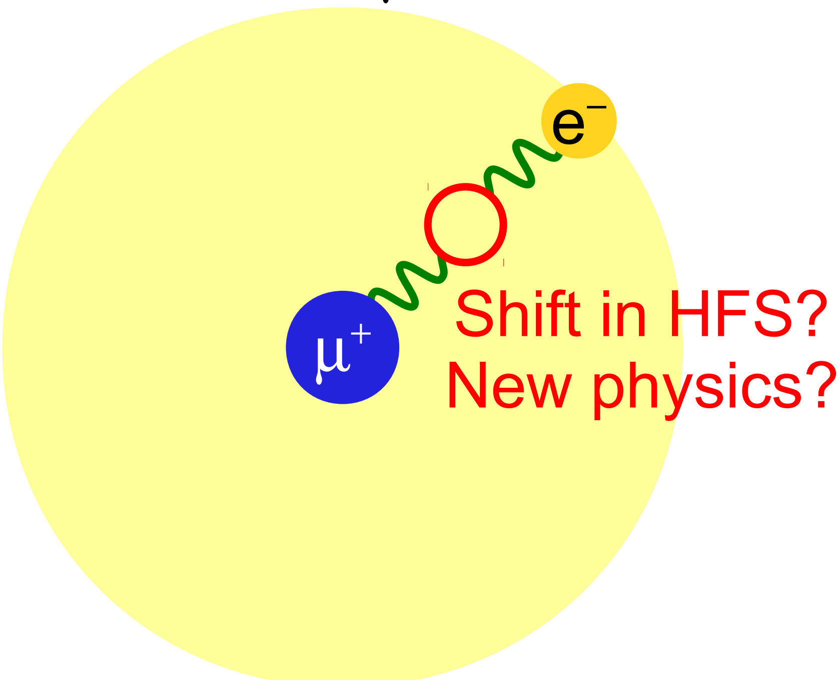
Muonium HFS measurement at J-PARC

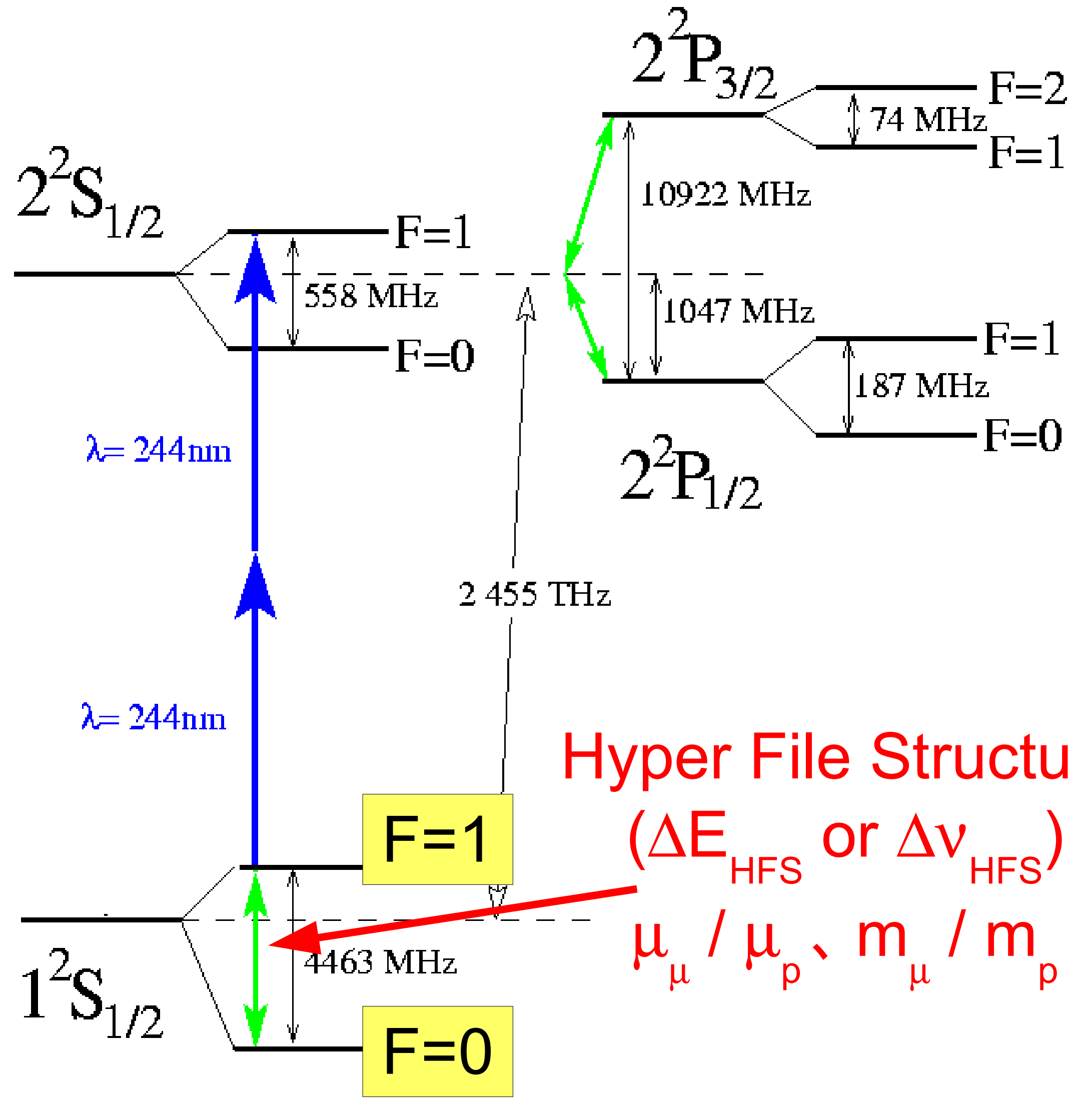
Jul. 25, 2012
Nufact 2012
KEK
Yoshinori Fukao
for MuHFS Collaboration

Physics Motivation

Muonium = $\mu^+ + e^-$



Two-body bound state
of pure leptons.

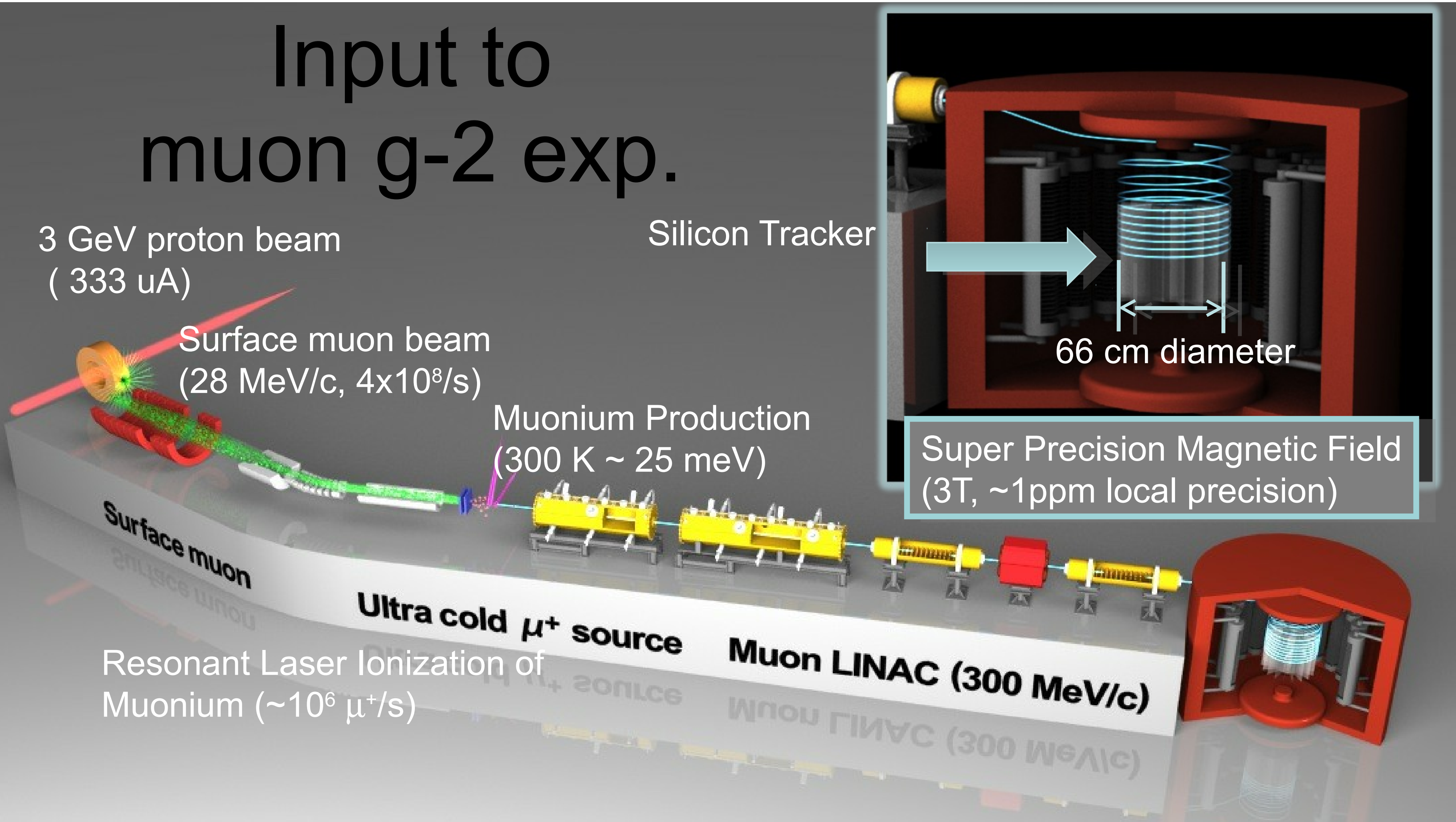


Hyper File Structure
(ΔE_{HFS} or $\Delta \nu_{HFS}$)
μ_μ / μ_p、m_μ / m_p

Precision measurement of ΔE_{HFS}、μ_μ / μ_p、m_μ / m_p

Sensitive test of two-body bound state QED

Input to muon g-2 exp.

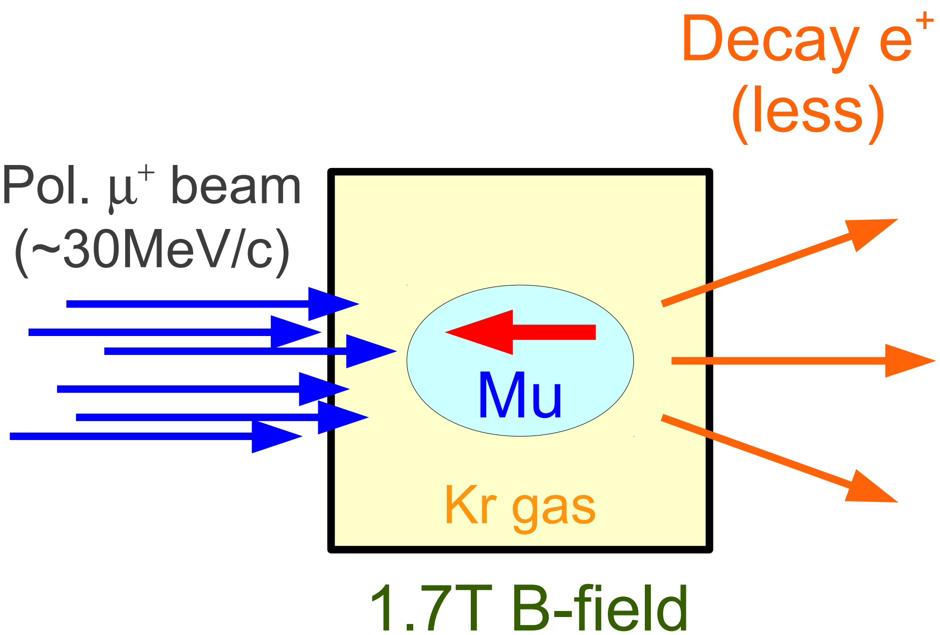


$$a_\mu = \frac{R}{\lambda - R}, \qquad R = \frac{\omega_a}{\omega_p}, \qquad \lambda = \frac{\mu_\mu}{\mu_p}$$

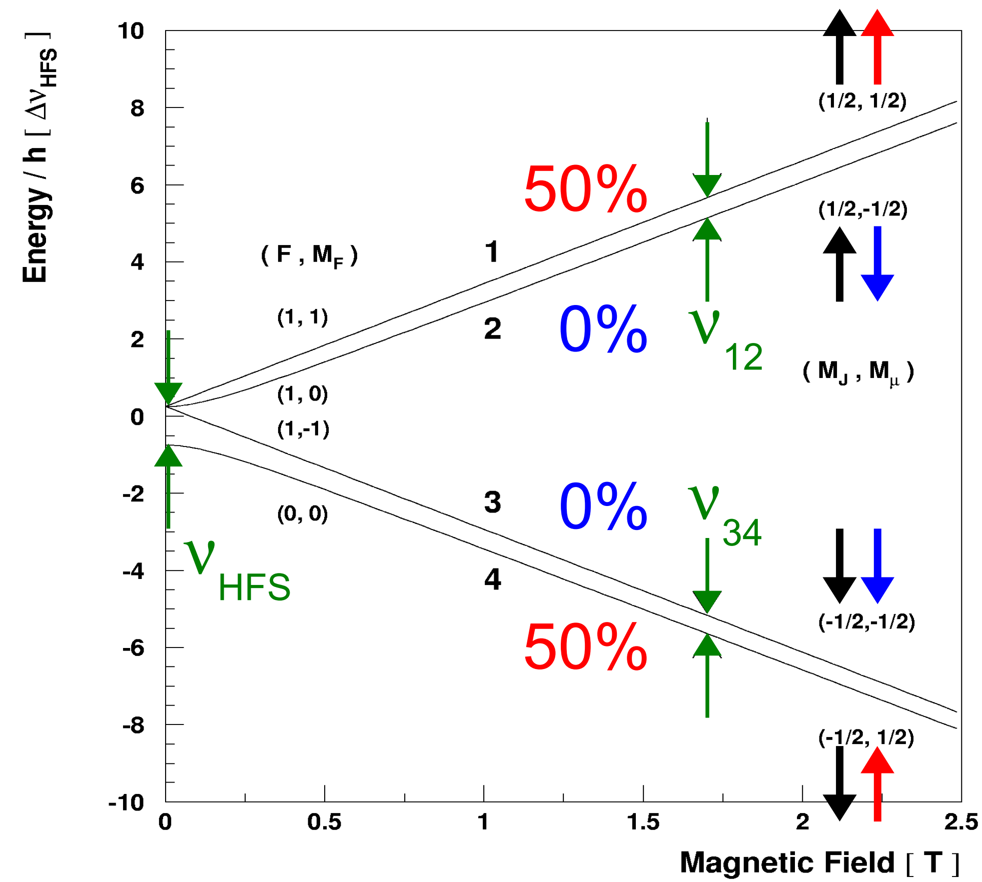
New Muon g-2/EDM Experiment at J-PARC with Ultra-Cold Muon Beam

From Muonium HFS measurement

Experimental Method

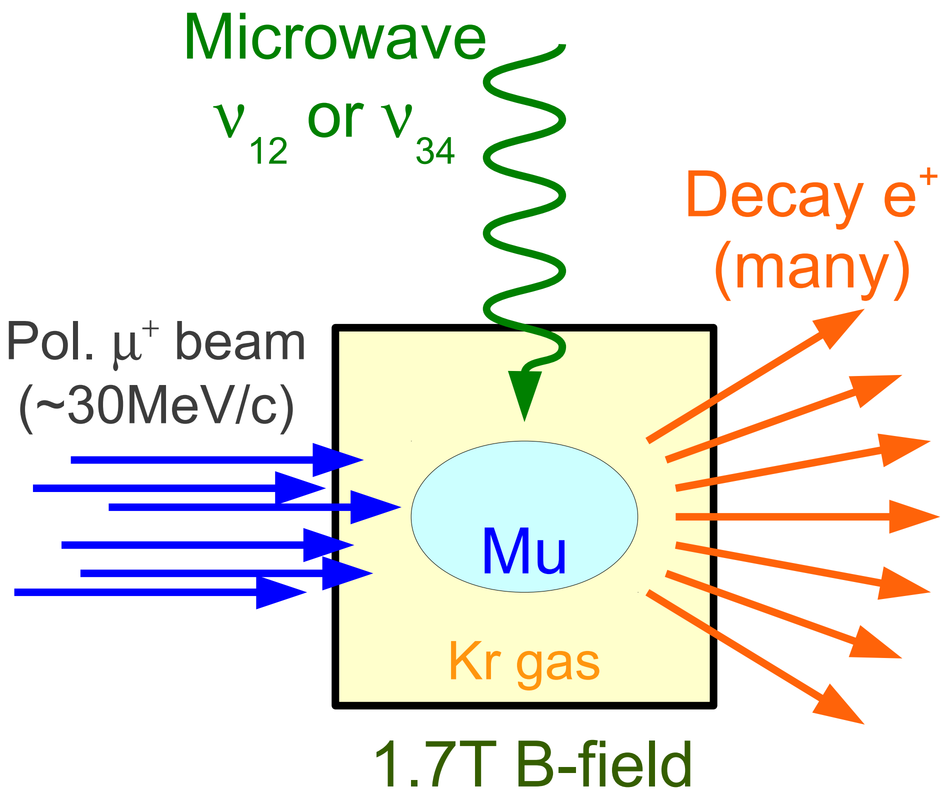


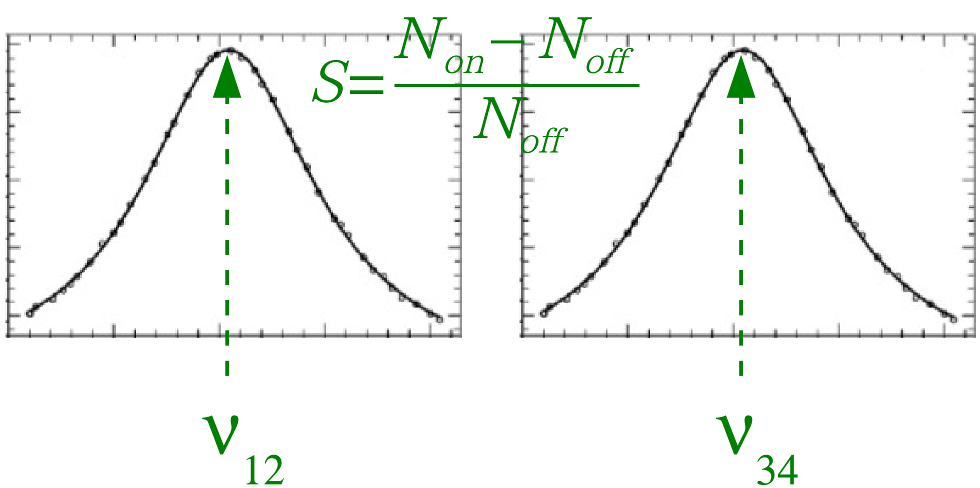
Control 4 states of μ-spin + e-spin with microwave ν_{12} and ν_{34}



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

Experimental Method





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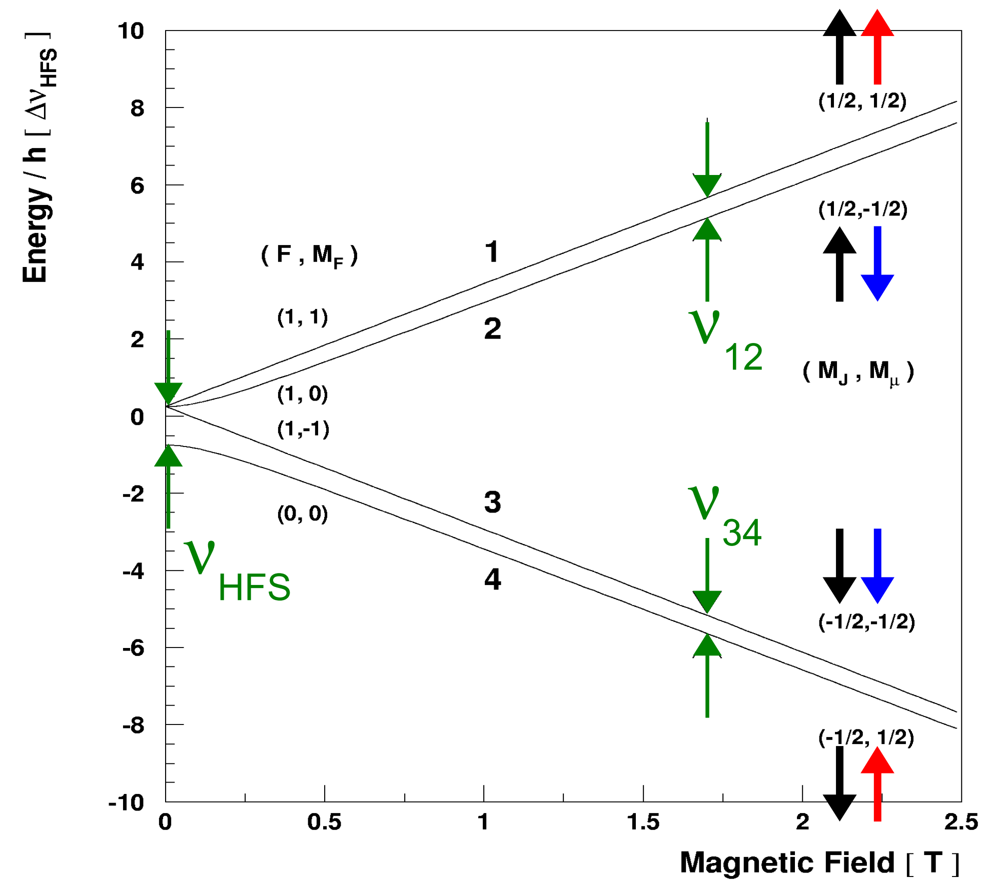

