PHIPSI13 - International Workshop on e+e- collisions from Phi to Psi 2013 (9–12 Sept. 2013)

Status and prospects of the muonium experiment at J-PARC

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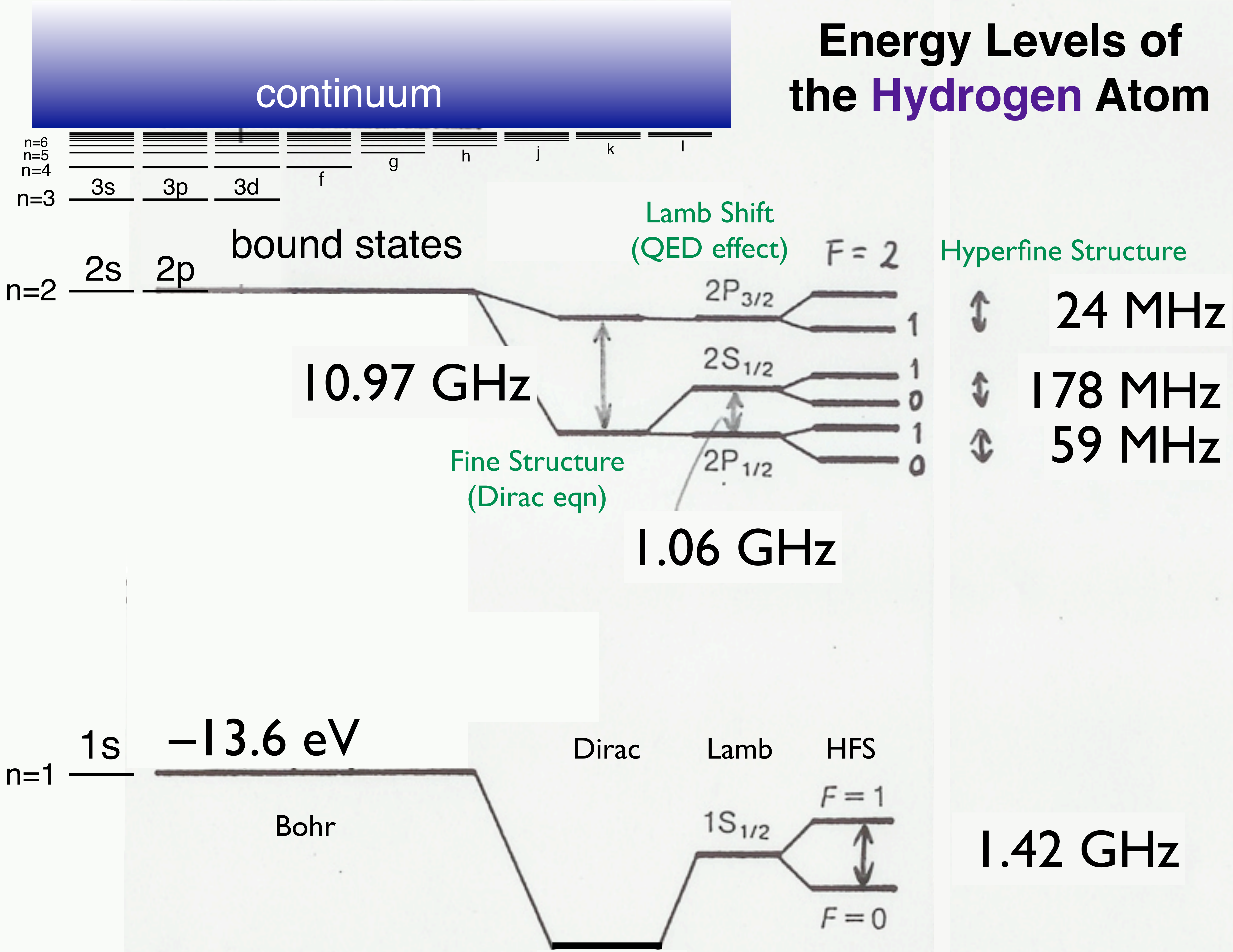
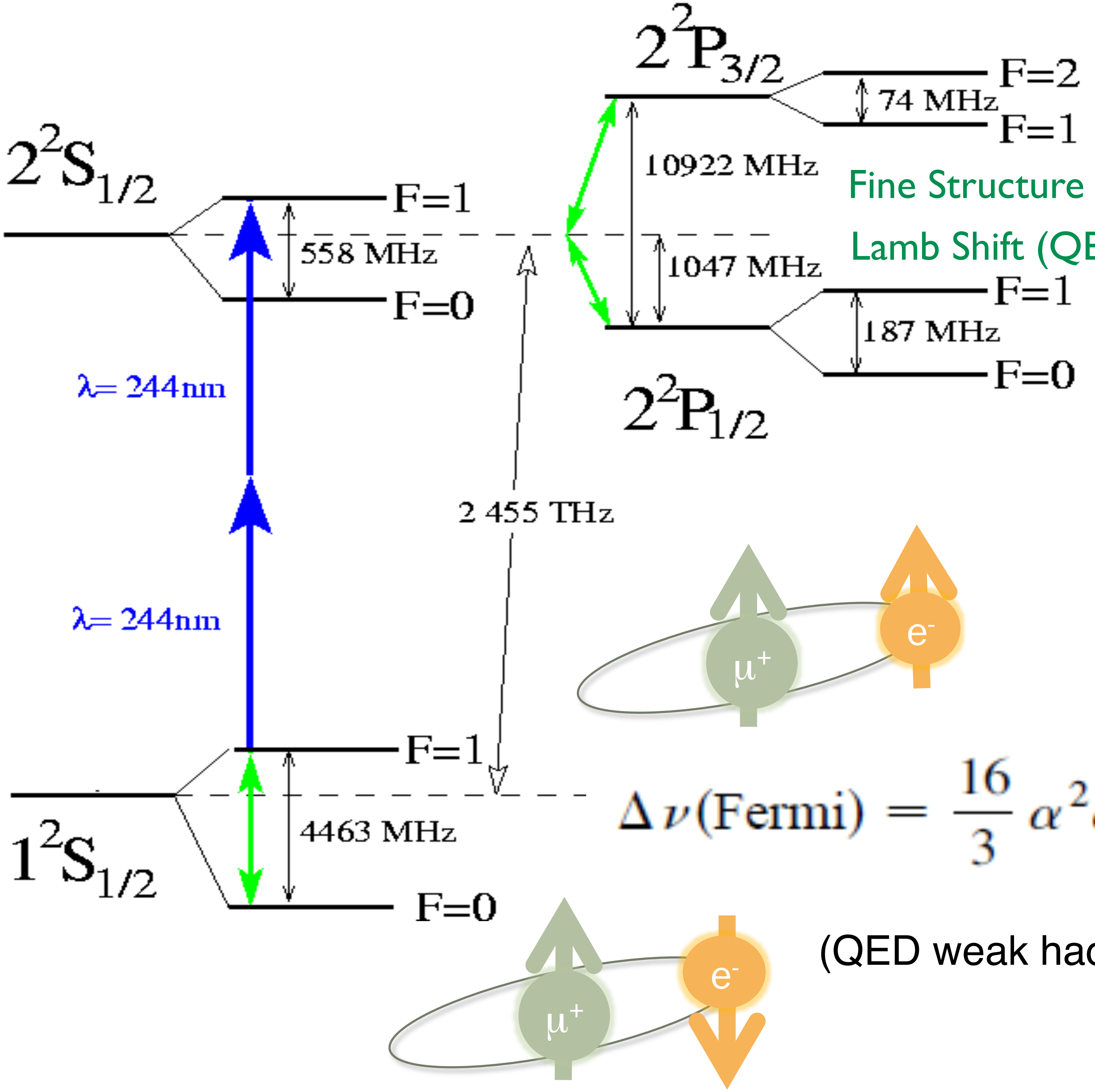
Univ. of Tokyo

12 Sept. 2013

Energy Levels of the **Hydrogen** Atom



Energy diagram of Muonium (Mu) Atoms



Hyperfine Structure

Fine Structure (Dirac eqn)

Lamb Shift (QED effect)

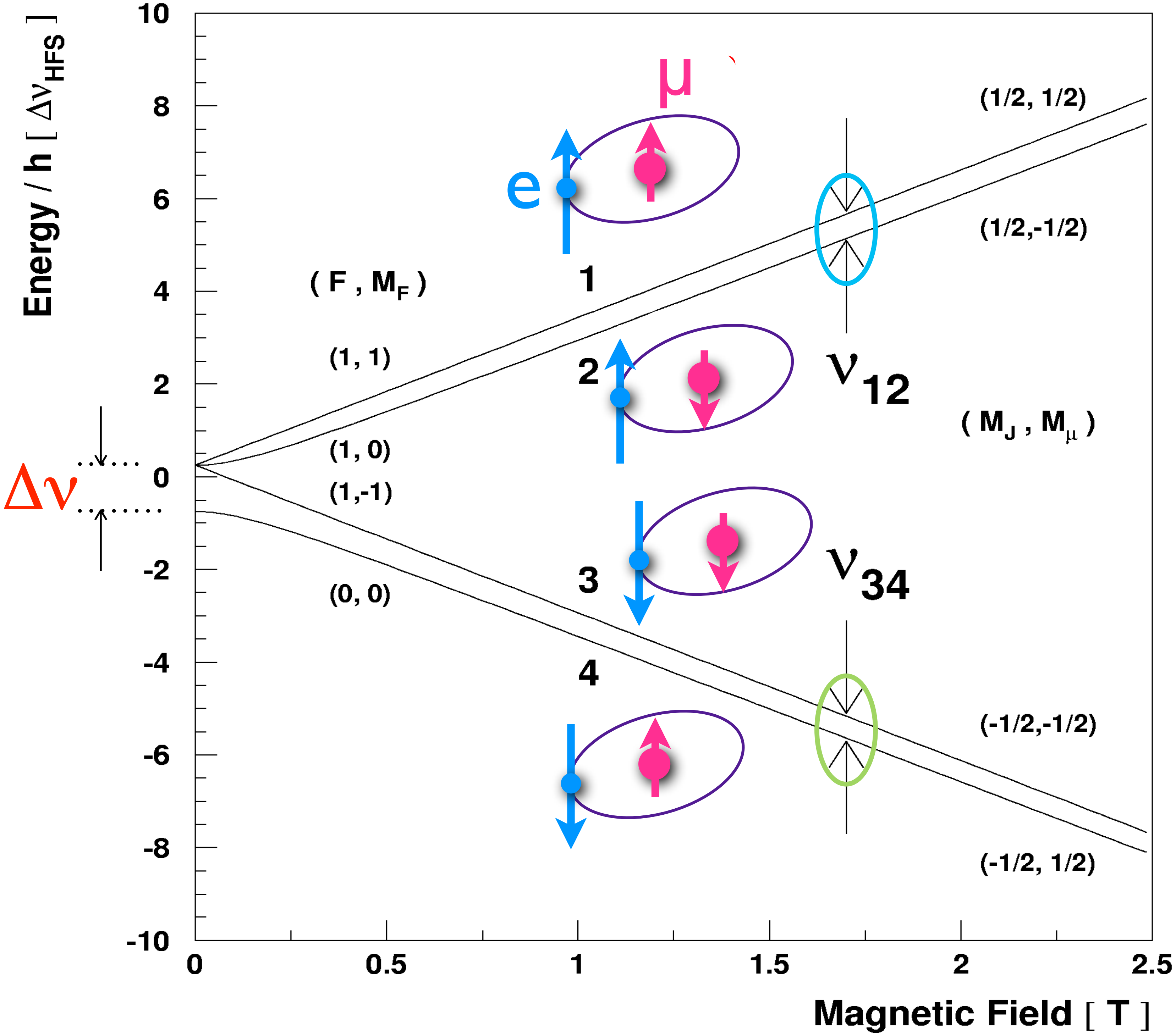
$$\Delta\nu(\text{Fermi}) = \frac{16}{3}\alpha^2 c R_\infty \frac{m_e}{m_\mu}\left[1 + \frac{m_e}{m_\mu}\right]^{-3}.$$

(QED weak hadronic correction not included)

HyperFine Structure (HFS) of Muonium Atoms (Mu)

$$\mathcal{H} = a\,\overrightarrow{I}\cdot\overrightarrow{J} + \mu_B^e g_J \overrightarrow{J}\cdot\overrightarrow{H} - \mu_B^\mu g_\mu^{'} \overrightarrow{I}\cdot\overrightarrow{H}$$

HFS Zeeman Splitting



Breit-Rabi diagram

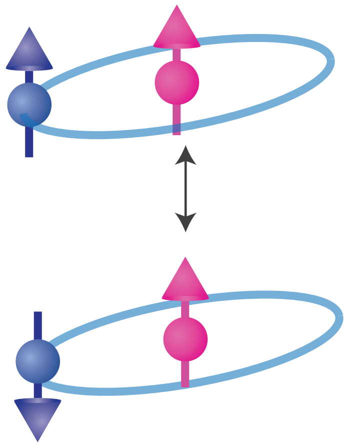
$$\Delta\nu = \nu_{12} + \nu_{34}$$

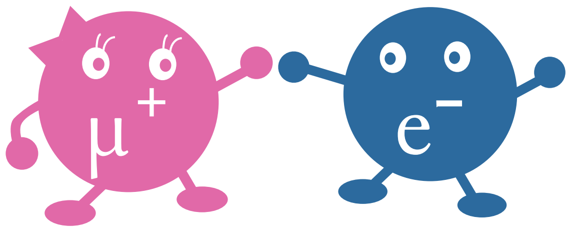
$$\mu_\mu/\mu_p \propto \nu_{12} - \nu_{34}$$

$$\propto m_p/m_\mu$$

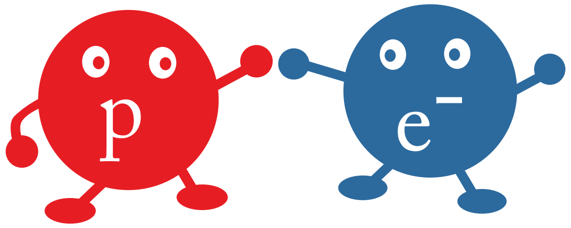
- Precise test of bound-state QED
- Magnetic moment mass of muon

Comparison: Muonium (Mu) and Hydrogen (H) Atoms





Muonium



Hydrogen

$$\Delta HFS_{\rm M}^{\rm th} = 4.46330288(55)\ {\rm GHz}\ (120{\rm ppb})\ ^{*}$$

$$\Delta HFS_{\rm M}^{\rm ex} = 4.463302765(53)\ {\rm GHz}\ (12{\rm ppb})\ ^{\dagger}$$

$$\Delta HFS_{\rm H}^{\rm th} = 1.4204031(8)\ {\rm GHz}\ (560{\rm ppb})$$

$$\Delta HFS_{\rm H}^{\rm ex} = 1.4204057517667(9)\ {\rm GHz}\ (0.6{\rm ppt})$$

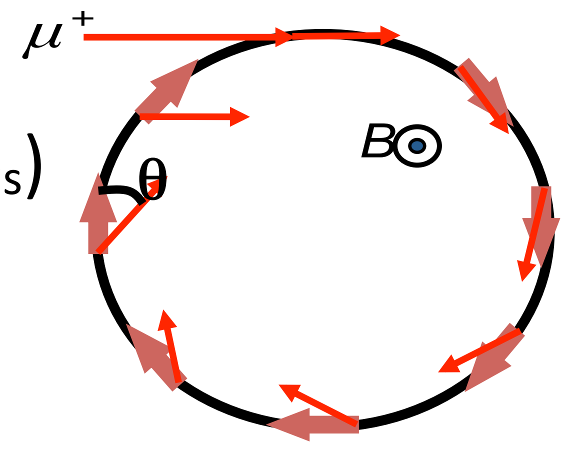
* Nucl. Phys. B (Proc. Suppl.) **162** (206) 260.

† Phys. Rev. Lett. **82** (1999) 711.

Term	Fractional contribution	ΔE (kHz)
E_F	1.000000000	4459031.88(50)(3)
α_e	0.001159652	5170.925(1)
QED2	−0.000195815	−873.145
QED3	−0.000005923	−26.411
QED4	−0.000000123(49)	−0.548(218)
Hadronic	0.000000054(1)	0.241(4)
Weak	−0.000000015	−0.067
Total	1.000957830(49)	4463302.88(55)

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

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

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

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

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

μ_μ/μ_p accuracy from direct measurement 0.12ppm

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

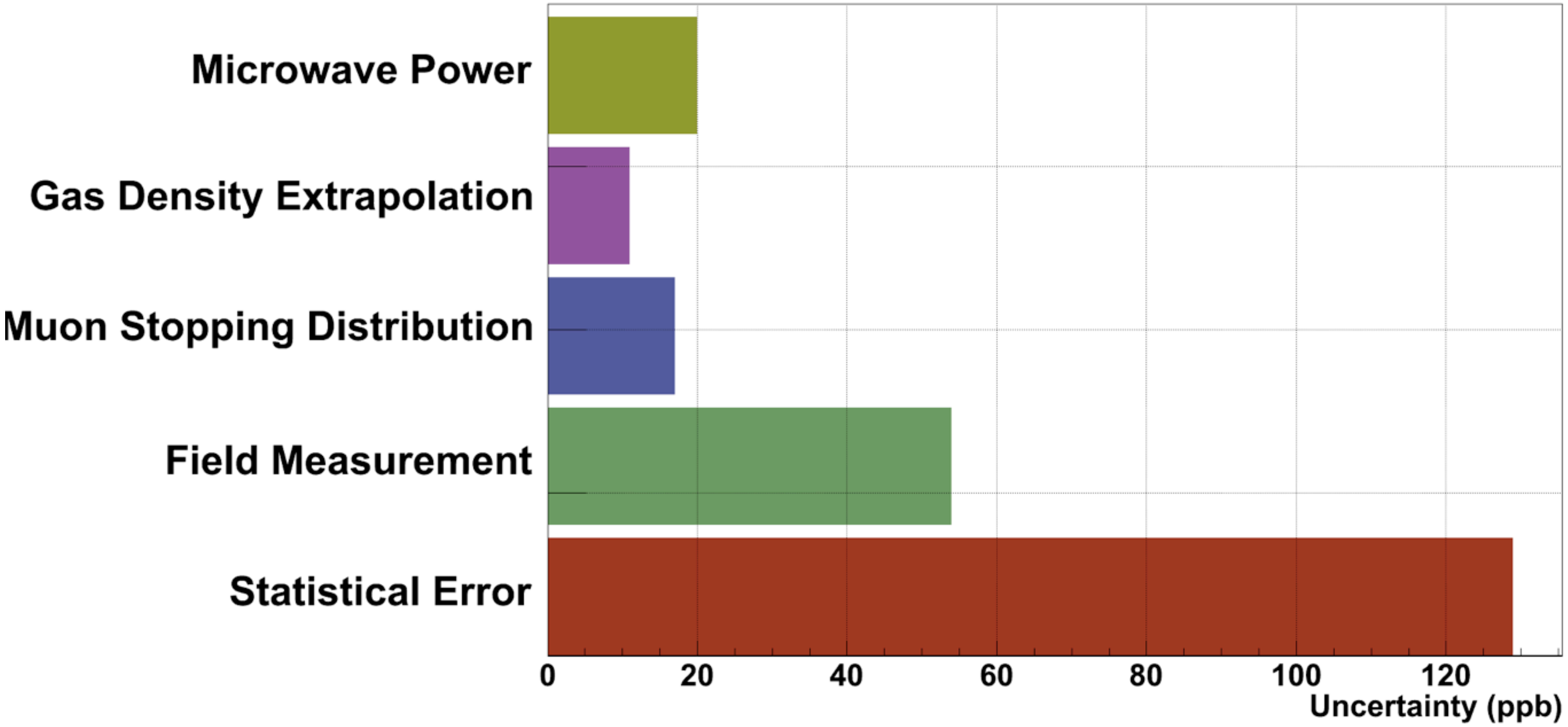
Statistical & Systematic Uncertainties

$\Delta\nu$ = 4.463 302 765(53) GHz (12 ppb)

μ_μ / μ_p = 3.183 345 24(37) (120 ppb)

LAMPF
(Los Alamos exp. in the 1990s)
W. Liu *et al.*, Phys. Rev. Lett. **82** (1999) 711

Uncertainty for μ_μ / μ_p (frequency sweep)



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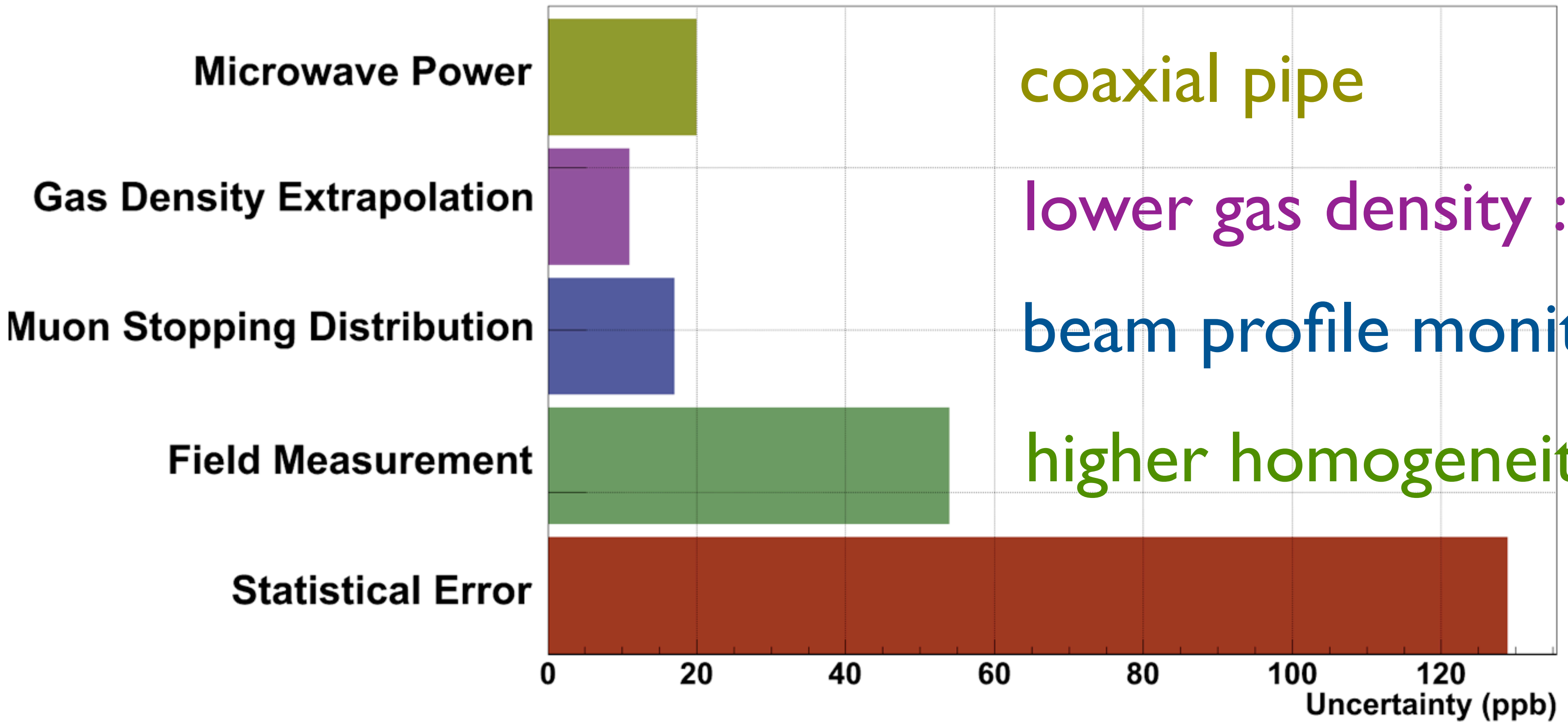


