Mu HFS experiment at J-PARC (MeSEUM)

Koichiro. Shimomura; KEK

Collaboration List

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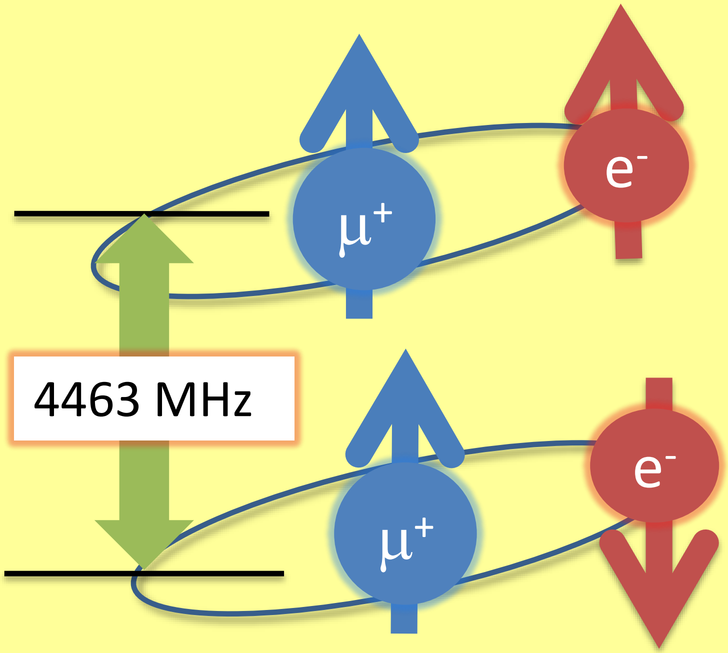
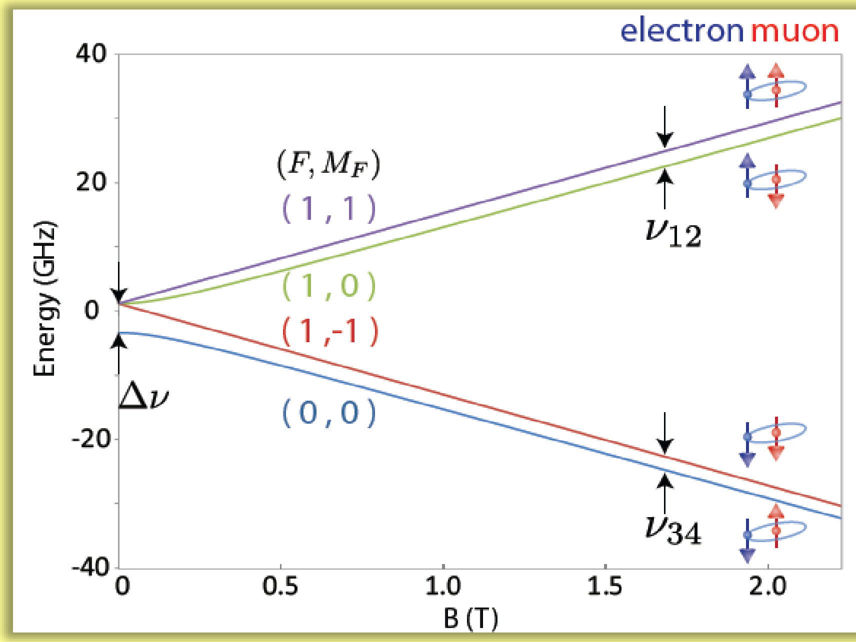
Mu Hyperfine Structure

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

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

Zeeman Splitting





Pure leptonic system
(No composite particle)

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

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

The most precise test for the bound state QED

ν_{HFS}(exp) 4463.302 765(53) MHz (12 ppb]) LAMPF1999

ν_{HFS}(theory) 4463.302 891 (272) MHz (63 ppb) D. Nomura (2013)

ν_{HFS}(QED) 4463.302 720 (253) (98) (3) MHz(m_μ/m_e) (QED) (α)

ν_{HFS}(weak) -65Hz

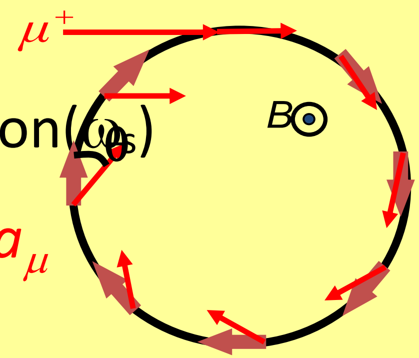
ν_{HFS}(had v.p) 232(1) Hz

ν_{HFS}(had. h.o) 5Hz

QED calculation →Effort for 10 Hz is in progress by Eides *et al*. Phys Rev A: 86, 024501 (2012), PRL.. 112, 173004 (2014), Phys. Rev. D 89, 014034 (2014)

Why Muonium HFS measurement is so important？

- *g*-2 E821(BNL) 0.5ppm 3σ deviation



-measurement of the deviation of muon spin direction(ω_s)

and muon momentum direction(ω_c) $\omega_a \propto (g-2)/2 = a_\mu$

$$\Rightarrow \vec{\omega}_a = \frac{e}{mc}\left[a_\mu \vec{B} - \cancel{\left(a_\mu - \frac{1}{\gamma^2-1}\right)\vec{\beta}\times\vec{E}}\right]$$

a_μ *an independent precise muon mass measurement is required*

-The ratio to proton NMR frequency is important!

$$\Rightarrow \boxed{a_\mu = \frac{R}{\lambda - R}} \qquad \boxed{R \equiv \frac{\omega_a}{\omega_p}} \qquad \boxed{\lambda \equiv \frac{\mu_\mu}{\mu_p}}$$

From g-2 strage ring　　From Muonium HFS

$$\frac{\omega_a}{\omega_L(\mu)} = \frac{a_\mu\left(\frac{eB}{mc}\right)}{g_\mu\left(\frac{eB}{2mc}\right)} = \frac{a_\mu}{\left(\frac{g_\mu}{2}\right)} = \frac{a_\mu}{\underline{1+a_\mu}}$$

$$= \frac{\omega_a}{\omega_L(p)}\frac{\omega_L(p)}{\omega_L(\mu)} = \frac{\omega_a}{\omega_p}\frac{\mu_p}{\mu_\mu} = \underline{R/\lambda}$$

μ_μ/μ_p accuracy from direct measurement 120ppb

W. Liu *et al., Phys. Rev. Lett.* ***82, 711 (1999).***

Test of CPT and Lorentz Invariance

CPT broken Theory⇒Lorentz symmetry is broken

R.Blihm, V.A. Kostele and C.D. Lane PRL84,1098(2000)
V.W. Hughs et al. PRL87,111804(2000

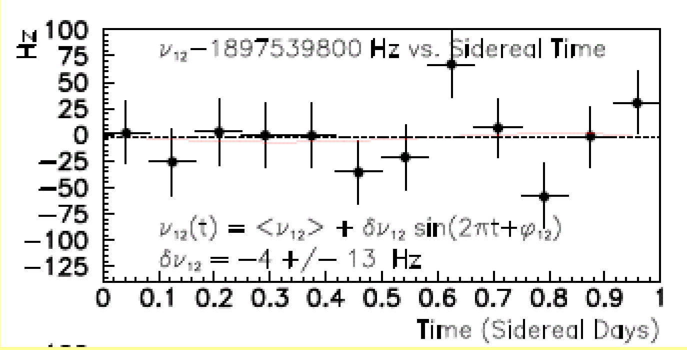
CPT violation search

Ex., Muon difference $g_{\mu+}$ $/g_{\mu-}$ 10^{-8}

g_{μ}-2/MuHFS precise measurement

Lorentz symmetry violating term in SME Lagrangian b
Corresponding MuHFS $\Delta\nu_{12/34}$
These value might change in sidereal time (23h56m)

$\tilde{b}_3^{\mu}/\pi = -\delta\Delta\nu_{12} = \delta\Delta\nu_{34}$



LAMPF Exp. Figure of Merit

$$2\sqrt{(b^{\mu+}{}_X)^2 + (b^{\mu+}{}_Y)^2}\,/\,m_\mu < 5\times10^{-22}$$

$m_\mu/M_P \sim 10^{-20}$

Plank scale sensitivity

Laboratory tests of Lorentz and CPT symmetry w/ muons
A.H. Gomes et. al., Phys.Rev.D90:076009,2014

On proton radius puzzle

Muonic hydrogen Lamb shift measurement* results 7 σ difference from CODATA on proton radius. Related on this subject, Mu HFS measurement contributes several insights.

*R. Pohl *et al.,* Nature 466,23(2010)

・Proton Zemach radius $\langle R^n_{Z,a,b}\rangle = \int d^3r_1 d^3r_2 \rho_a(r_1)\rho_b(r_2)|\boldsymbol{r}_1 - \boldsymbol{r}_2|^n$

can be obtained comparison of muonium HFS and hydrogen HFS*.

*SJ. Brodsy *et al.,* PRL.. 94, 022001 (2005),

・Suitable tool for new light (1eV~100MeV) particle search, inspired by proton radius puzzle (dark photon etc.).

$$\frac{\nu^{\rm exp} - \nu^{\rm th}}{\nu^{\rm exp}} = (-2.5 \pm 1.2 \pm 6.1) \times 10^{-8}.$$

$$\left|\frac{\Delta E_{\rm hfs}}{E_{\rm hfs}}\right| < 1.24 \times 10^{-7}.$$

S. G. Karshenboim *et al.*, PRL 104, 220406 (2010), PRD82, 113013(2010). PRA 84, 064502(2011) , PRD90, 073004(2014).

Exotic particle search

a pseudo vector boson

$$-\frac{\alpha}{r} \rightarrow -\frac{\alpha + \alpha''(\mathbf{s}_1 \cdot \mathbf{s}_2)e^{-\lambda r}}{r},$$

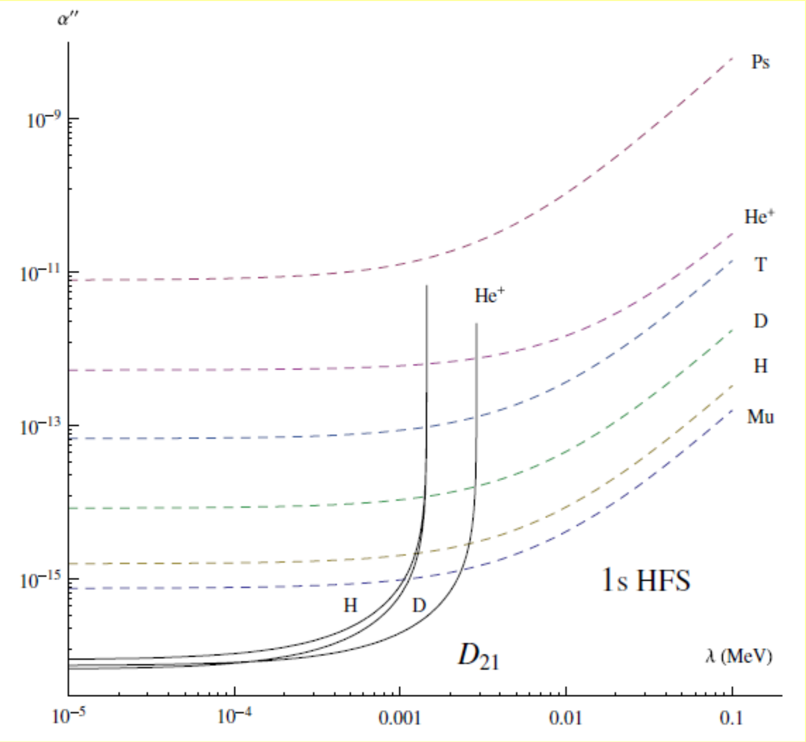


Fig. 2 on PRL 104, 220406 (2010)

a massive vector boson

$$\frac{\Delta E_{\rm hfs}}{E_{\rm hfs}} = \frac{8\alpha' m_e}{m_V} = \frac{8\alpha\kappa(\kappa + g_V/e)m_e}{m_V}.$$

