New project and results from FFAG accelerators in Japan

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History of FFAG Proton Accelerator

- 1953: Basic concept by Ohkawa

  Proton FF AG accelerator was not successful until recent

  difficulty in fabricating RF cavity with variable frequency & high gradient field

- 1998 Development of RF cavity using Magnetic Alloy

  Grant-in-Aid for Scientific Res. by MEXT Y. Mori, KEK

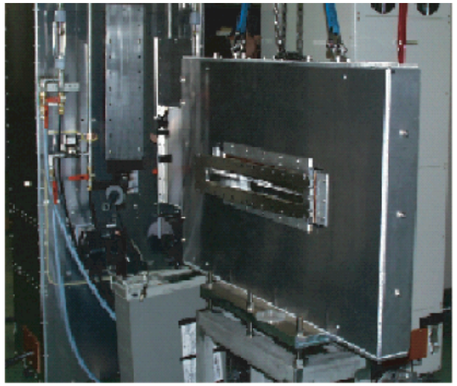
- 2000 Development of Proton FFAG Accelerator

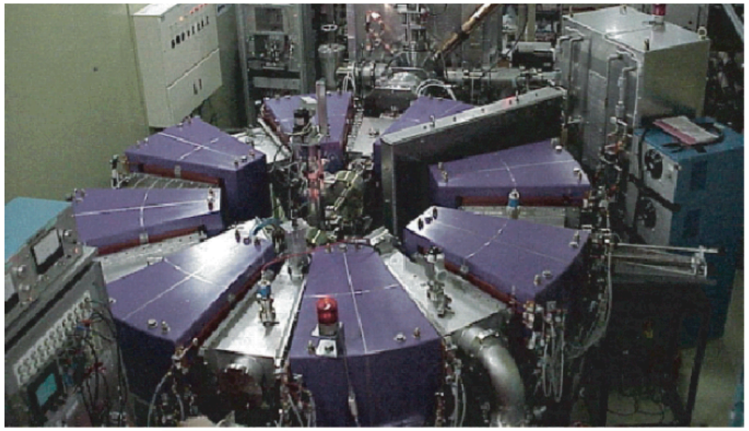
  Grant-in-Aid for Scientific Res. by MEXT: Y. Mori, KEK

- 2005 Development of 150MeV multipurpose FFAG accelerator

  100Hz Operation!

  Grant-in-Aid for Creative Basic Res.





Advantage of FFAG

- **Fast acceleration**

  DC magnetic field allows the beam acceleration only by RF pattern. No needs of synchronization between RF and magnets.

- **High average current with large repetition rate and modest number of particles in the ring**

  Space charge and collective effects are below threshold.

- **Large acceptance**

  Transverse (hor.)>10,000mm.mrad

  Longitudinal dp/p>10%

FFAG R&D Activities in Japan (1)

- **KEK**

  - POP FFAG 0.05-0.5MeV(1MeV):2000

    proof-of-principle, scaling(DFD),proton, MA rf cavity

  - 150MeV FFAG :2006

    scaling(DFD),prototype for particle therapy, 100Hz

- **PRISM project**

  - Mu-e conversion:

