R&D of Muon Storage Ring PRISM-FFAG to Improve a Sensitivity of mu-e conv. Experiment Beyond BR~10^{-17}

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Nufact08, 10th International Workshop on Neutrino Factories, Superbeams and Betabeams (30 June - 05 July 2008), Valencia, Spain
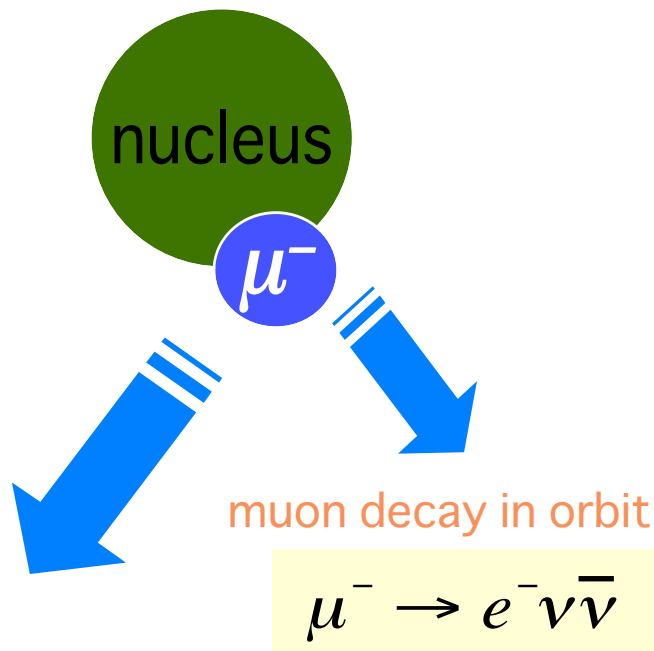
Outline

- Importance of a muon storage ring
  - BG in MECO-type
  - BG in PRISM-type
- PRISM and PRISM-FFAG
- R&D status of the PRISM-FFAG
- Summary

Muon - Electron Conversion

1s state in a muonic atom

muon decay in orbit

$$\mu^- \rightarrow e^- \nu \bar{\nu}$$

nuclear muon capture

$$\mu^- + (A,Z) \rightarrow \nu_\mu + (A, Z-1)$$

Neutrino-less muon nuclear capture (=μ-e conversion)

$$\mu^- + (A,Z) \rightarrow e^- + (A,Z)$$
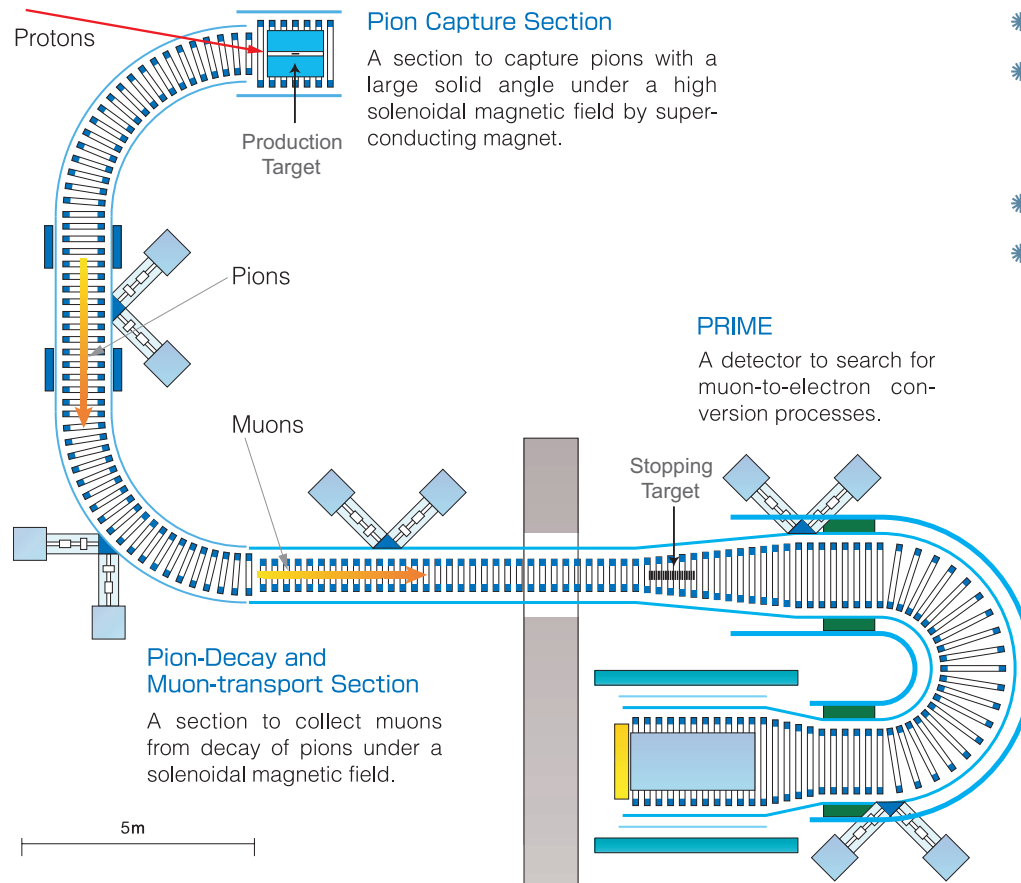
signal :

$$m_\mu - B_\mu \sim 105 MeV$$

$$B(\mu^- N \rightarrow e^- N) = \frac{\Gamma(\mu^- N \rightarrow e^- N)}{\Gamma(\mu^- N \rightarrow \nu N^{'})}$$

COMET (MECO-type): $B(\mu^- + Al \rightarrow e^- + Al) < 10^{-16}$

A proposal submitted to J-PARC in Dec. 2007.
Under discussion in J-PARC PAC.

Protons

Pion Capture Section

A section to capture pions with a large solid angle under a high solenoidal magnetic field by super-conducting magnet.

Production Target

Pions

Muons

PRIME

A detector to search for muon-to-electron conversion processes.

Stopping Target

Pion-Decay and Muon-transport Section

A section to collect muons from decay of pions under a solenoidal magnetic field.

5m

* Stop µ⁻ at the stopping targets.
* ID single electron from the target and measure its energy precisely.

* Suppress backgrounds strongly.
* The sensitivity would be limited by BG level.

PRISM

Background Sources

- **Intrinsic Physics Backgrounds**

  - Muon decay in orbit of a muonic atom,

  - Radiative muon capture on a nucleus,

- **Beam-related Prompt Backgrounds**

  - Radiative pion capture on a nucleus,

  - Pion decay in flight,

  - Muon decay in flight,

  - Antiproton interaction,

 - Scattering of electrons in a beam,

- **Non-Beam-related Backgrounds**

  - Cosmic-rays.

for MECO-type

measure E_e with a high accuracy $\sigma_{Ee}\sim350keV$ is dominated by dE distribution in the stopping target.

need extinction ratio $\sim 10^{-9}$
time window
collimators
foils on the beamline
kinematical cut

Beam Extinction Ratio

- In MECO-type experiments, signals of mu-e conv. events will be searched after waiting for while from the primary proton pulse hitting the production target to suppress prompt backgrounds,

- By doing this, the prompt background events produced by primary proton pulse will be suppressed down to a negligible level. The only remaining backgrounds are the prompt background events produced by off-timing protons coming between main pulses.
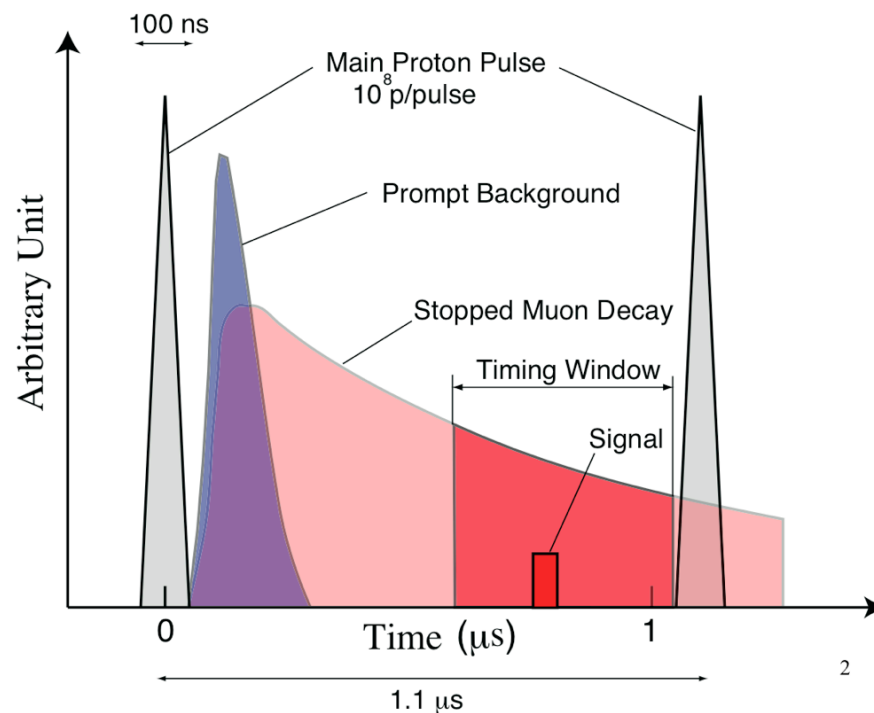
High extinction ratio is dispensable for MECO-type experiments.