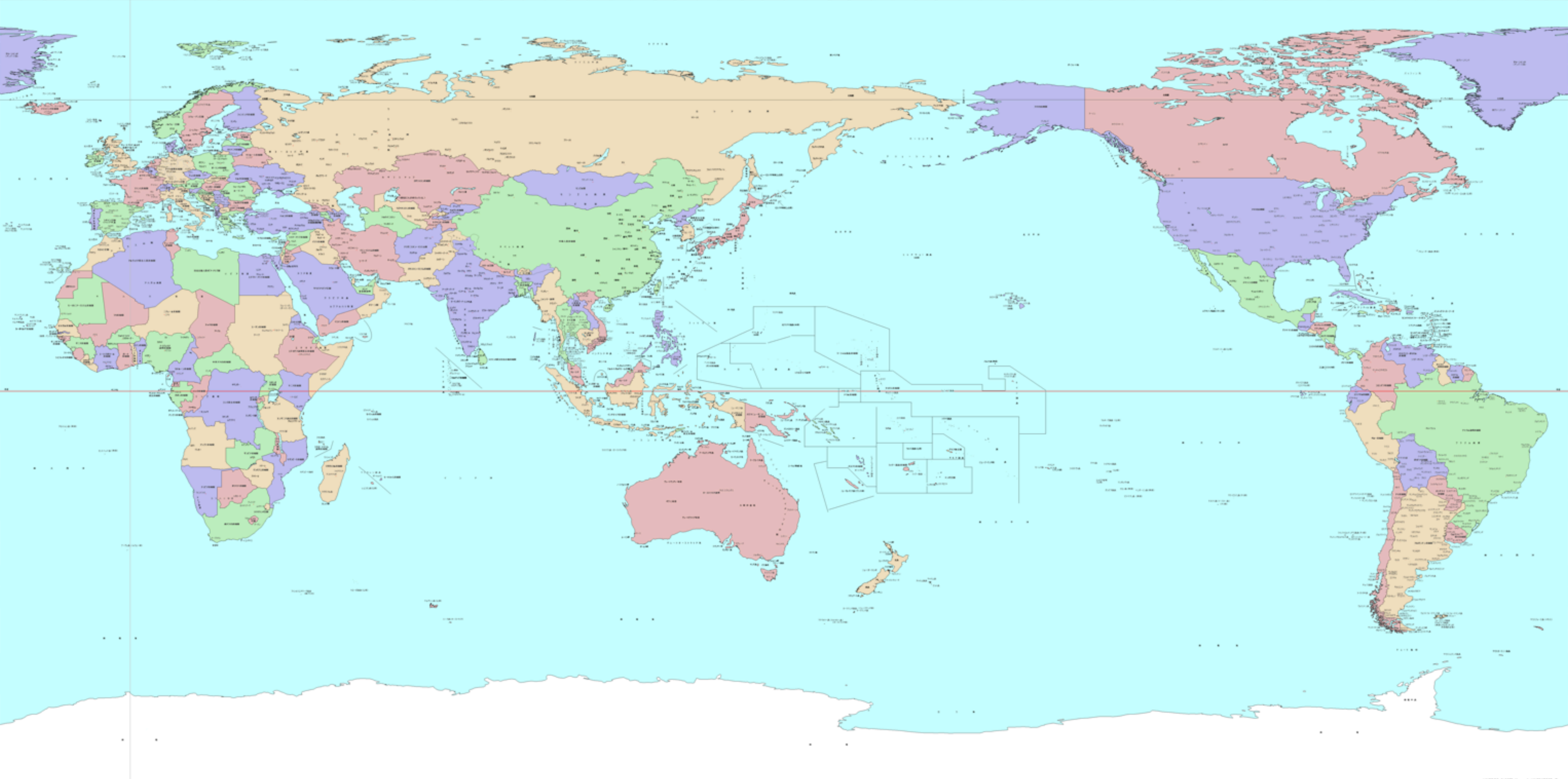
coaxial pipe

lower gas density : longer cavity

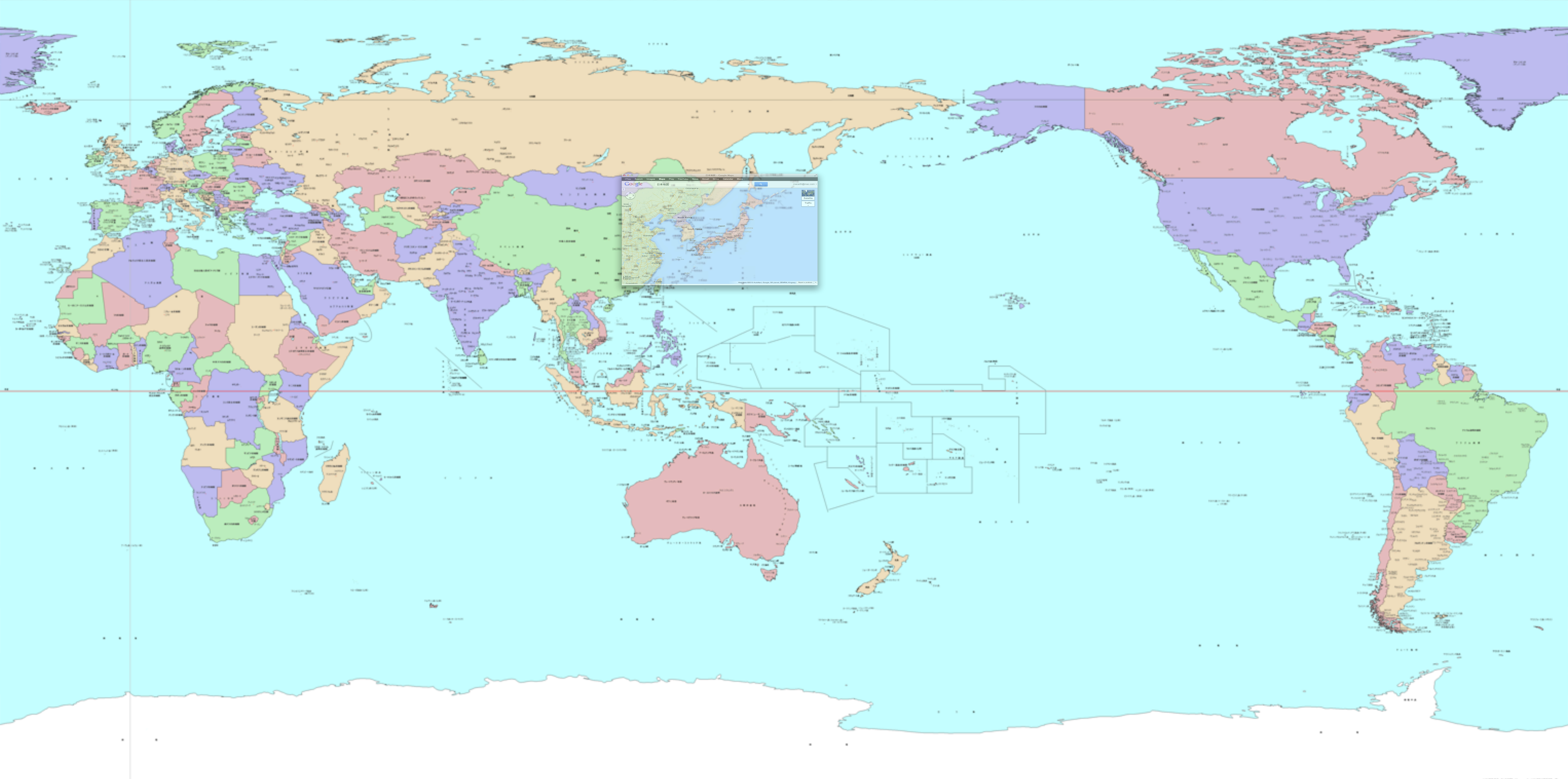
beam profile monitor

higher homogeneity of the magnetic field

higher muon intensity



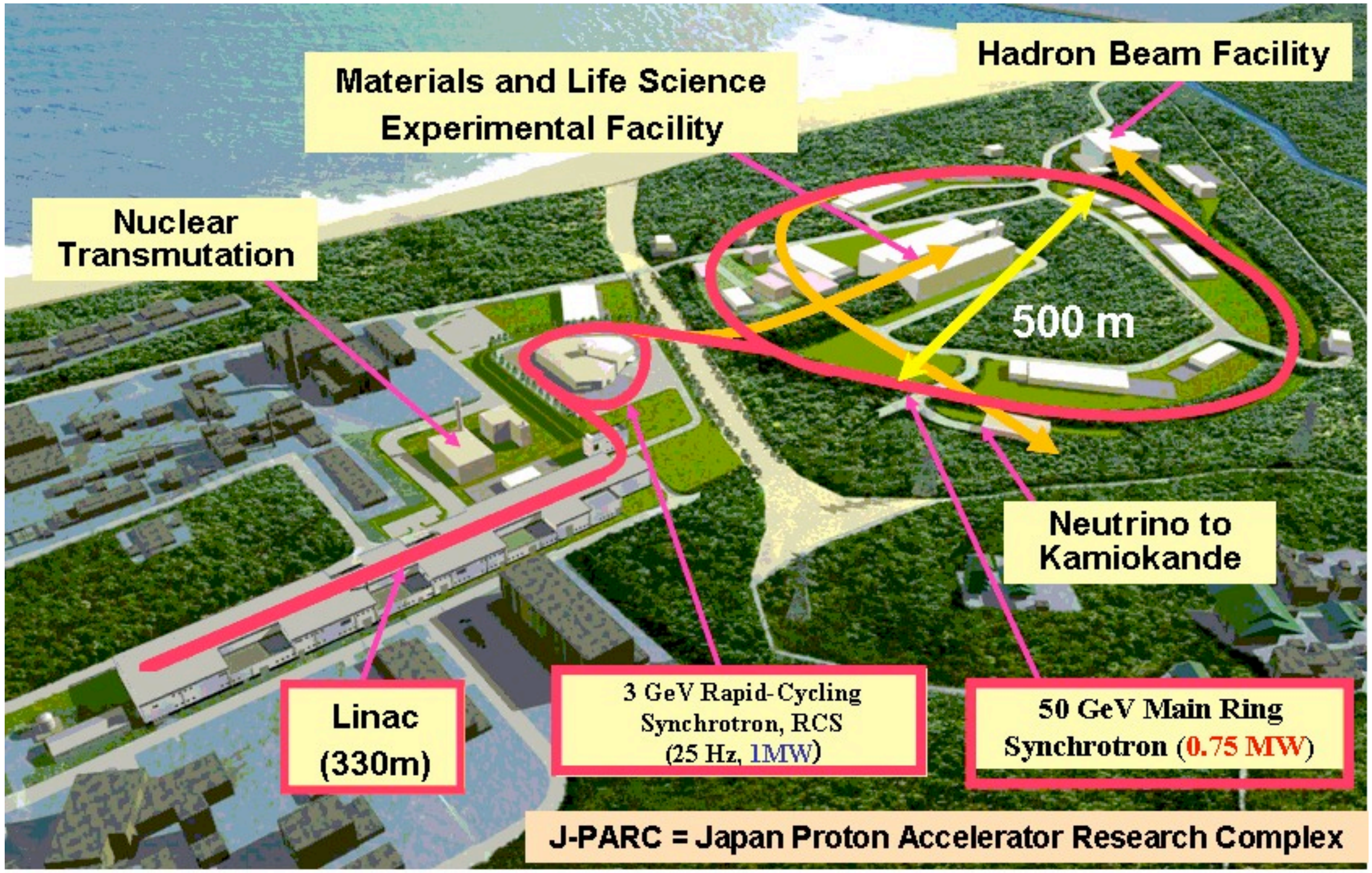
UNESCO (1987) through UNEP/GRID-Genev



UNESCO (1987) through UNEP/GRID-Genev


Harbin
Jilin
Shenyang
Liaoning
North Korea
Pyongyang
Seoul
South Korea
Shandong
Busan
Sea of Japan
Japan
Sapporo
Aomori
Akita
Morioka
Sendai
Niigata
Fukushima
Nagano
Utsunomiya
Kanazawa
Tottori
Matsue
Tokyo
Chiba
Nagoya
Osaka
Tsu
Shizuoka
Hiroshima
Fukuoka
Matsuyama
Saga
Oita
Nagasaki
Kumamoto
Miyazaki
Kagoshima
Jiangsu
Nanjing
Shanghai
Hangzhou
East China Sea
Zhejiang
Naha
Taiwan
J-PARC
TOKYO 2020

(Tokai)



大学共同利用機関法人
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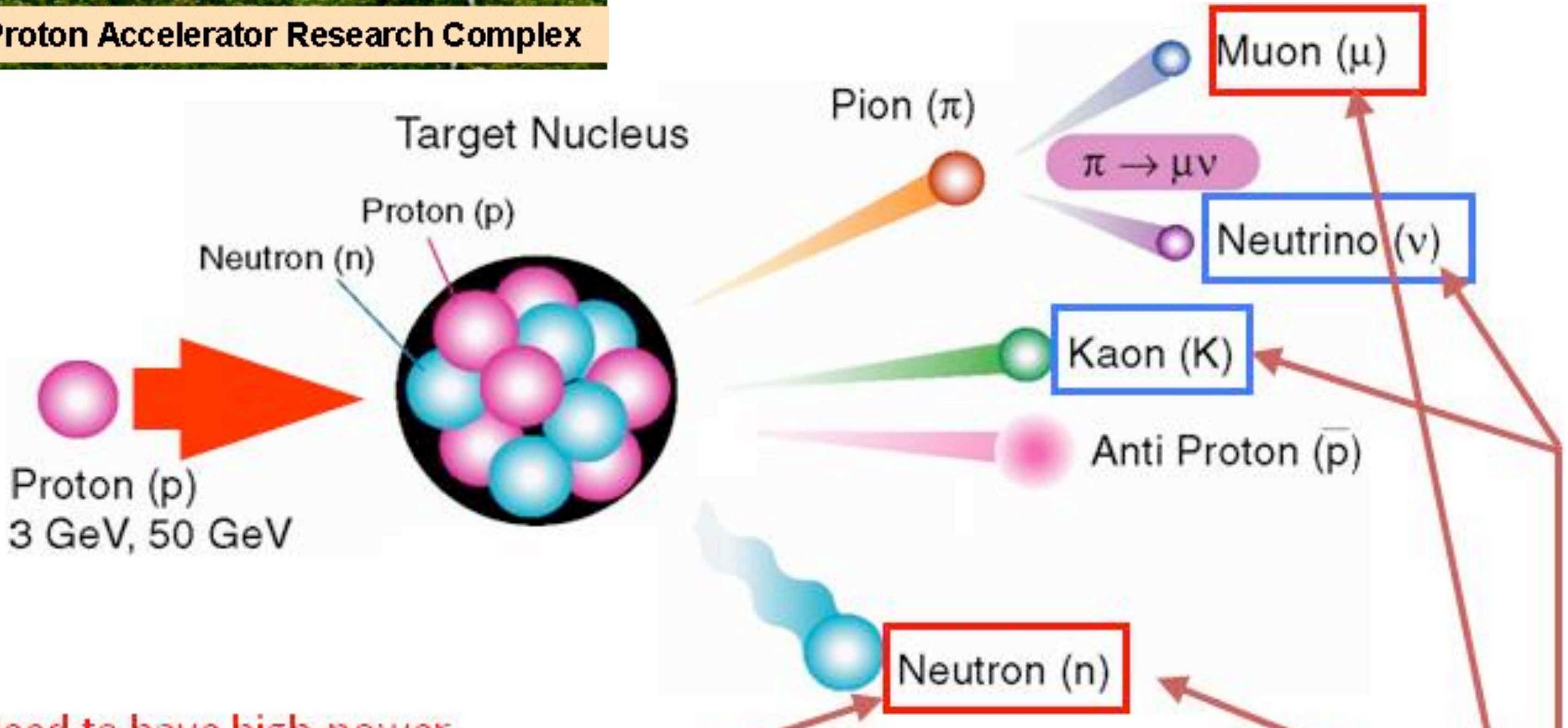
JAEA

J-PARC

独立行政法人 日本原子力研究開発機構
Japan Atomic Energy Agency

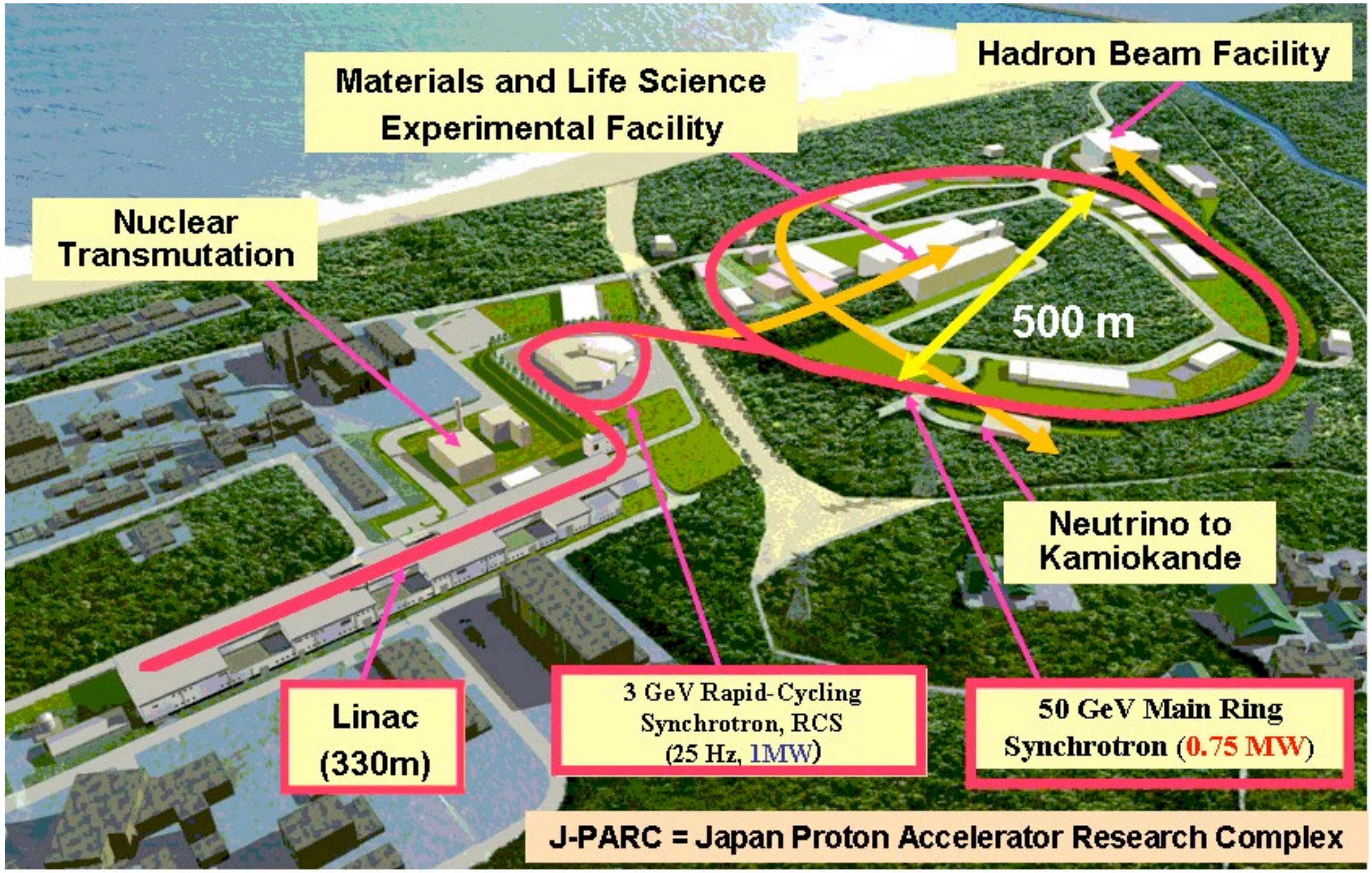
J-PARC 大強度陽子加速器施設
Japan Proton Accelerator Research Complex



Need to have high-power proton beams

→ MW-class proton accelerator
(current frontier is about 0.1 MW)

Materials & Life Science from RCS
Nuclear & Particle Physics from MR
R&D toward Transmutation from LINAC



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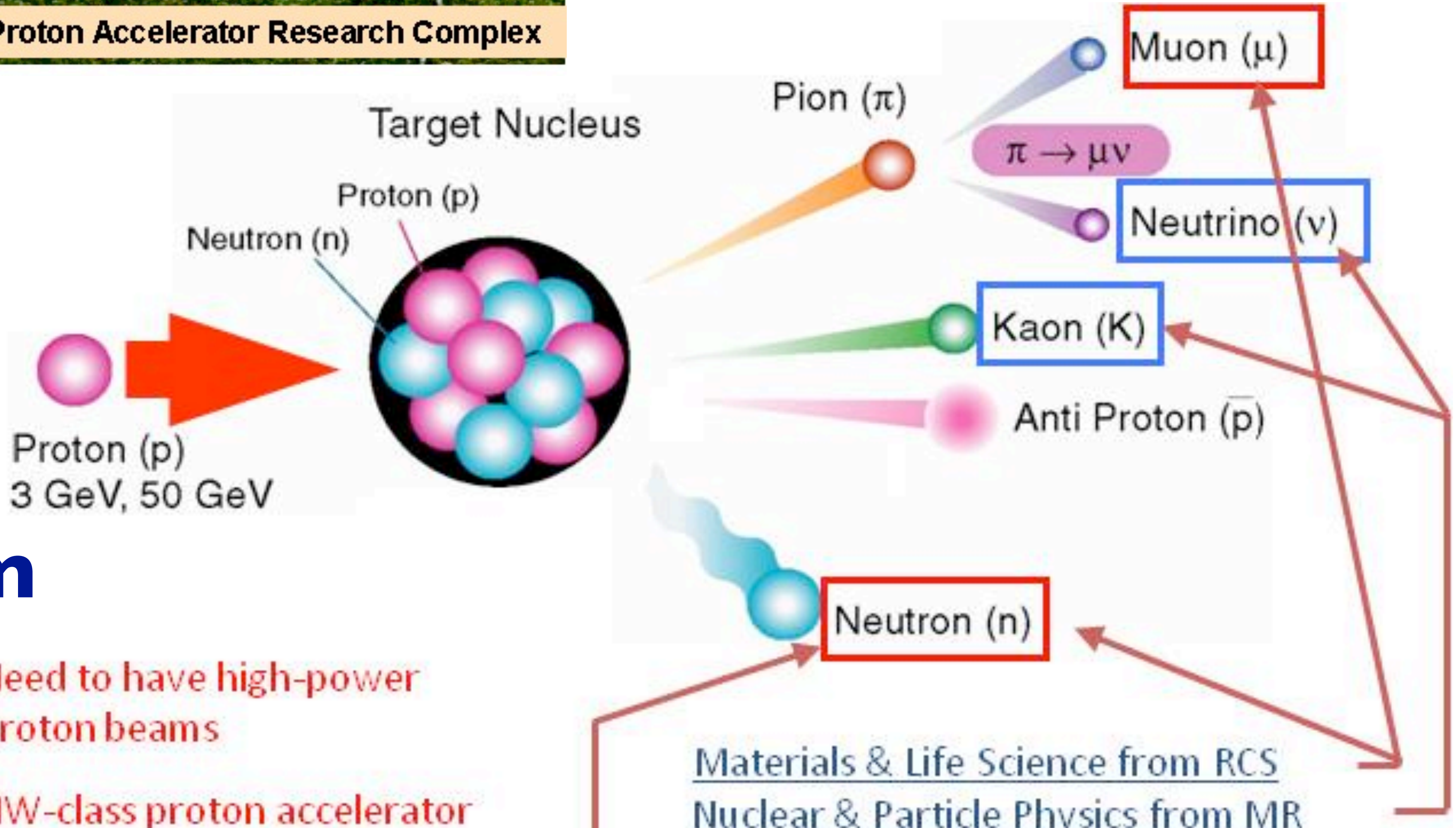
J-PARC

J-PARC 大強度陽子加速器施設
Japan Proton Accelerator Research Complex

Muon beam from intense proton beam at J-PARC



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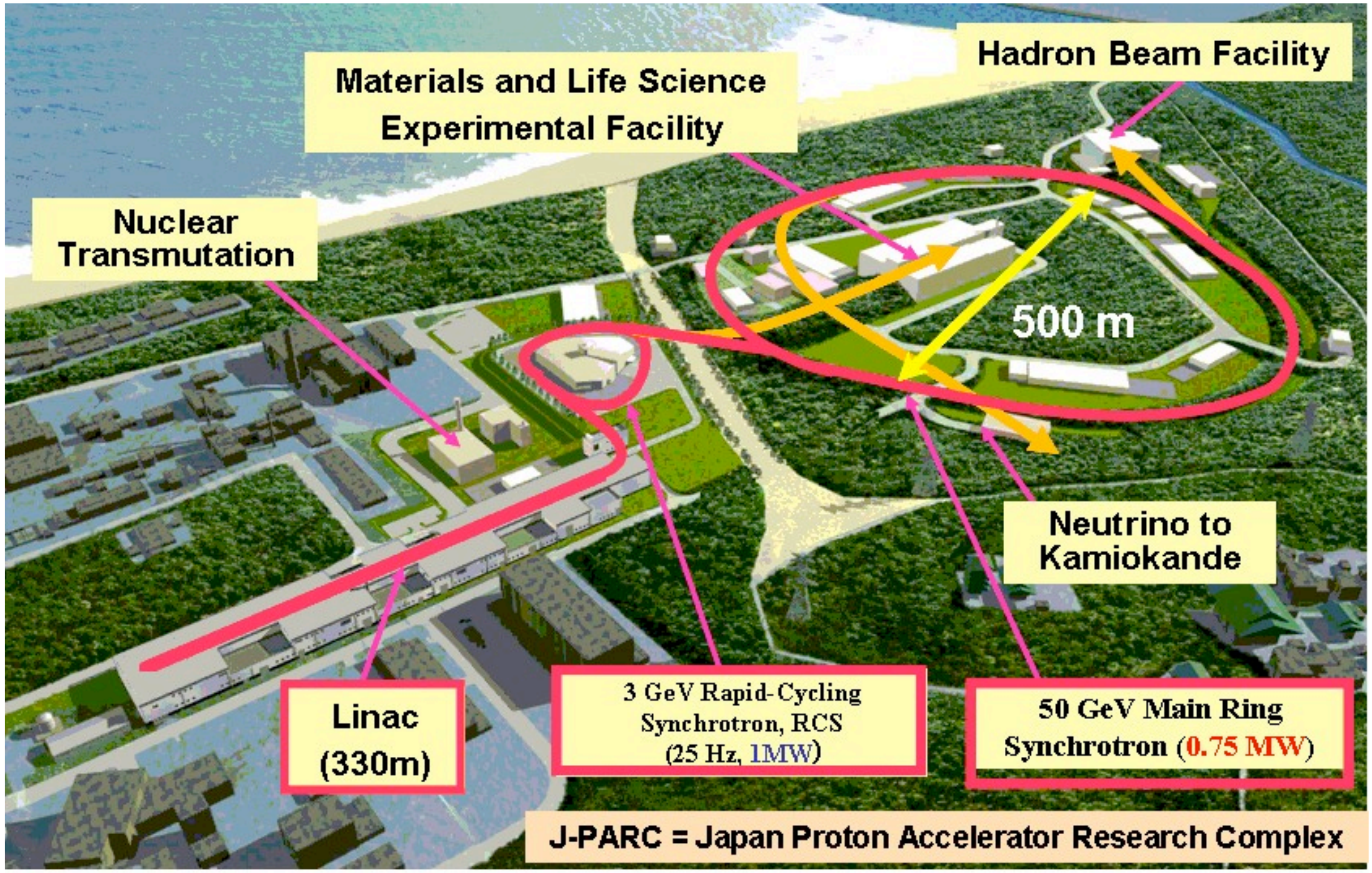

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J-PARC

J-PARC 大強度陽子加速器施設
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Beam Intensity @ J-PARC MUSE H line 1×10^{8} /s (expected)

Pulsed beam

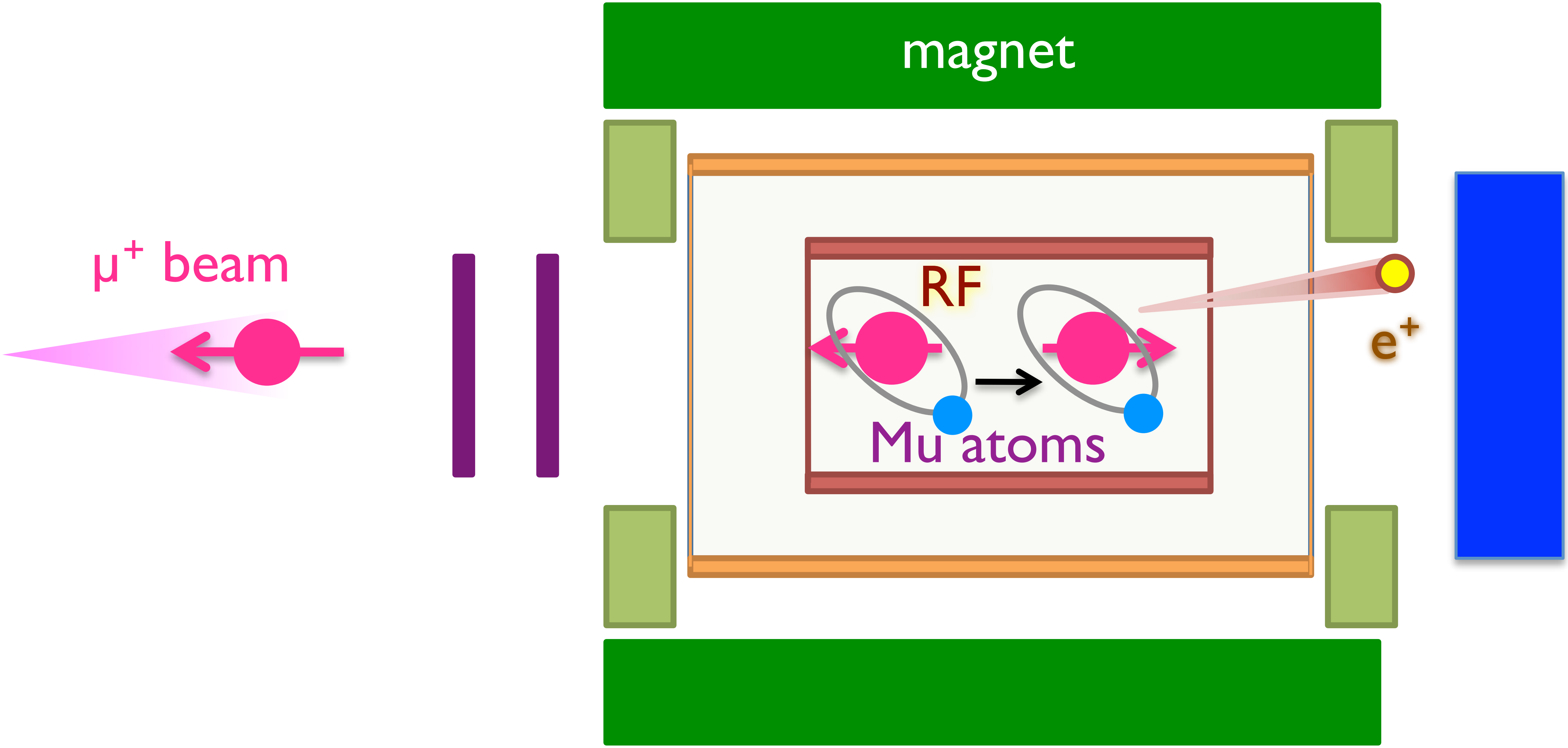
Total beam time ca. 100 days

Total Muon 1×10^{15}

10^{13}

100 times more statics than the Los Alamos experiment.