    Muon phase rotation ring

- **Mitsubishi Elect. Co.**

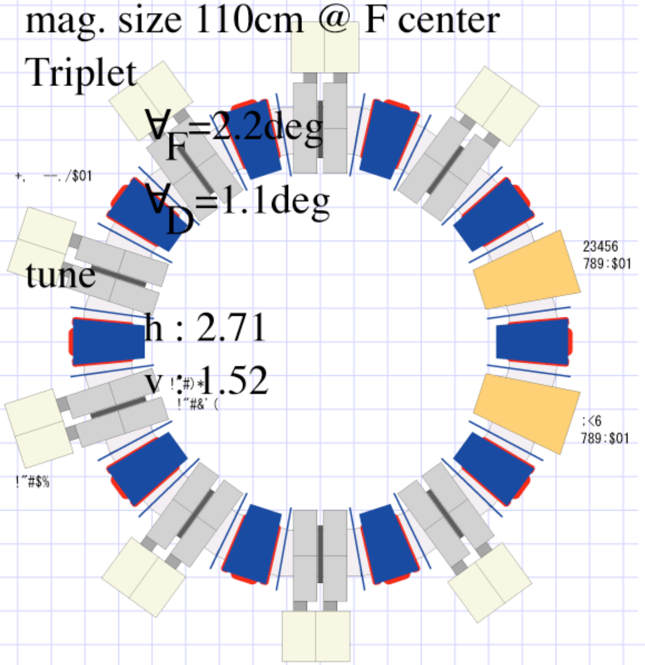
  - table-top electron accelerator

    X-CT:FFAG+synchrotron hybrid

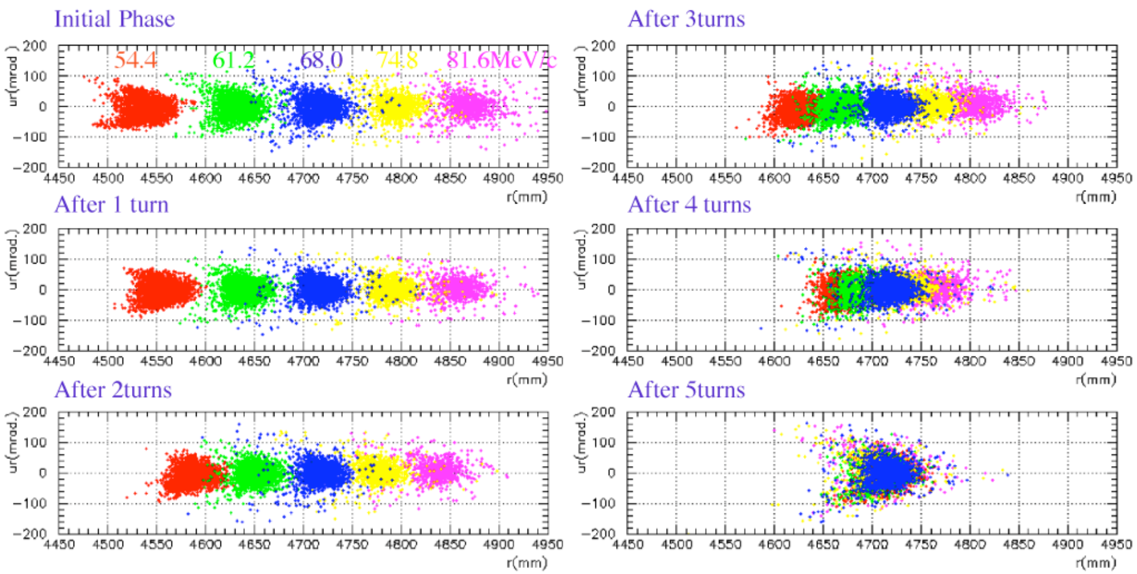
PRISM project

N=10
k=5(4.6-5.2)
F/D(BL)=
r0=6.5m for 68MeV/c
half gap = 17cm
mag. size 110cm @ F center
Triplet
$\forall_F$=2.2deg
$\forall_D$=1.1deg

tune
h : 2.71
v : 1.52



Phase Rotation Simulation: Horizontal Phase Space



FFAG R&D Activities in Japan (2)

- **Kyoto Univ., RRI**

  - ADS(Accelerator Driven System) project, FFAG+Reactor:2007

  3 rings (Injector(2.5MeV spiral), booster(20MeV DFD), main ring(150MeV,DFD)

