NUFACT2014, XVIth International Workshop on Neutrino Factories and Future Neutrino Facilities
University of Glasgow, 25-30 August 2014, Scotland.

Status of the New Muonium HFS Experiment at J-PARC/MUSE

P. Strasser (KEK)
on behalf of the MuSEUM Collaboration

Slides by K. Shimomura (KEK)

New Collaboration Name

MuSEUM

Muon Spectroscopy Experiment Using Microwave

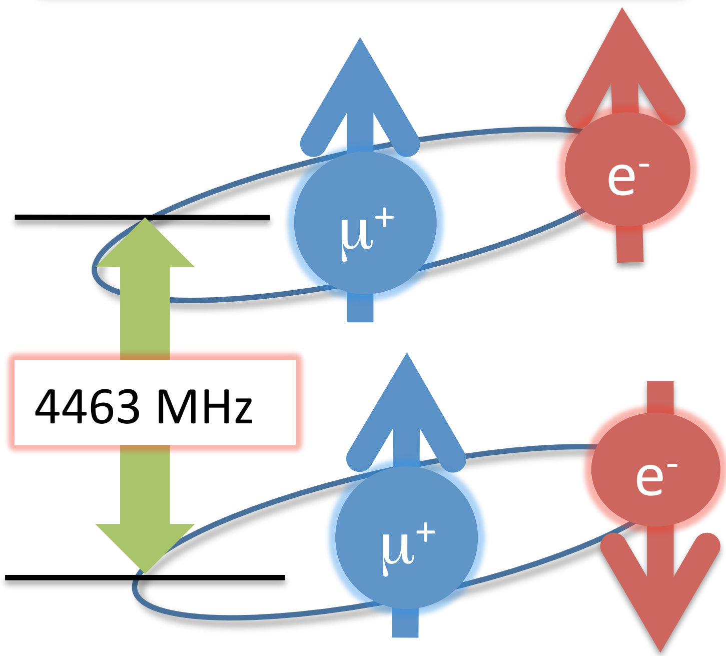
Muonium ground state

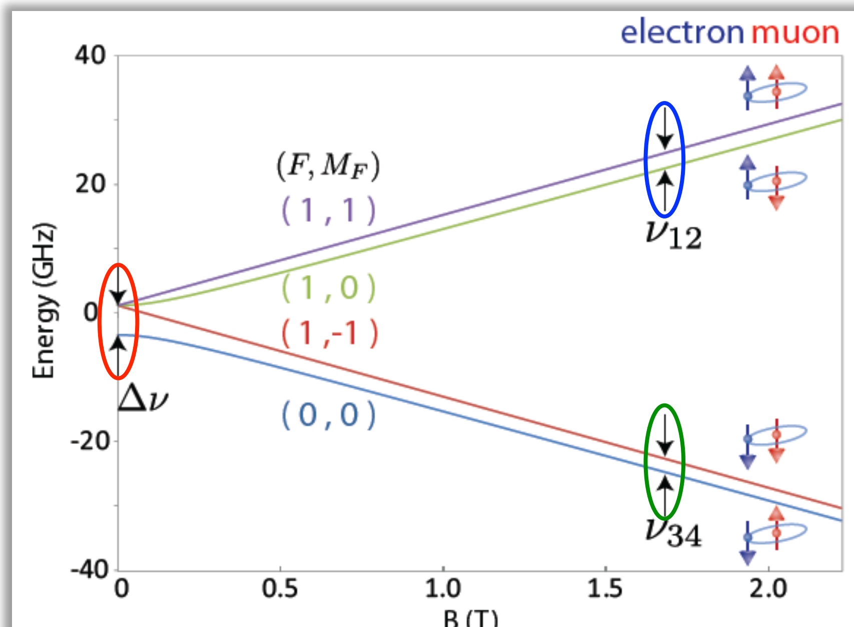
$$\mathcal{H} = h\Delta\nu \mathbf{I}_\mu \cdot \mathbf{J} - \mu_B^\mu g'_\mu \mathbf{I}_\mu \cdot \mathbf{H} + \mu_B^e g_J \mathbf{J} \cdot \mathbf{H}$$

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

Zeeman Splitting

Breit-Rabi diagram





Pure lepton
= point particle

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

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

Purpose of MuSEUM

- Measure two RF resonances (ν_{12} and ν_{34}) in 1.7 T magnetic field.
- Muonium ground state HFS
  - Precise test of bound-state QED
  - Current uncertainty: 12 ppb
  - Test of CPT and Lorentz Invariance
- Muon magnetic moment relative to that of proton
  - Basic property of muon
  - Current uncertainty: 120 ppb
  - Basic input parameter for muon g-2 experiment

We aim to improve the uncertainties of both quantities by a factor of 10, taking advantage of the high intensity beam at J-PARC/MUSE.

Recent Summary of experimental and theoretical data (by D. Nomura)

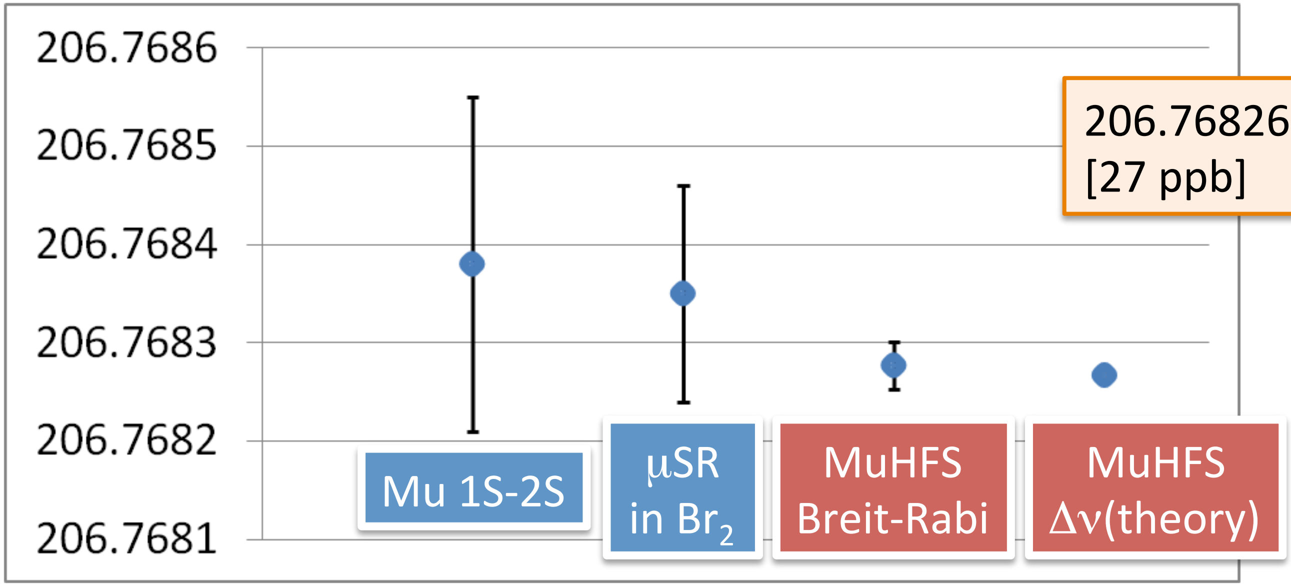
D. Nomura, Nucl. Phys. B 867 (2013) 236-243

Exp.	ν_{HFS}(exp.)	4463.302 765 (53) MHz [12 ppb]
The.	ν_{HFS}(theory)	4463.302 891 (272) MHz [63 ppb]
	ν_{HFS}(QED)	4463.302 720 (253)(98)(3)
		(m_μ/m_e)(QED)(α)
	ν_{HFS}(weak)	-65
	ν_{HFS}(had. v.p.)	232(1)
	ν_{HFS}(had. h.o.)	5

QED calculation → 10 Hz accuracy within a few years (by Eides)

Determination of the Muon Mass

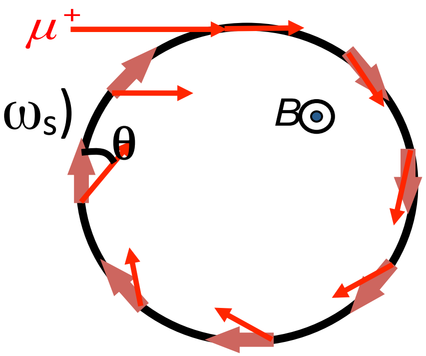
μ_μ/μ_p, a_μ, μ_p/μ_B → m_μ/m_e



Muon mass (CODATA2010) determined by MuHFS (LAMPF 1999)

Why Mu 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) $\omega_a \propto (g-2)/2 = a_\mu$

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

a_μ *an independent precise muon mass measurement is required!*

- The ratio to the proton NMR frequency is important!

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

From g-2 storage ring   From Muonium HFS

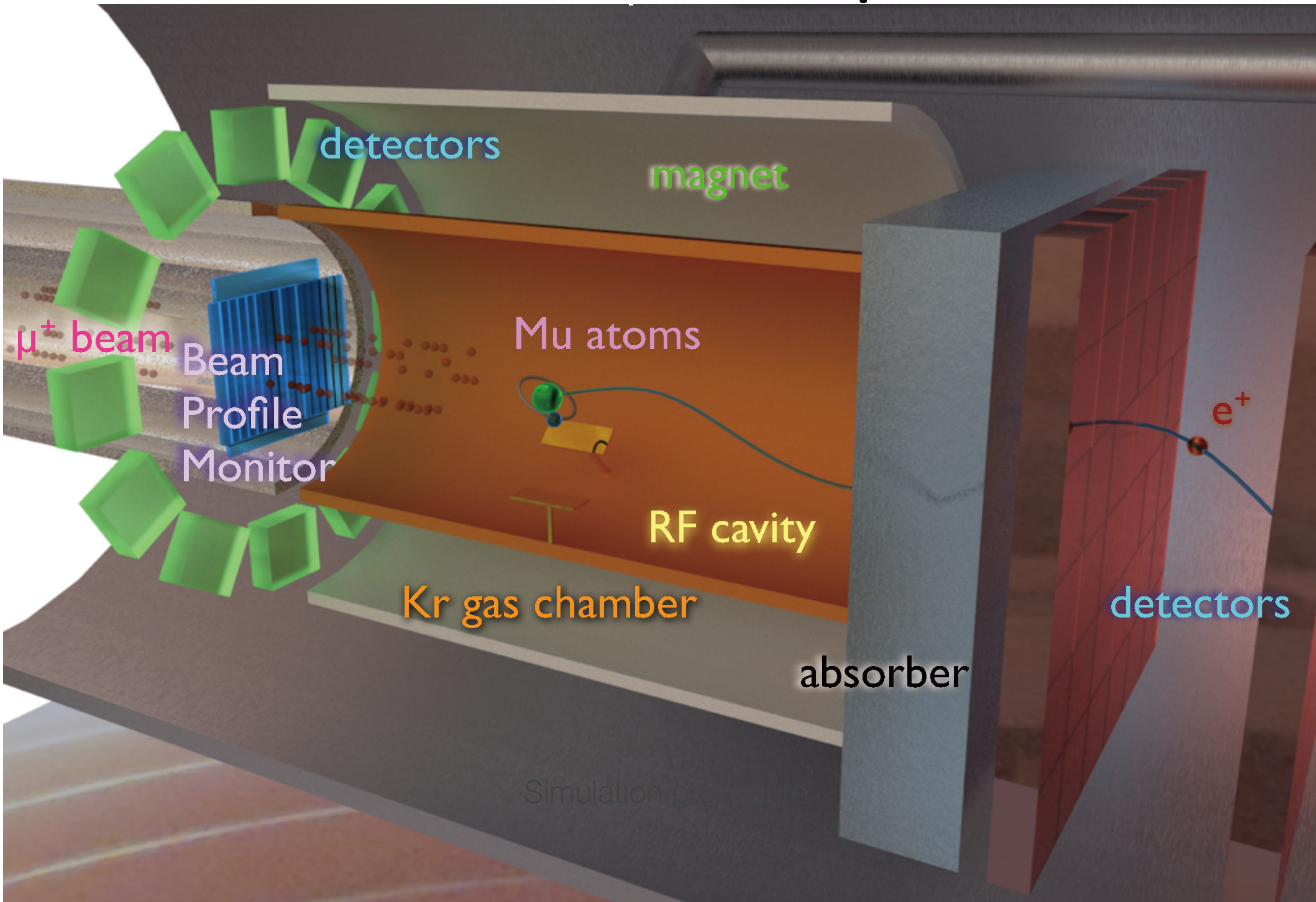
$$\frac{\omega_a}{\omega_L(\mu)} = \frac{a_\mu\left(\frac{eB}{mc}\right)}{g_\mu\left(\frac{eB}{2mc}\right)} = \frac{a_\mu}{\left(\frac{g_\mu}{2}\right)} = \frac{a_\mu}{1+a_\mu}$$

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

μ_μ/μ_p accuracy from direct measurement of 120 ppb.