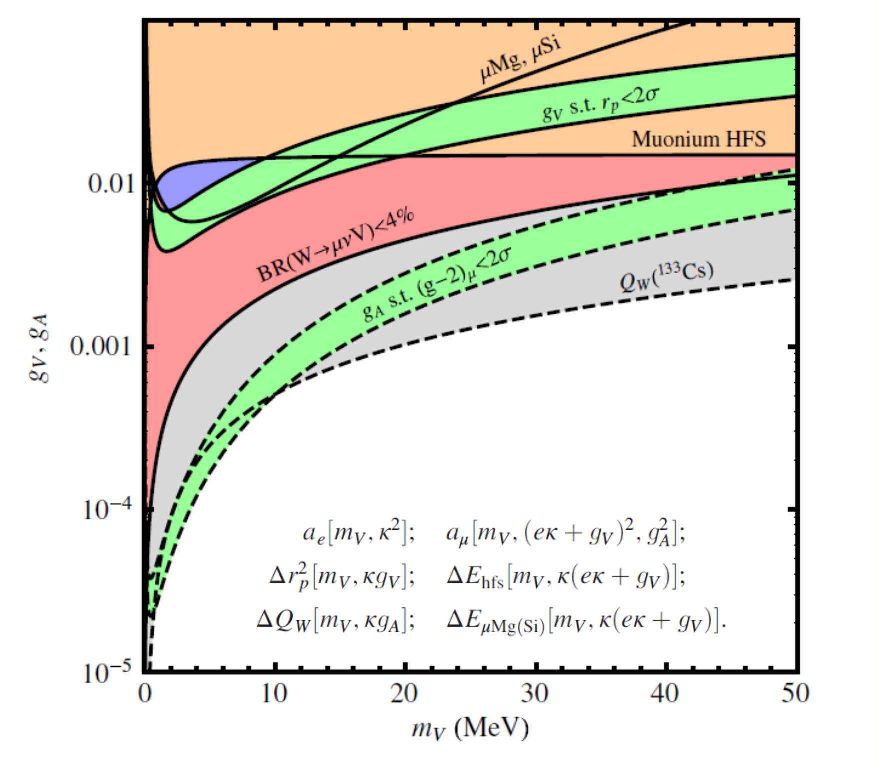
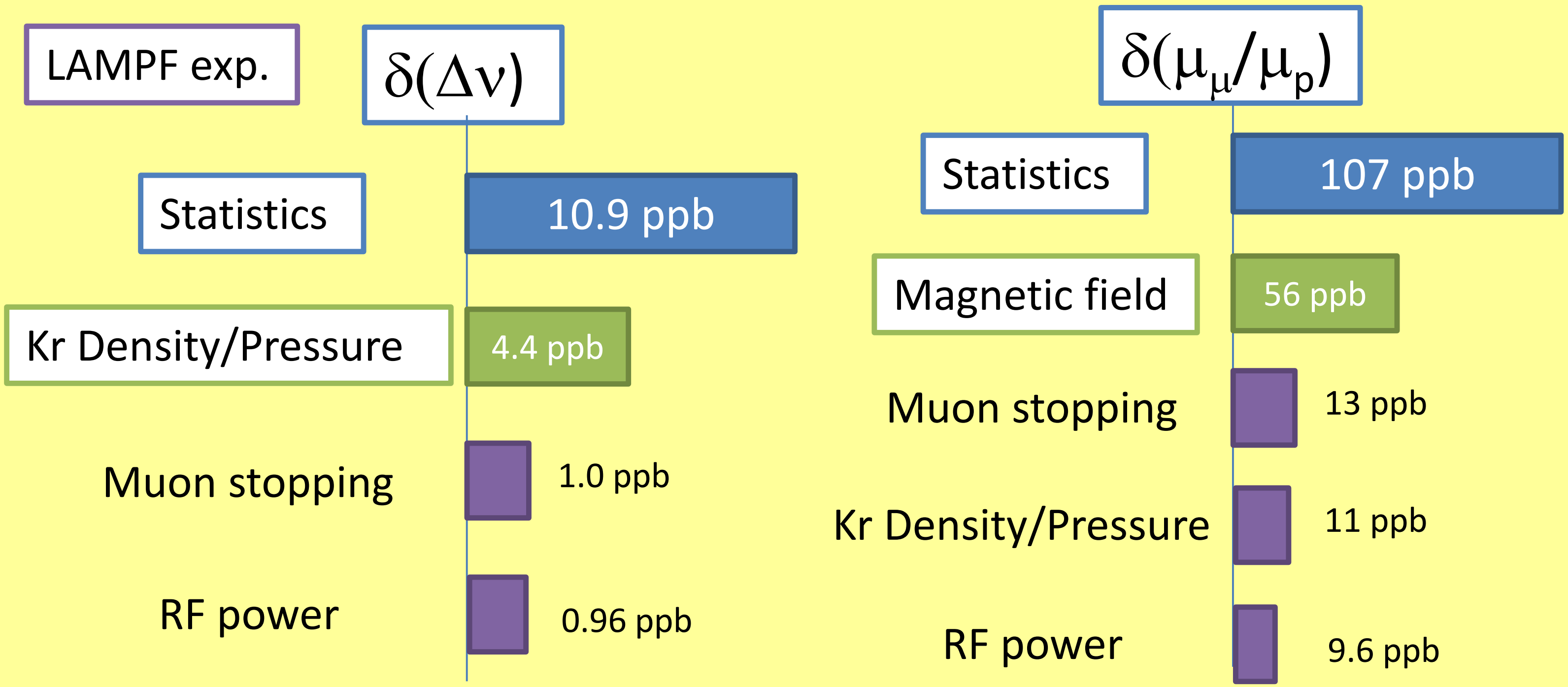


Fig. 6 on PRD90, 073004(2014).