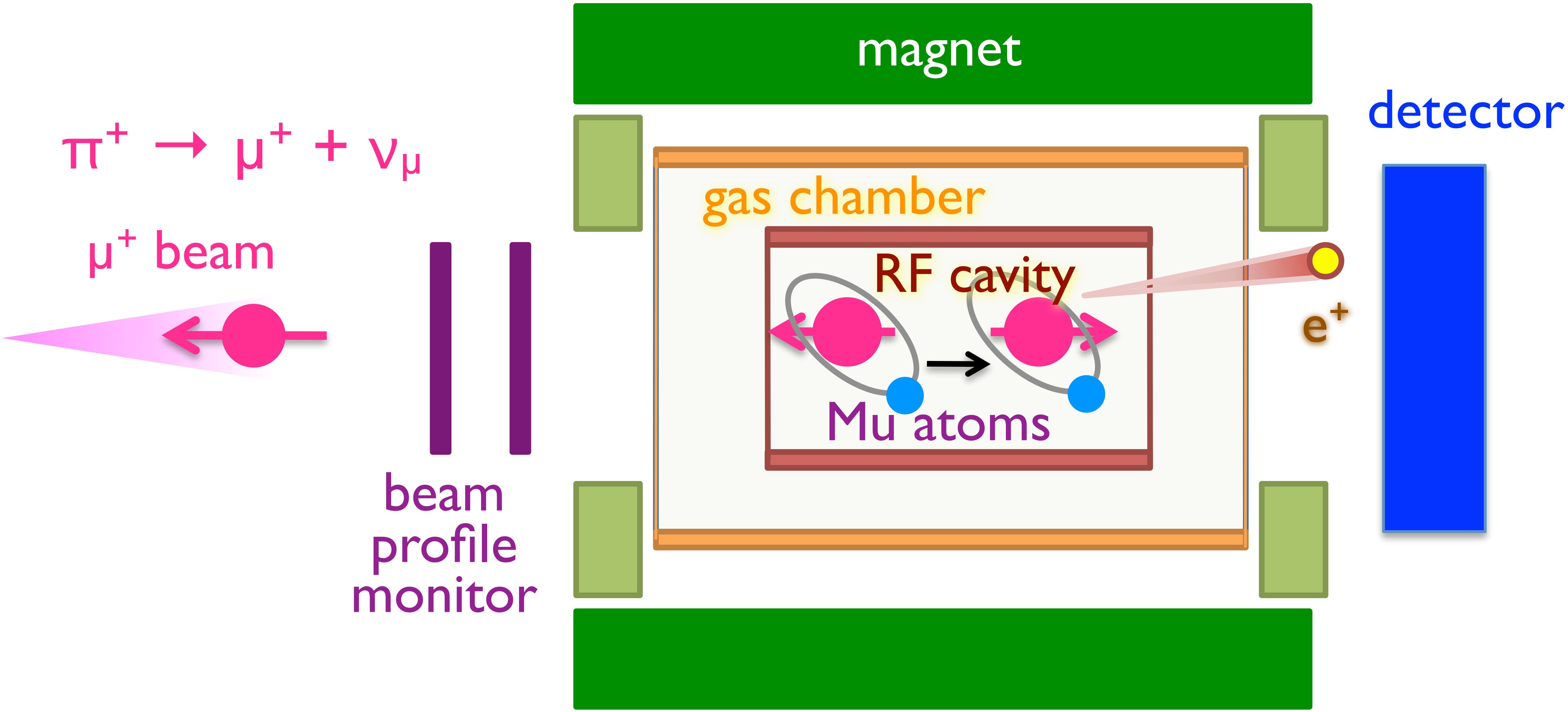
Schematic of the Experiment



Schematic of the Experiment

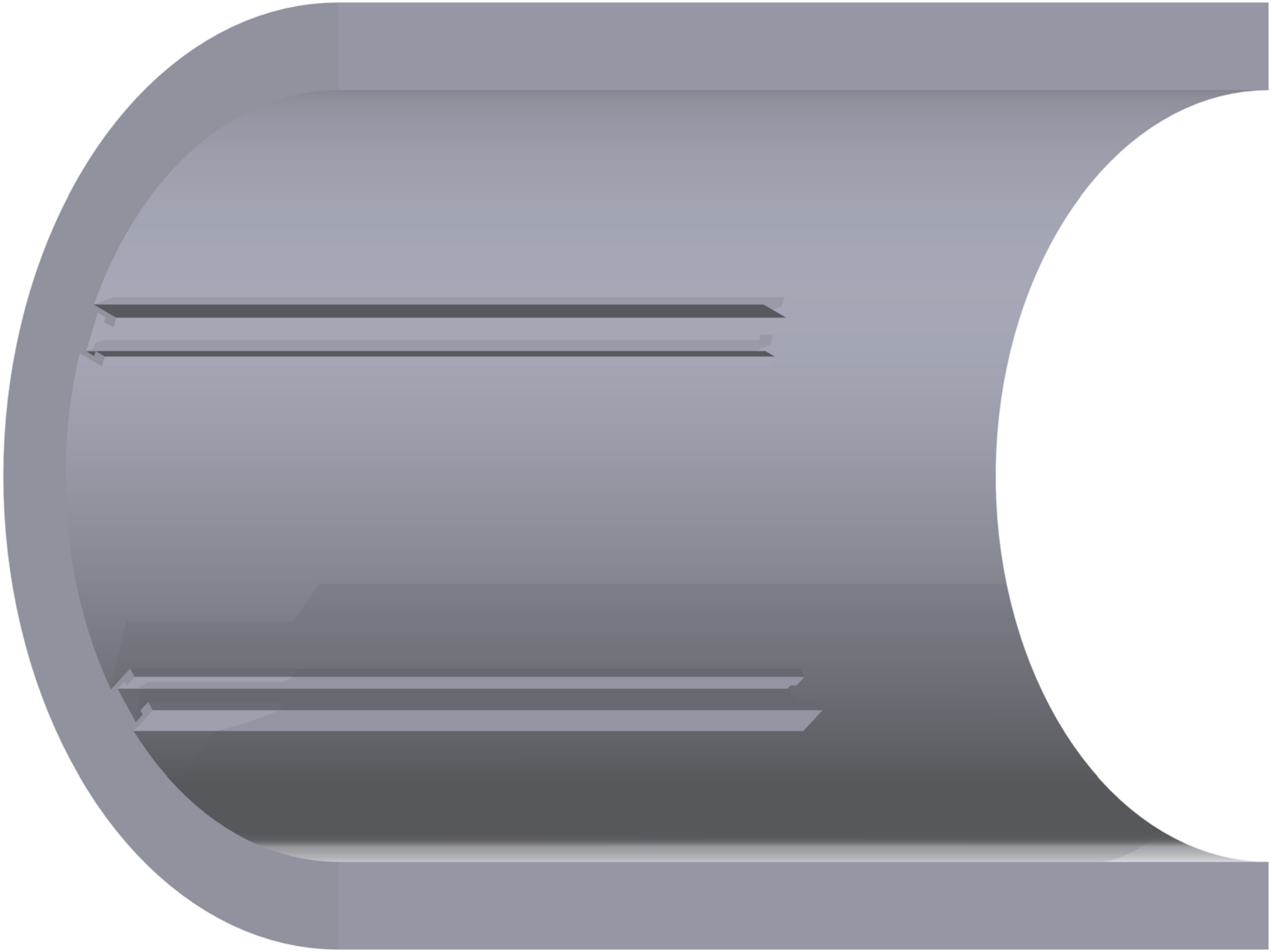
$\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu$

$\pi^+ \rightarrow \mu^+ + \nu_\mu$

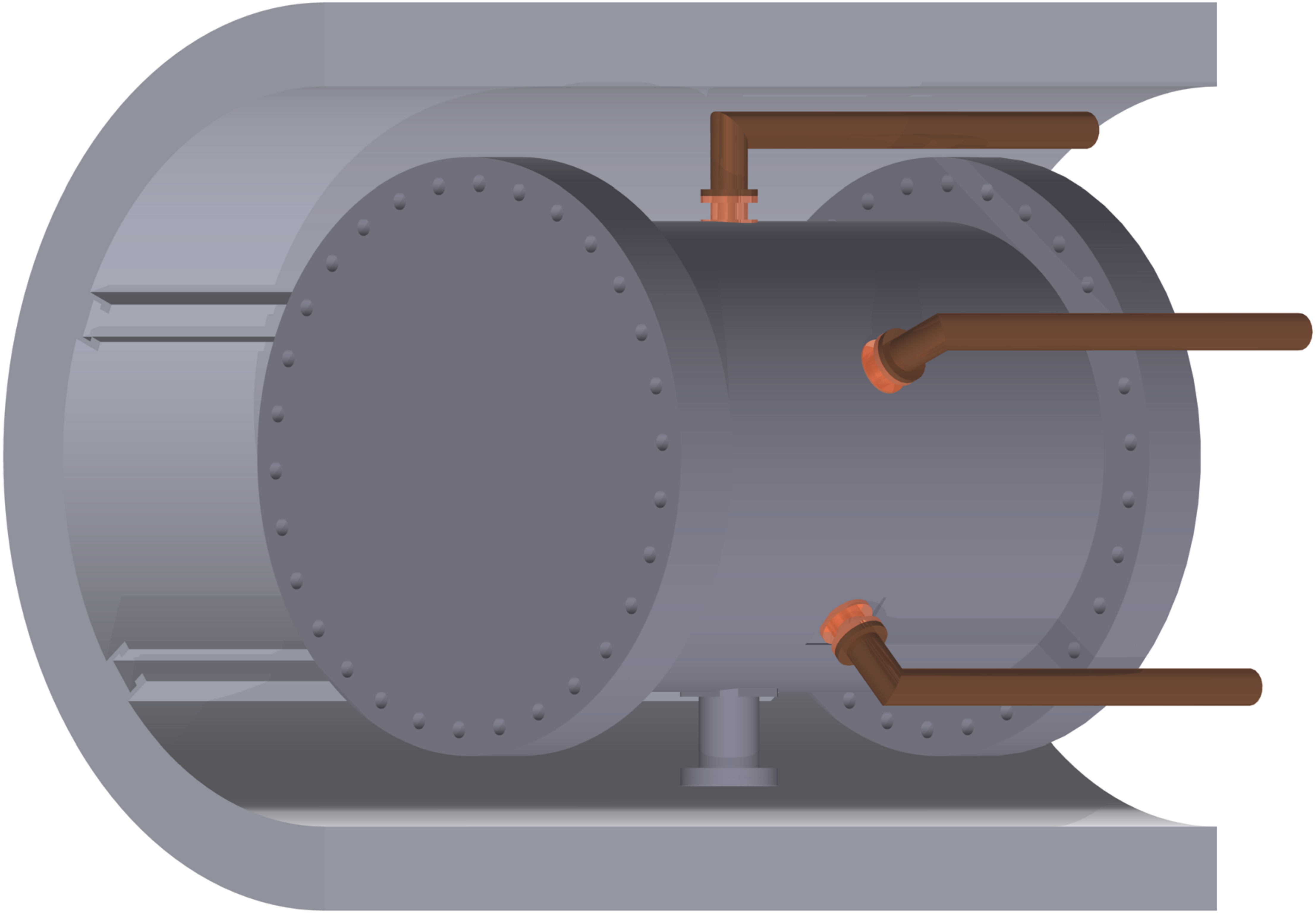


$\mu^+ + Kr \rightarrow Mu\ (\mu^+e^-) + Kr^+$

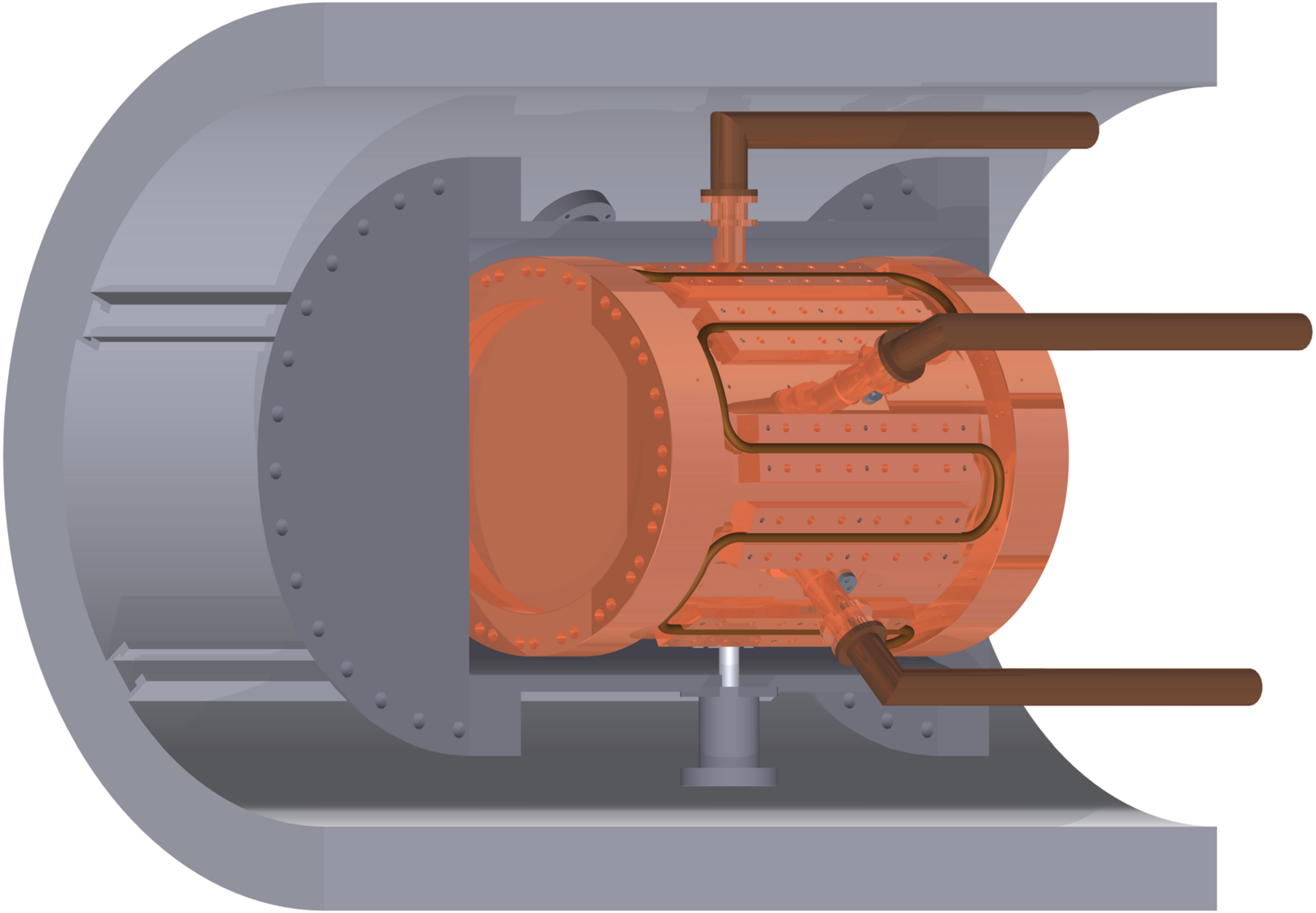
magnet



Gas Chamber



RF Cavity



magnet

1.7 T high-precision superconducting magnet

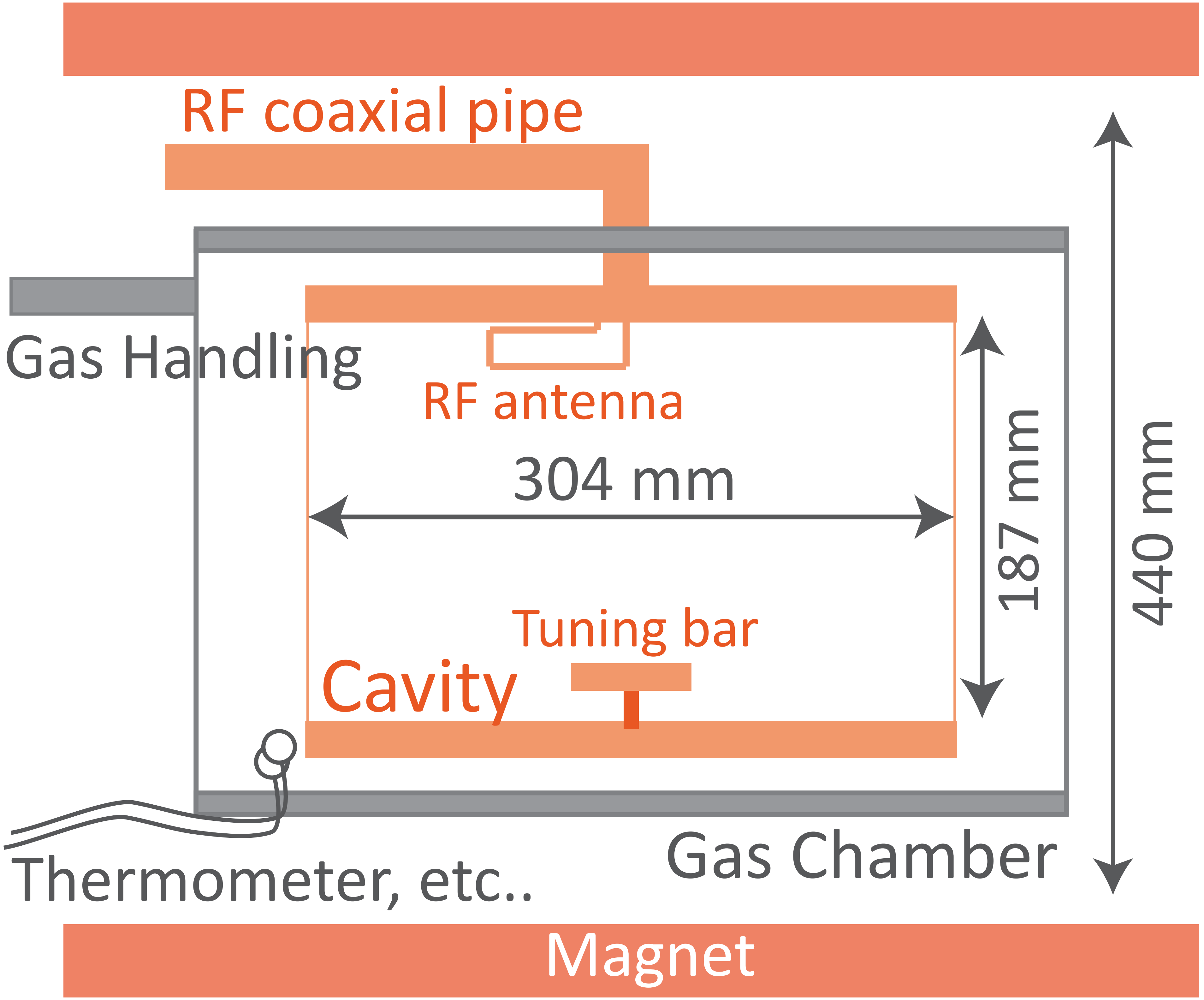
Bore diameter = ⌀925 mm

Requirement: **1 ppm** homogeneity + absolute calibration
in 300 mm x ⌀200 mm spheroidal region

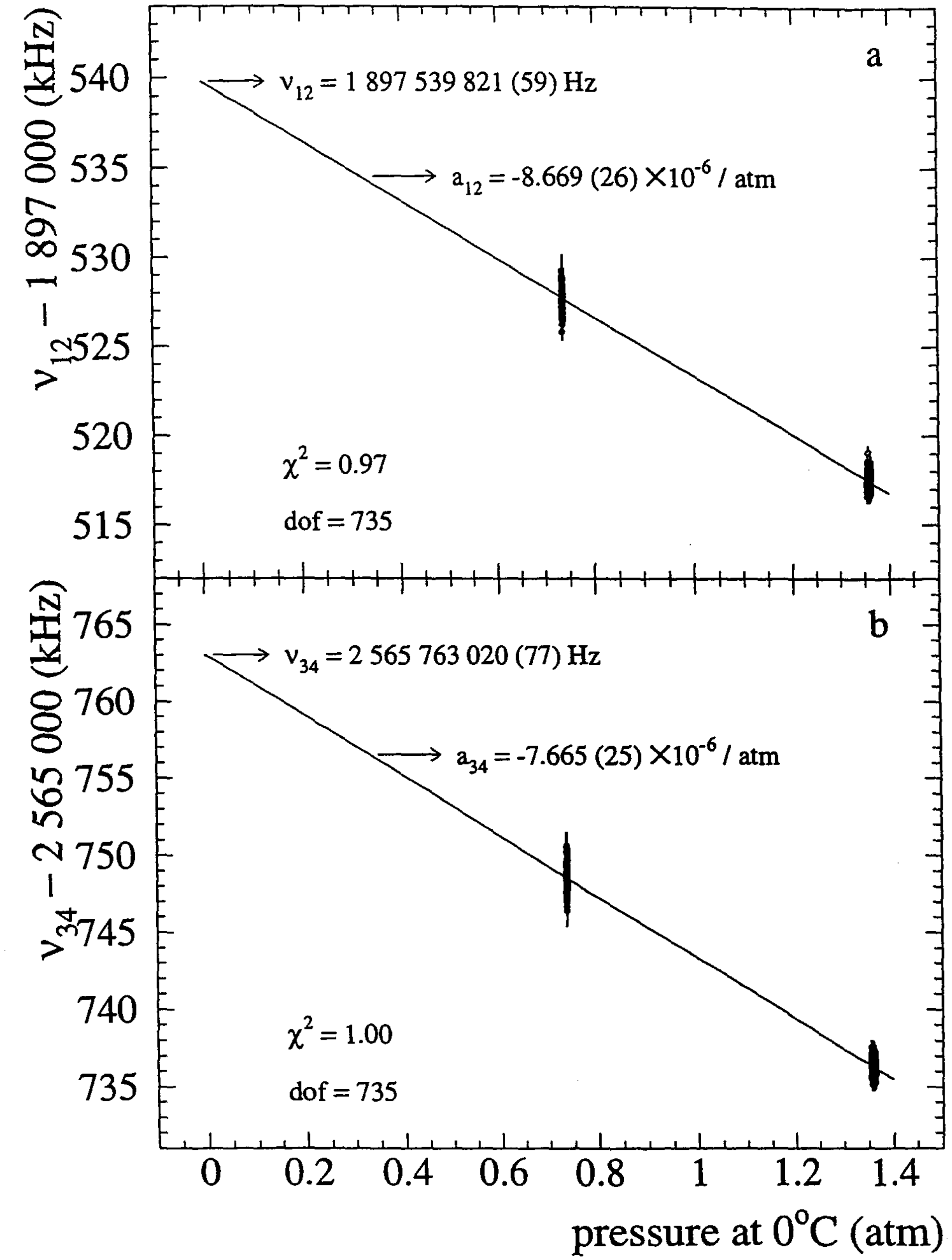
- Field strength to be measured by water NMR probes.
  - 24 probes x 24 positions
- Field correction by shim coils and insertion of iron shims.
  - iterative adjustment

RF Cavity & Gas Chamber

RF resonator Kr gas vessel



Pressure shift of the resonance line



Large shift

- Due to atomic collision
- Linear dependence

$$\nu(P) = \nu(0)\,(1 + aP + bP^2)$$

$a_{12} = -1.14 \times 10^{-8}$ Torr^{-1} @ 0 deg. C

$a_{34} = -1.01 \times 10^{-8}$ Torr^{-1} @ 0 deg. C

pressure: precise measurement

temperature: sub-K control

Pressure shift of the resonance line

Collision with reactive contaminant gases

Mu is an isotope of H.

Mu behaves chemically as an hydrogen radical (H·).

H_2 gas $\partial\Delta\nu(\mathrm{H}) / \partial P \approx 16$ Hz / mbar

$\partial\Delta\nu$ (0.8 atm, 300 ppm) $\approx$ 4 Hz

O_2 gas highly reactive (unpaired electrons)

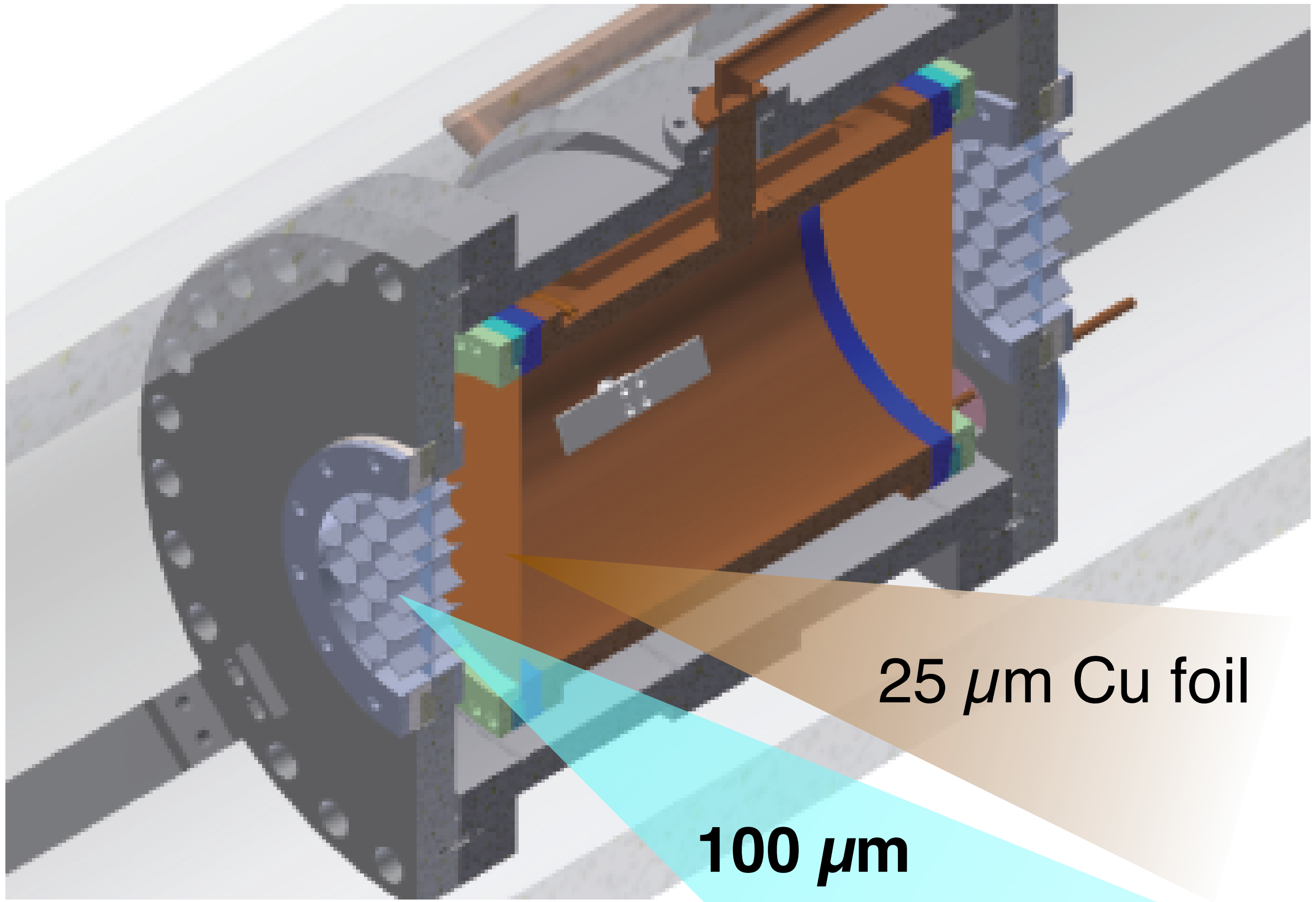
Shift of resonance lines

Quenching of Mu polarization ☞ signal vanishes

purity: < O(ppm)

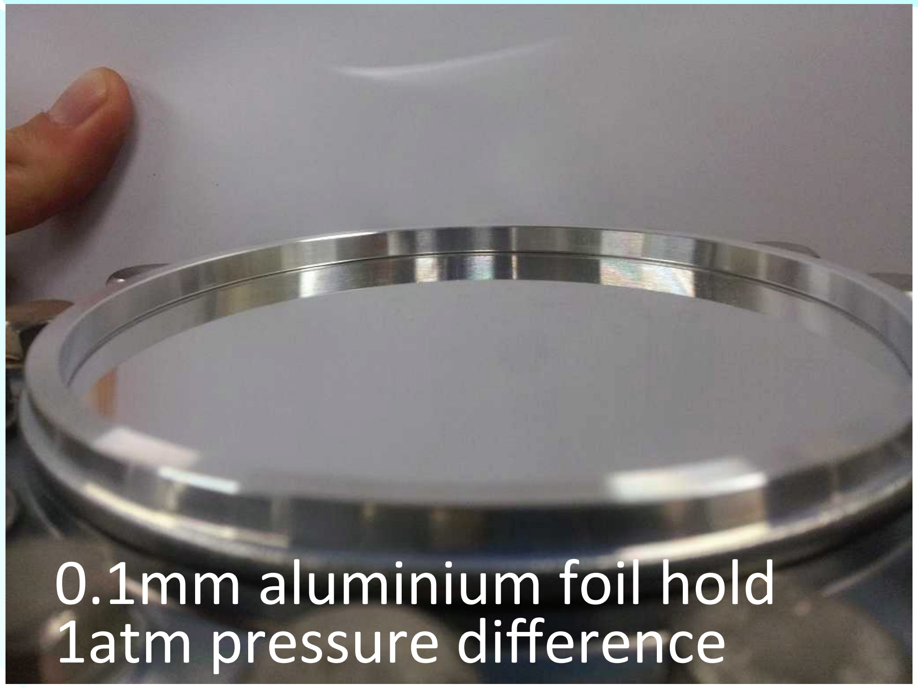
gas chromatograph or Qmass detector

Gas Chamber



Design drawing

foil-test



0.1mm aluminium foil hold
1atm pressure difference

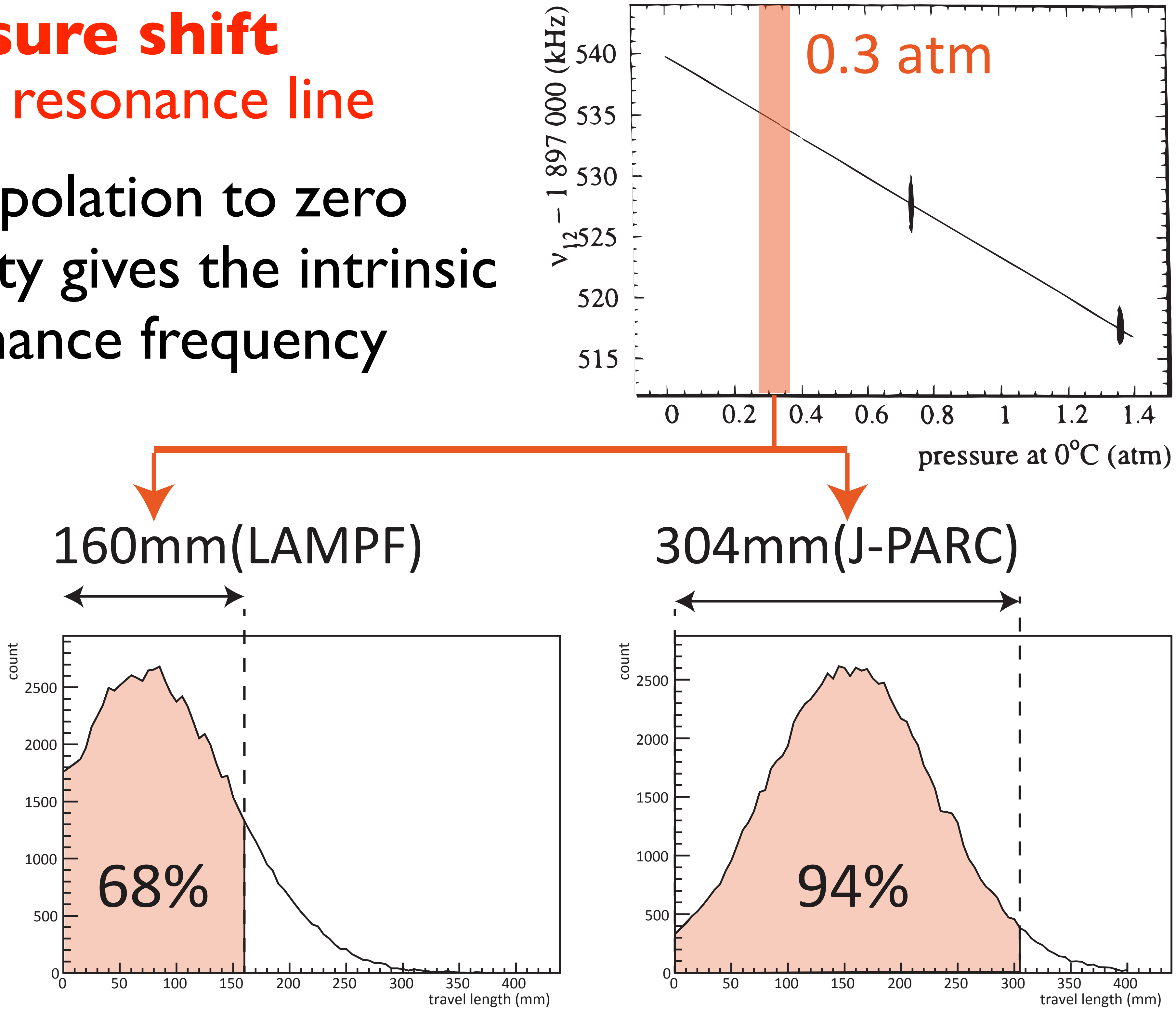
to-do list of designing

- gas-handling system
- measurement of gas purity
- temperature control

RF Cavity

Pressure shift
of the resonance line

Extrapolation to zero density gives the intrinsic resonance frequency



0.3 atm

160mm(LAMPF)

