Results and Status of PRISM-FFAG R&D

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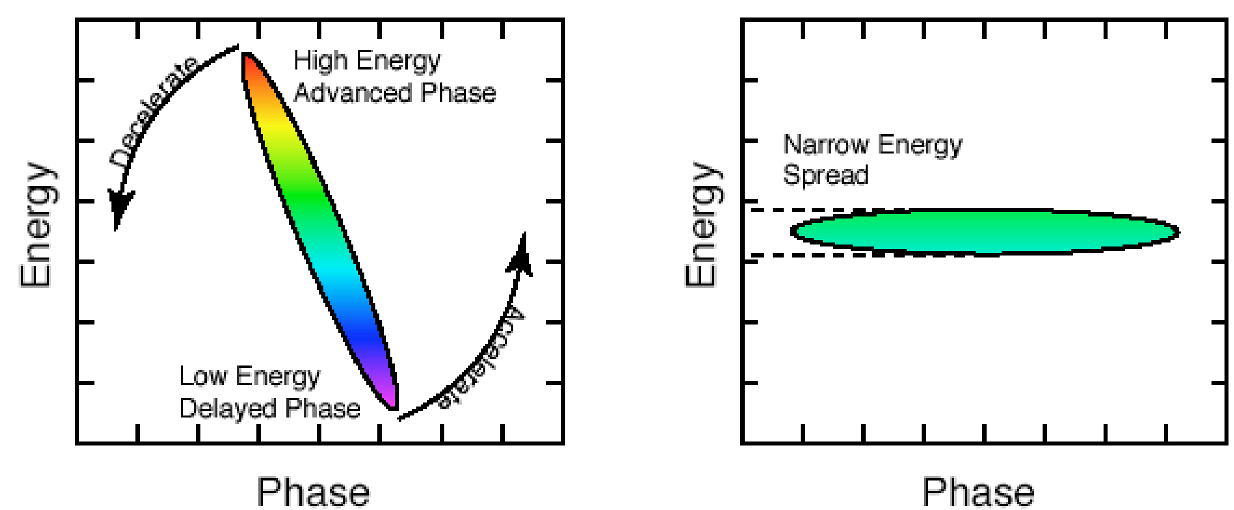
Overview

PRISM : Phase Rotated Intense Slow Muon source

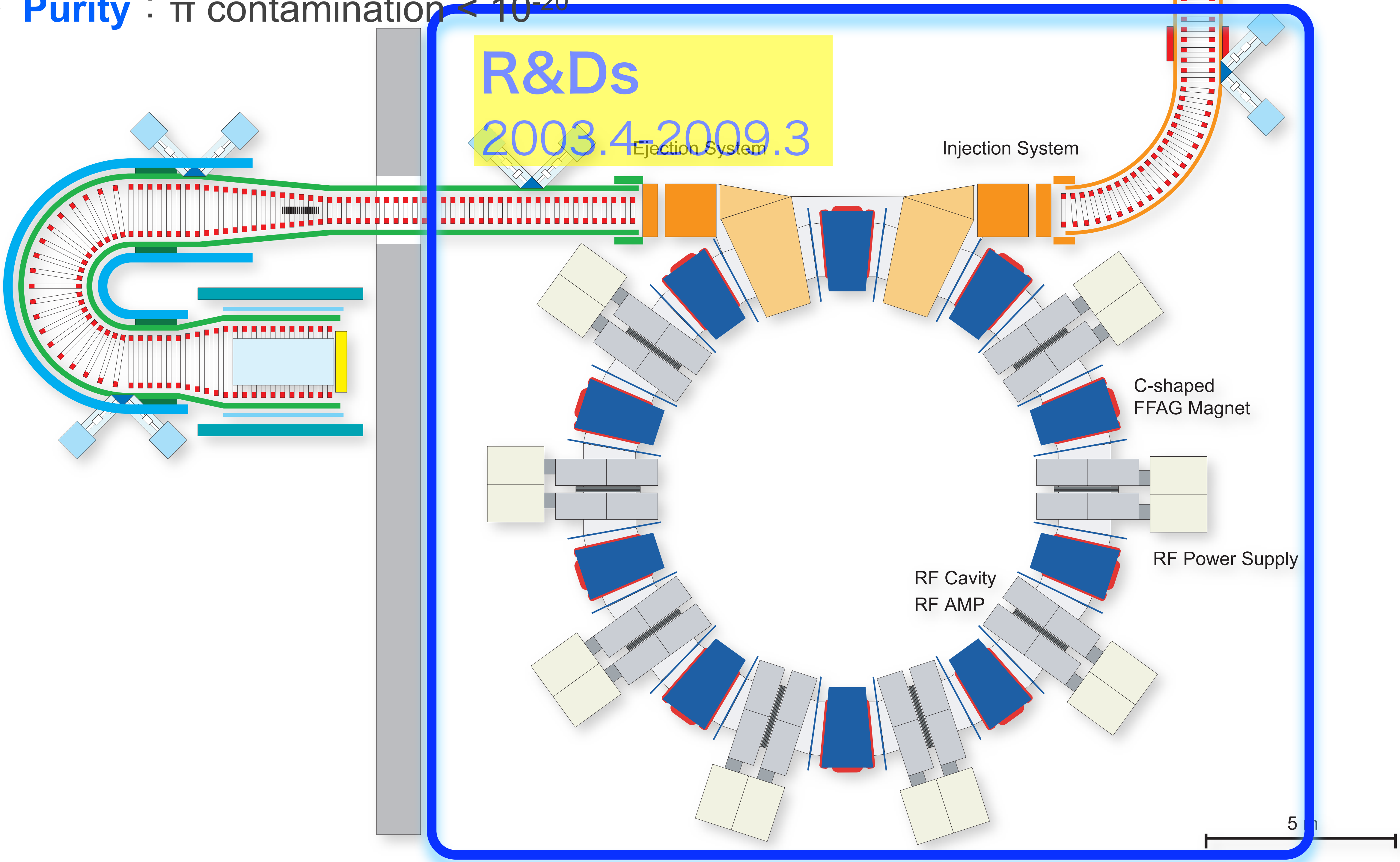
- Goal : Search for Lepton Flavor Violation with $B(\mu\text{-}N \rightarrow e\text{-}N) < 10^{-18}$
- We need a high intense and high quality muon beam, such as
  - ***High Intensity***
    - intensity : 10^{11}-$10^{12}\mu^{\pm}$/sec
    - beam repetition : 100-1000Hz
    - muon kinetic energy : 20 MeV (=68 MeV/c)
  - ***Narrow energy spread***
    - kinetic energy spread : ±0.5-1.0 MeV
  - ***Less beam contamination***
    - π contamination < 10^{-18}

phase rotation

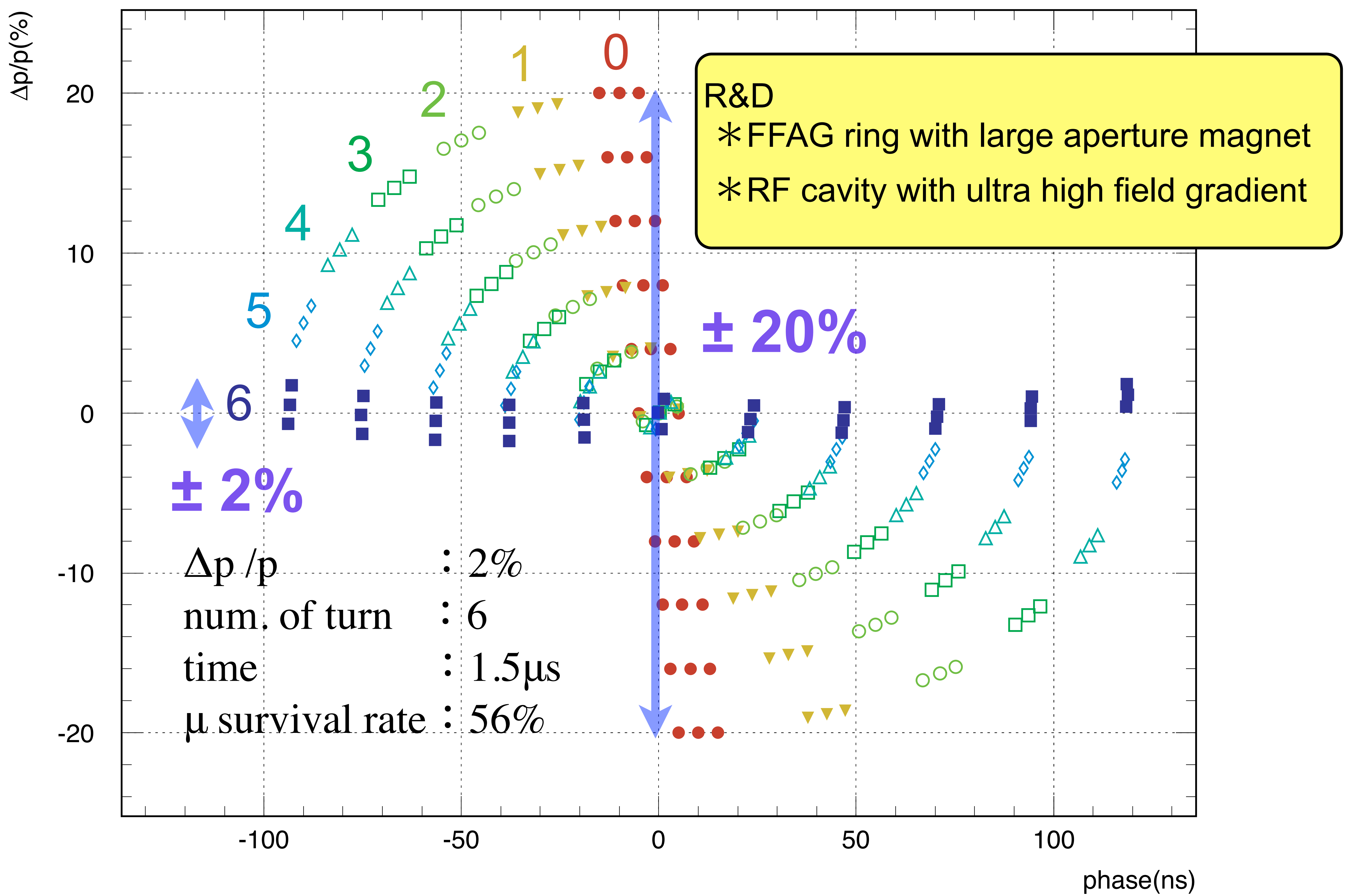


PRISM : Super-muon source
PRIME : μ-N→e-N Search with PRISM

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



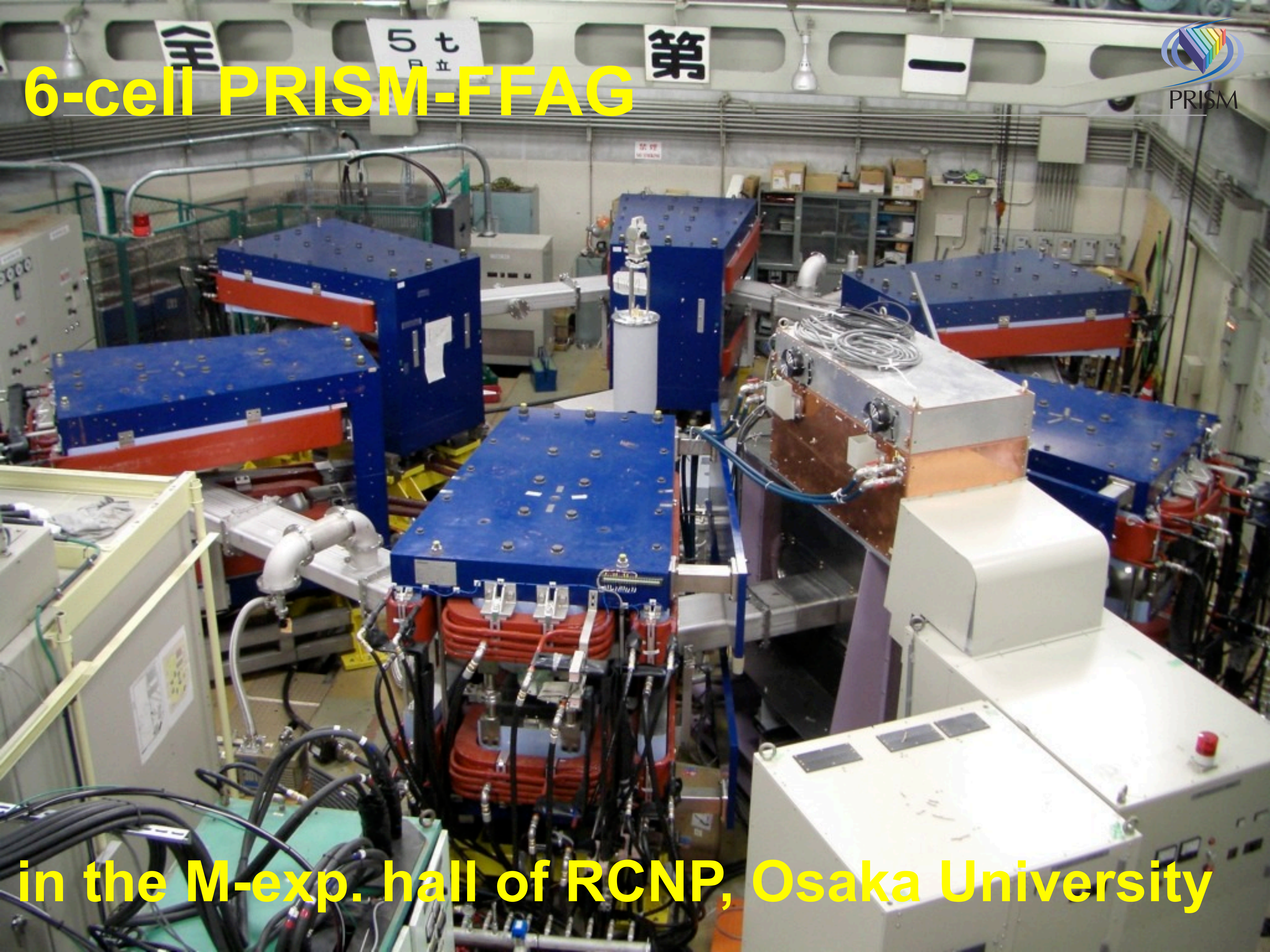
Expected phase rotation with PRISM-FFAG



R&Ds in the PRISM-FFAG project

- Design of PRISM-FFAG
- Development of large aperture FFAG magnet
  - 6 magnets have been build
  - magnetic field was measured for three
- Beam dynamics study using one magnet
- Development of RF system
  - 170kV/m sinusoidal @ 5MHz with a test cavity
  - 100kV/m sinusoidal @2.1MHz with PRISM-cavity
- Development of beam monitor for alpha-particle
- 6-cell PRISM-FFAG has bee constructed
  - Beam dynamics studies
  - Test for the phase rotation

6-cell PRISM-FFAG



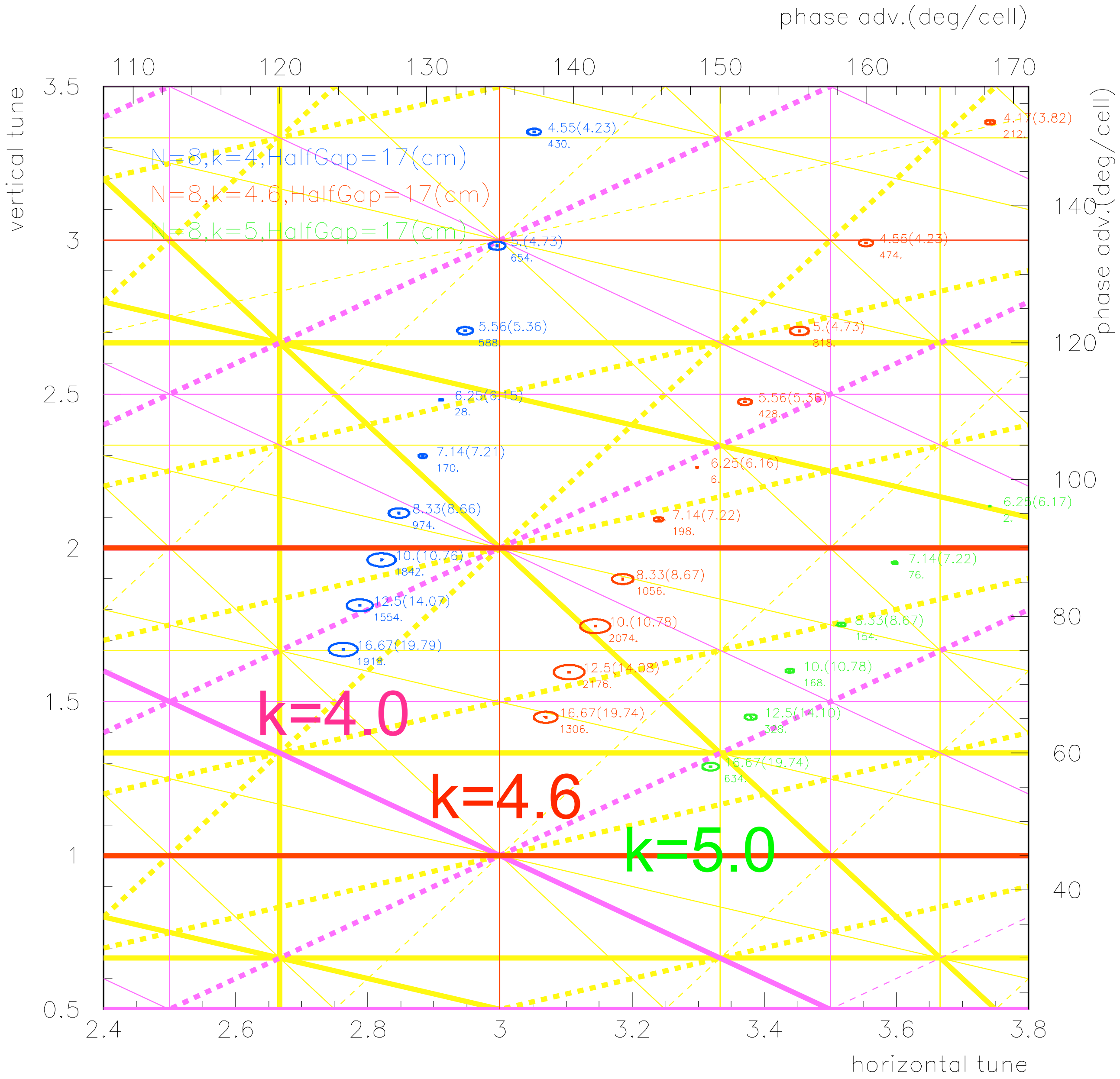
in the M-exp. hall of RCNP, Osaka University

Design of PRISM-FFAG

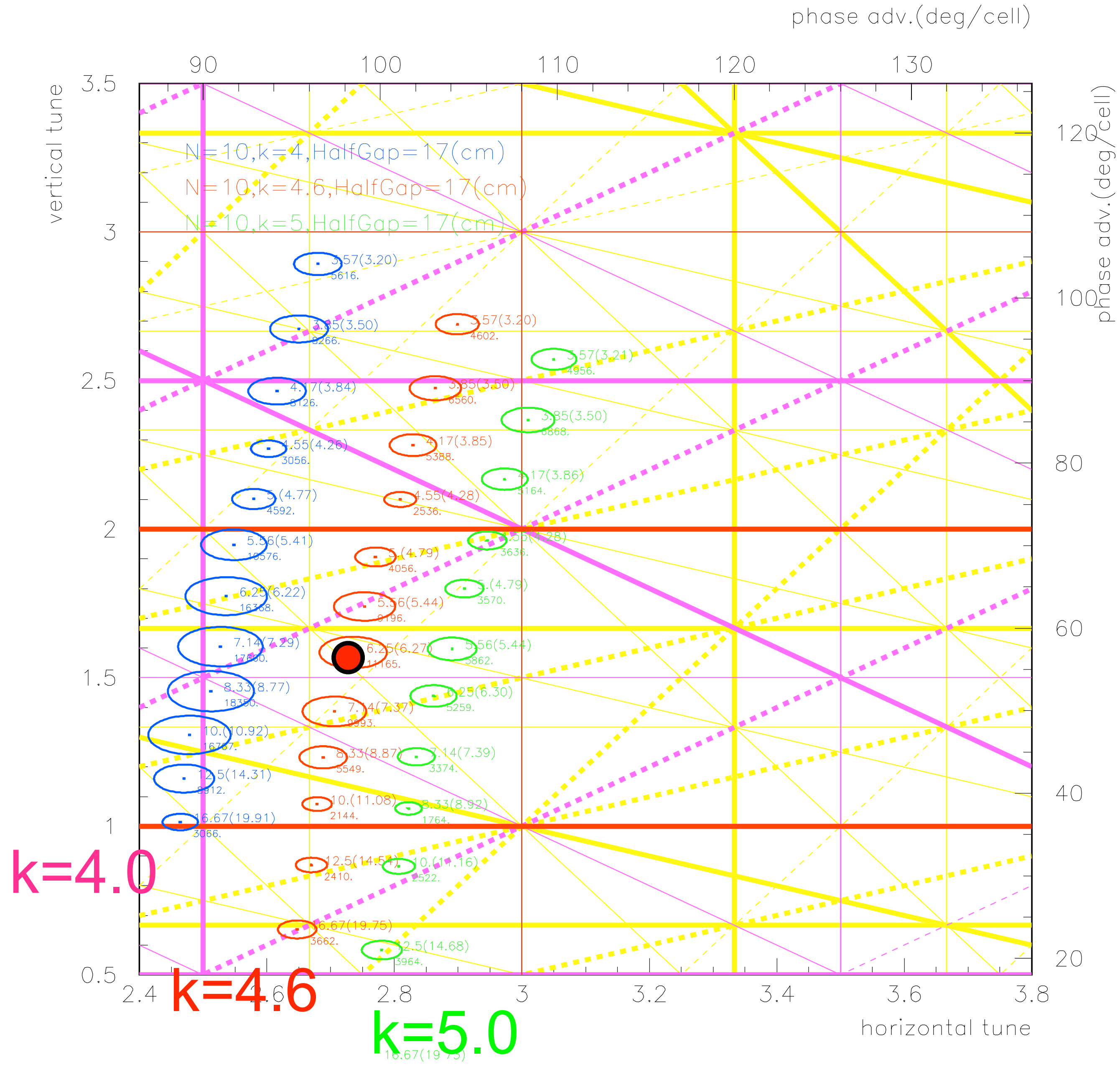
Requirements on the PRISM-FFAG

- **For the high intensity**
  - Large transverse acceptance is very important to achieve high intensity muon beam. A transverse acceptance of more than 20000π mm·mrad for the horizontal plane and more than 3000π mm·mrad for the vertical plane are required.
  - A momentum acceptance of 68MeV/c ± 20% is necessary.
- **For the quick phase rotation**
  - The field index k should be chosen so that a transition energy is enough far from energies of above momentum region.
  - RF cavities should be installed to ring as many as possible to achieve quick phase rotation with in a few micro-second. Therefore, long straight sections to install the cavities are required.
  - Stray fields to RF cores should be small, since DC magnetic flux can reduce a performance of the RF cores. Magnetic fluxes in the cores should be less than 100 gauss, although a distance between the magnet and the RF core would be small because of above requirement.
- **For the compact ring**
  - To locate PRISM in a possible site, J-PARC and so on, a compact FFAG ring, about 10m in diameter, is feasible.

Parameter search for N, k, and F/D



N=8

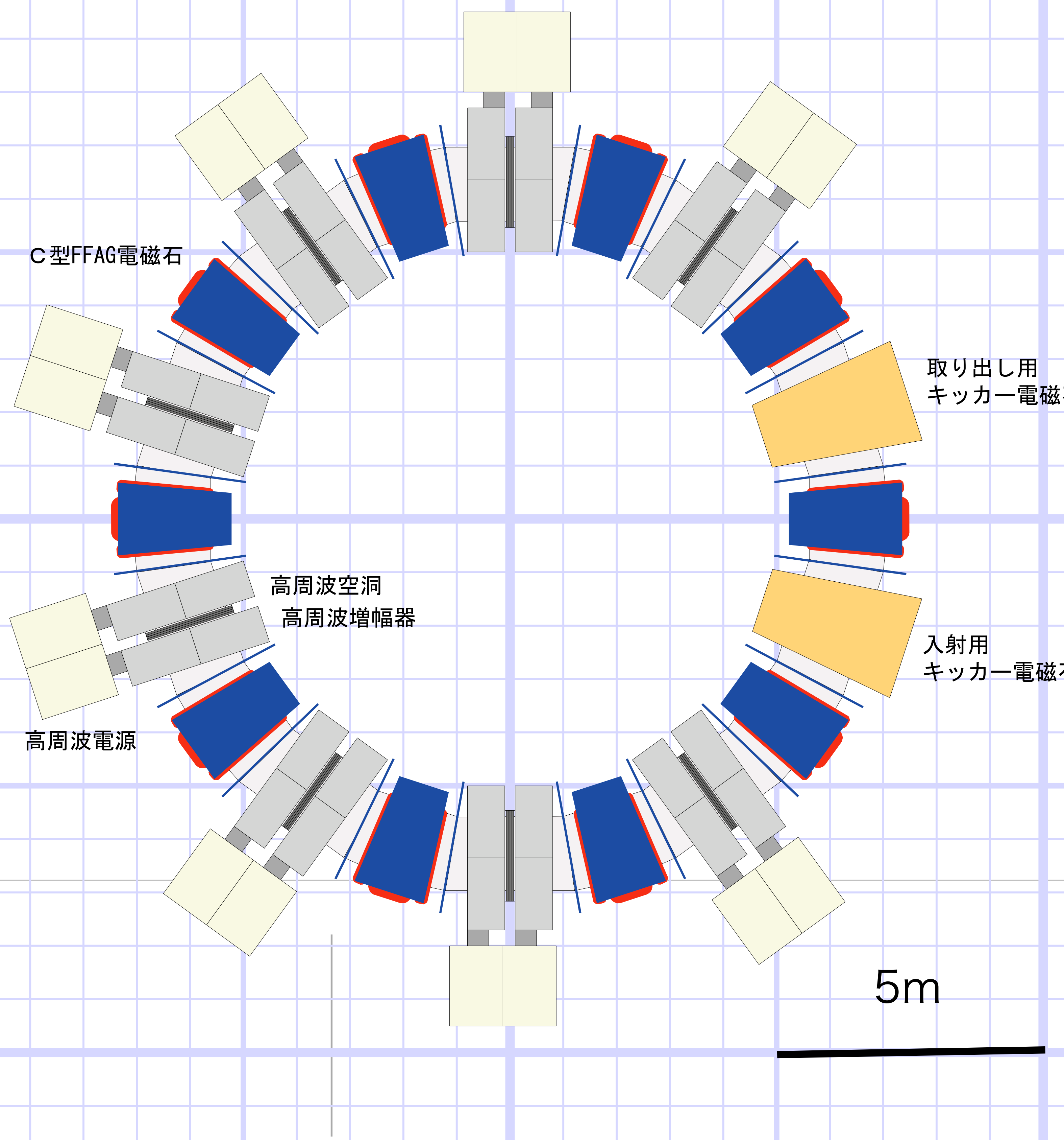


N=10

PRISM-FFAG

- 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

Phase Rotator



PRISM-FFAG Features

- Radial sector type, Scaling FFAG
- Large transverse acceptance
  - Horizontal : 38,000 π mm mrad
  - Vertical : 5,700 π mm mrad
- High field gradient RF system
  - field gradient ~200kV/m (~2MV/turn)
    - quick phase rotation (~1.5μs)
    - large mom. acceptance (68MeV/c +- 20%)

Tune and acceptance by TOSCA field

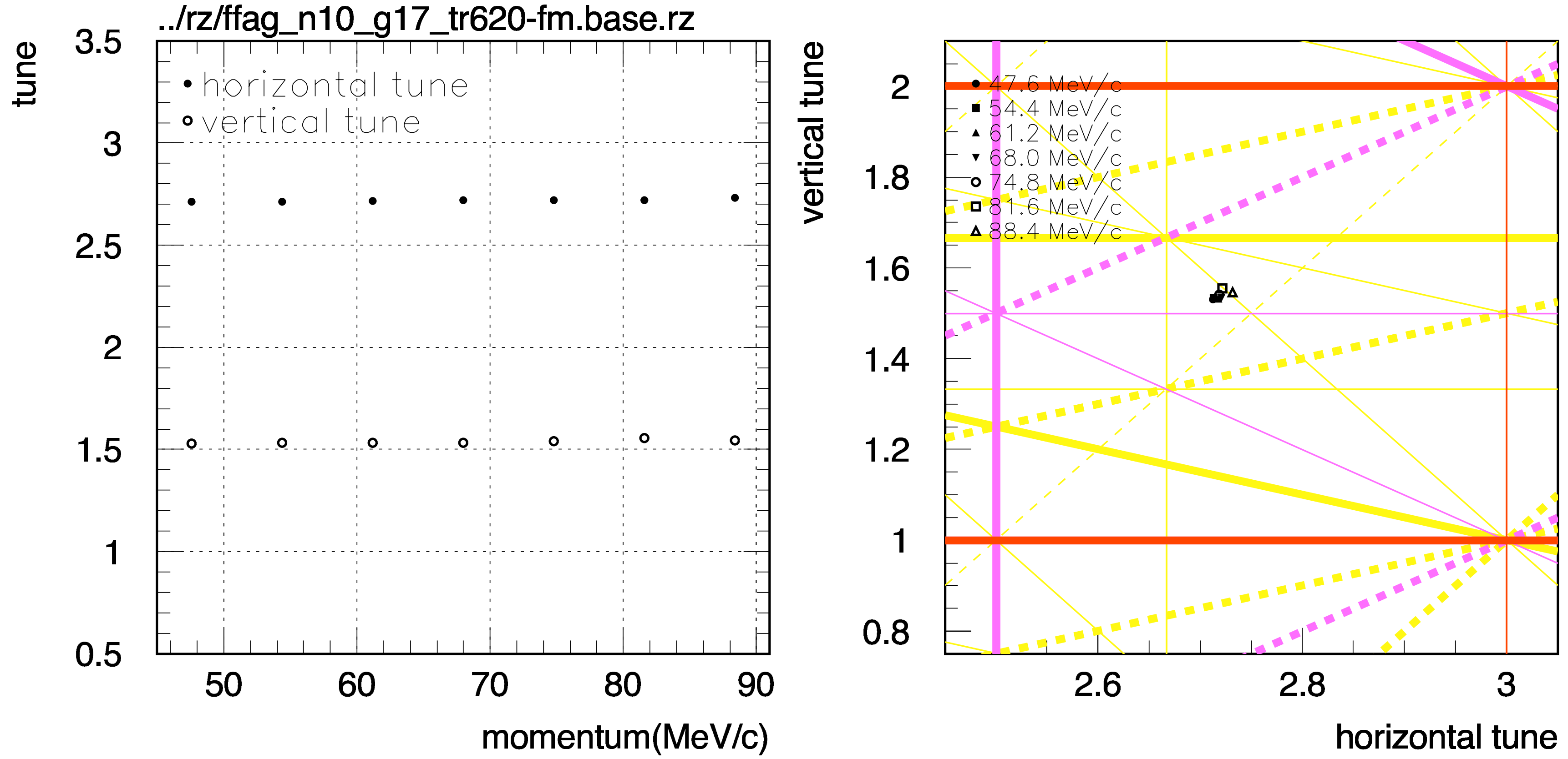


FIGURE 6. Momentum dependence of horizontal and vertical tune.