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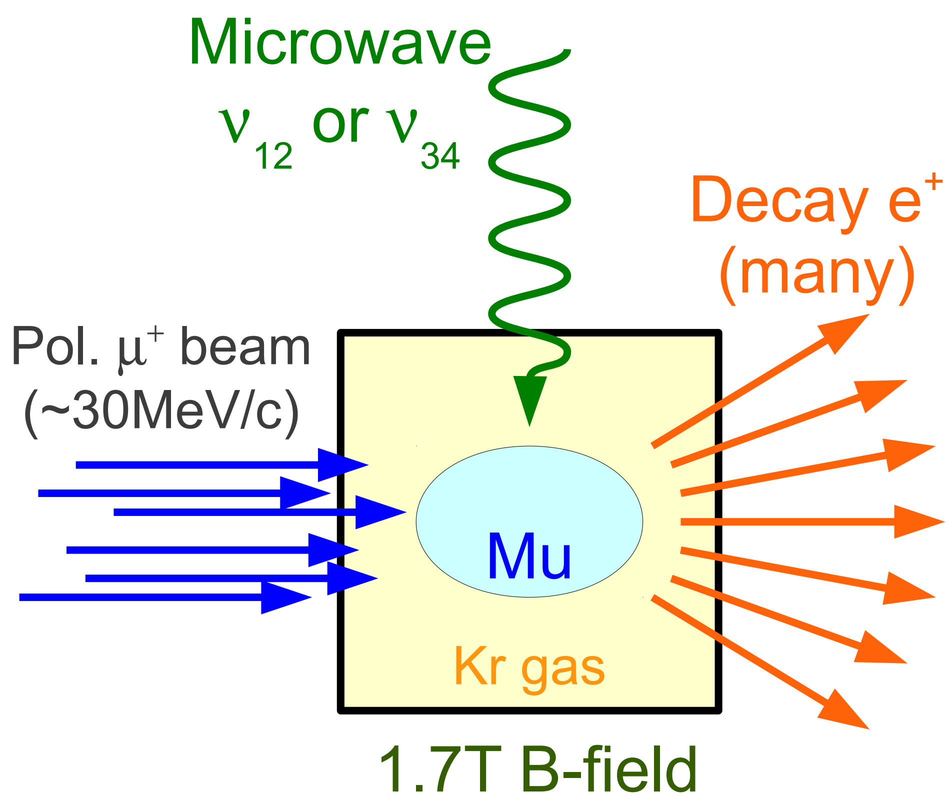
Experimental Method



Control 4 states of μ-spin + e-spin
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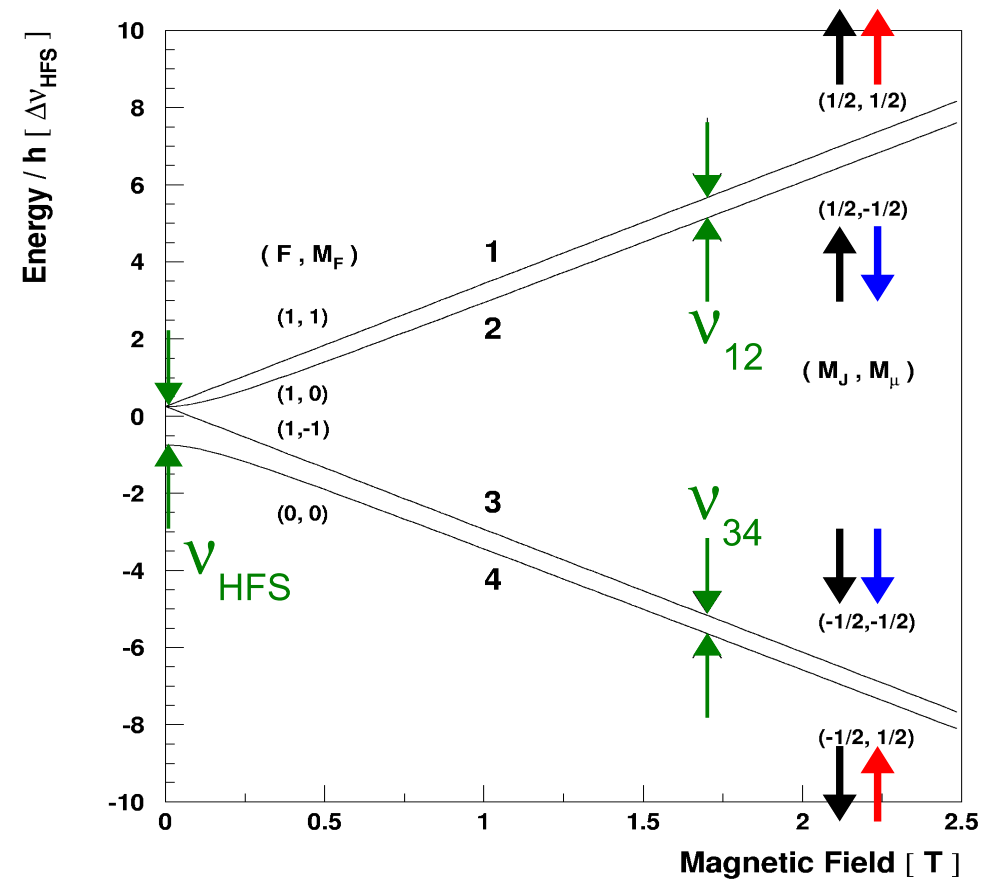
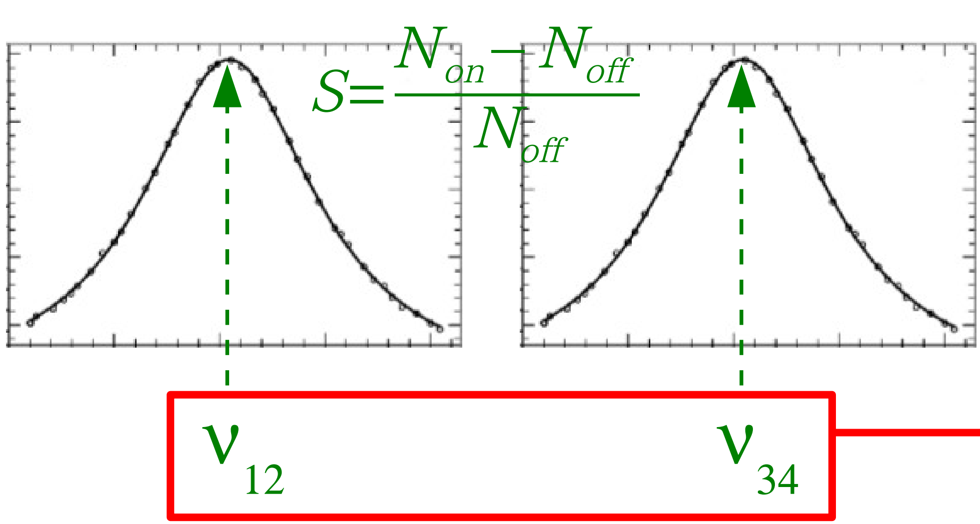
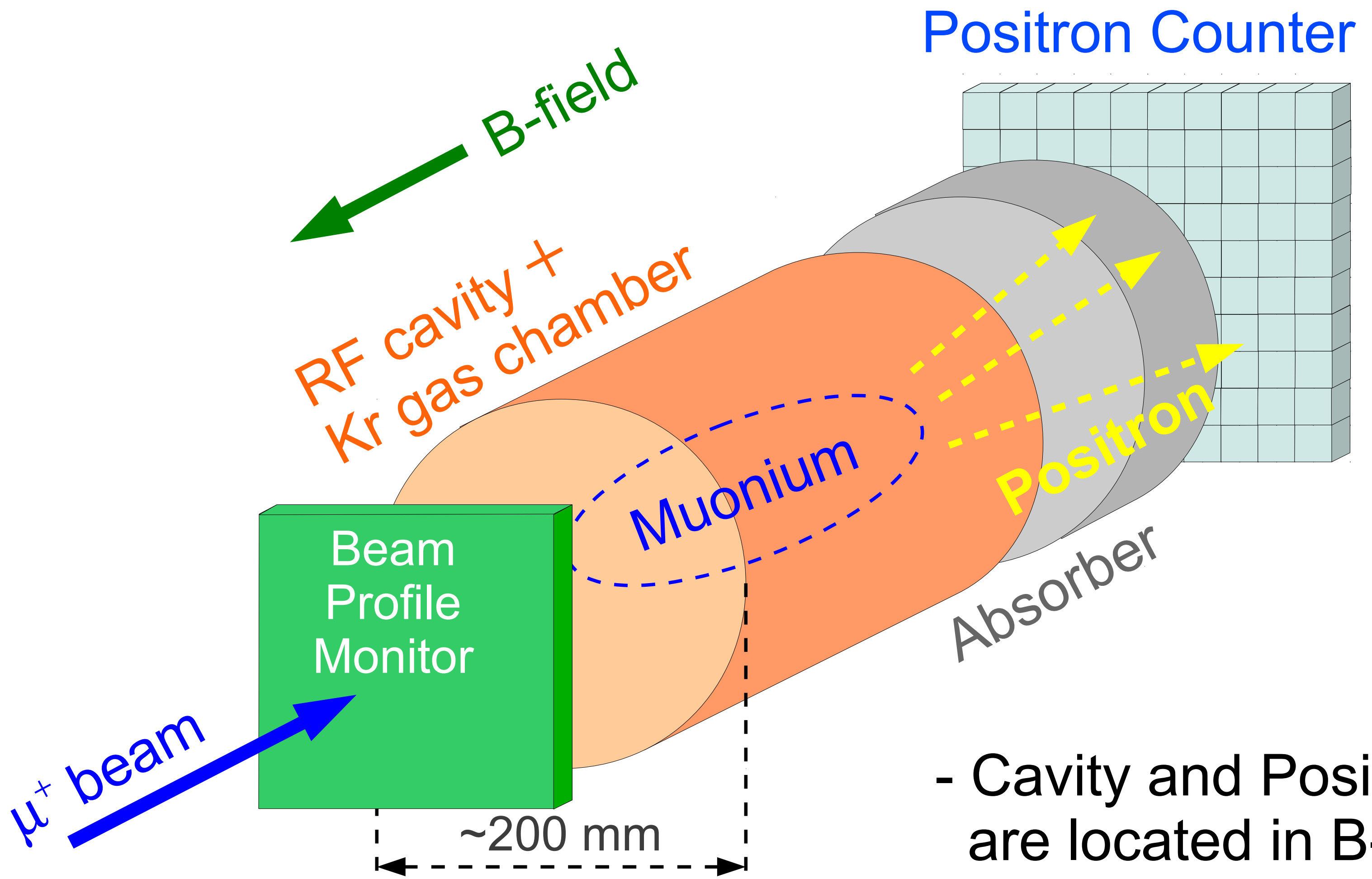




$$\nu_{HFS} = \nu_{12} + \nu_{34}$$

Experimental Setup

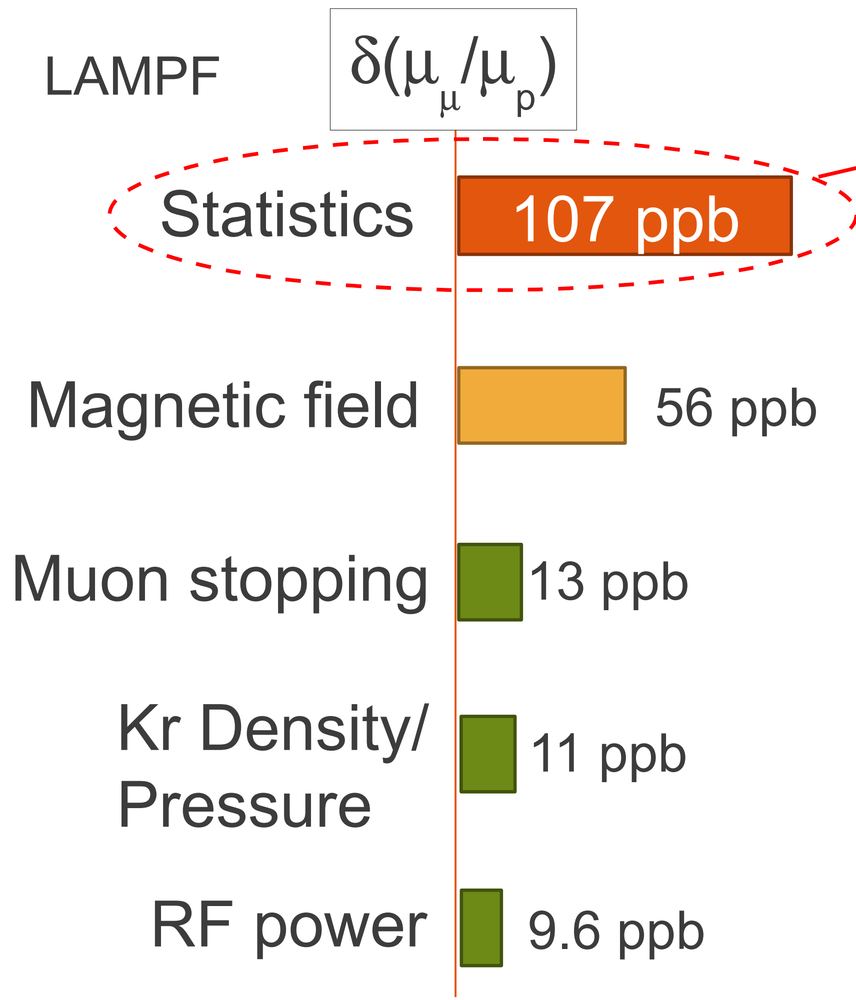


- Cavity and Positron Counter are located in B-field.
- Count decay positrons with and without microwave.
- Positron Counter is located upstream too.

Previous Exp. Results in 1999 @Los Alamos Meson Physics Facility

$\Delta\nu_{HFS}$ = 4463 302 776(51) Hz : (11 ppb)

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



J-PARC high intensity beam

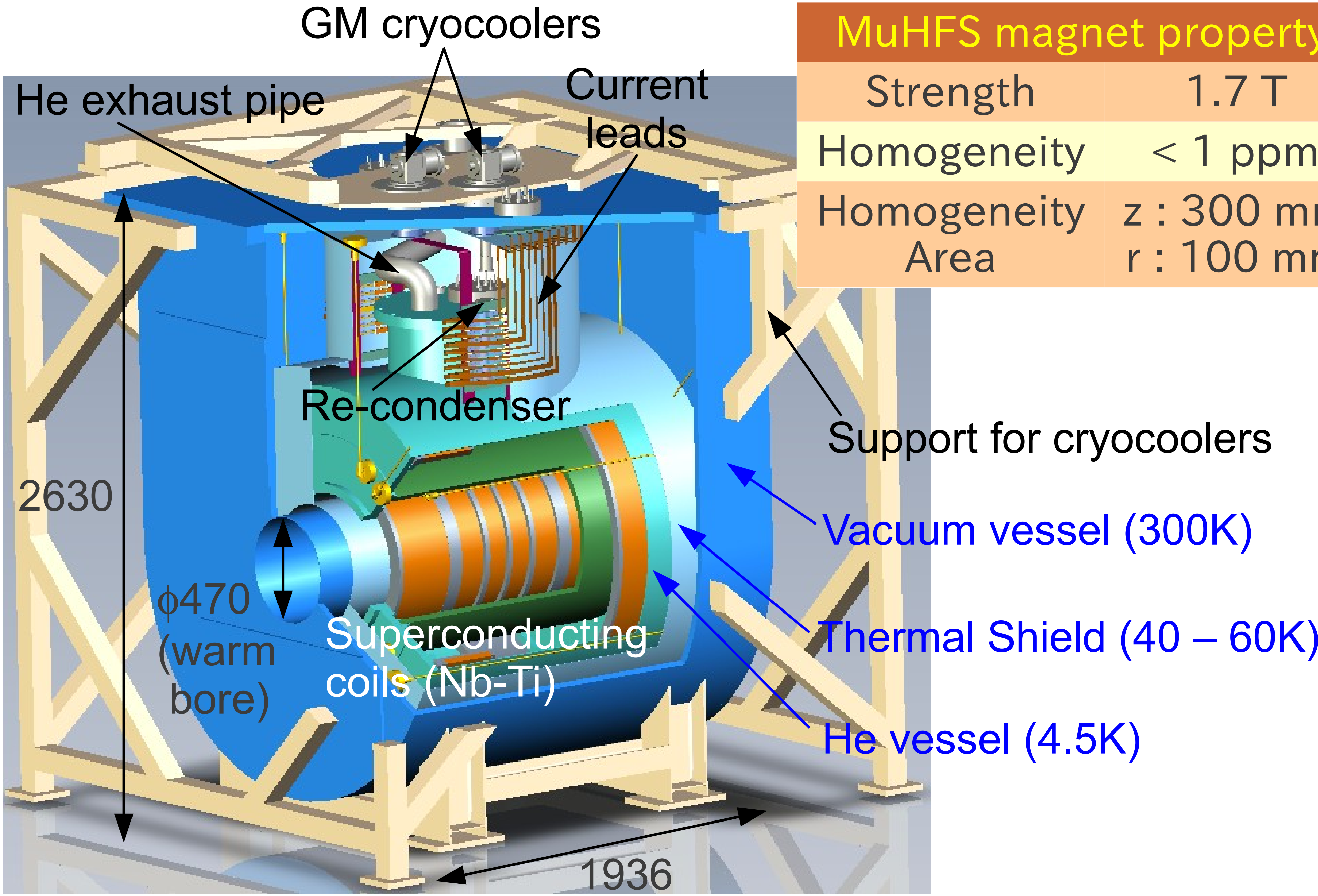
LAMPF statistics : 10^{13} muons
MUSE H-line : 1 x 10^8 muons / sec
Achieve LAMPF stat. in 28 hours

DAQ for 230 days : 2 x 10^{15} muons
200-times statistics

Systematic uncertainty must be suppressed.
Instruments need to work in high-rate condition.

Structure of Solenoid Magnet

MuHFS magnet property	
Strength	1.7 T
Homogeneity	< 1 ppm
Homogeneity Area	z : 300 mm r : 100 mm



Current status of Design and R&D

Main coil design is done.
Shim coil design is ongoing.
Trial winding is performed.

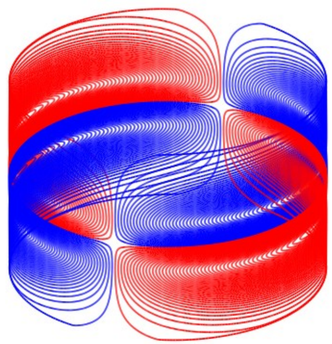
Cryogenic design (heat input, cryocoolers, current leads) is ongoing.

Mechanical design (He vessel, vacuum vessel, coil suport) is ongoing.

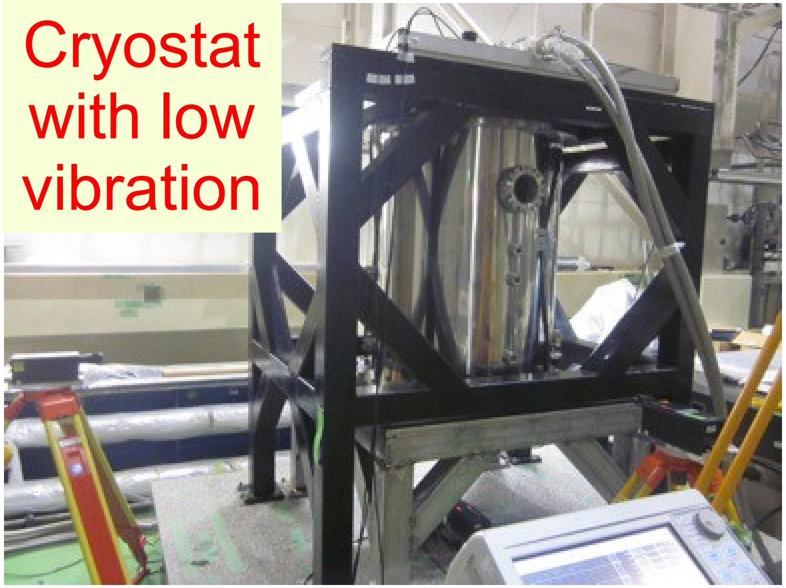
Vibration of a cryostat is evaluated.

Field monitoring system is being developed.

Shim Coil



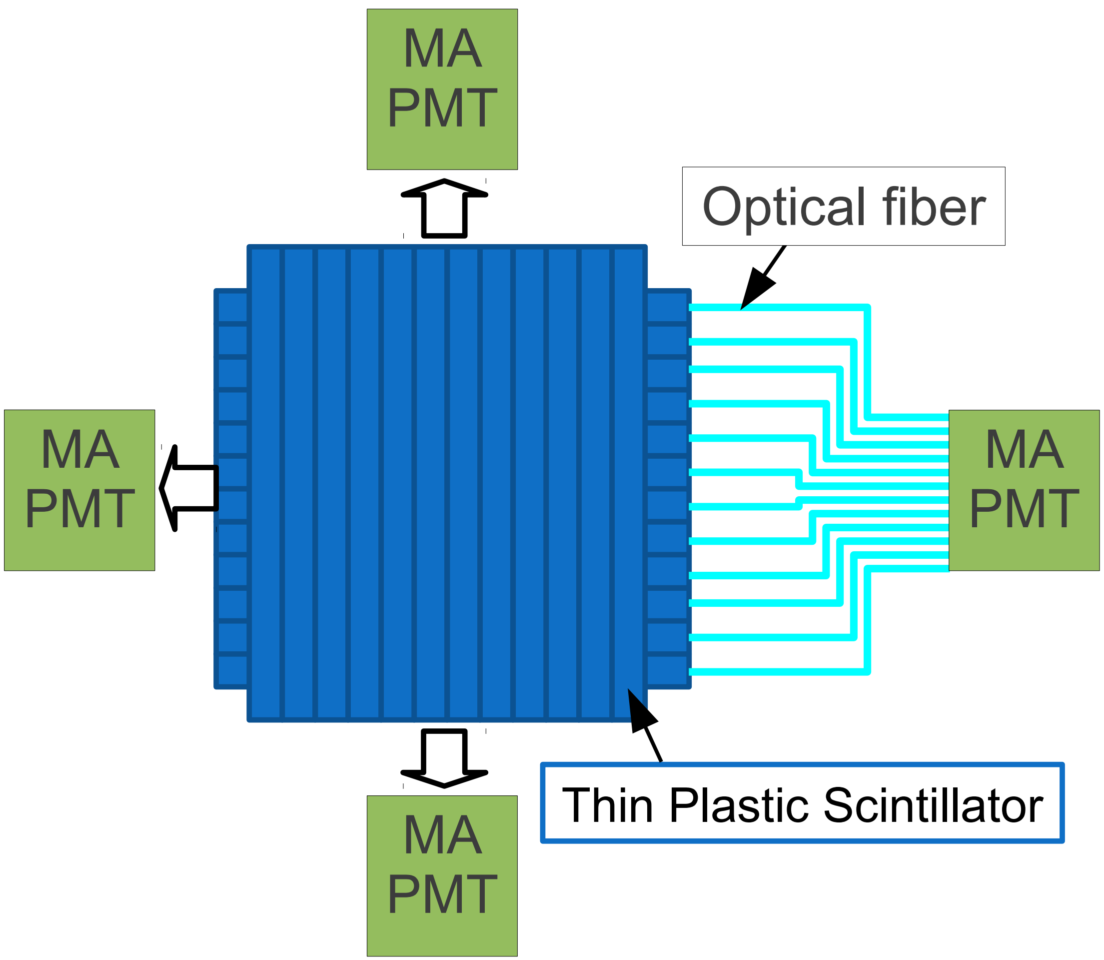
Cryostat with low vibration



NMR field monitoring

Trial winding

Front Beam Profile Monitor (FBPM)



(we have an option to use camera)

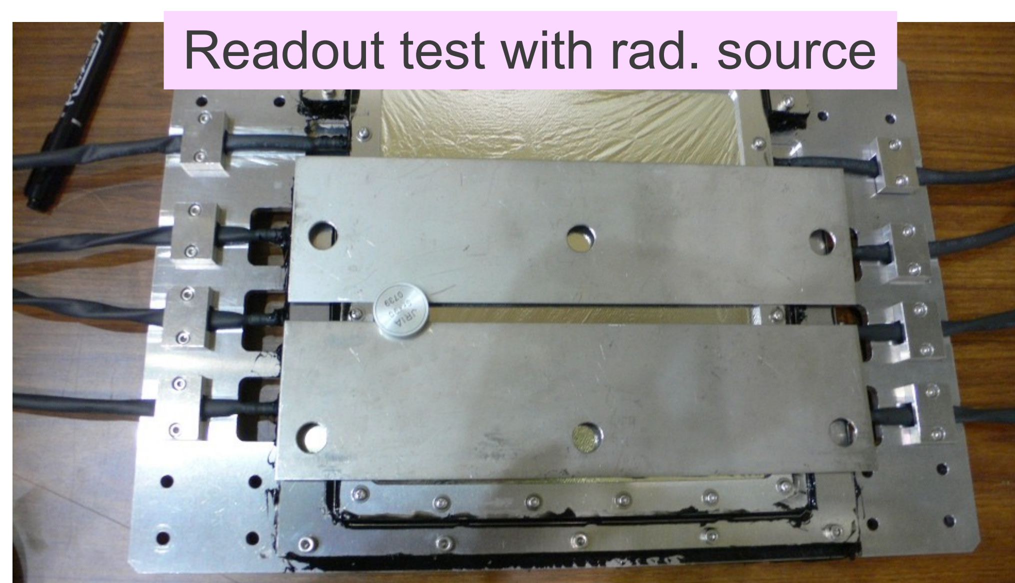
Purpuse
- Monitor beam flux
- Monitor beam profile

Challenge
- Uniform thickness to obtain uniform muon beam range.
- Thin scintillator for muon to be transparent.
- Thin scintillator requires efficient light transmission.

