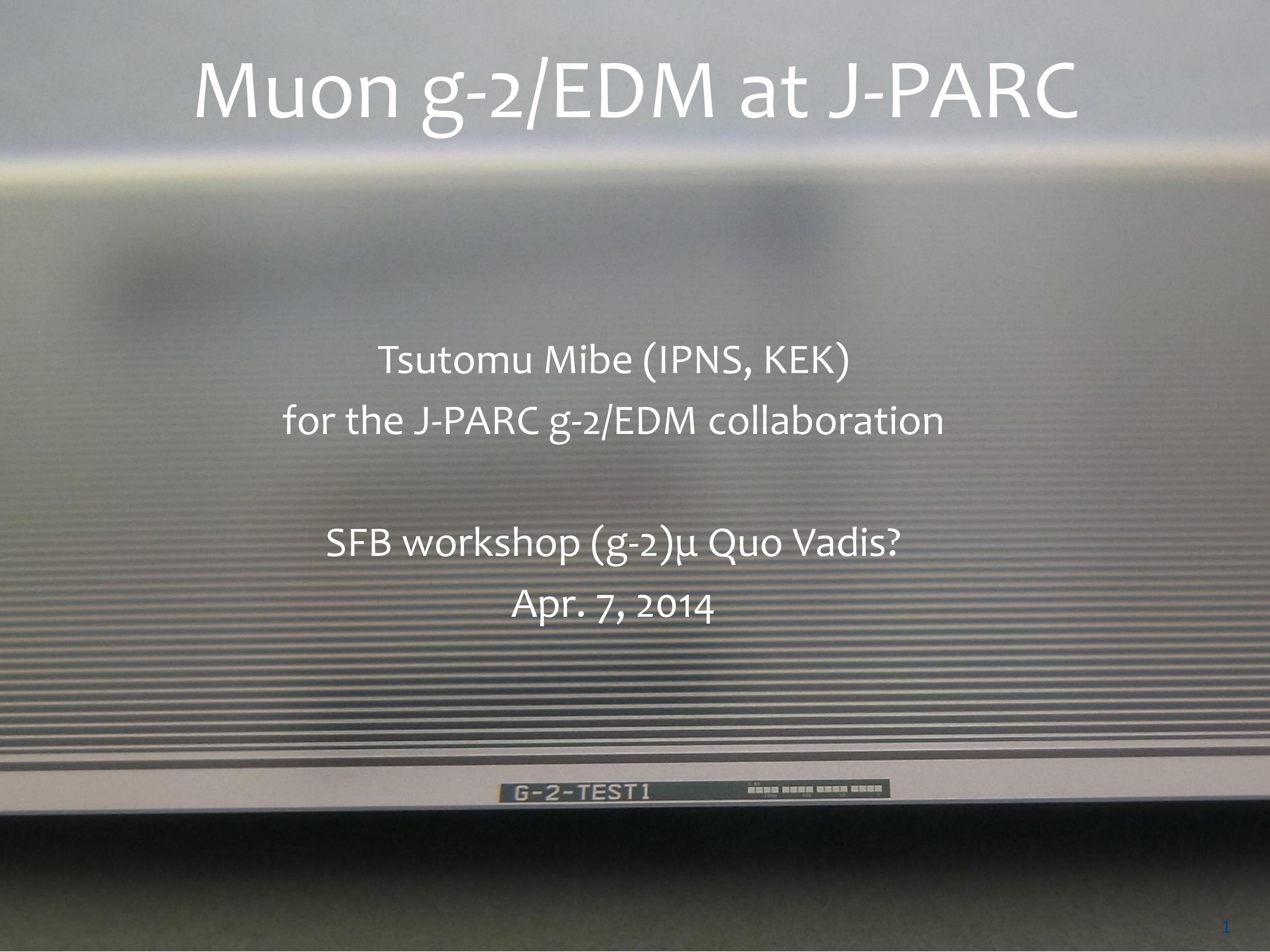
Muon g-2/EDM at J-PARC

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

SFB workshop (g-2)μ Quo Vadis?
Apr. 7, 2014



Muon physics gets public attentions in Japan

Recent news

- **FNAL muon g-2 ring "Big move", July 2013**

- **New electron EDM limits**
  - 10.6 x 10^{-28} ecm (90% CL) (UCL) New J. Phys 14, 103051 (2012)
  - 8.7 x 10^{-29} ecm (90%CL) (ACME) Science 343, 269 (2014)

- **MEG limit : 5.7 x 10^{-13} (90%CL)** PRL 110 (2013) 201801
  - Data taking completed summer 2013
  - To be upgraded for 10 times better sensitivity

- **J-PARC re-operation since Feb 2014**
  - Only for muon and neutron facilities for now
  - Beam power : 300kW (design 1MW)

- **COMET phase-I (mu-e conversion in Al at J-PARC)**
  - Single Event Sensitivity : 3.1 x 10^{-15}
  - Construction to be started in 2014

Lepton dipole moments

- Interactions with static B and E-fields:

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

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

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

Transition Dipole Moments

cLFV process with photon radiation (e.g. $\mu \rightarrow e\gamma$)

muon g-2/EDM measurements

Anomalous magnetic moment (g-2)

$a_\mu = (g-2)/2 \quad = 11\,659\,208.9\,(6.3) \times 10^{-10}$ (BNL E821 exp) **0.5 ppm**

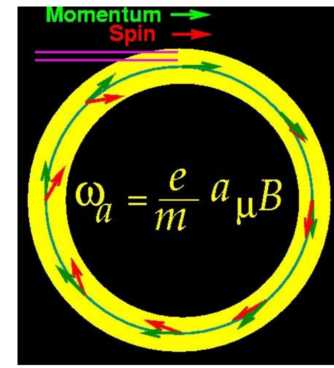
$\qquad\qquad 11\,659\,182.8\,(4.9) \times 10^{-10}$ (standard model)

$\Delta a_\mu =$ Exp - SM = $26.1\,(8.0) \times 10^{-10}$ **3σ anomaly**

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)

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

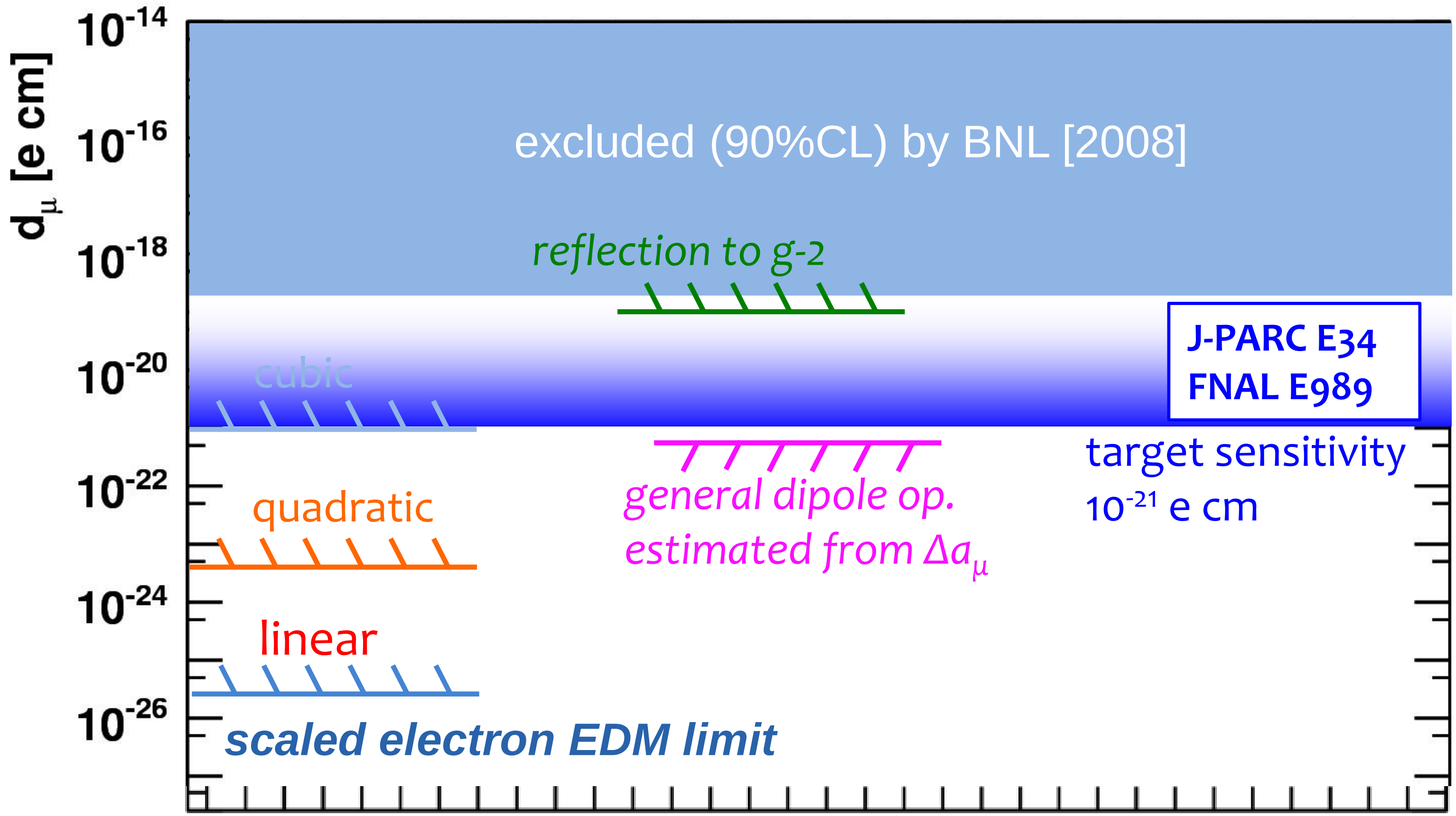
Continuation at FNAL with 0.1ppm precision (E989)

J-PARC approach
E = 0 at any γ

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

Proposed at J-PARC with 0.1ppm precision (E34)

muon EDM experimental reach



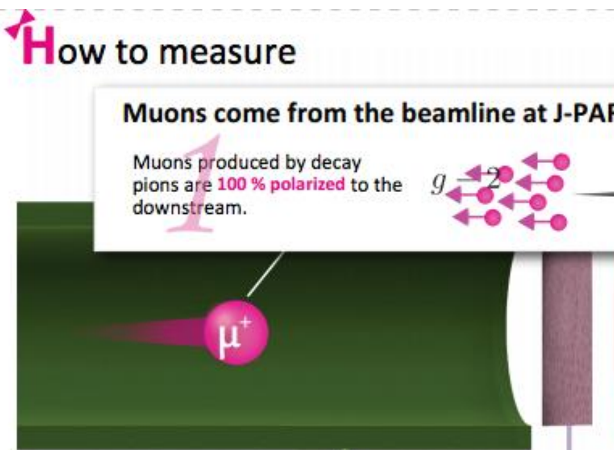
Standard model < 10^{-36} ecm

Main motivation driven by g-2 anomaly (from BNL E821).
→ The g-2 anomaly should be checked as well as EDM search

Muonium HFS and μ_μ/μ_p ratio

* Future g-2 experiments (~0.1ppm) require more precise determination of magnetic moment ratio μ_μ/μ_p (current uncertainty : 0.12ppm)

$$a_\mu = \frac{R}{\lambda -}$$

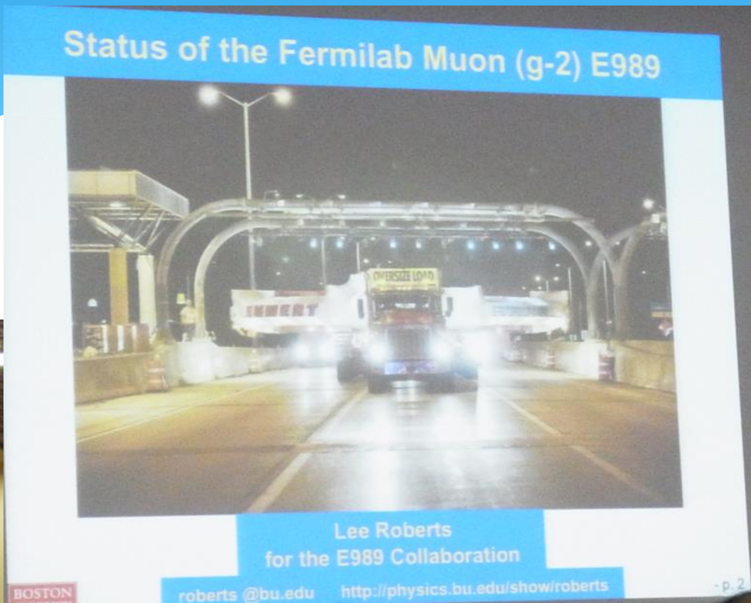


Picture by K. Tanaka

An improved measurement of Mu-HFS and μ_μ/μ_p is in preparation at J-PARC (KEK IMSS K. Shimomura et al.)

BNL effort continues at FNAL…

Matsue, Japan   August 9 (2013)



Our ring has transported to FNAL!

The Future: Fermilab E989 Goal:

$$\delta a_\mu \leq \pm 16 \times 10^{-11} \; (.14 \text{ ppm})$$

1.8 $\times$ 10^{11} detected high energy decays

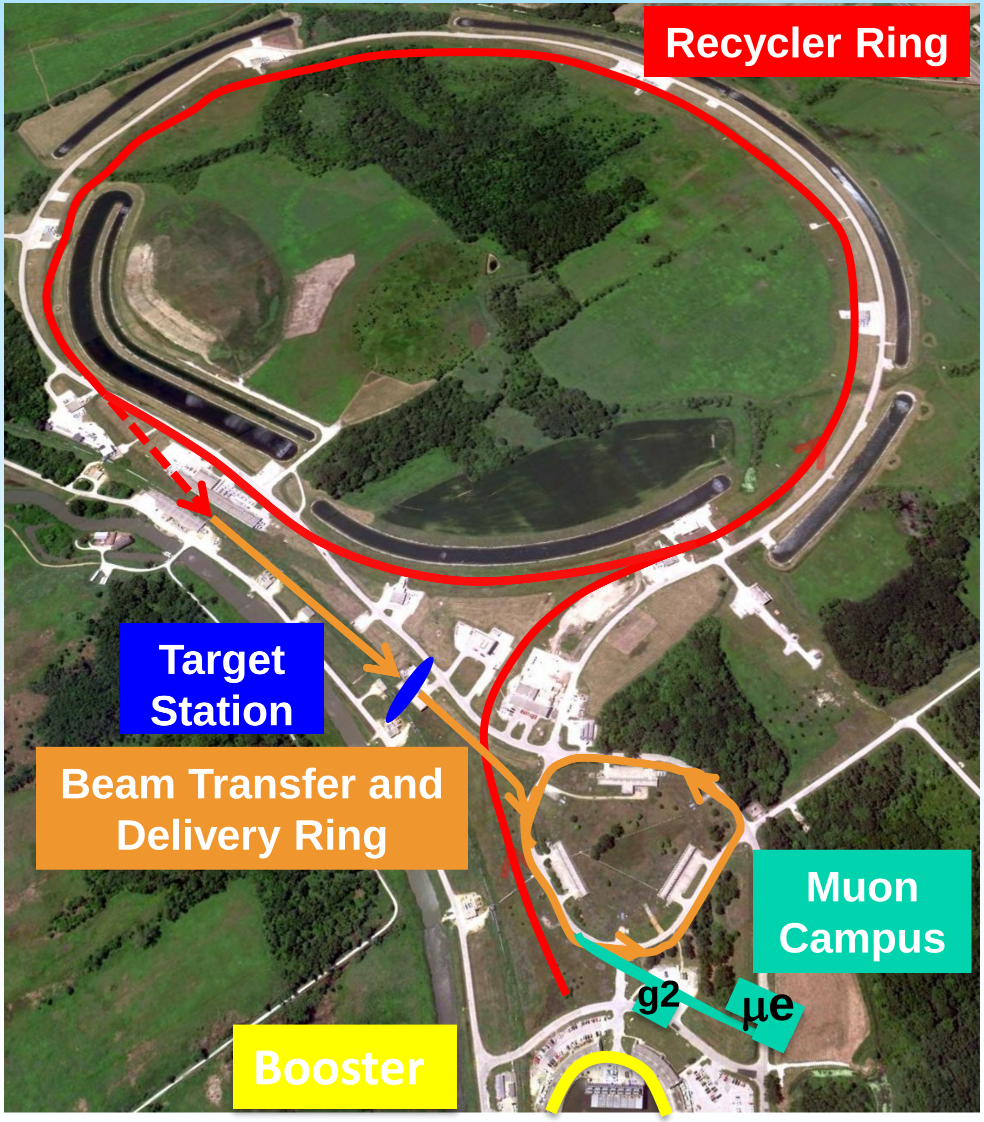
systematic errors ω_a, ω_p $\pm$0.07 ppm each

Slide by Lee Roberts (USM2013)

Fermilab Muon Campus

Multipurpose Building designed for future experiments as well

Fermilab Muon Beam



One 4×10^{12} p bunch to recycler

Re-bunch to 4 bunches

Extract one bunch at a time to target

Use the delivery ring as a >1,900 m decay line

Slide by Lee Roberts (USM2013)

