Scaling FFAGs

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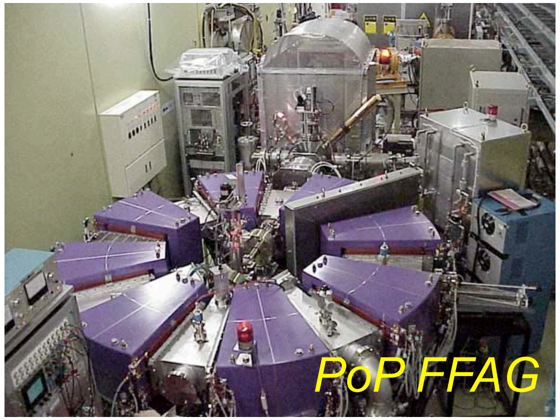
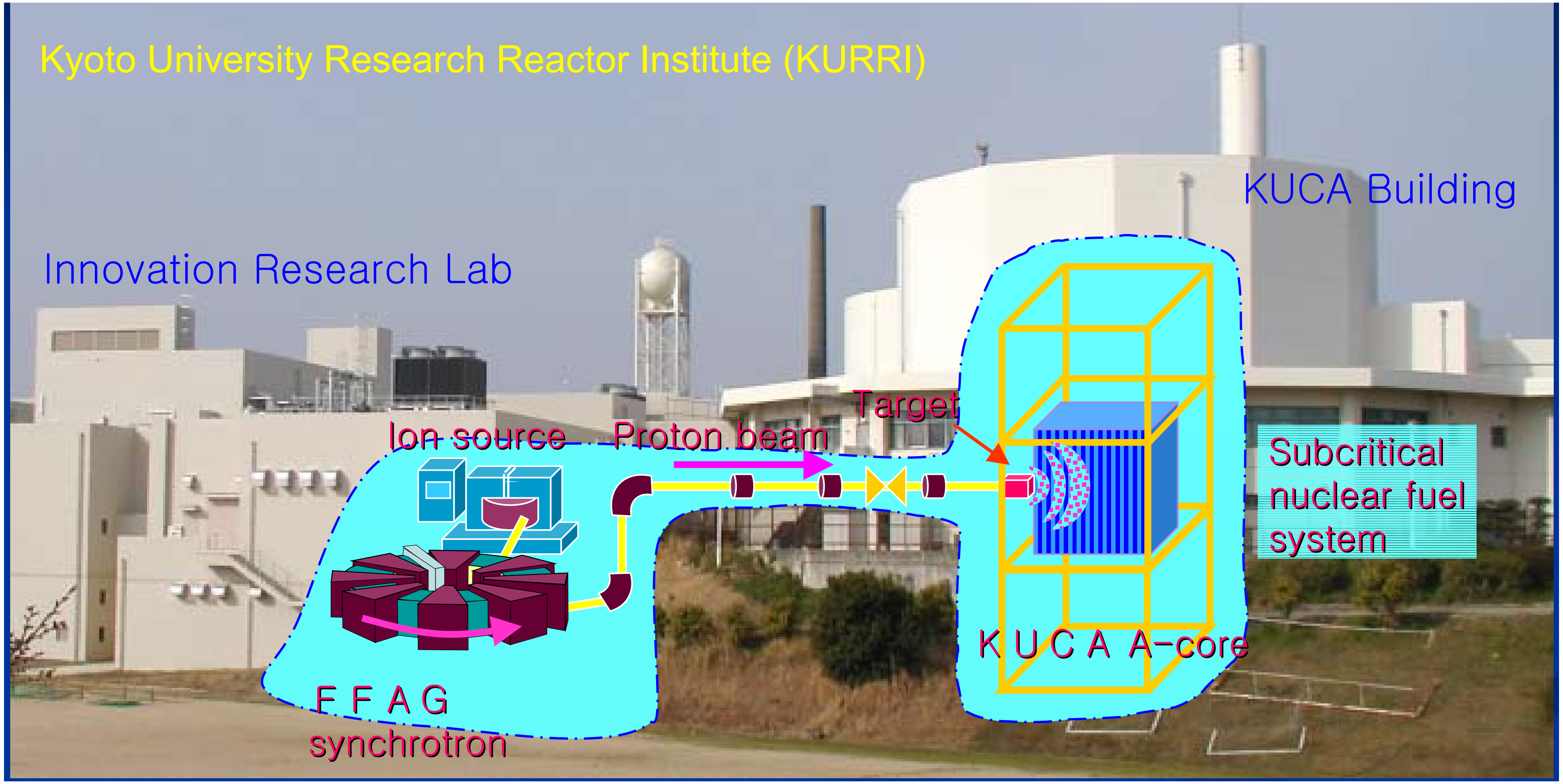


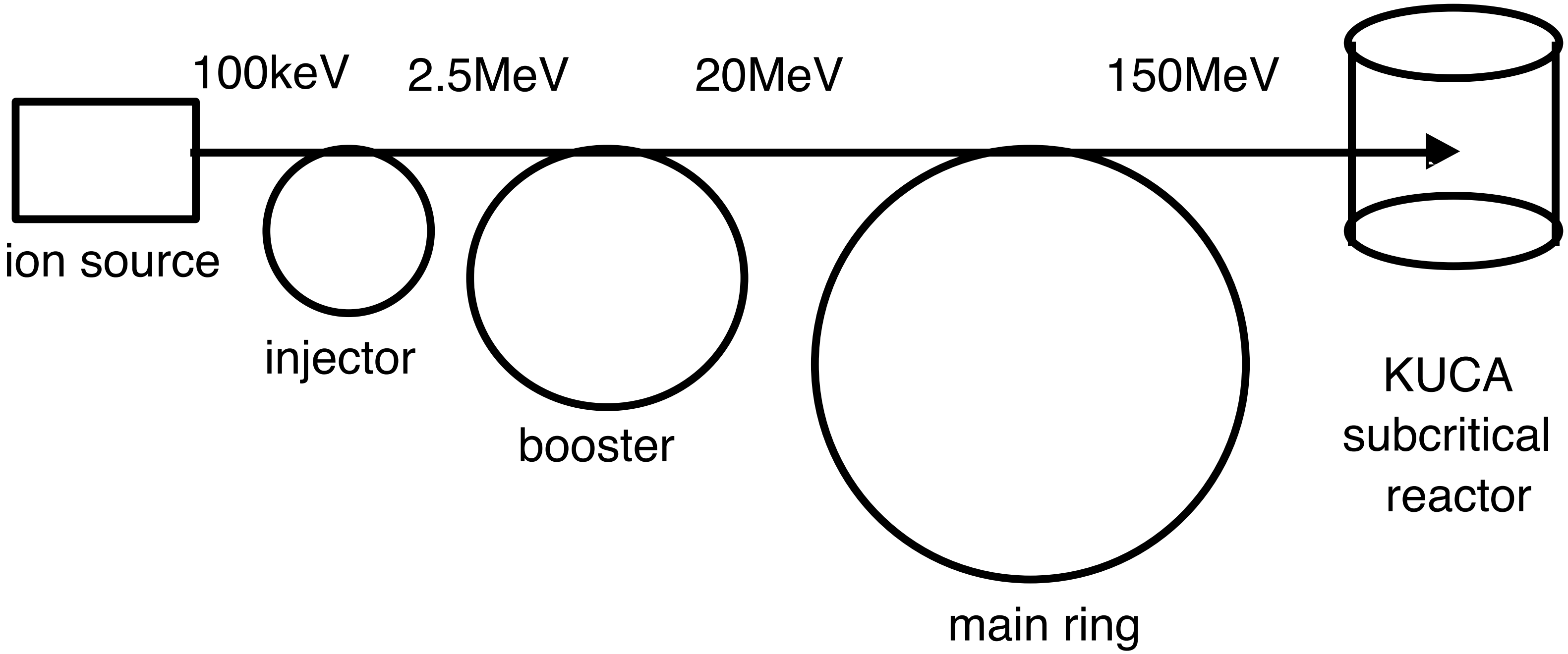
FFAG complex
for a feasibility study of accelerator driven reactor

Feasibility Study on ADSR Using FFAG Accelerator



Development of variable energy FFAG accelerator with high acceleration efficiency.