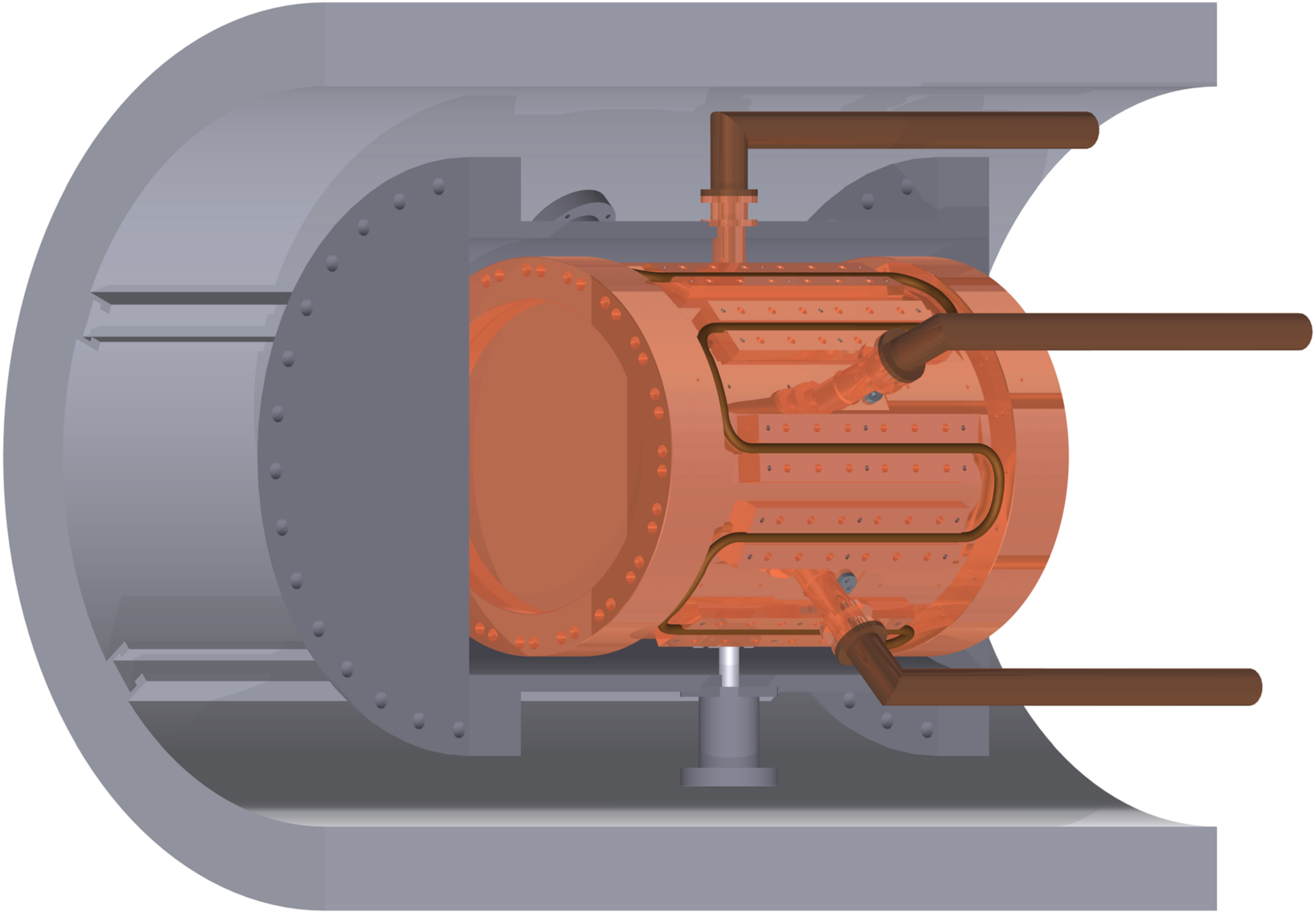
304mm(J-PARC)

68%

94%

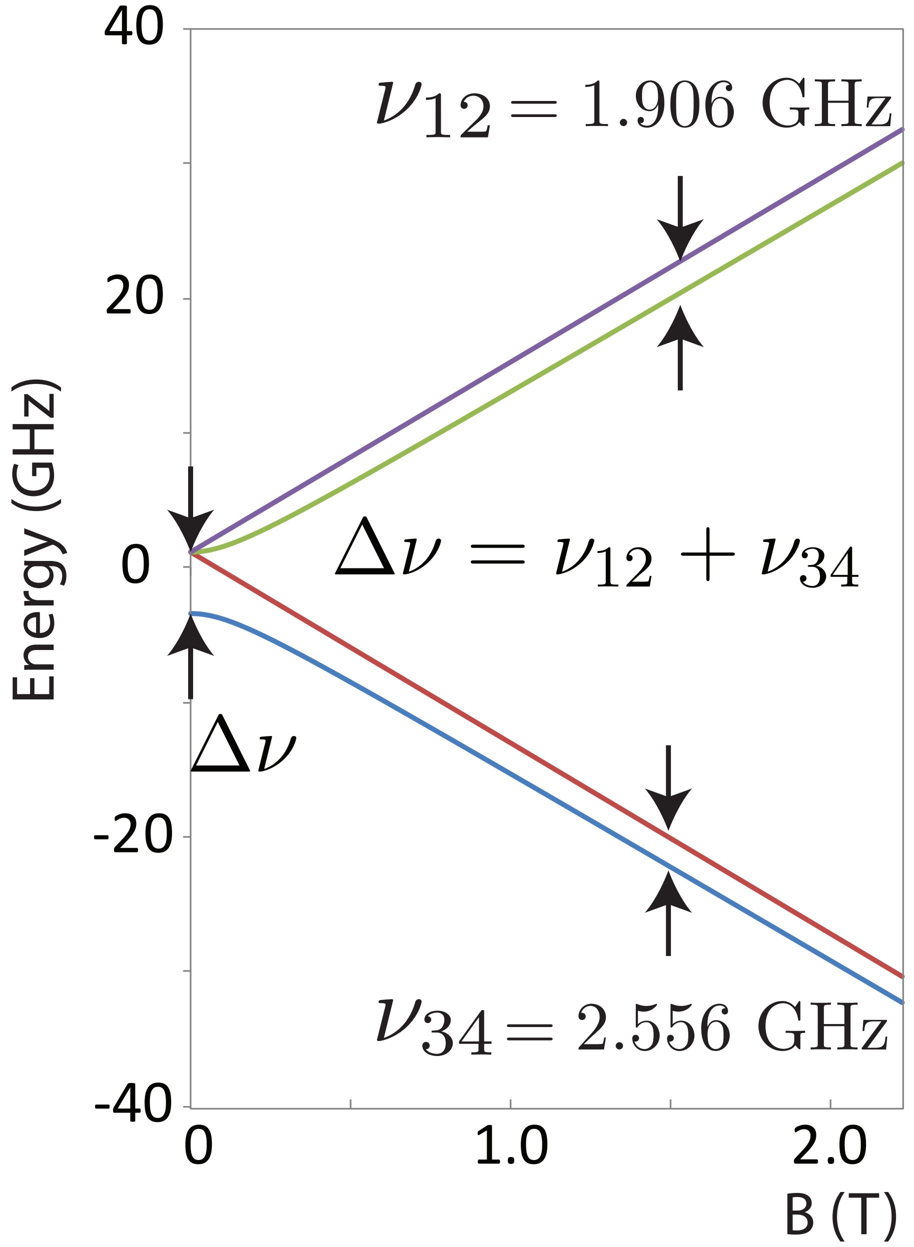
Longer cavity allows reliable measurements at lower pressure.

RF Cavity & Gas Chamber



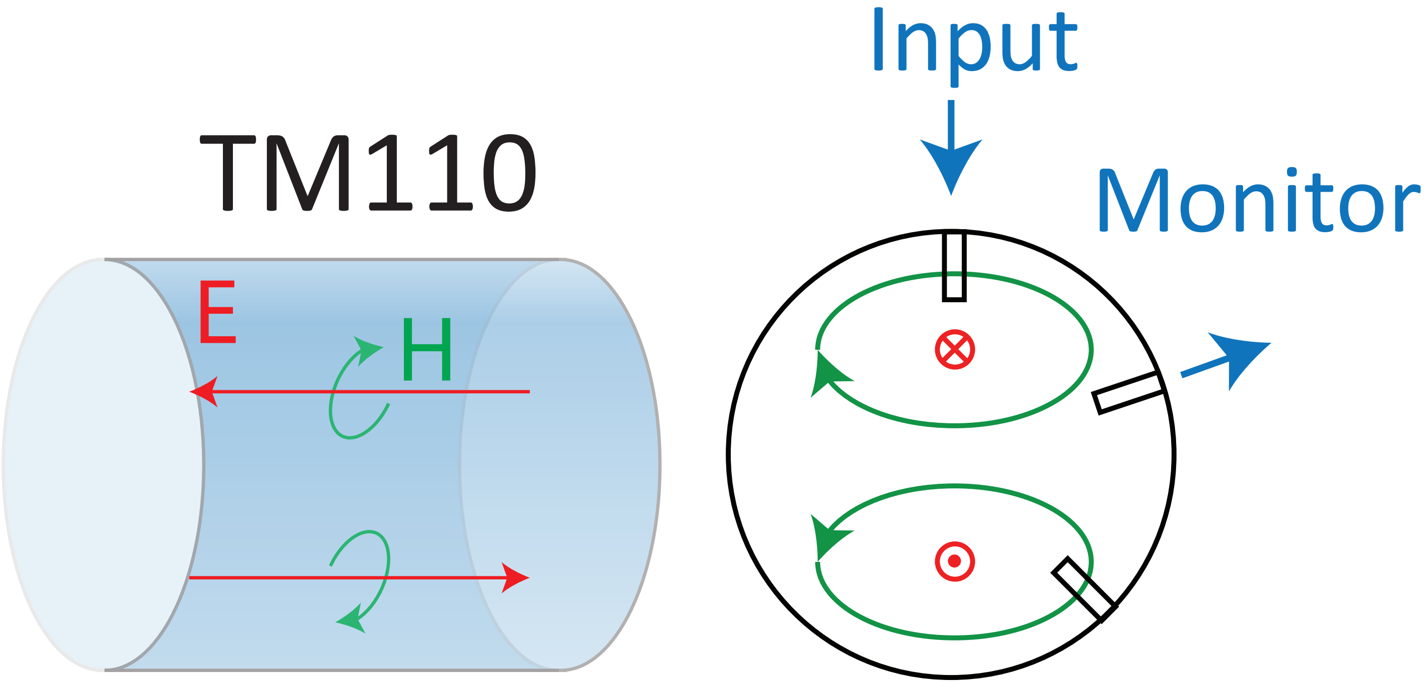
RF Cavity

two transitions

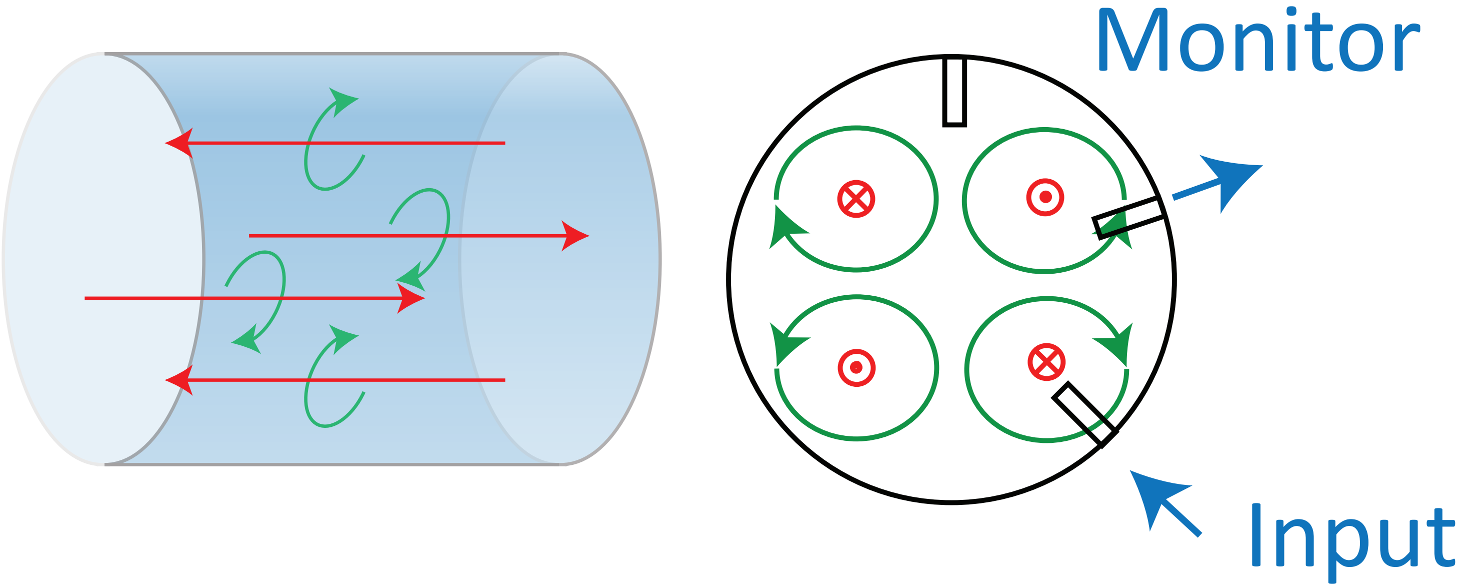


two resonance modes

TM110

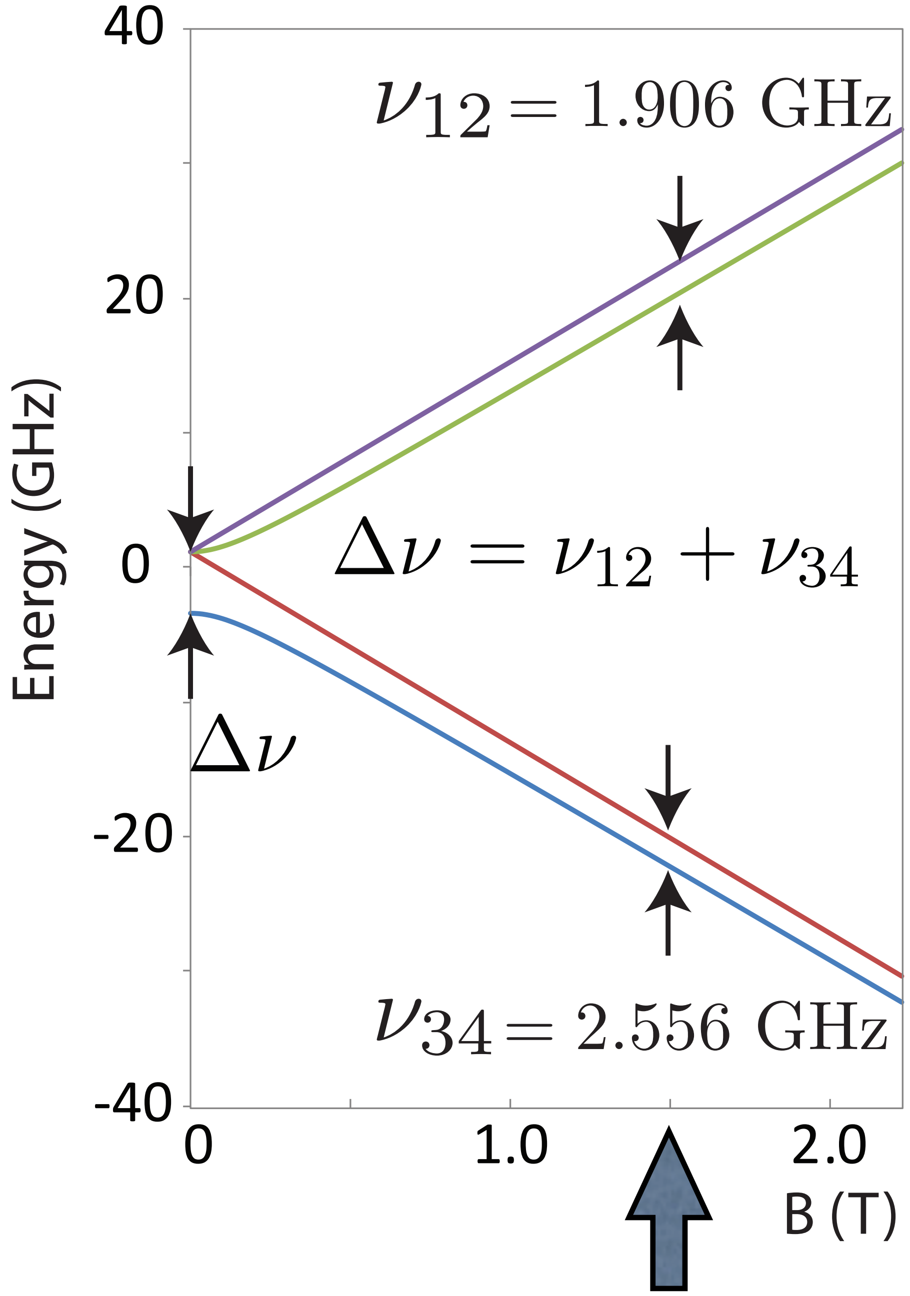


TM210

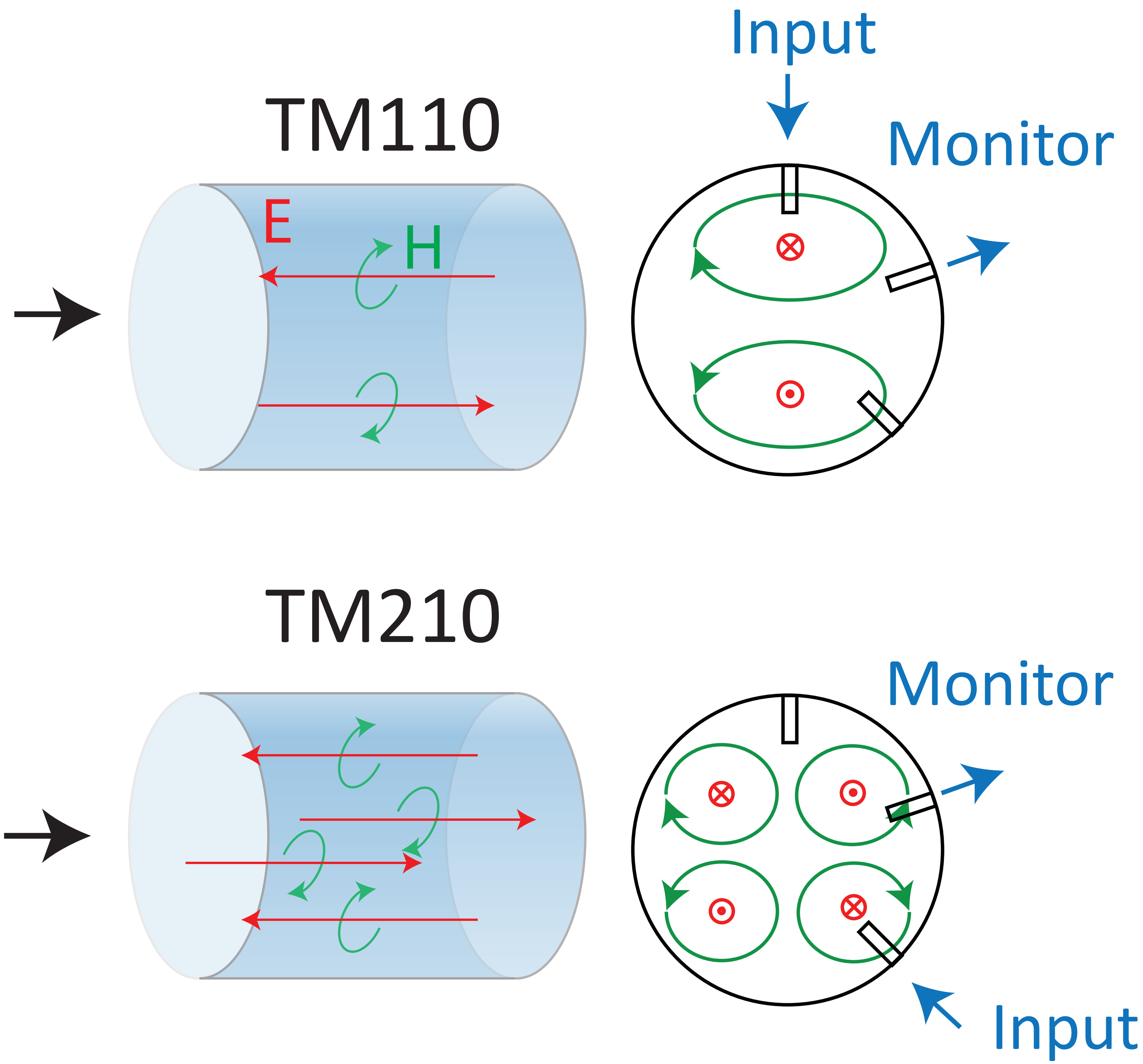


RF Cavity

two transitions

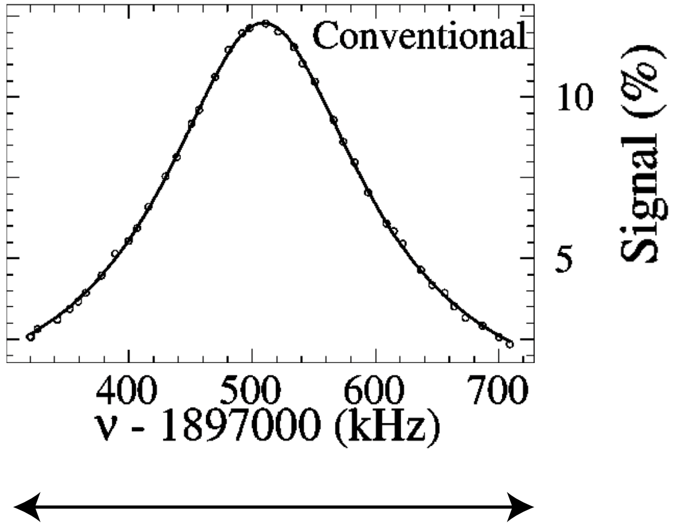


two resonance modes

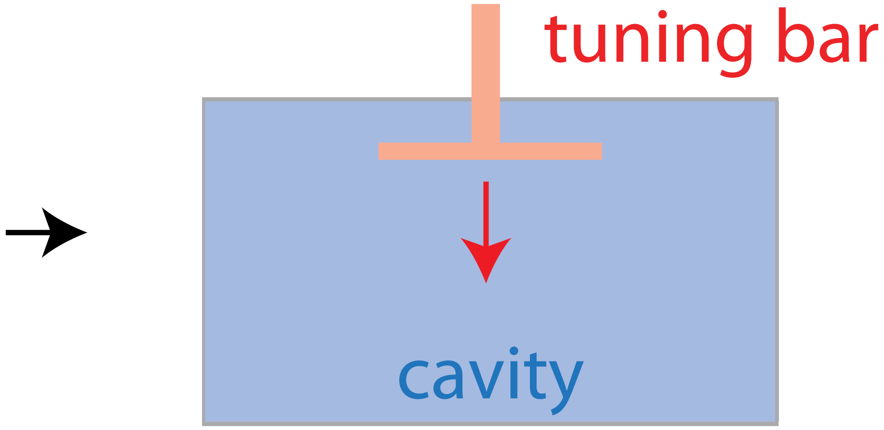


'magic' magnetic field = 1.7 T

RF Cavity



400 kHz



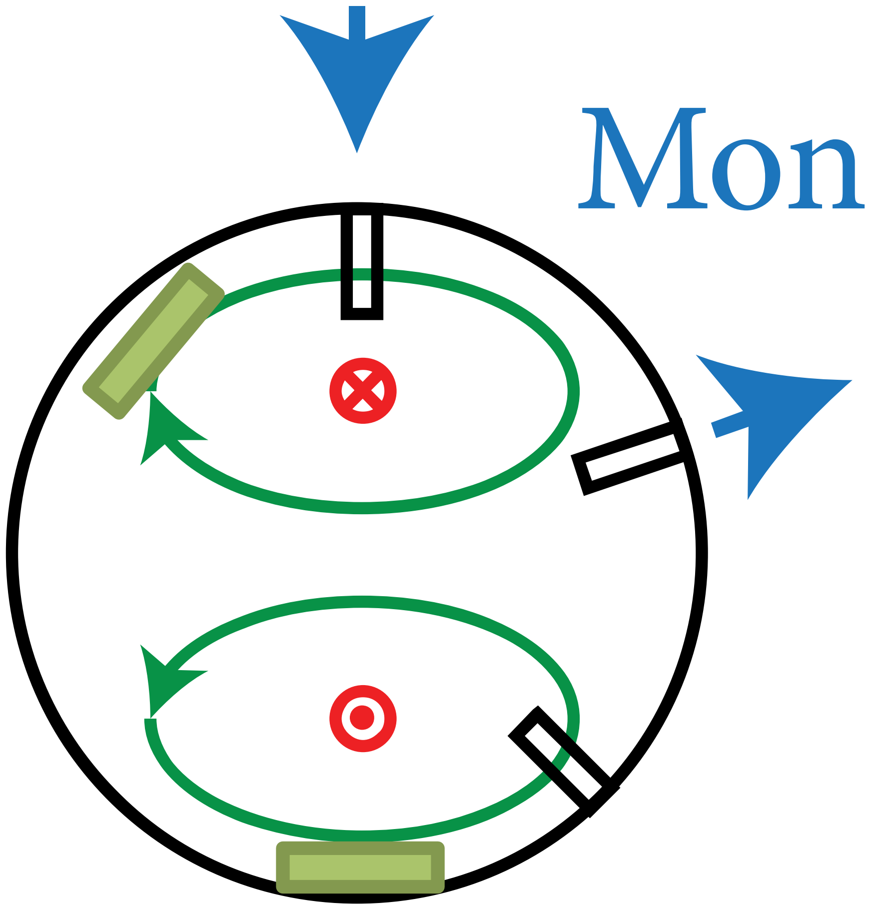
tuning bar

cavity

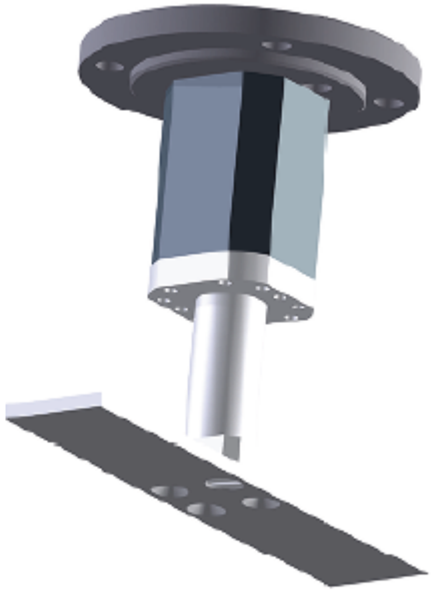
frequency tuning by physically moving tuning bars.