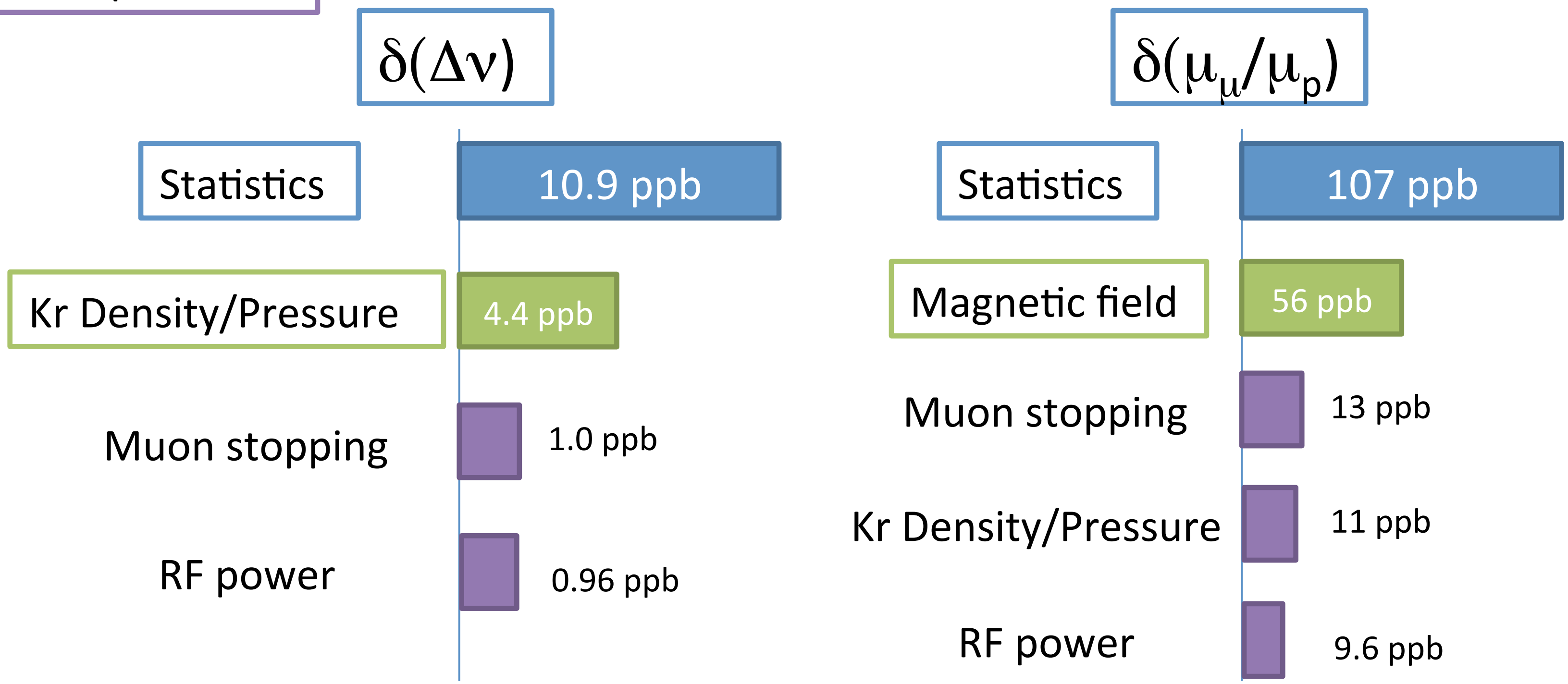
W. Liu et al., Phys. Rev. Lett. 82 (1999) 711

Schematic of the Experiment



Improvement of statistics

LAMPF Experiment



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

x200 →

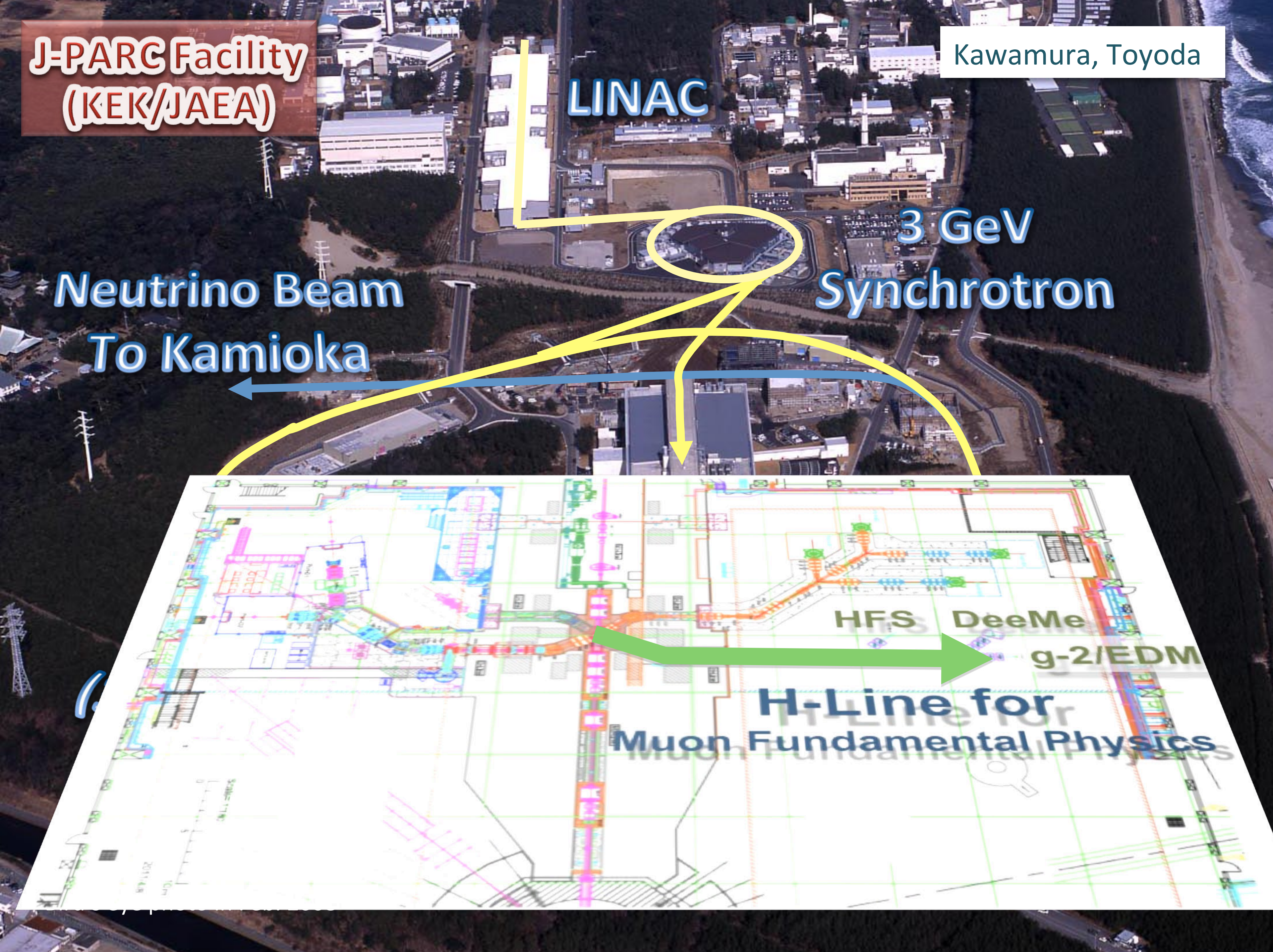
J-PARC/MUSE: **Pulsed 1x10^8**/s
H-Line total 2×10^{15}

Systematic error

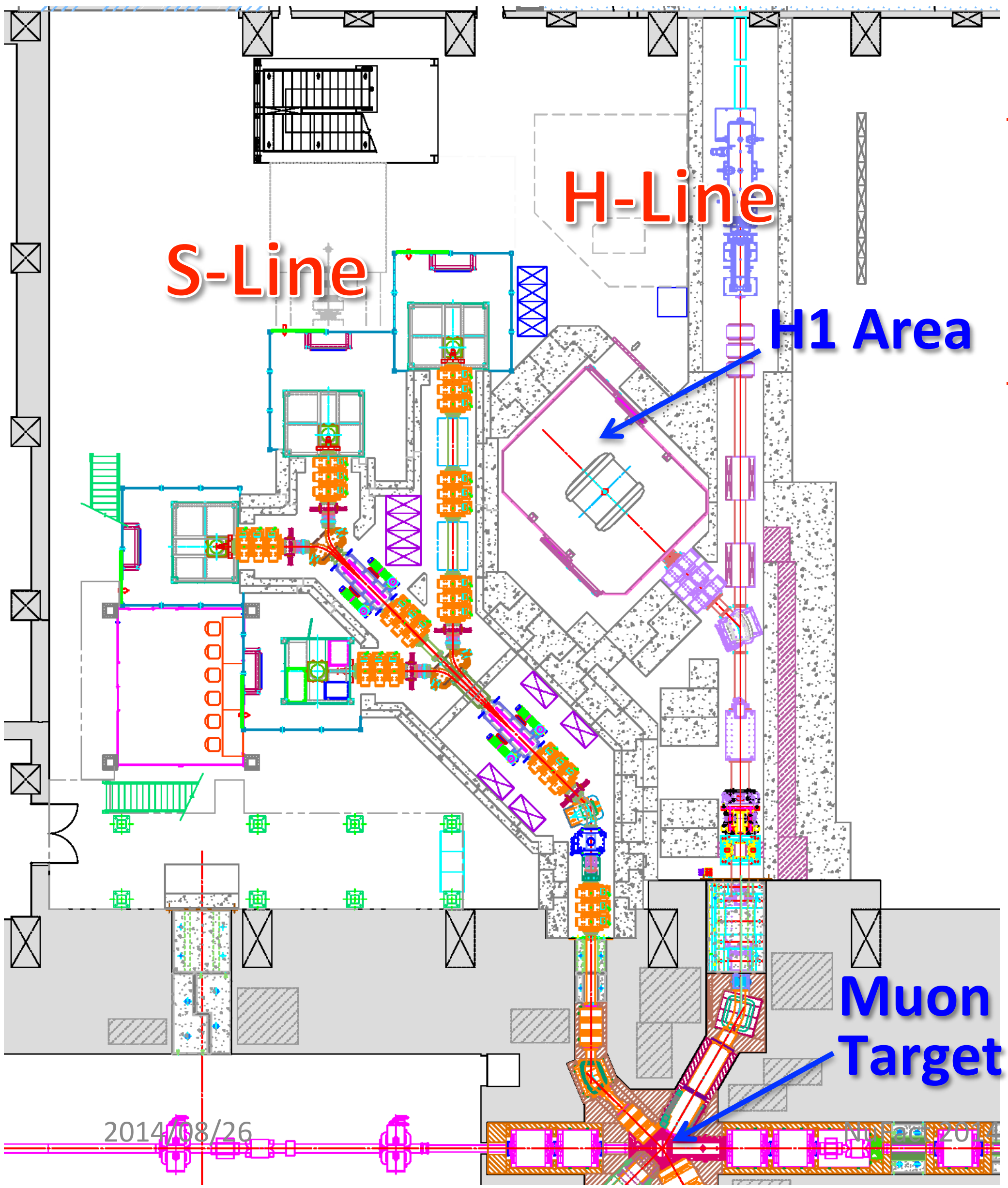
LAMPF $\delta(\mu_\mu/\mu_p)$				J-PARC MUSE
Statistics	107 ppb	x200		**Intense pulsed muon beam**
	DC 10^7/s, total 10^{13}		▶	**Pulsed** 10^8/s, total $2\text{x}10^{15}$
Magnetic field	56 ppb		▶	**More Uniform Field + Stability**
Muon stopping	13 ppb accuracy 5 mm		▶	**Beam profile monitor (accuracy ～1 mm)**
Kr Density/Pressure	11 ppb cavity length: 159.73mm		▶	**Low gas density : Long RF cavity (~300 mm)**
RF power	9.6 ppb		▶	**RF Input：Coaxial cable**

Key Components

• Intense Muon Beamline	Kawamura, Toyoda
• MuHFS S.C. Magnet	Sasaki, Mizutani, Ueno, Higashi
• RF Cavity	Tanaka, Matsuda
• Kr Chamber	Tanaka, Torii, Strasser
• Positron Detector	Kanda, Fukao, Mibe
• Beam Profile Monitor	Tajima, Toyoda, Ito
• Systematic Error Study	Tanaka, Kanda, Ishida


J-PARC Facility
(KEK/JAEA)
Kawamura, Toyoda
LINAC
3 GeV
Synchrotron
Neutrino Beam
To Kamioka
HFS
DeeMe
g-2/EDM
H-Line for
Muon Fundamental Physics

MLF Experimental Hall No.1

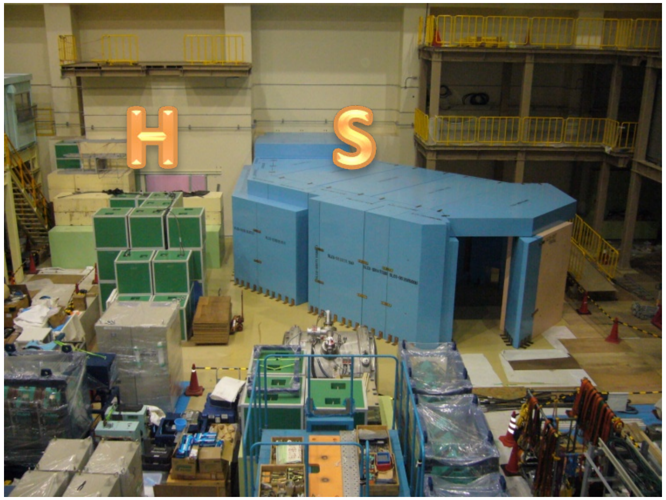


S-Line: suface muon

Surface muons are provided to four experimental areas simultaneously.

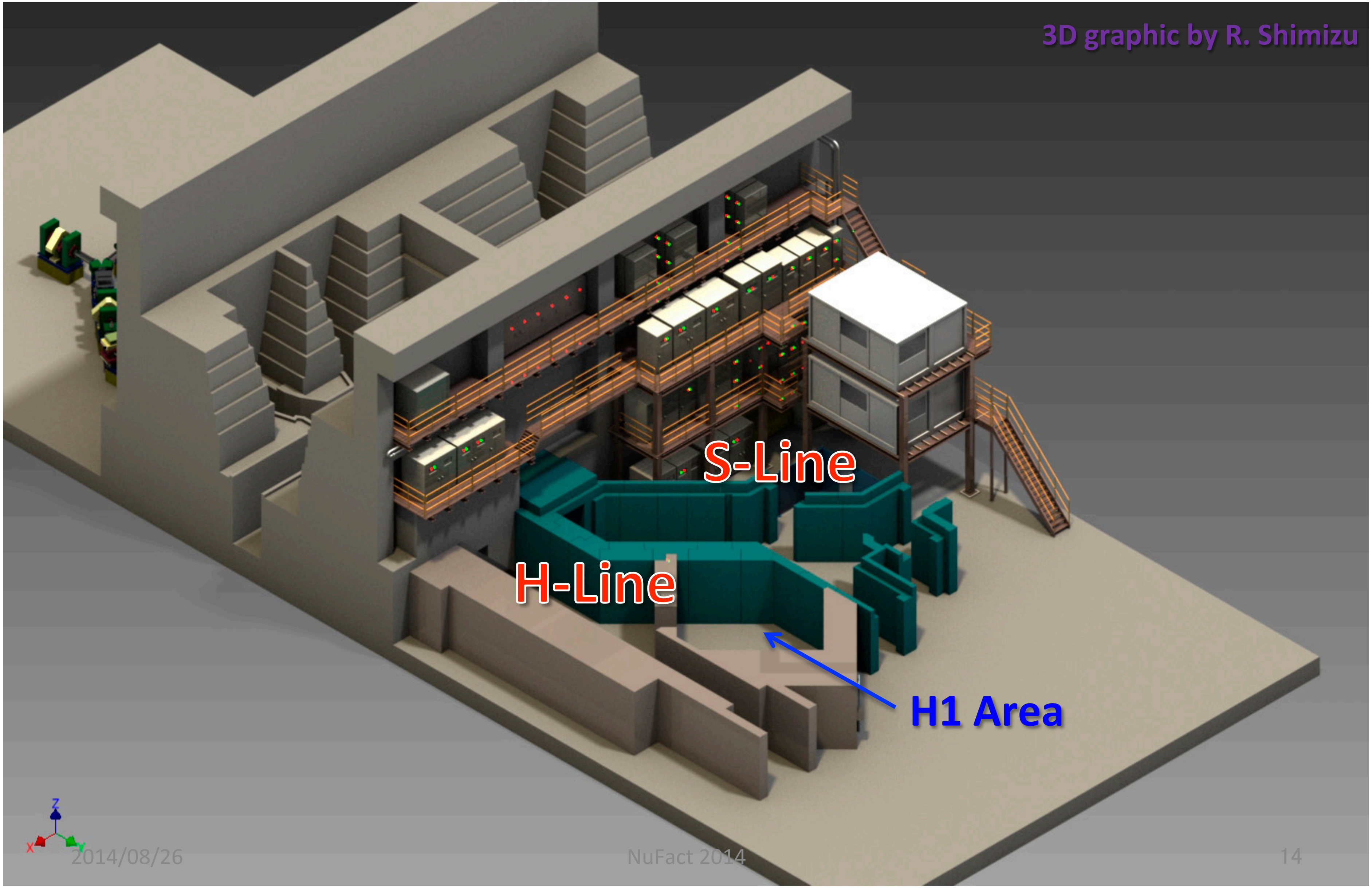
H-Line: large scale experiments

Higher intensity tunable (<120MeV/c) μ^+ and μ^- beams are provided.
(g-2, MuSEUM, Deeme, …)



Experimental Hall No. 1 (Dec. 20, 2013)

MLF Experimental Hall No.1



S.C. Magnet (MRI magnet)

Sasaki, Mizutani, Ueno

- Stability: 0.03 ppm/h
- Uniformity (30cm DSV) < 1 ppm
- Effective bore radius: 680 mm
- Multi NMR probe for precise field measurement.
- With shim coils (in the magnet), and Fe shimming plates.
- Twice 500L LHe refilling a year is needed.

