Magnet design of FFAG-ERIT ring

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- Summary

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

Injector(RFQ + IHDTL)

Full energy injection

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

FFAG ring

H^- injection

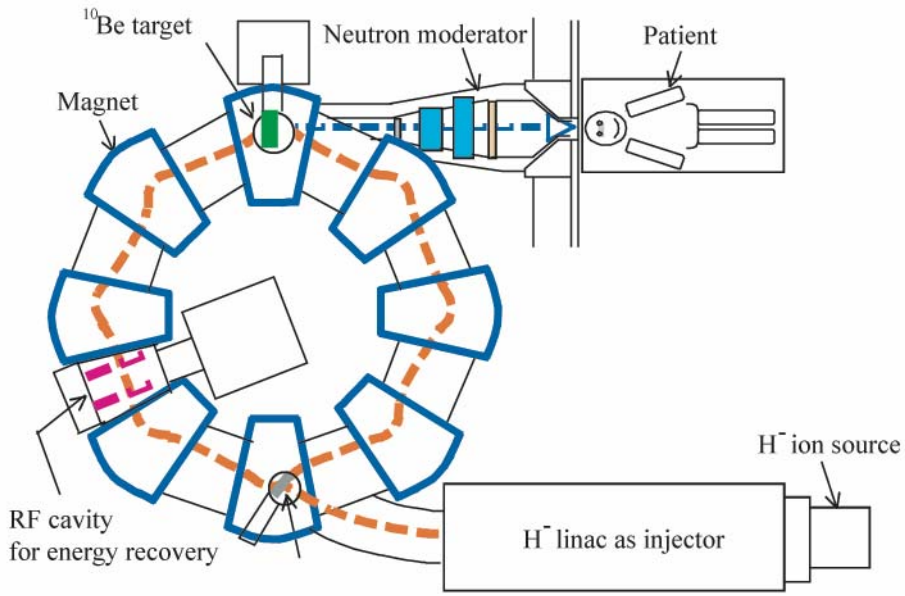
proton kinetic energy	10 [MeV]
Average beam current	~ 45 [mA]

ERIT system

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

RF cavity

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



Emittance growth in storage ring

- Using an internal target in the ring, the beam emittance can be increased in 3-D directions by Rattherford multiple scattering and straggling. In this reason, the storage ring require to large acceptance.

- In ERIT scheme, however, the beam emittance growth can be cured by Ionization Cooling effect.

Requirement for FFAG storage ring

- Large acceptance

  momentum acceptance dp/p ~ 5 [%] (from RF bucket height)
  transverse acceptance > 1000 [π mm mrad]
  It is necessary to adjust the phase advance to less than 90 degrees to secure a large acceptance. (from recent study, M.Aiba *et al*)

- Length of straight section (to install large RF cavity(width 55cm))

  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]

It is thought that 8 sector lattice is suitable. And to develop compact machine, we chose spiral sector type FFAG.