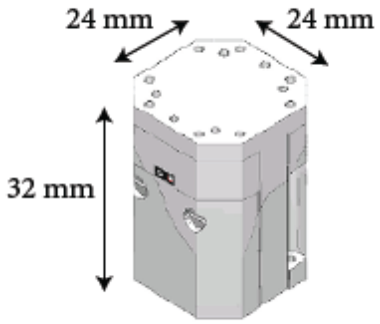
RF Input

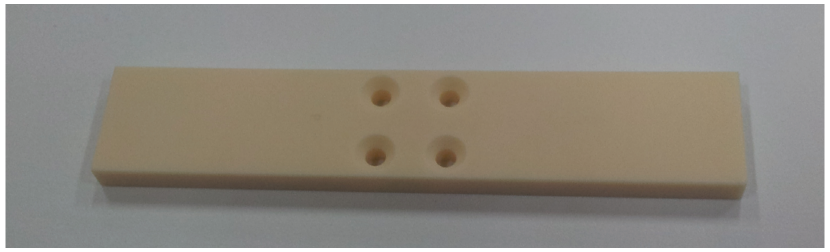
Monitor



tuning bar







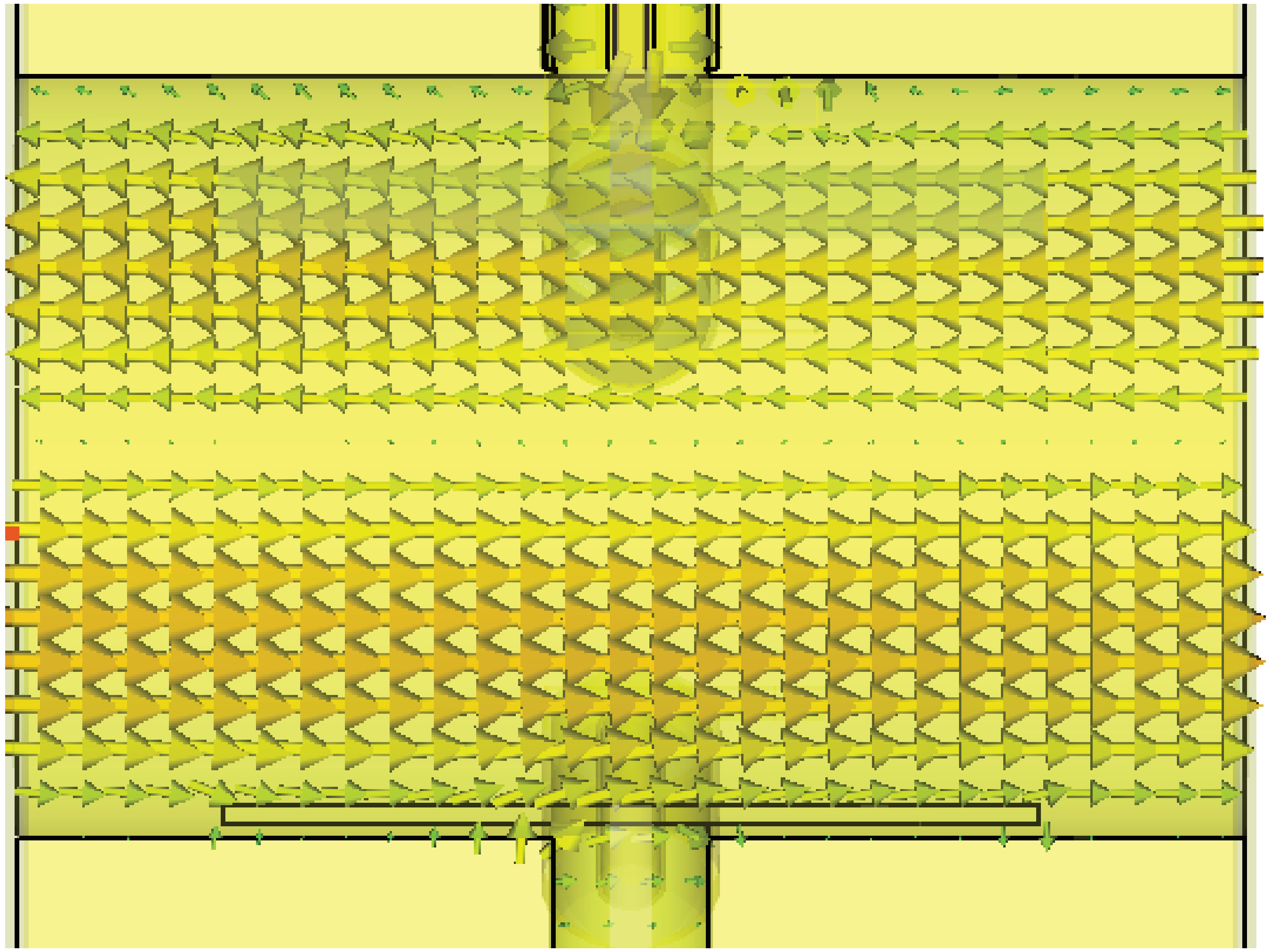
alumina tuning bar

$20 \times 100 \times 5\ \mathrm{mm}^3$

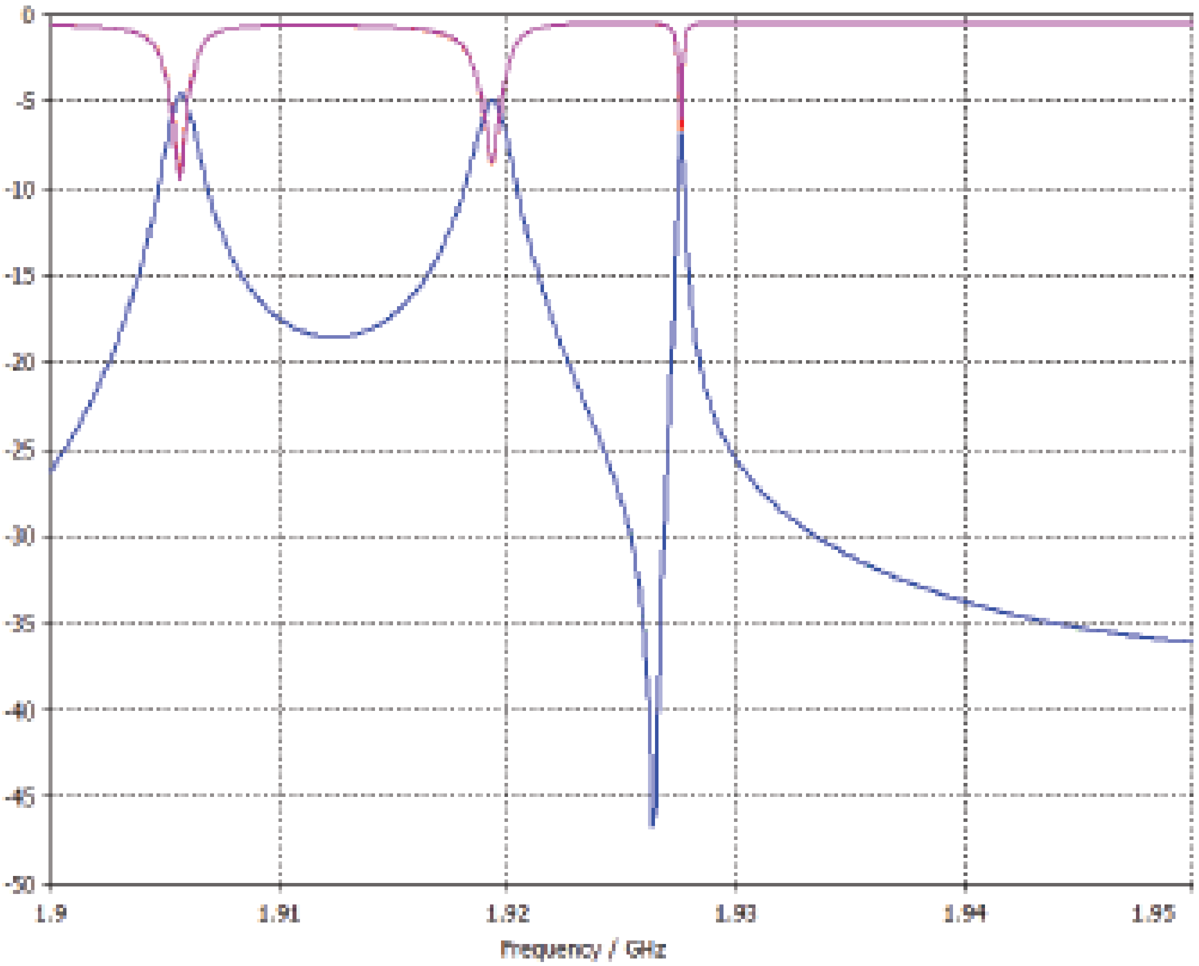
RF Cavity

RF simulations

RF field

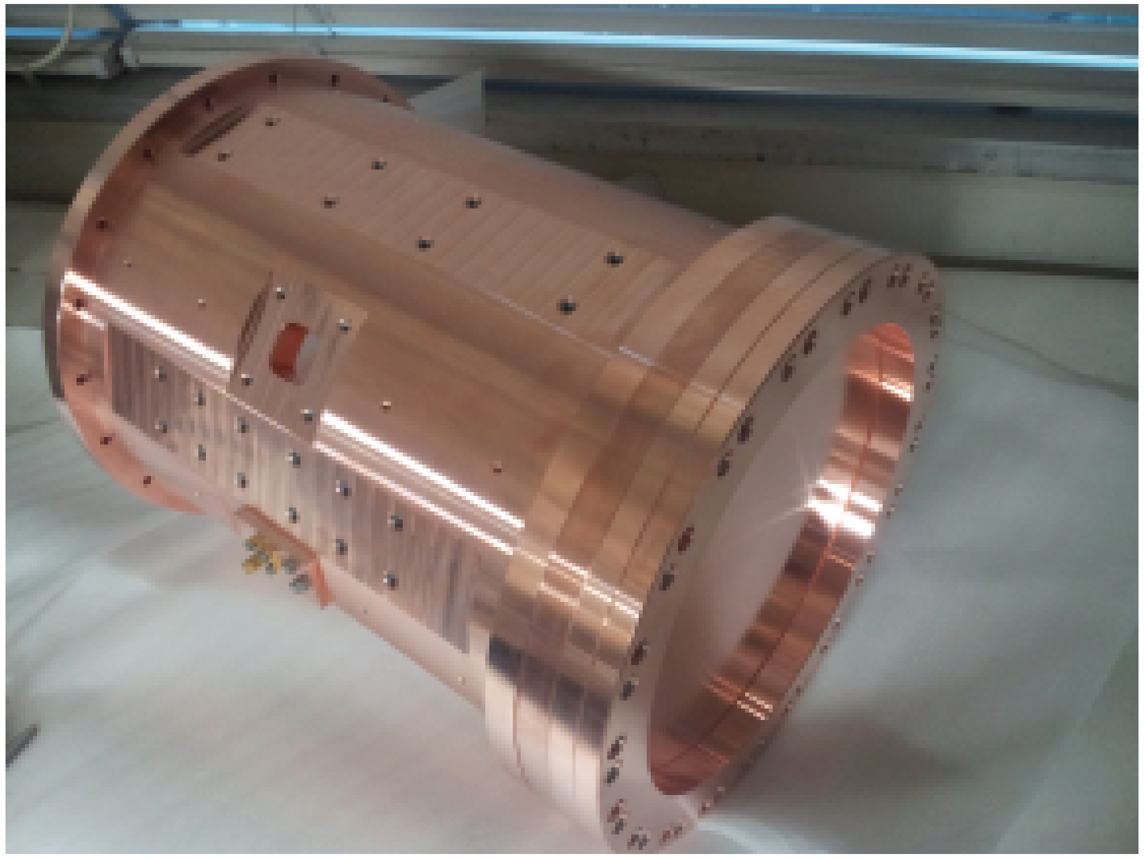


frequency characteristics



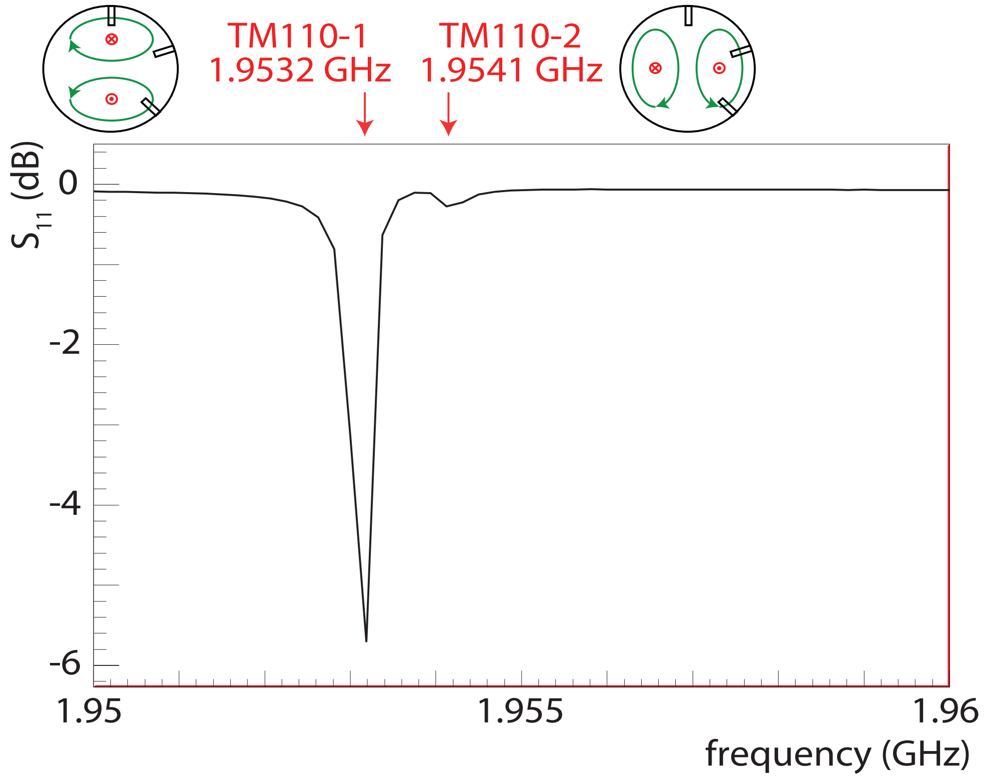
Simulation by CST studio (Microwave Studio)

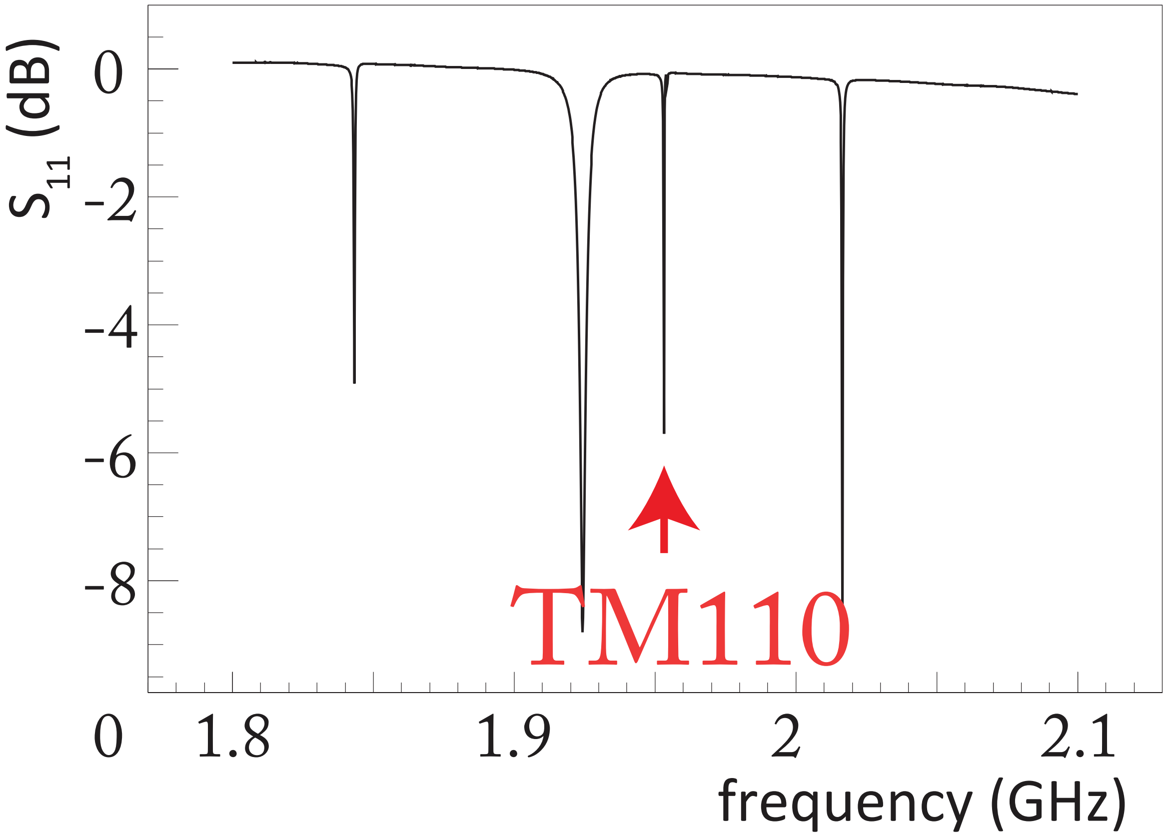
RF Cavity



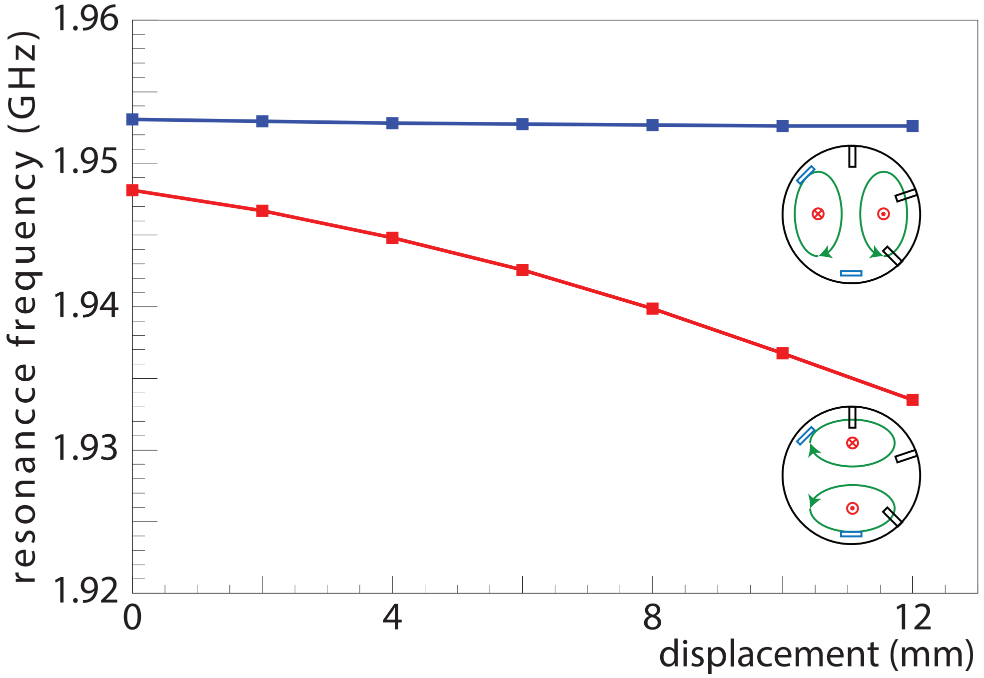
Cavity manufactured

frequency characteristics of TM110 mode

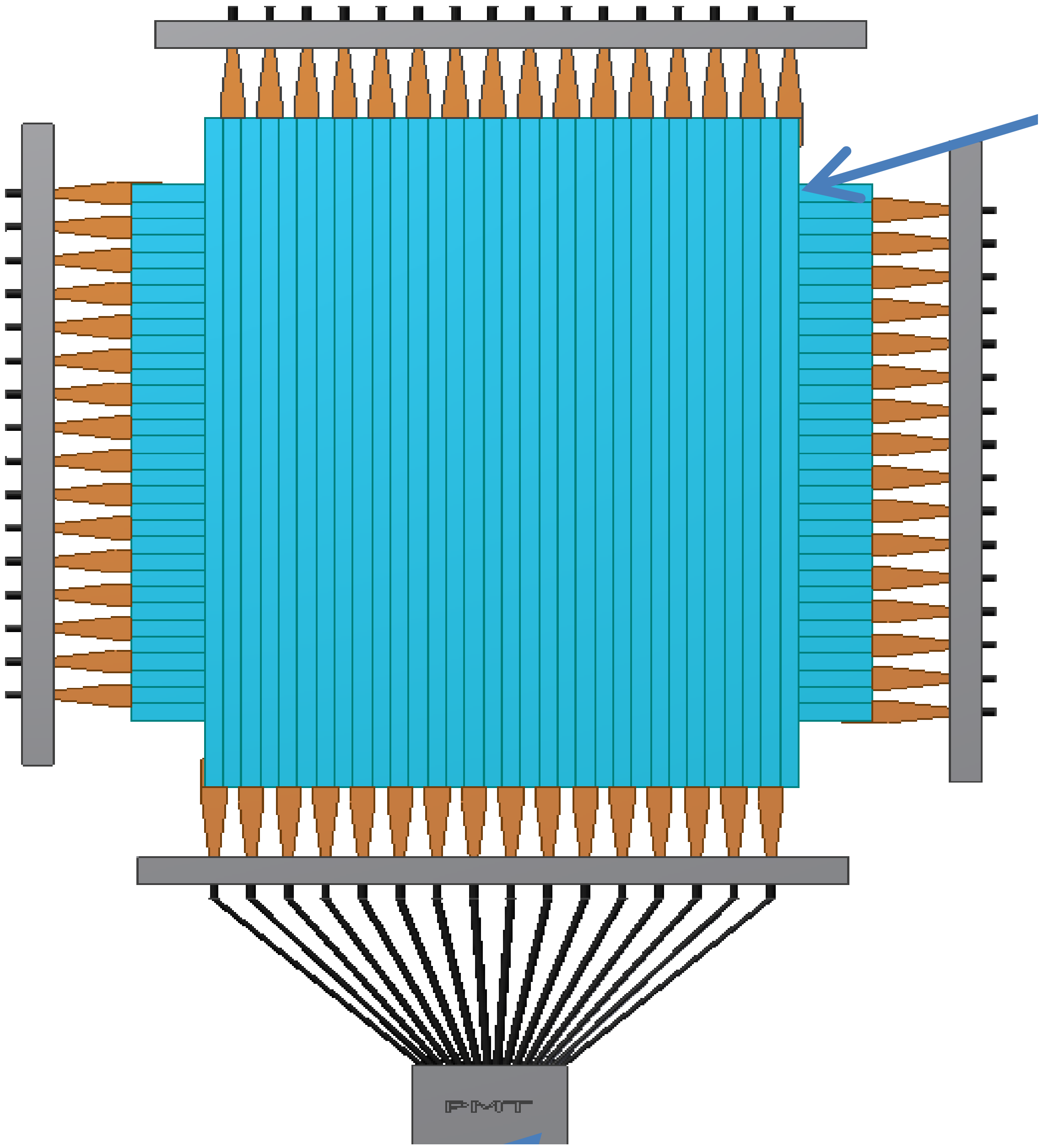




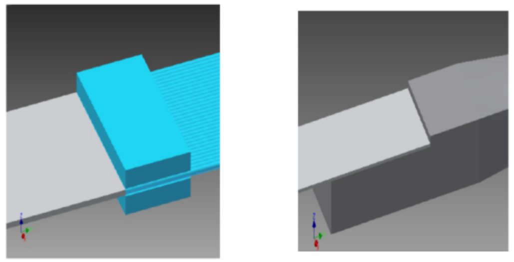
frequency tuning by tuning bars



Beam Profile Monitor

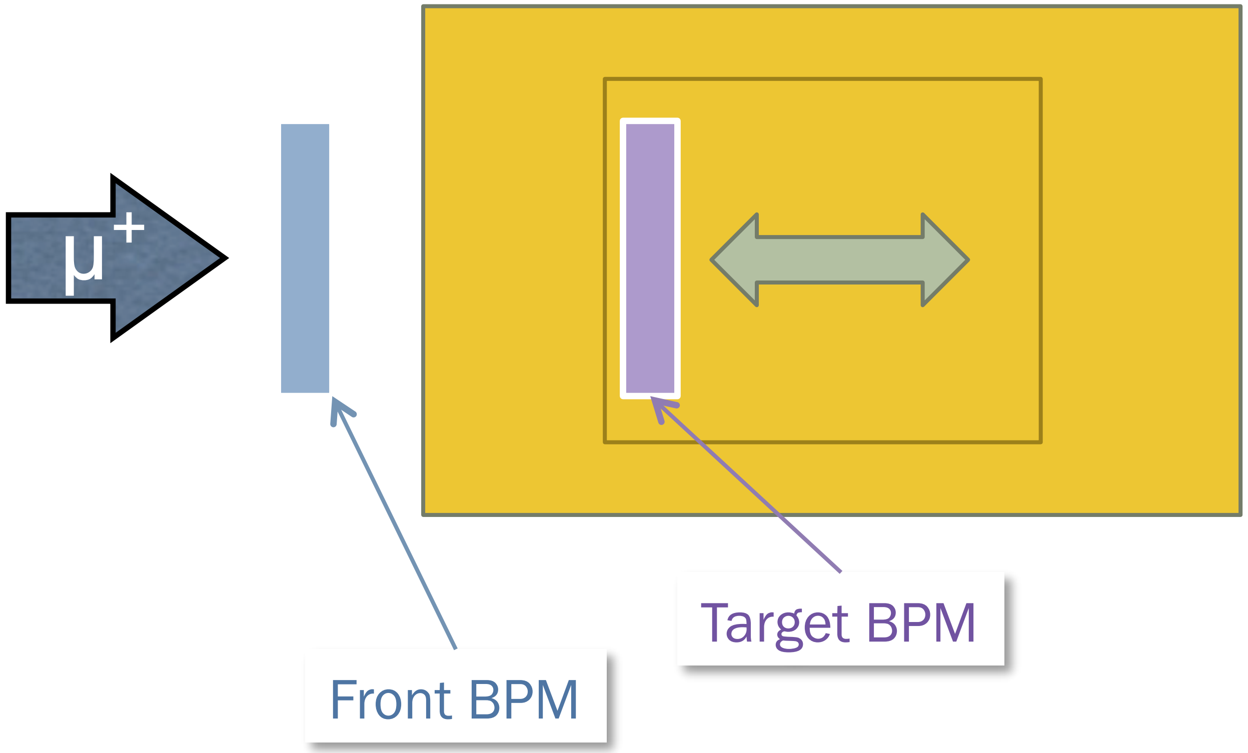


Prototype Front BPM

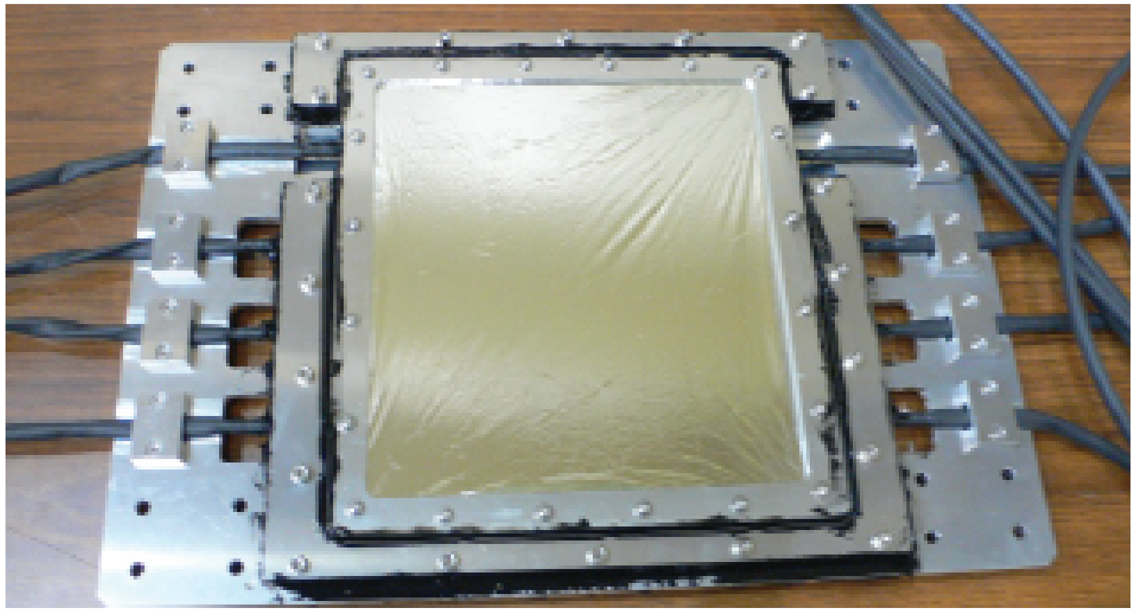


20 scintillators each for x & y
6 mm x 184 mm

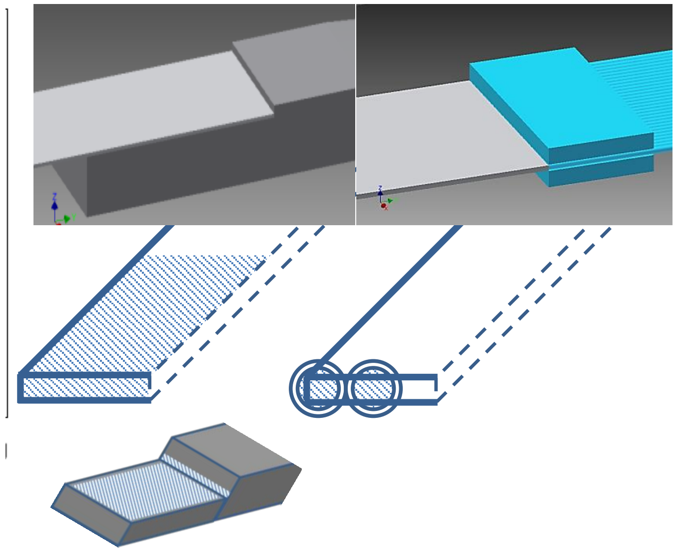
0.1 – 0.2 mm thickness !!