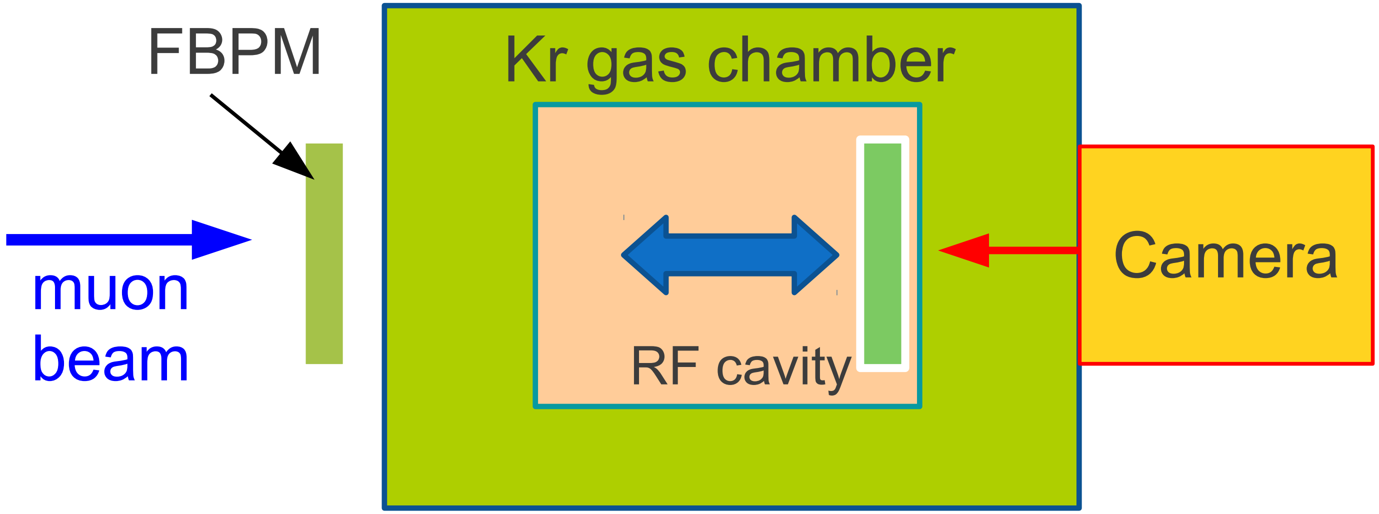
Prototype of FBPM

- Thickness : 0.20, 0.15, 0.10 mm.
- Width : 6 mm
- With/Without Al coating
- Direct fiber coupling / Light guide

No signal was observed with ^{137}Cs, ^{106}Ru, ^{90}Sr.
However, light yield is >1000 times larger with muon beam.



Target Beam Profile Monitor (TBPM)

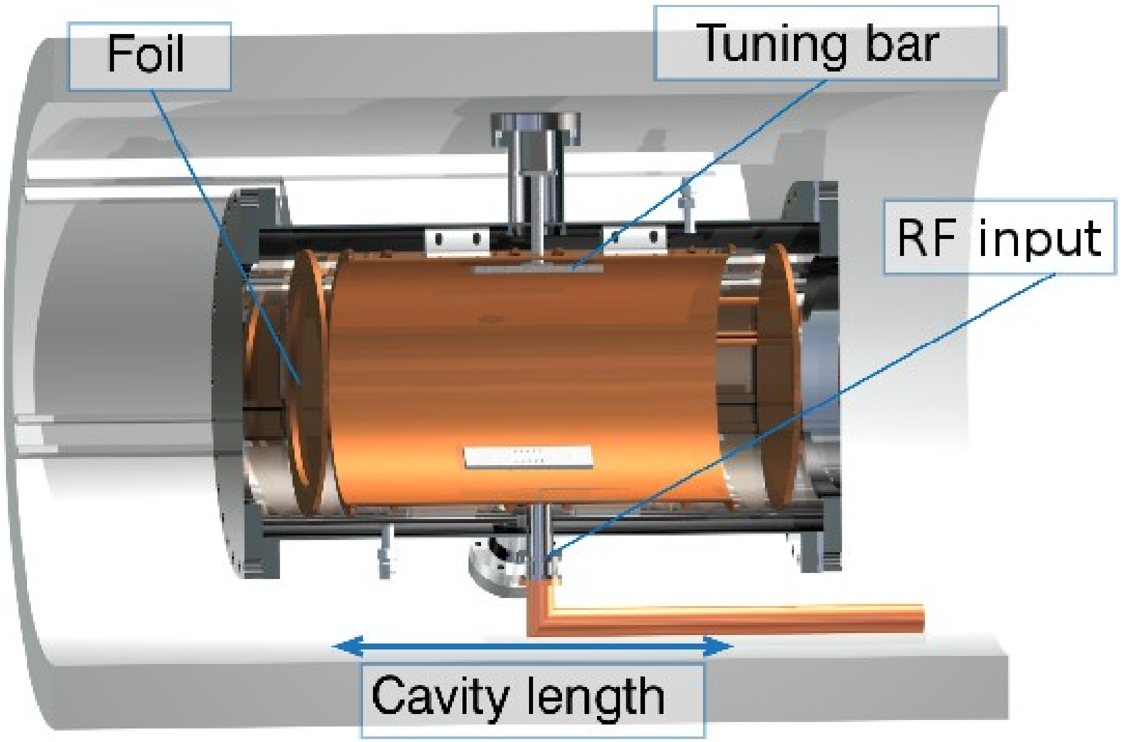


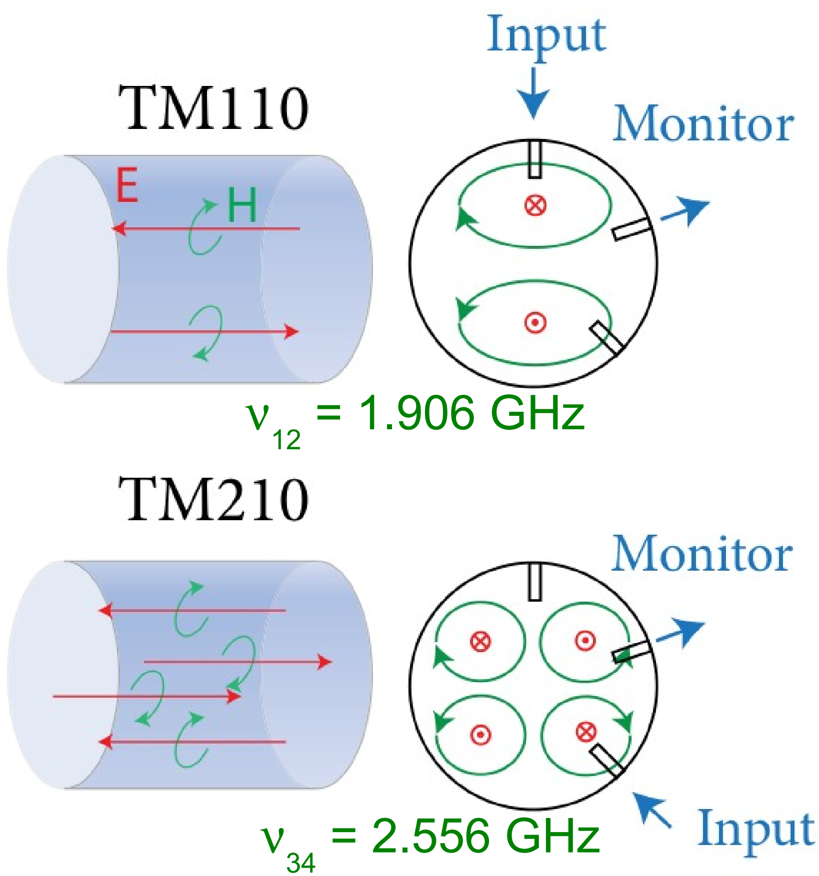
Measure 3-dimensional muon beam stopping distribution with real condition. (gas mixture, beam parameter, magnetic field)

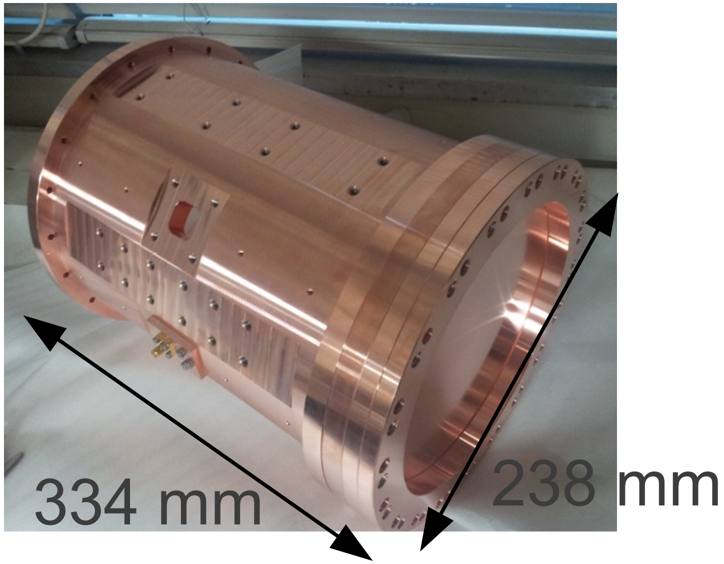
Periodical measurement. (not continuous measurement)

Design work is in progress.

RF cavity / Kr gas chamber



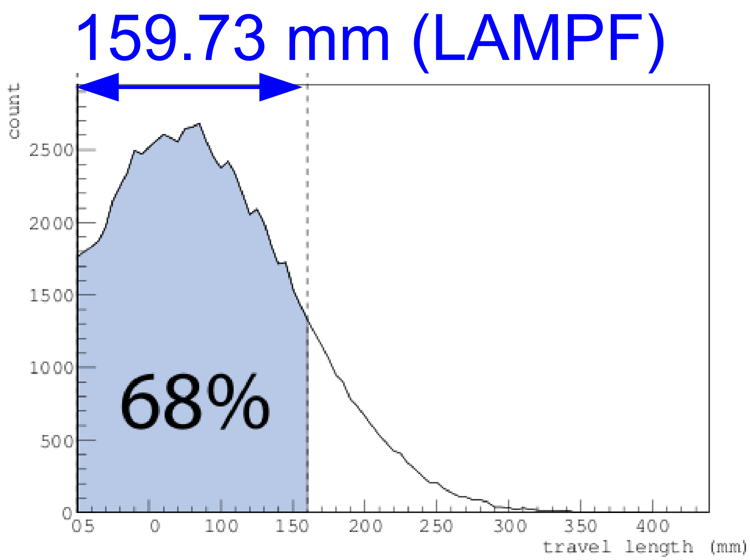


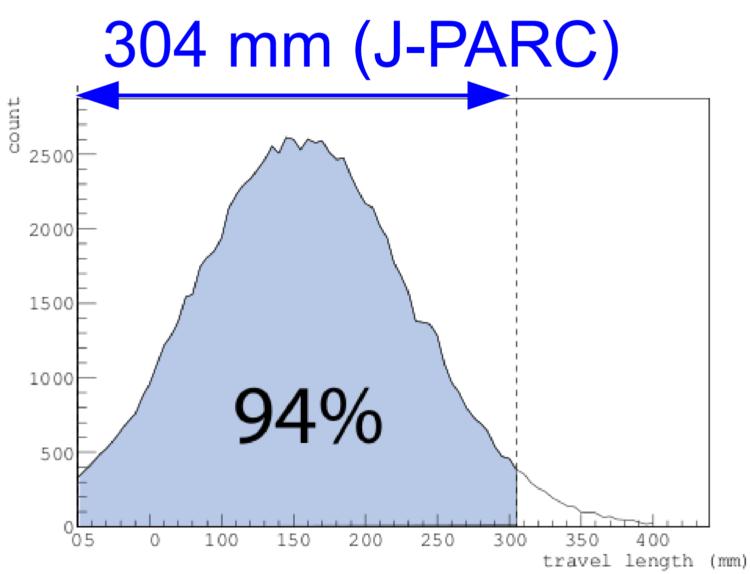


- Two frequencies can be provided with same RF cavity.
- Tuning bars realize frequency sweep to measure resonance curve.
- Prototype is developed and being tested.

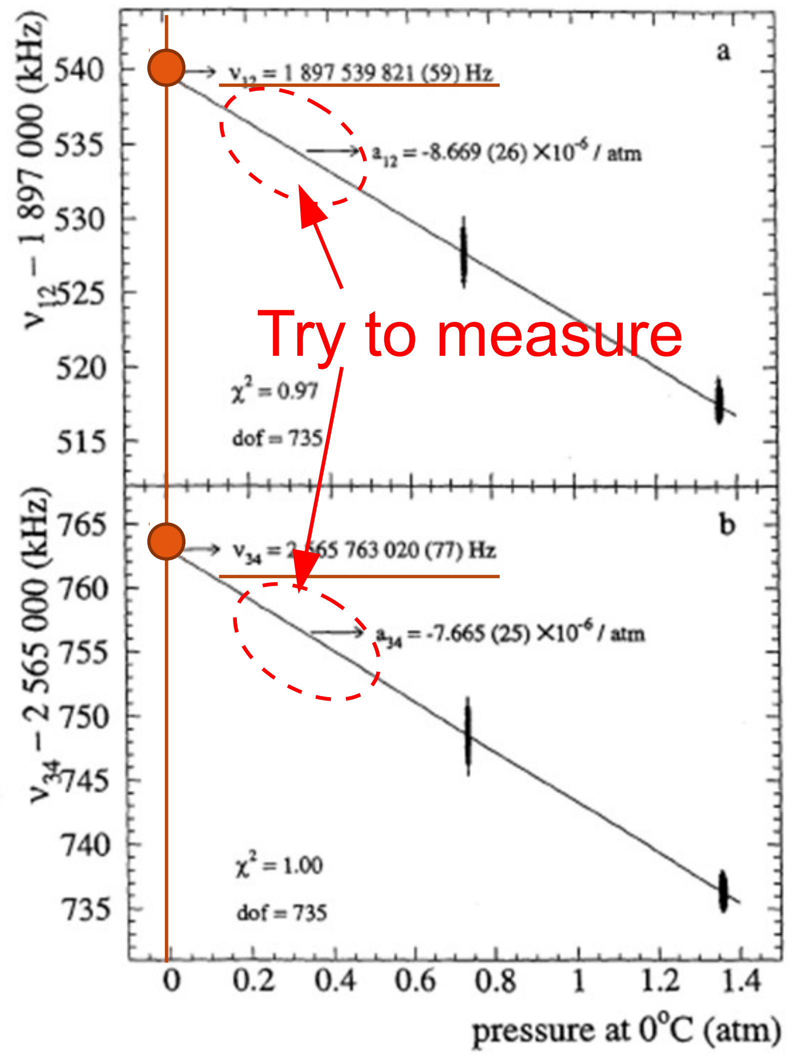
Kr gas density dependence

muon stopping distribution at 0.3 atm



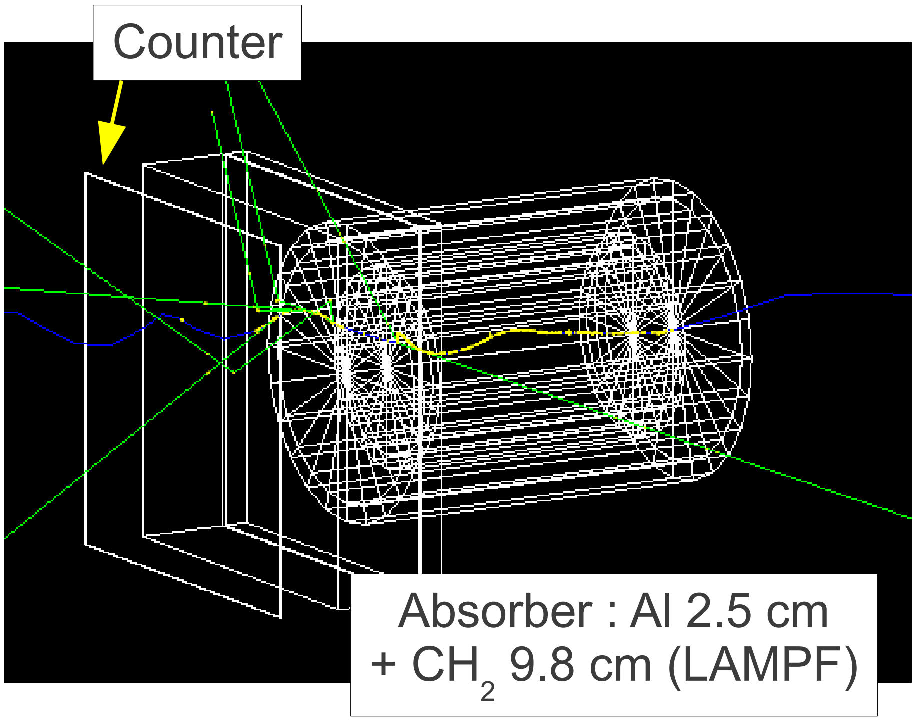


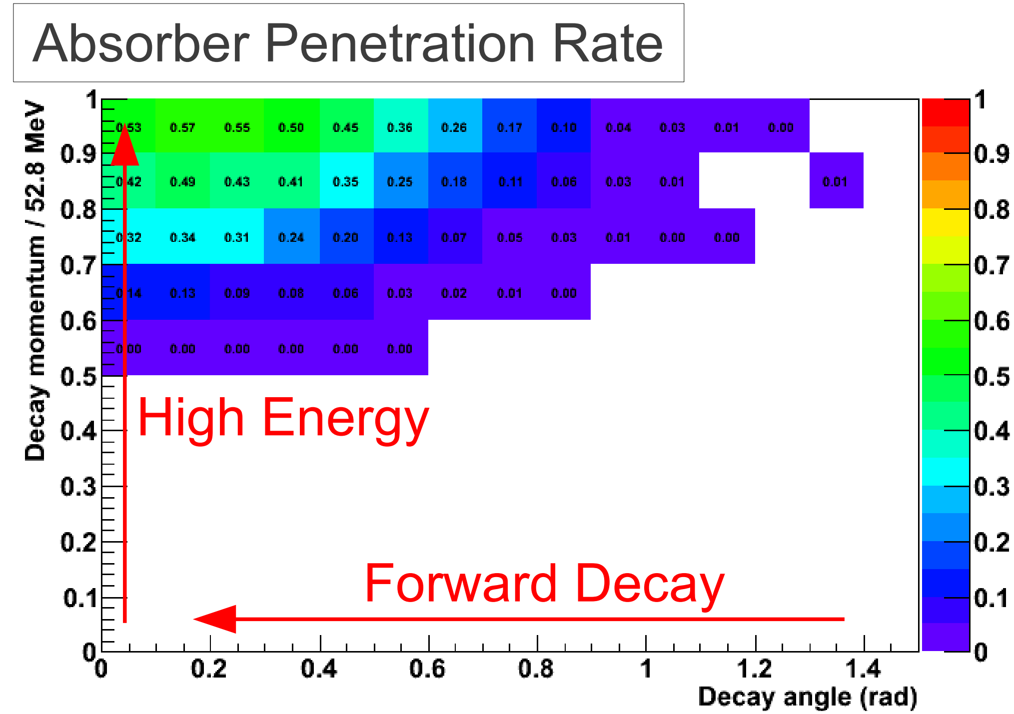
LAMPF exp.



Longer cavity enable measurement at near vacuum.

Positron Counter





Detector can be located far from the cavity.

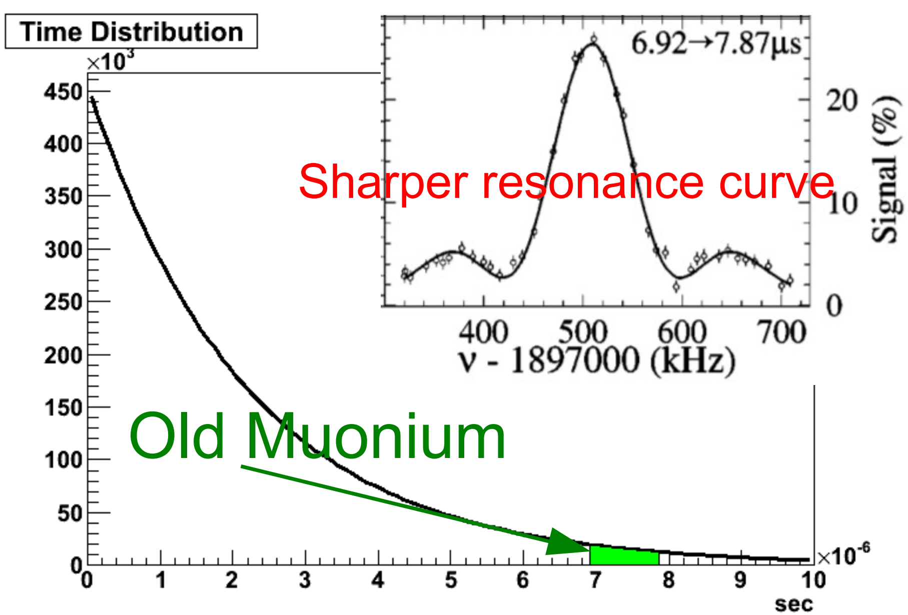
- Effect to B-field is small.
- Positrons are confined due to magnetic field
- Positron injection is more normal to detector surface.