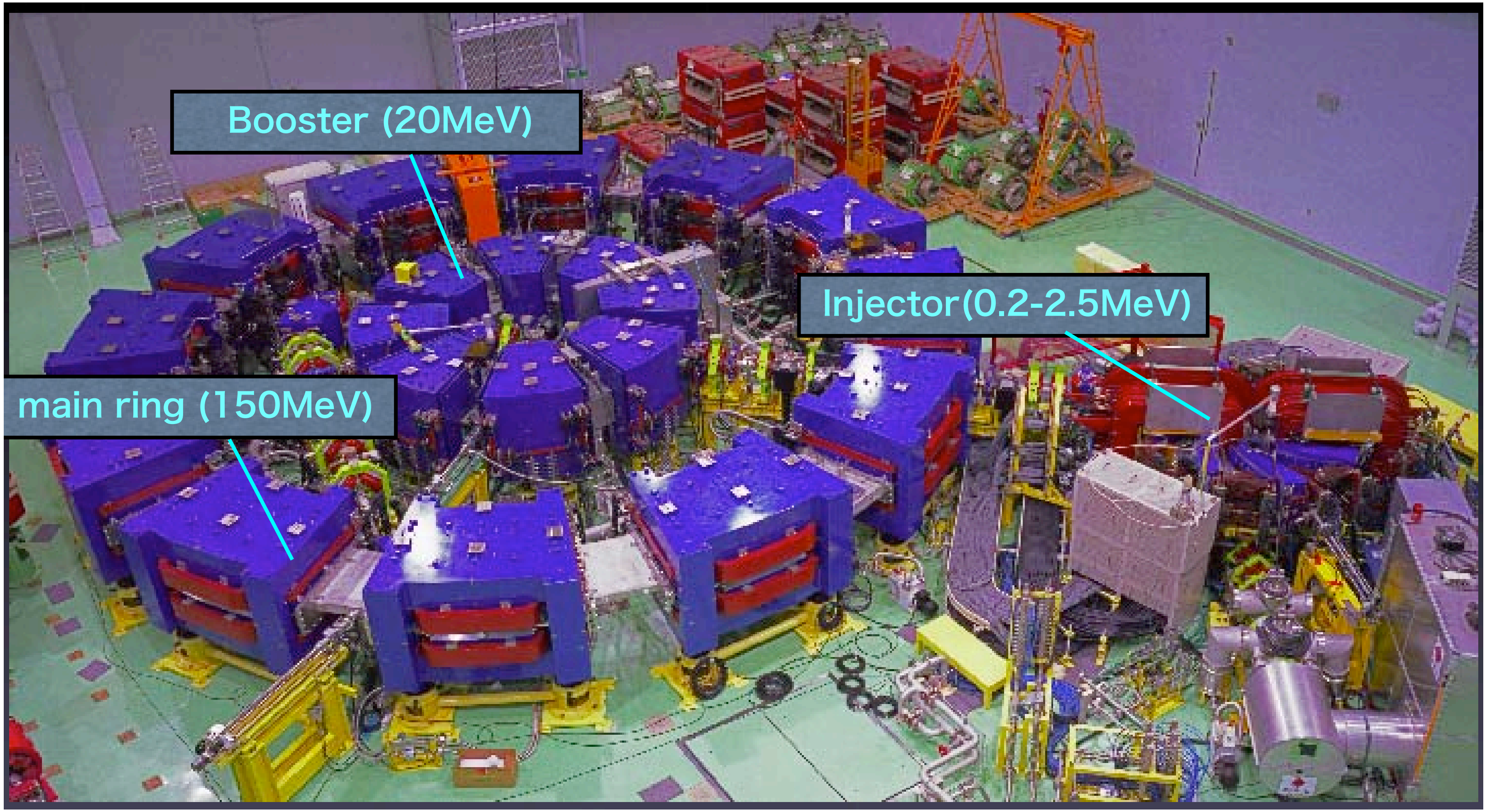
FFAG complex at KURRI

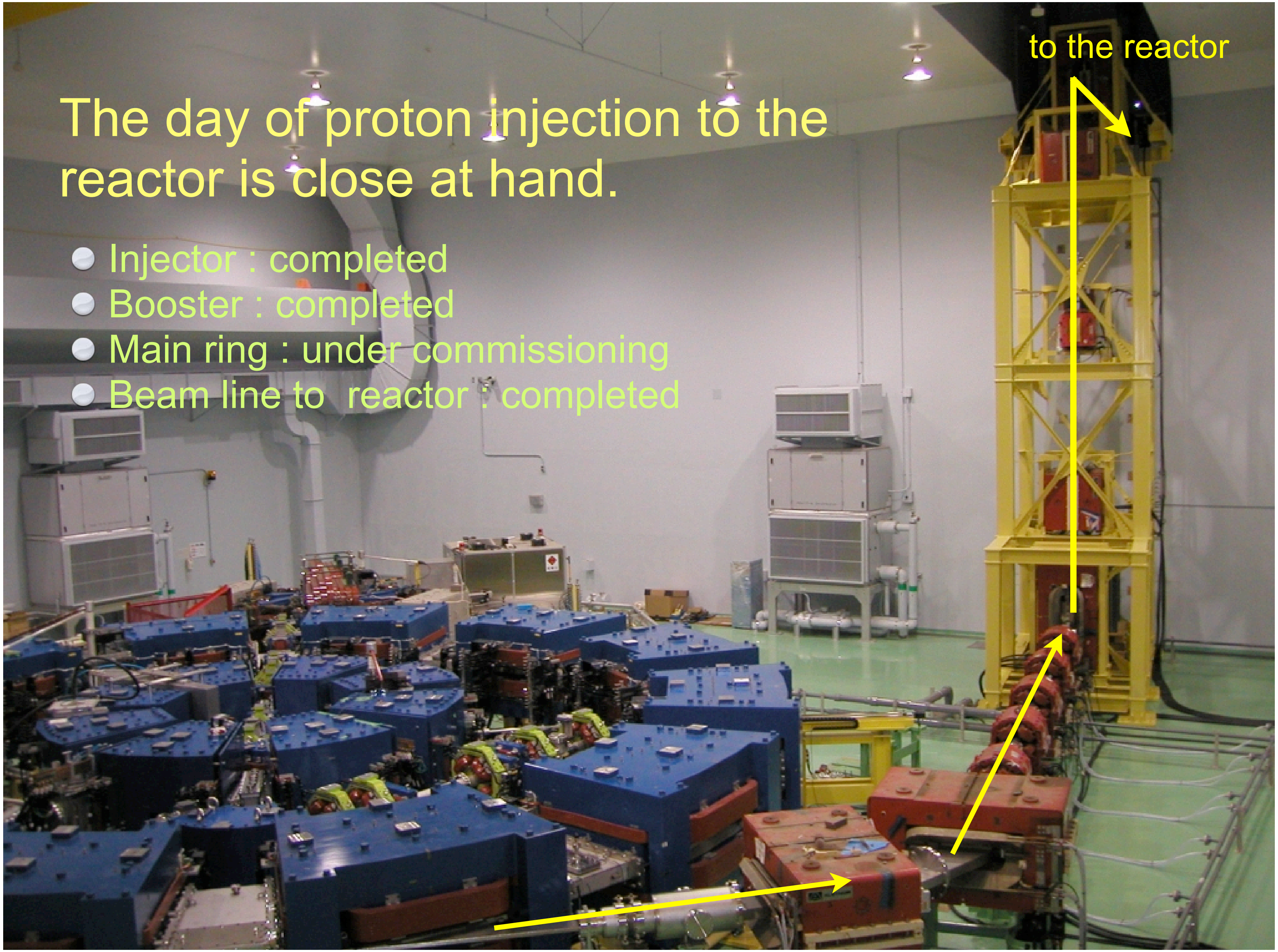


Parameters for FFAG complex

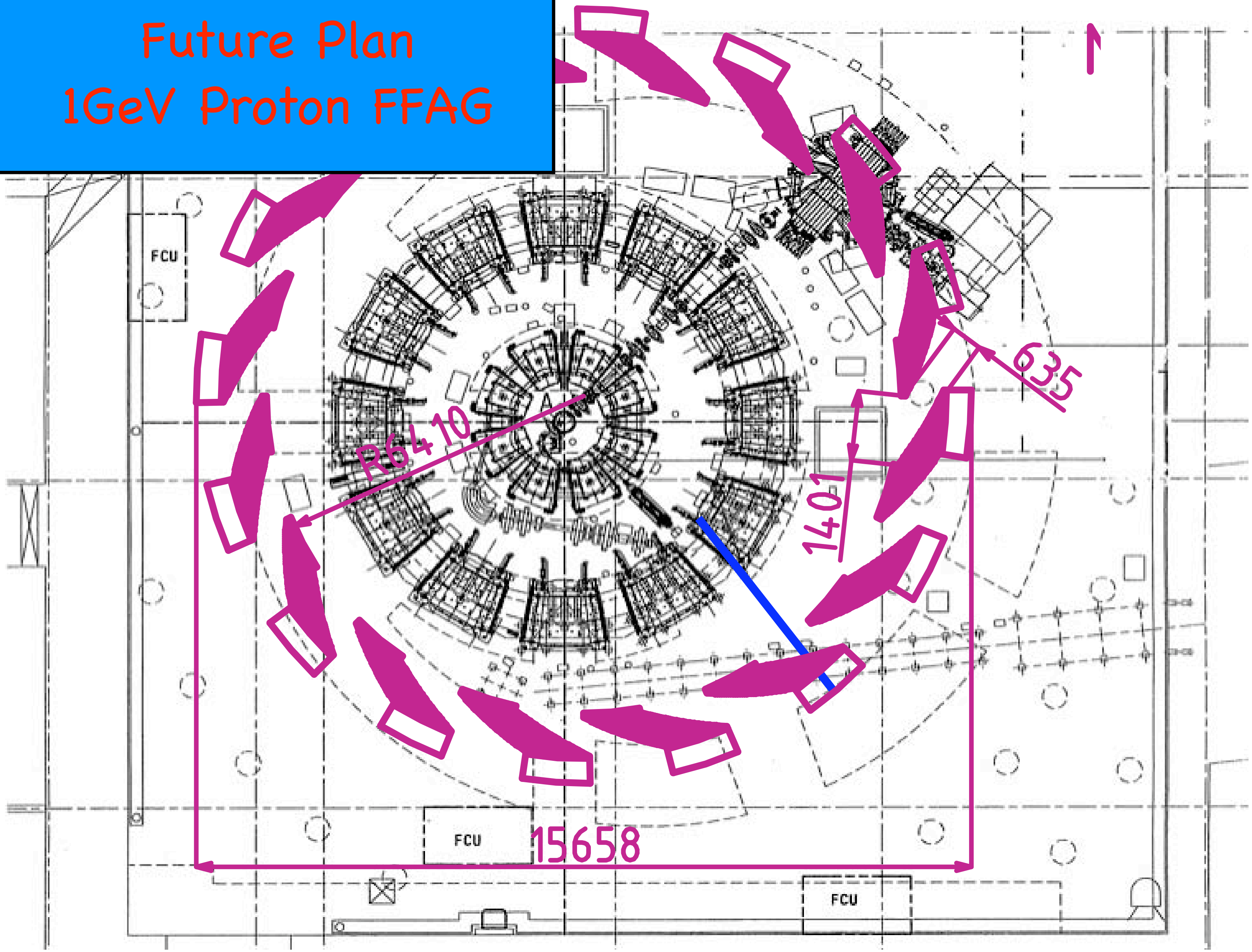
	Injector	Booster	Main
E_{inj}	100 keV	2.5 MeV	20 MeV
E_{ext}	2.5 MeV	20 MeV	150 MeV
Lattice type	Spiral	Radial DFD	Radial DFD
# of cells	8	8	12
Acc. scheme	Induction	RF	RF
k	2	2.45	7.5
coil/pole	coil	pole	pole
p_{inj}/p_{ext}	5.00	2.84	2.83
r_{inj}	0.60 m	1.17 m	4.54 m
r_{ext}	0.99 m	1.65 m	5.12 m