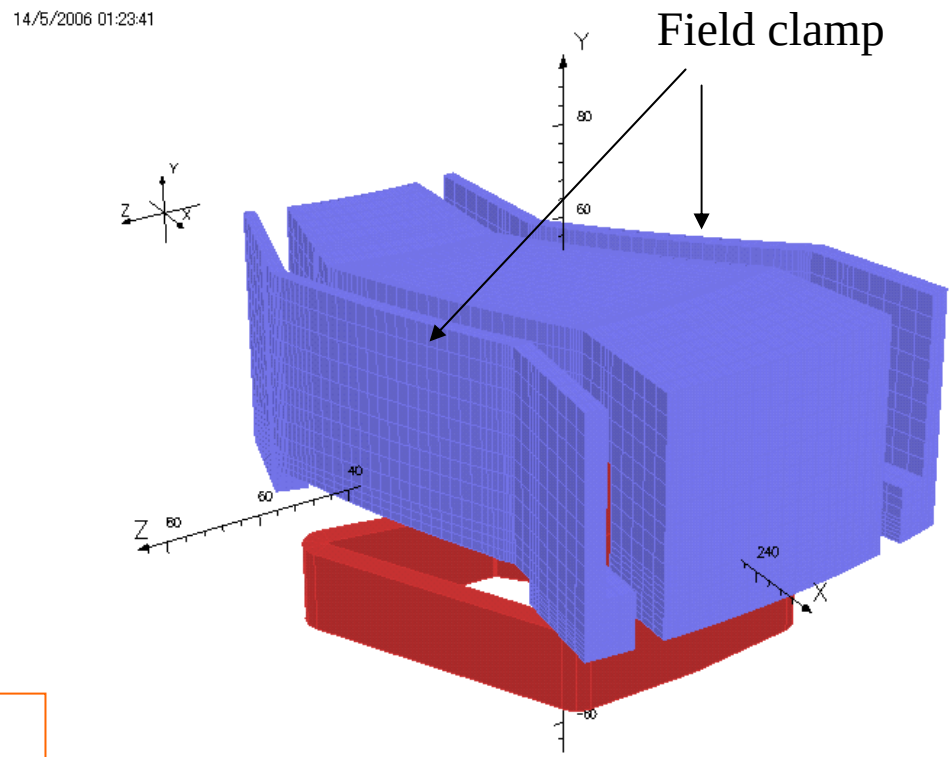
Magnetic field calculation (TOSCA)

Initial parameters

Cell num. = 8
Open sec. angle = 45 deg
Open F angle = 13.5 deg
Packing fac. = 0.3
K value = 2
Spiral angle = 26 deg
Average radius = 1.8 m

