Studies related to the PRISM-FFAG

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FFAG`09: International Workshop on FFAGs
September 21-25, 2009
Fermilab, Batavia, IL

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- Motivation of PRISM-FFAG
- **Overview of R&D results**
  - FFAG Design
  - Magnet
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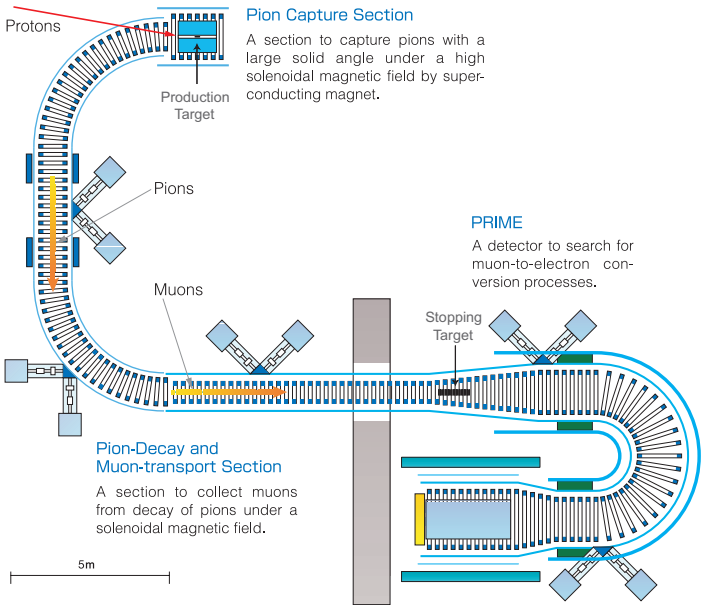
  - 6-cell FFAG
  - Phase rotation test
- PRISM Task Force (covered by Jaroslaw's talk)
- **Study for FFAG ring cooler**
- **New Muon beamline(MUSIC) at Osaka Univ.**
- Summary

Japanese staging plan of μ-e conversion

1st Stage : COMET

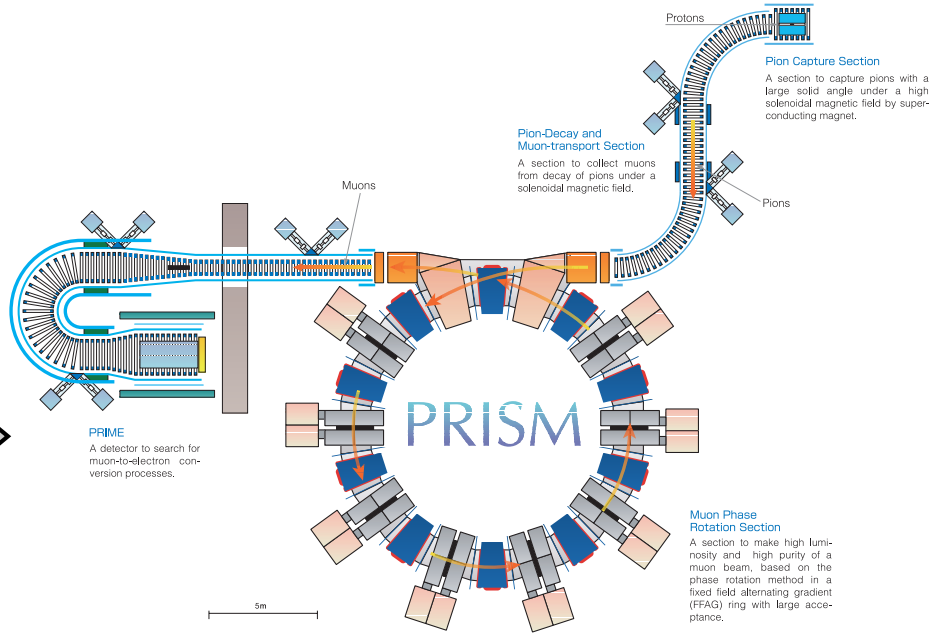


$$B(\mu^- + Al \rightarrow e^- + Al) < 10^{-16}$$

- 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.

2nd Stage : PRISM/PRIME



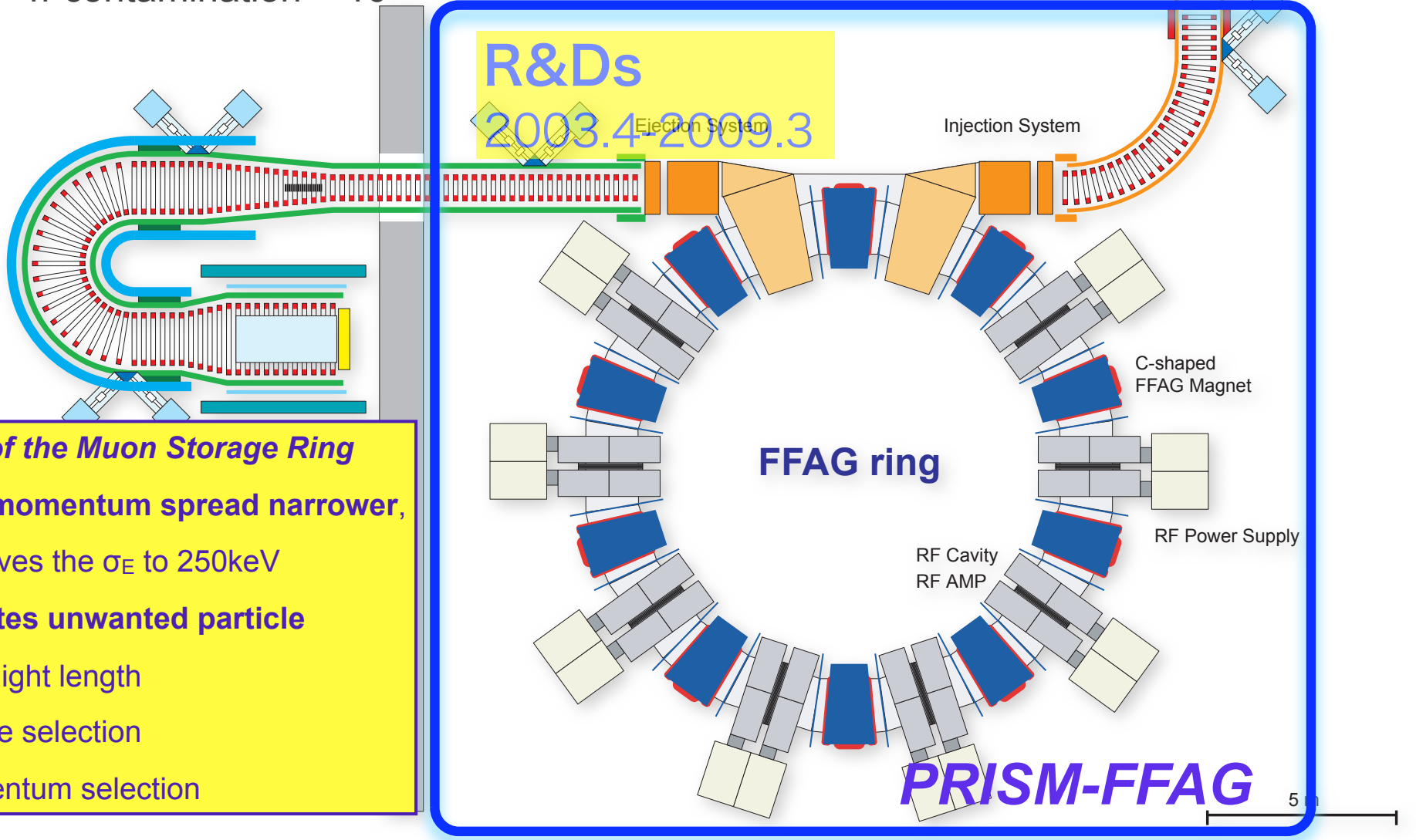
$$B(\mu^- + Ti \rightarrow e^- + Ti) < 10^{-18}$$

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

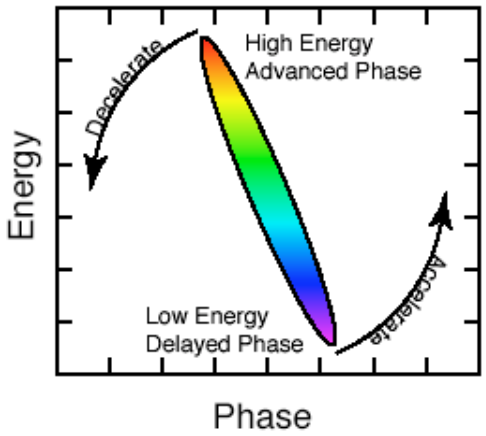


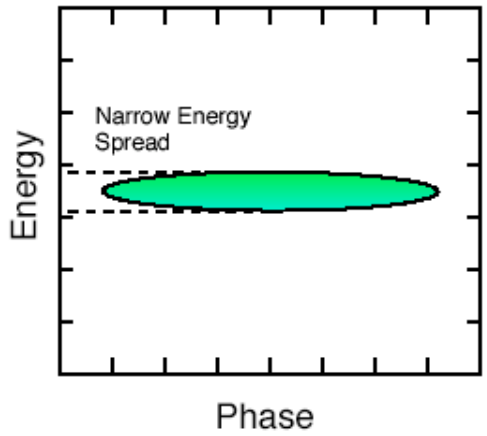
Functions of the Muon Storage Ring

- **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.