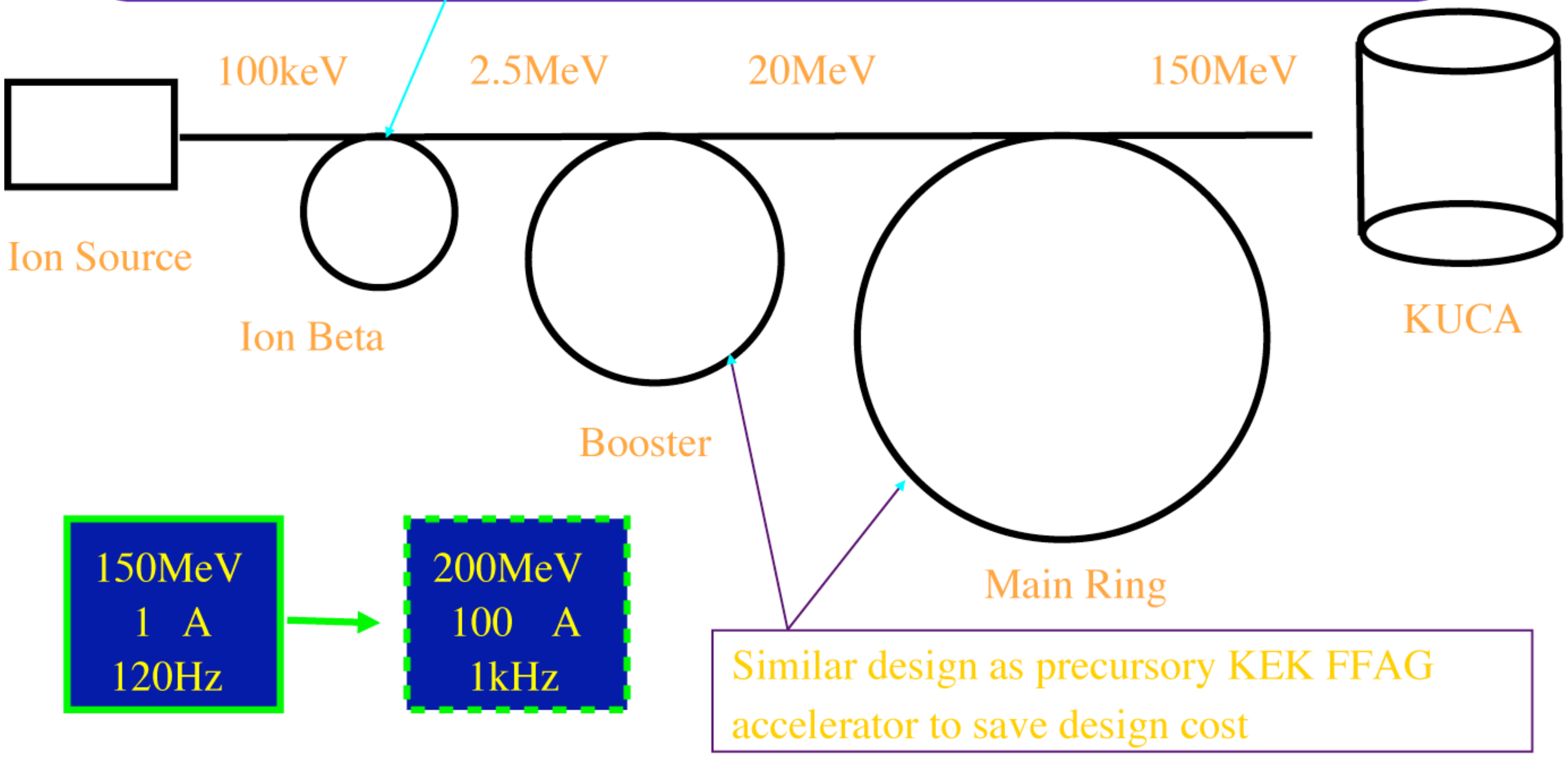
- **NEDO project/site KURRI**

  - ABNS(accelerator-based neutron source) for BNCT (boron neutron capture therapy):2008

  ERIT (emittance/energy recovery internal target): FFAG proton strorage ring + internal target, 11MeV proton+ Be target, ionization cooling

Configuration of FFAG Accelerator Complex (ADS)

- Spiral focusing 1st for ion accelerator in the world
- Acceleration by induction core 1st for ion accelerator in the world
- Magnetic field by multi-coil 1st in the world
- Continuous injection by static field 1st in the world



Layout of FFAG Accelerator Complex (ADS)

Neutron source for BNCT
FFAG-ERIT scheme

Requirements from BNCT(**Boron Neutron Capture Therapy**):
In order to remedy the tumor of $10cm^2$, $2*10^{13}$ neutrons are needed.
If we assume that remedy time is 30 minutes => Flux $\Phi > 10^9/cm^2$ sec.

Accelerator as a neutron source ;
Energy is low, but beam current is very large (I > 40mA [CW])
Technically hard and expensive

