

# Magnet design for a medium-energy Spiral FFAG Accelerator

Hidefumi Okita

FFAG Workshop 2015 Kyushu University

Sept 16, 2015



KYUSHU UNIVERSITY

# Outline

- Background
- Purpose
- Design Method
- Magnet Design (400 MeV Spiral FFAG)
- Summary

# Background

## Medium Energy Proton (~400 [MeV])

- Muon science
- Neutron science
- BNCT

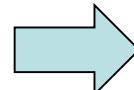
FFAG

Spiral FFAG (Compact size of accelerator and simple optics)

- only spiral shaping focusing magnet
- vertical focusing from edge focus of fringing field

vertical tune are sensitive to magnet design

# Design Method for Spiral FFAG

tune 

$$\nu_h \sim \sqrt{1 + k}$$
$$\nu_v \sim \sqrt{-k + f^2(1 + 2 \tan^2 \zeta)}$$

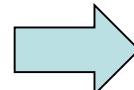
Zero chromaticity field

⇒ correction of  $k$  & flutter factor & spiral angle

## Ordinal method

index	<ul style="list-style-type: none"><li>· Local <math>k</math> (correction of <math>k</math>)</li><li>· <math>L_{\text{entrance} \text{exit}}^{\text{eff}}</math> (correction of flutter)</li><li>· <math>d\nu_V/d\zeta</math> (correction of spiral angle)</li></ul>
Optimization parameter	<ul style="list-style-type: none"><li>· pole gap geometry</li><li>· entrance side boundary of magnet</li><li>· exit side boundary of magnet</li><li>· width of chamfer</li><li>· depth of chamfer</li><li>· start point of chamfer</li><li>· spiral angle</li><li>· field clamp etc.</li></ul>

# Design Method for Spiral FFAG

tune 

$$\nu_h \sim \sqrt{1 + k}$$
$$\nu_v \sim \sqrt{-k + f^2(1 + 2 \tan^2 \zeta)}$$

Zero chromaticity field

⇒ correction of k & flutter factor & spiral angle

## Ordinal method

index

- Local k (correction of k)
- $L_{\text{entrance}|\text{exit}}^{\text{eff}}$  (correction of flutter)
- $d\nu_V/d\zeta$  (correction of spiral angle)

Optimization parameter

- pole gap geometry
- entrance side boundary of magnet
- exit side boundary of magnet
- width of chamfer
- depth of chamfer
- start point of chamfer
- spiral angle
- field clamp etc.

Correction of all  
factor contribute to  
vertical tune

Many optimization  
parameters



# Purpose

Proposition of simple design method for  
medium-energy Spiral FFAG

In this study...

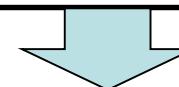
Design of the 400 MeV Spiral FFAG accelerator at  
Kyushu University using proposed method

# Outline

- Background
- Purpose
- Design Method
- Magnet Design (400 MeV Spiral FFAG)
- Summary

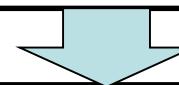
# Design method for spiral FFAG

Optics design with linear approximation



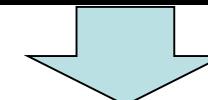
2D magnet modeling

Correction of field index :  $k$



3D Spiral magnet modeling

Correction of  
field index :  $k$ , flutter factor, spiral angle



Validate tune with tracking simulation

# Design method for spiral FFAG

Optics design with linear approximation

2D magnet modeling

Correction of field index :  $k$

3D Spiral magnet modeling

Correction of  
field index :  $k$ , flutter factor, ~~spiral angle~~

Validate tune with tracking simulation

change

# Concept of ordinal and proposed design method

	Ordinal method	Proposed method
Indexes	<ul style="list-style-type: none"><li>• local k (field index: k)</li><li>• <math>L_{entrance exit}^{eff}</math> (flutter factor)</li><li>• <math>d\nu_V/d\zeta</math> (spiral angle)</li></ul>	<ul style="list-style-type: none"><li>• local k (field index : k)</li><li>• <math>p\nu^{eff}</math> (flutter factor)</li></ul>
Optimization parameters	<ul style="list-style-type: none"><li>• pole gap geometry</li><li>• entrance and exit side of magnet boundary</li><li>• width of chamfer</li><li>• depth of chamfer</li><li>• start point of chamfer</li><li>• spiral angle</li><li>• field clamp</li></ul>	<ul style="list-style-type: none"><li>• pole gap geometry</li><li>• packing factor of magnet</li><li>• gap of field clamp</li><li>• position of field clamp</li></ul>

Correction 2 indexes & fewer optimization parameters

# Outline

- Background
- Purpose
- Design Method
- Magnet Design (400 MeV Spiral FFAG)
- Summary

# Requirements for 400MeV Spiral FFAG

- Injector : 150 MeV FFAG
- Injection momentum: 444.58 [MeV/c]  
(proton 100 MeV)
- Extraction momentum: 954.26 [MeV/c]  
(proton 400 MeV)

• Magnetic field :  $B = 1.55$  [T]

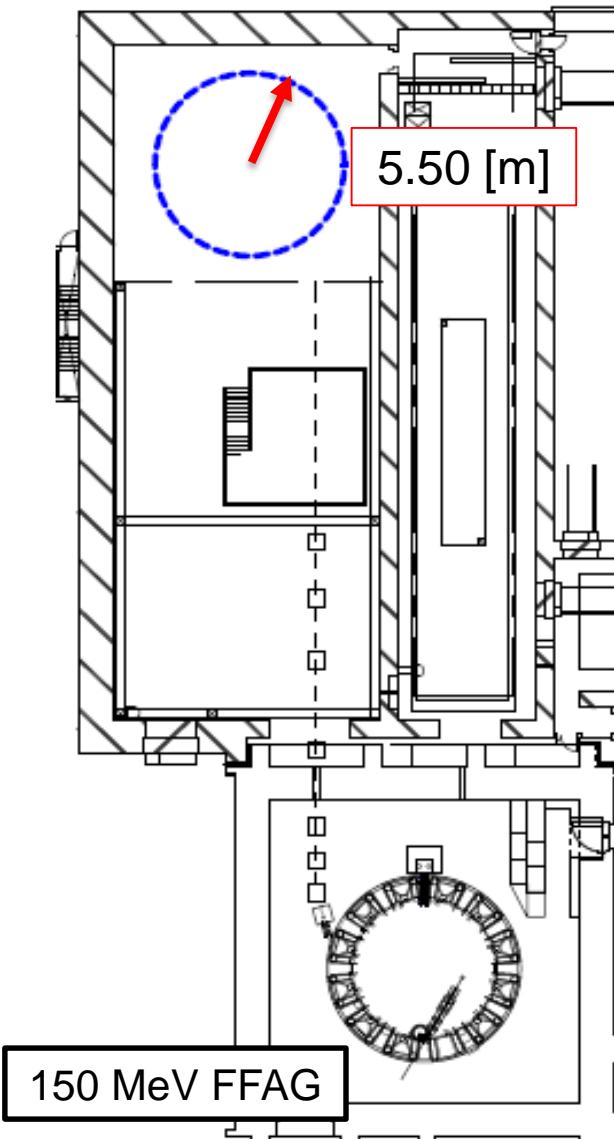
• Size of accelerator

Max radius of Magnet= 5.50 [m]

Max radius of beam orbit ~ 4.7 [m]

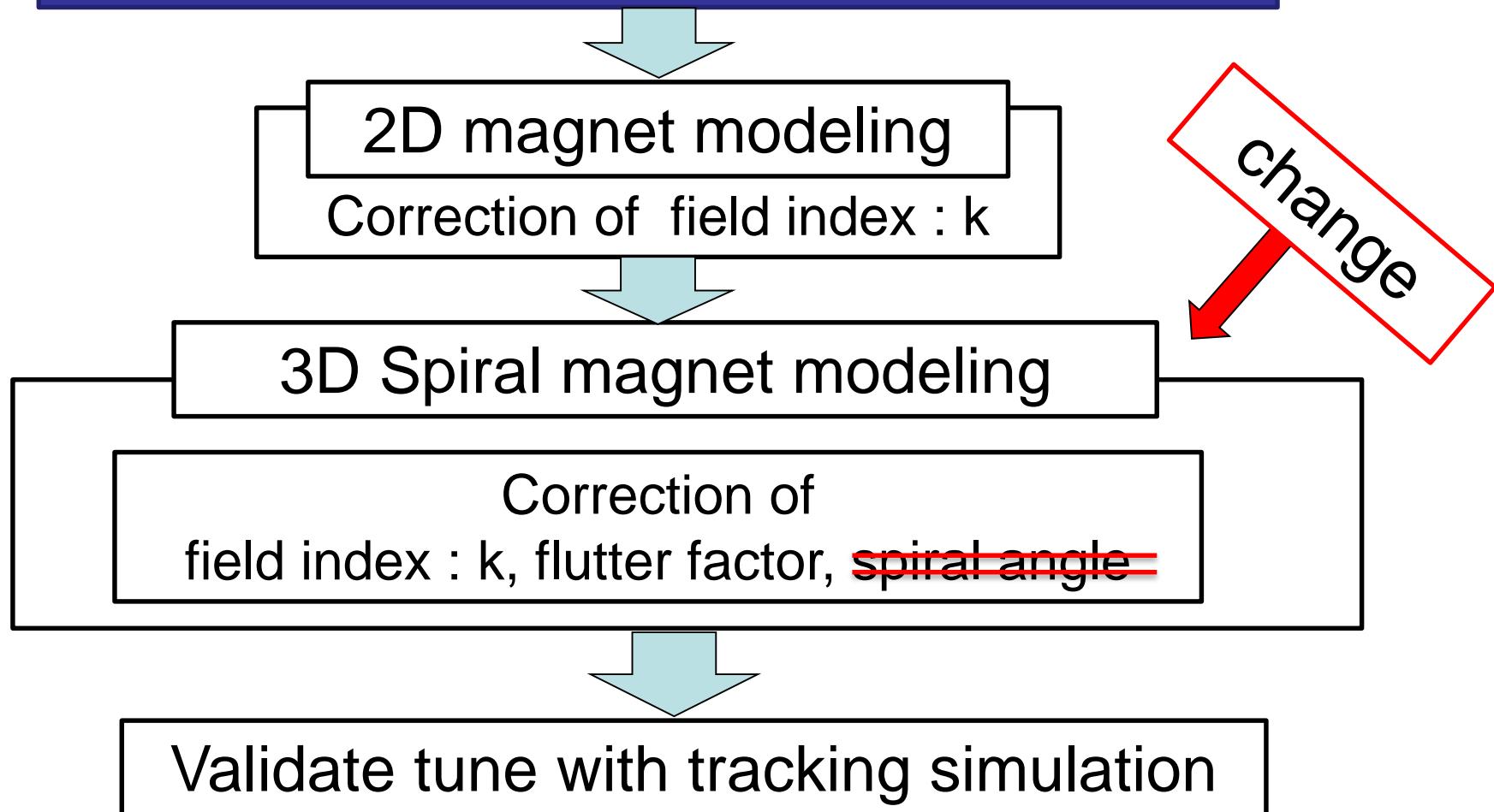
$\Rightarrow pf \sim 0.44$

- Horizontal phase advance per cell  
~90 [deg.]



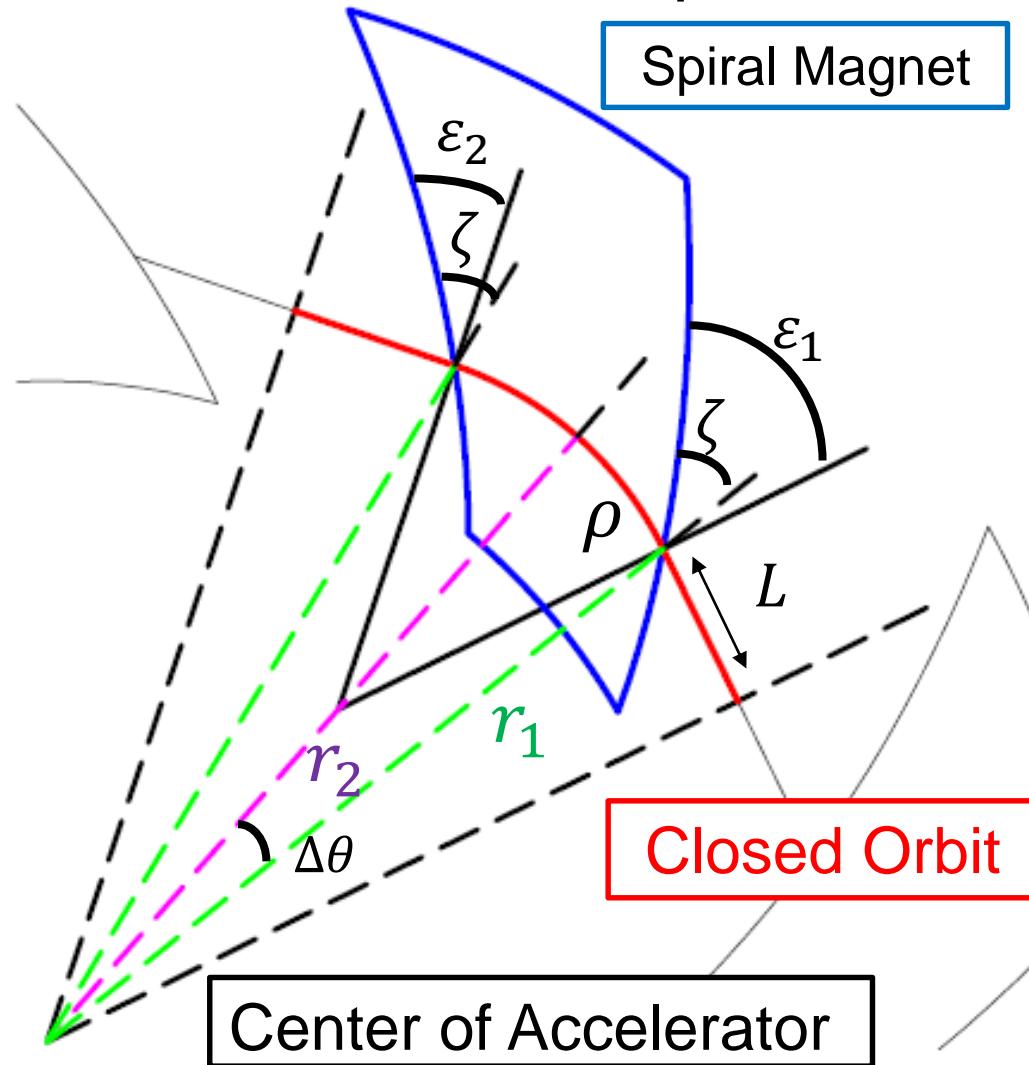
# Design method for spiral FFAG

## Optics design with linear approximation



# Linear Approximation

Definitions of lattice parameters



$2L$  : Length of straight section

$\rho$  : Radius of Curvature

$\zeta$  : Spiral Angle

$\varepsilon$  : Edge Angle

$$pf: \text{packing factor} = \frac{\Delta\theta}{\pi/N}$$

$$\varepsilon_1 = \pi/N - pf \times \pi/N - \zeta$$

$$\varepsilon_2 = \pi/N - pf \times \pi/N + \zeta$$

$$r_1/\rho = \sin(\pi/N)/\sin(pf \times \pi/N)$$

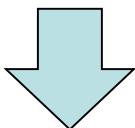
$$r_2/\rho = 1 + (r_1 - \sin(\pi/N - pf \times \pi/N)) / \sin(pf \times \pi/N)$$

$$L/\rho = \sin(\pi/N) \times \sin(\pi/N - pf \times \pi/N) / \sin(pf \times \pi/N)$$

