Results and Status of PRISM-FFAG R&D

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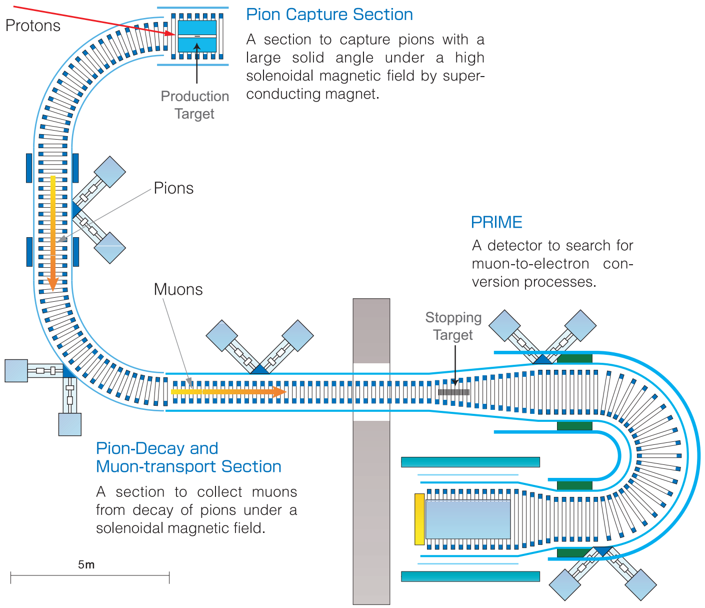
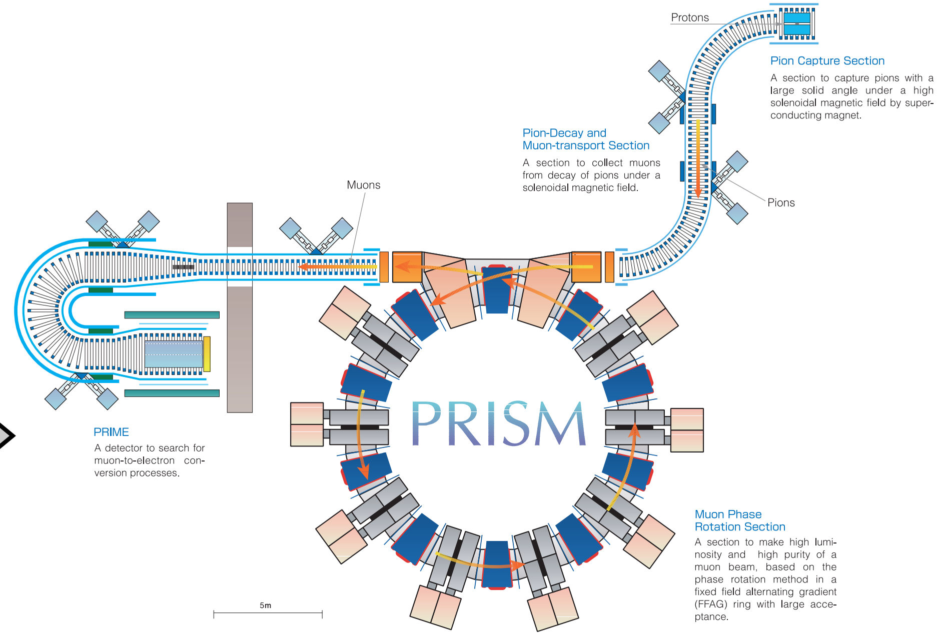
Japanese staging plan of μ-e conversion

1st Stage : COMET



2nd Stage : PRISM/PRIME



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

- without a muon storage ring. (MECO-type)
- with a slowly-extracted pulsed proton beam.
- at the J-PARC NP Hall.
- for early realization (~2017)

The sensitivity is limited by backgrounds: pion induced electrons, decay in orbit electrons, and so on.

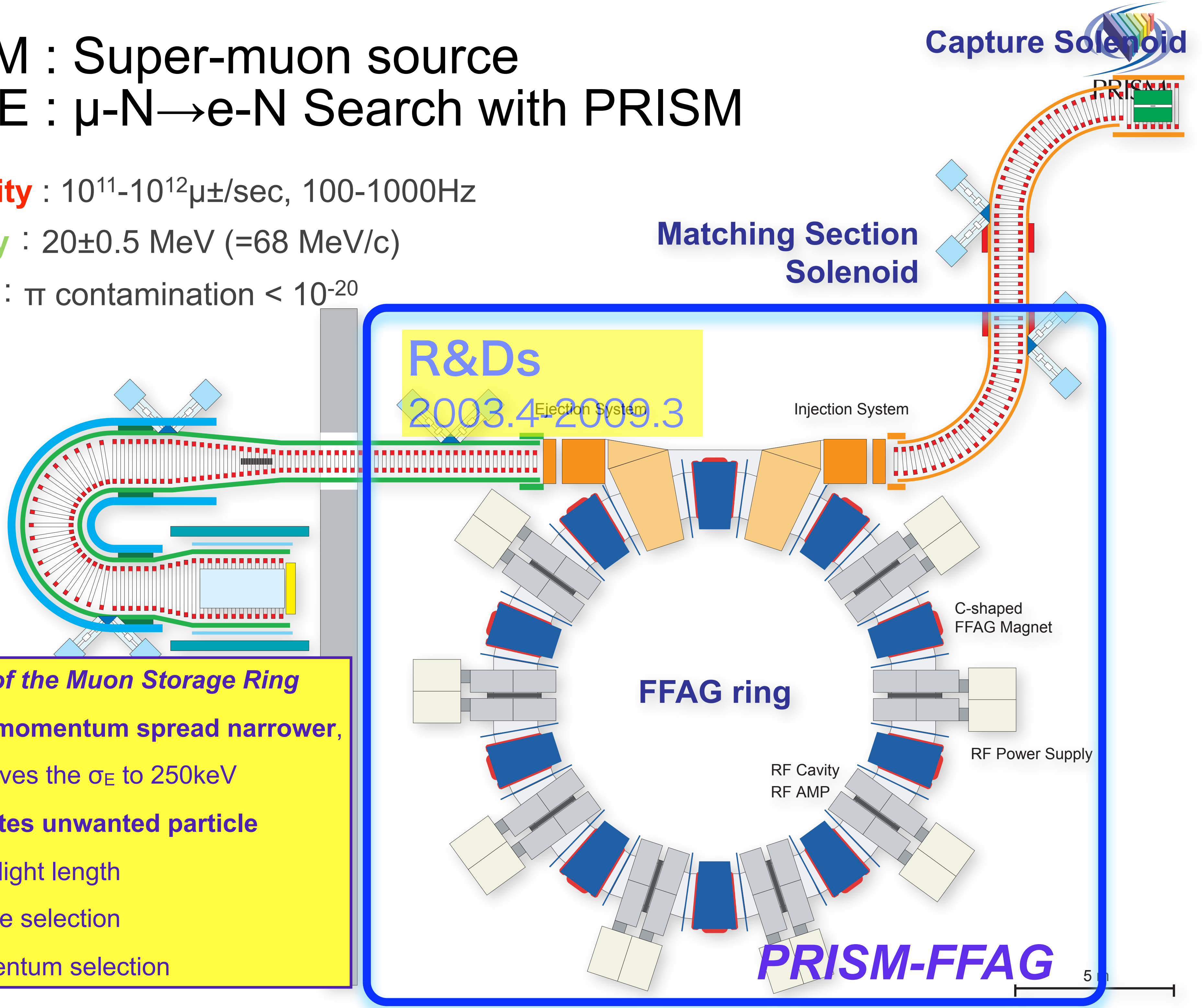
$$B(\mu^- + Ti \rightarrow e^- + Ti) < 10^{-18}$$

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

A muon storage ring can solve the problem.

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}

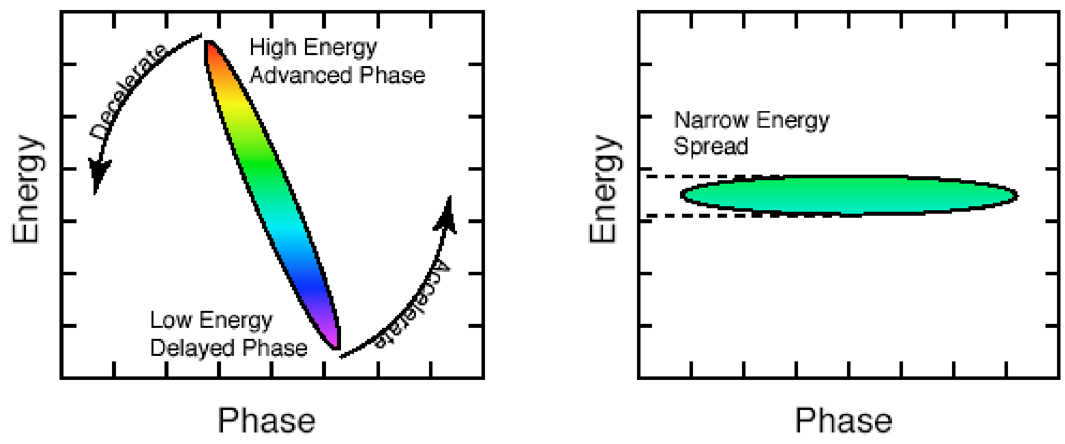


Functions of the Muon Storage Ring

- **Makes momentum spread narrower,**
  - improves the σ_E to 250keV
- **Eliminates unwanted particle**
  - long flight length
  - charge selection
  - momentum selection

Phase rotation in PRISM-FFAG

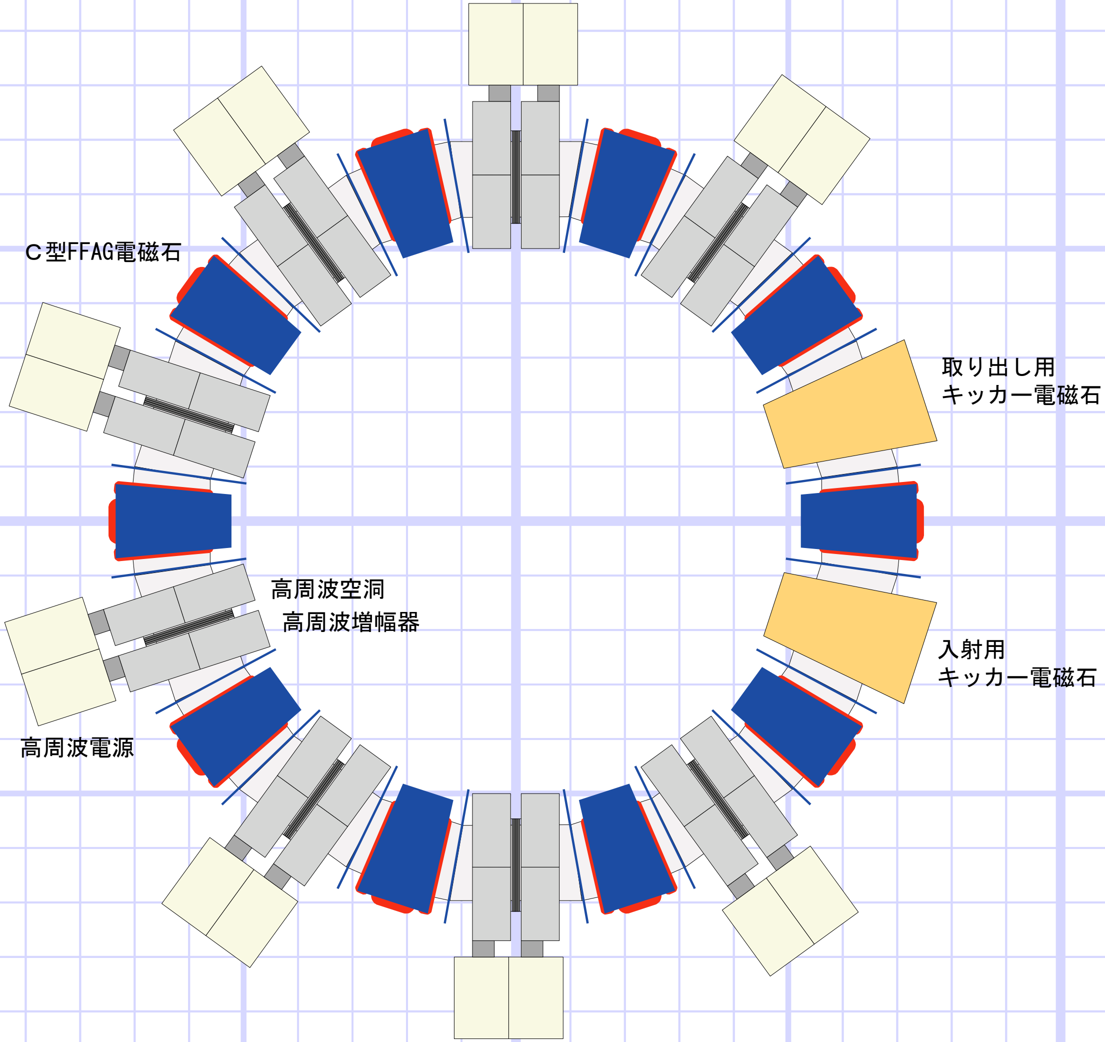
- A technique of phase rotation is adopted.
- The phase rotation is to decelerate fast beam particles and accelerate slow beam particles by RF.
- To identify energy of beam particles, a time of flight (TOF) from the proton bunch is used.
    - Fast particle comes earlier and slow particle comes late.
- Proton beam pulse should be narrow (< 10 nsec).
- Phase rotation is a well-established technique, but we need to apply this to a low energy muons (P_μ~68MeV/c) for stopping muon experiments.