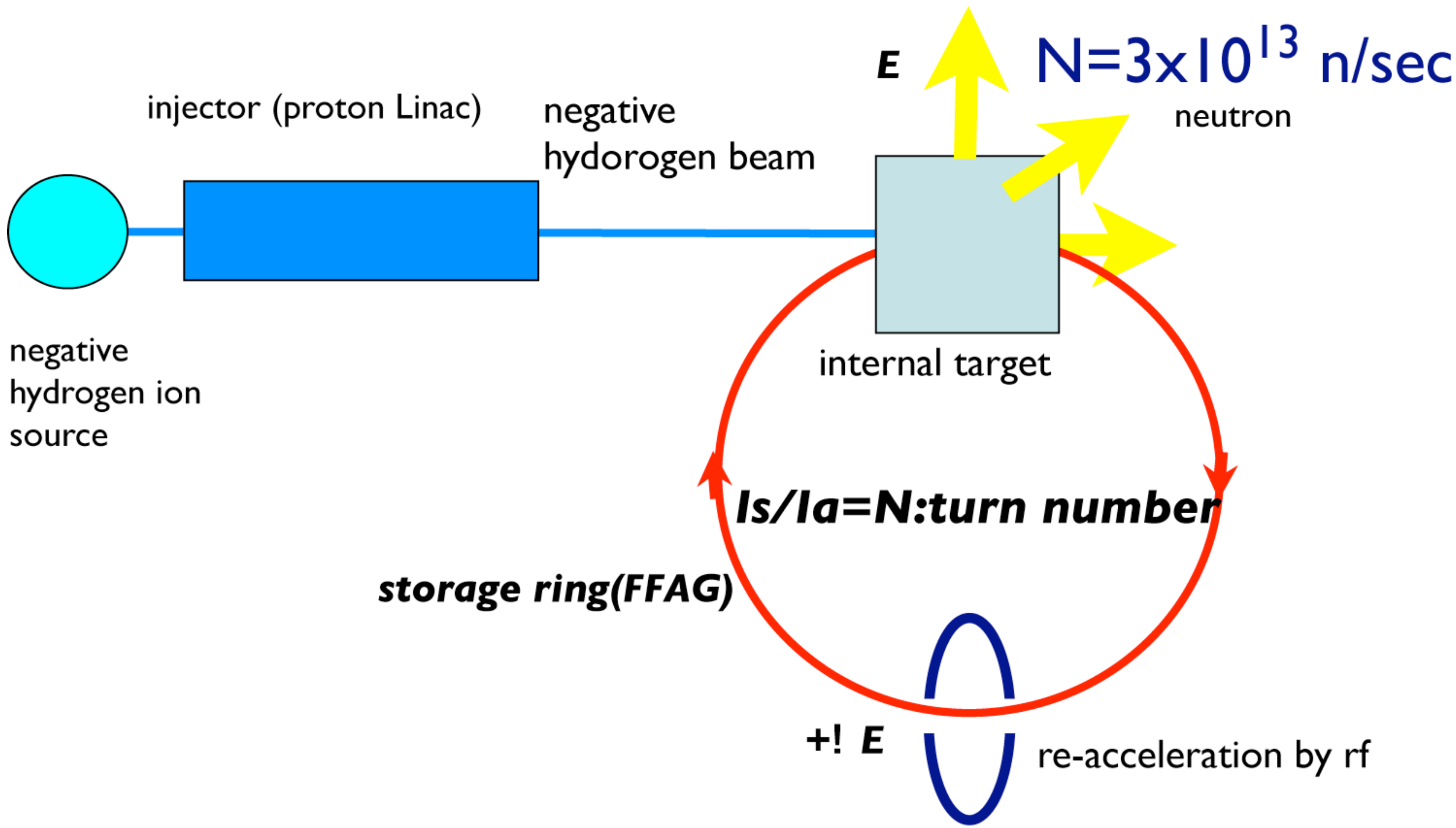
⇓

ERIT : Emittance-Energy Recovering Internal Target

The stored beam is irradiated to the internal target, it generates the neutron in the storage ring. The beam energy lost in the target is recovered by re-acceleration.

Feature of ERIT scheme
Beam current reduced by storage the beam in the ring.

Overview of FFAG-ERIT accelerator system



Requirement performance of FFAG-ERIT

Neutron flax enough for 1 hour treatment $\sim 10^9$ n/cm^2/s

Injector (LINAC) :	
Beam energy	11 MeV
Averaged beam current	70 ~ 75 μA(@ 1000turns storage)
Ion species	H^-
FFAG-ERIT ring :	
Circurated beam current	70 ~ 75 mA
Storage turn num.	500 ~ 1000 turns
Target (Be, 5,10μm) :	
Life time	> 1 month
Moderator :	
γ, fast neutron	Nuclear reactor level

Design issue of FFAG ring

Beam dynamics, Magnet, RF Cavity

Requirement performance (depend on injector beam current)

Storage turn num. **500 ~ 1000 turns**

- Beam dynamics and optics

momentum acceptance	dp/p ~ 5 [%] (full)
transverse acceptance	> 1000 [π mm mrad]
strong beam focusing at target	β_y ~ 0.7 [m] (@target)

- Large aperture magnet

gap height	~ 15 [cm]

- Ring size (to be the compact which can be installed in the hospital)

mean radius (r_0)	~ 2.35 [m]

- RF cavity

frequency	~ 20 [MHz] (h = 6)
rf voltage	> 200 [kV]