Length	2014 mm
Outside diameter	2152 mm
Minimum roof height	2688 mm
Weight	10.5 tons
Bore diameter	925 mm
Central magnetic field strength	2.9 T
B field leakage (5 Gauss)	Z6 m
	R3.5 m
Uniformity	2.0 ppm @ 40 cm DSV
	1.0 ppm @ R30 cm, Z20 cm

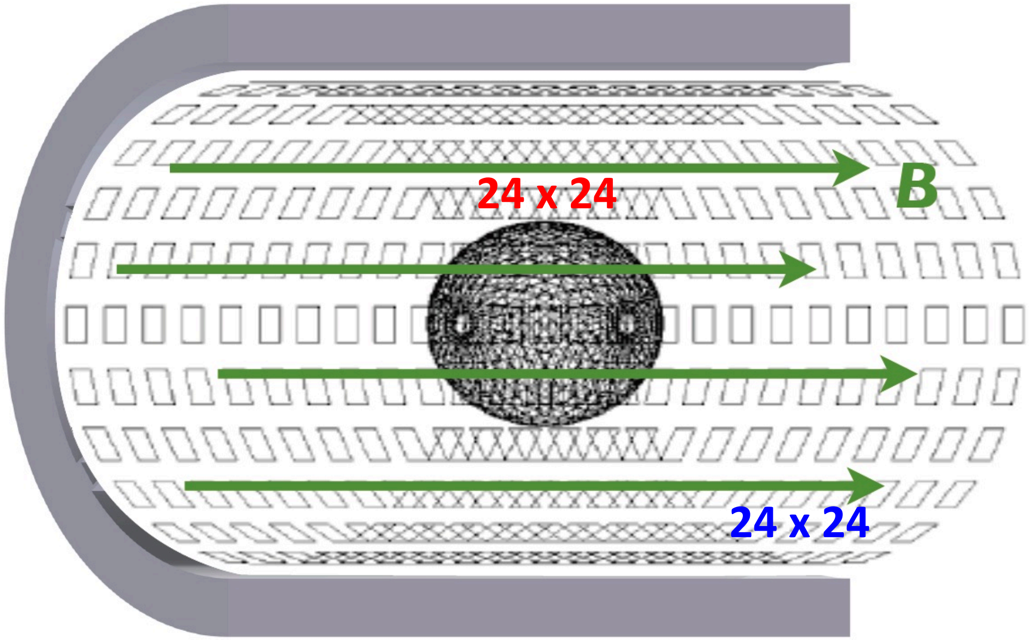
Superconducting Magnet

1.7 T high-precision superconducting magnet

Bore diameter = ø925 mm

Requirements: **O(0.1 ppm)** homogeneity + **absolute** calibration in 300 mm x ø200 mm spheroidal region

- Field strength to be measured by water NMR probes.
  24 probes x 24 positions
- Field correction by shim coils and insertion of Fe shim plates.
- Shim plate positioning to be calculated by Singular Value Decomposition Method.
- Iterative process of field adjustment.



B Field Monitoring System

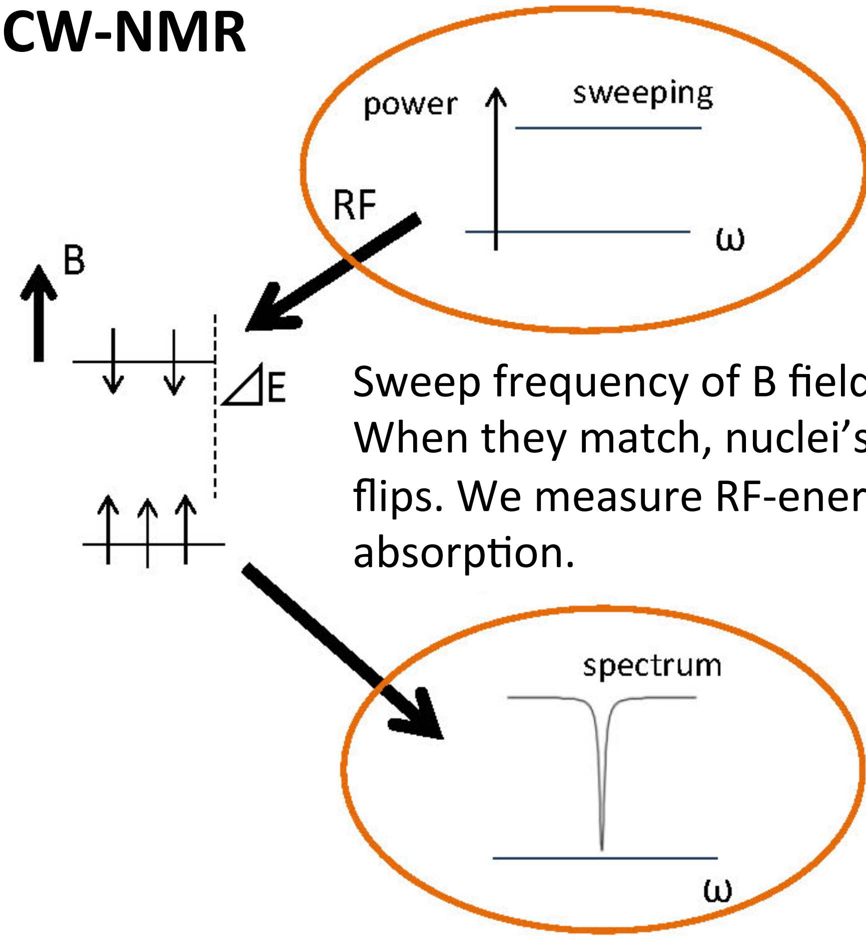
- The homogeneity of the B field in our magnet should be better than 0.1 ppm.

- So, we need to measure the B field with high accuracy, or 0.05 ppm.
- Measuring time should be short (a few hours).

B Field Monitoting System

By Mizutani

CW-NMR



Sweep frequency of B field. When they match, nuclei's spin flips. We measure RF-energy absorption.

NMR Unit

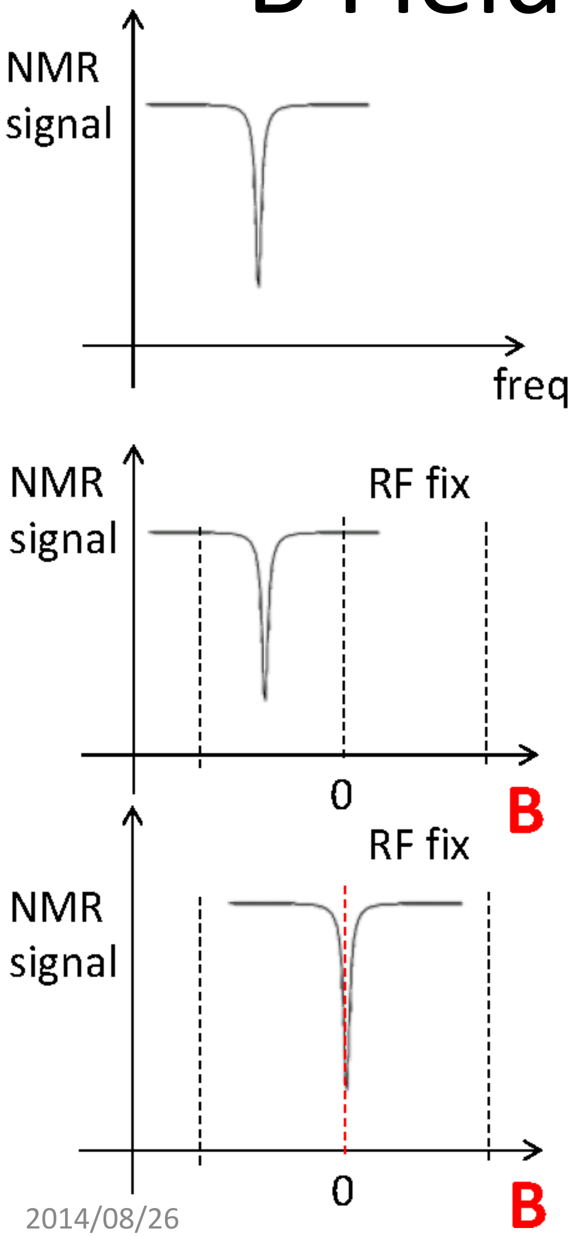
Echo-denshi

We use commercial NMR unit.

Some improvements are required.

B Field Monitoting System

By Mizutani



Sweeping RF frequency linearly is difficult. → We fix the RF frequency.

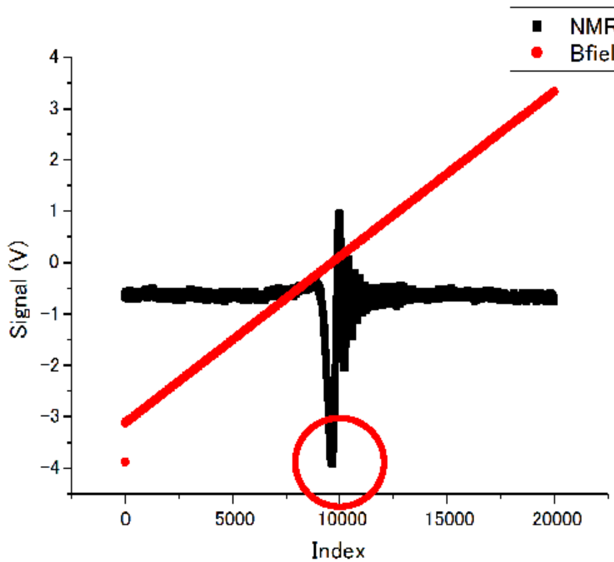
We sweep B field around a cell with another coil.

1. **Get NMR resonance signal.**
2. **Change RF frequency (resonance moves).**
3. **When the resonance peak comes to the zero-crossing point, we get the resonant frequency = B field.**

By this way, we can get rid of the uncertainty of the B field modulation coil.

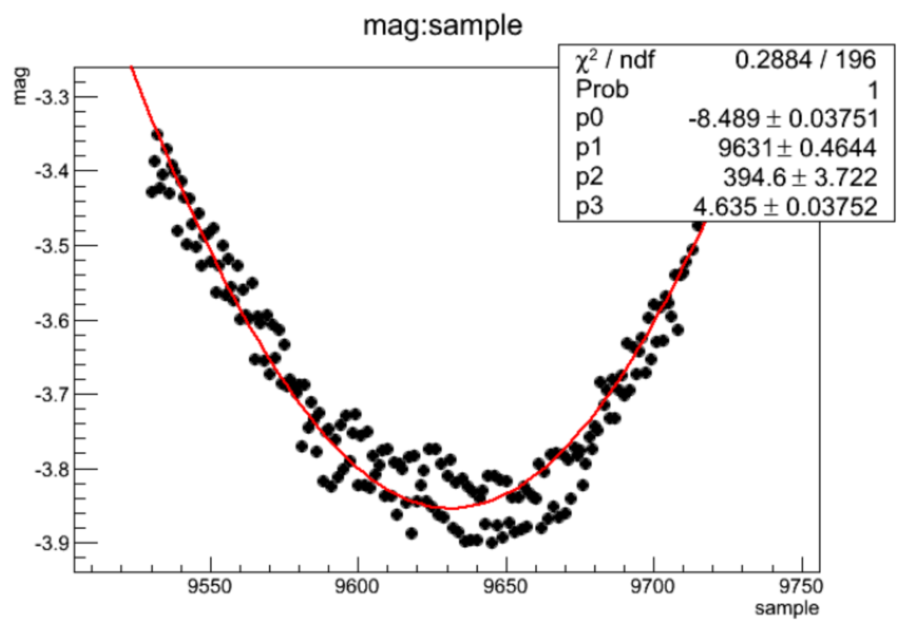
Fixed Point Measurement Test

By Mizutani



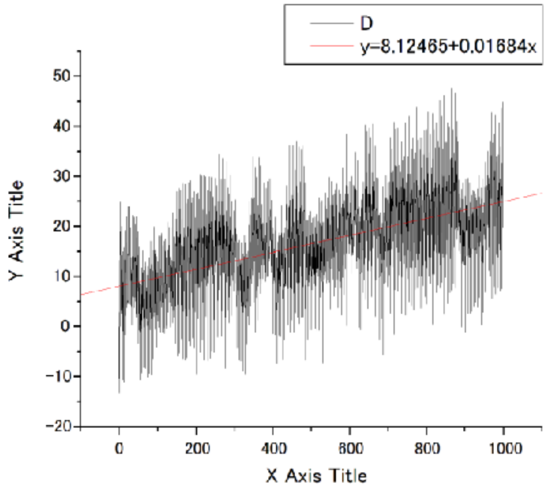
Z = 10 mm
Sampling rate 100 kHz
± 50 μT / 0.2 sec.
So this graph consists of 20,000 points.