Uncertainty of the previous measurement

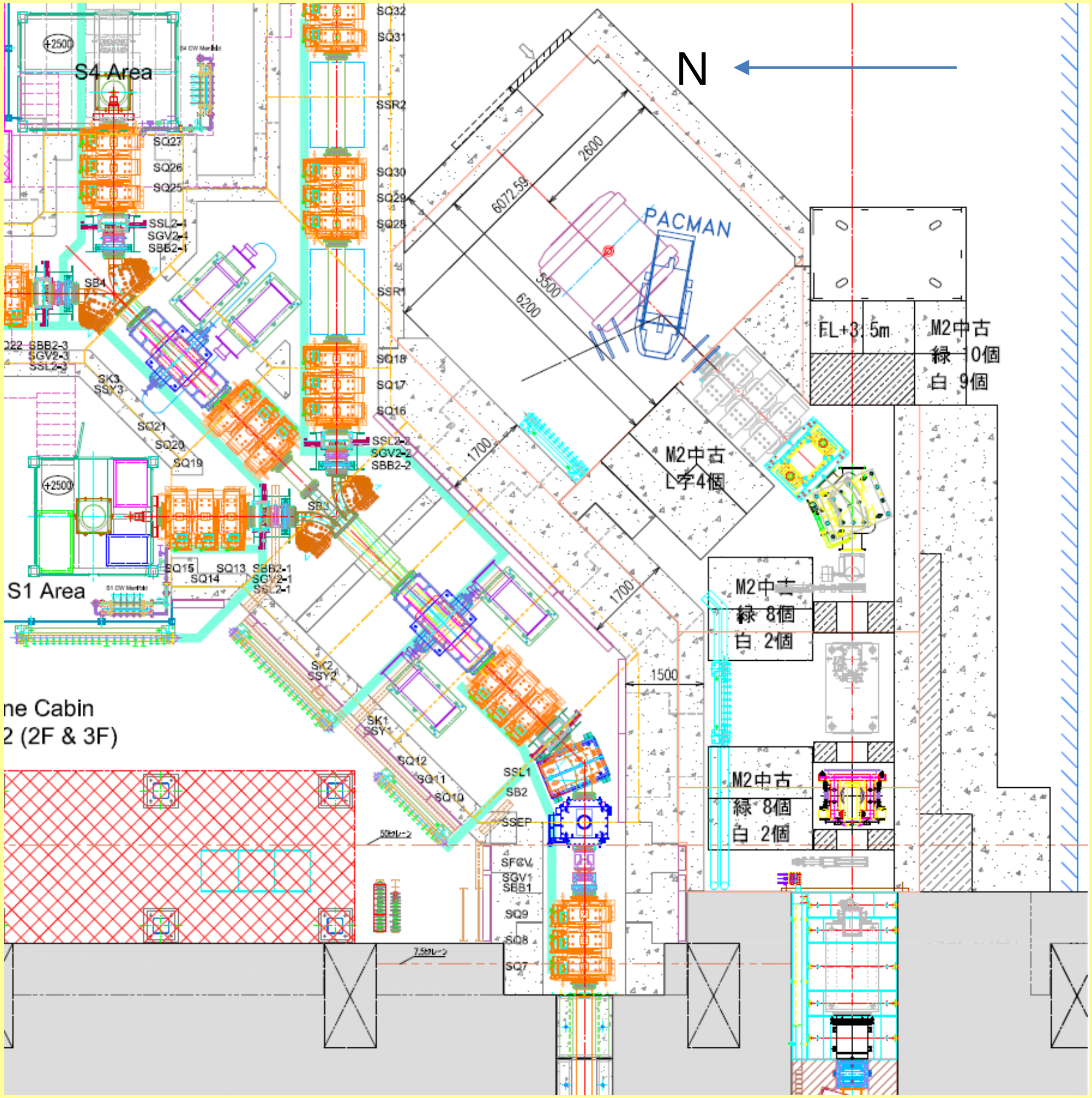


LAMPF DC 10^7 /s
total 10^{13}

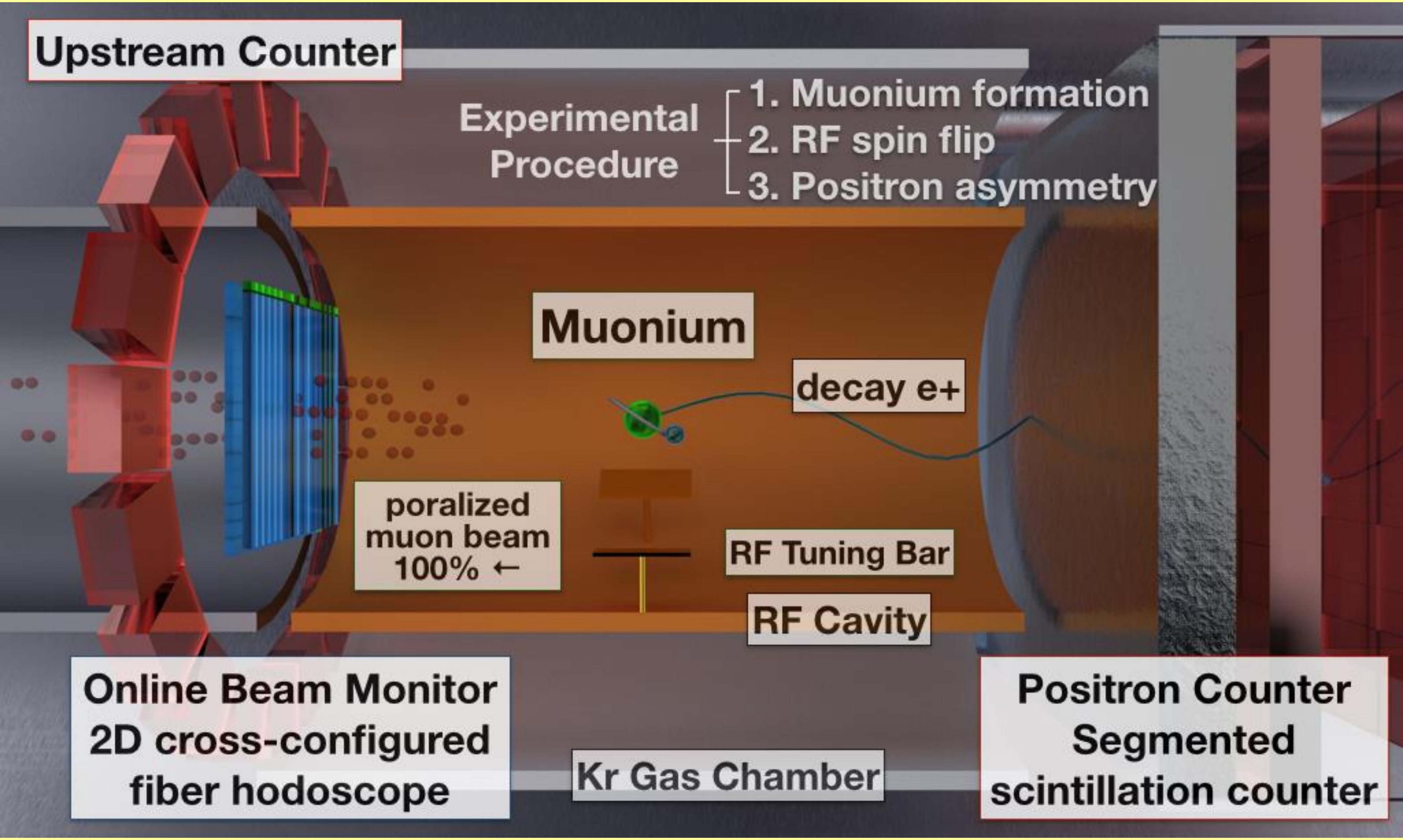
x200 →

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

Experimantal Area



Experimentl Setup



Key Components

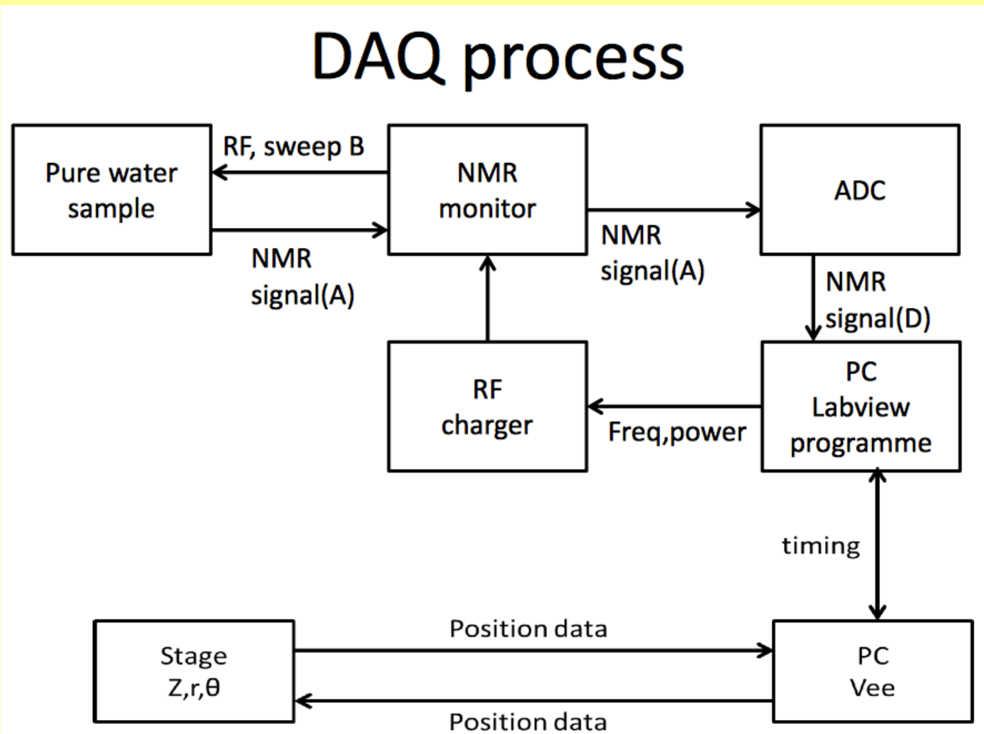
- Intense muon beam line — Kawamura ,Toyoda
- Super conducting magnet — Sasaki, Mizutani, Higashi, Ueno
- RF cavity — Tanaka, Matsuda, Yoshida
- Kr chamber and gas handling — Tanaka, Torii, Strasser
- Positron detector — Kanda, Fukao, Mibe, Kojima
- Beam profile monitors — Ueno, Kanda, Toyoda, Ito
- Systematic error study — Tanaka, Kanda, Ishida

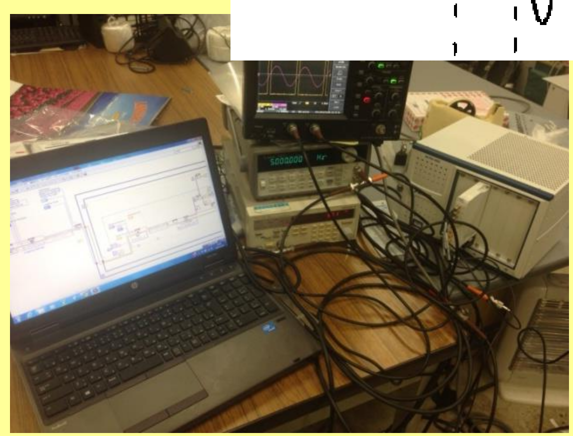
NMR field monitoring system

$$\delta_t = \sigma(H_2O) + \delta_b + \delta_p + \delta_s + \delta_e$$

- Analog process + Constant RF
  - Offset caused by voltage threshold
  - Variation of modulation coil field
  - Fluctuation of measured value by circuit noise

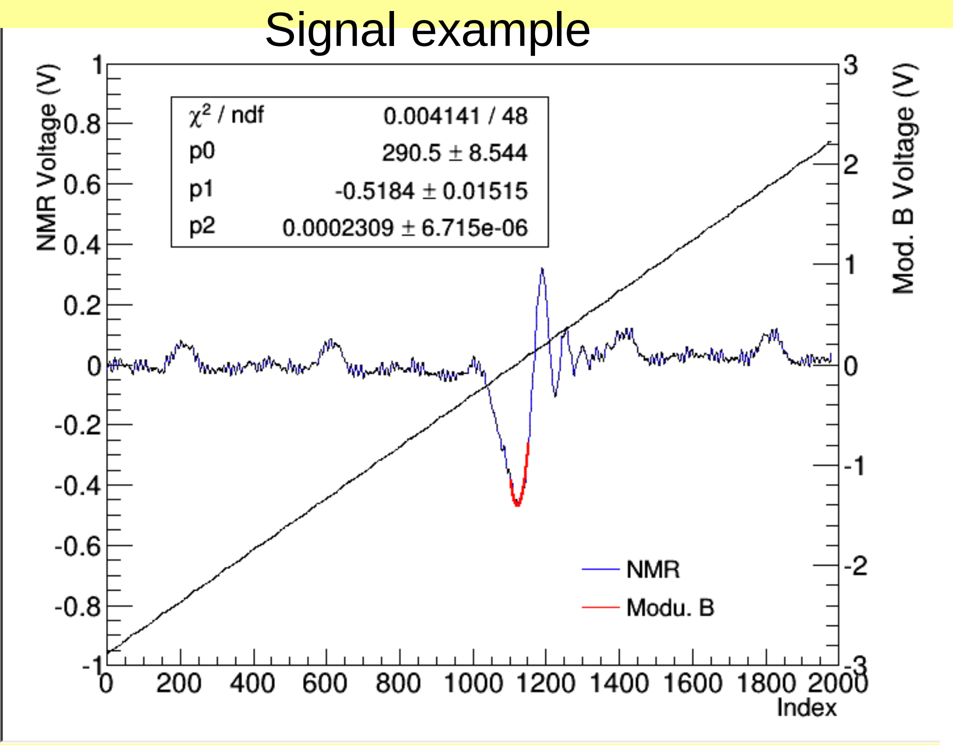
- Digital process + RF tuning
  - improve S/N ratio and minimize offset by data-fitting process
  - minimize variation of modulation coil

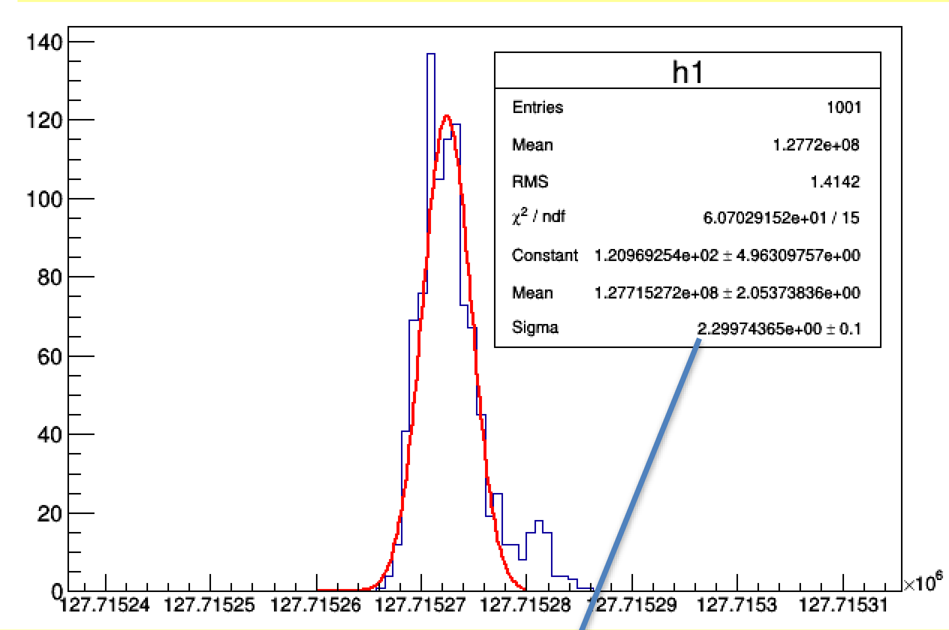




Signal example

- at Magnet center, RF is constant
- Measure 1000 times (~5 min)
- RF : 127.71525286 MHz



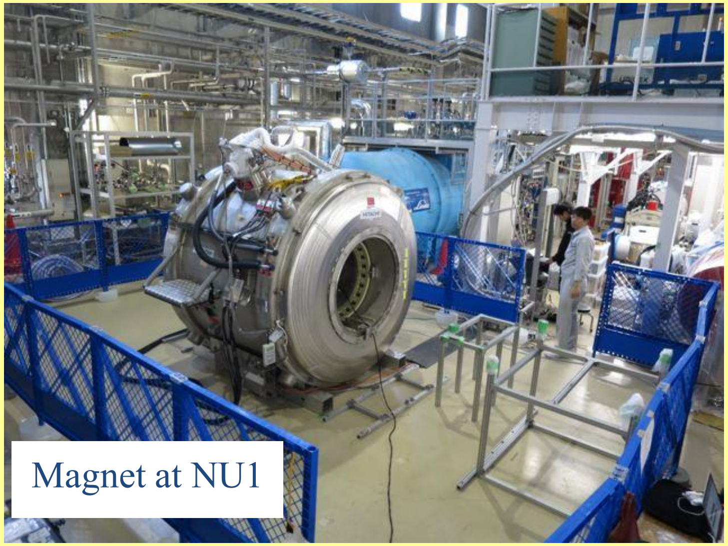


Red line : Quadratic approximation

Sigma : 2.3 Hz = 0.018 ppm

Test of MRI magnet for MuSEUM experiment

- Second-hand 2.9 T MRI magnet (March 2013)
- Performance test at NU1 in 2015
  - Feb. 2-16
    - Cooling from R. T.
  - Feb. 24-26
    - Shimming test #1
      - at 1.5 T, by Oxford (Hitachi medical)
  - Feb. 27 - Apr. 20
    - Measure
      - He evaporation rate
      - Long term stability
  - Apr. 21-23
    - Shimming test #2
      - at 1.7 T, by KEK
  - Jun. 17
    - Quench test

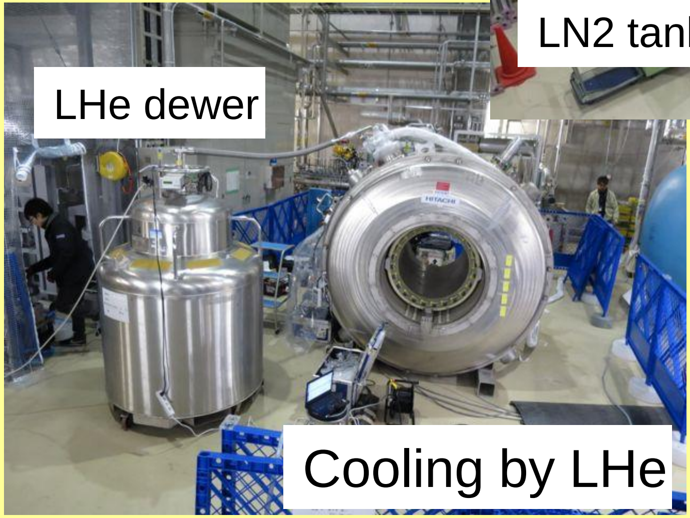


Cooling Summary

- From R. T. to 4.2 K
  - 2-3/Feb. : Pumping vacuum layer, pump and flush with He gas
  - 5-11/Feb. : Cooling by LN2 (3000 L)
  - 12/Feb. : Pump and flush with He gas
  - 13-14/Feb. : Cooling by LHe (2000L) -> 32 %
  - 16/Feb. : Additional LHe (500L) -> 60 %