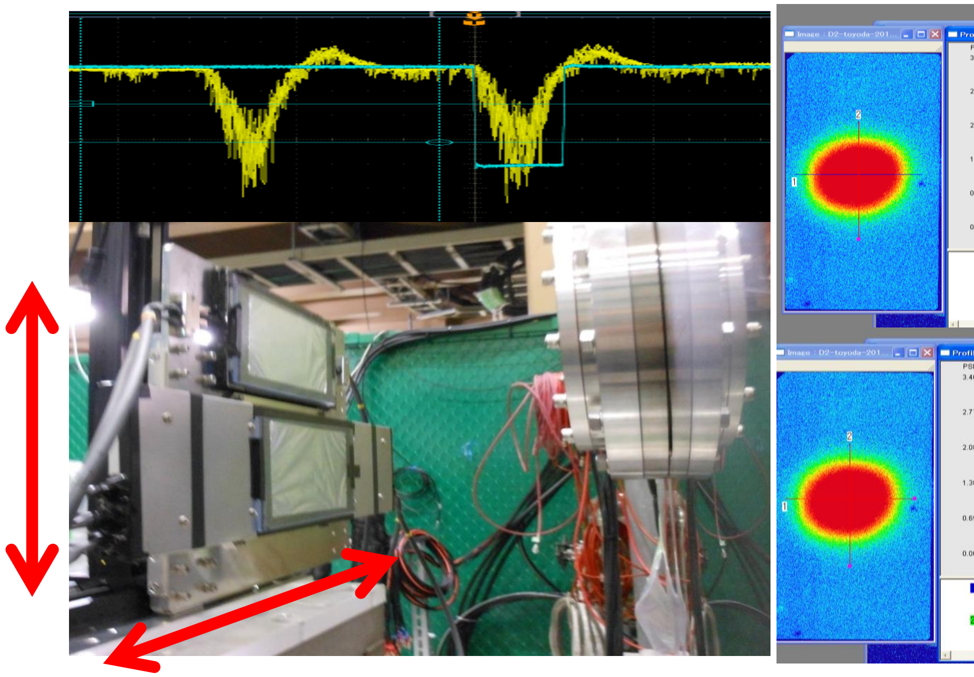
Beam Profile Monitor



- 0.15 mmt, w/o Al coated
- 0.15 mmt, w/ Al coated
- 0.2 mmt, w/o Al coated
- 0.2 mmt, w/ Al coated



test with ^{90}Sr source



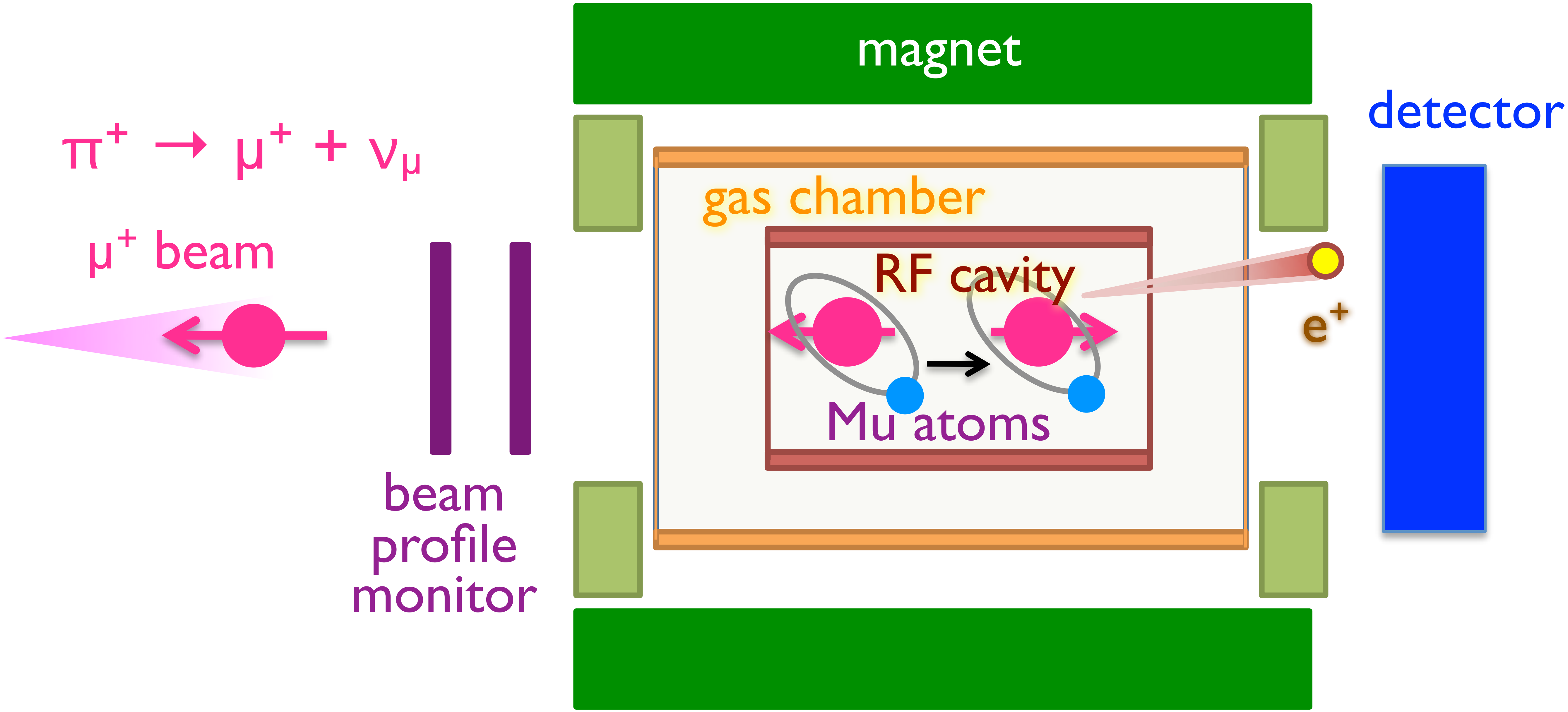
test with pulsed μ^+ beam

27 MeV/c, 25 Hz, 105 μ^+ / pulse

@ J-PARC/MLF

Schematic of the Experiment

$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$



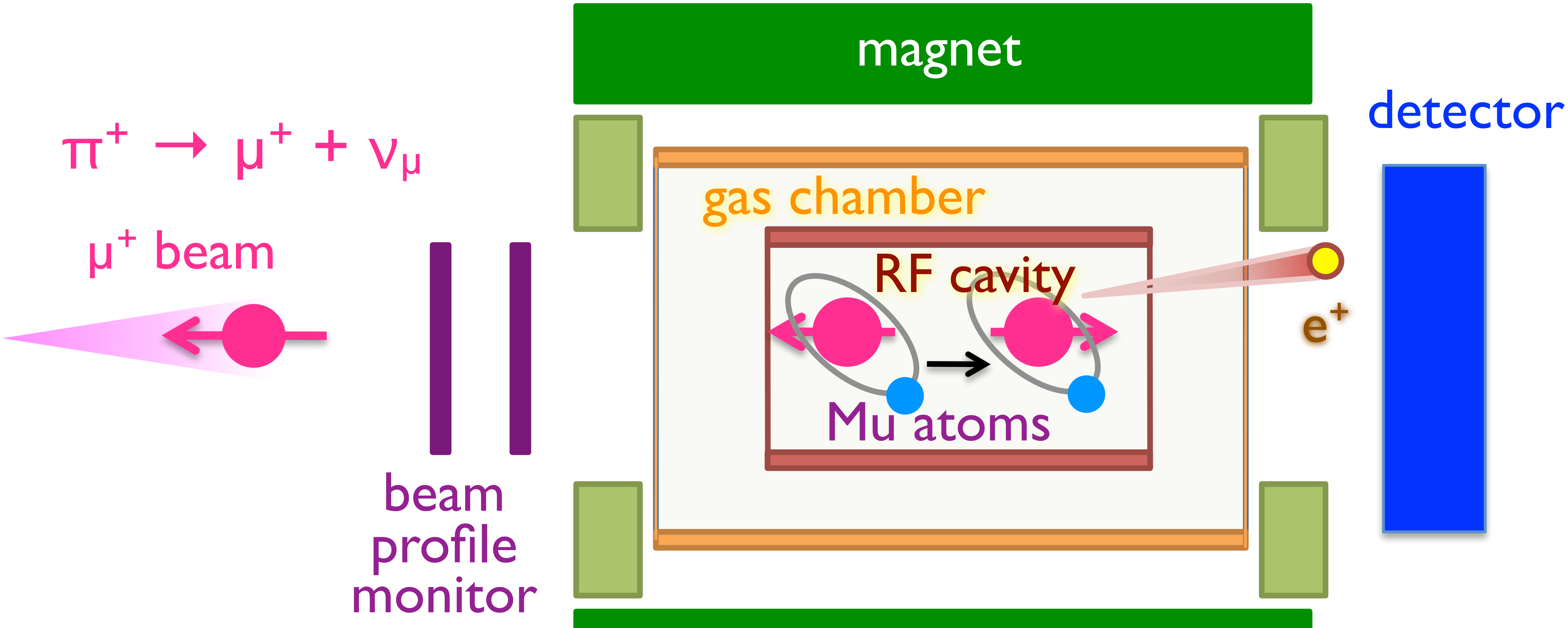
$\pi^+ \rightarrow \mu^+ + \nu_\mu$

$\mu^+ + \mathrm{Kr} \rightarrow \mathrm{Mu}\ (\mu^+ e^-) + \mathrm{Kr}^+$

Schematic of the Experiment

$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

max. 50 MeV



$\pi^+ \rightarrow \mu^+ + \nu_\mu$

μ^+ beam

beam profile monitor

magnet

gas chamber

RF cavity

Mu atoms

e^+

detector

$\mu^+ + \mathrm{Kr} \rightarrow \mathrm{Mu}\ (\mu^+ e^-) + \mathrm{Kr}^+$

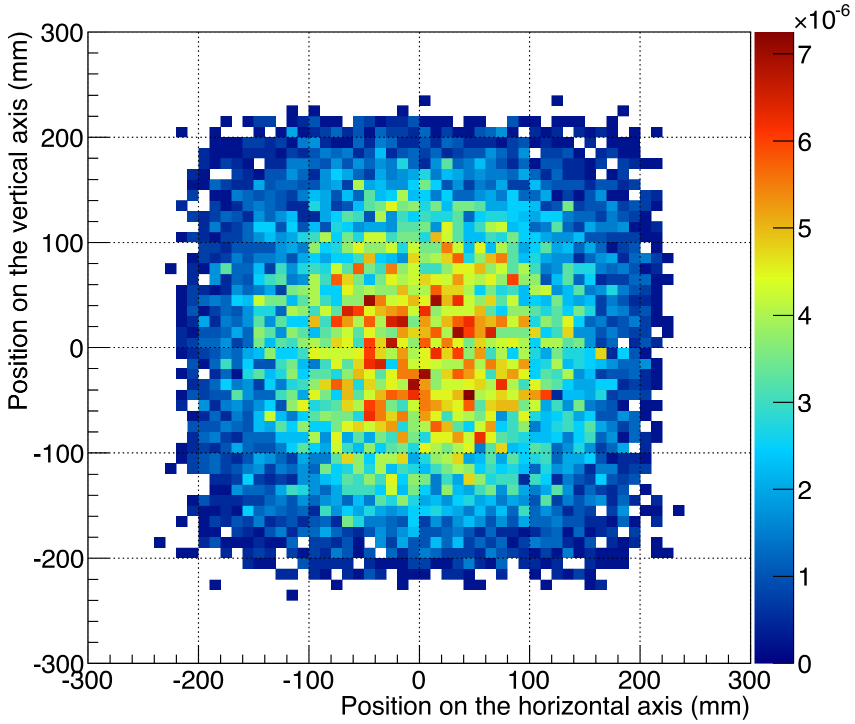
Detection of muon decay

Requirement: Suitable for high intensity pulsed beam

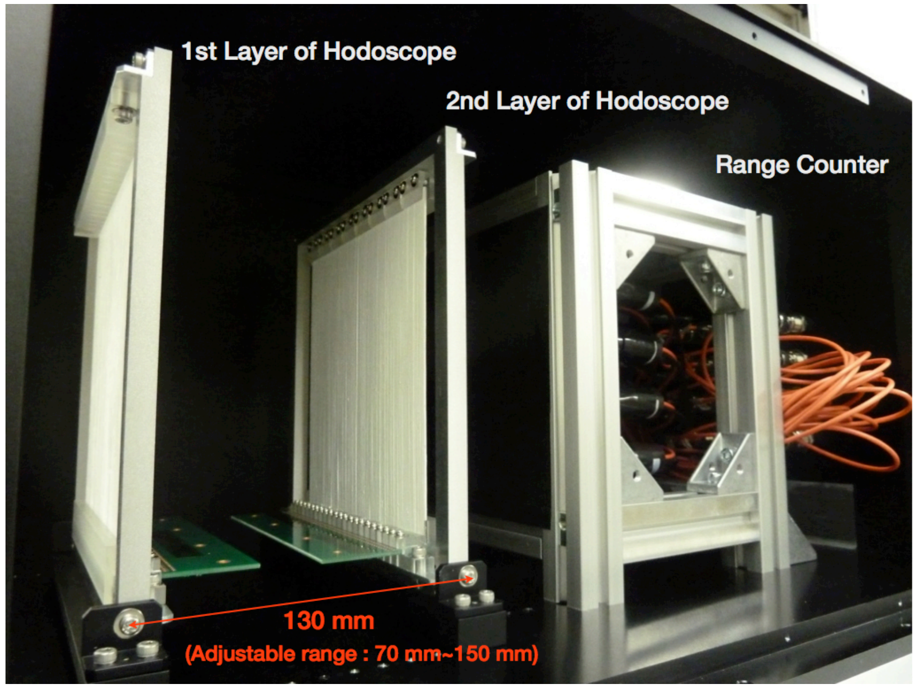
- (1 x 10^8 /s) / (25 pulses/s) ~ 4 x 10^6 muons / pulse
- Highly segmented positron counter
  ☞ 2~4 layers of scintillating fiber hodoscope
- Expected event rate ~ 3 MHz/cm^2 (‘old muonium’ method)

Scintillation fiber + MPPC + ASIC-based ASD + FPGA MHTDC

- Prototype has been developed and beam test performed.

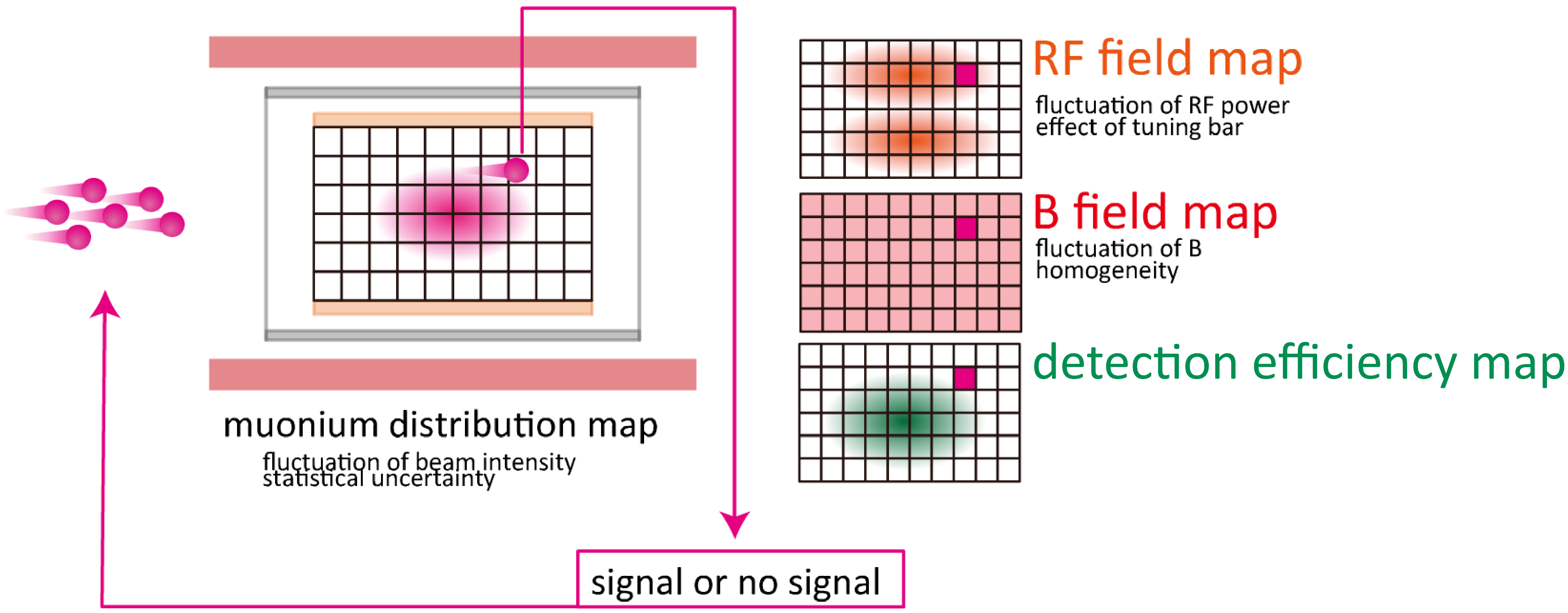


Simulated positron hits per stopped muon



Prototype of the detector

Evaluation of uncertainty by resonance-line simulations



Calculate transition probability.

RF field map

fluctuation of RF power
effect of tuning bar

B field map

fluctuation of B
homogeneity

detection efficiency map

muonium distribution map

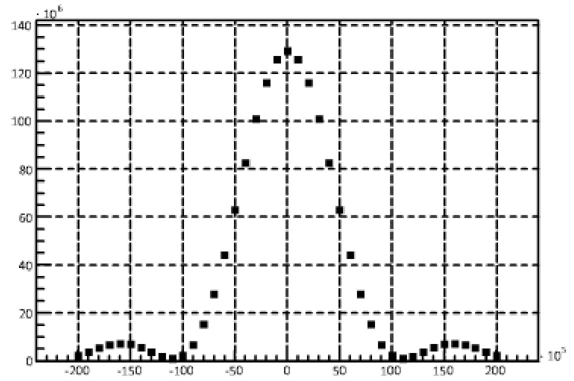
fluctuation of beam intensity
statistical uncertainty

signal or no signal

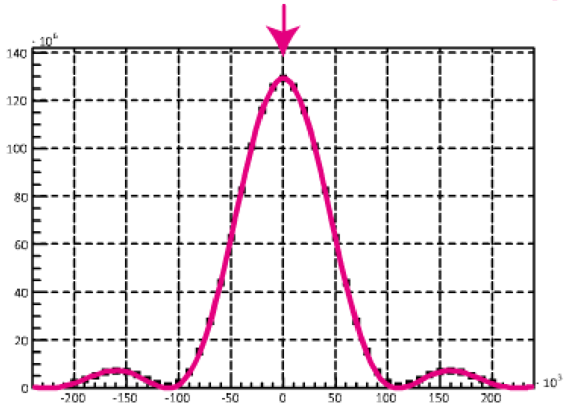
Repeat calculation for every muonium.

Center of the resonnce line
determined by fitting.

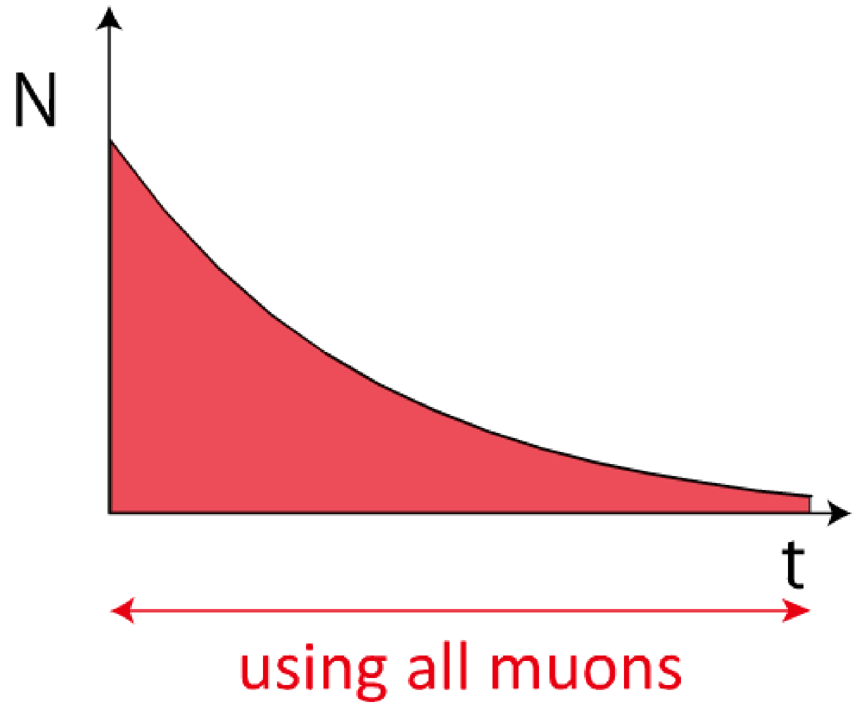
plotting

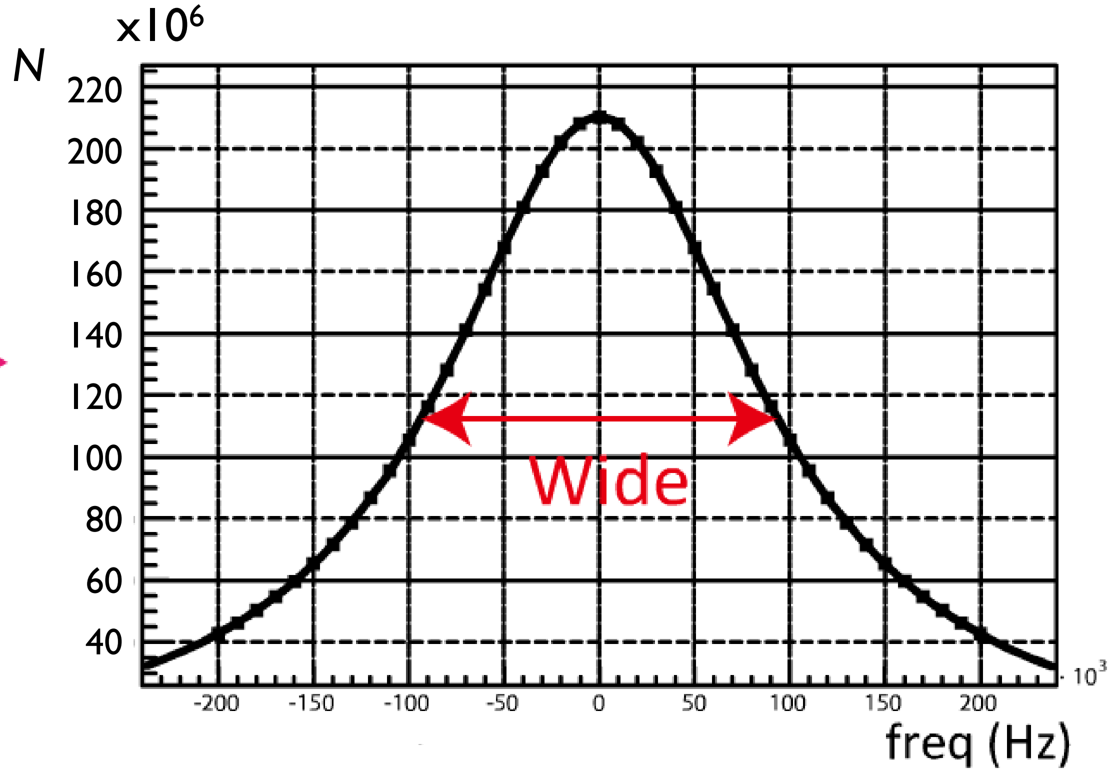


fitting



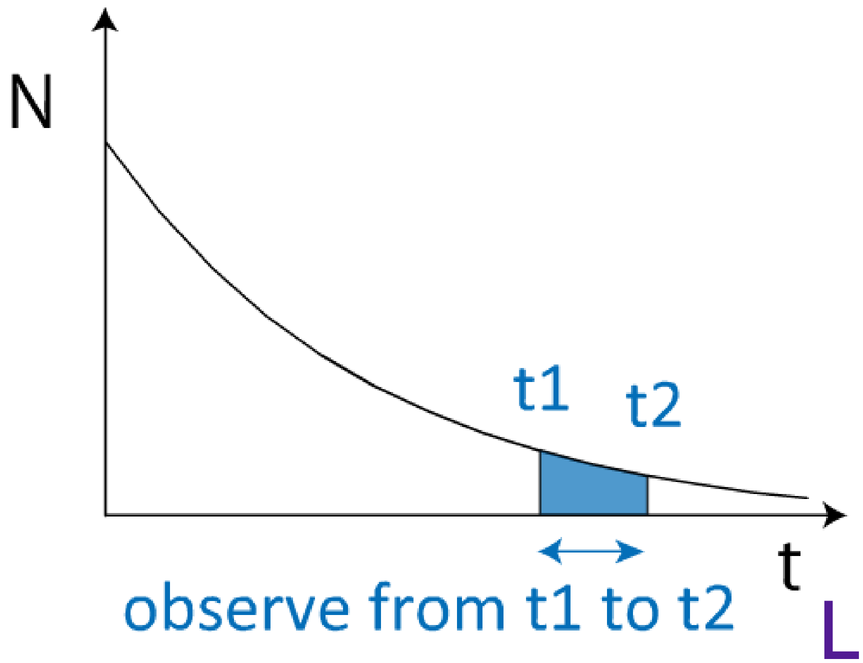
conventional method

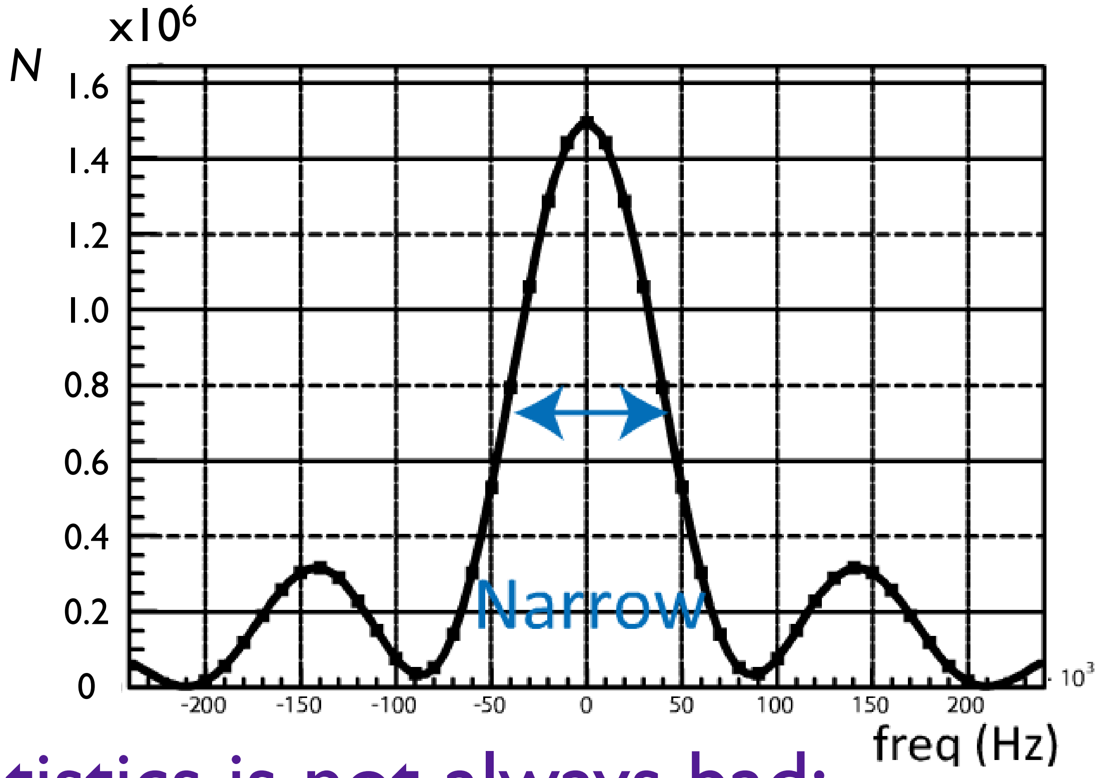




Selection of long-lived muonium narrows the resonance spectra, but reduces the statistics.

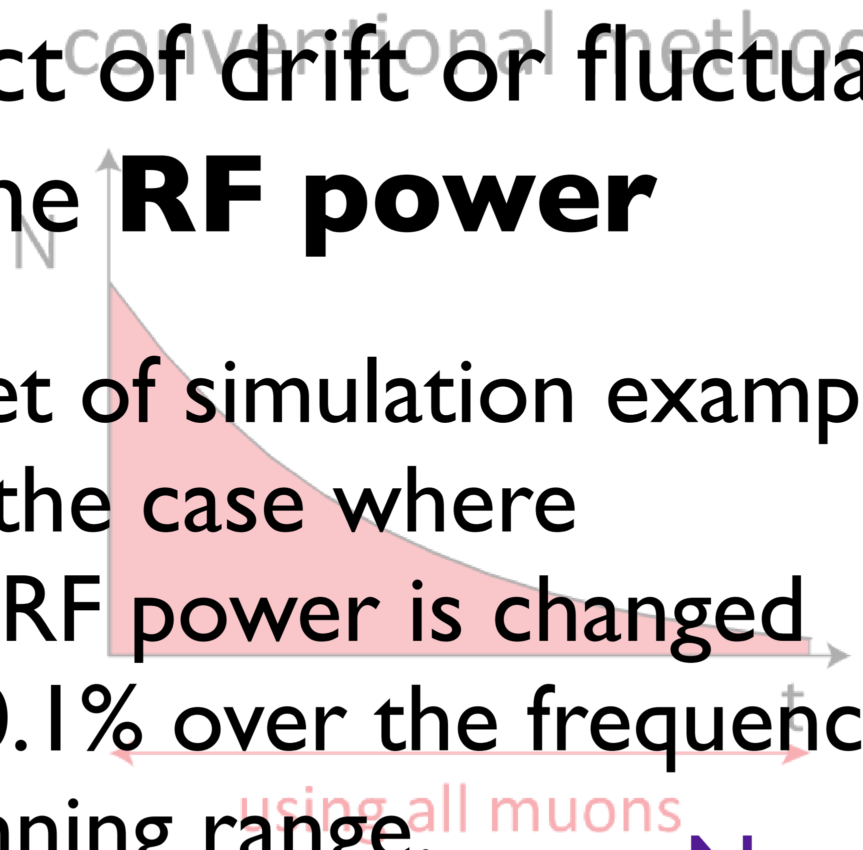
old muonium method



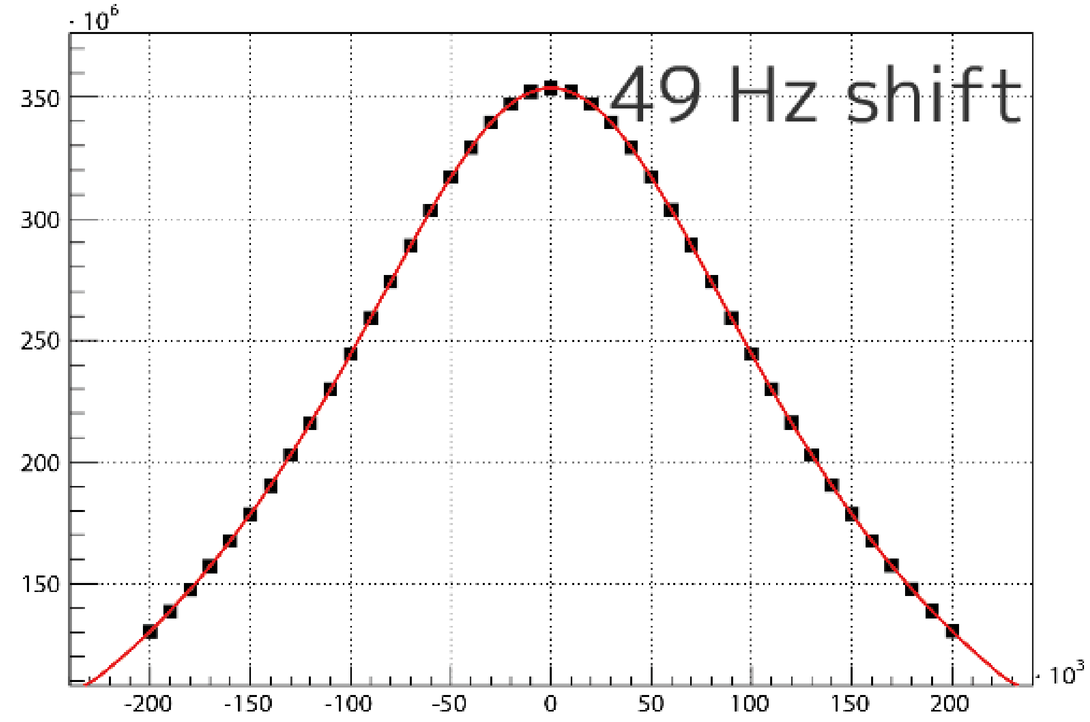


Less statistics is not always bad:
it supresses the high count rate at the detector.

