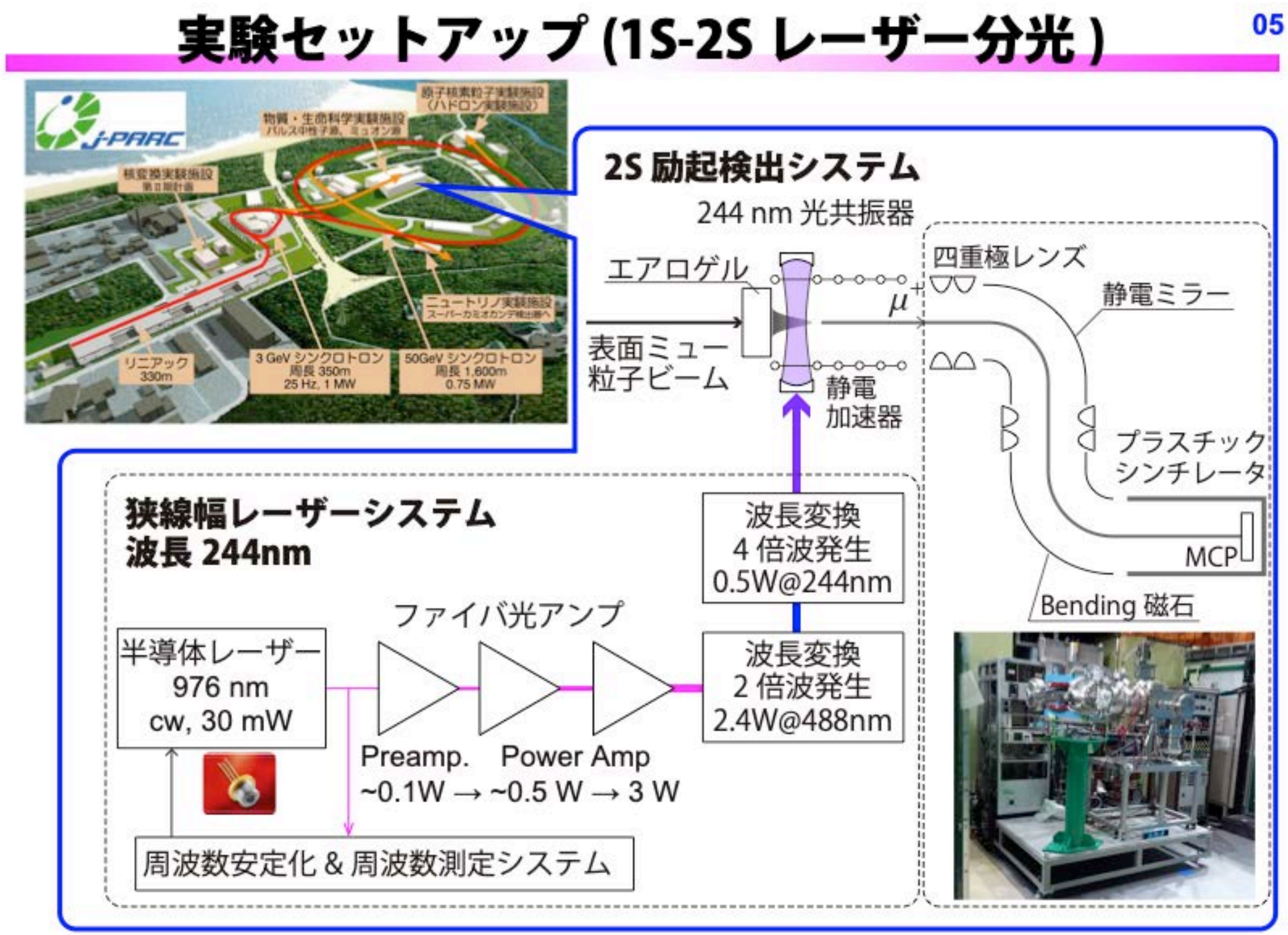
Summary

- Mu-MASS aims at improving 3 orders of magnitude on our current knowledge of the 1S-2S of Muonium
- Feasibility builds on expertise acquired during the last decade: Ps CW laser spectroscopy, cryogenic muonium
  production, high precision detectors development.
- Project funded by European Research Council: start beginning of 2019.
- First results expected in 2020-2021.