Pion Radiative Capture

- Expected number of background events coming from the radiative pion capture :

$$N_{\mathrm{RPC}} \quad = \quad N_p \cdot R_{\mathrm{extinction}} \cdot R_{\pi/p} \cdot P_{\pi-\mathrm{survive}} \cdot P_{\mathrm{RPC}} \cdot P_\gamma \cdot R_{\mathrm{acceptance}}$$

for COMET

N_p	a number of protons	16×10^{20} for BR10^{-16}
$R_{\mathrm{extinction}}$	the extinction ratio	10^{-9} for N$_{\mathrm{RPC}}$ = 0.1
$R_{\pi/p}$	a number of pions transport through the curved muon beam line per one proton hitting the production target	1×10^{-5}
$P_{\pi-\mathrm{survive}}$	a survival probability in the decay solenoid that follows the curved muon beam line	0.1 for L=7m
P_{RPC}	a probability of a gamma emission from a pion capture	0.02
P_γ	a probability of photon conversion in an Al target with a conversion electron in a signal region from 104.0MeV to 105.2MeV	3.5×10^{-5}
$R_{\mathrm{acceptance}}$	an signal acceptance without a timing-window factor	0.1

Expected Background in MECO Experiment

We expect ~ 0.45 background events for 10^7 s running with sensitivity of ~ 5 signal events for $R_{\mu e} = 10^{-16}$

Source	Events	Comments
μ decay in orbit	0.25	S/N = 20 for $R_{\mu e} = 10^{-16}$
Tracking errors	< 0.006	
Radiative μ decay	< 0.005	
Beam e^-	< 0.04	
μ decay in flight	< 0.03	Without scattering in stopping target
μ decay in flight	0.04	With scattering in stopping target
π decay in flight	< 0.001	
Radiative π capture	0.07	From out of time protons
Radiative π capture	0.001	From late arriving pions
Anti-proton induced	0.007	Mostly from π^-
Cosmic ray induced	0.004	Assuming 10^{-4} CR veto inefficiency
Total Background	0.45	Assuming 10^{-9} inter-bunch extinction

Expected Backgrounds in COMET

Table 6.6: Summary of the background rates at a sensitivity of 10^{-16}. Backgrounds identified with an asterisk are proportional to the beam extinction, and the rates in the table assume 10^{-9} beam extinction.

Background	Events	Comments
Muon decay in orbit	0.05	230 keV (sigma) assumed
Pattern recognition errors	<0.001	
Radiative muon capture	<0.001	
Muon capture with neutron emission	<0.001	
Muon capture with charged particle emission	<0.001	
Radiative pion capture*	0.12	prompt pions
Radiative pion capture	0.002	due to late arriving pions
Muon decay in flight*	< 0.02	
Pion decay in flight*	< 0.001	
Beam electrons*	0.08	
Neutron induced*	0.024	for high energy neutrons
Antiproton induced	0.007	for 8 GeV protons
Cosmic rays induced	0.2	with 10^{-4} veto inefficiency
Total	0.50	

$BR \sim 10^{-17} \rightarrow N_{BG} \sim 5$

Toward Higher Sensitivity Beyond BR~10^{-17}

- We can not go to the higher sensitivity than BR~10^{-17} with the current MECO-type setup, because the backgrounds limit the sensitivity.

- We need new ideas to improve the sensitivity. PRISM provides a solution using a muon storage ring.

- *Functions of Muon Storage Ring*

    - make momentum spread narrower,

    - eliminate unwanted particle

        - long flight length

        - charge selection

        - momentum selection

... To Make Narrow Beam Energy Spread

- A technique of phase rotation is adopted.

- The phase rotation is to decelerate fast beam particles and accelerate slow beam particles.

- To identify energy of beam particles, a time of flight (TOF) from the proton bunch is used.
  - Fast particle comes earlier and slow particle comes late.

- Proton beam pulse should be narrow (< 10 nsec).

- Phase rotation is a well-established technique, but how to apply a tertiary beam like muons (broad emittance) ?
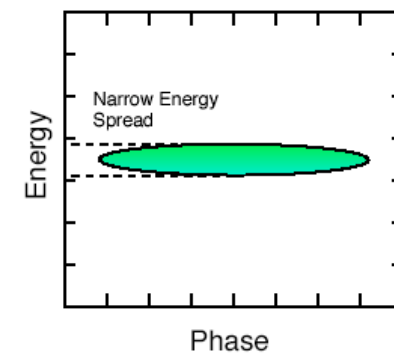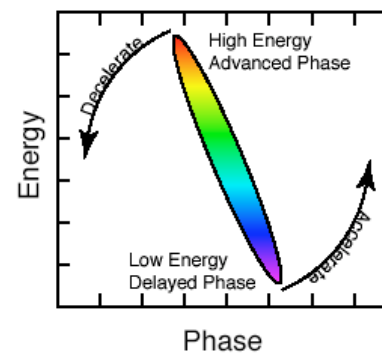
Background Sources

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  - Antiproton interaction,

  - Scattering of electrons in a beam,

- **Non-Beam-related Backgrounds**

  - Cosmic-rays.

for PRISM-type

measure E_e with much higher accuracy
$\sigma_{Ee}\sim$250keV is dominated by intrinsic resolution of the tracker.

mono-energetic muon beam enables to use thiner targets.

long flight length in the ring

Pion Radiative Capture for PRISM

- Expected number of background events coming from the radiative pion capture :

$$N_{\mathrm{RPC}} = N_p \cdot R_{\mathrm{extinction}} \cdot R_{\pi/p} \cdot P_{\pi-\mathrm{survive}} \cdot P_{\mathrm{RPC}} \cdot P_\gamma \cdot R_{\mathrm{acceptance}}$$

for PRISM

N_p	a number of protons	5×10^{21} for BR10^{-18}
$R_{\mathrm{extinction}}$	the extinction ratio	-
$R_{\pi/p}$	a number of pions transport through the curved muon beam line per one proton hitting the production target	-
$P_{\pi-\mathrm{survive}}$	a survival probability in the decay solenoid that follows the curved muon beam line	1.8×10^{-27} for L=39x6m
P_{RPC}	a probability of a gamma emission from a pion capture	-
P_γ	a probability of photon conversion in an Al target with a conversion electron in a signal region from 104.0MeV to 105.2MeV	-
$R_{\mathrm{acceptance}}$	an signal acceptance without a timing-window factor	-

No pion contamination in the muon beam.
Enable to open the detection window from t=0.

Japanese staging plan of mu-e conversion

1st Stage : COMET
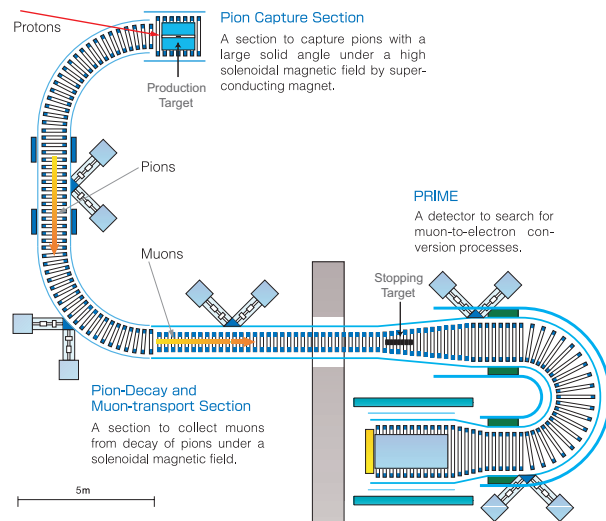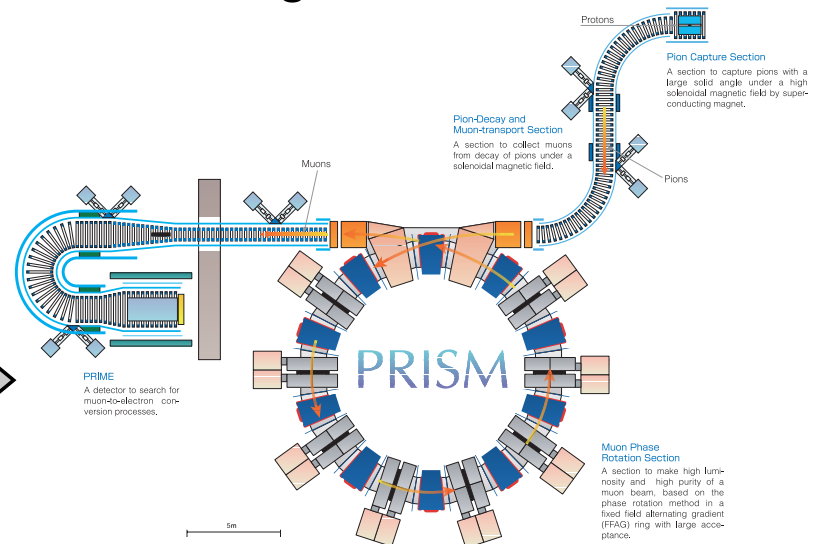
$$B(\mu^- + Al \rightarrow e^- + Al) < 10^{-16}$$

