Design process of FFAG-ERIT ring

FFAG09J(2009/11/13)

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Back ground

- Requirements from BNCT(Boron Neutron Capture Therapy)

  It is very difficult to realize an accelerator-based neutron source with external target, because very high beam current(~10mA) is required.

- ERIT(Energy/emittance Recovery Internal Target) scheme

  The ERIT scheme uses an internal target placed in the circulating orbit of a ring. This scheme utilizes the primary beam efficiently since circulating beam particles hit a thin target many times

- Emittance growth in a storage ring

  In ERIT scheme, the beam emittance is increased in 3-directions by multiple scattering and straggling. In this reason, the storage ring require to large acceptance. Huge momentum and transverse acceptance of FFAG is a big advantage to circulate a beam many turns.

  However, the beam emittance growth can be cured by Ionization Cooling. Internal target produces neutrons and the same target is used as material for ionization cooling in ERIT.

Requirements for FFAG storage ring

- Large acceptance

  momentum acceptance dp/p ~ 5 [%] (from RF bucket height)

  transverse acceptance > 1000 [π mm mrad]

- Length of straight section (to install large RF cavity(width 54cm))

  The numbers of sectors is few, length of the straight section is easy to guarantee.

- To be the compact which can be installed in the hospital

  Mean radius (r_0) ~ 2 [m]

Spiral sector type ? or Radial sector type ?

We compared radial sector type with spiral sector type.

Magnet design Method of FFAG

1. Basic parameters of FFAG ring has been determined with the linearized model.

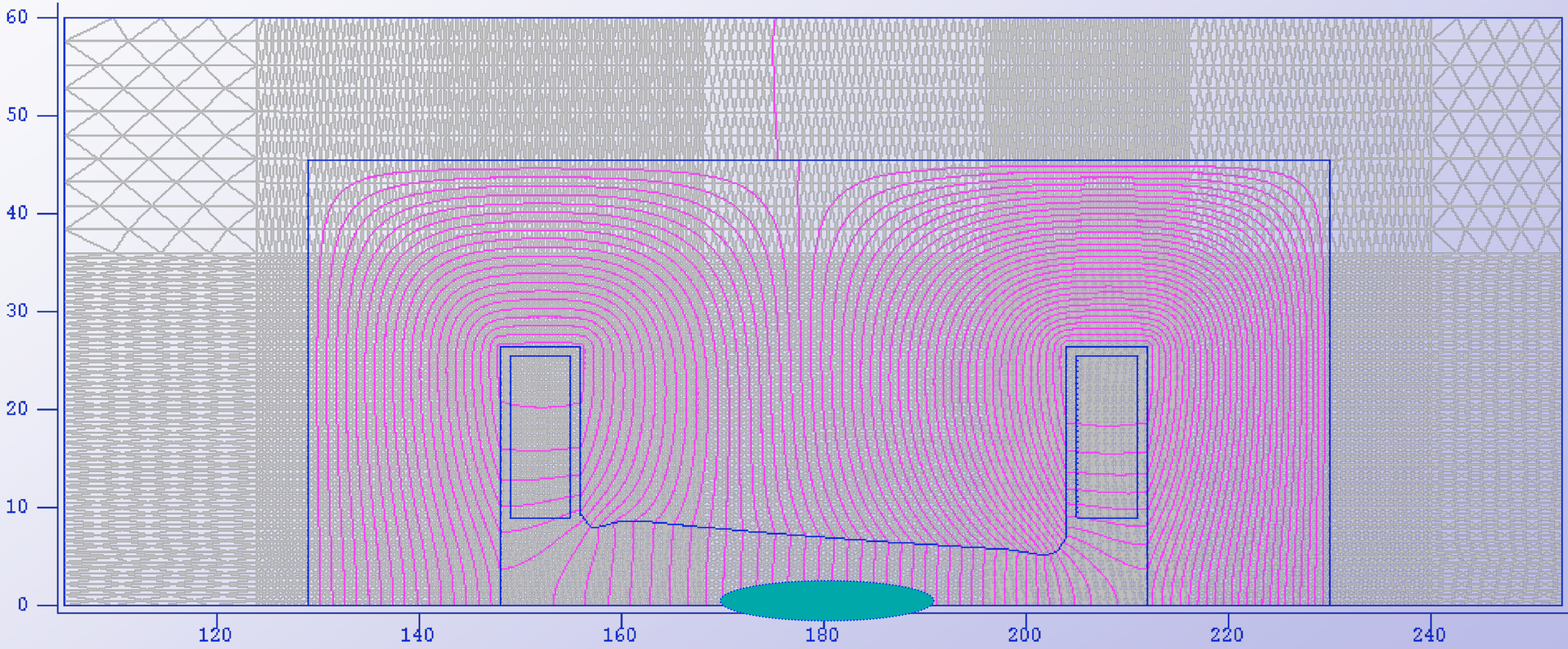
2. To design pole shape of magnets, an 2D simulation of FFAG magnetic field was calculated by POISSON

3. The design of the ring magnet was carried out with 3D magnetic field calculation by TOSCA code.

4. In order to achieve large transverse and longitudinal acceptance, we optimized magnet pole shape with particle tracking simulation in field maps based on TOSCA models.

2D magnetic field calculation (POISSON)

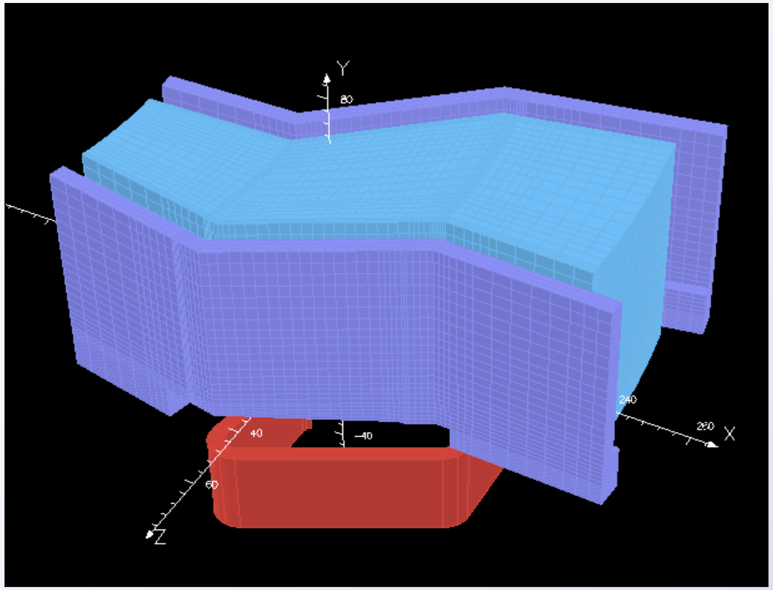
Radial scaling field law $B(r) = B_0 \left(\dfrac{r}{r_0} \right)^k$



2D optimization of pole shape converges rapidely.