Mu 1S-2S at J-PARC

Proposal in preparation

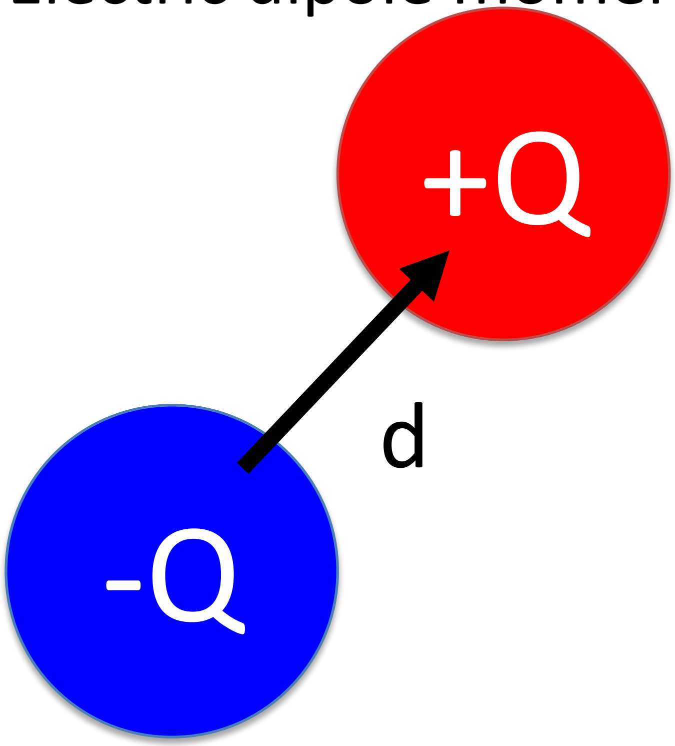


ELECTRIC DIPOLE MOMENT

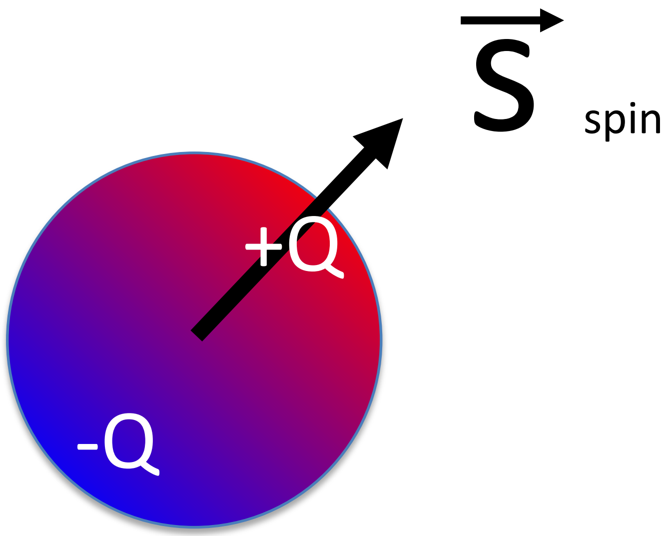
Dipole moments

- A pair of spatially separated (electric,magnetic) charges

Electric dipole moment

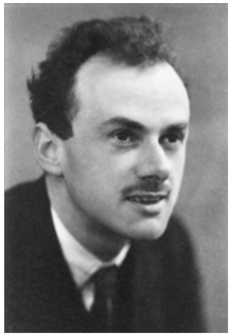


Particle's electric dipole moment



Quantum theory of the electron (1928)

Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences 117 (778): 610.



This differs from (1) by the two extra terms

$$\frac{eh}{c}(\sigma, \mathbf{H}) + \frac{ieh}{c}\rho_1(\sigma, \mathbf{E})$$

in F. These two terms, when divided by the factor $2m$, can be regarded as the additional potential energy of the electron due to its new degree of freedom. The electron will therefore behave as though it has a magnetic moment $eh/2mc \,.\, \sigma$ and an electric moment $ieh/2mc \,.\, \rho_1 \sigma$. This magnetic moment is just that assumed in the spinning electron model. The electric moment, being a pure imaginary, we should not expect to appear in the model. It is doubtful whether the electric moment has any physical meaning, since the Hamiltonian in (14) that we started from is real, and the imaginary part only appeared when we multiplied it up in an artificial way in order to make it resemble the Hamiltonian of previous theories.

Purcell and Ramsey’s letter (1950)

E.M. Purcell and N.F. Ramsey Phys. Rev. 78 (1950)

On the Possibility of Electric Dipole Moments for Elementary Particles and Nuclei

E. M. Purcell and N. F. Ramsey
Department of Physics, Harvard University, Cambridge, Massachusetts
April 27, 1950

It is generally assumed on the basis of some suggestive theoretical symmetry arguments[1] that nuclei and elementary particles can have no electric dipole moments. It is the purpose of this note to point out that although these theoretical arguments are valid when applied to molecular and atomic moments whose electromagnetic origin is well understood, their extension to nuclei and elementary particles rests on assumptions not yet tested.

One form of the argument against the possibility of an electric dipole moment of a nucleon or similar particle is that the dipole’s orientation must be completely specified by the orientation of the angular momentum which, however, is an axial vector specifying a direction of circulation, not a direction of displacement as would be required to obtain an electric dipole moment from electrical charges. On the other hand, if the nucleon should spend part of its time asymmetrically dissociated into opposite magnetic poles of the type that Dirac[2] has shown to be theoretically possible, a circulation of these magnetic poles could give rise to an electric dipole moment. To forestall a possible objection we may remark that this electric dipole would be a polar vector, being the product of the angular momentum (an axial vector) and the magnetic pole strength, which is a pseudoscalar in conformity with the usual convention that electric charge is a simple scalar.

The argument against electric dipoles, in another form, raises directly the question of parity. A nucleon with an electric dipole moment would show an asymmetry between left and right

- EDM not yet tested
- Ignored due to parity violation (Wu’s P-violation experiment was in 1956)
- Possible existence is purely an experimental matter

Slide by T. Fukuyama

Ramsey Prize of $5,000 for the first person, or group to discover non zero EDM of any particle.

"I am personally interested in the EDM tests, since I first proposed them and began looking for them 56 years ago, as tests of P, then T, and then CP. Originally I wanted to be the first person to discover an EDM, but now I at least want to know the answer. I have therefore personally established the time limited " Ramsey Prize of $5000 for the first person, or group, during my lifetime to announce the convincing discovery of a non zero electric dipole moment for any elementary particle or atomic nucleus." Since I am now 91 years old, please hurry. "

Norman Ramsey

International Conference on Atomic Physics, 2006, Innsbruck

Norman Ramsey先生は2011年11月に永眠されました。

After 60 years of original proposal…

Workshop photo, Lepton Moments 2010, Capecod, MA

Particle dipole moments

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

P,C,T-even P,T-odd (CP-odd)