- without a muon storage ring.
- with a slowly-extracted pulsed proton beam.
- doable at the J-PARC NP Hall.
- regarded as the first phase / MECO type
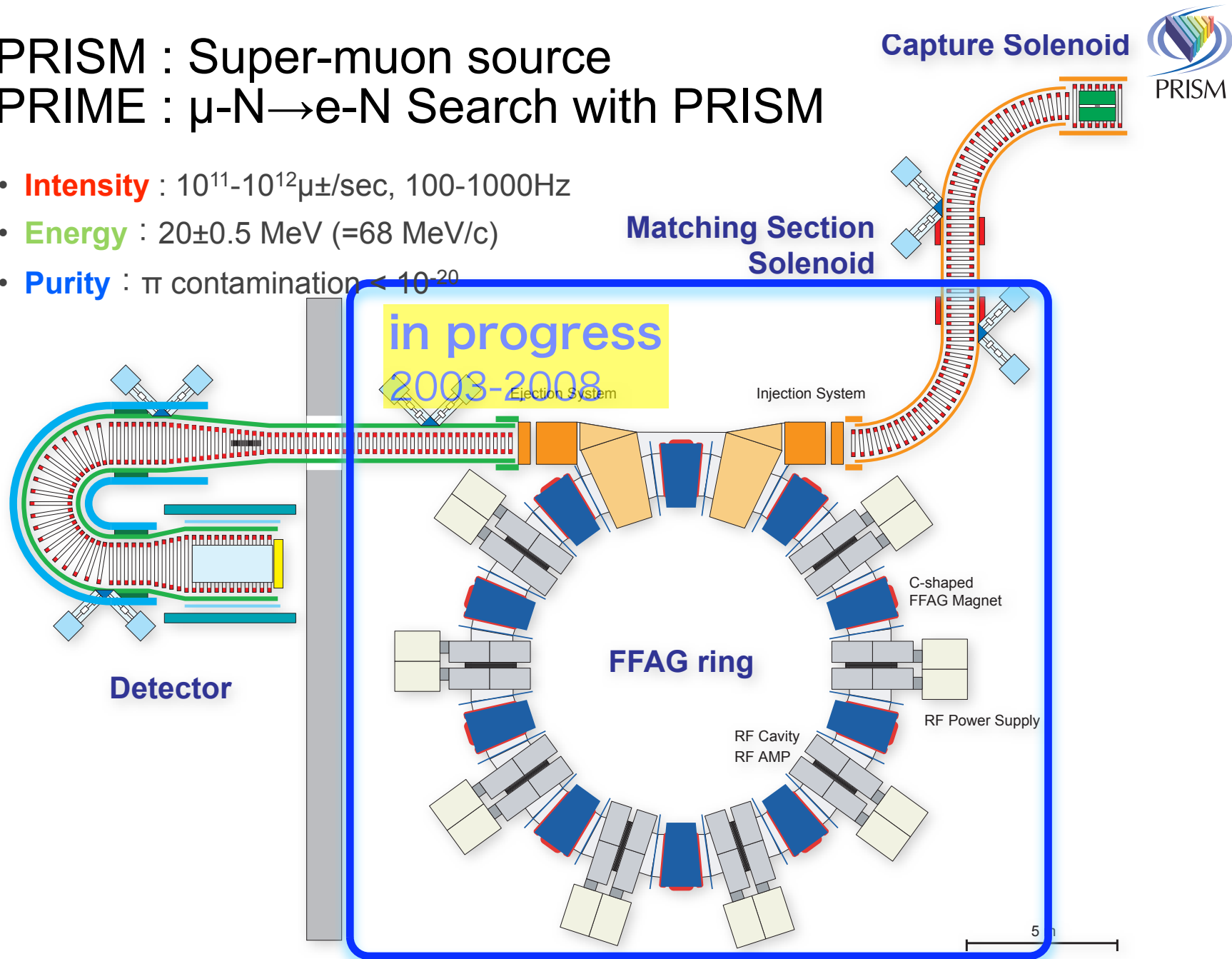- Early realization

2nd Stage : PRISM/PRIME

$$B(\mu^- + Ti \rightarrow e^- + Ti) < 10^{-18}$$

- with a muon storage ring.
- with a fast-extracted pulsed proton beam.
- need a new beamline and experimental hall.
- regarded as the second phase.
- Ultimate search

PRISM : Super-muon source
PRIME : μ-N→e-N Search with PRISM

- **Intensity** : 10^{11}-10^{12}μ±/sec, 100-1000Hz
- **Energy** ：20±0.5 MeV (=68 MeV/c)
- **Purity** ：π contamination < 10^{-20}

in progress
2003-2008

Capture Solenoid

Matching Section Solenoid

Ejection System

Injection System

Detector

FFAG ring

C-shaped FFAG Magnet

RF Power Supply

RF Cavity
RF AMP

5 m

PRISM-FFAG

- **Functions**
    - makes monoenergetic muons ：**phase rotation**
    - reduces π in the beam ：**long flight length**
- **Requirements & R&D items**
    - **Large acceptance FFAG-ring**
        - Horizontal ：38000 π mm mrad
        - Vertical ：5700 π mm mrad
        - Momentum ： 68MeV/c +- 20%
    - **High field grad. RF system** **(170kV/m = 2MV/turn)**
        - Quick phase rotation
            - ~1.5μs

Goal for this budget 2003-2007 (extended to 2008):
Build a full-size FFAG-ring and
test and establish the phase rotation to make
monoenergetic beams.

Status and Schedule : 2003-2008

- FFAG Design ： **completed**

- Development of FFAG Magnets：

  - FFAG Magnet x 6 ： **completed**

  - Field measurement for the three ： **completed**

- Beam dynamics study w/ one magnet ： **completed (Ph.D of Y.Kuriyama)**

- Development of RF：

  - 170kV/m sinusoidal @ 5MHz : **completed**
  - 100kV/m sinusoidal @ 2MHz : **completed**
  - Sawtooth-RF : **in progress**

- Construction of 6cell FFAG-ring ： **completed**

- Commissioning : **in progress (orbit and tune study)**

- Demo. of phase rotation ： **July 2008 ~**

PRISM-FFAG

Phase Rotator

- N=10
- k=4.6
- F/D(BL)=6.2

- r0=6.5m for 68MeV/c
- half gap = 17cm
- mag. size 110cm @ F center
- Radial sector DFD Triplet
- $\theta_F/2$=2.2deg
- θ_D=1.1deg
- Max. field
- F : 0.4T
- D : 0.065T
- tune
- h : 2.73
- v : 1.58

C型FFAG電磁石

取り出し用
キッカー電磁石

高周波空洞
高周波増幅器

入射用
キッカー電磁石

高周波電源

5m
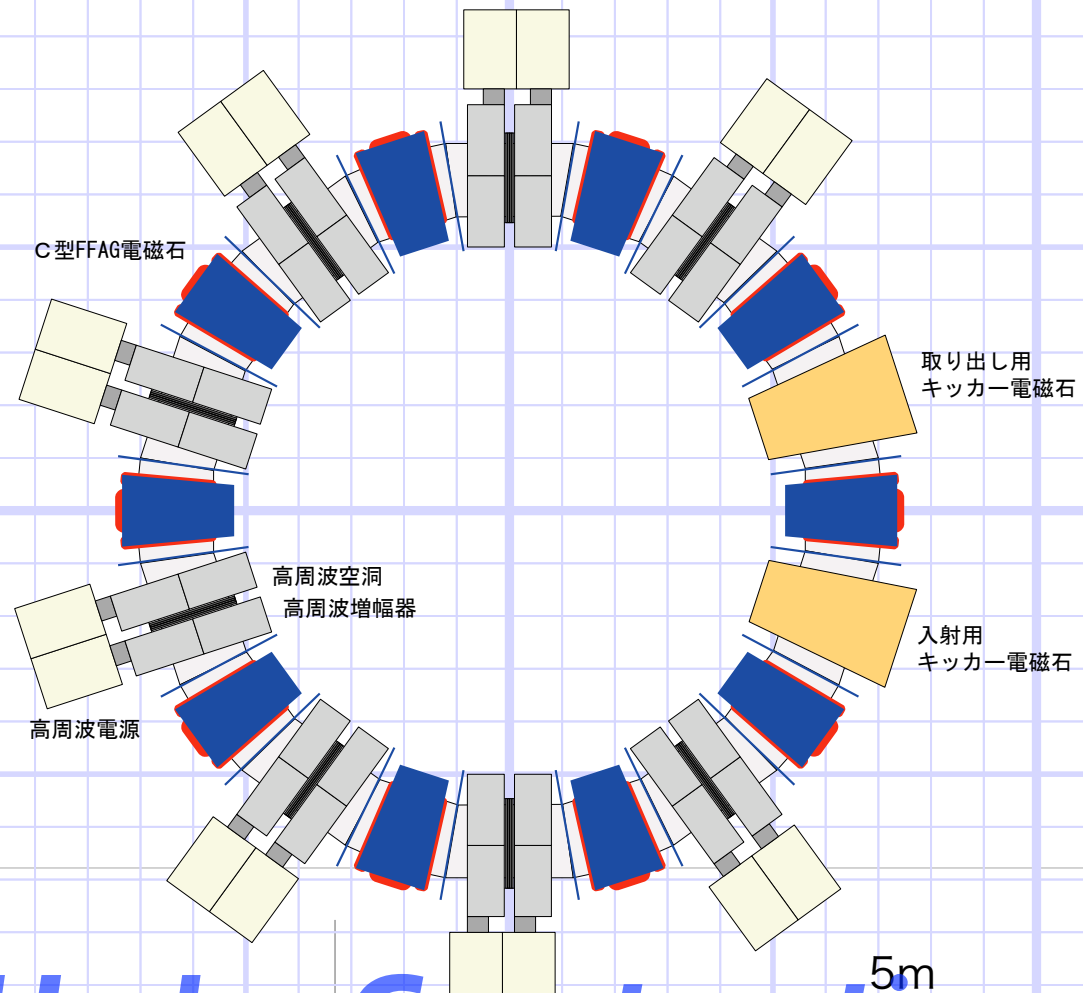
Under Construction
2003-2007 (with 6 magnets)