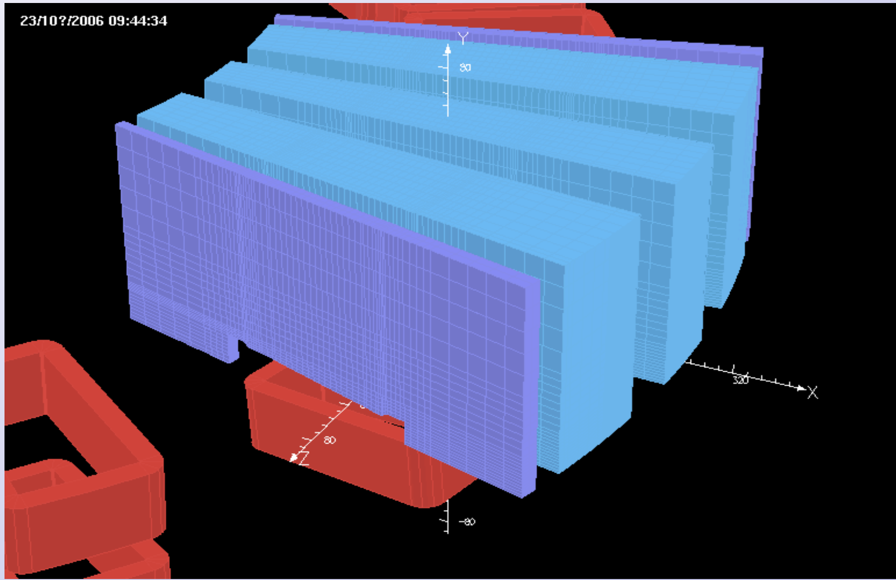
3D Magnetic field calculation (TOSCA)

Spiral sector type



- Cell num. = 8
- Open sec. angle = 45 [deg]
- Open F angle = 13.5 [deg]
- Clamp thick = 4[cm]
- Mean radius = 1.8[m]
- $\nu_x \sim 1.73$ $\nu_y \sim 1.14$
- k value = 1.7, spiral ang. = 35[deg]

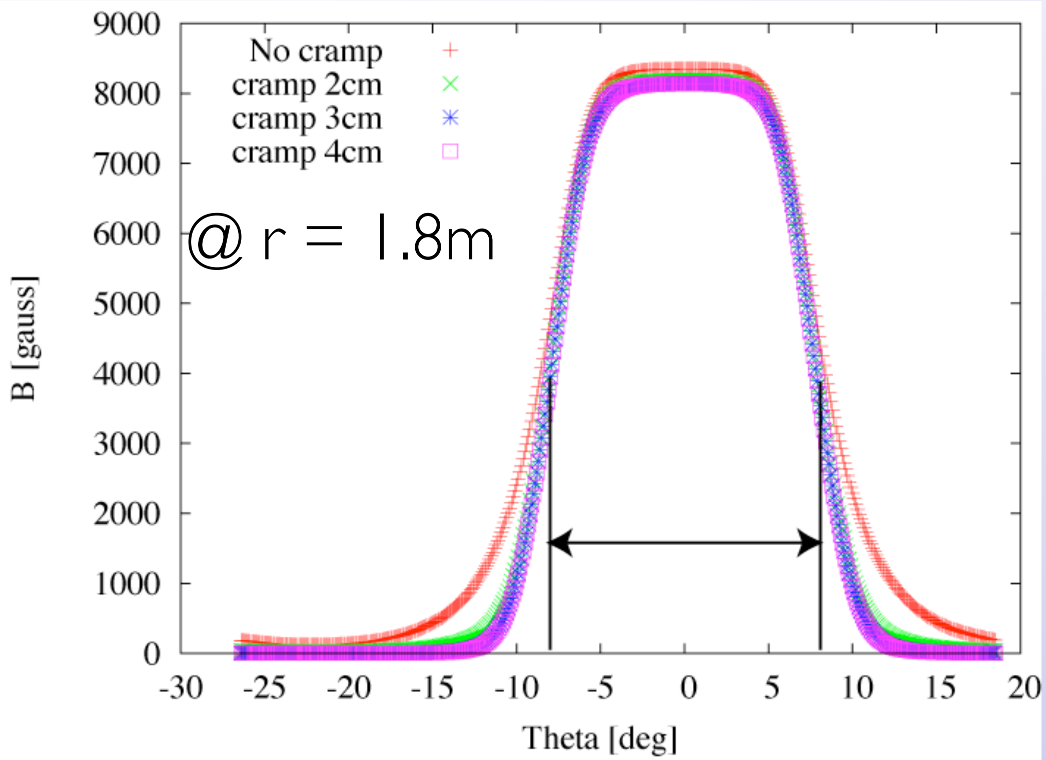
Radial sector type



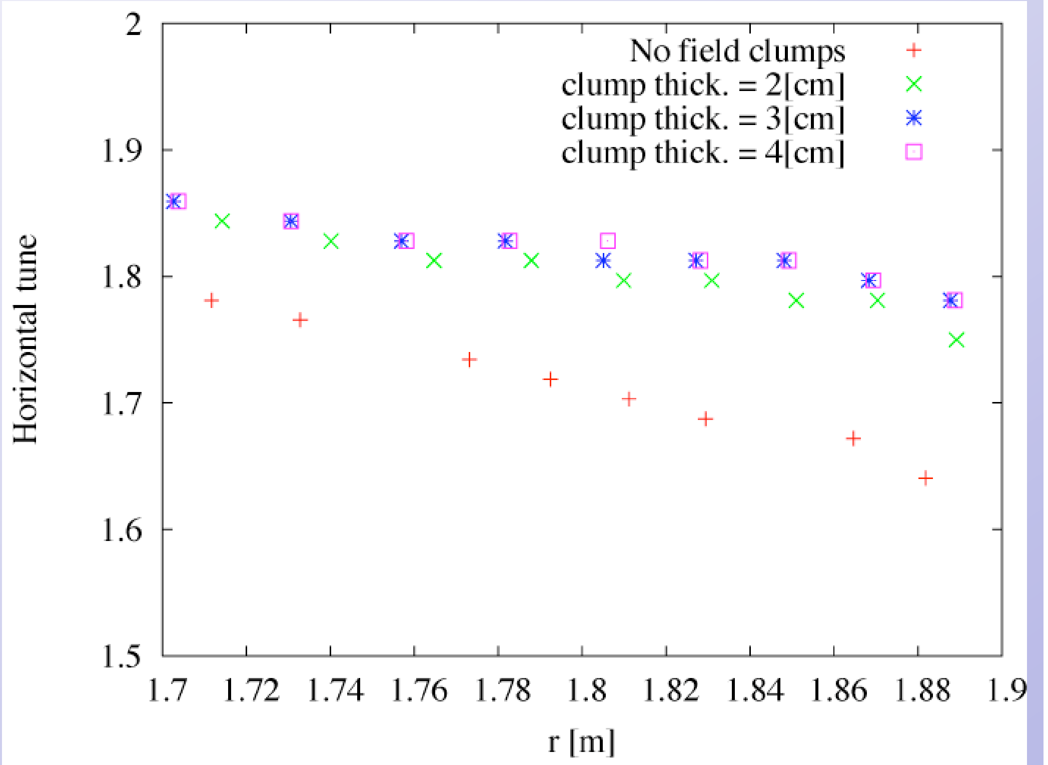
- FDF lattice(8cell)
- open F-Mag. = 6.4[deg],
- open D-Mag. = 5.1 [deg],
- F-D gap 3.75[deg],
- Clamp thick = 4[cm]
- Mean radius = 2.35[m]
- $\nu_x \sim 1.73$ $\nu_y \sim 2.29$
- k value = 1.92, FD ratio ~3

We install two field clamps at both magnet end to suppress the fringing field effects

Field clamp optimization



Horizontal tune variation



In order to suppress the fringing field effects, two field clamps are installed at both magnet ends.