Schedule

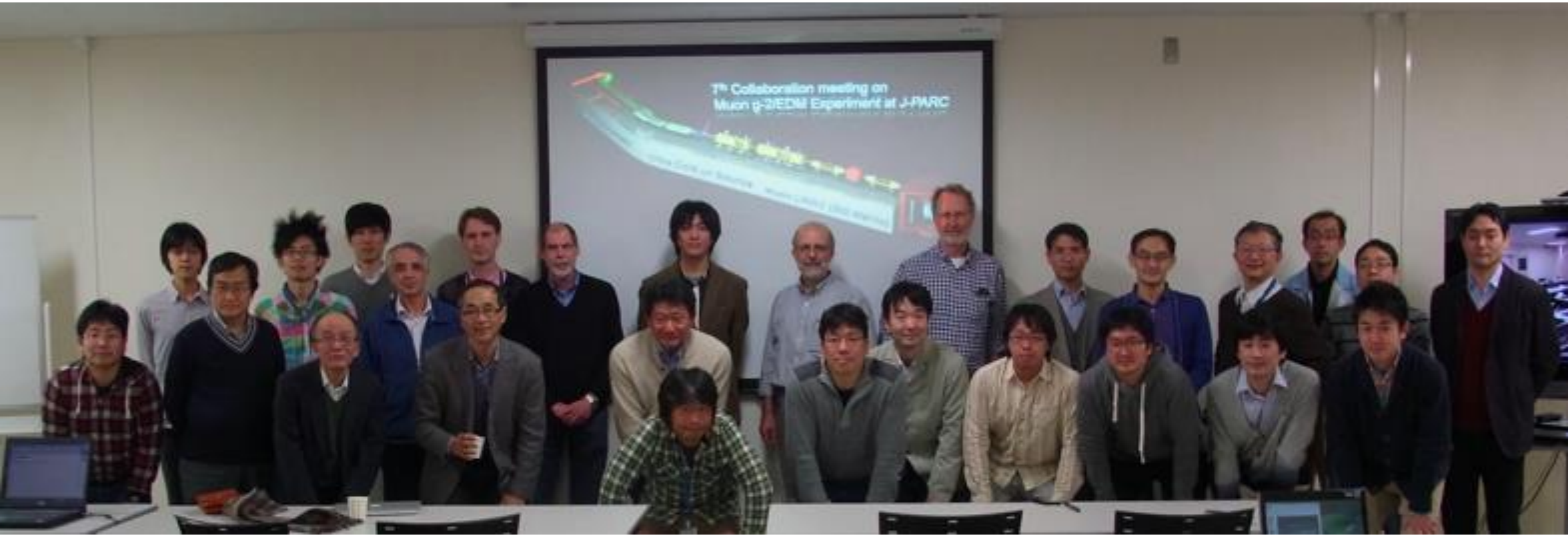
- Coils at Fermilab – half the steel is there
- Building under construction
  - beneficial occupancy February 2013
- g-2 is the only new start this year in OHEP
- Magnet powered 2015
- Beam in 2016 or 2017 depending on funding profile

24.4×24.4 m^2 high bay
84 cm thick floor
$\Delta T = \pm 1^{O}$ C

BOSTON UNIVERSITY

The J-PARC g-2/EDM

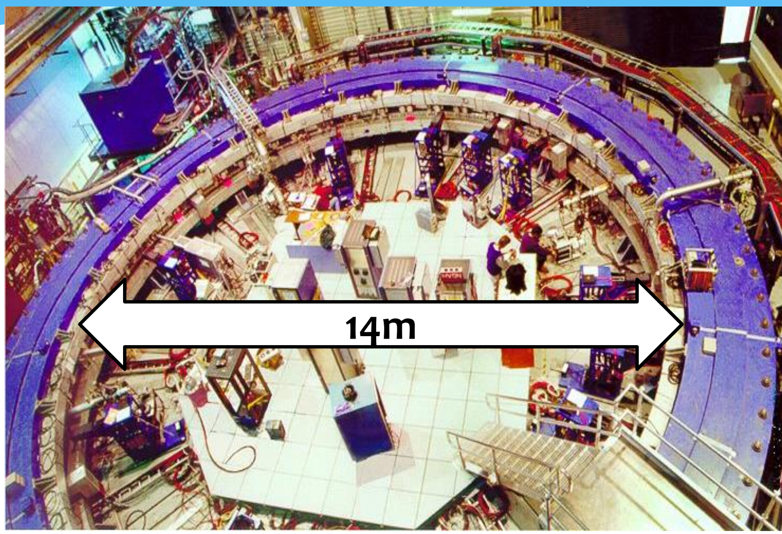
- 92 members (…still evolving)
- 28 Institutions: KEK, RIKEN, U-Tokyo, TRIUMF, BNL, PMCU, CYCRC-Tohoku, Osaka, Rikkyo, TITech, SUNYSB, RAL, UCR, UNM, Victoria, Kyushu, Korea-U, Seoul Nat'l U
- 8 countries: Czech, USA, Russia, Japan, UK, Canada, France, Korea



Dec 2009 : Proposal submitted
Dec 2012 : CDR submitted
Jan 2013 : Stage-1 status granted from PAC (IMSS,IPNS)
P34 →E34

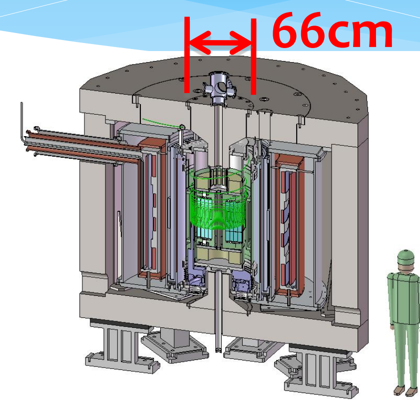
A compact muon g-2/EDM experiment

BNL E821 / FNAL



P= 3.1 GeV/c , B=1.45 T

J-PARC



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
  - **<u>Completely different systematics than the BNL E821 or FNAL</u>**

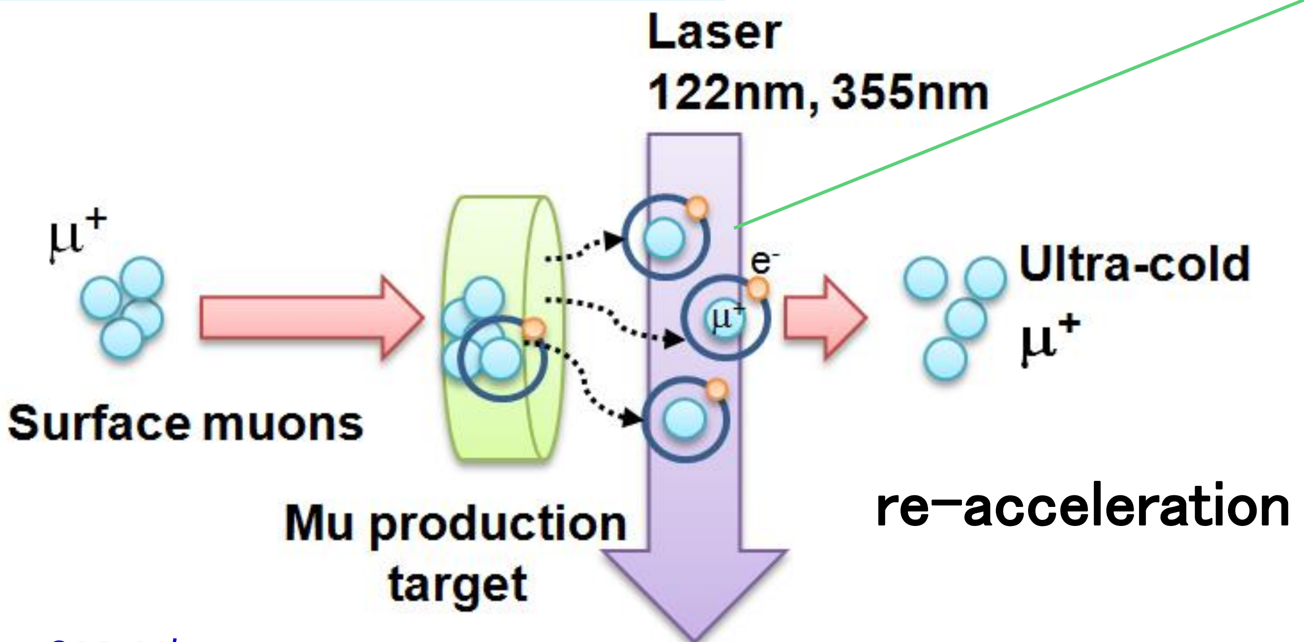
Ultra-cold Muon

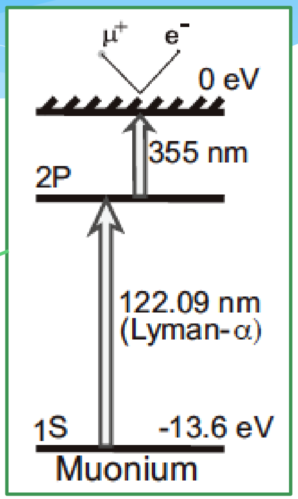
<u>Requirement for zero E-field:</u>

Muons should be kept stored without E-focusing

→ Beam with ultra-small transverse dispersion, i.e. $\Delta p_T/p \sim 0$

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





p = 28MeV/c

3 keV/c

300 MeV/c

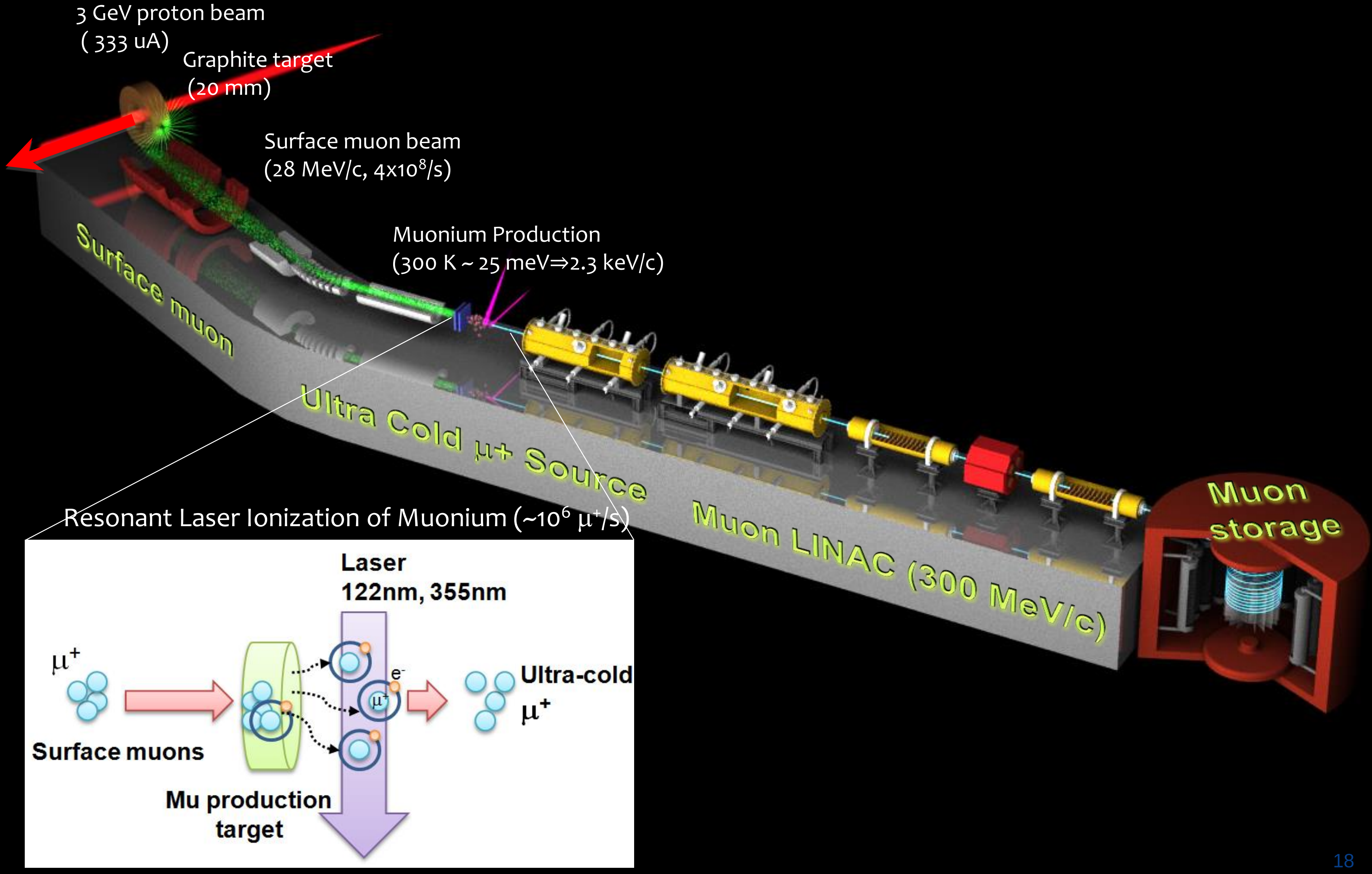
$\Delta p_T/p \sim$3 keV / 300 MeV =1E-5

Comparison of experiments

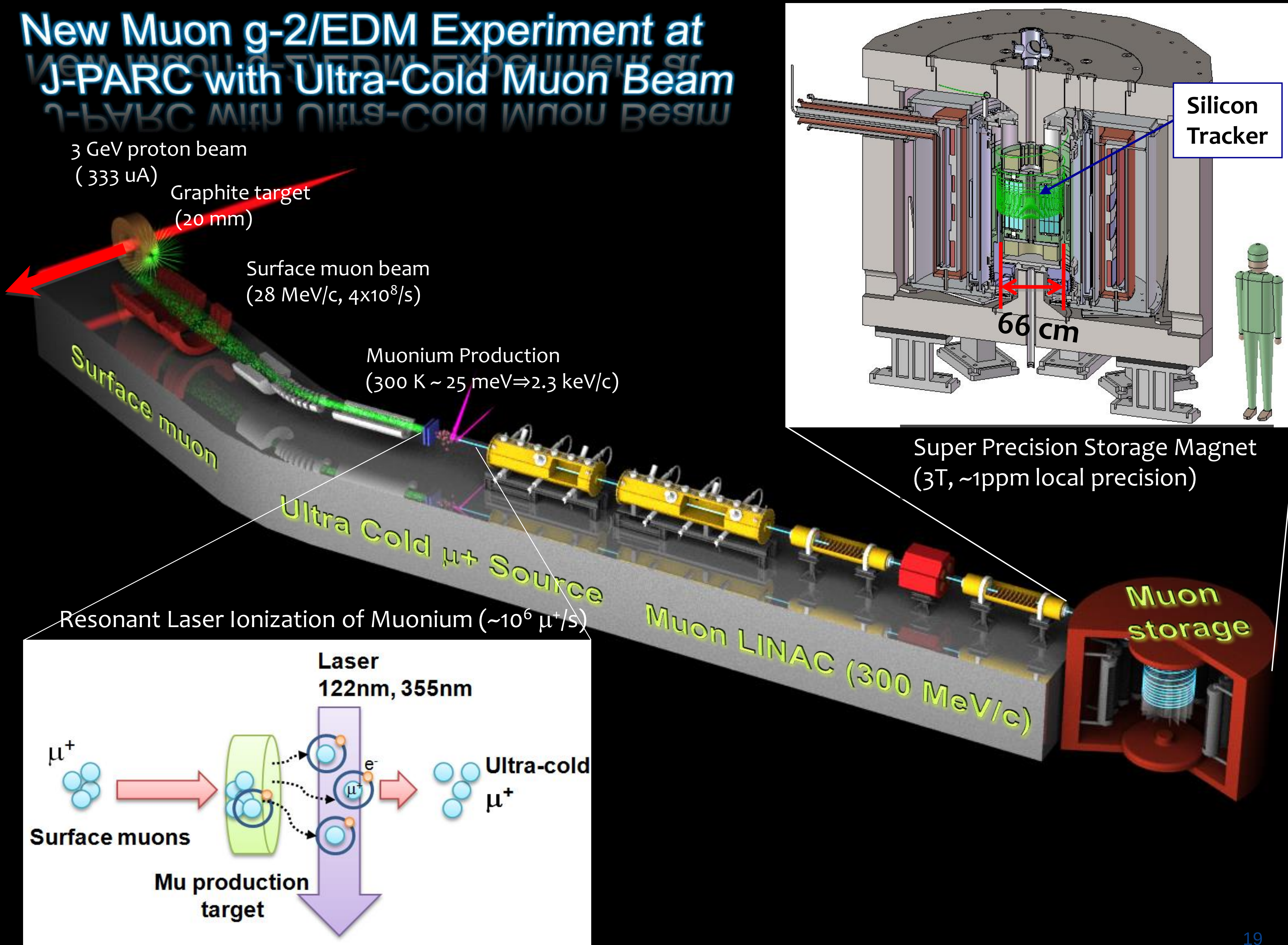
	BNL-E821	Fermilab	J-PARC
Muon momentum	3.09 GeV/c		0.3 GeV/c
gamma	29.3		3
Storage field	B=1.45 T		3.0 T
Focusing field	Electric quad		Very weak magnetic
# of detected μ+ decays	5.0E9	1.8E11	1.5E12
# of detected μ- decays	3.6E9	-	-
Precision (stat)	0.46 ppm	0.1 ppm	0.1 ppm