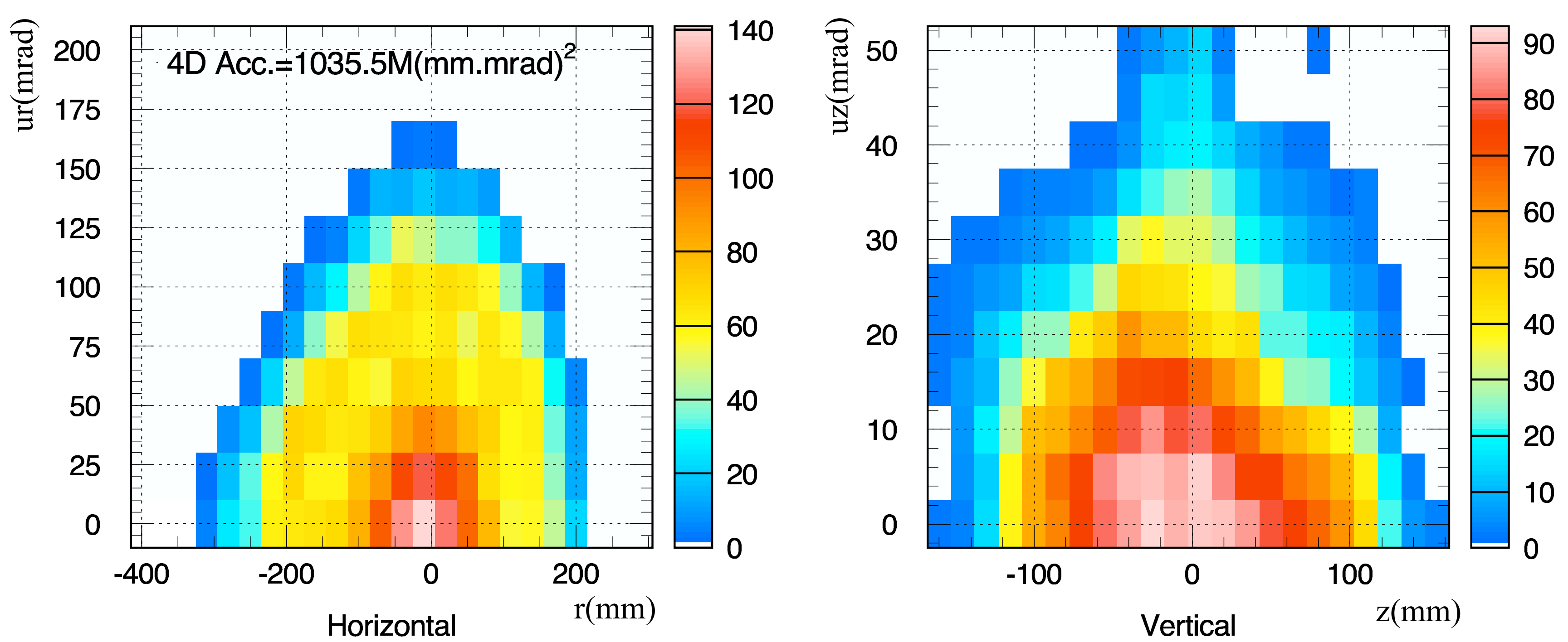
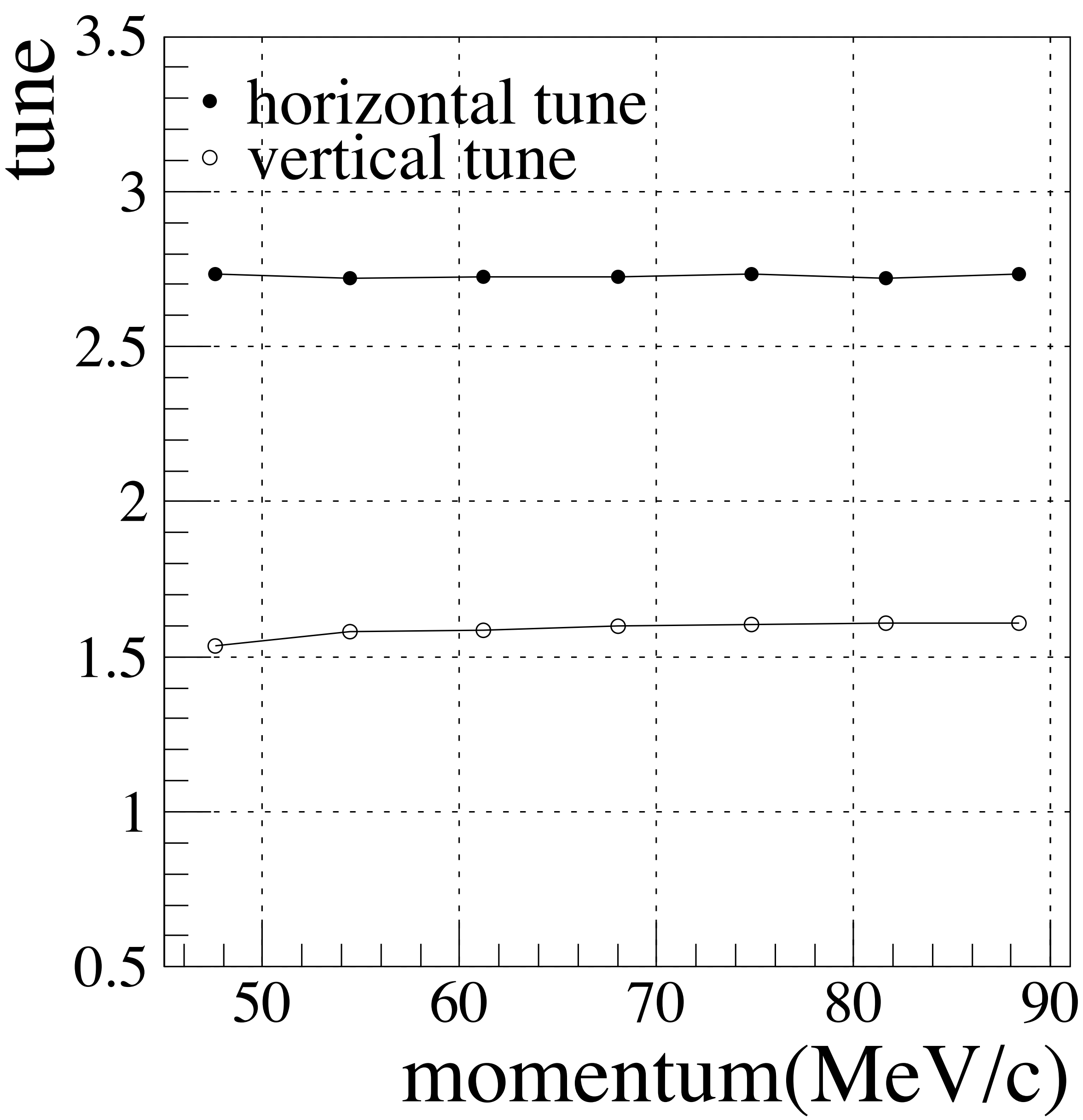
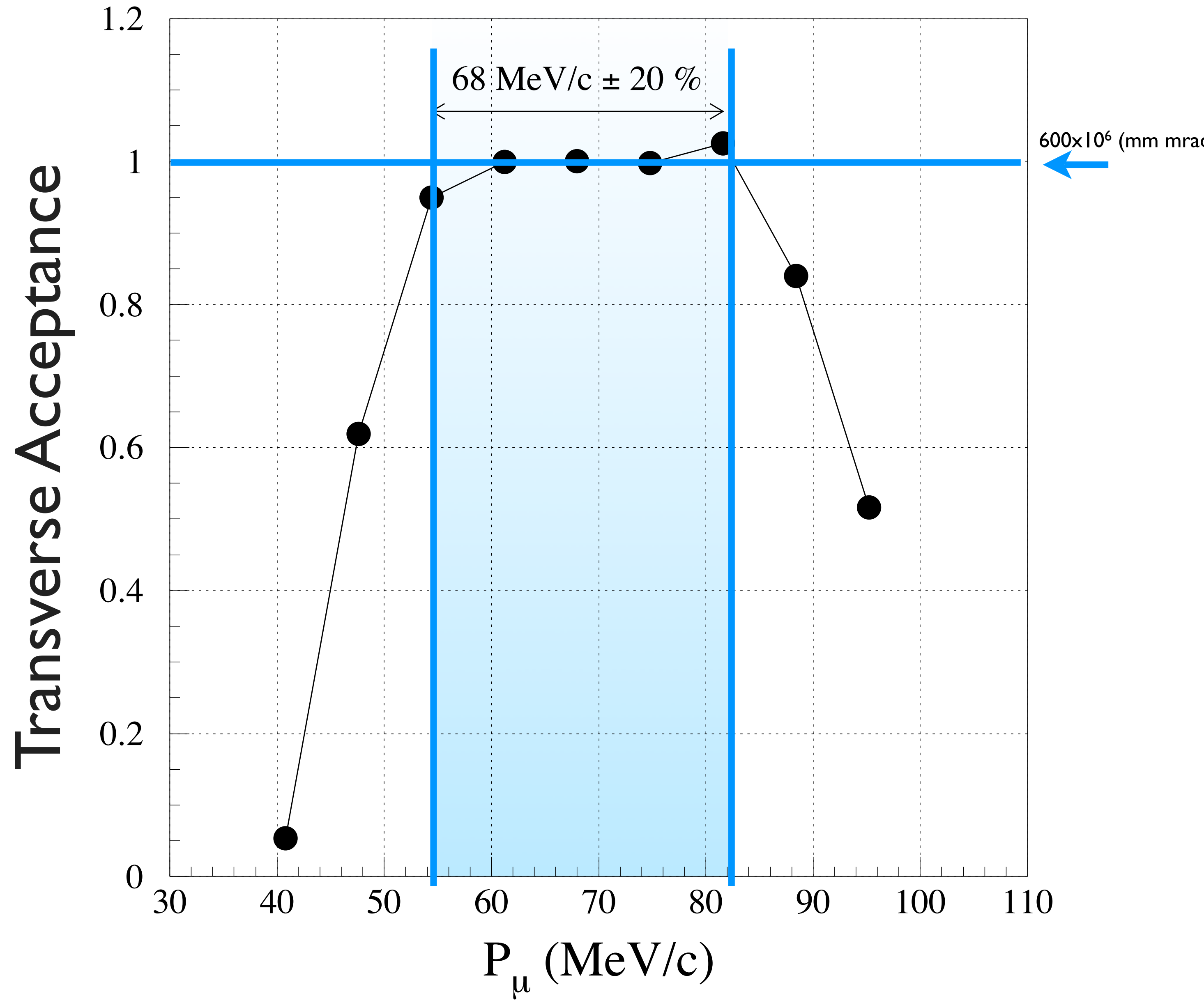


FIGURE 7. Projections of the 4D acceptance volume to horizontal and vertical planes.



tune
horizontal tune
vertical tune
momentum(MeV/c)



Transverse Acceptance
68 MeV/c ± 20 %
600x10⁶ (mm mrad)²
P_μ (MeV/c)

Magnets

Features of PRISM-FFAG Magnet

PRISM

scaling radial sector

Conventional type. Have larger circumference ratio.

triplet (DFD)

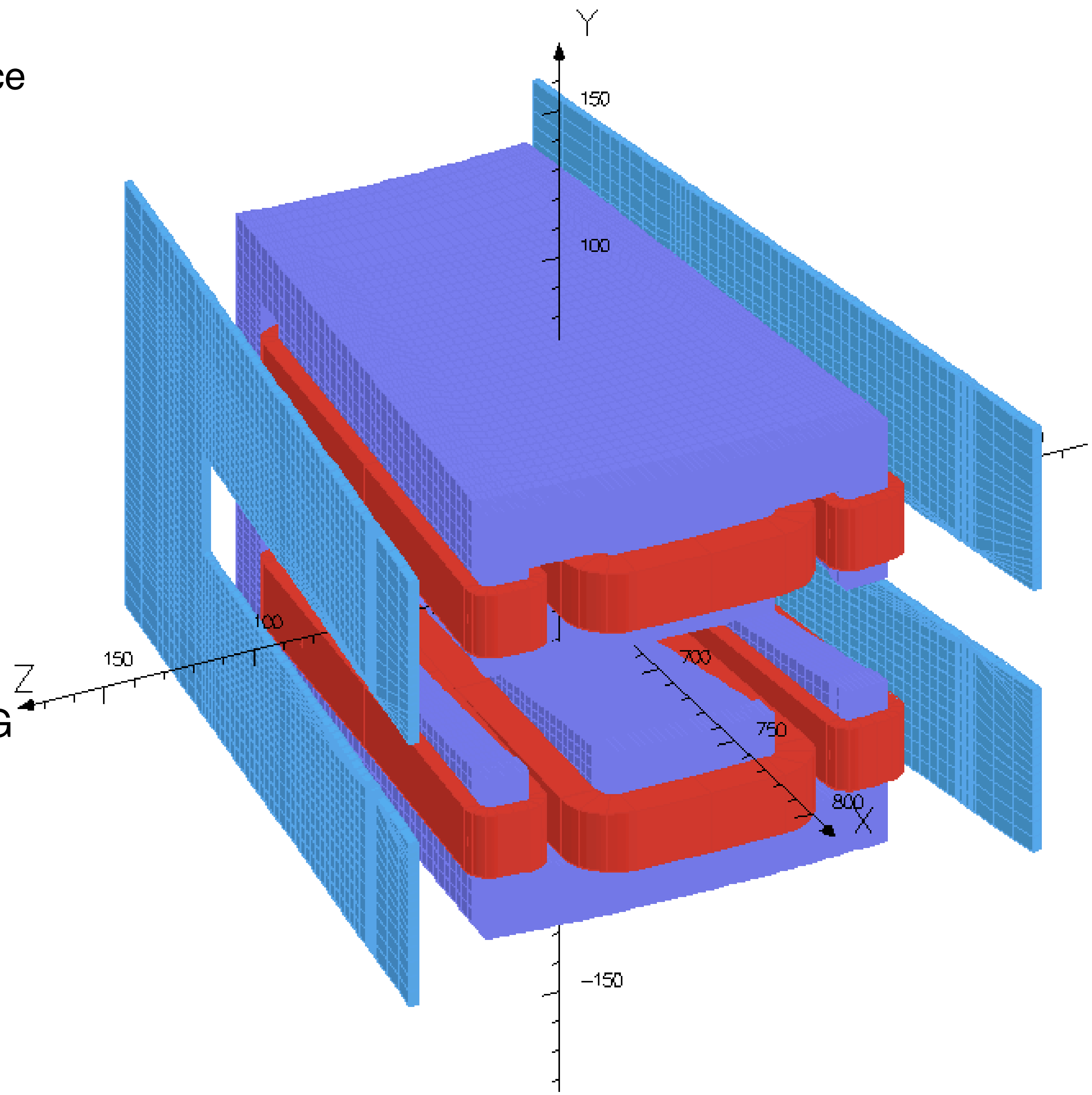
F/D ratio is variable. Ds have field crump effects to realize the large packing factor. the lattice functions has mirror symmetry at the center of a straight section.

large aperture

important for achieve a high intensity muon beam.

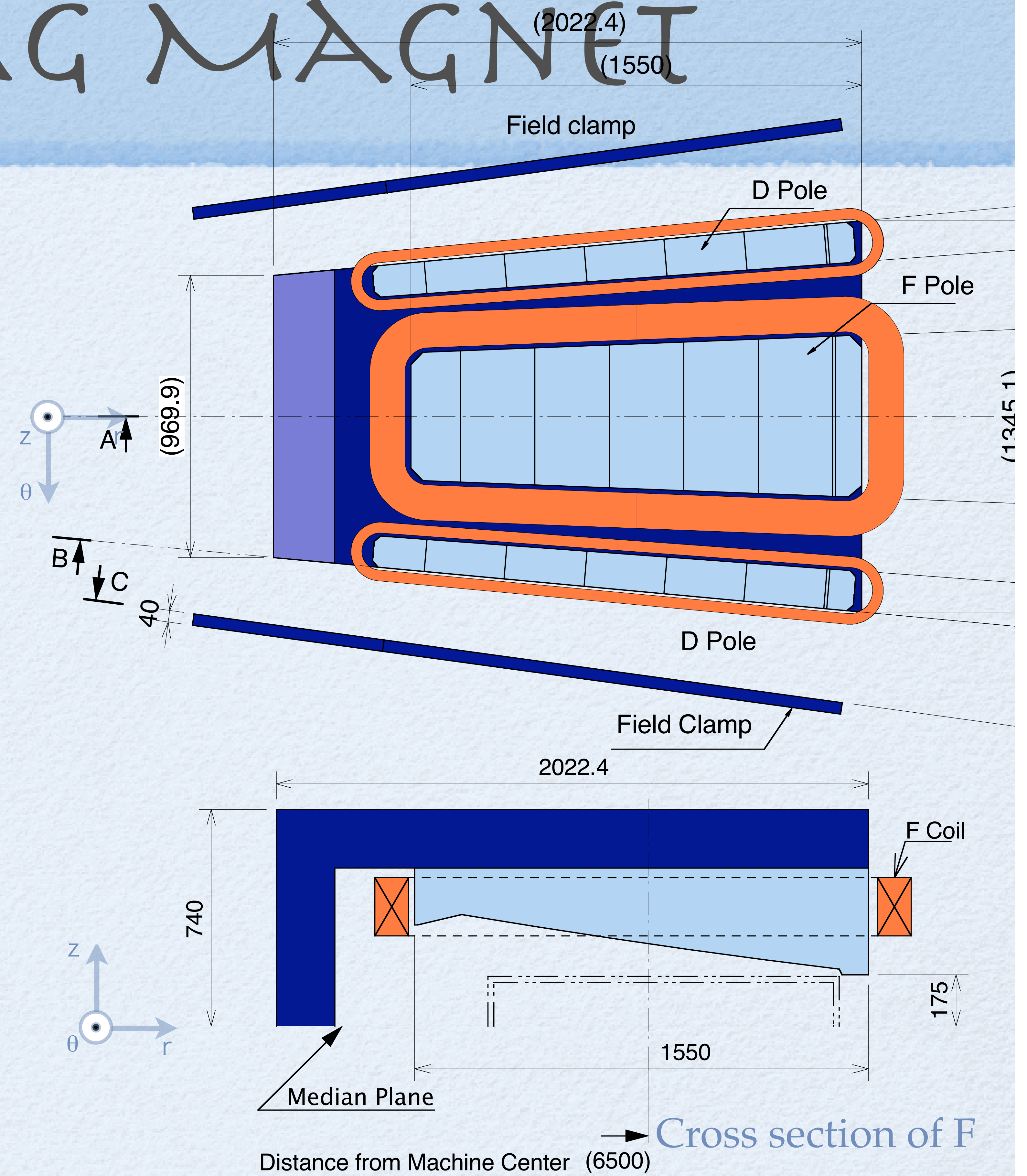
thin

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



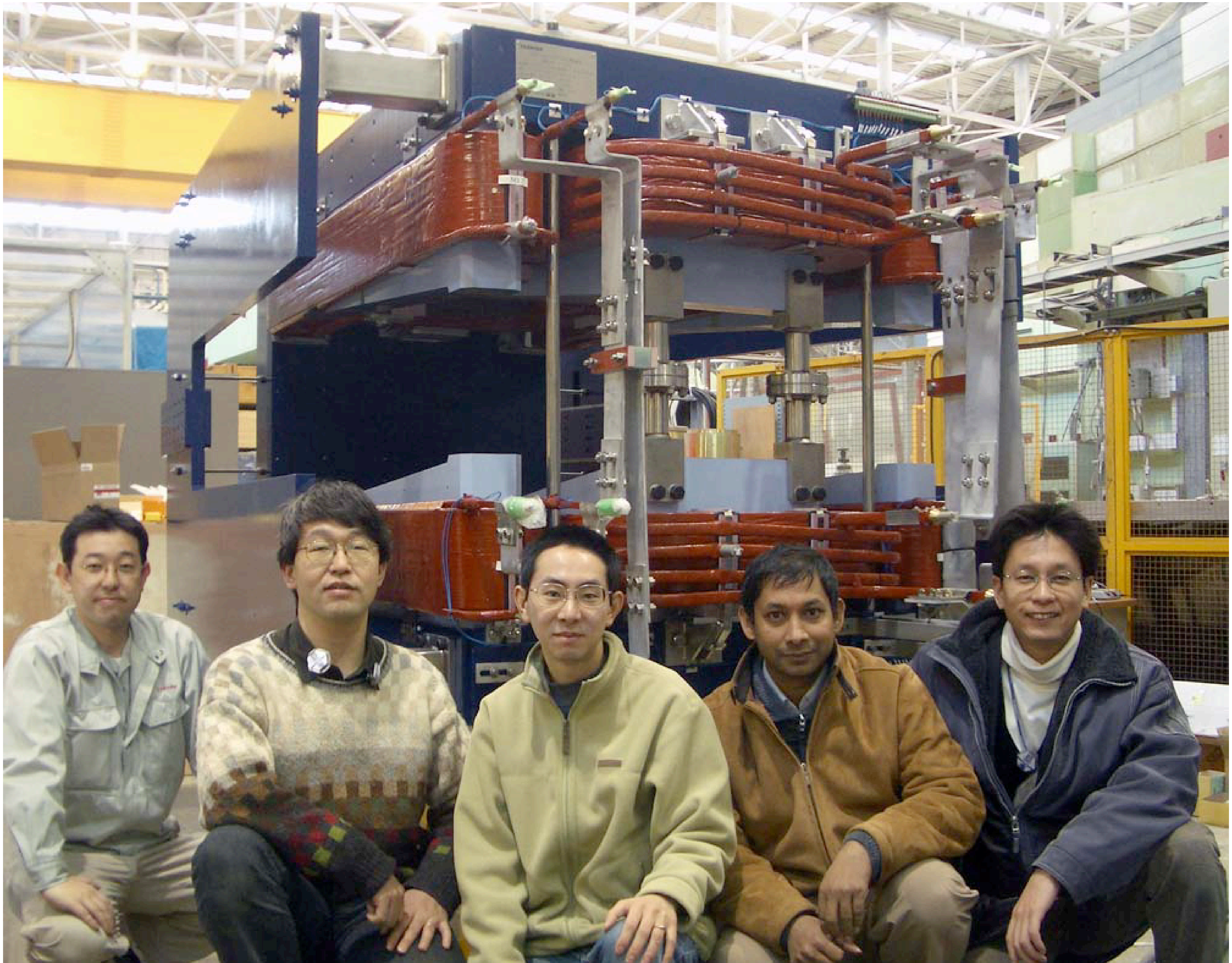
PRISM-FFAG Magnet

- 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

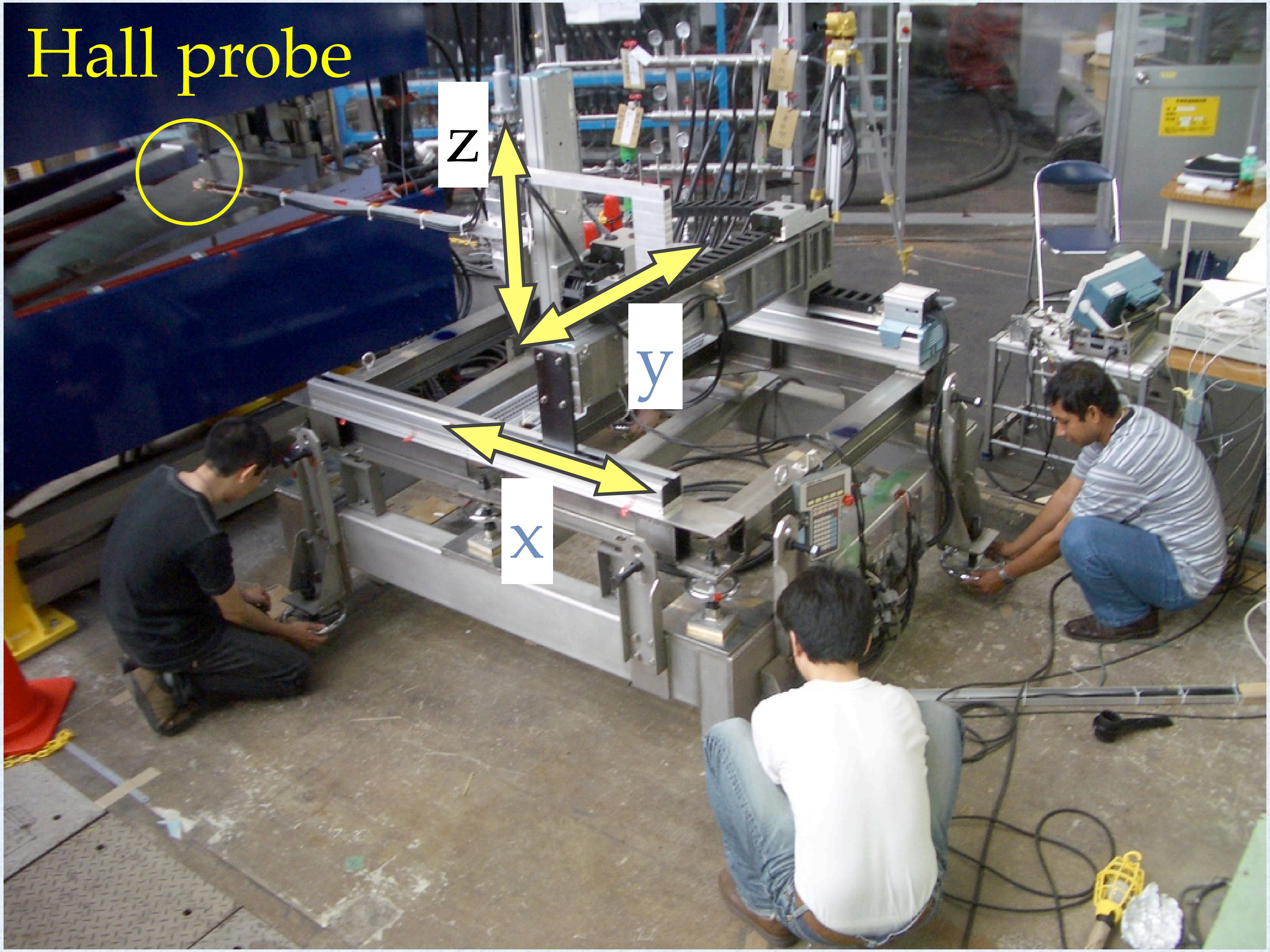


Cross section of F magnet

The First PRISM-FFAG Magnet



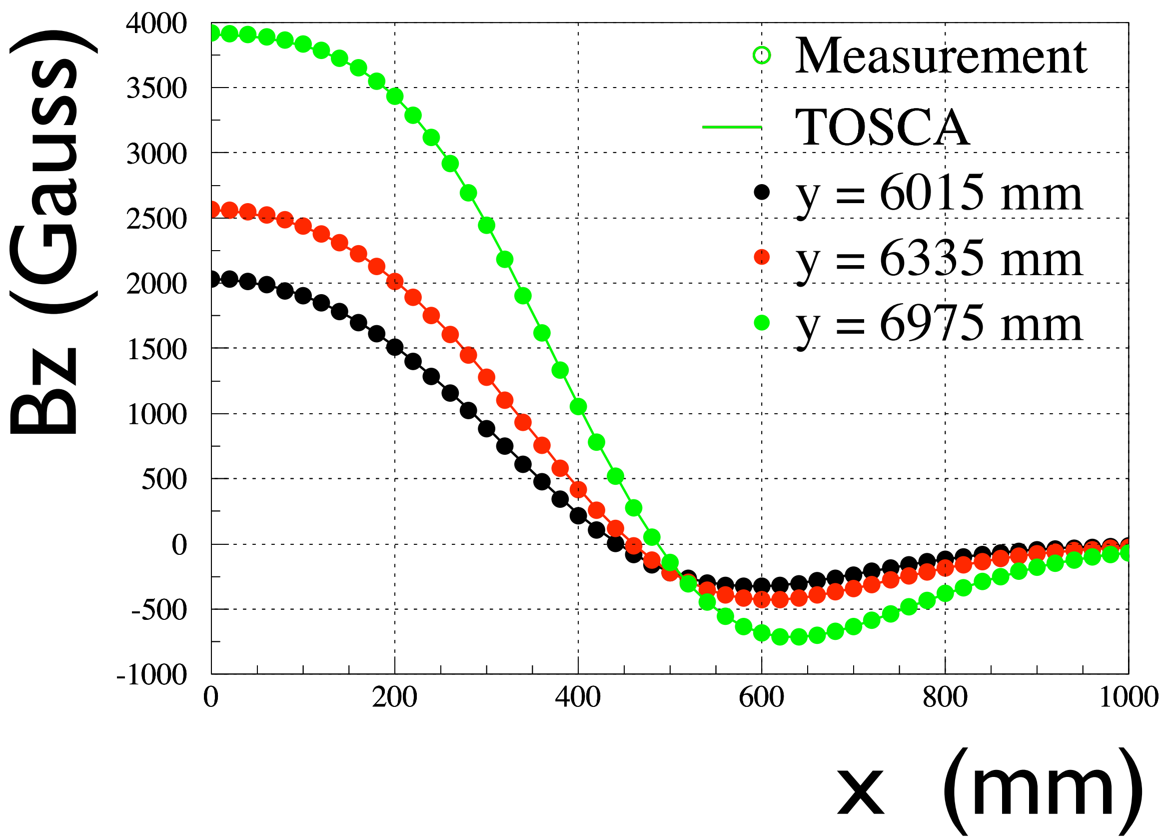
Field Measurements

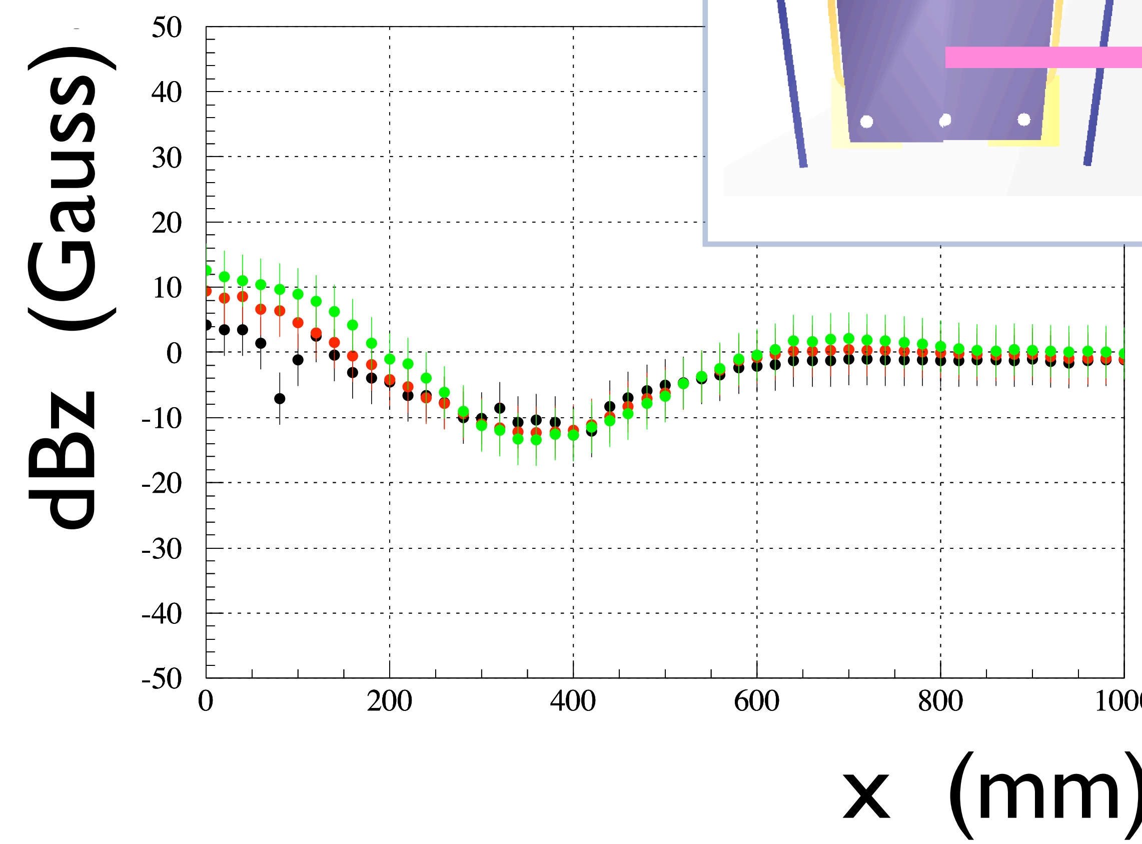


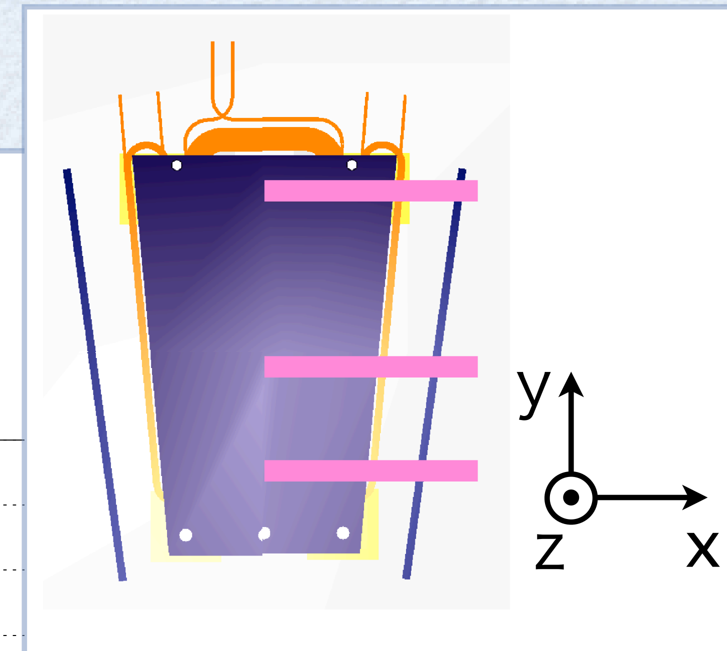
- Alignment tool
  - Theodrite and Autolevel
- Measurement tool
  - 3D axis robot
  - Hall probe : MPT-141 (Group3)