FFAG complex for ADS at KURRI




The day of proton injection to the reactor is close at hand.
Injector : completed
Booster : completed
Main ring : under commissioning
Beam line to reactor : completed
to the reactor

Future Plan
1GeV Proton FFAG



FFAG based neutron source
for Boron Neutron Capture Therapy (BNCT)

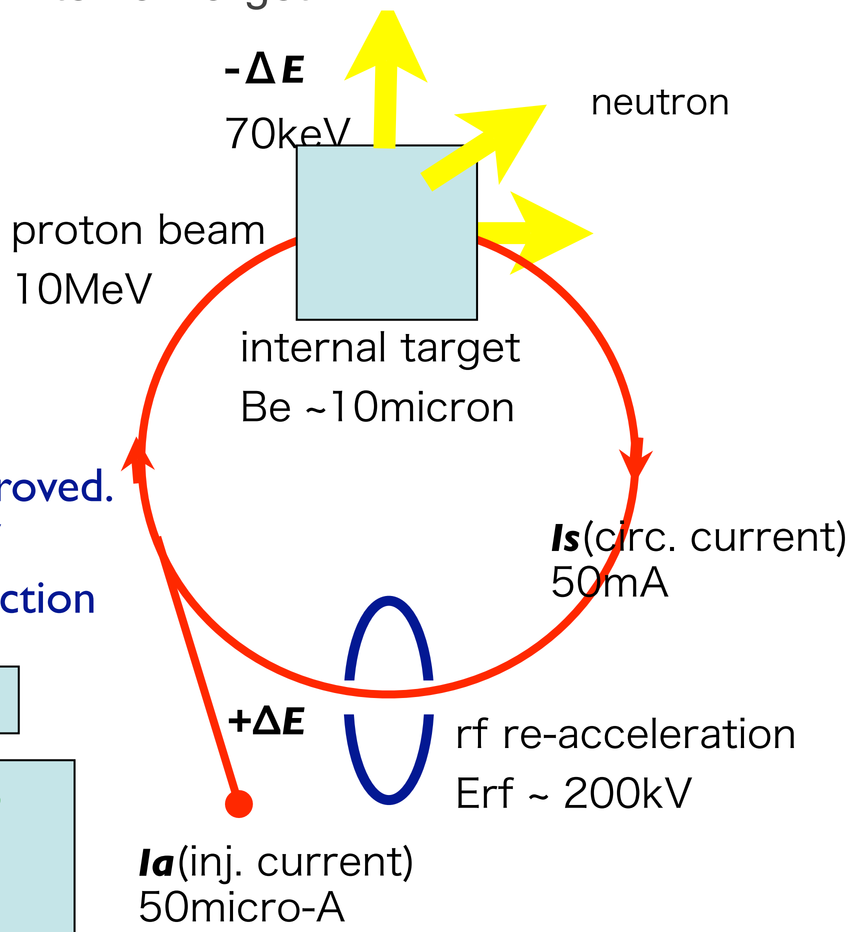
FFAG based neutron source for BNCT

- ERIT : Emittance-energy Recovery Internal Target
  - FFAG-ERIT scheme
    - internal target
    - energy loss
      recovered by rf
    - emittance growth
      ionization cooling
    - large acceptance
      FFAG(scaling)
    - target
      heat loss 1-2kW

Project was approved.
2005-2007
Under Construction

Ia=Is/Nt, Nt=1000turns

Need large momentum acceptance! -> FFAG



BNCT with FFAG-ERIT

Injector(RFQ + IHDTL)

Full energy injection

H^- kinetic energy	10 [MeV]
Average beam current	~ 45 [mA]
Repetition	>1 [kHz]

FFAG ring

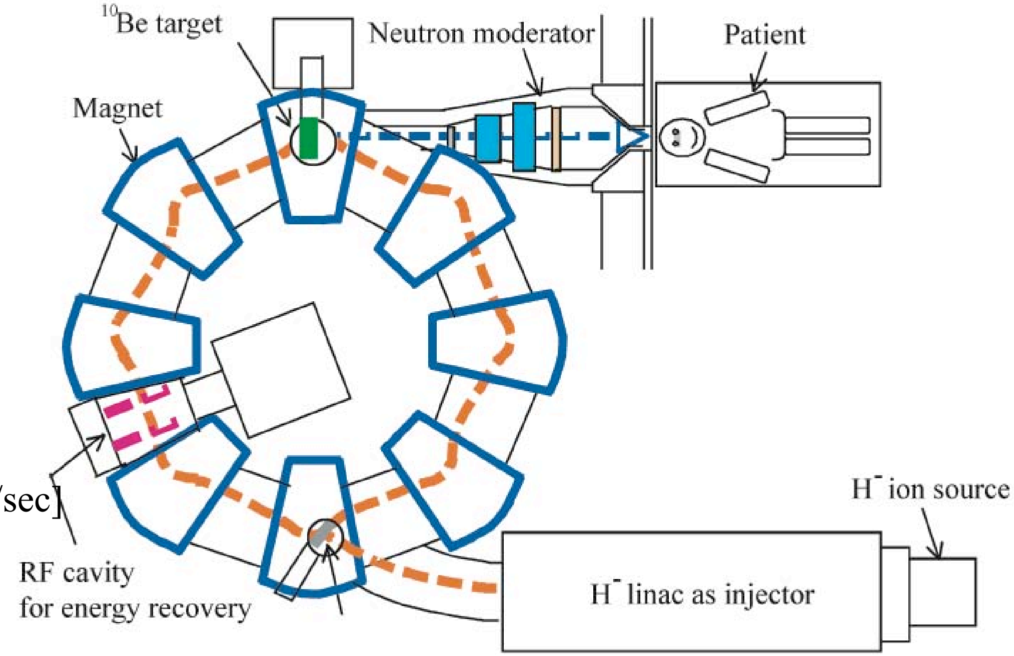
H^- injection	
proton kinetic energy	10 [MeV]
Average beam current	~ 45 [mA]

ERIT system

Turn number	> 1000 turn
Internal target thickness	~ 5 [mm]
Neutron beam intensity	> 10^9 [n/cm^2/sec]

RF cavity

RF voltage	> 200 [kV]
Harmonic num.	~ 5



Under construction at KURRI.

Neutron beam would be provided in 2007.