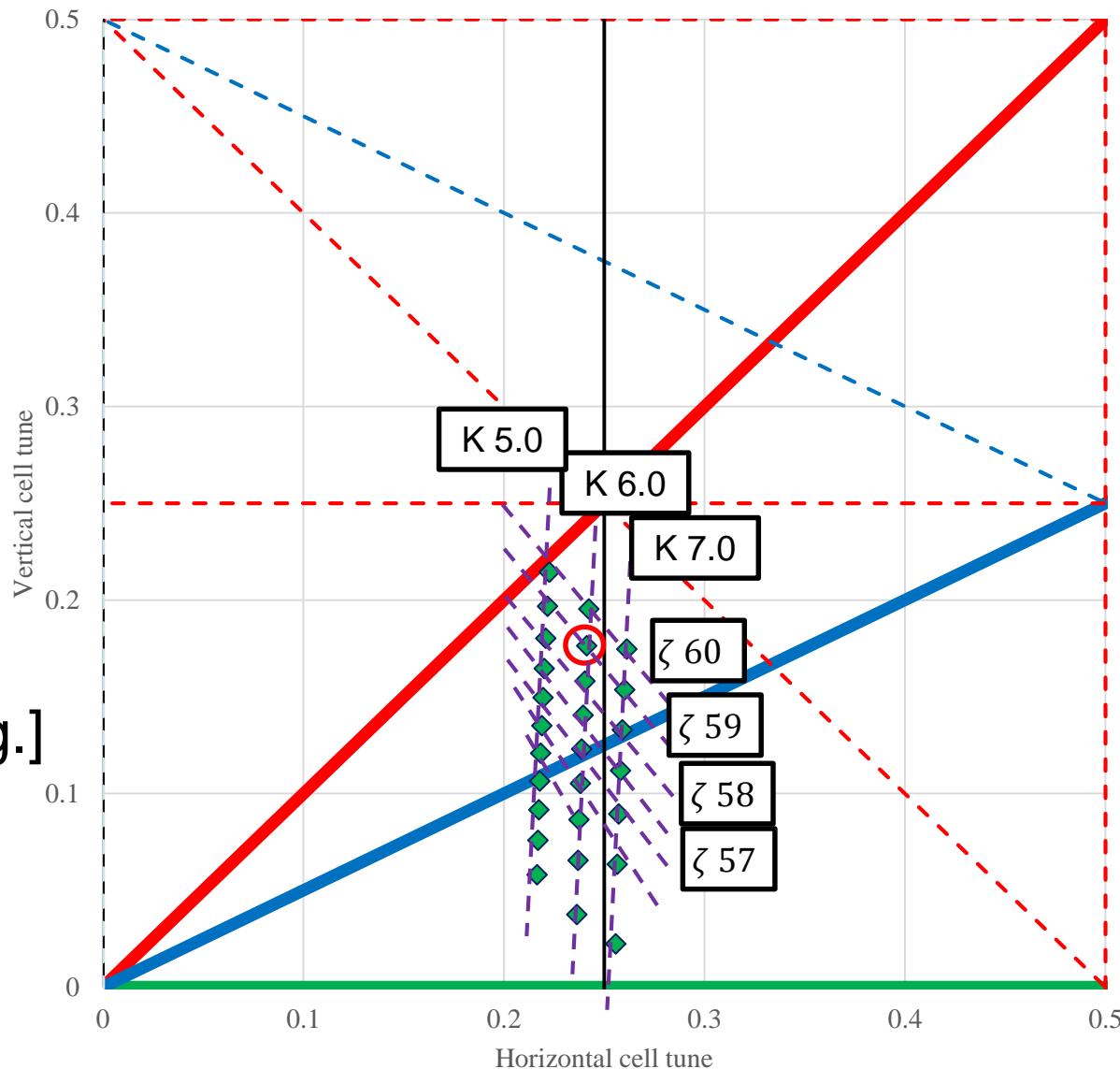
# Parameter search for 400 MeV Spiral FFAG with linear approximation

## Fixed parameters

- $p_f$ : 0.44
- Cell number : 12

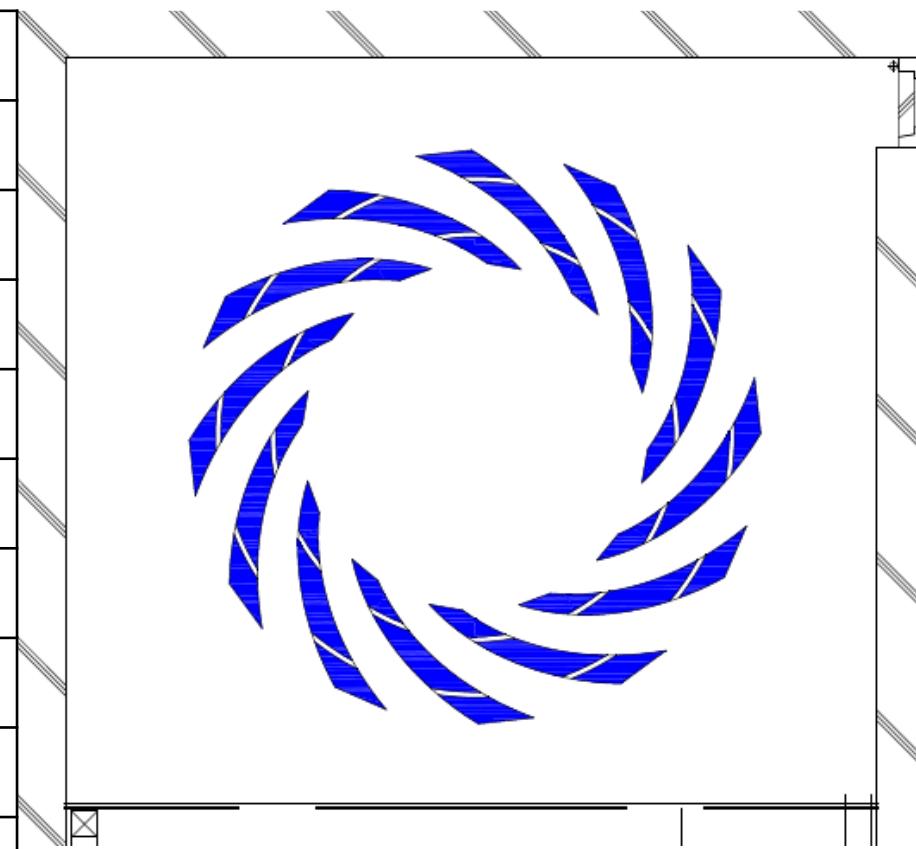


Field index :  $k = 6.0$   
Spiral angle : 59.0 [deg.]



# Optics parameter of 400 MeV Spiral

Injection/Extraction beam Radius	4.15 [m] / 4.63 [m]
Injection/Extraction Energy	100 [MeV] / 400 [MeV]
Momentum Ratio	2.15
Cell Number : $N$	12
Max. Magnetic Field	1.55 [T]
Packing Factor : $pf$	0.44
Field Index : $k$	6.0
Spiral Angle : $\zeta$	59.0 [deg.]
Horizontal Cell Tune	0.241
Vertical Cell Tune	0.176



Schematic view of 400 MeV  
Spiral FFAG @ Kyushu univ.

# Design method for spiral FFAG

Optics design with linear approximation

2D magnet modeling

Correction of field index : k

3D Spiral magnet modeling

Correction of  
field index : k, flutter factor, ~~spiral angle~~

Validate tune with tracking simulation

change

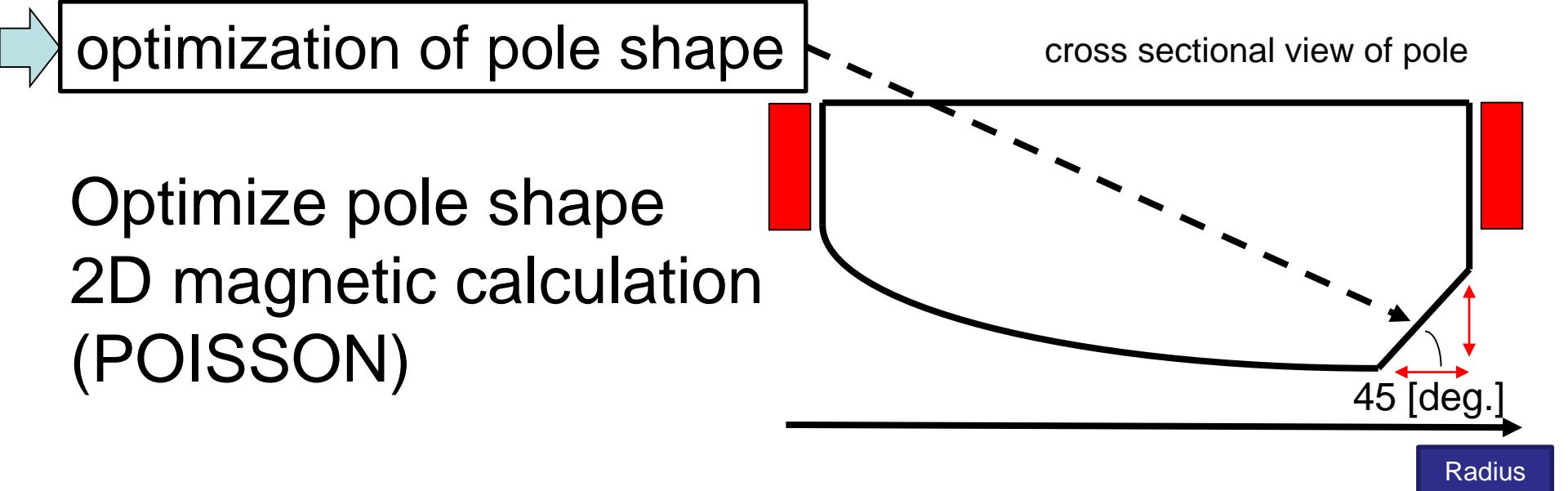
# 2D magnet modeling

One condition of Zero-chromaticity

Field gradient :  $k \Rightarrow$  constant (all momentum & excursion)

Magnetic saturation

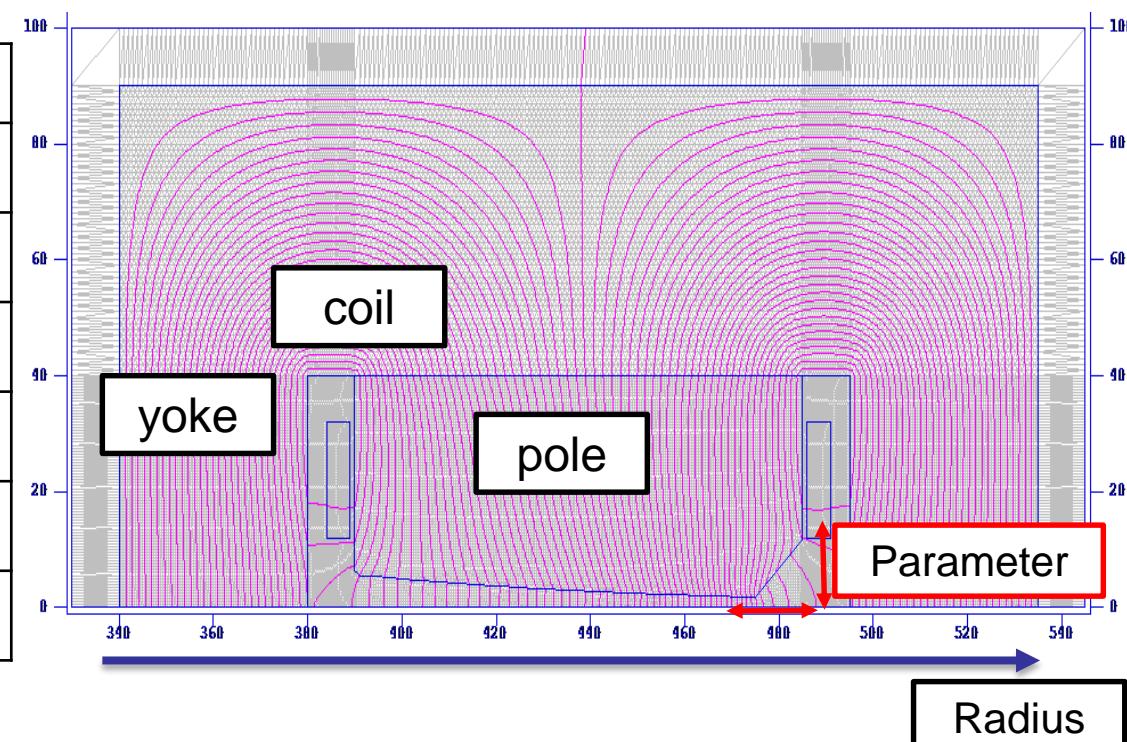
$\Rightarrow$  Valuation of local field gradient ; local  $k$



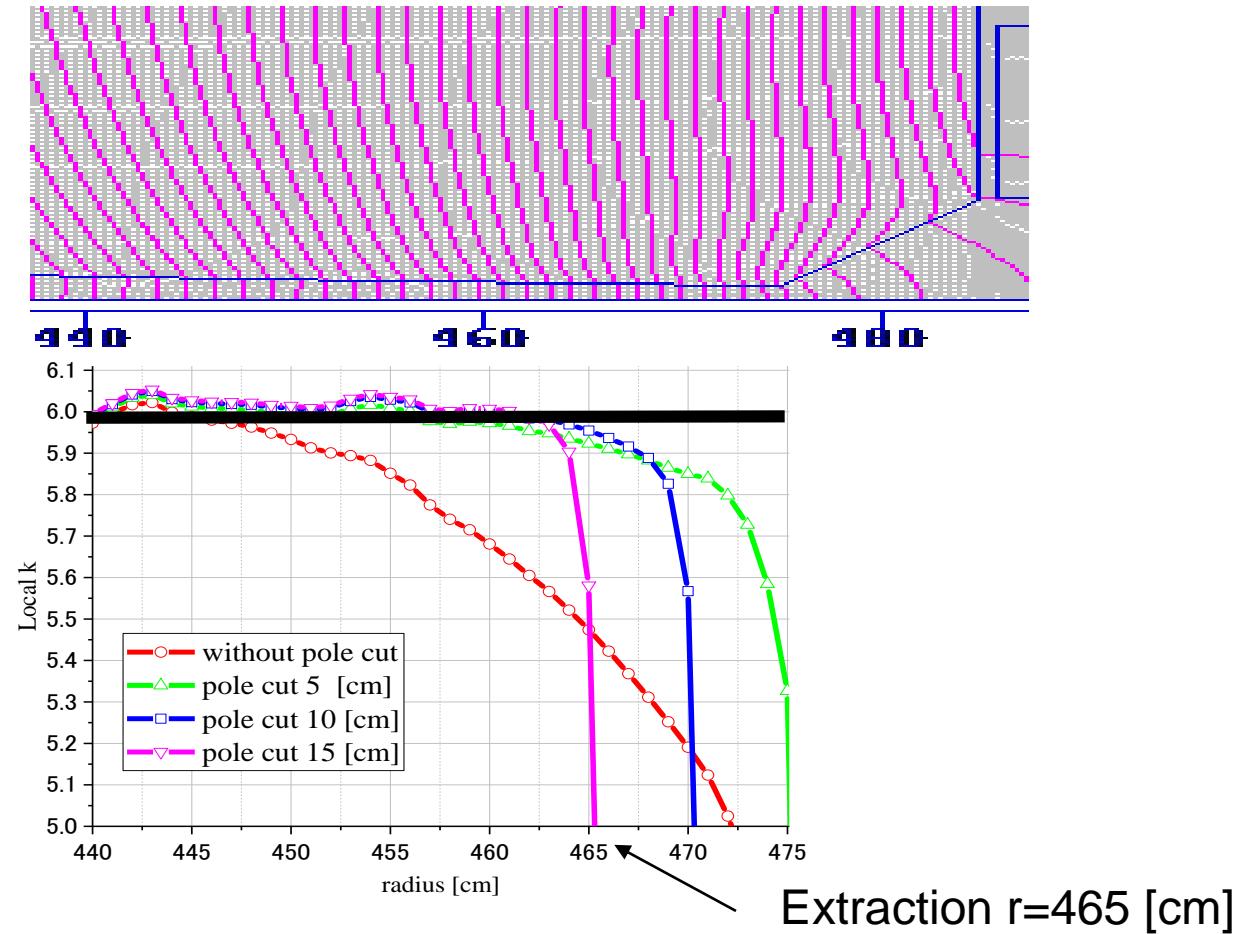
# 2D-magnet design

## Parameter of 2D magnet

Pole region	3.95 [m]/4.85 [m]
Yoke width	40.0 [cm]
Coil cross section	50 [mm] × 200 [mm]
Half Gap	2.0 [cm] @ R=4.65 [m]
Field Index : $k$	6.0
Current density	2.50 [A/mm <sup>2</sup> ]
Pole cut width	5.0 ~ 15.0 [cm]