Field Measurements

On median plane

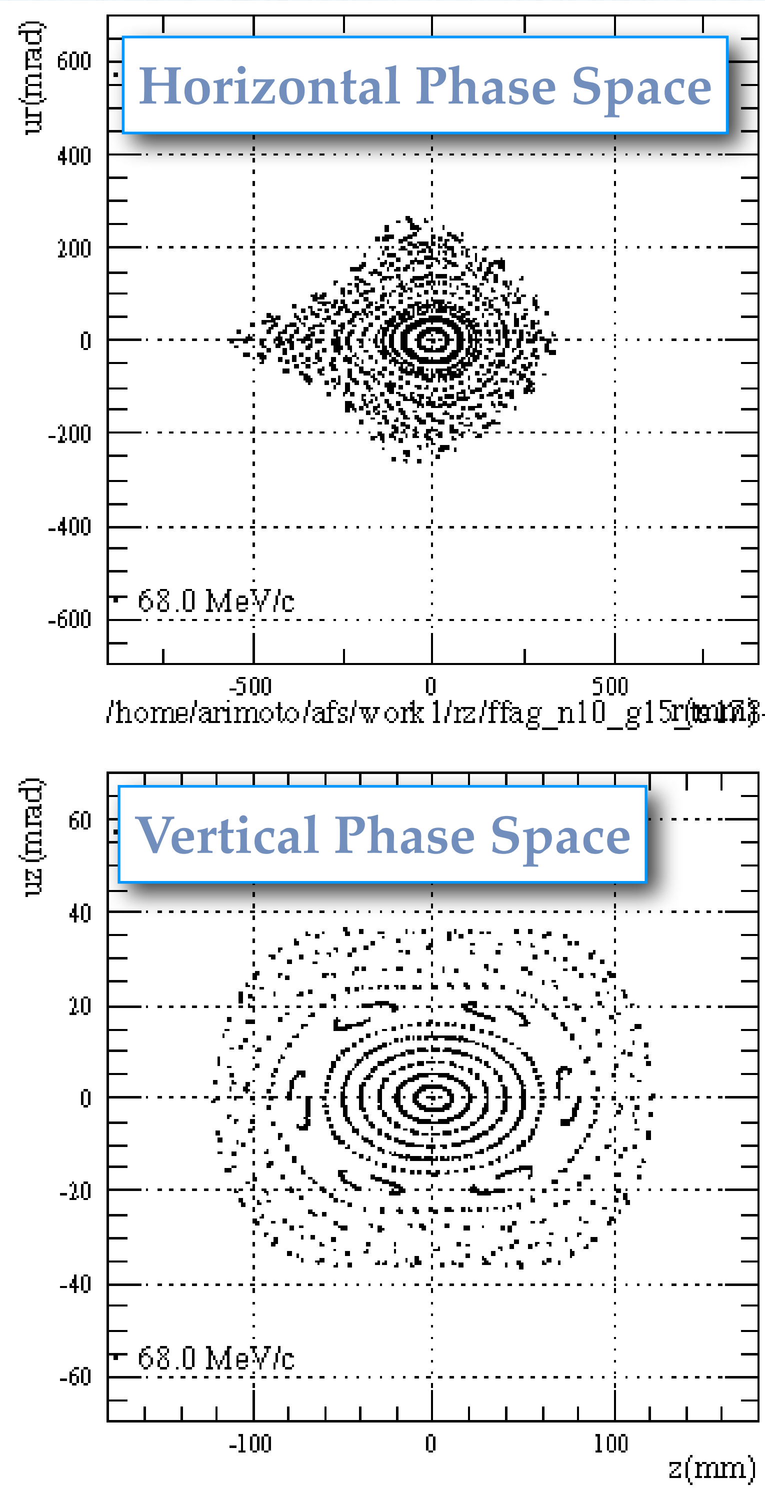


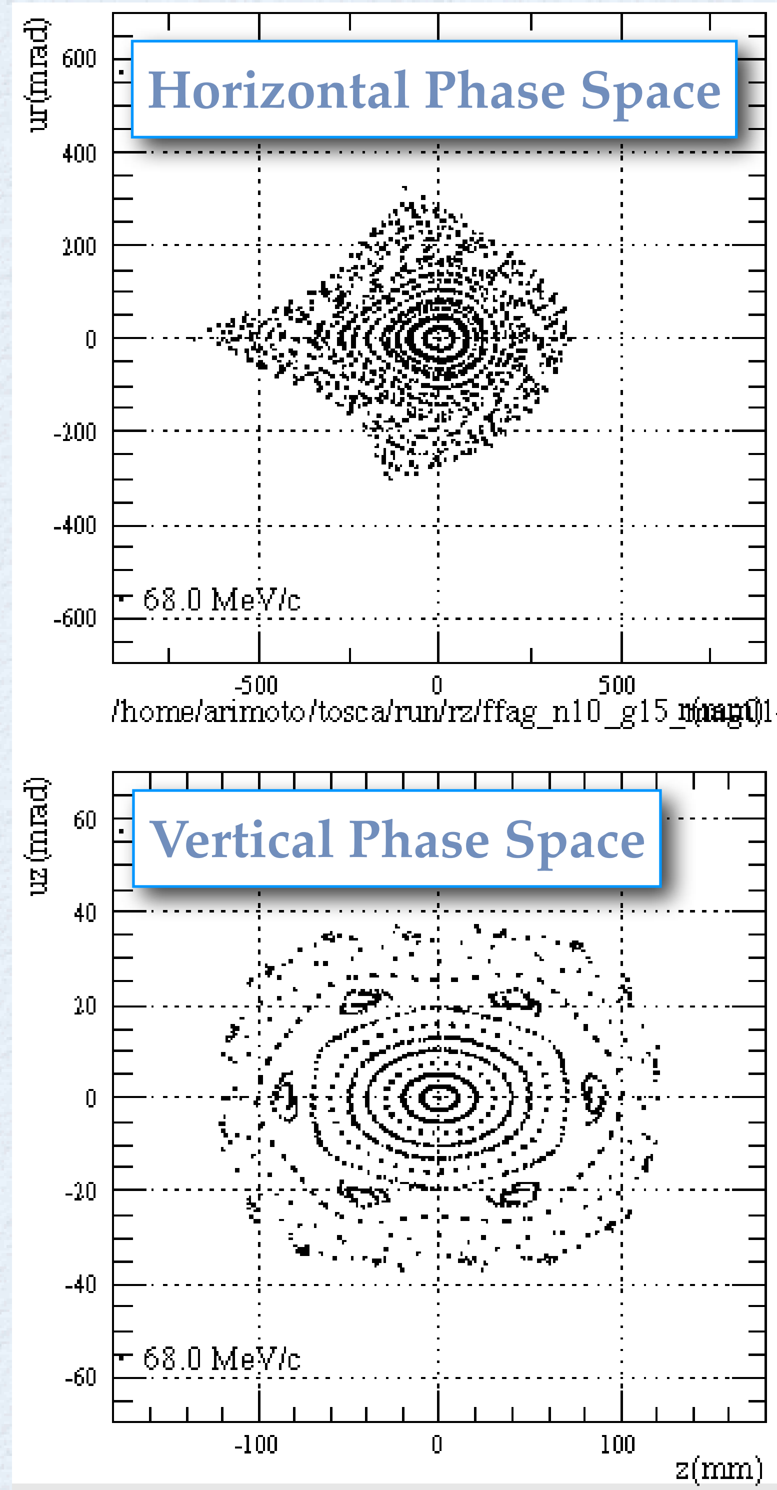




Difference between TOSCA and measurement is about 10 Gauss

Field Measurements : Acceptance

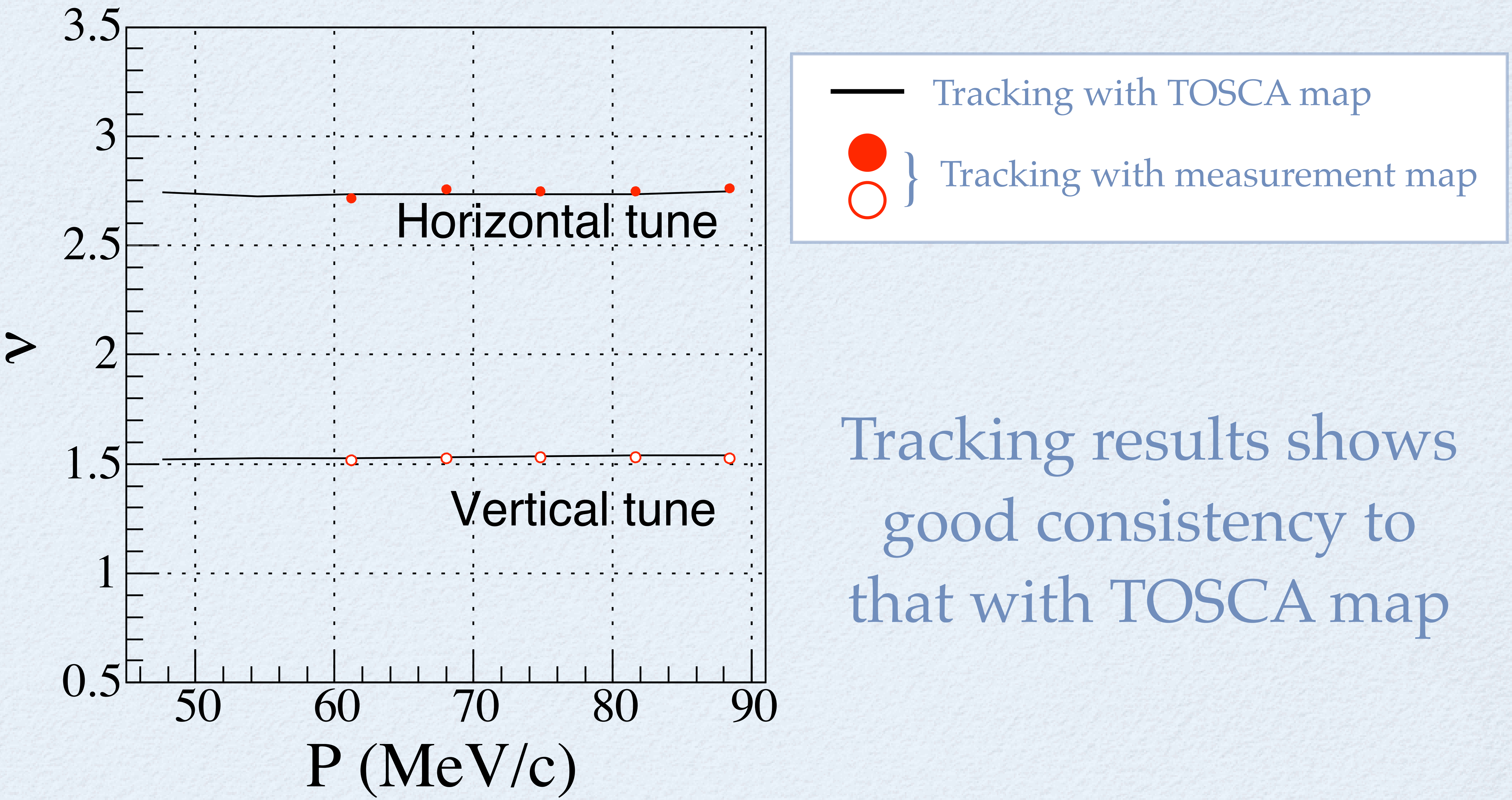




With TOSCA Map   With Measured Map

- by Geant3
- Both of phase-space distribution is almost same.

Field Measurements : Tune



Tracking results shows good consistency to that with TOSCA map

The RF system

Goal of the PRISM-FFAG project

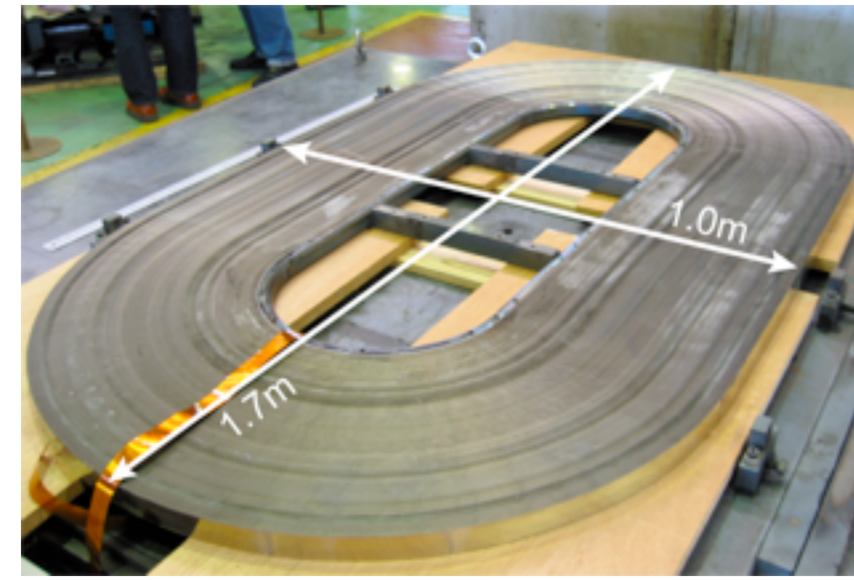
- Construct a full size FFAG ring to be used at the mu-e conv. experiment.
  - with Large transverse and Momentum acceptance
  - suitable for the phase rotator
- Develop a high-gradient RF system (-200kV/m)
- Demonstrate phase-rotation, which make narrower energy spread beam

10-cell FFAG ring ----> 6-cell FFAG ring

For the PRISM-Phase2 we need 10-cell ring with full RF system as a muon phase-rotator.

ハイブリッド空洞による4MHz sawtooth試験

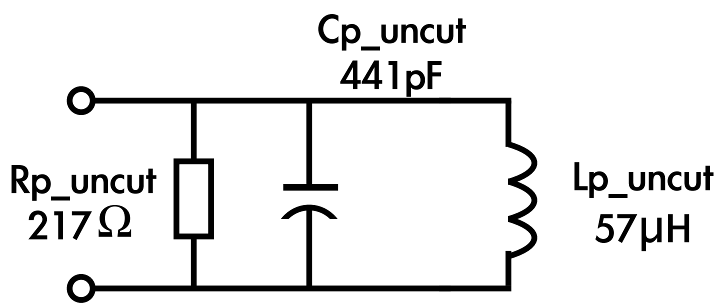
- ミューオンビームの高輝度化に必要なRF
  - 高電場勾配：＞170kV/m @4MHz
  - Sawtooth-RF電場
- Magnetic Alloy コアによる空洞を採用
  - Q値＜１：高調波の印加が可能
  - 大口径大型コア
- 共振周波数の調整
  - 解1：カットコア
    - J-PARC MRで採用、切断費用大
  - 解2：共振回路外付けハイブリッド空洞
    - J-PARC RCSで試験済み、PRISMに応用



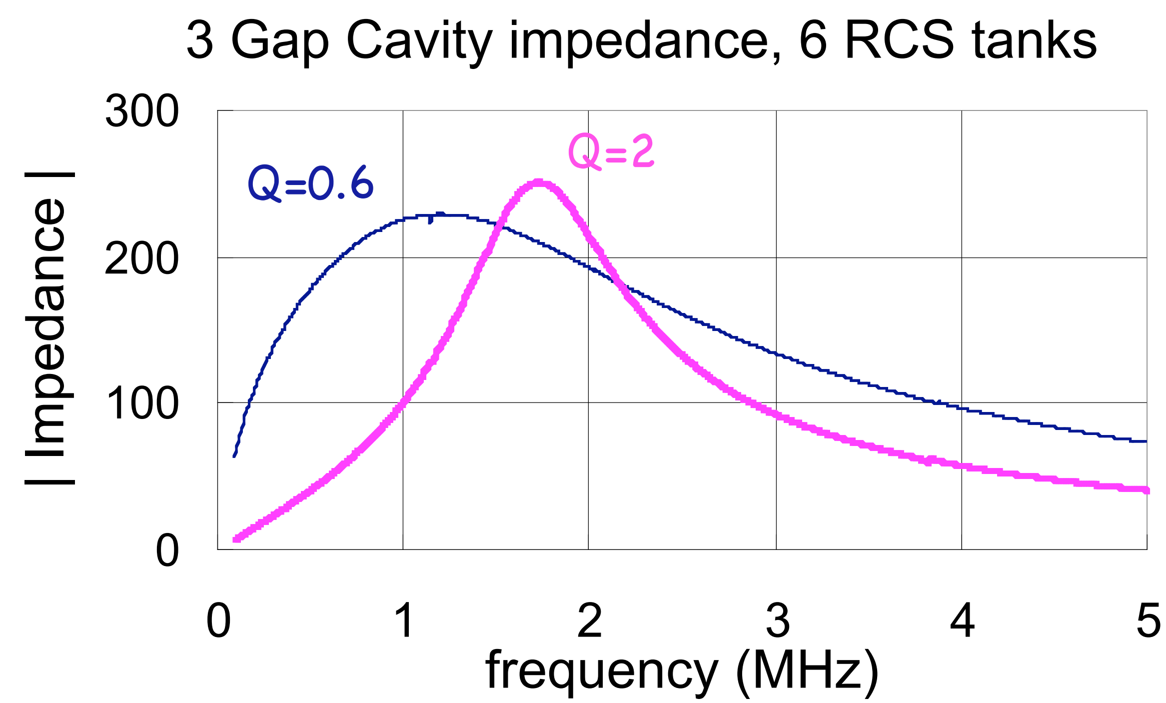
J-PARC RCSのテスト結果

Parallel L Configuration

- Equivalent circuit of 3-gap system with un-cores



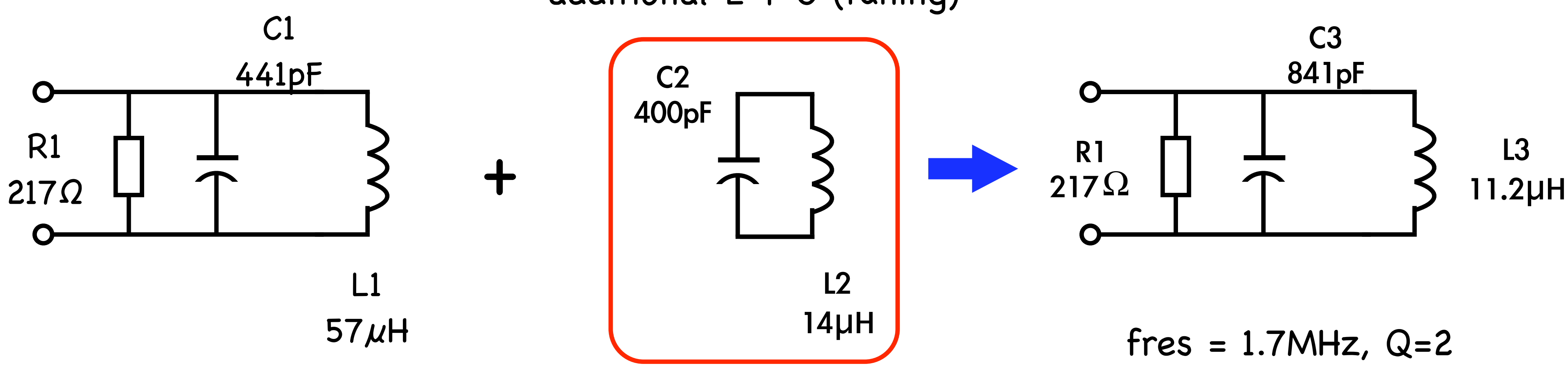
fres = 1.0MHz, Q=0.6



- Equivalent circuit of Parallel L set-up

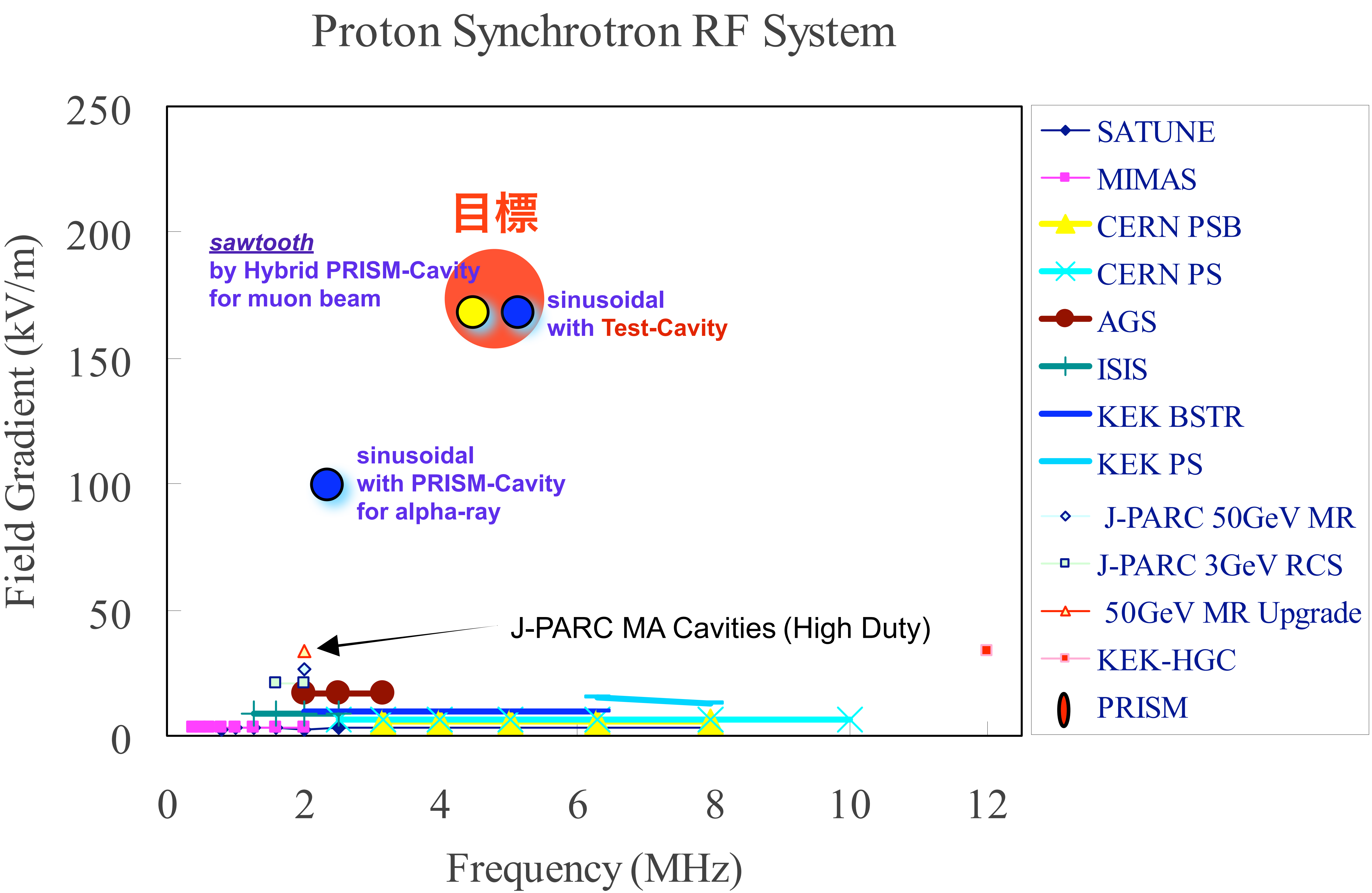
$Q = R_3/\omega L_3$

additional L + C (tuning)



fres = 1.7MHz, Q=2

ハイブリッド空洞による4MHz sawtooth試験



Evaluation of PRISM-FFAG - using one magnet and alpha particles

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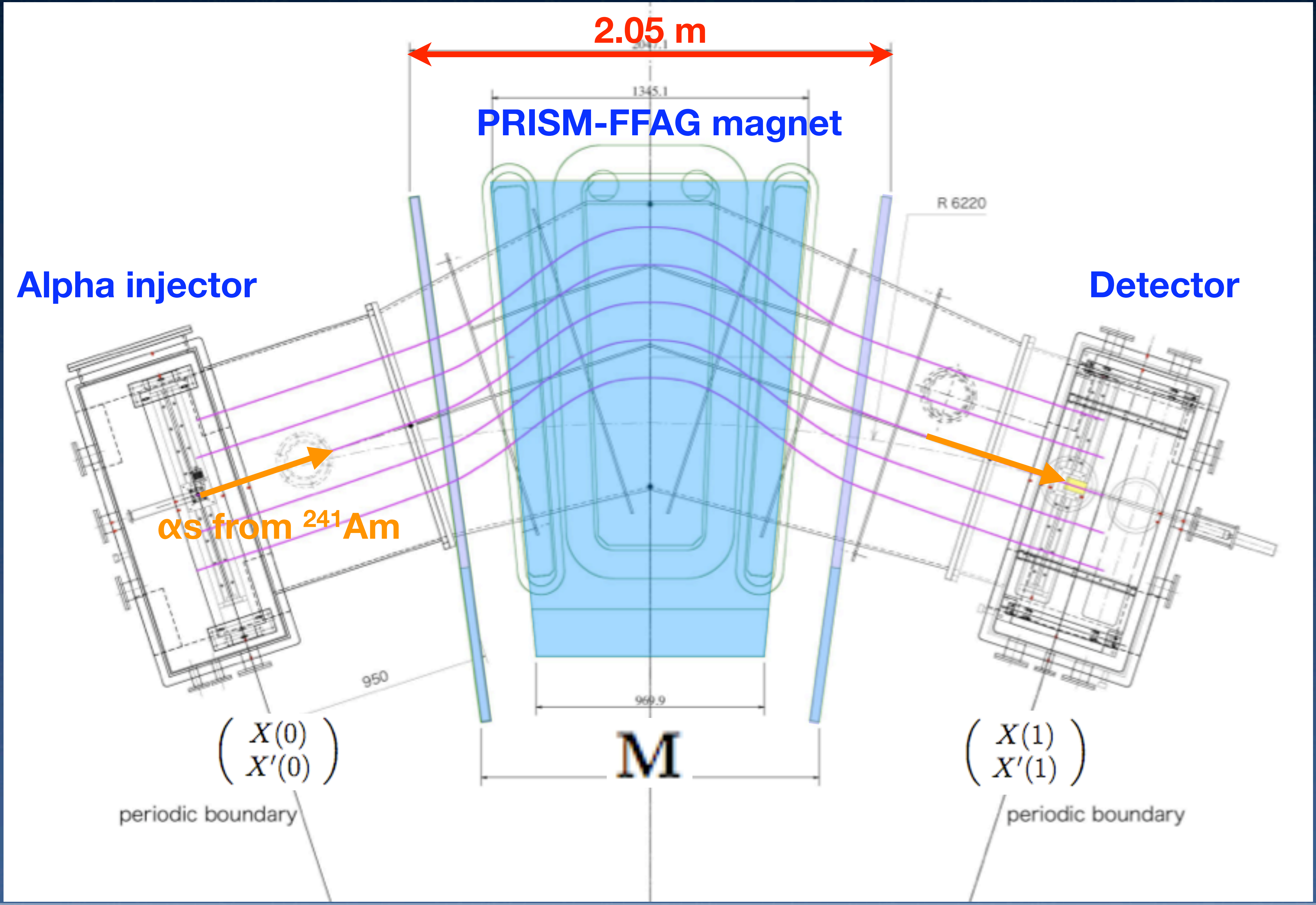
Osaka University

FFAG08 - 1st - 5th Sep. 2008, Manchester, UK

1-cell study using alpha particles

- Before the 6-cell PRISM-FFAG study, 1-cell study to evaluate the ring performance was carried out.
- A new method using a standard alpha source was proposed. From a Taylor expanded transfer map, closed orbit, tune, acceptance were determined.
- A main person on this work is by Y. Kuriyama for his Ph.D.. A paper is under preparation now.

Experimental



Alpha injector

- Alpha source : ^{241}Am
- Degrader
- Collimator
- Moving & rotating stages : x, x'

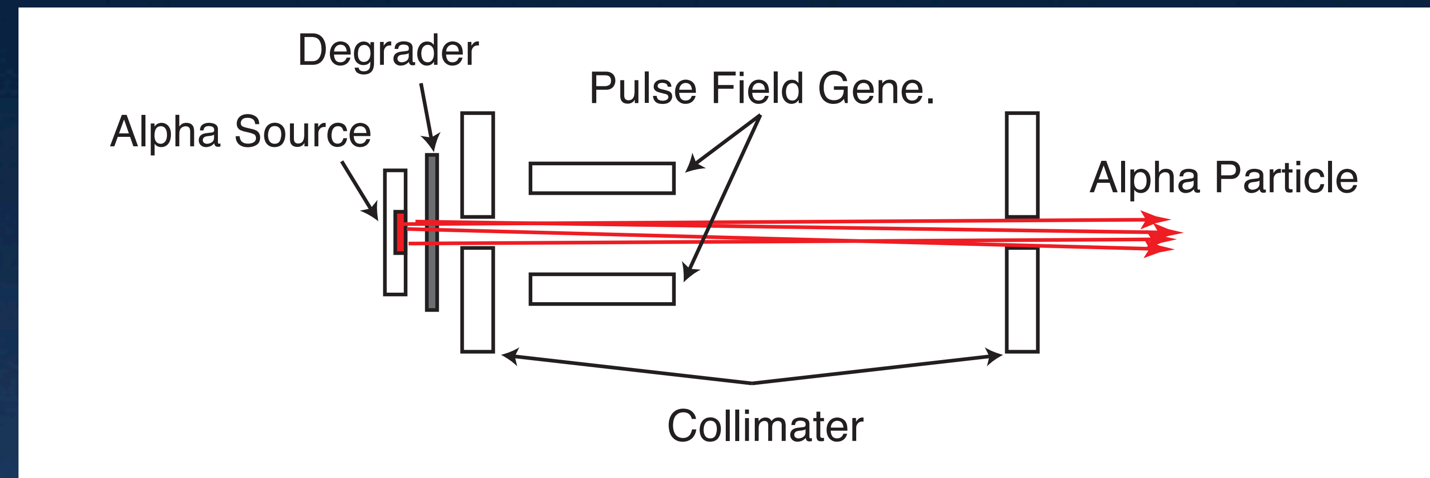
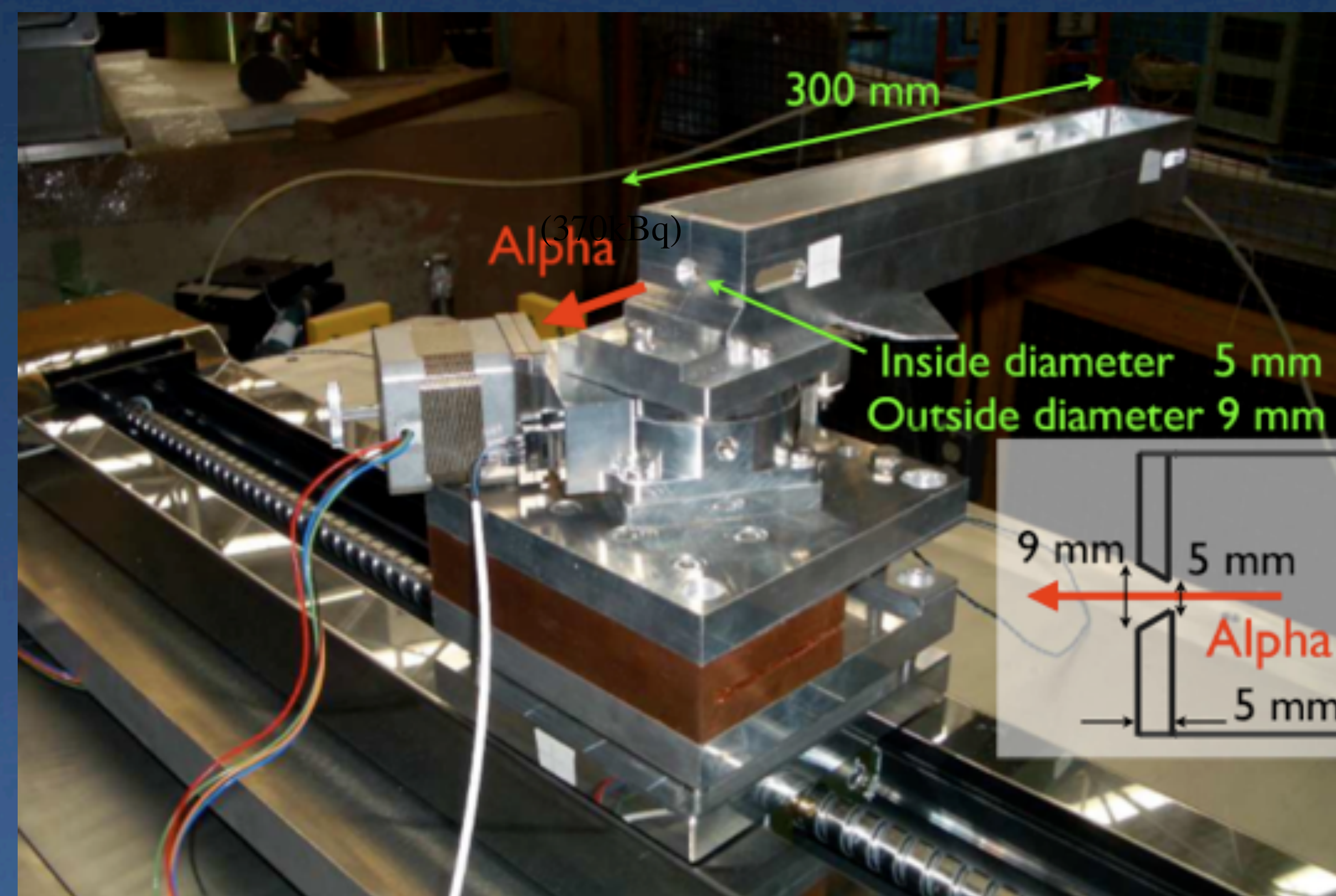


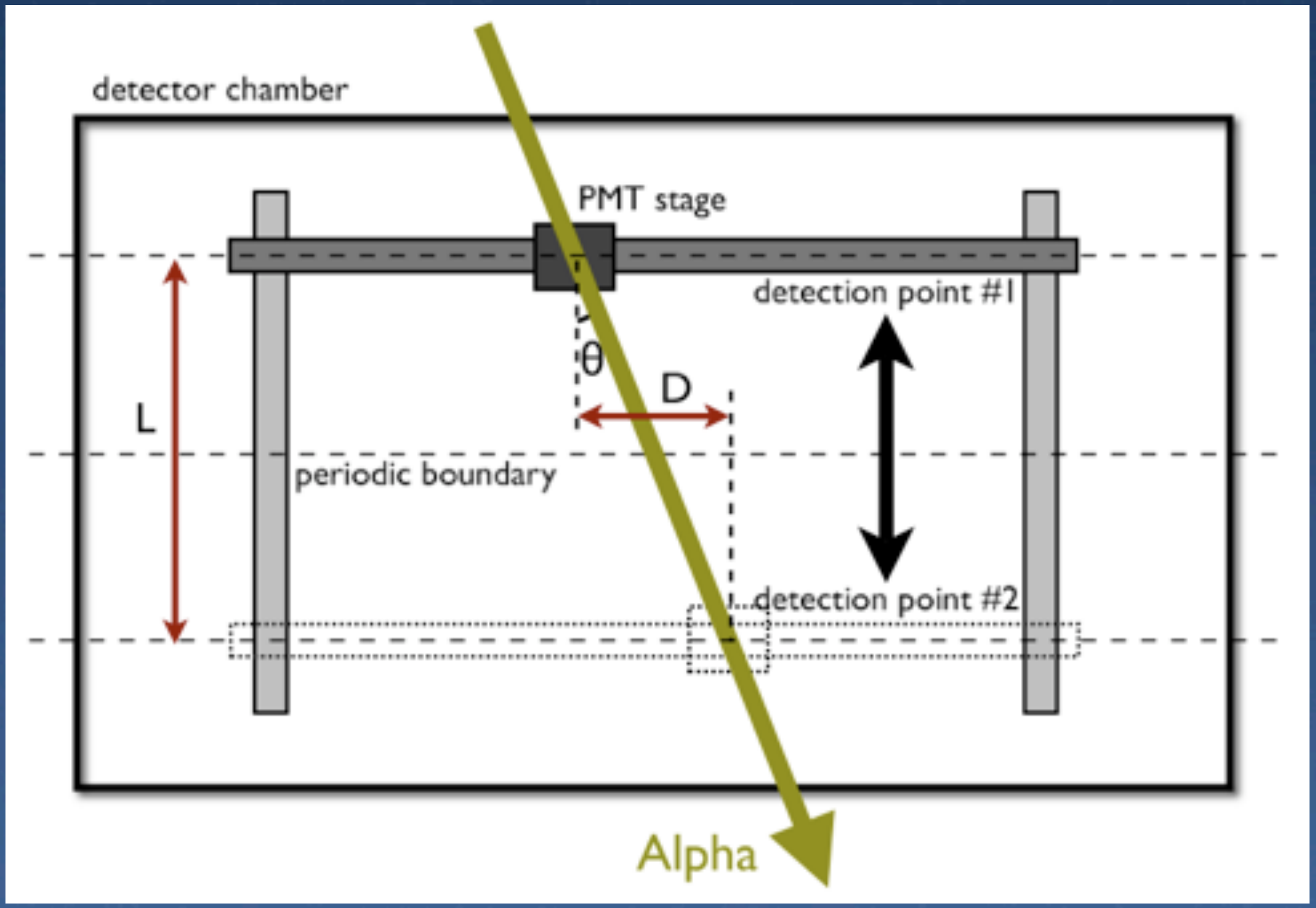
Table 4.4: Specifications of the alpha ray injector

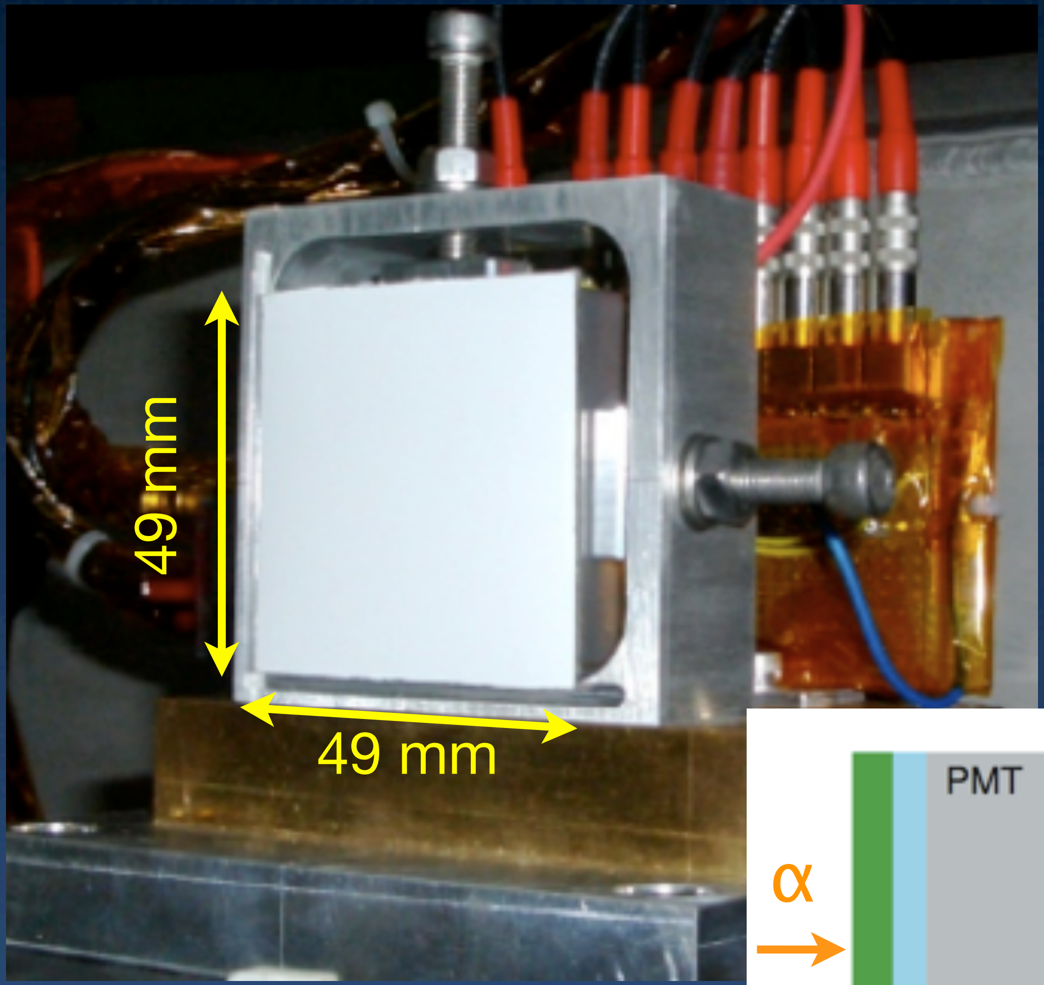
Alpha source	^{241}Am 5.486 MeV (85.2%)
Energy moderator	
Material	Aramid film
Thickness	21 μm
Energy loss	2.950 MeV
Average alpha energy	2.536 MeV
FWHM of alpha energy	0.121 MeV
Collimator	
Number of collimators	2
Diameter	5 mm ϕ
Interval	300 mm
Robots	
Stroke	800 mm along radius direction
Rotation angle	$\pm$ 45 degrees