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

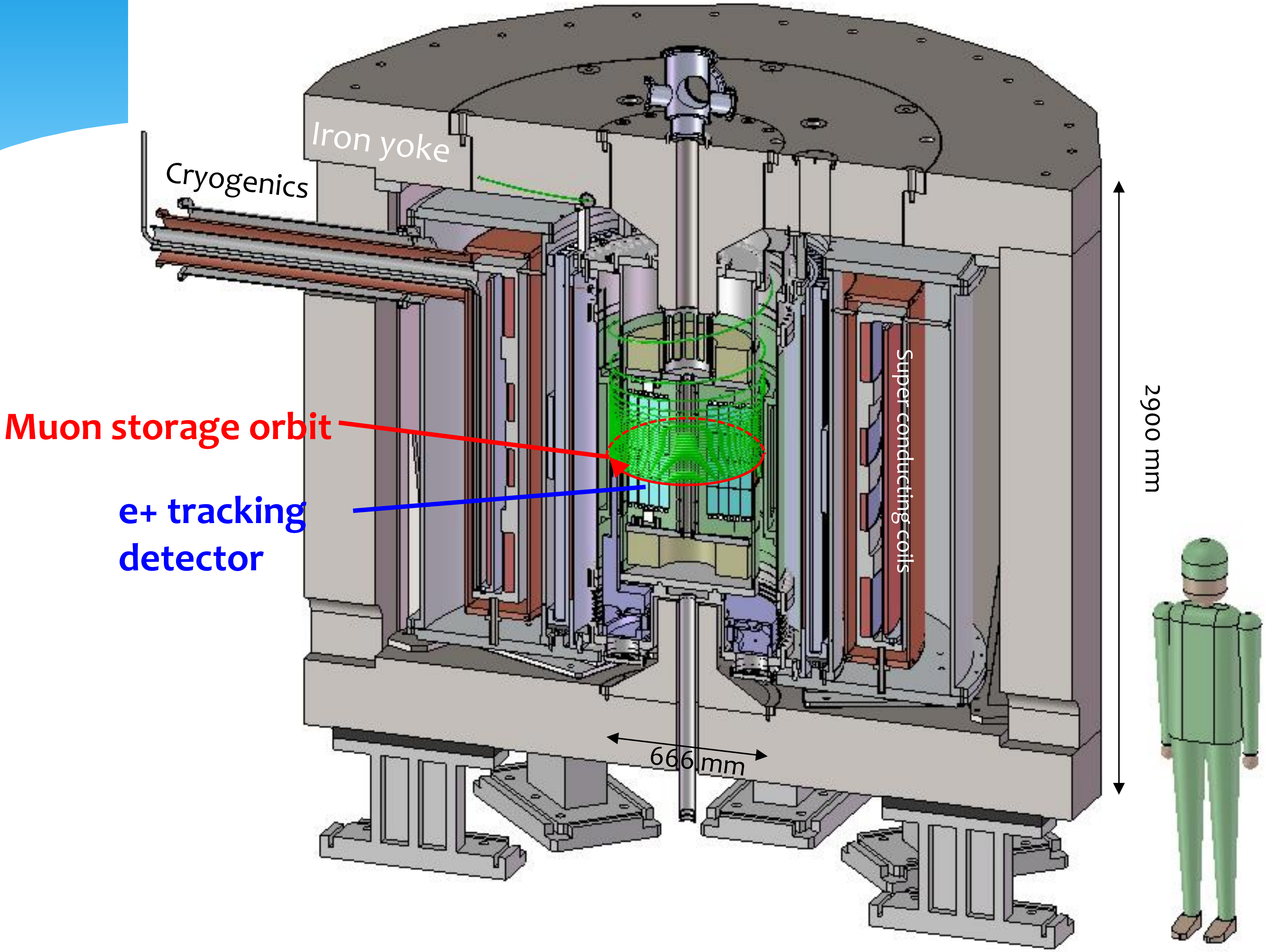
New Muon g-2/EDM Experiment at J-PARC with Ultra-Cold Muon Beam



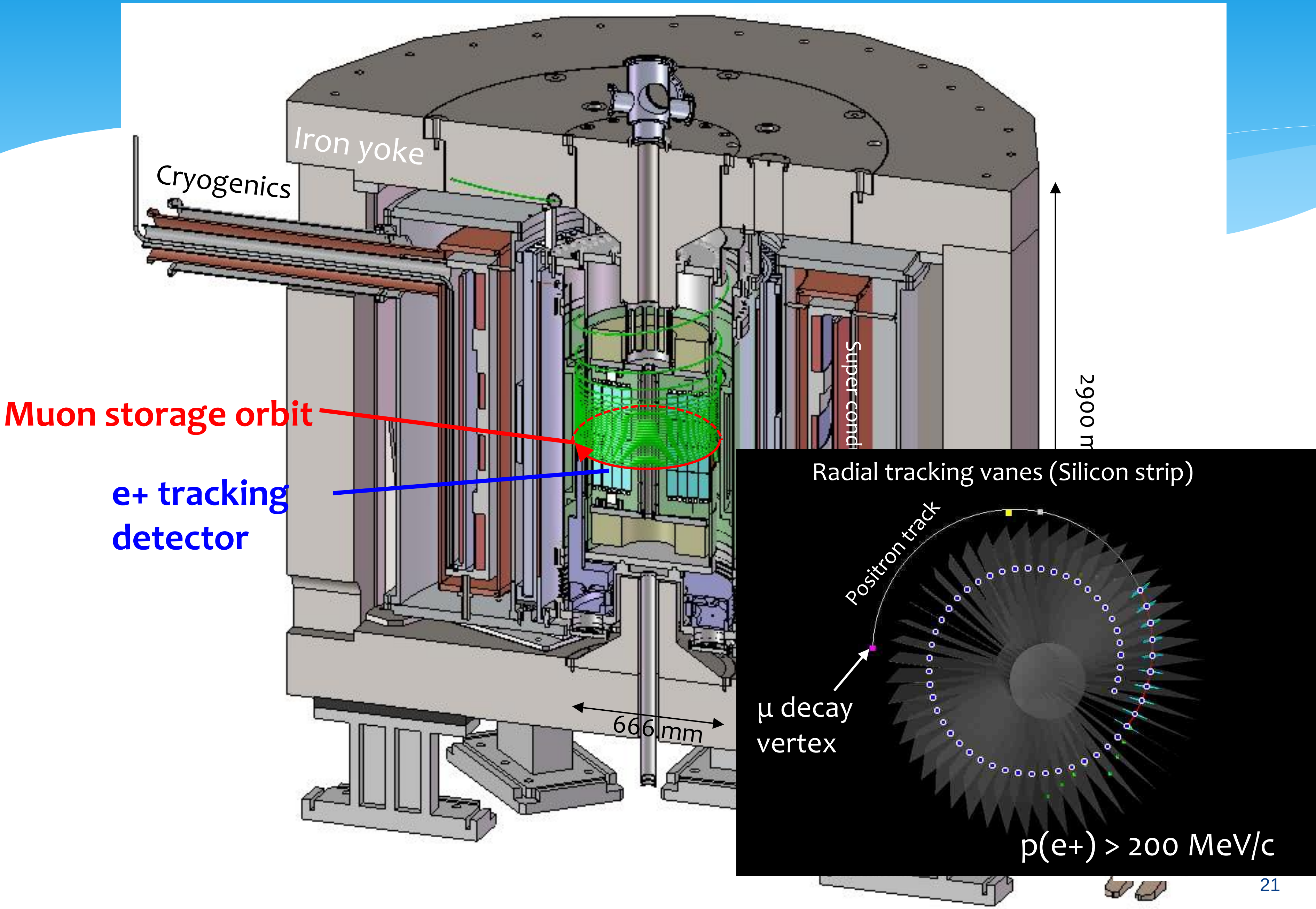
New Muon g-2/EDM Experiment at J-PARC with Ultra-Cold Muon Beam



Muon storage magnet and detector



Muon storage magnet and detector

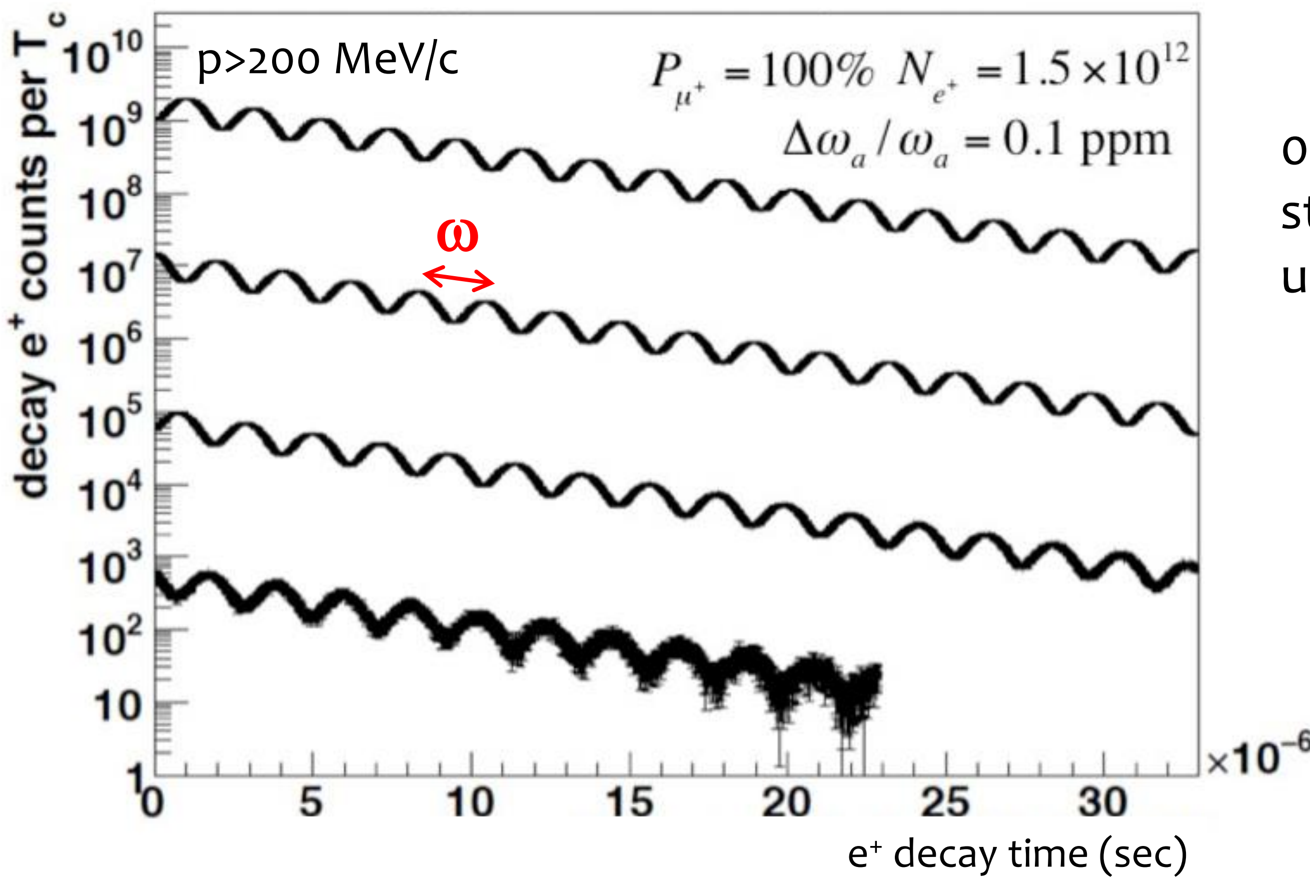


Expected time spectrum of $\mu \rightarrow e^+ \nu \bar{\nu}$ decay

Muon spin precesses with time.

→ number of high energy e⁺ changes with time by the frequency :

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

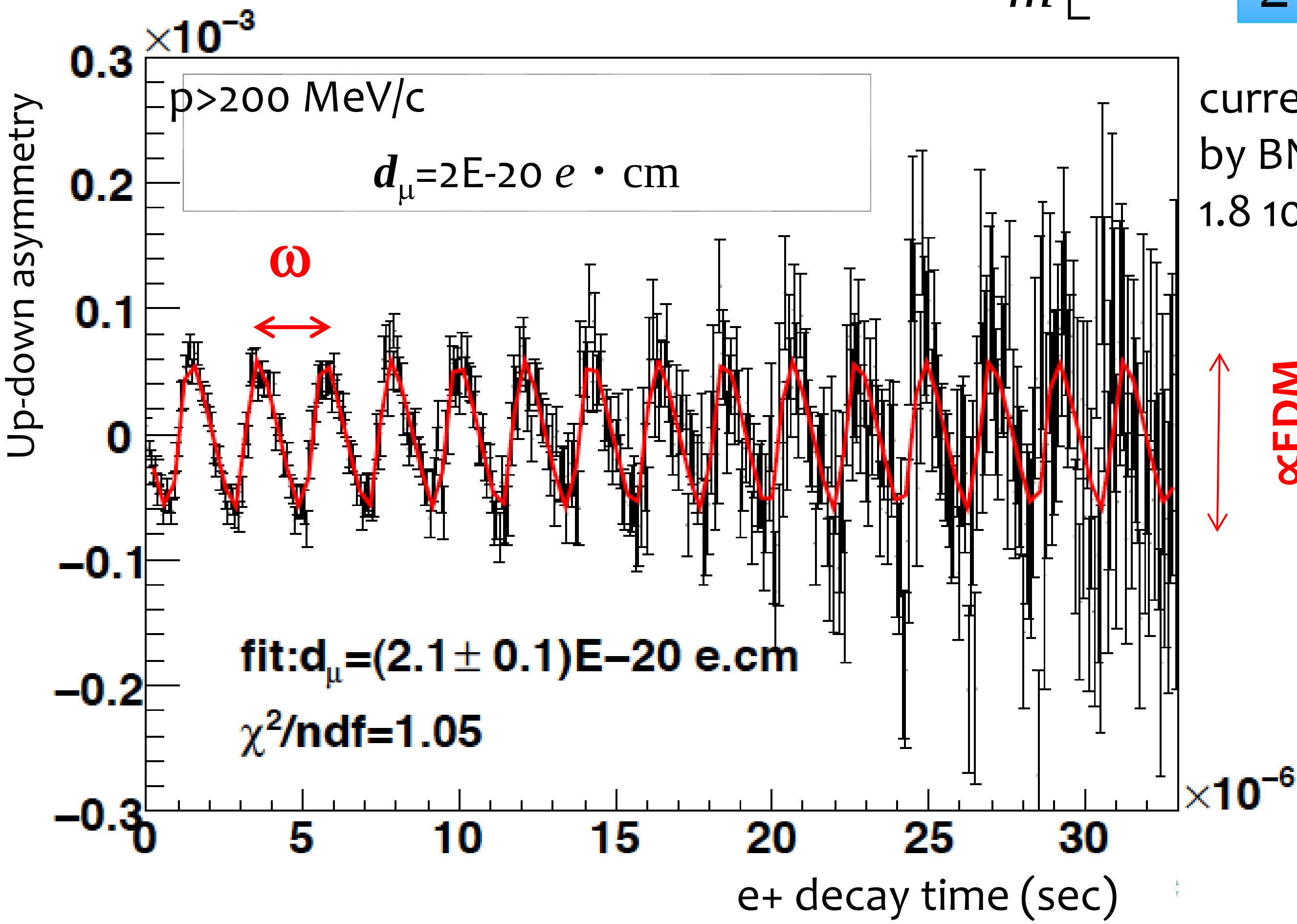


0.1ppm statistical uncertainty

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

EDM tilts the precession axis.
→ This yields an up-down decay asymmetry in number of e+
(oscillates with the same frequency ω)