Design of PRISM-FFAG

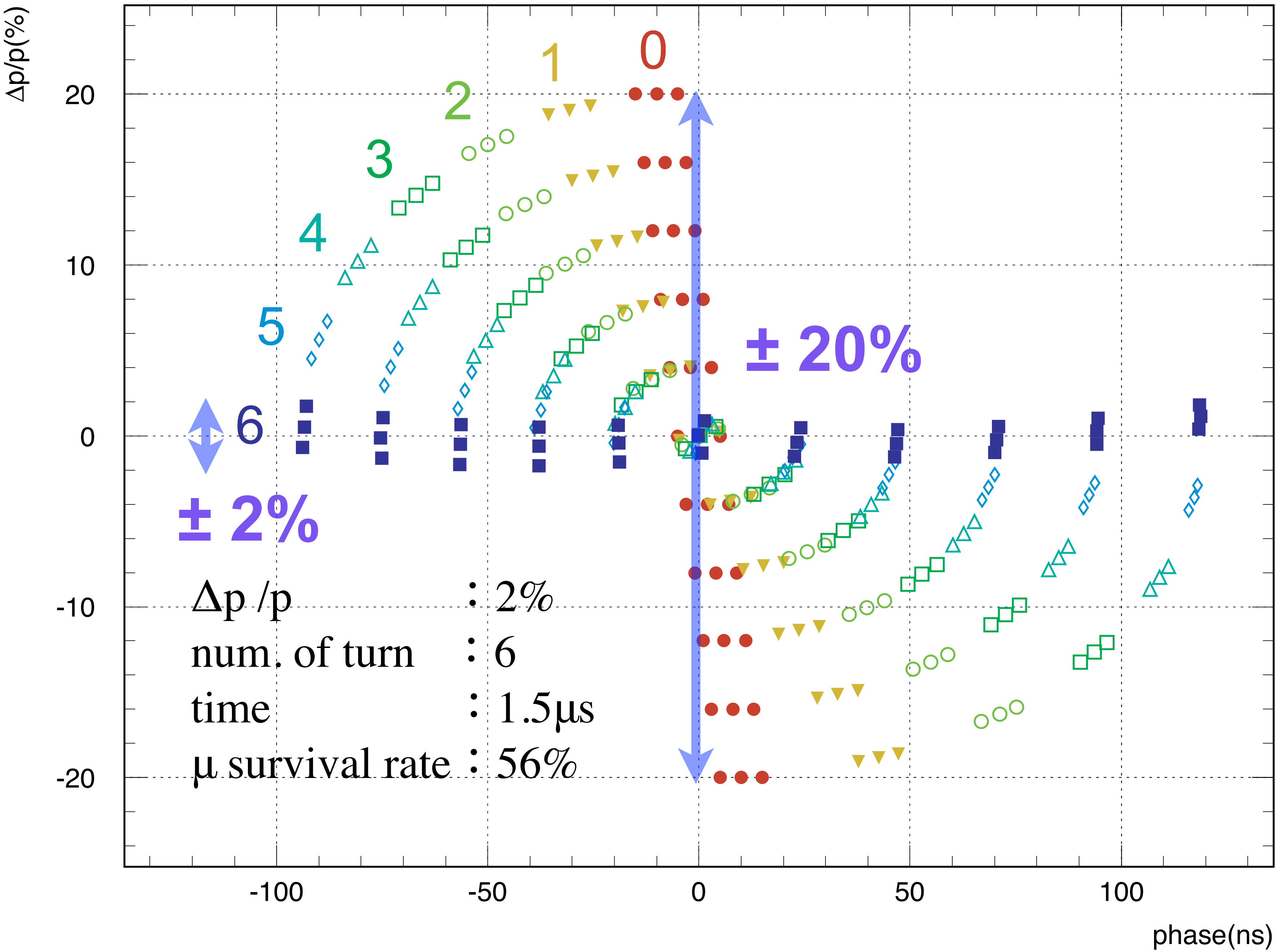
PRISM-FFAG

- 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
- $\theta_F/2=2.2$deg
- $\theta_D=1.1$deg
- Max. field
- F : 0.4T
- D : 0.065T
- tune
- h : 2.73
- v : 1.58

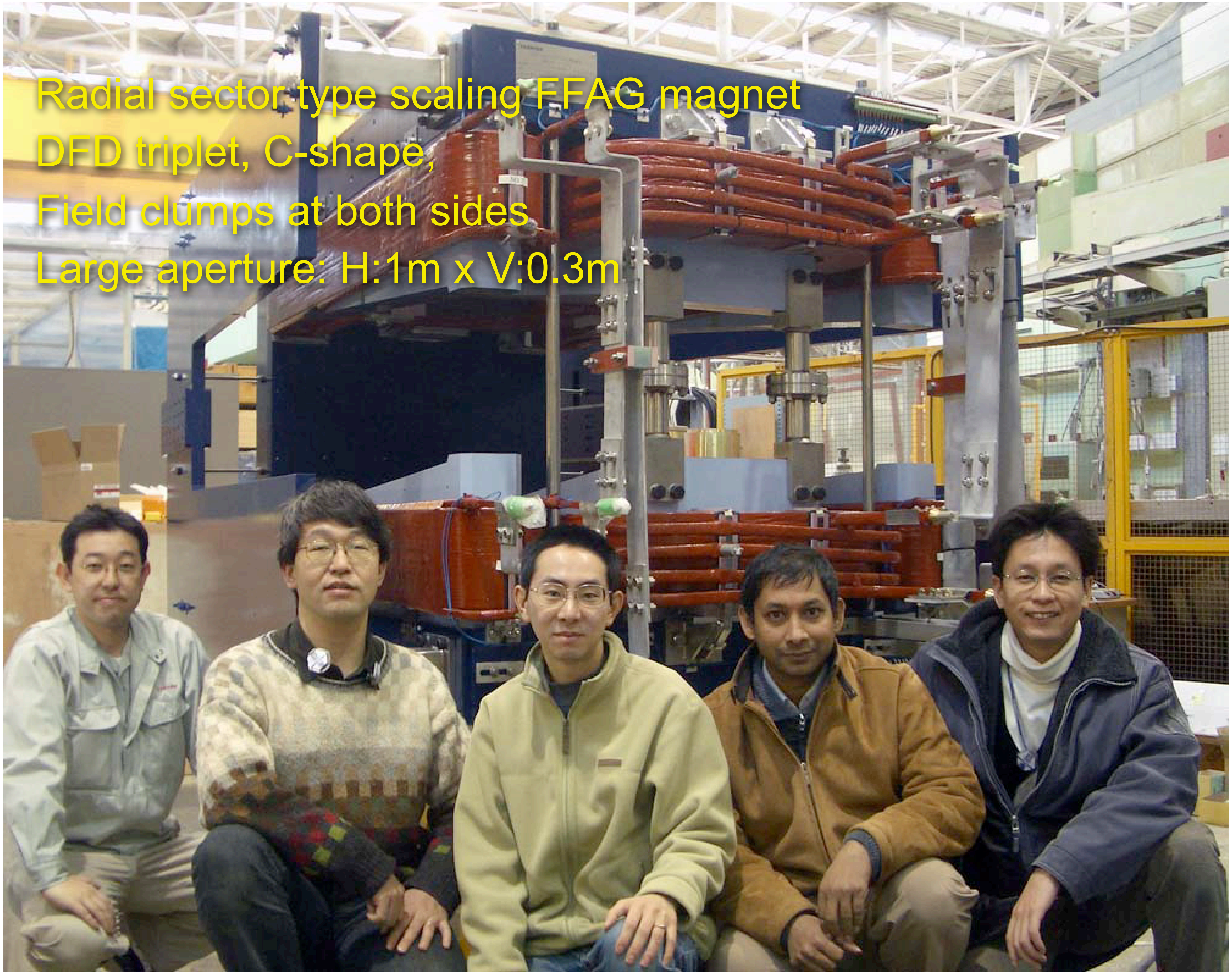


- Large transverse acceptance
  - Horizontal : 38,000 π mm mrad
  - Vertical : 5,700 π mm mrad
- High field gradient RF system
  - field gradient ~170kV/m (~2MV/turn)
    - quick phase rotation (~1.5μs)
    - large mom. acceptance (68MeV/c +- 20%)