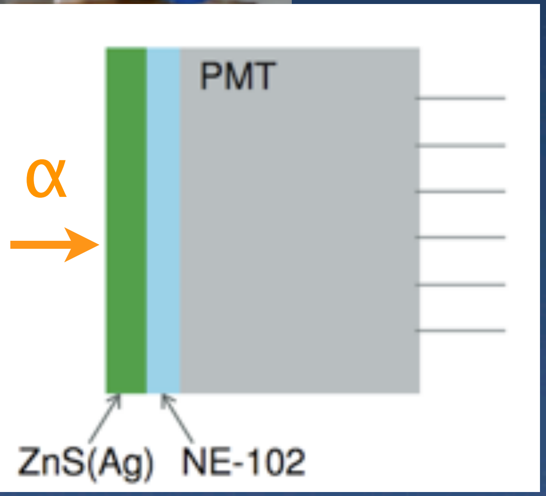


Detector

- Position sensitive detector
  - Multi anode PMT
  - phoswitch (ZnS(Ag)+Plastic)
  - charge ration method
- Moving stages : x, L







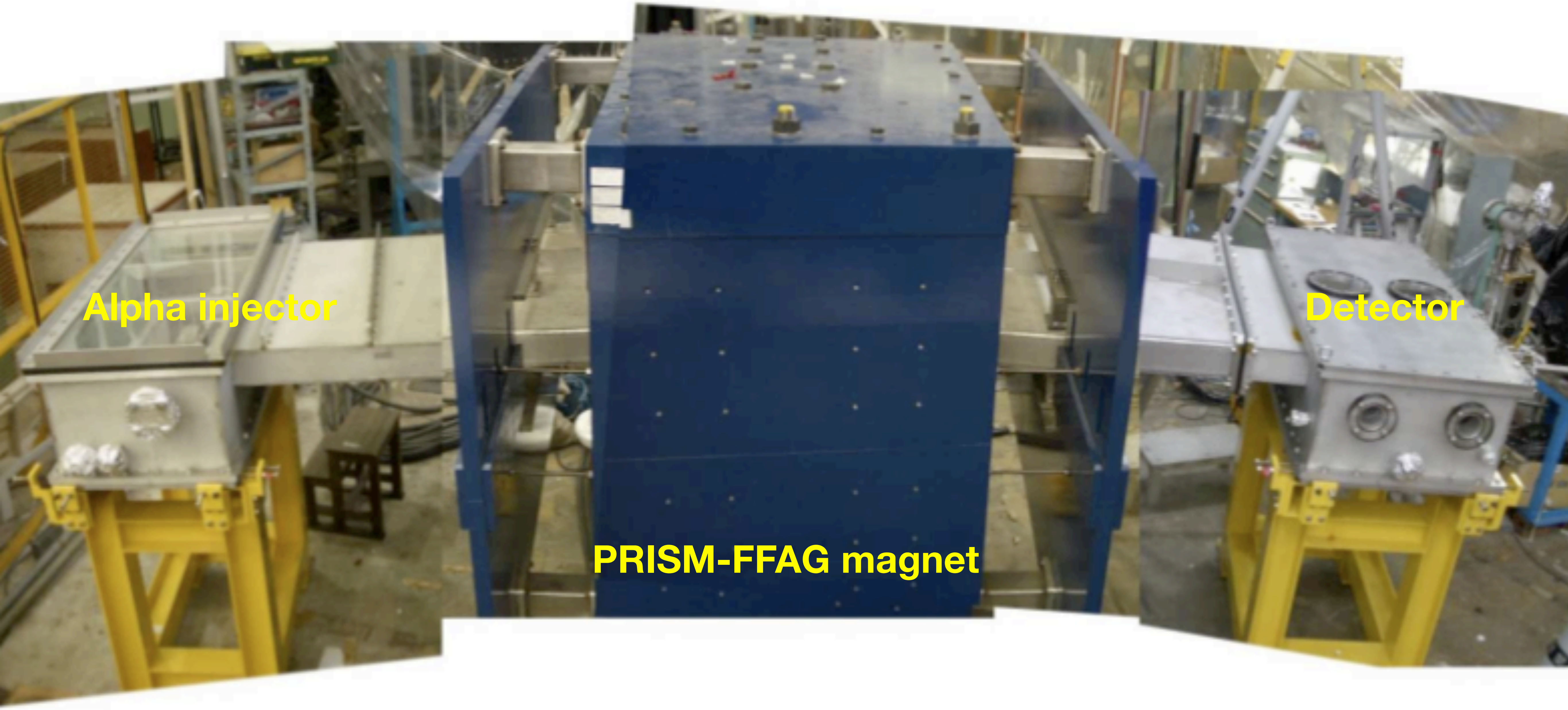
Achieved resolution

σ_x = 0.2-0.4 mm

$\sigma_{x'}$ = 1.6 - 2.6 mrad

with 1.4 x 10^4 alpha events

Experimental apparatus



- Data taking : 23 Jul. - 15 Sep. 2007
- at K2 area, KEK

Truncated Taylor map with Symplectic Condition

- To estimate the ring performance from the data of alpha particles, a transfer map of truncated Taylor expansion was used.

$$\begin{pmatrix} X(1) \\ X'(1) \end{pmatrix} = \mathbf{M} \begin{pmatrix} X(0) \\ X'(0) \end{pmatrix}, \quad \mathbf{M} = \begin{pmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{pmatrix}$$

$$\begin{aligned} X(1) &= R_{11}X(0) + R_{12}X'(0), \\ X'(1) &= R_{21}X(0) + R_{22}X'(0). \end{aligned}$$

- Taylor expansion :

$$X_a(1) = \sum_b R_{ab}X_b(0) + \sum_{b,c} T_{abc}X_b(0)X_c(0) + \sum_{b,c,d} U_{abcd}X_b(0)X_c(0)X_d(0) + \cdots ,$$

Procedure to get parameters

- 1) Calculation of a linear transfer map (a linear 2×2 transfer matrix)
  - to get equilibrium orbit (unknown param. in fitting)
  - the measured data of relatively small amplitudes were used.
- 2) with the parameters for the equilibrium orbit fixed, a linear chi-square fitting was made. The obtained parameters are used as initial values for higher-order fitting.

Chi-Square definition

To calculate the coefficients of transfer map, the chi-square must be defined. In this study, for the case that transportation particle from $[X_{in}, X'_{in}]$ to $[X_{out}, X'_{out}]$, the chi-square is defined by

$$\chi^2 = \sum_{i=1}^{n} \left(\frac{(\ (X_{cal})_i - (X_{exp})_i\ )^2}{\sigma^2_{X_i}} + \frac{(\ (X'_{cal})_i - (X'_{exp})_i\ )^2}{\sigma^2_{X'_i}} \right), \tag{6.1}$$

where σ_{X_i} and $\sigma_{X'_i}$ are the position and angle resolutions of the measurement, respectively and $(X_{cal})_i$ and $(X'_{cal})_i$ are the calculated position and angle displacement, respectively from the equilibrium orbit, given by

$$\begin{pmatrix} (X_{cal})_i \\ (X'_{cal})_i \end{pmatrix} = \mathbf{M} \begin{pmatrix} (X_{in})_i - X_0 \\ (X'_{in})_i - X'_0 \end{pmatrix} \qquad (i = 1, 2, 3, \cdots), \tag{6.2}$$

where $\mathbf{M}$ is the transfer map, and X_0 and X'_0 are the equilibrium orbit. $(X_{exp})_i$ and $(X'_{exp})_i$ are the measured position and angle displacements from the equilibrium orbit, given by

$$\begin{aligned} (X_{exp})_i &= (X_{out})_i - X_0 \\ (X'_{exp})_i &= (X'_{out)})_i - X'_0 \qquad (i = 1, 2, 3, \cdots) \end{aligned} \tag{6.3}$$

Symplectic condition

- To get a long-term stability to predict dynamic aperture for circular accelerator, the symplectic condition is required for the transfer map.

The symplectic condition is required by the conservation of Hamiltonian describing a beam. Then the transfer map should be constrained by the symplectic condition. By defining a Jacobian matrix $\mathbf{J}$ of the transfer map M by

$$J_{ab} = \frac{\partial(X(1))_a}{\partial(X(0))_b}, \tag{7.1}$$

the symplectic condition can be expressed by

$$\mathbf{J}^t(\mathbf{X}(\mathbf{0}))\ \mathbf{S}\ \mathbf{J}(\mathbf{X}(\mathbf{0})) = \mathbf{S} \quad for\ all\ \mathbf{X}(\mathbf{0}), \tag{7.2}$$

where $\mathbf{J}^t$ denotes a transposed matrix of $\mathbf{J}$, and $\mathbf{S}$ is a block matrix expressed by

$$\mathbf{S} = \begin{pmatrix} 0 & \mathbf{I}_n \\ -\mathbf{I}_n & 0 \end{pmatrix}, \tag{7.3}$$

where $\mathbf{I}_n$ is a n-dimensional unit matrix.

To satisfy the condition of Eq.(7.2), the Jacobian matrix $\mathbf{J}$ should have a unit determinant, given by

$$det\ (\mathbf{J}) = 1. \tag{7.4}$$

Considering one-dimension (X, X') system, the Jacobian matrix is expressed by

$$\mathbf{J} = \begin{pmatrix} \frac{\partial X(1)}{\partial X(0)} & \frac{\partial X(1)}{\partial X'(0)} \\ \frac{\partial X'(1)}{\partial X(0)} & \frac{\partial X'(1)}{\partial X(0)} \end{pmatrix}. \tag{7.5}$$

Therefore, the symplectic condition for the linear transfer map can be given by

$$R_{11}R_{22} - R_{12}R_{21} = 1. \tag{7.6}$$

When the transfer map is symplectic, the trajectories of particles in their phase space should be closed and the phase space volume should be conserved. Then the Liouville theorem holds.

Symplectic condition for 2nd order

$$\mathbf{J}_2 = \begin{pmatrix} R_{11} + 2T_{111}X(0) + T_{112}X'(0) & R_{12} + T_{112}X(0) + 2T_{122}X'(0) \\ R_{21} + 2T_{211}X(0) + T_{212}X'(0) & R_{22} + T_{212}X(0) + 2T_{222}X'(0) \end{pmatrix}. \quad (7.7)$$

Therefore, the determinant of $\mathbf{J}_2$ is given by

$$\begin{aligned} &det\ (\mathbf{J}_2) = \\ &X(0)^0 X'(0)^0\ (-R_{12}R_{21} + R_{11}R_{22}) + \\ &X(0)^1 X'(0)^0\ (+2R_{22}T_{111} - R_{21}T_{112} - 2R_{12}T_{211} + R_{11}T_{212}) + \\ &X(0)^0 X'(0)^1\ (+R_{22}T_{112} - 2R_{21}T_{122} - R_{12}T_{212} + 2R_{11}T_{222}) + . \\ &X(0)^2 X'(0)^0\ (-2T_{112}T_{211} + 2T_{111}T_{212}) + \\ &X(0)^1 X'(0)^1\ (-4T_{122}T_{211} + 4T_{111}T_{222}) + \\ &X(0)^0 X'(0)^2\ (-2T_{122}T_{212} + 2T_{112}T_{222}) \end{aligned} \quad (7.8)$$

with the symplectic condition

$$\begin{aligned} 1 &= -R_{12}R_{21} + R_{11}R_{22}, \\ 0 &= +2R_{22}T_{111} - R_{21}T_{112} - 2R_{12}T_{211} + R_{11}T_{212}, \textit{and} \\ 0 &= +R_{22}T_{112} - 2R_{21}T_{122} - R_{12}T_{212} + 2R_{11}T_{222}. \end{aligned} \quad (7.9)$$

Supposing 2nd order is exact, all of the higher order terms should vanish exactly. Then, the necessary and sufficient conditions are

$$\begin{aligned} 0 &= -2T_{112}T_{211} + 2T_{111}T_{212}, \\ 0 &= -4T_{122}T_{211} + 4T_{111}T_{222}, \textit{and} \\ 0 &= -2T_{122}T_{212} + 2T_{112}T_{222}, \end{aligned} \quad (7.10)$$

Table 7.1: Total numbers of the coefficients necessary for a truncated Taylor transfer map

Map Order	1	2	3	4	5
Without symplectic restriction	4	10	18	28	40
With symplectic restriction	3	7	12	18	25

Closed orbit

- Momentum of alpha particles

$$P_{alpha} = 137.50^{+0.02}_{-0.02} \text{ MeV/c.}$$

- obtained closed orbit from the transfer map

$$X_0^{exp} = 6.1902 \pm 0.0001 \quad \text{m} \quad \text{and}$$
$$X_0'^{exp} = -0.0007 \pm 0.0001 \quad \text{rad,}$$

- from Zgoubi with TOSCA field map

$$X_0^{sim} = 6.1970^{+0.0002}_{-0.0001} \quad \text{m,} \quad \text{and}$$
$$X_0'^{sim} = 0.0000^{+0.0001}_{-0.0001} \quad \text{rad.}$$

Acceptance

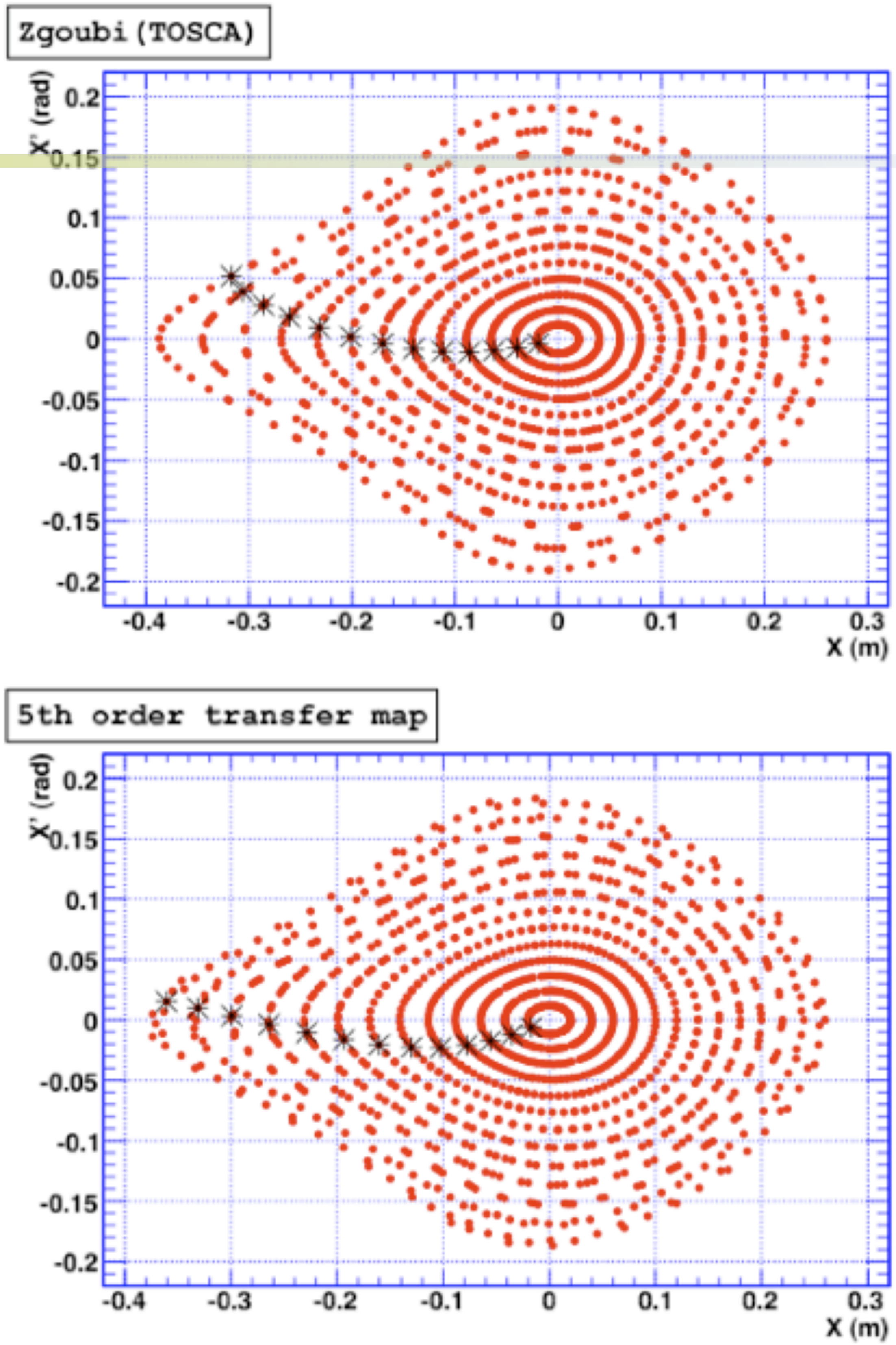


Figure 8.2: The tracking of 13 particles for 10 turns. Black asterisks indicate the positions of particles after passing 6 turns. The upper and lower figures are those of Zgoubi and the truncated Taylor transfer map with the order up to the 5th, respectively.

Tune

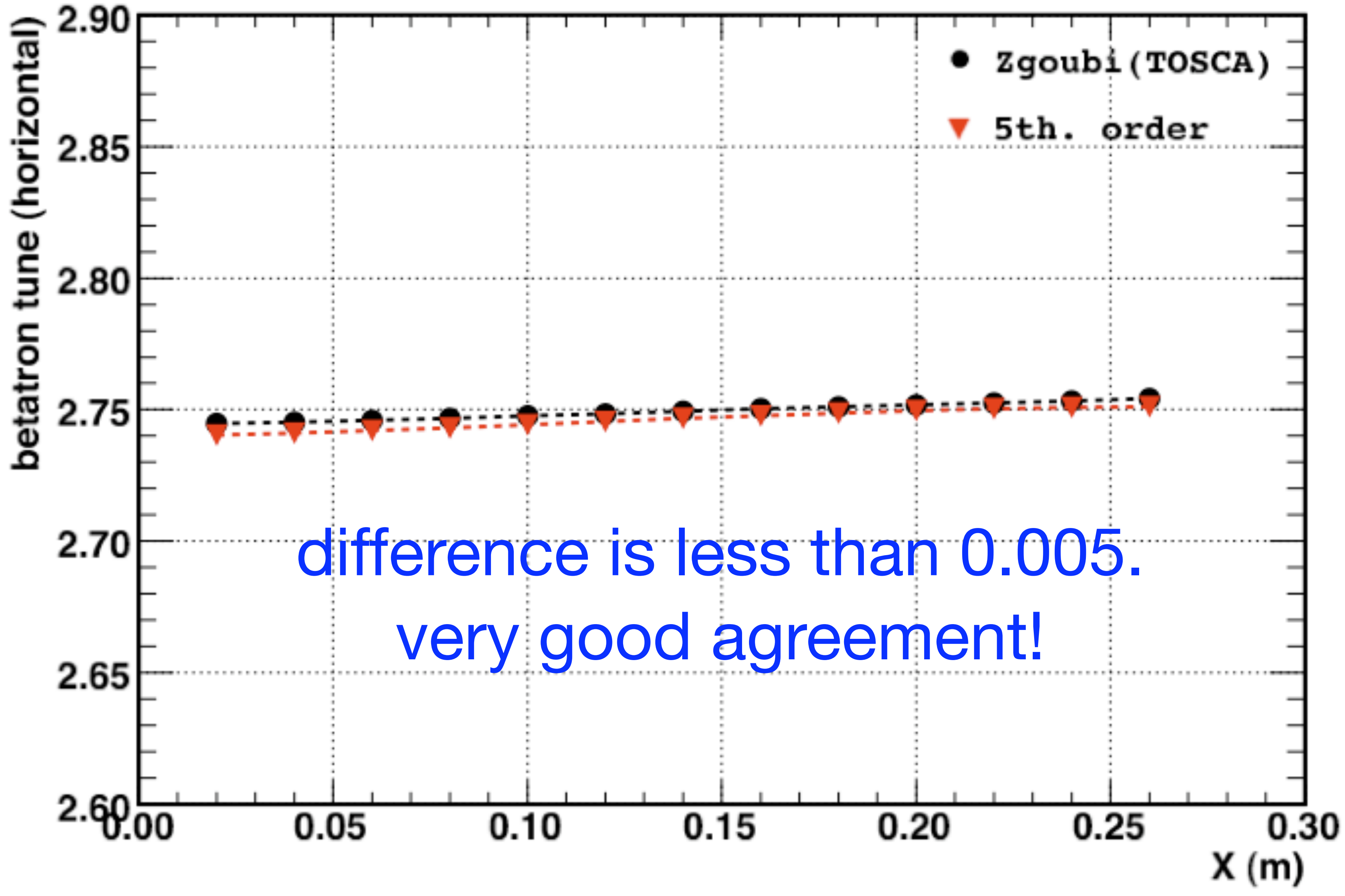
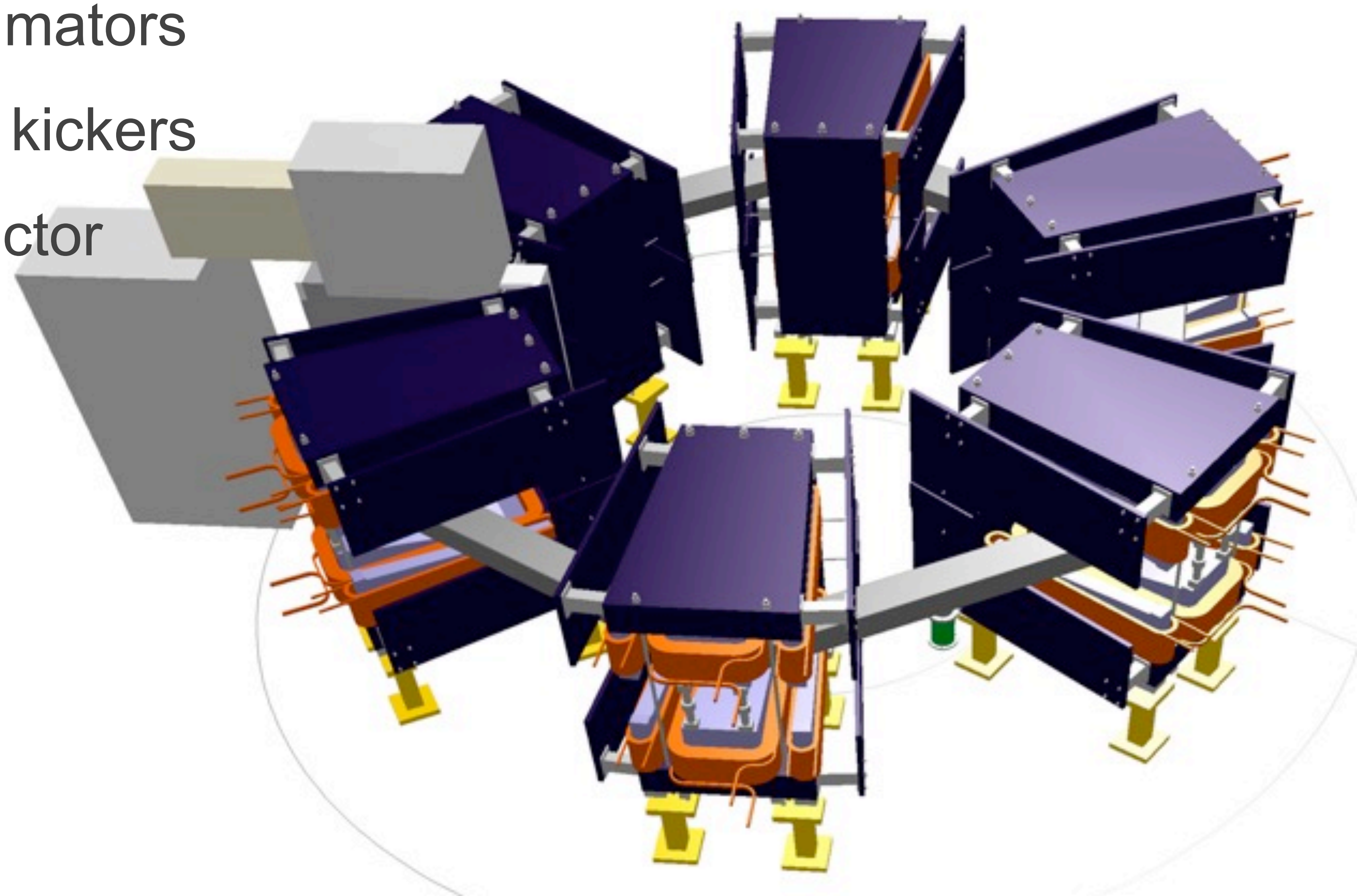


Figure 8.3: Horizontal tune as a function of initial amplitude. Closed circles represent the betatron tunes obtained by Zgoubi, and red triangles represent those obtained by the 5th ordered truncated Taylor transfer map.

6-cell PRISM-FFAG

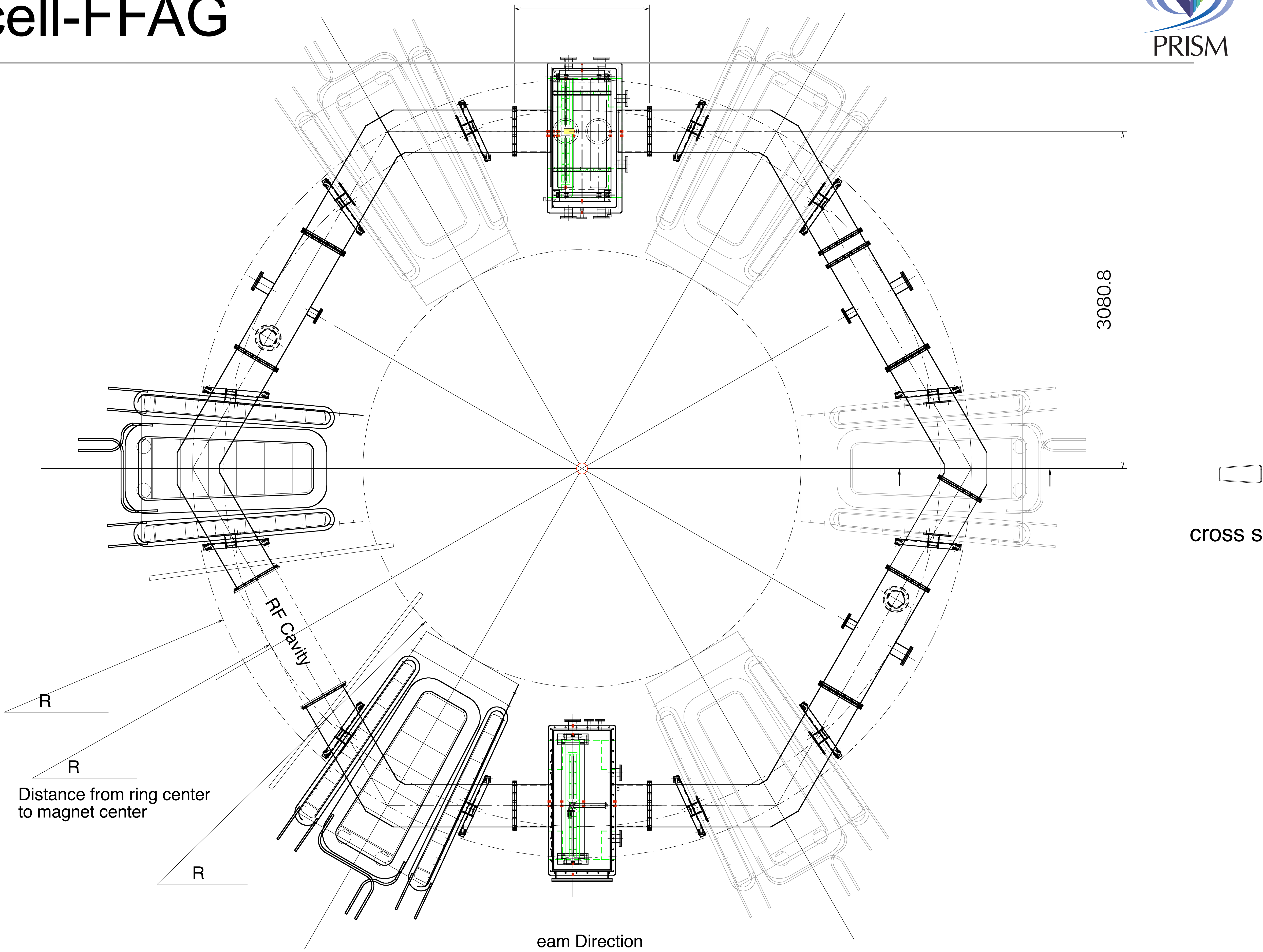
Demo. of Phase Rotation with α-particles

- FFAG-ring
  - PRISM-FFAG Magnet x 6、RF x 1
- Beam : α-particles from radioactive isotopes
  - ^{241}Am 5.48MeV(200MeV/c) → degrade to 100MeV/c
  - small emittance by collimators
  - pulsing by electrostatic kickers
- Detector : Solid state detector
  - energy
  - timing



6cell-FFAG

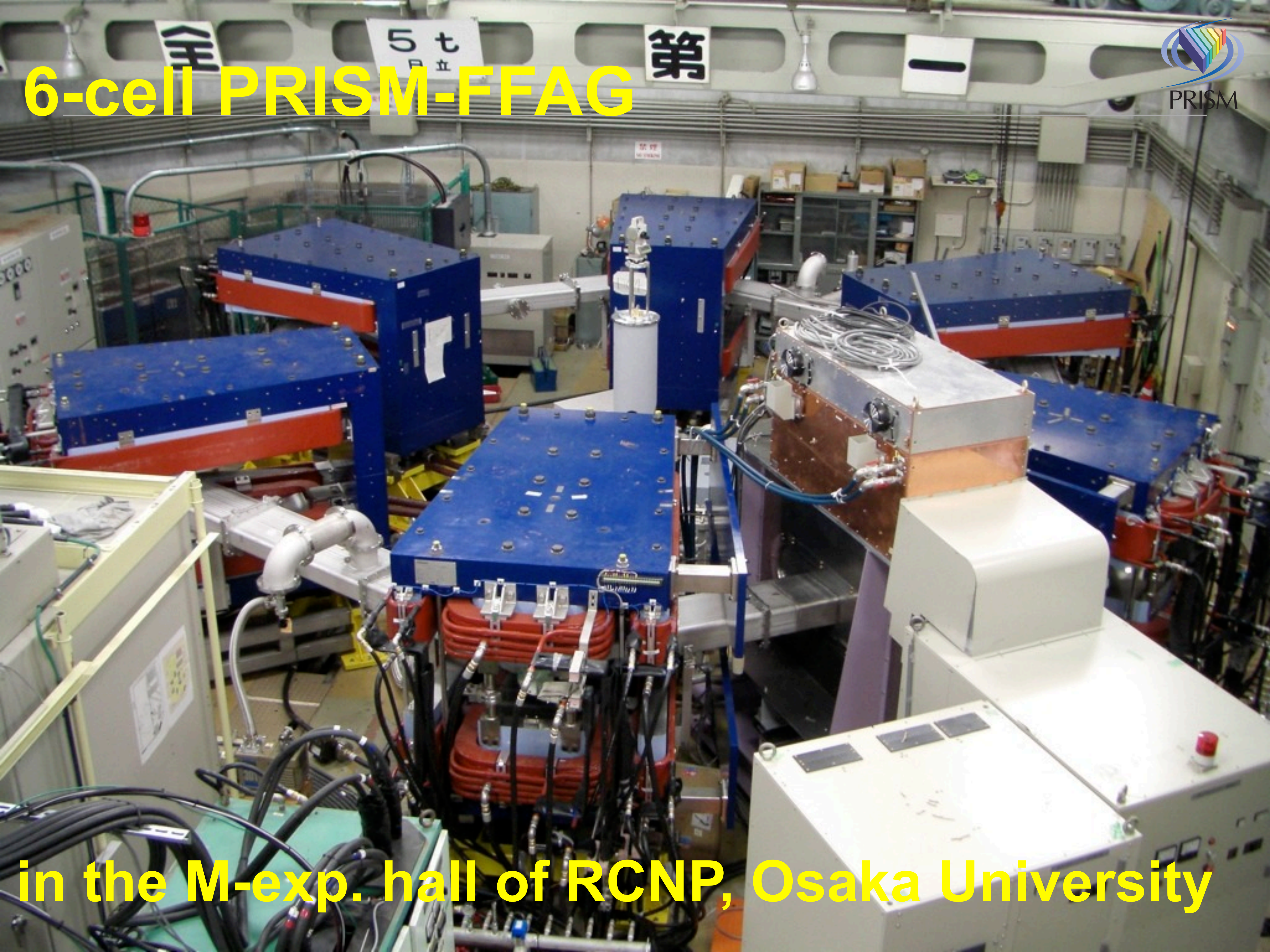
PRISM



Comparison b/w 6-cell and 10-cell FFAG

		Six-Cell FFAG	Full PRISM-FFAG
# of Cells		6	10
Particles		Alpha	Muon
Momentum	MeV/c	100	68
Ring Radius	m	3.5	6.5
Magnet Aperture	cm	100 x 30	100 x30
BL (F)	$\times 10^4$ Gauss/cm	8.53 @r=3.3m	8.55 @r=6.5m
BL (D)		-1.37	-1.43
Field index (k_F/k_D)		1.8 / 1.3	4.6 / 4.6
$\Delta k_F/\Delta k_D$		±0.2 / ±0.3	const.
F/D ratio		6~7	6.0
Field Clamp		Attached to 2 Magnets	Attached to All Magnets