- Two weeks
  - Amount of
    - LN2 : 3000 L
    - LHe : 2500 L

Cooling by LN2

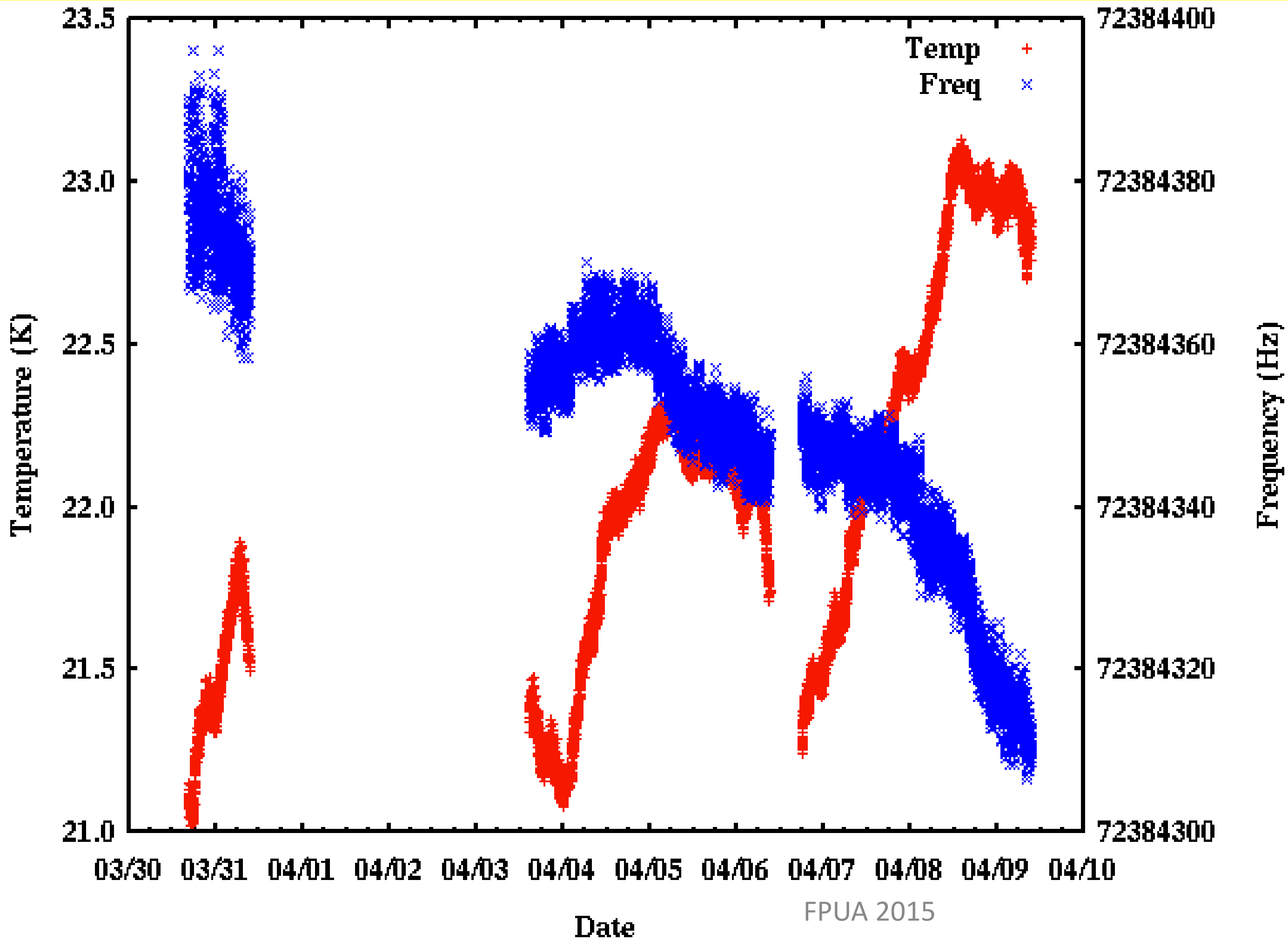


Cooling by LHe

Long Term Stability

- 2015/3/30 - 4/9 Mod. field : 20 μT p-p,
  Mod. span : 200 ms

Temperature calibration



64 Hz / 9.7 days

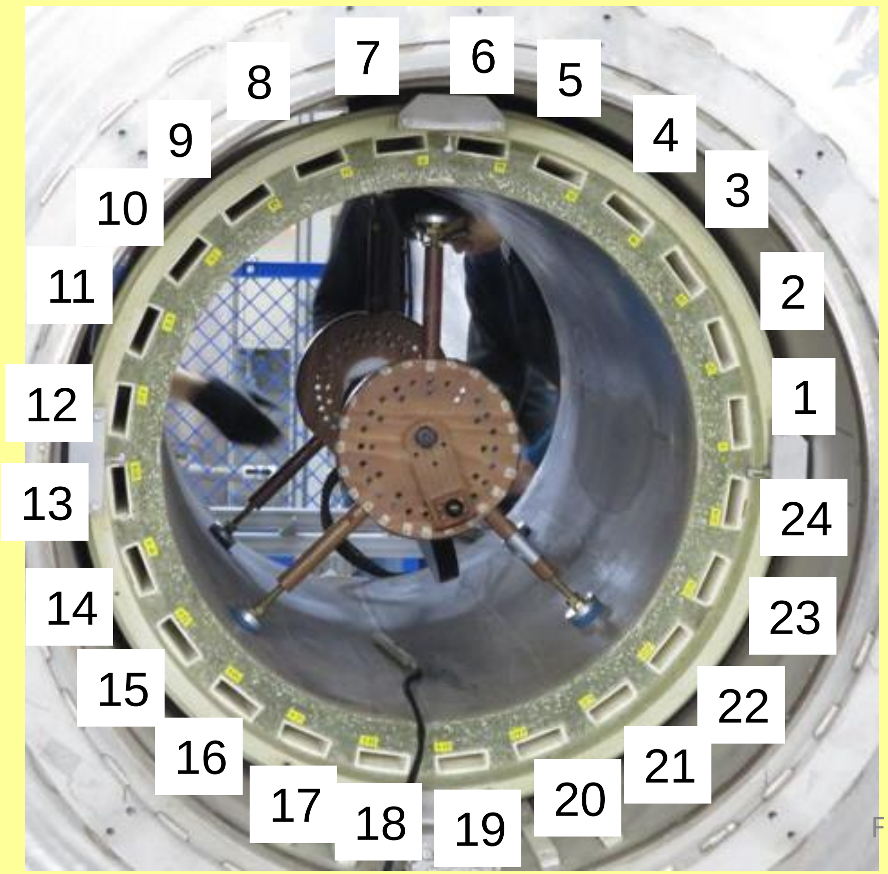
0.003 ppm /h

Water temp. depend
10.36e-9/℃

Magnet spec.
< 0.03 ppm/h

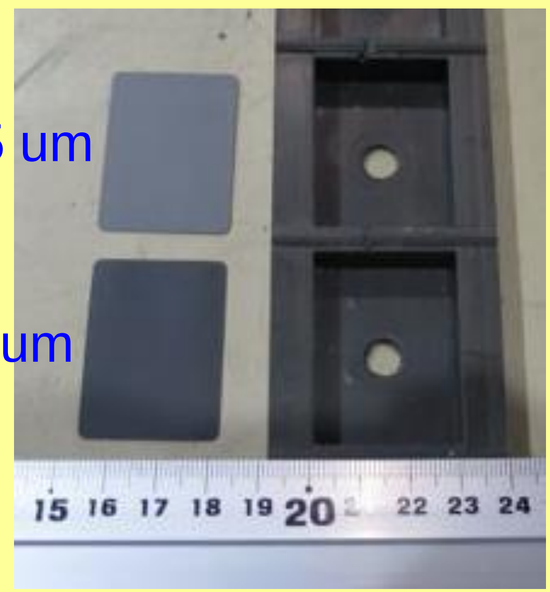
Shim tray, Iron piece

- 24 trays
  - 24 pockets per each tray (576 pockets in total)
- Iron piece
  - W 40 mm, D 30 mm
  - Thick and Thin piece (t : 25 μm, 5 μm)



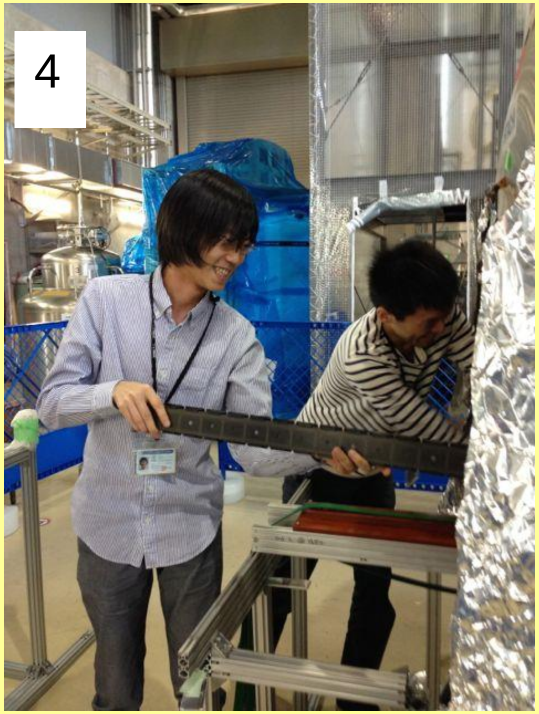
t 5 um

t 25 um



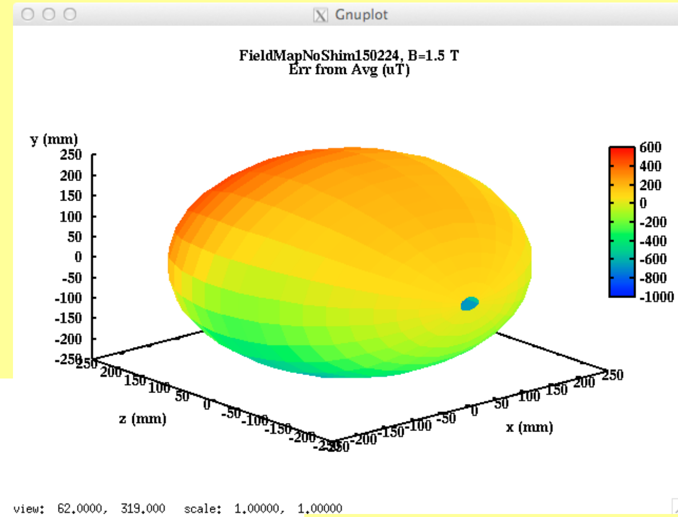
Shimming work

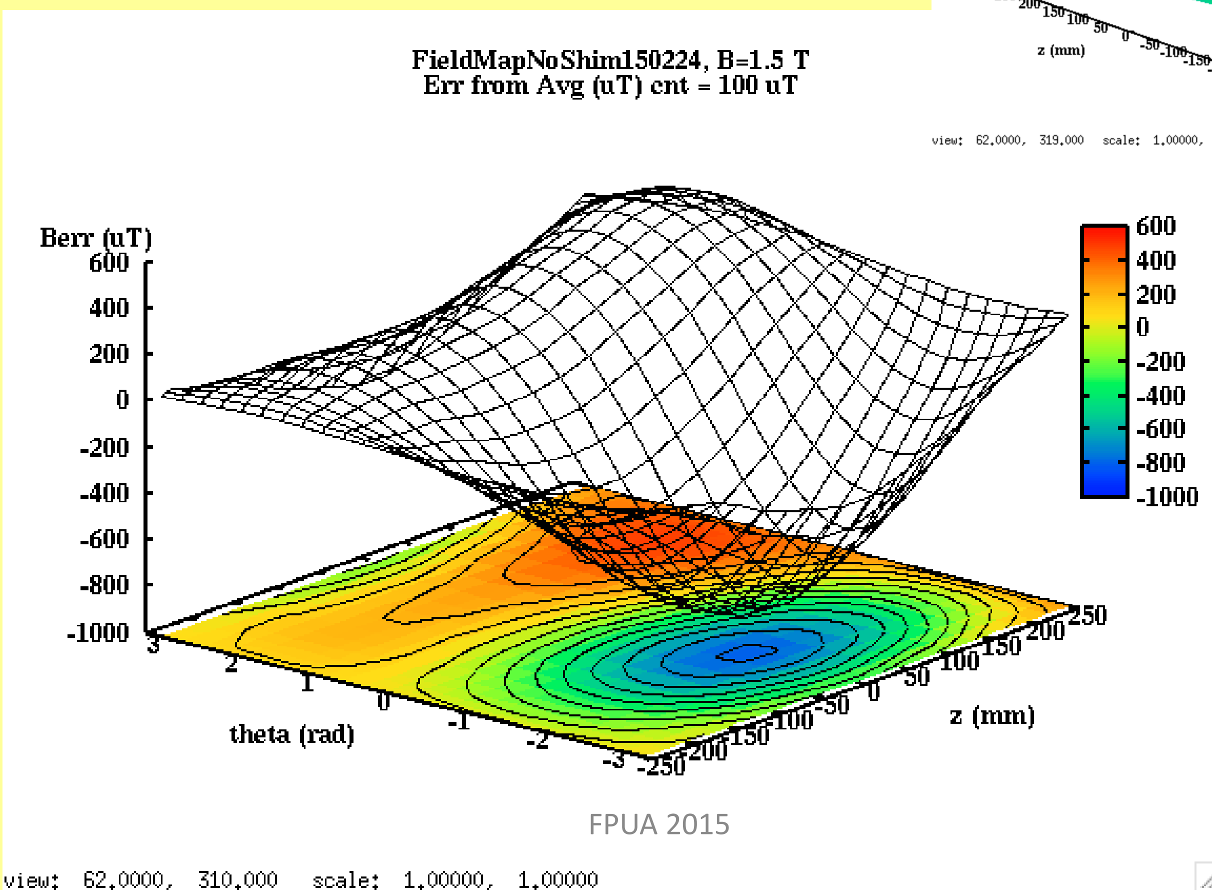
1. Measure magnetic field at 576 points (< 3 hour)
2. Calculate optimum arrangement of iron shim (< 1 hour)
3. Down magnetic field to Zero (~1 hour)
   – don’t need if small amount of iron piece would be installed
4. Put iron pieces into pockets according to calculation results (< 3-4 hours)
5. Excite magnet up to 1. 7 T (~ 1 hour)