# Result of calculation; POISSON



Pole cut width 10.0

⇒local k is the most closest  $k=6.0$  @extraction

# Design method for spiral FFAG

Optics design with linear approximation

2D magnet modeling

Correction of field index :  $k$

3D Spiral magnet modeling

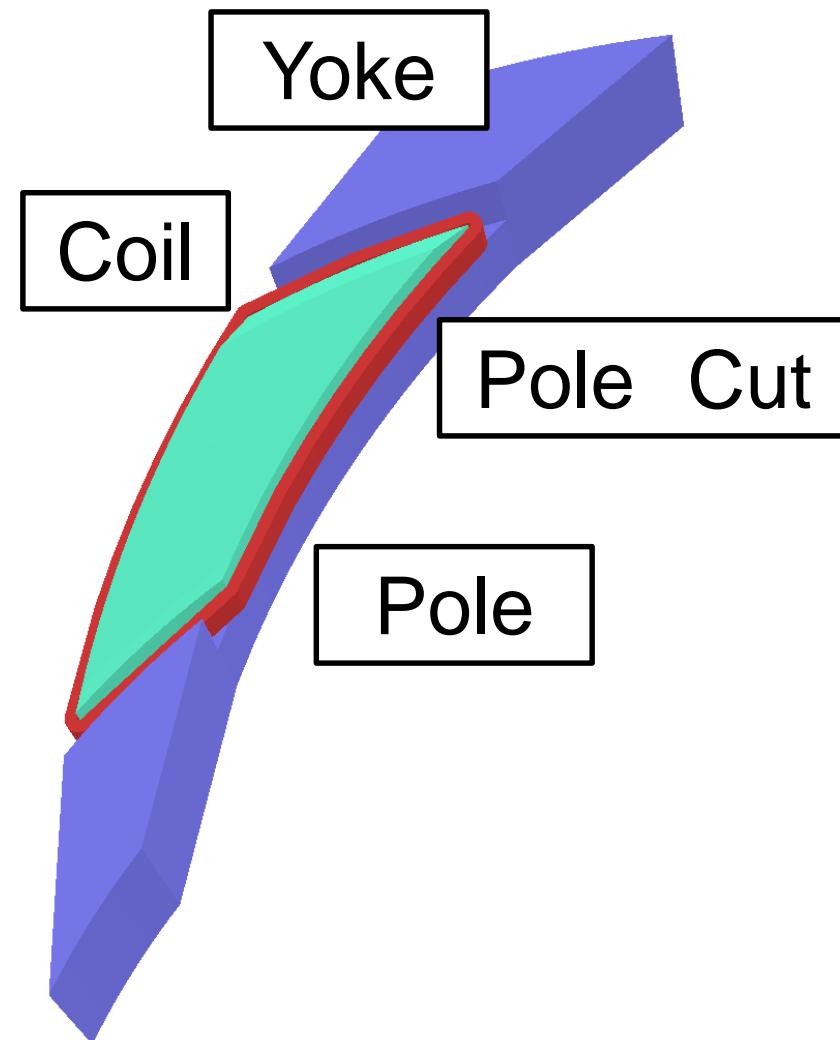
Correction of  
field index :  $k$ , flutter factor, ~~spiral angle~~

Validate tune with tracking simulation

change

# 3D magnet design for Spiral magnet

Max. Radius of Magnet	5.45 [m]
Injection/Extraction beam Radius	4.15 [m] / 4.63 [m]
Injection/Extraction Energy	100 [MeV] / 400 [MeV]
Momentum Ratio	2.15
Cell Number : $N$	12
Max. Magnetic Field	1.55 [T]
Packing Factor : $pf$	0.44
Field Index : $k$	6.0
Spiral Angle : $\zeta$	59.0 [deg.]
Half Gap	2.0 [cm] @ R=4.15[m]
Current density	3.2 [A/mm <sup>2</sup> ]
Weight of half magnet	12.7 [t]

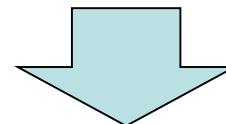


# 3D Spiral magnet design

Flutter Factor of Spiral Magnet in Hard Edge Model

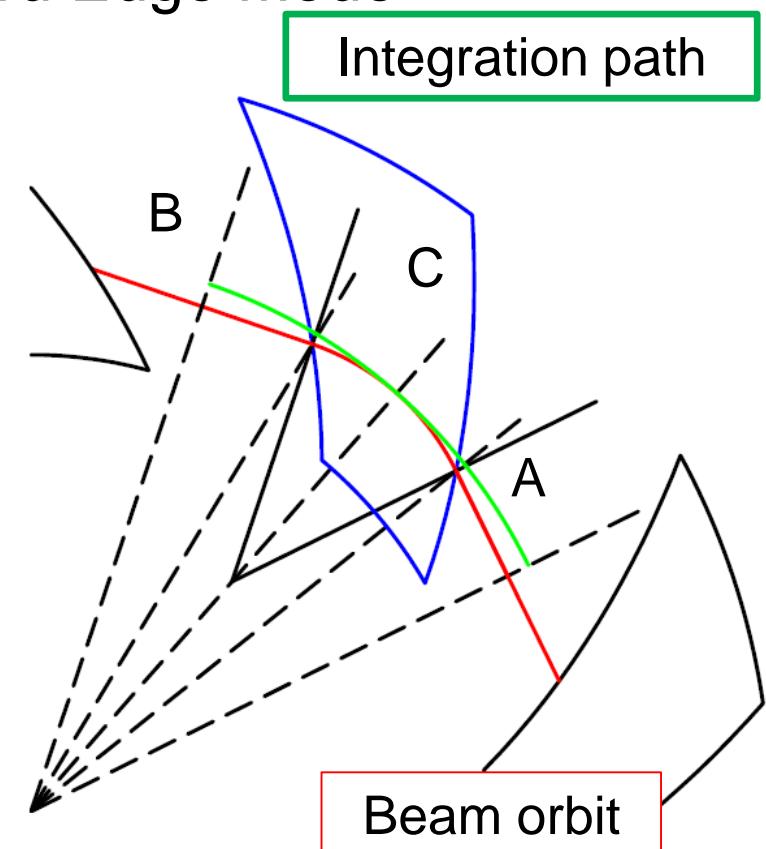
$$F^2 = \frac{<(B(\theta) - \bar{B})^2>}{\bar{B}^2} = \frac{R}{\rho} - 1 = \frac{1}{pf} - 1$$

In realistic magnet, flutter is variable because of variation of fringing field



Packing Factor including field  
⇒ Effective Packing Factor :  $pf^{eff}$

$$pf^{eff} = \frac{\left( \int_A^B B dl / B_{center} \right)}{\int_A^B dl} = \frac{L^{eff}}{\int_A^B dl}$$



In order to correct  $pf^{eff}$

① Optimization of boundary of magnet ( $pf$ )

② Optimization of gap geometry of field clamp

In order to correct  $pf^{eff}$

① Optimization of boundary of magnet ( $pf$ )

② Optimization of gap geometry of field clamp

# ① Optimization of boundary of magnet ( $pf$ )

Due to the fringe field

$$\Rightarrow pf^{eff} > pf_{optics}$$

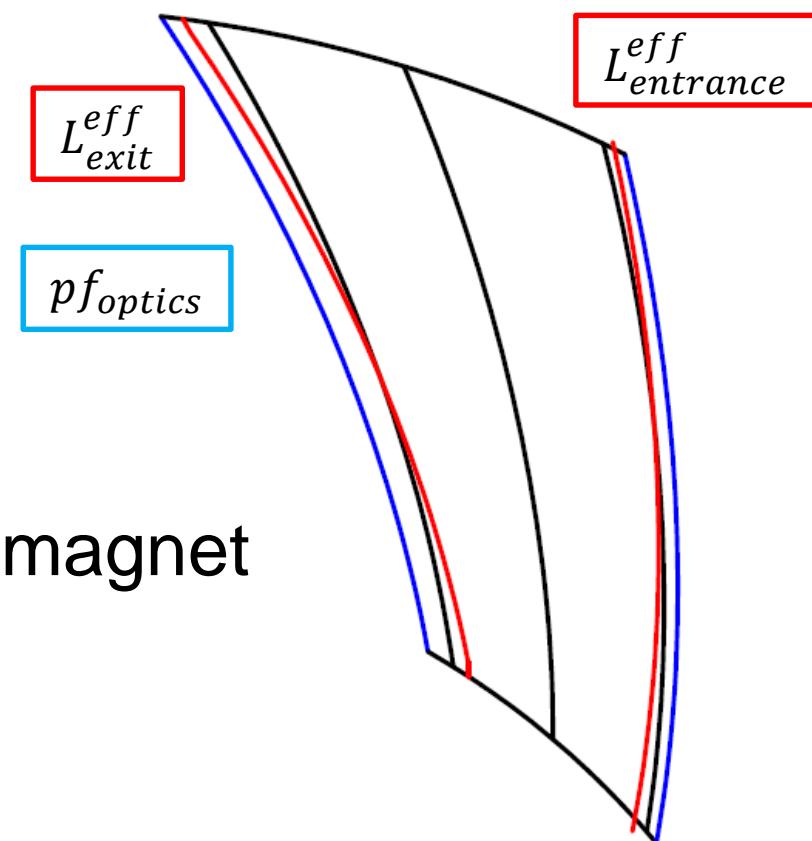
Ordinal : using index :  $L_{entrance|exit}^{eff}$

Optimization of  $pf$  of main magnet

$$\Rightarrow pf_{optimized} = pf_{optics} - (pf_{minimum}^{eff} - pf_{optics})$$

Using this method...

- constant spiral angle of spiral magnet
- symmetric geometry
- correction of  $pf^{eff}$  in general



# ① Optimization of boundary of magnet ( $pf$ )

Due to the fringe field

$$\Rightarrow pf^{eff} > pf_{optics}$$

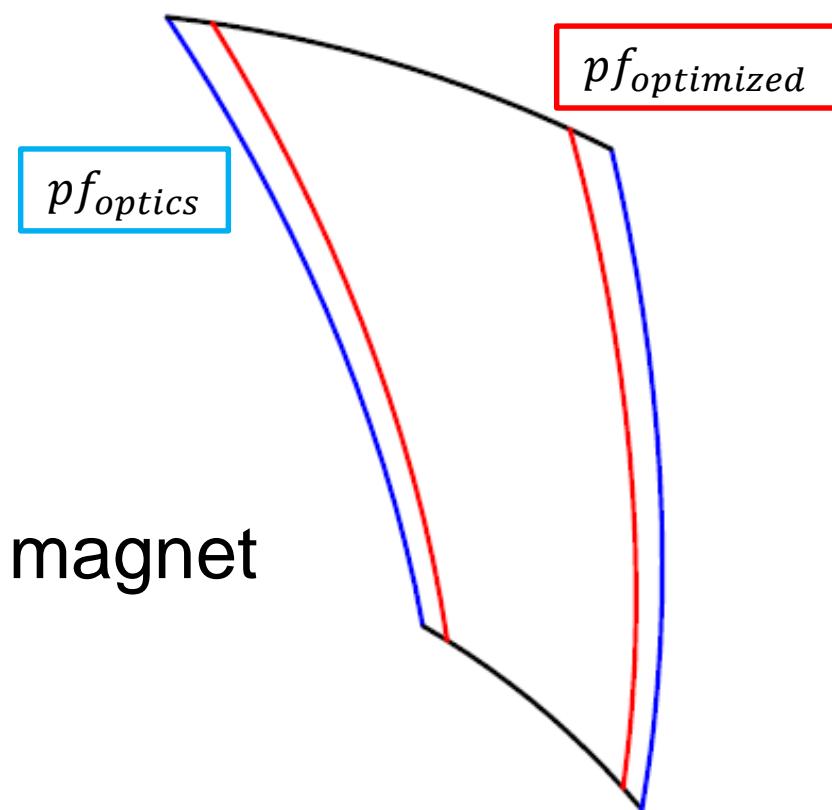
proposed : using index :  $pf^{eff}$

Optimization of  $pf$  of main magnet

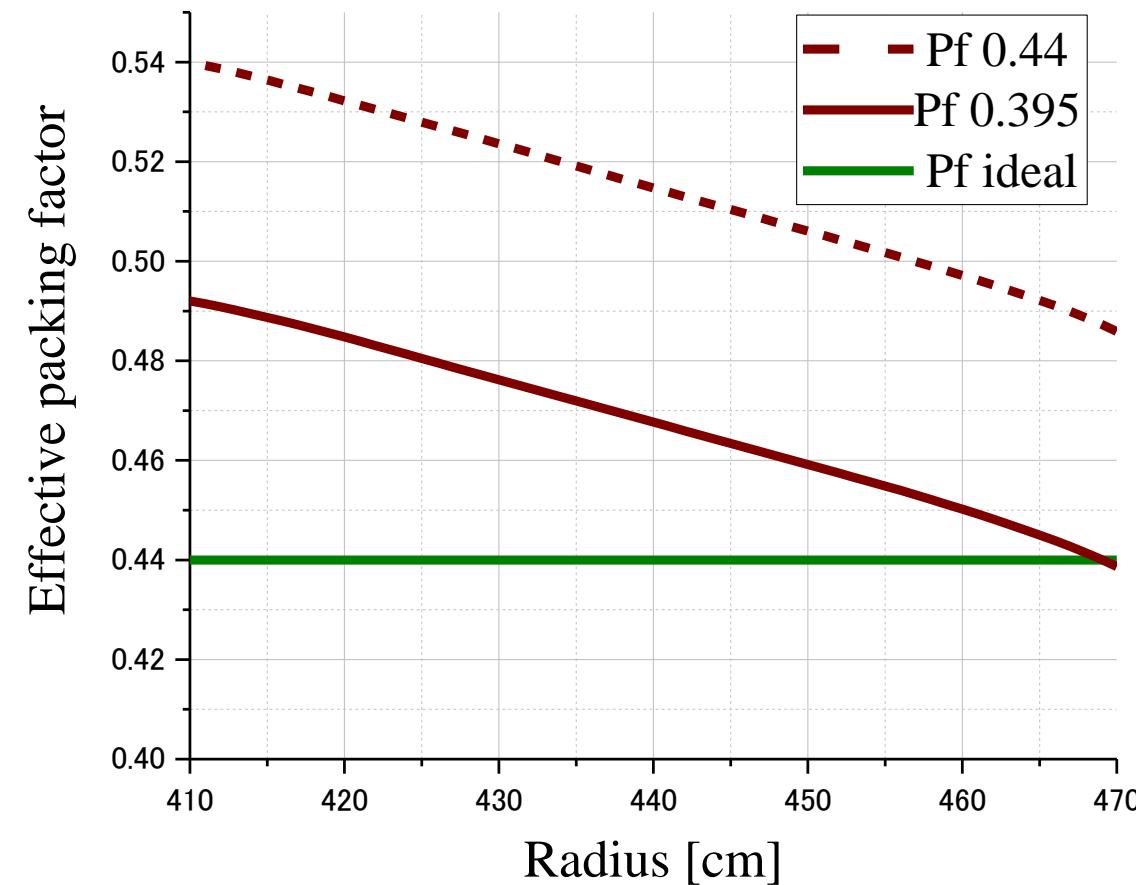
$$\Rightarrow pf_{optimized} = pf_{optics} - (pf_{minimum}^{eff} - pf_{optics})$$

Using this method...

- constant spiral angle of spiral magnet
- symmetric geometry
- correction of  $pf^{eff}$  in general