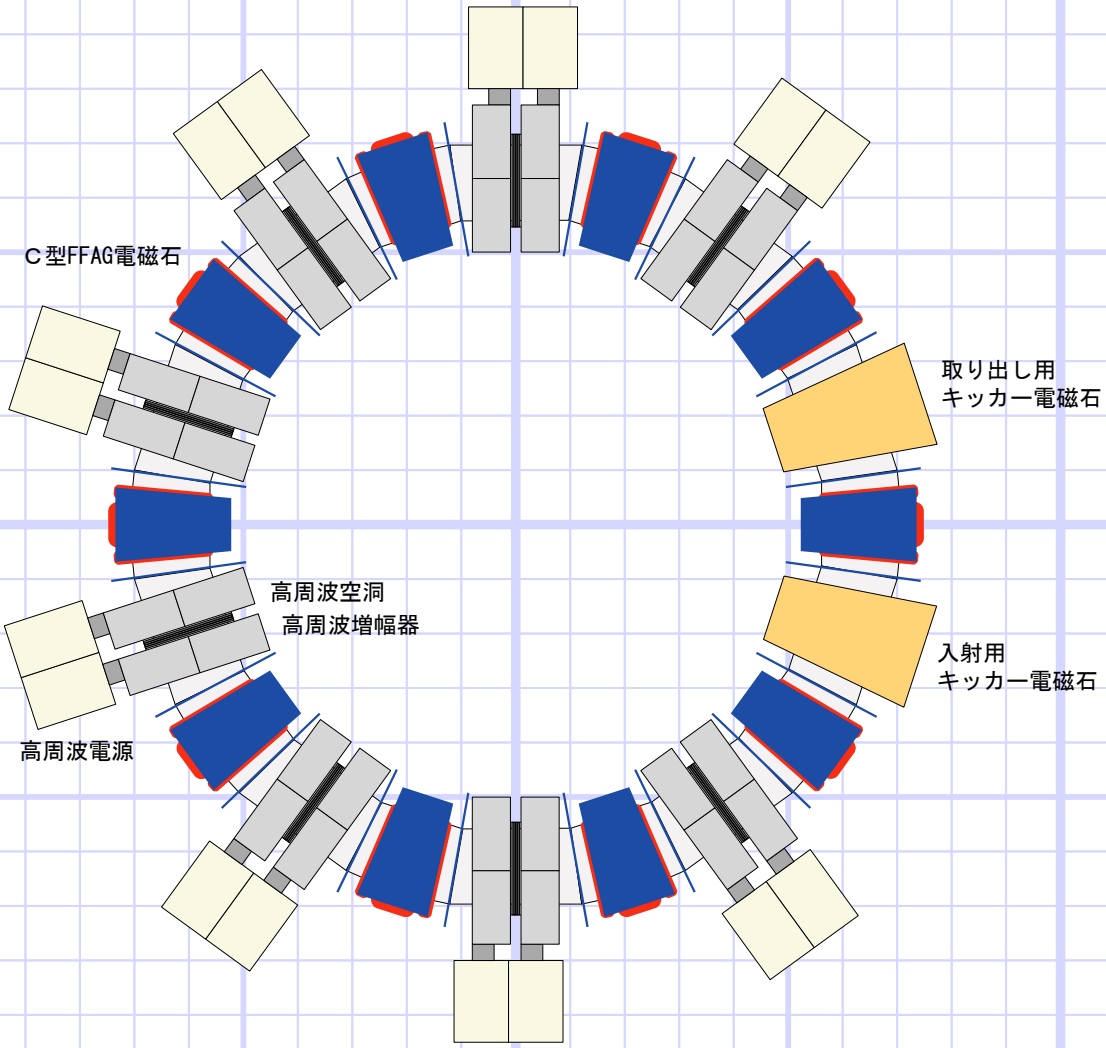




Design of PRISM-FFAG

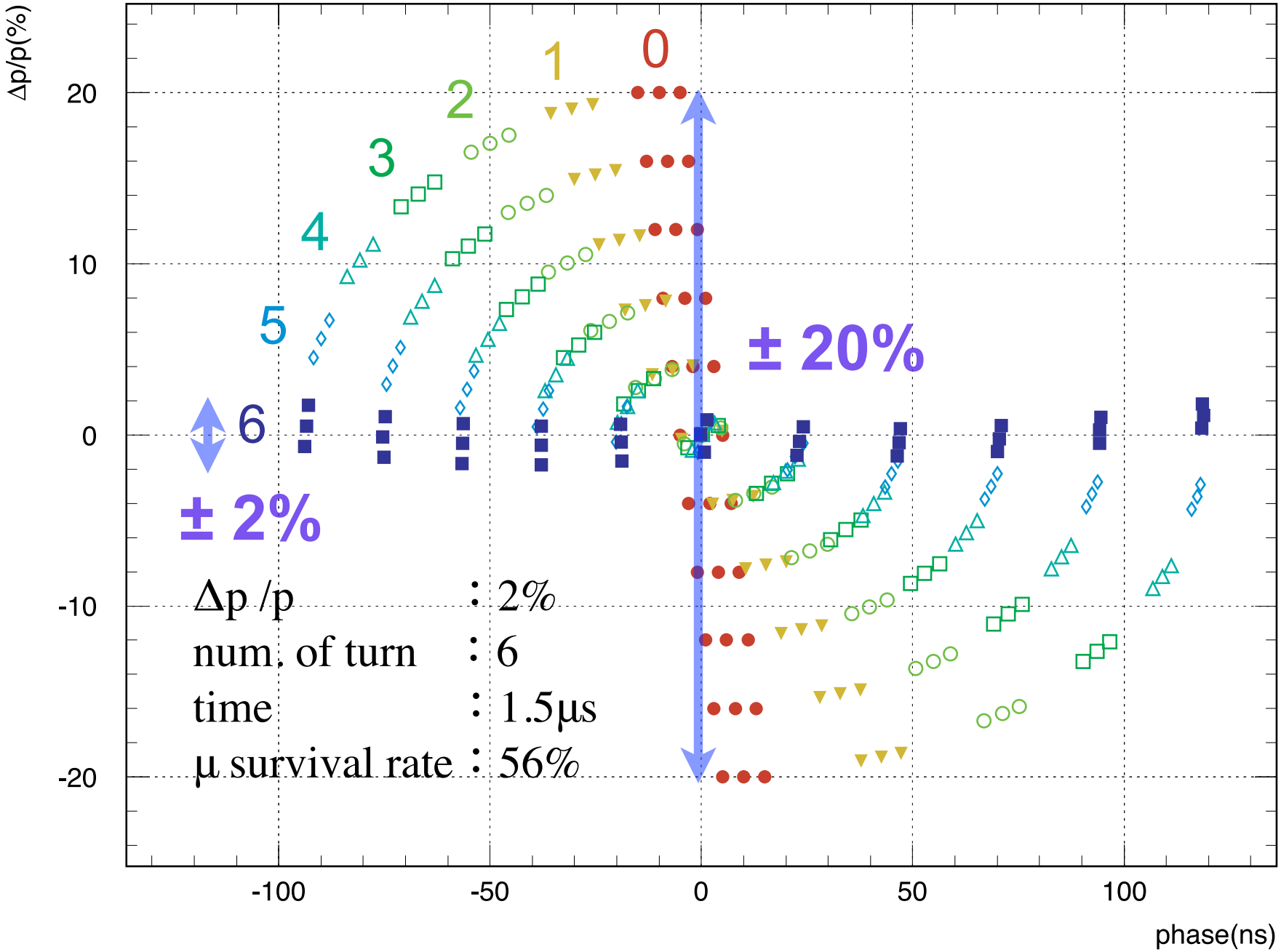
PRISM-FFAG

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

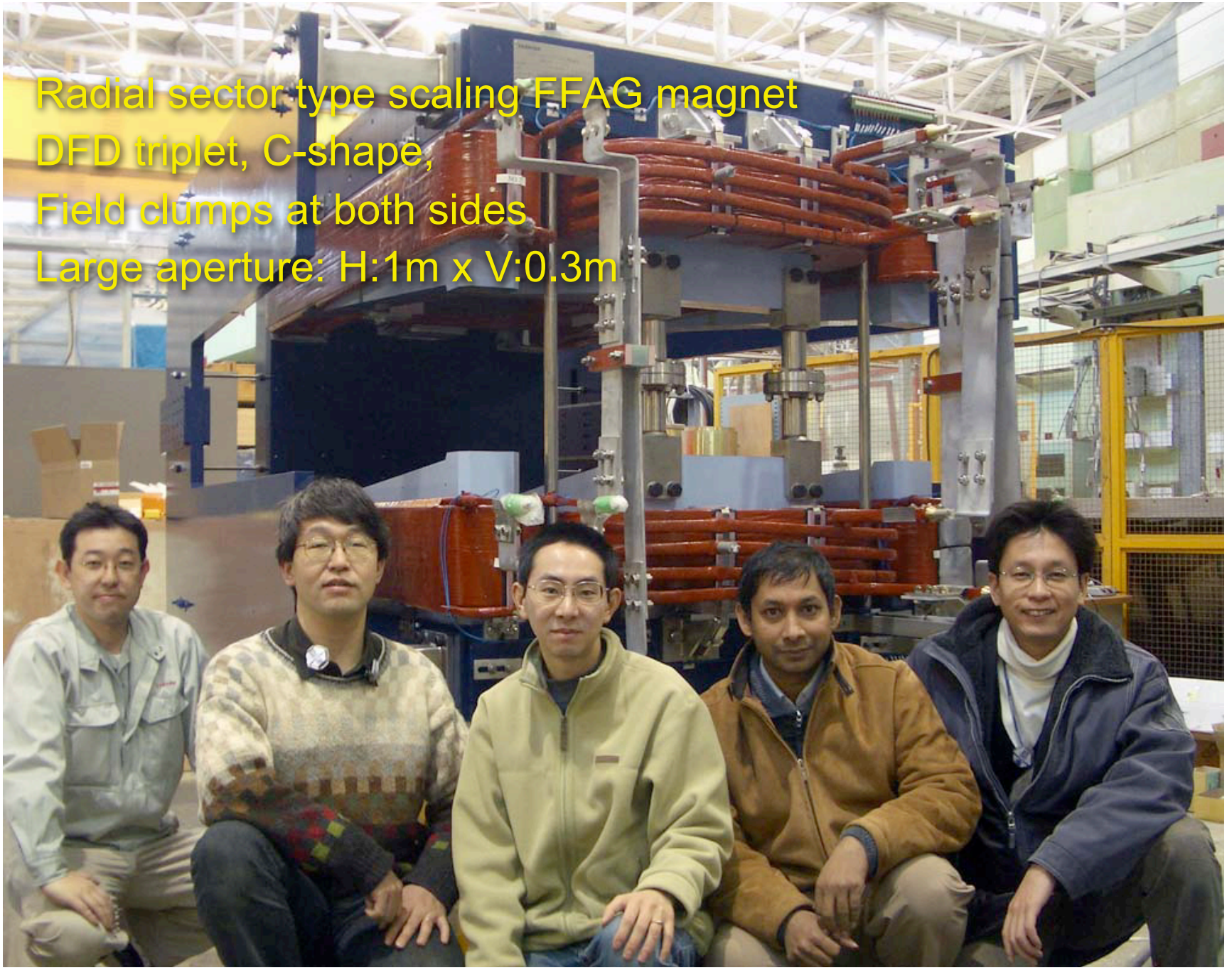


- Large transverse acceptance
  - Horizontal : 38,000 π mm mrad
  - Vertical : 5,700 π mm mrad
- High field gradient RF system
  - field gradient ~170kV/m (~2MV/turn)
    - quick phase rotation (~1.5μs)
    - large mom. acceptance (68MeV/c +- 20%)