No shimming

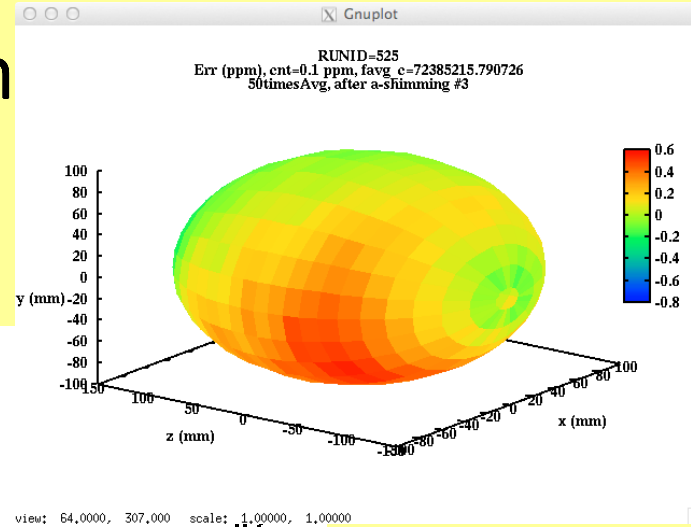
- Measured by field camera
  - 50cm DSV
    - 1.5 T : measured
    - 1.7 T : extrapolated from 1.5 T field map





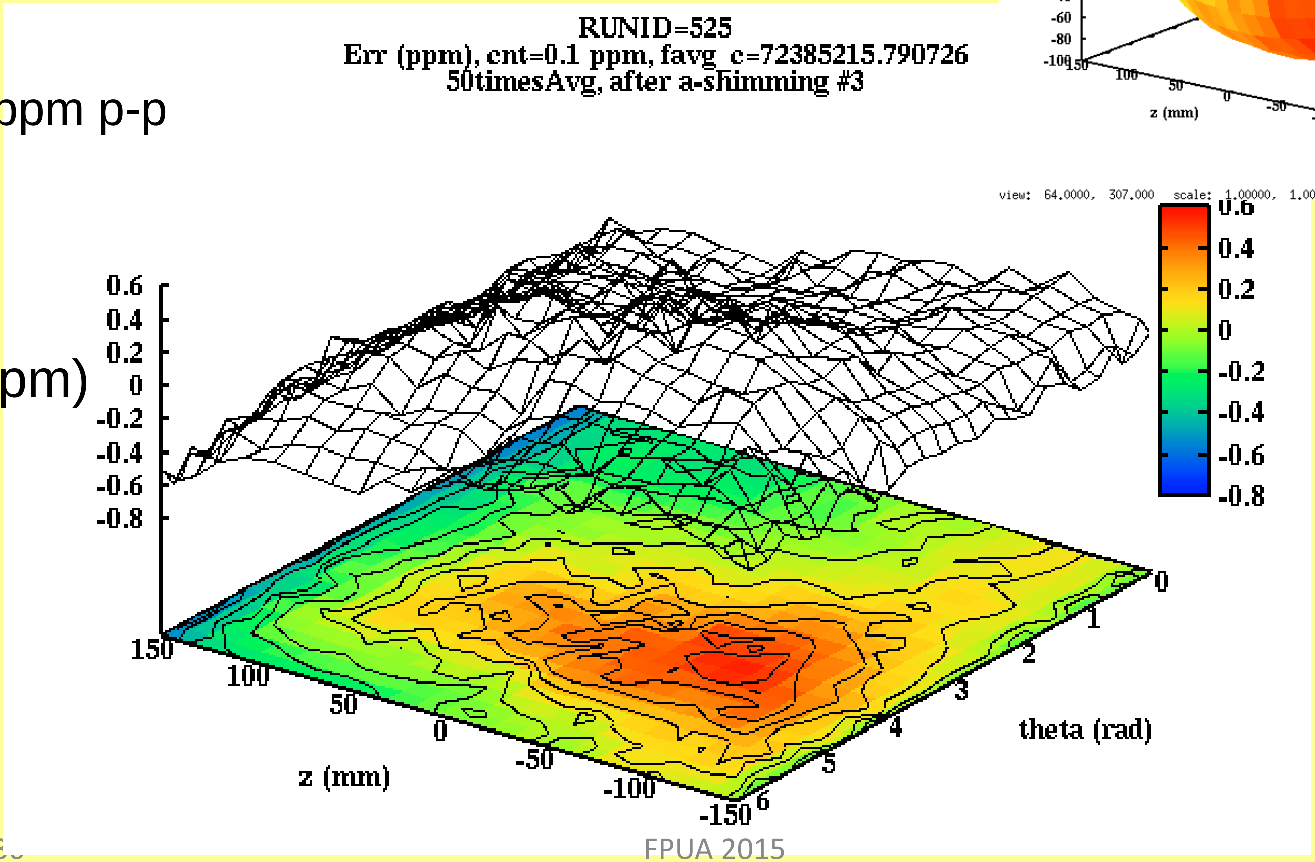
After shimming #3

- Measured by single probe system
  - Spheroid : r=100 mm, z=300 mm



1.4 ppm p-p

(ppm)



Summary of the second shimming test

	Iron volume	Measured homogeneity
No shim (expected from 1.5 T)		860 ppm p-p in 50cm DSV
After shimming #1	1063 cc	45 ppm p-p in Spheroid (r=140 mm, L=380 mm)
After shimming #2	103 cc	5 ppm p-p in Spheroid (r=140 mm, L=380 mm)
After shimming #3	8 cc	1.6 ppm p-p in Spheroid (r=140 mm, L=380 mm) 1.4 ppm p-p in Spheroid (r=100 mm, L=300 mm)
total : 1175	cc	

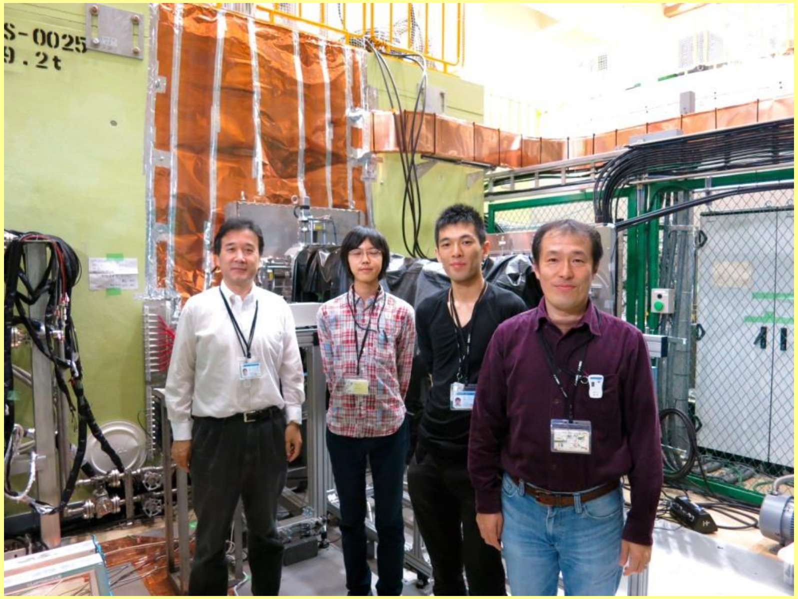
- Shimming at 1.5 T by Oxford
  - Total iron : 1264 cc
  - 3.884 ppm p-p in 30 cm DSV (0.338 ppm avg in 30 cm DSV)

Expected systematic error

	Accuracy	v12 v34	HFS	μ_μ/μ_p	
Magnetic Field	30 ppb		0.0 ppb	15 ppb	
RF power	0.2%	4Hz	0.8 ppb	8 ppb	
Kr gas temp.	0.2 K	< 2Hz	0.4 ppb	4 ppb	
Kr gas pressure	0.01 hPa	1Hz	0.2 ppb	0 ppb	
H impurity	<50 ppm	1Hz	0.5 ppb	0 ppb	
Quadratic pressure dependence		5Hz	1.0 ppb	5 ppb	
Muonium Position (x,y)	1mm	3 Hz	0.6ppb	6 ppb	
Muonium position(z)	1mm	< 1 Hz	0.2ppb	2 ppb	
Beam intensity	1e-4	< 1 Hz	0.2ppb	2 ppb	
Detector pile up		2.8 Hz 0.3 Hz	0.5 ppb <0.1 ppb	3 ppb <1 ppb	Without ab. With ab.

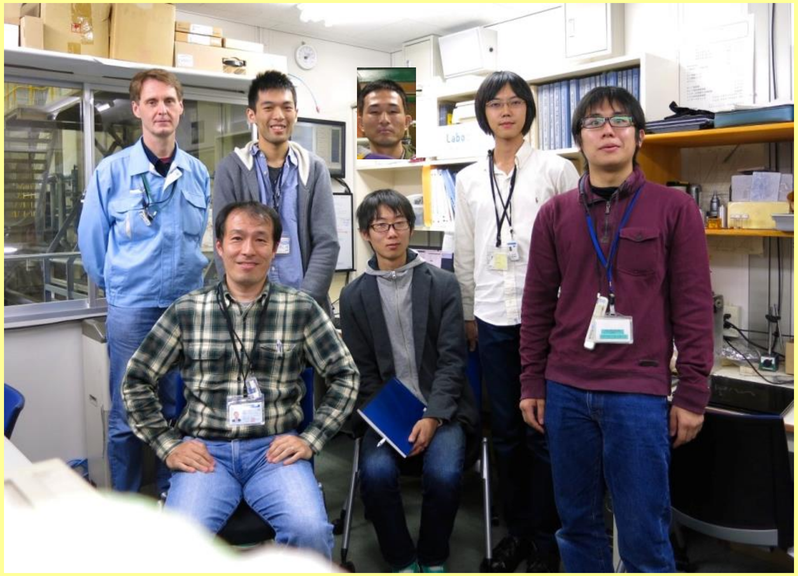
Total Systematic Error of HFS ~2 ppb, μ_μ/μ_p ~ 25 ppb