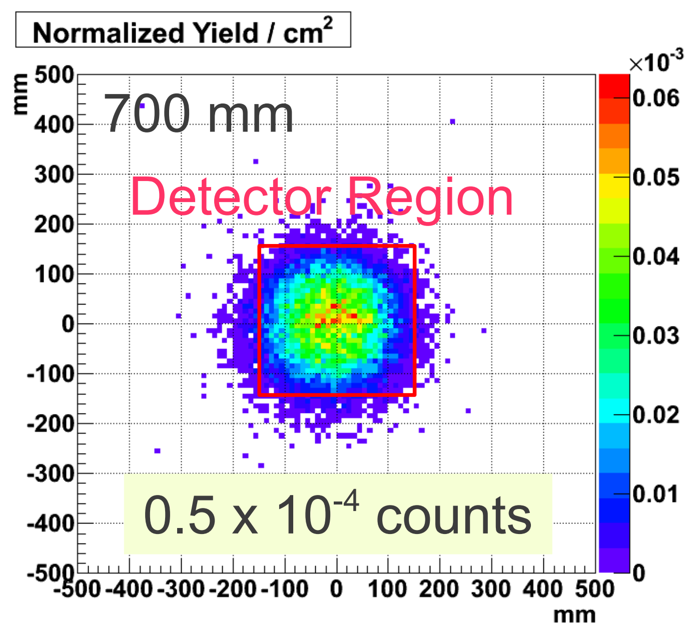
Only positrons with high energy and with forward decay survive. Such positrons are sensitive to the parent muon spin direction.

Event Rate
(Difficulty in detector design)

Beam Intensity : 1 x 10^8 muons / sec
→ 1 x 10^8 / 25 Hz ~ 4 x 10^6 muons / pulse

Detector Acceptance (z = 700 mm)
5 x 10^{-5} e^+ / muon / cm^2 (@ detector location of 700 mm)
→ 200 e^+ / pulse / cm^2 (90 MHz / cm^2) : all positrons
→ 3 e^+ / usec / cm^2 (3 MHz / cm^2) : from Old Muonium
900 segments / layer (1 segment = 1 cm^2)

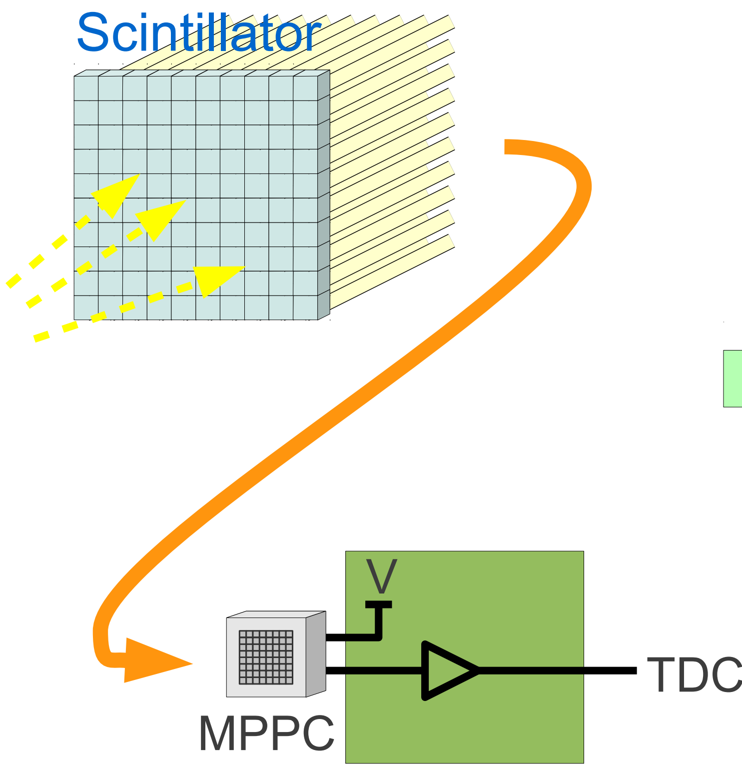




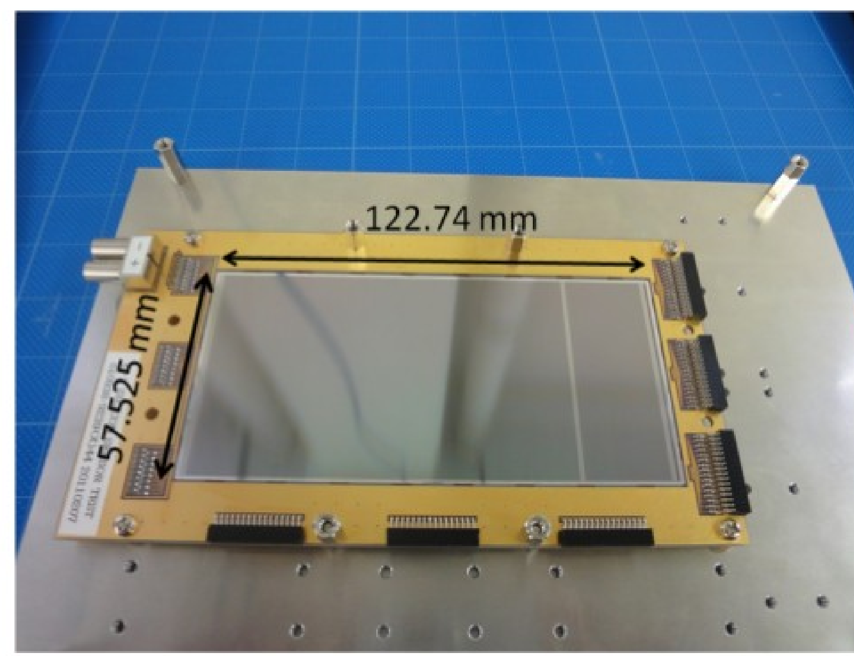
Detector Option

1. Start with Scintillator + MPPC detector at initial low intensity period + Old Muonium Method. (late 2014)

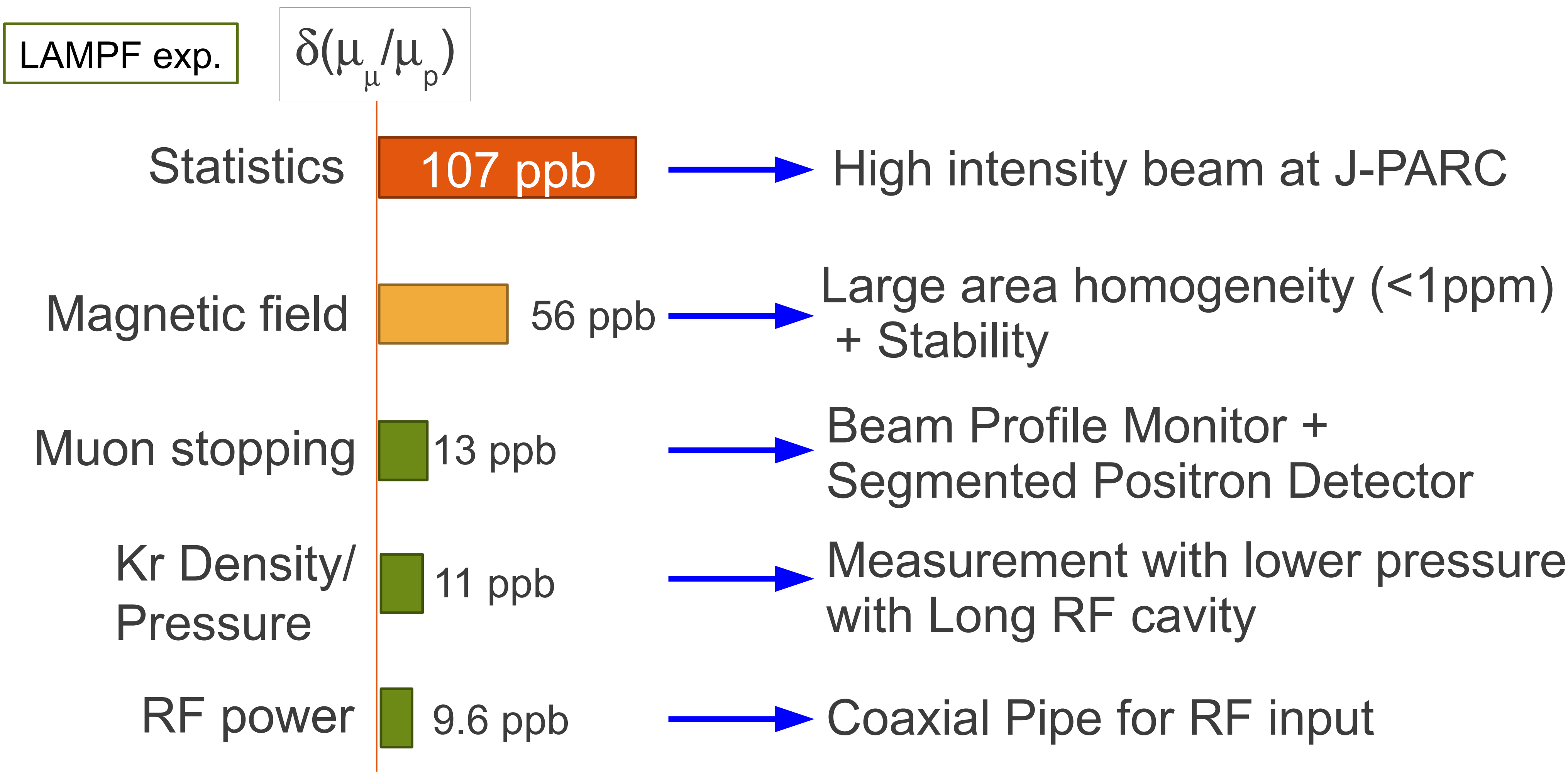
2. Install Silicon Strip Detector for g-2 when it's ready.
   Accumulate full statistics at maximum beam intensity.
   This can be demonstration before mass production for g-2.



Upgrade



LAMPF → JPARC MUSE
Improve Precision



Summary

Experiment for Muonium Hyper Fine Structure measurement at J-PARC is planned.

- Precision test of bound-state QED
- Input of magnetic moment ratio to J-PARC g-2 experiment

Expected statistics is 200 times larger than previous experiment at LAMPF.

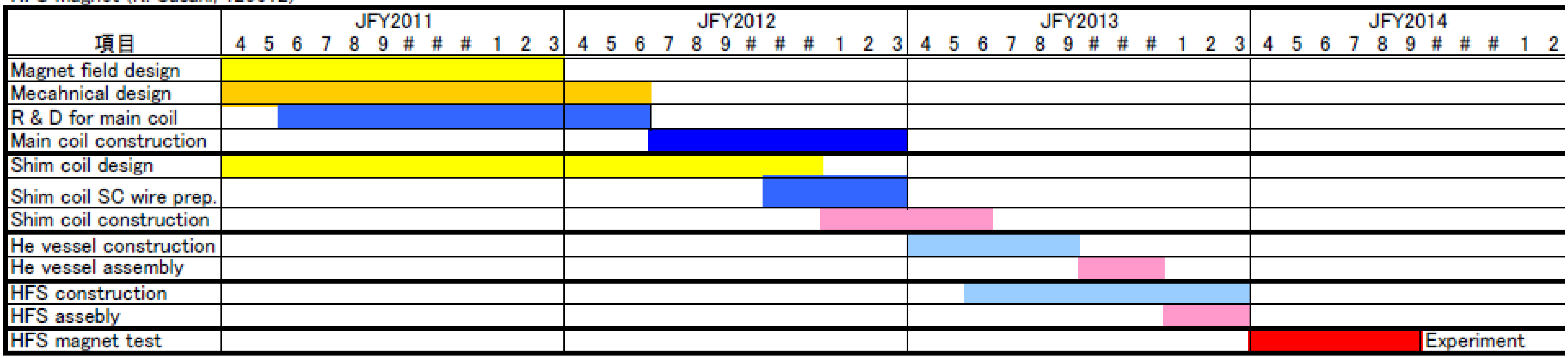
Development is underway to start experiment in 2014.

- Beam Profile Monitor : Prototype is developed and being tested.
- Magnet : Design work and R&D is ongoing.
- RF cavity : Prototype is developed and tested.
- Gas chamber : Design work is ongoing.
- Positron counter : GEANT simulation is ongoing.

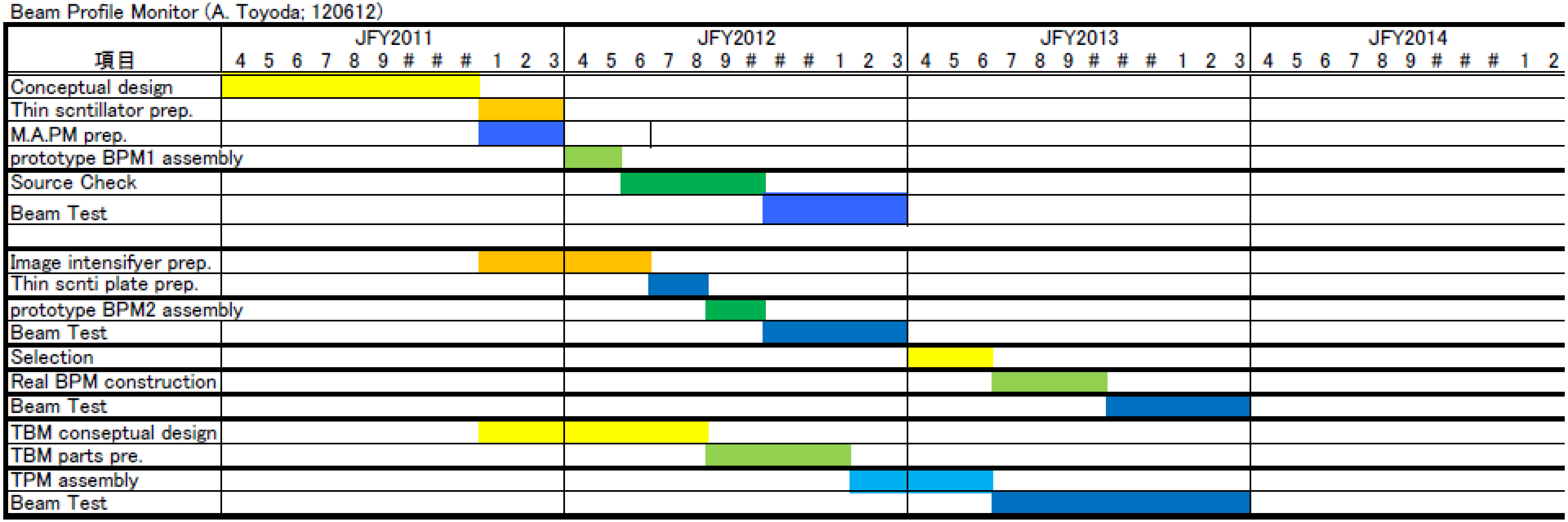
Backup

R&D plane (Magnet, BPM)

HFS magnet (K. Sasaki; 120612)

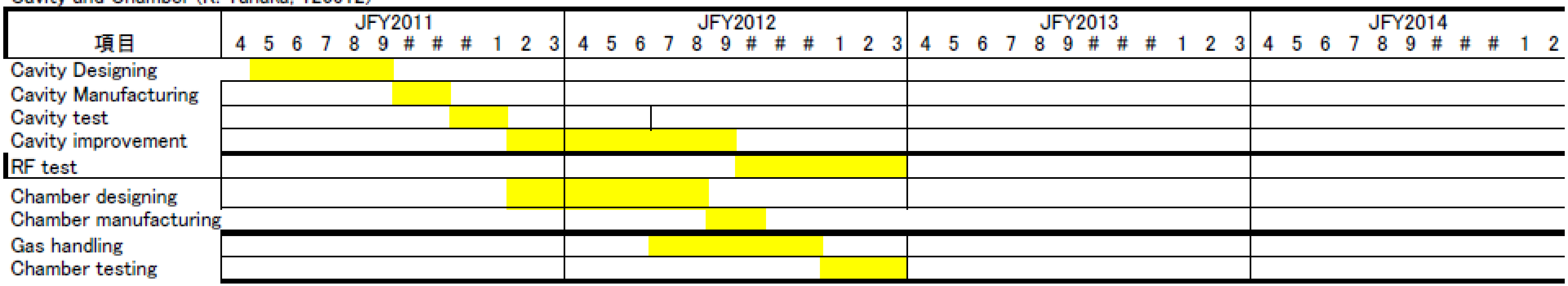


Beam Profile Monitor (A. Toyoda; 120612)

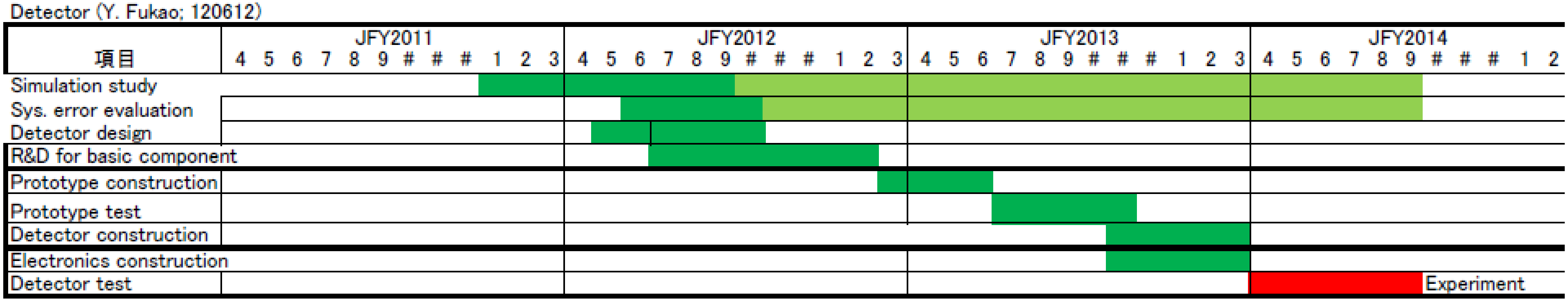


R&D plan (Cavity, Detector)

Cavity and Chamber (K. Tanaka; 120612)



Detector (Y. Fukao; 120612)



Case of Hydrogen and Postronium

Hydrogen Atom

Experiment : 1420. 405 751 766 7(9) MHz [0.6 ppt]

Theory : 1420. 403 1(8) MHz [560 ppb]

3.3 σ : Large uncertainty of proton structure

Positronium

Experiment : 203 389. 10(74) MHz [3.6 ppm]

Theory : 203 391. 7(6) MHz [2.9 ppm]

2.7 σ : New physics?

Muonium

Experiment : 4463. 302 765(53) MHz [12 ppb]

Theory : 4463. 302 880(550) MHz [120 ppb]

0.2 σ : Theory uncertainty is from m_e / m_μ

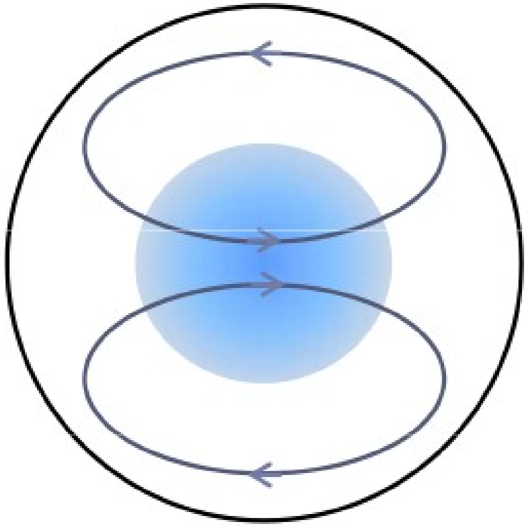
Requirement for FBPM

- LAMPF result : Δν=4 463 302 765(53)Hz
  - Liu et al. PRL82, 711 (1999)

- In their analysis, the uncertainty of the measured center of the beam (~0.6cm) and of the measured FWHM width (~2cm) contributes to ~5 Hz of systematic error.
- This analysis assumes an ideal RF power distribution. It may not be the case (→ Mr. Tanaka's talk)

→ FBPM to measure the center and the width of the beam within 0.3cm accuracy or better (the width of current scintillator ~ 0.6 cm).

→ Rigorous testing of FBPM's performance is needed.