Expected phase rotation with PRISM-FFAG



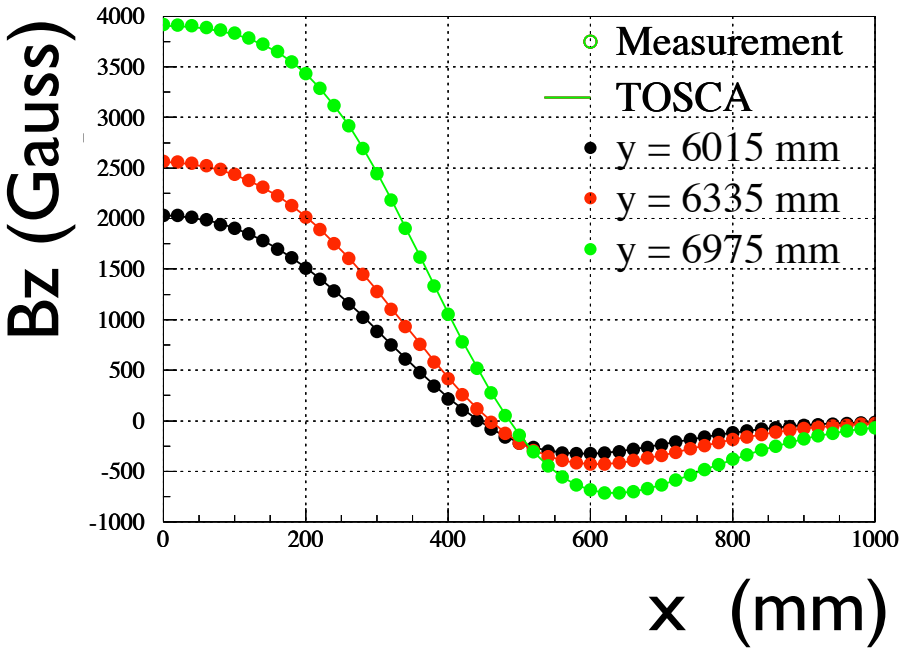
The First PRISM-FFAG Magnet

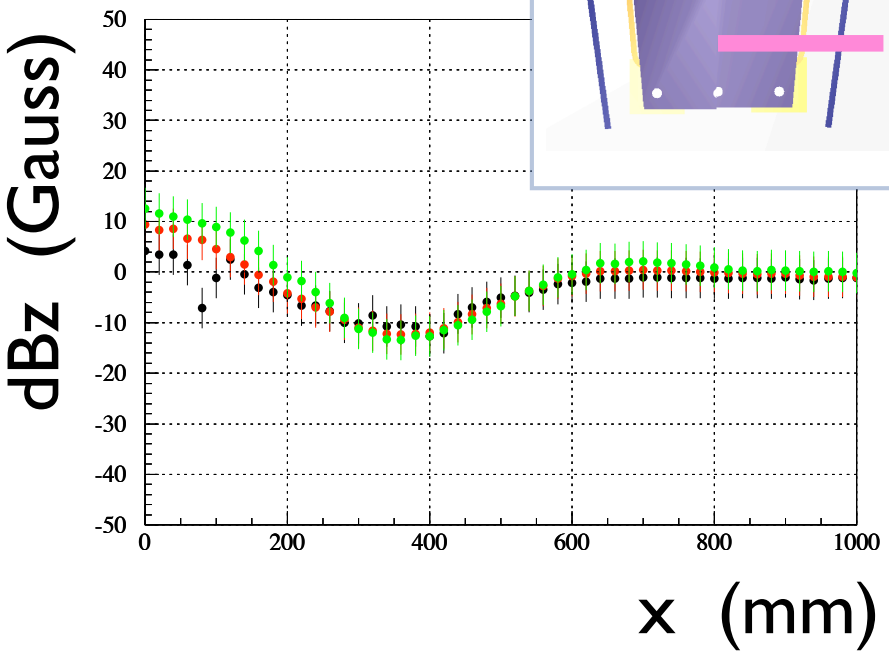


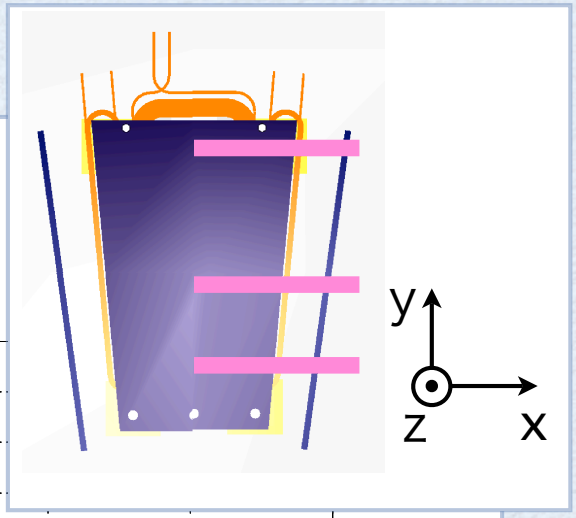
Results of Field Measurements

On median plane

tosca_vs_meas.kumac



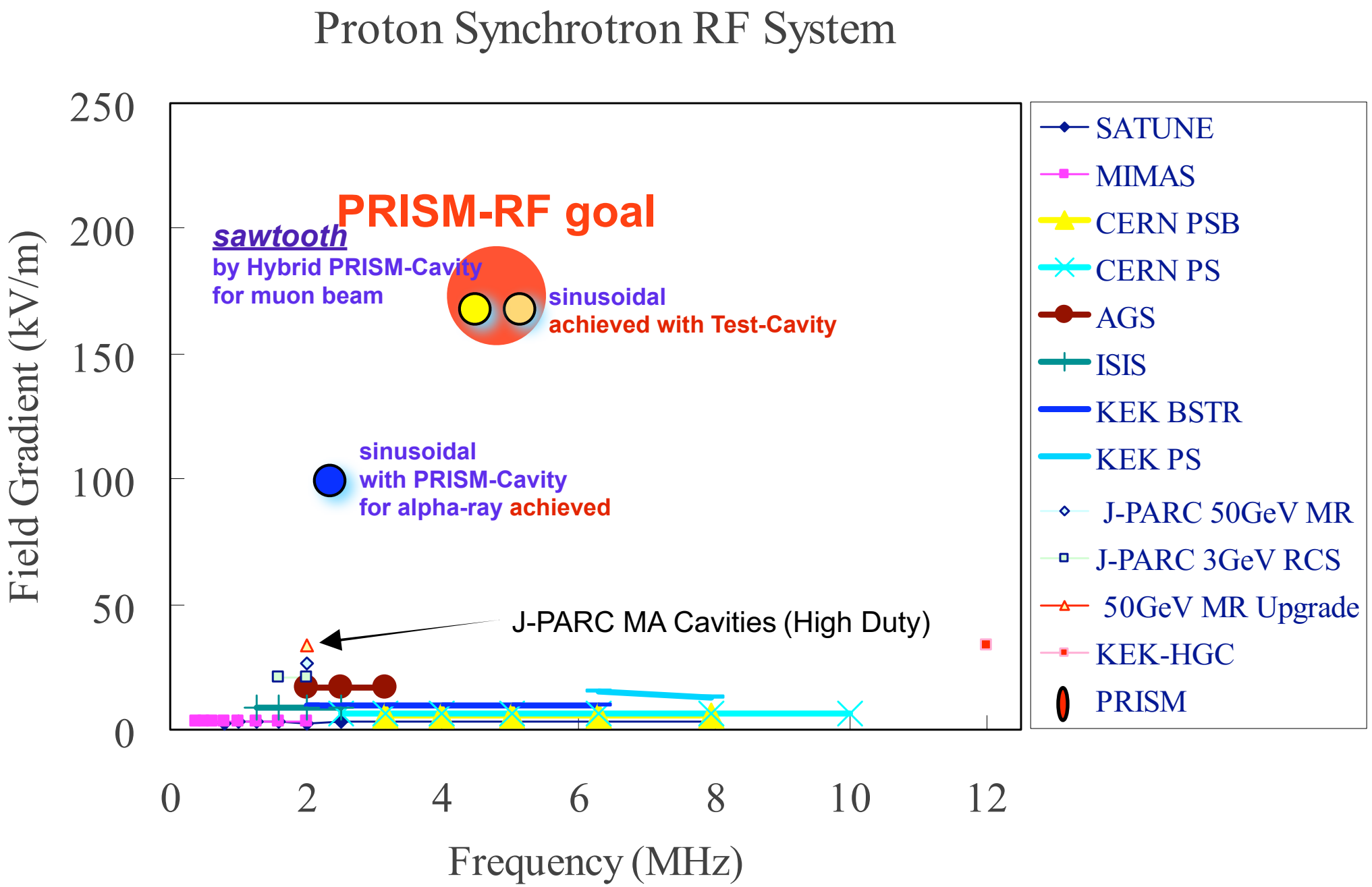




Difference between TOSCA and measurement is about 10 Gauss

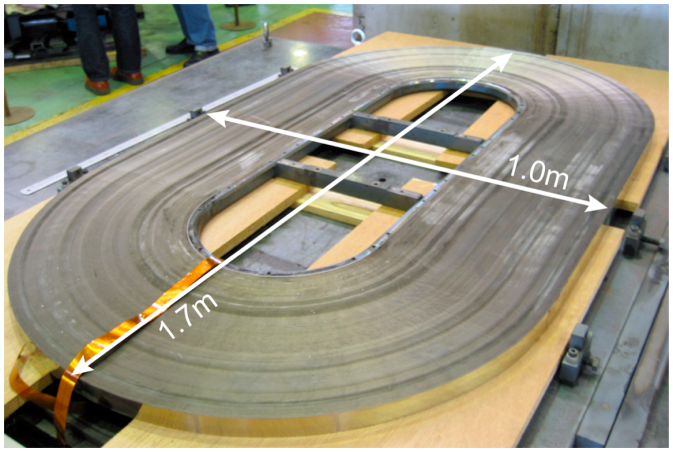
The RF system

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 size
- **Solution 2：hybrid RF system**
  - tested for J-PARC RCS
  - can use for PRISM-cavities



Hybrid RF system

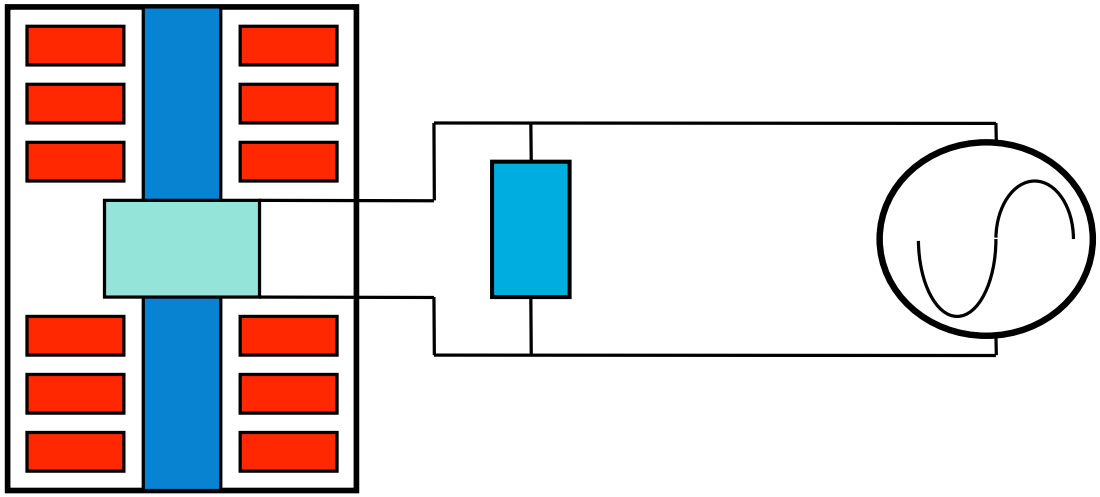
- Proposed by A. Schnase.
- Combination of MA cavity with a resonant circuit composed by inductor and capacitor.
- Developed for J-PARC RCS cavities.

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

$$1/L=1/Lcore+1/Lind$$

$$Q=Rp/\omega L$$

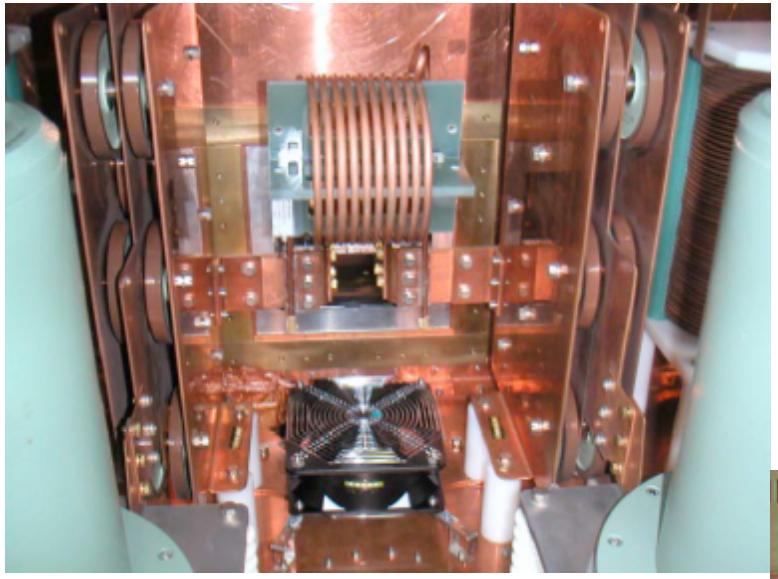
Rp: shunt



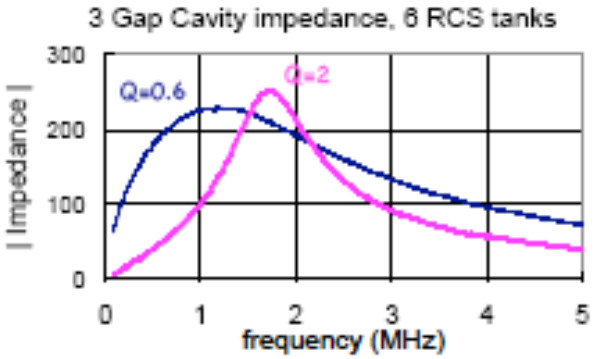
J-PARC: add C and L to control Q and f

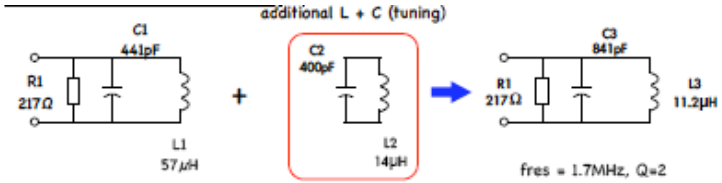
PRISM : add L to control f

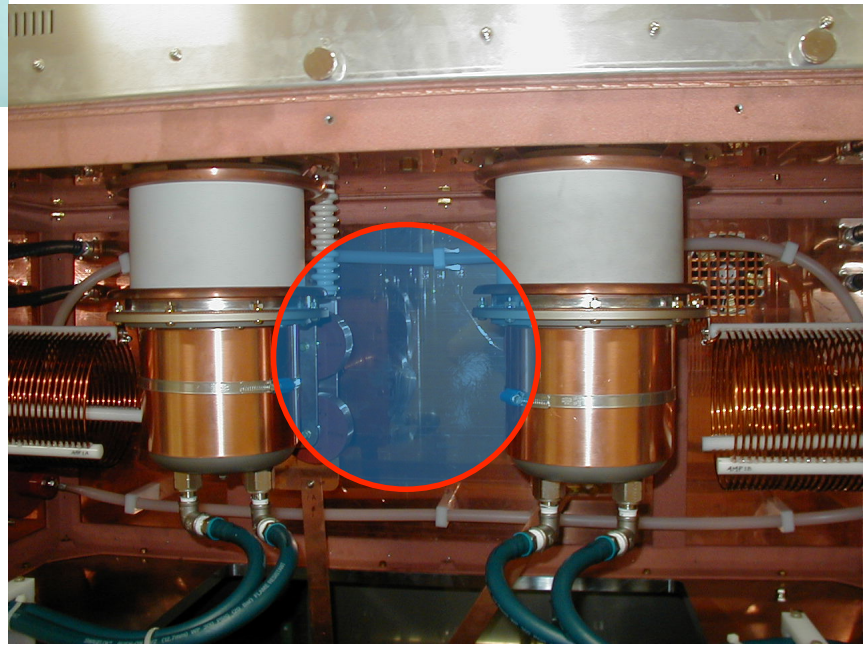
Hybrid RF system



Parallel inductor for J-PARC







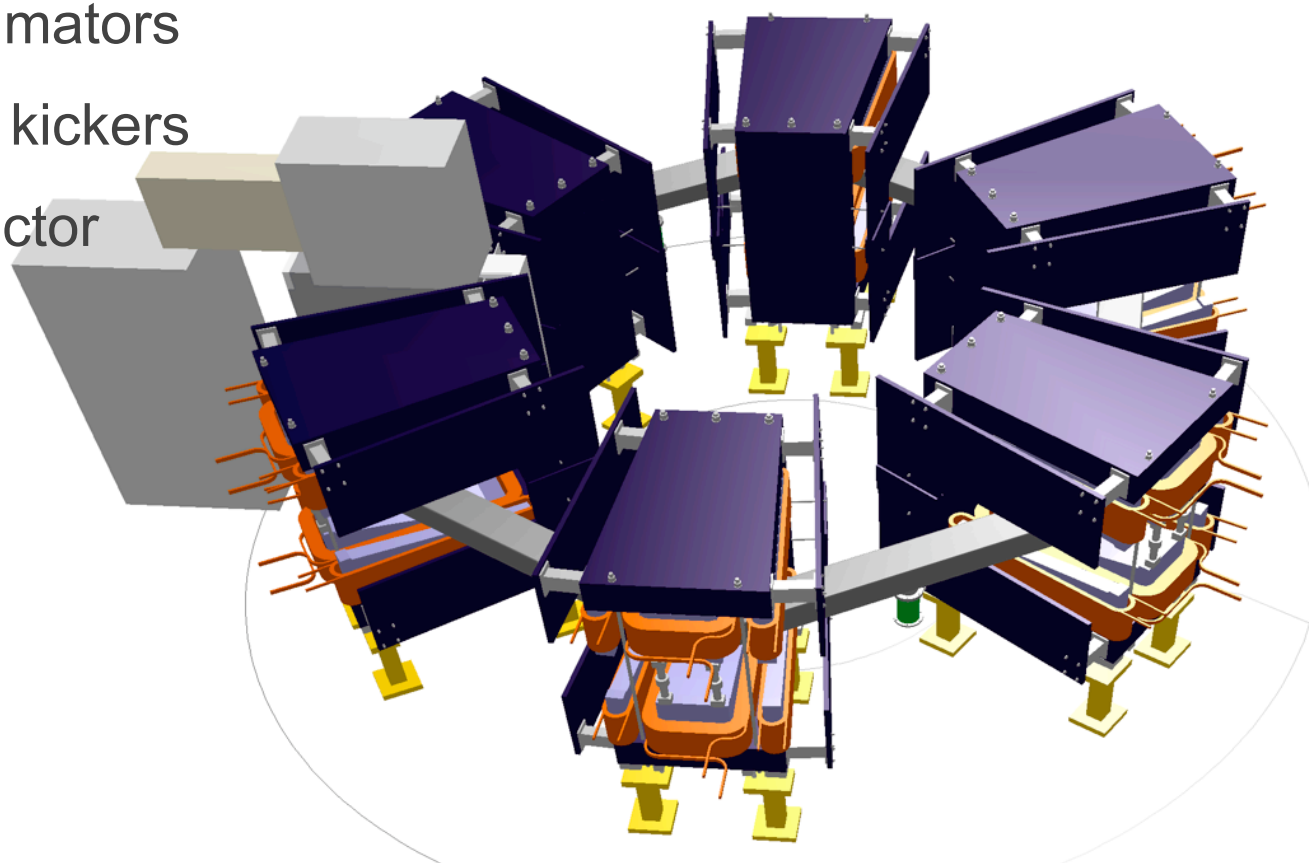
Inside of PRISM AMP

This will be tested in this year.