# Correction of packing Factor of magnet



Correction of effective packing factor at outside radius by this optimization

In order to correct  $pf^{eff}$

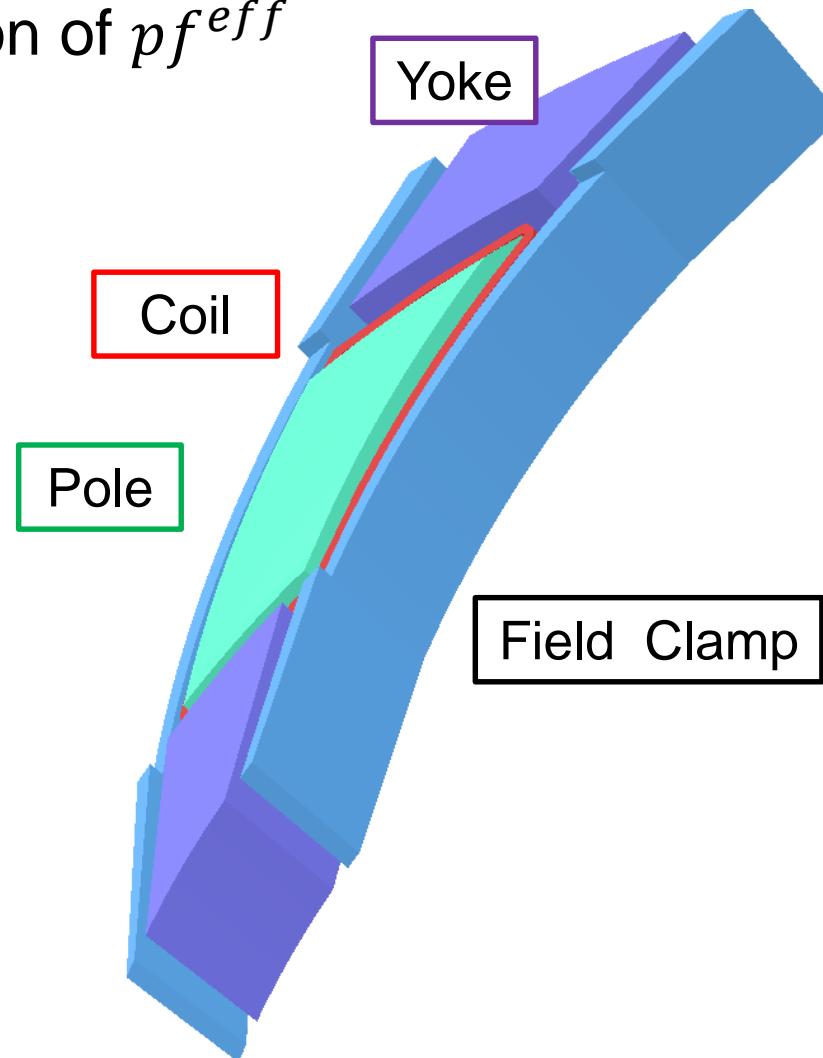
① Optimization of packing factor

② Optimization of gap geometry of field clamp

## ② Optimization of gap geometry of field clamp

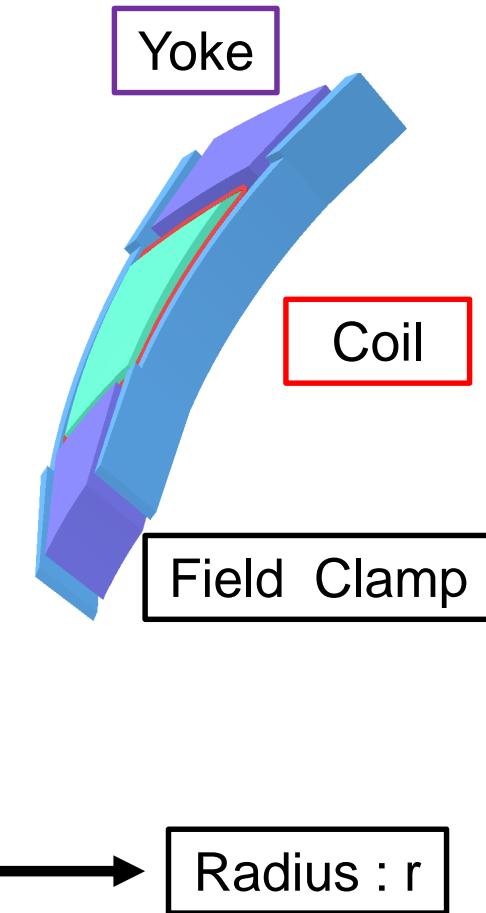
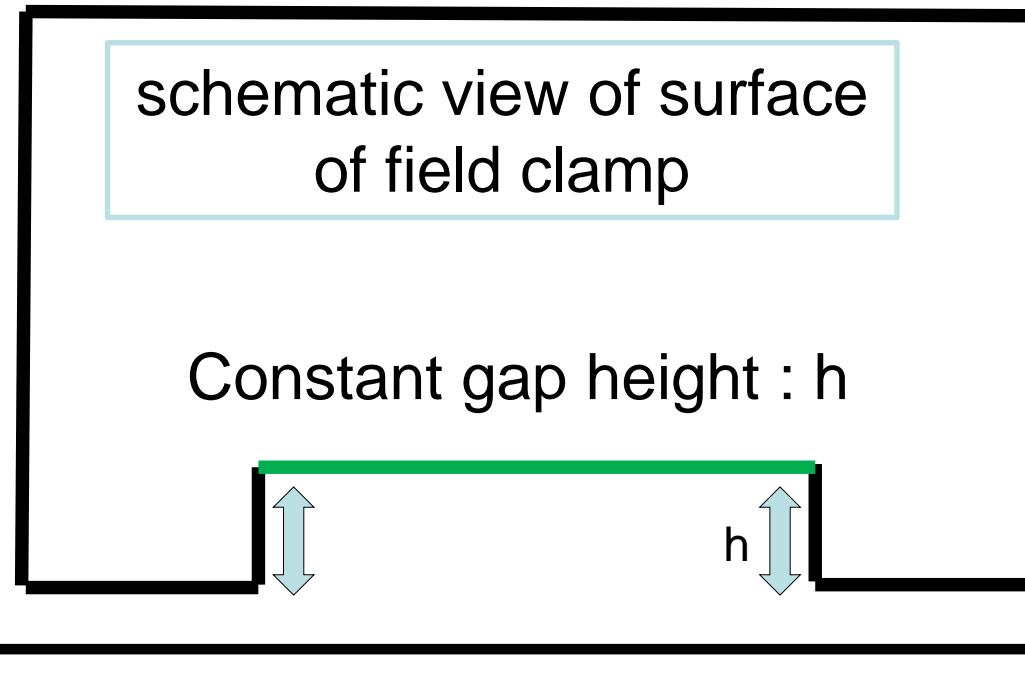
Variable gap height of field clamp depend on radius

⇒ correct variation of  $p f^{eff}$



## ② Optimization of gap geometry of field clamp

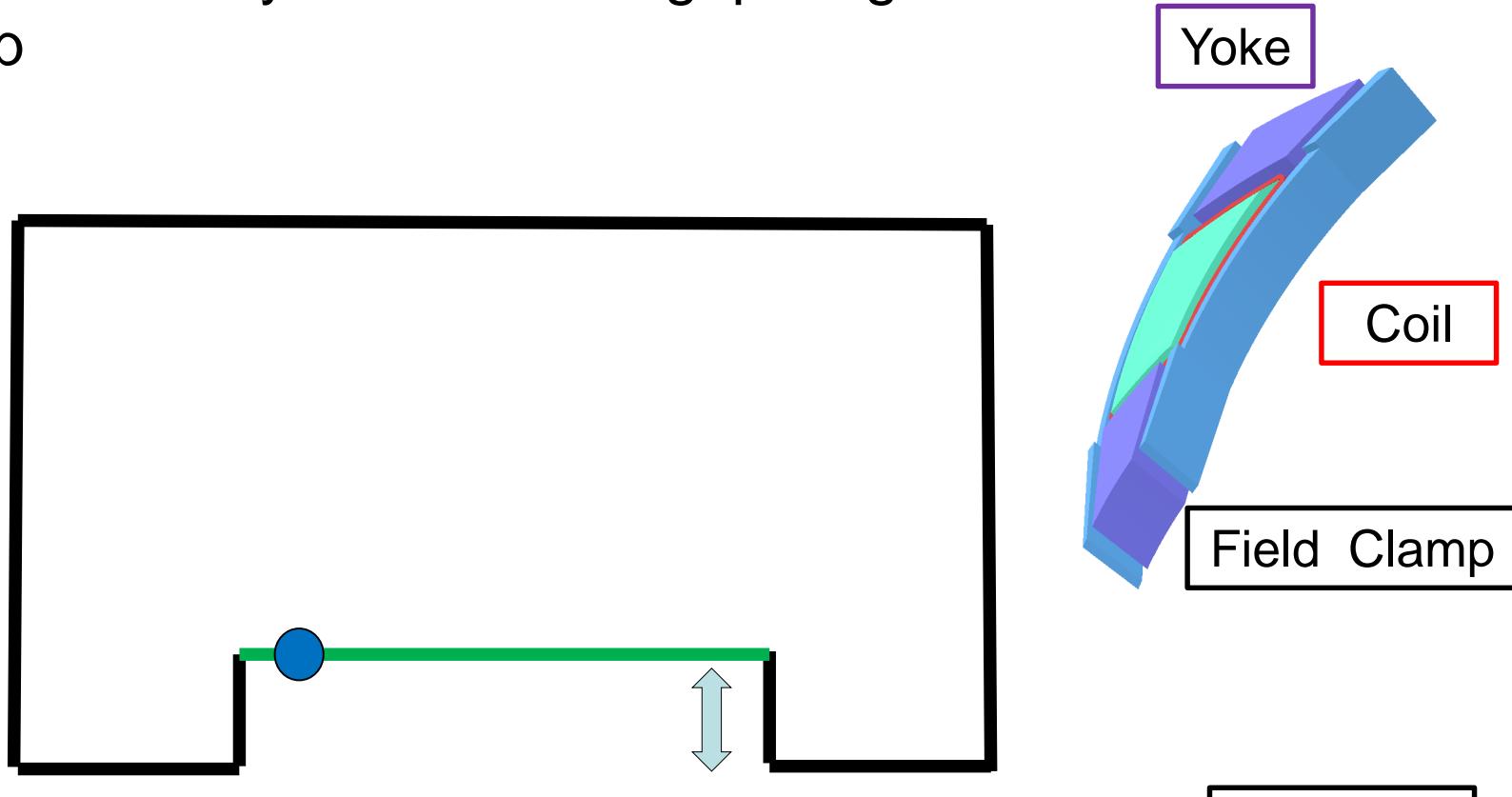
Correct  $p_f^{eff}$  locally with variable gap height of field clamp



Calculation of  $p_f^{eff}$  while changing gap height

## ② Optimization of gap geometry of field clamp

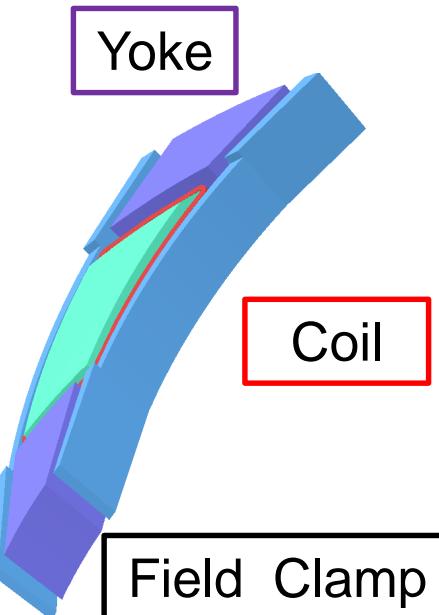
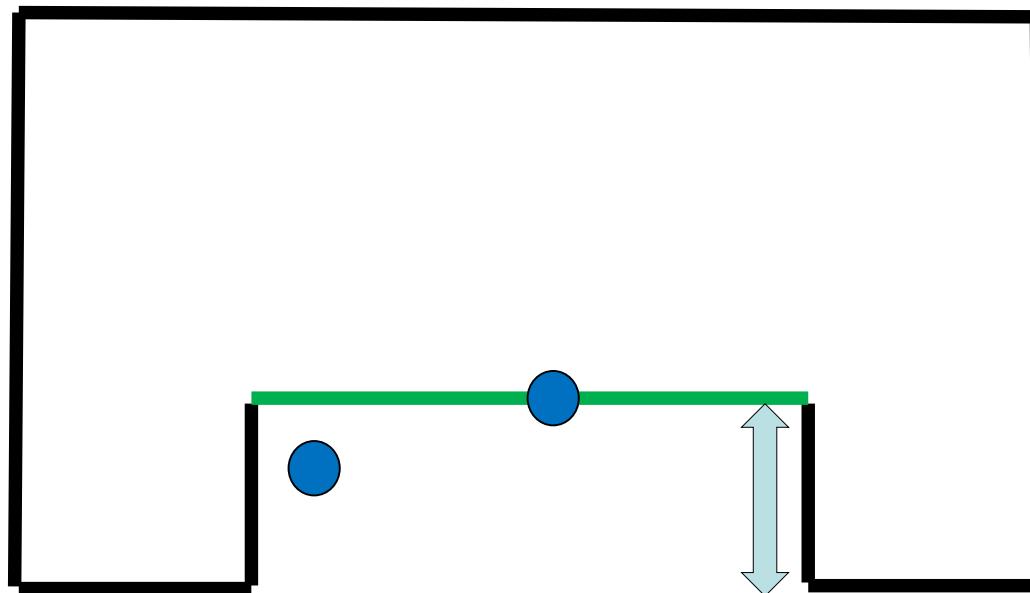
Correct  $p_{f^{eff}}$  locally with variable gap height of field clamp



Pick up points  $(r,h)$  in case  $p_{f^{eff}} = p_{f^{optics}}$

## ② Optimization of gap geometry of field clamp

Correct  $p_{f^{eff}}$  locally with variable gap height of field clamp



Field Clamp

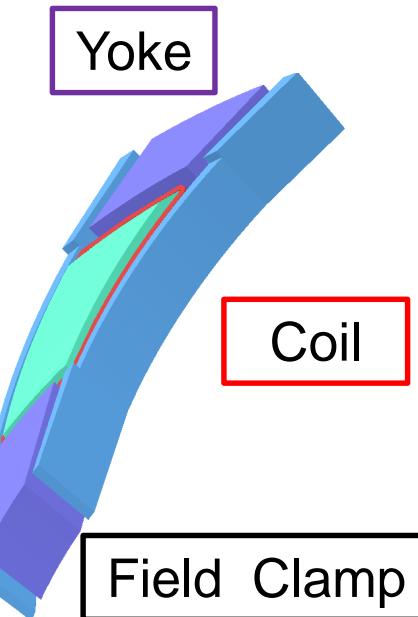
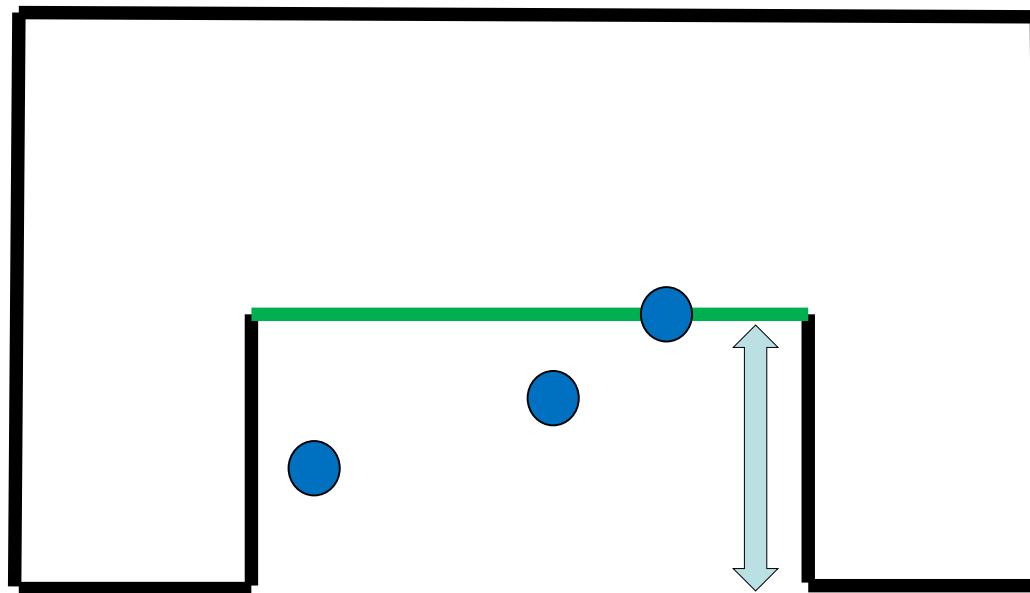
Coil

Radius : r

Pick up points  $(r,h)$  in case  $p_{f^{eff}} = p_{f^{optics}}$

## ② Optimization of gap geometry of field clamp

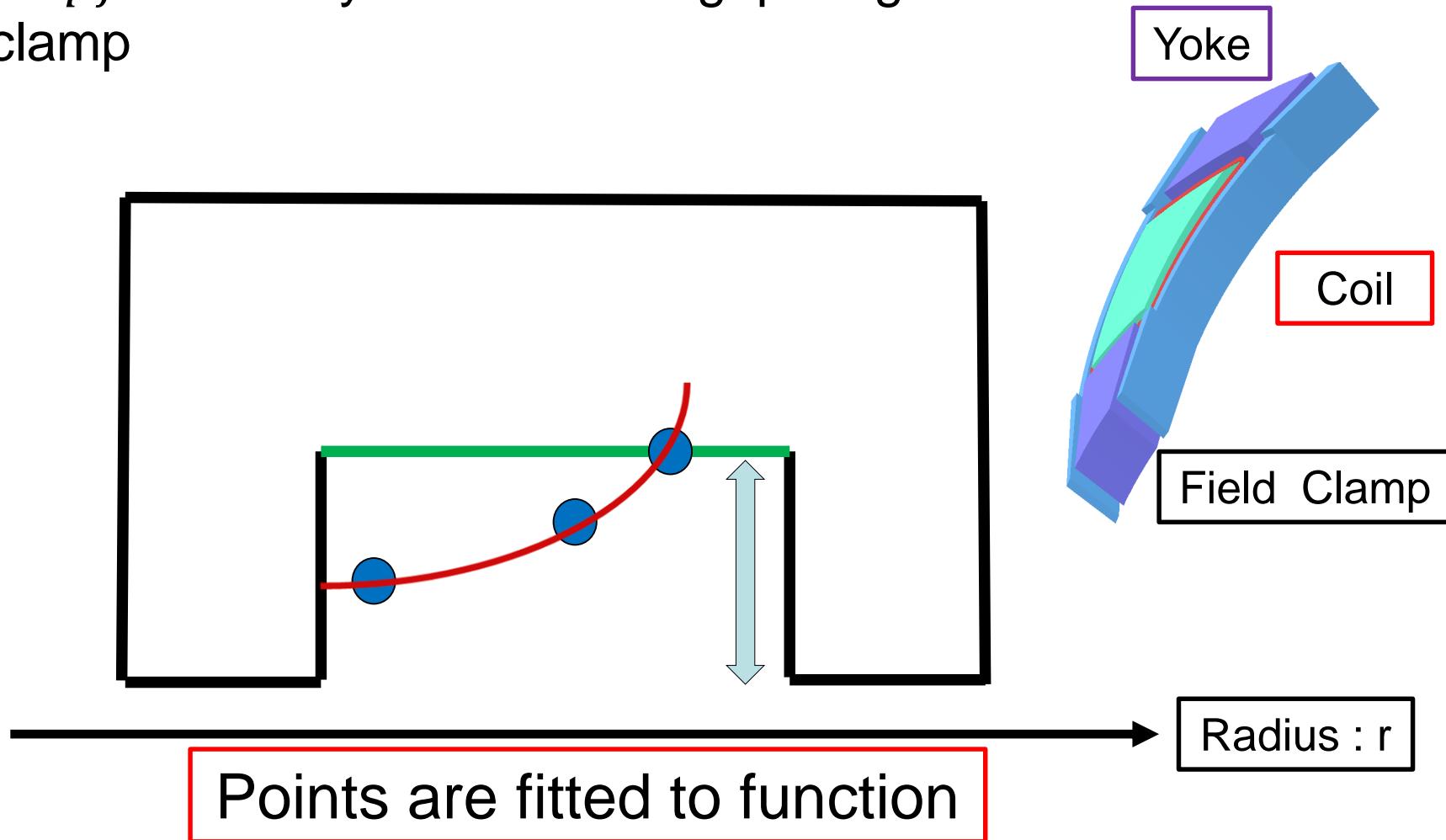
Correct  $p_{f^{eff}}$  locally with variable gap height of field clamp