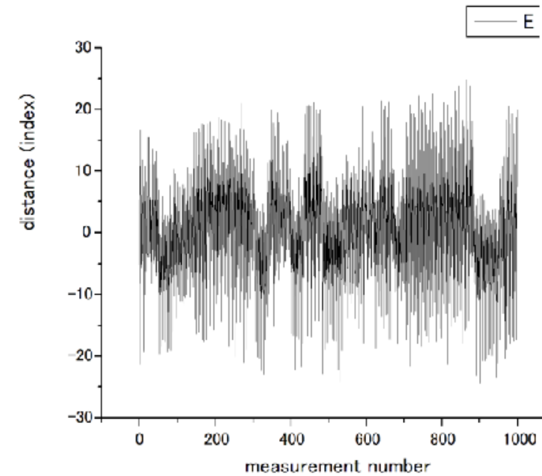
We get 1000 sets of data.
(so we can draw 1000 similar graphs)
And so we can make a histogram of peak points. ⇒
experimental uncertainty
We can also fit or smooth the wave shapes.



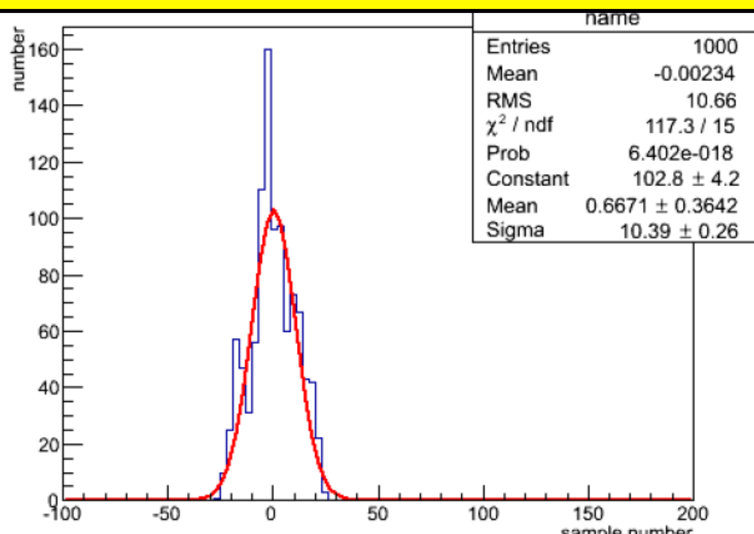
Fixed Point Measurement Test

By Mizutani





Index number × (sweeping rate)[T/sec] × 42.576396 [MHz/T] ÷ 100 [kHz]



2.246 Hz / 67.98 MHz = 33 ppb

Simulation study of NMR probe

By Sasaki

- For precise magnetic field measurement using NMR, some effects should be carefully considered.
- In the previous g-2 experiment at BNL, following contributions were evaluated.

$$\delta_t = \sigma(H_2O) + \delta_b + \delta_p + \delta_s. \qquad (3)$$

- σ (H2O) : Internal diamagnetic shielding in the water molecule
- δ_b: Bulk diamagnetism of the water sample (shape effect)
- δ_p: Paramagnetic impurities in the water sample
- δ_S: Paramagnetic and diamagnetic materials in the probe structure

Simulation study of NMR probe

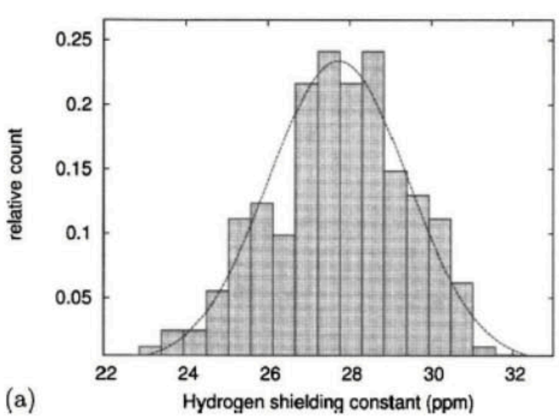
By Sasaki

- σ (H2O) : Internal diamagnetic shielding in the water molecule
  - Dominant contribution to the correction factor

$$\sigma(H_2O, 34.7^\circ C) = 25.790(14) \times 10^{-6}. \quad (5)$$

- Derived from the comparison with the oscillation frequency of a hydrogen maser in the same magnetic field

Ref: "Nuclear magnetic shielding constants of liquid water: Insights from hybrid quantum mechanics/molecular mechanics models," J. Chem. Phys. 126(2007)



(a)

TABLE II. The hydrogen shielding, σ^H, and the shift related to vacuum, $\Delta\sigma^H = \sigma^H_{liq} - \sigma^H_{vac}$, calculated using different potentials and number of water molecules in the part of the system treated using DFT [DFT (x = 1,5,10)]. The results have been obtained by averaging over 1500 configurations except for the DFT(10)/MM results which are based on 300 configurations. The error in the mean values is calculated according to $\sigma/\sqrt{N}$. The results are in ppm.

	Potential	DET(1)/MM	DFT(5)/MM	DFT(10)/MM	Expt.[a,b]
σ^H	TIP3P	29.84±0.02	28.63±0.04	28.36±0.08	25.79
σ^H	SPCpol	29.39±0.03	28.14±0.05	27.7±0.1	25.79
$\Delta\sigma^H$	TIP3P	−1.05±0.02	−2.26±0.04	−2.53±0.08	−4.26
$\Delta\sigma^H$	SPCpol	−1.50±0.03	−2.75±0.05	−3.3±0.1	−4.26

~28.6 ppm ?

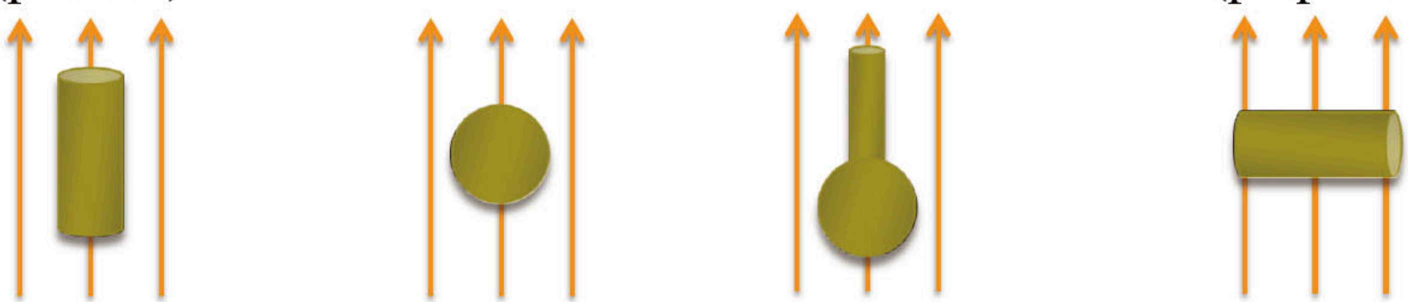
Study of shape effect by FEM simulation

By Sasaki

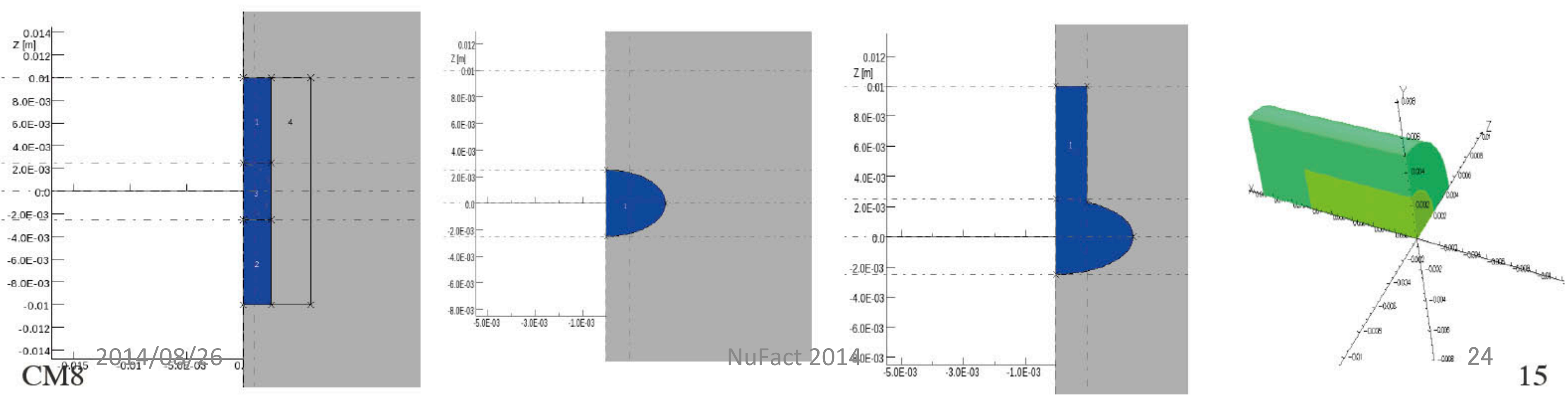
- Model
  - Water relative permeability : 0.999992

(a) Cylinder (parallel) | (b) Bulb | (c) Bulb+Cylinder | (d) Cylinder (perpendicular)

1 T



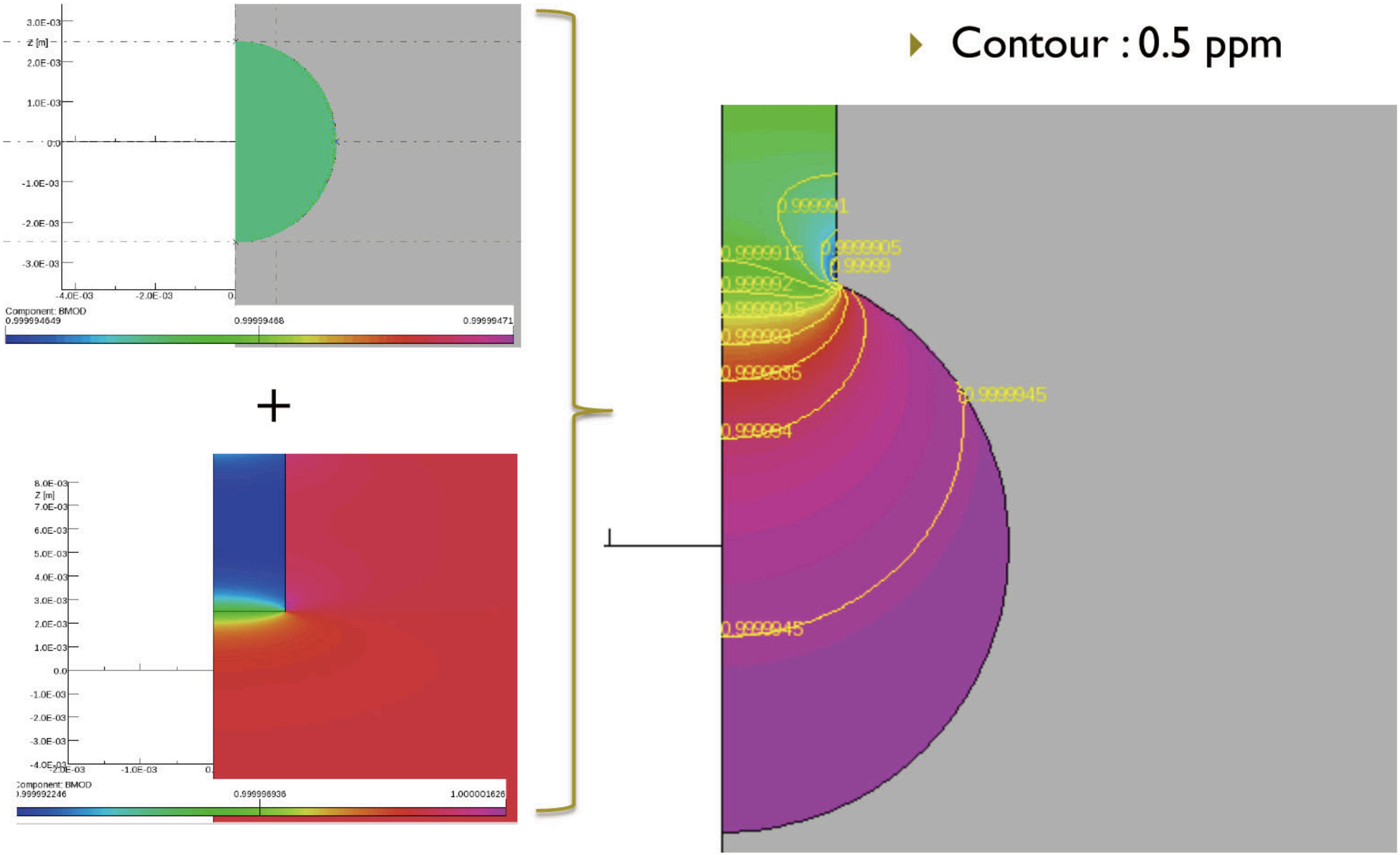
(a)	(b)	(c)	(d)
R: 2.5 mm L: 20 mm	R: 2.5 mm	Bulb R: 2.5 mm Tube R: 1.0 mm Tube L: 7.5 mm	R: 2.5 mm L: 20 mm