Spiral angle and k value optimization

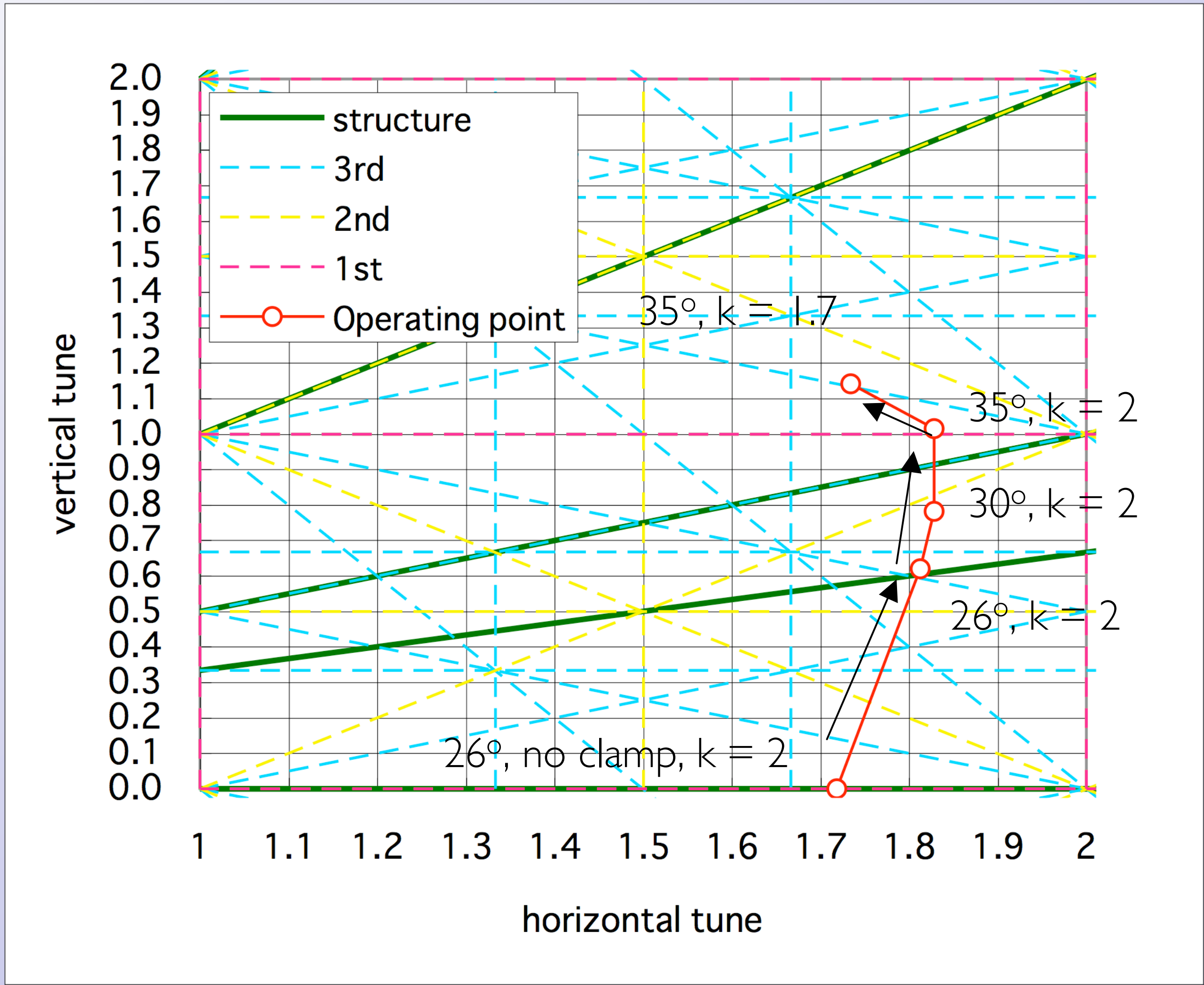
We optimize k value and spiral angle.

Initial parameter(linear model)

K value = 2,
Spiral angle = 26 deg

Optimized parameter

K value = 1.7,
Spiral angle = 35 deg

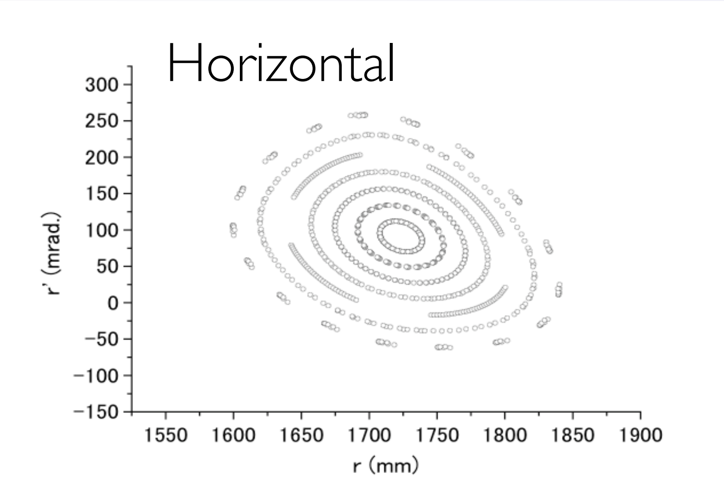


Design method of radial sector magnets is more simple than spiral's one

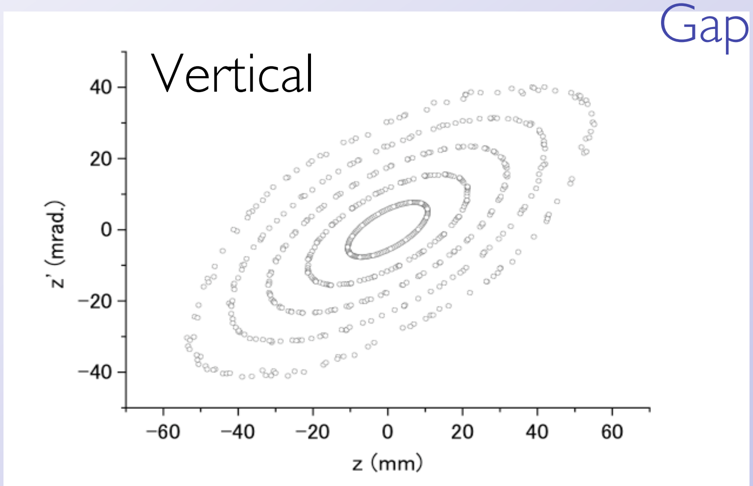
Acceptance study

Spiral sector type

Gap 14 [cm]



~7000π mm-mrad



~1400π mm-mrad

	Hori. Acceptance,	Vert. acceptance
Gap 14 [cm]	~7000π [mm-mrad],	~1400π [mm-mrad]
Gap 17.5 [cm]	~7000π [mm-mrad],	~2400π [mm-mrad]
Gap 20.0 [cm]	~6100π [mm-mrad],	~3200π [mm-mrad]

Radial sector type

	Hori. Acceptance,	Vert. acceptance
Gap 15 [cm]	~7000π [mm-mrad],	~3200π [mm-mrad]

Tracking simulation in storage ring

In order to study the efficacy of ERIT scheme, detailed beam simulation for ionization cooling have been carried out with ICOOL