Features of PRISM-FFAG Magnet

scaling radial sector

Conventional type. Have larger circumference ratio.

triplet (DFD)

F/D ratio is variable. Ds have field crump effects to realize the large packing factor. the lattice functions has mirror symmetry at the center of a straight section.

large aperture

important for achieve a high intensity muon beam.

thin

Magnets have small opening angle. so FFAG has long straight sections to install RF cavities as mach as possible
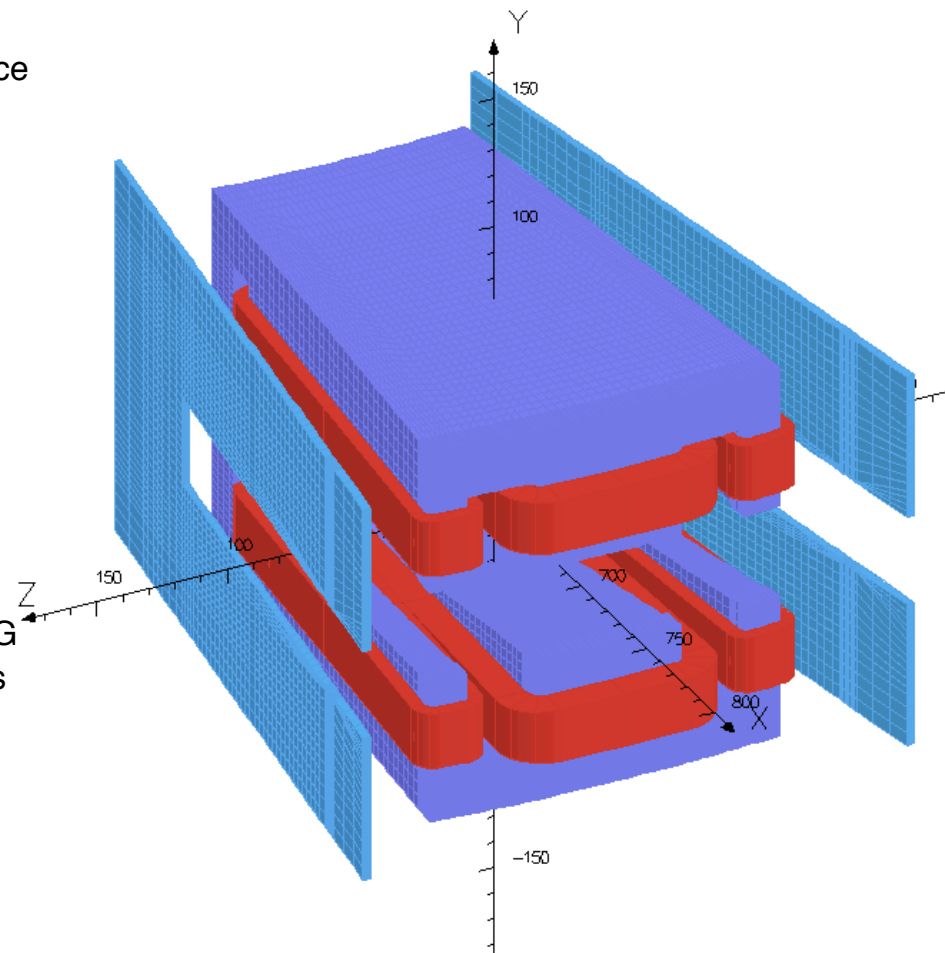
PRISM-FFAG Magnet

- DFD Triplet
- C type
- Large Aperture
  - 100 cm (horizontal)
  - 30 cm (vertical)

- Thin Shape
  - Length along beam axis : ~1.2 m

- Slant pole shape
  - Field index = 4.6

(2022.4)

(1550)

Field clamp

D Pole

F Pole

(969.9)

A

B

C

40

D Pole

Field Clamp

(1345.1)

2022.4

F Coil

740

175

1550

Median Plane

Distance from Machine Center (6500)