Ionization cooling

The rate equation of beam emittance passing through a target material is,

Heating term

Cooling term

Longitudinal

$$\frac{d\langle \sigma_E{}^2 \rangle}{ds} = -2\left(\left.\frac{\partial (dE/ds)}{\partial E}\right|_0 + \frac{dE}{ds}\frac{1}{pc\beta} D \frac{\rho'}{\rho_0} \right) \langle \sigma_E{}^2 \rangle + \frac{d\langle \Delta E^2{}_{rms} \rangle}{ds}$$

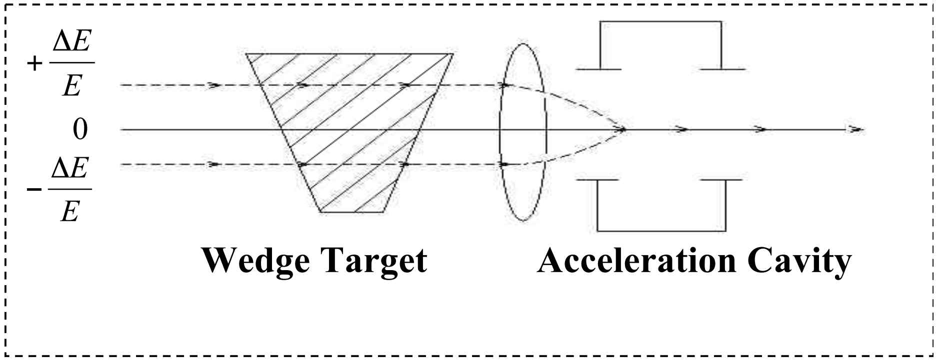
Horizontal

$$\frac{d\varepsilon_x}{ds} = -\frac{1}{\beta^2 E}\frac{dE}{ds}\left(1 - \frac{D\rho'}{\rho_0}\right)\varepsilon_x + \frac{\beta_x E_s{}^2}{2\beta^3 m_p c^2 L_R E}$$

When the wedged target is placed at dispersive point, $\frac{\partial (dE/ds)}{\partial E}$ can be possible.

Vertical

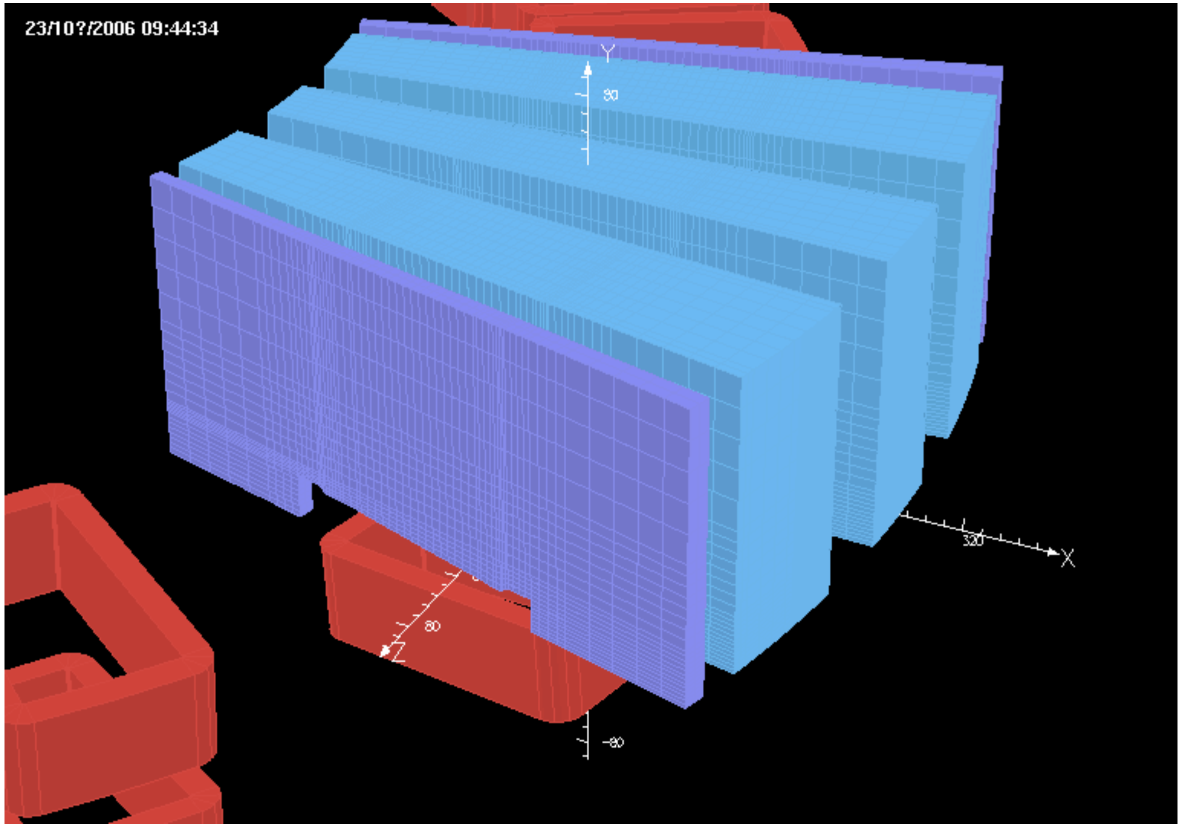
$$\frac{d\varepsilon_y}{ds} = -\frac{1}{\beta^2 E}\frac{dE}{ds}\varepsilon_y + \frac{\beta_y E_s{}^2}{2\beta^3 m_p c^2 L_R E}$$