Requirement for the TBPM

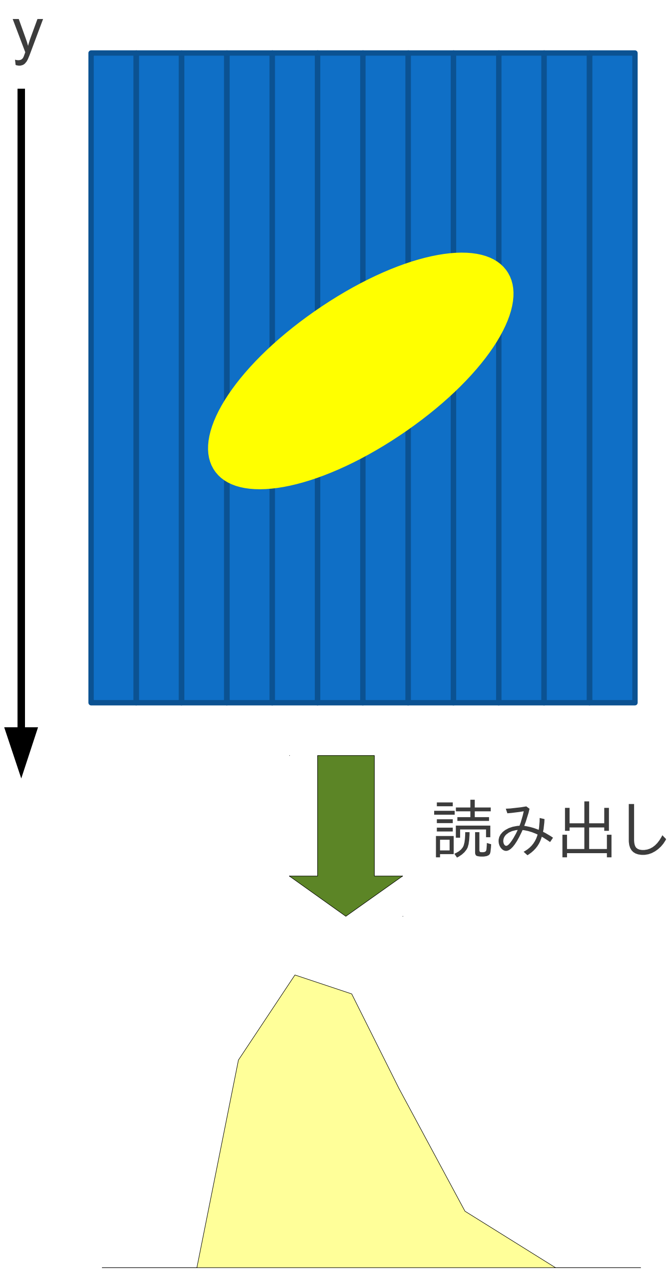
- LAMPF result : $\Delta\nu$=4 463 302 765(53)Hz

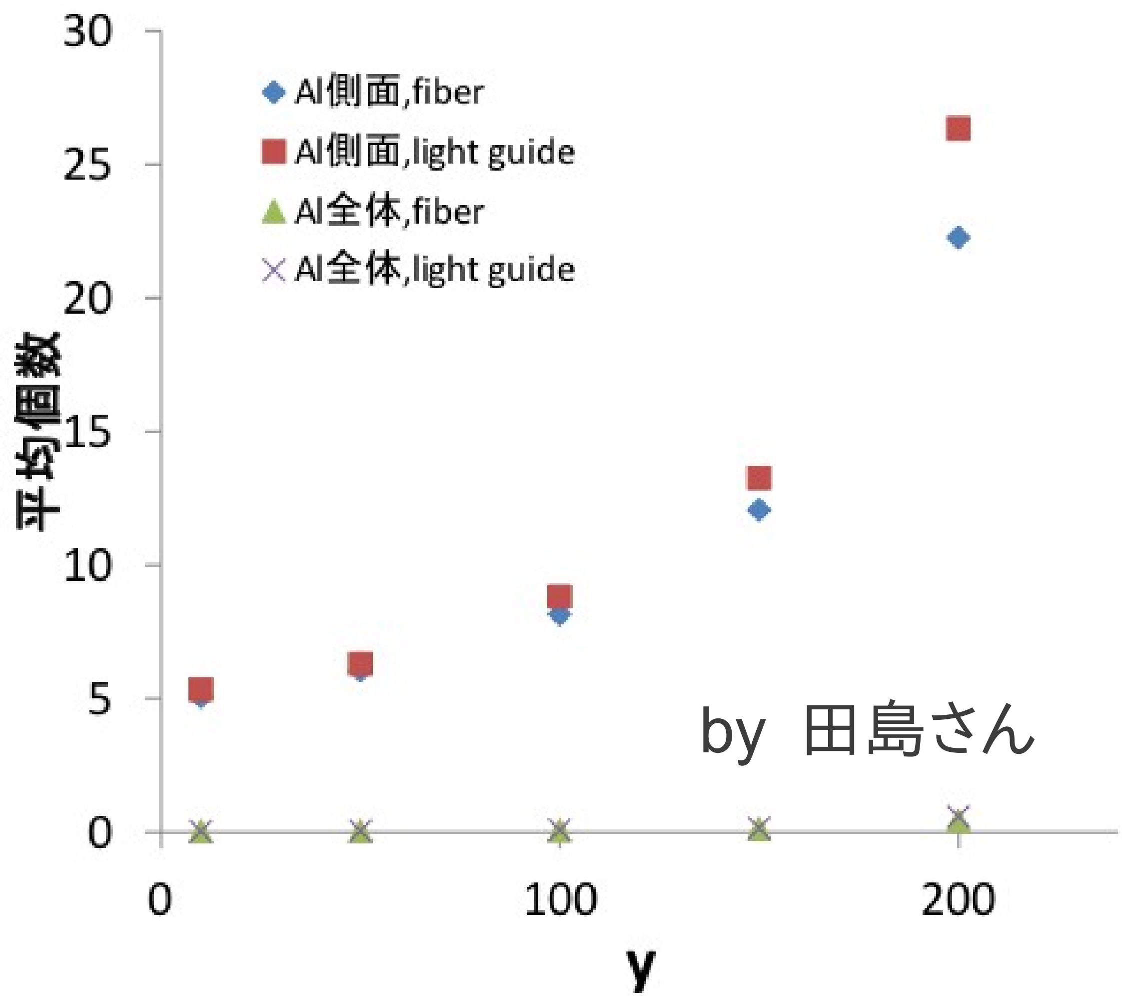
- In their analysis, the longitudinal uncertainty of the measured center of the beam (~1.0cm) and of the measured FWHM width (+2−1cm) contributes little to the systematic error.
  - the cavity is in TM110 or TM210 mode
  - the change of the solid angle is suppressed because positrons travel along the magnetic field lines.
- But again, the former statement might not be the case (→ Mr. Tanaka's talk)
  - the knowledge of longitudinal distribution also becomes important.

→ Requirement for the transverse resolution is same as the FBPM (<0.3cm), the uniformity of the scintillator plates is important.

- "proof of principle" beam test planned for October (?)

光量の位置依存性の問題



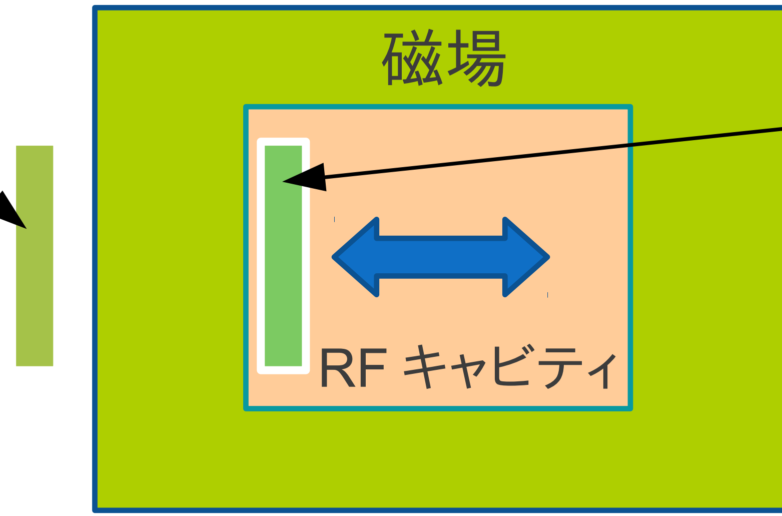


by 田島さん

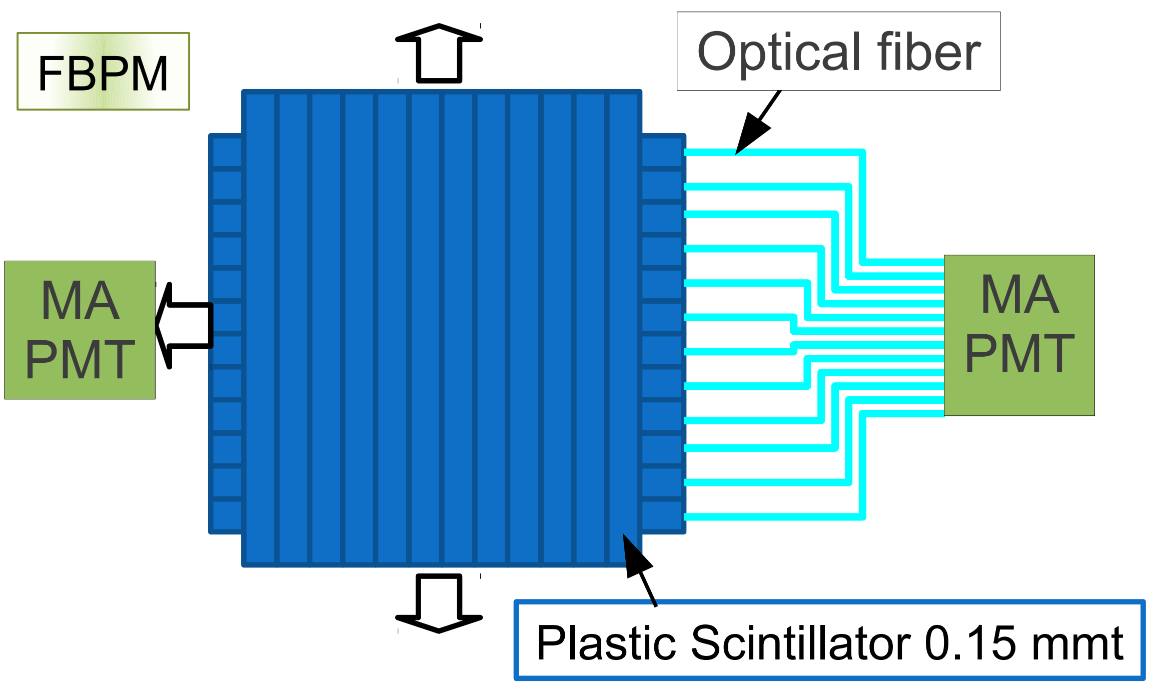
Energy deposit = 0.019 MeV
→ 190 photons

ビームプロファイルモニター (BPM)

FBPM (Front BPM)
- 2次元情報
- データ取得中も
  常時測定

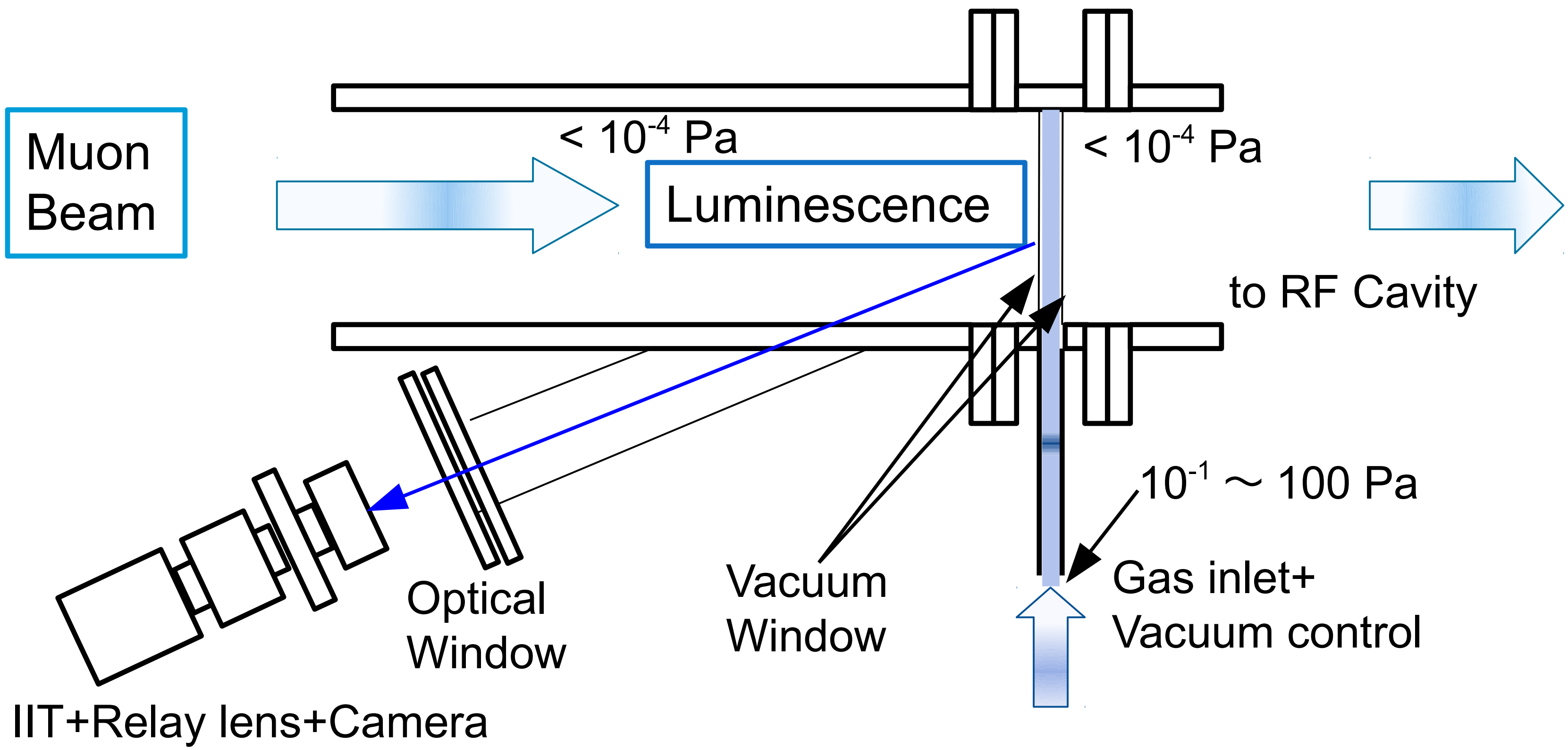


TBPM (Target BPM)
- 3次元情報
  (可動型カウンター)
- データ取得の間に
  定期的に計測



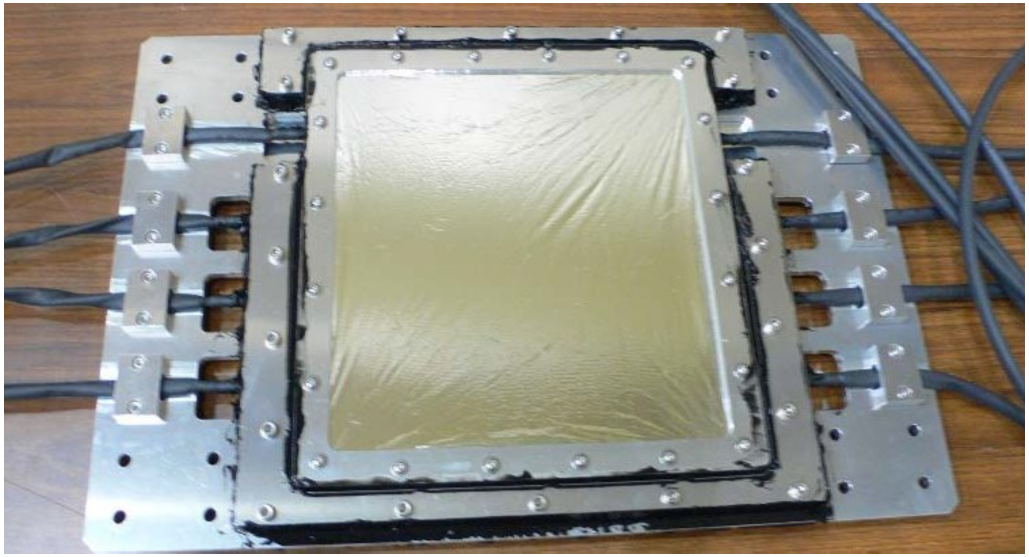
FBPM プロトタイプを制作中
- 低速ミュオンビームを
  止めない → 薄い
- 光量は十分か?
- ビームタイムに向けて準備中

FBPM (Front BPM) : Type2



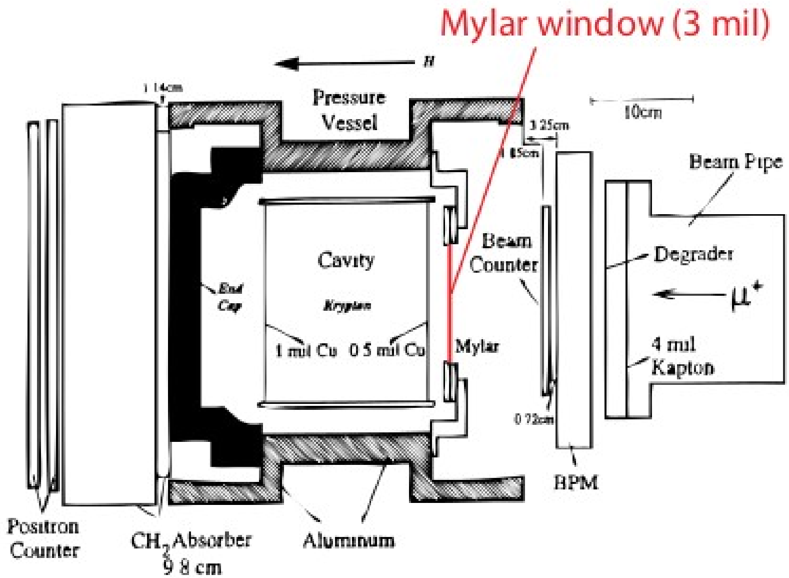
by 豊田さん

スクリーン
- シンチレーター ： 均一性
- ガス ： 十分な光量 (ガス圧を上げる。N2 or N2/Ar)



Kr Gas Purity

LAMPF

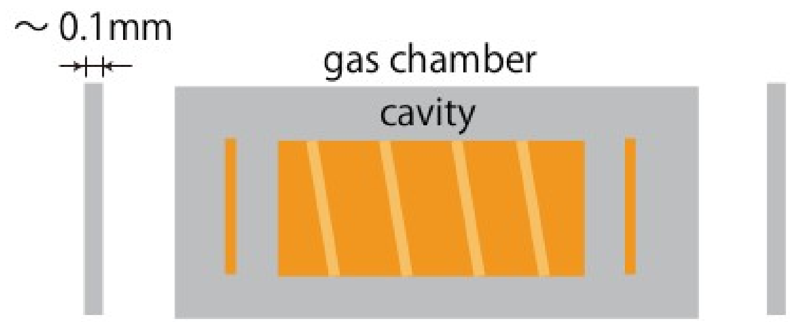


Mylar window

water vapor entering through the mylar window and break up of water molecutre by the high temperature furnace.

unable to bake

J-PARC

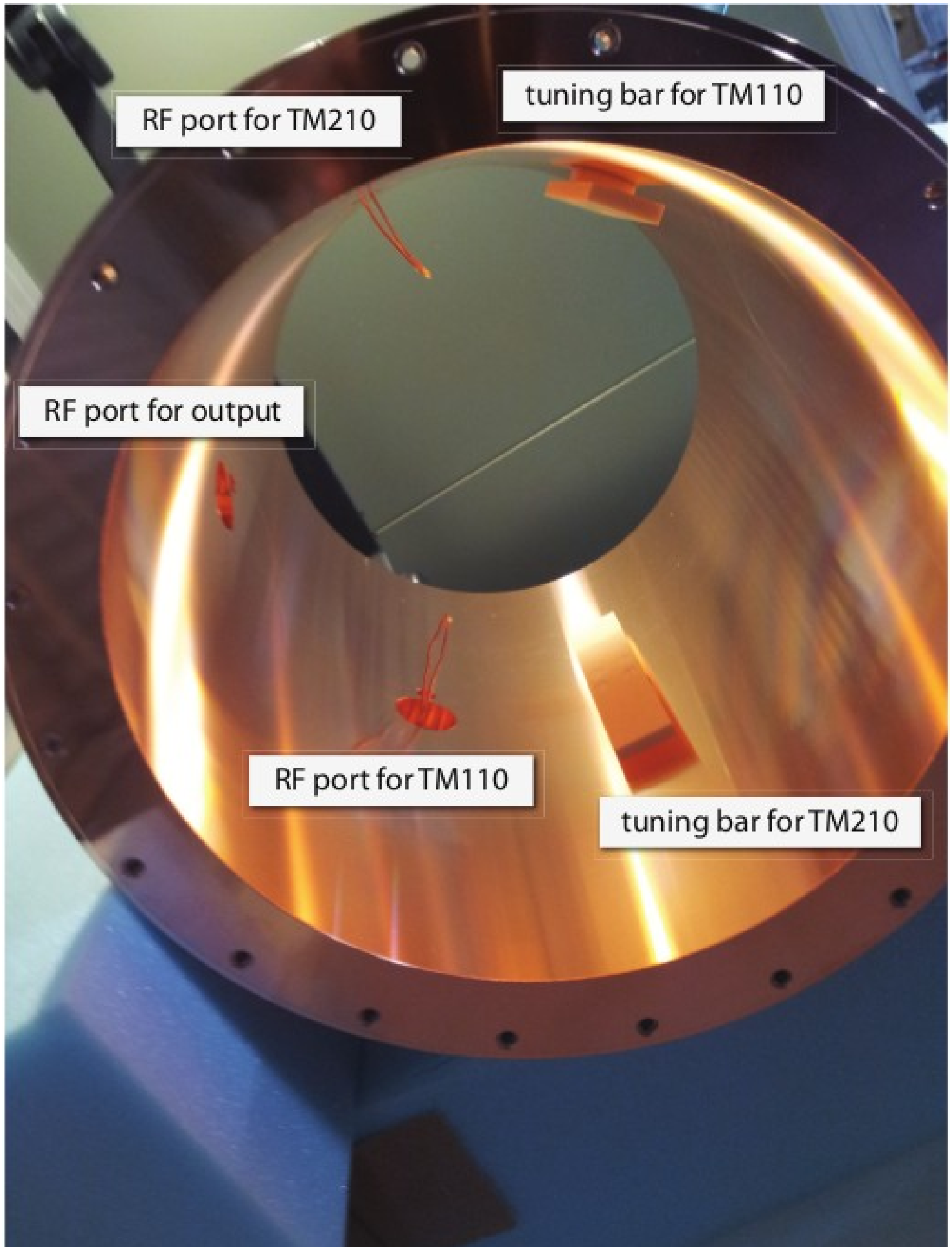


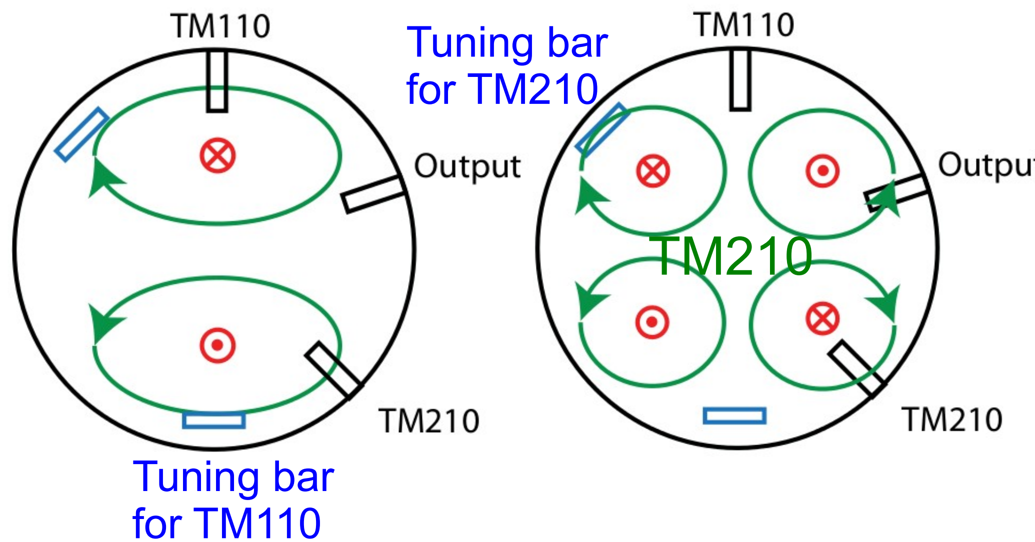
Alminium foil

hydrogen contamination may be diminished.

enable to bake.