Expected phase rotation with PRISM-FFAG



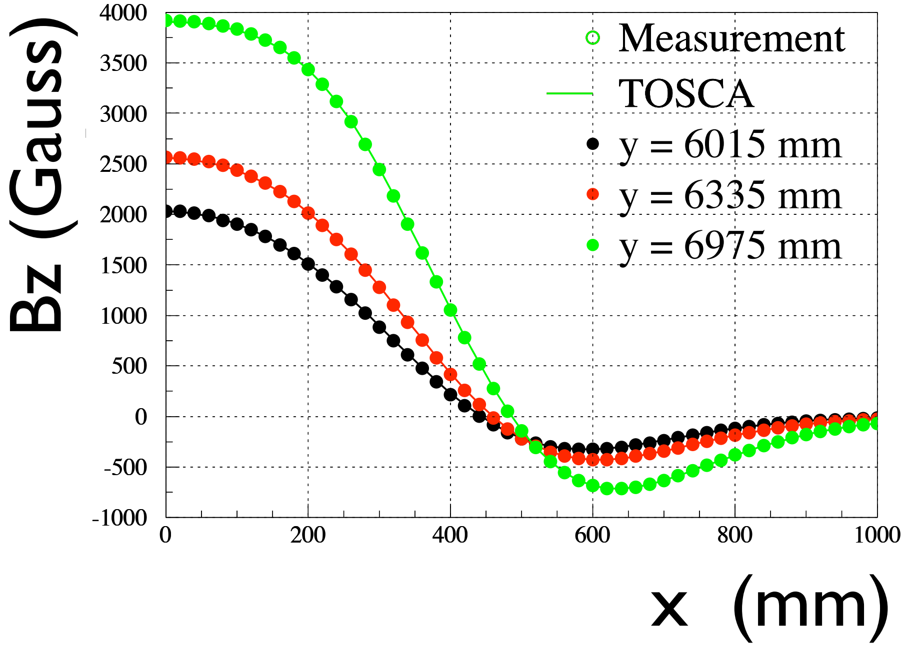
The First PRISM-FFAG Magnet

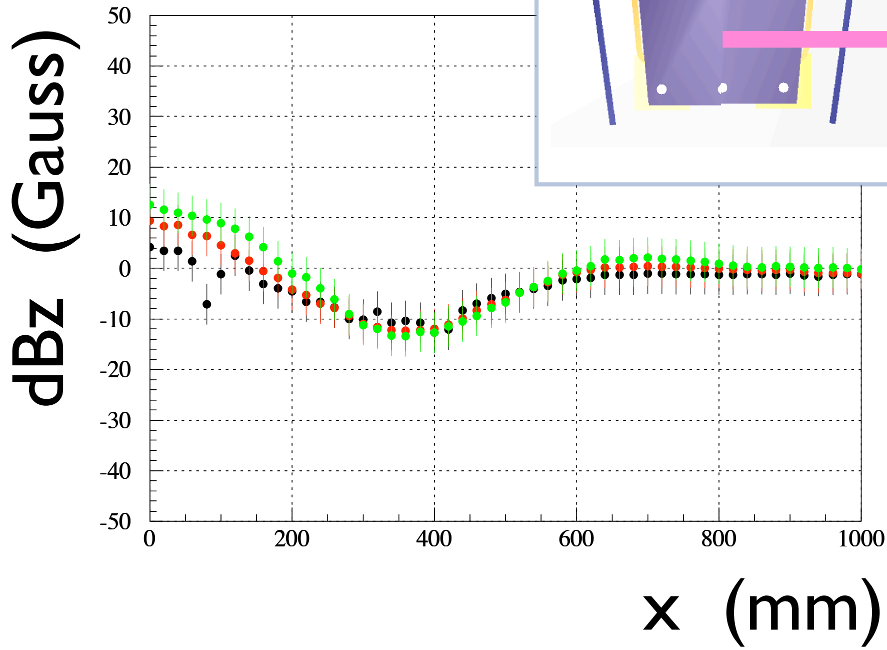


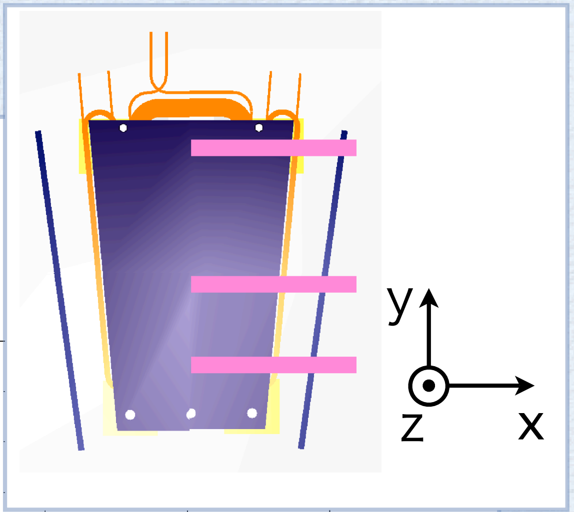
Results of Field Measurements

On median plane

tosca_vs_meas.kumac



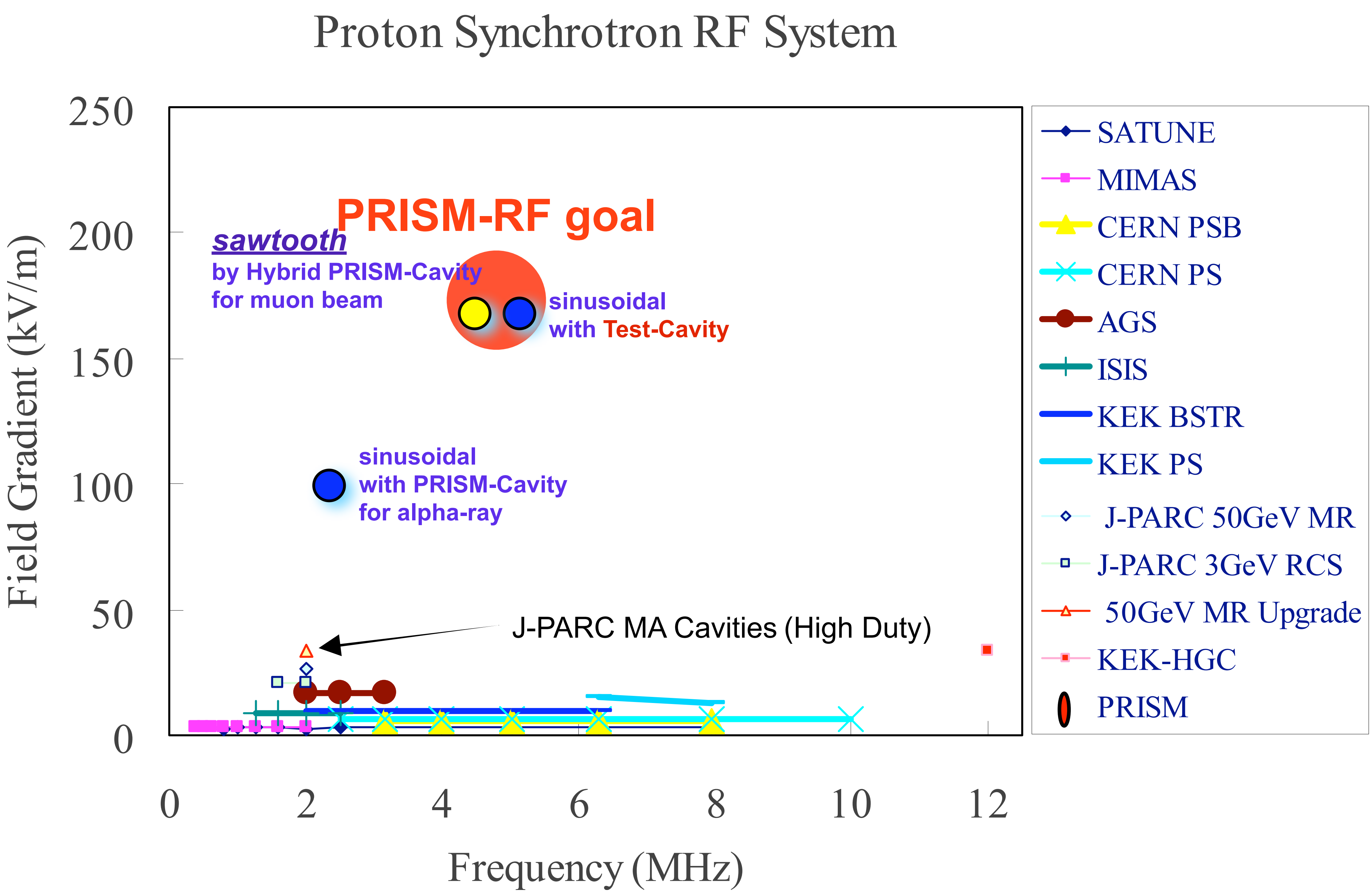




Difference between TOSCA and measurement is about 10 Gauss

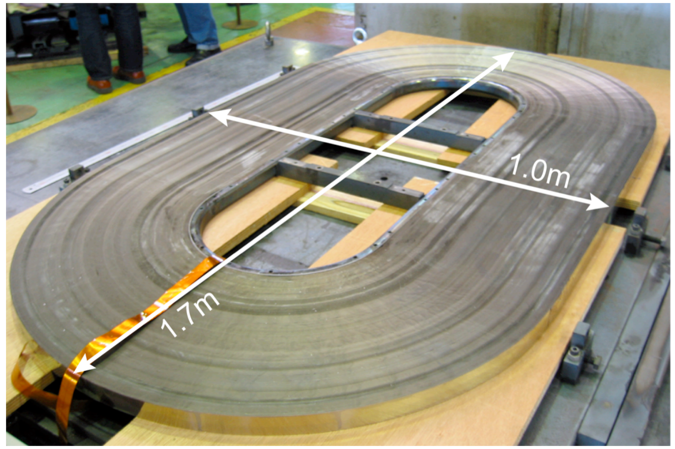
The RF system

Field gradient of PRISM-FFAG



How to realize the 4MHz sawtooth RF

- Requirements on RF system for PRISM-FFAG
  - high field gradient：＞170kV/m @4MHz
  - Sawtooth-RF
- Magnetic Alloy cores have been adopted
  - Q＜１：enable to add higher harmonics
  - large aperture is possible
- Adjust the frequency
- solution 1：cut core
  - used in RF cores for J-PARC MR
  - too expensive for PRISM-cores due to their ze
- solution 2：hybrid RF system
  - tested for J-PARC RCS
  - can use for PRISM-cavities



Hybrid RF system

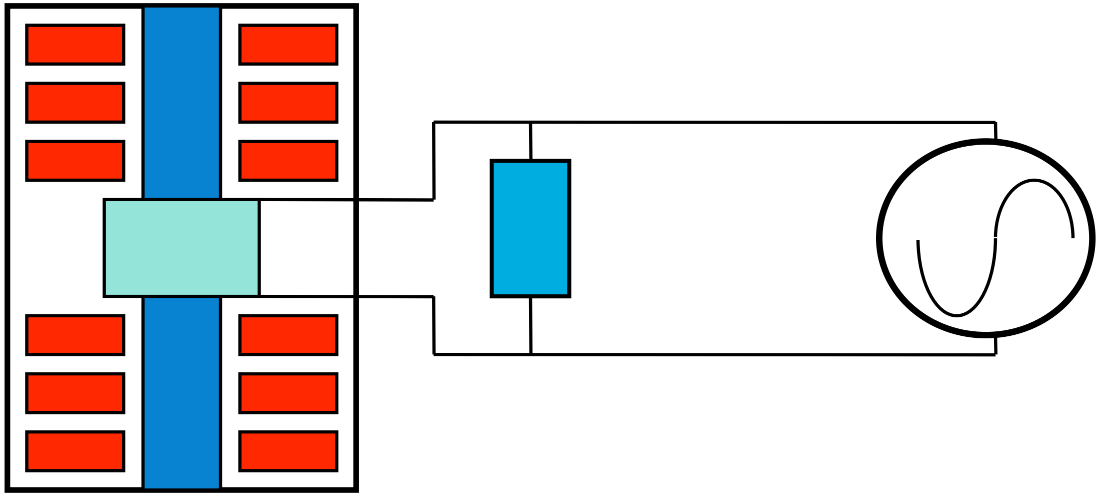
- Proposed by A. Schnase.
- Combination of MA cavity with a resonant circuit composed by inductor and capacitor.
- Developed for J-PARC RCS cavities.