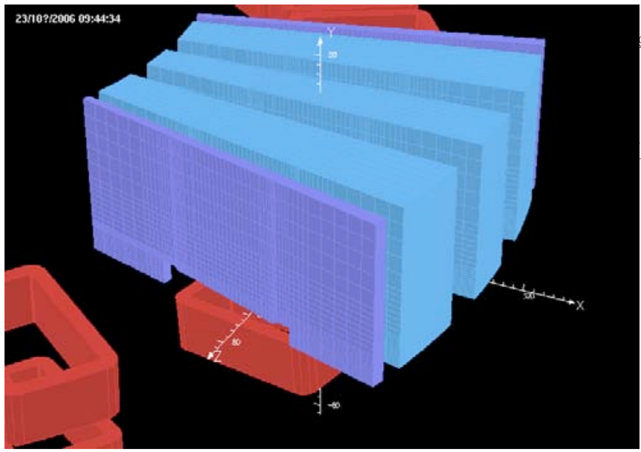
FFAG-ERIT : radial-sector scaling FFAG

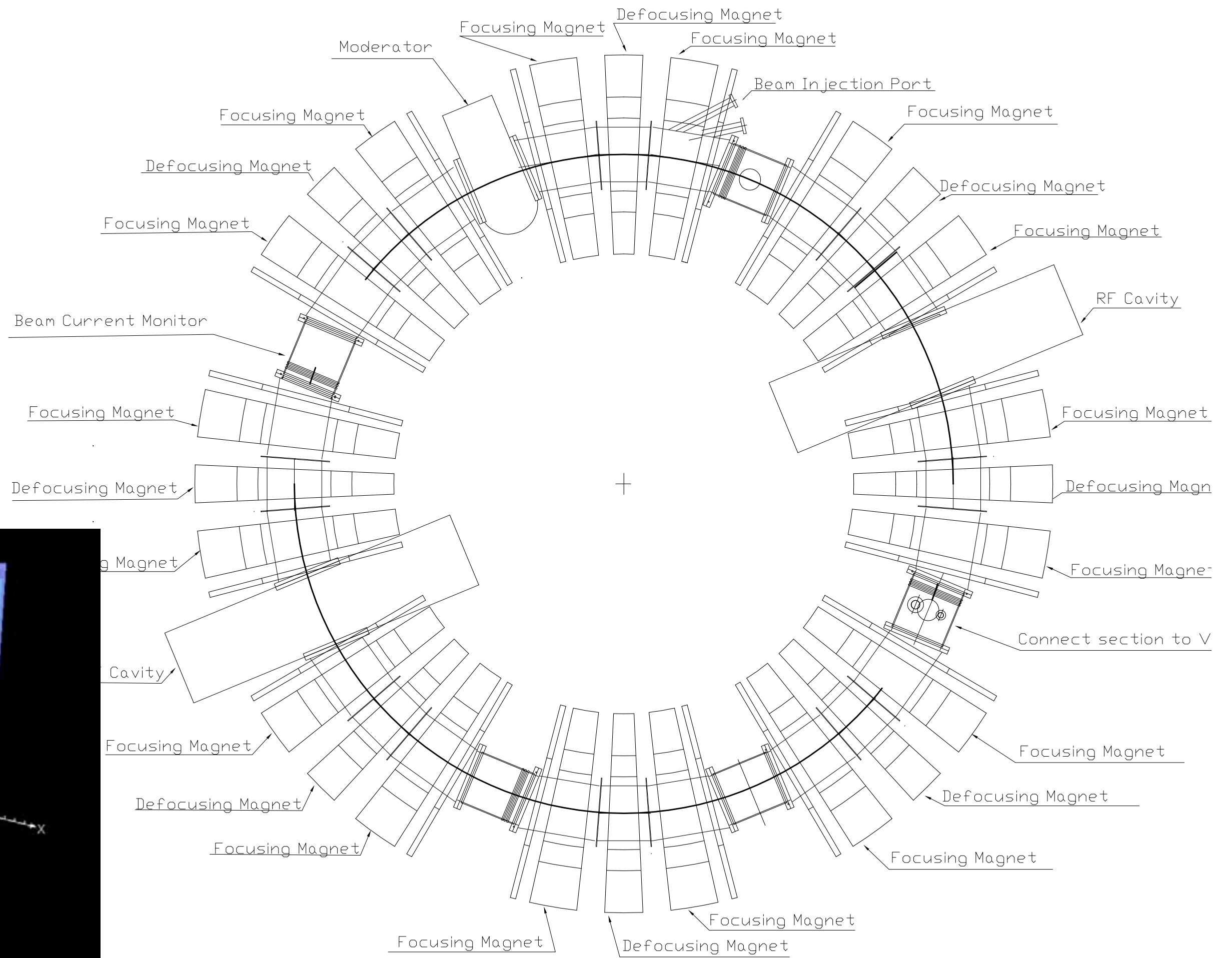
N = 8
FDF lattice
F-Mag. = 6.4[deg],
D-Mag. = 5.1 [deg],
F-D gap 3.75[deg],
F-Clamp gap = 1.9[deg],
Clamp thick = 4[cm]
Mean radius = 2.35[m]

11MeV proton beam

$\nu_x \sim 1.75, \nu_y \sim 2.23$

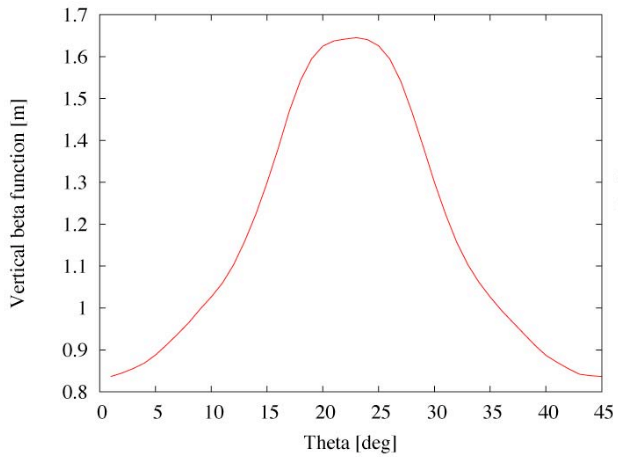
FD ratio ~3

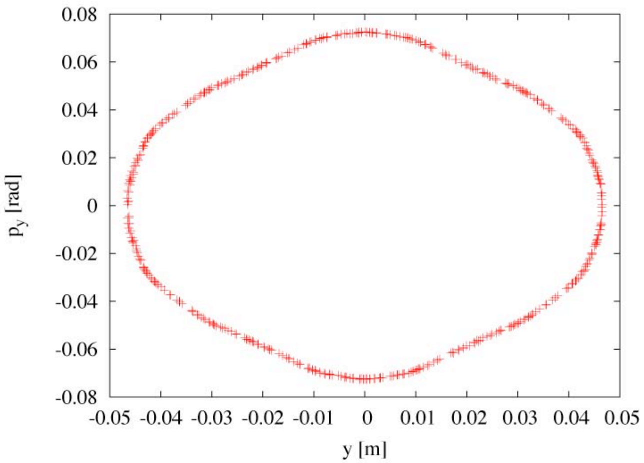




FFAG-ERIT : Vertical beta function & acceptance

Tracking results used TOSCA field.



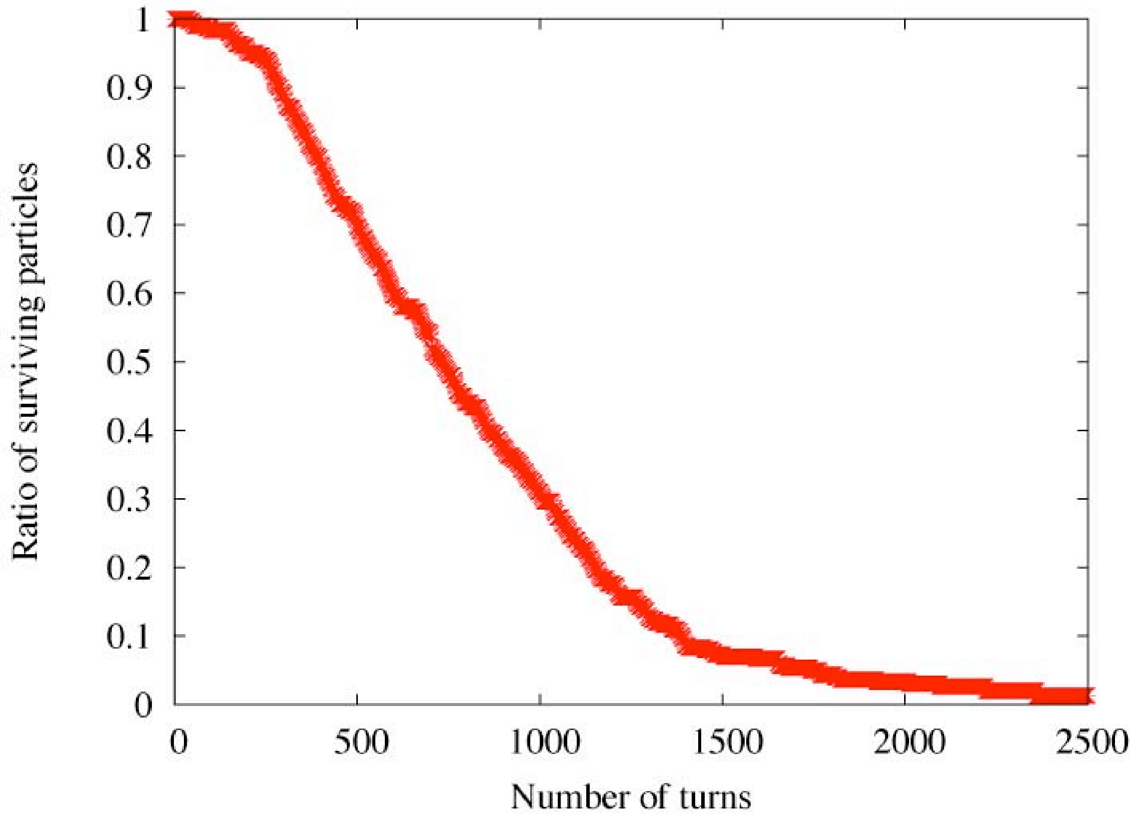


Vertical beta function@target ~ 0.83 [m]

Vertical acceptance ~ 3000π [mm-mrad]

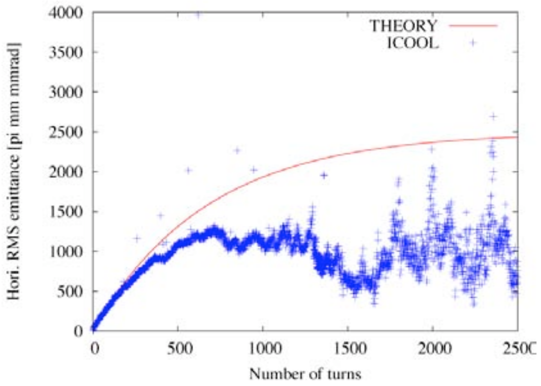
(Horizontal acceptance > 7000π [mm-mrad])