RF キャビティのプロトタイプ製作





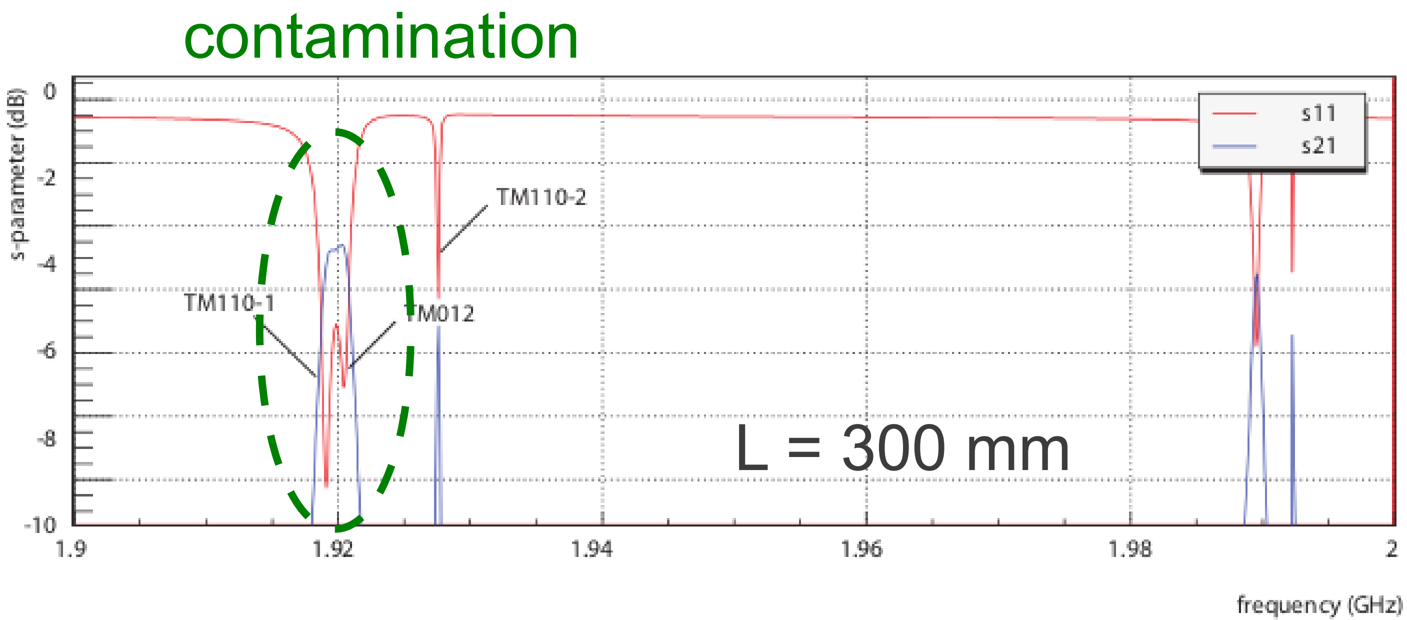
TM110 for ν_{12}

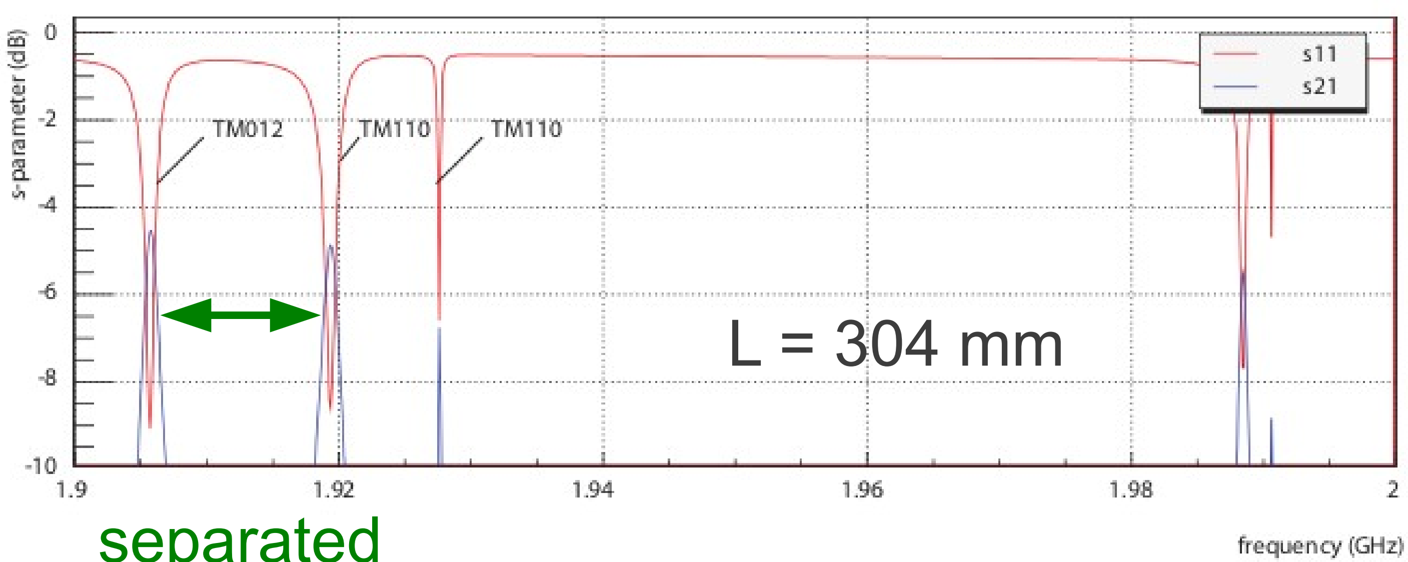
TM210 for ν_{34}

性能評価中
- 共鳴周波数
- Tuning bar

田中さんの修論

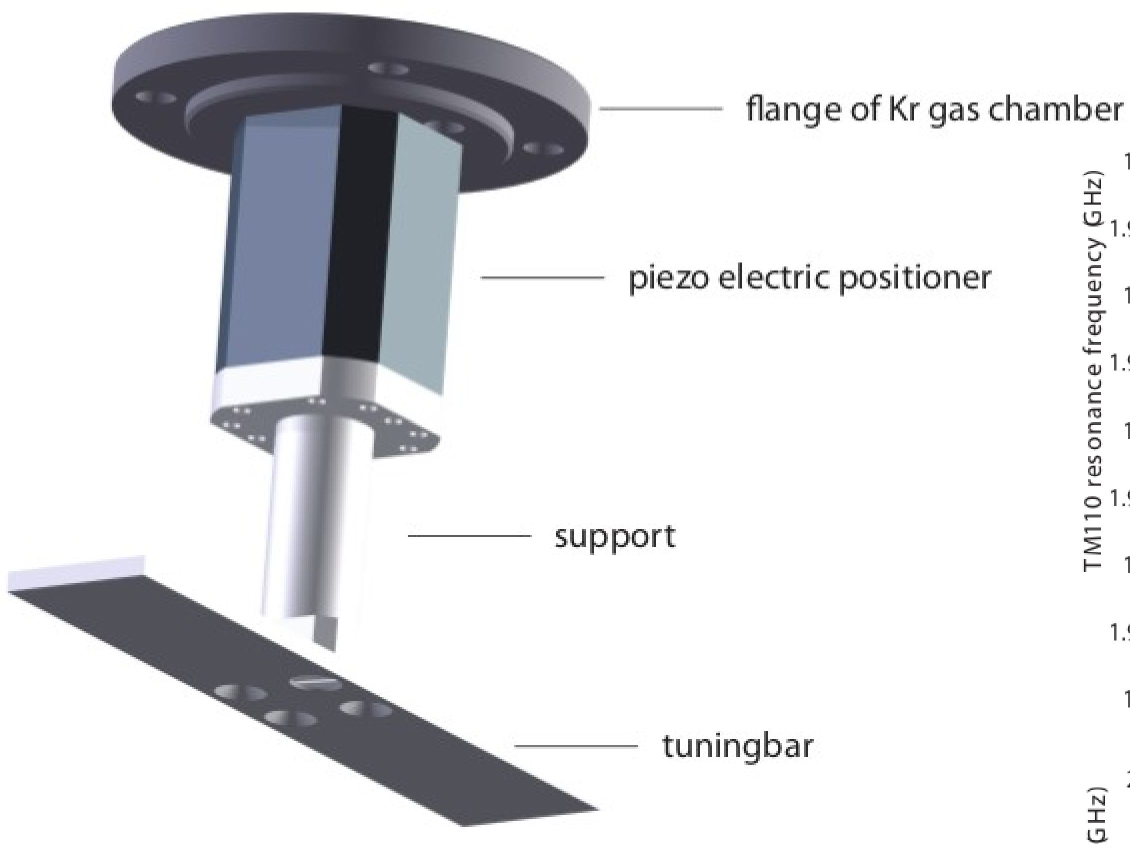
RF キャビティ長の最適化



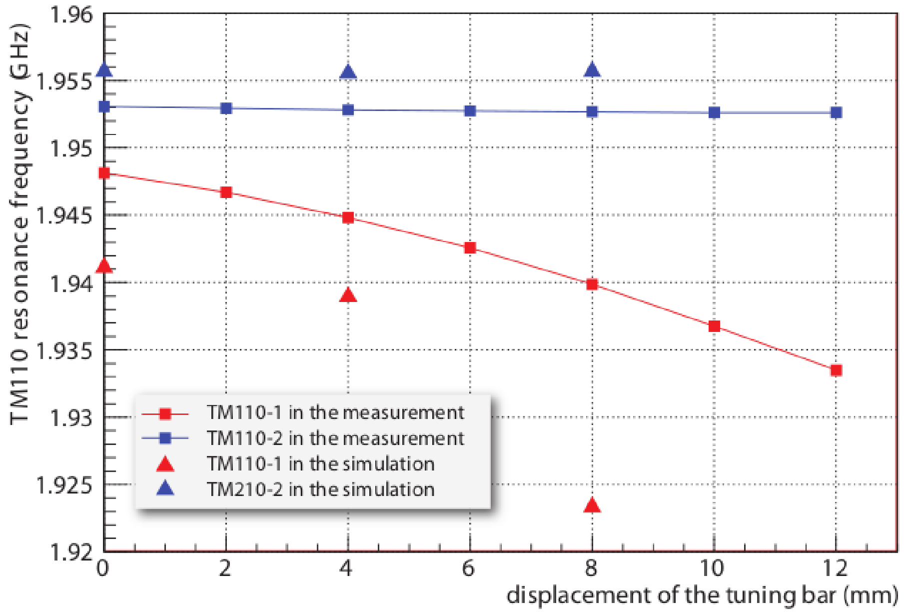


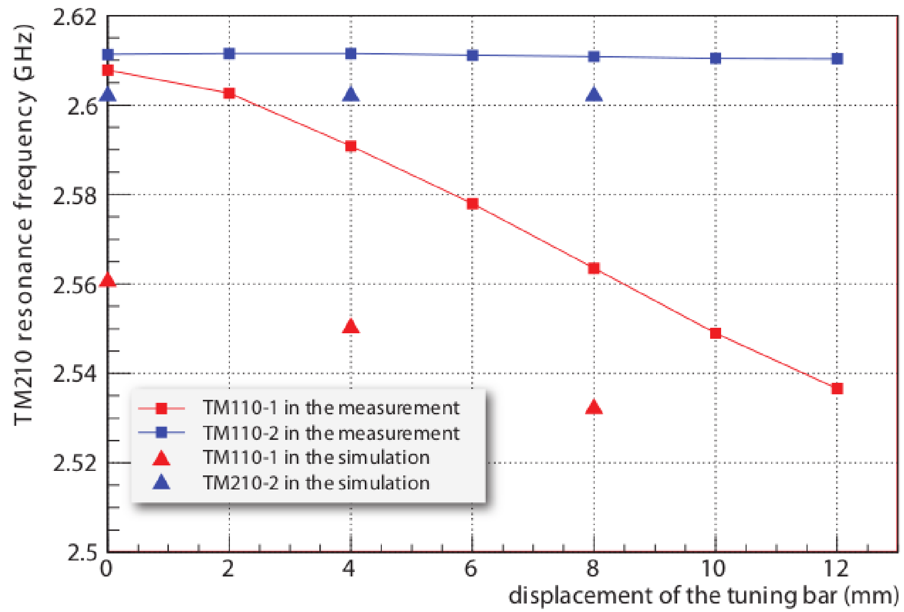
by 田中さん

Tuning Bar



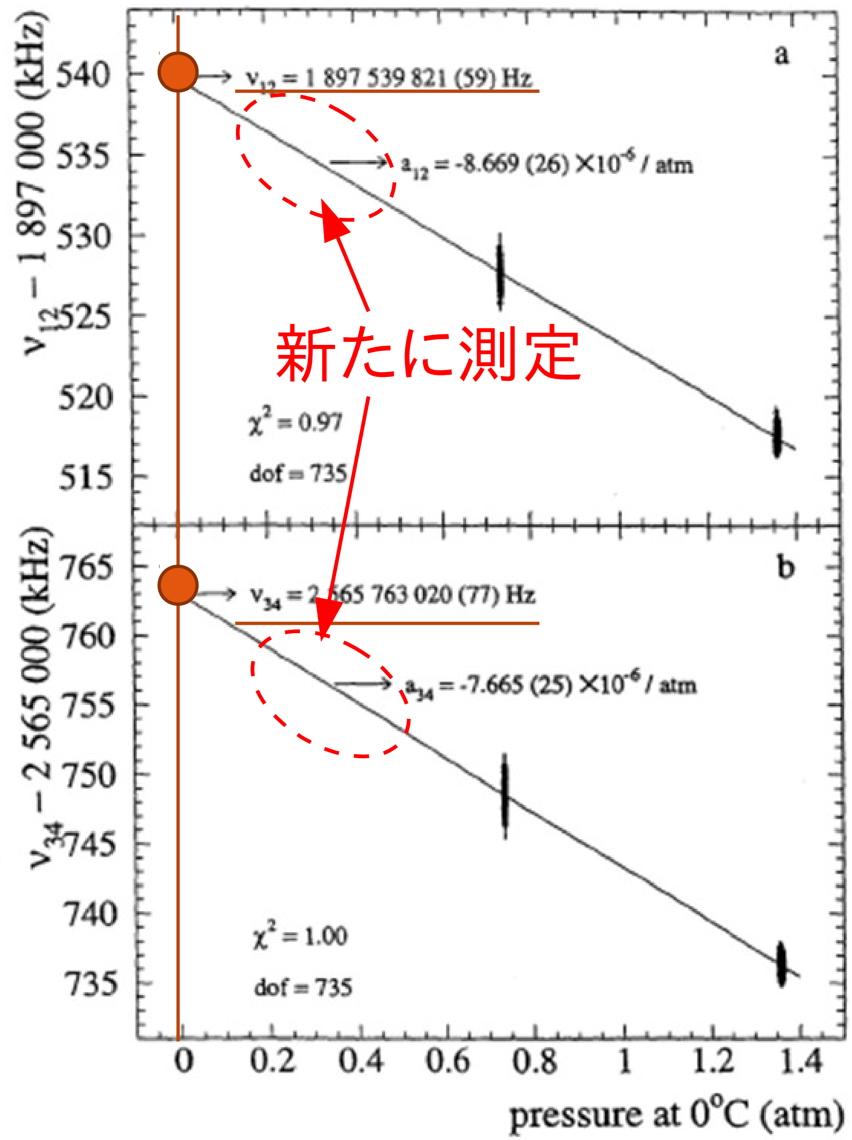
by 田中さん





Kr ガス圧（密度）による依存性

LAMPF exp.



先行実験の系統誤差の一つ

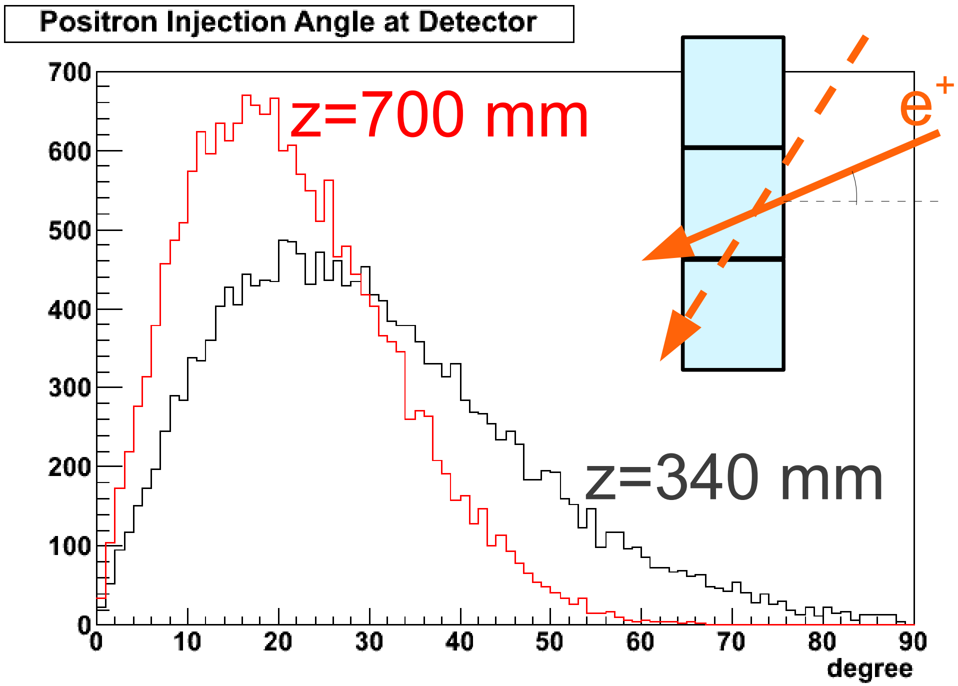
$\nu(P) = \nu(0)*(1+aP+bP^2)$

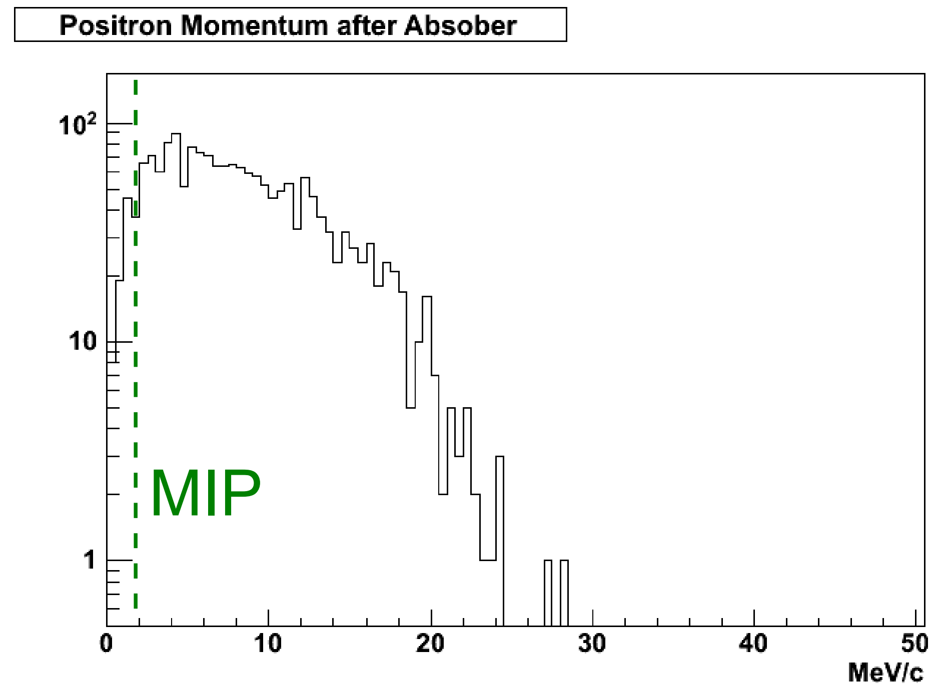
- 3点以上を測定
- より長い RF キャビティ
  (16 cm → 30 cm)

キーポイント

- 圧力をモニター
- 温度コントロール（密度変化）
- 水素などの混入

Positron Momentum and Injection Angle



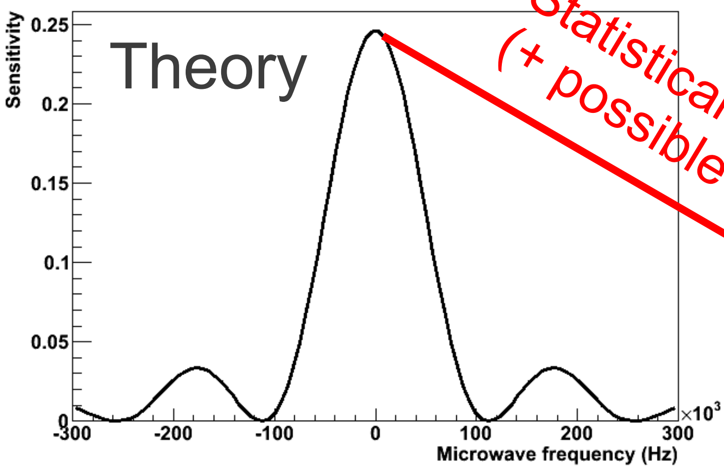


Detector thickness
- Thick → Penetrate multiple segment
- Thin → Small light yield.

Better at farther location.

Multiple Coulomb scattering cannot be ignored for a few MeV/c positrons.
→ Absorber location need to be optimized too.