$$f = 1/2\pi\sqrt{LC}$$

$$1/L = 1/L_{core} + 1/L_{ind}$$

$$Q = R_p/\omega L$$

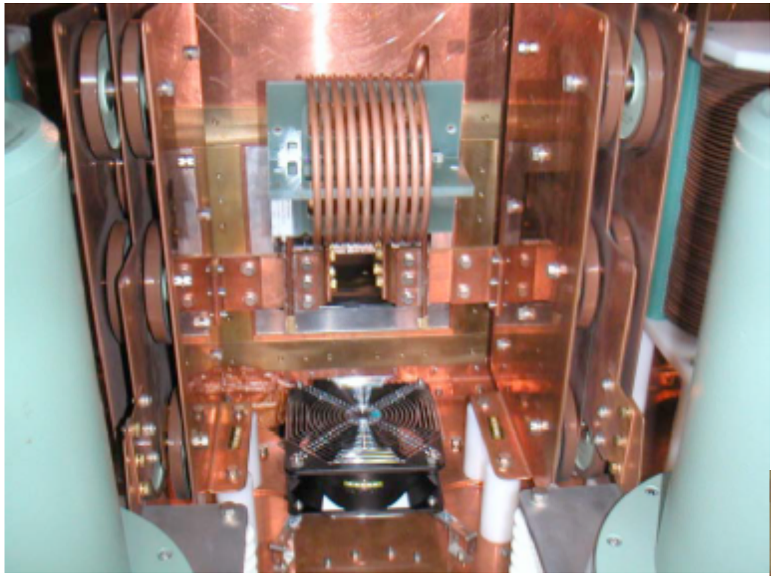
Rp: shunt



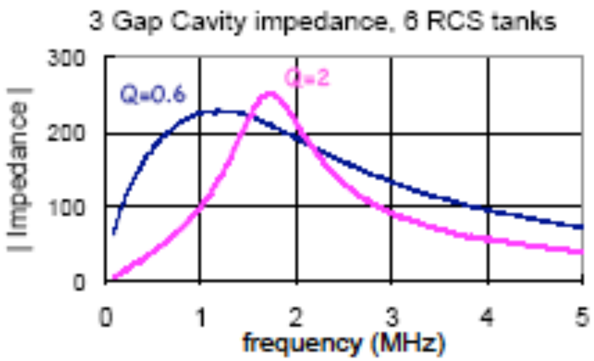
J-PARC: add C and L to control Q and f

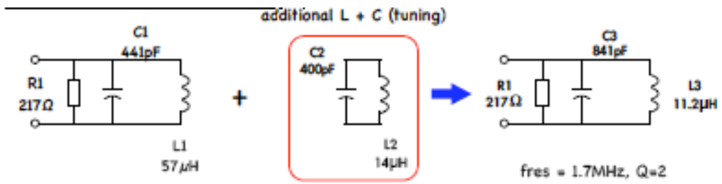
PRISM : add L to control f

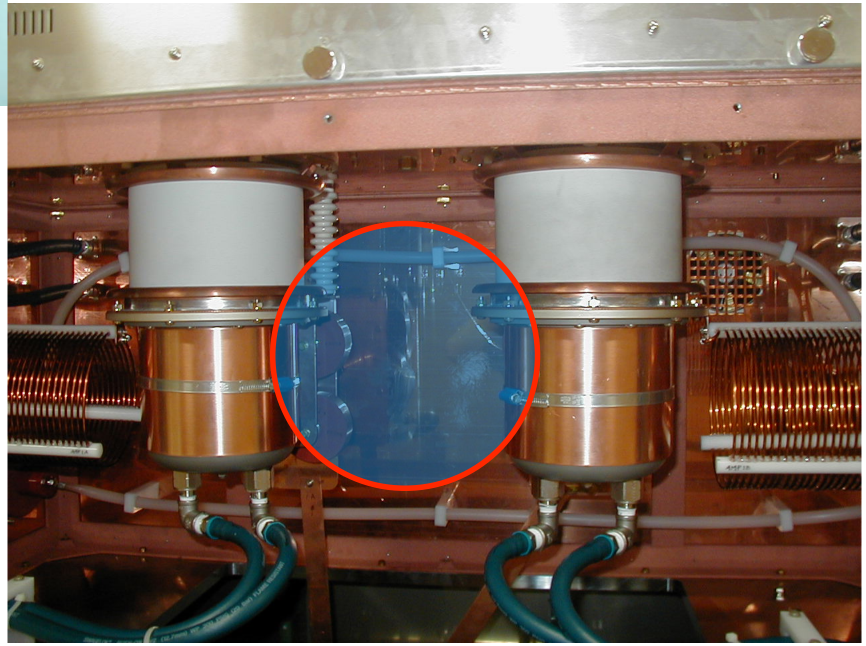
Hybrid RF system



Parallel inductor for J-PARC







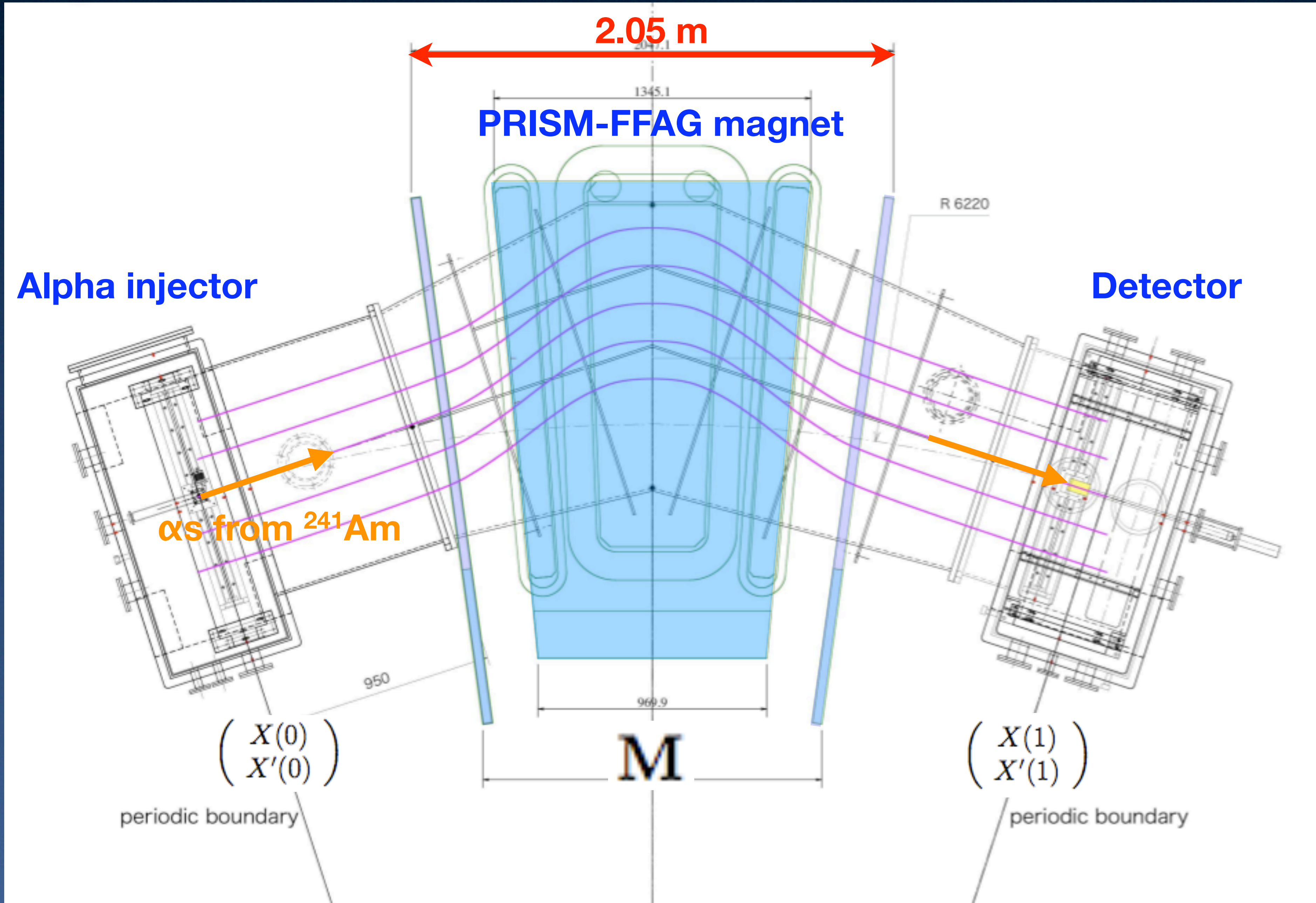
Inside of PRISM AMP

It will be tested in this year.

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'

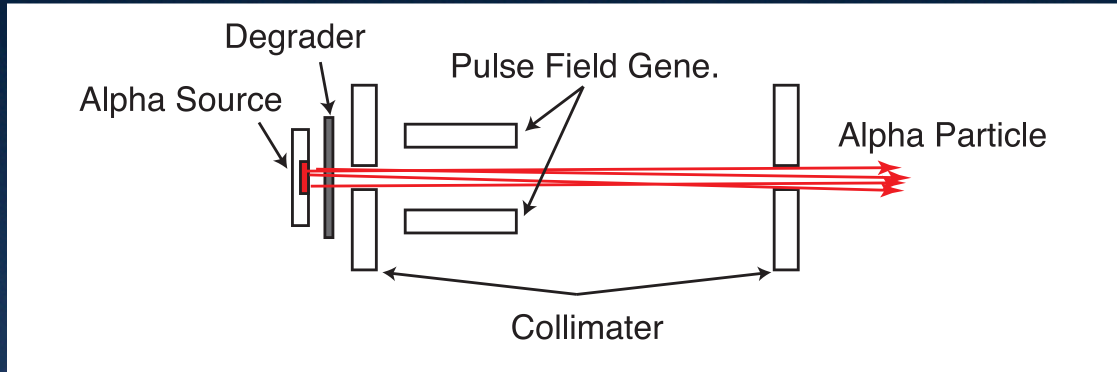
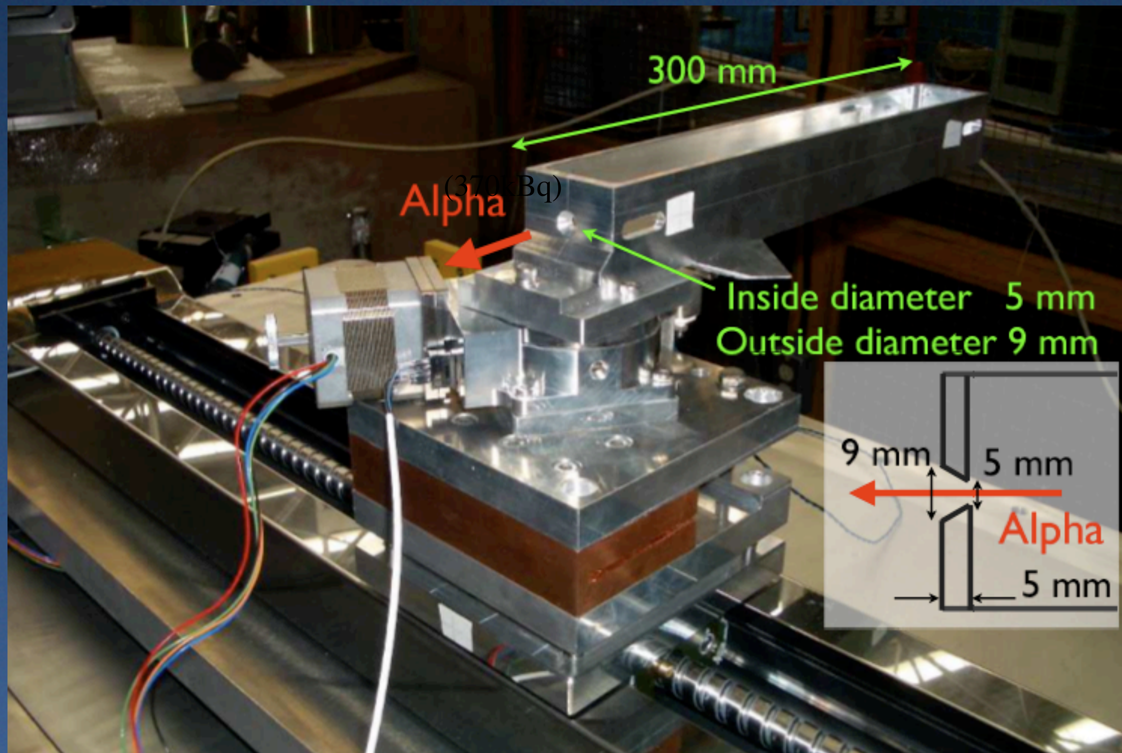


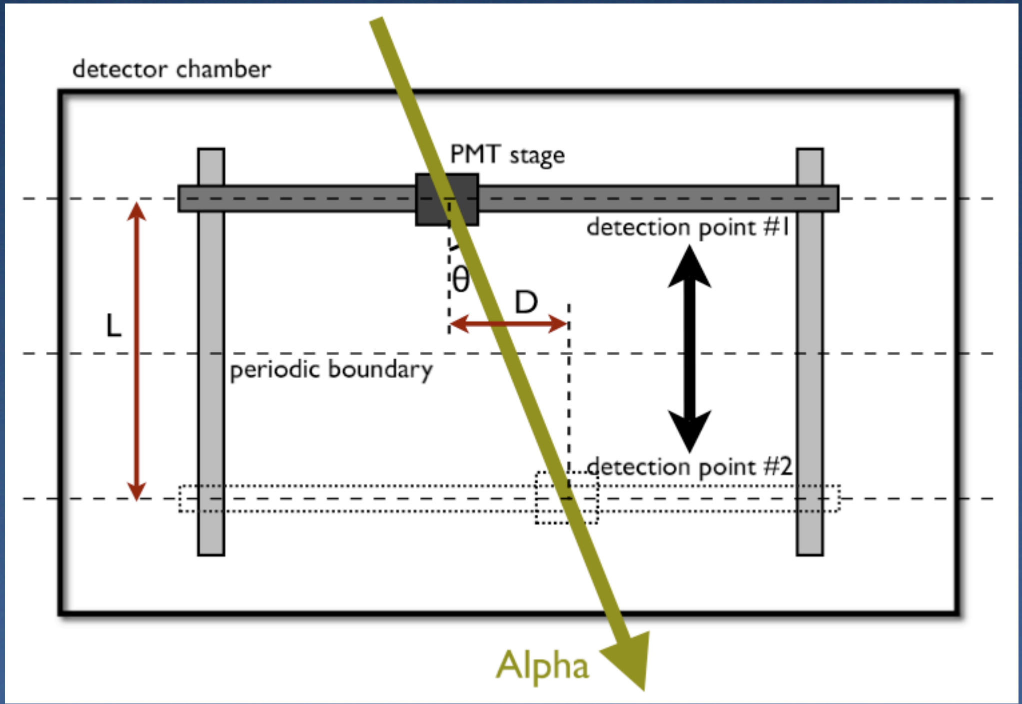
Table 4.4: Specifications of the alpha ray injector