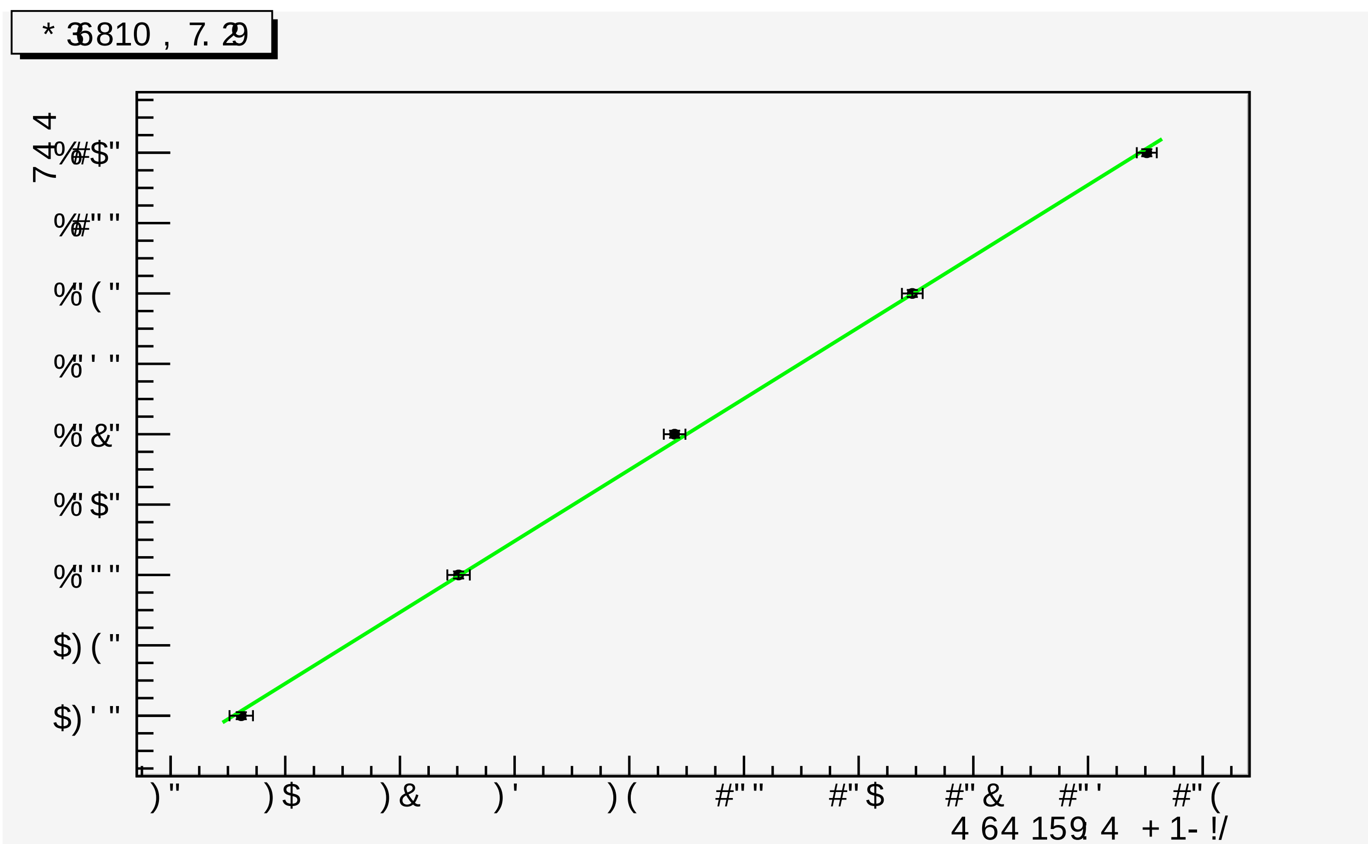
6-cell PRISM-FFAG

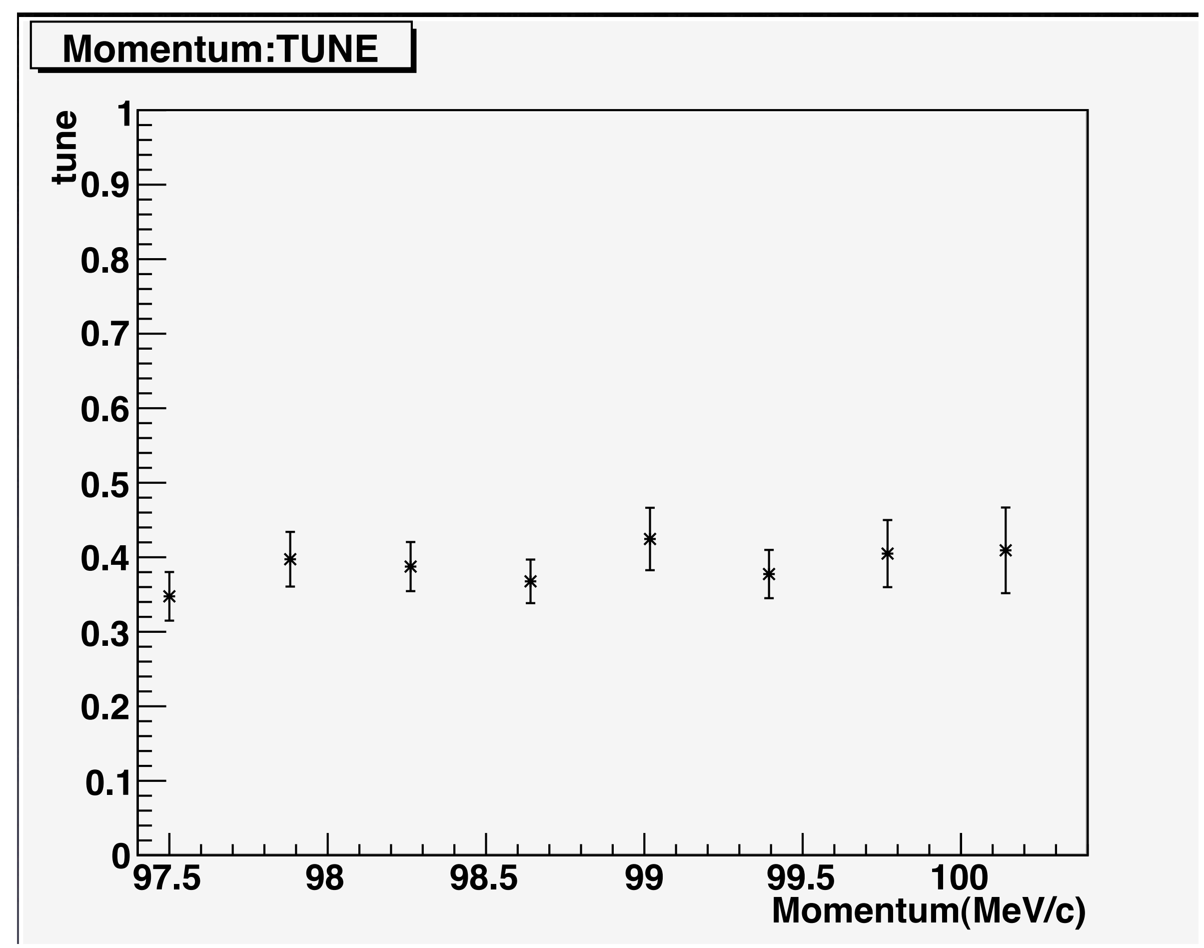


in the M-exp. hall of RCNP, Osaka University

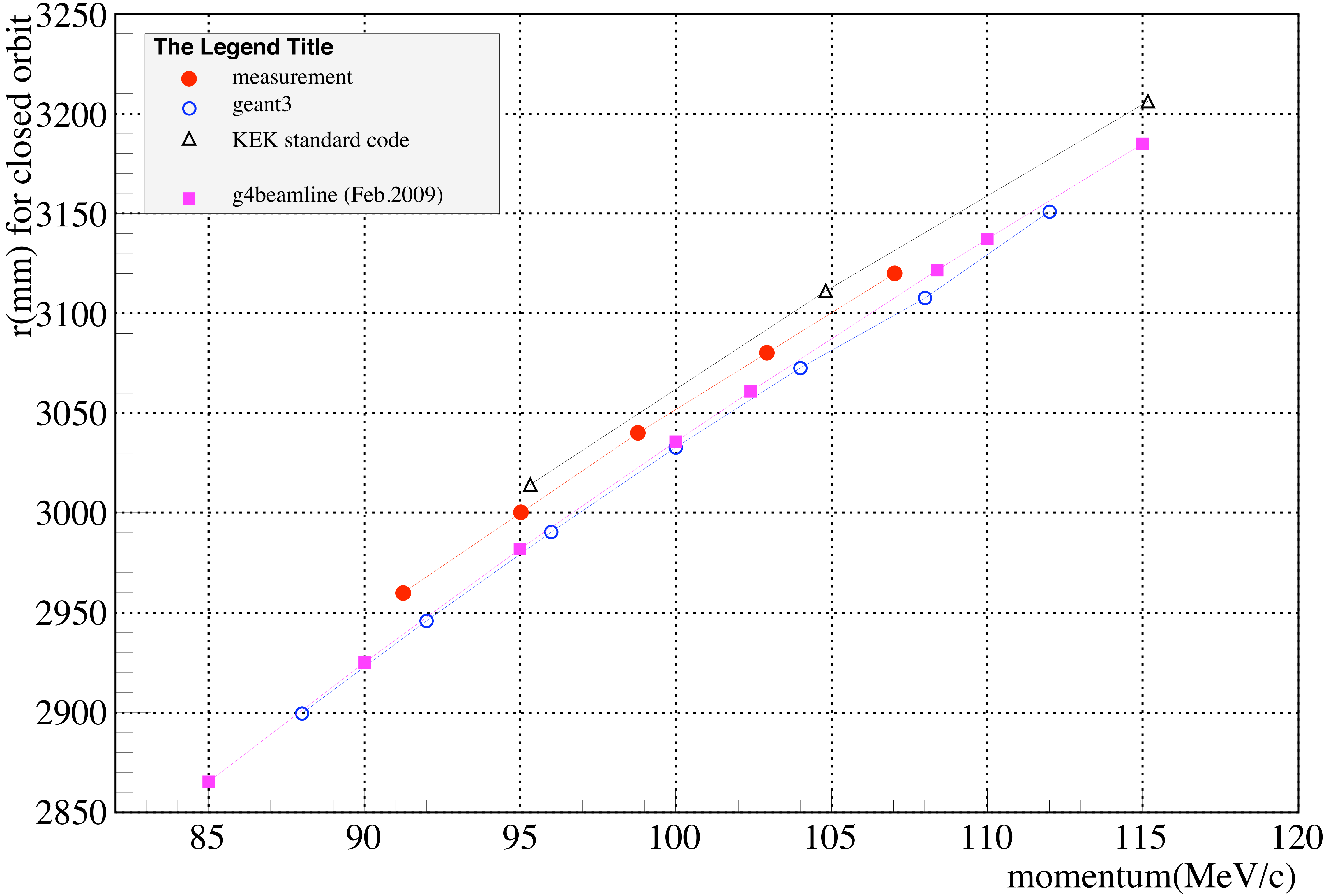
Tune and closed orbit measurements

- At first, horizontal tunes and closed orbit for a several momenta were measured roughly.
- The error is dominated by the energy resolution and statistics.



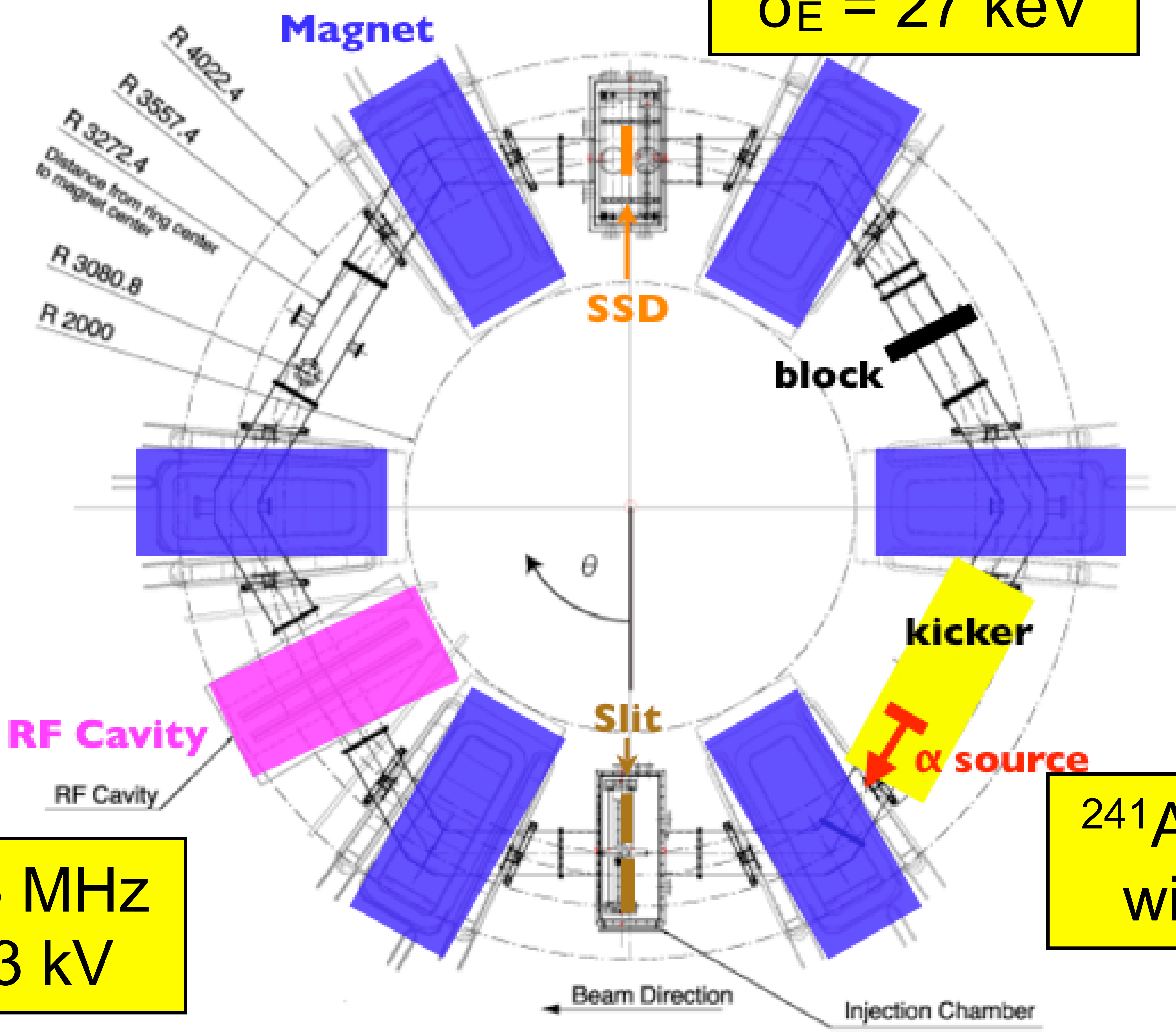


Closed orbit comparison b/w data and simulations



Apparatus for the test of phase rotation

SSD φ2cm,
σ_E = 27 keV

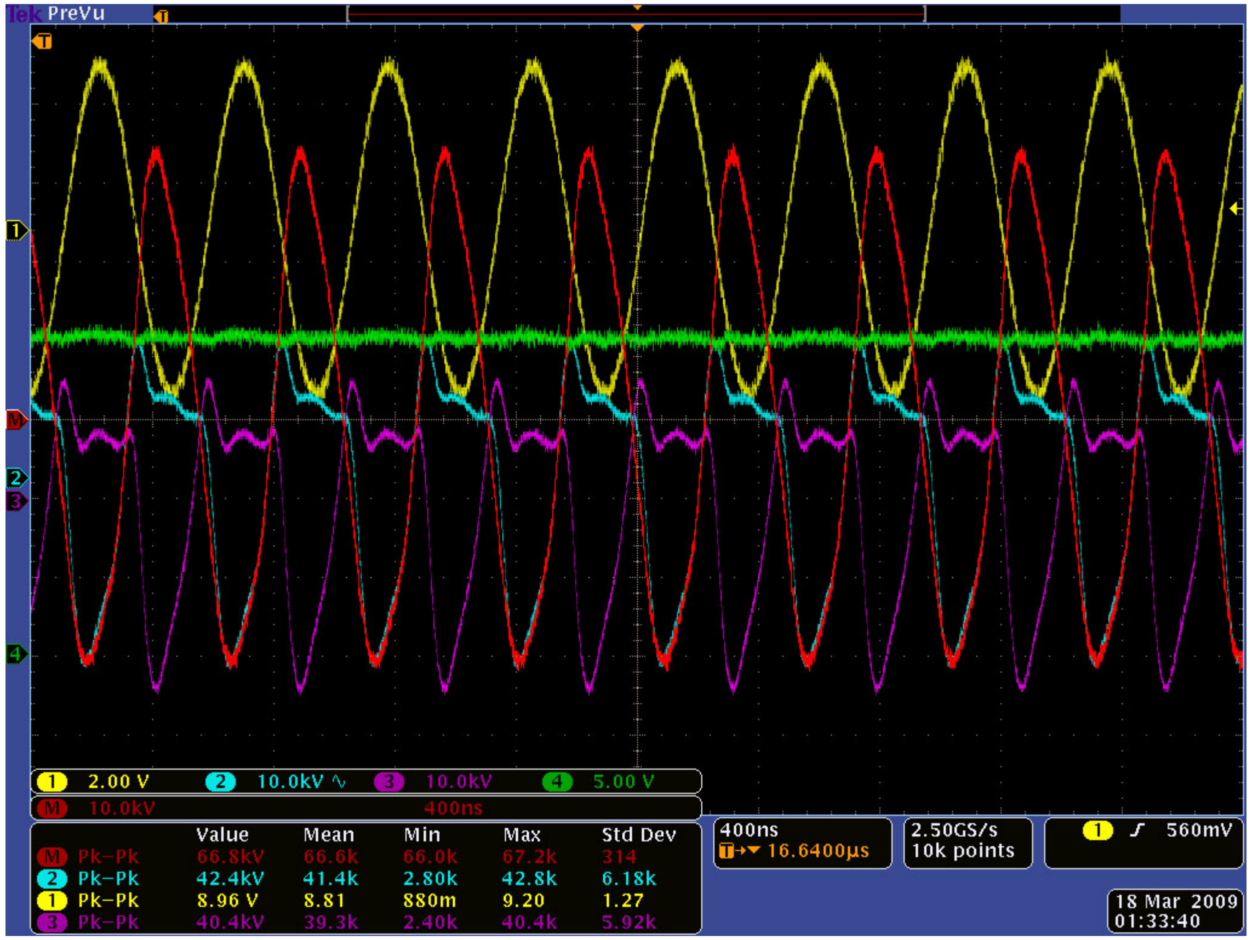


^{241}Am, 3MBq
with Al foil

f=1.916 MHz
V_{pp}=33 kV

RF voltage

red lines show the gap voltage.

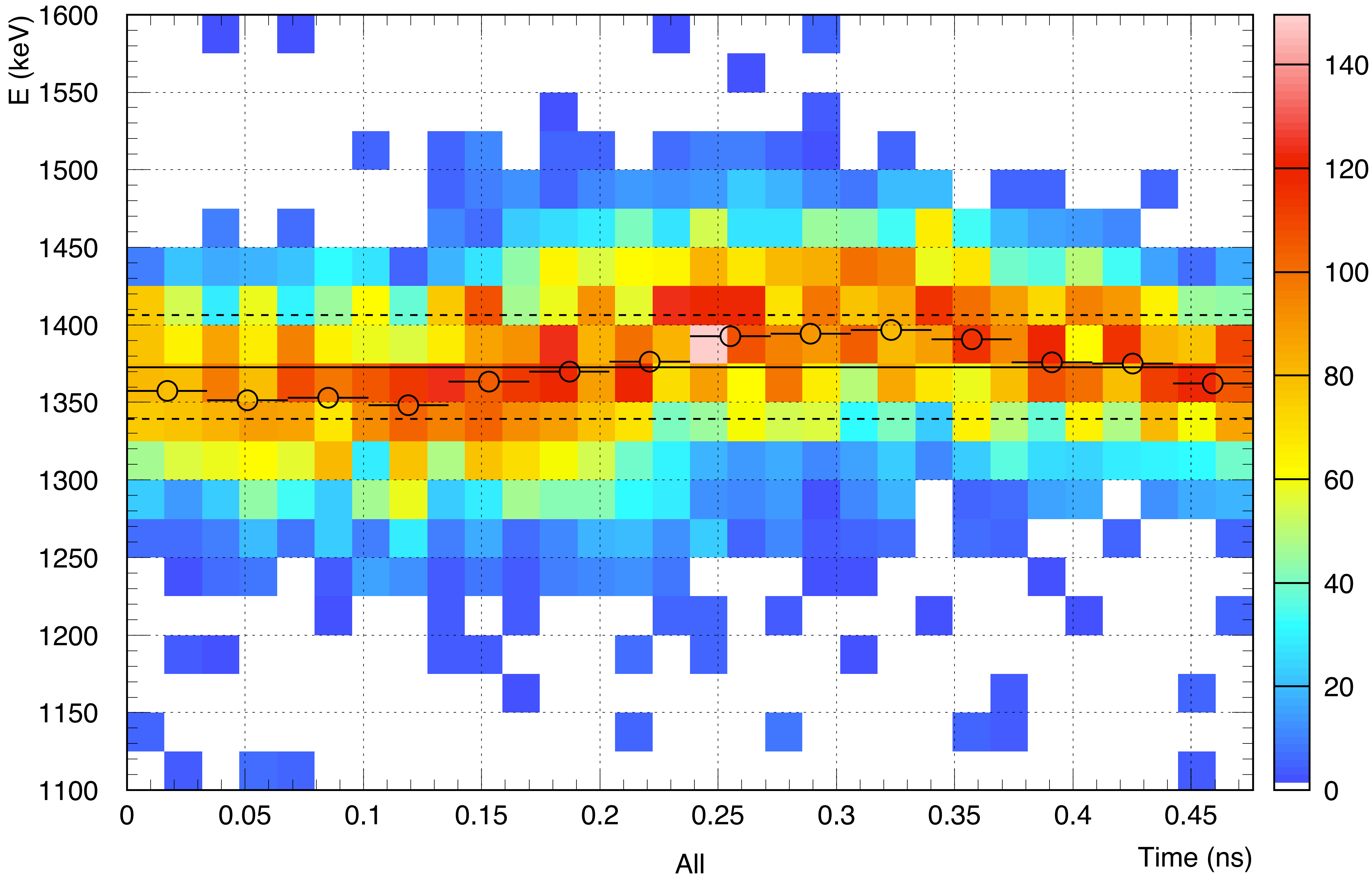


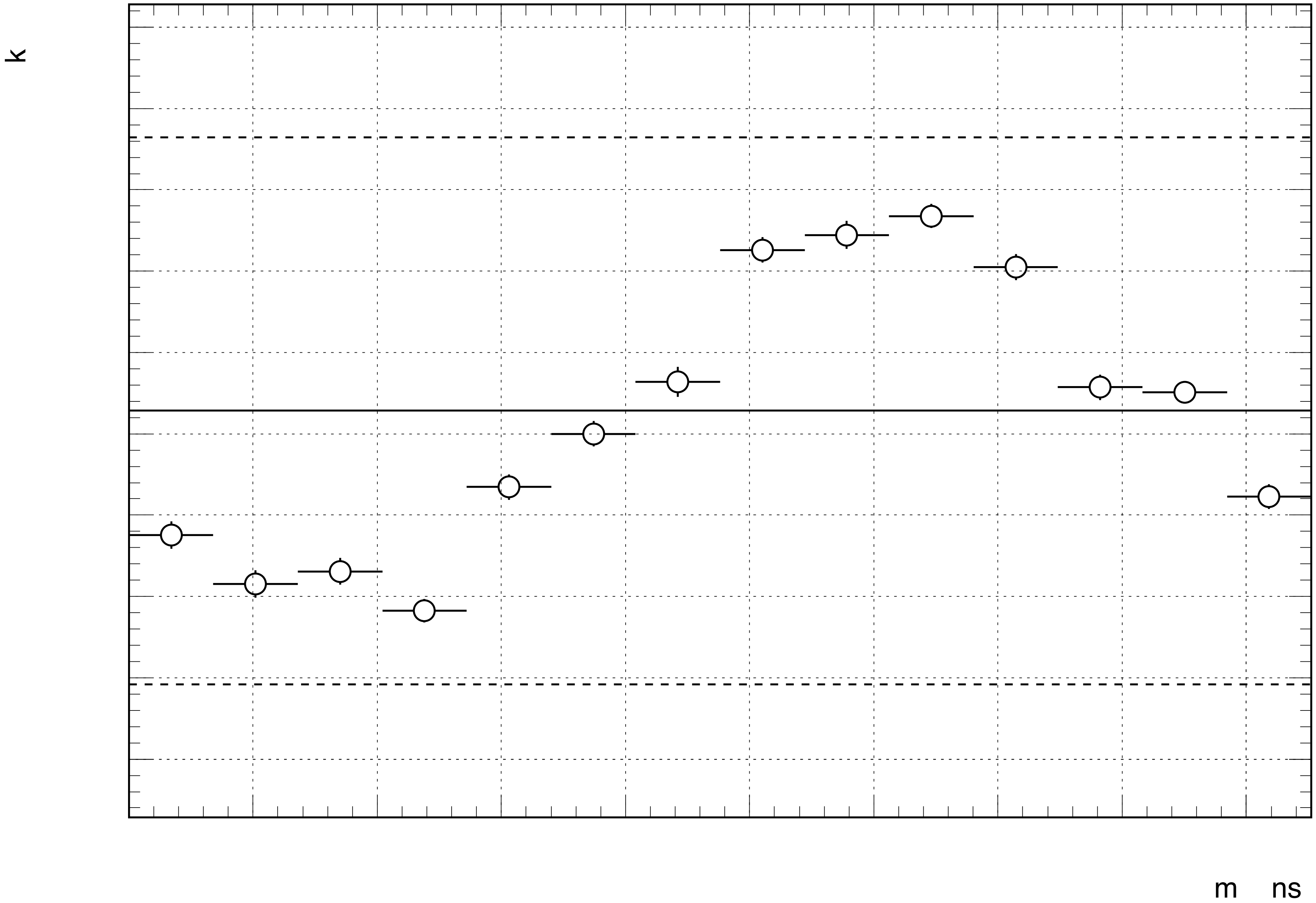
max. voltage for f=1.9MHz

V_{pp}=66kV

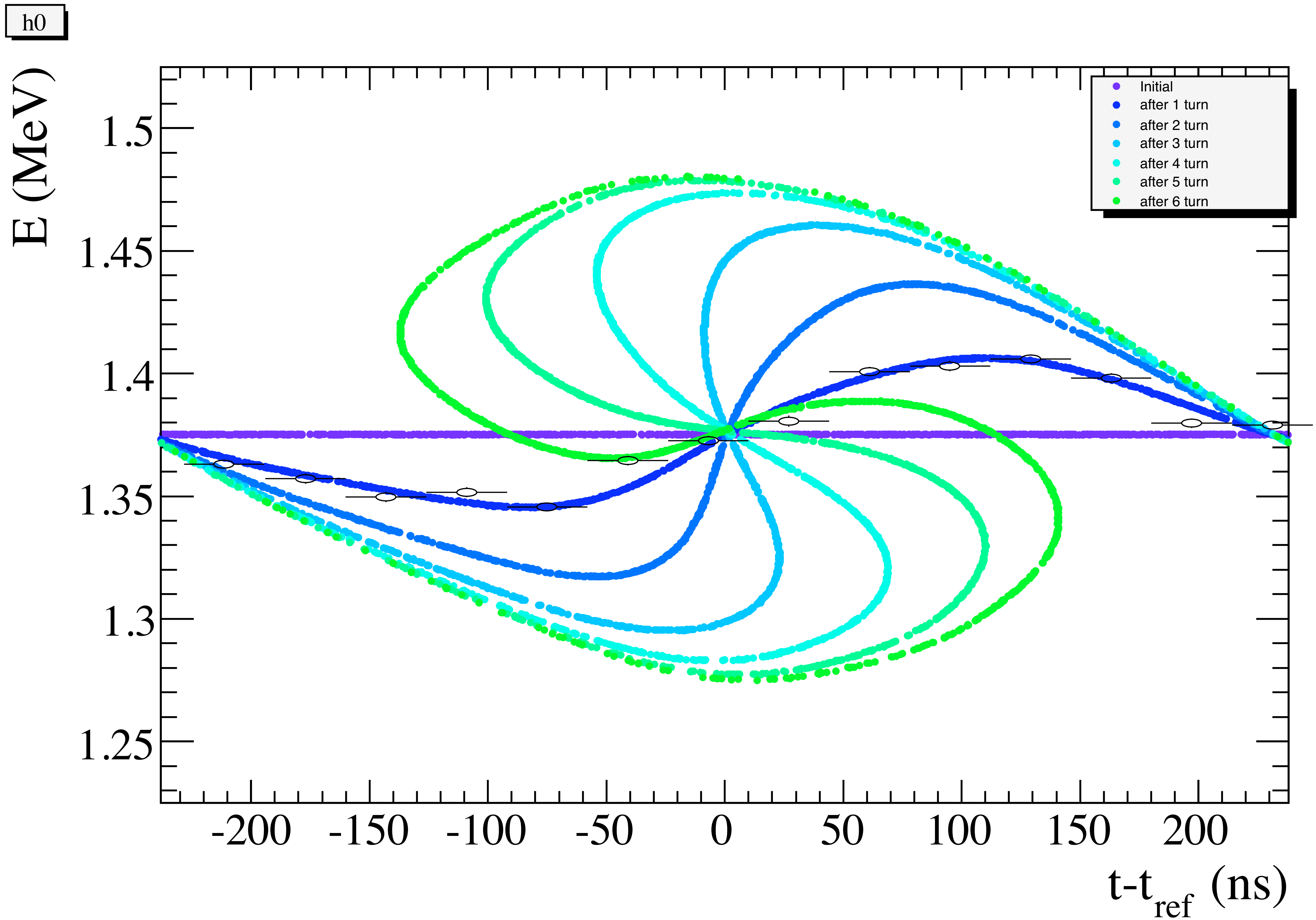
RF wave used in the experiment,

f=1.9MHz, V_{pp}=33kV


E (keV)
1600
1550
1500
1450
1400
1350
1300
1250
1200
1150
1100
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
Time (ns)
All
140
120
100
80
60
40
20
0


k
m
ns

Comparison b/w data and simulation



Summary of PRISM-FFAG project 2003-2009.3

- Design of PRISM-FFAG
- Development of large aperture FFAG magnet
  - 6 magnets have been build
  - magnetic field was measured for three
- Beam dynamics study using one magnet
- Development of RF system
  - 170kV/m sinusoidal @ 5MHz with a test cavity
  - 100kV/m sinusoidal @2.1MHz with PRISM-cavity
- Development of beam monitor for alpha-particle
- 6-cell PRISM-FFAG has bee constructed
  - Beam dynamics studies
  - Test for the phase rotation

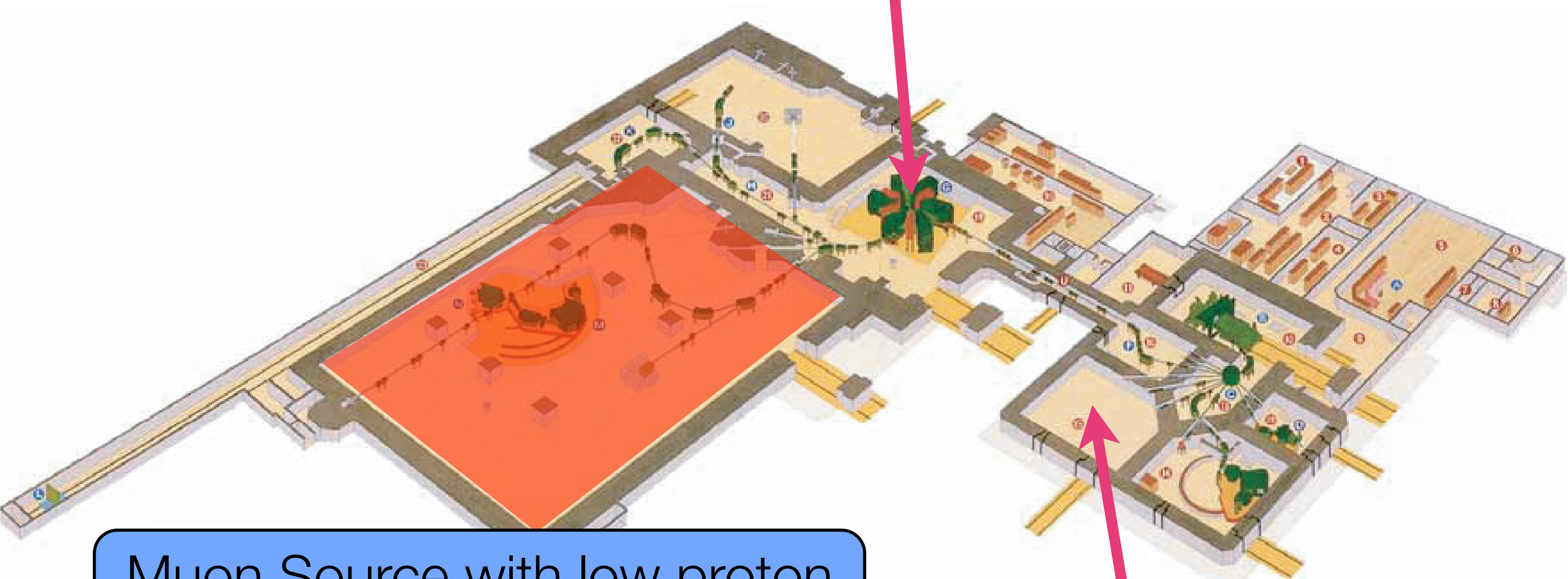
Feasibility of the PRISM-FFAG was shown for magnet and RF. The PRISM-FFAG can be build using these devises, if budgets are approved for that. But there are still some issues ...

MUSIC project

Muon beam is coming to the RCNP, Osaka-Univ.

Research Center for Nuclear Physics (RCNP), Osaka University

Research Center for Nuclear Physics (RCNP), Osaka University has a cyclotron of 400 MeV with 1 microA. The energy is above pion threshold.



Muon Source with low proton power at Osaka U.?

PRISM-FFAG R&D

Motivations for MUSIC

PRISM

- The Research Center for Nuclear Physics (RCNP), Osaka University has a ring cyclotron that has beam energy of 420 MeV. The energy is above the pion threshold. And therefore it can produce pions as well as muons.
- All the muon beam facilities in (and related to) Japan have a beam of pulsed time structure. But, the cyclotron provides a continuous beam.
- There are no muon beam facilities in the west (Kansai) of Japan.
- Potential muon users in Osaka U. and nearby exist.
- A large space for new instruments is available at the west experimental hall at RCNP.
- R&D on muon beams is highly demanded from the worldwide in terms of neutrino factory and muon collider.