Results ~ bulb + tube

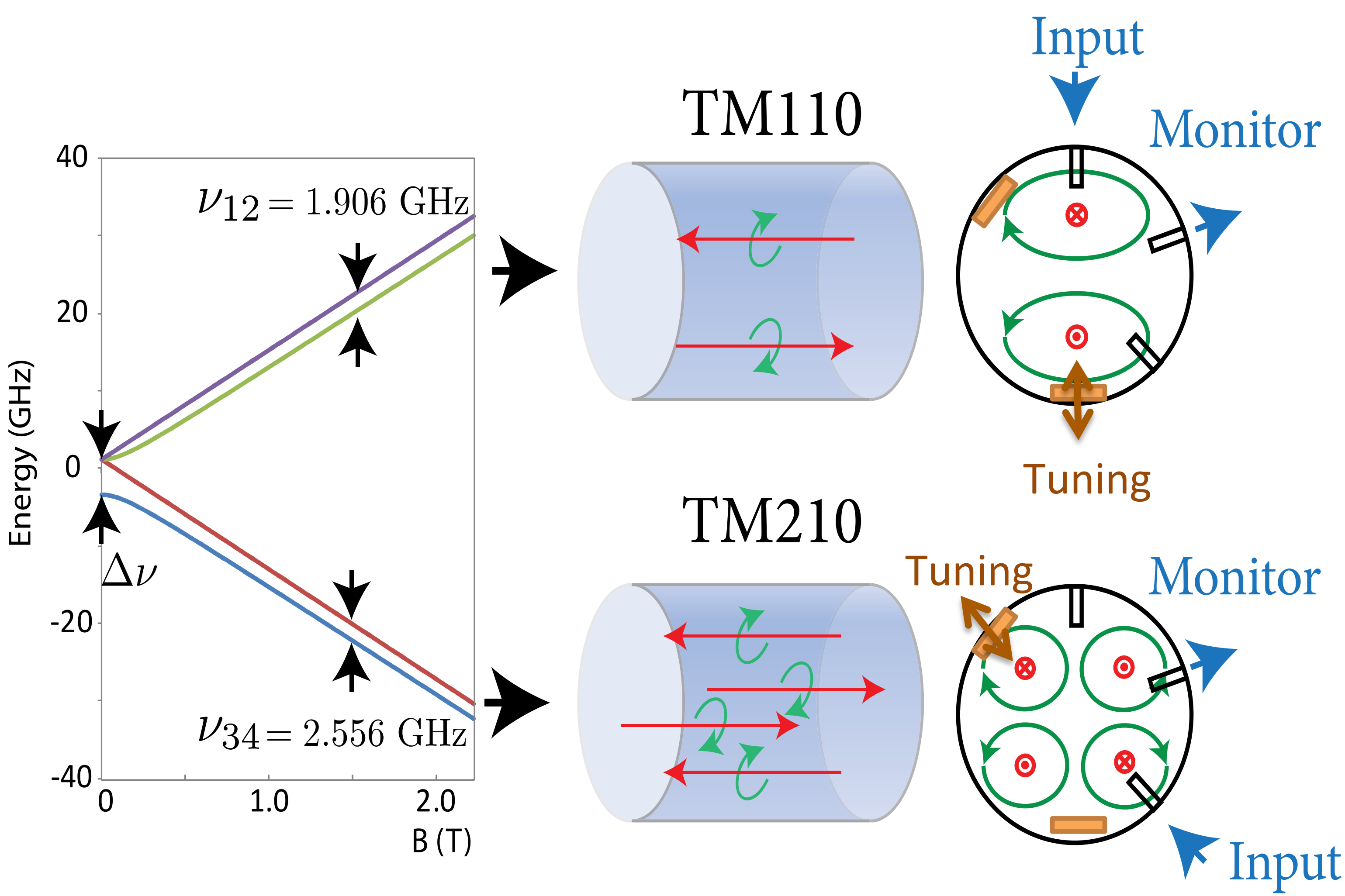
By Sasaki

- Contour : 0.5 ppm



RF Cavity

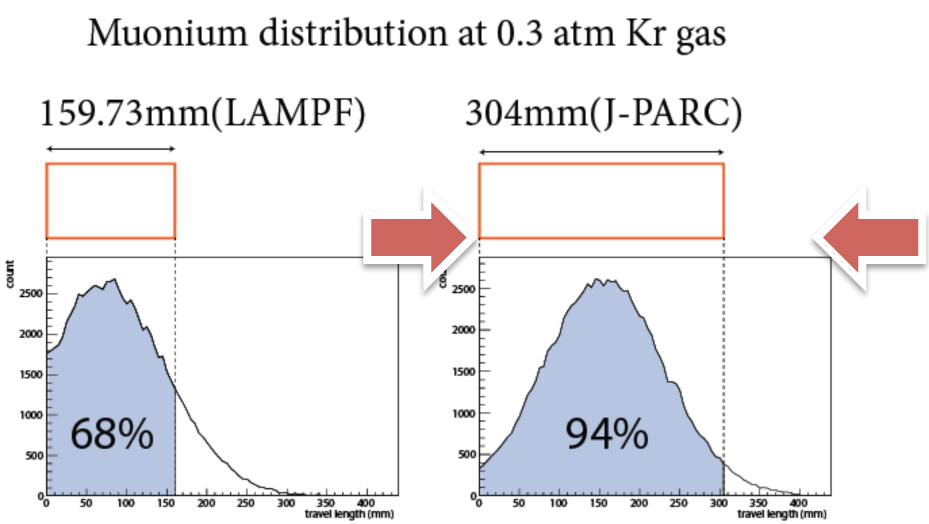
Tanaka, Matsuda, Torii

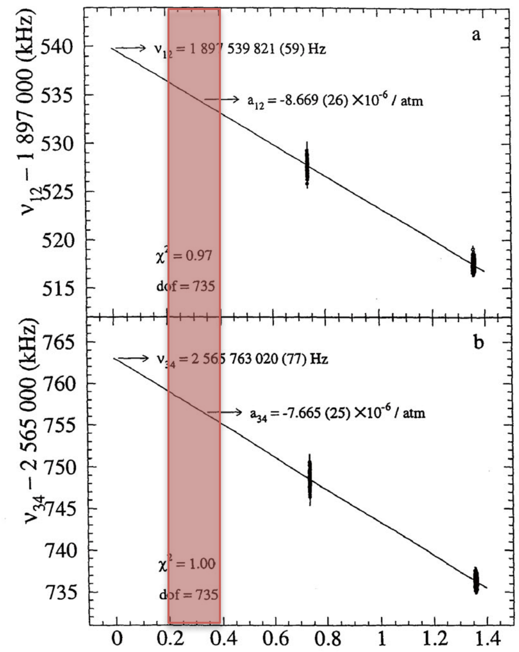


Improvement from LAMPF

Tanaka, Matsuda, Torii

Cavity Length





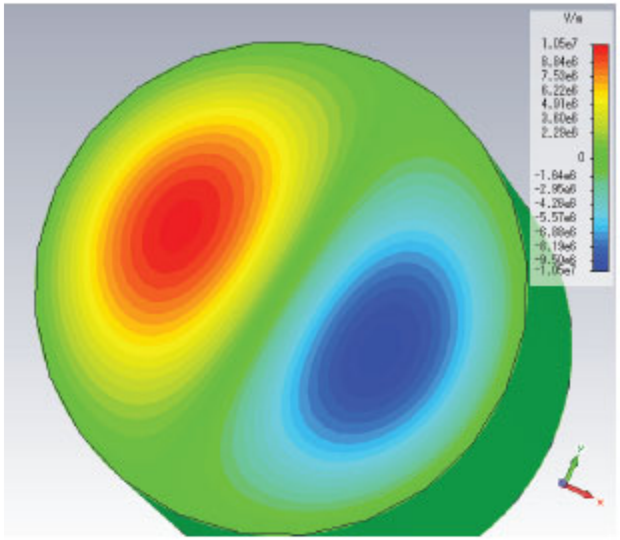
The transition frequency of muonium in gas vary with the gas pressure due to atomic collision between Mu and Kr.

⇒ Fitting 0.8 and 1.5 atm data, old quadratic dependence parameter was used (Los Alamos).

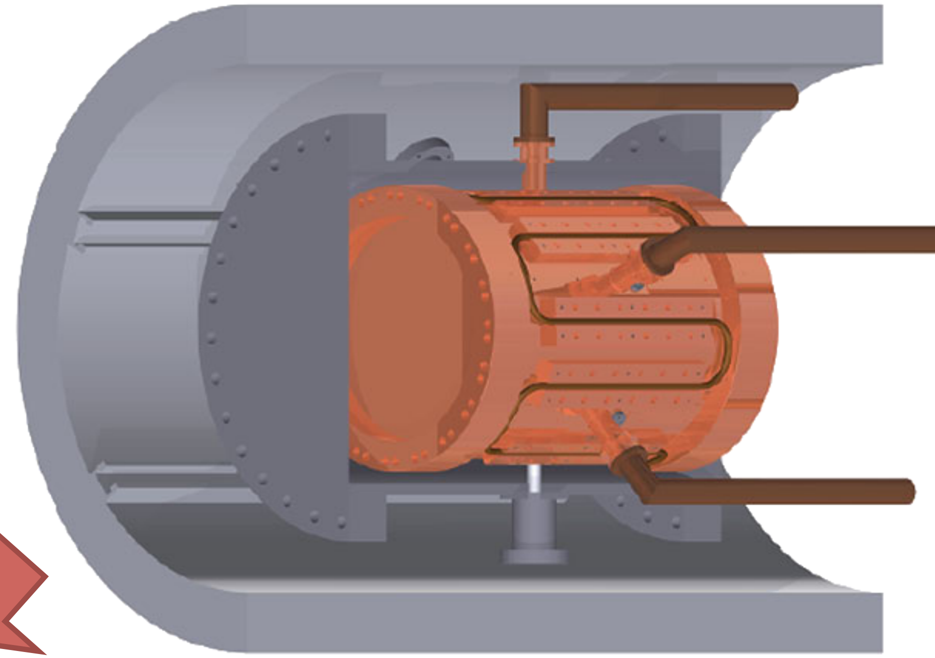
⇒ We need data at lower pressure for improved fitting.