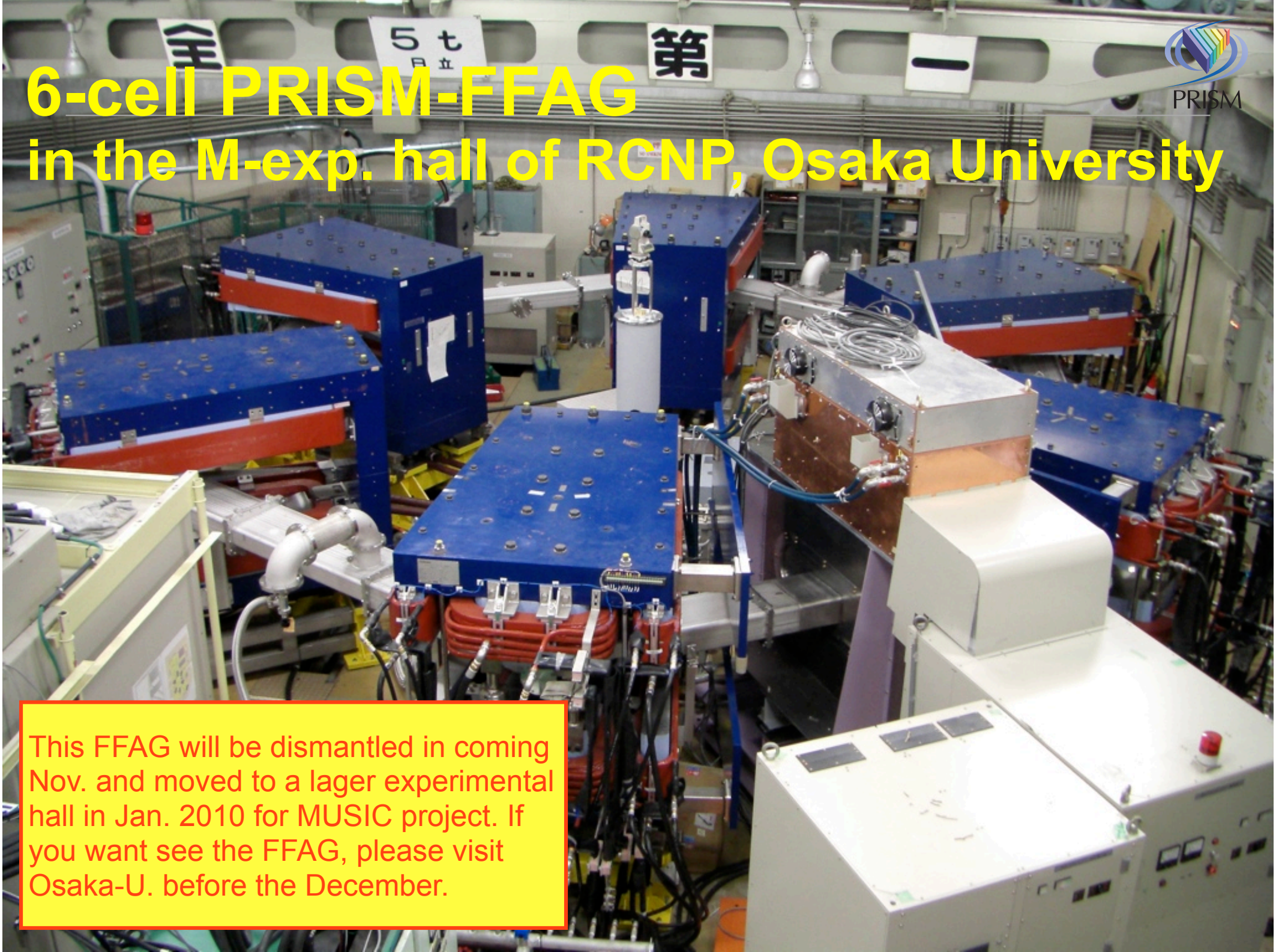
6-cell PRISM-FFAG

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

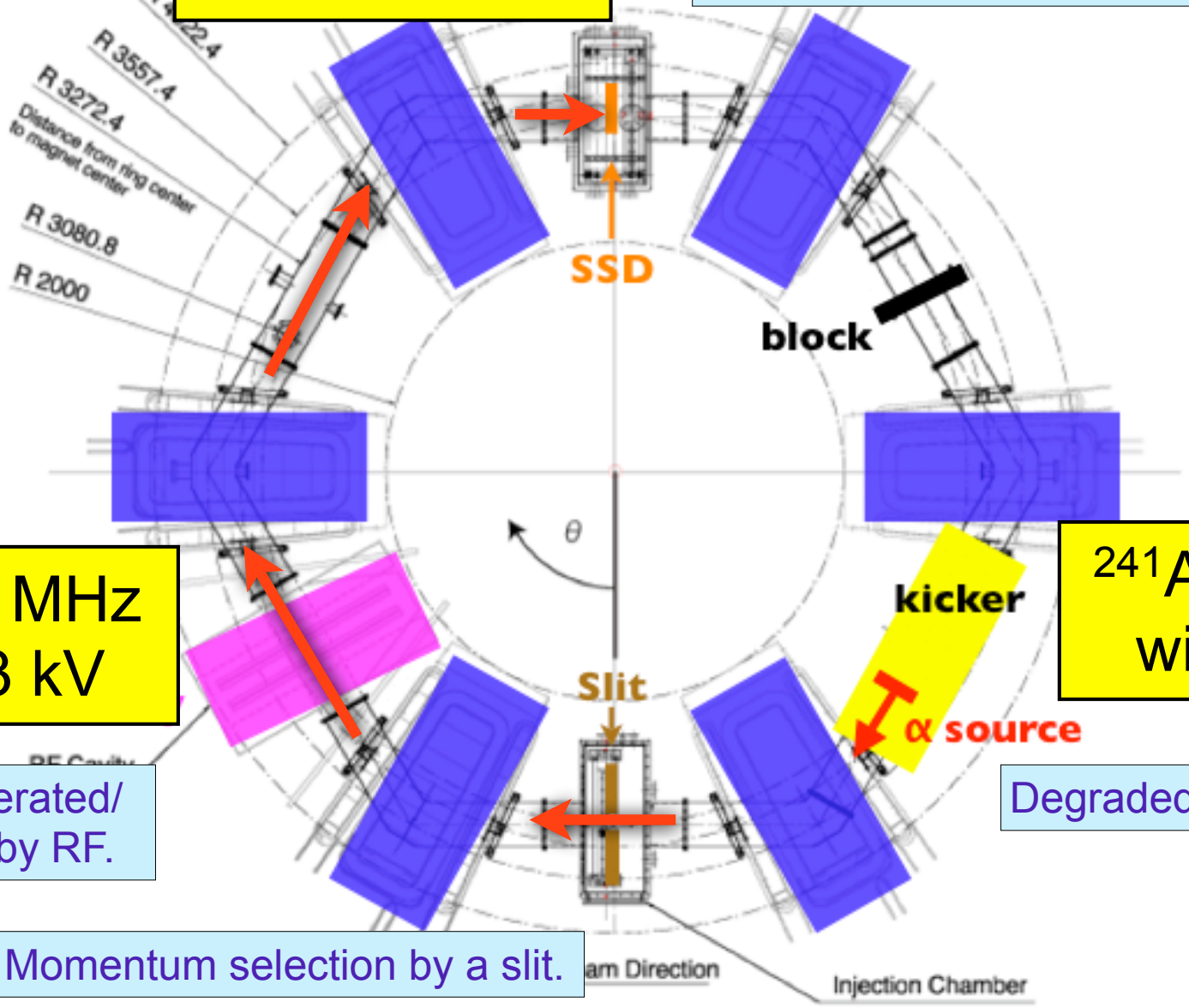


This FFAG will be dismantled in coming Nov. and moved to a lager experimental hall in Jan. 2010 for MUSIC project. If you want see the FFAG, please visit Osaka-U. before the December.

Apparatus for the test of phase rotation

SSD φ2cm,
σ_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

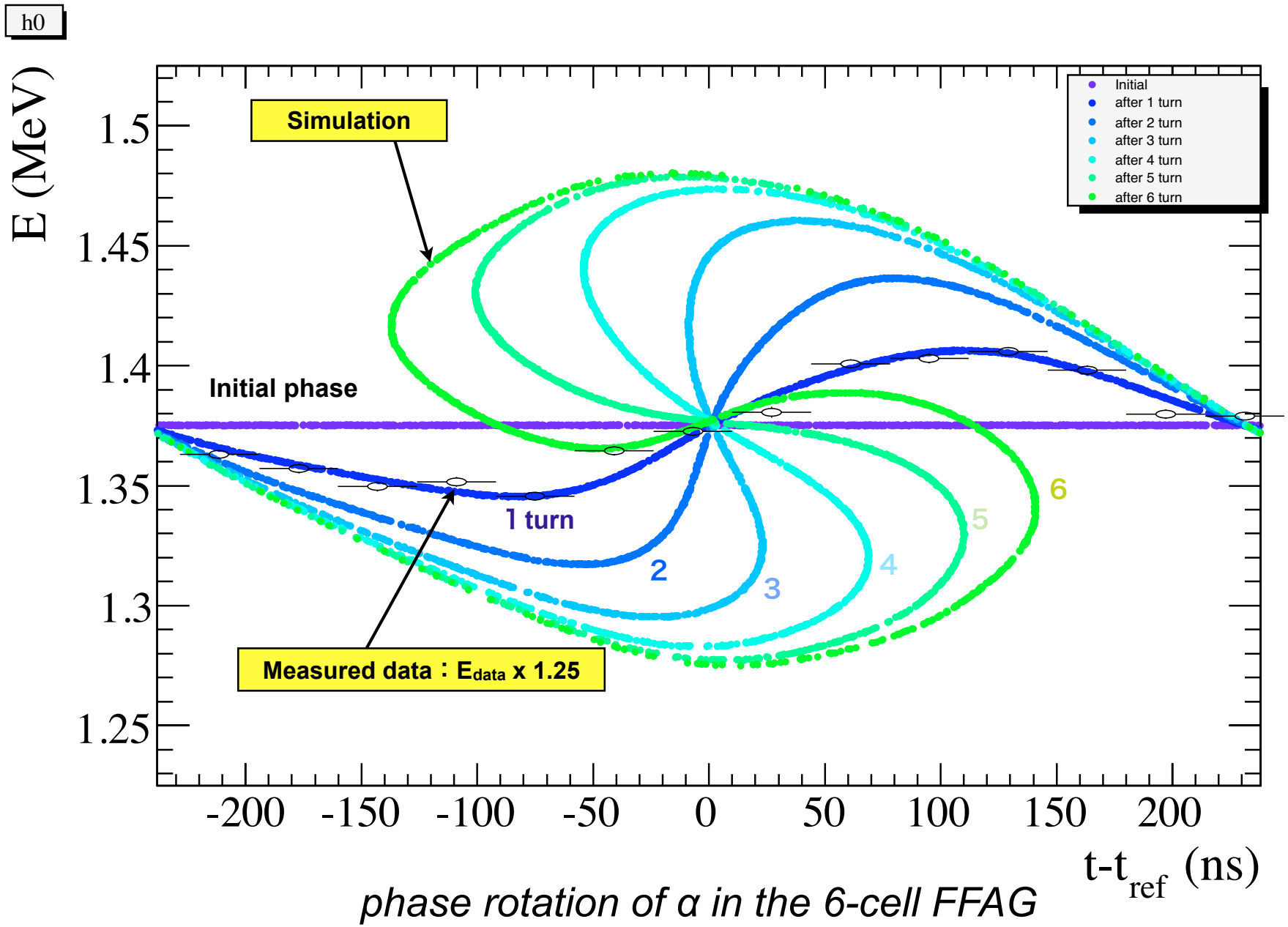
^{241}Am, 3MBq with Al foil

αs are accelerated/ decelerated by RF.

Degraded by an Al foil.

Momentum selection by a slit.

Comparison b/w data and simulation



phase rotation of α in the 6-cell FFAG

PRISM-FFAG Task Force

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,

- The 1st new PRISM-FFAG workshop was held 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

see Jaroslaw's talk

Muon cooling in the PRISM-FFAG - the first attempt to study a racetrack FFAG ring cooler

Motivation of This Study

- The 6D-emittance reduction of a muon beam is essential for future neutrino factories and a muon collider. No realistic design for the muon cooling section, however, have been designed yet.
- A cooling section using a ring (ring cooler) would be more cost effective than that of with a straight channel, science a number of RF and absorbers would be reduced.
- Some designs for the ring cooler have been proposed. These designs have some issues must be solved:
  - injection/extraction and its kicker system,
  - window of absorbers and RFs.
- This study is the first attempt to design a realistic ring cooler using the following ideas.
  - racetrack FFAG
    - FFAG has a large transverse acc. and dispersion in horizontal.
  - superfluid helium wedge absorbers

Ionization Cooling in FFAGs

- **There are few simulation studies for the ionization cooling in FFAG rings. Needs more studies.**
  - **in a nufact-j FFAG ring**
    - (superconducting FFAG for 0.3-1.0GeV/c muon acceleration)
      - H Schonauer, J. Phys. G: Nucl. Part. Phys. 29 (2003) 1739
      - H. Schonauer, NIM A503 (2003) 318–321
    - Thin absorbers in the symmetry plane of all RF cavity gaps were inserted to the ring.