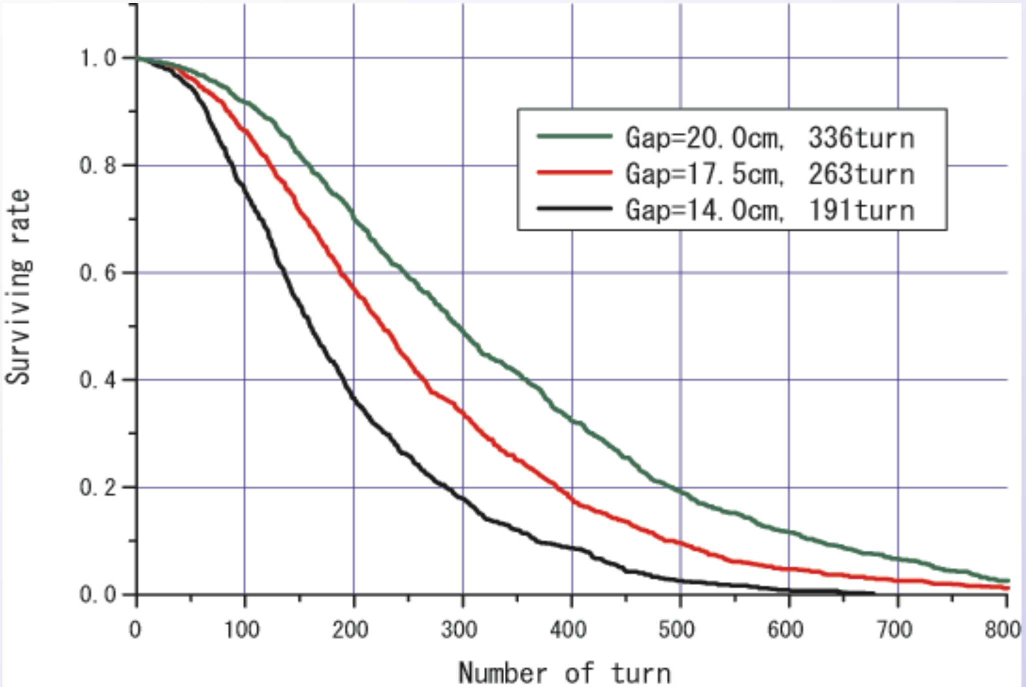
ICOOL

- Particle tracking simulation in field maps based on TOSCA models.
- 11MeV proton beam
- Particle num. = 1000
- Be target is rectangle (no wedge). Target thickness = 5 μm
- RF amplitude V_{rf} = 200 kV, (mom. Acceptance ~ 4%)

ICOOL takes into account decays and interactions of low energy protons in matter

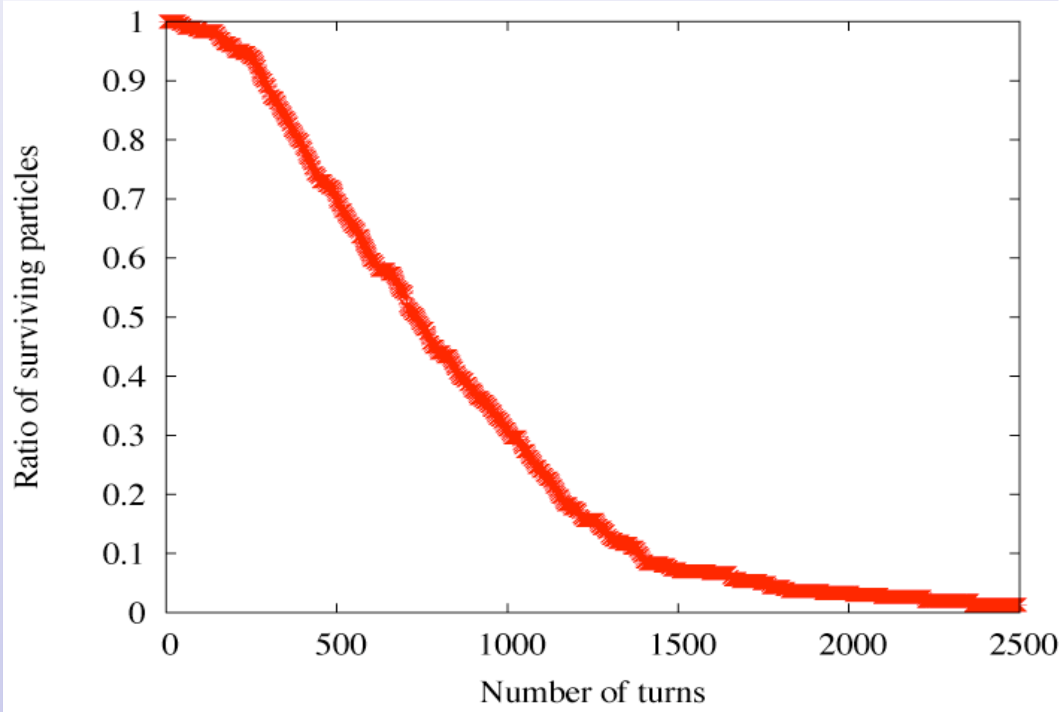
Simulation results from ICOOL

Spiral sector



Vertical beta function@target ~ 1.35 [m]

Radial sector



Vertical beta function@target ~ 0.79 [m]

It is obvious that surviving turn number depends on vertical acceptance in spiral sector.

Discussion

- From simulation results, the most cause of beam loss is heating of the vertical direction.
- The surviving turn number of radial sector is about 900 turns. Spiral's one is less than radial sector type.
- It is important to suppress overheating of the vertical direction to increase the surviving turn number.
- In the spiral type ring, it is difficult to achieve strong focusing the vertical direction(β_y=1.35). On the other hand, to achieve strong focusing of the vertical plane is easy in the radial sector ring(β_y=0.79).

$$\frac{d\varepsilon_\perp}{ds} = -\underline{\frac{1}{\beta^2 E}\frac{dE}{ds}}\varepsilon_\perp + \underline{\frac{\beta_\perp E_s^{\,2}}{2\beta^3 m_p c^2 L_R E}}$$

Heating term ——

Cooling term ——

In this reason, radial sector is more suitable than the spiral sector type for ERIT scheme.

A summary of comparison of spiral sector with radial sector

Spiral sector type FFAG ring

- Small size
- Beam focusing force in vertical plane is weak
- Operation of betatoron tunes after construction is difficult
- Low cost