SAD Calculation

$\nu_x = 1.89$
$\nu_y = 1.34$

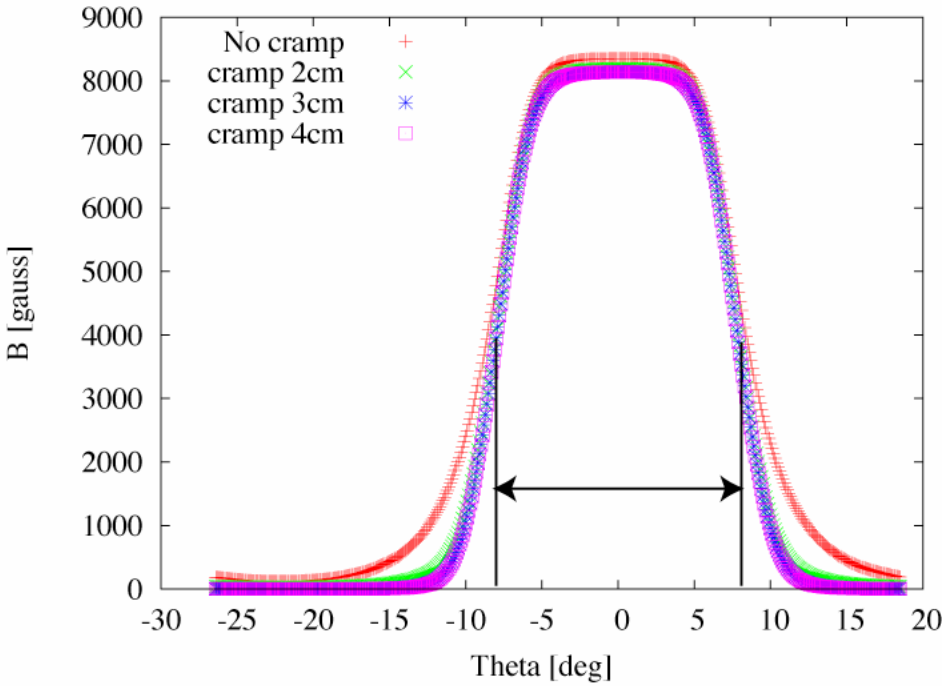


Optimization

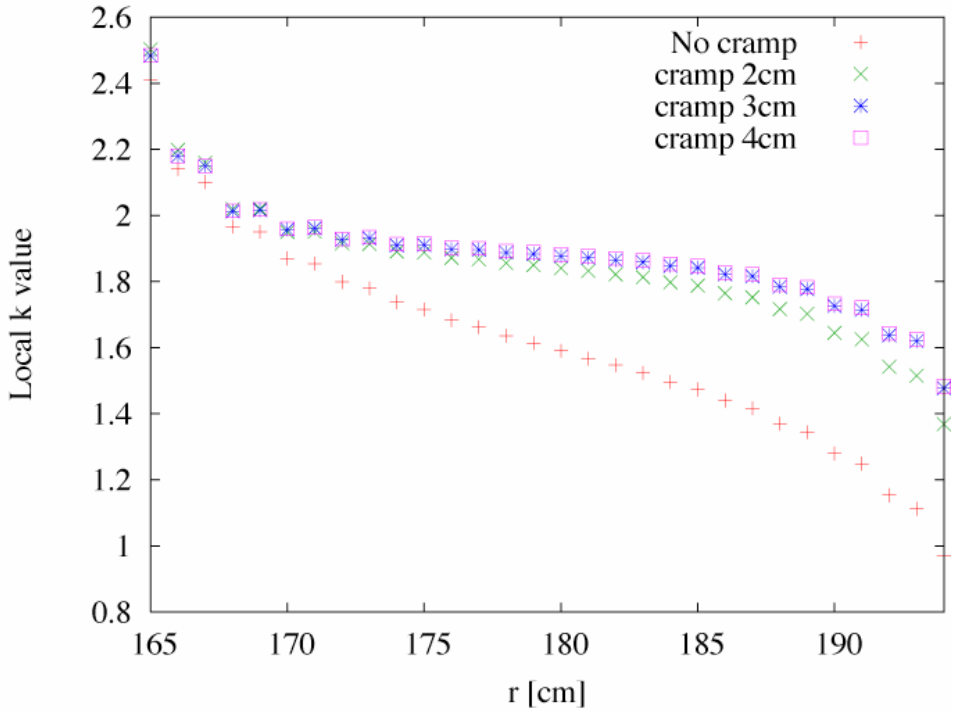
1. Field clamp
2. Spiral angle and K value

VECTOR FIELDS

Field clamp optimization



Local k value from BL



Field clamp thickness 0 ~ 4 [cm]

The change of the magnetic field is suppressed by setting field clamp.