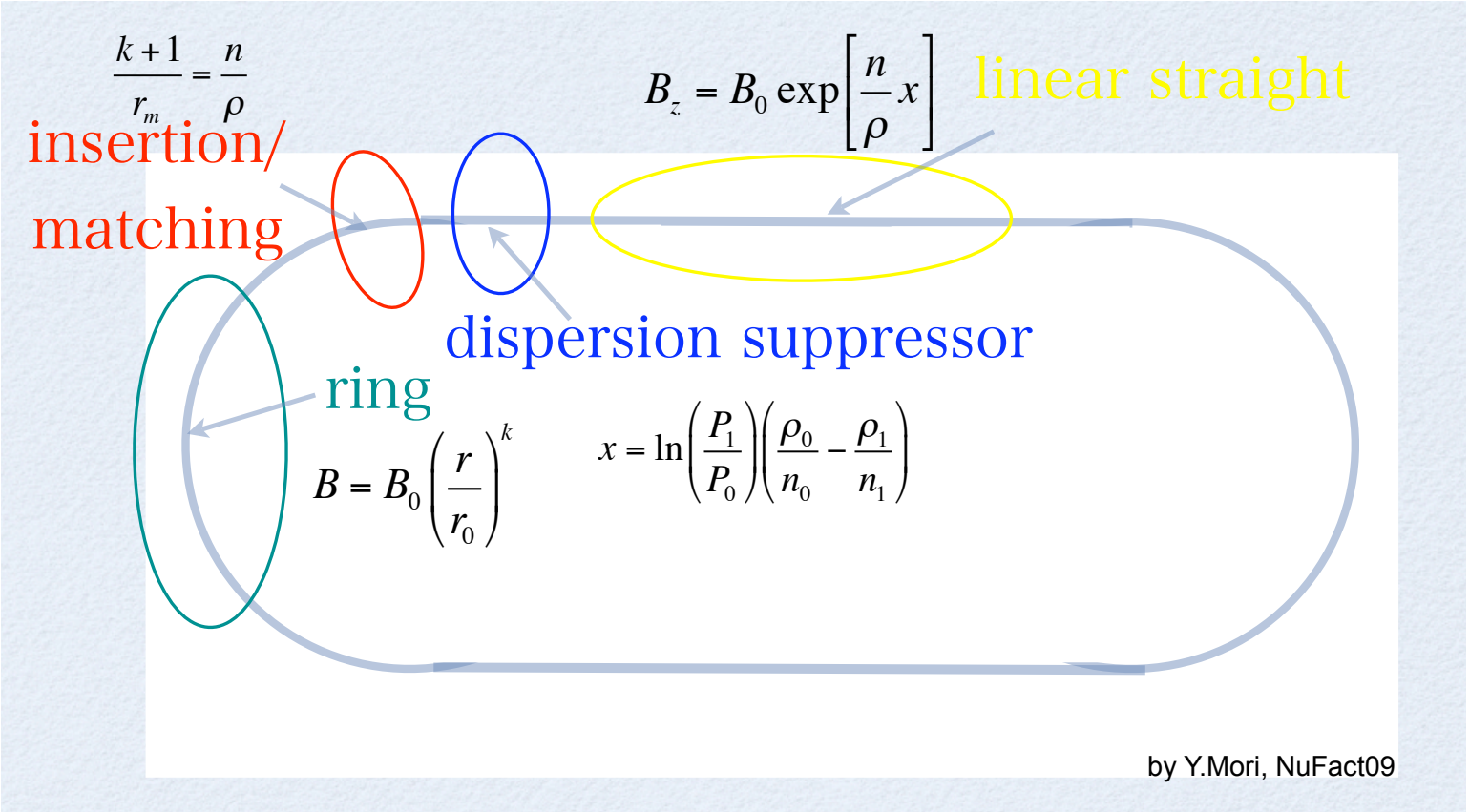
Table 1. Comparison of cooling performances of Be, Li and LiH_2 windows.

Material thickness	Energy gain per turn (max.) (MeV)	Muon transmission	Cooling factor of rms normalized emittance		Figure of merit: muon transmission/cooling	
			Horizontal	Vertical	Horizontal	Vertical
None	62.7	0.965	1	1	0.965	0.965
Be 7 mm (old reference Nufact'01)	25	0.91	0.959	0.856	0.944	1.057
Be 7 mm (new reference)	25	0.91	0.985	0.909	0.928	1.006
LiH_2 13.3 mm	20	0.89	0.892	0.799	0.992	1.107
LiH_2 10.6 mm	30.3	0.93	0.974	0.883	0.65	1.048
Li 20 mm	21.4	0.89	0.825	0.756	1.085	1.184
Li 10 mm	40.6	0.95	0.95	0.91	0.991	1.042

  - **in the PRISM-FFAG ring by H.Kirk ???**

New Ideas for Scaling-FFAG

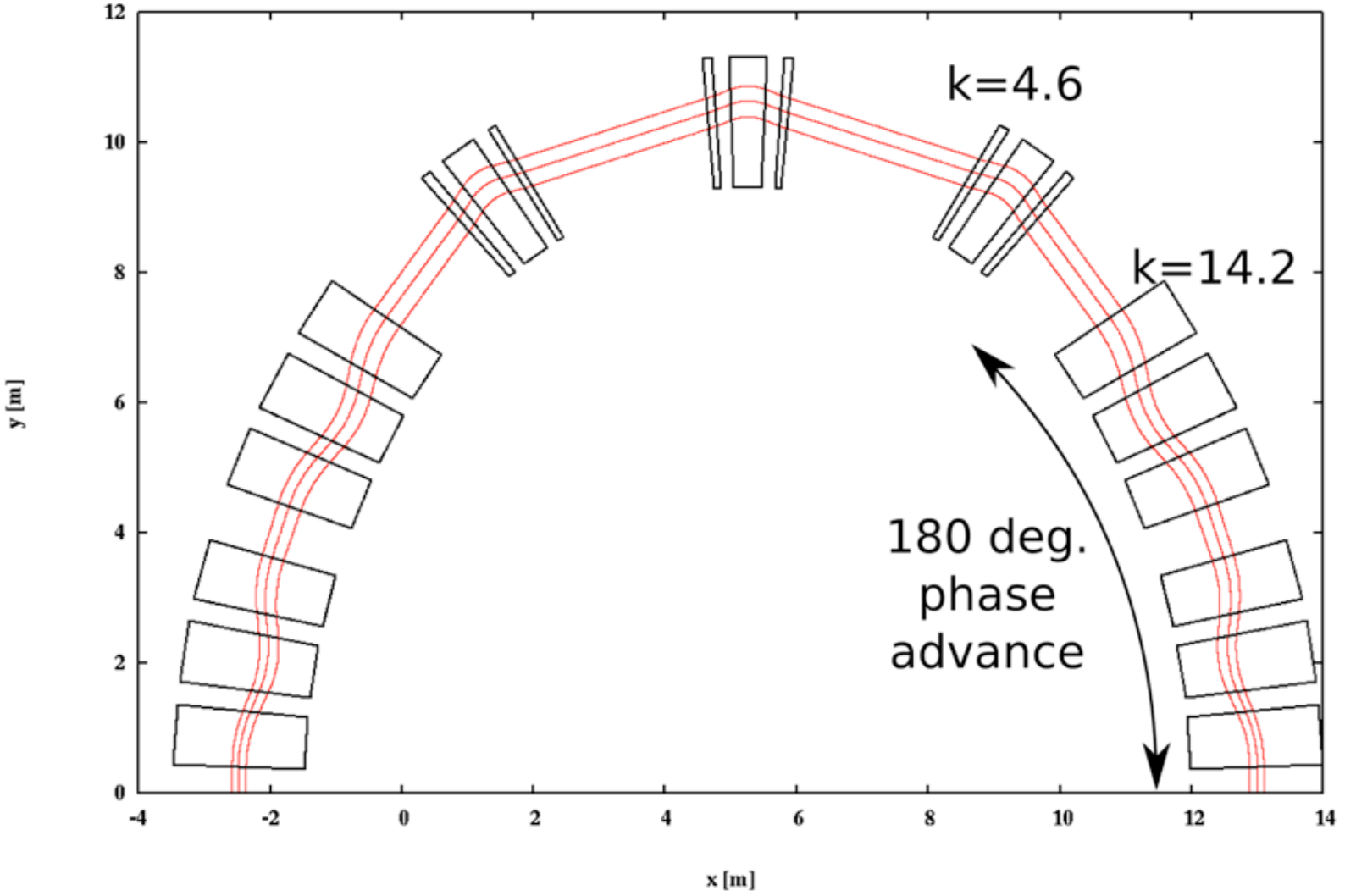
- Recently, some new ideas for the scaling FFAG have been proposed by Y.Mori and S.Machida et. al.
  - Insertion of straight section into the FFAG ring
  - Dispersion suppress in a FFAG ring/channel.



- These ideas would be useful for inj/ext of the FFAG ring cooler.

New Ideas for Scaling-FFAG (cntd.)