Magnetic Dipole Moment

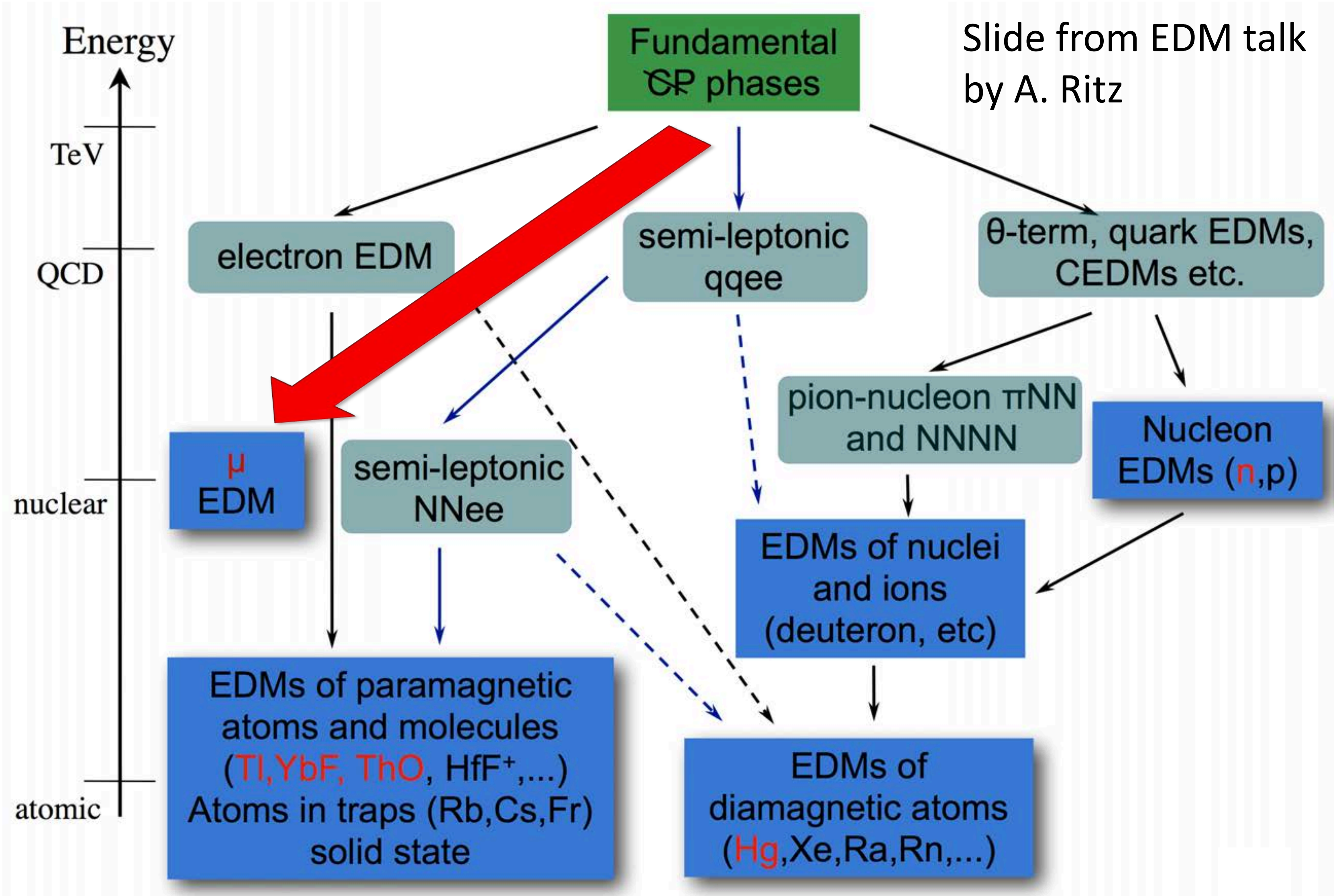
$$\vec{\mu} = g \left(\frac{q}{2m} \right) \vec{s}$$

Electric Dipole Moment

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

	$\vec{E}$	$\vec{B}$	$\vec{\mu}$ or $\vec{d}$
P	-	+	+
C	-	-	-
T	+	-	-

Scales of CPV sources and EDM



Slide from EDM talk
by A. Ritz

Spin precession in E and B field

Spin precession vector in static E and B fields ($\vec{\beta}\cdot\vec{B}=0, \vec{\beta}\cdot\vec{E}=0$)

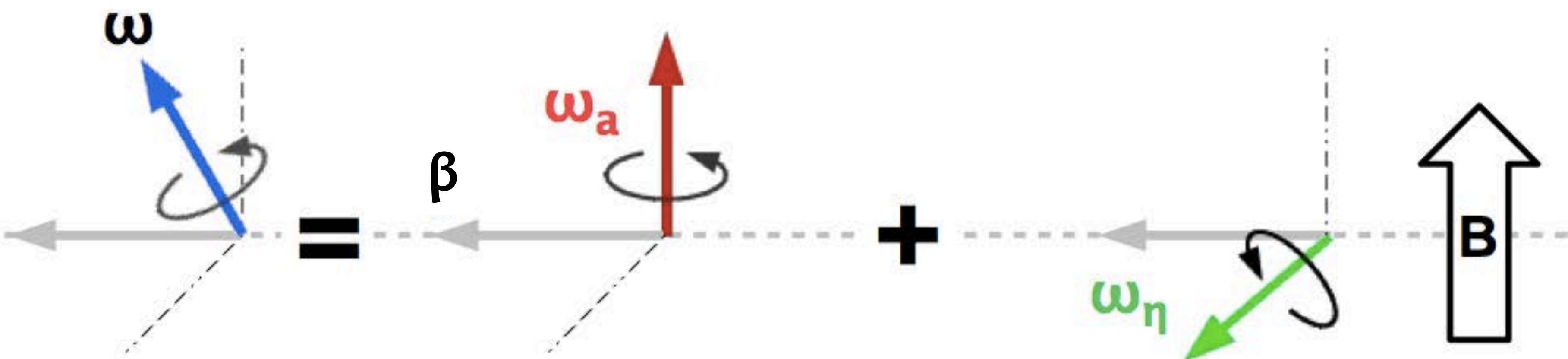
Fukuyama, Silenko, arXiv:1308.1580 (reference therein)

$a_\mu = (g-2)/2$

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

Anomalous magnetic moment

EDM



courtesy G. Onderwater

EDM introduces vertical component in spin precession

Spin precession in E and B field

Spin precession vector in static E and B fields ($\vec{\beta}\cdot\vec{B}=0, \vec{\beta}\cdot\vec{E}=0$)