RF Cavity

MWS simulation

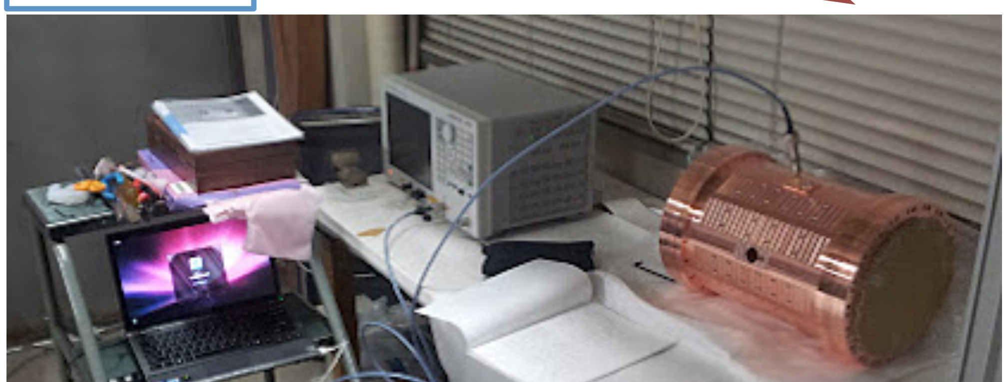


Tanaka, Matsuda, Torii

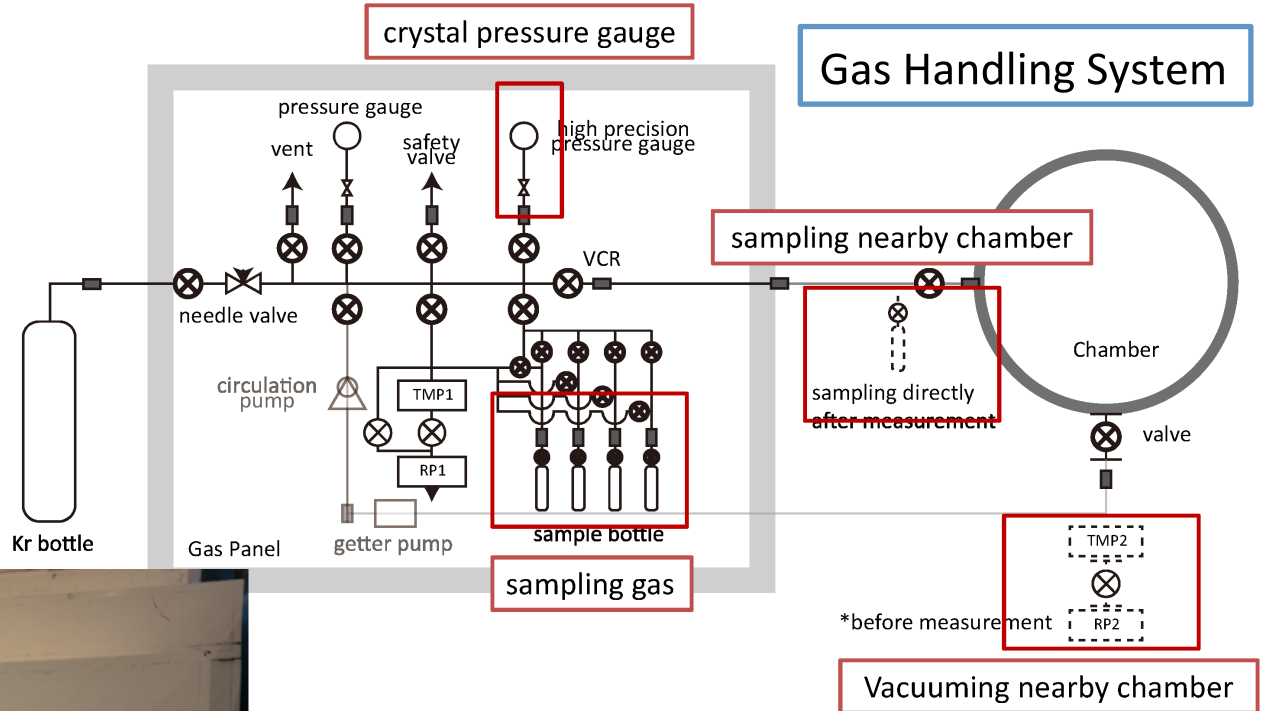


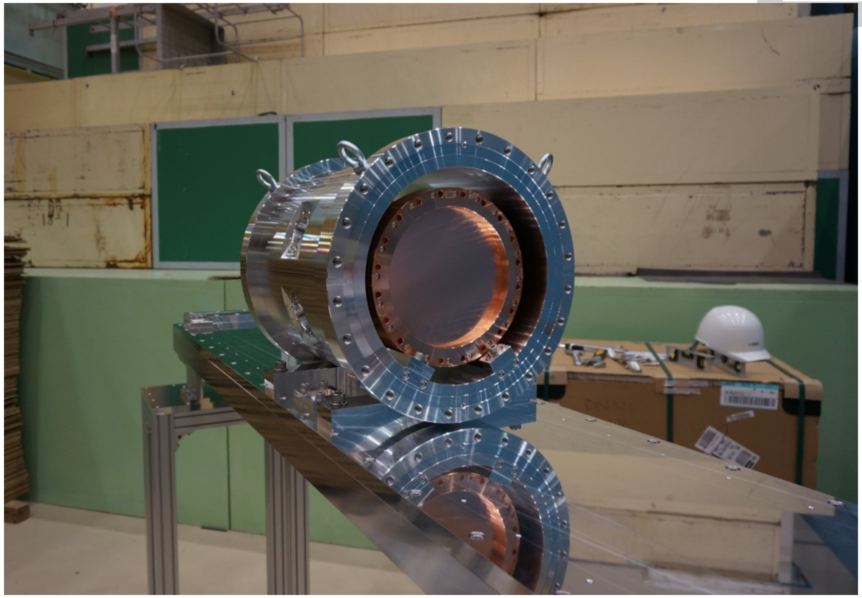
3D CAD

Test Cavity



RF Cavity & Gas Chamber

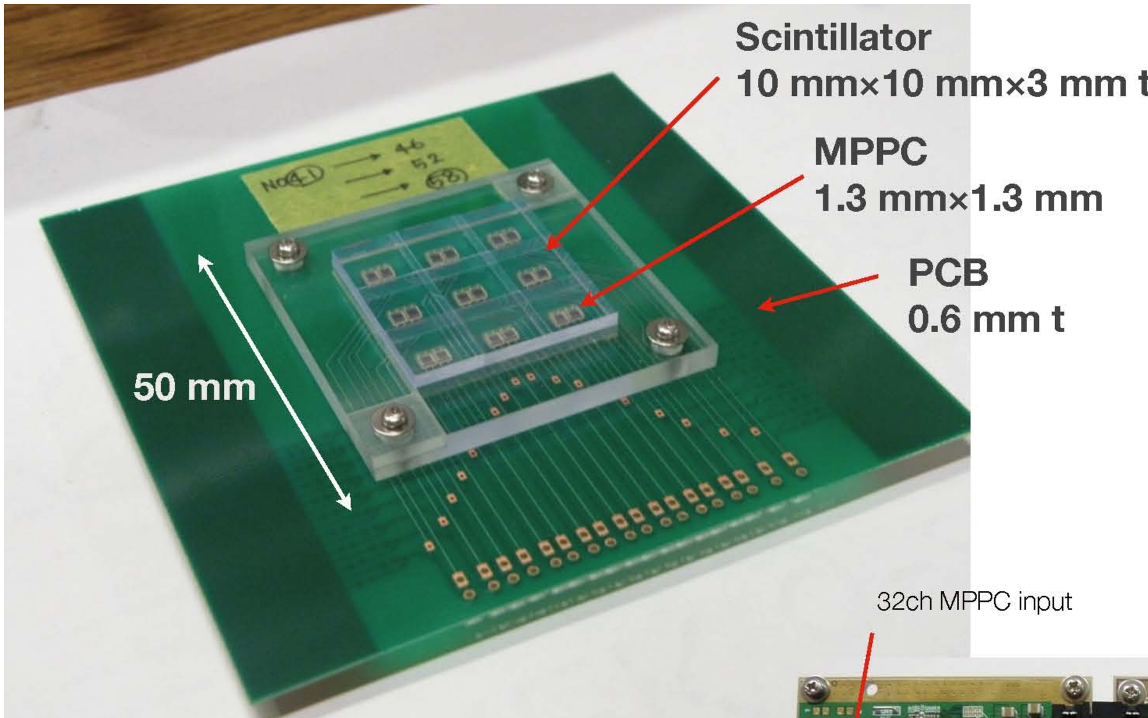


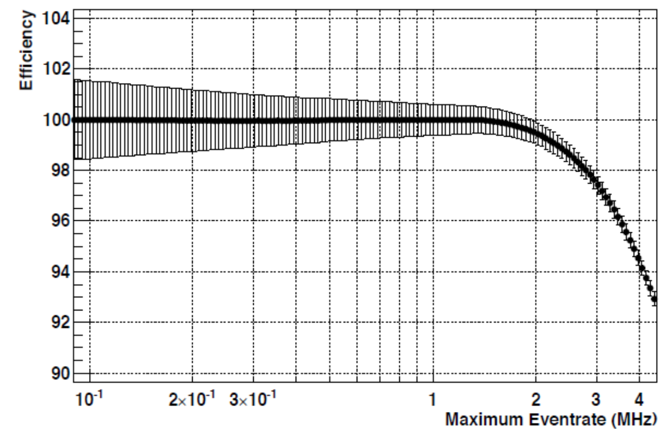


- Pressure: 0.5 – 1.5 atm
- Readout precision: several ppm (crystal gauge: 0.008% of full range)
- Contamination: below 1ppm.
- gas sampling before, during and after the experiment (several weeks).

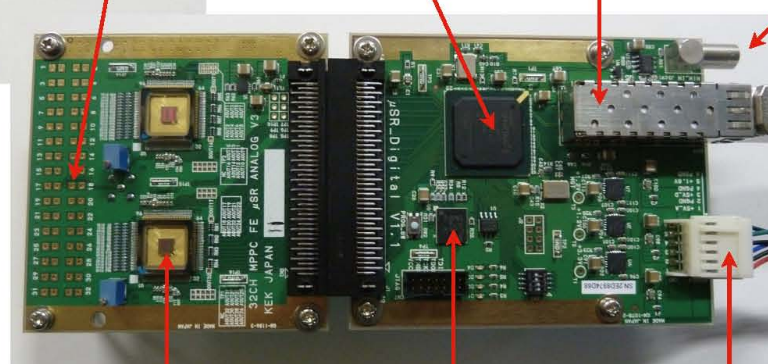
Positron Detector

Kanda, Mibeuda, Kojima





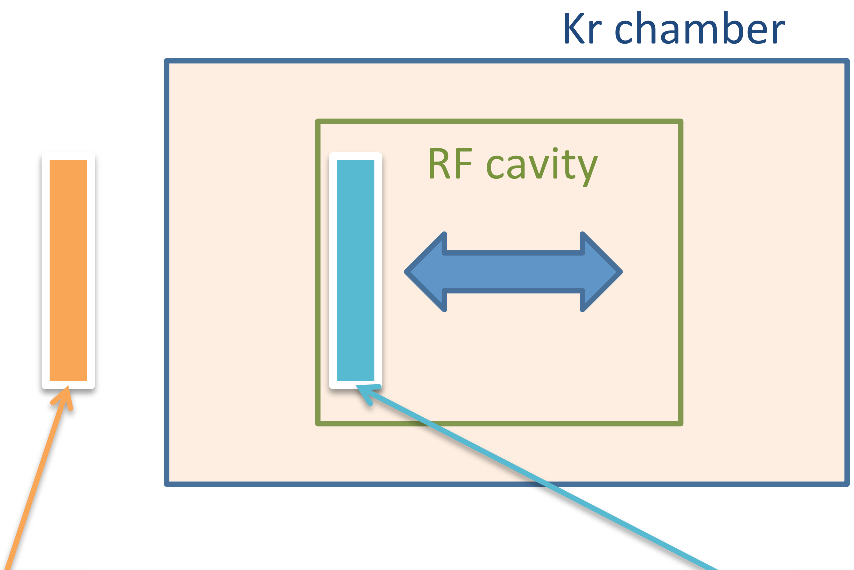
Pileup loss at 3MHz/ch ~ 2%



Plastic scintillator + MPPC
+ Kalliope readout circuit.
18 channels of 9 scintillator segments.

Beam Profile Monitor

Tajima, Toyoda, Ito (JAEA)



- 3^{rd} maximum systematic error in Los Alamos experiment (13 ppb).
- Accuracy 5 mm → 1 mm

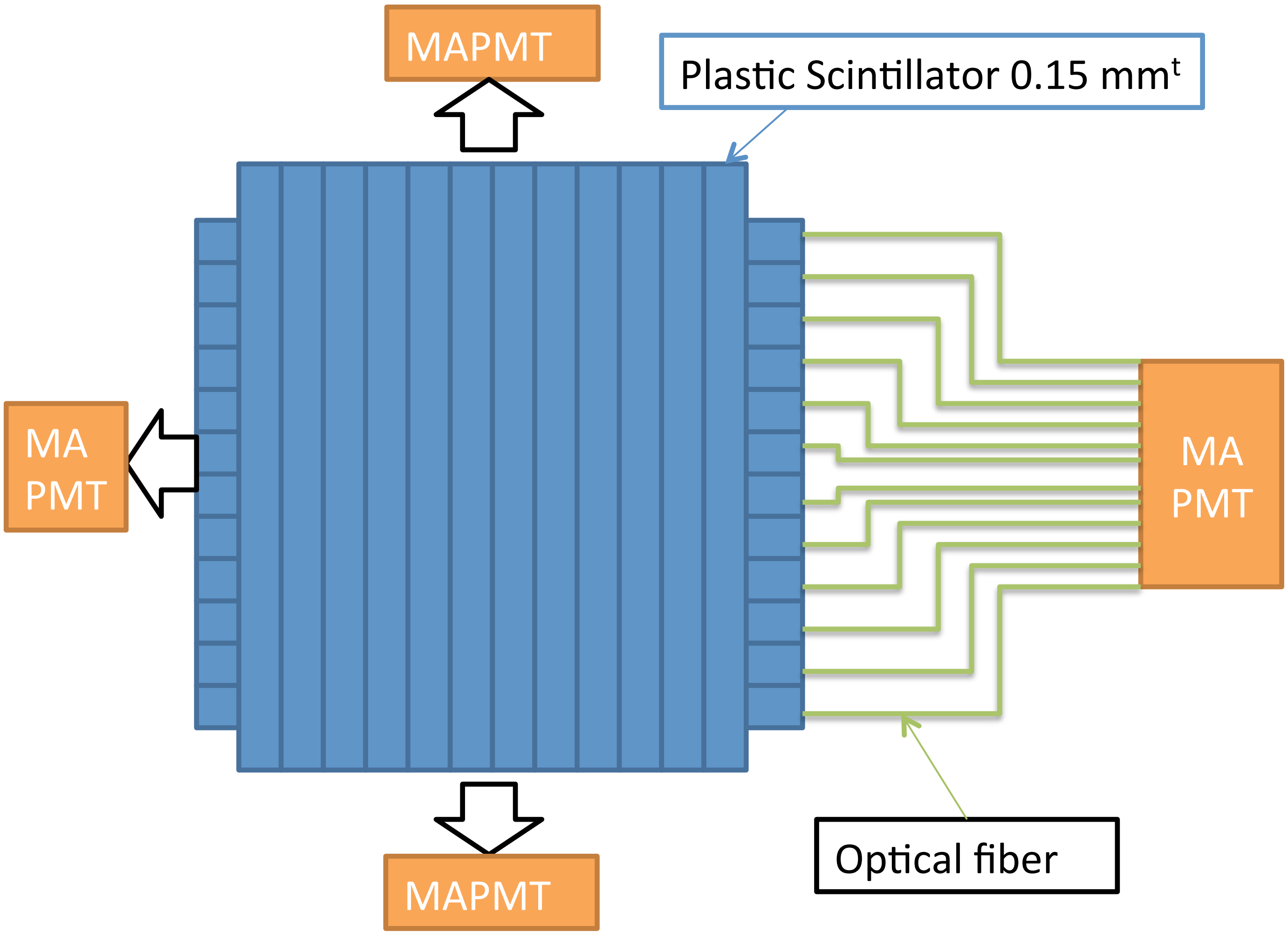
FBPM (Front BPM)

- 2D monitor (pulse by pulse)
- Less than 300 μm thickness in total
- Work under magnetic field

TBPM (Target BPM)

- 3D monitor (scaning capability)
- 0-2 atm Kr gas pressure
- size < 200 mm (RF cavity)

FBPM



Challenge 1

Uniform muon beam range

uniform thickness

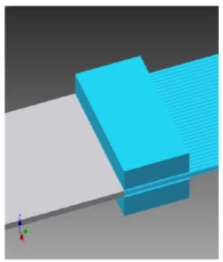
Challenge 2

Enough light transmission

light guide or fiber

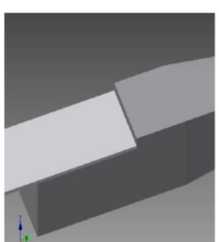
FBPM (Prototype)

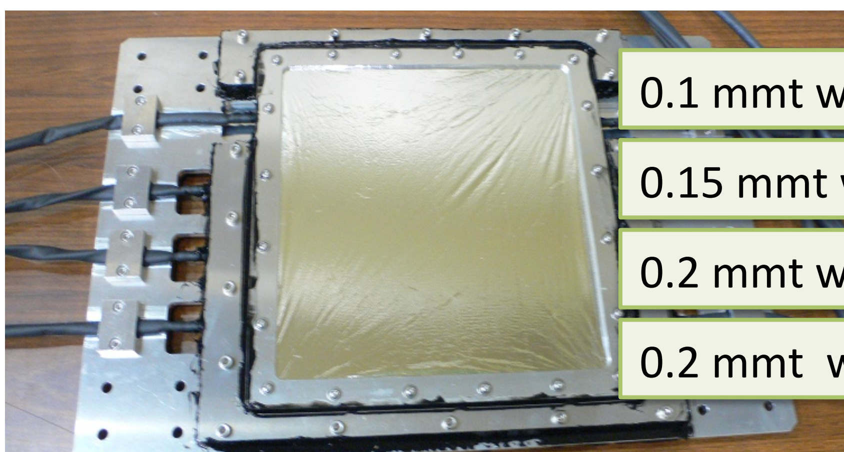
Fiber
light guide



Plastic scintillator sheet
6 mm in width
180 mm in length
5m Fiber
Multianode PMT

Acryl
light guide

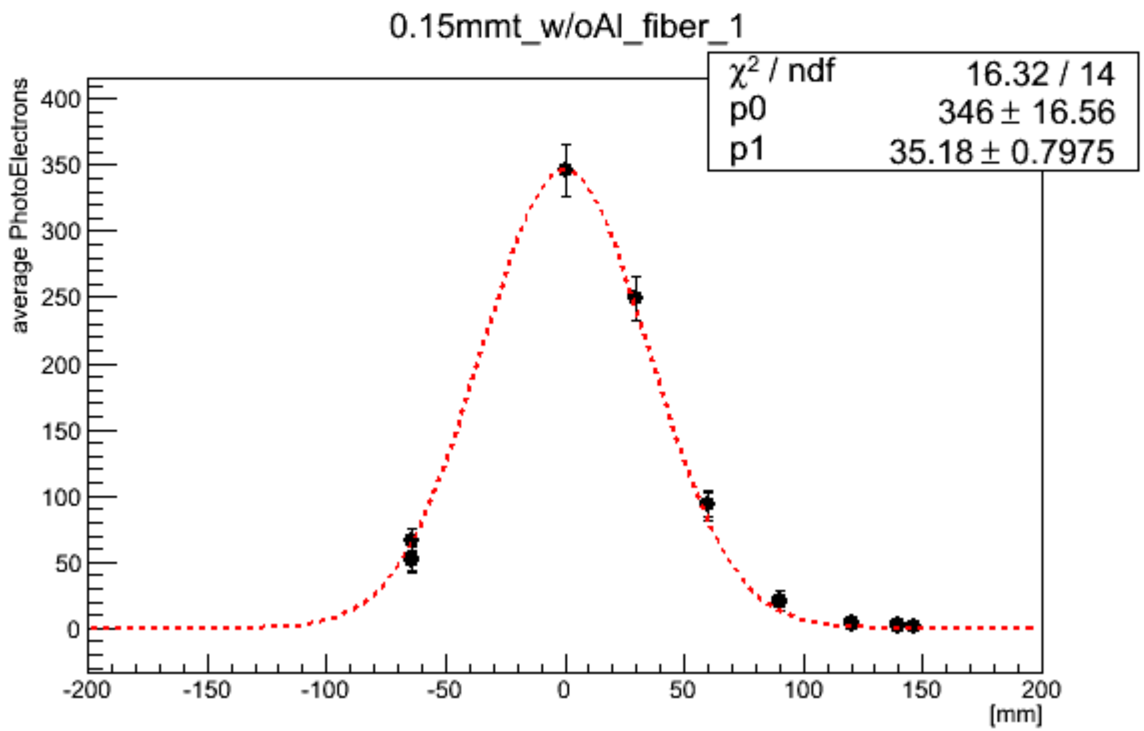




Check List

- Effect of Al coating
- Thickness dependence
- Light guide selection
- Position dependence