Spiral angle and k value optimization

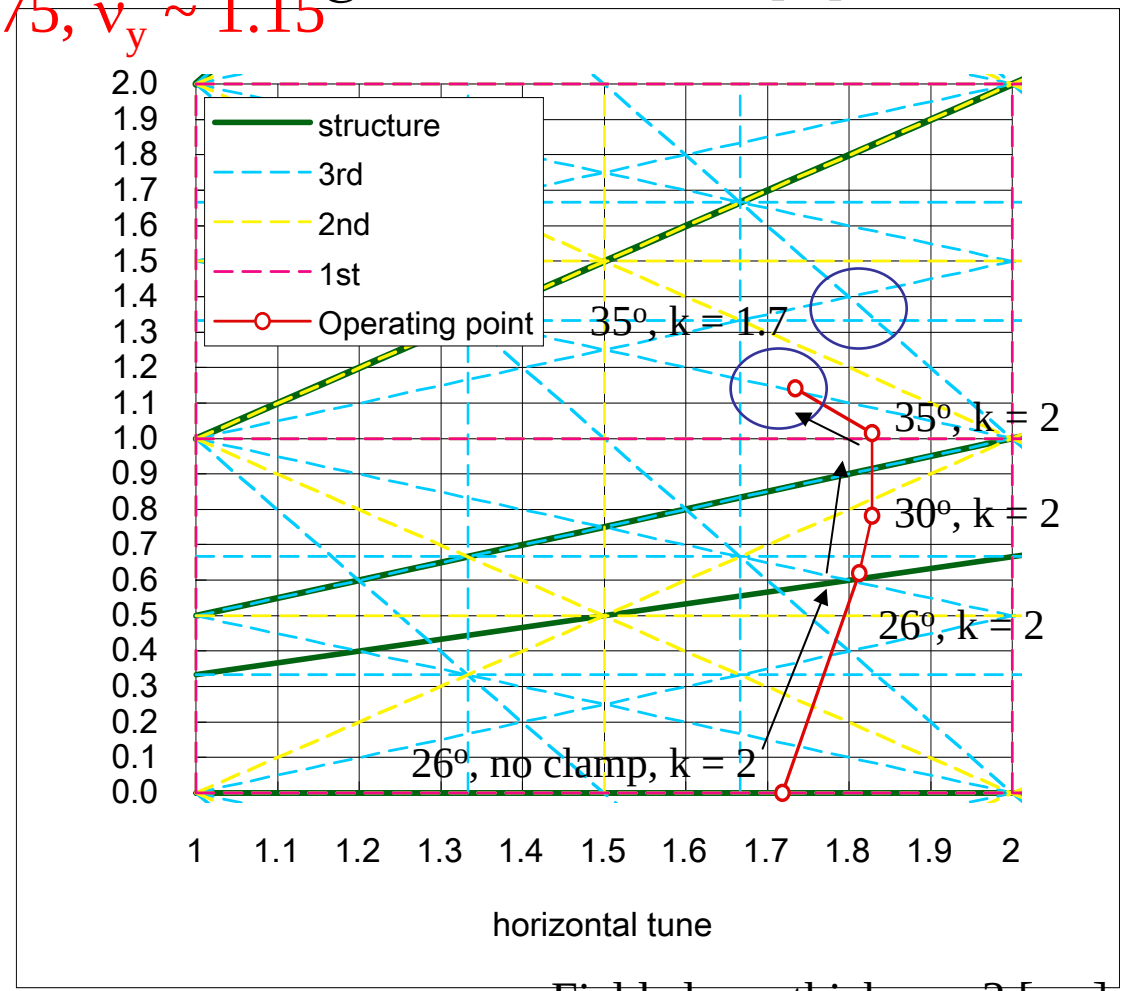
Design target $\nu_x \sim 1.85, \nu_y \sim 1.31$
or $\nu_x \sim 1.75, \nu_y \sim 1.15$

@Mean radius = 1.8 [m]

A far low value was obtained about the vertical tune according to the SAD results.($\nu_y = 1.34$)

Spiral angle optimization

If the spiral angle is enlarged, the vertical tune increases surely. However, the length of an effective straight section shortens.