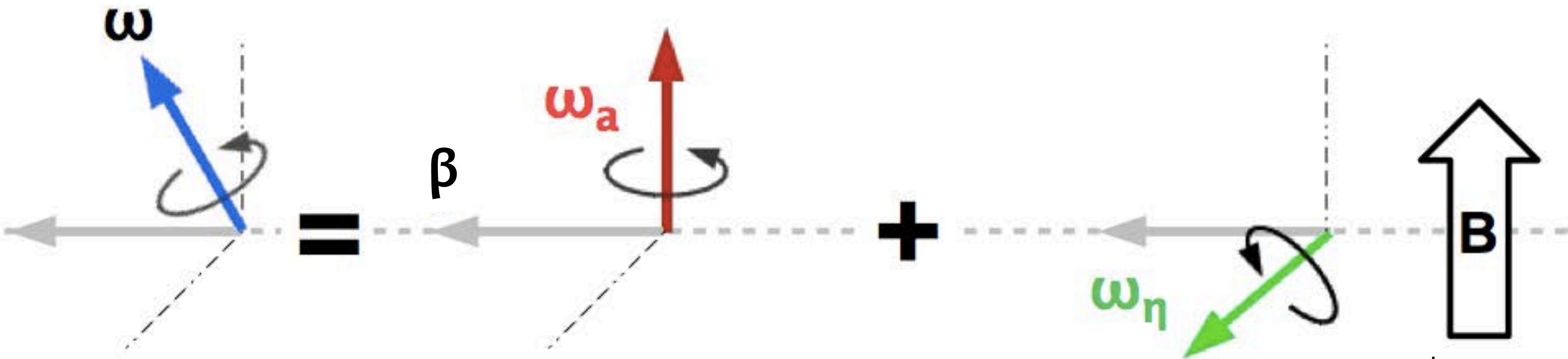
Fukuyama, Silenko, arXiv:1308.1580 (reference therein)

$a_\mu = (g-2)/2$

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

Anomalous magnetic moment

EDM



courtesy G. Onderwater

But, it is a tiny : $\omega_\eta/\omega_a \sim(\eta\beta/2a_\mu) < \sim 10^{-5}$

Three experimental approaches

Spin precession vector in static E and B fields ($\vec{\beta}\cdot\vec{B}=0, \vec{\beta}\cdot\vec{E}=0$)

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

(1) Magic momentum (g-2 + EDM)

γ=30 (P=3 GeV/c)
(BNL E821,FNAL)

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

(2) Zero E-field (g-2 + EDM)

E = 0 at any γ
(J-PARC E34)

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

(3) Spin frozen (EDM only)

$E_r = a_\mu B c \beta \gamma^2$
to kill g-2 precession

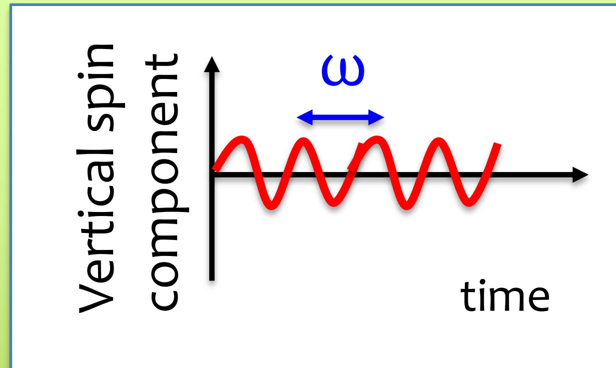
$$\vec{\omega} = -\frac{e}{m}\frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)$$

Three experimental approaches

(1) Magic momentum (g-2 + EDM)

(2) Zero E-field (g-2 + EDM)

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



$$\frac{e}{m}\frac{\eta\beta}{4a_\mu}$$

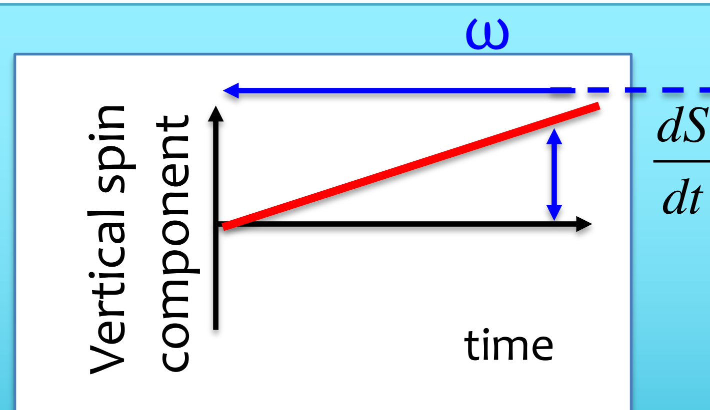
Oscillation with g-2 frequency. Amplitude constrained by g-2

(3) Spin frozen (EDM only)

$E_r = a_\mu B c \beta \gamma^2$

to kill g-2 precession

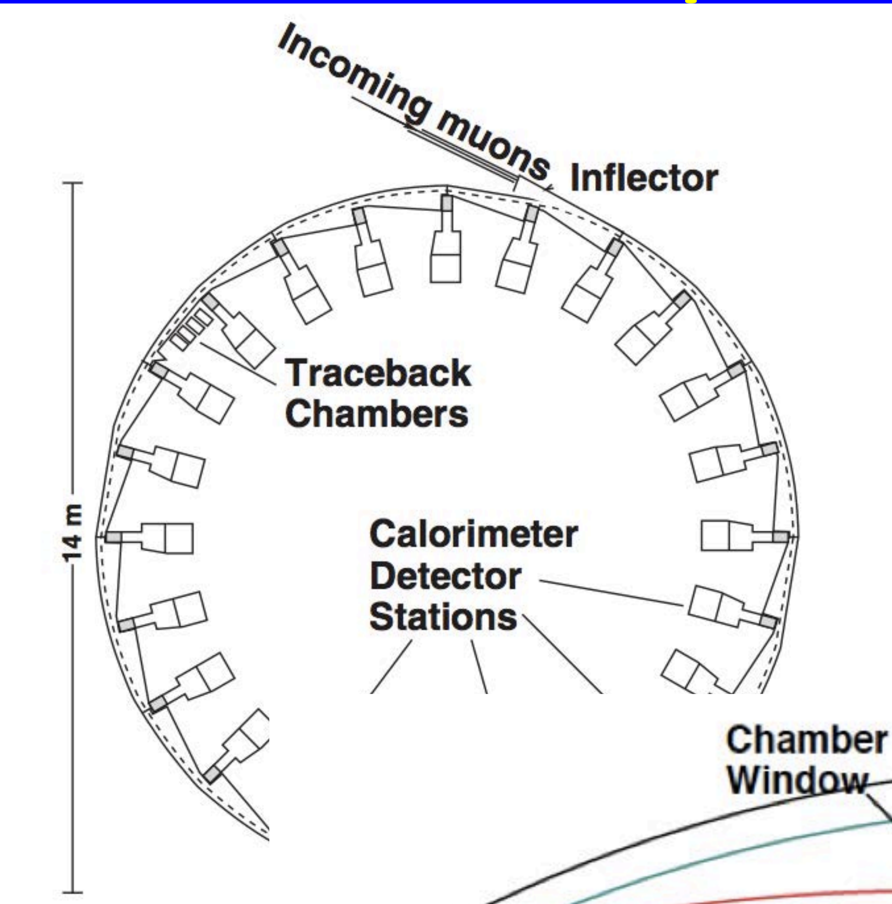
$$\vec{\omega} = -\frac{e}{m}\frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)$$