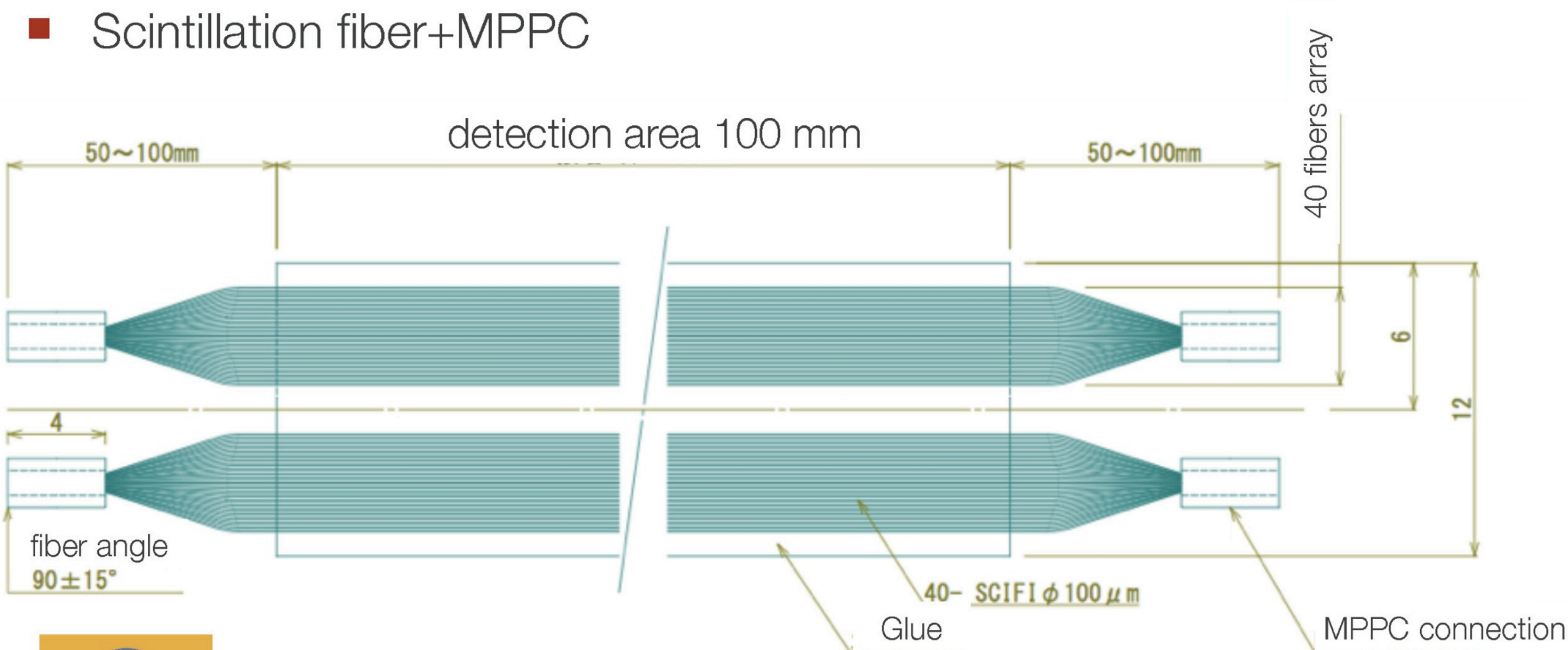
Beam Profile Measurement at D-Line

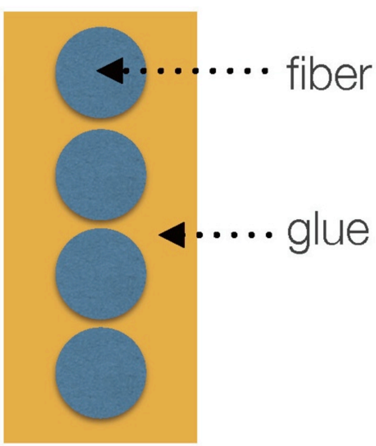


1mm accuracy is achieved.

FBPM (New Design)

- Scintillation fiber+MPPC



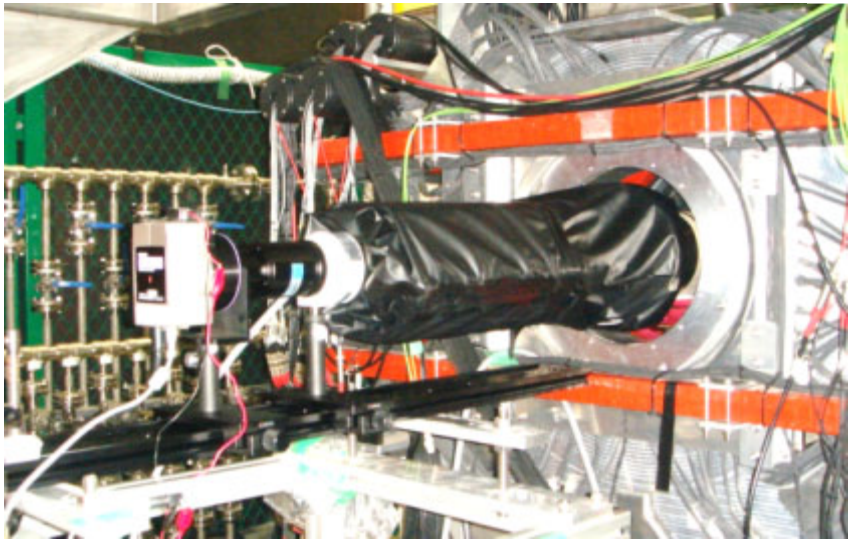


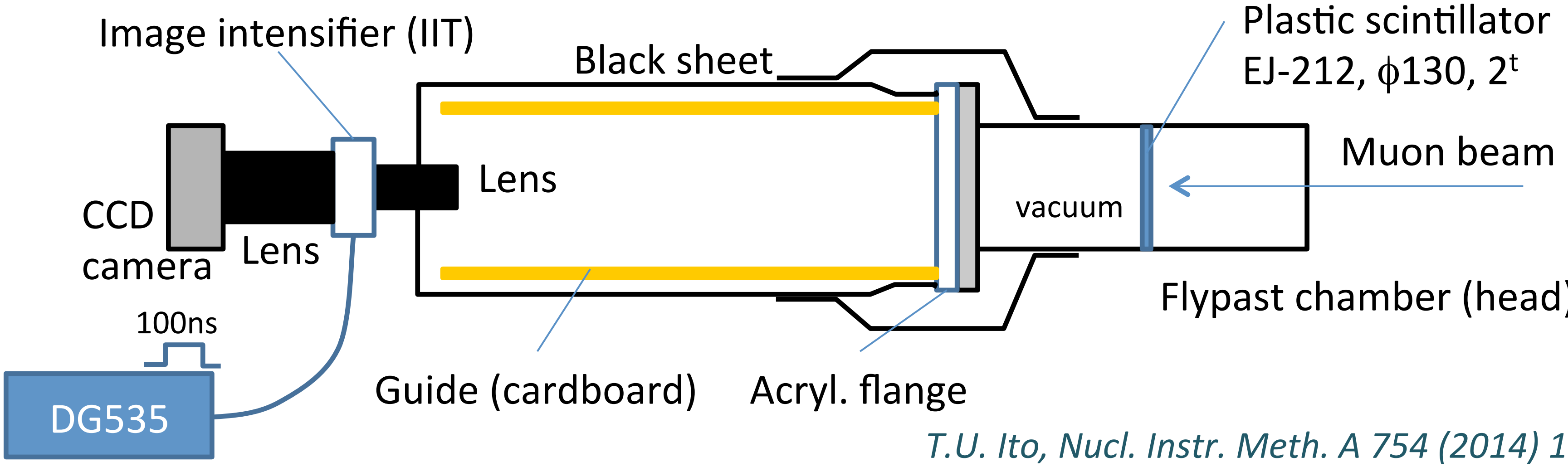
Use a bundle of fine scintillation fibers (ø0.10 mm).

- Better optical coupling to MPPC
- Less position dependence along the fiber
- Better control of (effective) thickness ??

TBPM (IIT muon beam profile monitor)

Tajima, Toyoda, Ito (JAEA)





T.U. Ito, Nucl. Instr. Meth. A 754 (2014) 1-9

TBPM

Tajima, Toyoda, Ito (JAEA)

Setup

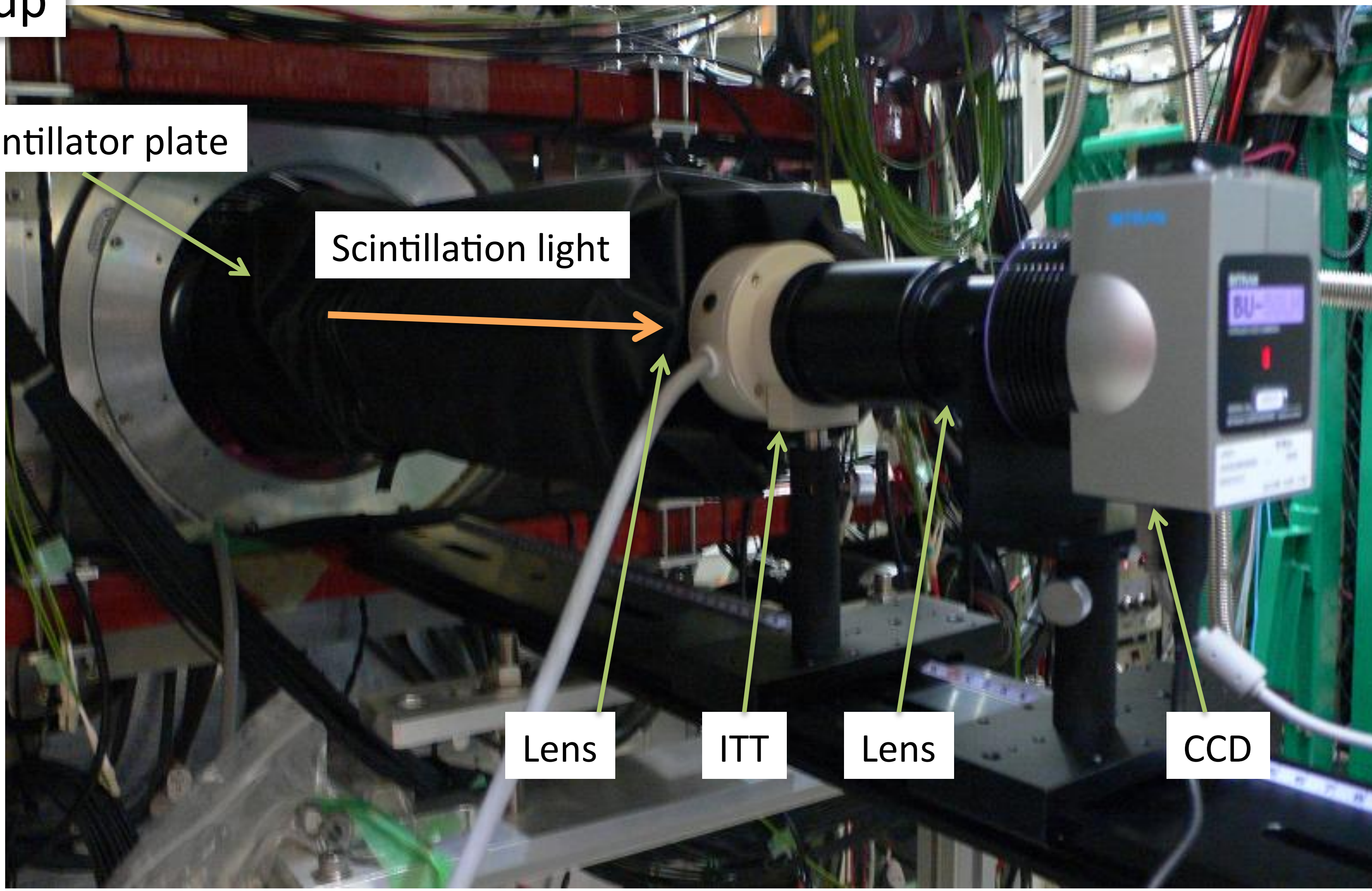
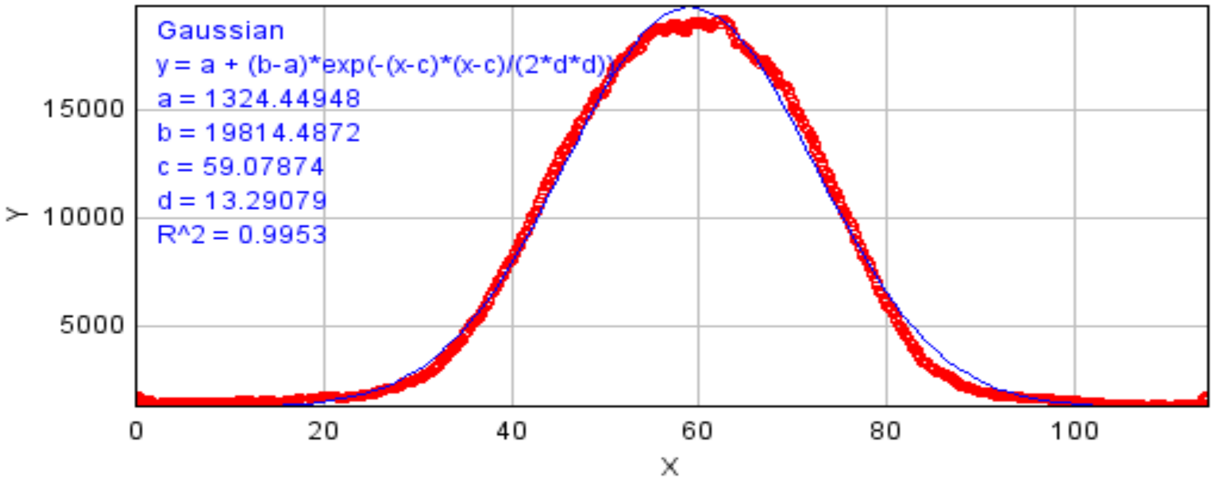
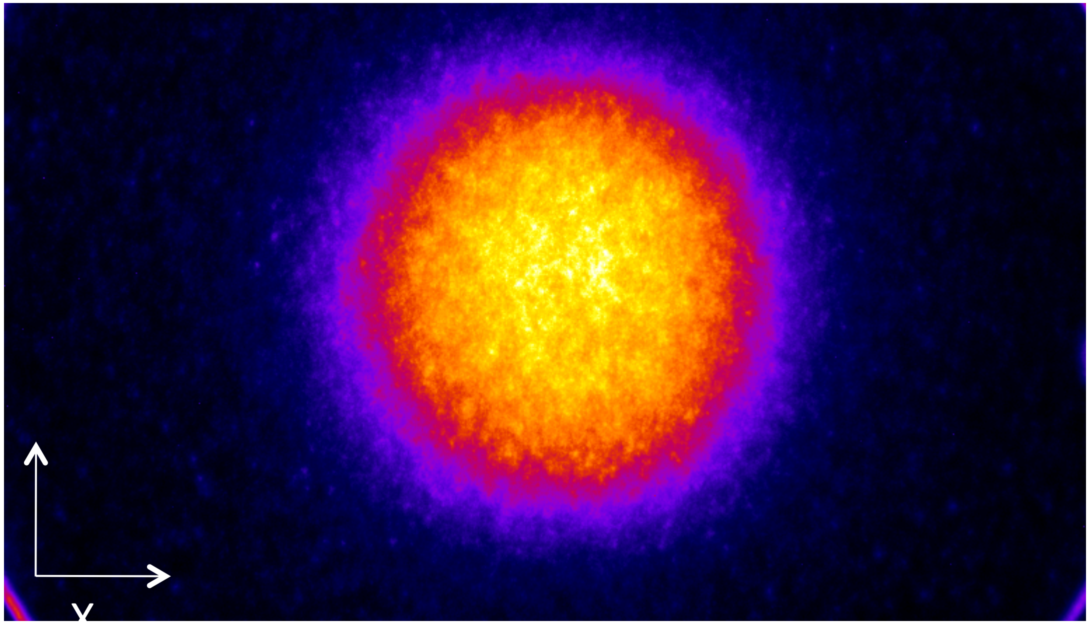
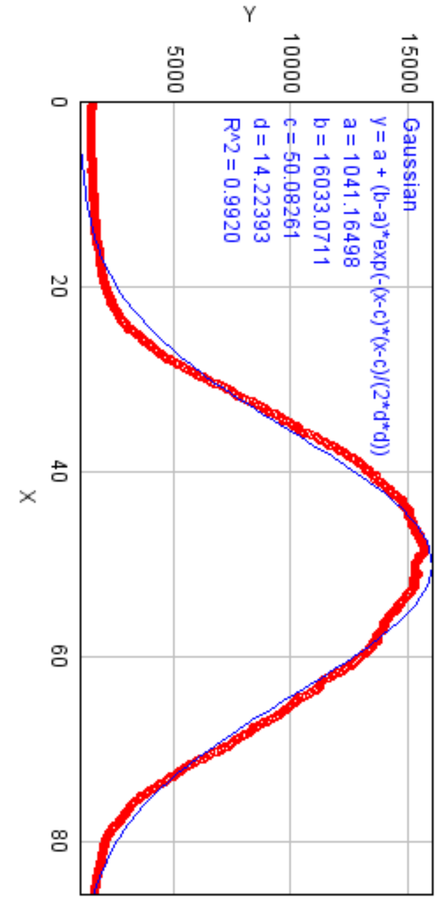