Magnetic field calculation (TOSCA)

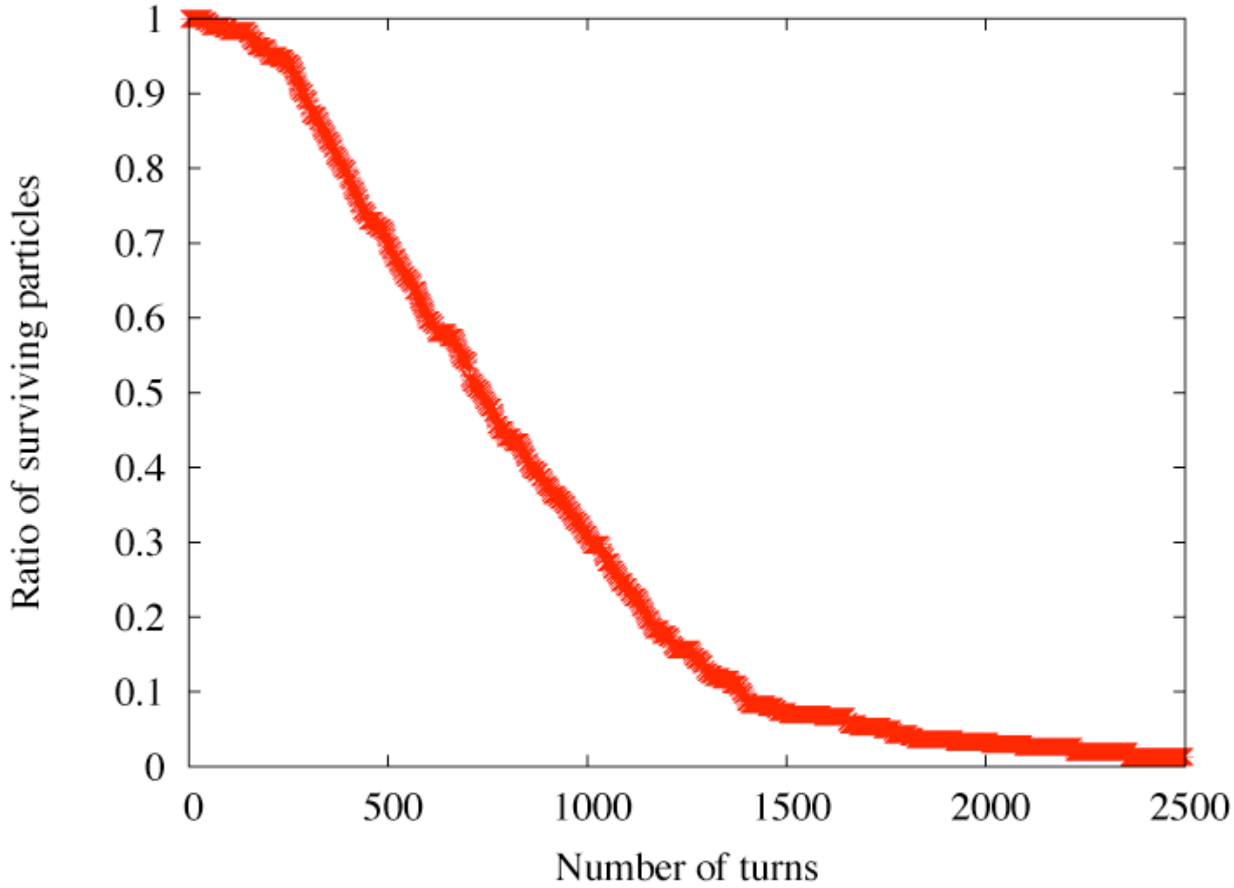
FDF lattice
F-Mag. = 6.4[deg],
D-Mag. = 5.1 [deg],
F-D gap 3.75[deg],
F-Clamp gap = 1.9[deg],
Clamp thick = 4[cm]
Mean radius = 2.35[m]