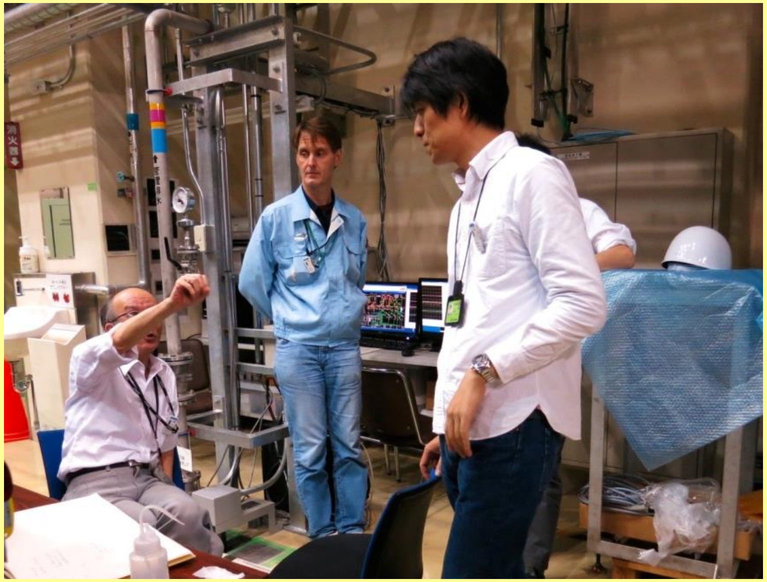
R& D MLF beam test



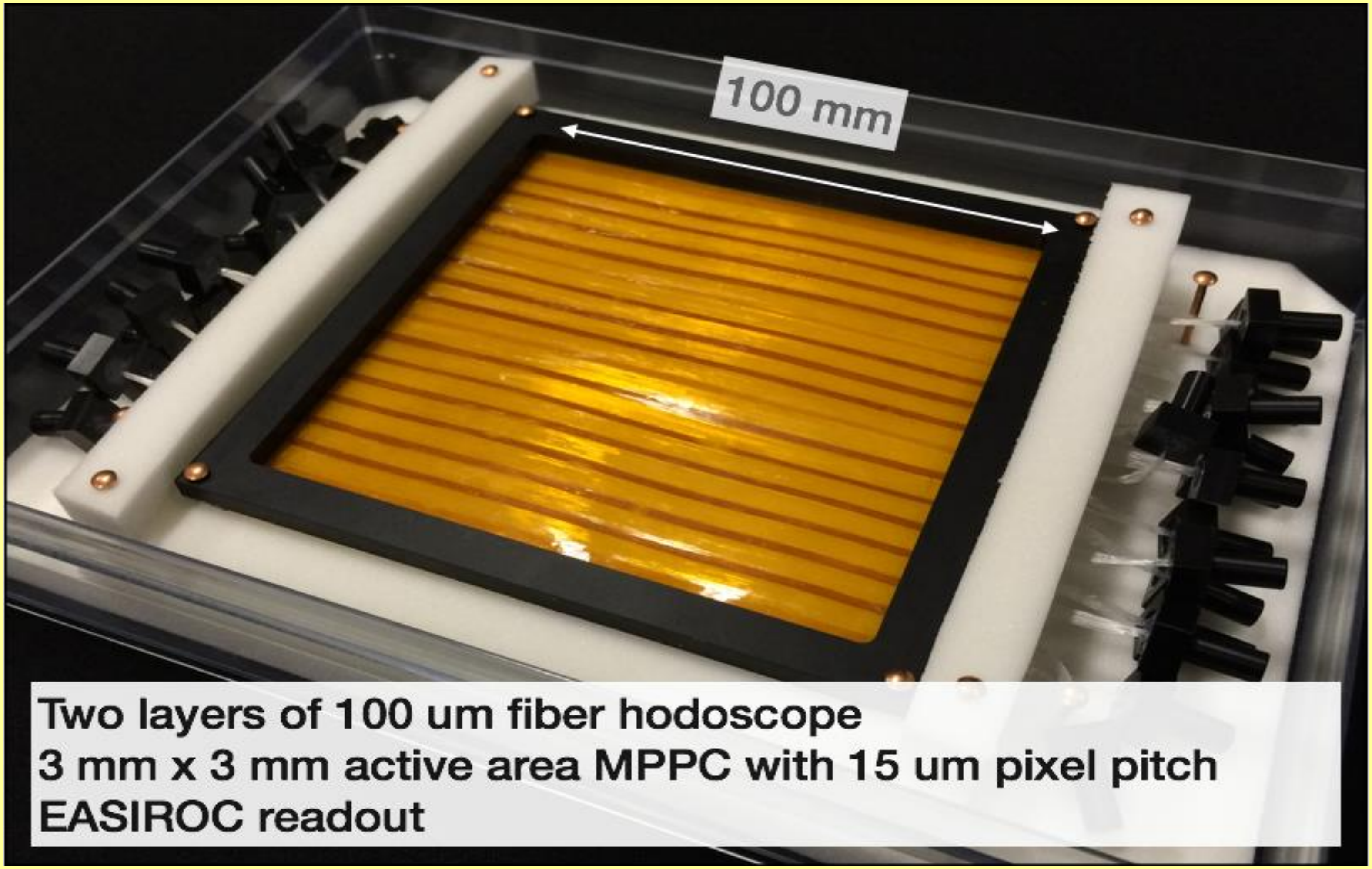
2014. Feb. 24-26
Test experiment for a positron counter prototype

2014. Nov. 8-9
Test experiment for an online beam profile monitor prototype and an offline beam profile monitor

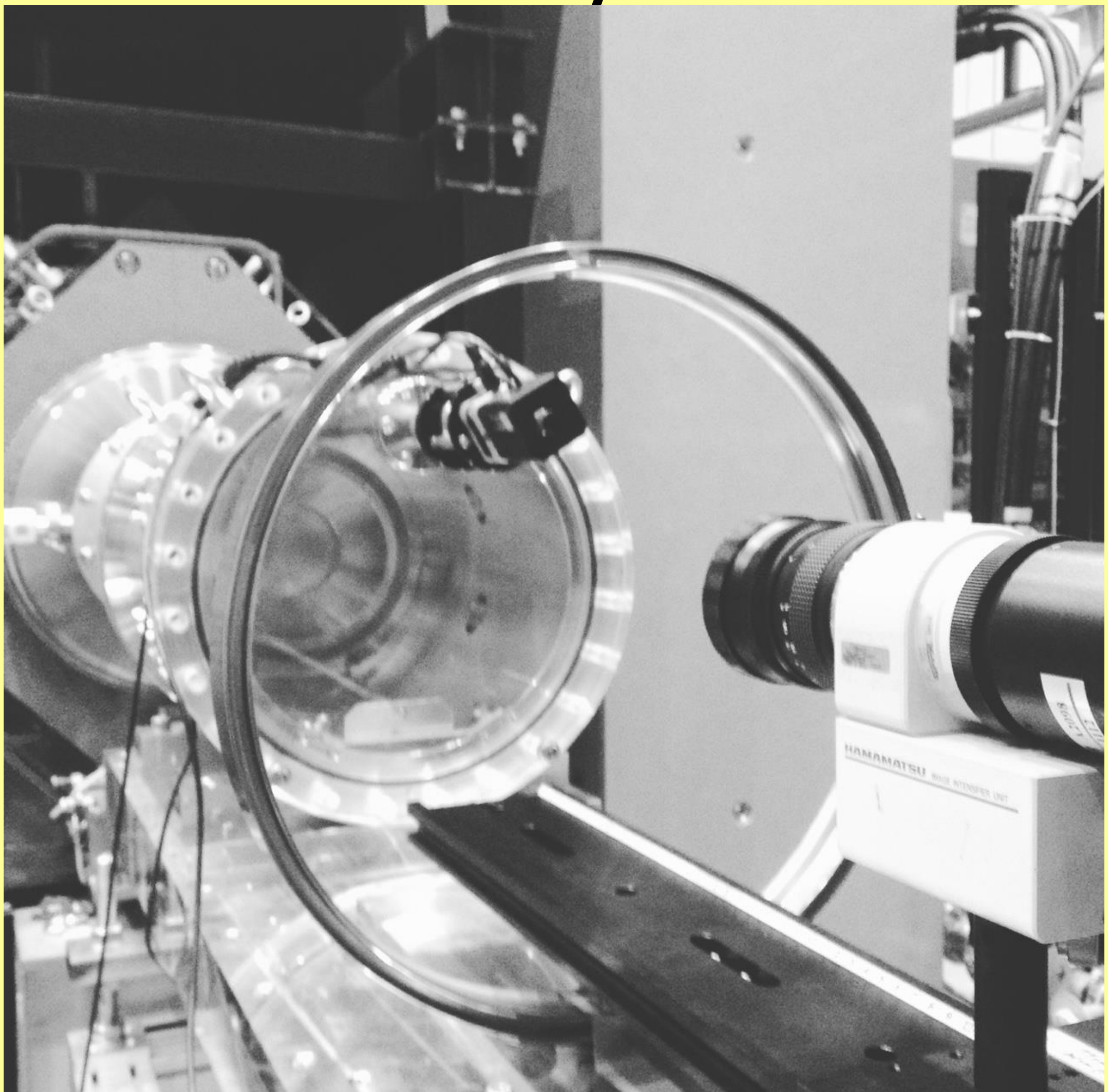




FBPM by Kanda



TBPM by Ueno



Positron Counter by Kanda

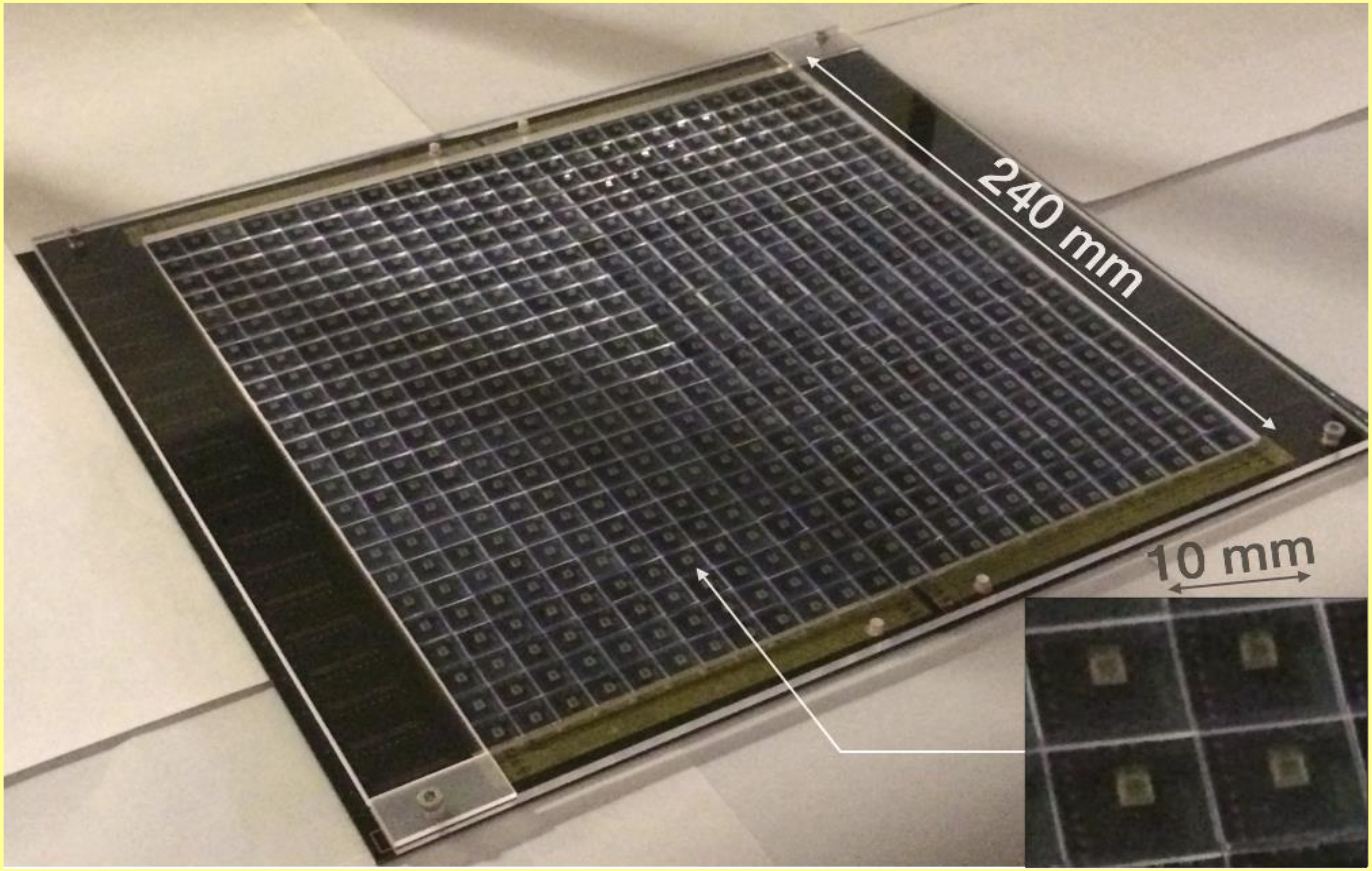
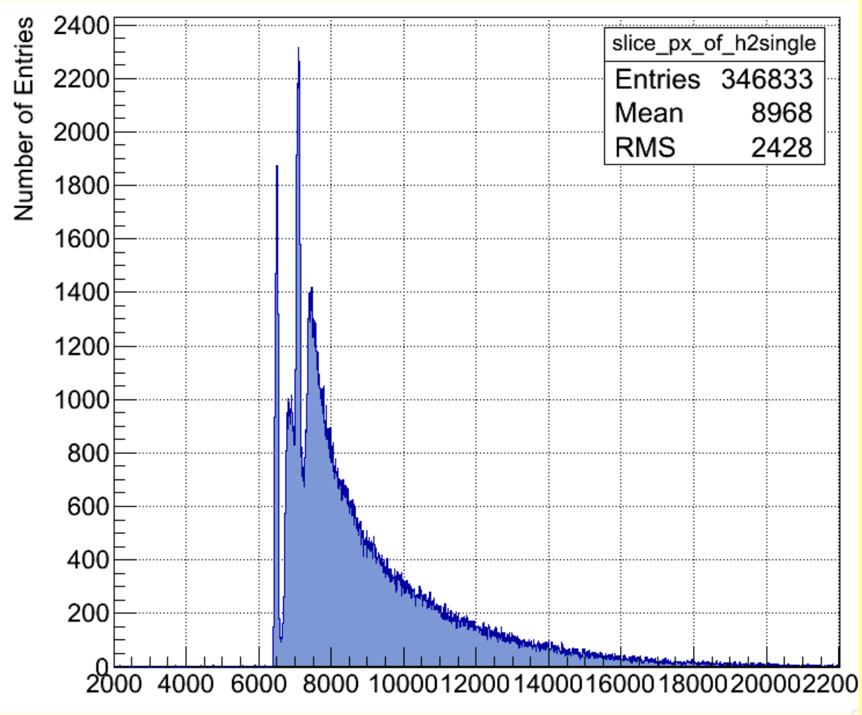