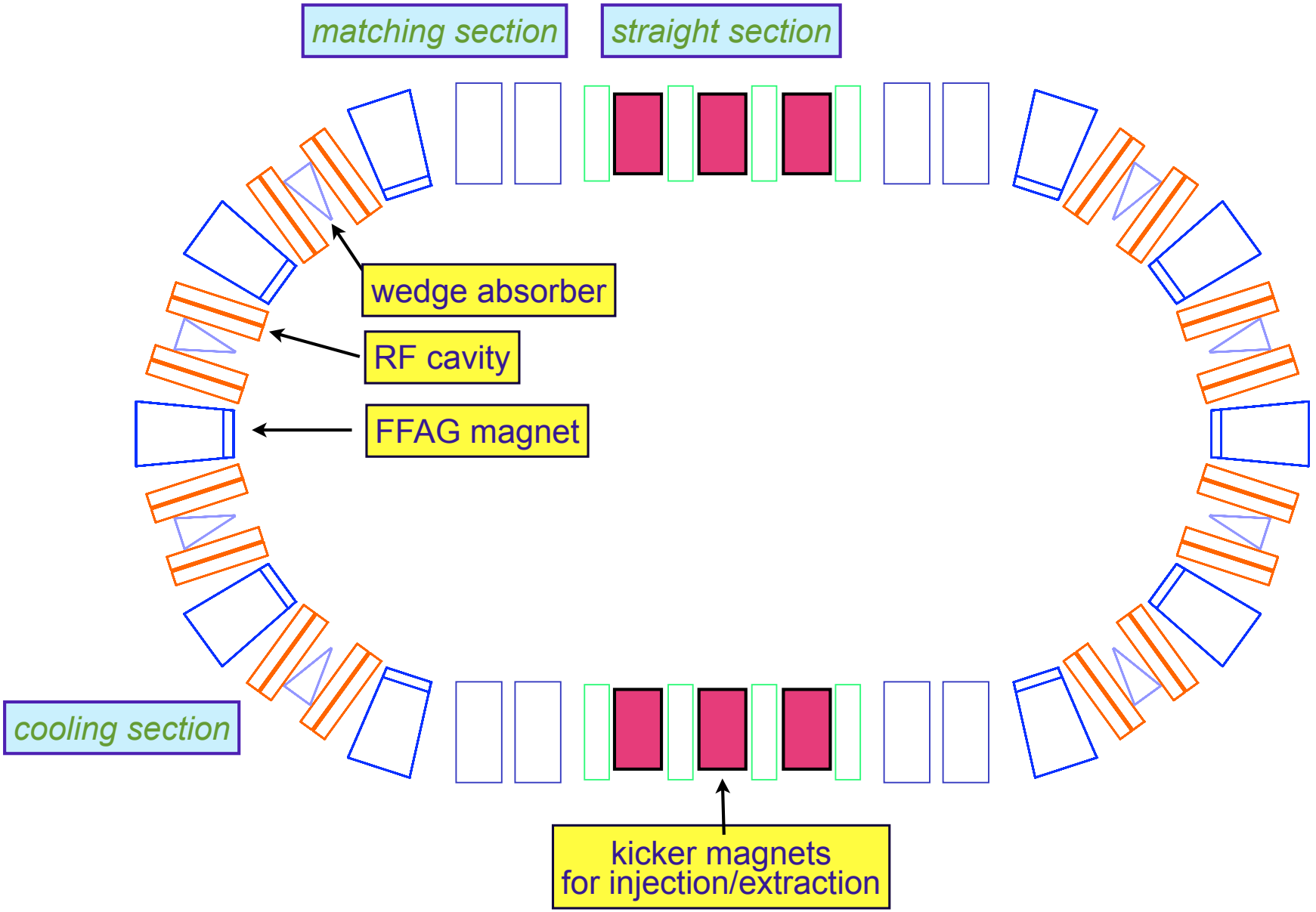
APPLICATION: PRISM



Y. Mori, JB Lagrange

Racetrack FFAG for Muon Cooling

Just an illustration for a conceptual design



Racetrack FFAG for Muon Cooling

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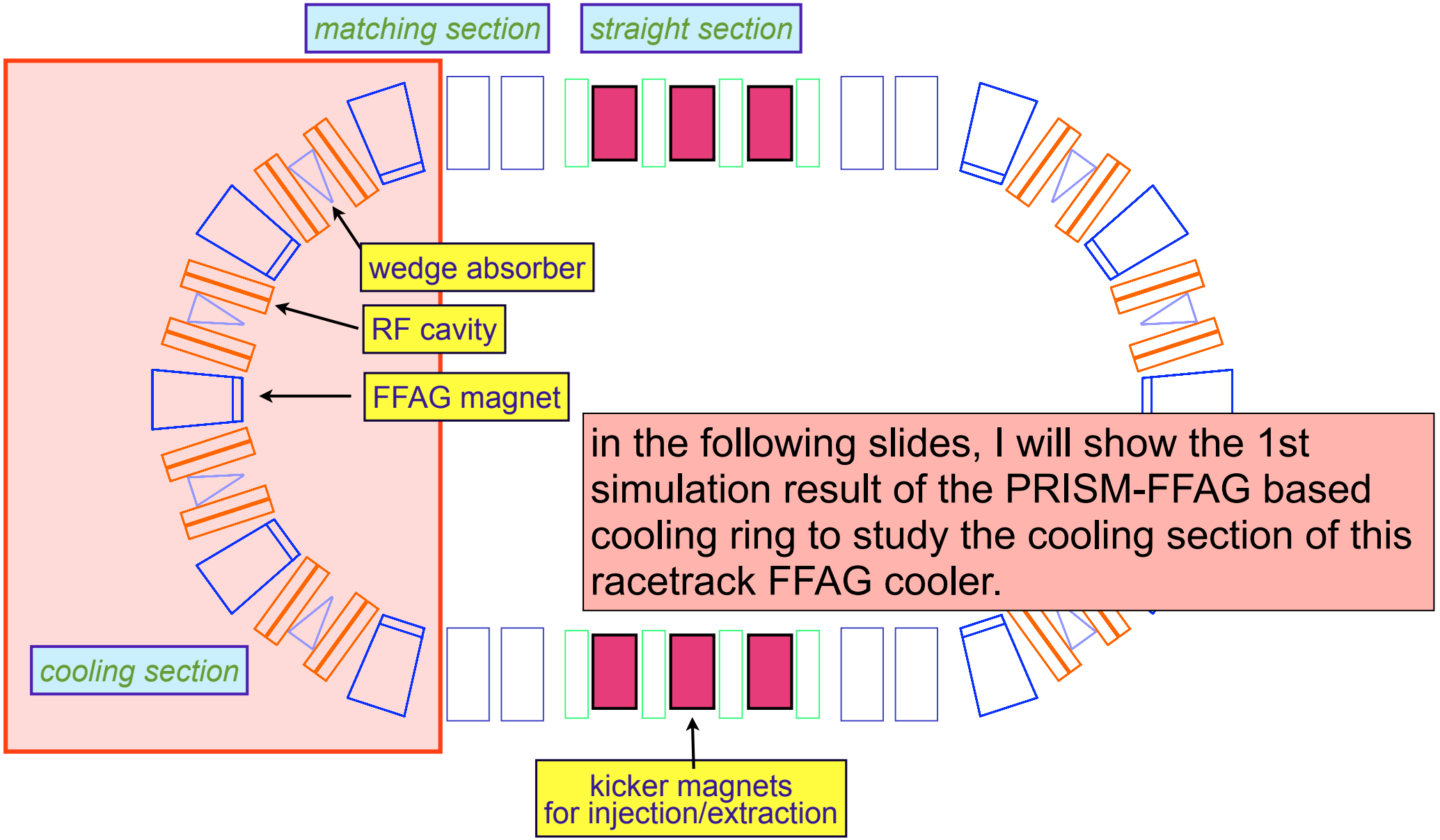
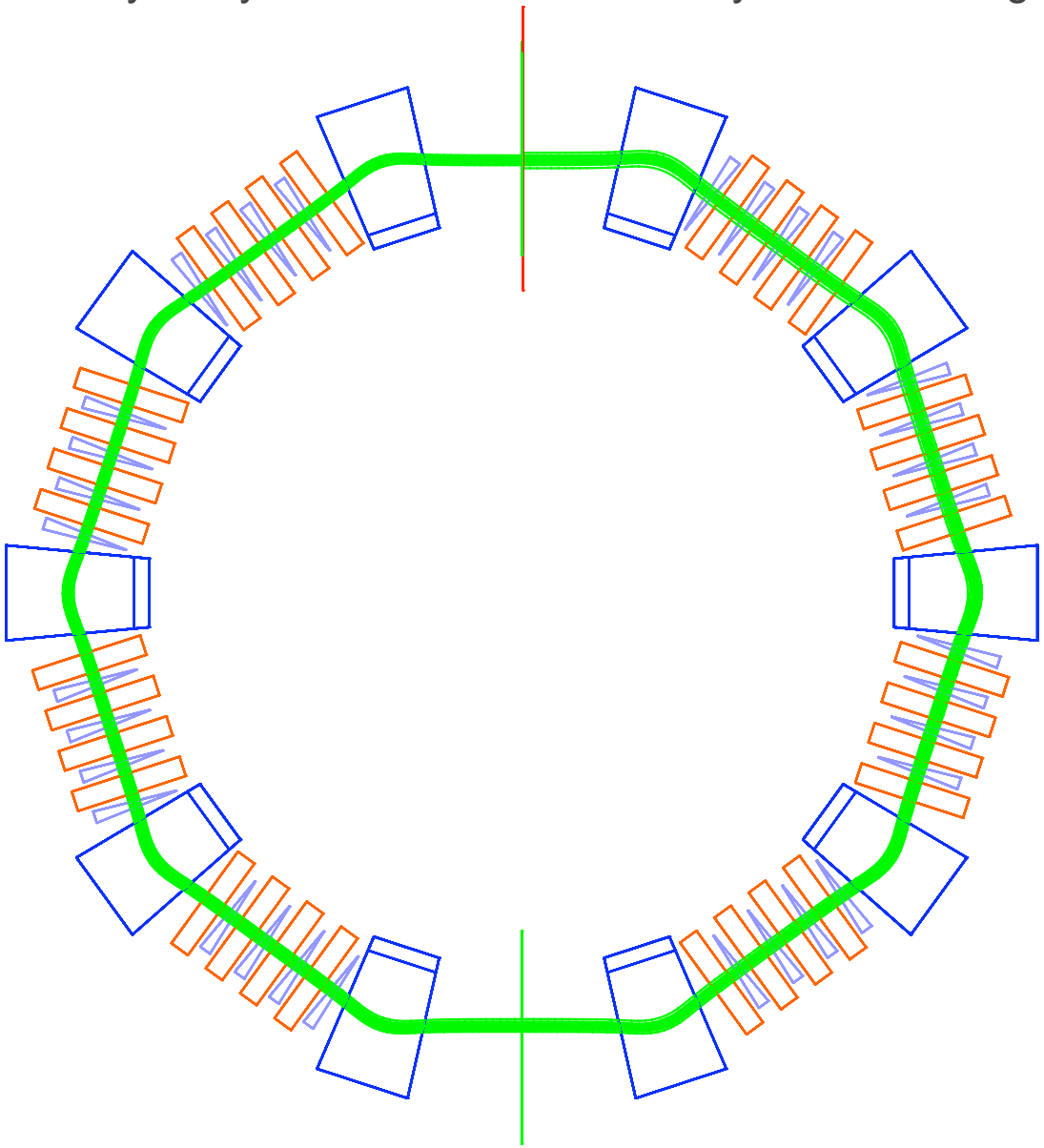


in the following slides, I will show the 1st simulation result of the PRISM-FFAG based cooling ring to study the cooling section of this racetrack FFAG cooler.

PRISM-FFAG Based Ring Cooler

- This presentation shows a result of a ring cooler based on PRISM-FFAG lattice as the first trial of my study. This is a simulation study for the cooling section of the racetrack FFAG cooler.



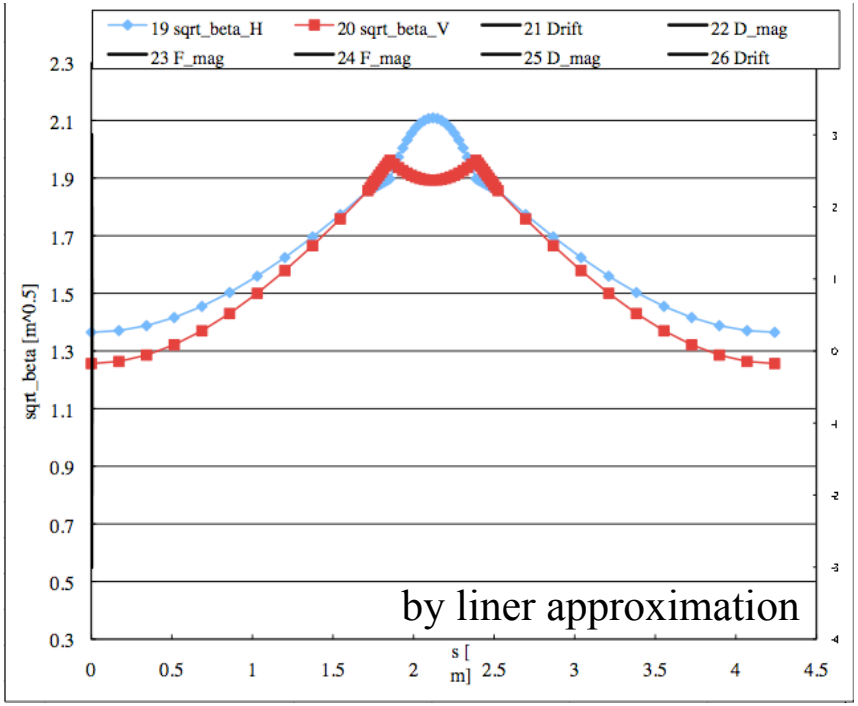
Circumstance (m)	38
Number of cells	10
Field index k	4.6
F/D ratio	6.0
Maximum field (T)	1.6
Central momentum (MeV/c)	308
Magnet type	DFD triplet
Magnet aperture	H:100 cm x V: 30 cm
Horizontal tune	2.73
Vertical tune	1.58

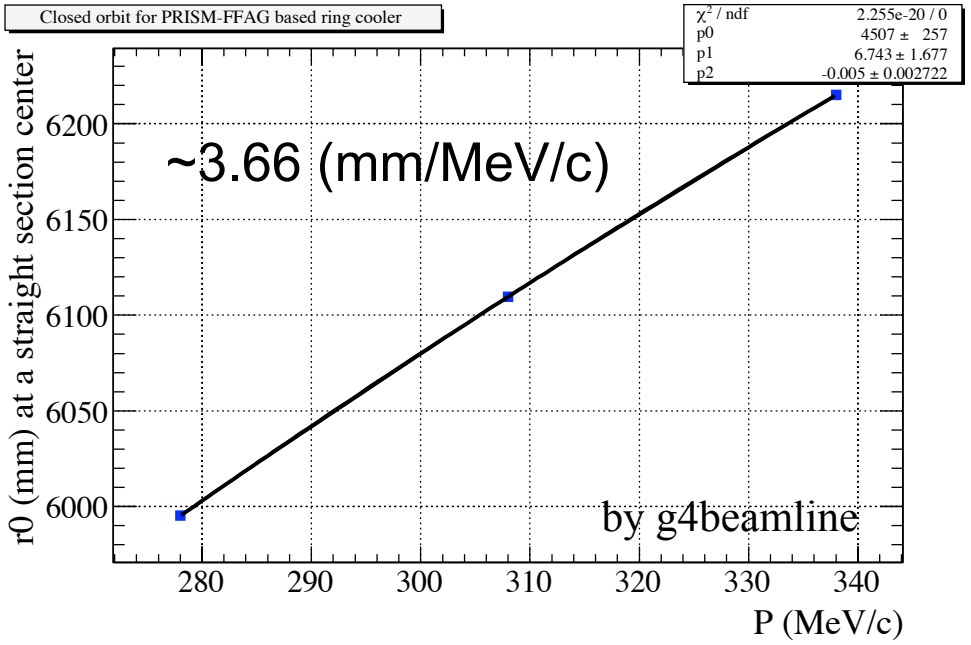
The magnetic field of the original PRISM-FFAG is multiplied by 4.0.

Param of PRISM-FFAG Based Ring Cooler

Circumstance (m)	38
Total number of cells	10
Cell with RF cavities and absorbers	8
Central momentum P_0 (MeV/c)	308
Number of wedge absorbers per cell	4
Wedge thickness on r_0 for P_0(cm)	8.672
Wedge opening angle (degree)	3.86
Absorber material	LH2
Number of cavities per cell	4
Cavity length (cm)	28.75
RF gradient (MV/m)	8.709