Image of Muon Beam at D-Line

Tajima, Toyoda, Ito (JAEA)

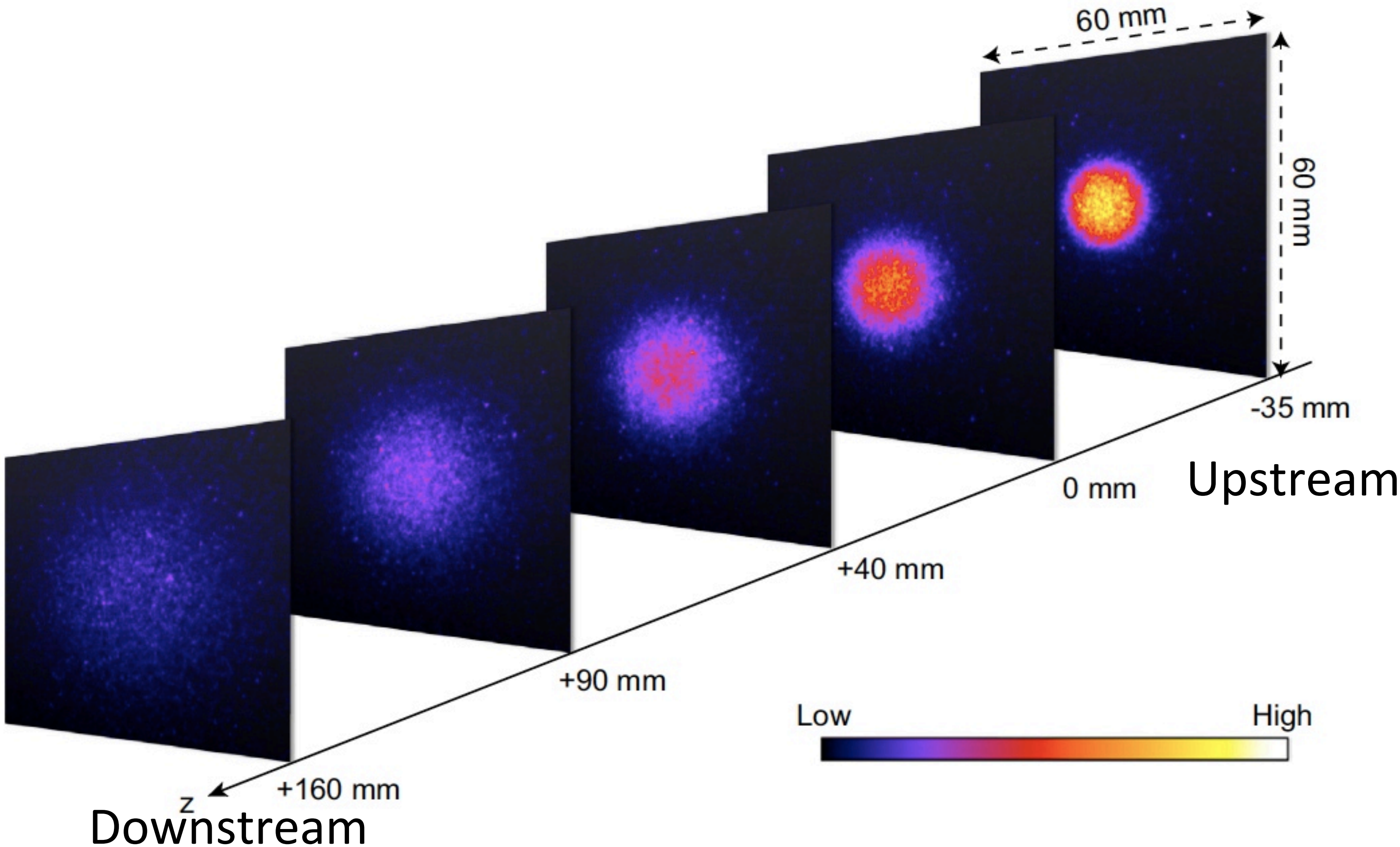






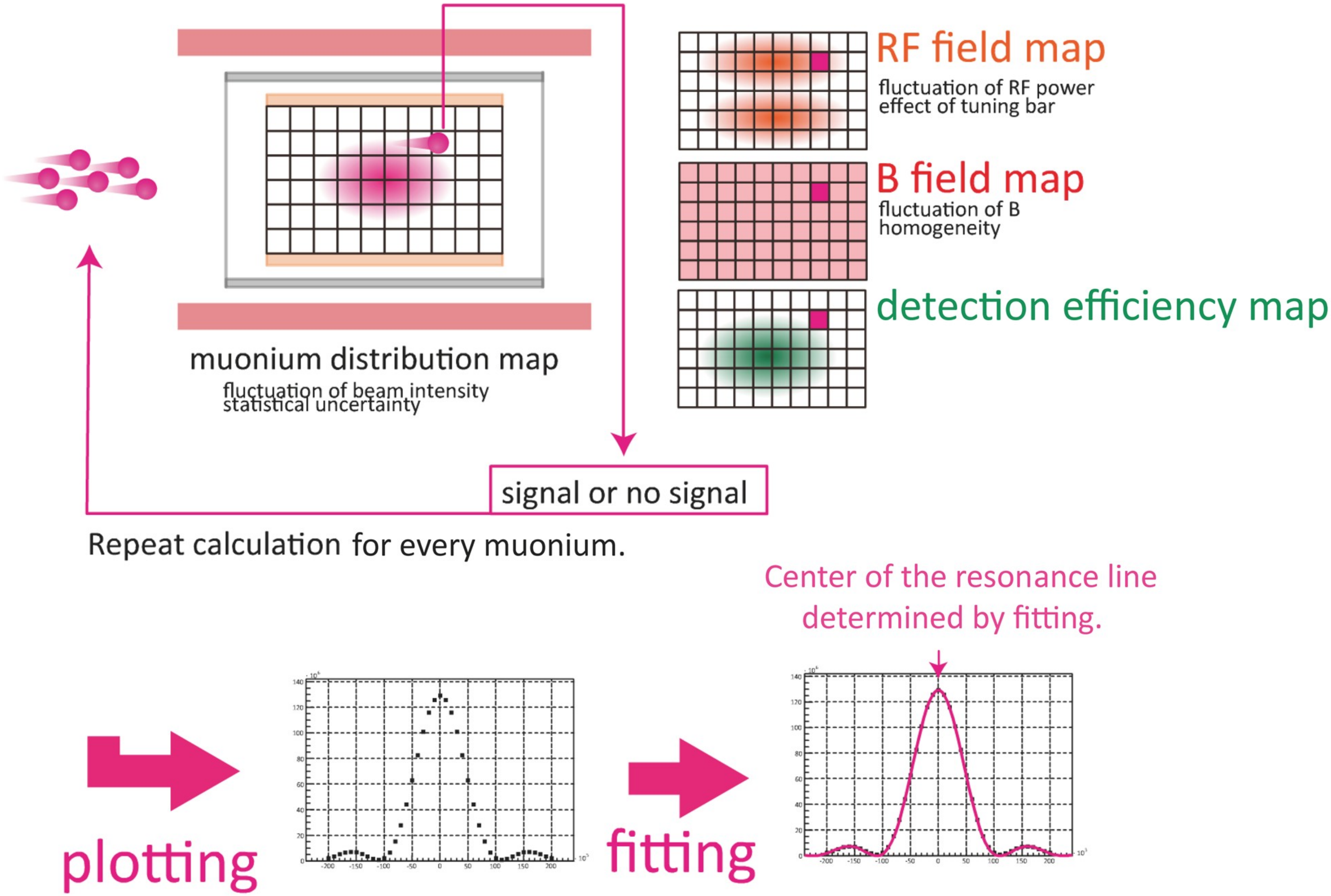
3D Image in Air

Tajima, Toyoda, Ito (JAEA)



Systematic Error

Tanaka, Kanda, Ishida



Systematic Error

Tanaka, Kanda, Ishida

	Accuracy	ν_{12} and ν_{34}	$\delta(\Delta\nu_{HFS})$	$\delta(\mu_\mu/\mu_p)$
Magnetic Field	30 ppb		0.0 ppb	15 ppb
RF power	0.10 %	10 Hz	2.0 ppb	20 ppb
Kr gas temperature	0.1 deg.	< 1 Hz	0.2 ppb	2 ppb
Kr gas pressure	0.01 hPa	1 Hz	0.2 ppb	0 ppb
H impurity	<50 ppm	1 Hz	0.5 ppb	0 ppb
Quadratic dependence		5 Hz	1.0 ppb	5 ppb
Muonium position (x,y)	1 mm	3 Hz	0.6 ppb	6 ppb
Muonium position (z)	1 mm	< 1 Hz	0.2 ppb	2 ppb
Beamline	10(e-4)	< 1 Hz	0.2 ppb	2 ppb
Detector pile-up		2.5 Hz 0.3 Hz	0.5 ppb < 0.1 ppb	3 ppb < 1 ppb

Summary and Next Step

- Present total systematic error roughly estimated as

HFS	2.4 ppb
Magnetic moment	27 ppb

- RF power, stability and homogeneity:
  → need more study!

- Stability and homogeneity of magnetic field:
  → need magnetic shield around the magnet.
  → demonstration using a magnet at KEK.

- Beam test (without magnetic field) at MUSE D2 Area.
  → Gas chamber, cavity, beam profile monitor, …

MuSEUM Collaborators

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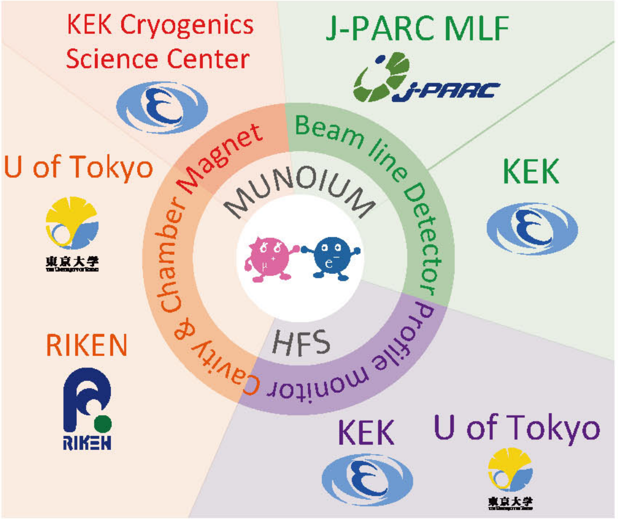


Extra Slides

Close relationship to $g_\mu-2$

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

Exp. 0.001 165 920 89 (68) [580 ppb]

$\updownarrow$ 3.2 σ

The. 0.001 165 918 28 (49) [420 ppb]

$a_\mu=R/(\lambda-R)$

$R_{exp}(g_\mu-2)$: 500 ppb

λ_{exp}(MuHFS): 120 ppb

Test of CPT and Lorentz Invariance

CPT broken Theory ⇒ Lorentz symmetry is broken

O.W. Greenberg, Phys. Rev. Lett. 89 (2002) 231602

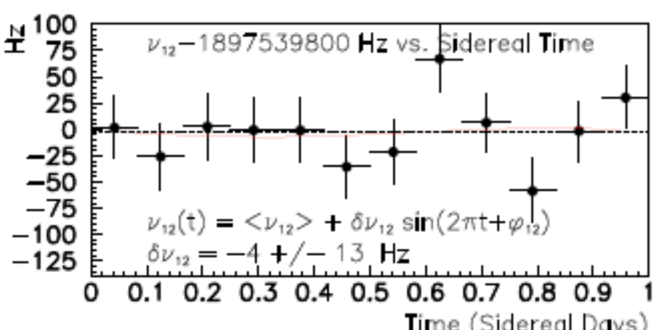
CPT violation search

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

g_{μ}-2/MuHFS precise measurement

Lorentz symmetry violating term in STE 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