Cross section of F magnet
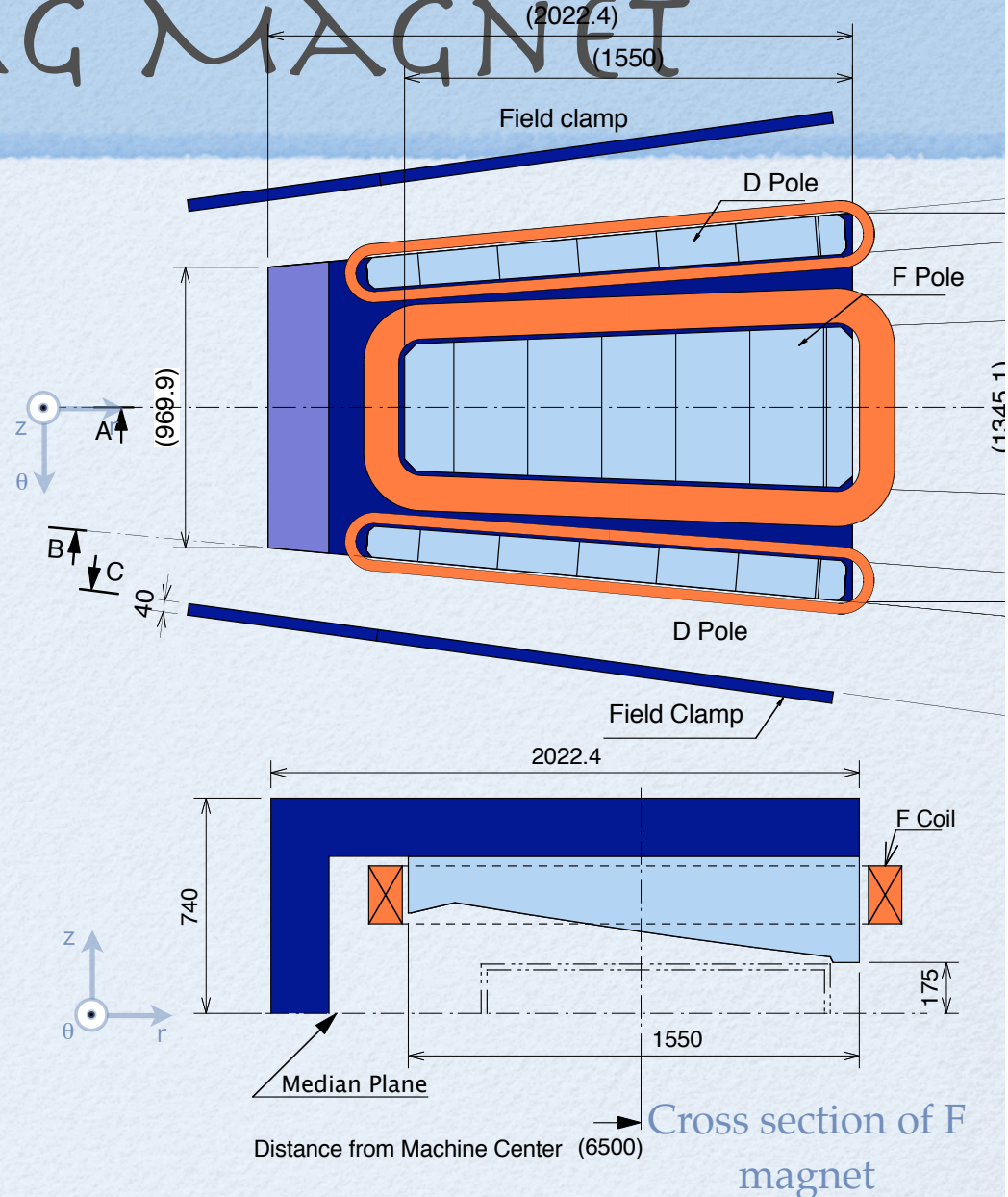
The First PRISM-FFAG Magnet
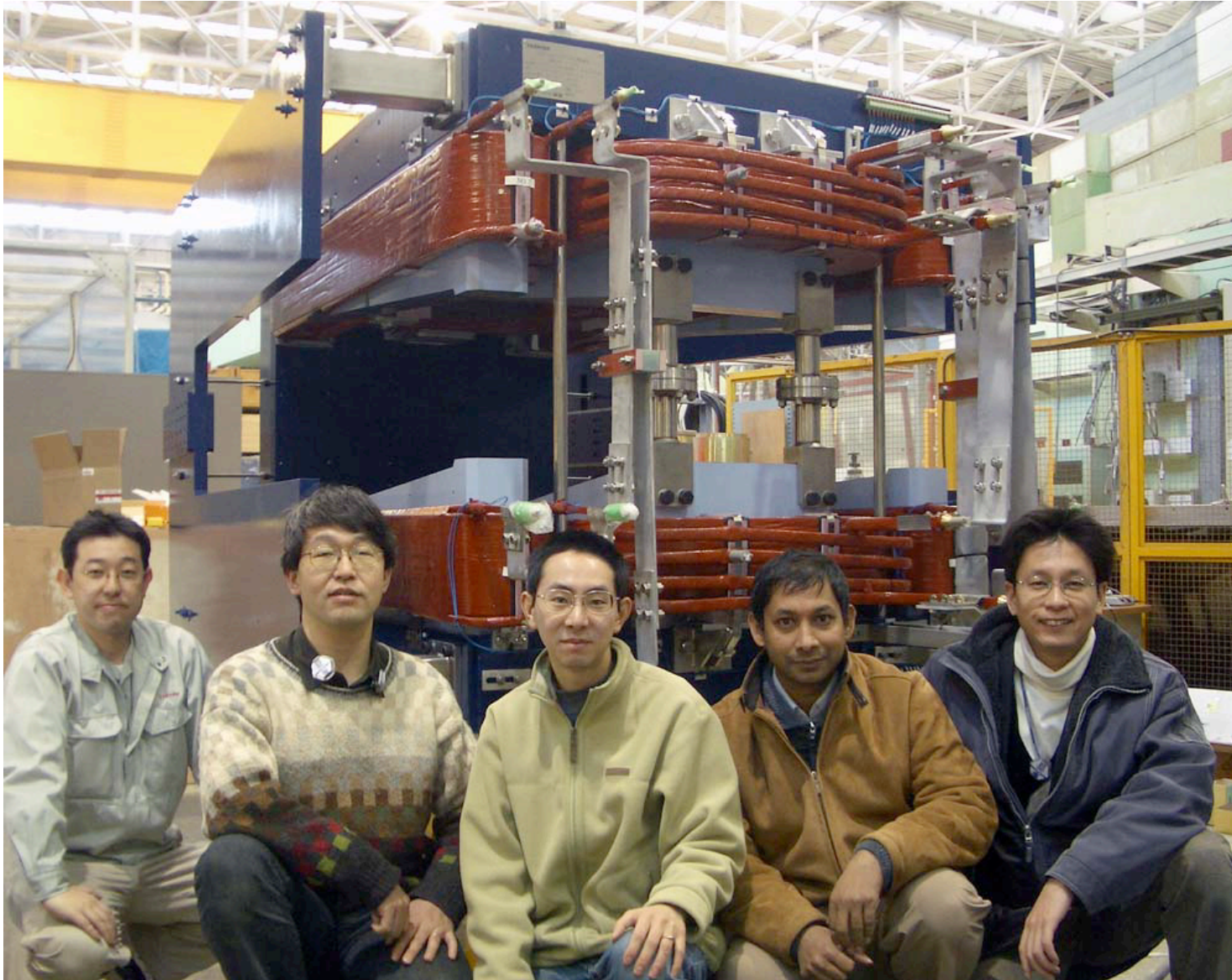
Field Measurements : Acceptance
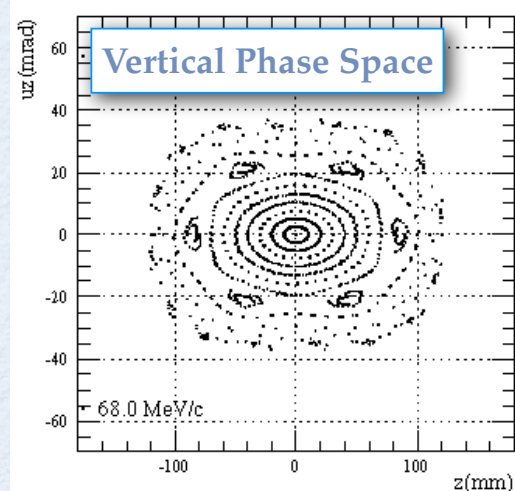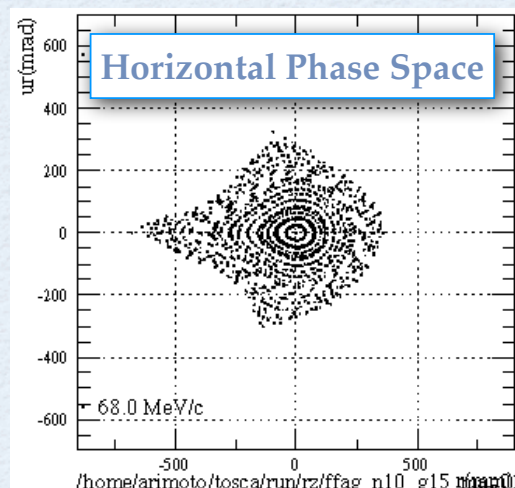
- by Geant3
- Both of phase-space distribution is almost same.

With TOSCA Map   With Measured Map

RF System for PRISM-FFAG

Power Supply

Dummy Cavity

AMP

Tetrodes in AMP

86.6kVp-p
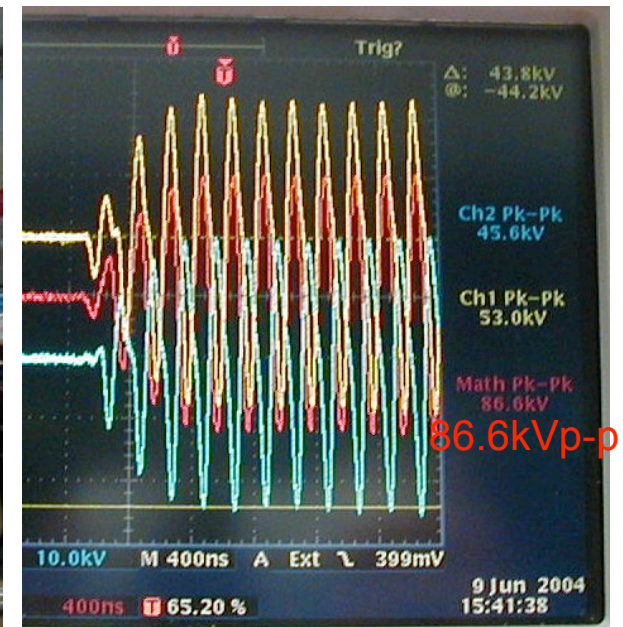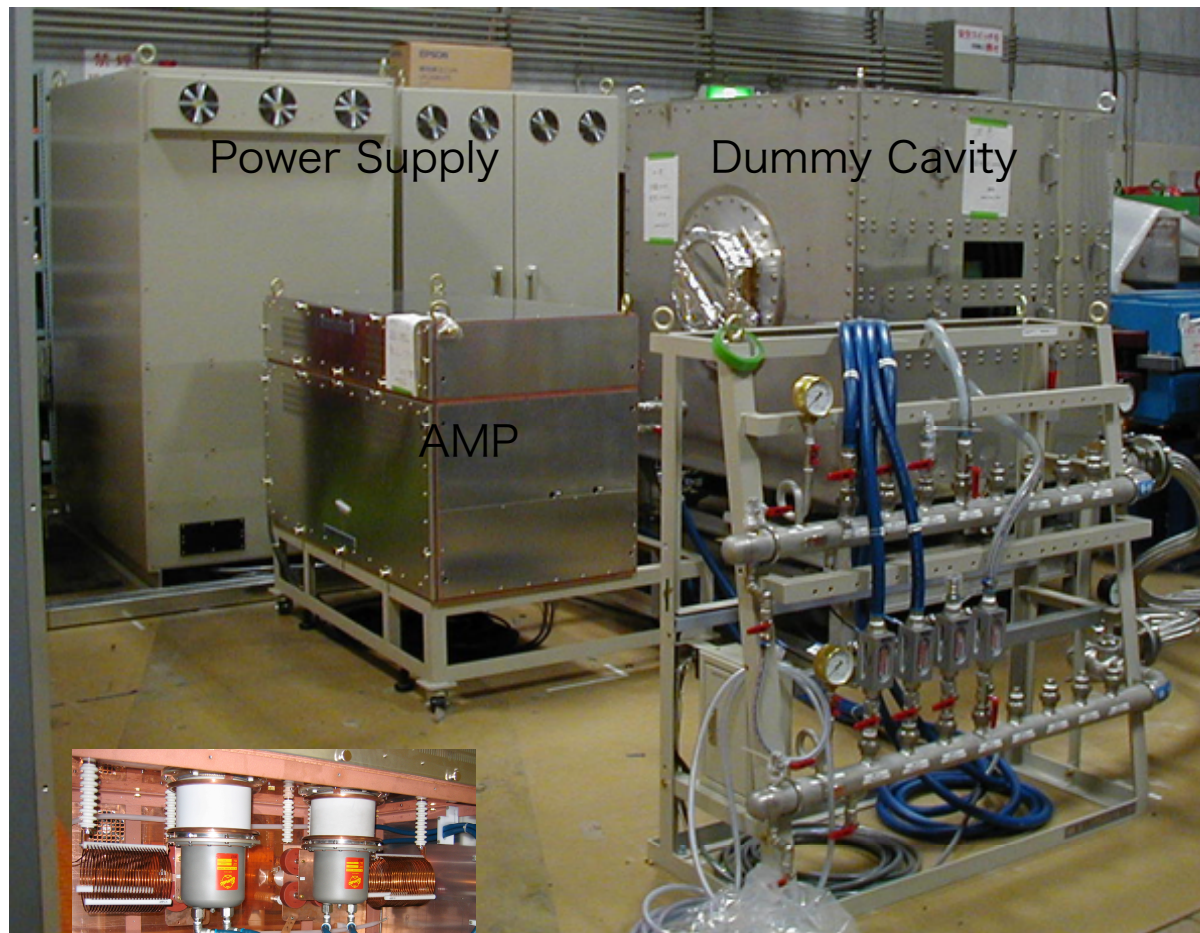
43kV/gap
w/ 734Ω dummy cavity
@5MHz