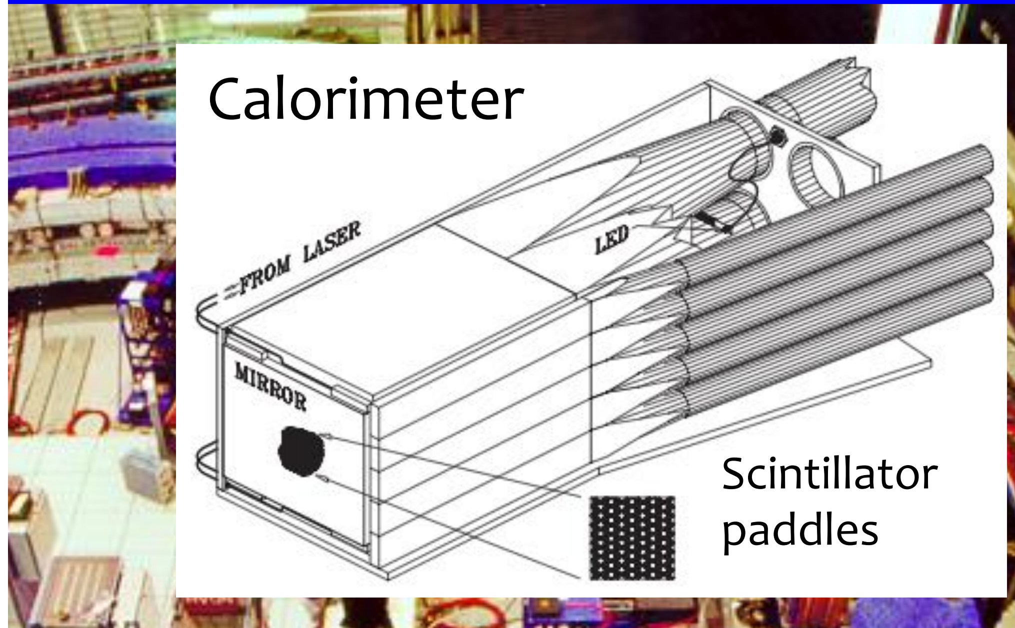


$$\frac{dS}{dt} \approx \frac{e}{m}\frac{\eta\beta}{4}B$$

No constraint in amplitude by g-2 → Better sensitivity

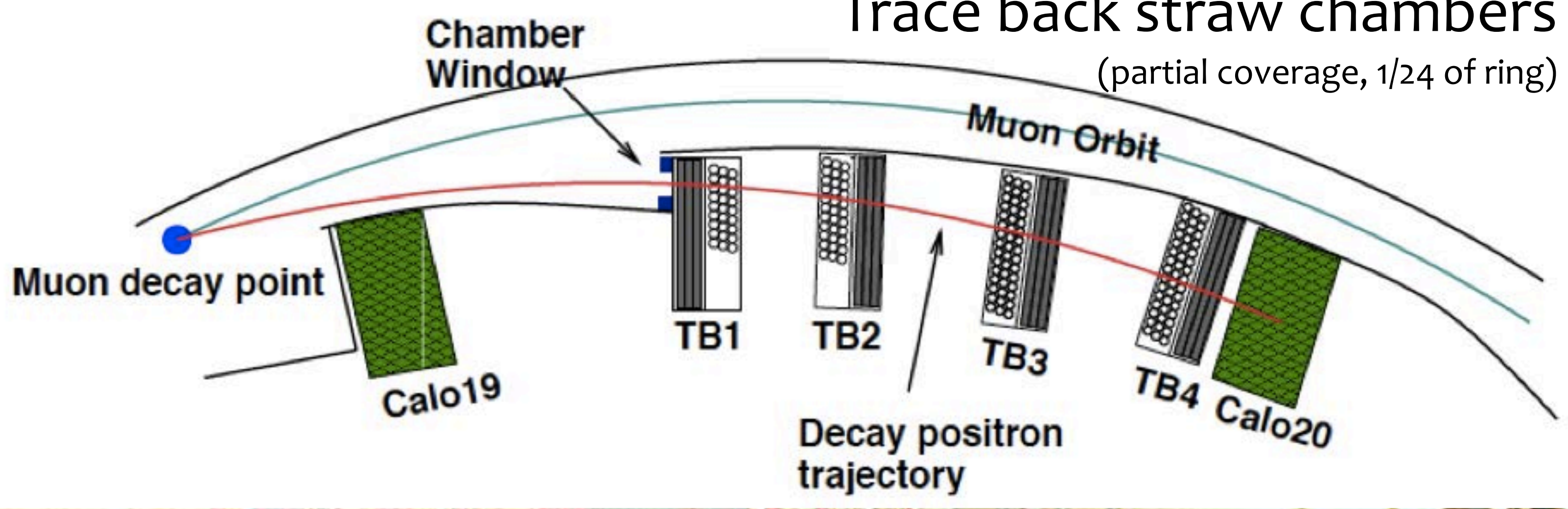
The Experiment at BNL





Trace back straw chambers

(partial coverage, 1/24 of ring)