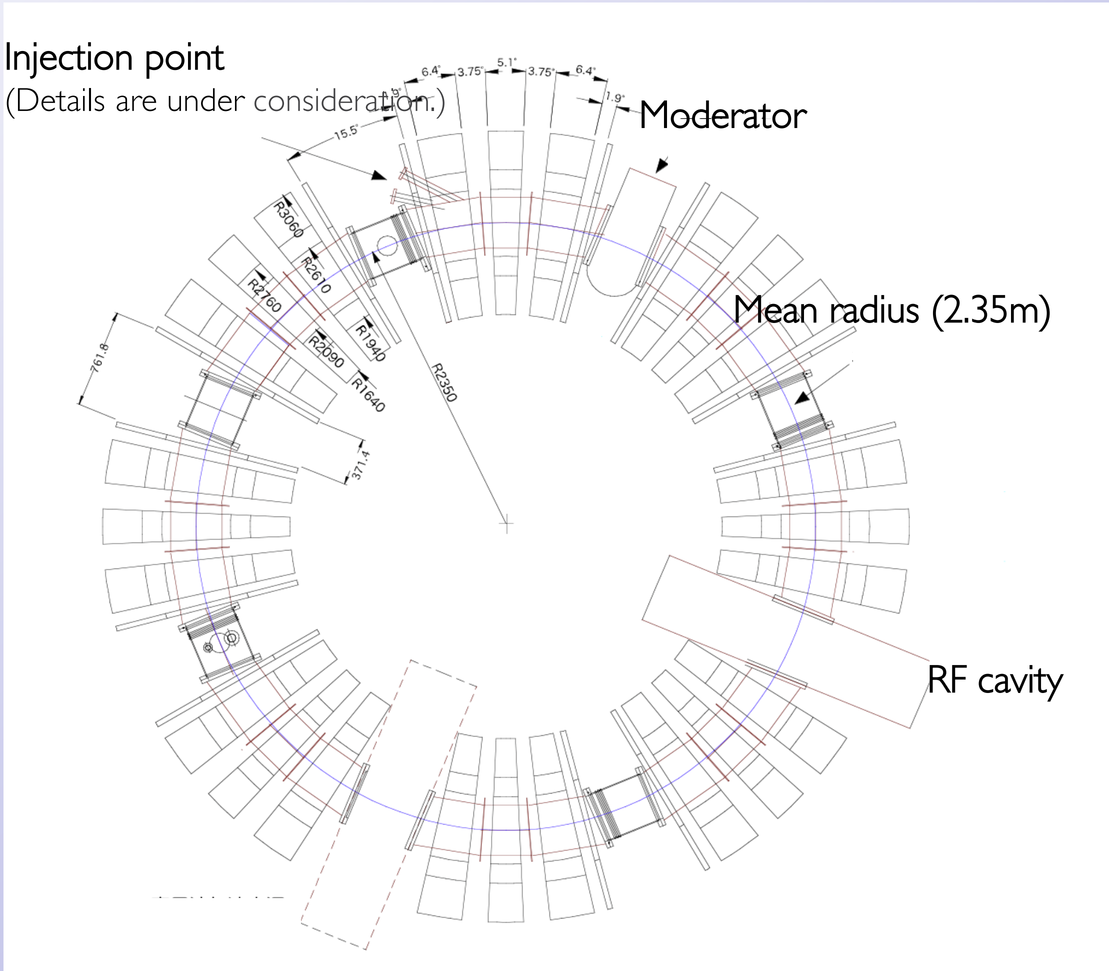
Radial sector type FFAG ring

- Large size
- Beam focusing force in vertical plane is strong
- The operating point is able to be controlled after construction
- High cost

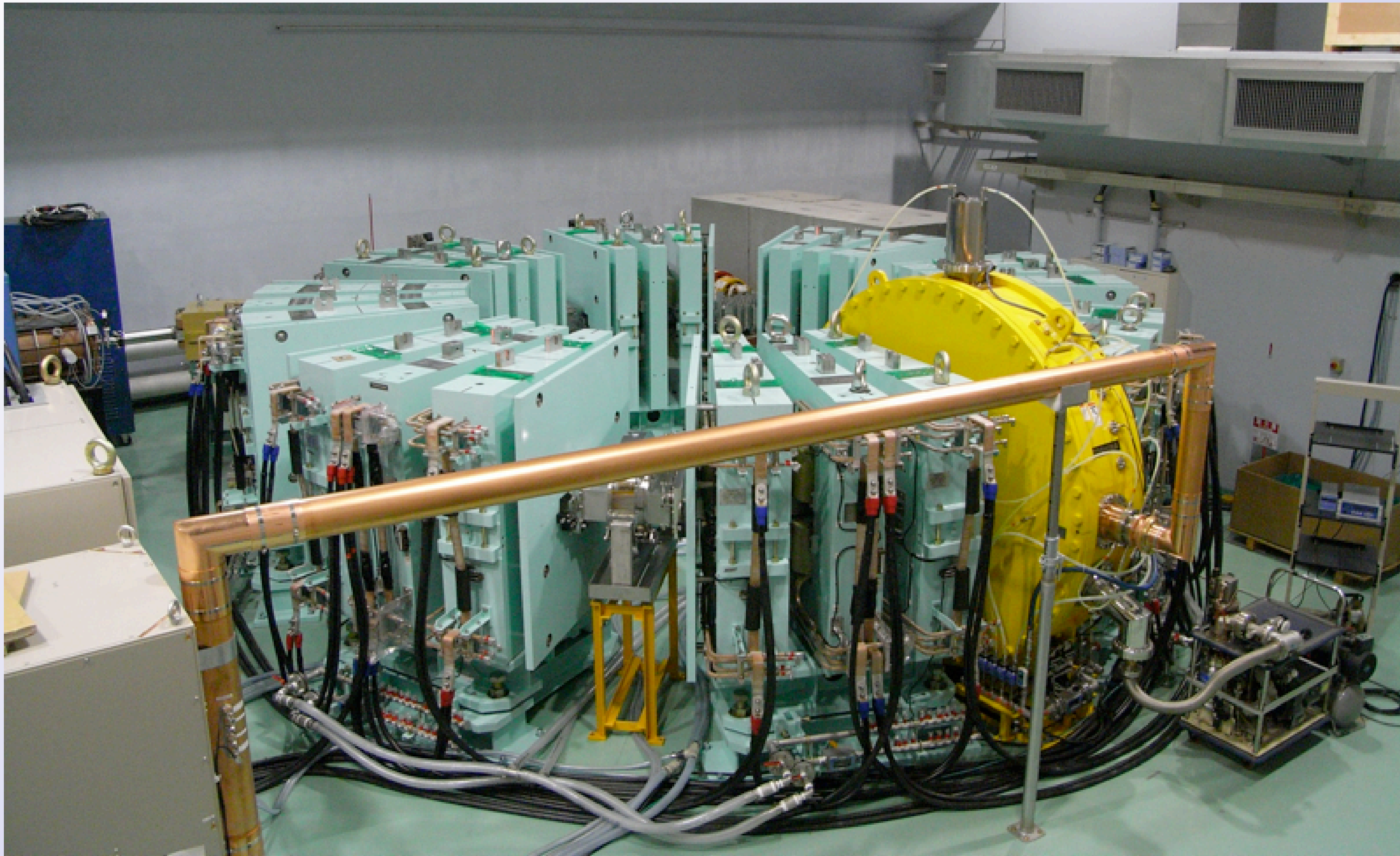
We chose radial sector type FFAG storage ring for ERIT system.

FINAL FFAG ring for ERIT parameters (Radial sector type)

Beam energy	11 MeV
Mean radius	2.35 m
Most ext. radius of magnet	3.06 m
F-magnet	
field strength	0.825 T
AT	58500 AT
mag. length (@ave. radi.)	26.25 cm
mass	4.1 ton
D-magnet	
field strength	0.727 T
AT	54500 AT
mag. length (@ave. radi.)	20.92 cm
mass	3.4 ton