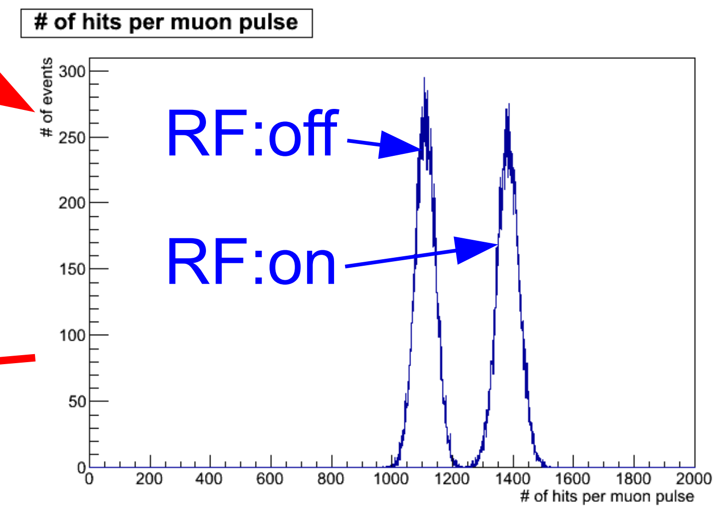
Precision and Sys. Error Estimation



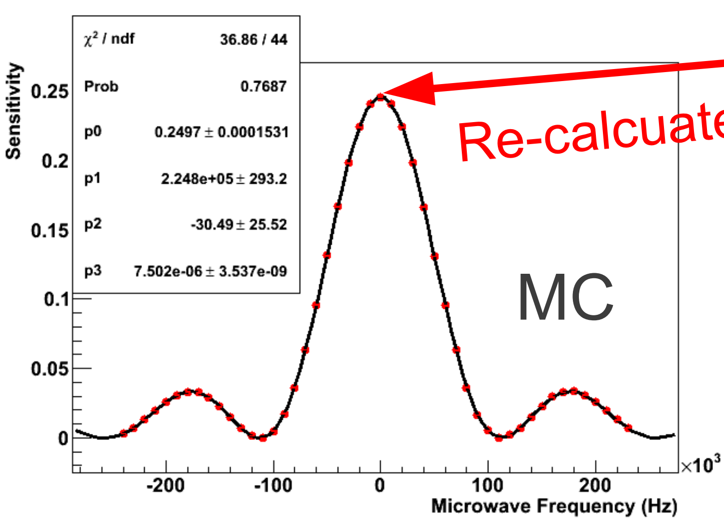
Statistical Fluctuation
(+ possible sys. error)

$$S = \frac{N_{on} - N_{off}}{N_{off}}$$

Event rate is estimated by GEANT



Re-calcuate Sensitivity



Statistics : 1 day (for one ν meas.)

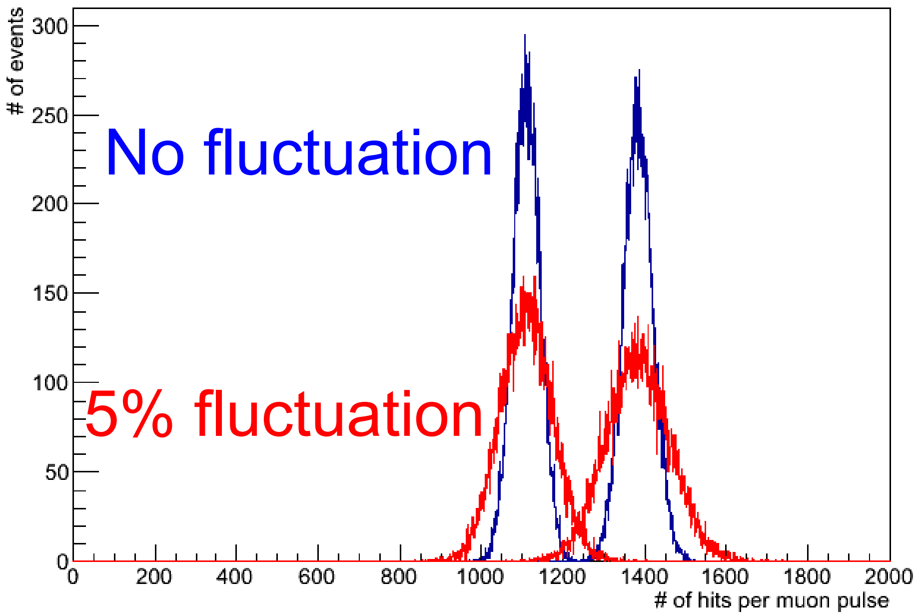
χ^2/NDF = 37 / 44

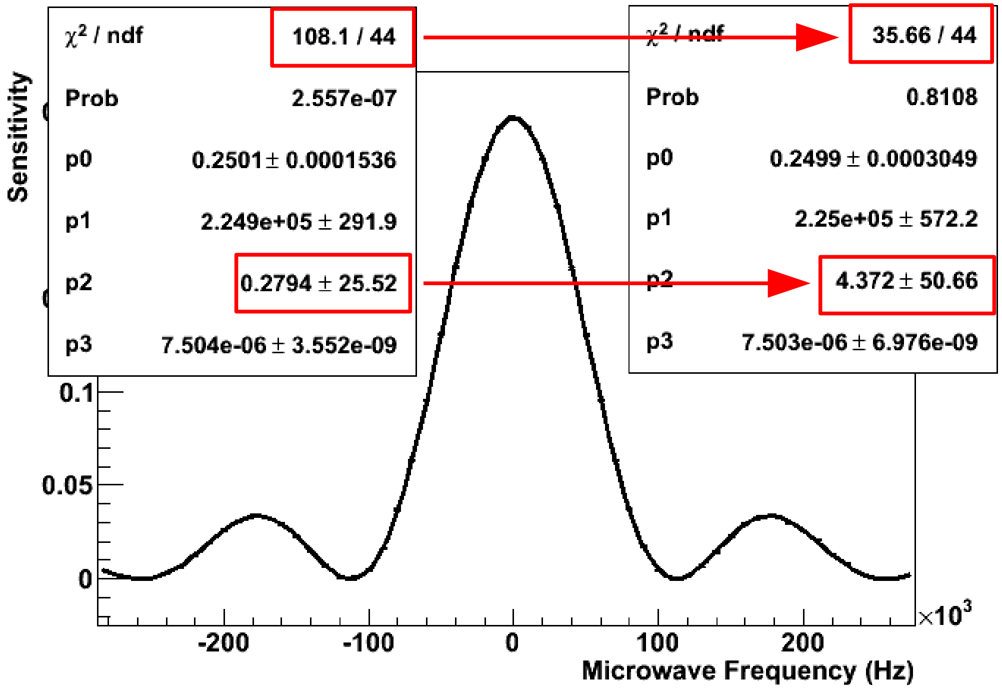
$\Delta\nu$ = 25.5 Hz (~40 Hz at LAMPF final)

Matching of data and theory certificates validity of experiment

Fluctuation of Beam Intensity (Frequency >> 25 Hz)

Fluctuation of Efficiency induces same effect.

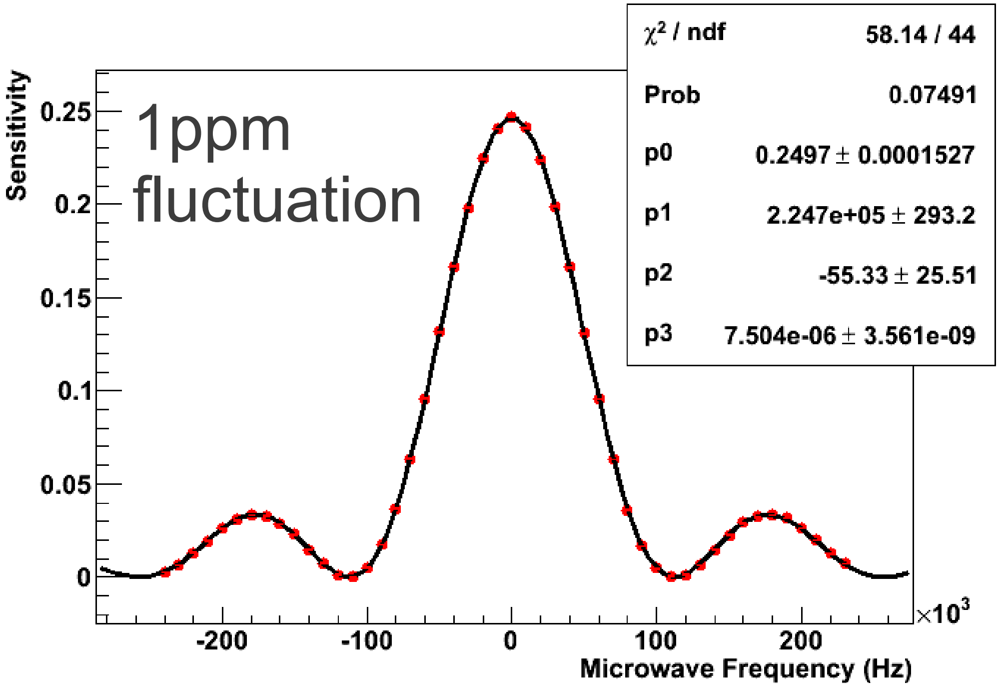


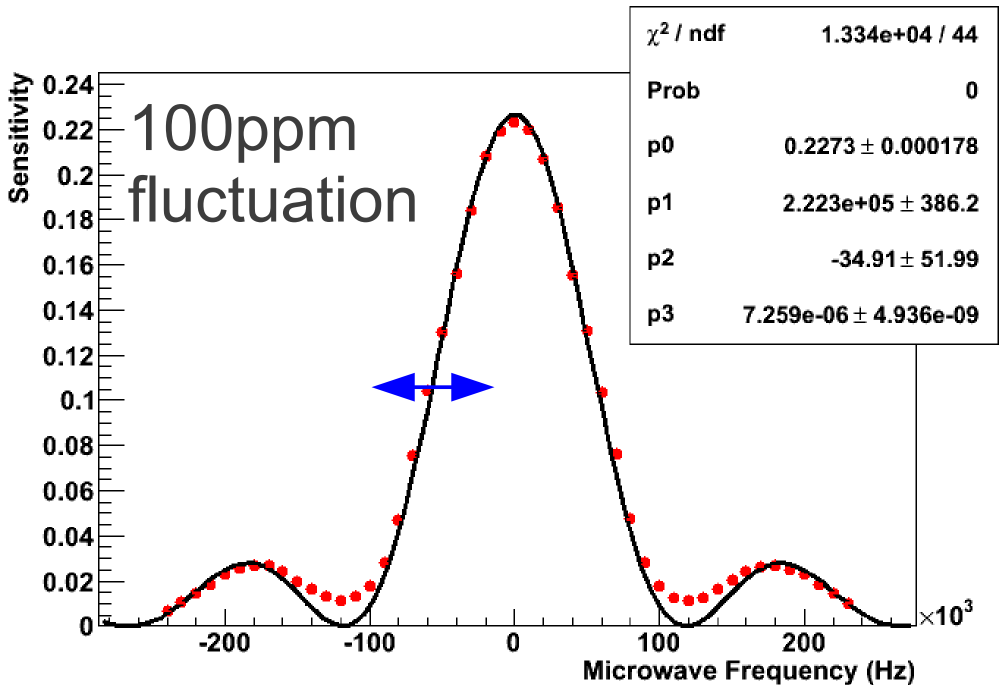


- (Random) Fluctuation can be evaluated from data.
- Increasing statistics, fluctuation is being suppressed.
- Monitoring and correction can suppress degradation.

Fluctuation of B-Field (Frequency >> 25 Hz)

RF value fluctuation induces same effect.

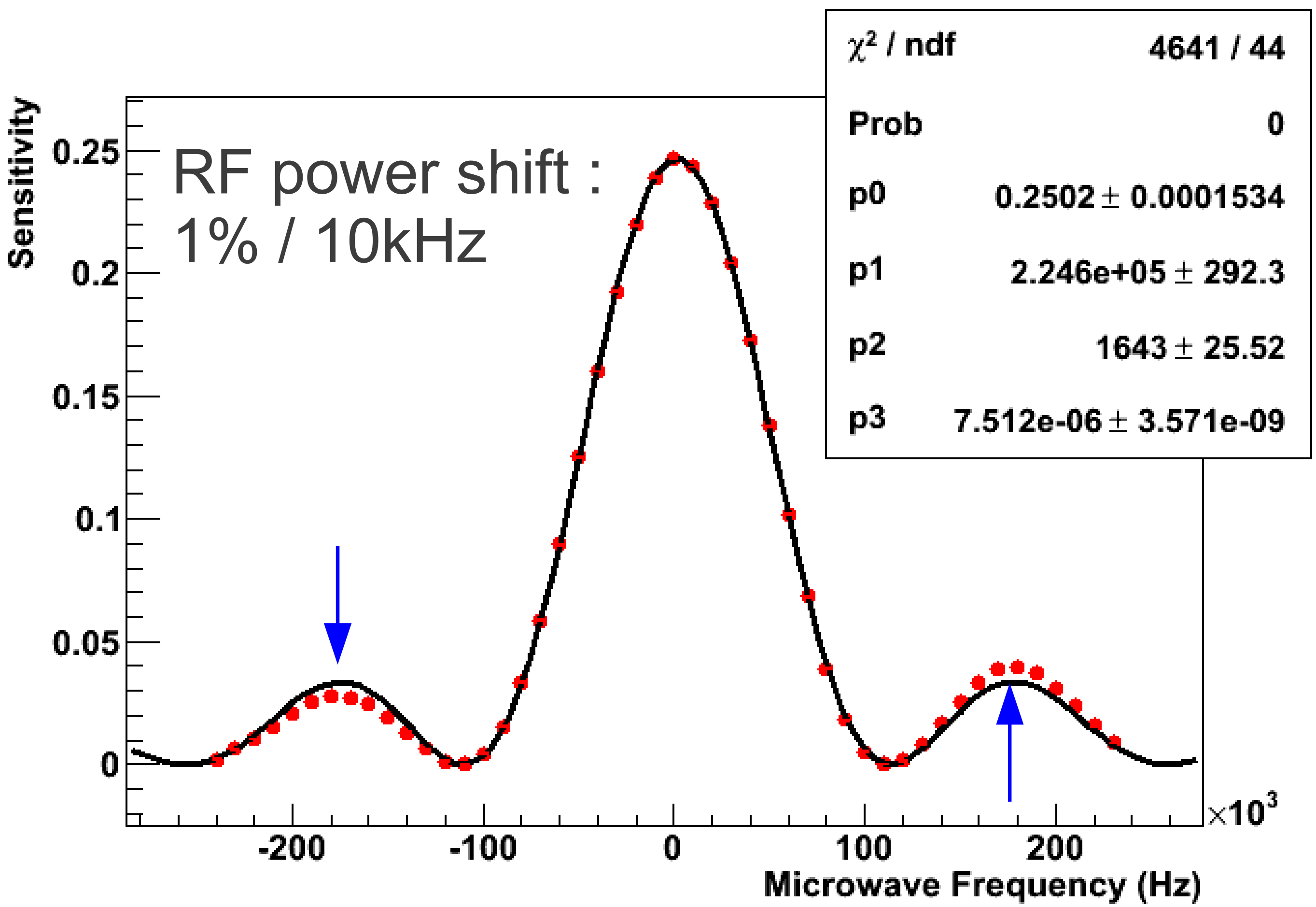




- Smearing effect is induced.
- It would be impossible to correct data.
  → Fluctuation must be convoluted in theoretical function

Time-dependent RF Power

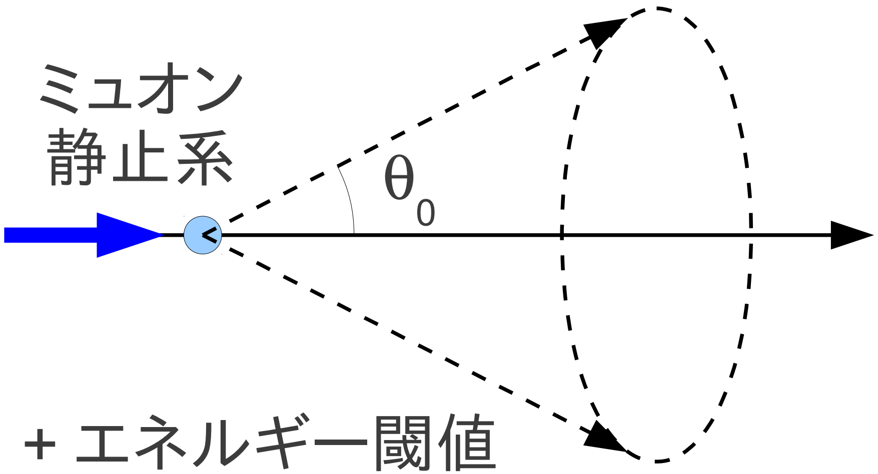
- Long period (<< 25Hz) fluctuation induces same effect
- RF/B-field-correlated fluctuation induces same effect



This effect must be monitored and corrected.

Including precision of correction, systematic uncertainty can be evaluated.

検出領域と測定感度（理論計算）



+ エネルギー閾値

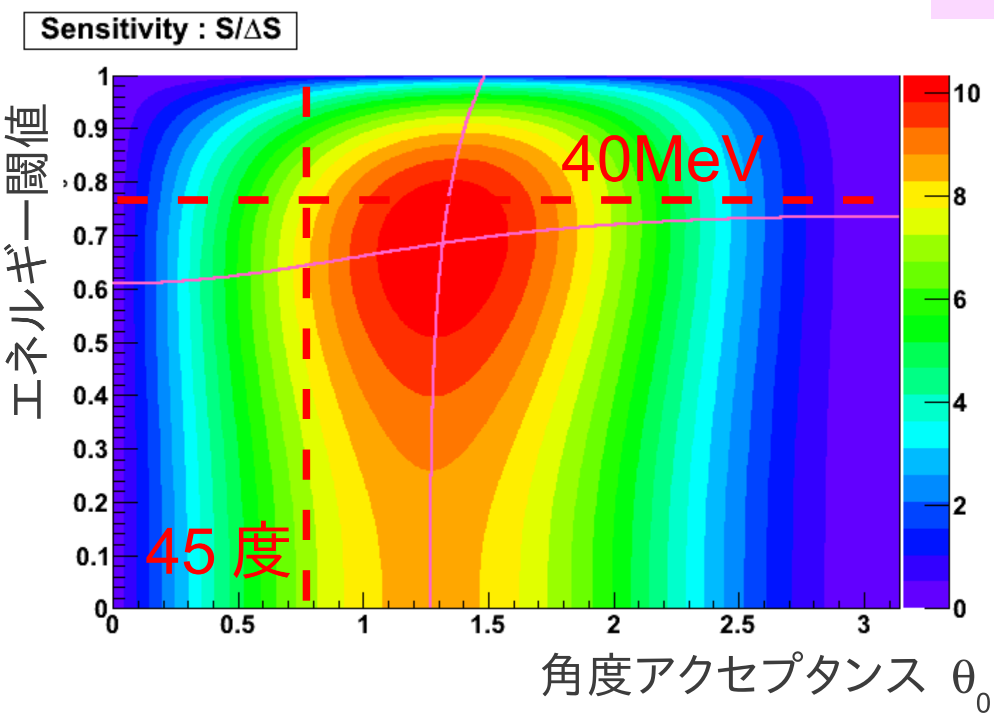
$$S = \frac{N_{on} - N_{off}}{N_{off}} \qquad Sensitivity\ :\ \frac{S}{\Delta S}$$

RF の ON/OFF
↓
ミュオンスピンのフリップ
（アシンメトリー）を検出

前後方 + 高運動量
に敏感

⇔

統計量

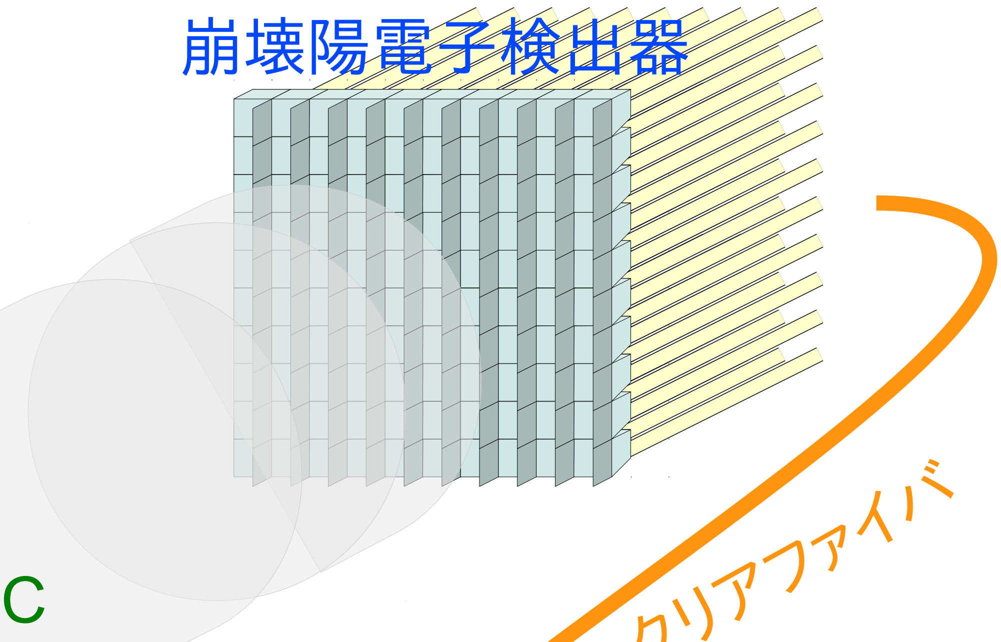


- エネルギー閾値　　：40 MeV
でも感度は保持

例えば
- 角度アクセプタンス ：45 度
  → 収量 ：5%

より現実的な Geant4
シミュレーションを構築中

崩壊陽電子検出器のデザイン



高イベントレート
→ シンチレーターアレイを
採用予定

セグメント：
2x2 mm^2 程度 (~10000ch)