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



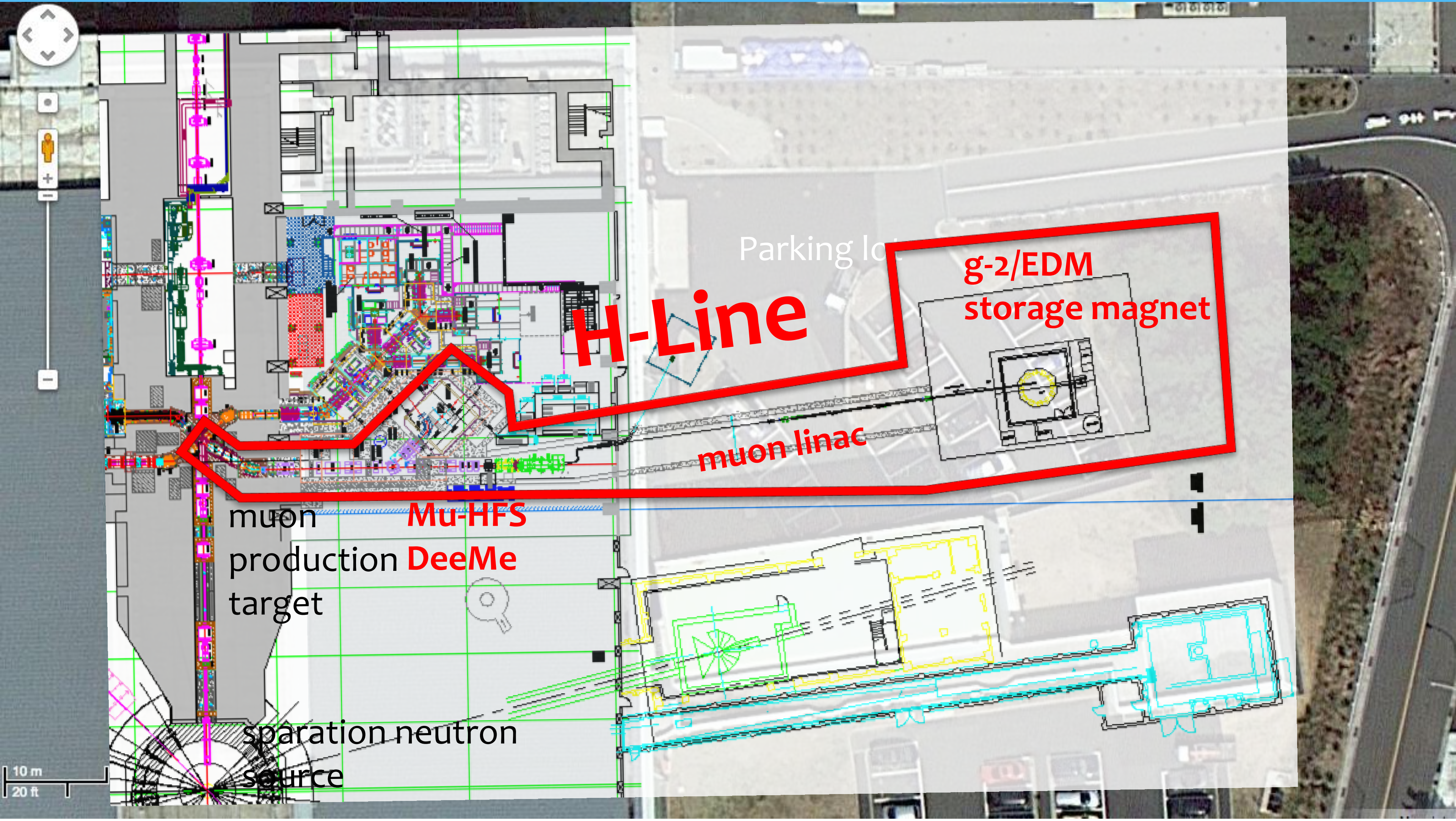
current upper limit by BNL E821
1.8 10^{-19} e · cm

Milestones (shown at PAC13)

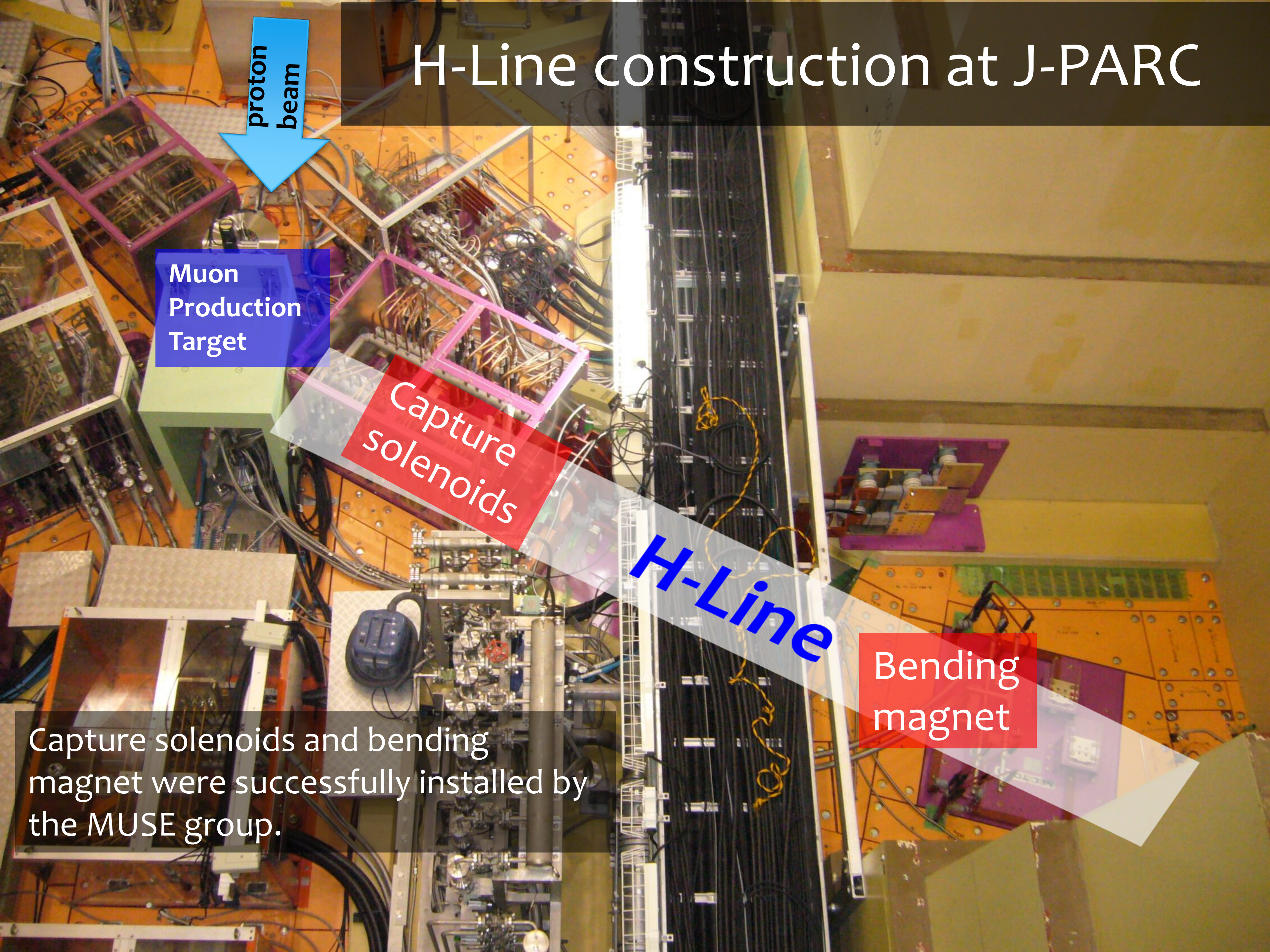
- Demonstration of UCM Production
- Muon acceleration test
- Prototyping Precision Magnet
- Demonstration of injection and Kicker
- Demonstration of high-rate tracker

Proposed experimental site

Material and Life science Facility

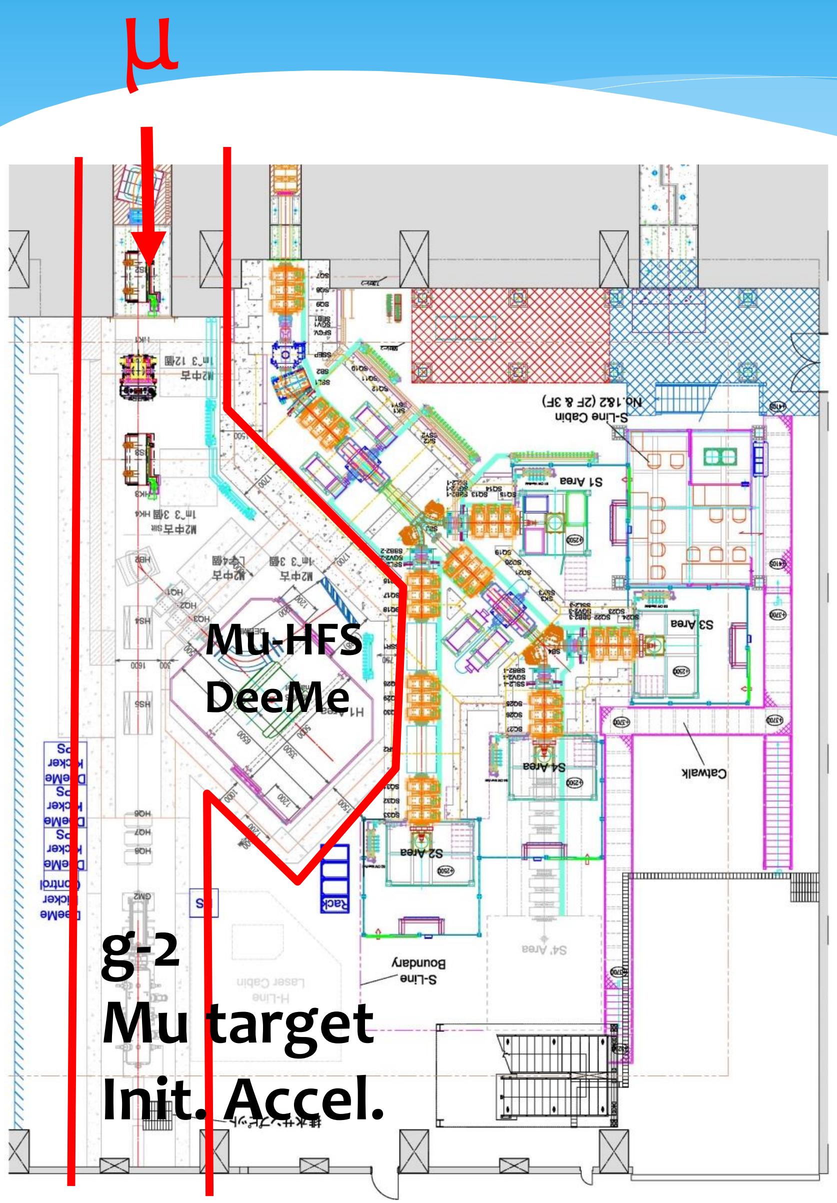


H-Line construction at J-PARC



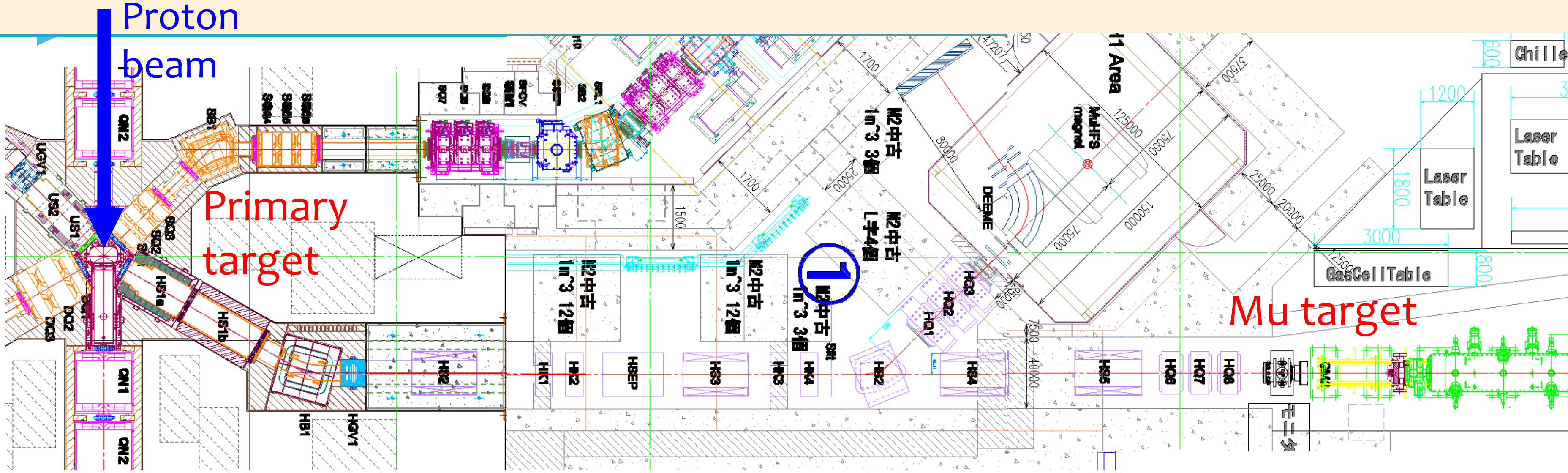
Capture solenoids and bending magnet were successfully installed by the MUSE group.

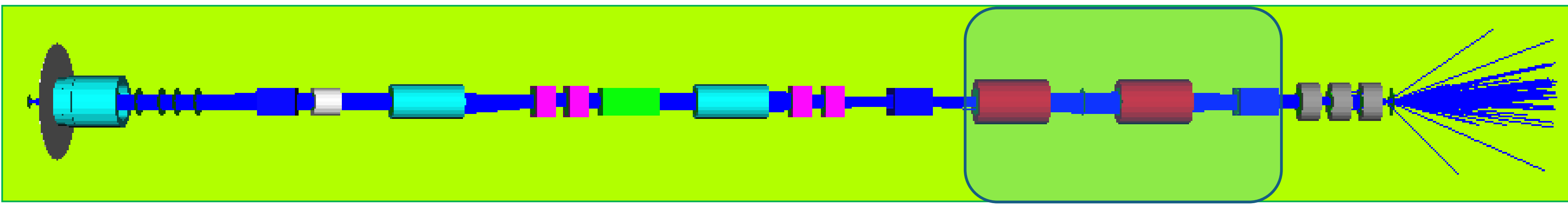
H-line in the MLF experimental hall



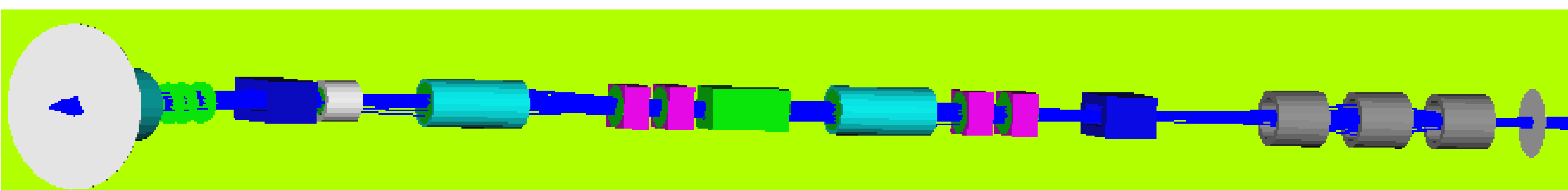
Slide by M. Yoshida

H-line beam tracking simulation





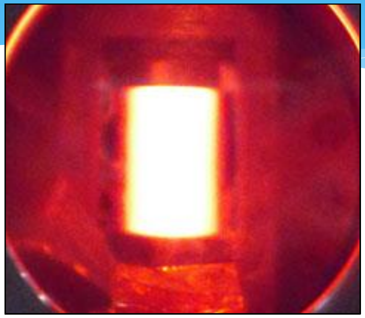
Primary target, radiation shield, superconducting solenoid, bending magnet, kickers, separator, transport solenoids, triplet



final focusing point

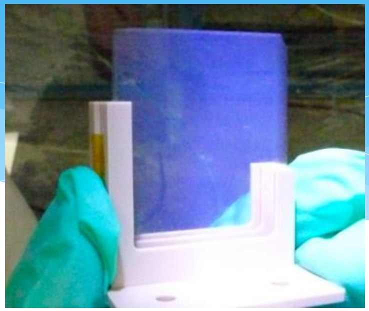
Materials for muonium production in vacuum

Heated tungsten



* T=2000K (E=0.2 eV)
* Used in previous experiments (KEK-MSL, RIKEN-RAL)
* Re-evaluation in progress at J-PARC
* Expected yield at H-line
  * Production rate : 1%
  * Ultra slow muon: 0.12 x 10^6/sec