FFAG-ERIT ring have been constructed in KURRI



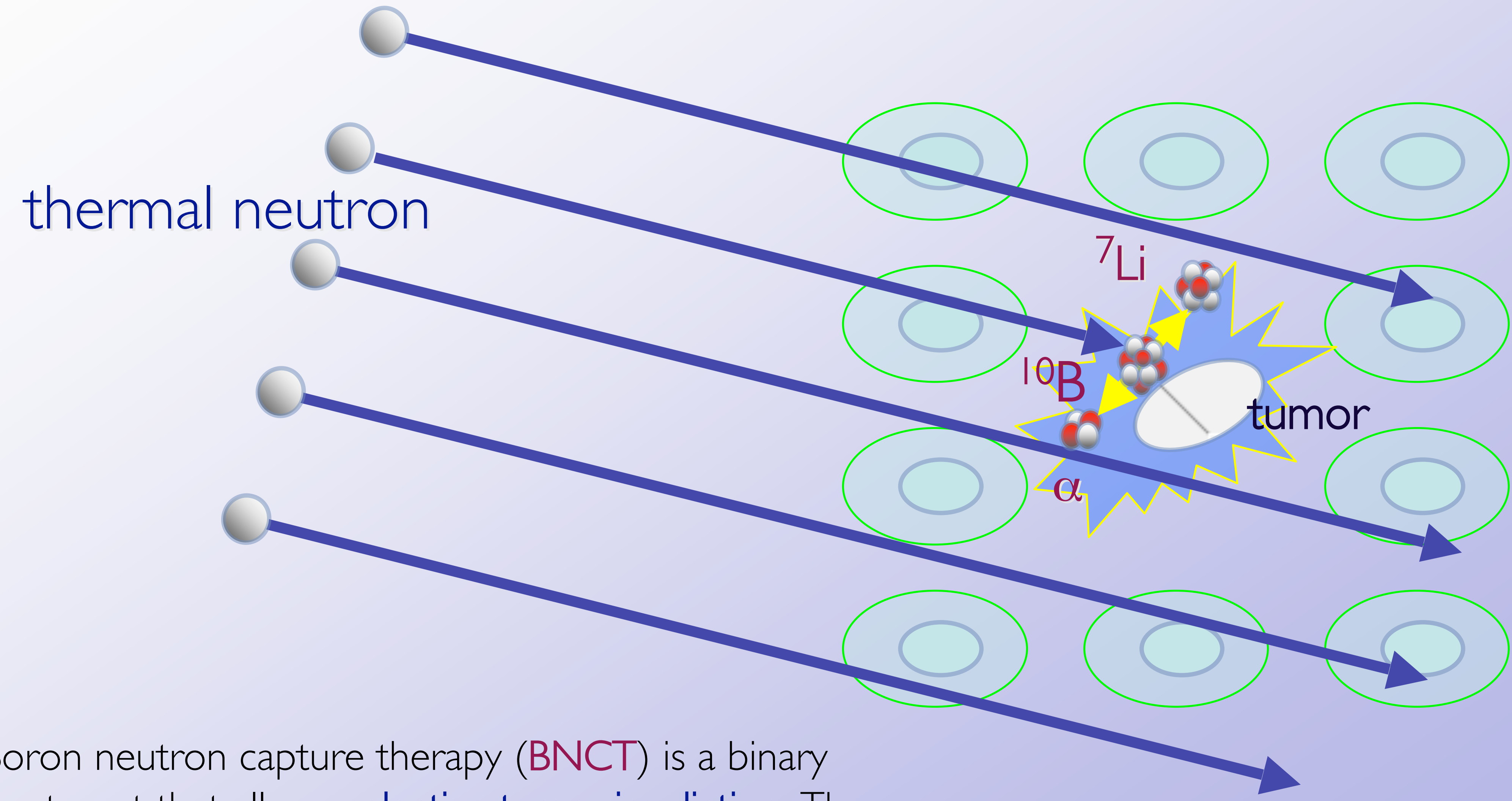
Fabrication and construction at KURRI have been completed. Basic study for neutron generation is done.

Summary

- A FFAG storage ring with ERIT scheme has been developed in KURRI.
- To develop storage ring for ERIT scheme, spiral sector and radial sector type FFAG ring have been designed and compared about performance in ERIT system.
- The design of the ring magnet was carried out with 3-dimensional magnetic field calculation by TOSCA code.
- We optimized magnet pole shape with particle tracking simulation in field maps based on TOSCA models.
- From results of tracking simulation, it have been confirmed that the transverse acceptance more than 3,000 pi mm mrad can be achieved.
- In order to increase efficiency of ERIT scheme, radial sector type FFAG is more suitable than the spiral sector type.
- Fabrication and construction at KURRI have been completed. Basic study for neutron generation is done.

Appendix

Principle of Boron neutron capture therapy (BNCT)



Boron neutron capture therapy (BNCT) is a binary treatment that allows **selective tumor irradiation.** The only intense neutron source for BNCT which has been used so far is a nuclear reactor.

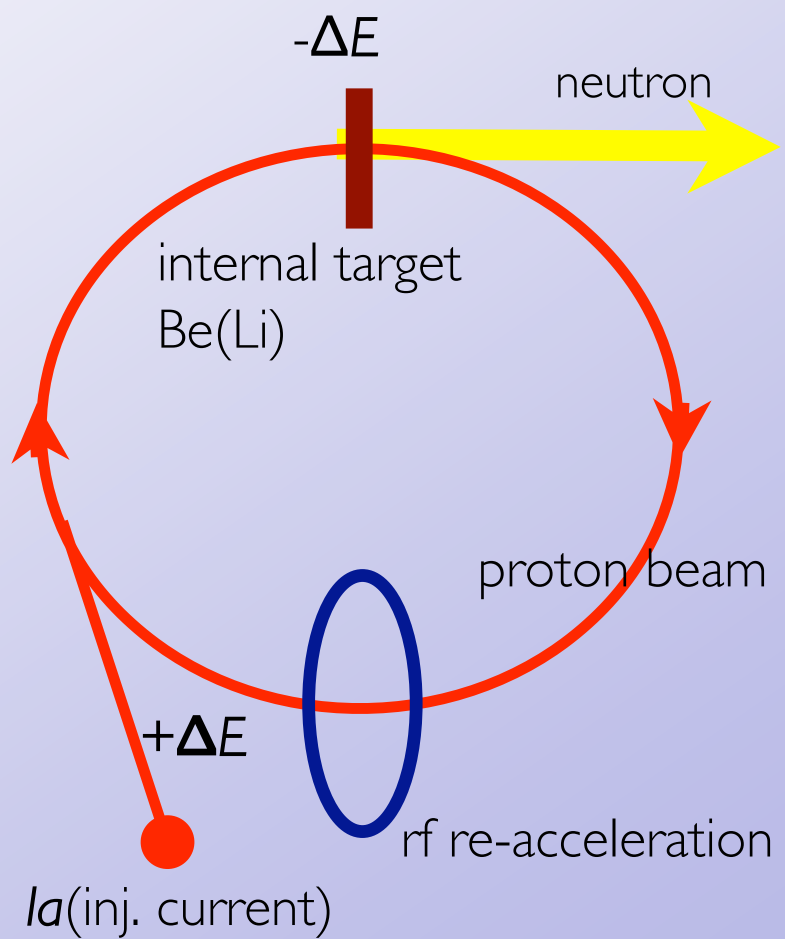
ERIT Emittance Recovery Internal Target for neutron production with FFAG accelerator

- Emittance growth
  - recovered by rf re-acceleration and Ionization Cooling
- Beam current
  - reduced by storaging the beam in the ring