expected gradient
w/ PRISM-cavity (954Ω)
56kV_gap = 170kV/m

RF Cavity for PRISM-FFAG

1.0m

1.7m

t=35mm

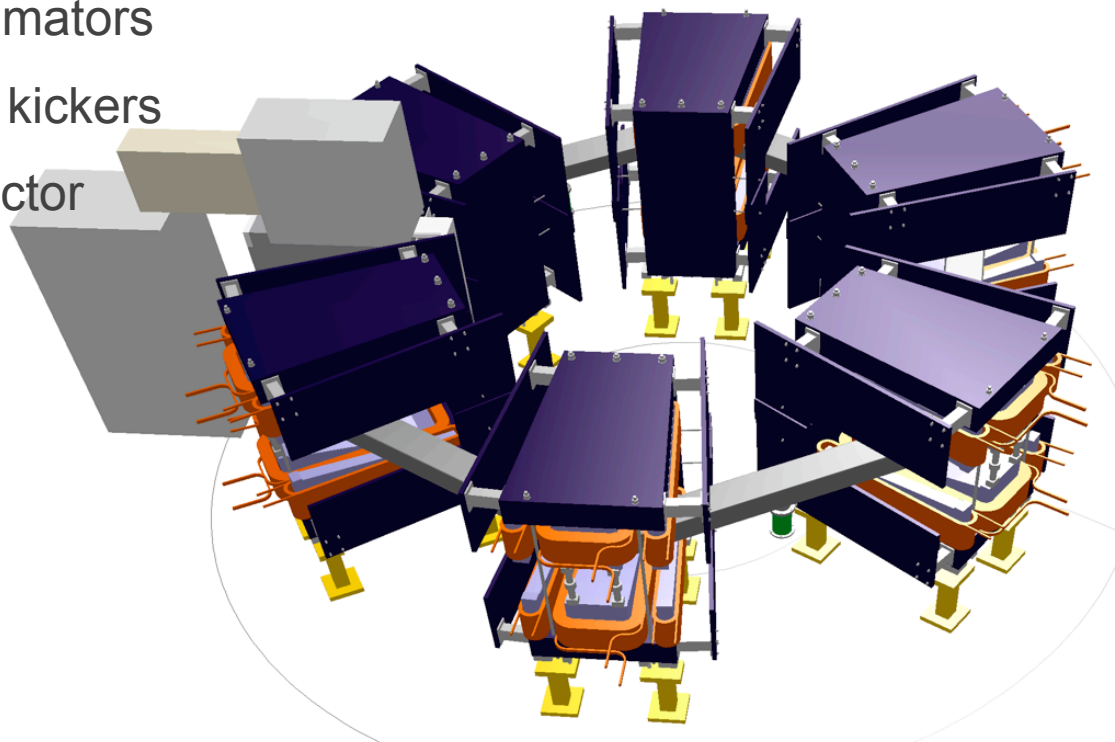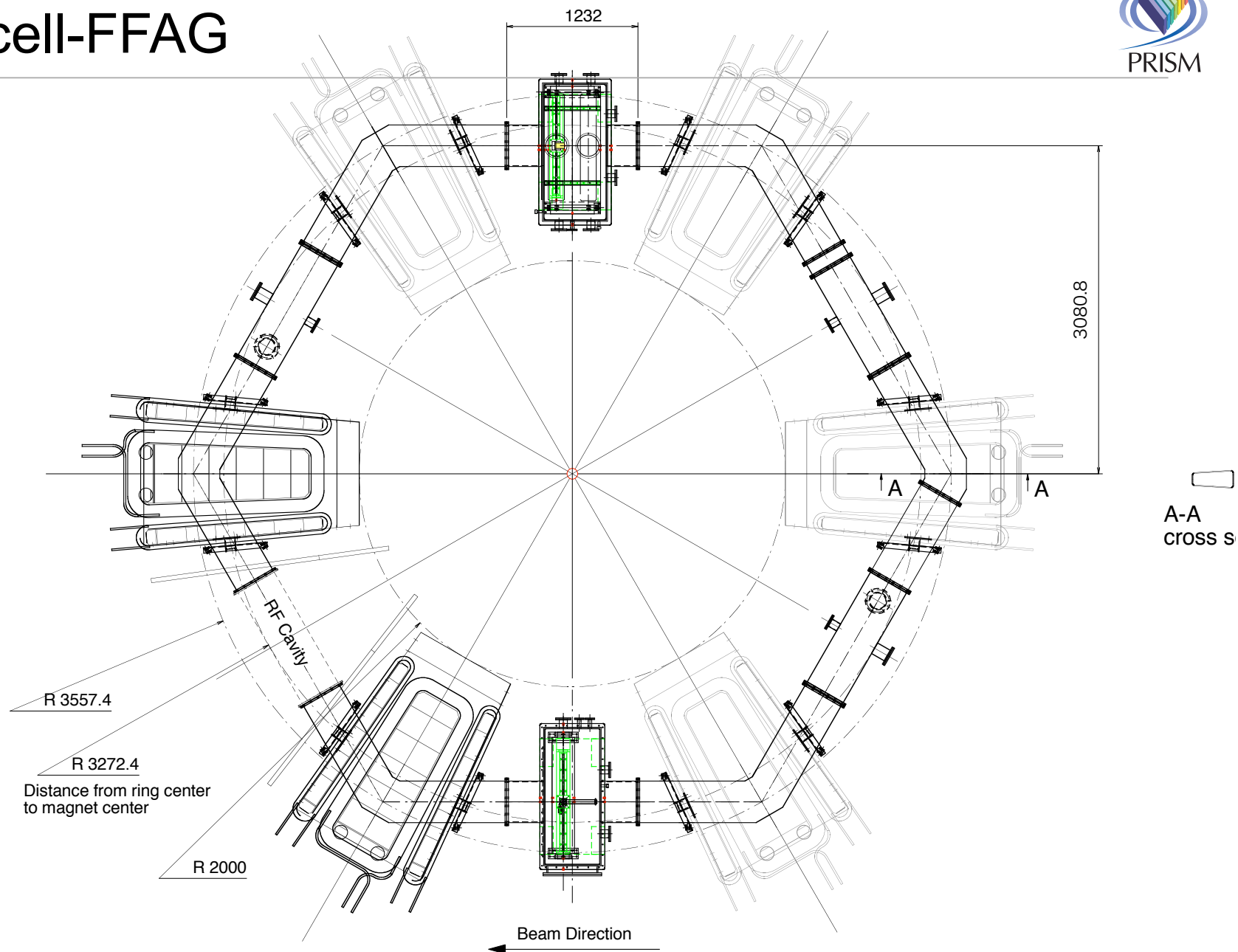156Ω @ 5MHz
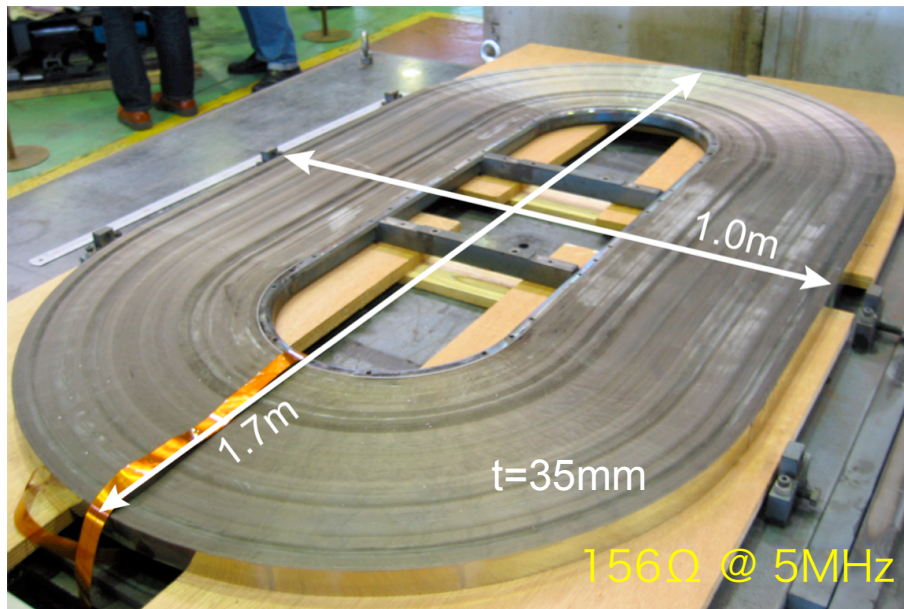
Phase Rotation Simulation for Muons
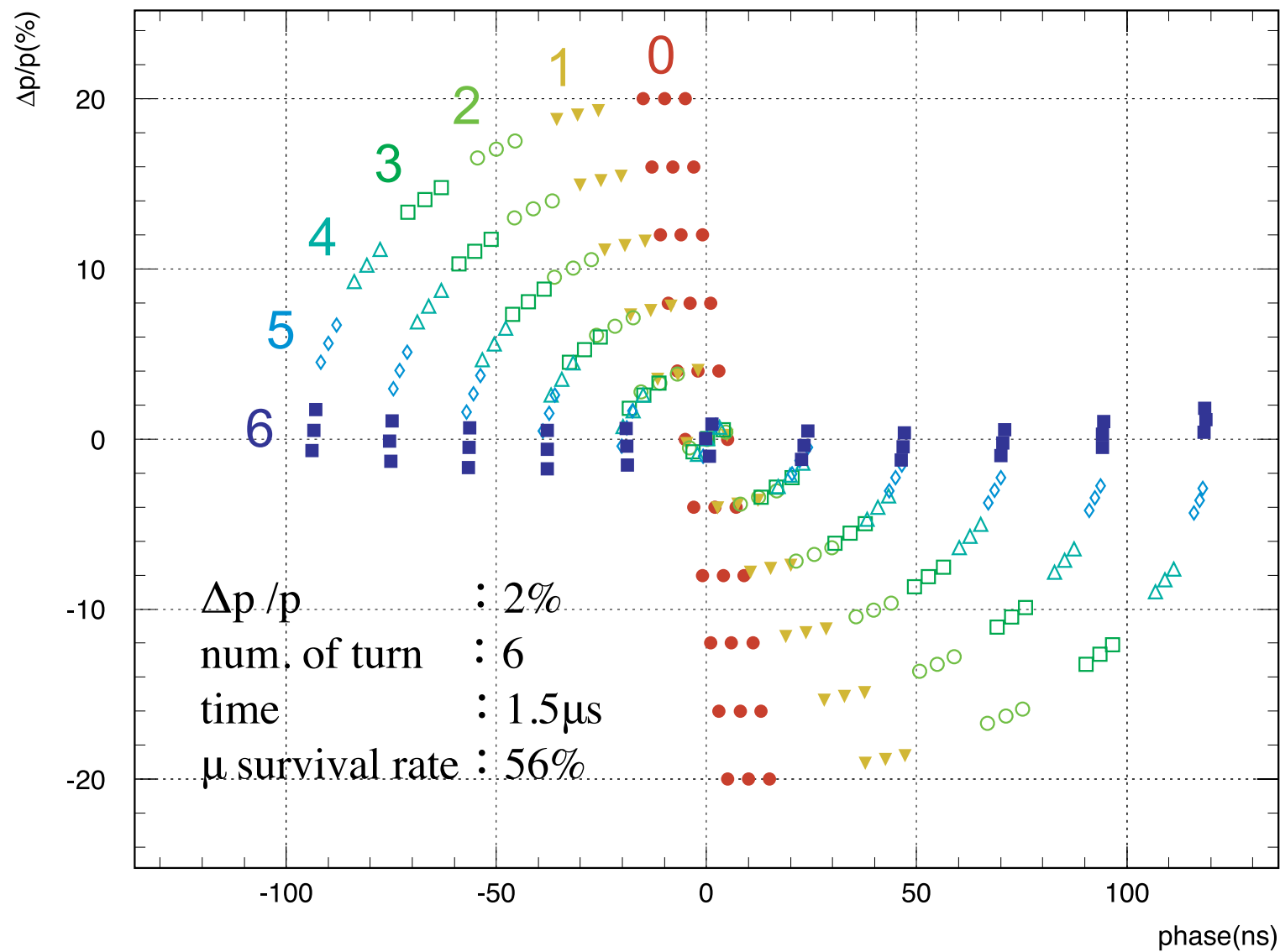
Demo. of Phase Rotation with α-particles