11MeV proton beam
$\nu_x \sim 1.75$, $\nu_y \sim 2.23$
FD ratio ~3



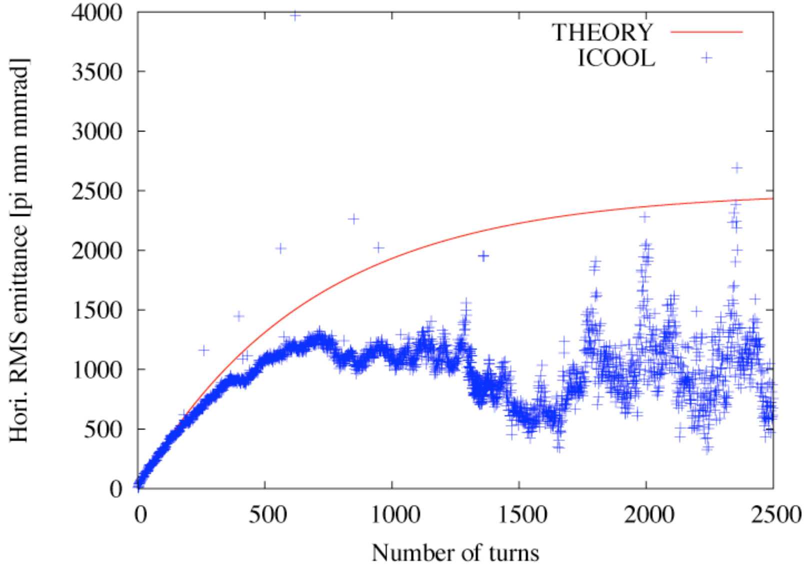
Surviving turn number

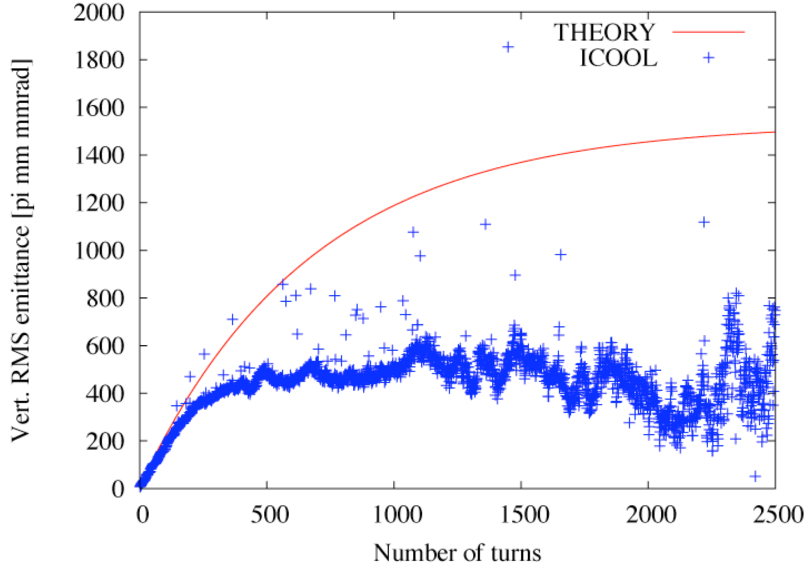
ICOOL (Used TOSCA field map)