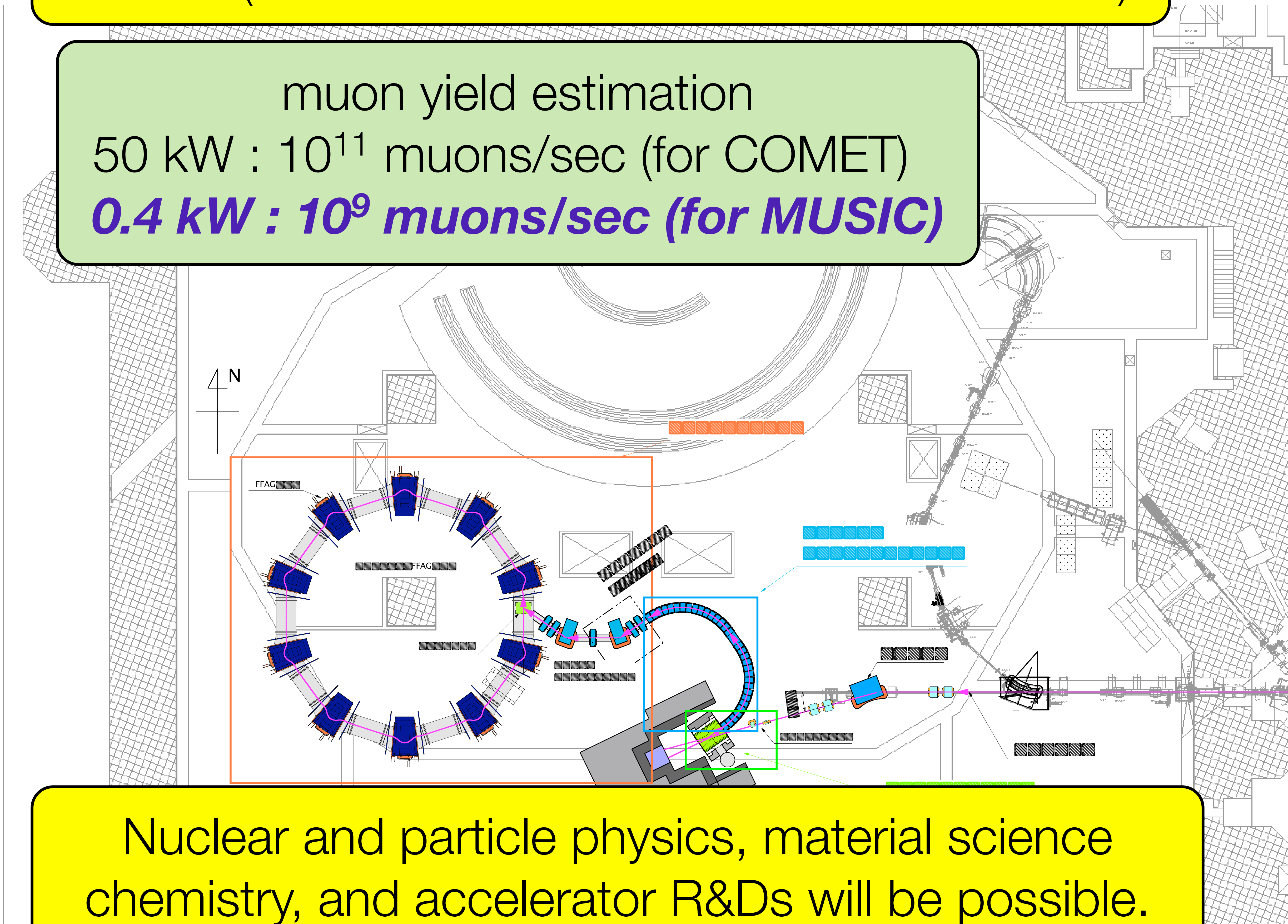
A muon beam facility at RCNP

MUSIC (=MUon Science Innovative Commission)

muon yield estimation

50 kW : 10^{11} muons/sec (for COMET)

0.4 kW : 10^{9} muons/sec (for MUSIC)



Nuclear and particle physics, material science chemistry, and accelerator R&Ds will be possible.

Muon Physics Examples at MUSIC

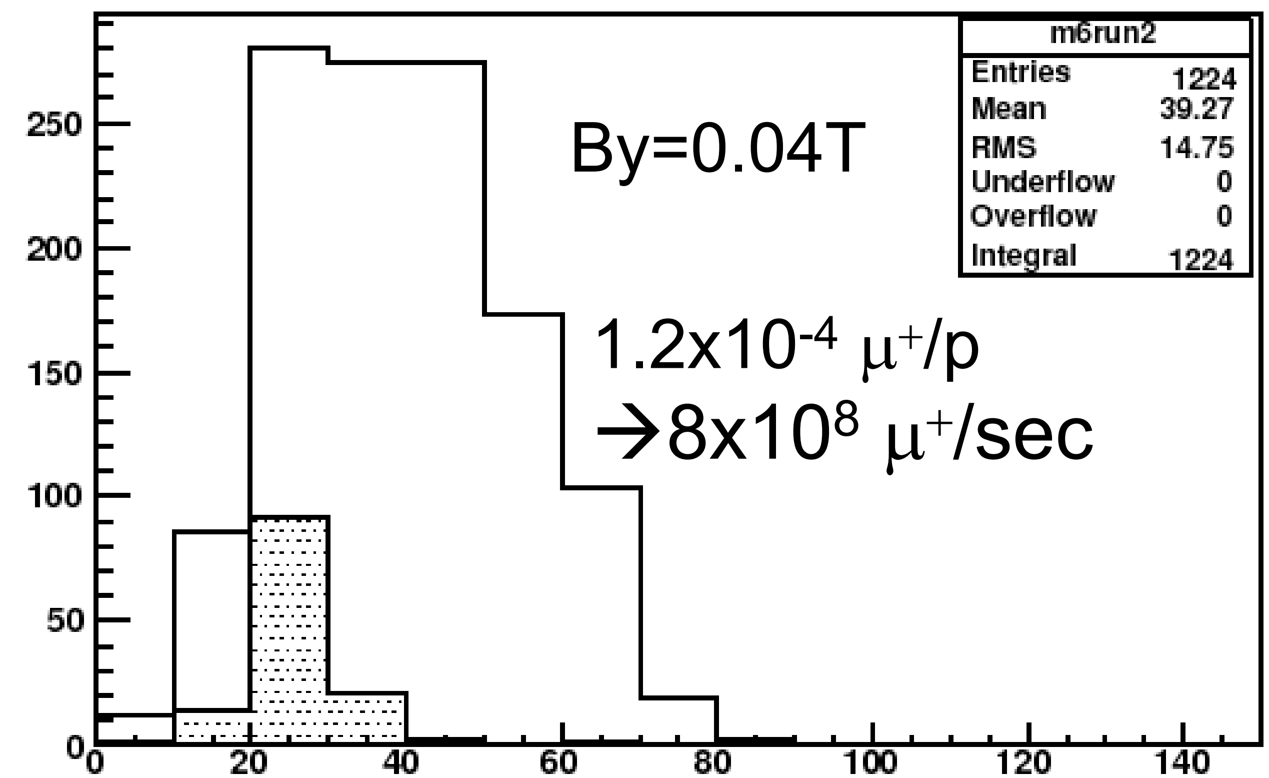
- Particle Physics :
  - search for μ→eee (muon LFV)
    - DC continuous beam is critical
    - TPC to track 3 electrons/positrons
- Nuclear Physics :
  - nuclear muon capture (NMC)
  - pion capture and scattering
- Materials Science :
  - μSR (a μSR apparatus is needed)
- Chemistry
  - chemistry on pion/muon atoms
- Accelerator / Instruments R&D (for neutrino factory/muon collider)
  - Superconducting solenoid magnets
  - FFAG, RF
  - cooling methods

10^8 muons/sec

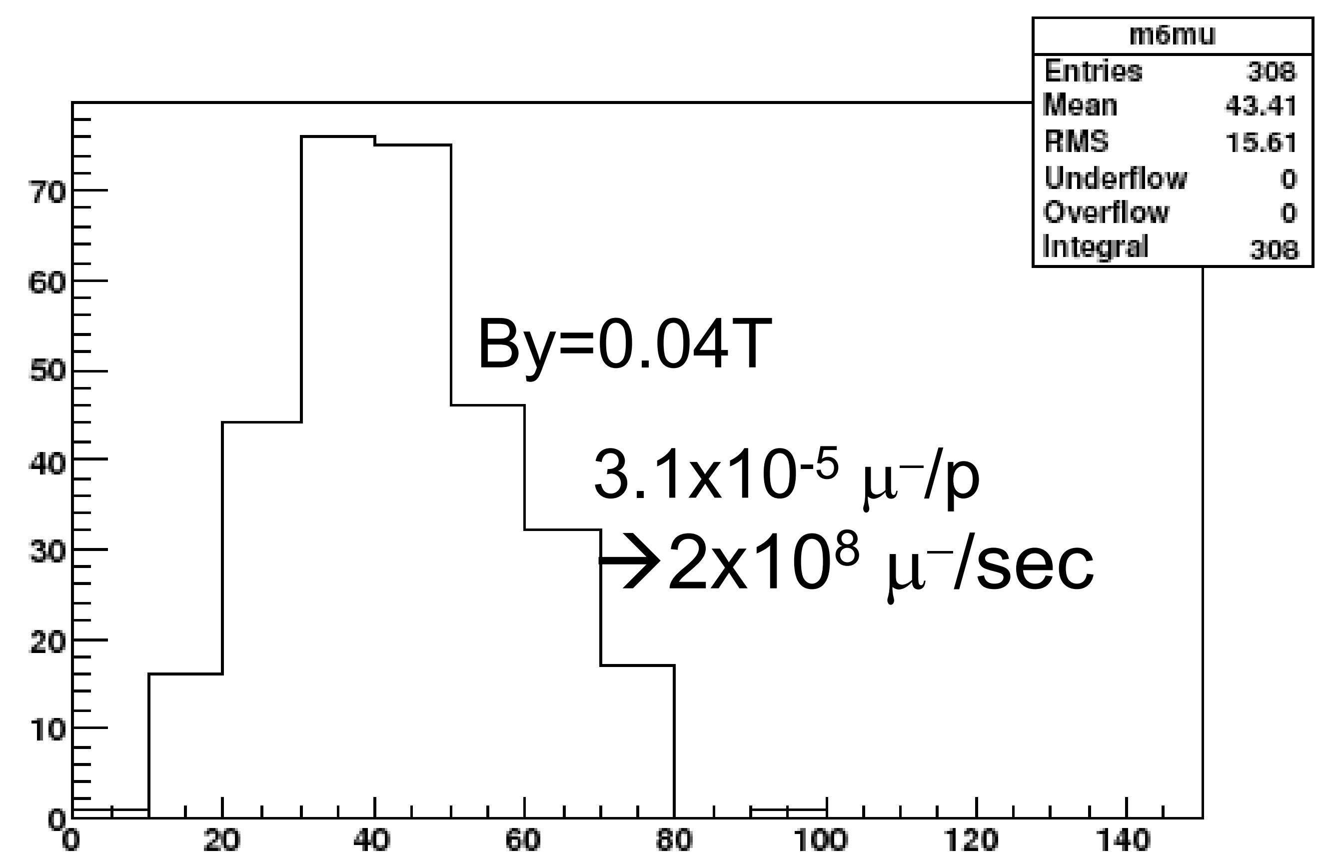
We are also considering to finalize the 10-cell PRISM-FFAG R&D using the muon beams in the MUSIC project.

Muon intensity

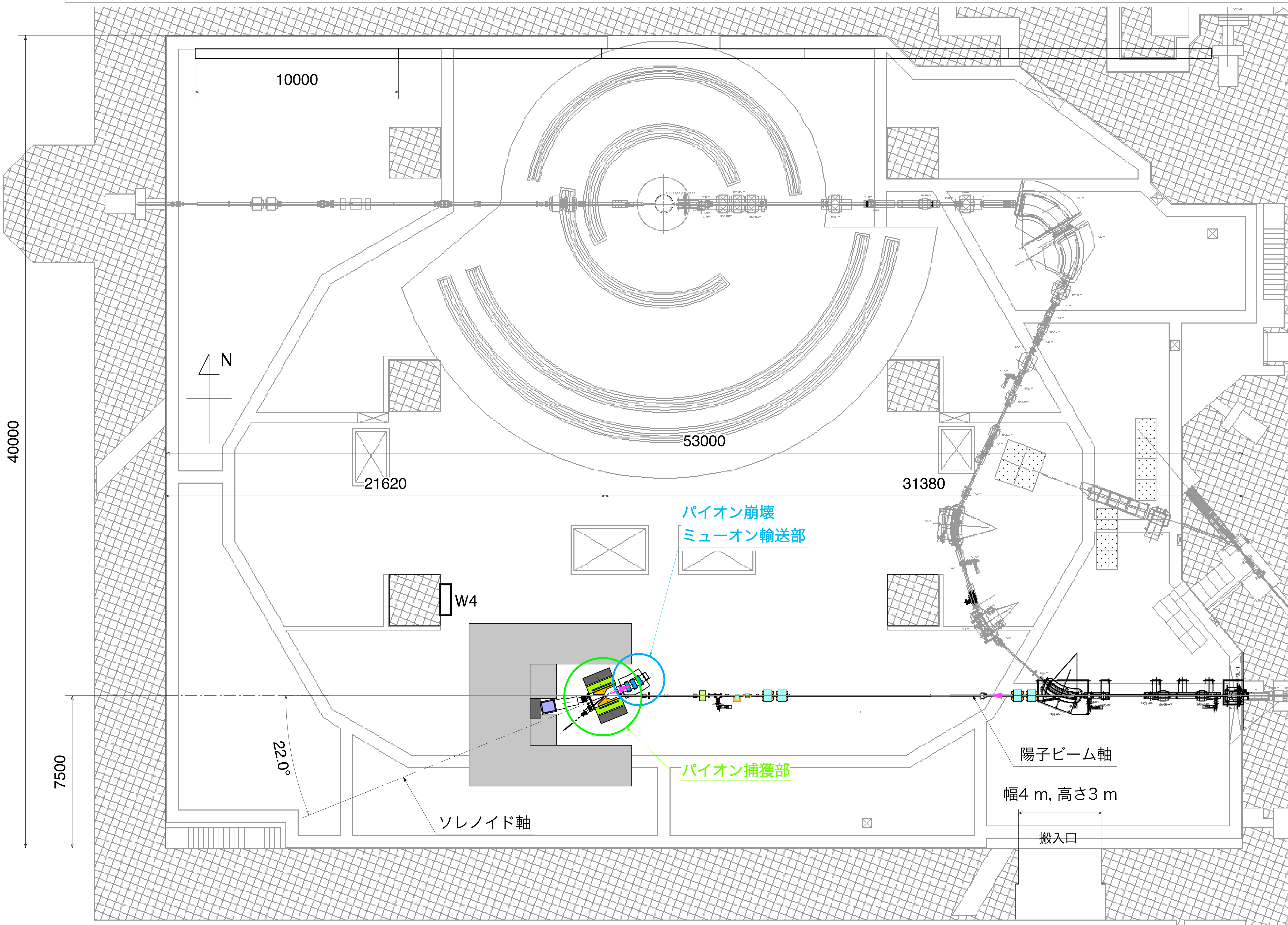
- 400MeV x 1 microA proton beam
- MARS interactions in graphite target
- G4Beamline tracking



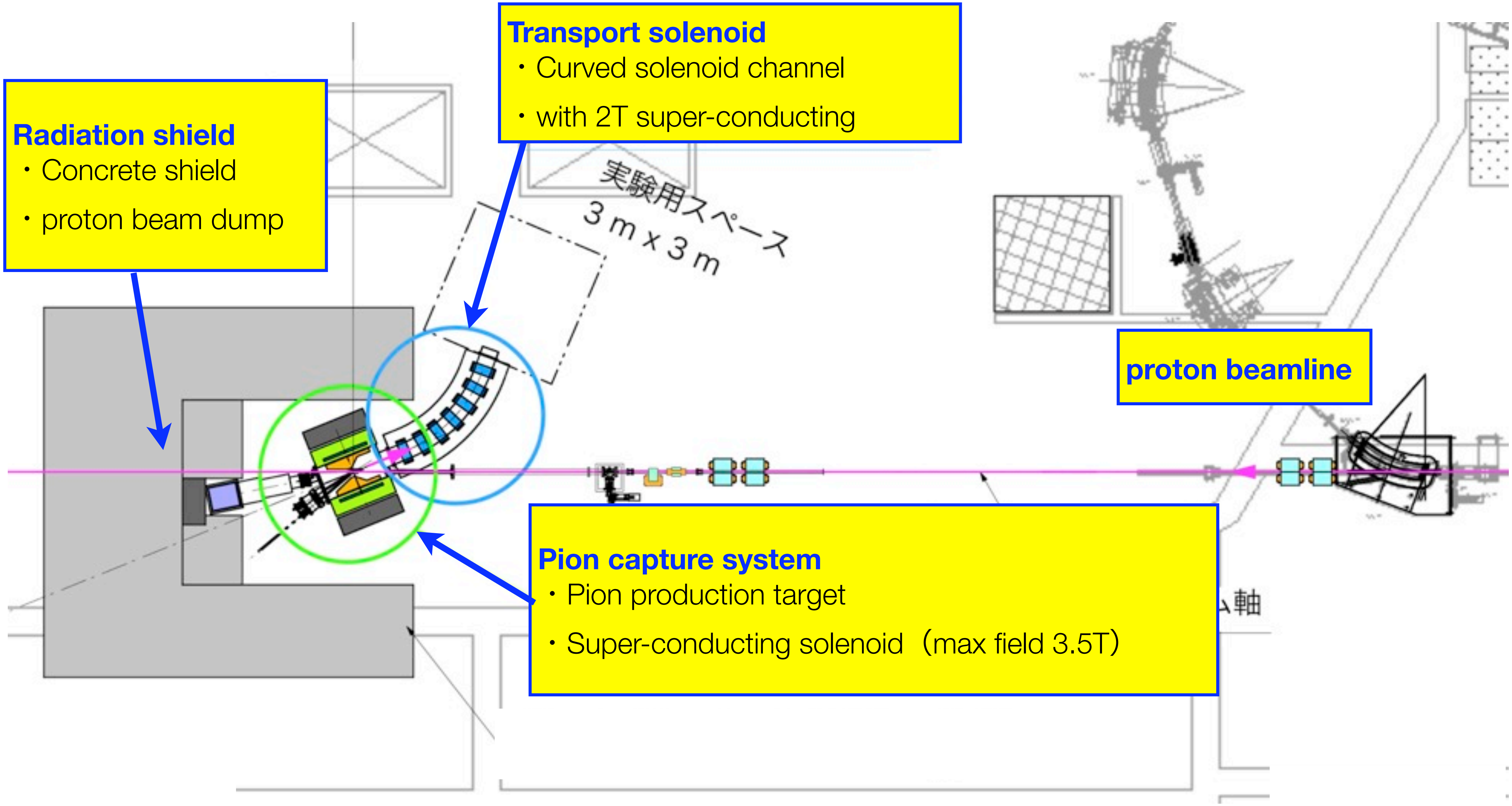
- 8×10^{8} μ^{+}/sec with By=0.04T
  - surface muons of 8×10^{7} μ^{+}/sec
- 2×10^{8} μ^{+}/sec with By=0
- 2×10^{8} μ^{-}/sec with By=0.04T
- 5×10^{7} μ^{-}/sec with By=0



Layout of the MUSIC at March 2010



Layout of the MUSIC at March 2010



平成21年度西実験室内の建設計画（仮）

スケジュールは5月の業者決定後、RCNP側と相談して決定する。

- 5月：
  - 建設業者決定
  - 工場にて各機器の製作開始
- 7-9月：
  - 西実験室内の整頓
  - 実験室整備（冷却水配管、電源ケーブルなど）
  - 遮蔽材搬入
  - FFAG移設（or 1月頃）
- 1-3月：
  - 西実験室へ各機器の据付・アライメント
  - 現地試験

Muon Physics Examples at MUSIC

- Particle Physics :
  - search for $\mu \rightarrow eee$ (muon LFV)
    - DC continuous beam is critical
    - TPC to track 3 electrons/positrons
- Nuclear Physics :
  - nuclear muon capture (NMC)
  - pion capture and scattering
- Materials Science :
  - μSR (a μSR apparatus is needed)
- Chemistry
  - chemistry on pion/muon atoms
- Accelerator / Instruments R&D (for neutrino factory/muon collider)
  - Superconducting solenoid magnets
  - FFAG, RF
  - cooling methods

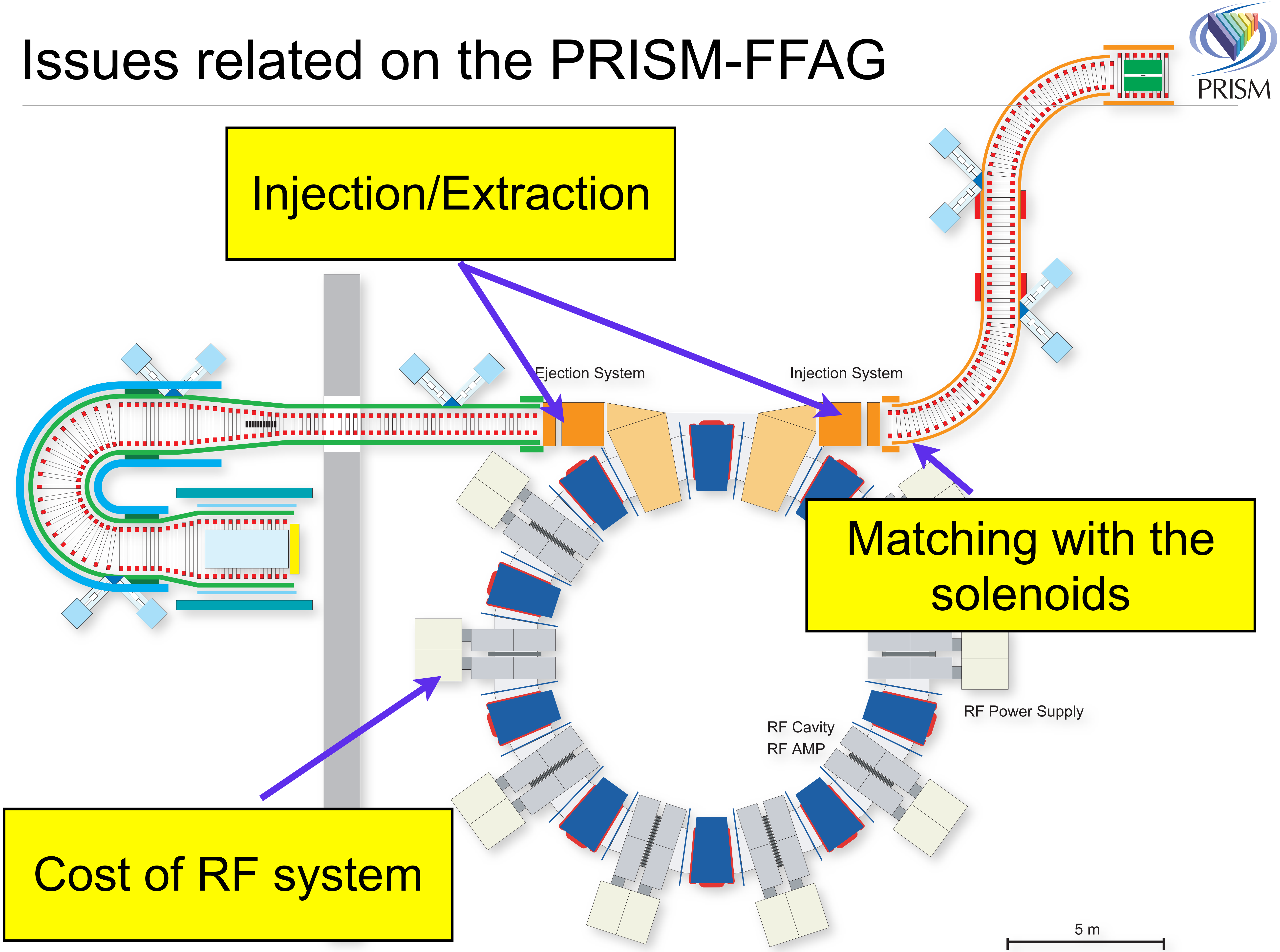
10^8 muons/sec

MUSE vs. MUSIC

	MUSE	MUSIC
location	J-PARC	RCNP
beam power	1000 kW	0.4 kW
intensity	10^8/sec	10^7-10^8/sec
time structure	pulsed (25 Hz)	continuous
beam polarization	high	medium
multiple use	many channels	only one channel

Issues

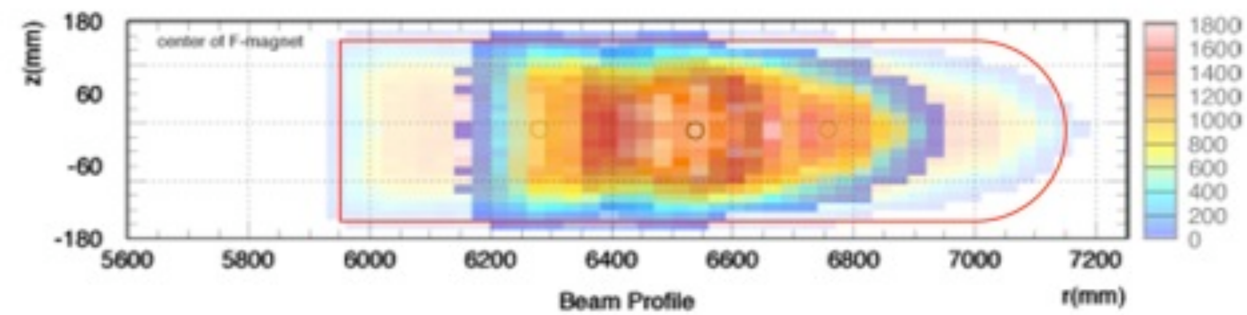
Issues related on the PRISM-FFAG

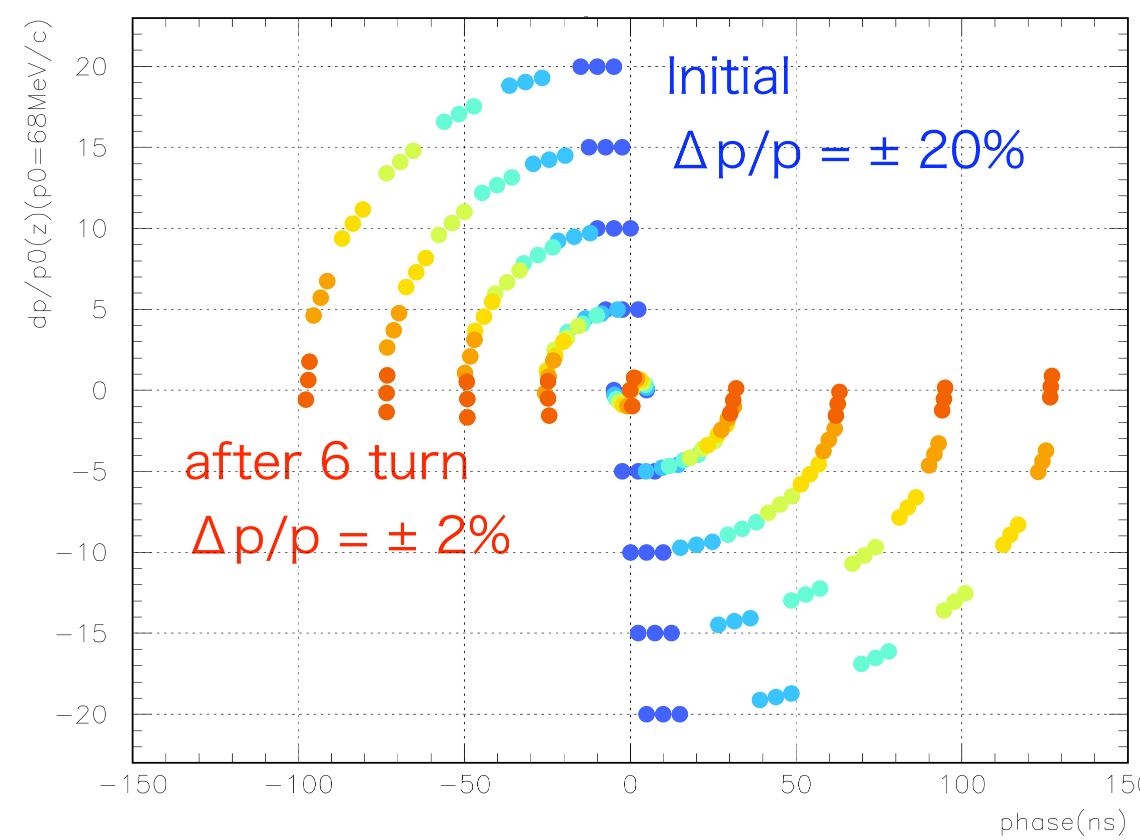


Injection and Extraction

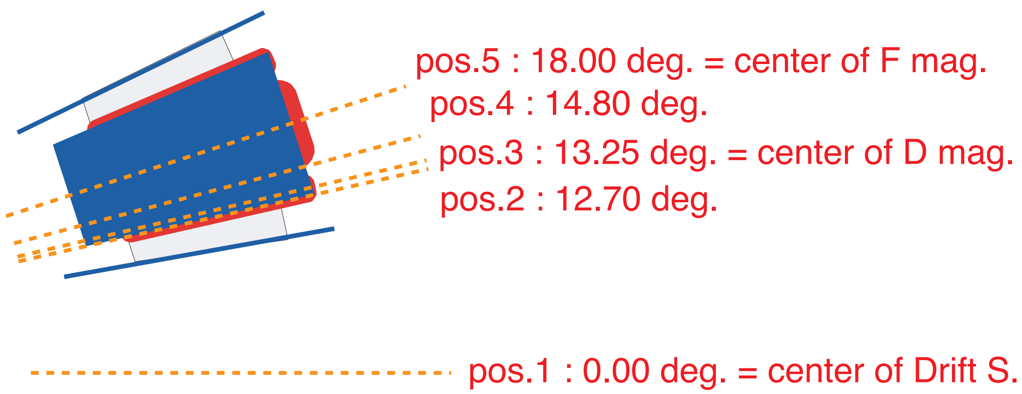
Muon Beam at Inj./Ext.

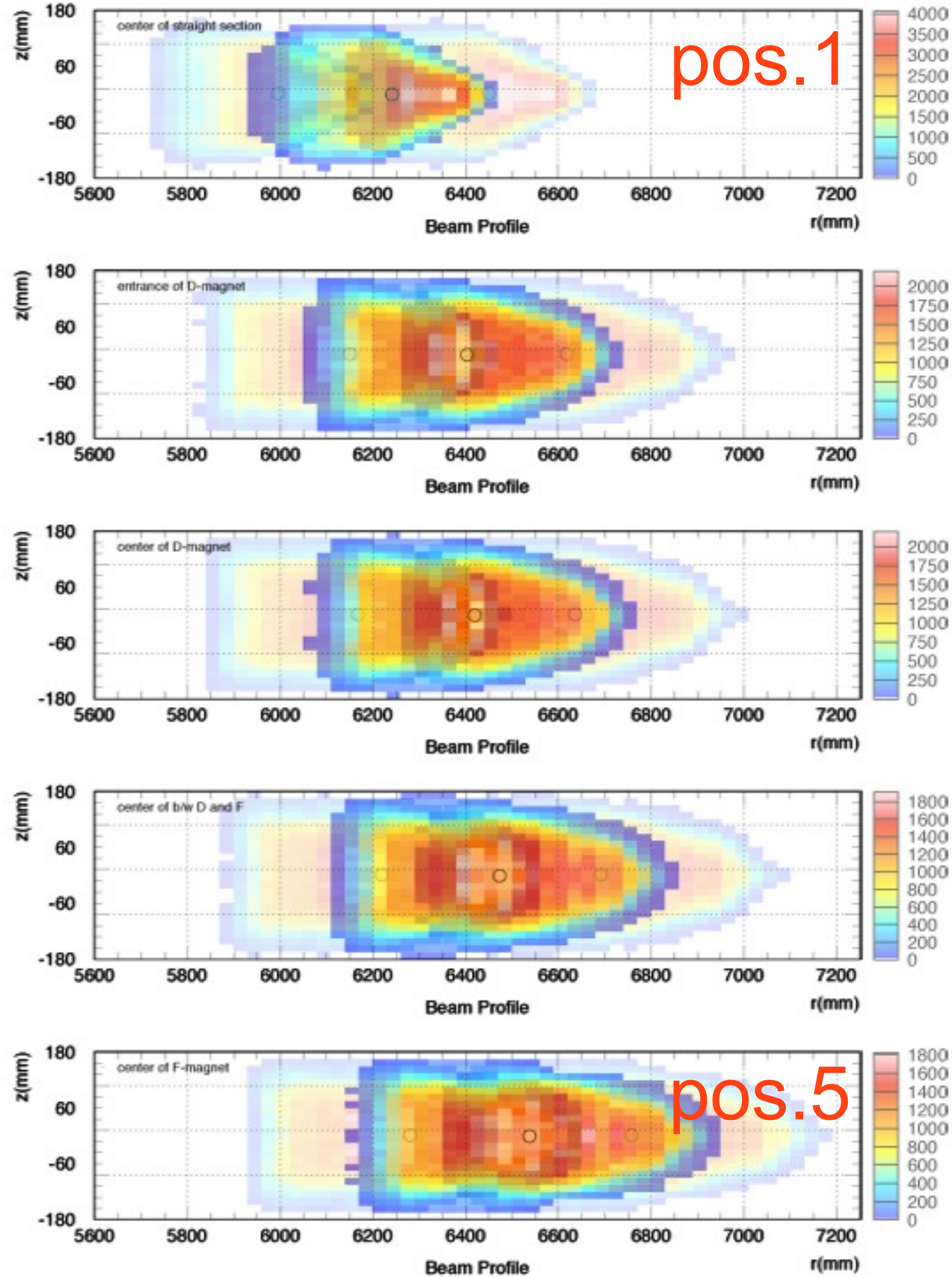
- at Injection
  - momentum : 68MeV/c+-20%
    - beam size
      - 100cmx30cm
  - time dist.: 40ns(/270ns)
    - kicker fall time < 230ns
- at Extraction
  - momentum : 68MeV/c+-2%
    - beam size
      - 70cmx30cm
  - time dist. : 200ns(/270ns)
    - kicker rise time < 70ns-100