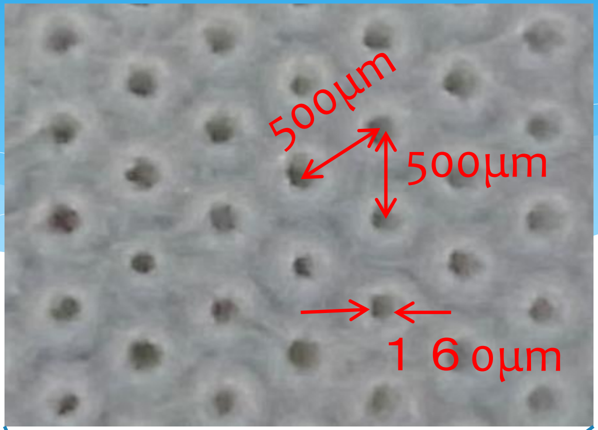
Silica aerogel

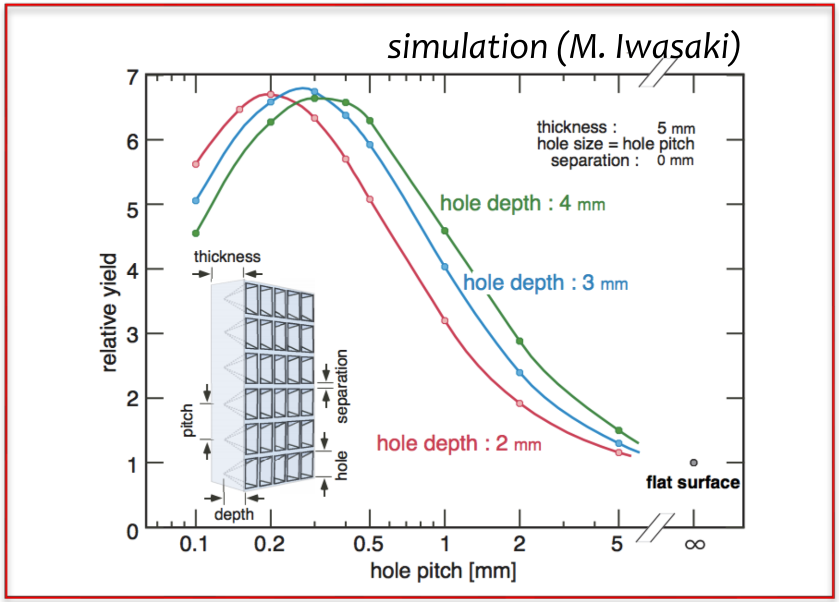


* T = 300K (E=0.03eV)
* Not yet used for ultra-slow muon production
* Initial evaluation at TRIUMF
  * Prog. Theor. Exp. Phys. (2013) 103C01
* Expected yield at H-line (as of 2013)
  * **Production rate : 0.1%**
  * Ultra slow muon: 0.02 x 10^6 /sec

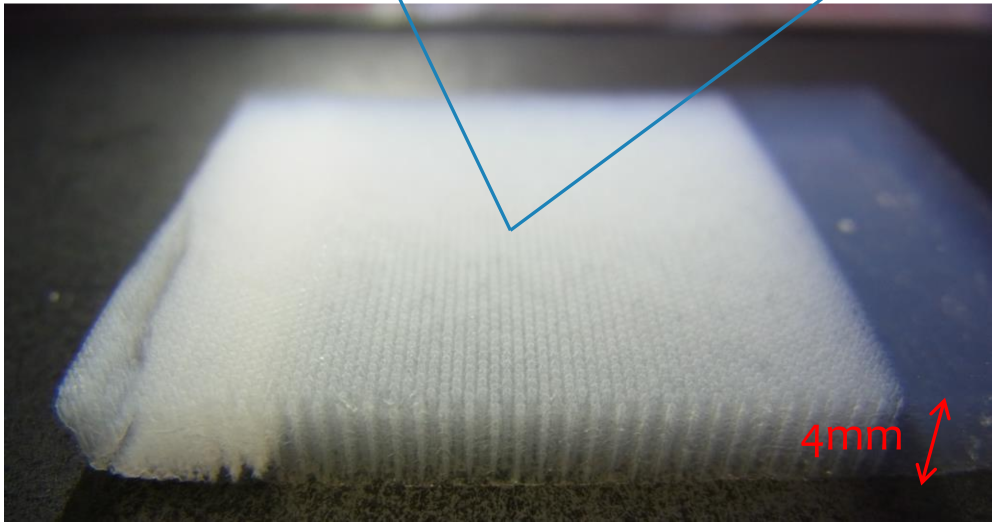
Aerogel with sub-mm structure

- Effective diffusion depth for muonium emission into vacuum ~ 100μm
- New aerogel samples with holes were developed.
- Simulation with experimental inputs suggests a factor of 5~7 enhancement with sub-structures





Silica aerogel with holes (laser ablation)

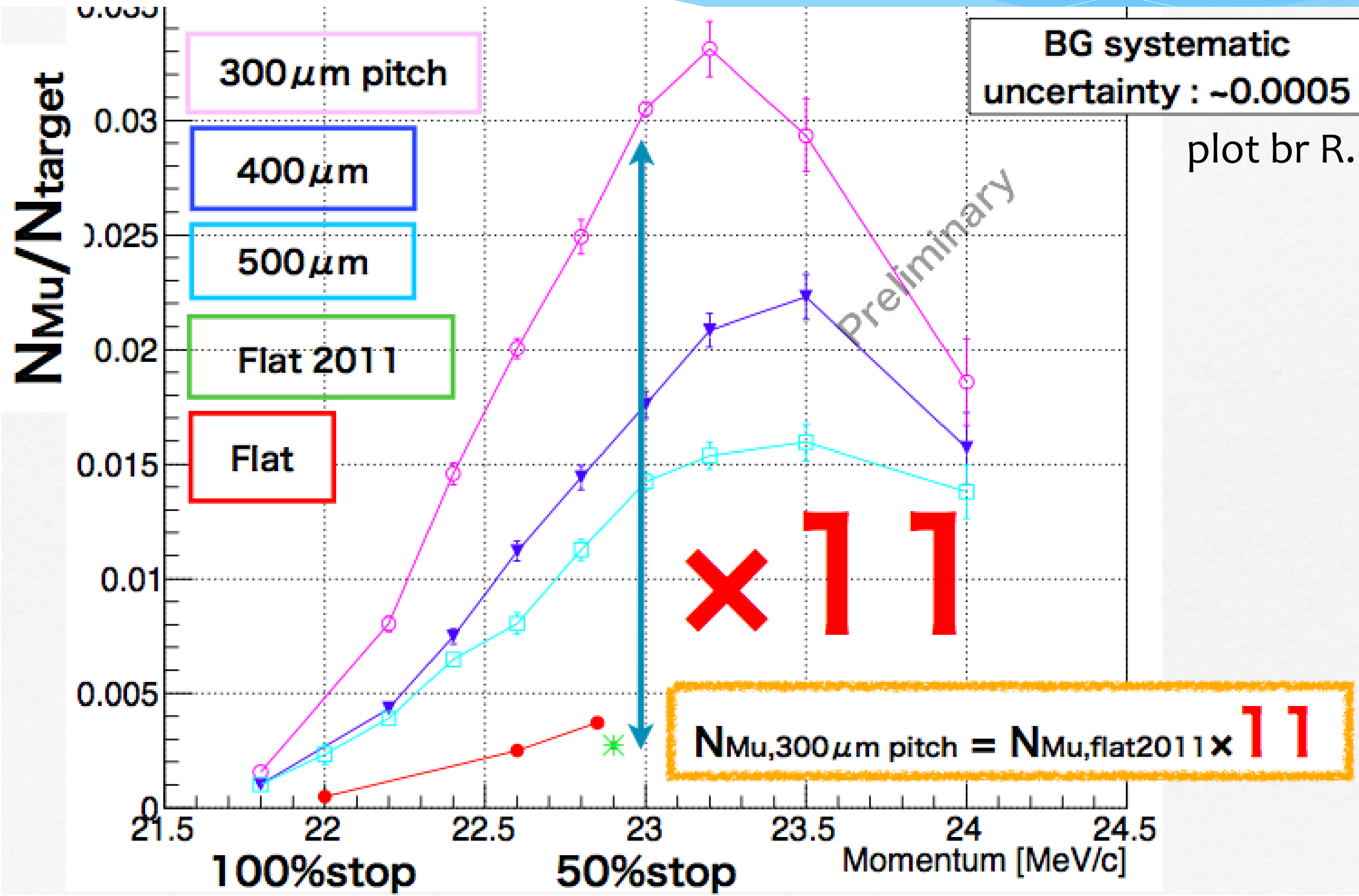


Prepared by M. Tabata (Chiba) and Y. Oishi (RIKEN)

Evaluated at TRIUMF from Oct 8-22, 2013

TRIUMF data on Mu production

A factor of 11 increase of Mu production yield with substructure



plot br R. Kitamura

Implication to statistical sensitivity

- With drilled aerogel target, one expects
  - Ultra-cold muon rate : 0.2E+6/sec (*)
  - Running time : 1E+7 sec (120 day)

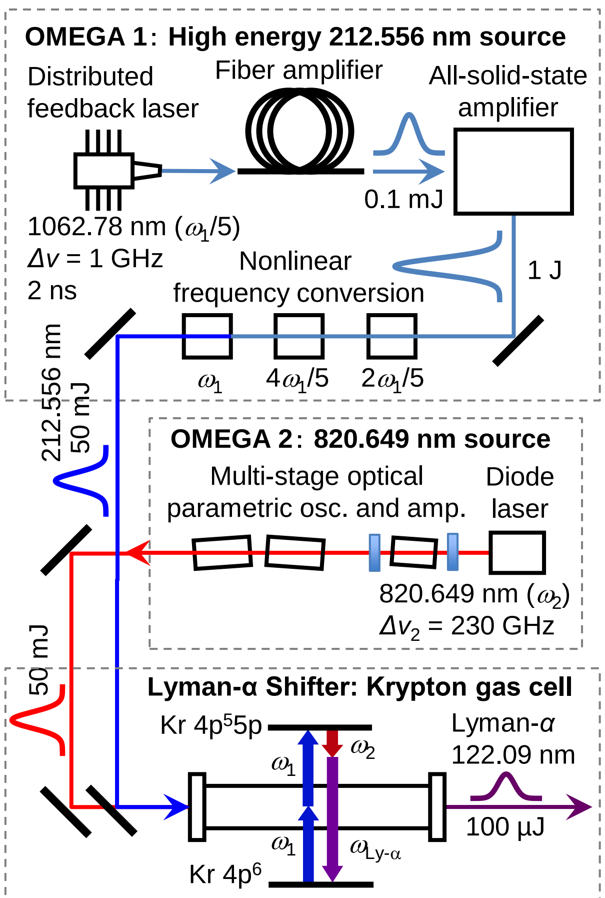
	polarization 100 %	50%
Statistical uncertainty on ω_a:	0.22ppm	(0.44ppm)
Statistical uncertainty on d_μ:	4.4E-21 ecm	(8.8E-21 ecm)

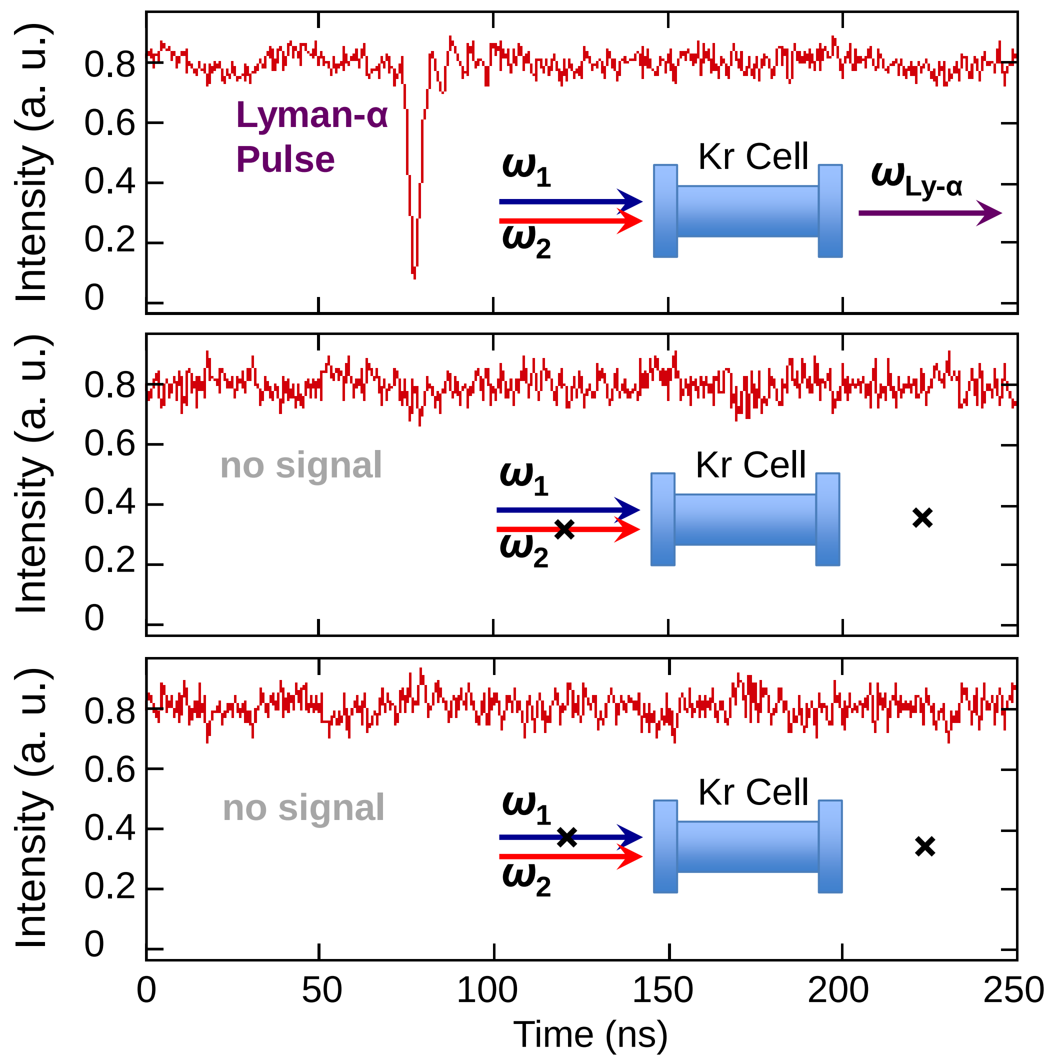
Good enough to test BNL E821 g-2 results

* factor of two more muons with SiC target is not included.