Pick up points  $(r,h)$  in case  $p_{f^{eff}} = p_{f^{optics}}$

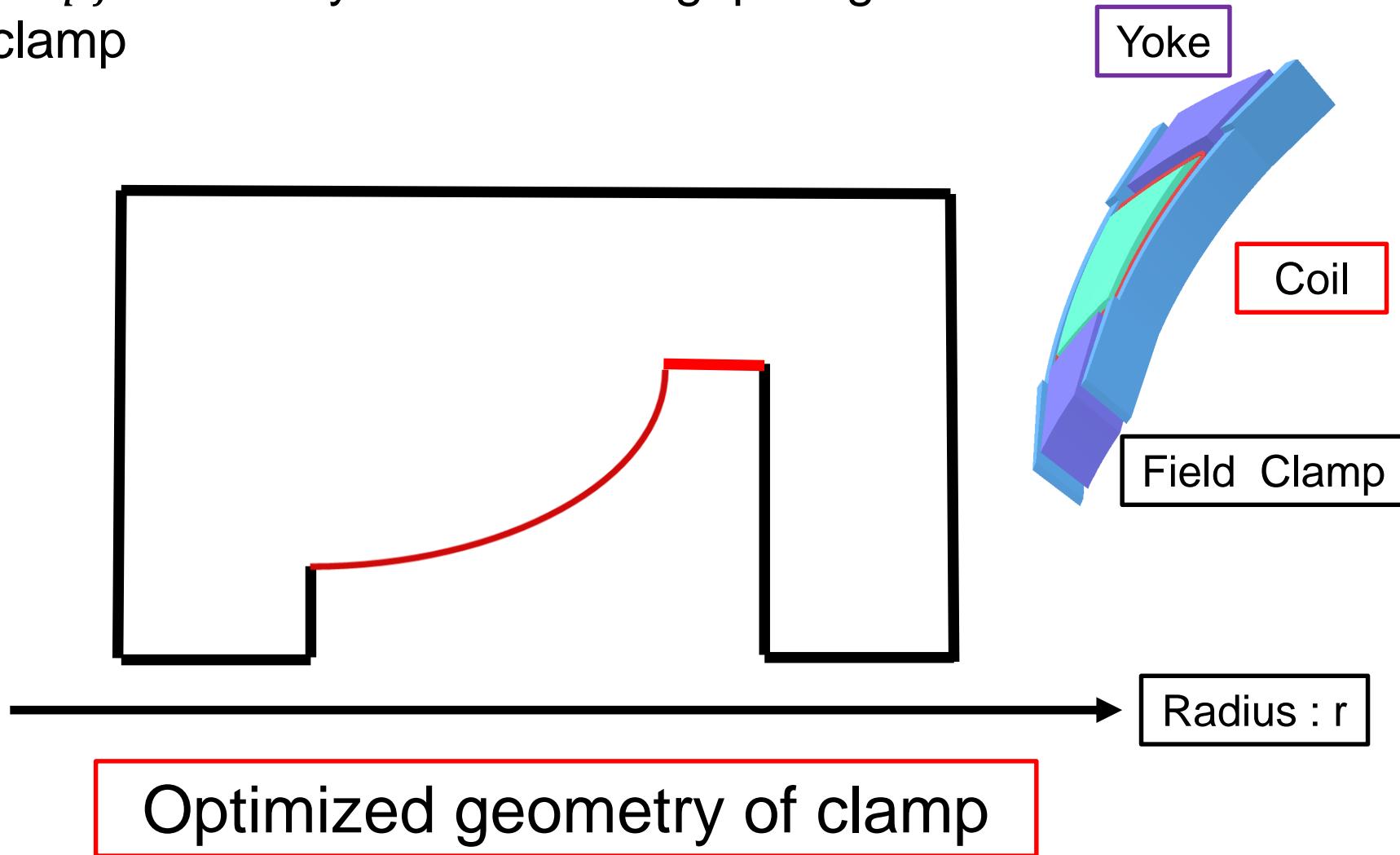
## ② Optimization of gap geometry of field clamp

Correct  $p_f^{eff}$  locally with variable gap height of field clamp

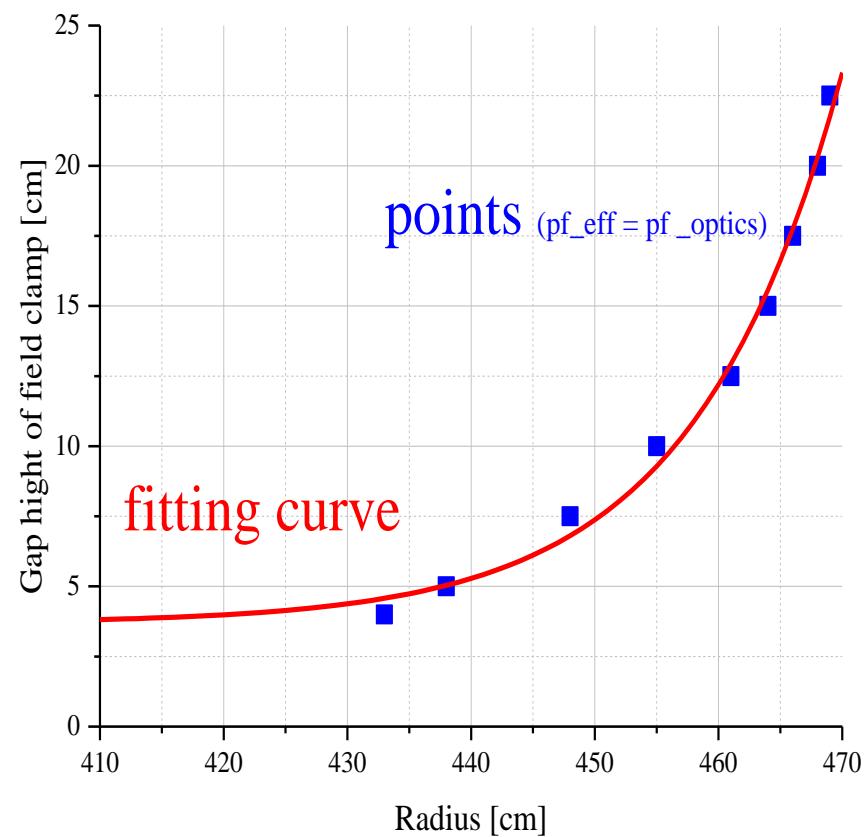
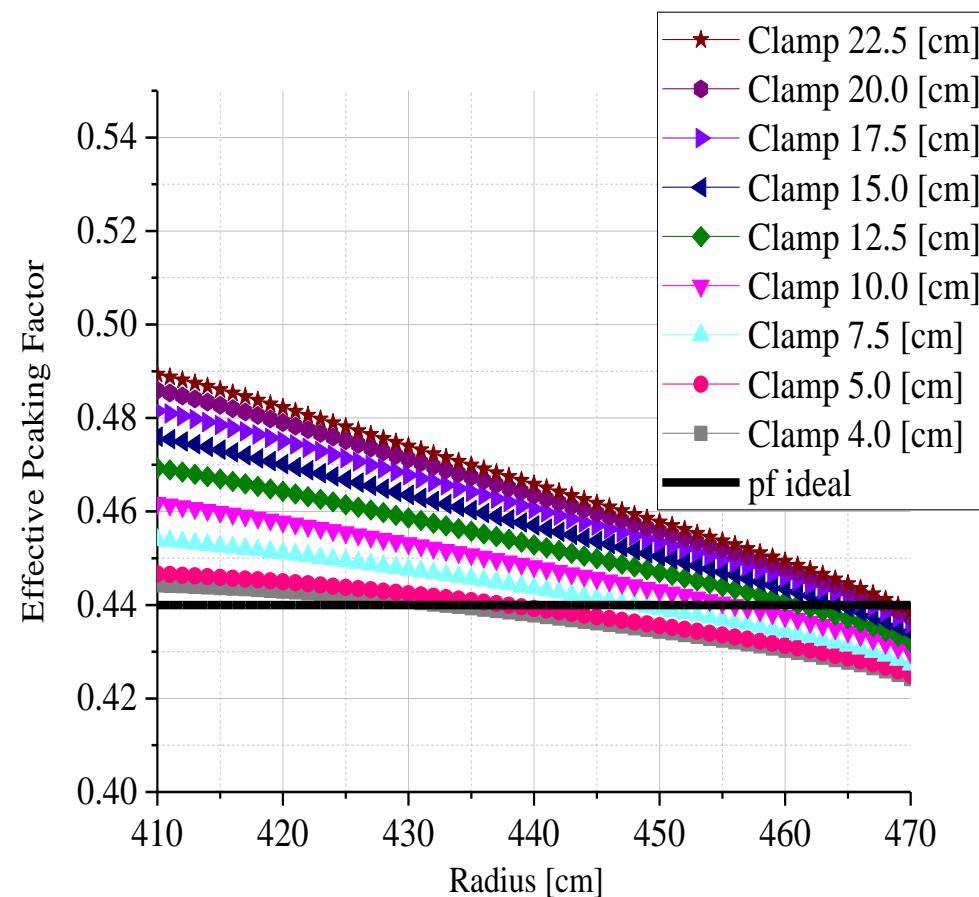


## ② Optimization of gap geometry of field clamp

Correct  $p_f^{eff}$  locally with variable gap height of field clamp



# Optimization of Field Clamp geometry

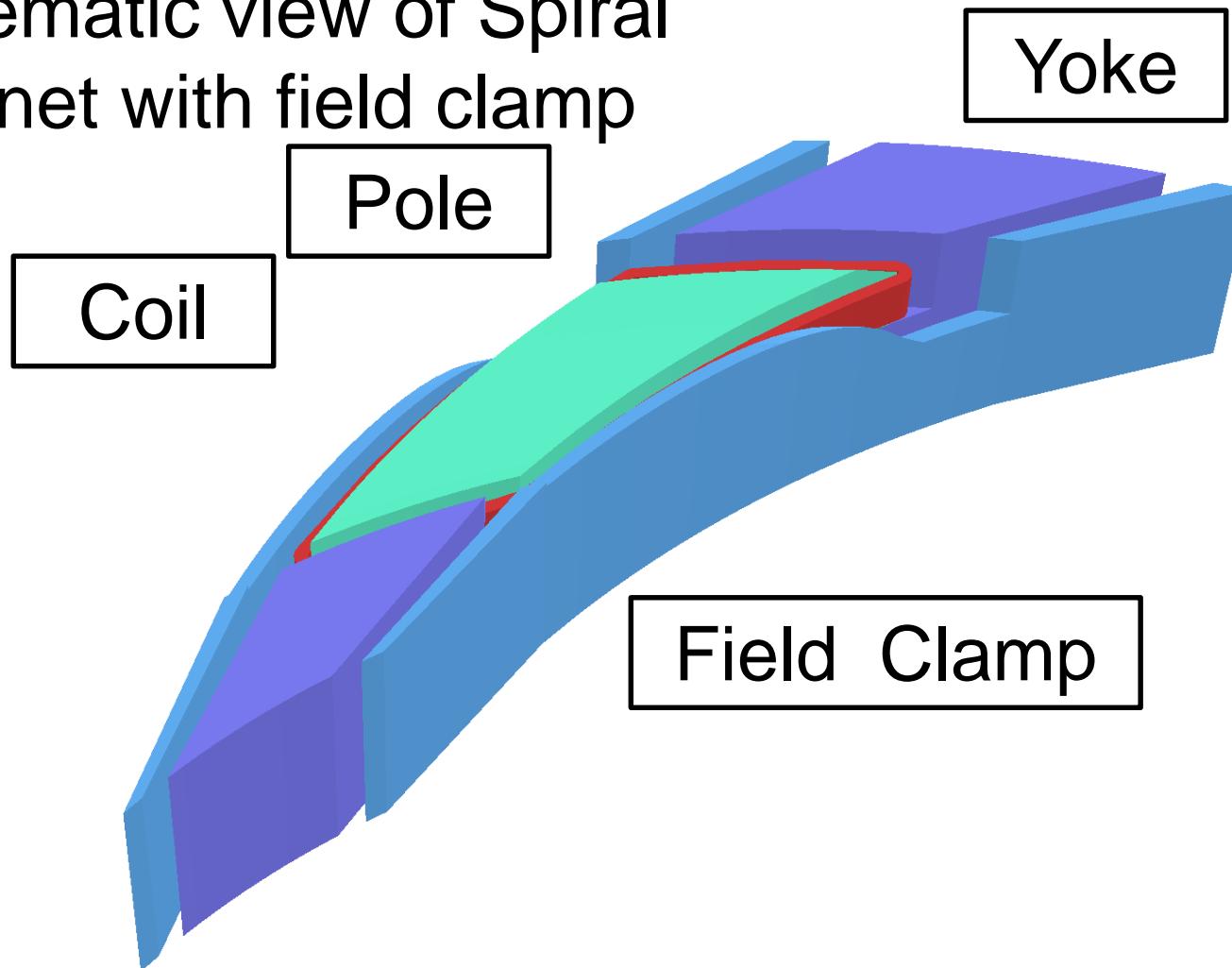


In this model...