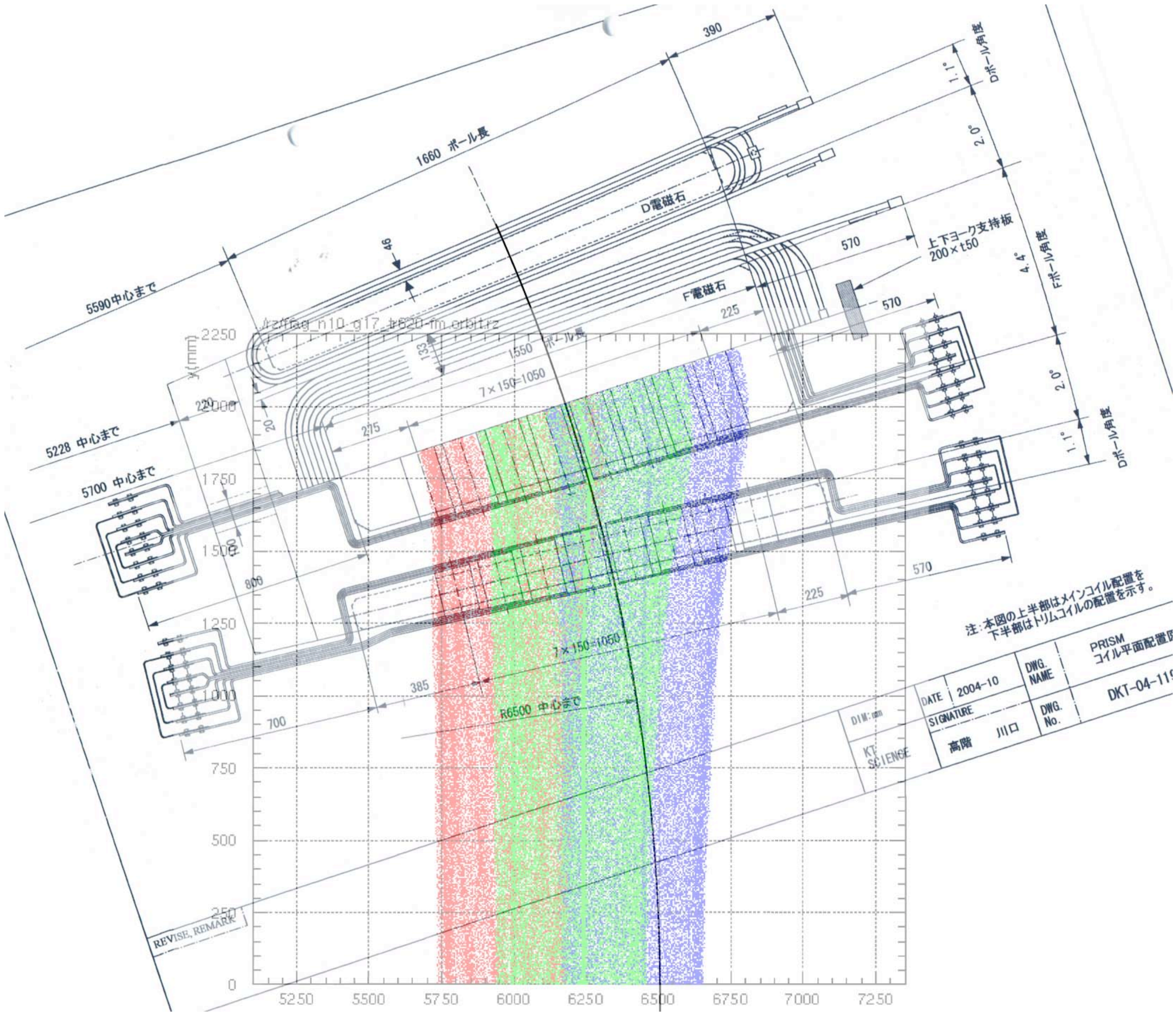




Muon beam size at the injection






390
1660 ポール長
D電磁石
F電磁石
Dポール角度
Fポール角度
上下ヨーク支持板
200×t50
570
225
46
5590中心まで
5228 中心まで
5700 中心まで
1550 ポール長
7×150=1050
275
133
20
220
800
385
700
R6500 中心まで
注:本図の上半部はメインコイル配置を
下半部はトリムコイルの配置を示す。
PRISM
コイル平面配置図
DKT-04-119
DATE
2004-10
DWG. NAME
DWG. No.
SIGNATURE
高階
川口
DIM: mm
KT-SCIENCE
REVISE, REMARK
y (mm)
0
250
500
750
1000
1250
1500
1750
2000
2250
5250
5500
5750
6000
6250
6500
6750
7000
7250

PRISM-FFAG
injection/extraction studies introduction

Osaka University
Akira SATO

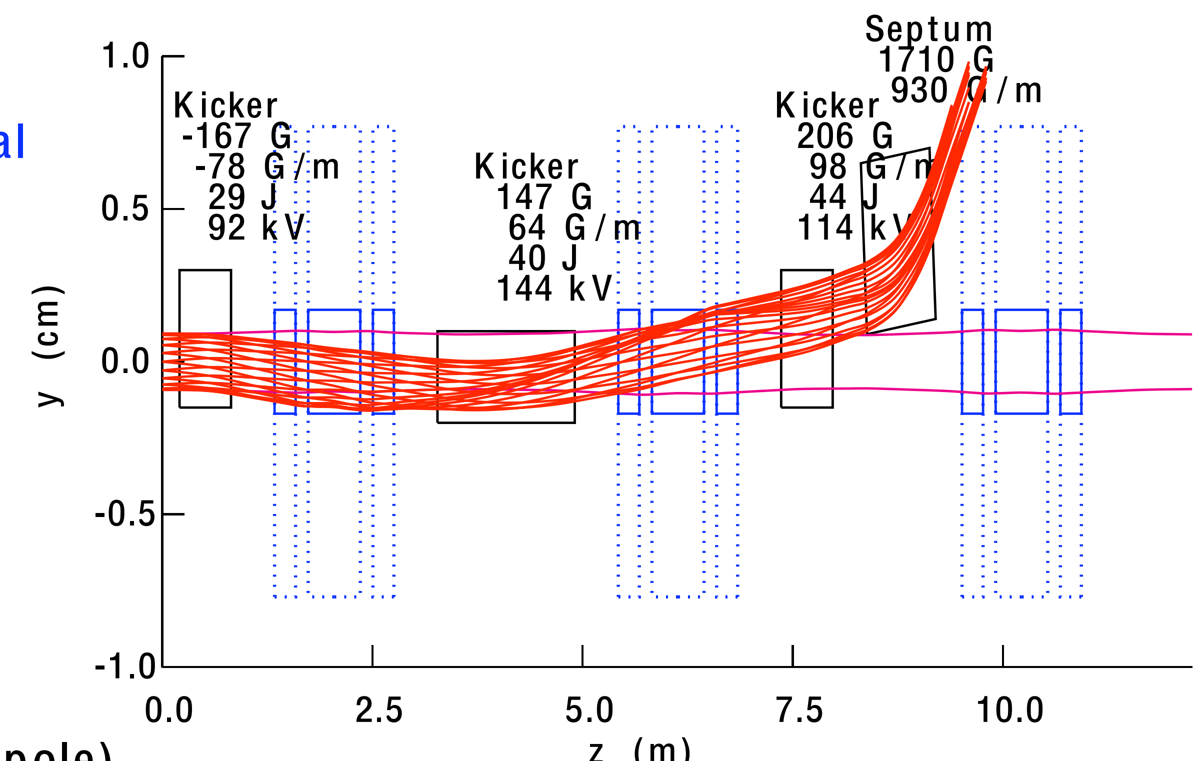
30th Nov. 2005 / PRISM-Workshop @ Osaka-U.

Injection/Extraction Issue

- B.Palmer proposed vertical injection/extraction

Conclusions on Injection/Extraction

- Vertical injection/extraction much easier than horizontal
  - Needs Much less Magnetic energy
  - Needs much lower Voltage
  - Chromatic correction easy
- But Remaining Design Questions
  - Needs larger vertical apertures in special magnets
  - Kicker Energy still much greater than normal kickers
  - Need two pulses in each kicker
  - Kicker aspect ratio unnatural
  - Needs gradient in kicker field (dipole + skew quadrupole)
- Study needs repeating with real fields and beam
- But this looks plausible

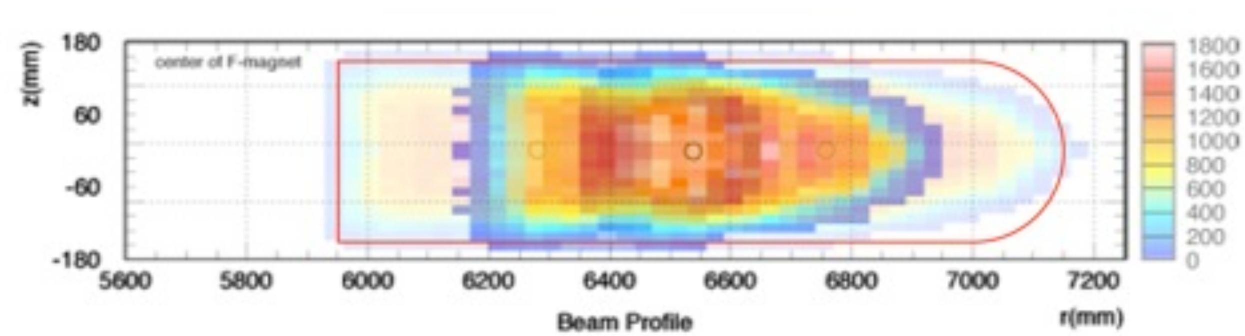


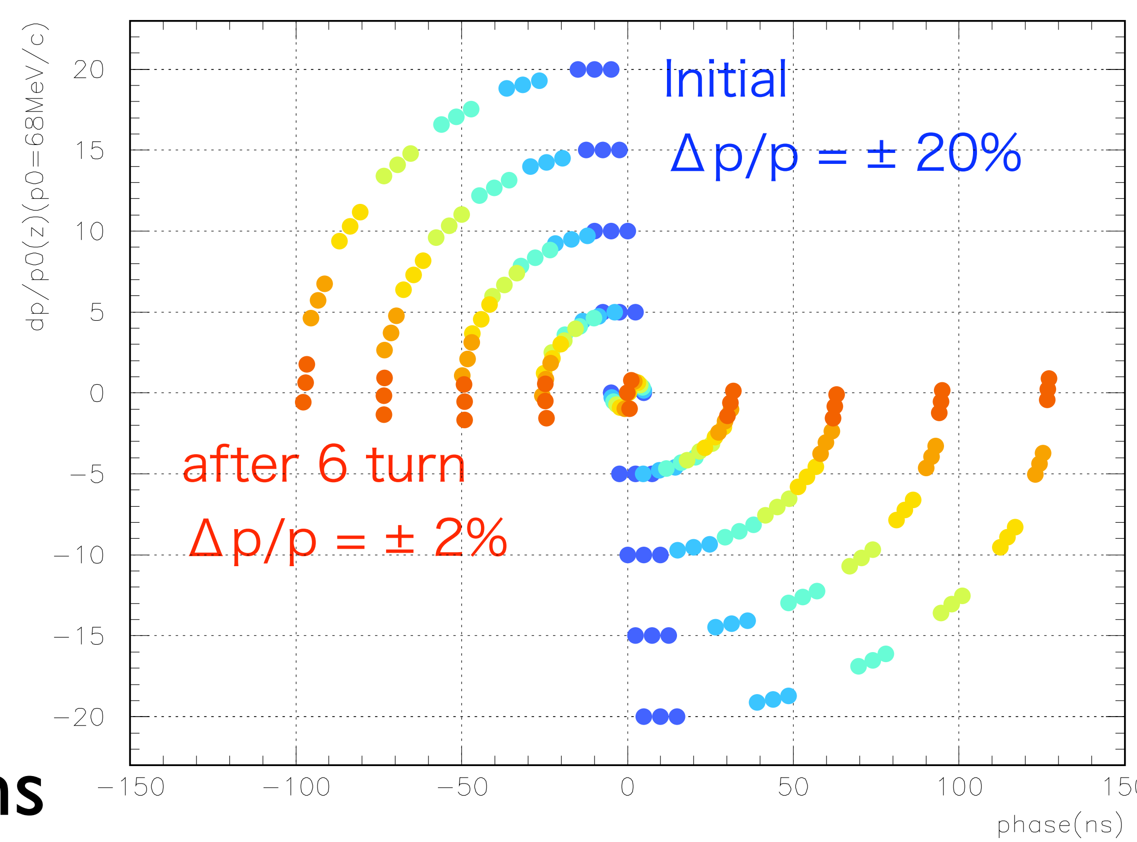
* I studied that scheme with the present PRISM design.

field clumps, real gap size,
TOSCA field for FFAG magnets,
hard edge field for kickers and septums, geant3 tracking code

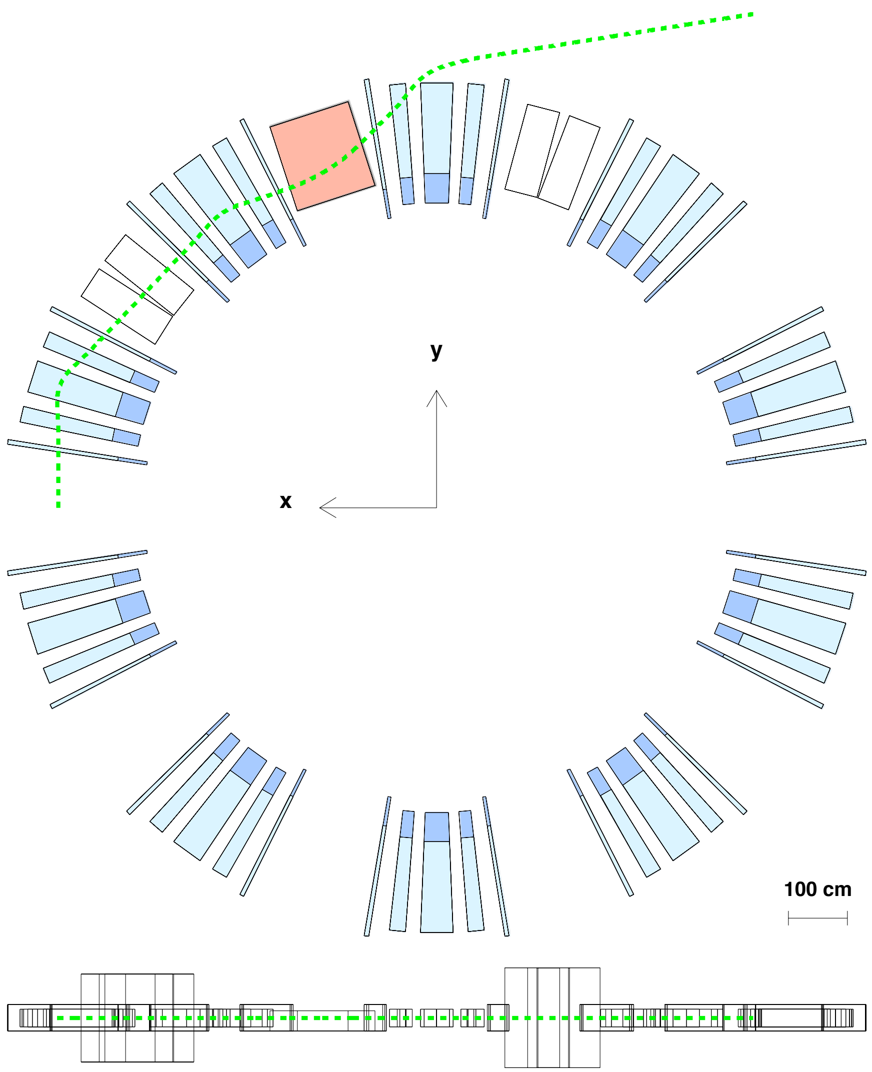
Muon Beam

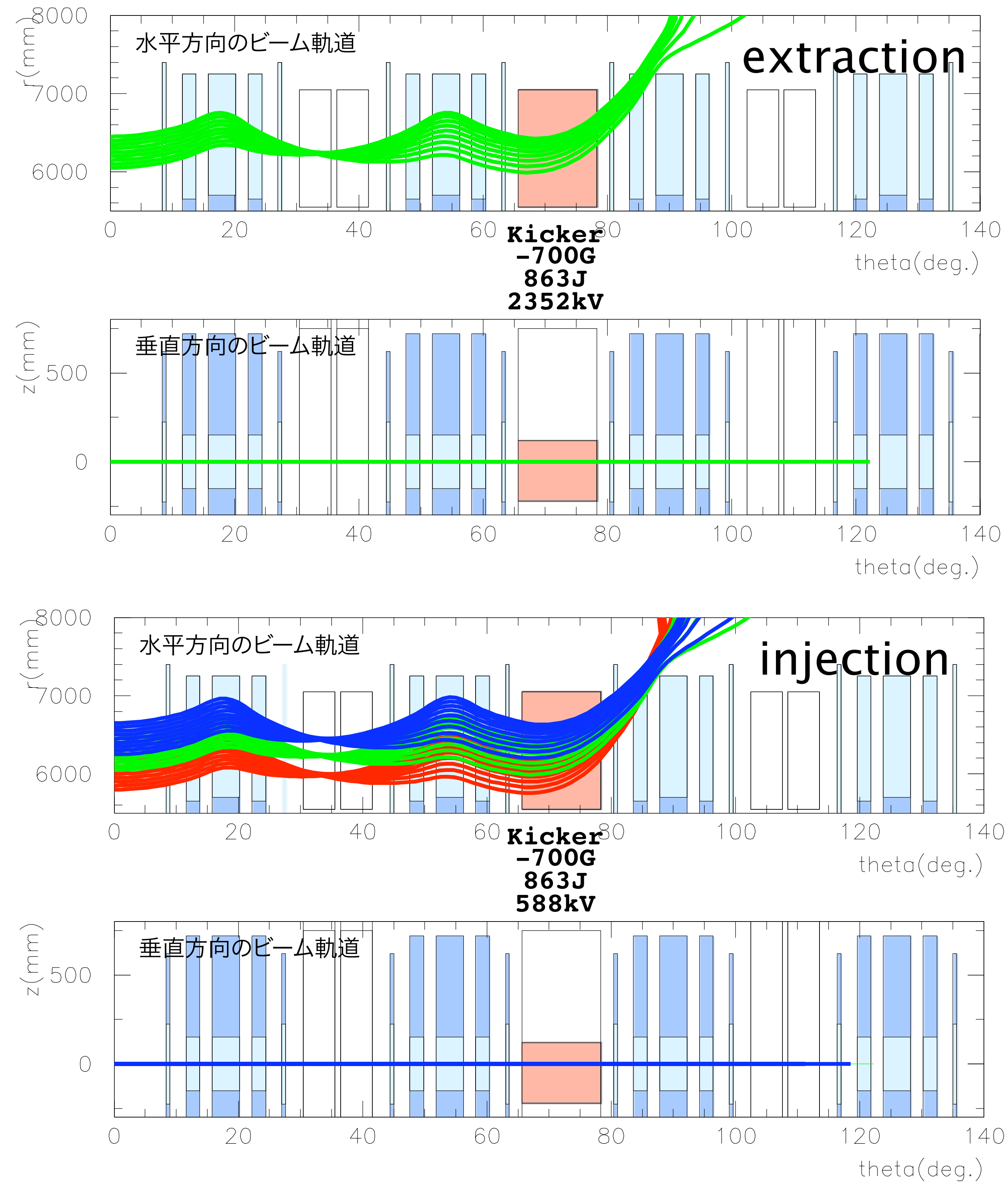
- at Injection
  - momentum : 68MeV/c+-20%
    - beam size
      - 100cmx30cm
  - time dist.: 40ns(/270ns)
    - kicker fall time < 230ns
- at Extraction
  - momentum : 68MeV/c+-2%
    - beam size
      - 70cmx30cm
  - time dist. : 200ns(/270ns)
    - kicker rise time < 70ns-100ns





Horizontal Injection/Extraction





Horizontal Injection/Extraction

	B (T)	Gradient (T/m)	rise time (ns)	fall time (ns)	Length (cm)	Height (cm)	Width (cm)	Single Turn Voltage (kV)	Stored Energy (J)
Injection	-0.07	0	200	200	140	120	30	-588	863
Extraction	-0.07	0	50	1000	140	120	30	-2352	863

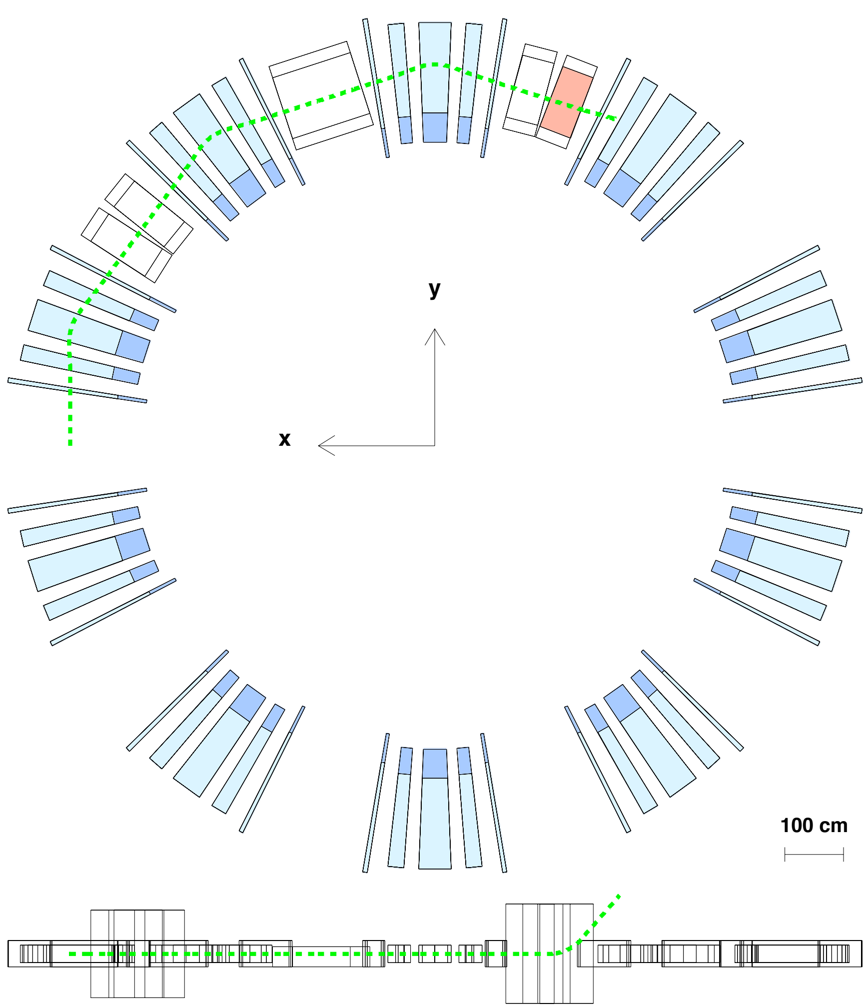
B.Palmer's results

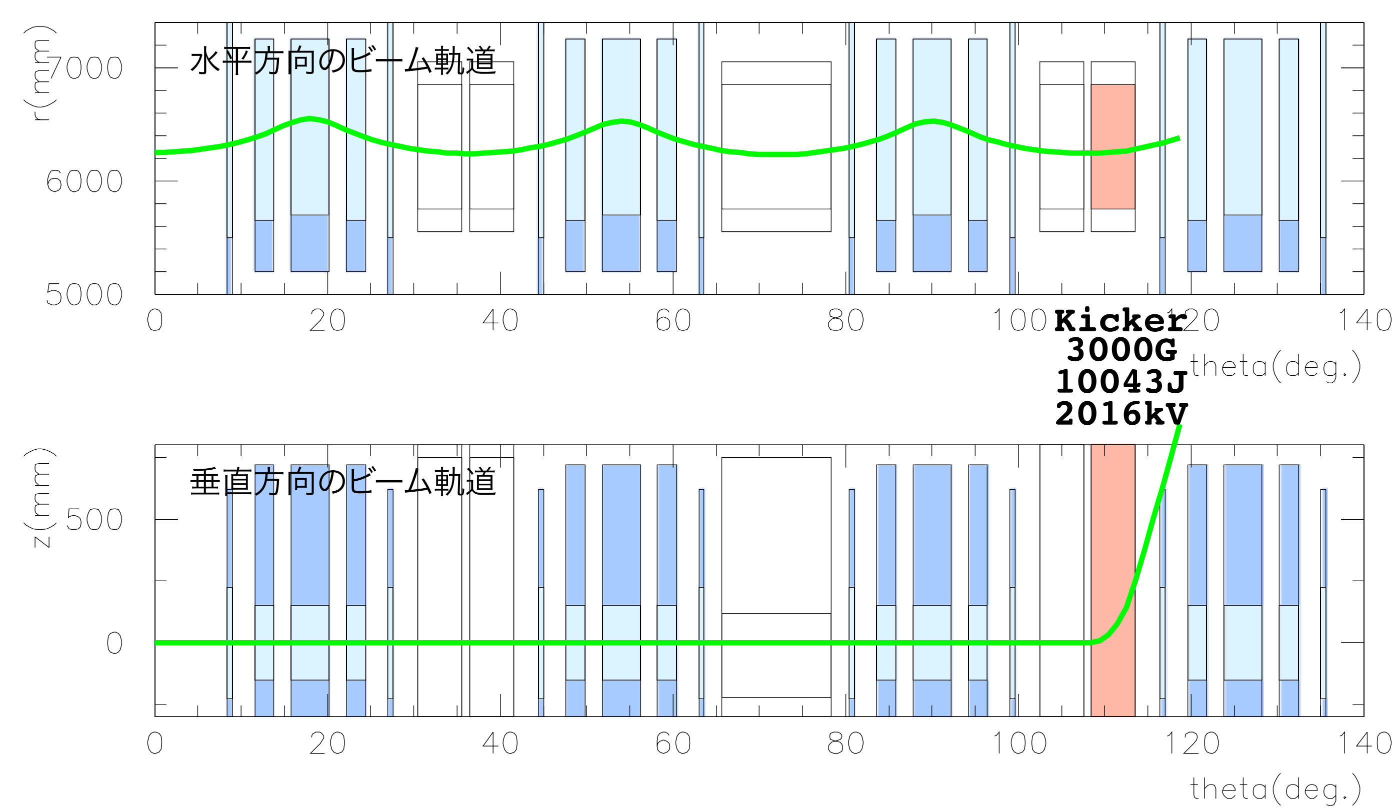
Length	cm	122.5
Width	cm	120
Height	cm	34
Kicker Field	T	0.108
Rise time	ns	50
Stored Energy	J	2038
Single turn Voltage	kV	3162

$$U = \frac{B_y^2 \cdot L \cdot X \cdot Y}{2\mu_0}, V = \frac{B_y \cdot X \cdot L}{t_{rise}}$$