- FFAG-ring

  - PRISM-FFAG Magnet x 6、RF x 1

- Beam : α-particles from radioactive isotopes

  - ^{241}Am 5.48MeV(200MeV/c)　→　degrade to 90-100MeV/c

  - small emittance by collimators

  - pulsing by electrostatic kickers

- Detector : Solid state detector

  - energy

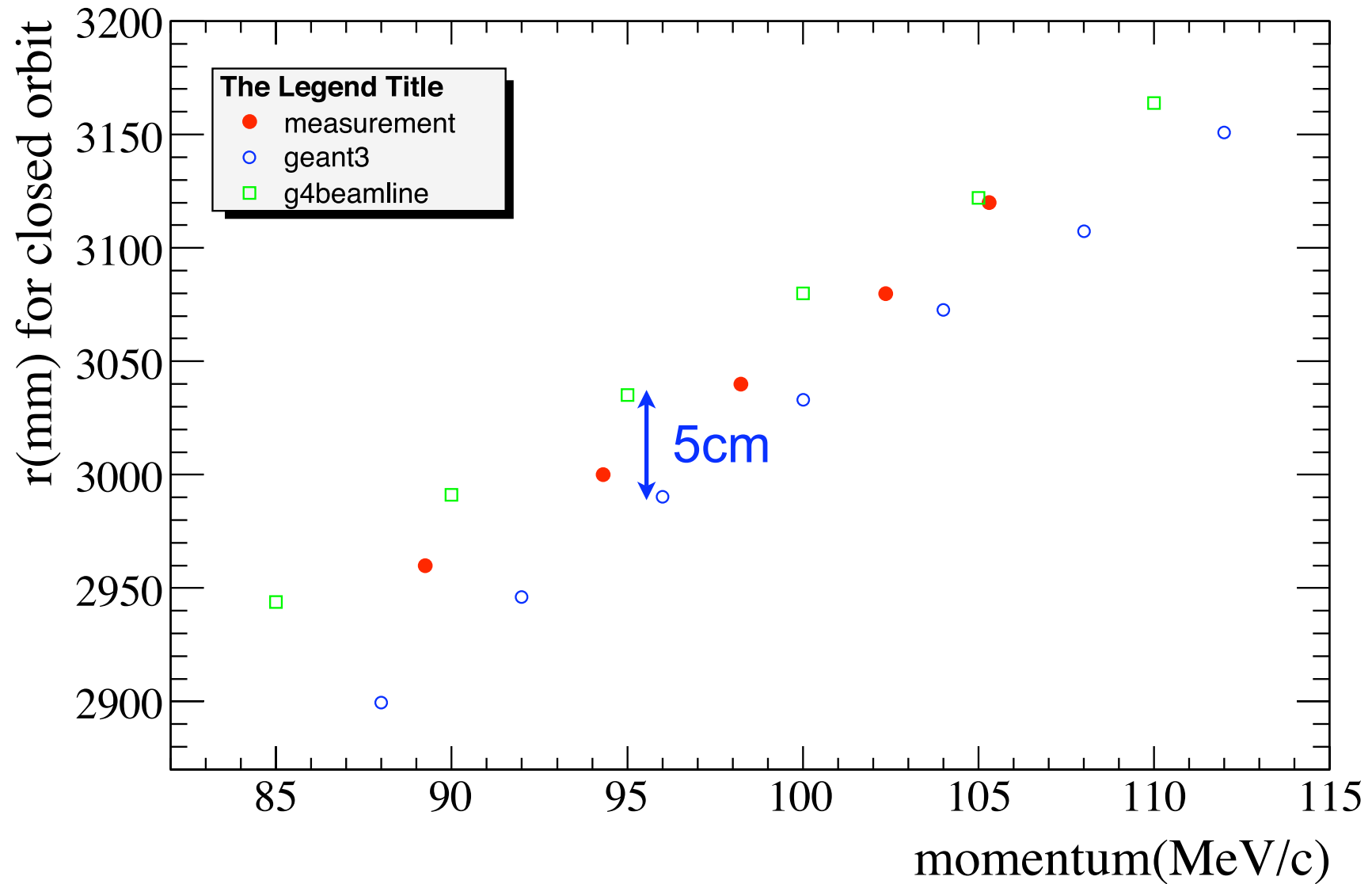 - timing

6cell-FFAG

1232

3080.8

A-A
cross s[...]

R 3557.4

R 3272.4

Distance from ring center
to magnet center

R 2000

RF Cavity

A

A

Beam Direction

PRISM

6-sector PRISM-FFAG at RCNP, Osaka Univ.