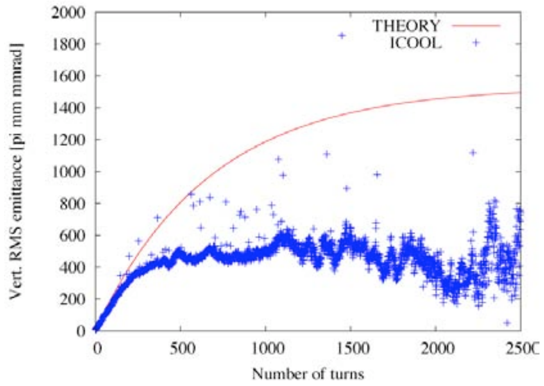
FFAG-ERIT : Surviving turn number

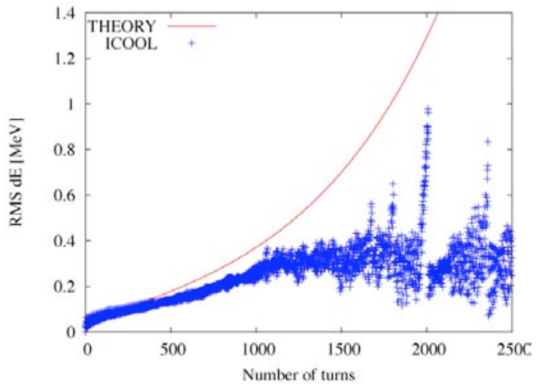


Mean surviving turn num.   810 turns

FFAG-ERIT : RMS emittance and energy spread







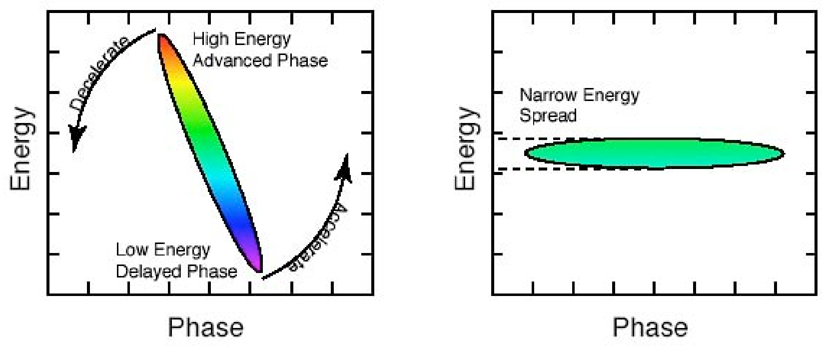
An analytical solution and the simulation results are corresponding well while beam loss is few.

FFAG as a phase rotator
for the mu-e conversion experiment ; PRISM

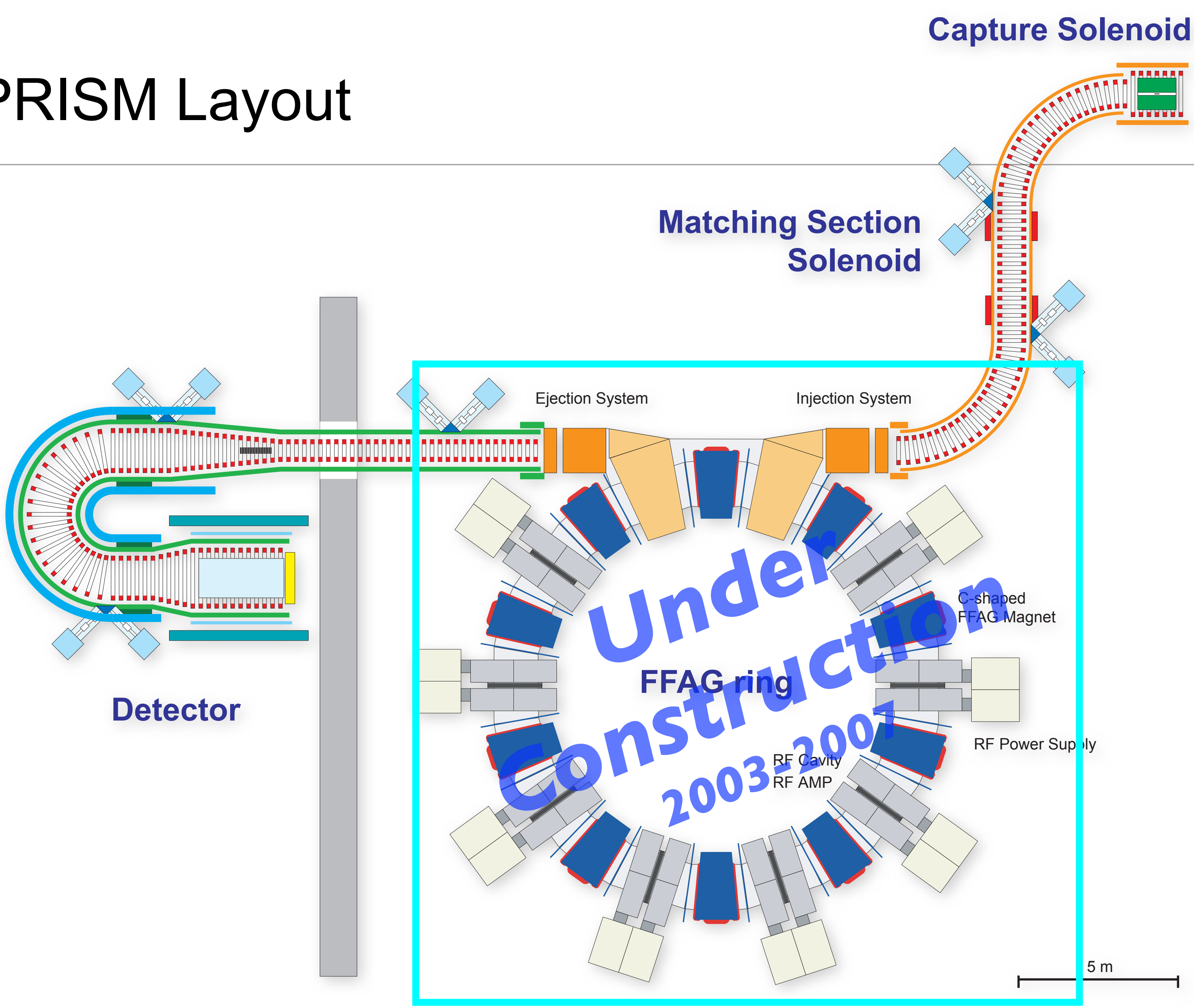
PRISM : Phase Rotated Intense Slow Muon source

- 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 Layout



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

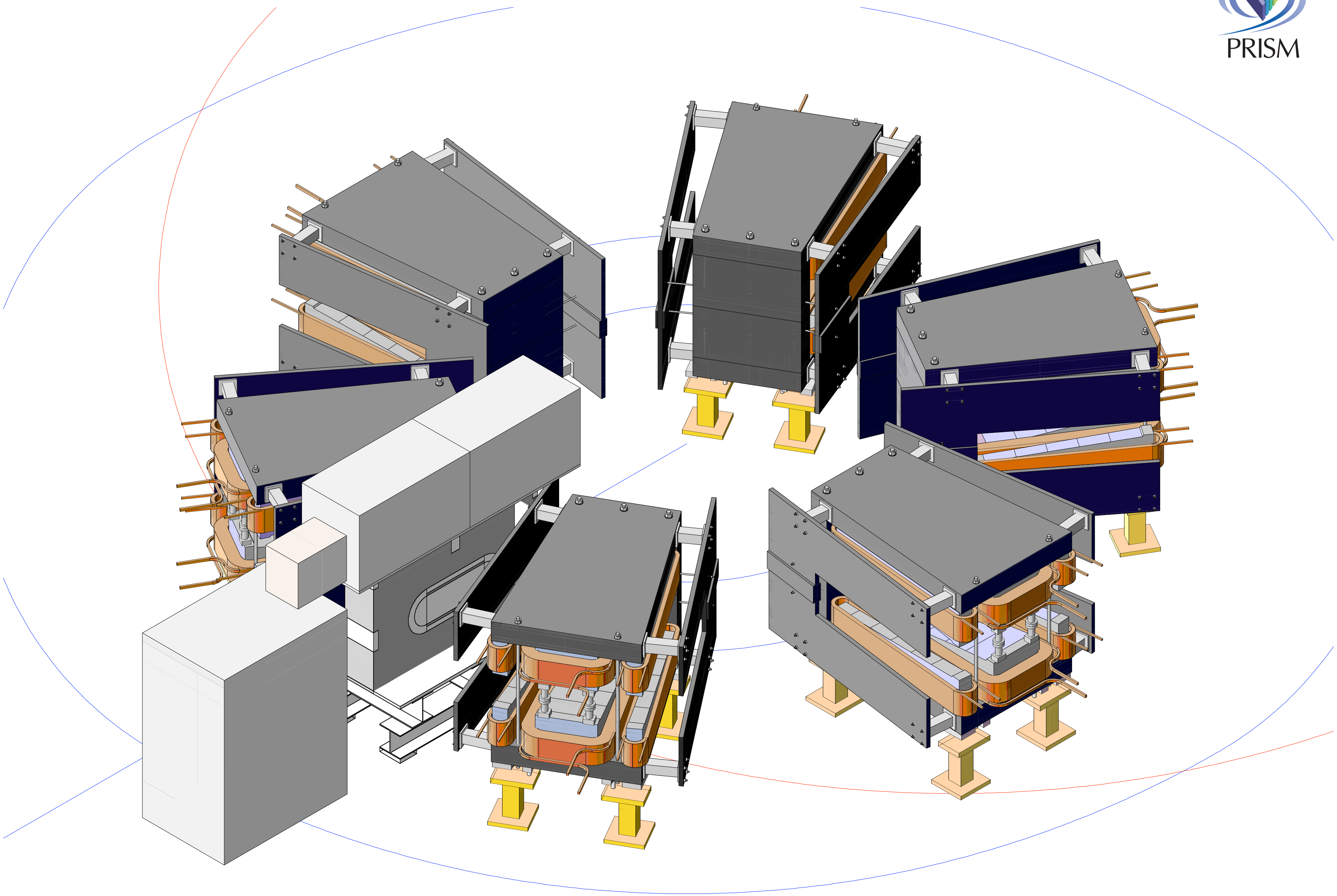
10-cell FFAG ring ----> 6-cell FFAG ring