Effect of drift or fluctuation of the **RF power**

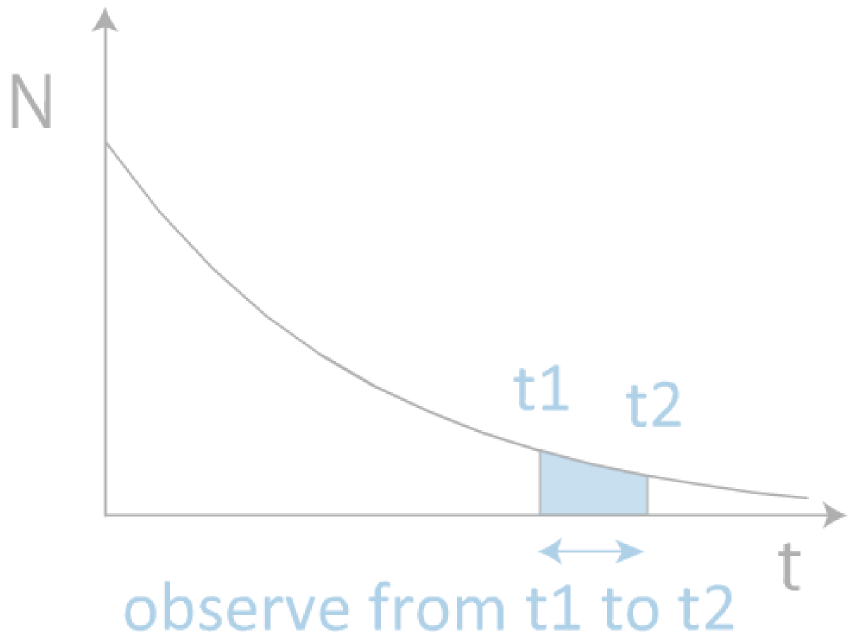


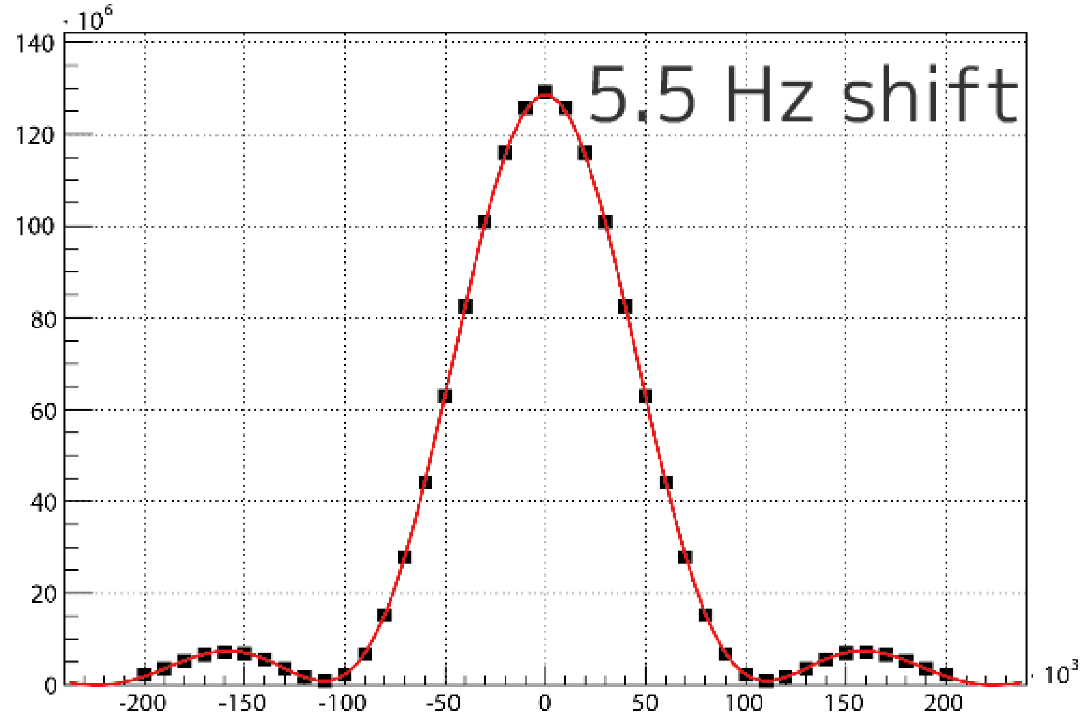
A set of simulation examples for the case where the RF power is changed by 0.1% over the frequency scanning range.



Narrower spectrum is more robust against drifts & fluctuations of e.g. RF power.

old muonium method





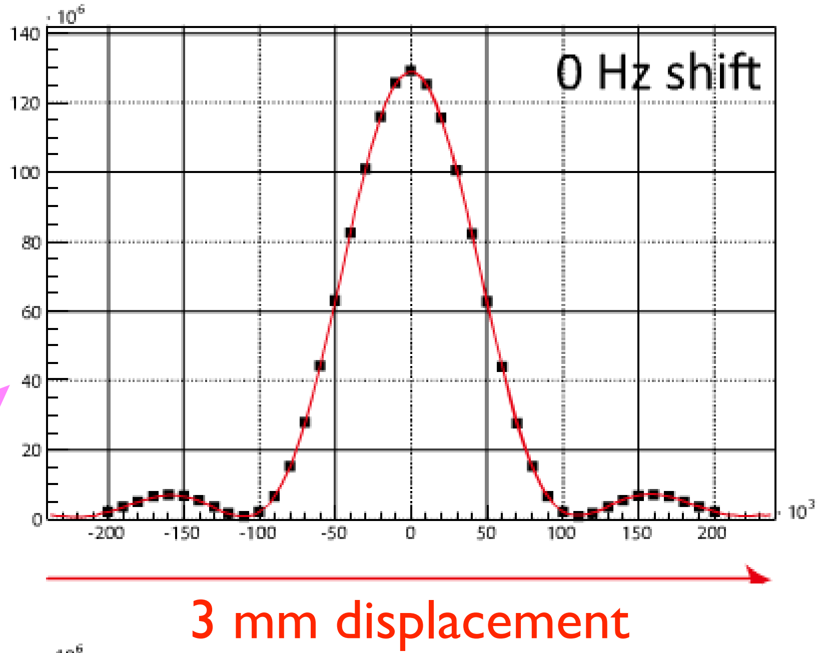
RF power 100.0% → → → → → → → 100.1%

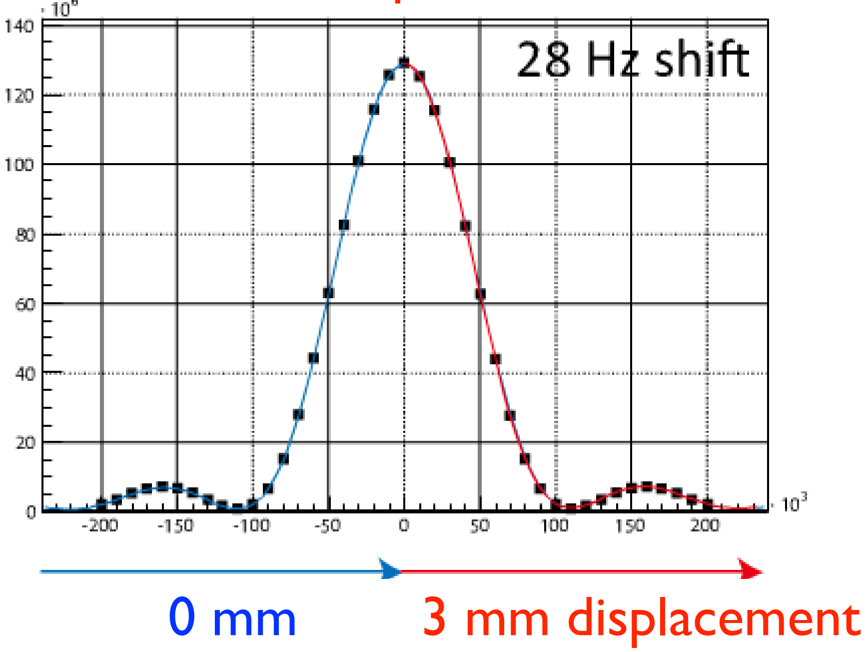
Effect of misalignment of the **muon distribution**

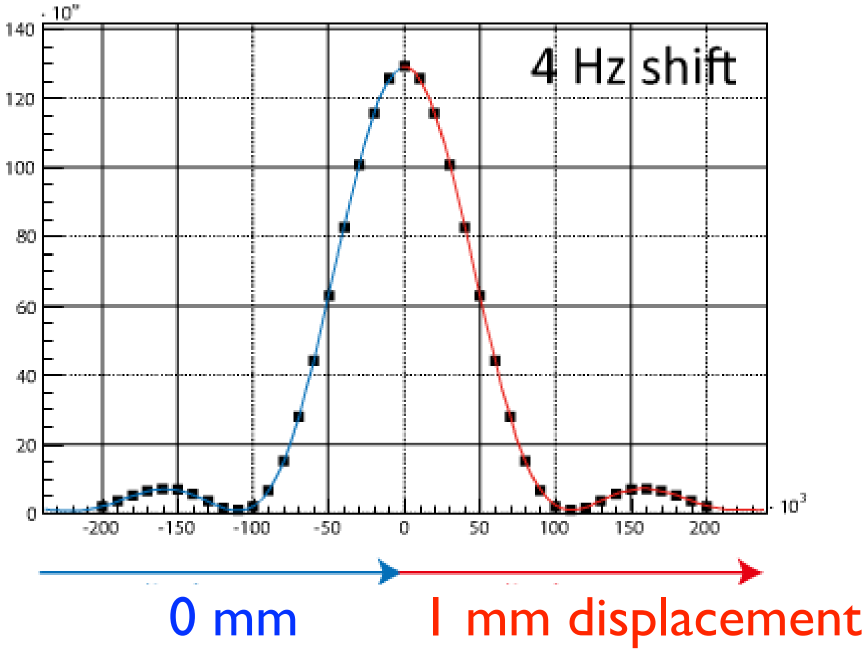
A set of simulation examples for the case where the muon stopping position is displaced.

Constant displacement does not shift the center frequency of the resonance line.

Displacement during the scan (dependent on the frequency) shifts the center frequency.







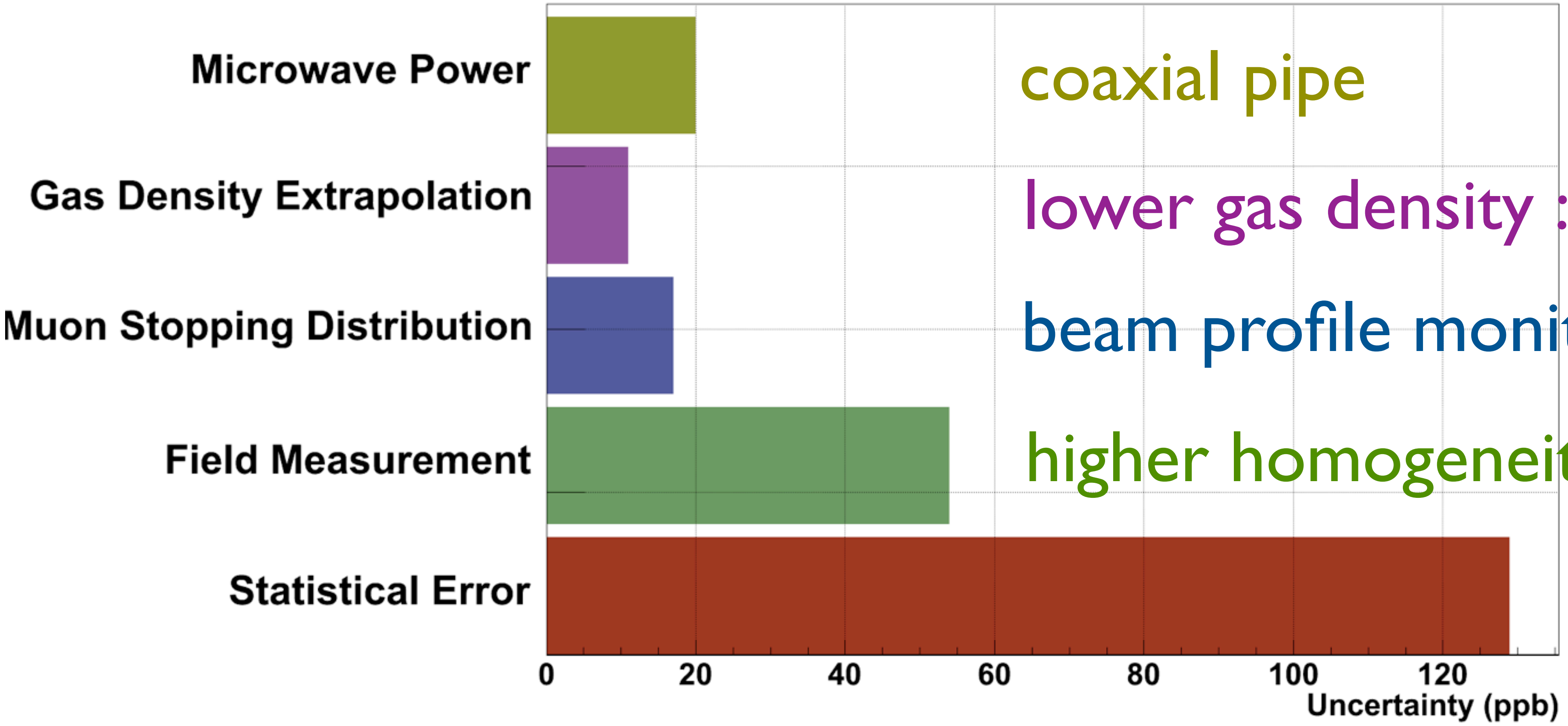
Statistical & Systematic Uncertainties

$$\Delta\nu = 4.463\,302\,765(53)\ \text{GHz}\quad (12\ \text{ppb})$$

$$\mu_\mu/\mu_\text{p} = 3.183\,345\,24(37)\quad (120\ \text{ppb})$$

LAMPF
(Los Alamos exp. in the 1990s)
W. Liu *et al.*, Phys. Rev. Lett. **82** (1999) 711

Uncertainty for μ_μ/μ_p (frequency sweep)



coaxial pipe

lower gas density : longer cavity

beam profile monitor

higher homogeneity of the magnetic field

higher muon intensity

Collaborators

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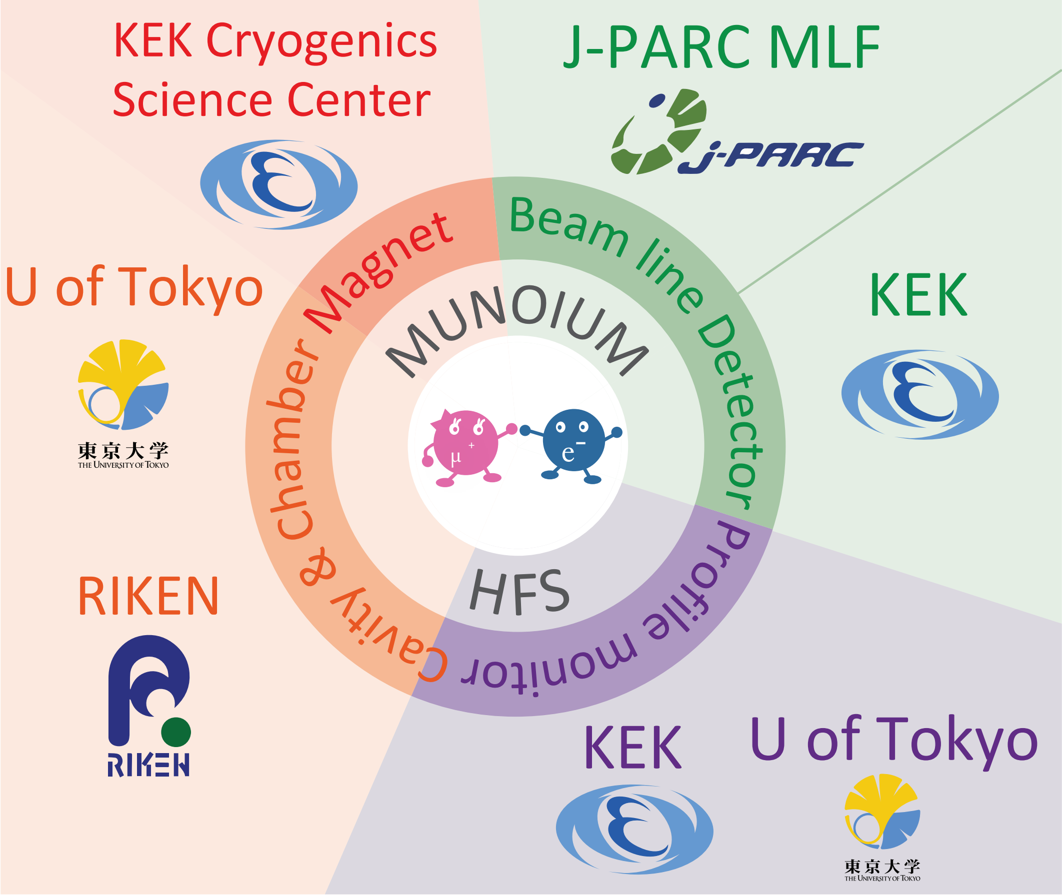


Summary

- Microwave spectroscopy of Mu GS-HFS (the ground-state hyperfine structure of the muonium atom) determines μ_μ and m_μ (magnetic moment and mass of the muon), important properties also for $(g-2)_\mu$.
- Experiment planned at J-PARC (KEK-JAEA joint facility) aims at one-digit more precision = O(ppb): O(Hz) uncertainty out of O(GHz) resonances.
- Development is on-going in various parts of the exp.: magnet, pure-gas chamber, RF cavity, muon profile monitor, positron detector etc.
- Evaluation of systematic uncertainties are under way.

Fine.

Grazie per vostro attenzione.
Gratias ago pro audientia vestra.
Спасибо за внимание.
Merci de votre attention.
Thank you for your attention.
경청해 주셔서 감사합니다.
ご清聴ありがとうございました。

鳥居 寛之
Hiroyuki A. TORII

Microwave Spectroscopy Experiment of Mu-HFS

ν_{12} = 1.897 539 800(35) GHz (18 ppb)
ν_{34} = 2.565 762 965(43) GHz (17 ppb)
$\Delta\nu = \nu_{12} + \nu_{34}$

LAMPF
(Los Alamos exp. in the 1990s)
Phys. Rev. Lett. **82**, 711

$\Delta\nu$ = 4.463 302 765(53) GHz (12 ppb)
μ_μ/μ_p = 3.18 334 524(37) (120 ppb)

Magnetic moment
to be determined

$$\frac{m_\mu}{m_e} = \left(\frac{g_\mu}{2}\right)\left(\frac{\mu_p}{\mu_\mu}\right)\left(\frac{\mu_B^e}{\mu_p}\right)$$

☞ Contribution to (g – 2) exp.

$g_\mu = 2\,(1 + a_\mu)$, a_μ = 0.011 659 23(8.5) (4 ppb for g_μ)
μ^e_B/μ_p = 1.521 032 202(15) (1 ppb)

m_μ/m_e = 206.768 277(24) (120ppb)

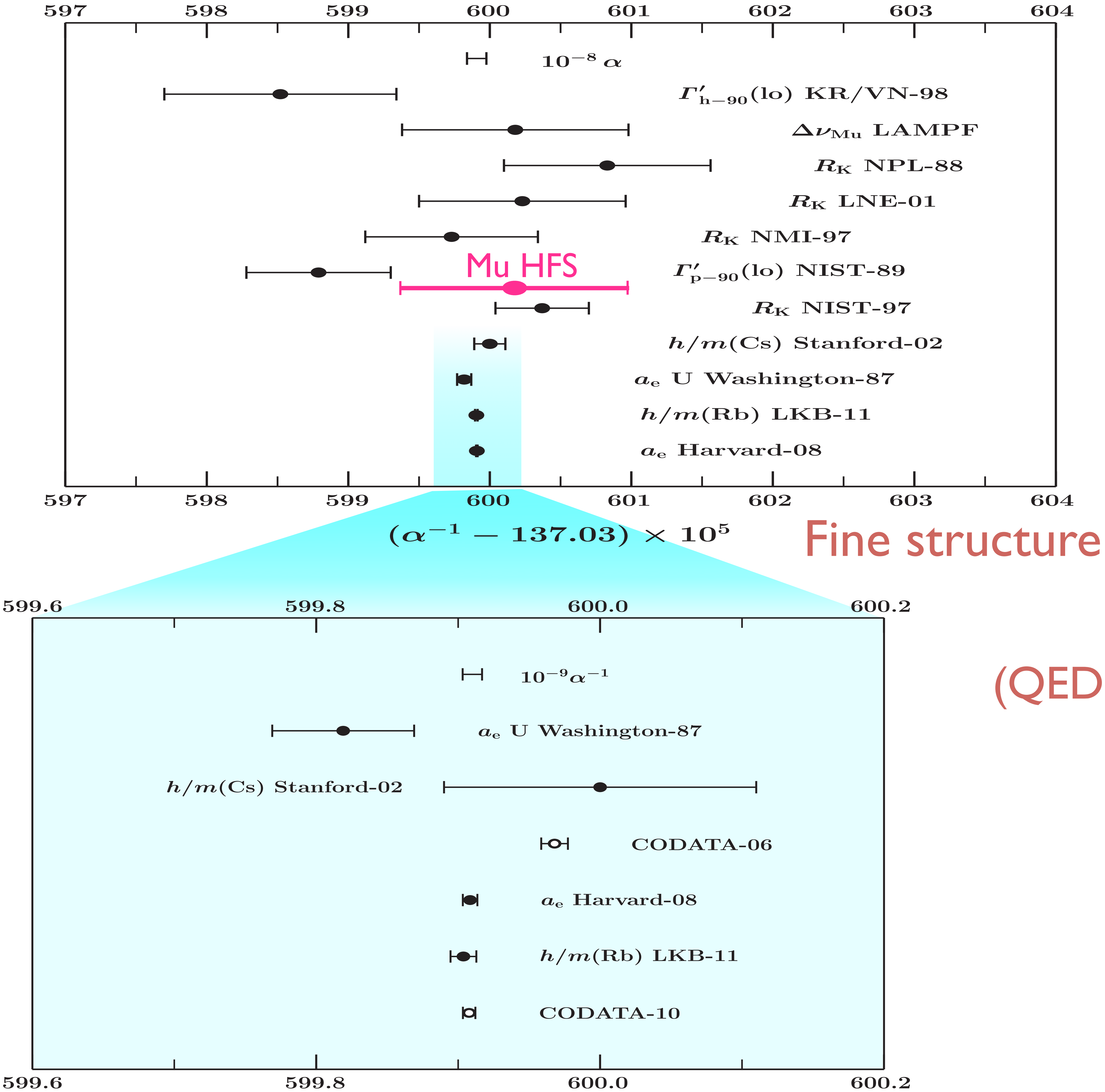
Muon mass
to be determined

$$\Delta\nu(\text{Fermi}) = \frac{16}{3}\alpha^2 c R_\infty \frac{m_e}{m_\mu}\left[1 + \frac{m_e}{m_\mu}\right]^{-3}.$$

$$\Delta\nu_{\text{Mu}}(\text{th}) = \Delta\nu(\text{Fermi})\ \mathcal{F}(\alpha, m_e/m_\mu)$$

数値が最新のものでないが…。

Contribution to the value of fine structure constant α



Fine structure constant α

CODATA 2010

(QED consistency)

Microwave Spectroscopy Experiment of Mu-HFS

Fine structure constant α
given by CODATA ($a_e = (g - 2)/2$ of e^-)

$\Delta\nu(\mathrm{exp}) = 4.463\,302\,765(53)$ GHz (12 ppb)

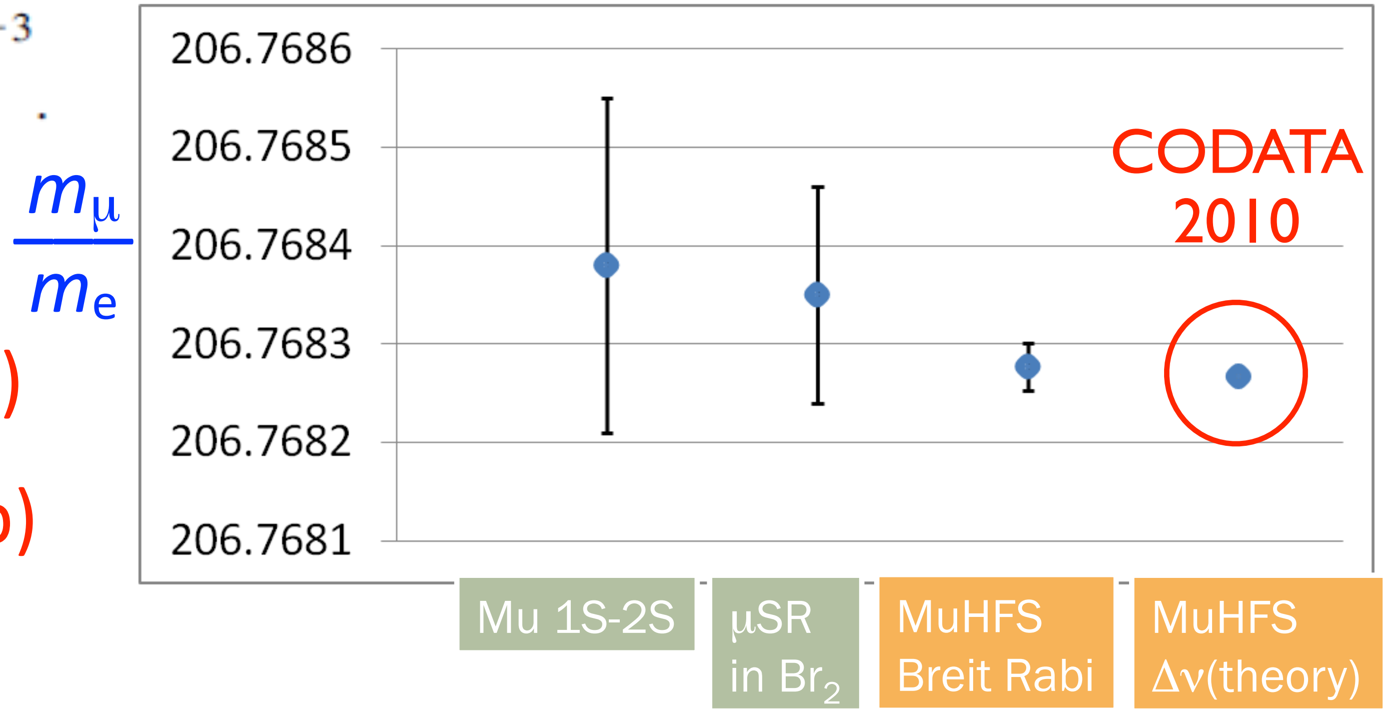
Comparison gives a more precise value
of the mass ratio m_μ/m_e.

One of the most precise tests of
Bound-state QED by comparing theory & exp.

$$\Delta\nu_{\mathrm{Mu}}(\mathrm{th}) = \Delta\nu(\mathrm{Fermi})\ \mathcal{F}(\alpha, m_e/m_\mu)$$

cf. Ps HFS gives a precision of a few ppm.