Current Status of Coherent Lyman α

Coherent Lyman-α Resonance Radiation Source





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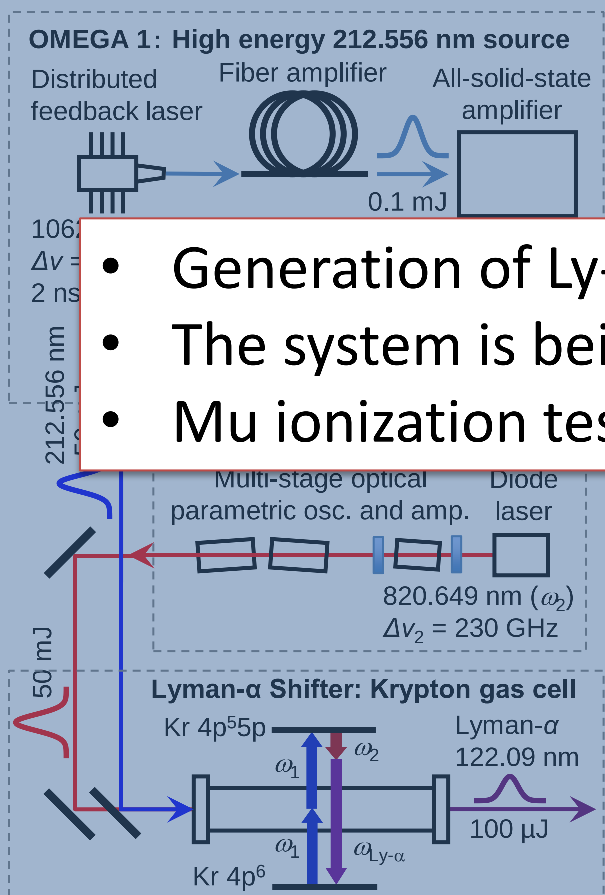
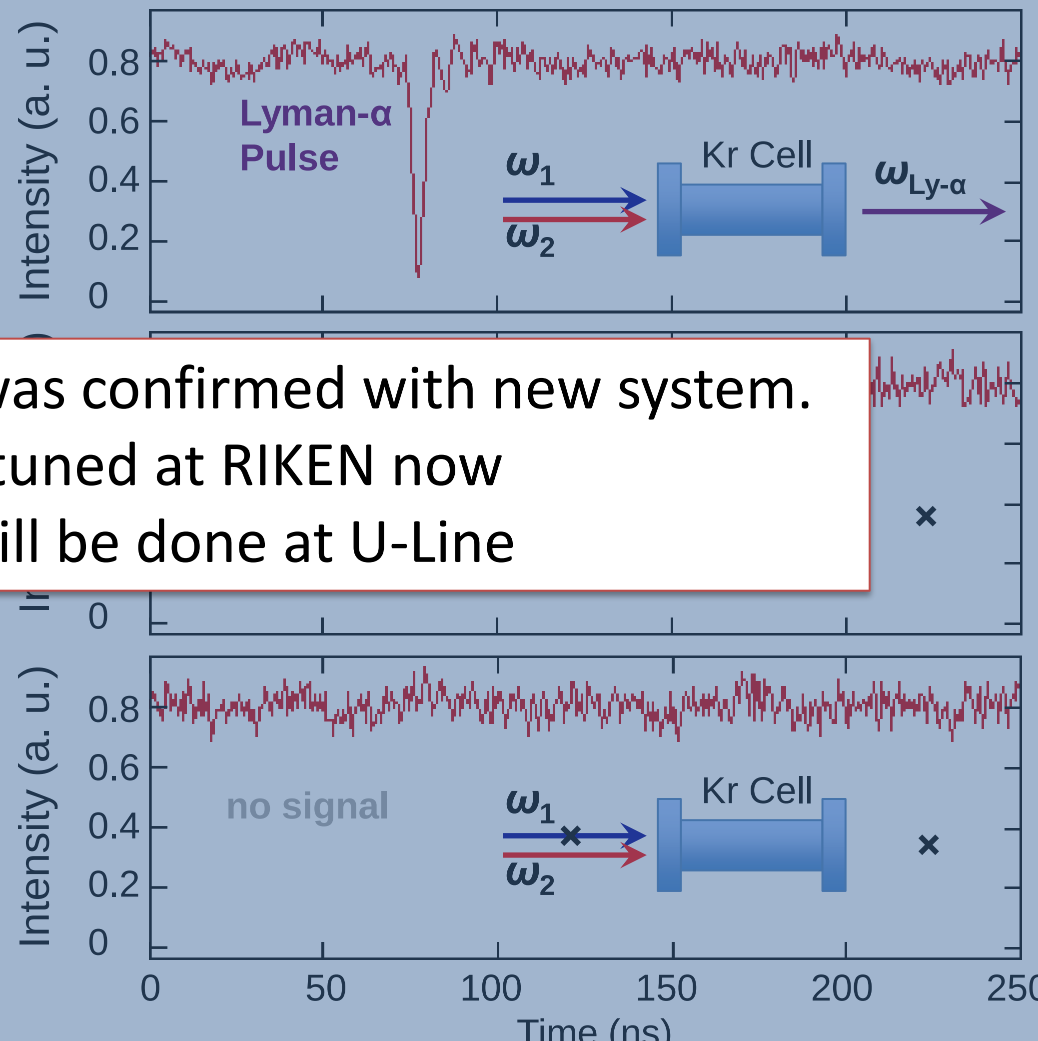
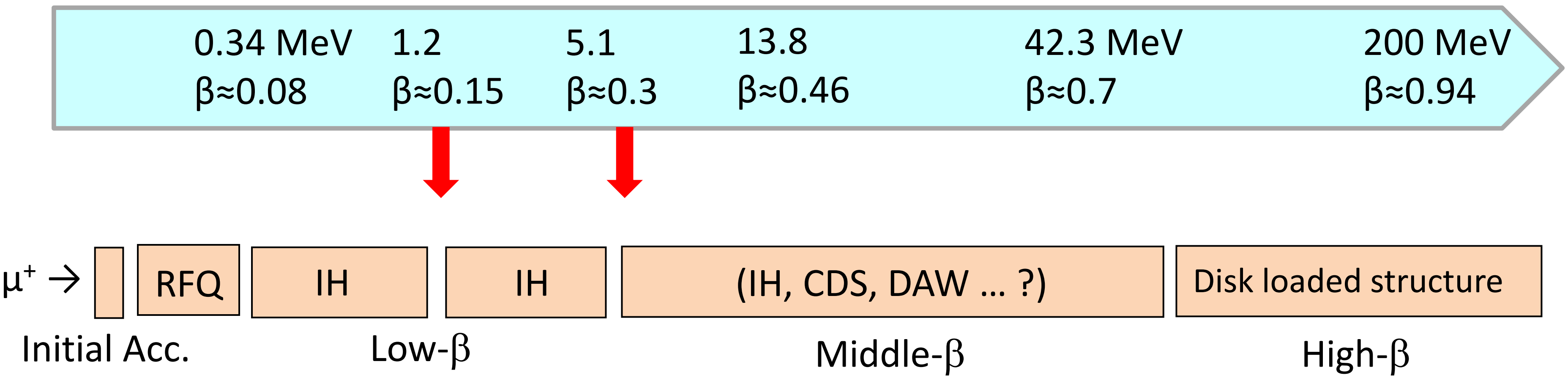
Coherent Lyman-α Resonance Radiation Source



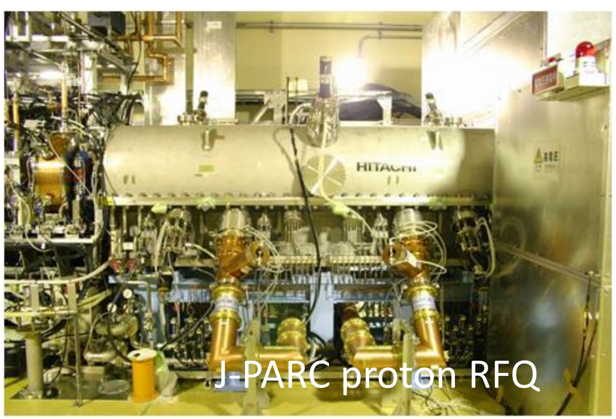


- Generation of Ly-α was confirmed with new system.
- The system is being tuned at RIKEN now
- Mu ionization test will be done at U-Line

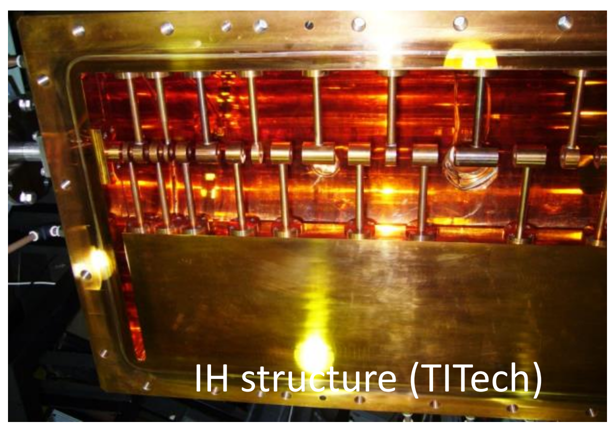
Muon acceleration



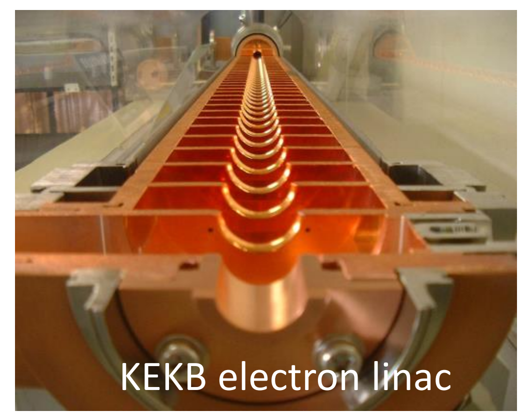
RFQ



IH linac



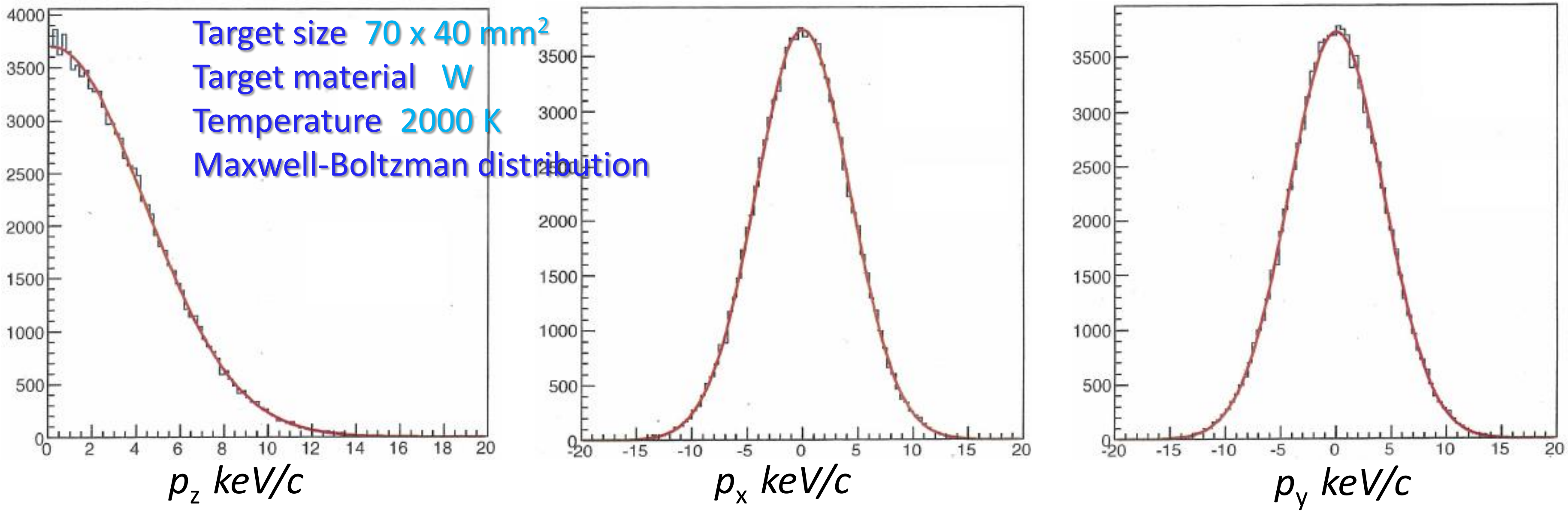
Disk loaded structure



Ultra cold muon acceleration

Slide by M. Yoshida

Target size 70 x 40 mm^2
Target material W
Temperature 2000 K
Maxwell-Boltzman distribution



Target voltage 5.66 kV
1st electrode 5.62 kV
2nd electrode 5.35 kV
3rd electrode 3.41 kV
4th electrode 0 kV

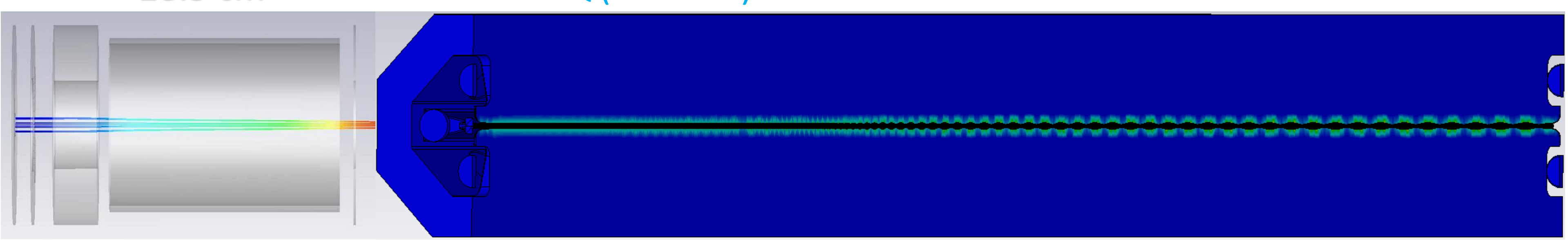
Initial acc. time 256.3 ns
RFQ acc. time 455.7 ns
Total 712 ns
Losses due to μ^+ lifetime 18.5%
Efficiency 45 %

N(out)=62.21%

N(712 ns)/N(0)=0.723513

N(out)*0.723513=45%

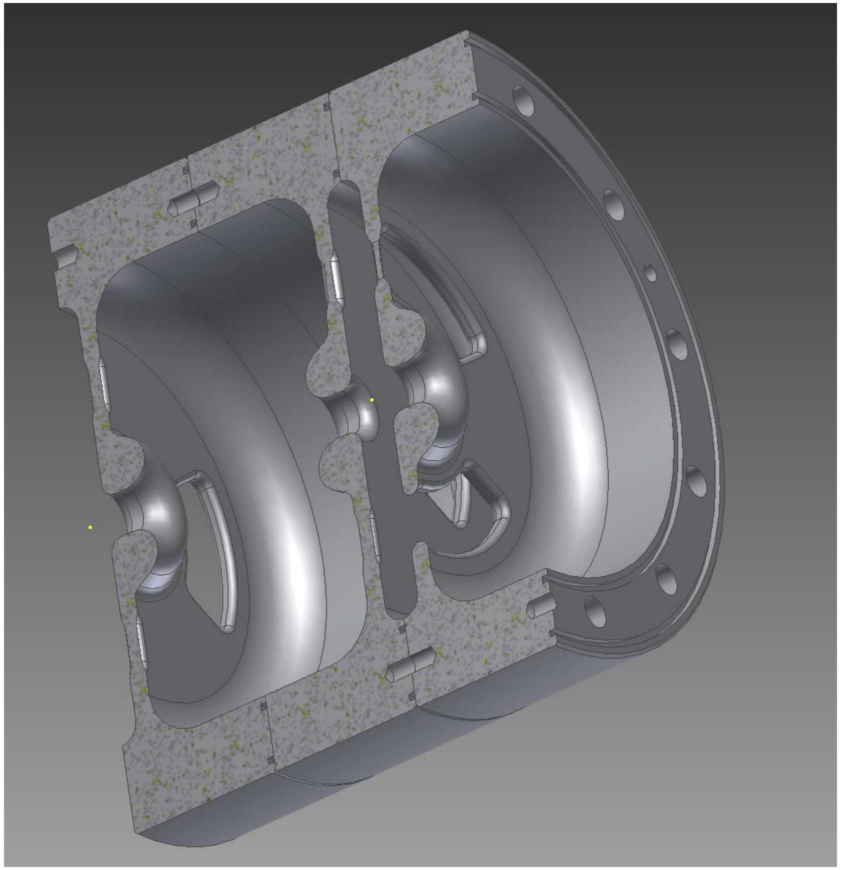
28.5 cm RFQ (3.192 m)