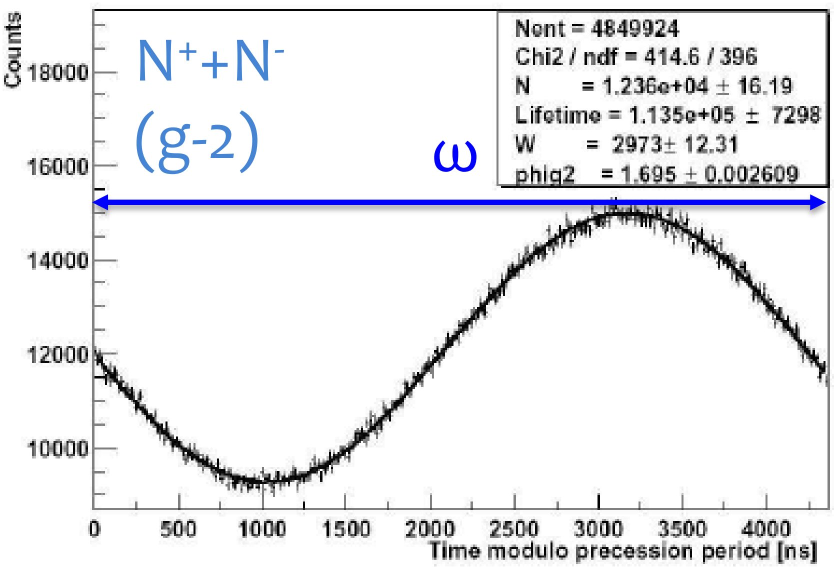


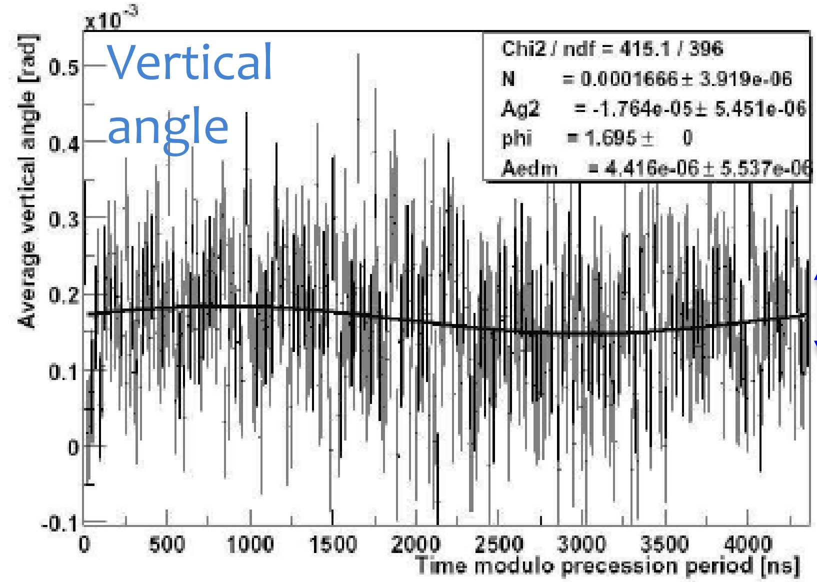
BNL E821 trace-back results

Trace back system

→ Direct measurement of vertical decay angle

$$N^{\pm}(t) \propto [1 \mp A_{EDM} \sin(\omega t + \phi) + A_{\mu} \cos(\omega t + \phi)]$$





$$\propto \frac{e}{m} \frac{\eta \beta}{4 a_{\mu}}$$

$$d_{\mu+} = [-0.04 \pm 1.6(\text{stat}) \pm 0.14(\text{syst})] \times 10^{-19}\ e\text{cm}$$

E821 EDM results

Analysis	Mean value	Stat. error	Syst. error	Total error	95% C.L.
CERN (1978)					
(μ^+)	8.6	4.0	2.0	4.5	
(μ^-)	0.8	3.8	2.0	4.3	
Combined $\mu^+\mu^-$	−3.7	2.8	2.0	3.4	10.5
E821					
Traceback (μ^+)	0.0	1.6	0.1	1.6	
FSD (μ^+)	−0.1	0.7	1.2	1.4	
PSD (μ^-)	−0.1	0.3	0.7	0.7	
Combined $\mu^+\mu^-$	0.0	0.2	0.9	0.9	1.8

Counting method (CERN μ^+, μ^-, Combined)

Counting method (E821 FSD, PSD, Combined)

Traceback method :

- Better systematic control than counting methods.
- Statistically limited (partial coverage in the ring)