Status and Schedule of PRISM-FFAG

- Beam optics design : done
- RF R&D : done, 170kV/m with sinusoidal wave @ 5MHz is expected.
- Construction of magnets
  - -2006/03 : 3 magnets: done
  - -2007/05 : 3 magnets: coming soon
- Field measurement for the first 3 magnets : done and in analysis
- Beam dynamics study using 1 cell magnet : in preparation, will start from Feb.?
- R&D for high-gradient sawtooth RF : in progress
- Construction of FFAG-ring : 2007
- Demonstration of phase-rotation using 6-cell ring with alpha particles : 2007

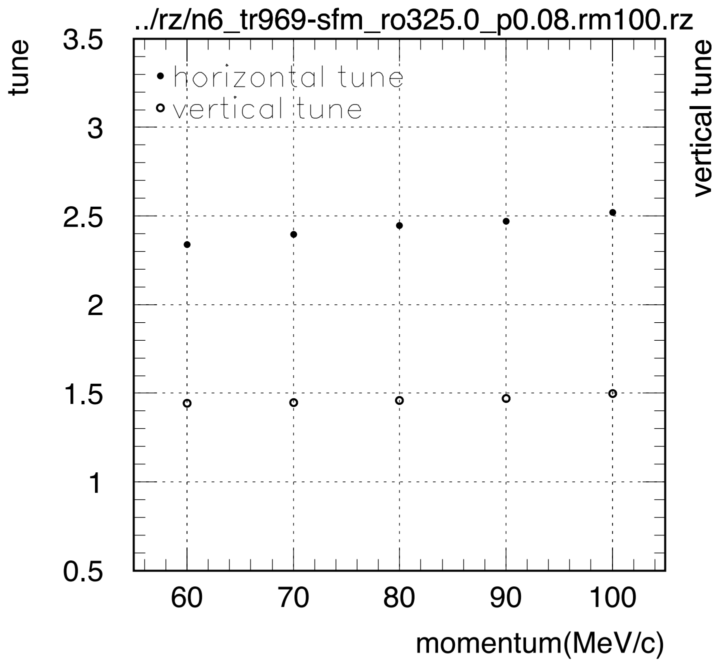
Demonstration of Phase rotation using 6-cell FFAG ring

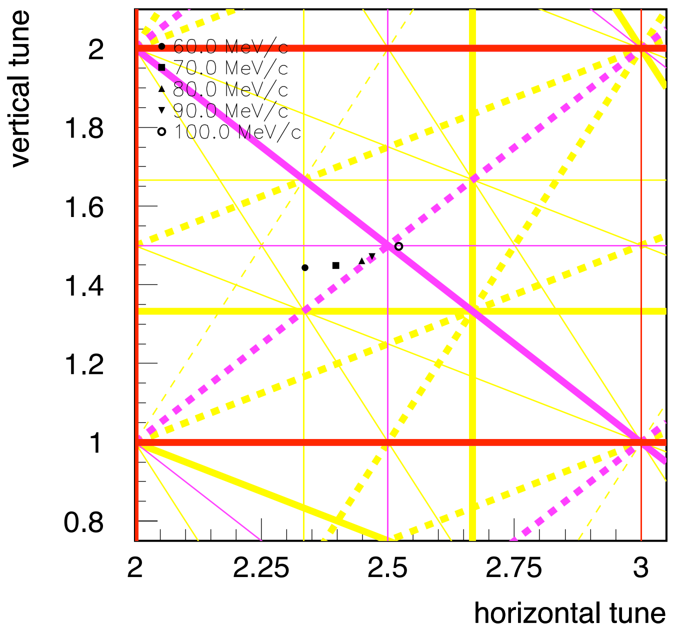
- use 6-cell ring instead of 10-cell full PRISM-FFAG ring.
- inject alpha particles to the ring
    - 241-Am 5.48MeV(200MeV/c)
    - degraded to 80MeV/c
    - collimate for small eminence beam