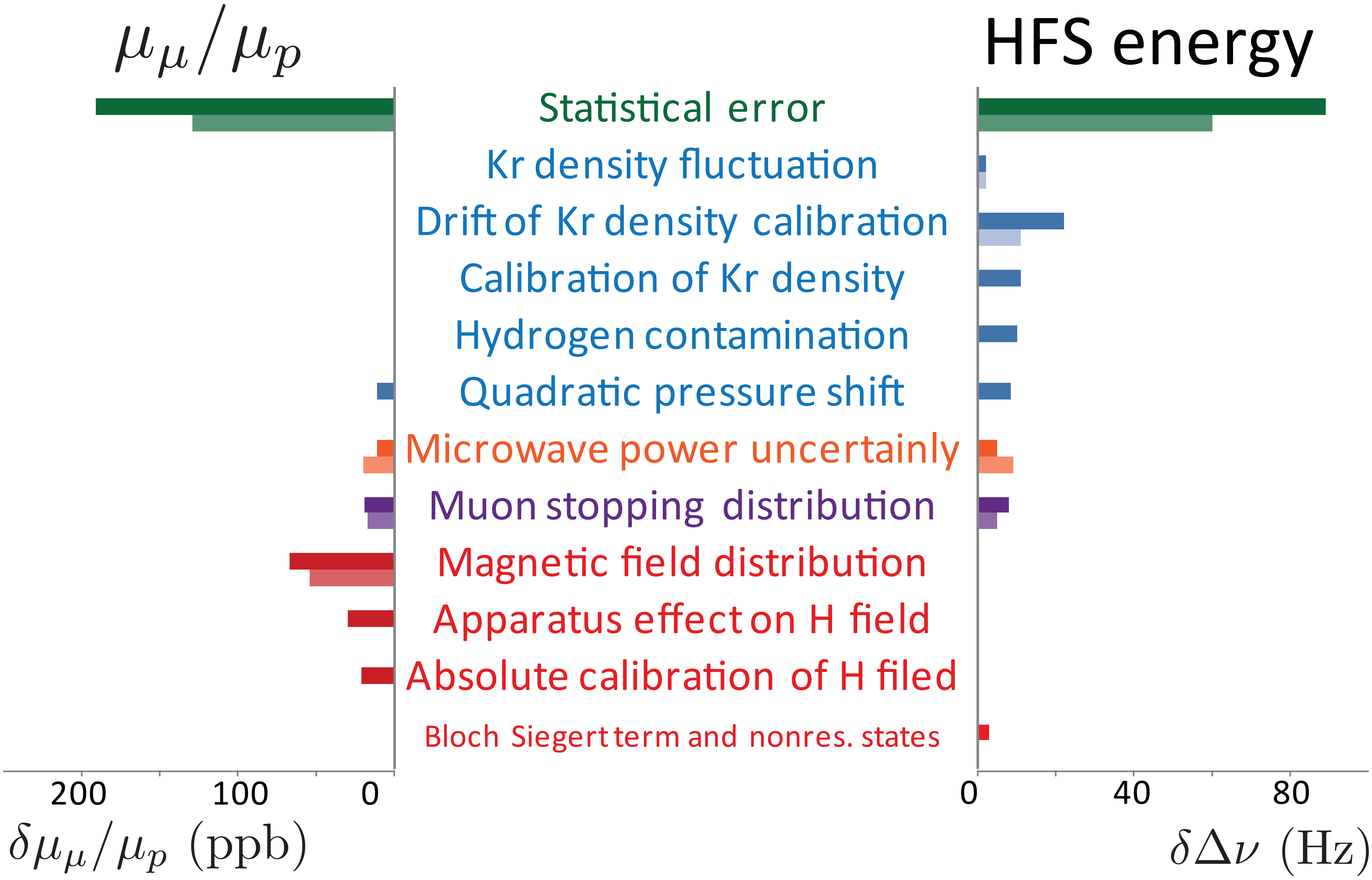
$$\Delta\nu(\mathrm{Fermi}) = \frac{16}{3}\alpha^2 c R_\infty \frac{m_e}{m_\mu}\left[1 + \frac{m_e}{m_\mu}\right]^{-3}.$$



$m_\mu/m_e = 206.768\,2670(55)$ (27 ppb)

$\mu_\mu/\mu_p = 3.18\,334\,5396(94)$ (30 ppb)

Uncertainties



Pressure shift of the resonance line of **Mu HFS**

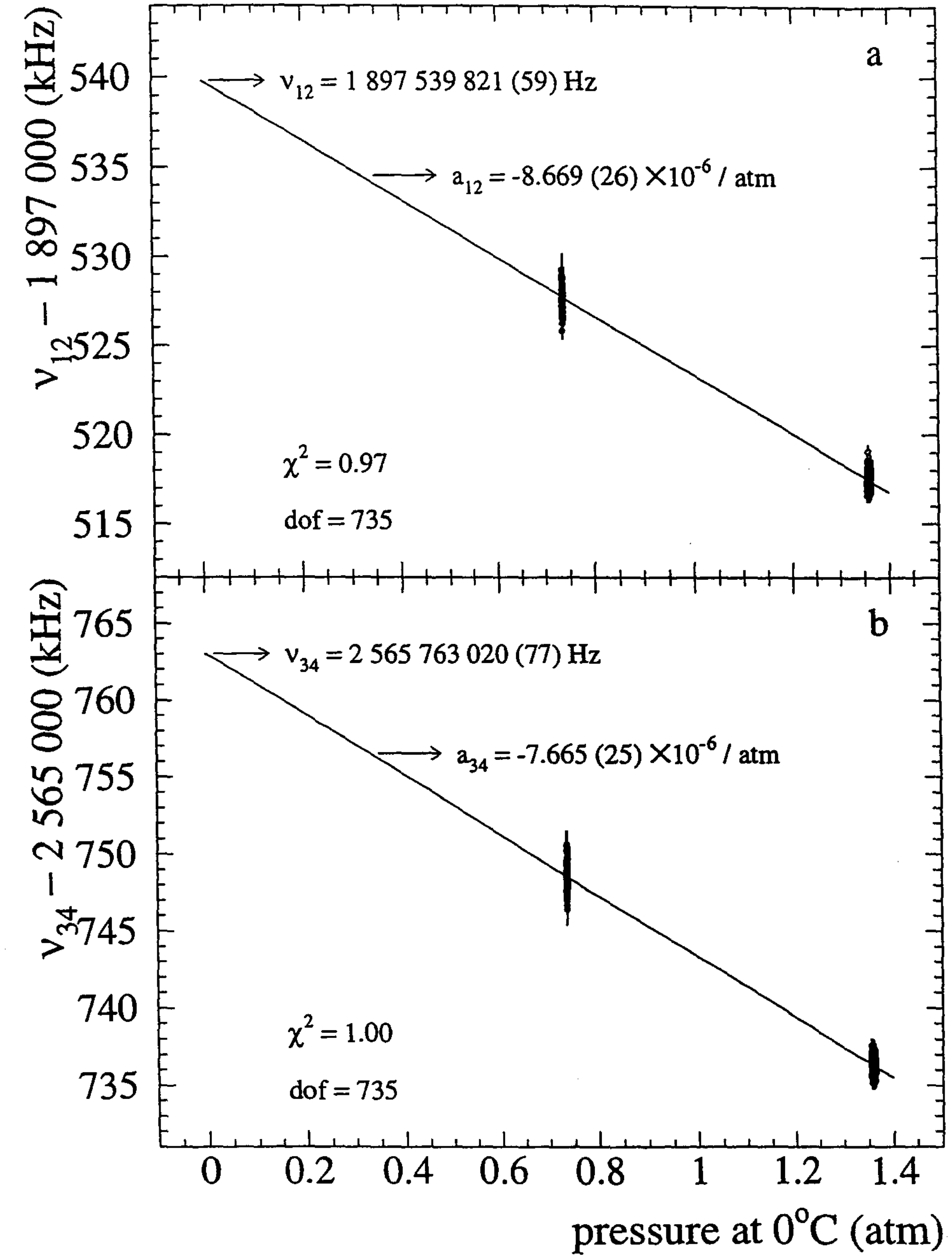


Figure 4.6: Pressure extrapolation of the old muonium data. Plot a shows the extrapolation for ν_{12}, and Plot b shows that for ν_{34}. The transition frequencies in vacuum and the pressure shift coefficients are also shown in the figures.

$$\nu(P) = \nu(0)\,(1 + aP + bP^2)$$

$$a_{12} = -1.14 \times 10^{-8}\ \text{Torr}^{-1}\ @\ 0\ \text{deg. C}$$
$$a_{34} = -1.01 \times 10^{-8}\ \text{Torr}^{-1}\ @\ 0\ \text{deg. C}$$

$$b = (9.7 \pm 2.0) \times 10^{-15}\ \text{Torr}^{-2}$$

D. E. Casperson *et al.*, Phys. Lett. B 59, 397 (1975).
cited in Liu's thesis

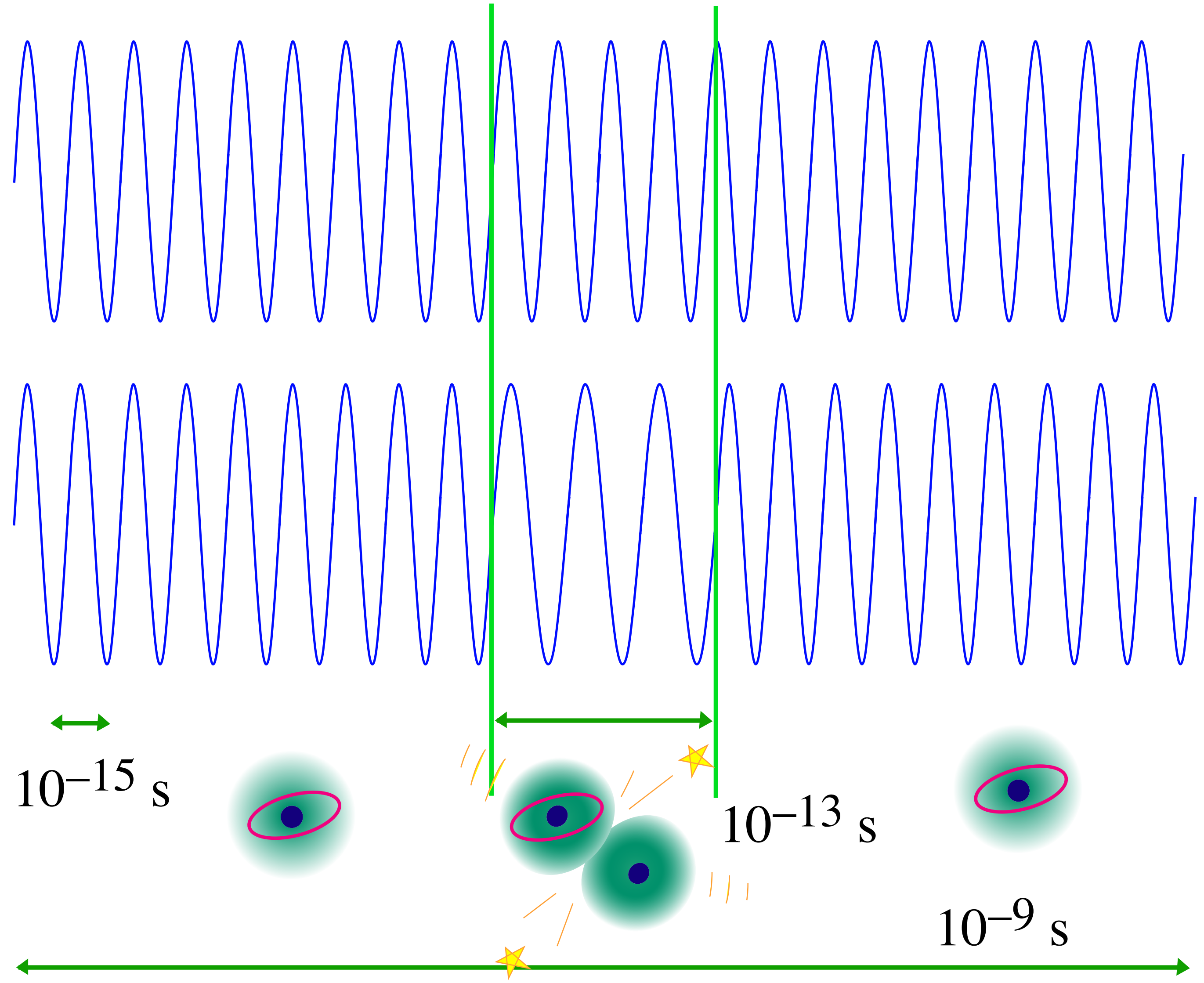
$$\frac{da}{dT} = 1 \times 10^{-11}\ \text{deg.C}^{-1}\,\text{Torr}^{-1}$$

C. L. Morgan *et al.*, Phys. Rev. A 7, 1494 (1973).
cited in V. W. Hughes *et al.*, Phys. Rev. Lett. 87, 111804 (2001).

$T^{3/10}$ dependence ?

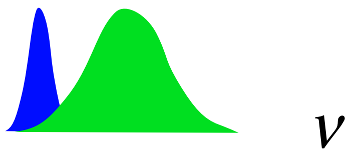
from Liu's thesis

Collisional phase shift

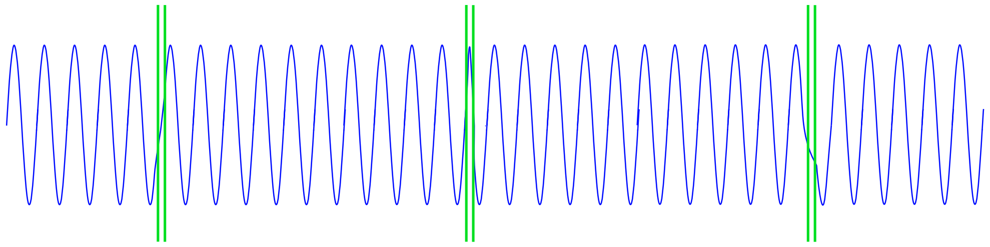


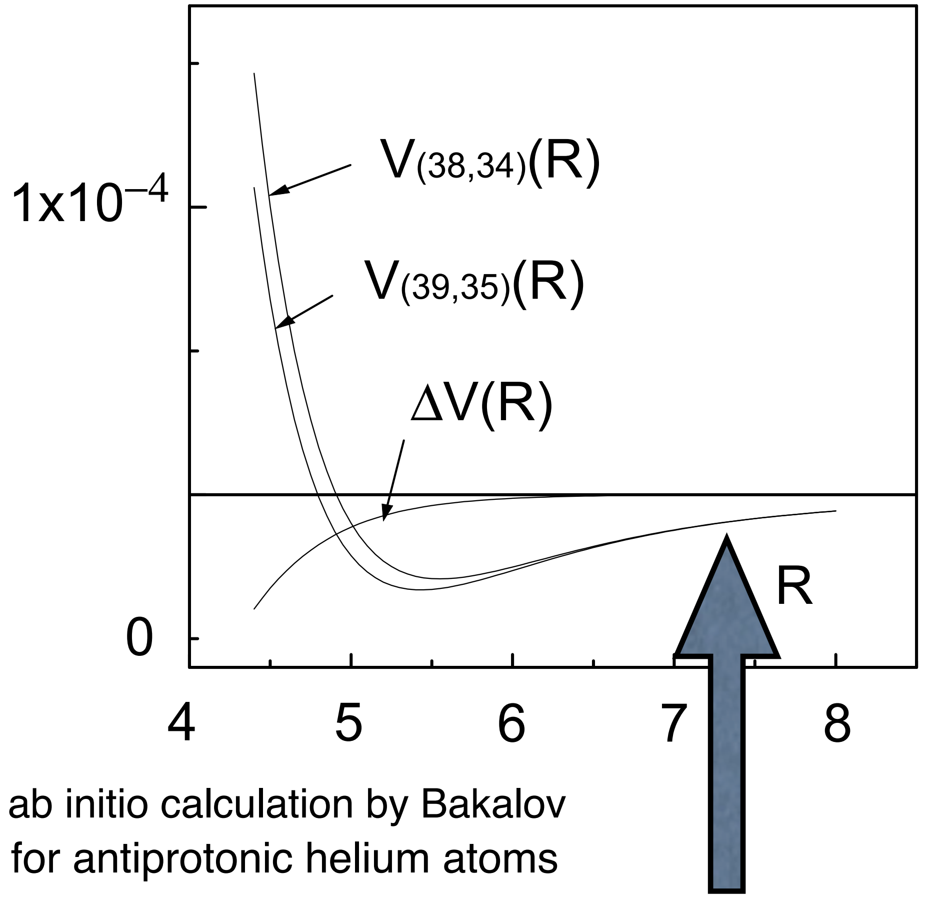
Phase shift due to collision ⇒ shift and width of resonance

$$\eta_j(b) = \int_{-\infty}^{\infty} V_j(R(t))\,\mathrm{d}t$$



$$\Delta - \mathrm{i}\gamma = -\,\mathrm{i}Nv\int_{b_1}^{\infty}\left(1-\mathrm{e}^{\,\mathrm{i}\eta(b)}\right)2\pi b\,db \equiv -\,\mathrm{i}Nv\,(\sigma_\Delta - \mathrm{i}\sigma_\gamma)$$





ab initio calculation by Bakalov for antiprotonic helium atoms

$$V_j(R) = -\frac{C_6}{R^6} = -\frac{\alpha\langle j\,|\,\boldsymbol{\mu}^2\,|\,j\rangle}{R^6}$$

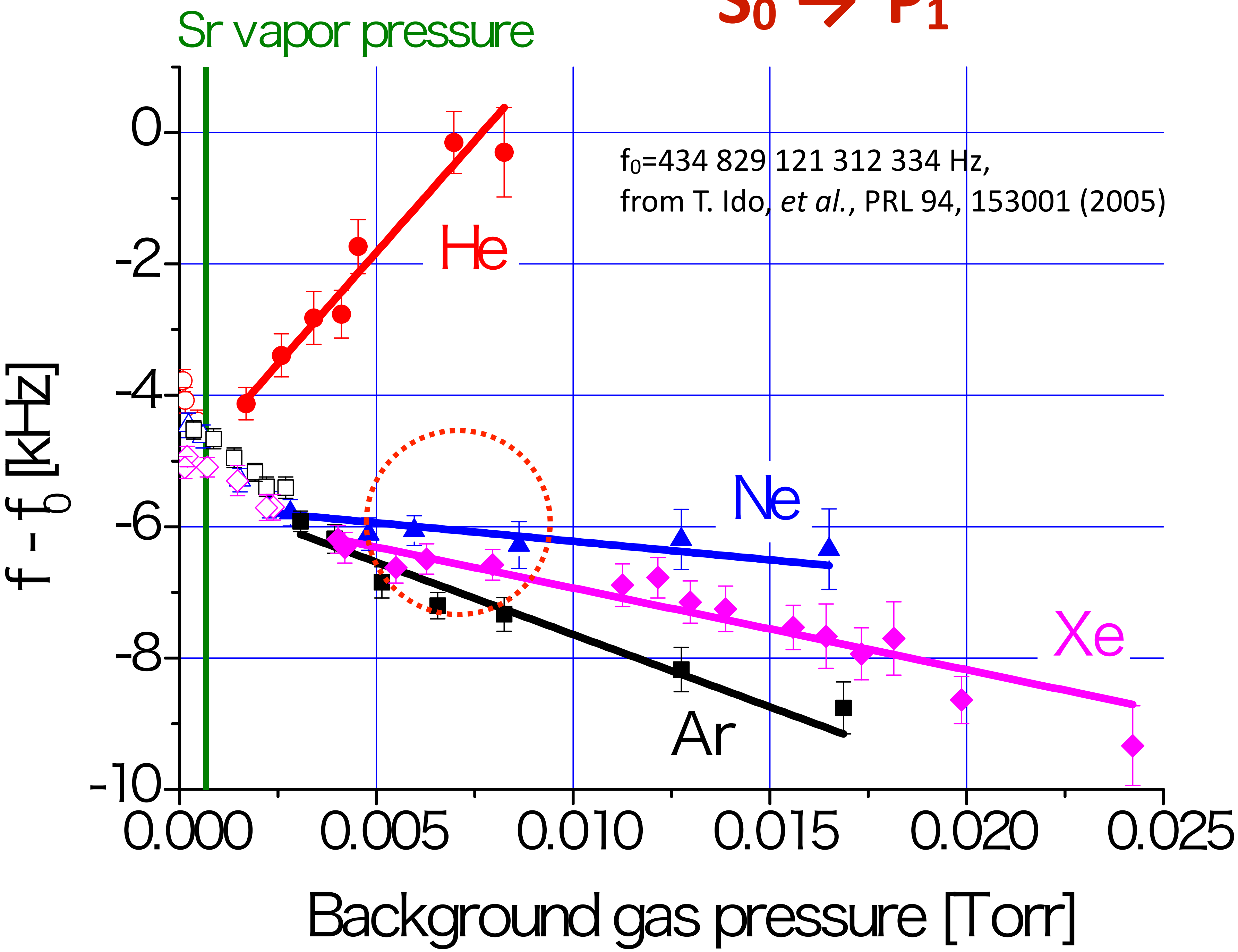
van der Waals attraction

impact approx.
(sudden collision)
binary collision
random collision

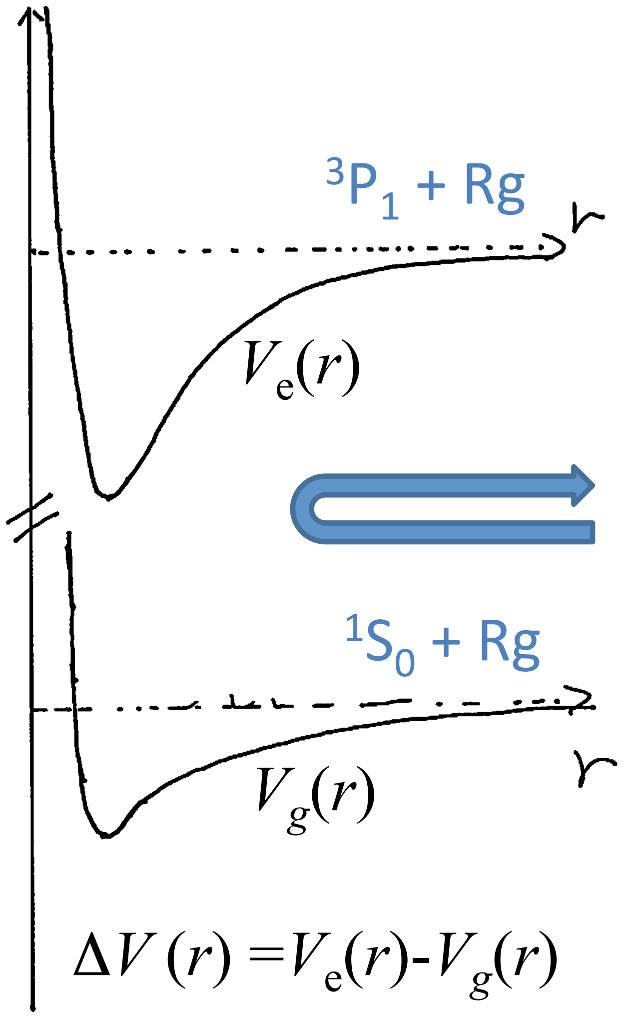
Shift is linear with the buffer-gas density.

Collisional shift of Sr atoms with rare gases

$^1S_0 \rightarrow {}^3P_1$

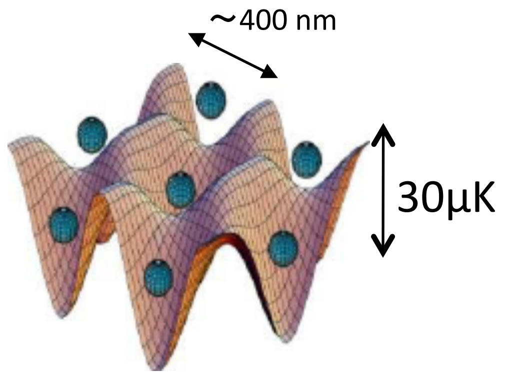


f$_0$=434 829 121 312 334 Hz,
from T. Ido, *et al.*, PRL 94, 153001 (2005)



N. Shiga, *et al.*, PRA 80, 030501 (2009)

optical lattice clock

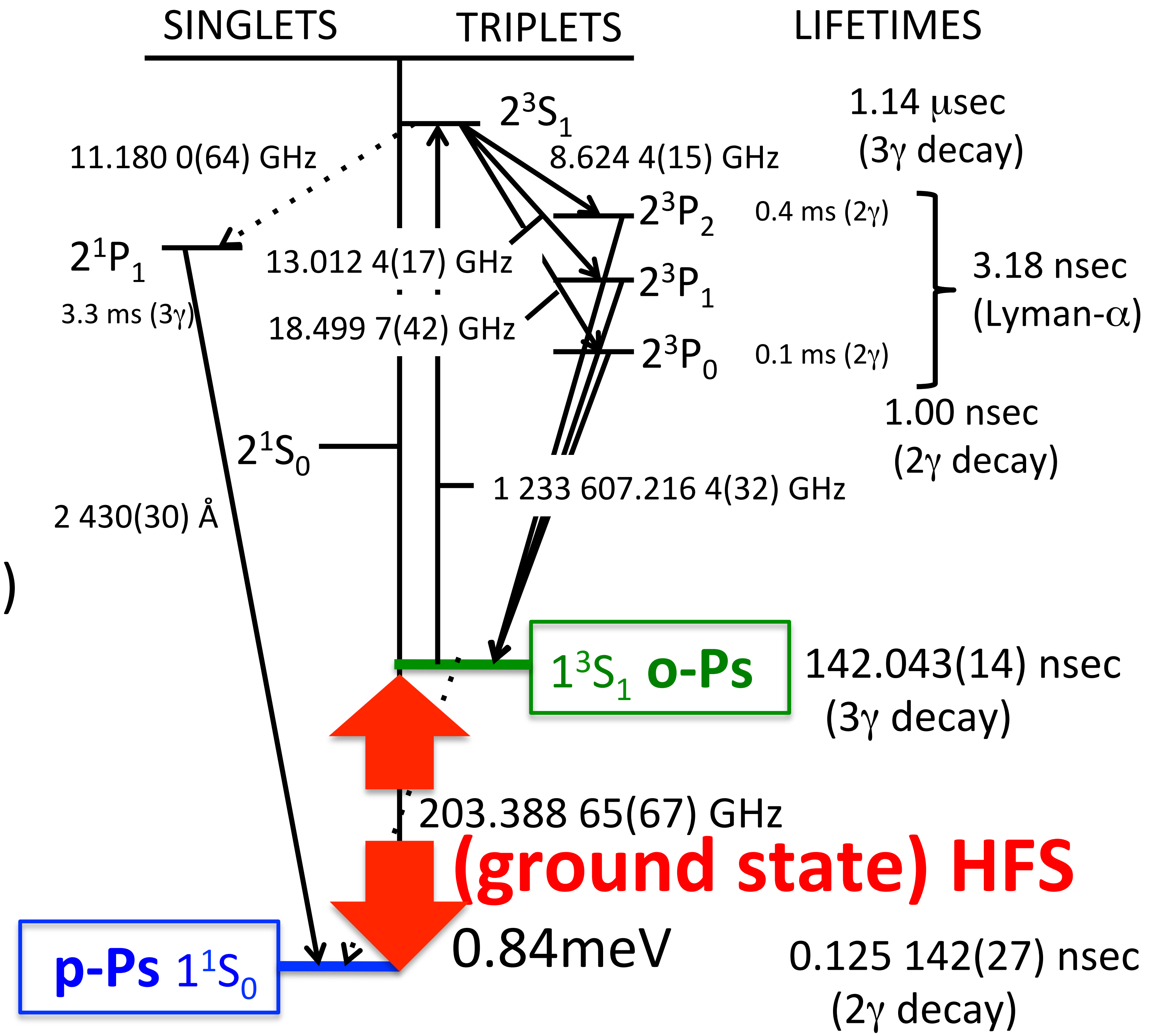


Slide from T. Ido, NICT, Tokyo

Positronium Hyperfine Splitting (Ps-HFS)

Energy difference between two spin eigenstates of the ground state Ps

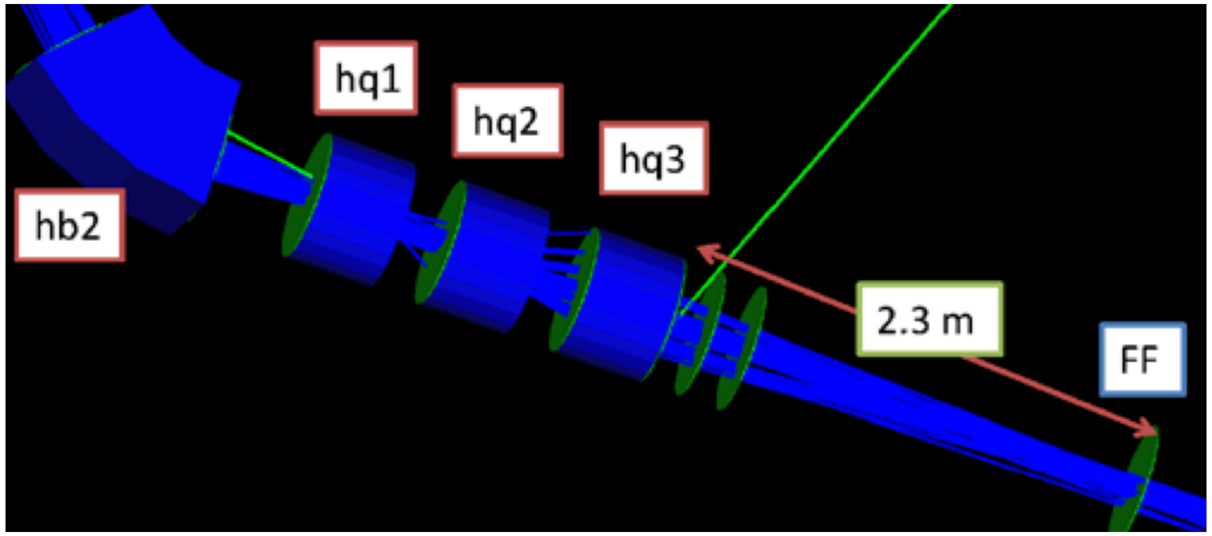
→ Ps-HFS (203 GHz)



Slide from
A. Ishida, ICEPP,
Univ. Tokyo

Muon beam and Magnet

- H-Line : The highest intensity pulsed muon beam at J-PARC



Simulated muon beam by G4Beamline

Simulation Result:
  Profile at final focus
    σx=13 mm, σy=13 mm
    xp=161.5 mrad, yp=137.4 mrad
  93.6% transmission efficiency
  Leakage field 0.5 Gauss
  (Requirement < 1.7 Gauss)

A. Toyoda *et al.* J.Phys.Conf.Ser. 408 (2013)

- Magnet : 1.7 T high precision superconducting magnet

Magnet at J-PARC

Requirement to the magnet:
  1ppm homogeneity in z300 mm, r100 mm region
Specification of the magnet:
  Field strength 1.7 T
  Bore diameter 925 mm

Field correction is performed by main coil, iron shim, and shim coil

Field strength is monitored by NMR probes

K. Sasaki, M. Sugano, The 5th and 6th g-2/EDM Collaboration Meeting (2012)
T. Mizutani *et al*, Japan Phys. Soc. Autumn Meeting (2013)

Estimation of the Event Rate

Beam intensity: 1 x 10^8 muons / s

→ (1 x 10^8 /s) / (25 pulses/s) ~ 4 x 10^6 muons / pulse

Acceptance of the detector (*z* = 700 mm)

5 x 10^{-5} e^+ / cm^2 / muon (@ 700 mm)

→ 200 e^+ / cm^2 / pulse (90 MHz / cm^2)

→ 3 e^+ / μs / cm^2 (3 MHz / cm^2) for “Old Muoniums”

900 segments / layer (1 segment = 1 cm^2)