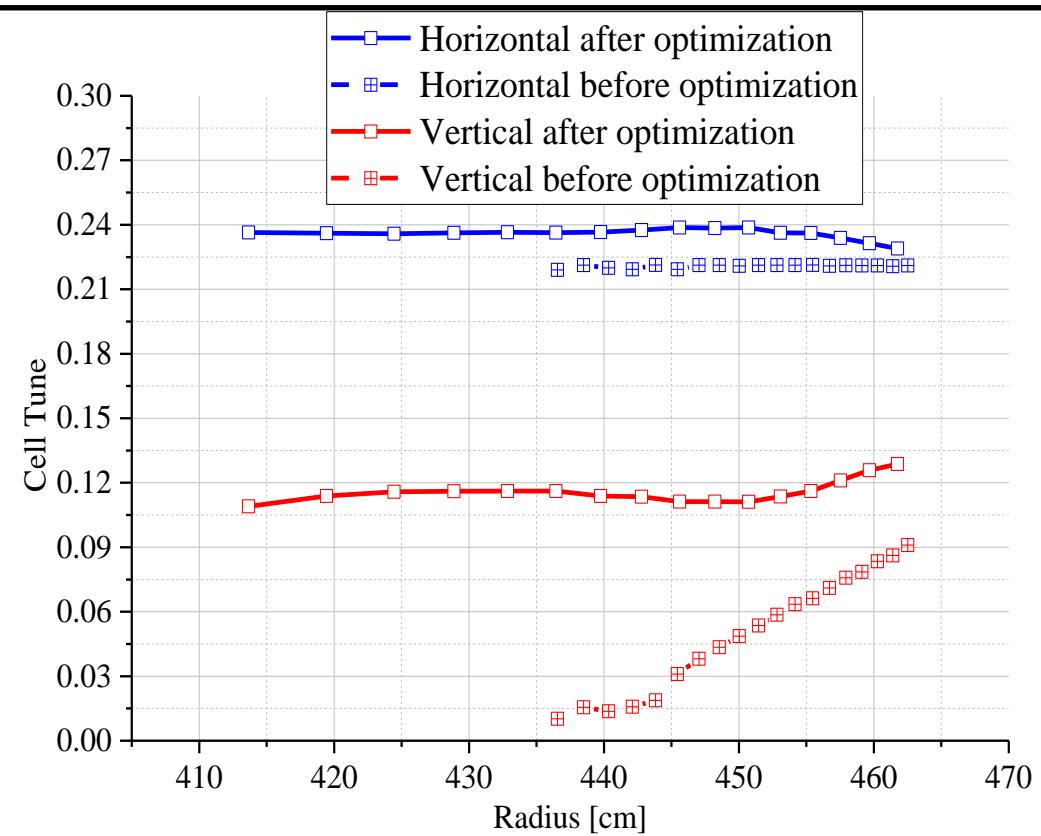
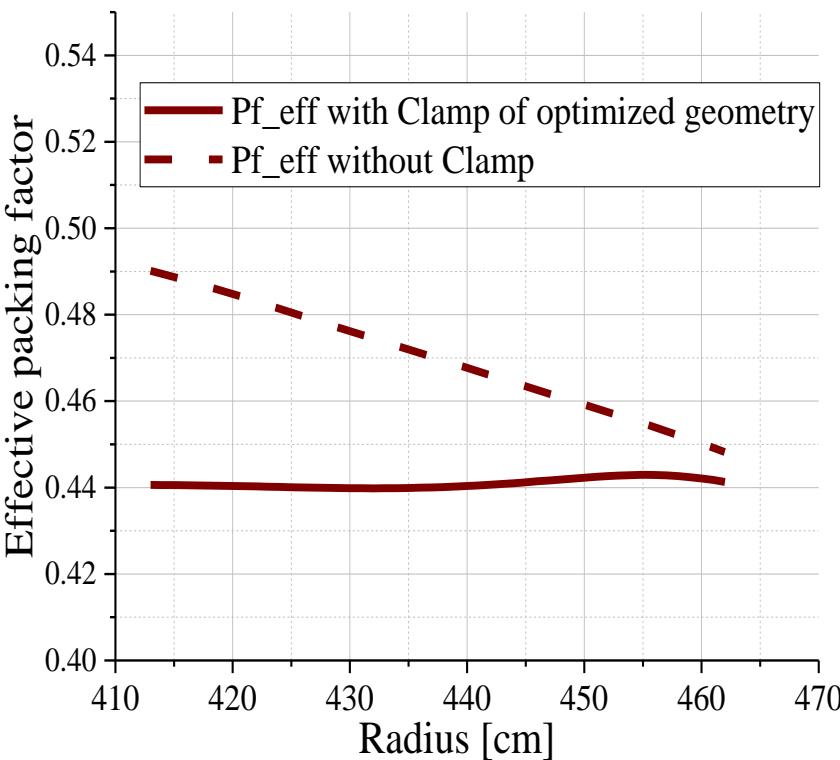
$$\text{Gap height of field clamp} = 1.66 \times 10^{-16} \exp\left(\frac{\text{radius}}{12.0}\right) + 3.69$$

# 3D Modeling for Spiral magnet

Schematic view of Spiral Magnet with field clamp



# Tune Validate & effective packing factor



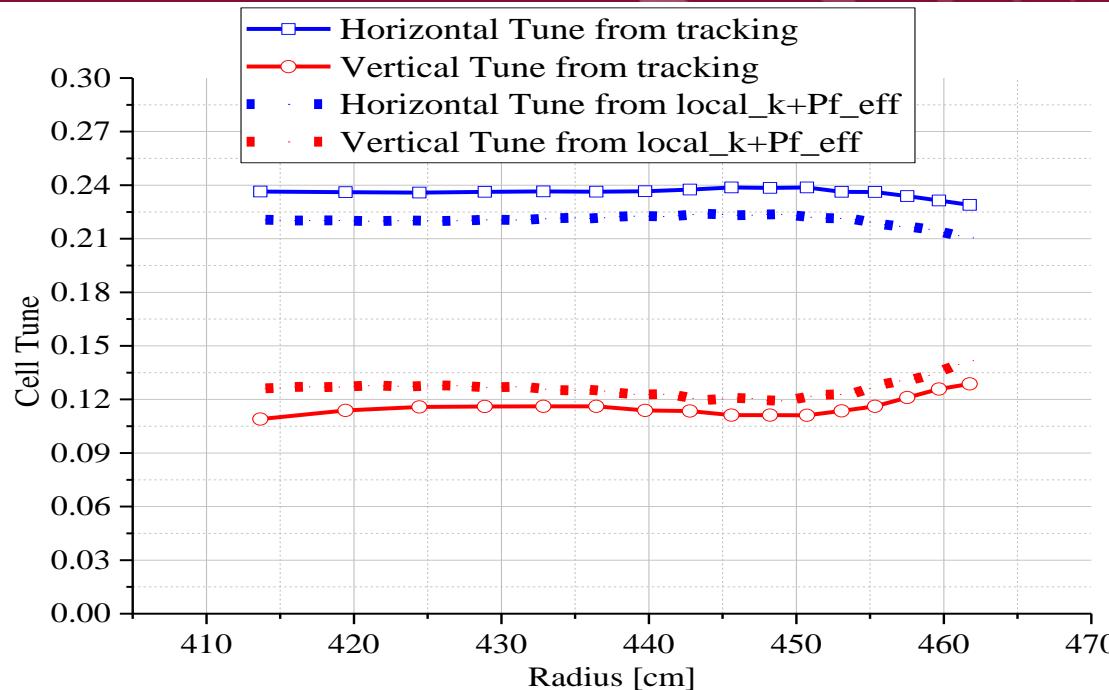
Before and after the optimization, vertical beam stability,  
220 [MeV]  $\Rightarrow$  100 [MeV]

tune shift



$$\Delta\nu_H = 0.007 \quad \Delta\nu_V = 0.020$$

# Consideration of tune shift



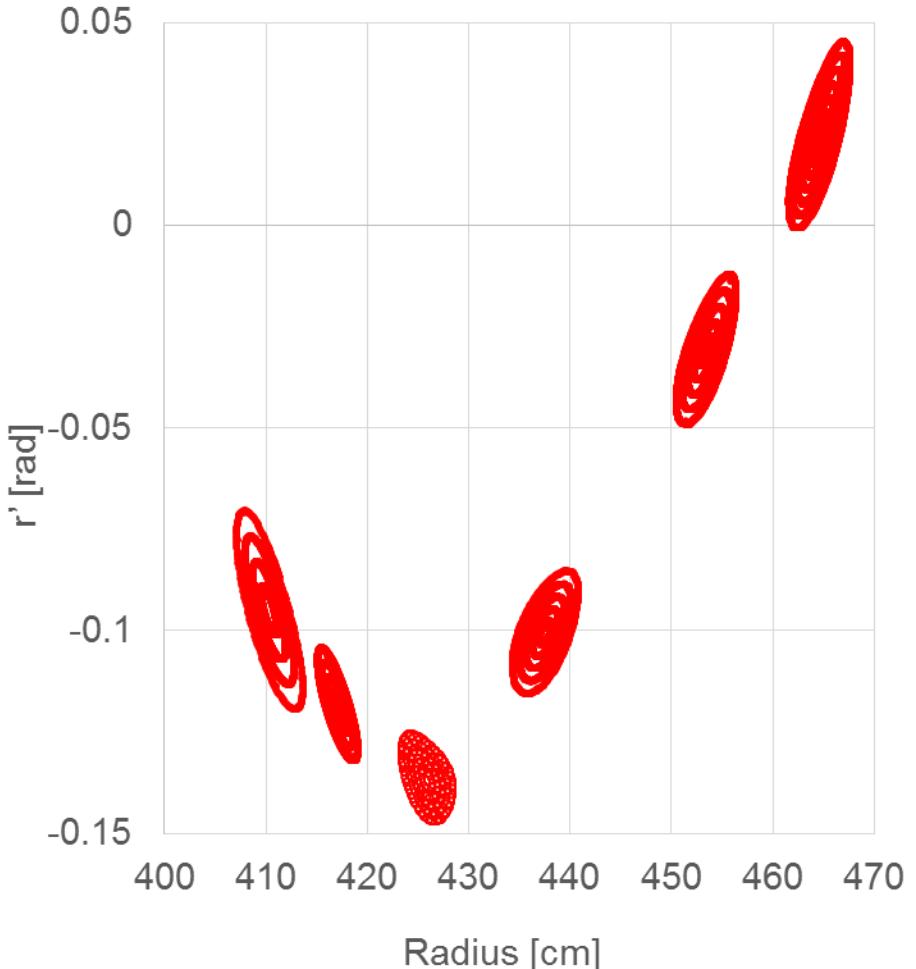
$$\nu_h = \sqrt{1 + loca\ k} \quad (1)$$

$$\nu_v = \sqrt{-local\ k + (1/pf^{eff} - 1)(1 + 2 \tan^2 \zeta)} \quad (2)$$

- tune shift calculated from simulation and eq.(1)&(2) denote the same tendency.
  - ⇒ tune shift derives from error of local  $k$  &  $pf^{eff}$ .
  - ⇒ possibility of spiral magnet design which satisfy the zero-chromaticity using this method have been indicated.

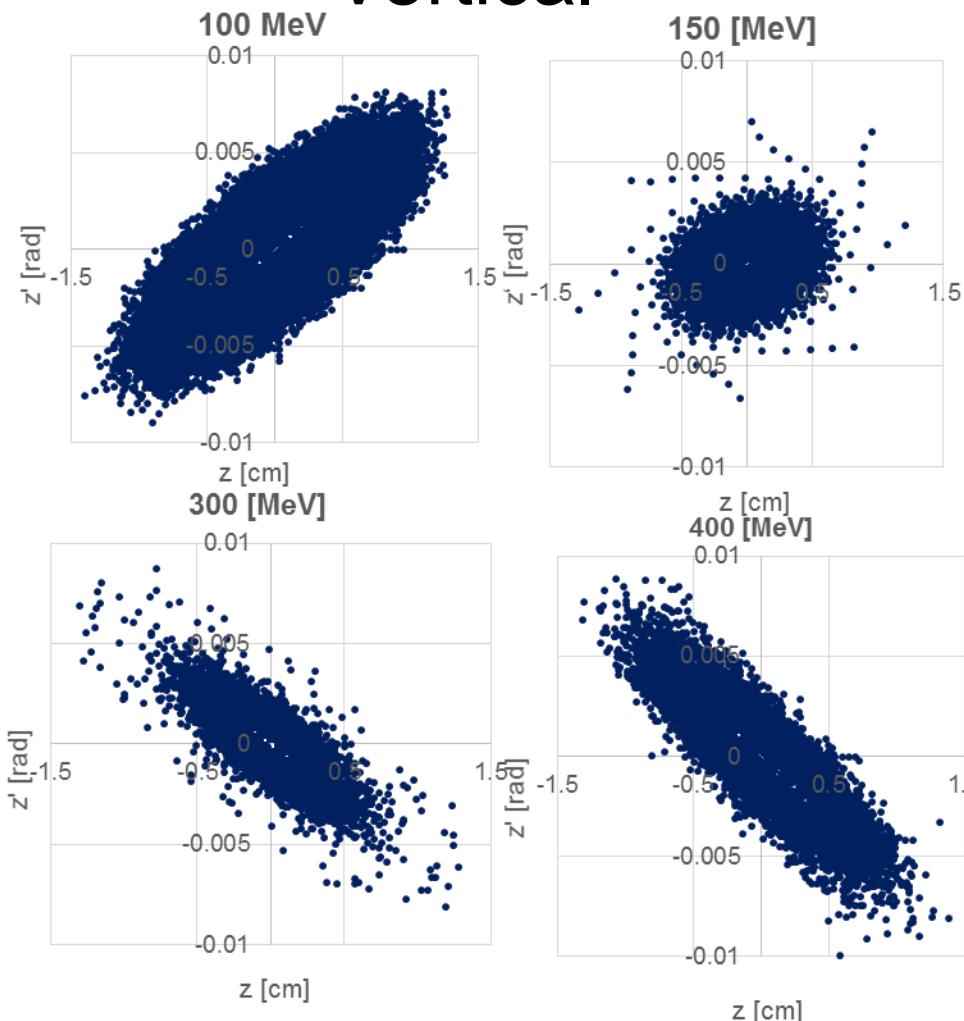
# Acceptance

horizontal



horizontal acceptance  $\sim 2500 \pi \text{ mm rad}$  @injection

Vertical



Vertical acceptance  $\sim 50 \pi \text{ mm rad}$  @injection

# Summary

Preposition of simple design method for medium-energy  
Spiral FFAG

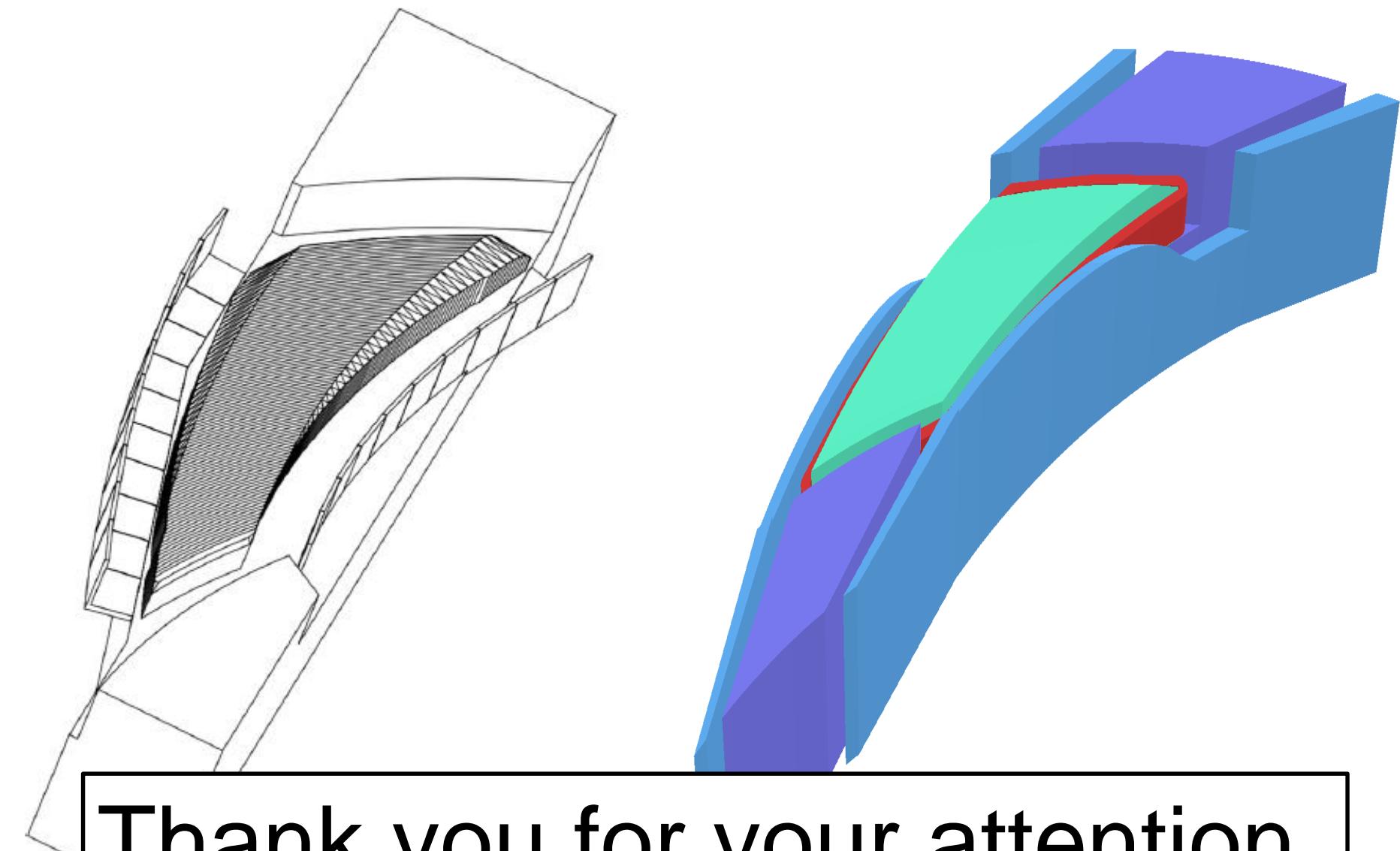
- Control tune variation with two indexes (local k & effective packing factor)
- Correction of the two indexes with fewer optimization parameters  
⇒ Simple main magnet geometry

## Design of 400 MeV Spiral FFAG

- Possibility of spiral magnet design that satisfied zero-chromaticity using the proposed method