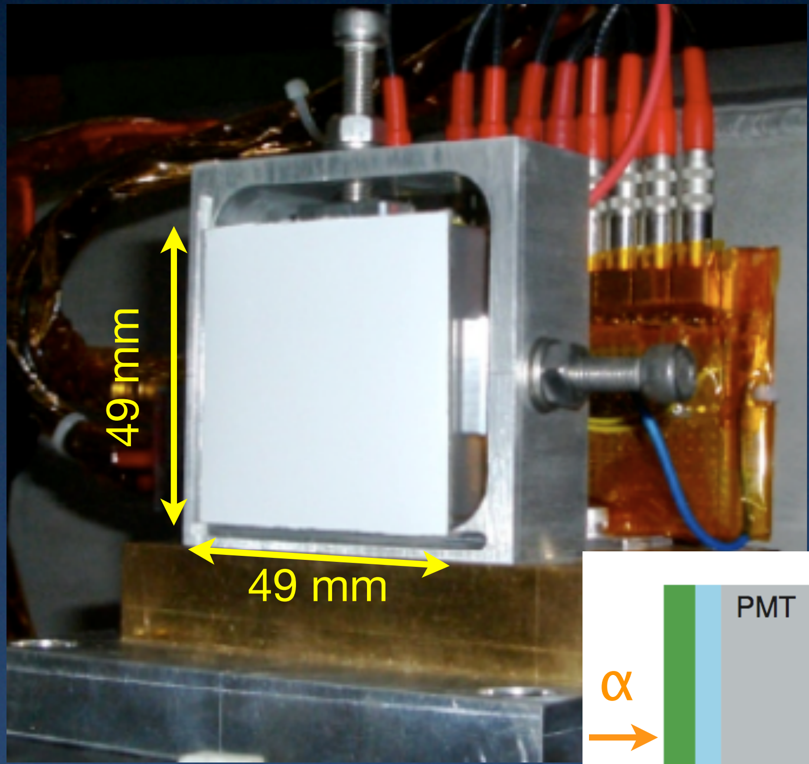
Alpha source	^{241}Am 5.486 MeV (85.2%)
Energy moderator	
Material	Aramid film
Thickness	21 μm
Energy loss	2.950 MeV
Average alpha energy	2.536 MeV
FWHM of alpha energy	0.121 MeV
Collimator	
Number of collimators	2
Diameter	5 mm ϕ
Interval	300 mm
Robots	
Stroke	800 mm along radius direction
Rotation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

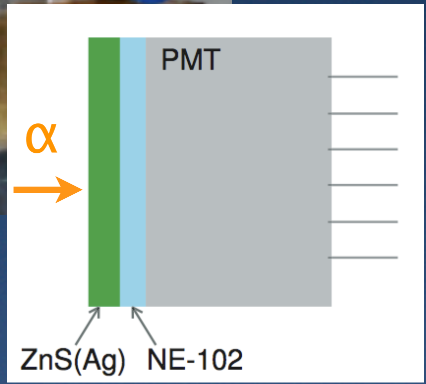


Detector

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







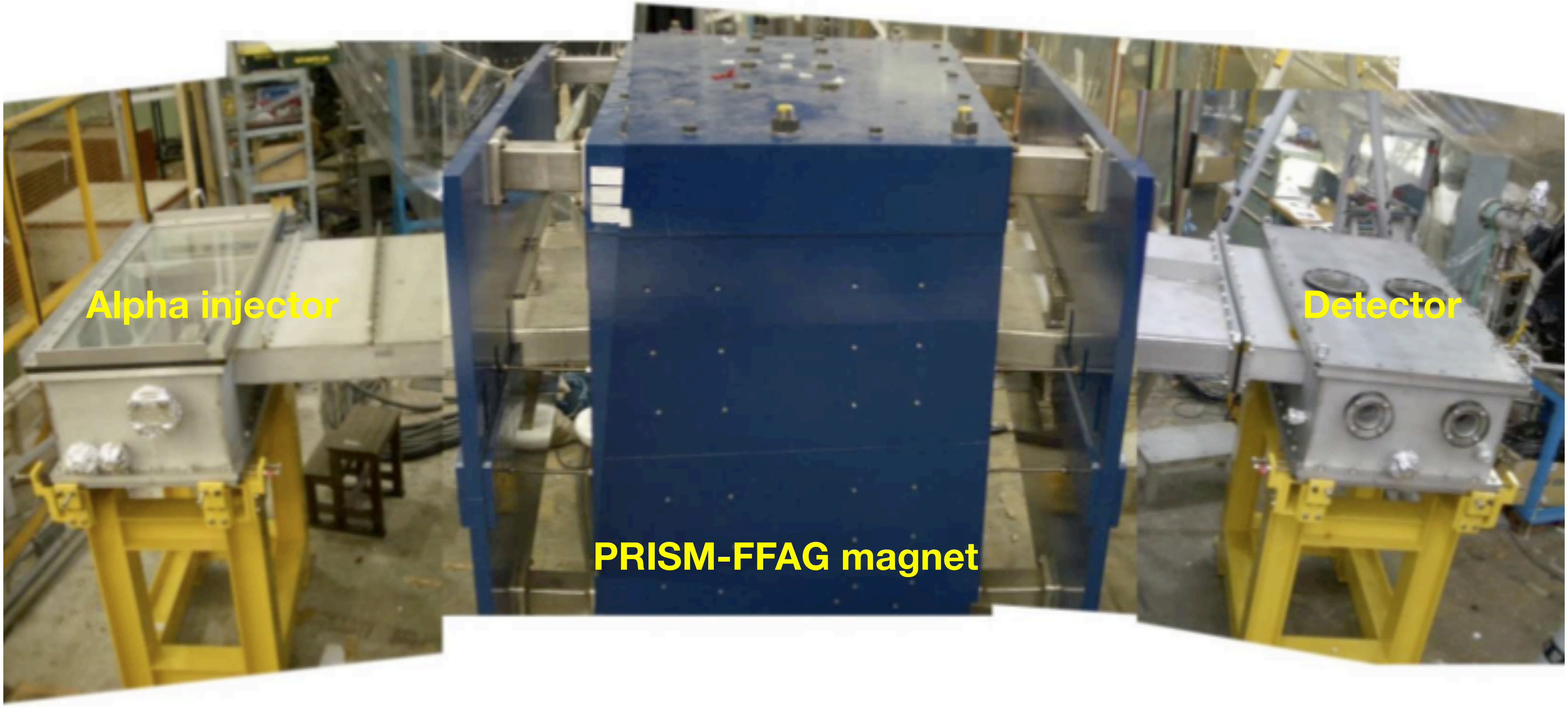
Achieved resolution

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 :

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

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

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

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

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

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

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

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

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

where $\mathbf{J}^{\mathrm{t}}$ 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

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

- obtained closed orbit from the transfer map

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

- from Zgoubi with TOSCA field map

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

Acceptance

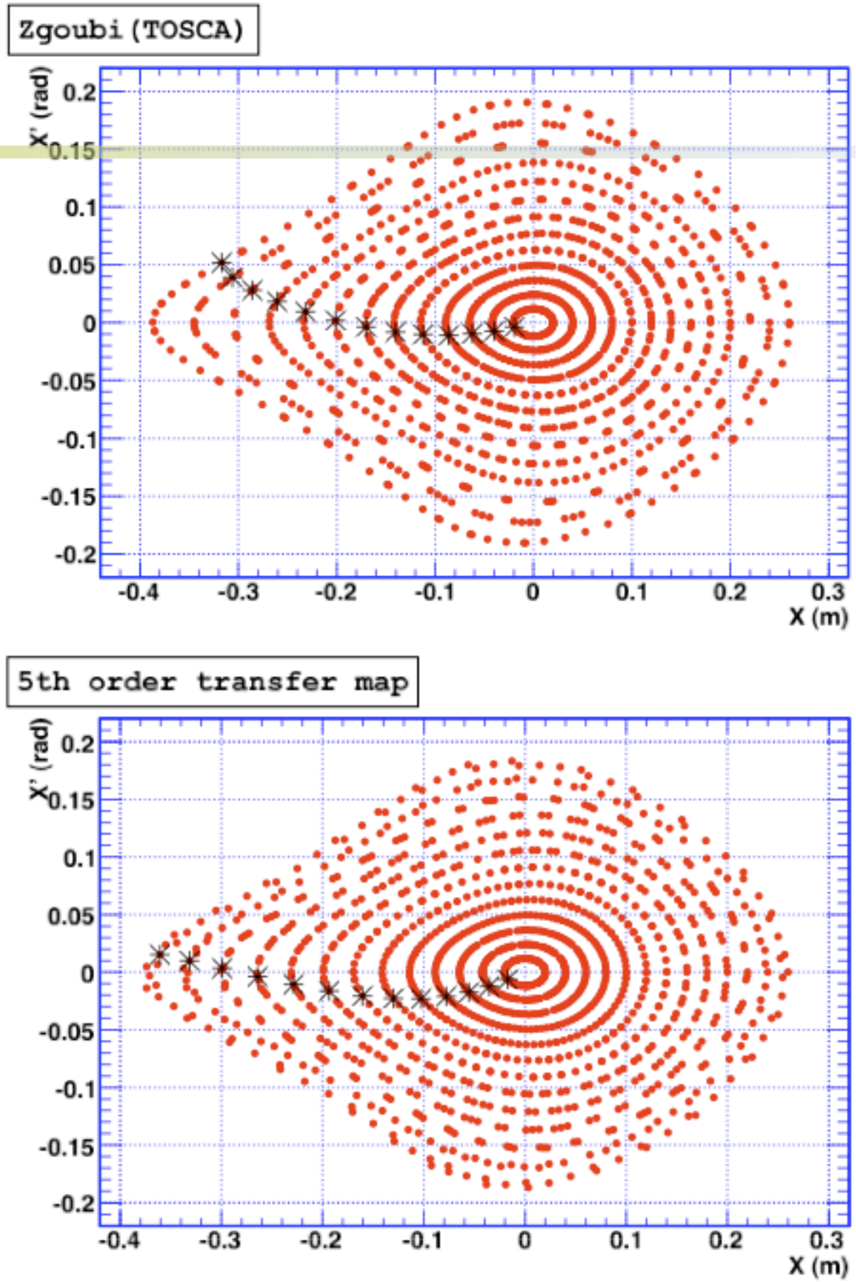


Figure 8.2: The tracking of 13 particles for 10 turns. Black asterisks indicate the positions of particles after passing 6 turns. The upper and lower figures are those of Zgoubi and the truncated Taylor transfer map with the order up to the 5th, respectively.