Ia=Is/Nt

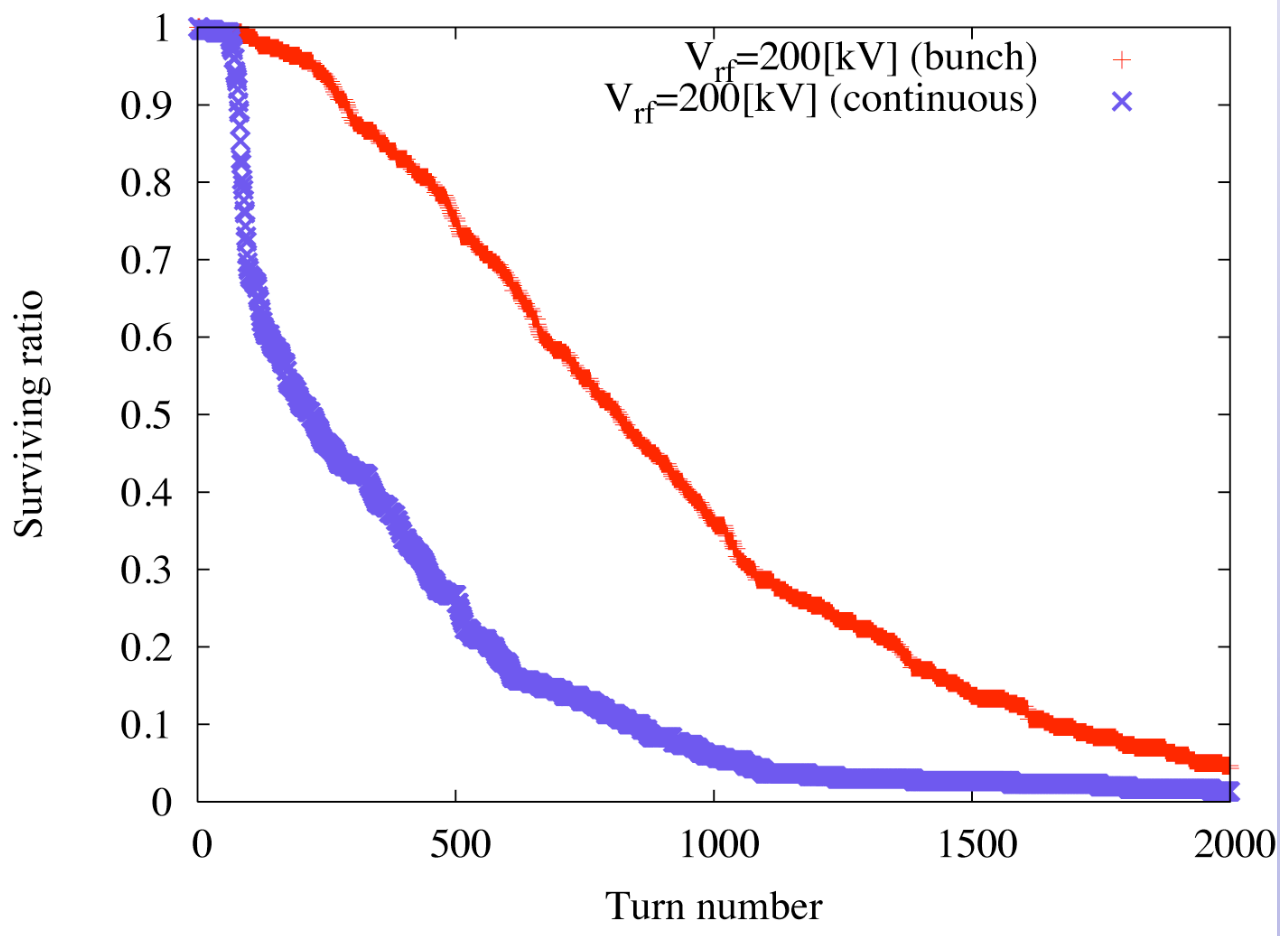
Stored turn number (*Nt*)is increase

➡ More efficient neutron production



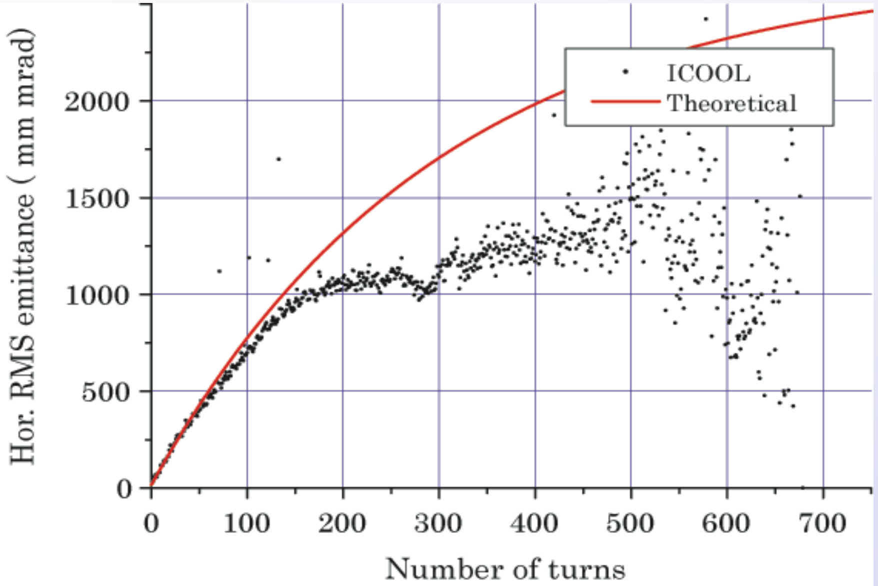
For a proton storage ring with ERIT scheme, huge momentum and transverse acceptance of FFAG is a big advantage to circulate a beam whose emittance and momentum spread gradually increase.

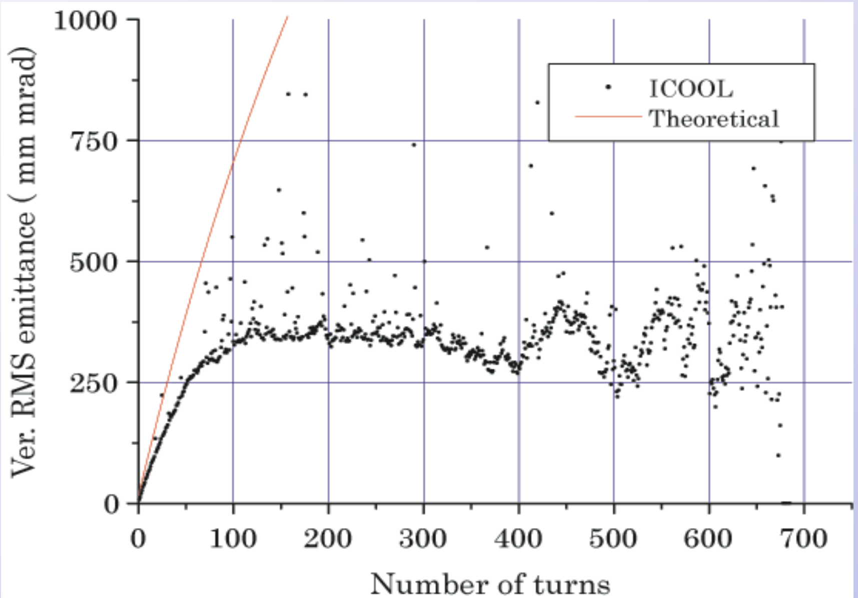
Longitudinal miss match



The average turn number for beam survival of matched beam is about 900 turns. However, mismatched beam is rapidly lost from the ring.