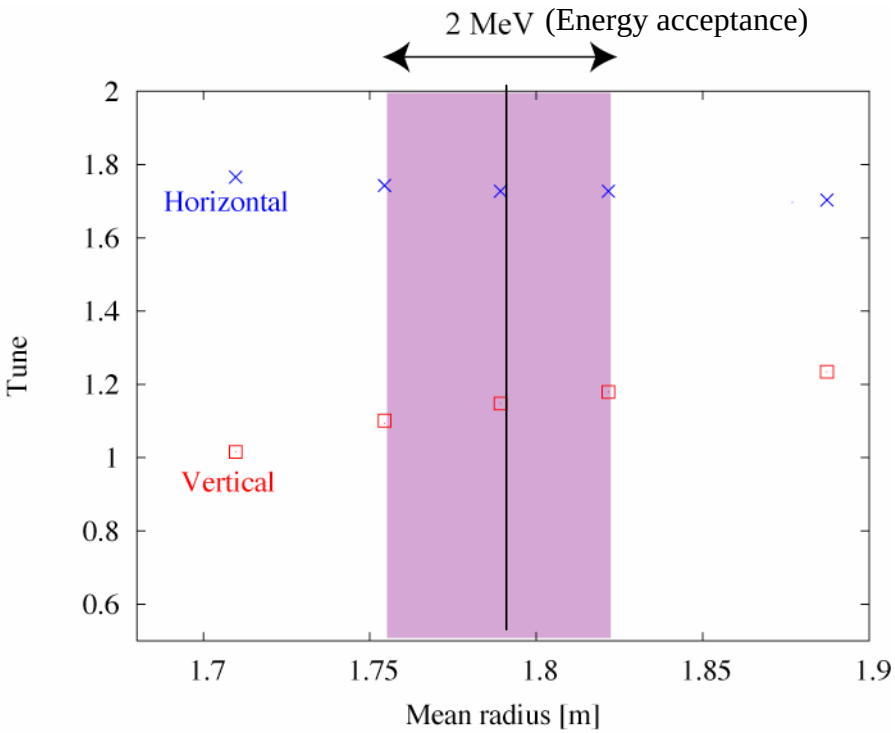
Optimized parameter

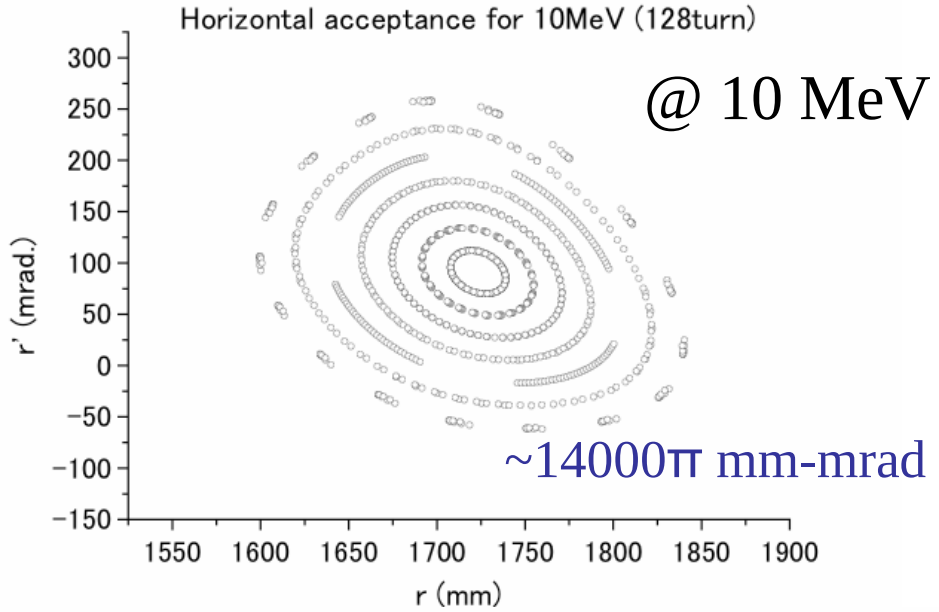
K value = 1.7,
Spiral angle = 35 deg
(With field clamp)
$\nu_x \sim 1.73, \nu_y \sim 1.14$

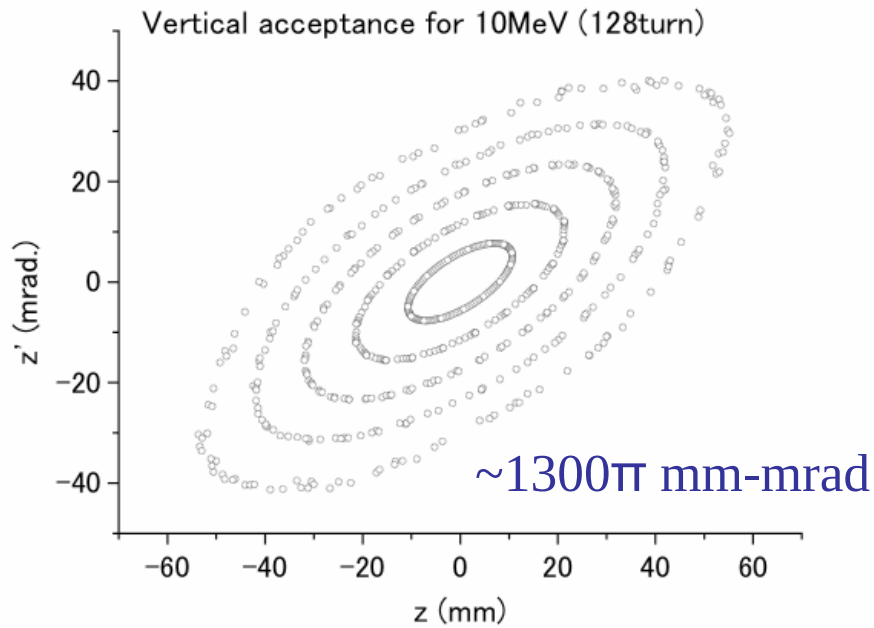
Field clamp thickness 3 [cm]