Beta Functions and Dispersion



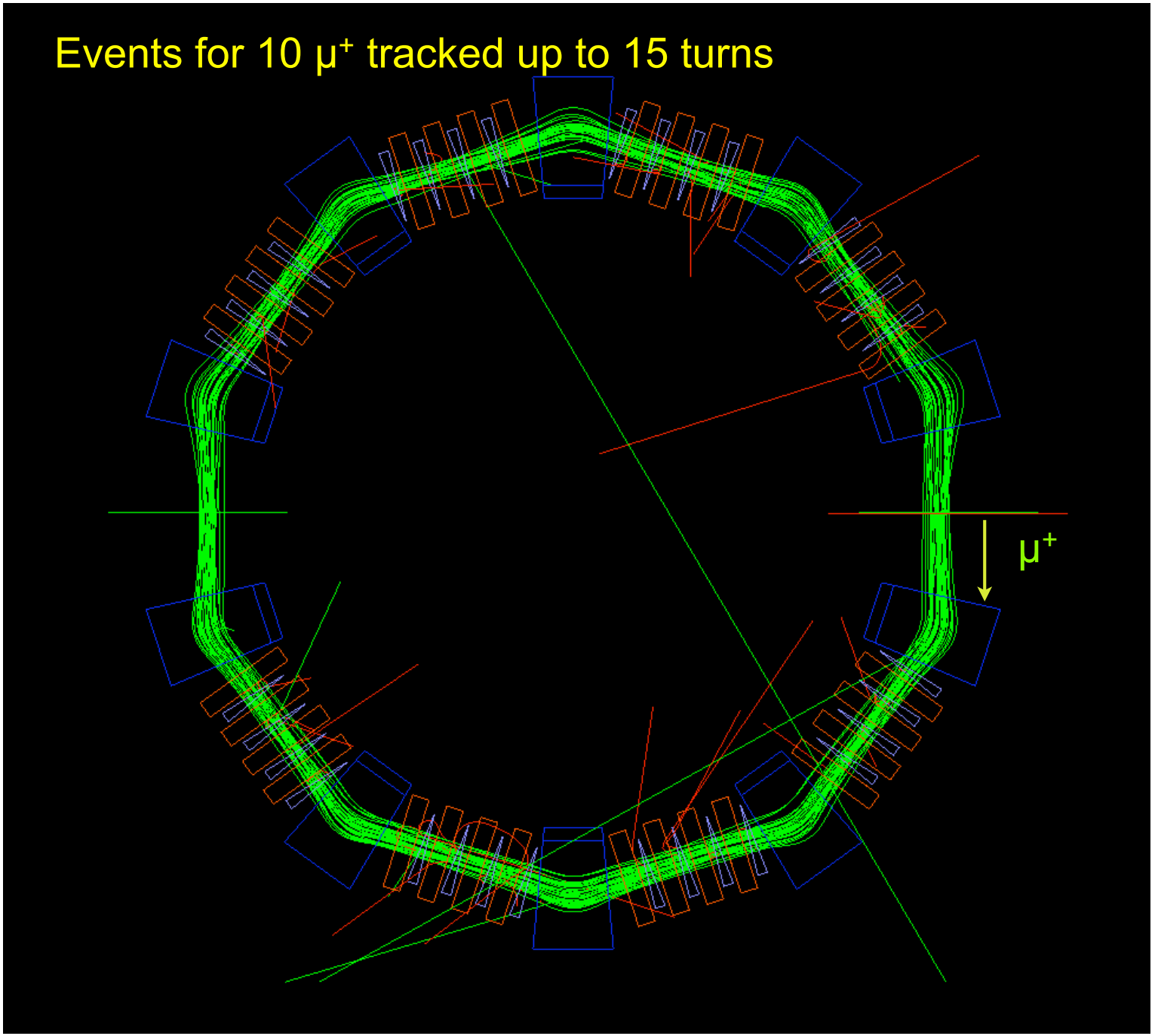


Cooling Simulation

- Tracking code: g4beamline-1.16 on Mac OS X
  - with stochastic processes
  - without decay
  - physics model: QGSP_BIC
  - RF cavities were simulated as electrostatic parallel plates.
- 5 x 10^4 μ^+ have been tracked.

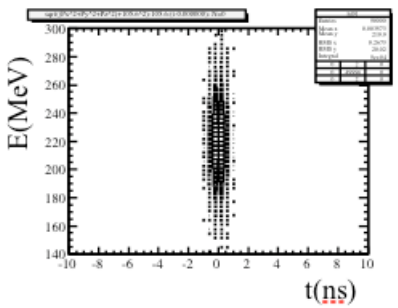
Initial Beam Condition

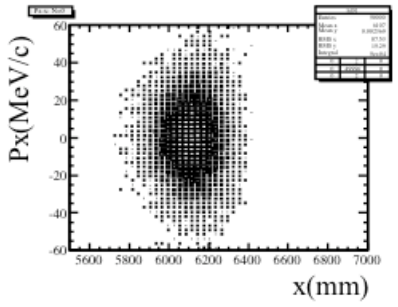
$E_{0_kinetic}$		MeV	220
E_{0_total}		MeV	326
P_0		MeV/c	308
β			0.9457
γ			3.0755
βγ			2.9084
σx		cm	4
$σp_x$		MeV/c	15.4
σx'	$σpx/P_0$		0.0500
normalized εx	βγ*σx*σx'	cm	0.582
σy		cm	4
$σp_y$		MeV/c	4.6
σy'	$σpy/P_0$		0.0150
normalized εy	βγ*σy*σy'	cm	0.175
σcT		cm	8
σT		ns	0.2667
σdE		MeV	20
σpz		MeV/c	21.1
normalized εL	$βγ*σcT*(σpz/P_0)$	cm	1.591
ε6D	εx*εy*εL	cm^3	0.16

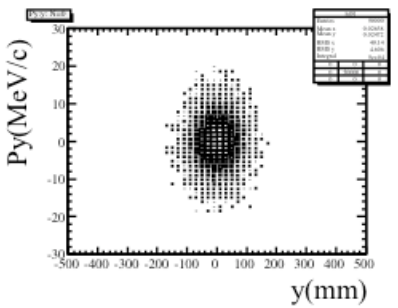

Events for 10 μ+ tracked up to 15 turns
μ+

Result

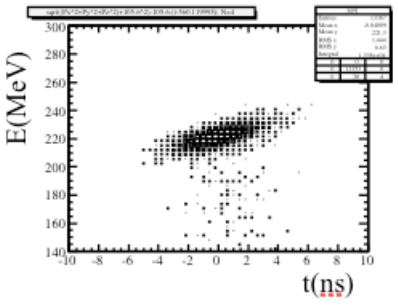
Initial

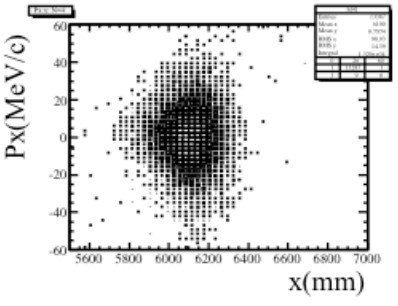


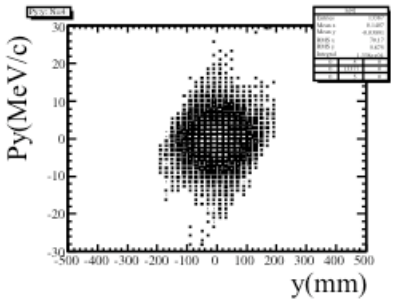




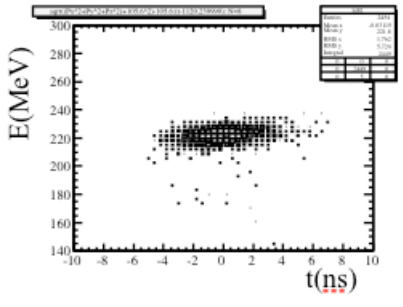
after 4 turns

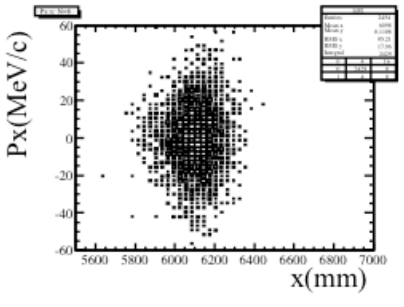


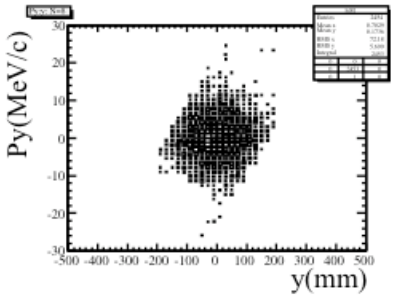




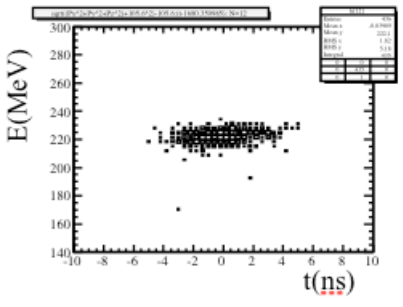
after 8 turns

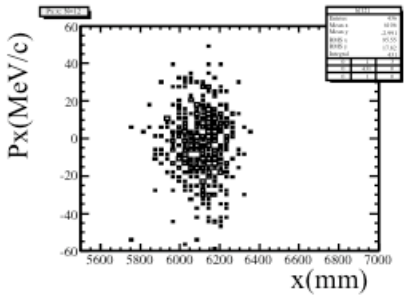


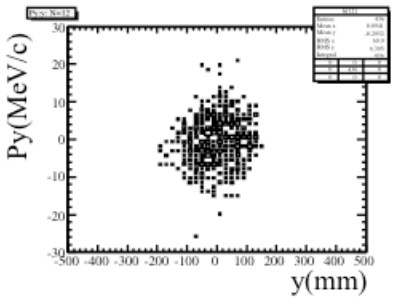




after 12 turns

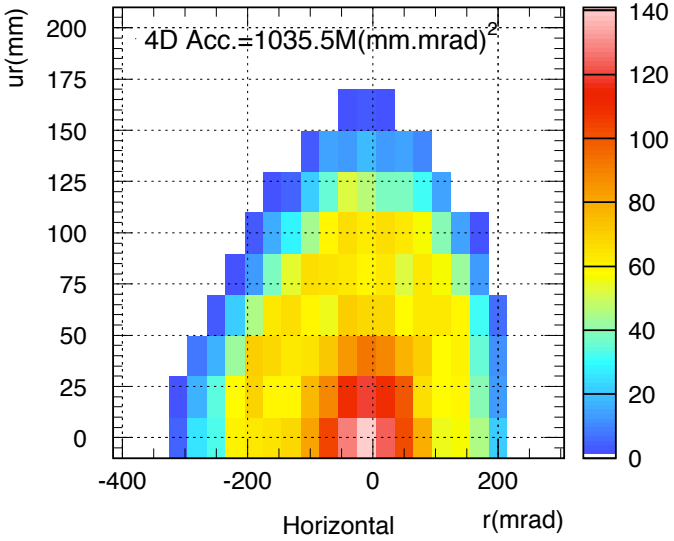




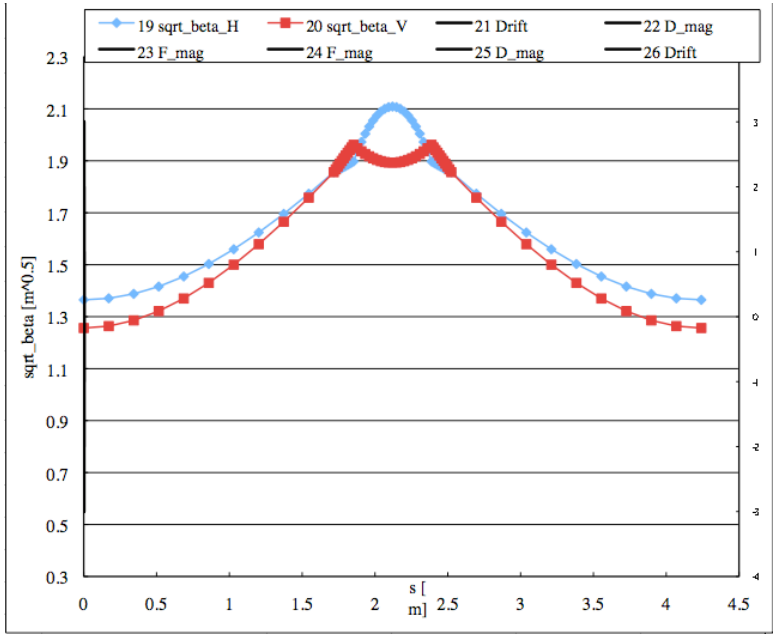


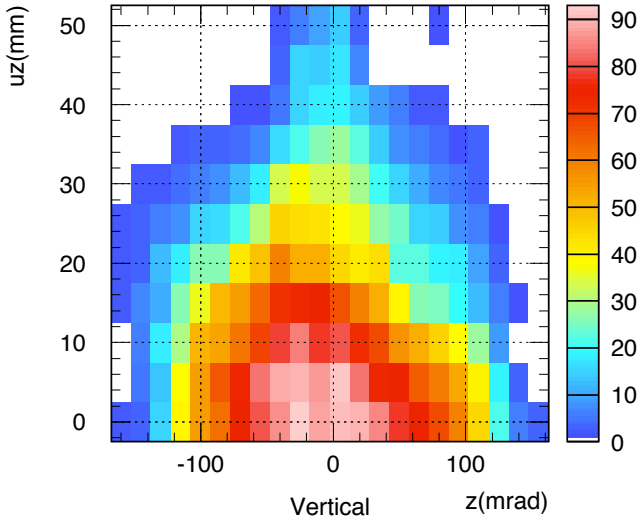
No cooling effect is observed with PRISM-FFAG based ring. Since, probably, β function is too large, angler acceptance is not enough. Need new lattice design.