Simulation results from ICOOL(1)





Results of spiral sector type

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

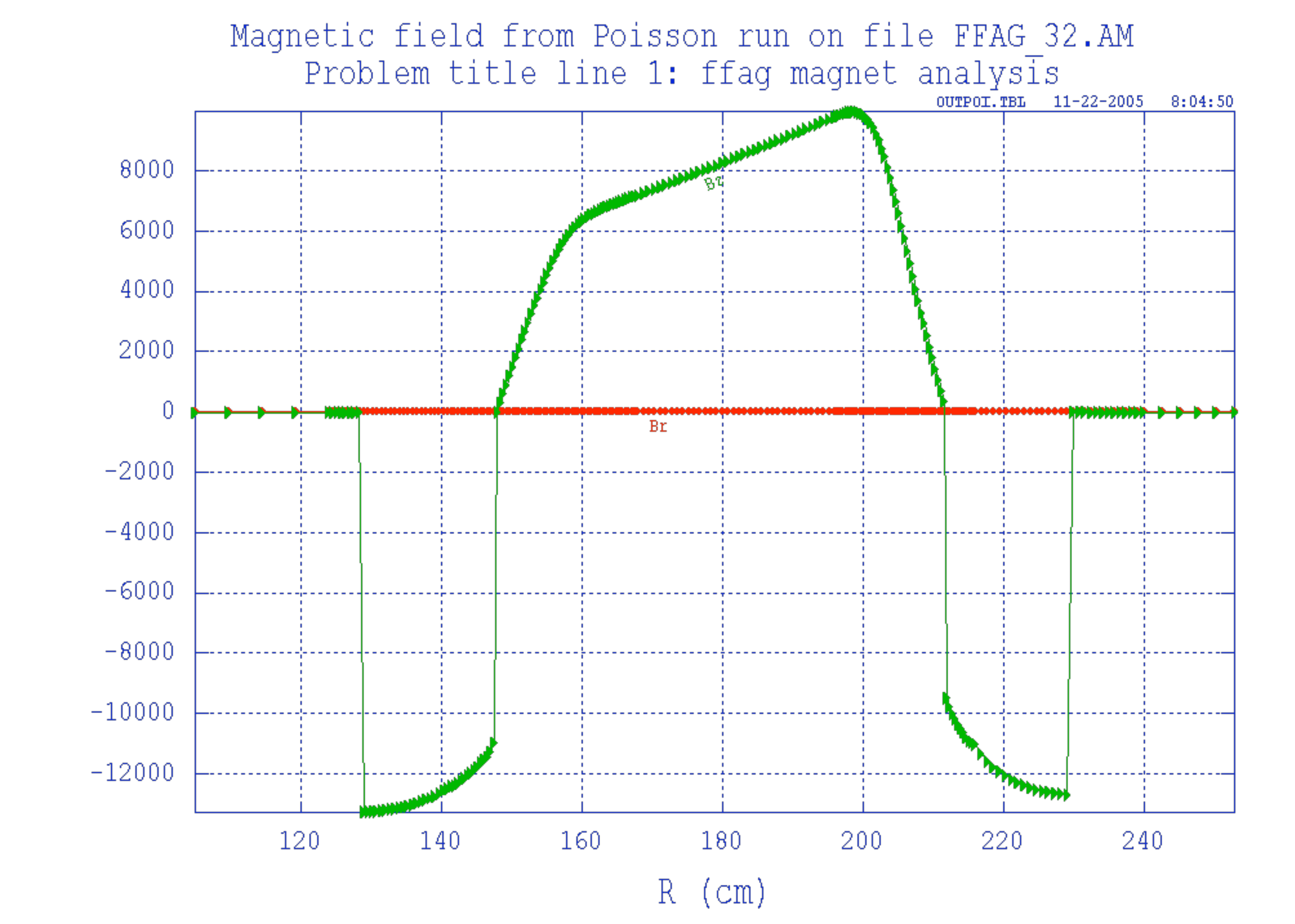
$$\frac{d\varepsilon_\perp}{ds} = -\frac{1}{\beta^2 E}\frac{dE}{ds}\varepsilon_\perp + \frac{\beta_\perp E_s^{\ 2}}{2\beta^3 m_p c^2 L_R E}$$

The beam emittance is increased by multiple scattering within material.

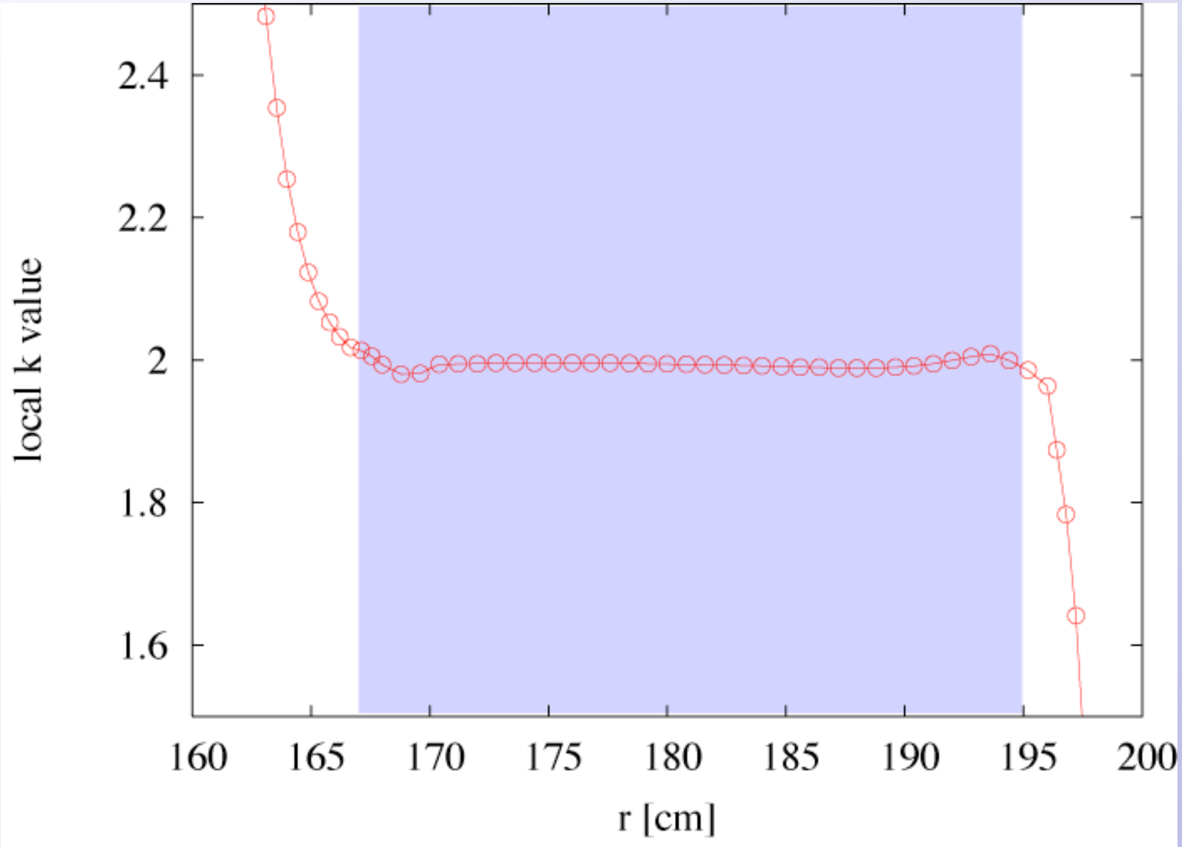
An analytical solution and the simulation results are corresponding well while a little the beam loss.

Particle of the large amplitude is lost as the turn number increases. ⇨ Emittance is saturated

2D magnetic field calculation medium plane



2D magnetic field calculation
local k value



166.5 < r < 195.0 [cm] : error of k value < 1%