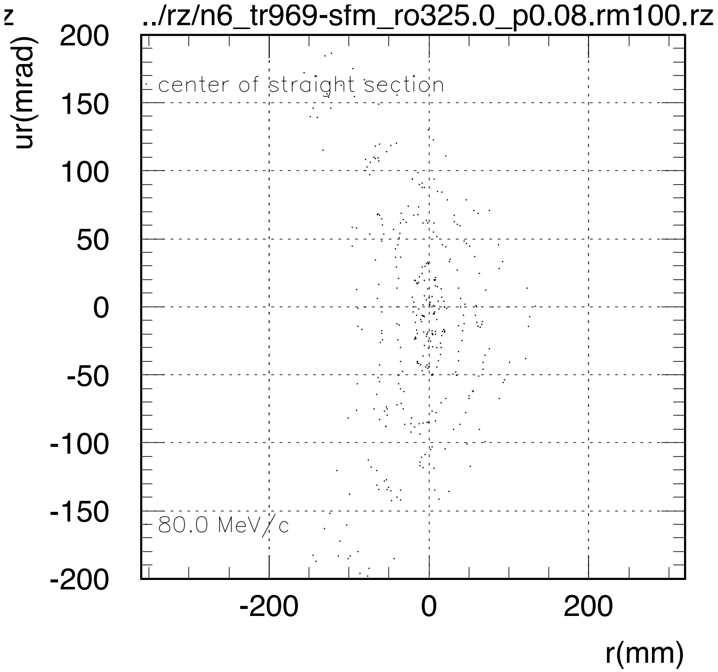
PRISM

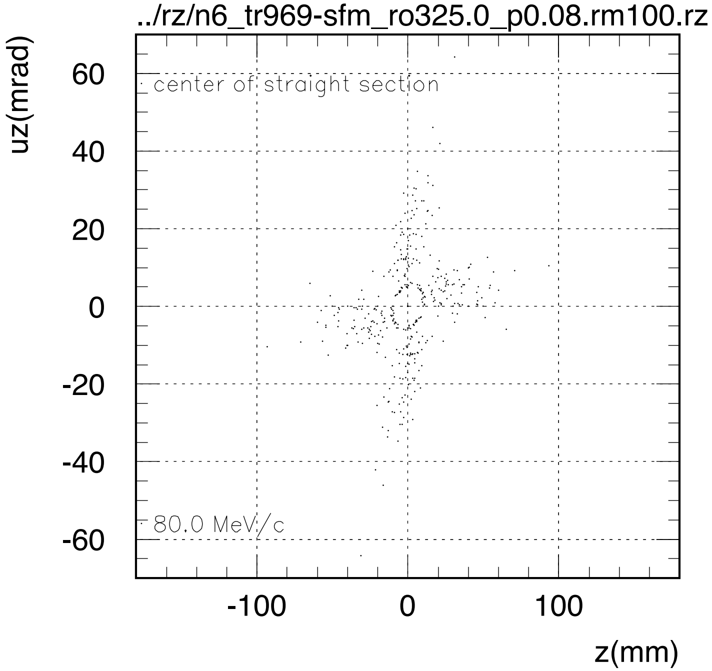
Tune Diagram of 6-cell FFAG





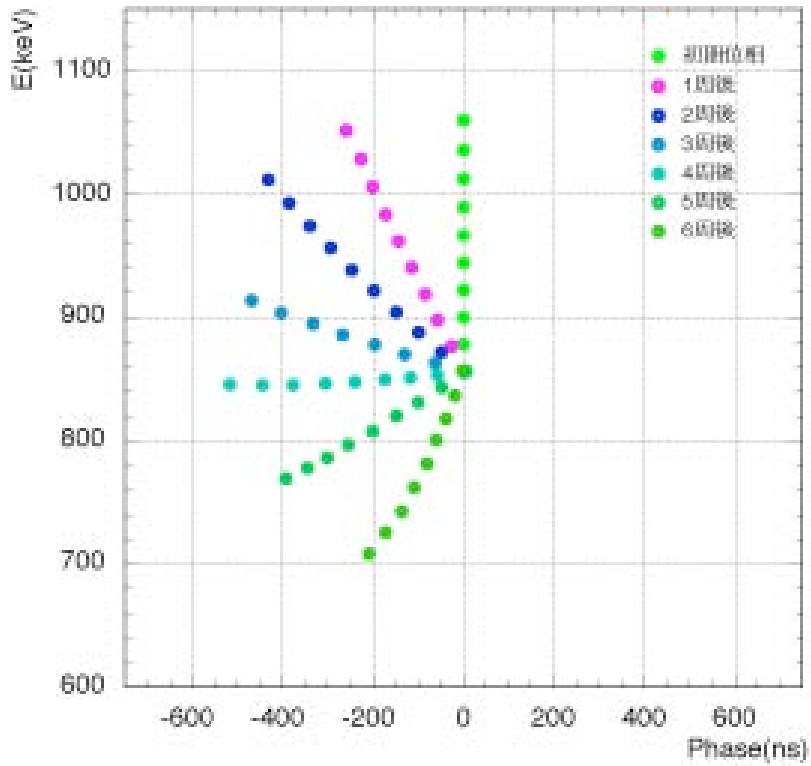
Phase Space of 6-cell FFAG



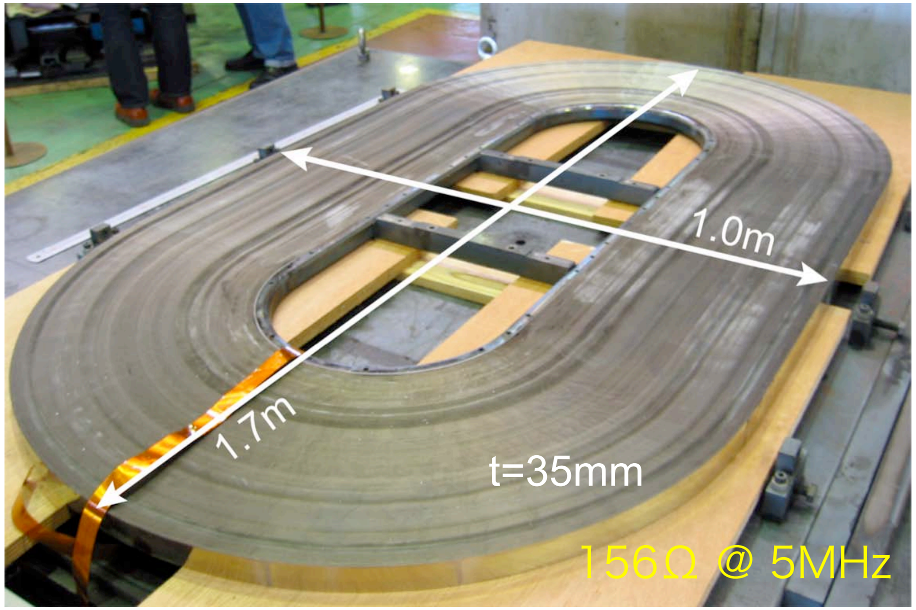


Requirements on RF for the study

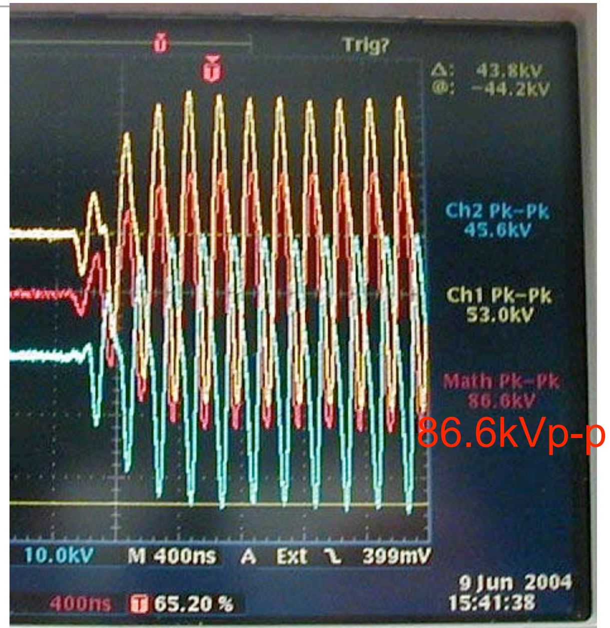
- Large aperture cavity
- Vpp=30kV at 1MHz (100kV/m)
- h=3 (Trevo.=3.18us for 80MeV/c alpha)
- sawtooth is better



RF Cavity for PRISM-FFAG



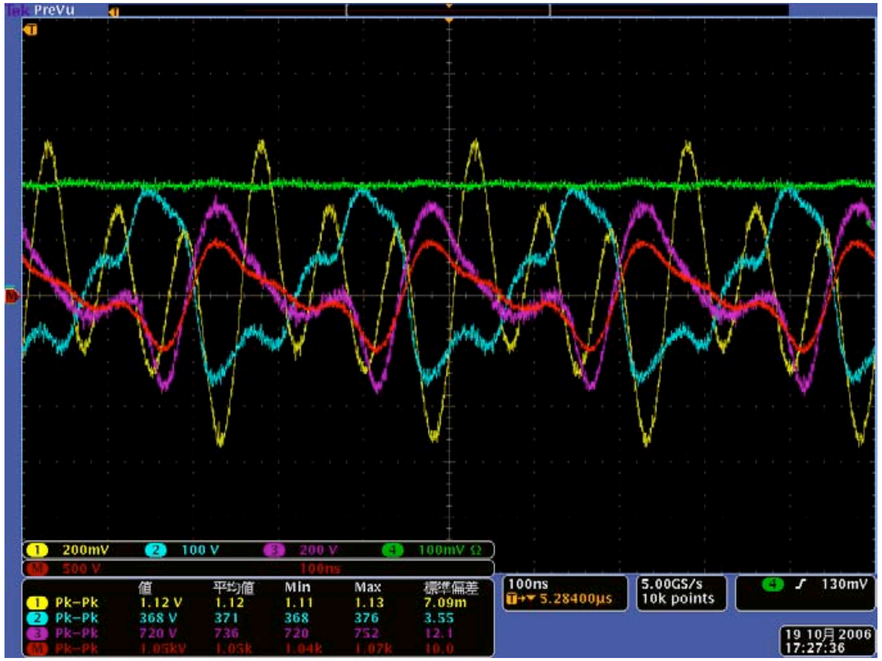
RF AMP R&D



43kV/gap
w/ 734Ω dummy cavity
@5MHz

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

Towards to the high voltage sawtooth



underway

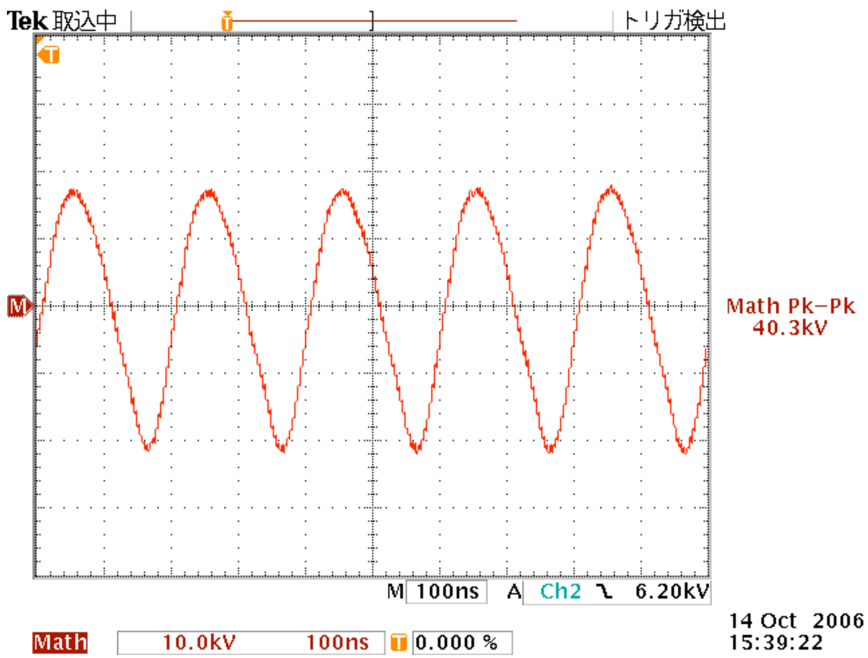


Figure 16: Image-16: Math(red)=gapB-gapA, wave=sawtooth01.csv with Atte.=8dB.

Muon Acceleration with Scaling FFAG using Harmonic Number Jump

Muon Acceleration with FFAG Accelerator

- Scaling FFAG
  - advantages
    - *no resonance crossing : zero chromaticity*
    - *large dynamic aperture*
  - problems (issues)
    - *variable rf frequency : broad-band (low frequency & low field)*
    - *not small beam pipe (may not be an issue)*
- Non-scaling FFAG
  - advantages
    - *rf acceleration : constant rf frequency (high frequency & high field)*
    - *small beam pipe : small momentum compaction*
  - problems (issues)
    - *resonance crossing*
    - *time of flight (path length) for large beam amplitude : cascade rings*

Scaling FFAG with HNJ(harmonic number jump) Acceleration

- Scaling FFAG + HNJ acceleration
  - Harmonic Number Jump(HNJ) acceleration
    - *const. rf frequency --> high frequency & high field*
  - Higher frequency (200-400MHz) rf cavity : good matching -> Phase Rotation & non-scaling FFAG
- Scaling FFAG with HNJ for low energy (5-10GeV) muon ring as an injector of non-scaling FFAG
- Scaling FFAG with HNJ for high energy (10-20GeV) ring

HNJ Acceleration

- Revolution period for n-th turn

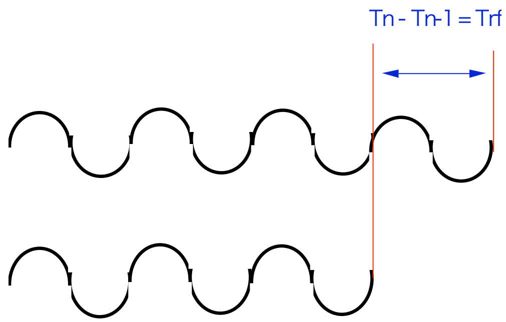
$$\left(\frac{T_n}{T_1}\right) = \left(\frac{C_n / v_n}{C_1 / v_1}\right)$$

  - C: circumference, v: particle velocity

- Scaling FFAG

$$\frac{C_n}{C_1} = \left(\frac{p_n}{p_1}\right)^{\frac{1}{k+1}}$$

- For muon acceleration (v~c)



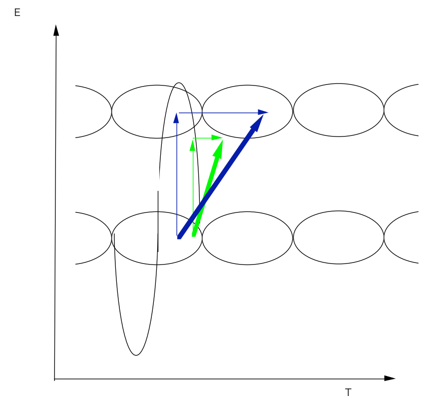
Tn - Tn-1 = Trf x m

  - When k increases, or ring size decreases,
    - *No. of turns decreases.*
    - *Energy gain/turn increases.*
  - Need optimization!