Tune

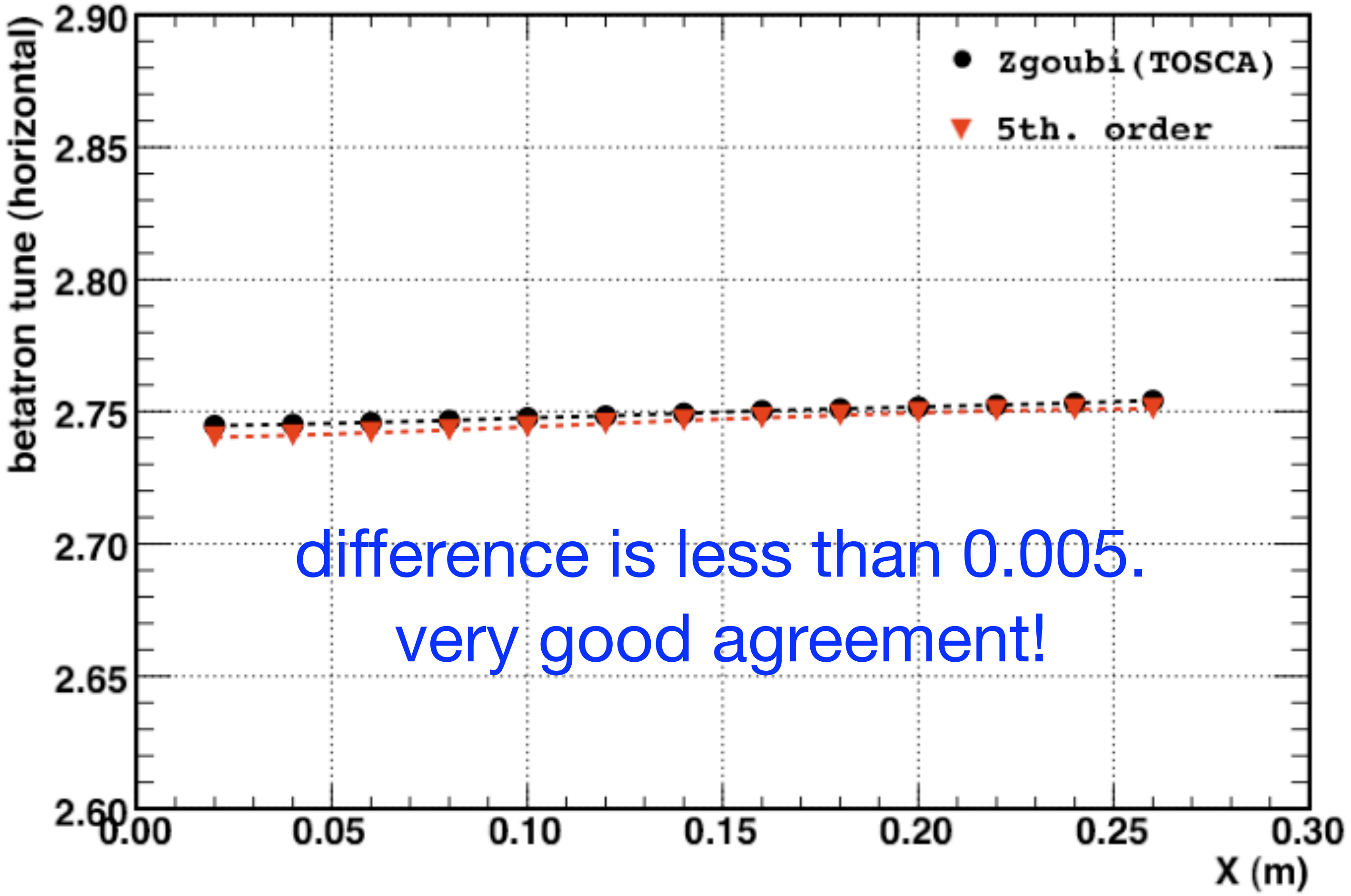
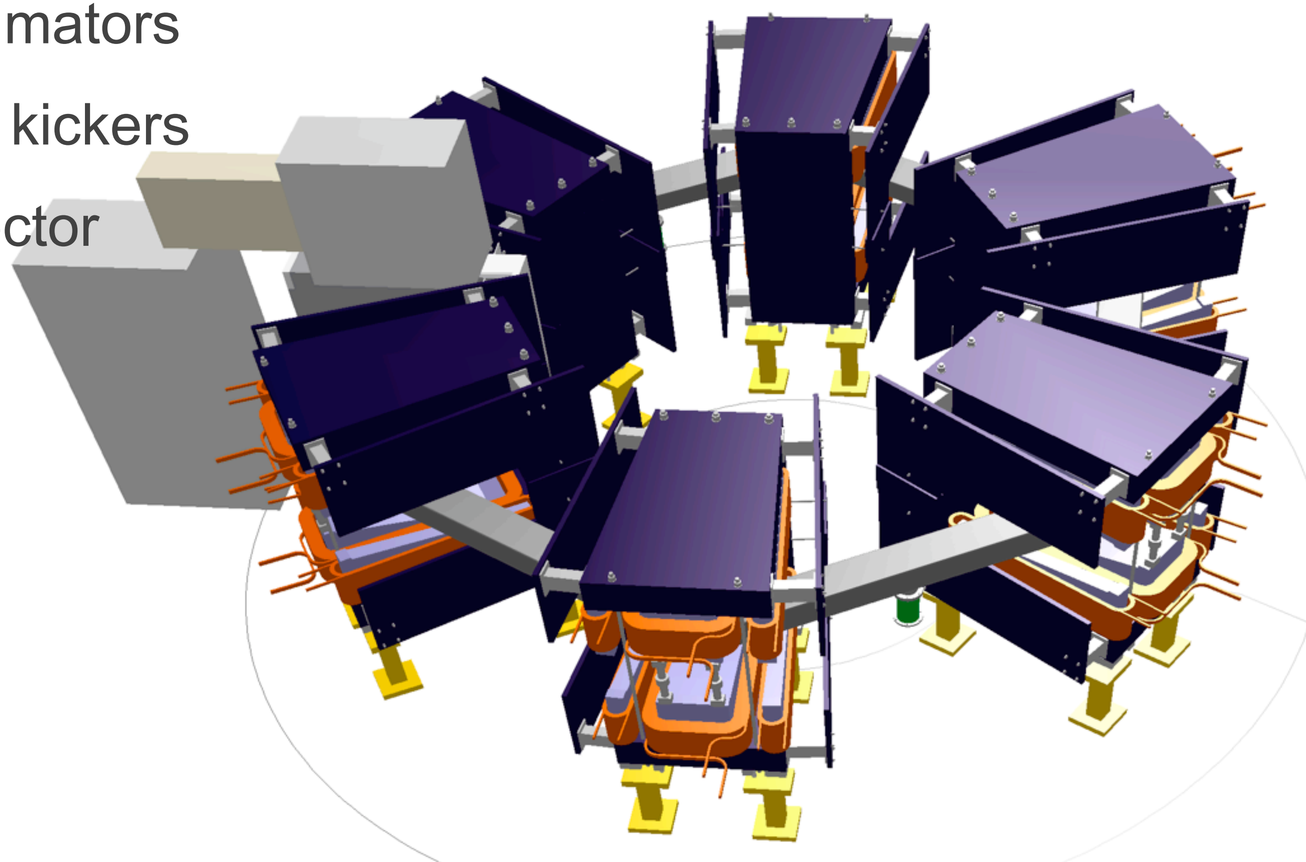


Figure 8.3: Horizontal tune as a function of initial amplitude. Closed circles represent the betatron tunes obtained by Zgoubi, and red triangles represent those obtained by the 5th ordered truncated Taylor transfer map.

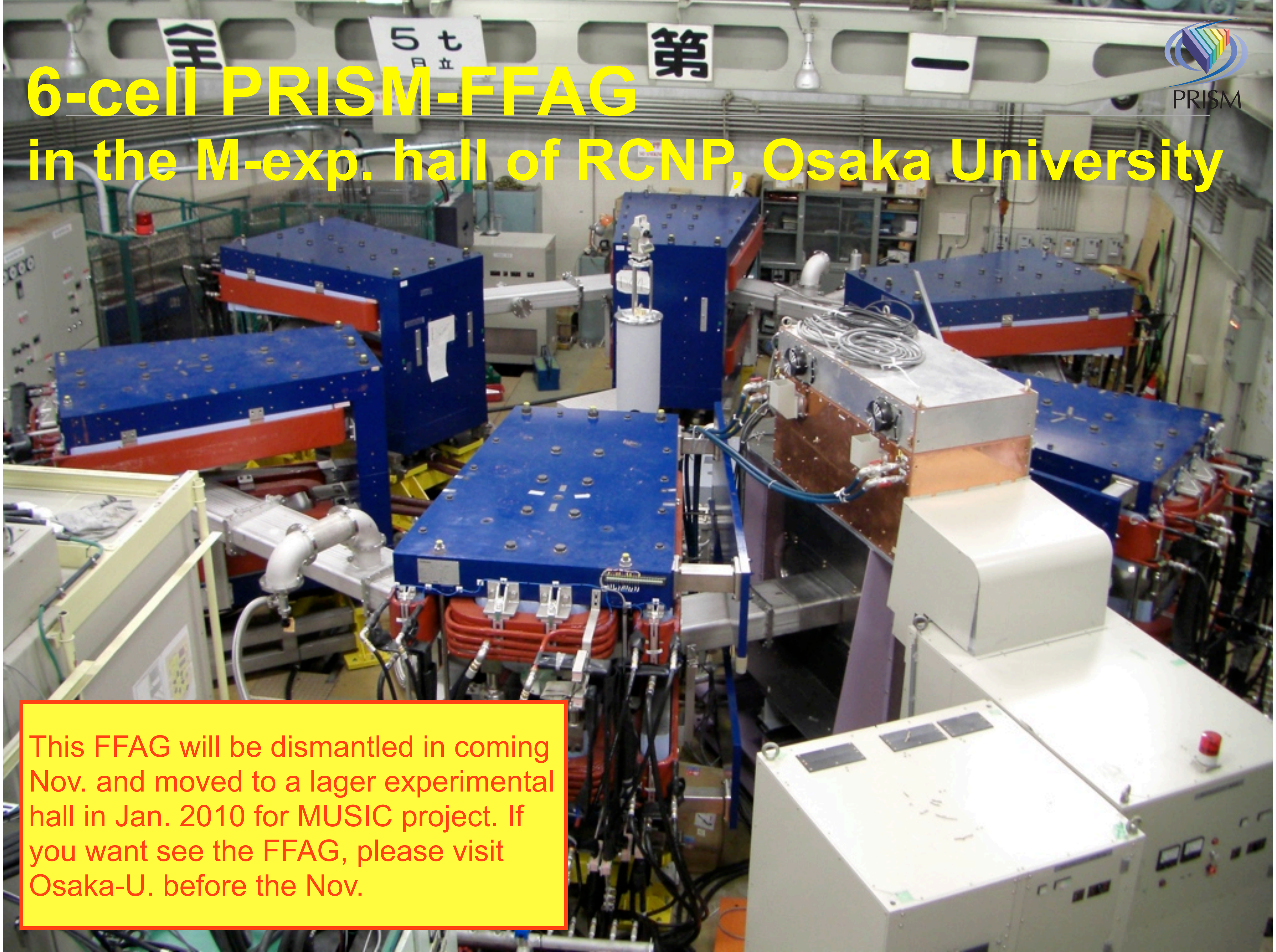
6-cell PRISM-FFAG

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

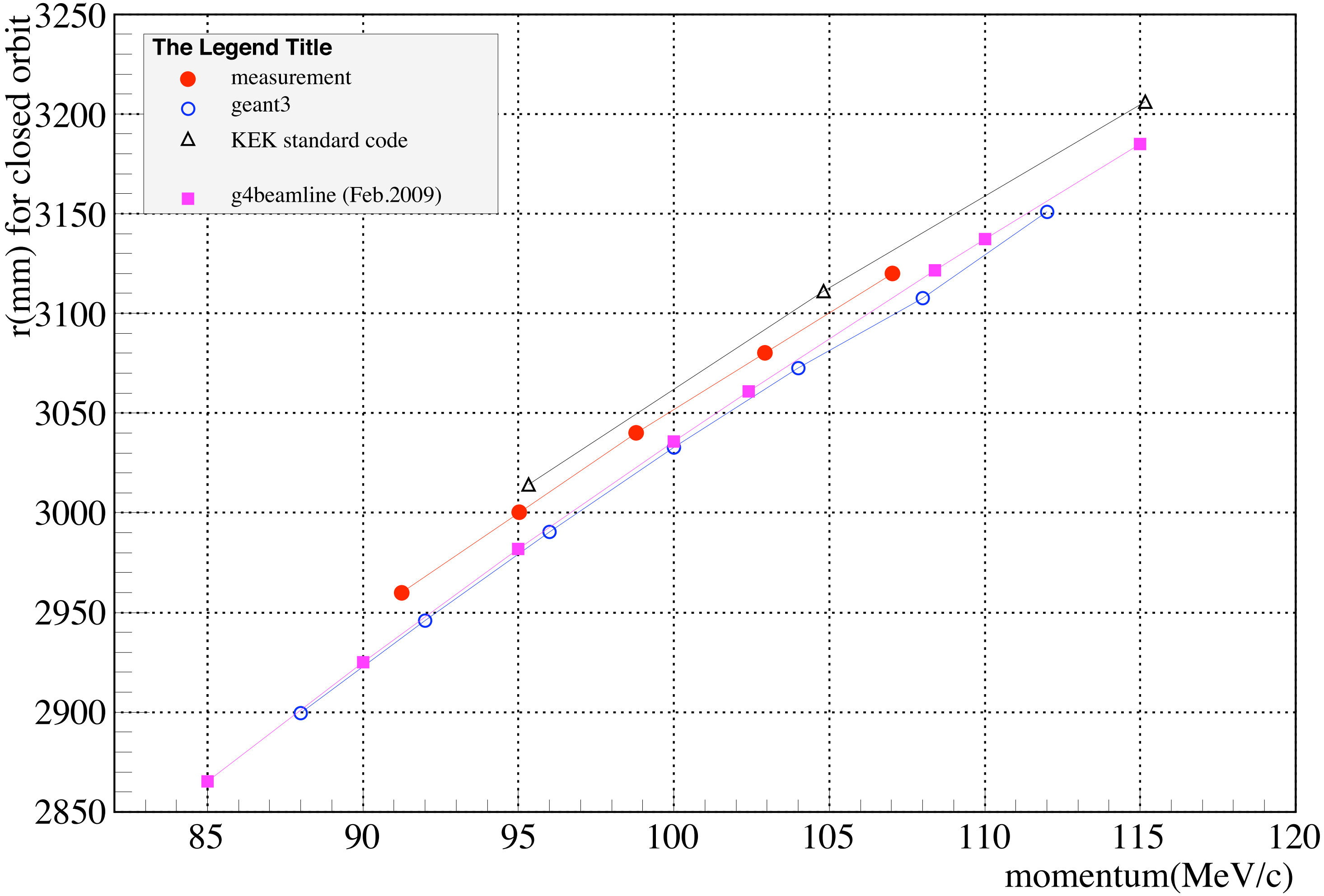


6-cell PRISM-FFAG in the M-exp. hall of RCNP, Osaka University



This FFAG will be dismantled in coming Nov. and moved to a lager experimental hall in Jan. 2010 for MUSIC project. If you want see the FFAG, please visit Osaka-U. before the Nov.