E821 : systematic uncertainties

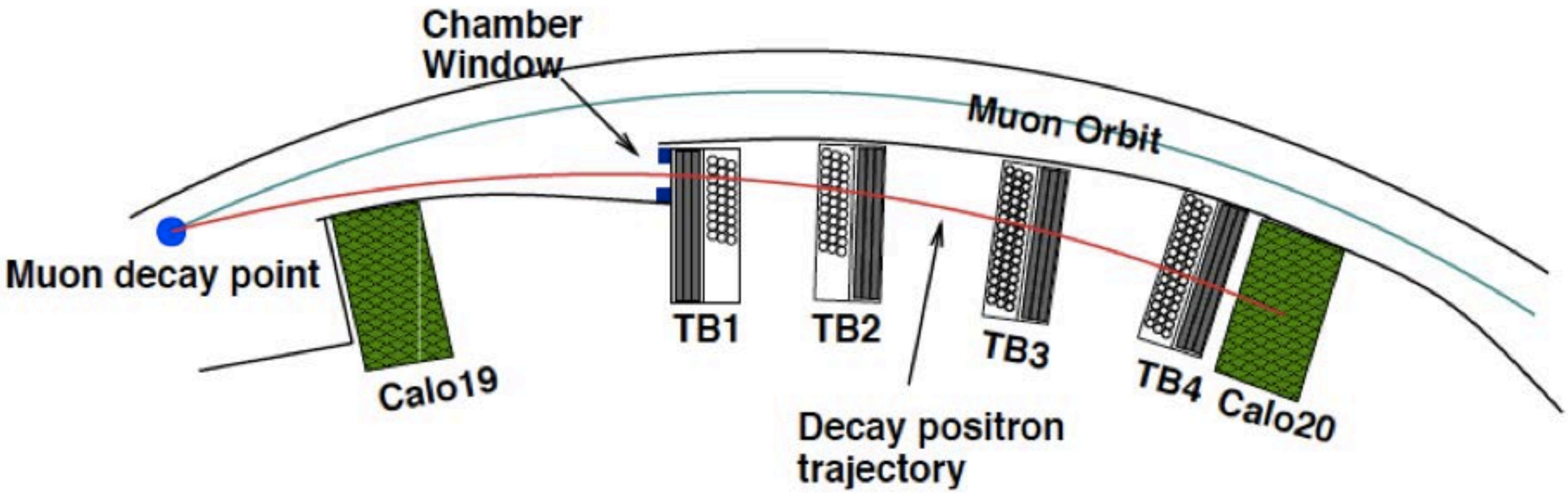


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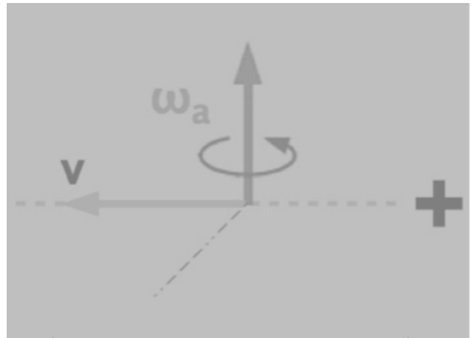
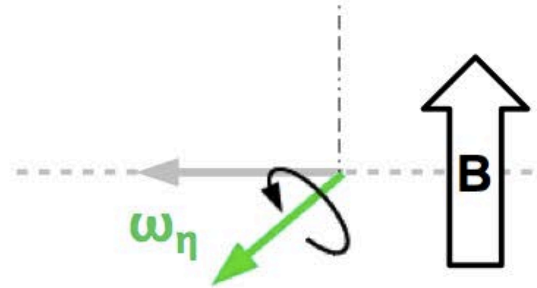
TABLE II. Table of systematic errors from the traceback analysis.

Systematic error	Vertical oscillation amplitude (μ rad lab)	Precession plane tilt (mrad)	False EDM generated 10^{-19} (e cm)
Radial field	0.13	0.04	0.045
Acceptance coupling	0.3	0.09	0.1
Horizontal CBO	0.3	0.09	0.1
No. oscillation phase fit	0.01	0.003	0.0034
Precession period	0.01	0.003	0.0034
Totals	0.44	0.13	0.14

Acceptance / CBO coupled with path length difference (incoming vs outgoing decay)

Future prospect: spin frozen technique





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

$= 0$

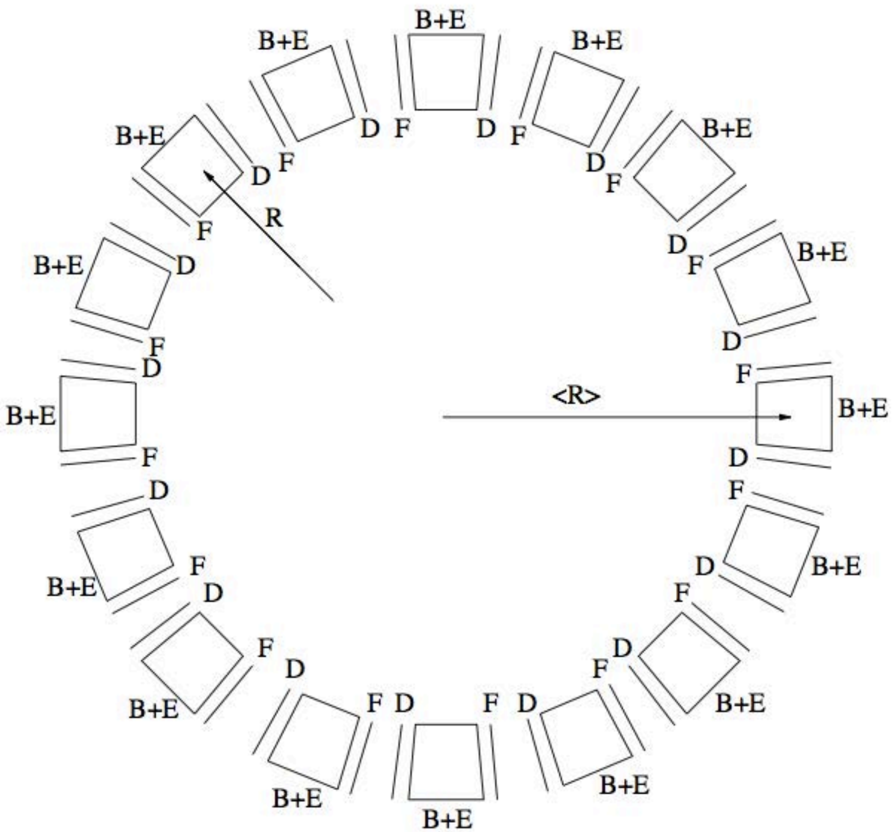
Apply radial E-field
to eliminate this term