## Further Improvement

Design Spiral FFAG of high-momentum ratio using this method

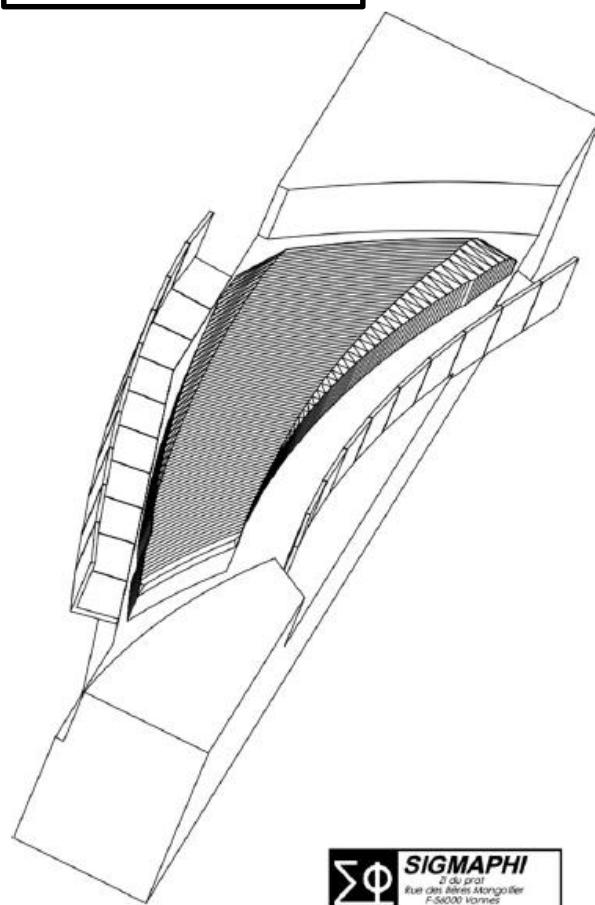


Thank you for your attention



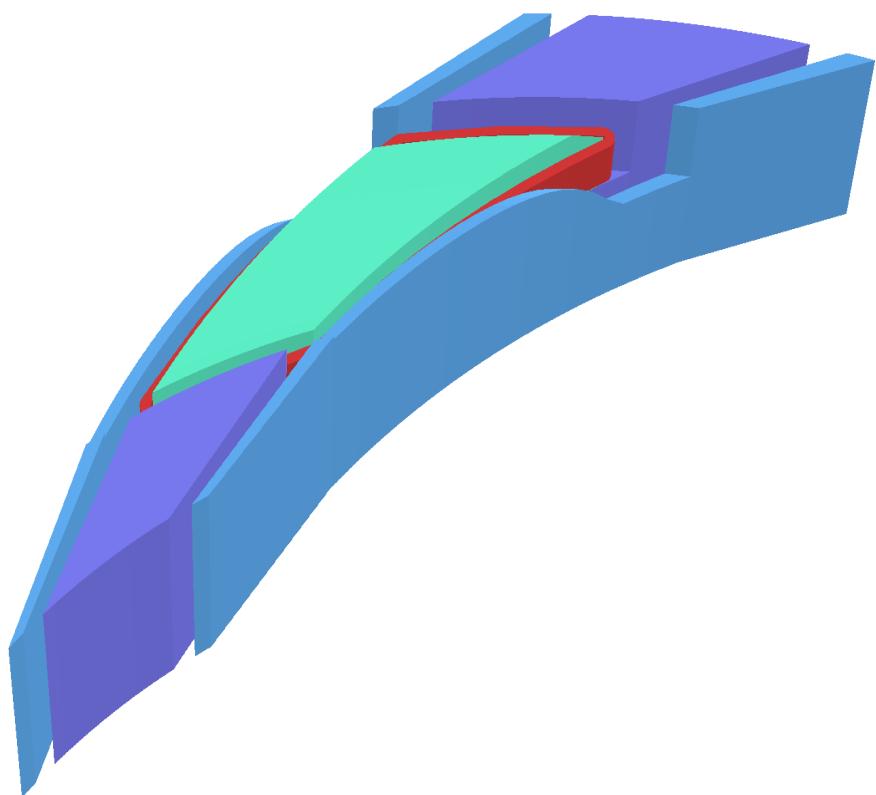
# Discussion

RACCAM

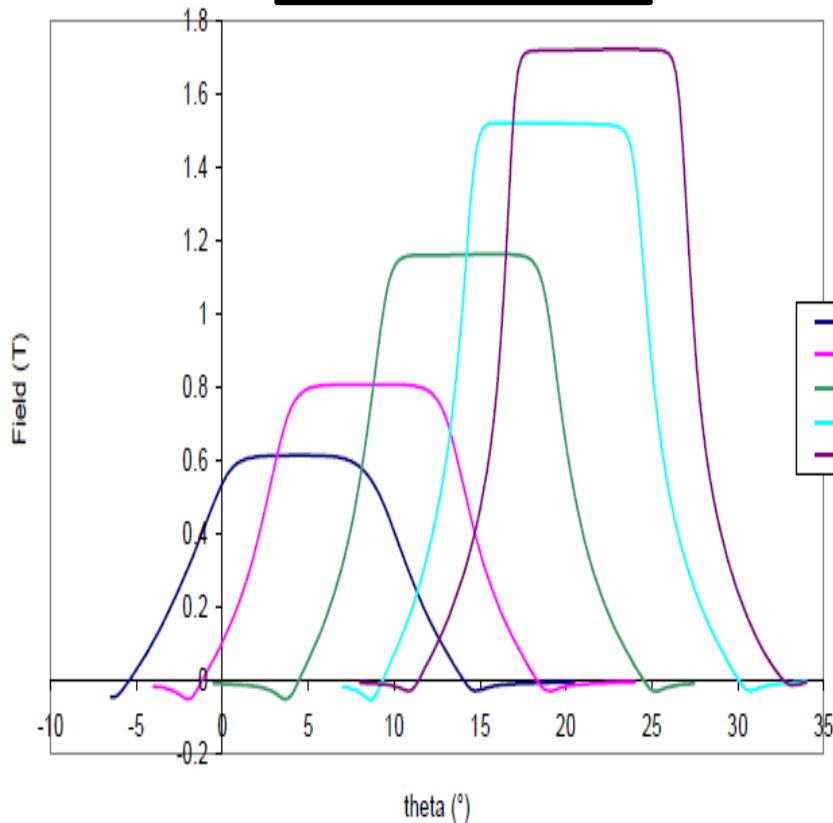


$\Sigma\Phi$  SIGMAPHI  
5 av Joffre  
Rue des Irlandais Monge  
F-94000 Vaires

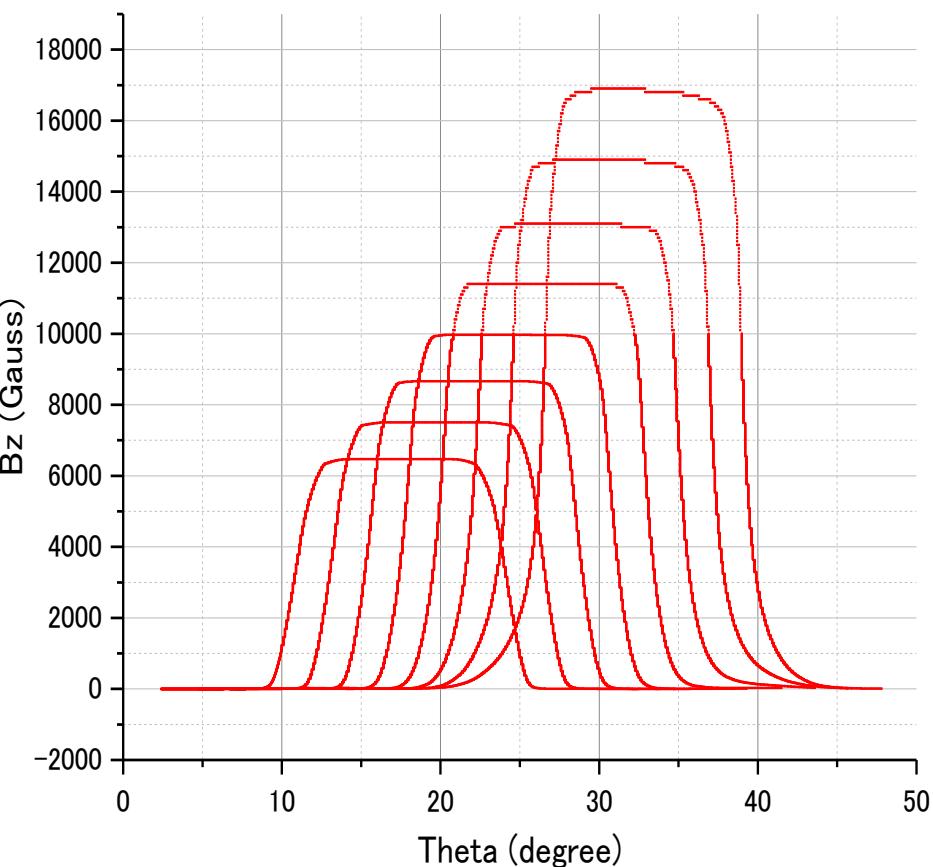
400 MeV Spiral



## RACCAM

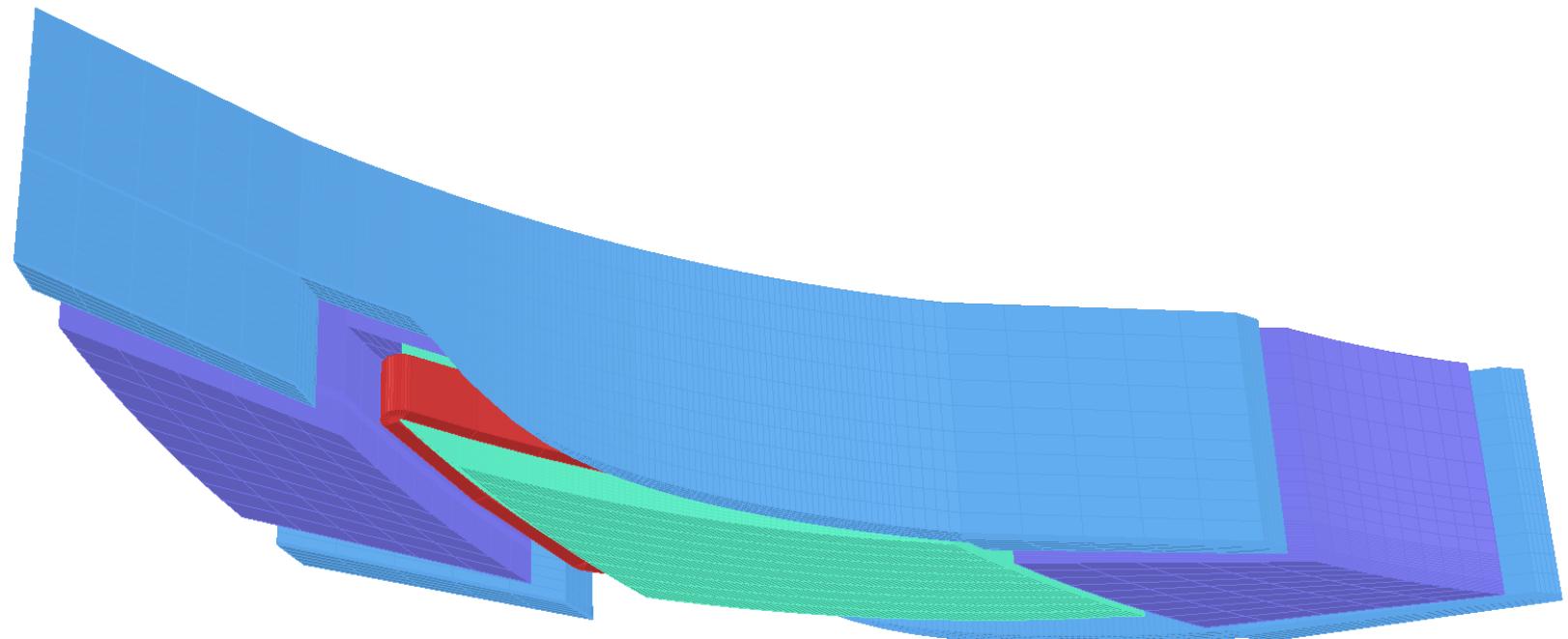


400 MeV



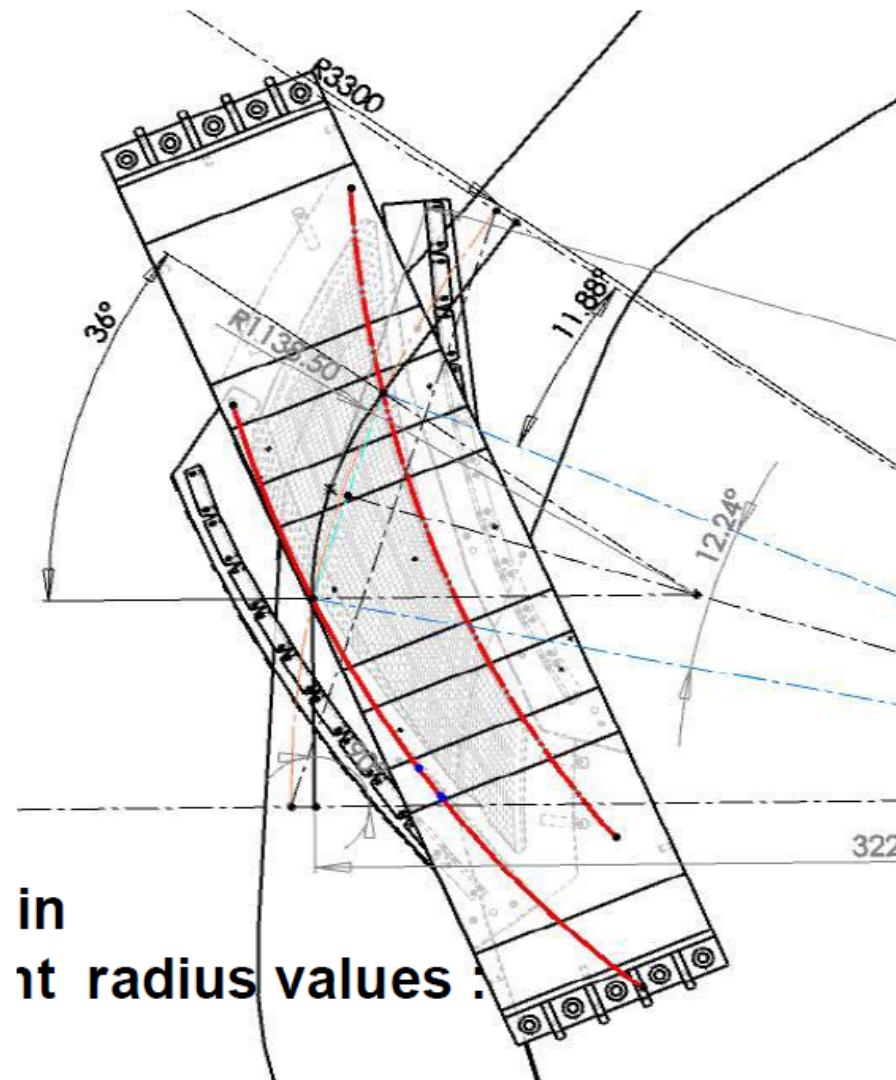


# 400 MeV Spiral





# RACCAM





# RACCAM

Measurements at SIGMAPHI, end 2008

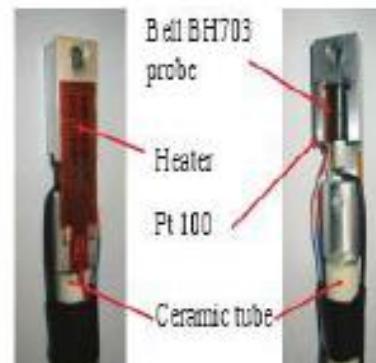


## MEASUREMENT SYSTEM AND ACCURACY



MAPPING system

- 3 axis Hall probe Bell BH703, temperature regulated  $30^{\circ}\text{C} \pm 0.1^{\circ}\text{C}$
- Air-conditioned laboratory ( $20^{\circ}\text{C} \pm 1^{\circ}\text{C}$ )
- Field acquire in 3D with a 20 channels multimeter
- Automated Mapping table  $1600 \times 600 \times 300$
- Hall probe calibration until 1.8T, accuracy  $3.10^{-5}$
- Current stability  $< 5.10^{-5}$
- Hall tension stability  $< 0.1$  Gauss



3 AXIS HALL PROBE



# ERIT (Okabe-san)

## 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<sup>2</sup>]

(Effective coil area 65%)