2D acceptance study

clamp thickness = 3 [cm]
K value = 1.7
Spiral angle = 35 deg





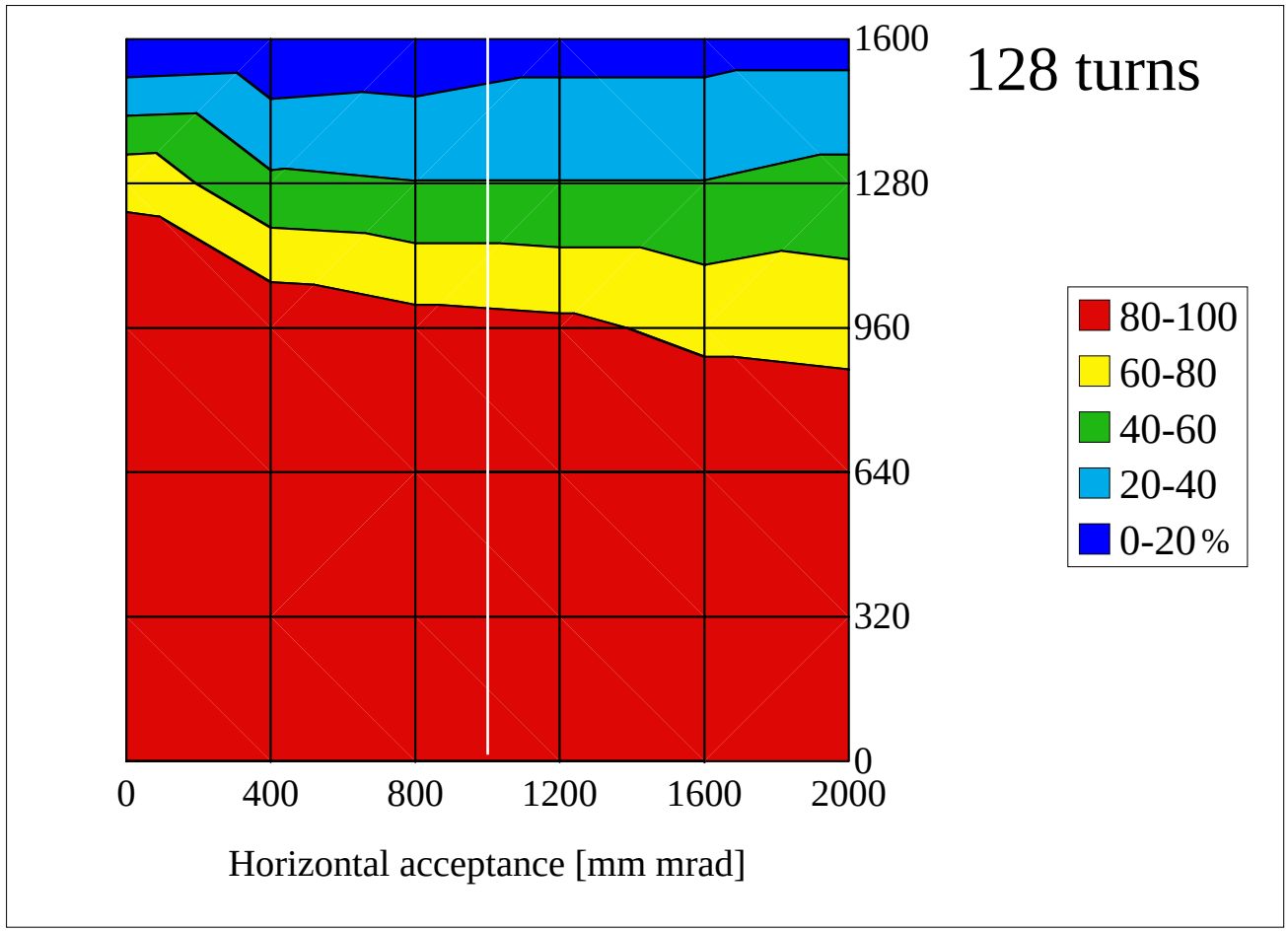


When only one of axes have the amplitude, large acceptance achieved.