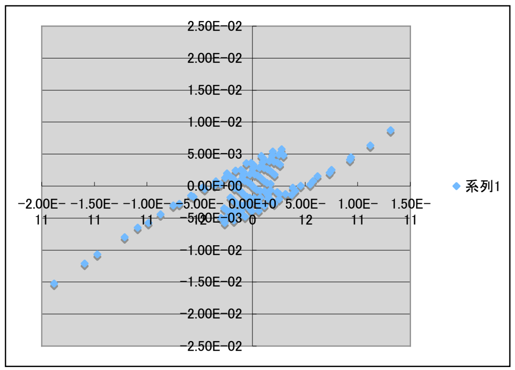
$$\frac{C_n}{C_1} = \frac{h_n}{h_1}, \quad p_n = p_1\left(\frac{h_n}{h_1}\right)^{k+1}, h_n = h_1 + n \times m$$

Issues of HNJ

- Phase acceptance
  - Smaller for HNJ   cf. synchronized acceleration
  - Because energy gain/turn is so large for HNJ that phase slip/turn should be 2π. If stable phase is away from $\pi/2$, phase slip/turn should be much less than 2π.

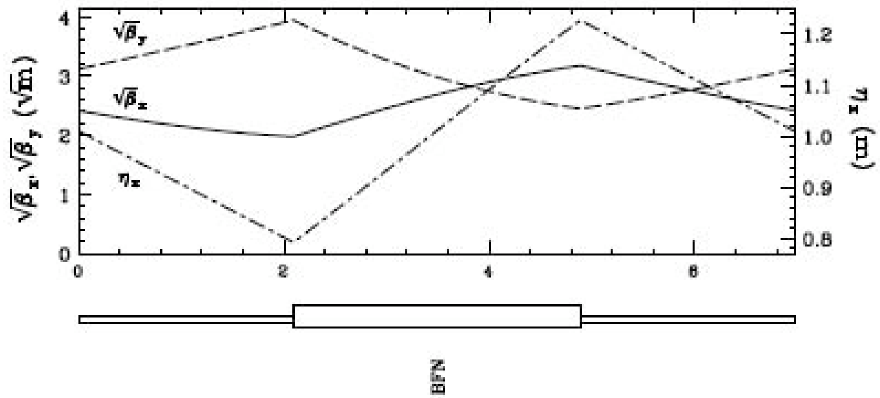


- Non-linear source dynamic aperture problems in longitudinal direction
  - Sinusoidal rf field contains non-linear components.
  - Synchroton tune is high enough to see non-linear resonances. mQs=n



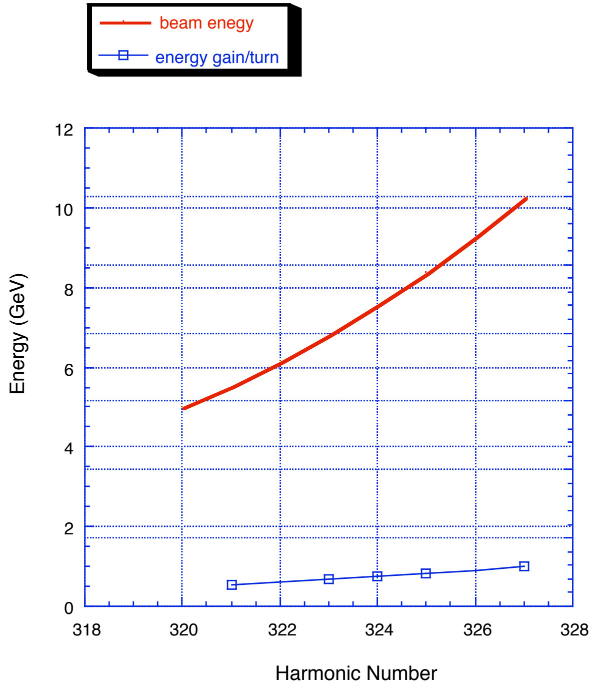
5-10GeV scaling FFAG spiral sector - design example

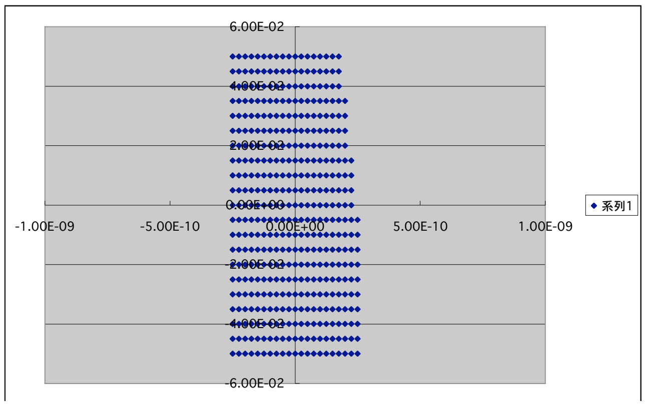
- Ring parameters
  - r=40m
  - N=32cells
  - spiral angle: 74degree
  - Bmax ~2.1T (p.f.=0.4)
  - k=38
  - Orbit excursion
    - *71.7cm*
  - Beam size(half, dp/p=0.03) at 10GeV
    - *H: 4.3cm+3.0cm=7.3cm, V=5.2cm @s.s.*
    - *H: 5.2cm+3.6cm=9.3cm, V=6.9cm @magnet*

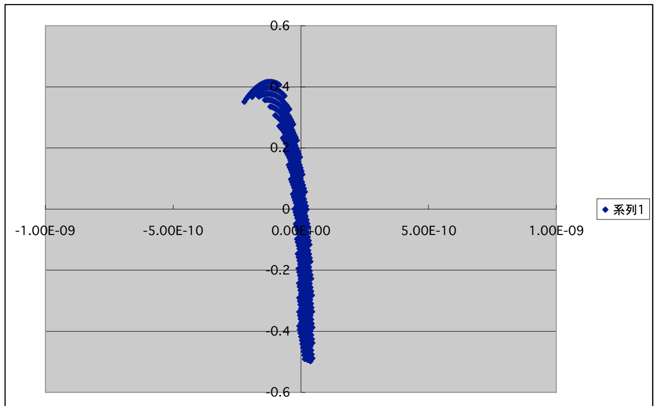


Spiral FFAG 5-10GeV

- **Parameters**
  - r=40m
  - k=38
  - rf parameters
    - *h=320*
    - *f=400MHz*
    - *fai_s=2 π /3*
    - *18.8MV/m:4-cell cavity*

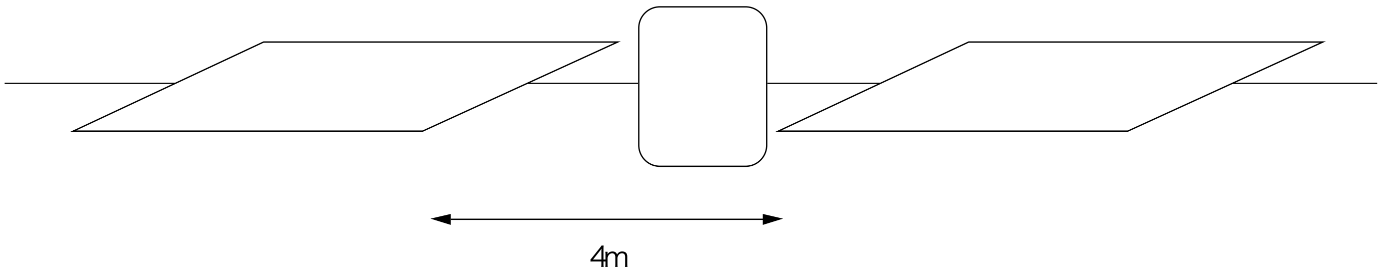






Spiral FFAG 5-10GeV

- Lattice
  - almost satisfied but more optimaization is needed.
    - *k-value:lower, Bmax:lower, packing factor, circumference etc.*
- HNJ acceleration
  - seems to have enough acceptance
  - frequency of rf cavity
    - *400MHz --->200MHz (depends on lattice design)*
  - No. of turns: should be larger >10 turns (now 7turns)
    - *reduce rf voltage 18.8MV/m --> 15MV/m*
  - Increase ring radius and reduce k-value



Summary

- Three projects on scaling FFAGs are in construction/commissioning phase. All of these projects will be completed in JPY2007.

	Beam	Site	
FFAGs for ADSR	proton	KURRI	- JPY2007 (only for FFAGs)
FFAG-ERIT	proton	KURRI	- JPY2007
PRISM-FFAG	muon	Osaka U.	- JPY2007

- Scaling FFAG with HNJ acceleration for muons looks looks like good. But more tracking study and hardware R&Ds are needed.