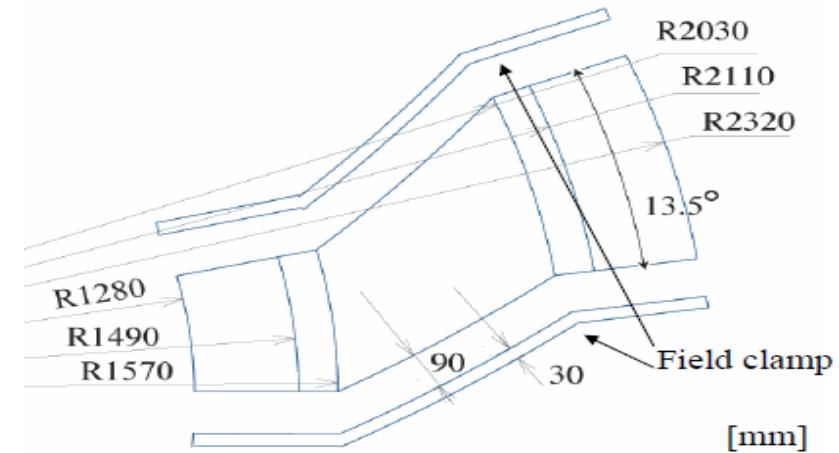
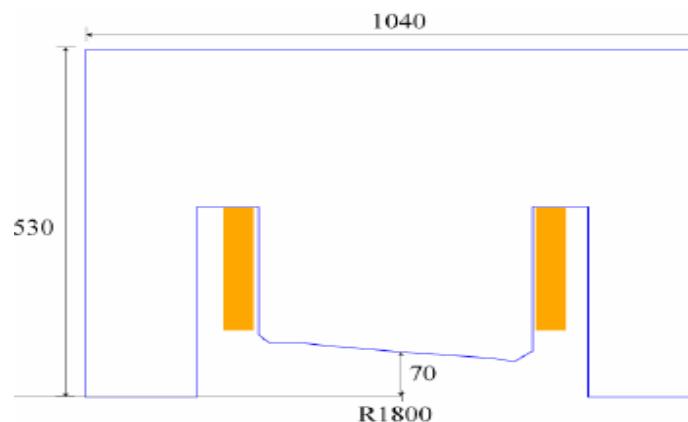
Spiral sector type

Sector num. = 8

Spiral ang. = 35 [deg]

$r_0$  = 1800 [mm]

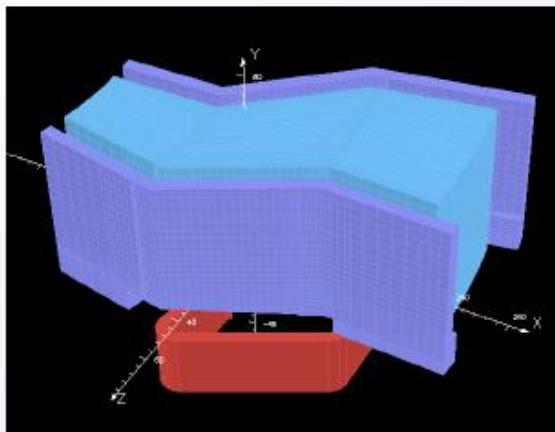
Opening ang. = 13.5 [deg]



# ERIT

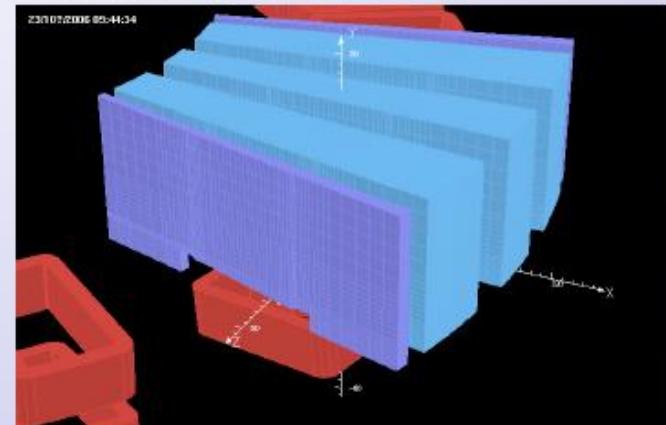
## 3D Magnetic field calculation (TOSCA)

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]
- $v_x \sim 1.73$   $v_y \sim 1.14$
- k value = 1.7, spiral ang. = 35[deg]

Radial sector type

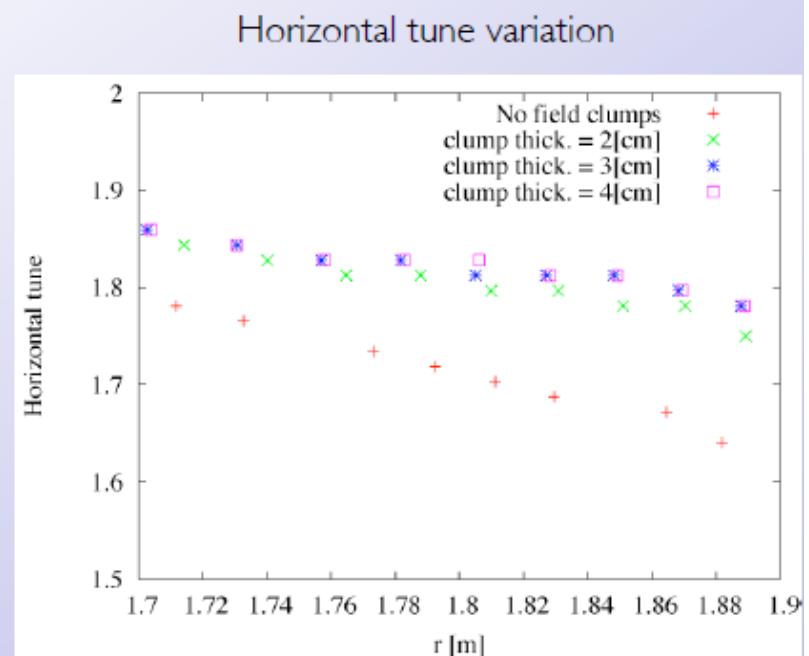
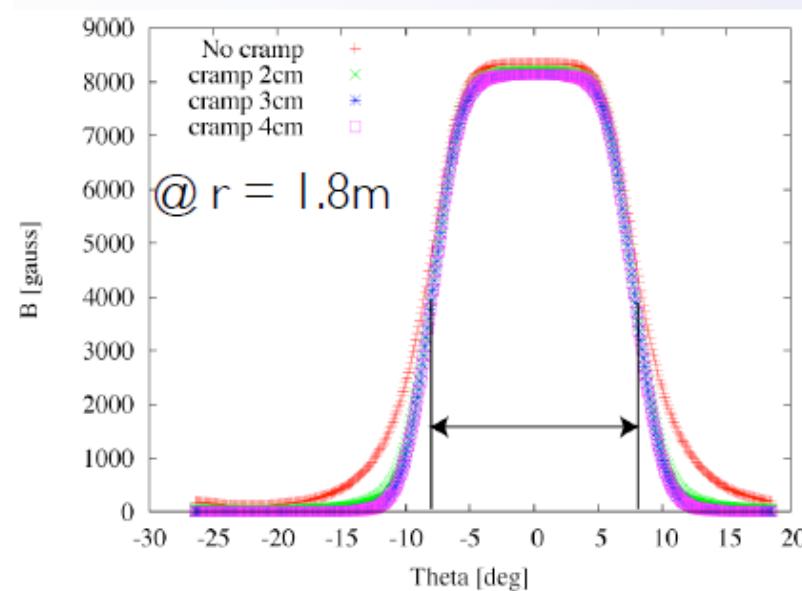


- FDF lattice(8cell)
- open F-Mag. = 6.4[deg],
- open D-Mag. = 5.1 [deg],
- F-D gap 3.75[deg],
- Clamp thick = 4[cm]
- Mean radius = 2.35[m]
- $v_x \sim 1.73$   $v_y \sim 2.29$
- k value = 1.92, FD ratio ~3

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

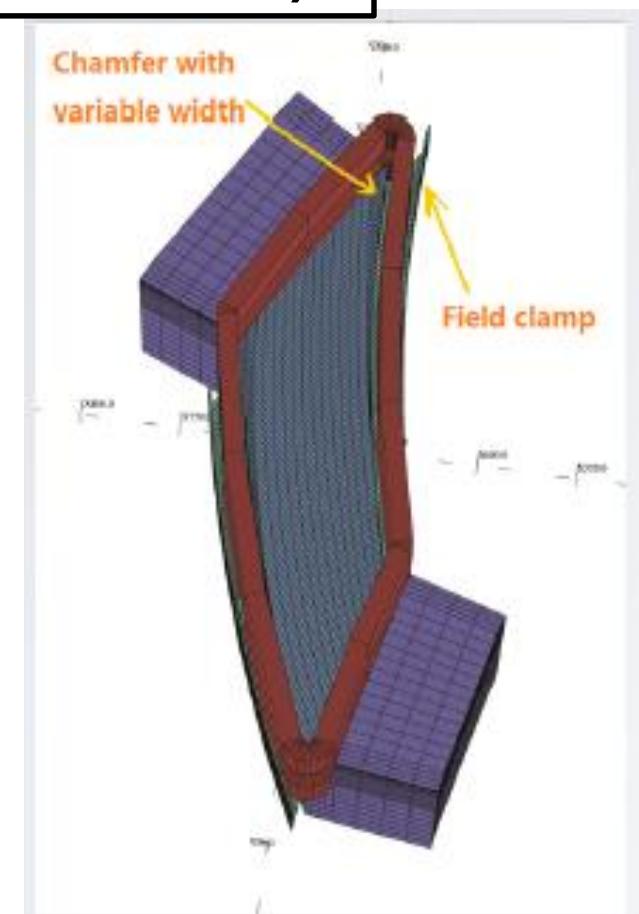
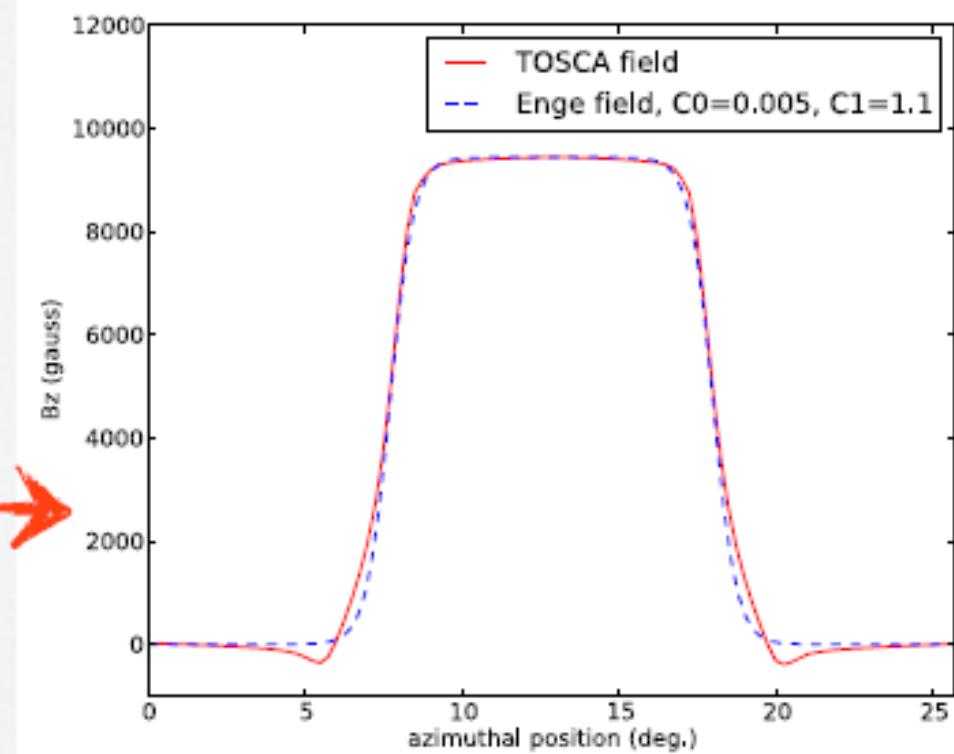
ERIT

# Field clamp optimization



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

# 700MeV Spiral (B. Qin-san)





# Spiral design

400 MeV Spiral

RACCAM

700 MeV

Max. Radius of Magnet	5.45 [m]
Injection/Extraction beam Radius	4.15 [m] / 4.63 [m]
Injection/Extraction Energy	100 [MeV] / 400 [MeV]
Momentum Ratio	2.15
Cell Number : $N$	12
Max. Magnetic Field	1.55 [T]
Packing Factor : $pf$	0.44
Field Index : $k$	6.0
Spiral Angle : $\zeta$	59.0 [deg.]
Half Gap	2.0 [cm] @ $R=4.15[m]$
Current density	3.2 [ $A/mm^2$ ]
Weight of half magnet	12.7 [t]

Table 1: Parameters of the spiral FFAG ring

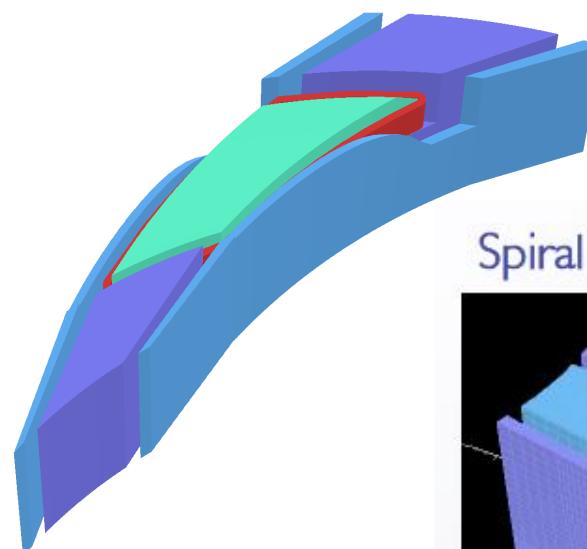
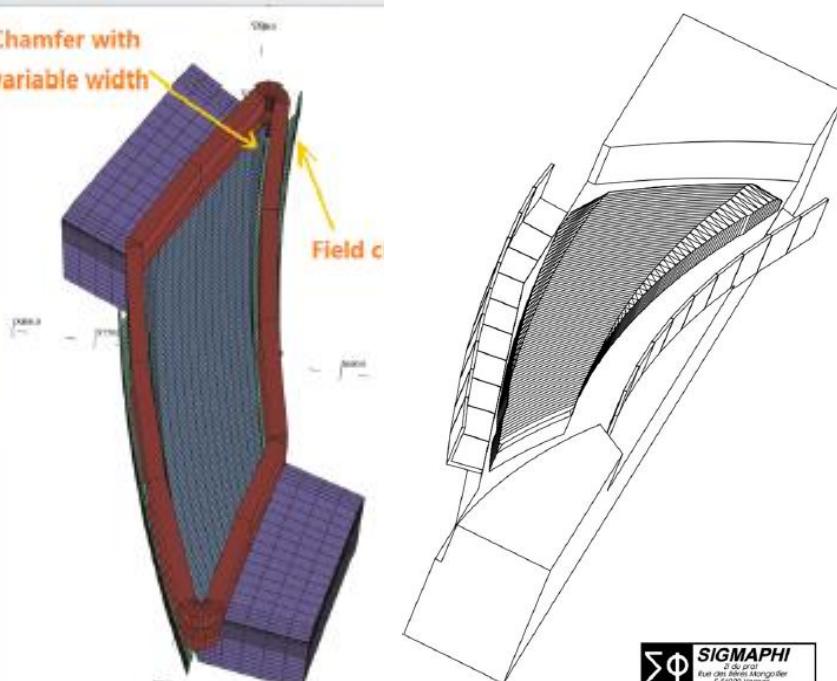
Number of cells	10
Injection energy range	5.549 – 15 MeV
Extraction energy range	70 – 180 MeV
Field index $k$	5.00
Spiral angle $\zeta$	53.7°
Packing factor	0.34
$B_{max}$ on extraction orbit	1.7 T
Orbit radius (extr / inj)	3.46 m / 2.79 m
Gap at extr / inj radius	4 cm / 11.64 cm
( $Q_H, Q_V$ ): extr. orbit at 180 MeV	(2.761, 1.603)
( $Q_H, Q_V$ ): inj. orbit at 15 MeV	(2.758, 1.549)
Maximum gap voltage	6 kV
Harmonic number	1
RF swing: 15 – 180 MeV	3.03 – 7.54 MHz
RF swing: 5.549 – 70 MeV	1.86 – 5.07 MHz
Cycle time, 180 MeV / 17 MeV	9.74 ms / 5.44 ms
Acceleration rate with 1 gap	> 100 Hz
Number of turns, 180 MeV / 70 MeV	55000 / 21500

Table 2: Parameters of the magnet (TOSCA model)

Field index	6.2
Spiral angle	58.0 degree
Packing factor	0.38
$v_x/v_z$ per cell	0.20 / 0.13
$R_{inj}/R_{ext}$	6.85 / 7.75 m
$B_{max}@R_{ext}$	1.55T
Half gap size	2.0cm @ extraction
Coil current density	1.52A/mm <sup>2</sup>
Coil cross section	160mm × 100mm
Approx. weight of magnet	20 t



# Spiral design



Spiral sector type