Vertical Injection/Extraction

One Kicker

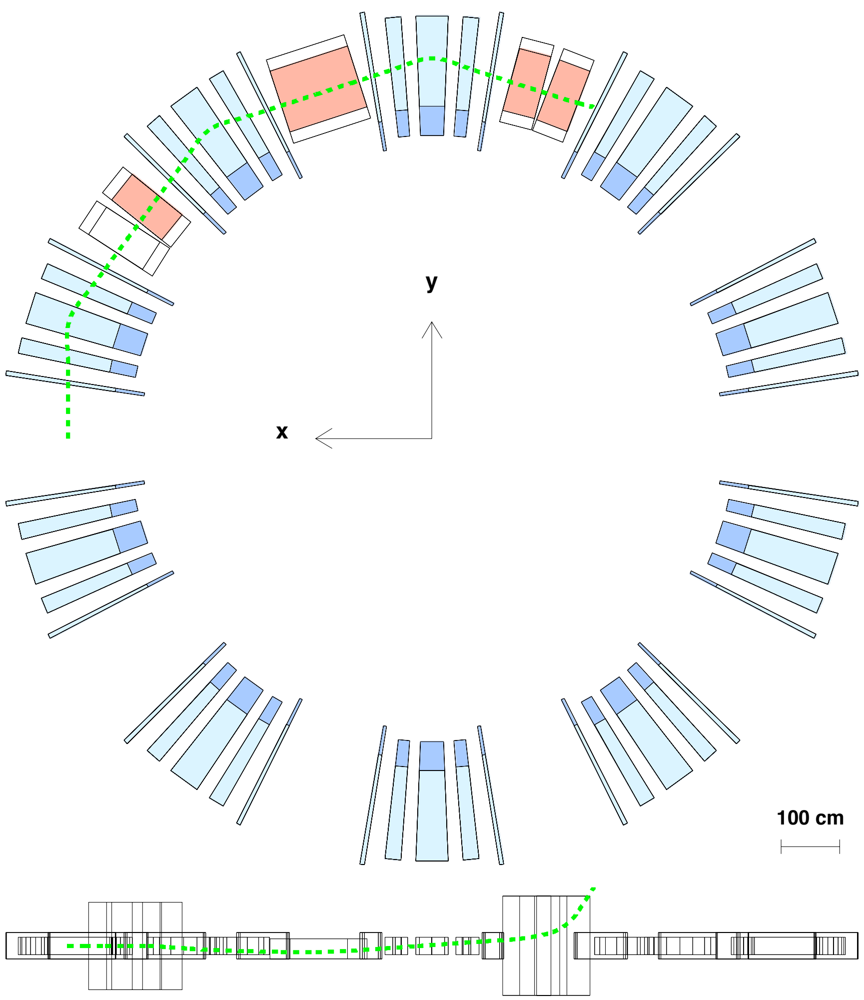


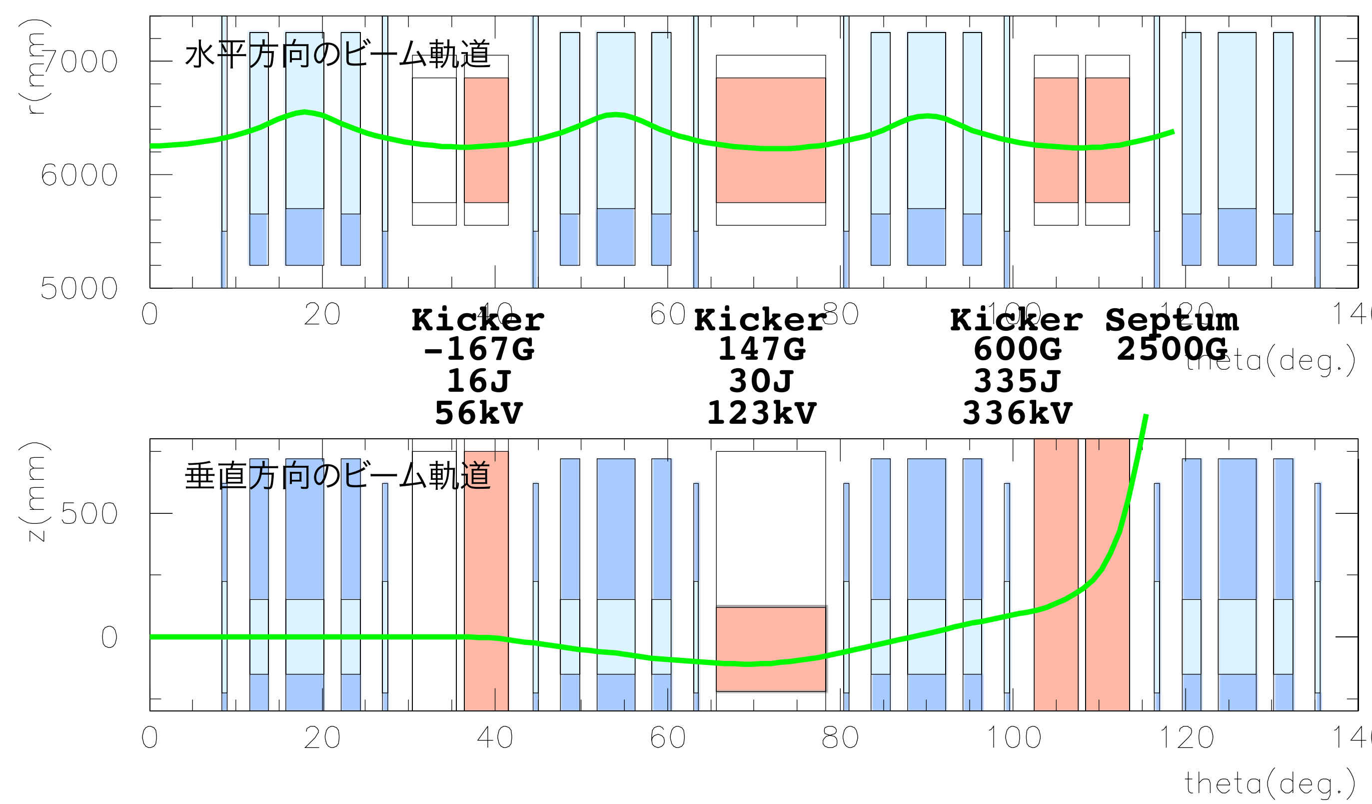


Vertical Injection/Extraction

Kicker x3 + Septum

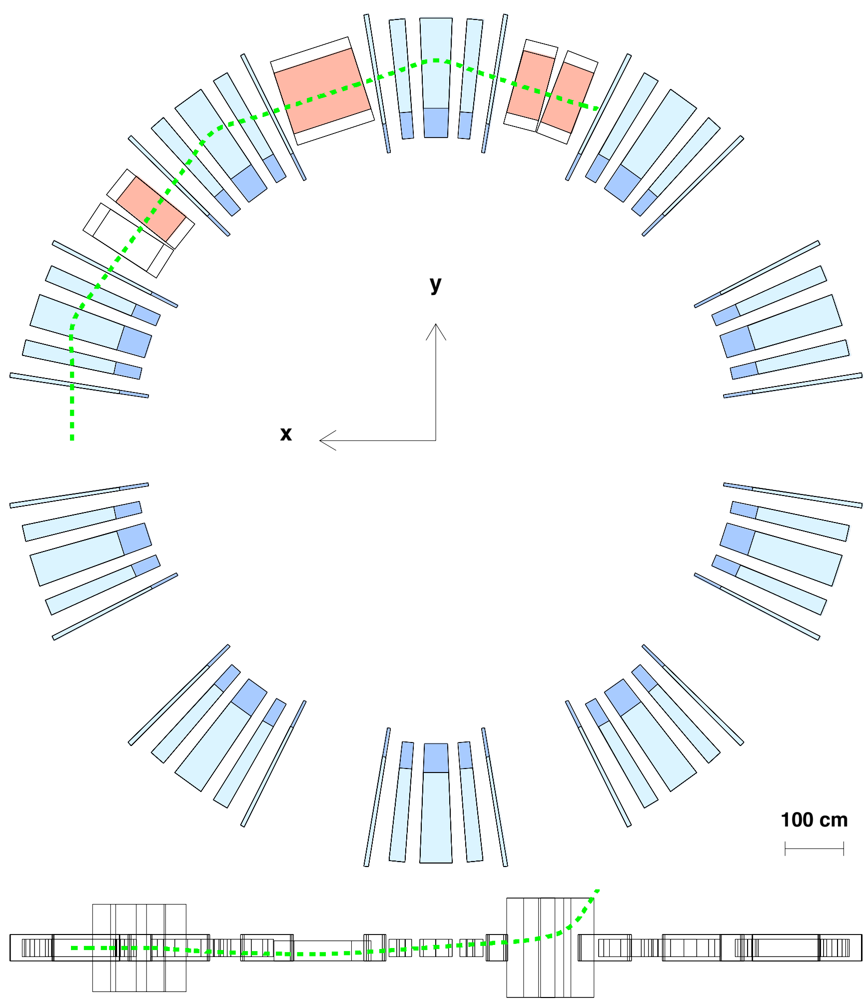
R.B.Palmer @ FFAG04

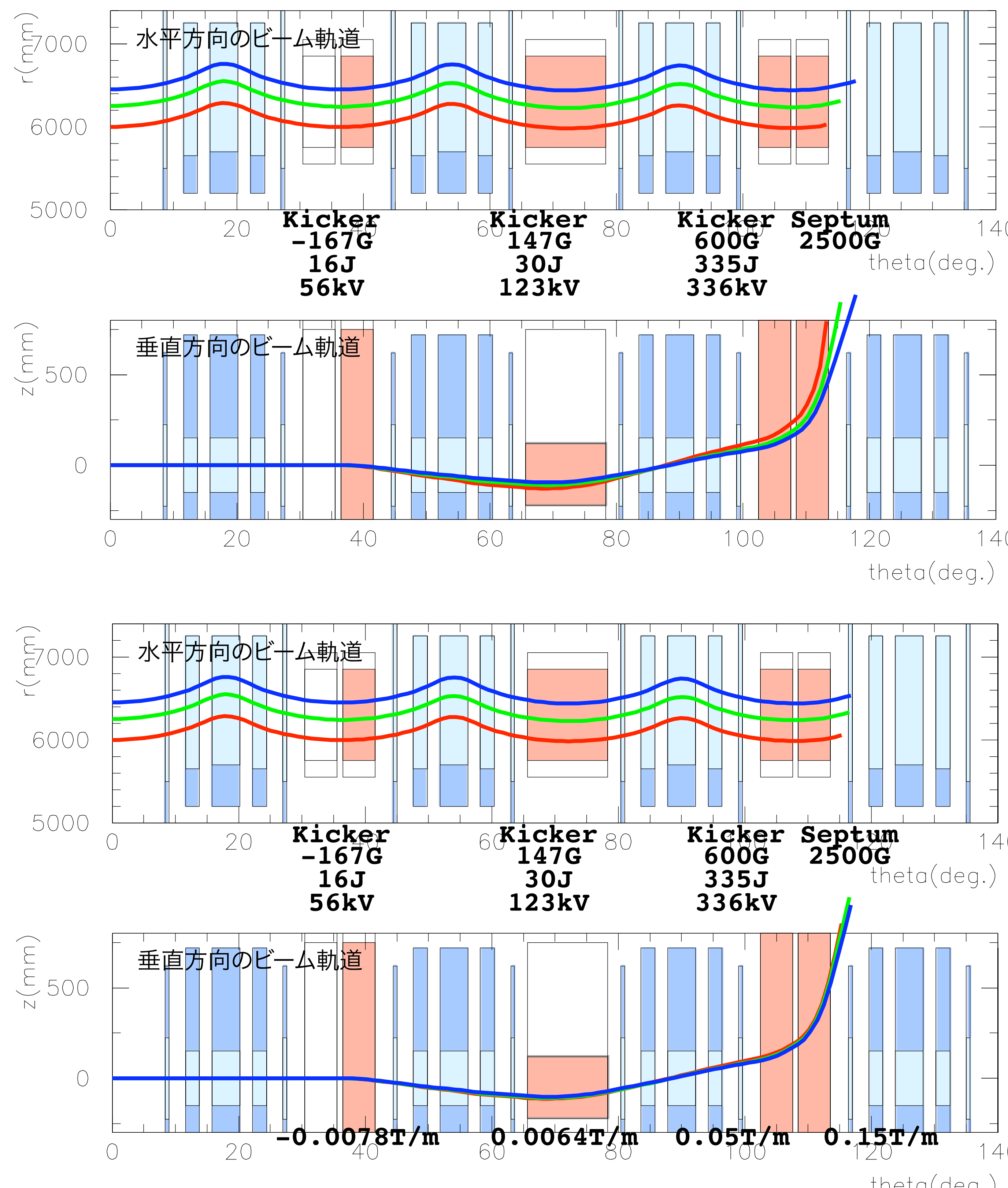




Vertical Injection/Extraction

Momentum Dispersion

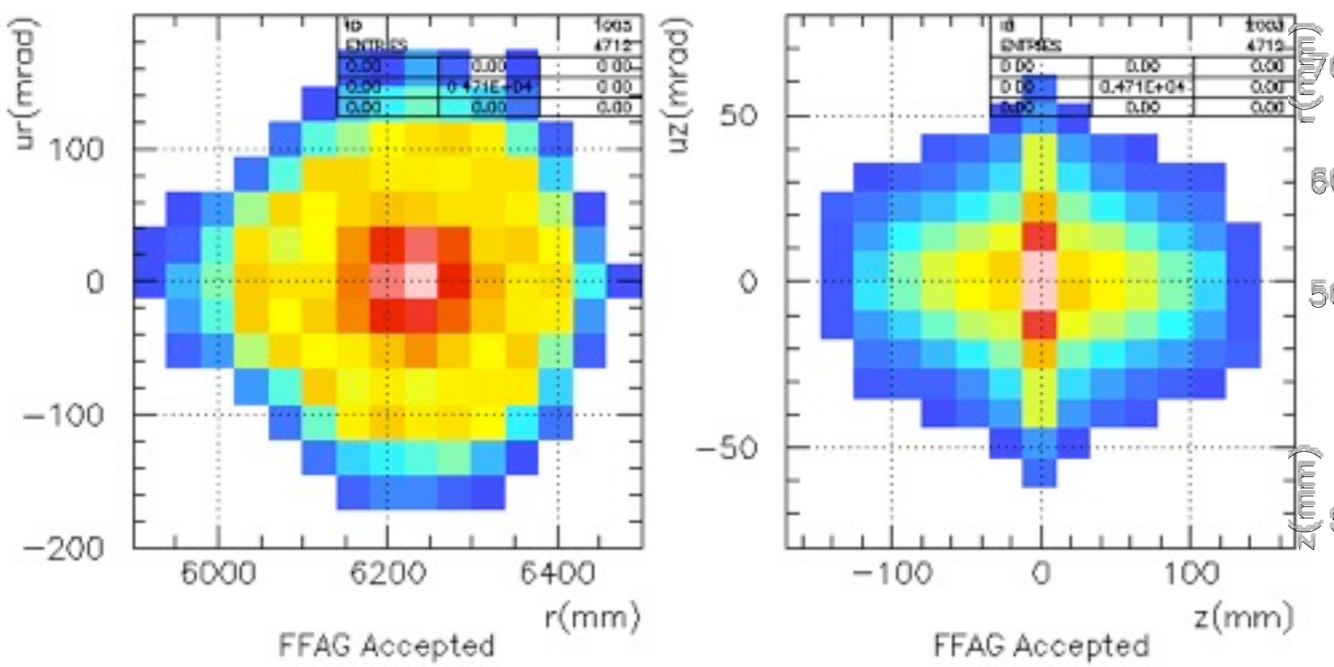


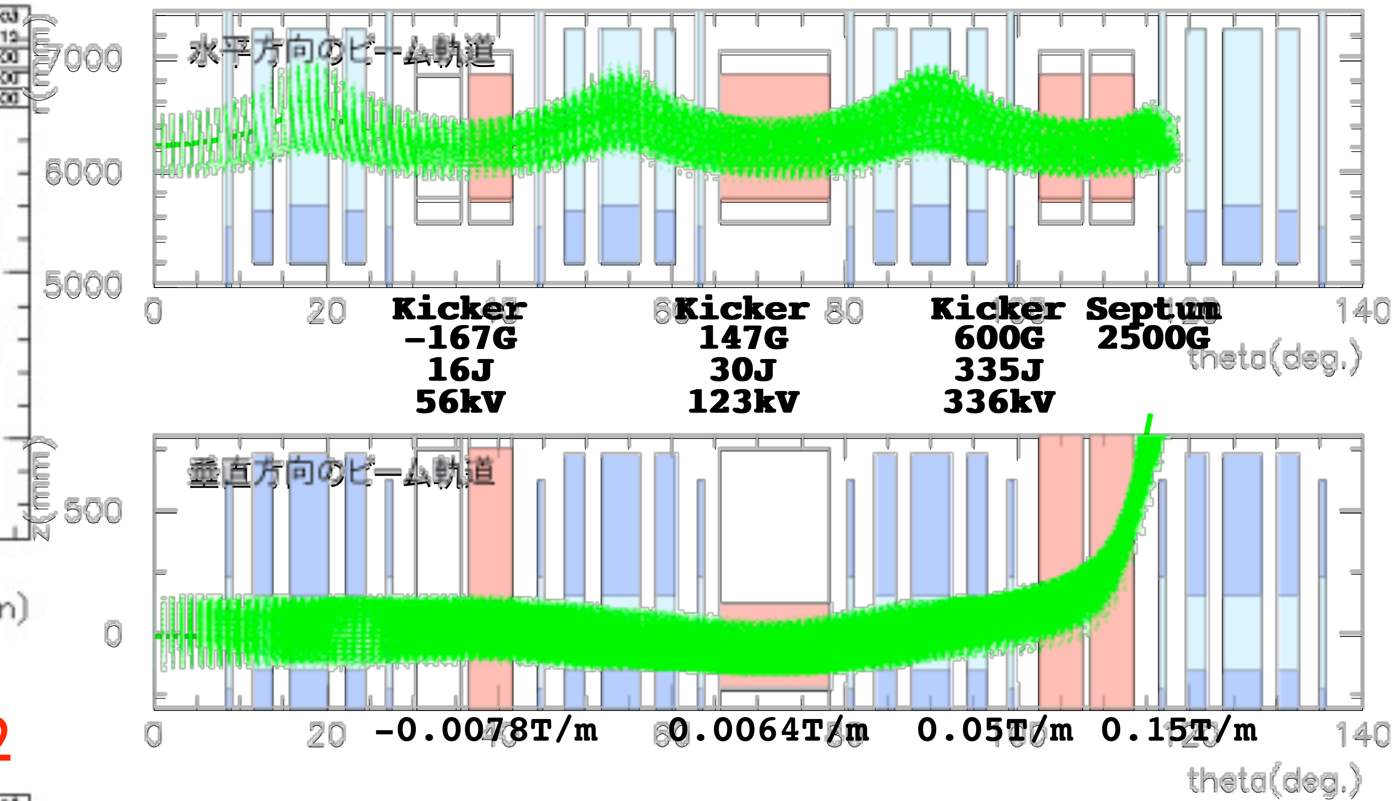


Add Skew Quadrupole moment

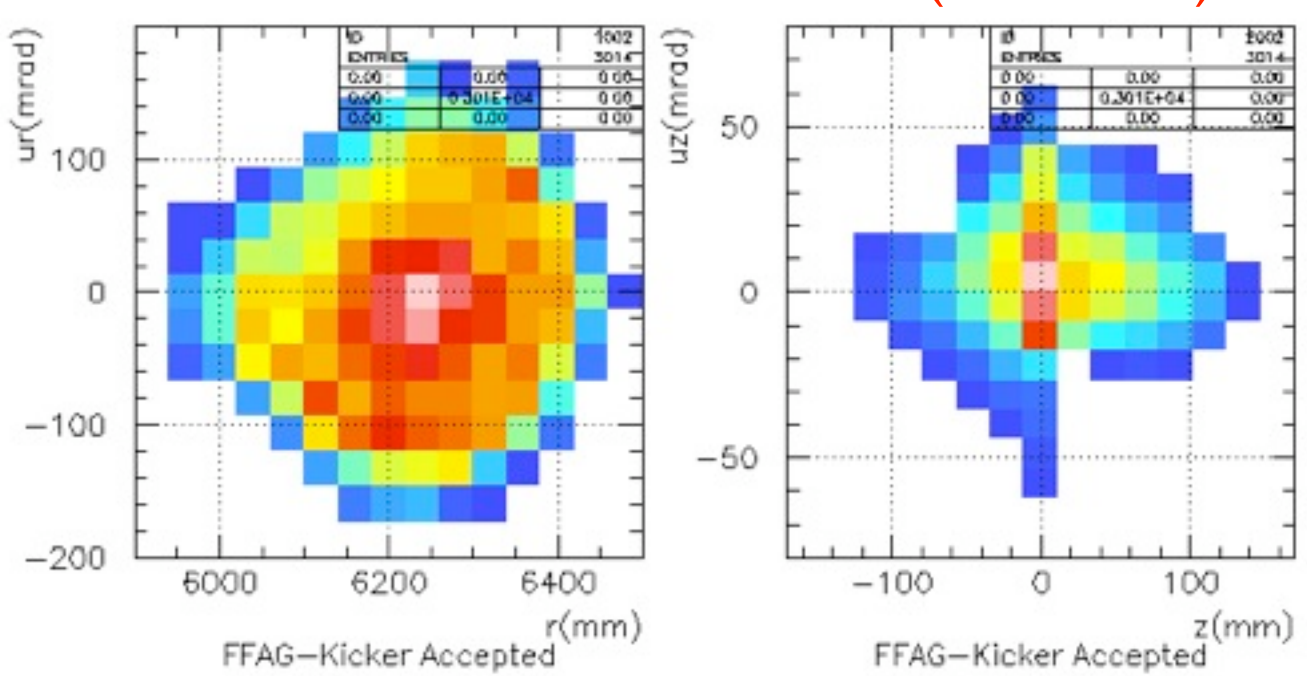
Vertical Injection/Extraction

FFAG's 4D Acc. : 1.0G(mm mrad)^2





FFAG-Kicker's 4D Acc. : 0.64G(mm mrad)^2



- (FFAG)/(FFAG-Kicker) = 64%

Vertical Injection/Extraction

	B (T)	Gradient (T/m)	rise time (ns)	fall time (ns)	Length (cm)	Height (cm)	Width (cm)	Single Turn Voltage (kV)	Stored Energy (J)
Kicker1	-0.0167	-0.0078	50	200	56	30	95	-56	16
Kicker2	0.0147	0.0064	50	200	140	30	95	123	30
Kicker3	0.0600	0.0500	50	200	56	50	95	336	335
Septum	0.2500	0.1500	50	200	56	80	95		

B.Palmer's results

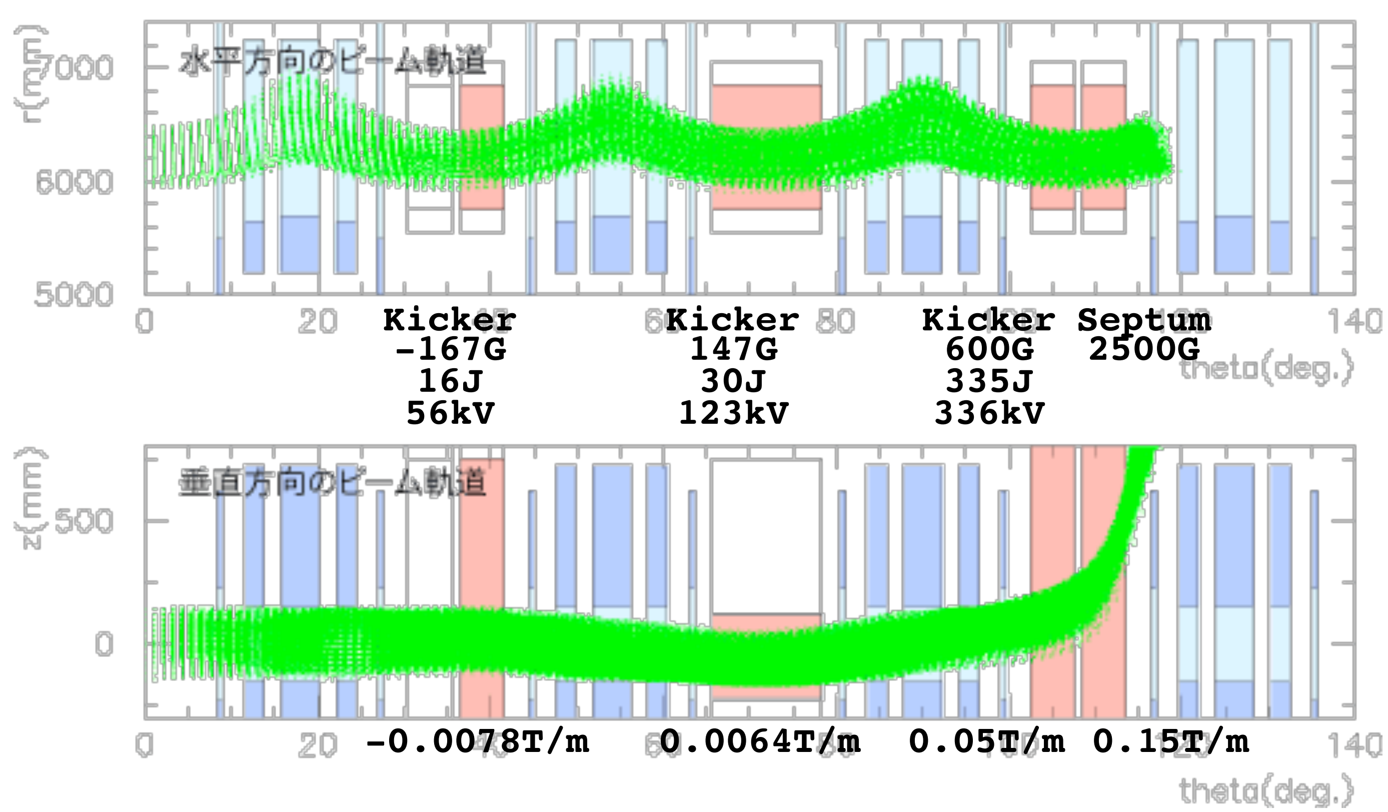
		dz m	len m	ht m	wid m	tilt deg	B G	Grad G/m	V_o kV	U J
1	Kicker	0.51	0.61	0.45	0.95	0	-167	-78	92	29
2	Kicker	0.00	1.63	0.30	0.95	0	147	64	144	40
3	Kicker	-.51	0.61	0.45	0.95	0	206	98	114	44
4	Septum	0.61	0.82	0.56	0.95	4	1710	930		
Max	(Total)								144	(113)
Horiz		0	1.22	.34	1.2		1080		3160	2038

- It would work with the present PRISM design.

Problems

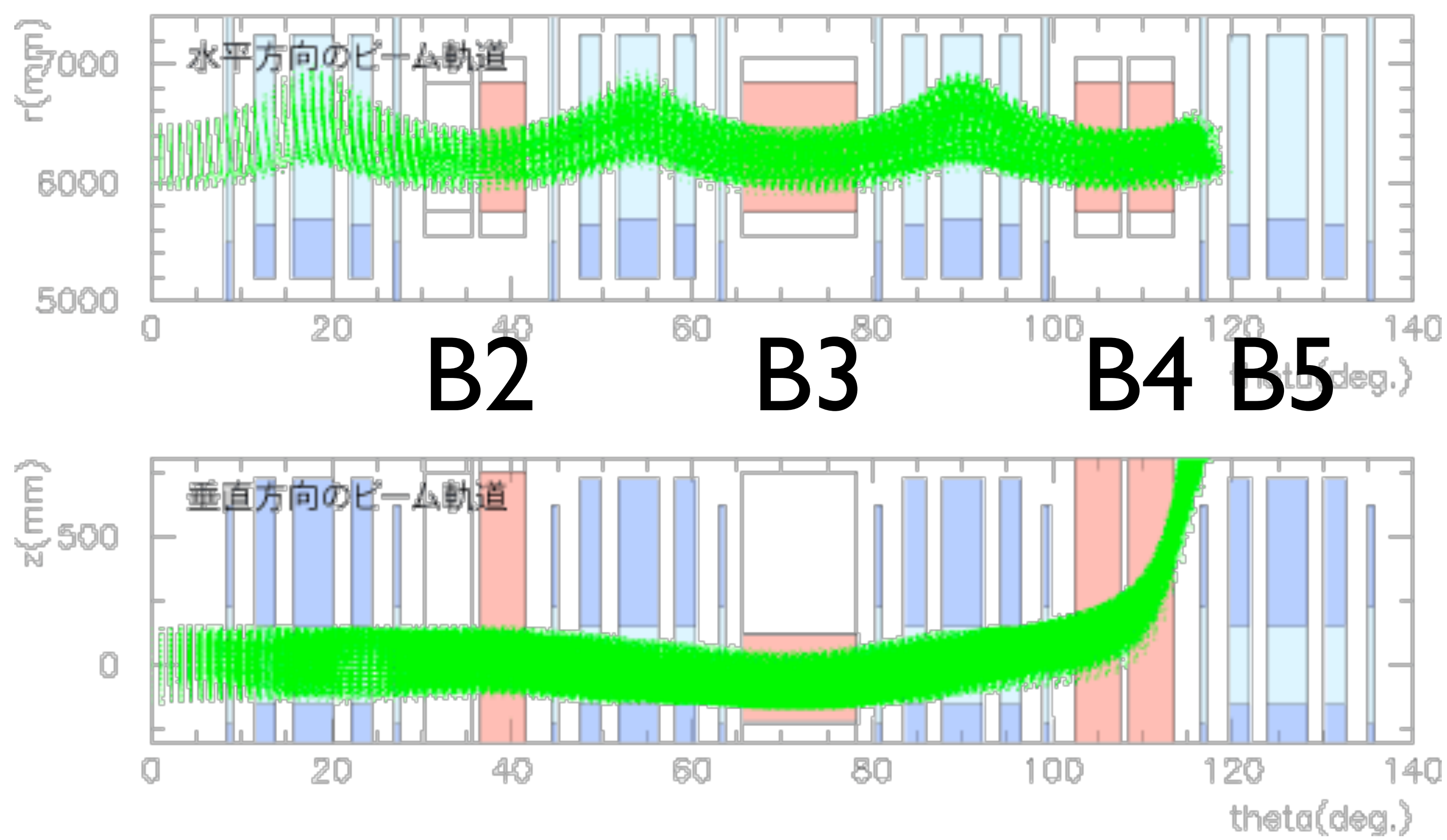
- B of Kicker3 is too high
- Septum conflicts the ring orbit
- Fringing effects and COD

optimize B



Optimization

- Field magnitudes of magnets B2-B5
- mini. # of lost muon by SIMPLEX method



very preliminary params.

FCN= 0.5054945 FROM SIMPLEX STATUS=PROGRESS 30 CALLS 31 TOTAL
EDM= 0.77E-01 STRATEGY= 0 NO ERROR MATRIX

EXT PARAMETER			CURRENT GUESS	PHYSICAL LIMITS	
NO.	NAME	VALUE	ERROR	NEGATIVE	POSITIVE
2	k2b0	-0.29989	0.40000E-01	-0.30000	0.0000
3	k3b0	0.15000	0.40000E-01	0.0000	0.30000
4	k4b0	0.20000	0.40000E-01	0.0000	0.30000
5	k5b0	1.7000	0.20000	0.0000	4.0000

(kG)

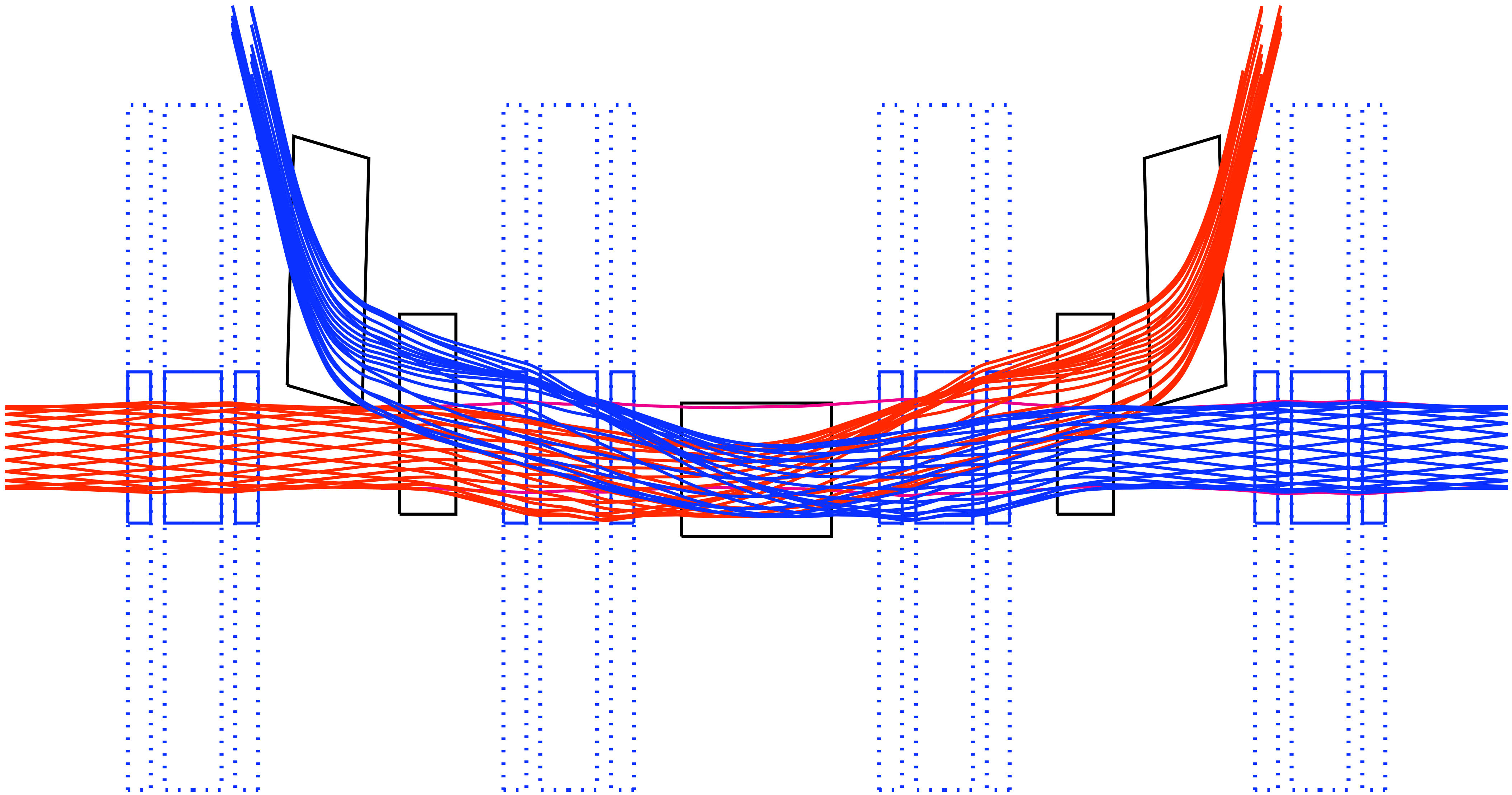
54.650u 115.370s 2:52.58 98.5% 0+0k 0+0io 47855pf+0w

		dz	len	ht	wid	tilt	B	Grad	V_o	U
		m	m	m	m	deg	G	G/m	kV	J
1	Kicker	0.51	0.61	0.45	0.95	0	-167	-78	92	29
2	Kicker	0.00	1.63	0.30	0.95	0	147	64	144	40
3	Kicker	-.51	0.61	0.45	0.95	0	206	98	114	44
4	Septum	0.61	0.82	0.56	0.95	4	1710	930		
Max	(Total)								144	(113)
Horiz		0	1.22	.34	1.2		1080		3160	2038

Injection and Extraction in same 3 cells

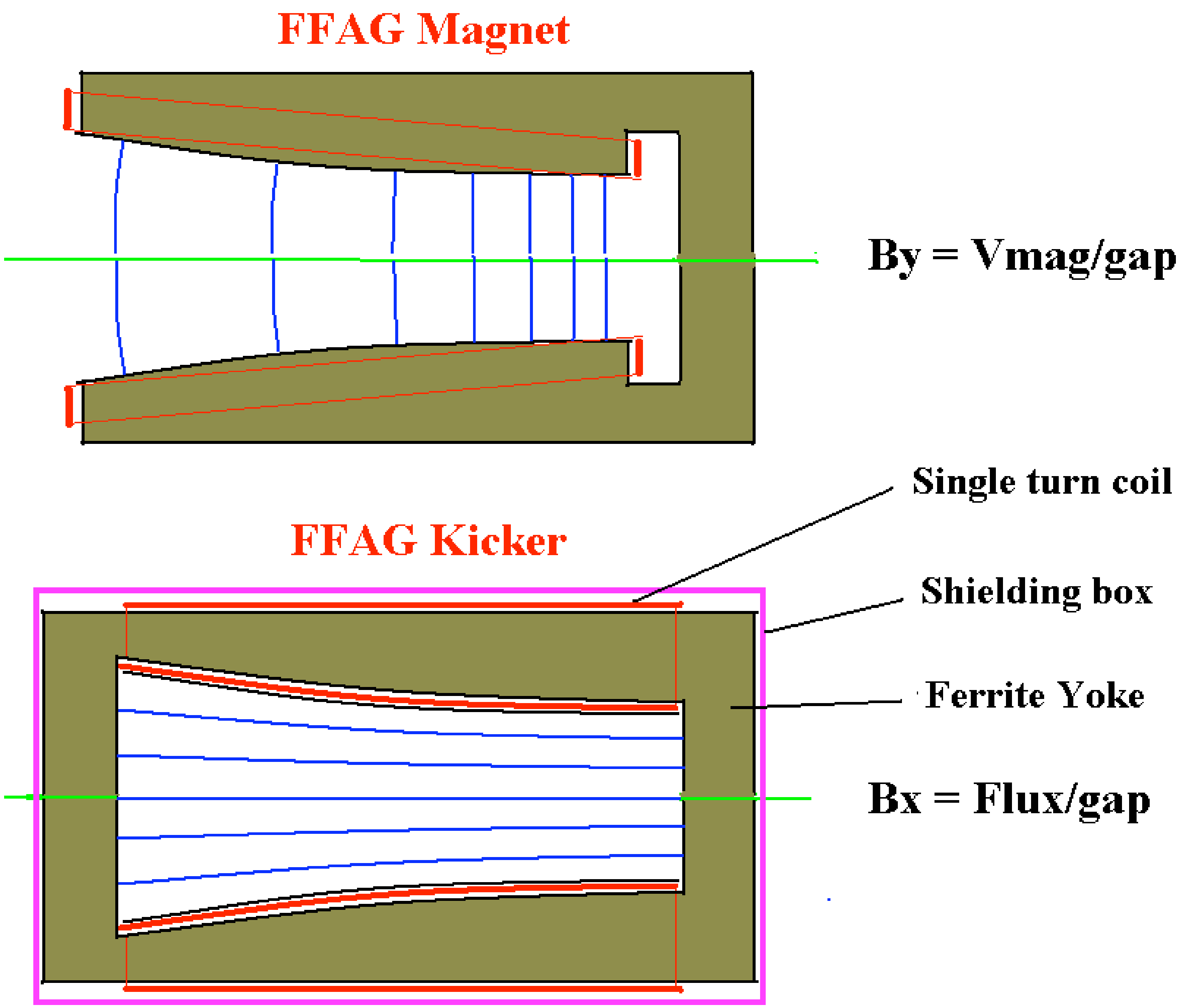
Central kicker must be pulsed twice

End kickers pulsed once



What does a Combined Function Kicker Look Like

You already know



Conclusions on Injection/Extraction

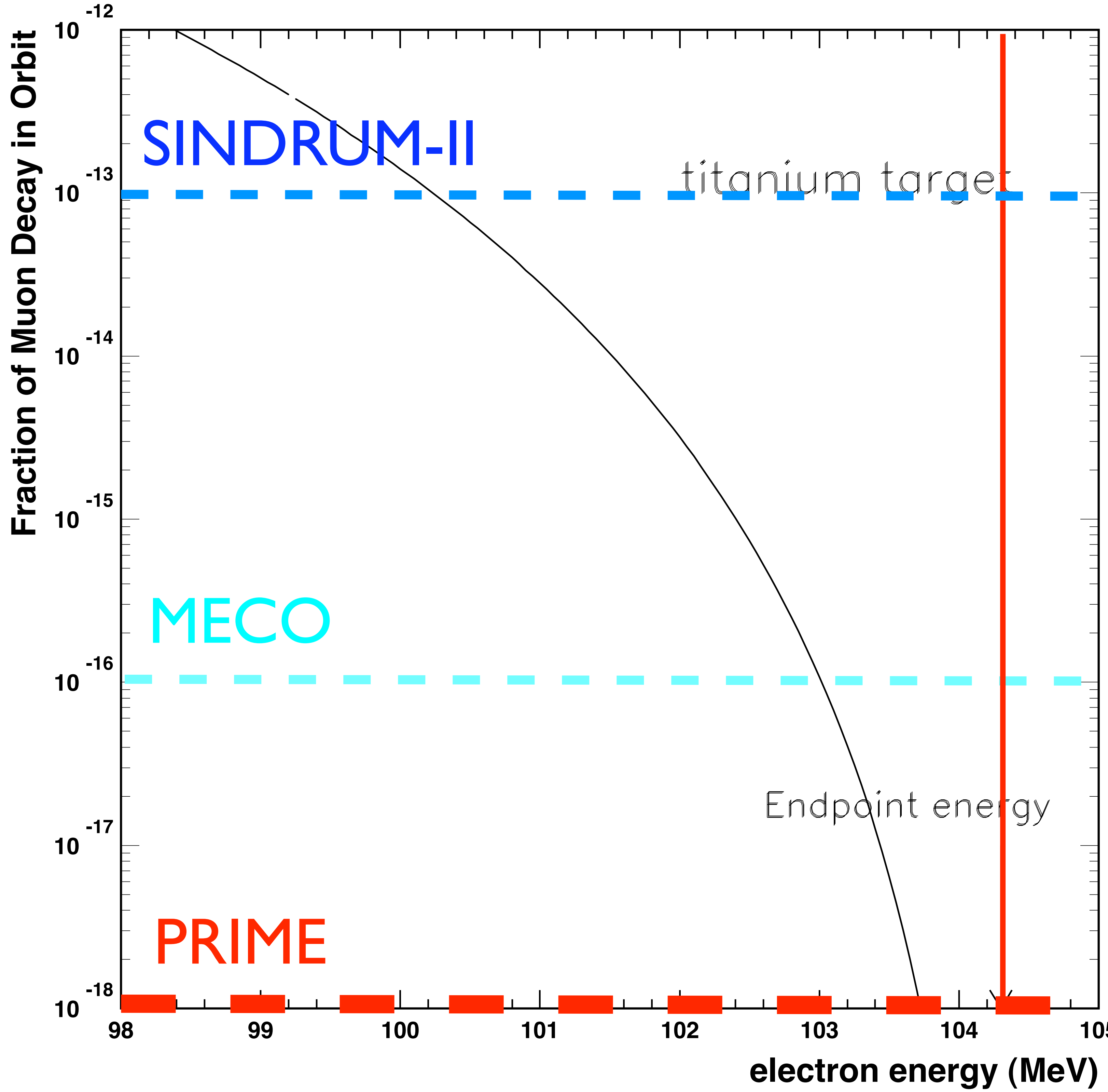
- Vertical injection/extraction much easier than horizontal
  - Needs Much less Magnetic energy
  - Needs much lower Voltage
  - Chromatic correction easy
- But Remaining Design Questions
  - Needs larger vertical apertures in special magnets
  - Kicker Energy still much greater than normal kickers
  - Need two pulses in each kicker
  - Kicker aspect ratio unnatural
  - Needs gradient in kicker field (dipole + skew quadrupole)
- Study needs repeating with real fields and beam
- But this looks plausible

Summary

- The PRISM-FFAG would enable a mu-e conv. experiment with a sensitivity of BR~10^{-18}.
- Feasibility of the PRISM-FFAG was shown by the R&D (2003-2009) for magnet and RF. The PRISM-FFAG can be build using these devises, if budgets are approved for that.
- Issues we have to solve to realize the mu-e conv. experiment with PRISM-FFAG are:
  - Injection and extraction
  - Matching with solenoid
  - Cost of RF system
- Let's work together!

Backup Slides

Electron from DIO



Requirement on E_e resolution for DIO suppression

PRISM

- **SINDRUM-II :BR~10^{-13}**
  - 2.8 MeV
  - energy loss in the targets.
- **MECO : BR~10^{-16}**
  - 900 keV
  - energy loss in the targets
  - multiple scat. in the detector.
- **PRISM : BR~10^{-18}**
  - 350 keV
  - mono-energetic muon beam
    - to realize thinner targets
  - massless detector