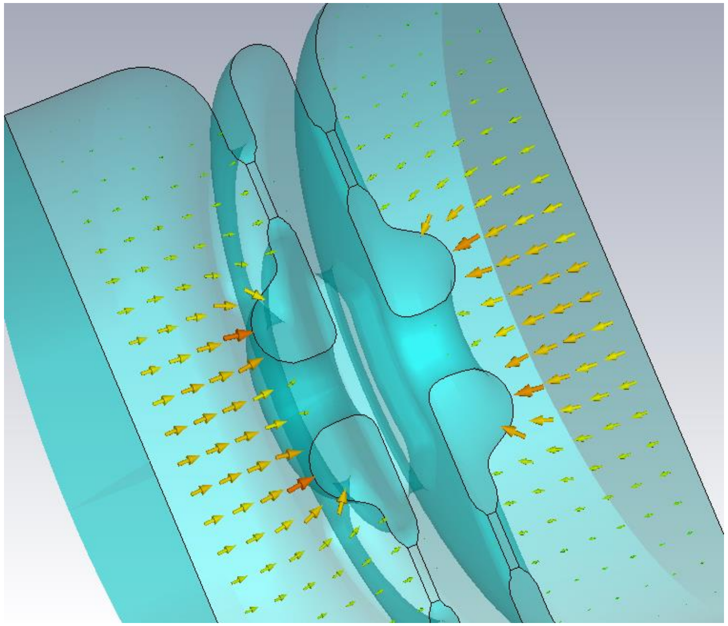


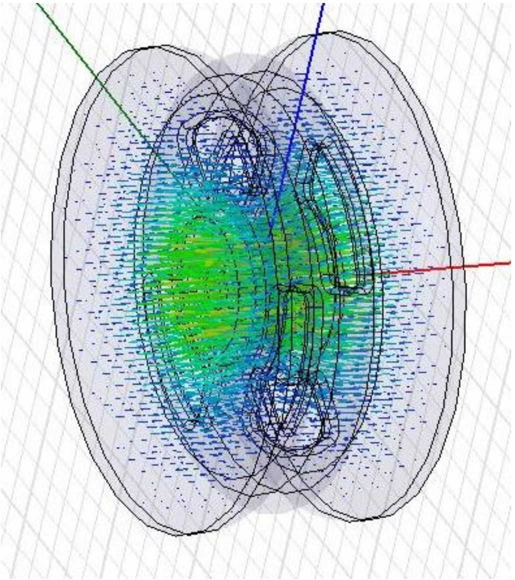
Slide by M. Yoshida

Middle-β design / CDS

- Cut Disk Structure



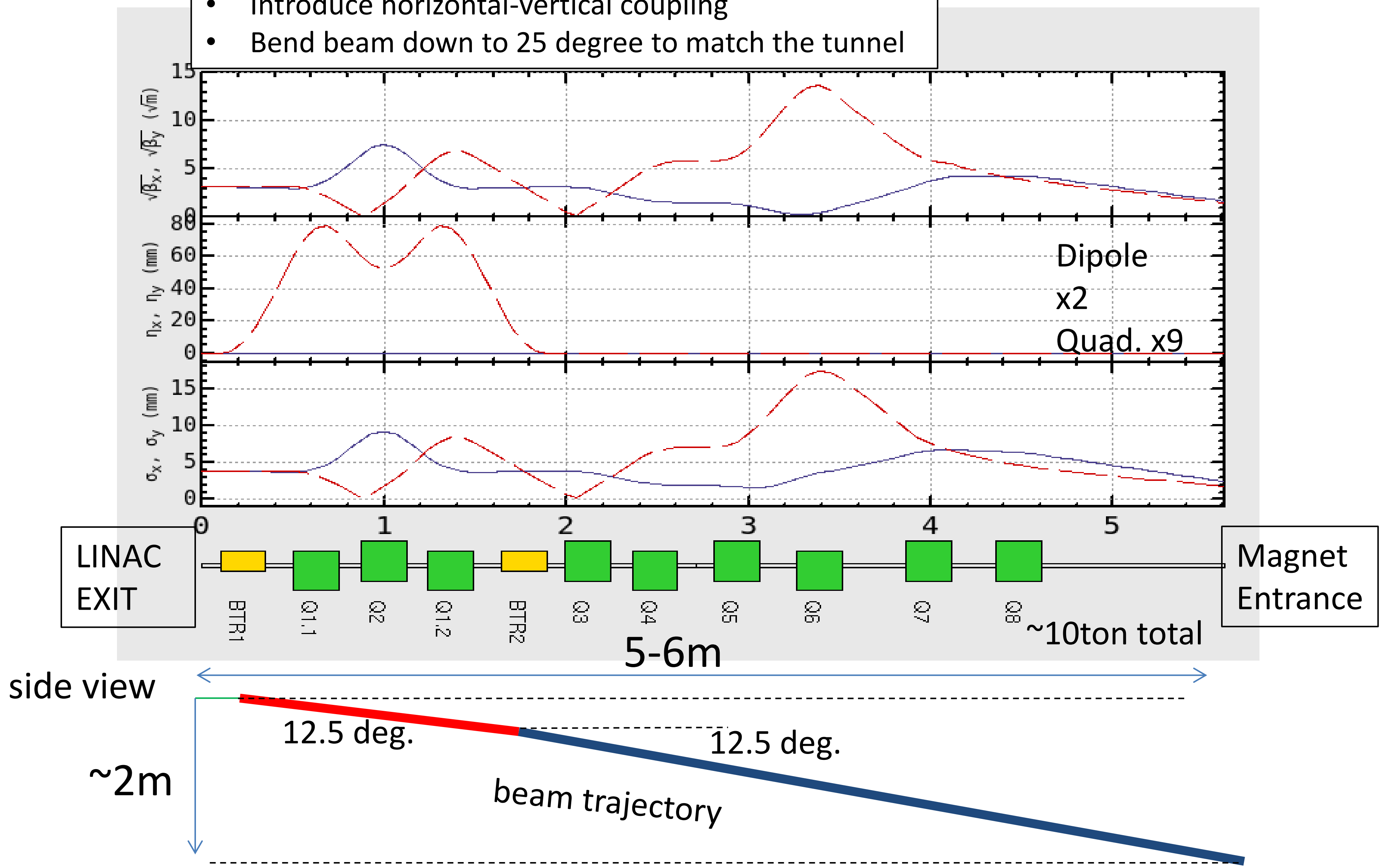




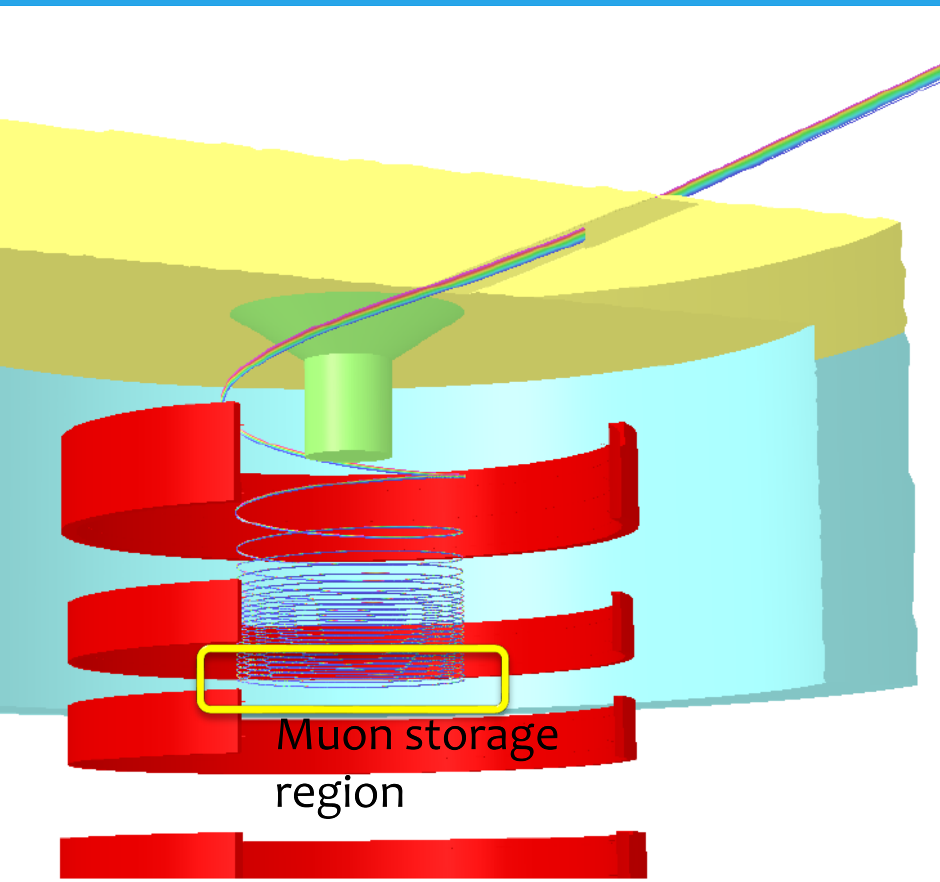
Middle-β

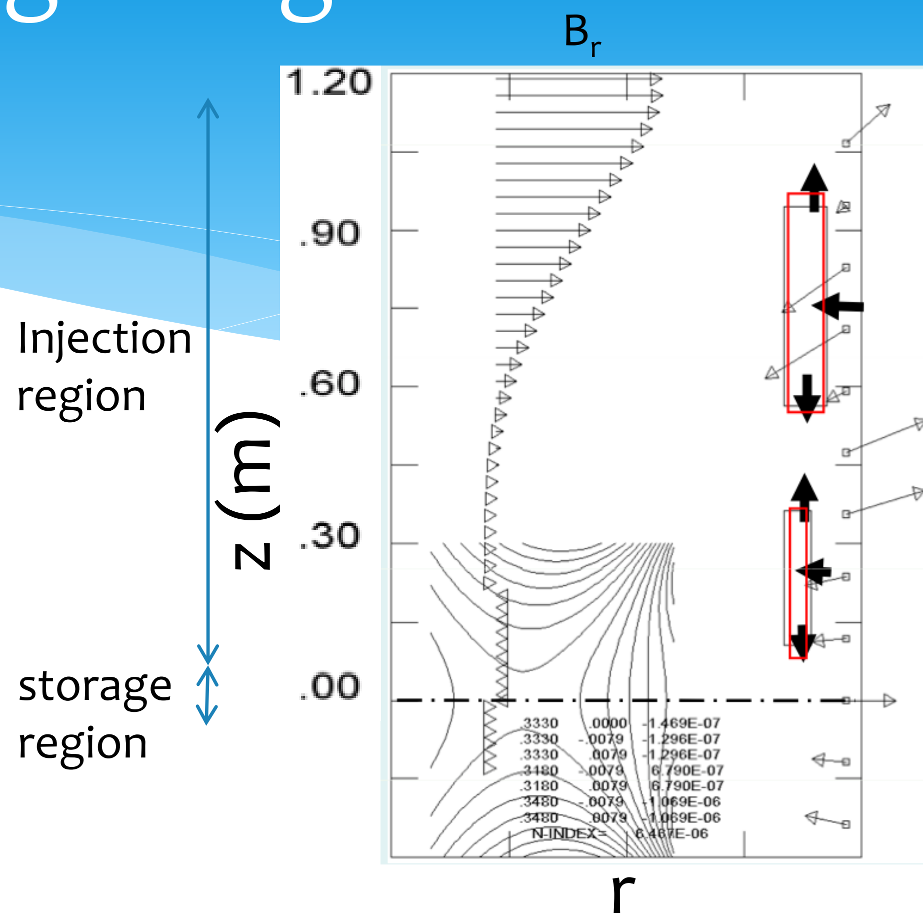
Conceptual design of beam transport line

- Introduce horizontal-vertical coupling
- Bend beam down to 25 degree to match the tunnel



Muon storage magnet



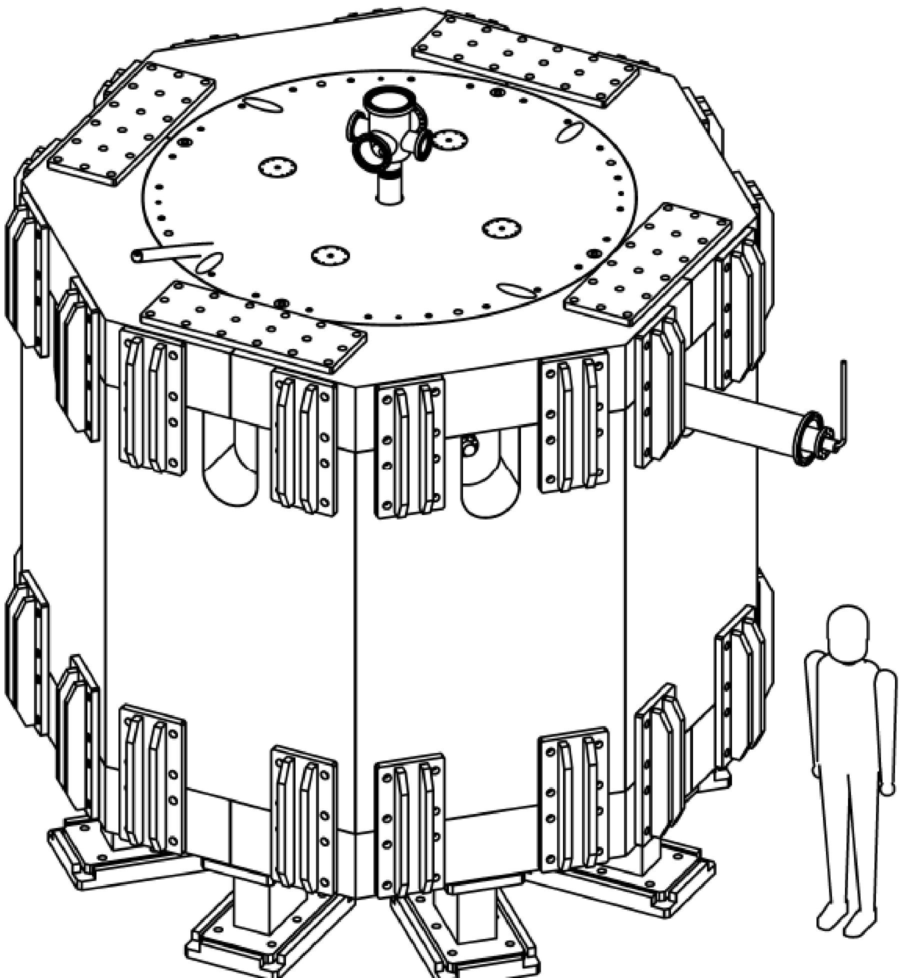


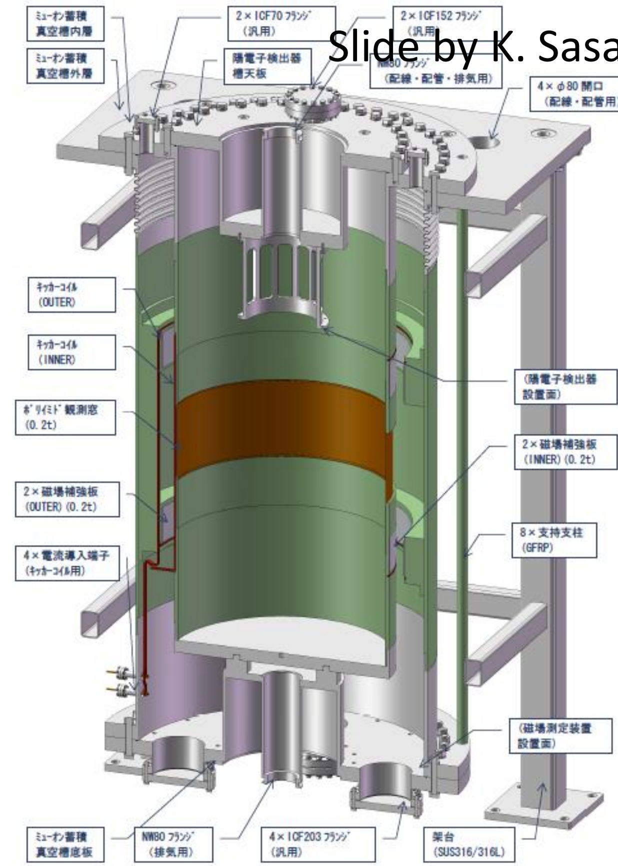
- Magnet consists of four super-conducting coils surrounded by correction coils and iron yoke.
  - main field : B = 3 T (local uniformity 1ppm)
  - injection field : $B_r > 0$ ($z > 5$ cm)
  - focusing field : B_r/B_0 = 10ppm/cm (n=1E-4) ($|z| < 5$ cm)

Magnet Latest Design

Slide by K. Sasaki

- Detail design is being developed considering the actual assembly





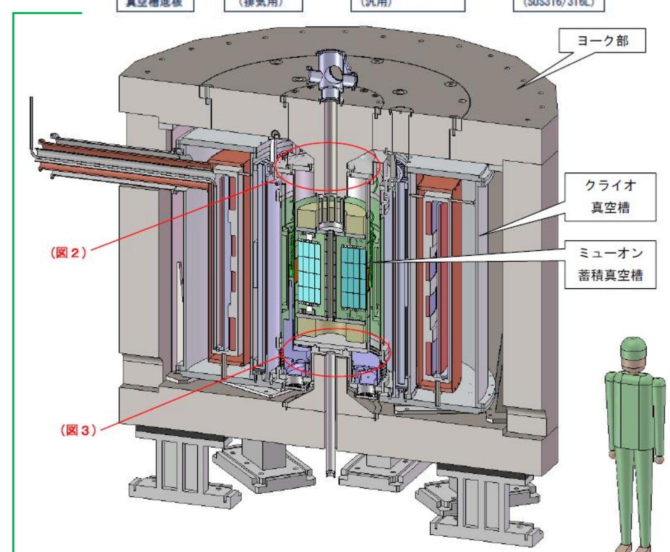


図1 ミューオン蓄積リング用電磁石全体構造案（正面断面図）

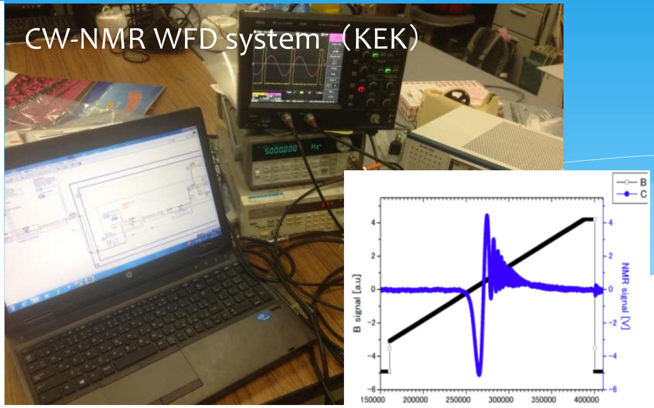
Precision field measurement

- Required precision : <0.1ppm

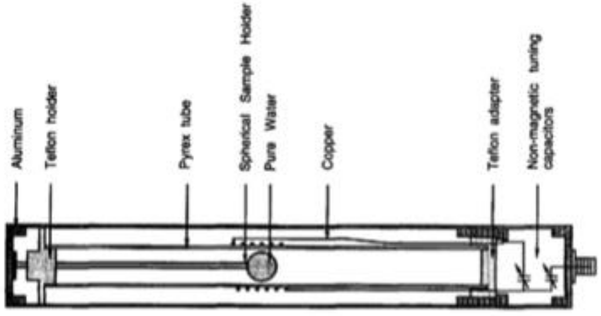
* CW-NMR system (KEK, UTokyo)
  * New waveform sampling system and analysis algorithm
  * Precision improvement : 0.15ppm → 0.05-0.10ppm
  * Absolute calibration probe (KEK)

* pulsed-NMR system (Umass, BNL)
  * To be used in FNAL g-2
  * Design and prototype of Pulsed-RF distribution circuits (BNL)
  * Absolute calibration probe (UMass)

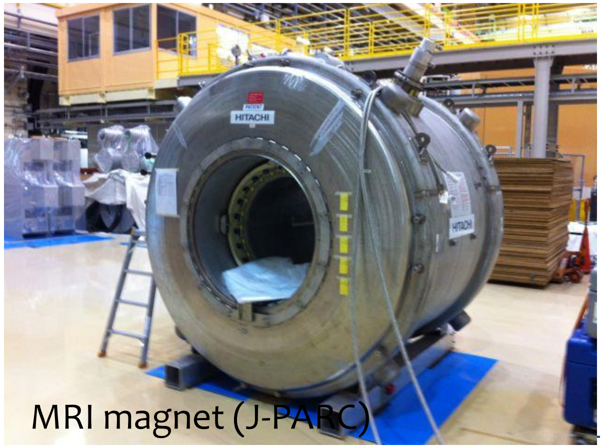
- Comparison and cross calibration of the NMR systems and probes is essential to identify systematics
  * Will start with a small MRI at Umass (bore 89mmΦ)
  * Need a magnet with good uniformity and large bore → MRI magnet at J-PARC