Closed orbit comparison b/w data and simulations

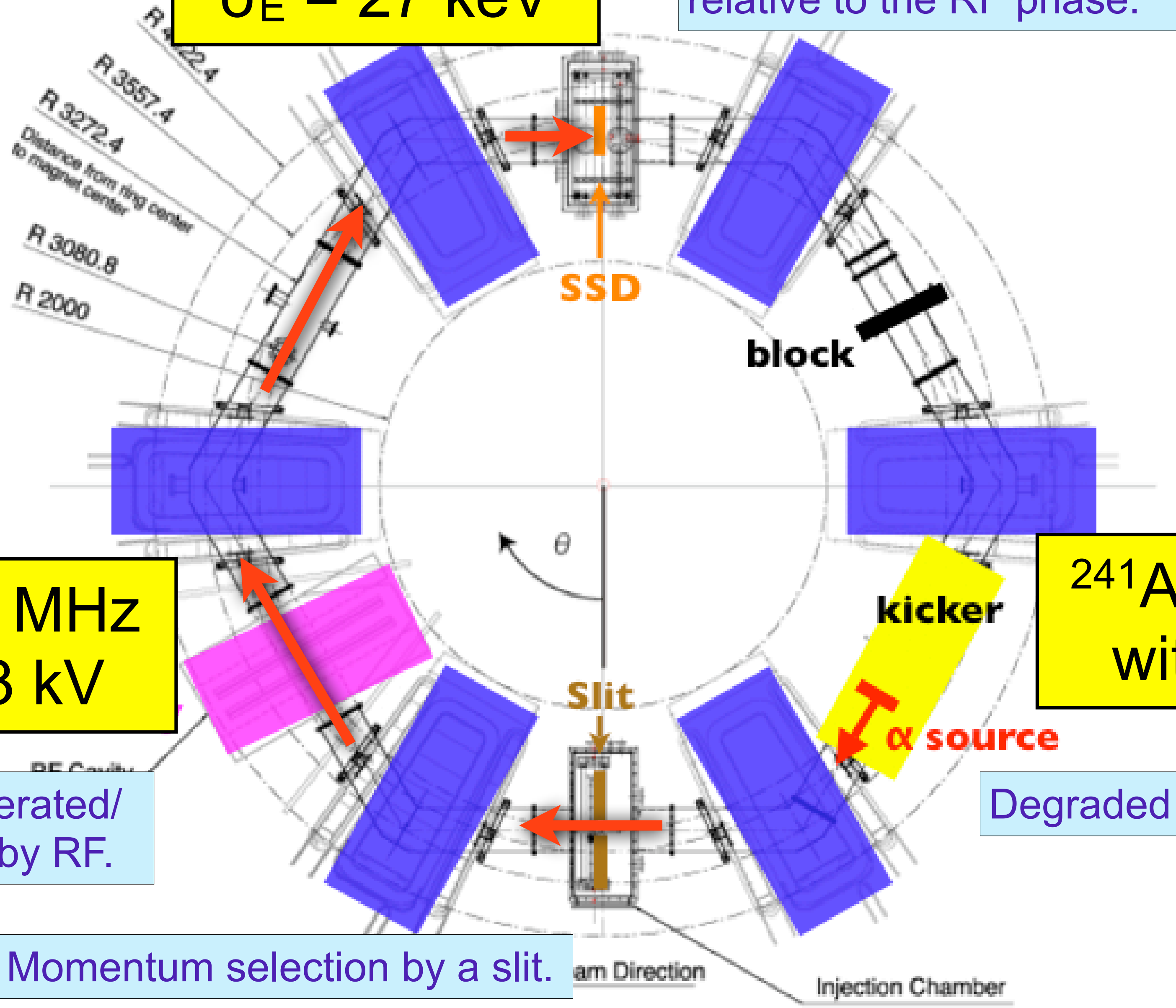


- Tracking for the 6-dell FFAG has been performed by 3 different codes using same field maps, which calculated by TOSCA. Tracking with Zugoubi will be done.
- There are discrepancies need to be understood. We need to check
  - interpolation of the field maps, step size, and so on...

Apparatus for the test of phase rotation

$SSD\ \varphi 2cm$,
$\sigma_E = 27\ keV$

αs stop. SSD can measure their energy and arrival timr relative to the RF phase.



f=1.916 MHz
V_{pp}=33 kV

[241]Am, 3MBq with Al foil

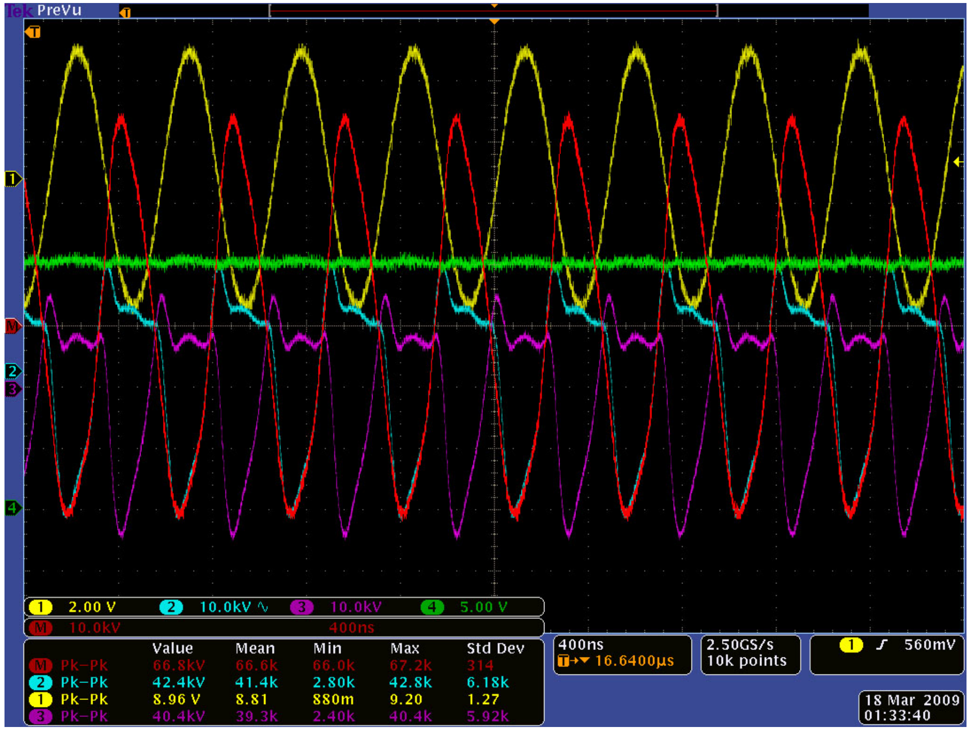
αs are accelerated/ decelerated by RF.

Degraded by an Al foil.

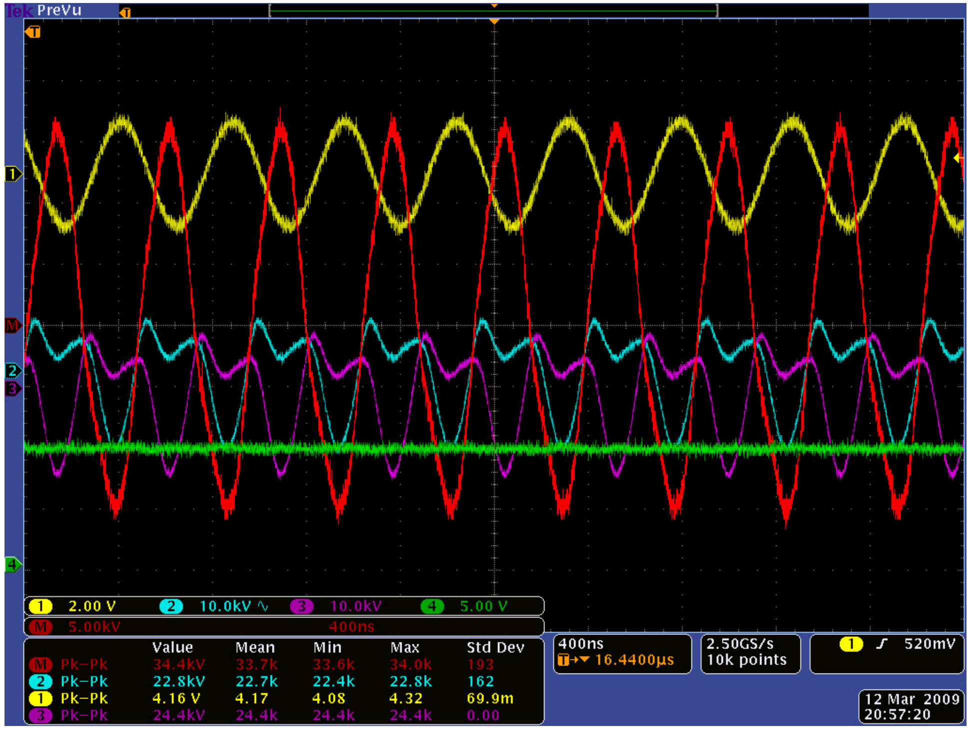
Momentum selection by a slit.

RF voltage

red lines show the gap voltage.