Fig. 3 Developed positron detector

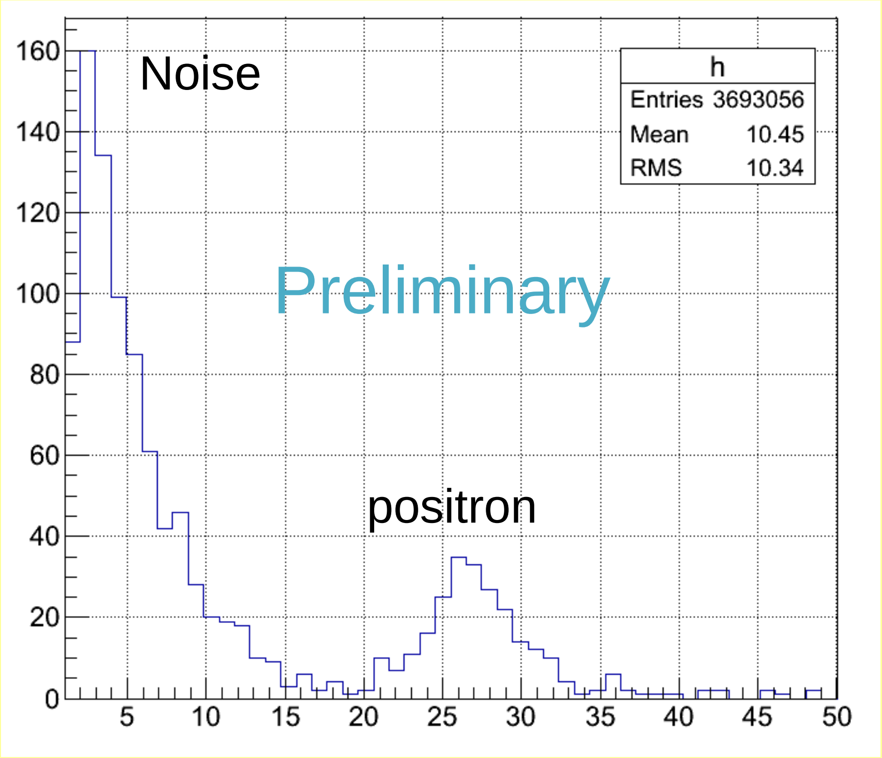
Operation check with muon beam

muon decay time spectrum



time (ns)

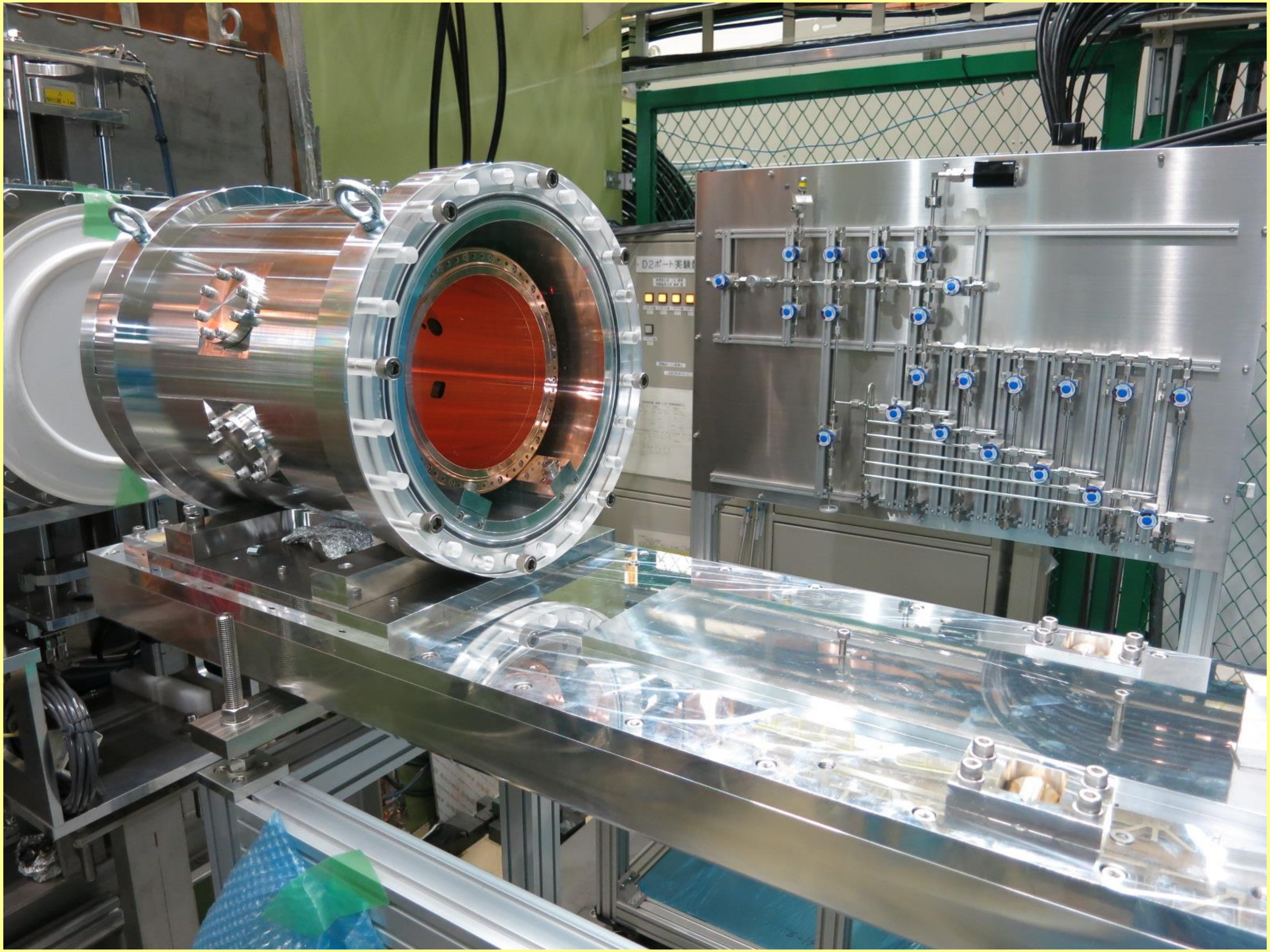
TOT spectrum



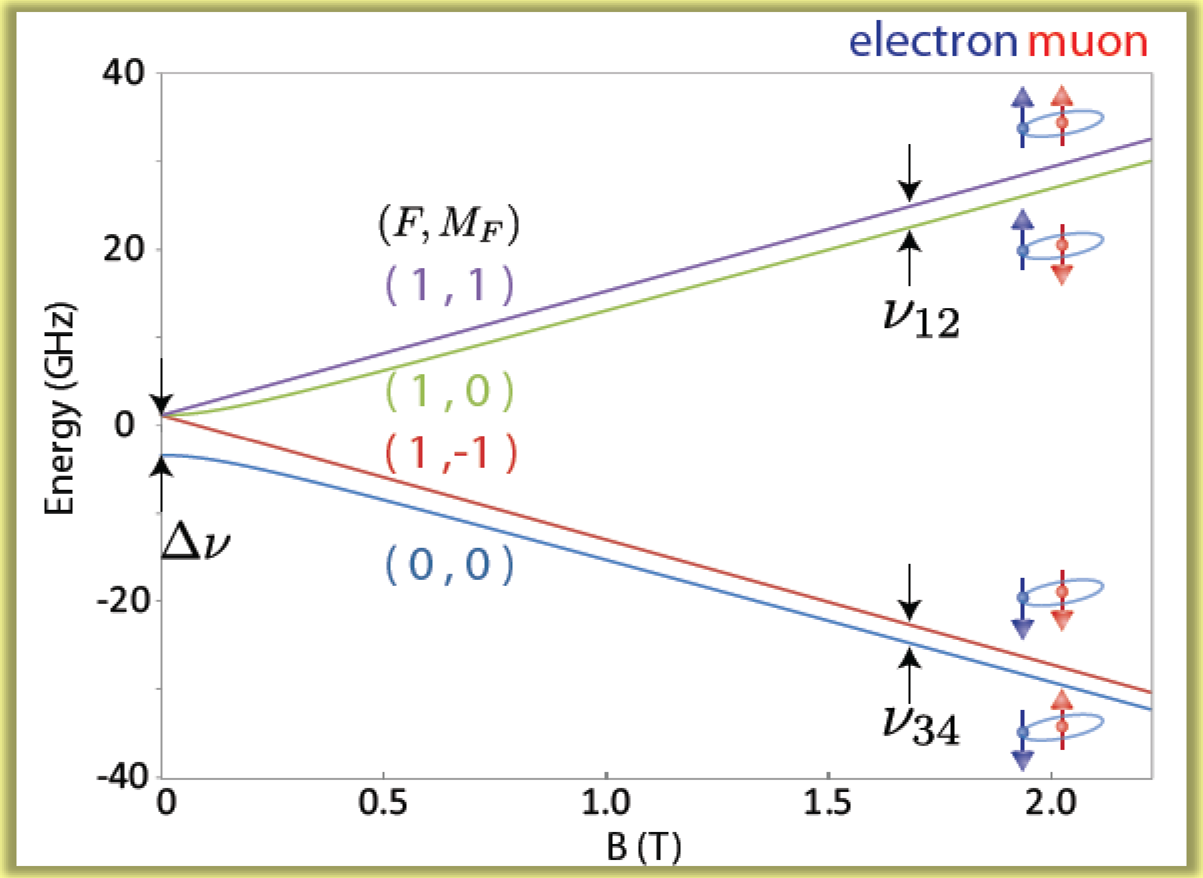
# of photon converted from TOT

Basic operation check of a positron counting system was done
detailed study is in progress