信号: Amp → Discri → TDC
シンチレーターは複数レイヤーに
したい + 上流にも置きたい

読み出し ：
MPPC+ 多チャンネル読み出し回路

KEK 小嶋さんのグループ製作中の
読み出し回路の開発に参加

25aCL-8　村上さんの発表

先行実験からの改善点
期待される統計精度

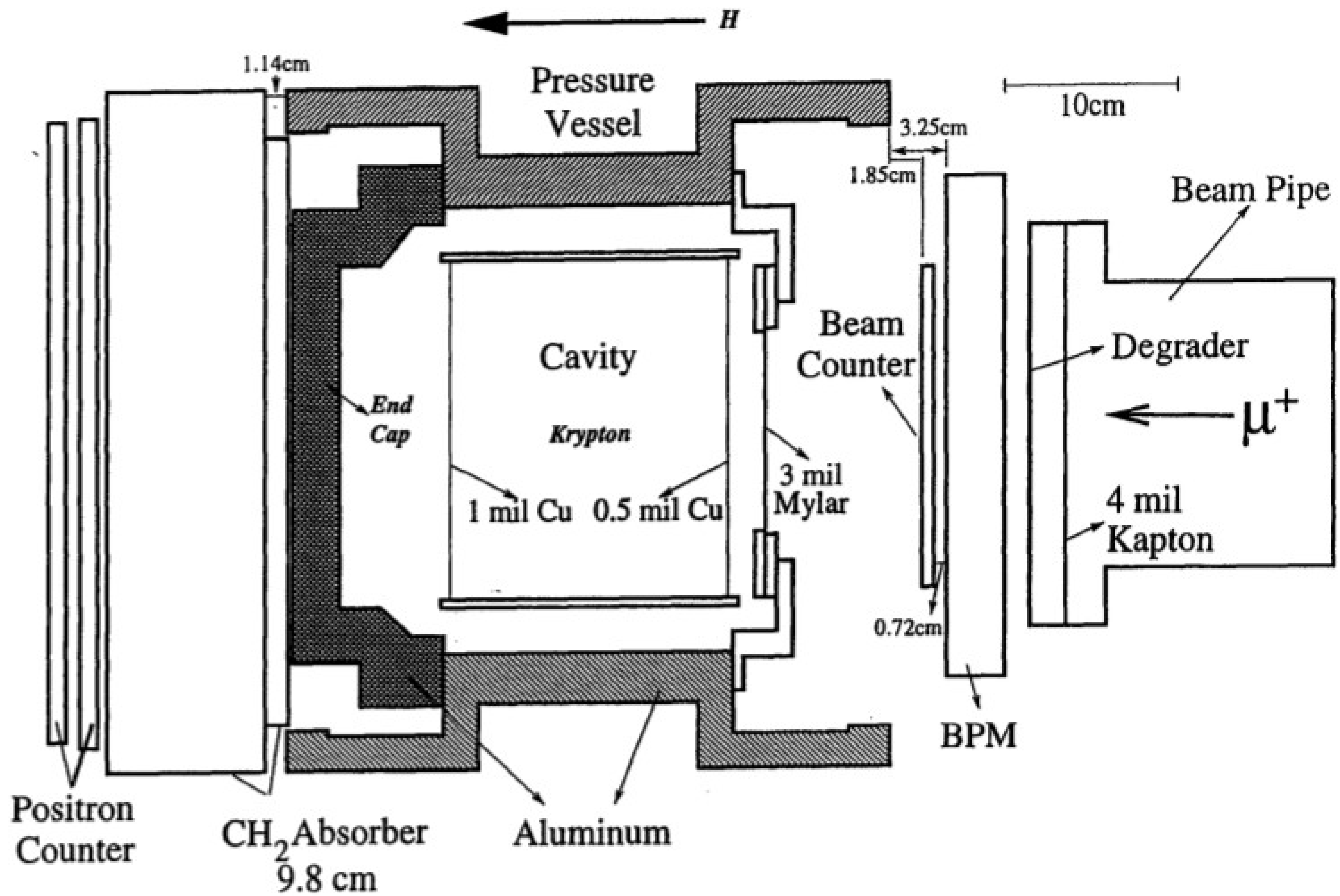
先行実験（LAMPF）: 10^{13} muons

J-PARC MUSE H-line : 2×10^{8} muons / sec
→ 10^{13} muons / 14 hours
先行実験と同等の統計量を 14 時間で達成

200 日のデータ取得 : $\delta(\mu_{\mu}/\mu_{p}) = 107 \rightarrow 5.7$ ppb
$\delta(\Delta E_{HFS}) = 10.9 \rightarrow 0.58$ ppb
最終的に統計誤差を 20 倍近く改善

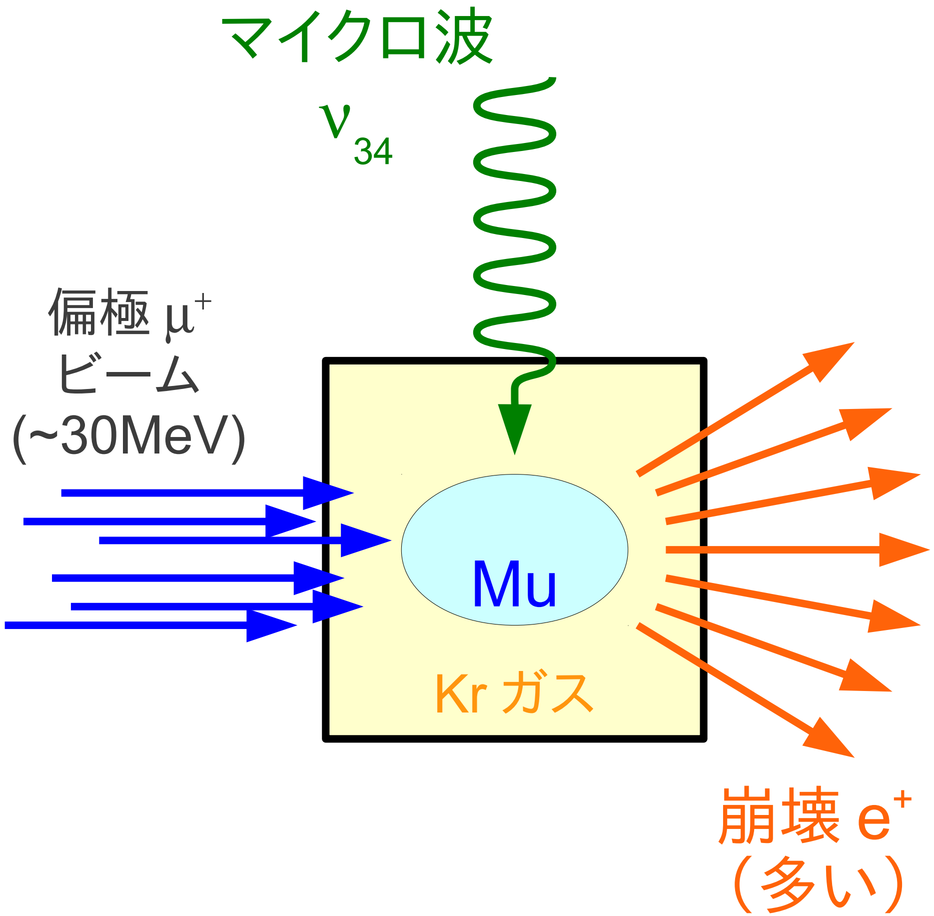
先行実験より系統誤差を抑える必要がある
高イベントレートに耐えられる測定装置の開発が必須

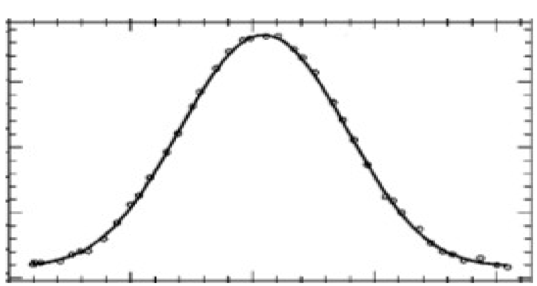
先行実験セットアップ



H
1.14cm
Pressure
Vessel
10cm
3.25cm
1.85cm
Beam Pipe
Cavity
Krypton
End
Cap
Beam
Counter
Degrader
μ+
3 mil
Mylar
1 mil Cu
0.5 mil Cu
4 mil
Kapton
0.72cm
BPM
Positron
Counter
CH2Absorber
9.8 cm
Aluminum

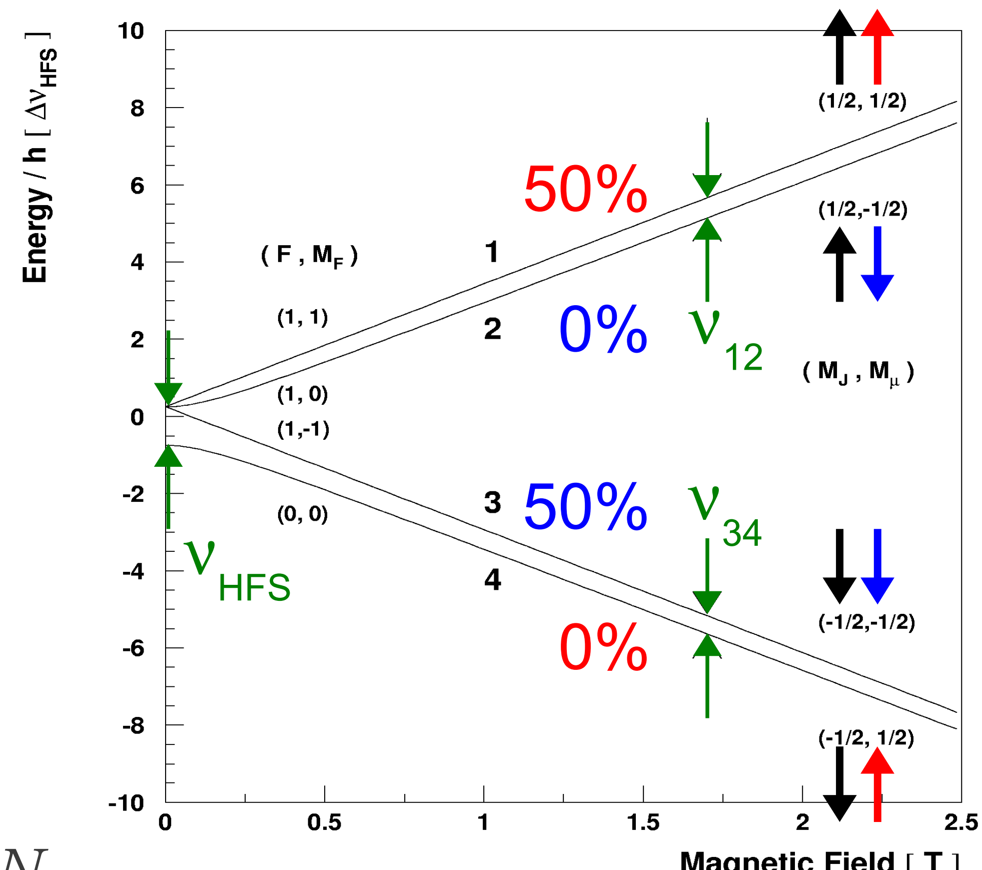
測定原理





ν_{34} 付近をスキャン

$$S = \frac{N_{on} - N_{off}}{N_{off}}$$



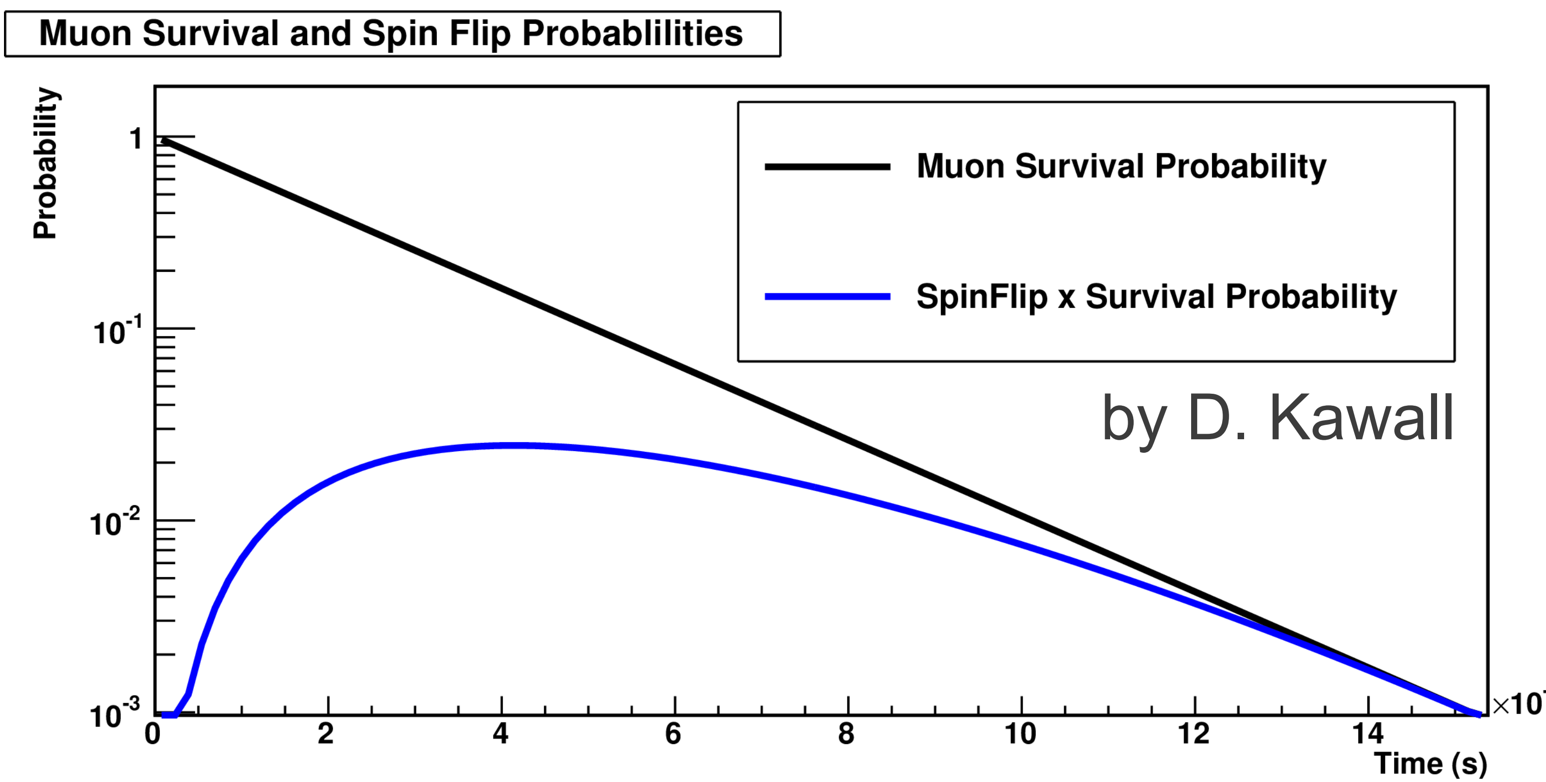
$$\nu_{HFS} = \nu_{12} + \nu_{34}$$

オールド·ミュオニウム法

- Spin flip probability : $P \sim \dfrac{\int_0^\infty \sin^2(bt)\, e^{-t/\tau}\, dt}{\int_0^\infty e^{-t/\tau}\, dt}$

b is related to Rabi frequency, b ~ 1 x 10^5 rad/sec

- Corresponds to microwave magnetic field of few Gauss



イベントレート

1. ビーム強度 : 2 x 10^8 muons / sec
   → 2 x 10^8 / 25 Hz ~ 8 x 10^6 muons / pulse

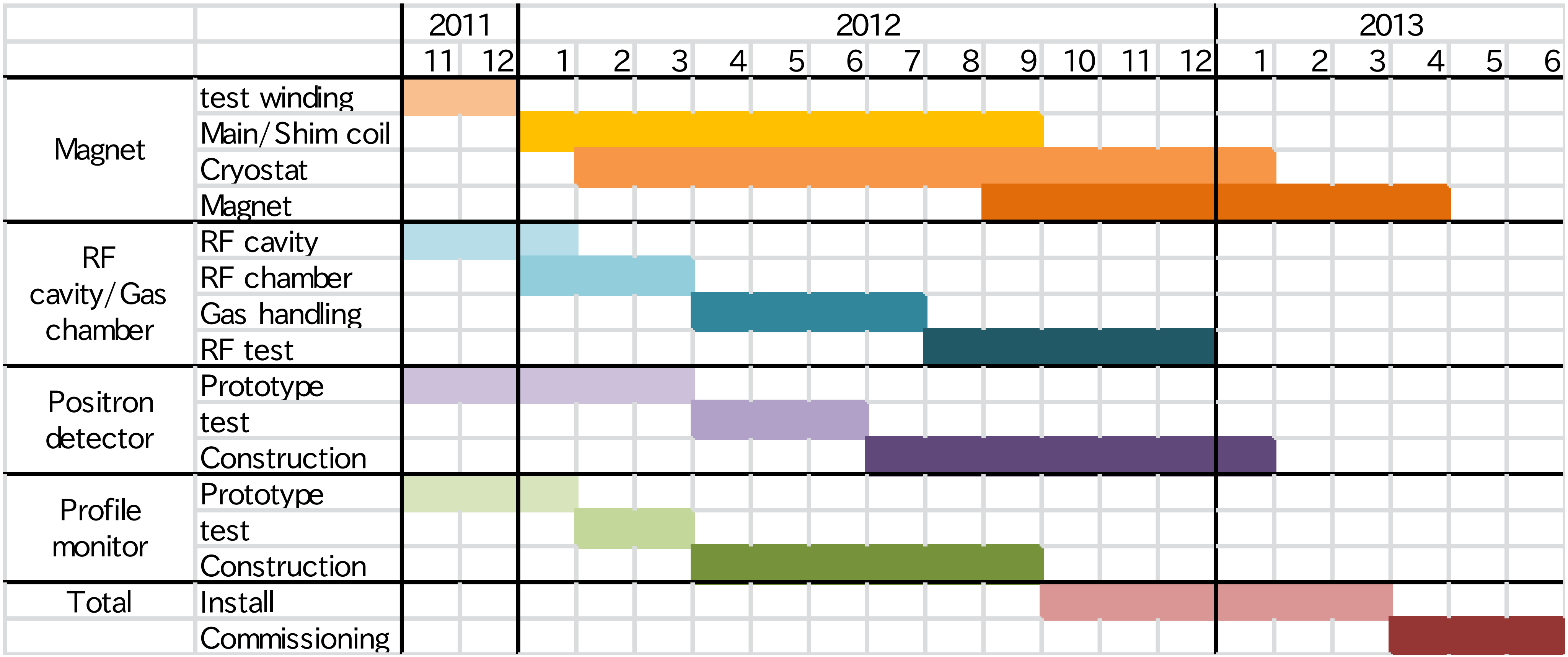
2. 検出領域 : ~5% (> 40MeV/c, 極角 45°)

3. 最初の 10 nsec の間に検出領域に入ってくる崩壊陽電子
   (8x10^6 / 2.2 usec) x 10 nsec x 5%
   ~ 1800 muons / acceptance / 10 nsec
   (~ 180 GHz muons / acceptance)

4. 検出器を 10000 セグメントに分割
   (検出領域が 200 x 200 mm^2 の場合、セグメント: 2 x 2 mm^2)
   1800/10000 = 0.18 muons / segment / 10 nsec
   (18 MHz muons / segment)

高速応答＋多チャンネル＋細分化
→ シンチレーター＋ MPPC ＋多チャンネル読み出し回路
の開発

開発スケジュール

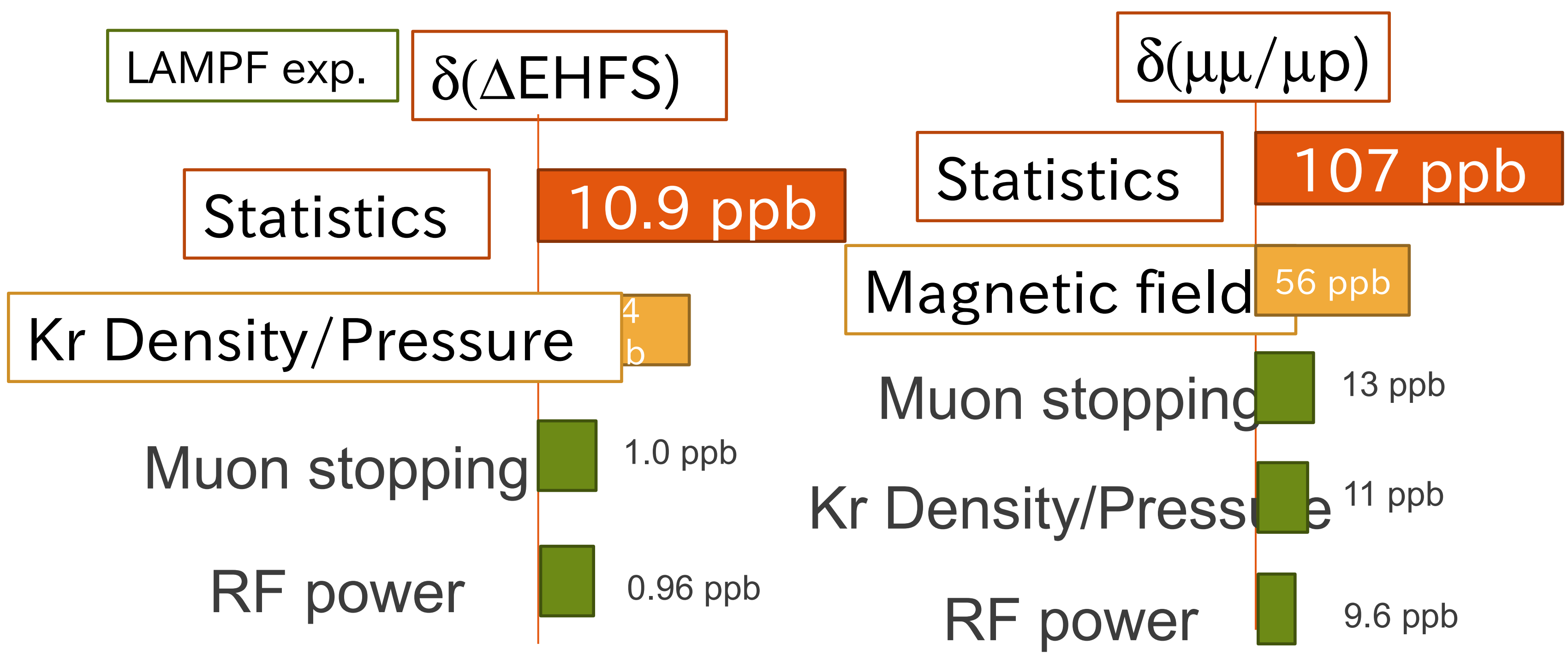


2013 年度の実験開始を目標

Goal

Our goal Reduce uncertainty to half or more

δ(ΔEHFS) 12 -> 6 ppb, δ(μμ/μp) 120 -> <60 ppb



MuHFS 測定による影響

$$a=\frac{g-2}{2}=\frac{R}{\lambda-R} \qquad \lambda=\frac{\mu_\mu}{\mu_p}, \qquad R=\frac{\omega}{\omega_p}$$

磁場測定プローブを MuHFS 、g-2 実験で共有することで
系統誤差を減らすことが可能

$$\delta a=\frac{\lambda R}{(\lambda-R)^2}\,\delta\frac{(\lambda\,\omega_p)}{\lambda\,\omega_p}$$

g-2 MuHFS

$$\frac{\Delta(\lambda\omega_p)}{\lambda\omega_p} = \left[\left(\frac{\Delta_u\omega_p}{\omega_p}\right)^2+\left(\frac{\omega_p^{HFS}}{\lambda}\frac{\partial\lambda}{\partial\omega_p^{HFS}}\right)^2\left(\frac{\Delta_u\omega_p^{HFS}}{\omega_p^{HFS}}\right)^2 + \left(\frac{\Delta_c\omega_p}{\omega_p}+\left(\frac{\omega_p^{HFS}}{\lambda}\frac{\partial\lambda}{\partial\omega_p^{HFS}}\right)\left(\frac{\Delta_c\omega_p^{HFS}}{\omega_p^{HFS}}\right)\right)^2\right]^{-\frac{1}{2}}$$

相関項