CW-NMR WFD system (KEK)



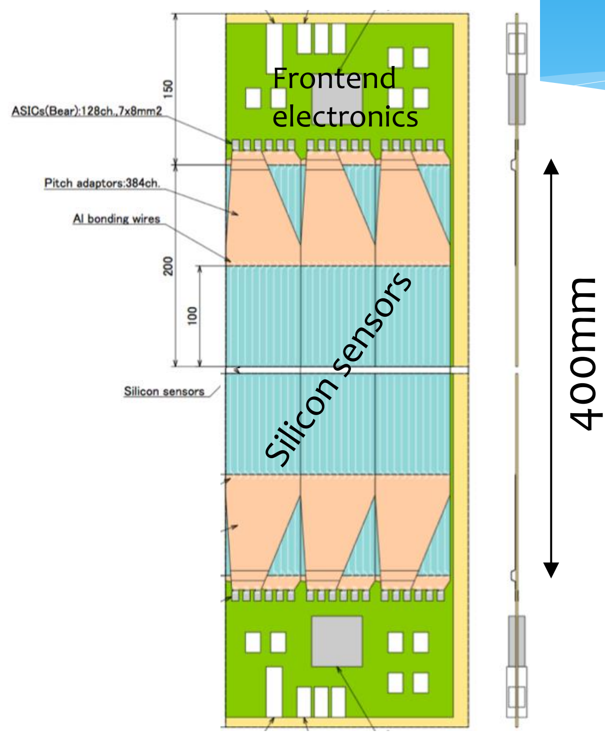
Absolute calibration probe (Umass)

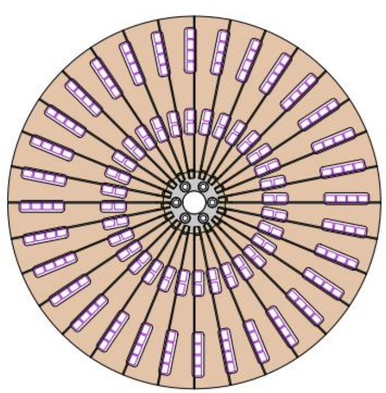


MRI magnet (J-PARC)

Silicon strip tracker

Detector module

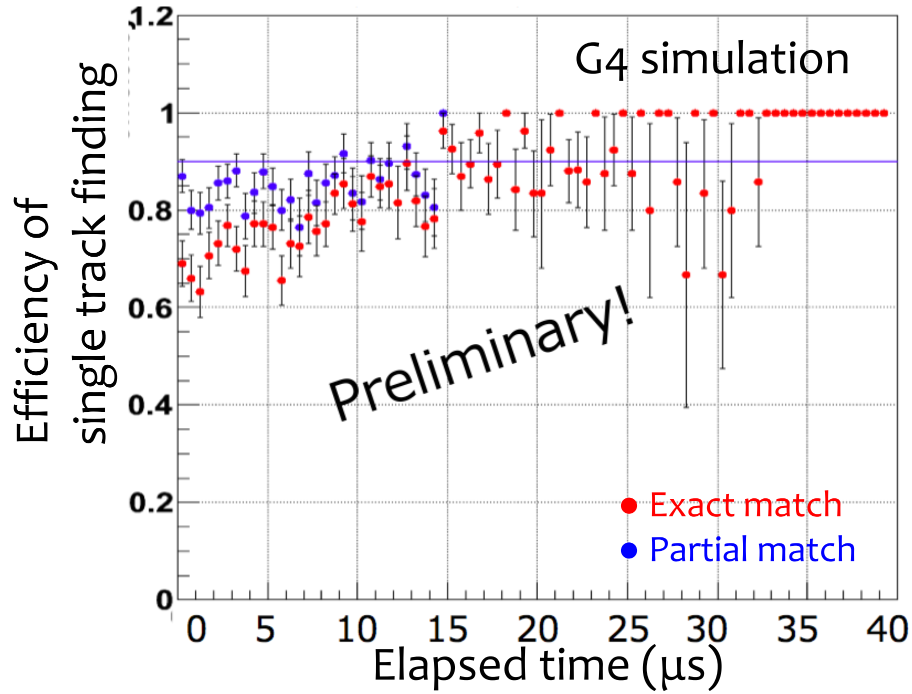




Number of vanes: 24-48

* Tracking e+ from muon decay (p = 200-300 MeV/c)
* No contamination of B-field (< 1ppm) and E-field (<10mV/cm) in the muon storage region.
* Efficient and stable over ~5 lifetimes (33μs)
  * Instantaneous rate changes by two orders of magnitude.

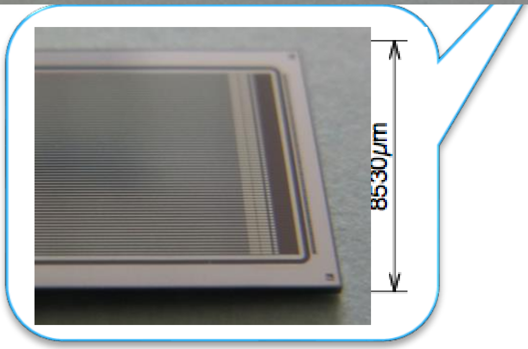
K. Ueno IEEE-NSS 2012



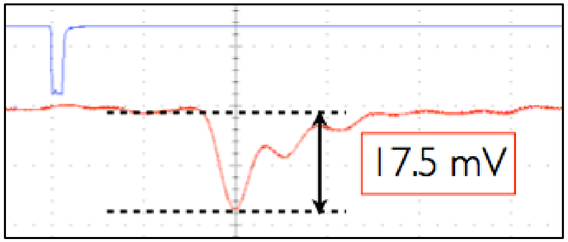
Silicon-strip sensor

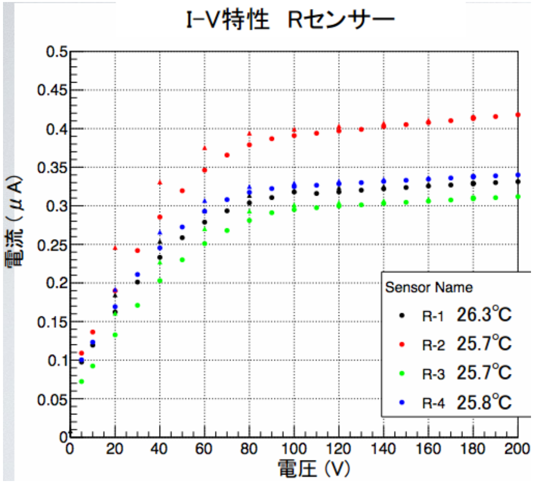
S. Nishimura (Master thesis, 2013)

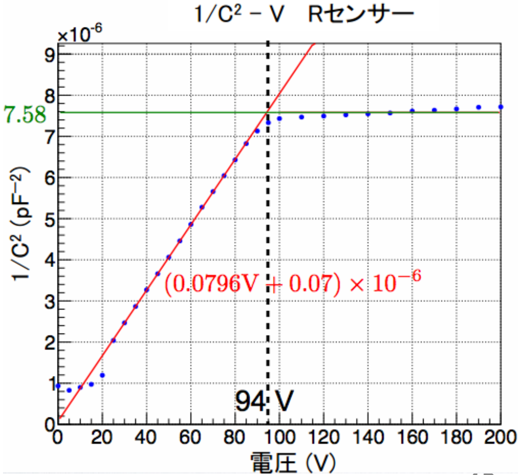
* Optimal strip pitch determined by G4 simulation
  * 220 µm for radial strip
  * 100 µm for axial strip
* Test sensor
  * Single-sided sensors
  * 64 strip / sensor
  * Lab characterization completed.
  * To be tested with beam.



waveform taken with IR laser



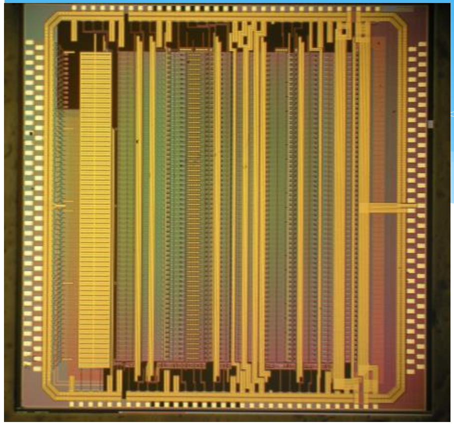


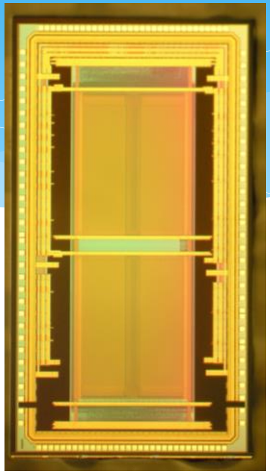


Frontend ASIC

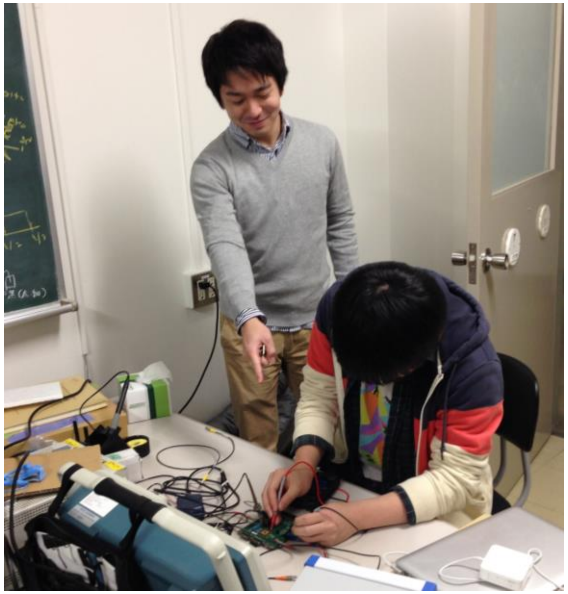
- 2nd prototype were developed and evaluated.
  - Silterra 0.18 /64 ch
  - ENC 1300 e- at 15pF
  - No major problem found
- Test with sensor started.

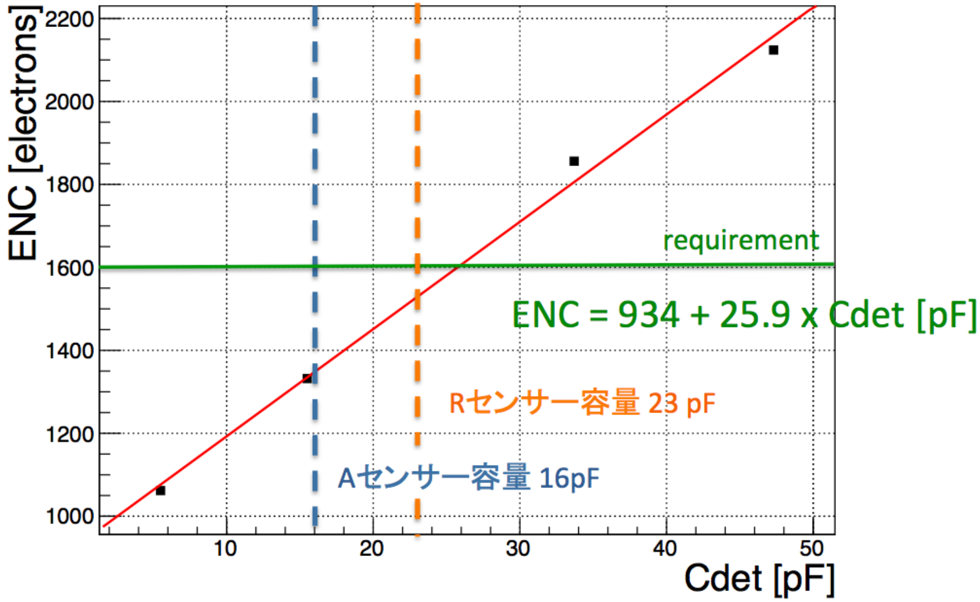
designed by M. Tanaka, T. Uchida





Evaluation by S. Shirabe, S. Koura (Kyushu), K. Ueno





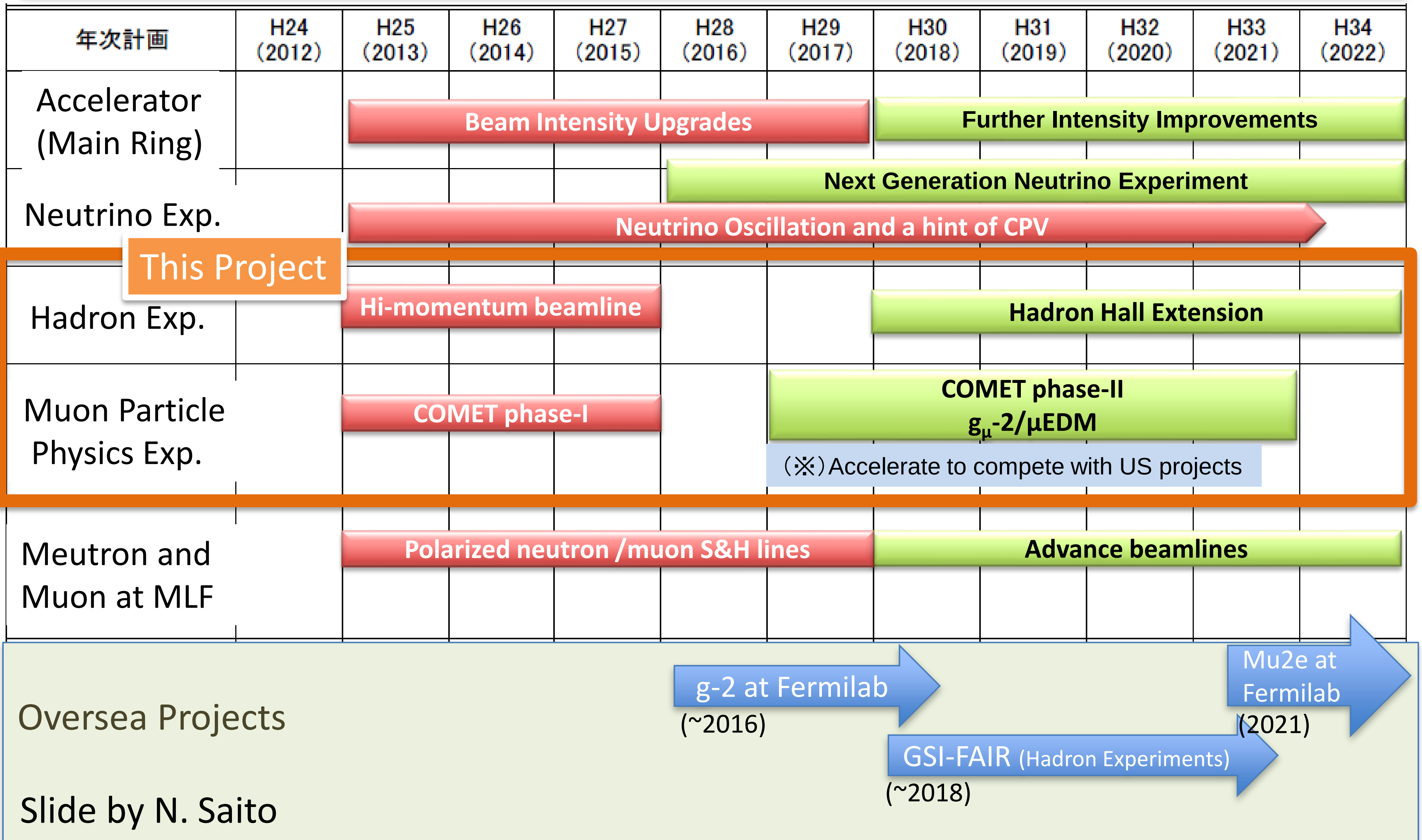
Milestones and prospects

Milestones	Status & Prospects
Demonstration of UCM Production	**Major improvement in Mu yield** Full demonstration at H-line
Muon acceleration test	Secured J-PARC RFQ for test. Demonstration at U-line&H-line
Prototyping Precision Magnet	Partial demonstration by Mu-HFS magnet.
Injection and Kicker	Prototype test completed. Grant-in-aid awarded for electron injection test
High-rate tracker	Beam tests at J-PARC and Tohoku planned. Grant-in-aid awarded for alignment R&D

A part of the master plan of Science council of Japan

Elucidation of the origin of matter with an upgrade of J-PARC experimental facility

Intended Schedule (JFY2017-)



Summary

- J-PARC g-2/EDM experiment aims to measure g-2 in 0.1ppm, EDM <2E-21 e・cm sensitivity with **completely different experimental technique**.
- R&Ds for all components are in progress.
- Intensity of ultra-cold muon beam can be large **enough to test the BNL g-2 anomaly** better than 0.5ppm precision. Further improvements are in progress.