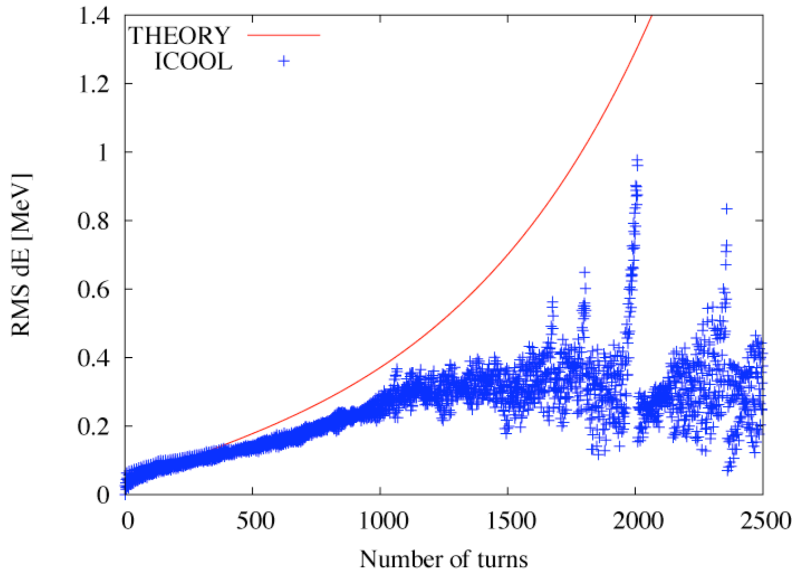


Mean surviving turn num. 810 turns

RMS emittance and energy spread





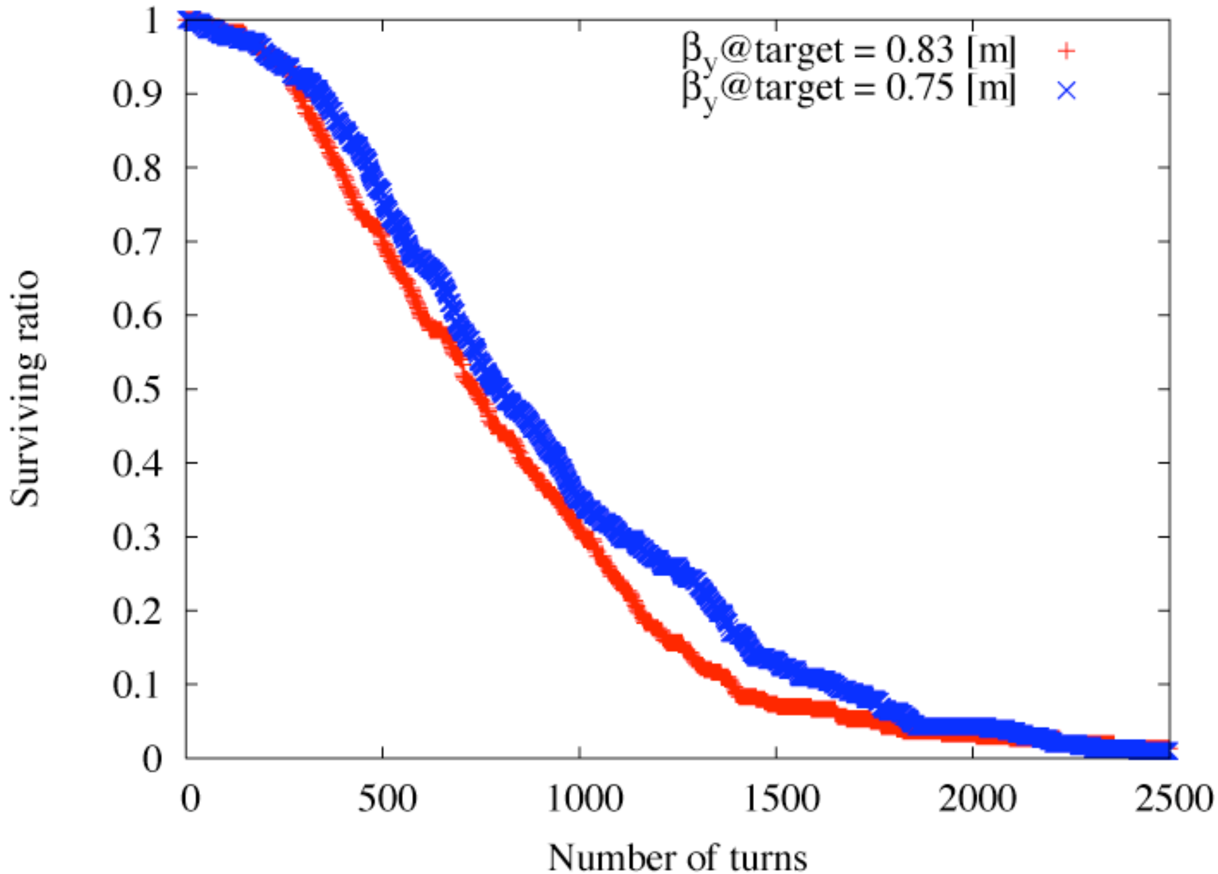


RMS emittance and energy spread v.s. turn number

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

Surviving ratio v.s. Number of turns

Mean surviving turn num. 910 turn



β_y = 0.83[m] : ν_y = 2.22, Mean surviving turn num. 810 turn

β_y = 0.75[m] : ν_y = 2.32, Mean surviving turn num. 910 turn

Summary (FFAG-ERIT)

- Physical design is completed.
- Preparation of infrastructure(water, electricity, etc.) at KURRI is completed.
- Installation of machine is in process at KURRI.