RF cavity, Kr Chamber, Gas handling

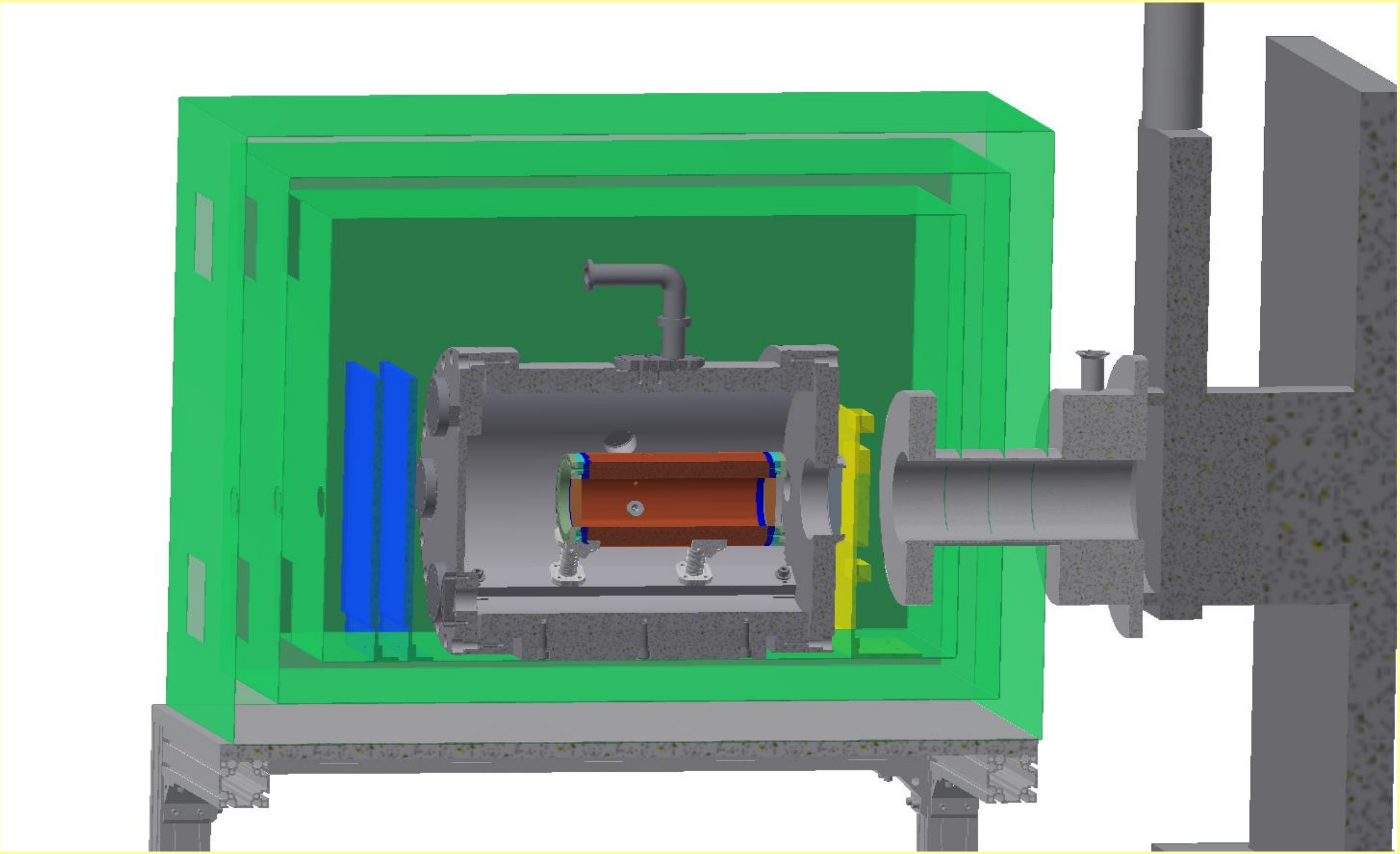


Zero field measurement at D2 (1/15~1/19) 4days

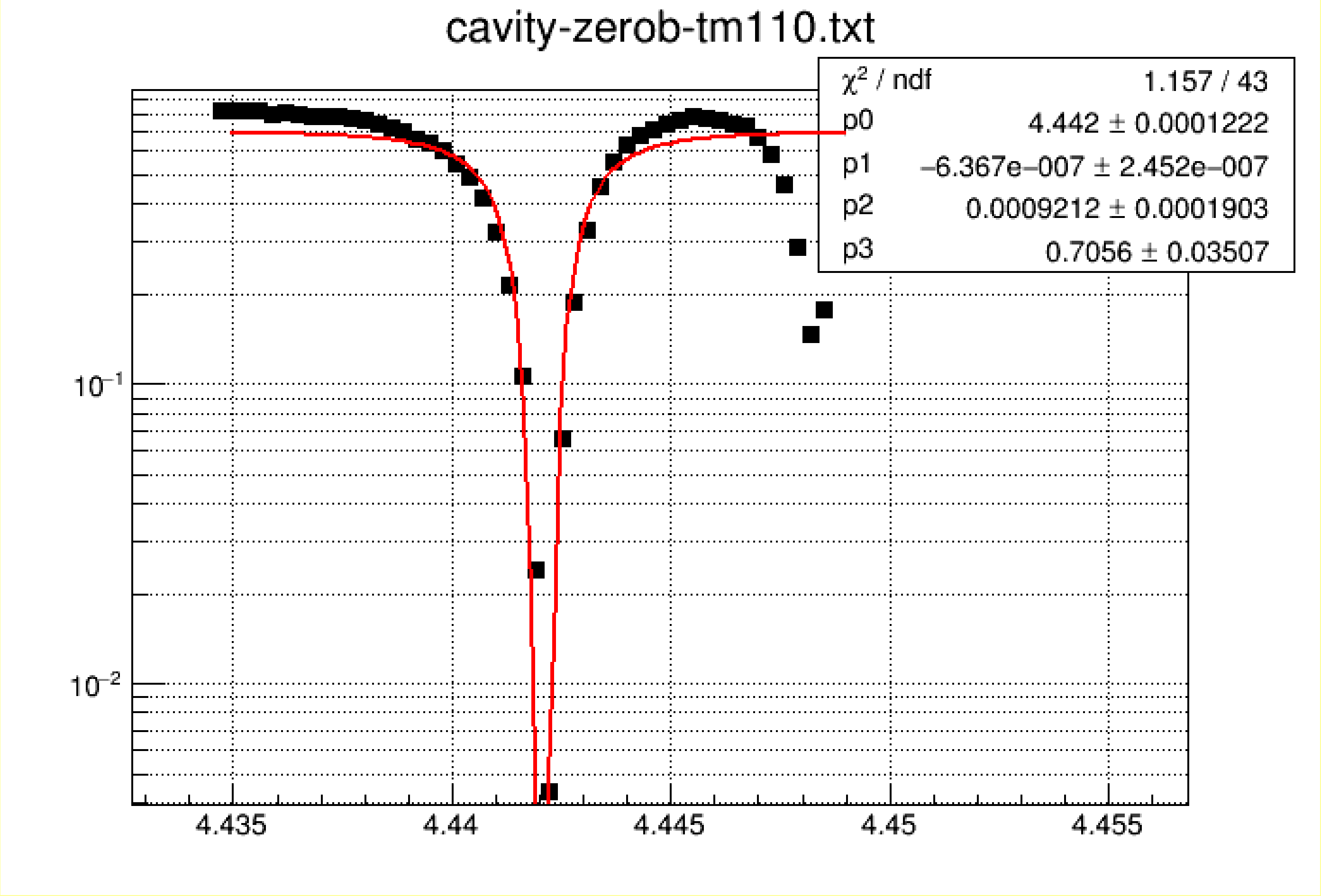


Expected accuracy 70ppb

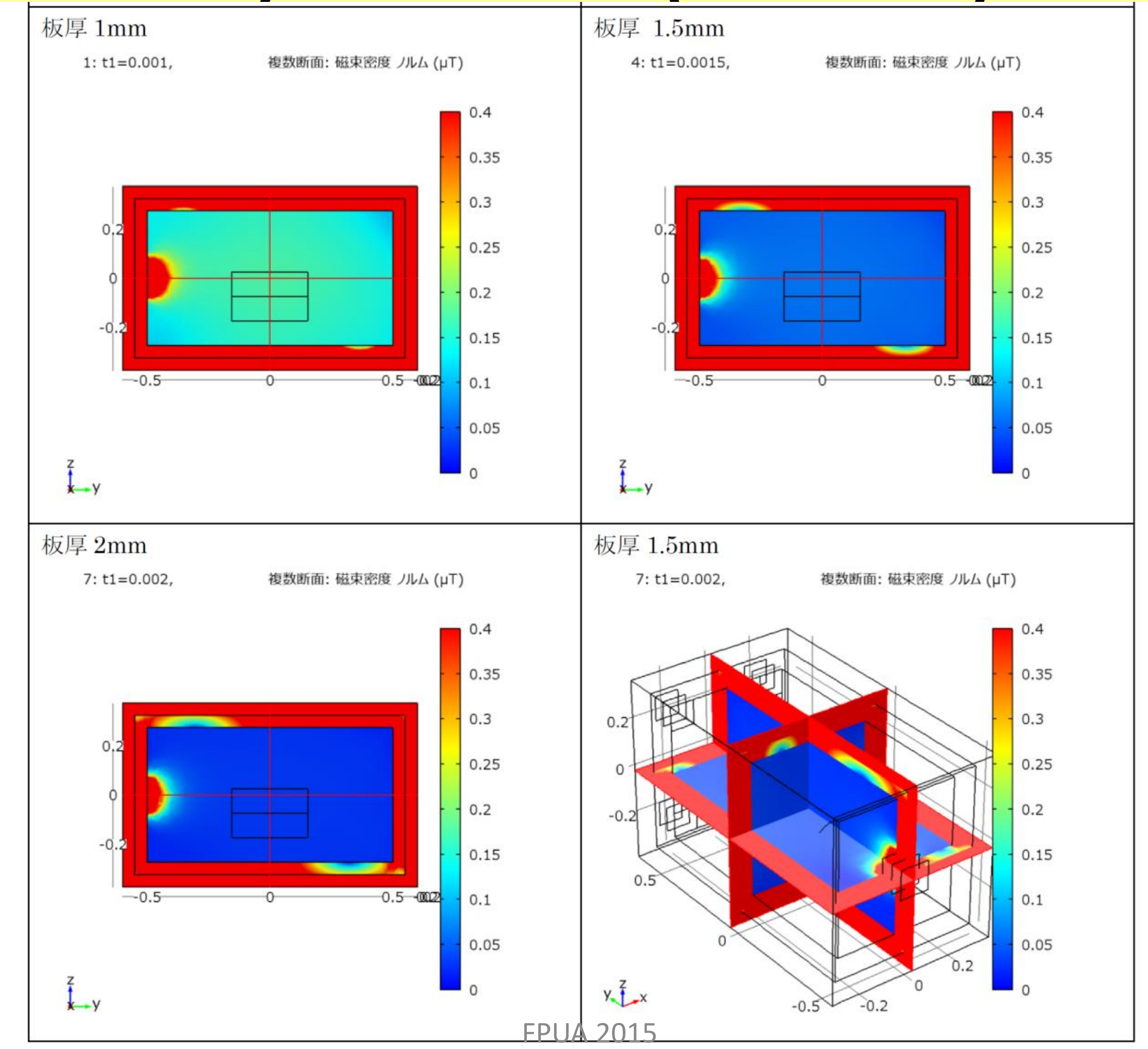
Setup for zero field measurement by Tanaka

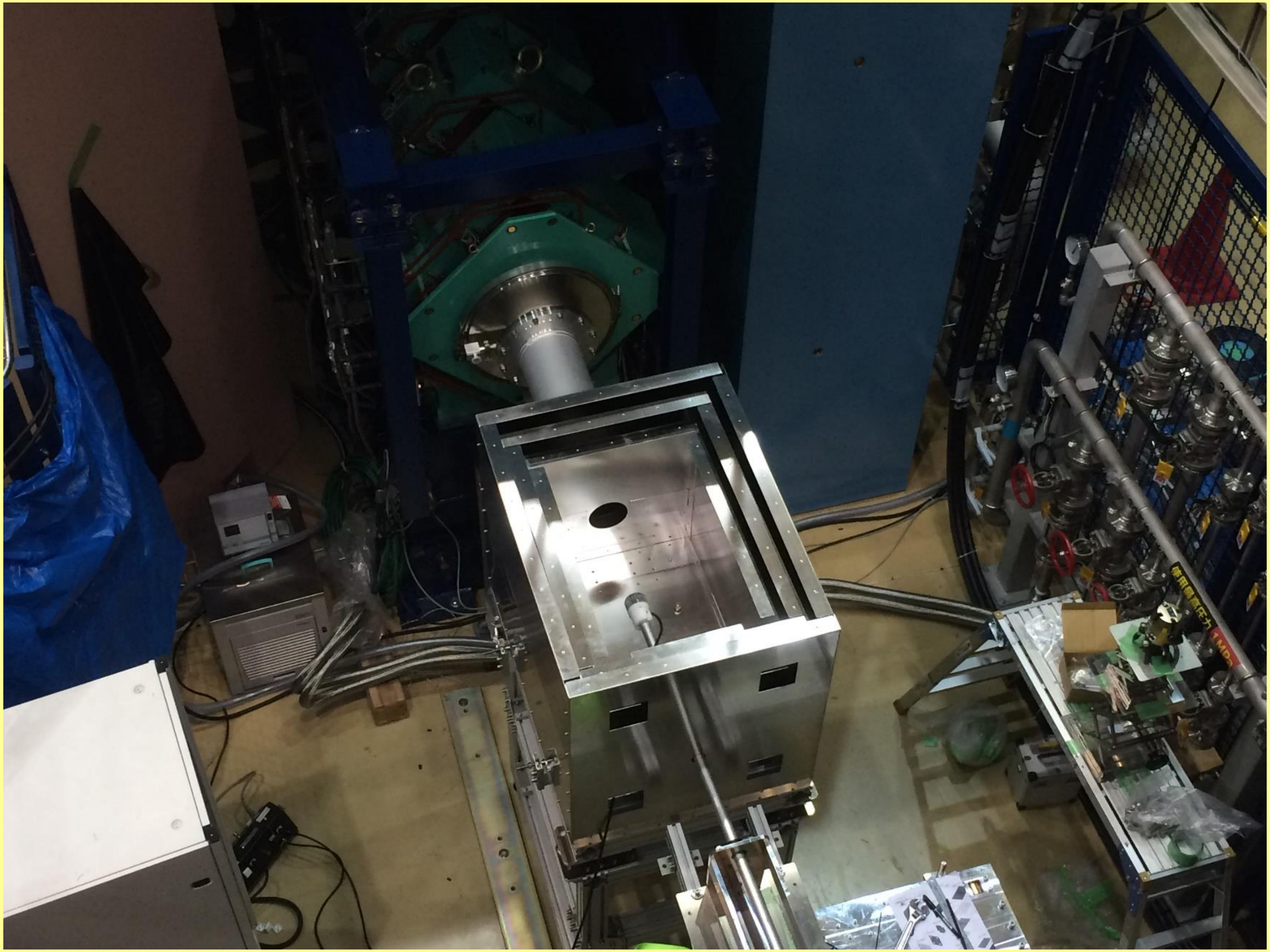


Measurement of Q value



Magnetic field simulation by Tanaka (~1mG)





0.1mG is established

Summary

Next muonium HFS measurement at high magnetic field will be carried out within a year.

The expected accuracy will be ~ 2ppb(~8Hz) in HFS
~25ppb in μ_μ/μ_p

Next beam time at D2, we will perform ZF measurement for engineering run of apparatus