Performance of the Orig. PRISM-FFAG

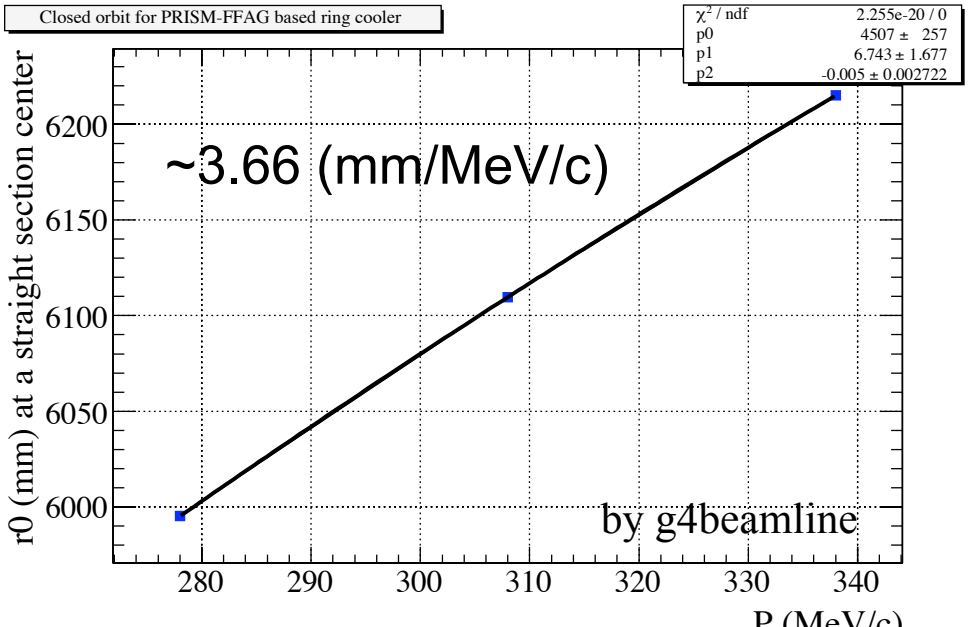


Horizontal Acceptance
40000π mm mrad





Vertical Acceptance
6500π mm mrad



MUSIC project

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

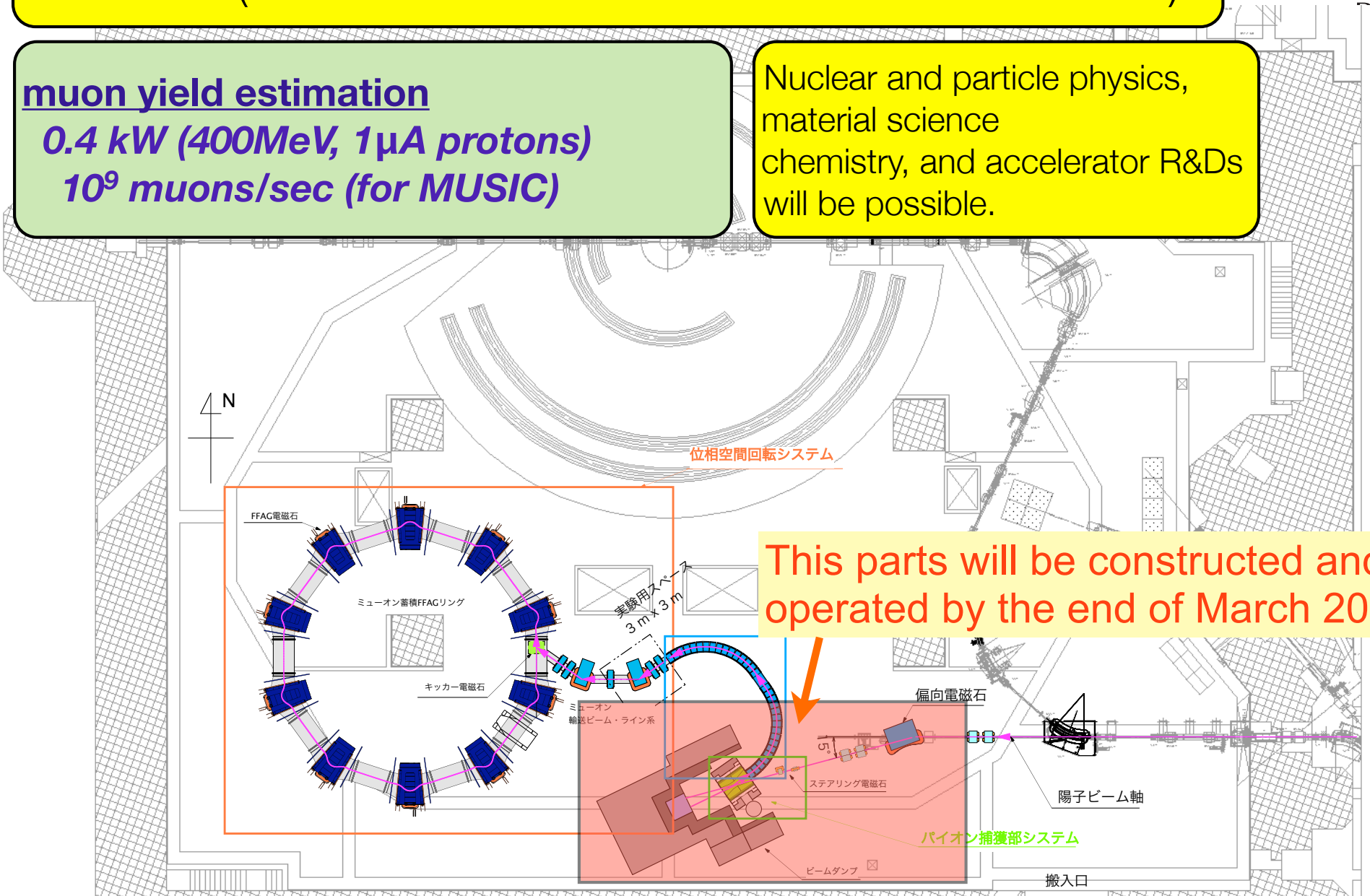
MUSIC (=MUon Science Innovative Commission)

muon yield estimation

0.4 kW (400MeV, 1μA protons)

10^9 muons/sec (for MUSIC)

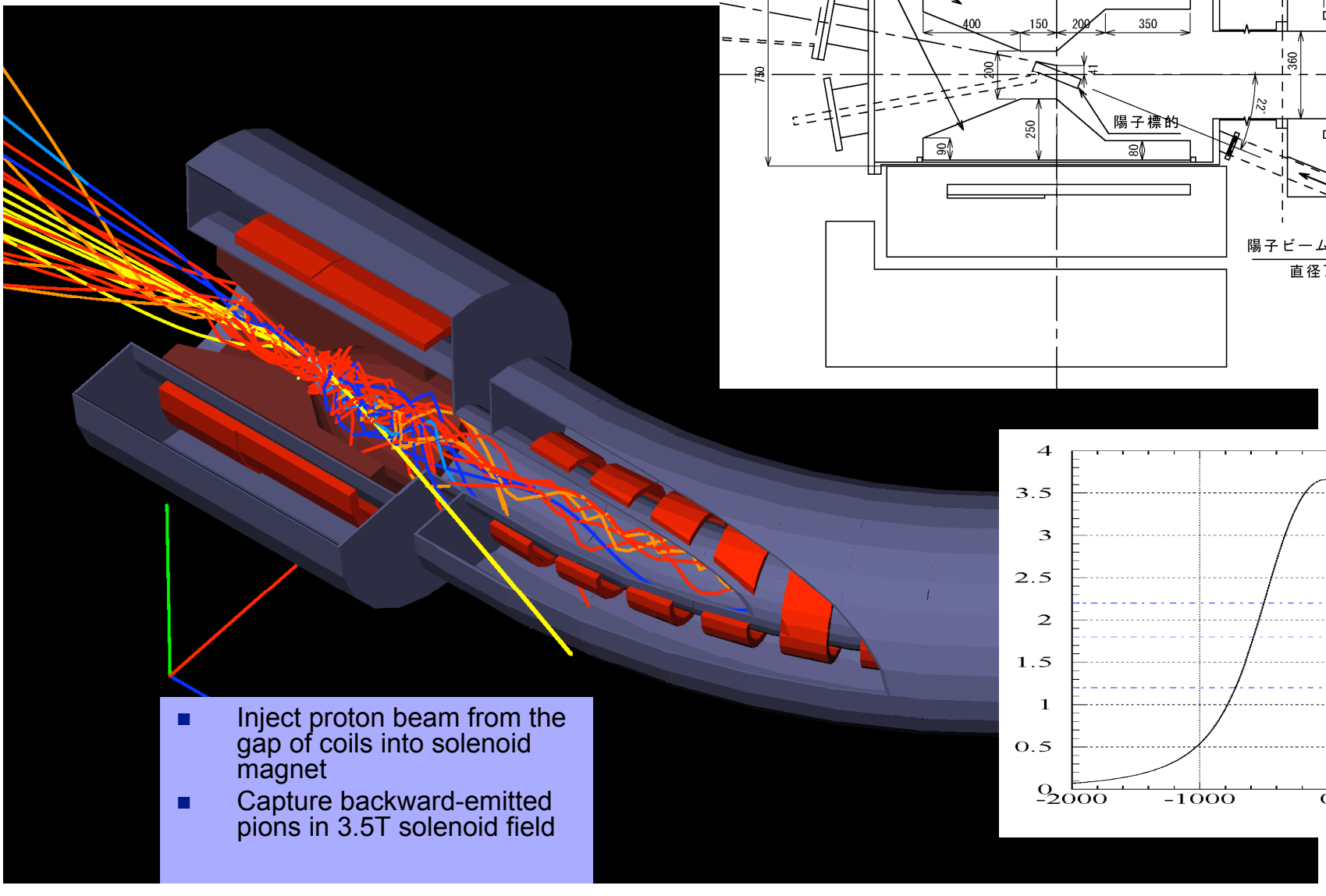
Nuclear and particle physics, material science chemistry, and accelerator R&Ds will be possible.

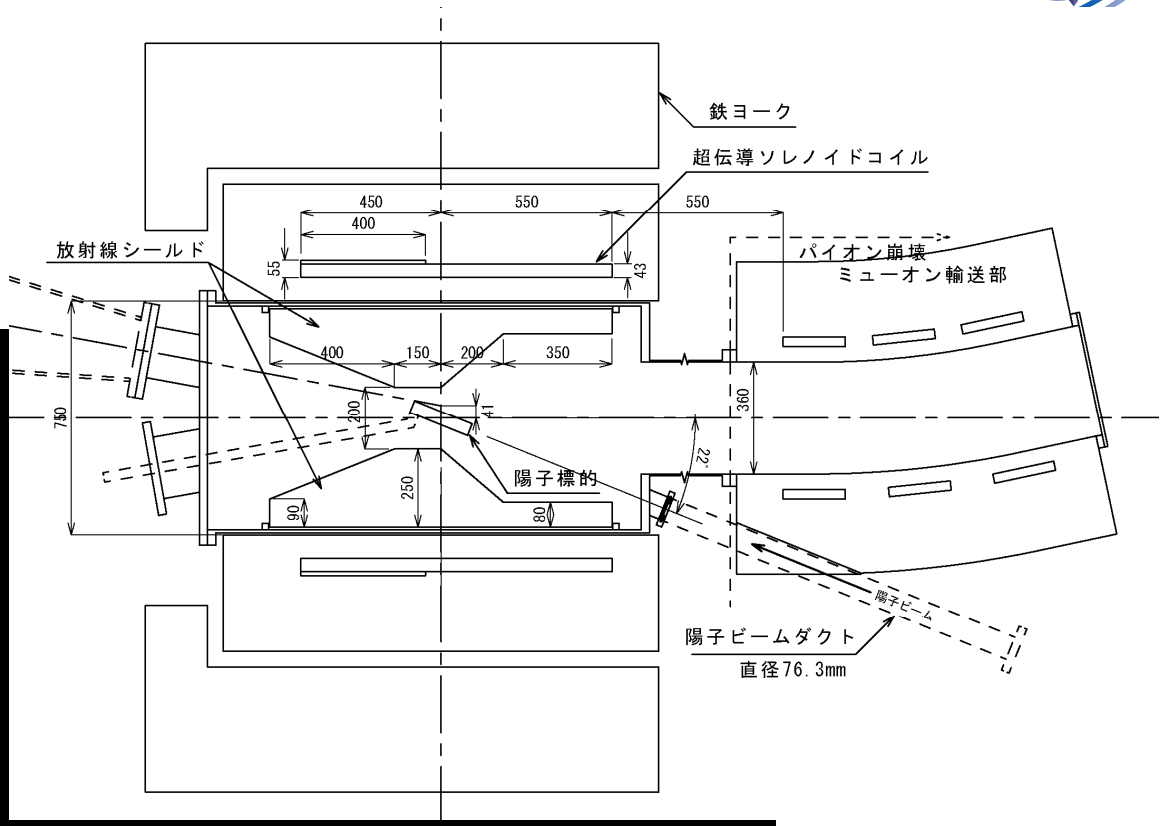


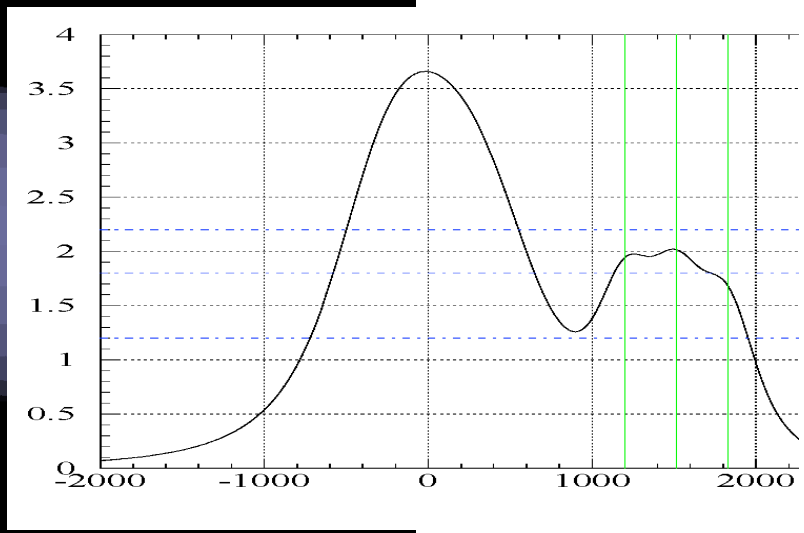
This parts will be constructed and operated by the end of March 2010.

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

Pion Capture System







- Inject proton beam from the gap of coils into solenoid magnet
- Capture backward-emitted pions in 3.5T solenoid field

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.
  - Hybrid RF to realize the 4MHz sawtooth (this year)
- *Prospects*
  - **The collaboration and task force for the PRISM-FFAG** were created. We will continue to study the PRISM-FFAG to realize the ultimate μ-e conv. experiment.
  - PRISM-FFAG based ring cooler have been studied. New lattice design is necessary to realize a **racetrack FFAG ring cooler**.
  - **A new muon beamlin (MUSIC) is now under construction** at RCNP, Osaka Univ., and PRISM-FFAG study can be continue with the muon beam.