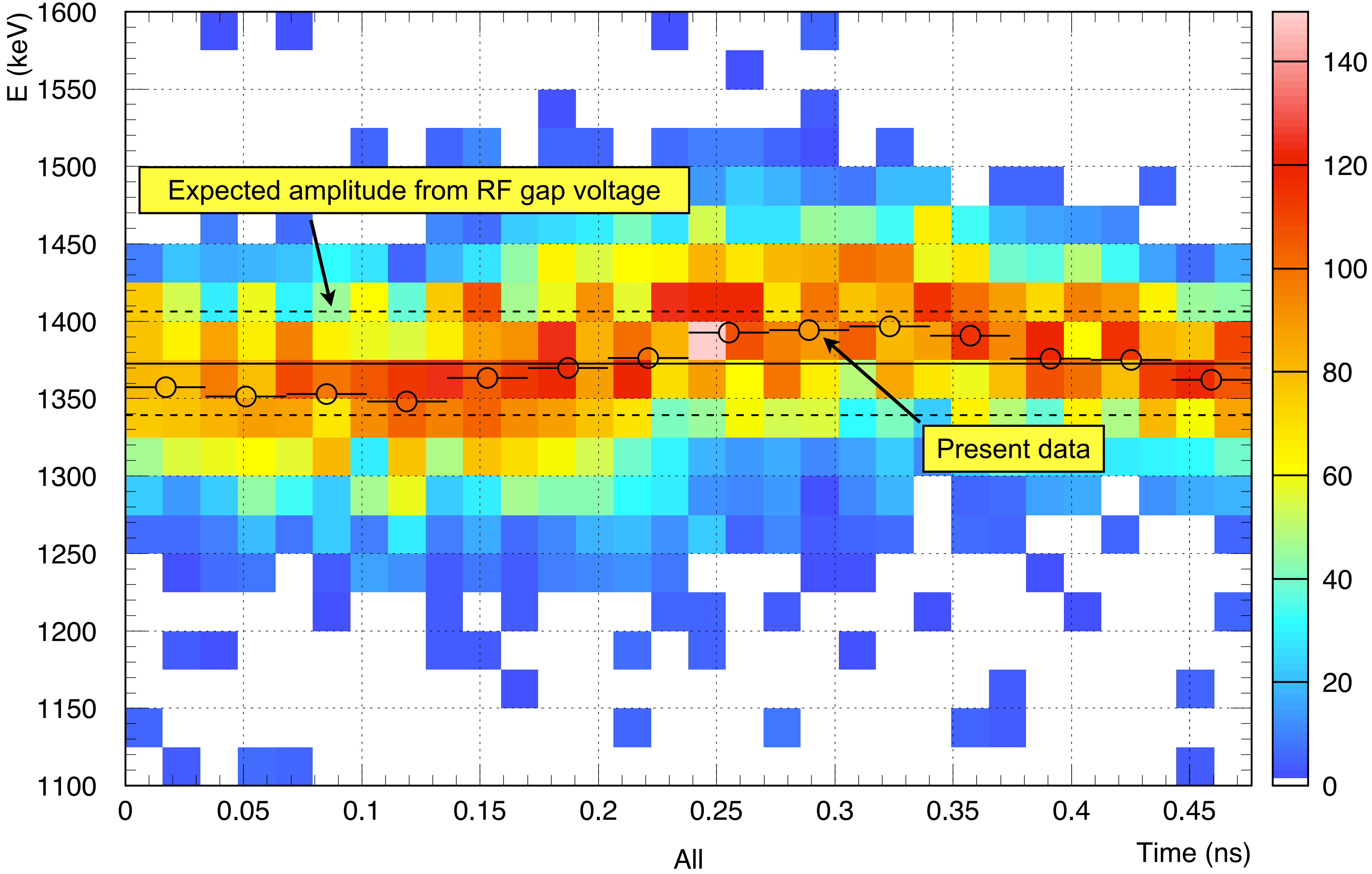


max. voltage for f=1.9MHz
V_{pp}=66kV



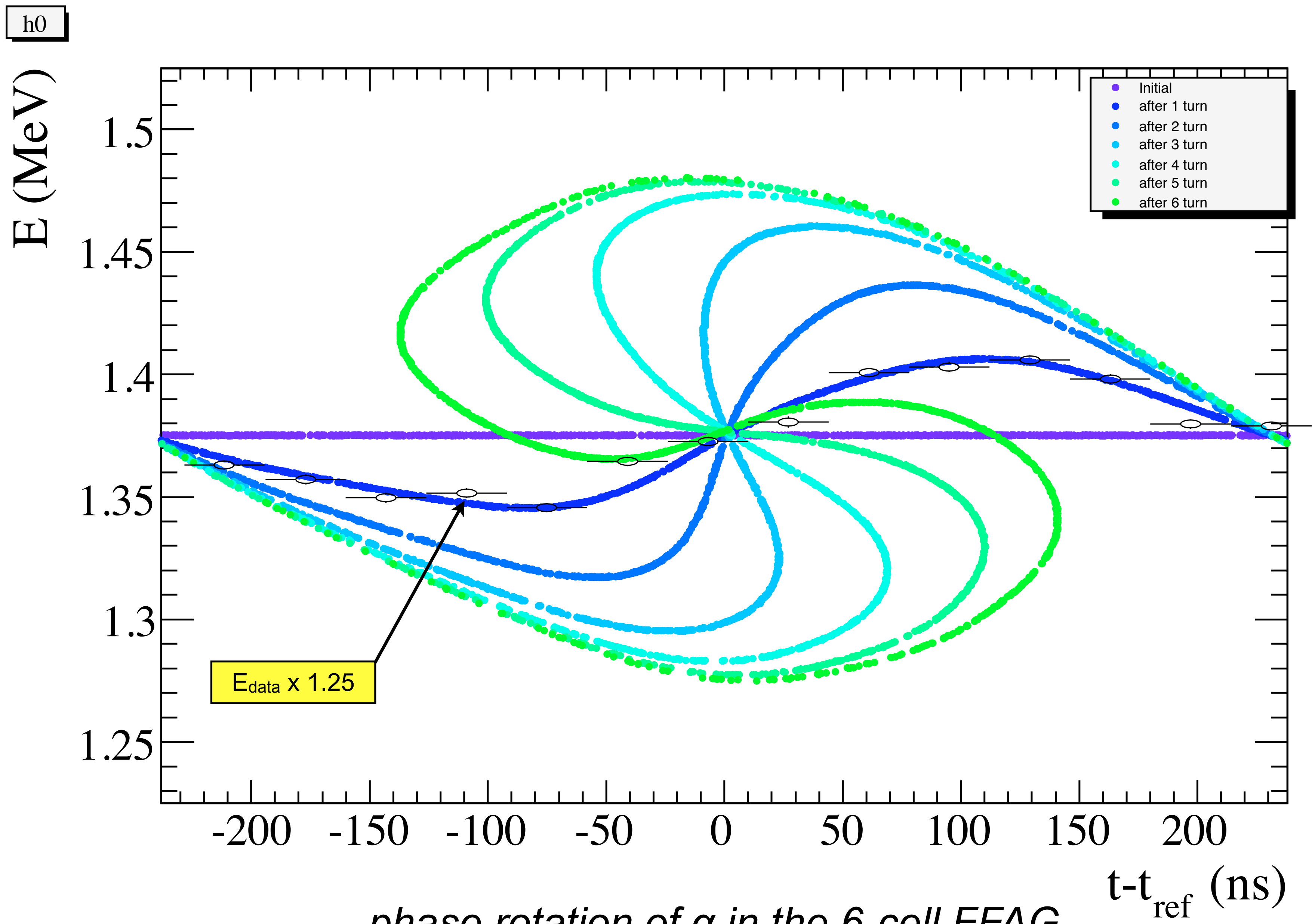
RF wave used in the experiment,
f=1.9MHz, V_{pp}=33kV

Result of the phase rotation test



- Modulation by the RF was observed. The observed amplitude is 80% of expected value. It would be explained by HV probe calibration of detector calibration.

Comparison b/w data and simulation



phase rotation of α in the 6-cell FFAG

PRISM-FFAG workshop

- at Imperial College London, UK, 1st- 2nd July, 2009
  - organized by J.Pasternak
    - http://www.hep.ph.ic.ac.uk/muec/meetings/20090701/agenda.html
- The workshop aims to cover the technological challenges in realizing an FFAG based muon-to-electron conversion experiment which has a sensitivity of $<10^{-18}$
  - Physics of Muon-to-Electron Conversion.
  - Status of PRISM-FFAG.
  - Beam dynamics, design and simulation studies for PRISM.
  - Hardware developments for FFAG accelerators.
  - Challenges of beam injection and extraction.
  - Recent developments in FFAG accelerators.
- The **Collaboration** and **PRISM Task Force** are proposed in the workshop, and being organized and created. You are welcomed to join.
  - injection/extraction, kicker design
  - re-optimization of the PRISM-FFAG design
  - possibility of new lattice
    - long straight section, dispersion suppressor, ...

Preliminary agenda.

Location

Day 1: Room 539 Blackett Laboratory
Day 2: Room 1004 Blackett Laboratory

Wednesday 1st July 2009

Registration: 10.00 to 10:30, (Coffee at 10:20)

Session 1: 10.30am
Welcome and Introduction to Muon-to-Electron Conversion and COMET/PRISM
Session Chair: Y. Uchida

10:30	Welcome	P. Dornan
10:35	Introduction to Physics of Muon-to-Electron Conversion and COMET/PRISM experiments	Y. Kuno
11:35	Results and Status of PRISM-FFAG R&D	A. Sato
12:35	Muon-to-Electron Conversion from the UK Perspective	Y. Uchida

Session 2: 14:00 to 15:40
Towards PRISM 1
Session Chair: TBC

14:00	Advanced FFAG for PRISM	Y. Mori
14:40	Magnetic Alloy Cavities (lecture)	C. Ohmori

15:40 Coffee

Session 3: 16:00 to 16:40
Towards PRISM 2
Session Chair: J. Pasternak

16:00	FFAG Lattice with Insertion	S. Machida
16:40	New ideas of the muon phase rotation	A. Sato

Session 4: 17:10 to 18:00
Discussion on Challenges in Injection/Extraction, Simulations, etc.
Session Chair: J. Pasternak

19:00 Dinner,

Thursday 2nd July 2009

Session 5: 9:15 to 10:40
Hardware for FFAG 1
Session Chair: TBC

9:15	EMMA Hardware Status	N. Bliss
10:15	EMMA Commissioning	B. Muratori

10:40 Coffee

Session 6: 11:00 to 13:00
Hardware for FFAG 2
Session Chair: TBC

11:00	ISIS Pulsed Power for Injection and Extraction	A. McFarland
12:00	PRISM RF System	C. Ohmori

Session 7: 14:00 to 15:40
Recent Progress in FFAG Development
Session Chair:

14:00	Beam Extraction in Proton FFAG, PAMELA	T. Yokoi
14:40	Discussion on Injection/Extraction, Matching, Simulations etc	J. Pasternak

15:40 Coffee

Session 8: 16:00 to 17:45
Discussion on Challenges in Hardware for PRISM and Key Steps Towards Future
Session Chair: TBC

17:45 Summary,

MUSIC project

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

Details will be presented by M.Yoshida in this afternoon.

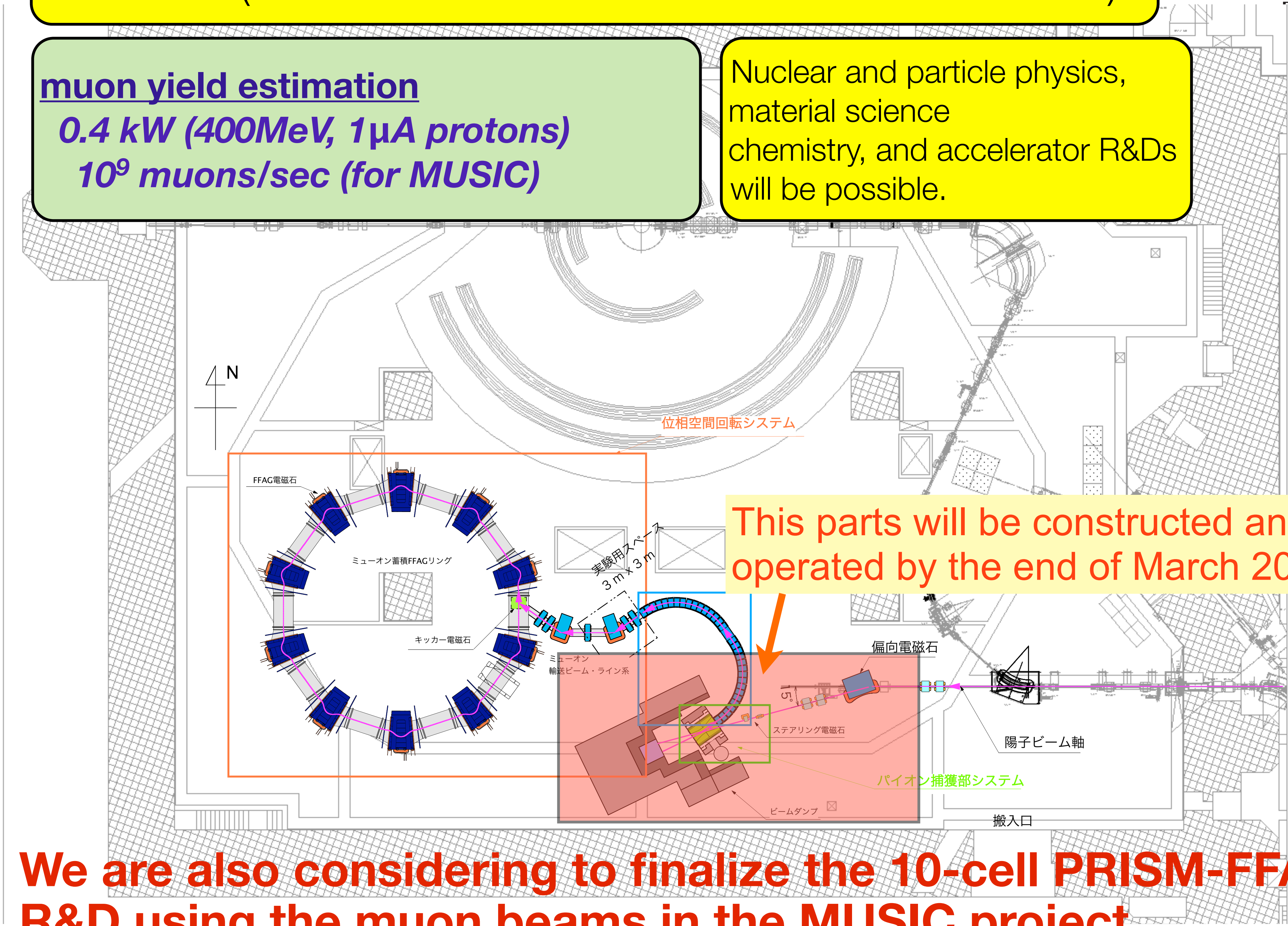
MUSIC (=MUon Science Innovative Commission)

muon yield estimation

0.4 kW (400MeV, 1μA protons)

10^9 muons/sec (for MUSIC)

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



This parts will be constructed and operated by the end of March 2010.

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

Summary

- PRISM provides a solution to improve the μ-e conv. sensitivity less than 10^{-17} adopting a muon storage ring, which make mono-energetic and pure muon beam. A staging scenario of mu-e conversion experiment (COMET - PRISM) was proposed in Japan.
- We had R&D program on the muon storage ring from 2003 to 2009. Many successful outcomes were achieved.
  - large aperture FFAG,
  - high field gardened RF system
  - 6-cell FFAG and phase rotation test.
- The collaboration and task force for the PRISM-FFAG were created at the workshop in UK. We will continue to study the PRISM-FFAG to realize the ultimate μ-e conv. experiment.