$$E_r = \frac{a_\mu \beta c B}{1 - (1 + a_\mu)\beta^2}$$

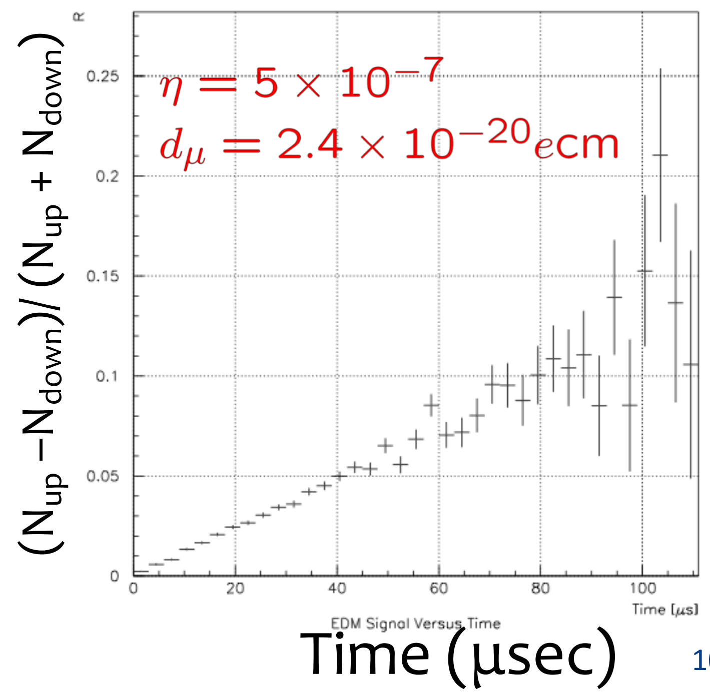
- Initially suggested by Yannis Semertizidis, PRL 93, 052001 (2004)
- Muon spin precesses solely by EDM (cf. pEDM experiment)
- Statistical sensitivity:

$$\sigma\left(d_\mu\right) = \frac{\hbar}{2c(\gamma\tau)(\beta B)A\sqrt{N}}$$

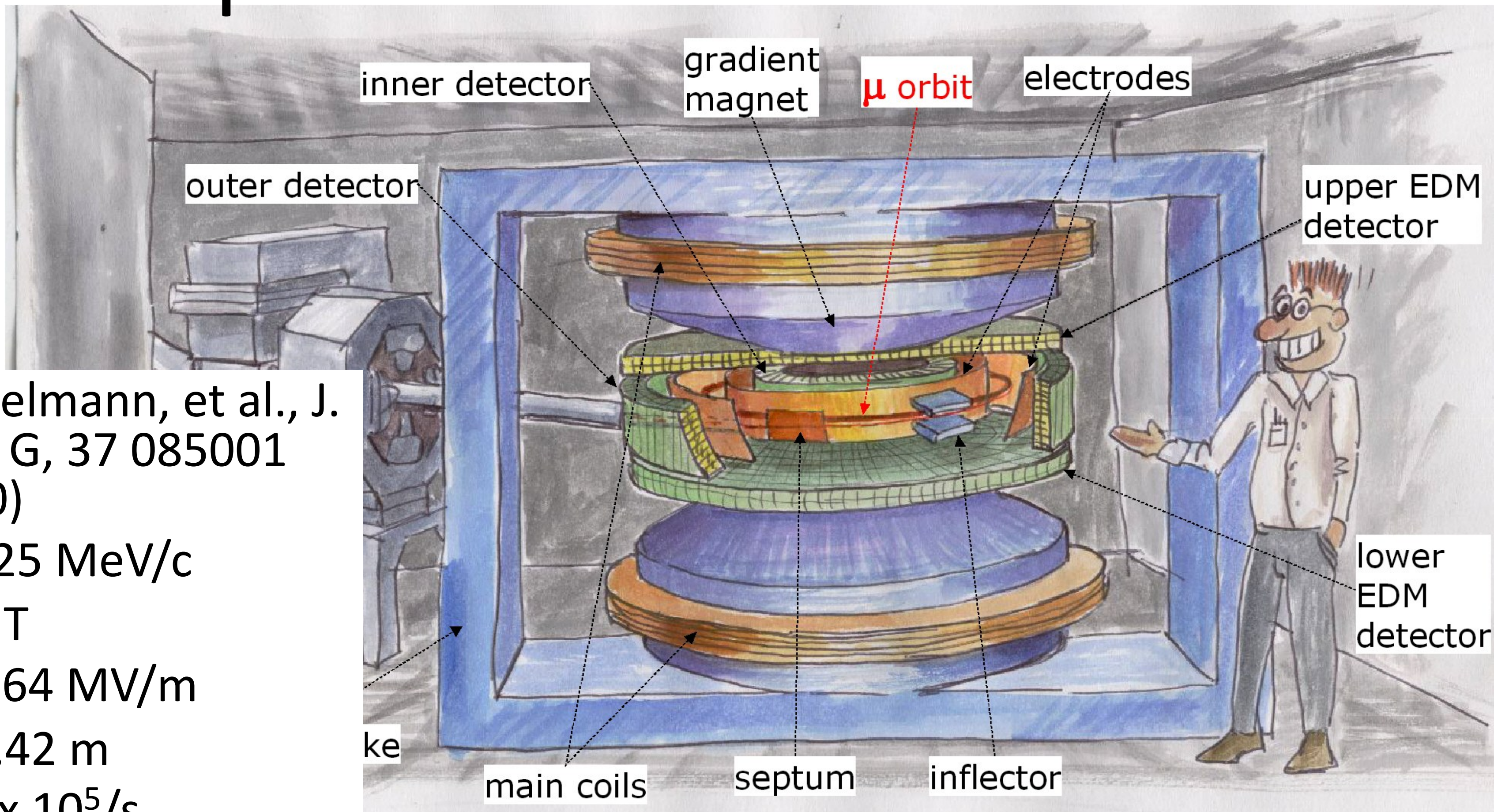
Spin-frozen EDM experiment at J-PARC



- J-PARC LOI 22, A. Silenko et al. (2003)
- B = 0.25 T
- E = 2 MV/m
- R = 7 m
- $NP^2 = 5 \times 10^{16}$ (assume PRISM FFAG)
- sensitivity $\sigma(d_\mu)$=8x10-^{25} ecm



Spin-frozen EDM at PSI



- A. Adelmann, et al., J. Phys. G, 37 085001 (2010)
- p = 125 MeV/c
- B = 1 T
- E = 0.64 MV/m
- R = 0.42 m
- $N = 2x\ 10^5/s$
- sensitivity $\sigma(d_\mu)=5x10\text{-}^{23}$ ecm / year

Summary

- Muon offers rich physics cases to study beyond the standard model in **quantum loops**.

- **BNL muon g-2 results**
  - More than 3σ deviation from the SM.

- **Fermilab muon g-2 experiment** is taking physics run.
- **J-PARC muon g-2/EDM experiment** is in preparation with completely different method.

- **Many new results will come in next 10 years.**