4D acceptance study

When the particle has amplitudes both the horizontal and vertical axis, the acceptance becomes small in the effect.

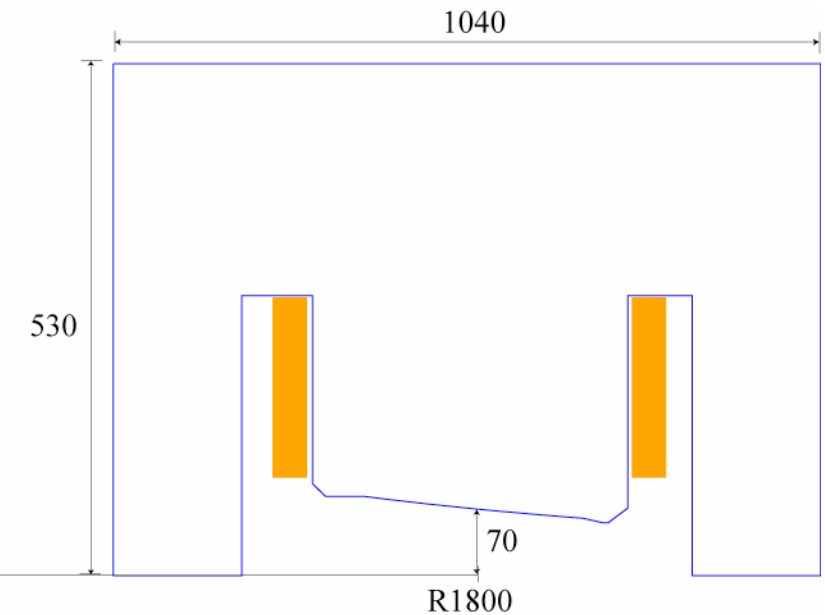
The target value(1000 [π mm mrad]) is almost achieved.

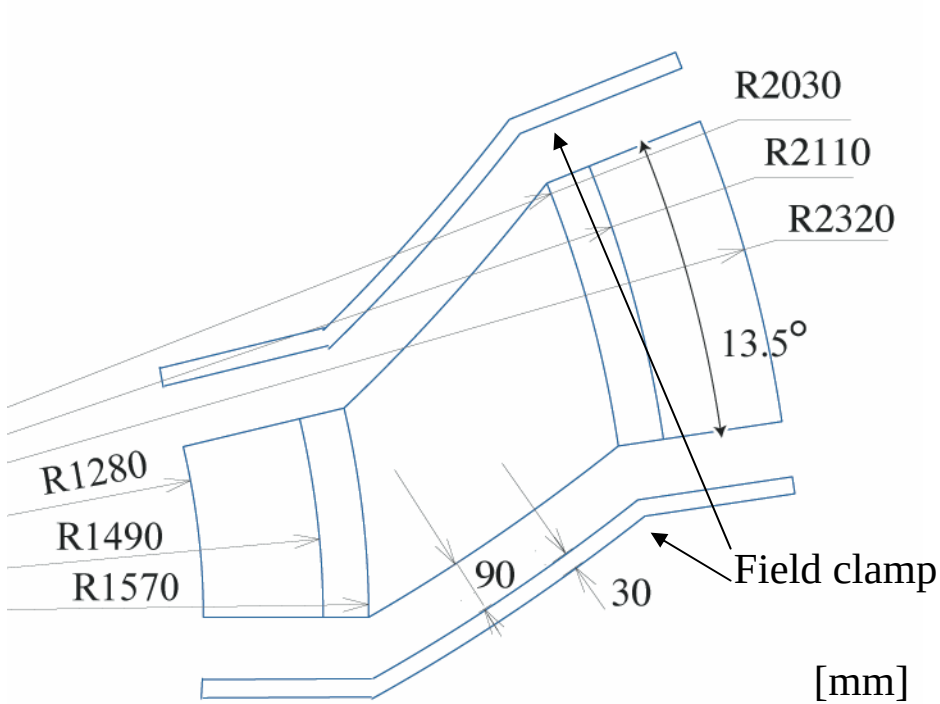


Parameters of FFAG-ERIT ring magnet

k value = 1.7
Half gap = 70 [mm] @10MeV
r_0 = 1.8 [m] : ~7250 [G]
MMF ~ 42000 [Ampere turns]
Current density ~ 7.4 [A/mm^2]
(Effective coil area 65%)