Closed Orbits

RF Cavity with 4 MA cores

RF for 6cell-FFAG

$(36kV_{pp}/2)\times2/33\times100=108kV/m$

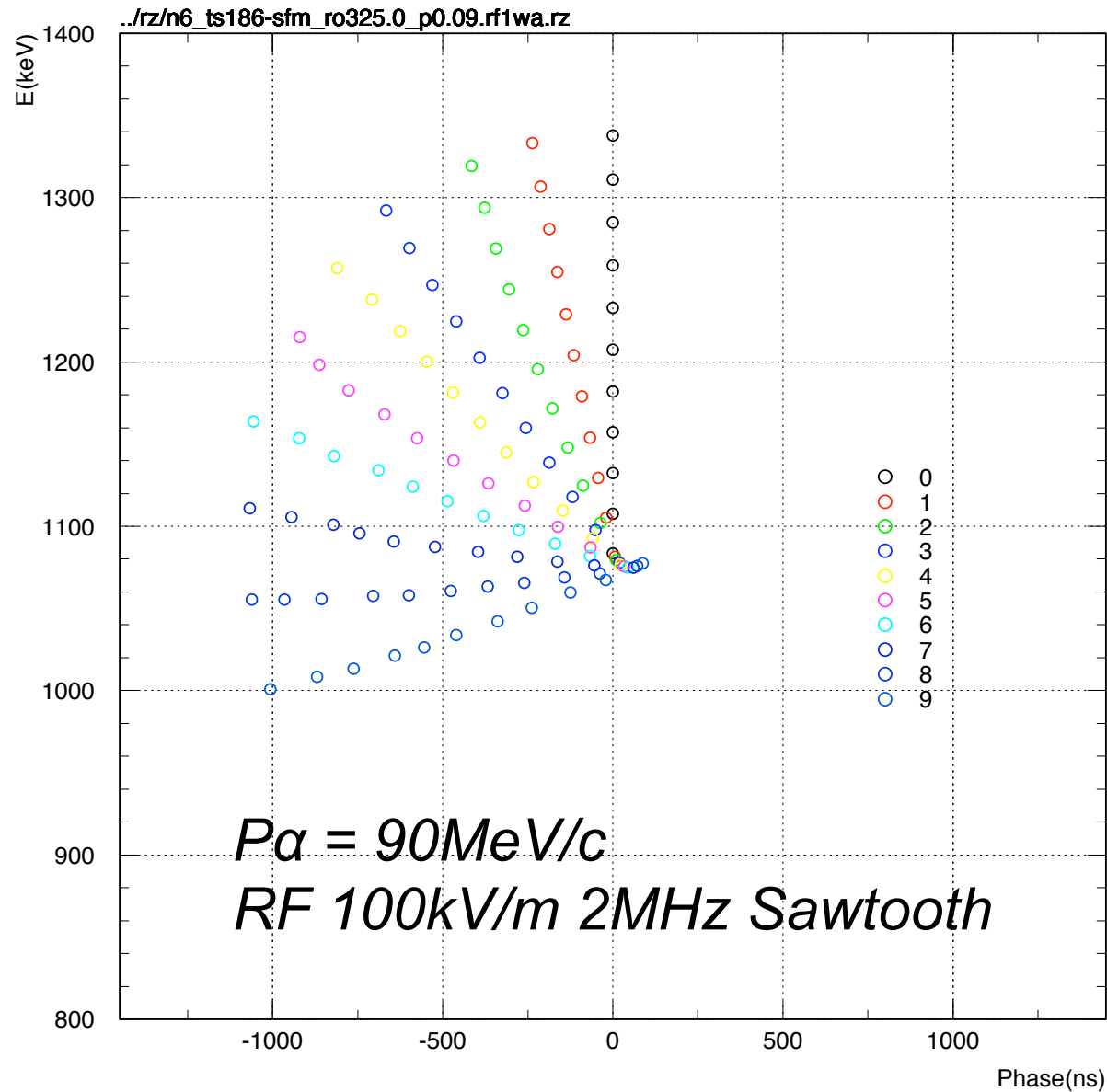*preliminary*
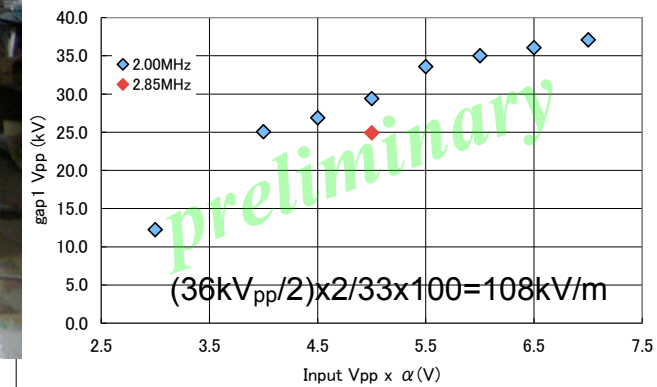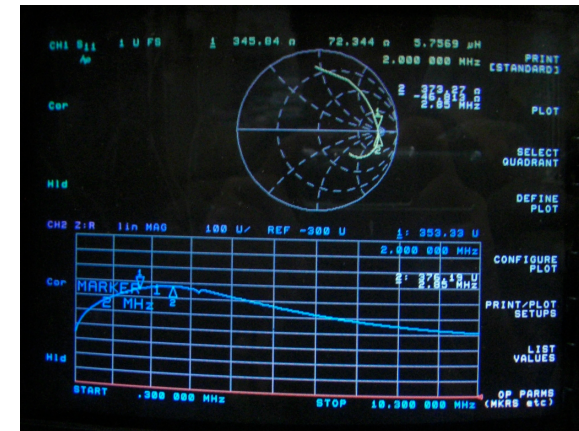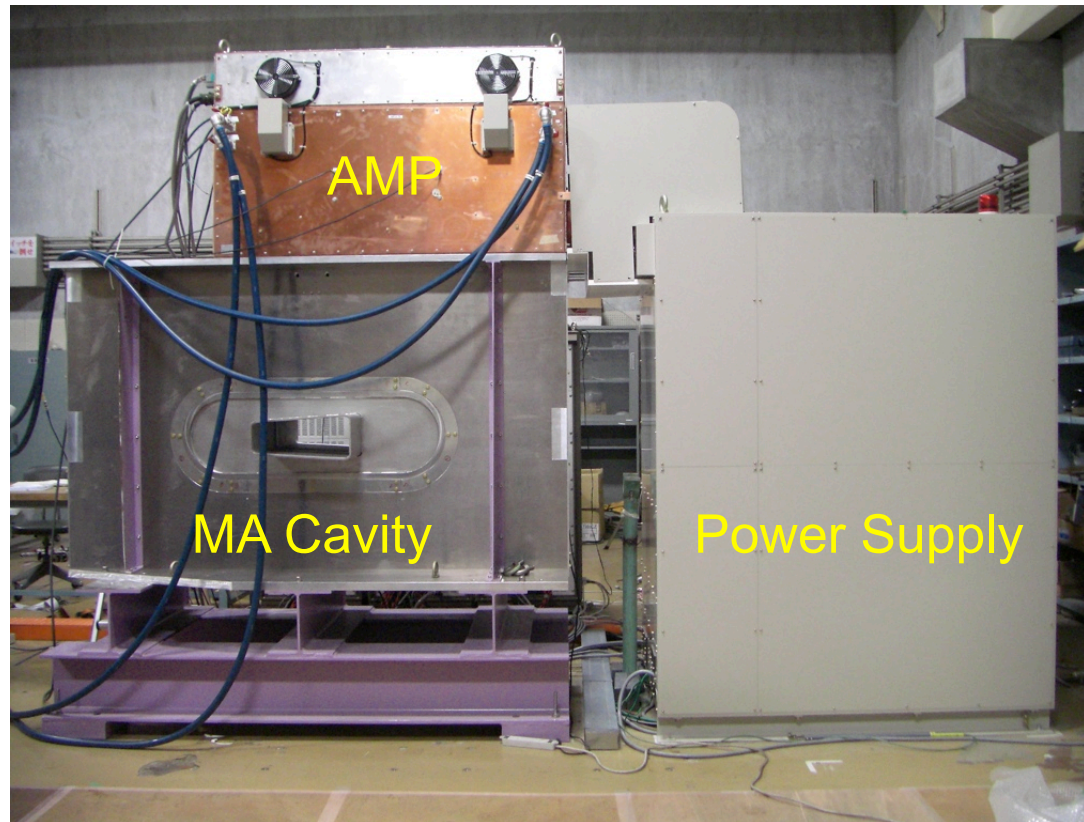
RF system for 6cell-FFAG has been developed.
100kV/m @ 2MHz is promising.

Phase Rotation Simulation for α-particles

Pα = 90MeV/c
RF 100kV/m 2MHz Sawtooth

Summary

- The current MECO-type experiment can not achieve a sensitivity beyond BR~10^{-17}, because of the backgrounds limitation.

- Not only beam intensity but also its quality is necessary for the (2+N)th generation mu-e conversion experiments.

- PRISM provides a solution adopting a muon storage ring, which make mono-energetic and pure muon beam to aim the sensitivity of BR~10^{-18}. A staging scenario of mu-e conversion experiment was proposed in Japan.

- R&D program on the muon storage ring was started in 2003. A large aperture FFAG and a high field gardened RF system, which are necessary for PRISM, were successfully developed.

- A FFAG with six-PRISM-FFAG magnets was build at Osaka, and its commissioning is now underway. Demonstration of phase rotation would be carry out soon (in this year).

Backup Slides