Spiral sector type
Sector num. = 8
Spiral ang. = 35 [deg]
r_0 = 1800 [mm]
Opening ang. = 13.5 [deg]





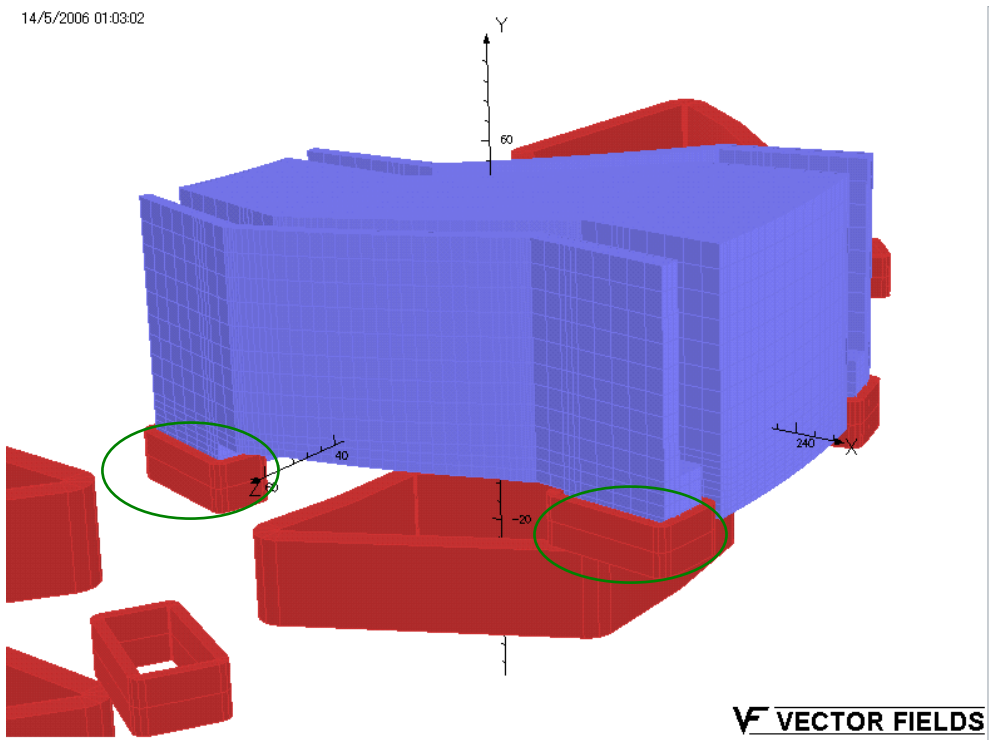
Summary

- FFAG-ERIT will enables greater neutron production from the internal target.

- FFAG-ERIT storage ring

  1. Optics design : Large acceptance achieved.
     (ε_x, ε_y > 1,000 [π mm mrad], dp/p ~ 5%)
  2. Magnet design : almost completed.

  3. The adjustment with other components(RF cavity, etc.) is being now.



UNITS

Length	cm
Magn Flux Density	gauss
Magn Field	oersted
Magn Scalar Pot	oersted cm
Magn Vector Pot	gauss cm
Elec Flux Density	C cm^{-2}
Elec Field	V cm^{-1}
Conductivity	S cm^{-1}
Current Density	A cm^{-2}
Power	W
Force	N
Energy	J

PROBLEM DATA

ffag40_spang35_num1_coil200.op3
TOSCA Magnetostatic
Non-linear materials
Simulation No 1 of 1
74976 elements
318265 nodes
120 conductors
Nodally interpolated fields

Local Coordinates

Origin: 0.0, 0.0, 0.0
Local XYZ = Global XYZ