Preliminary design of a 300 MeV Spiral FFAG

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Outline

- Background
- Motivation
- Purpose
- Parameter search
- Magnet design
- Tracking simulation
- Summary

Background

150 MeV FFAG

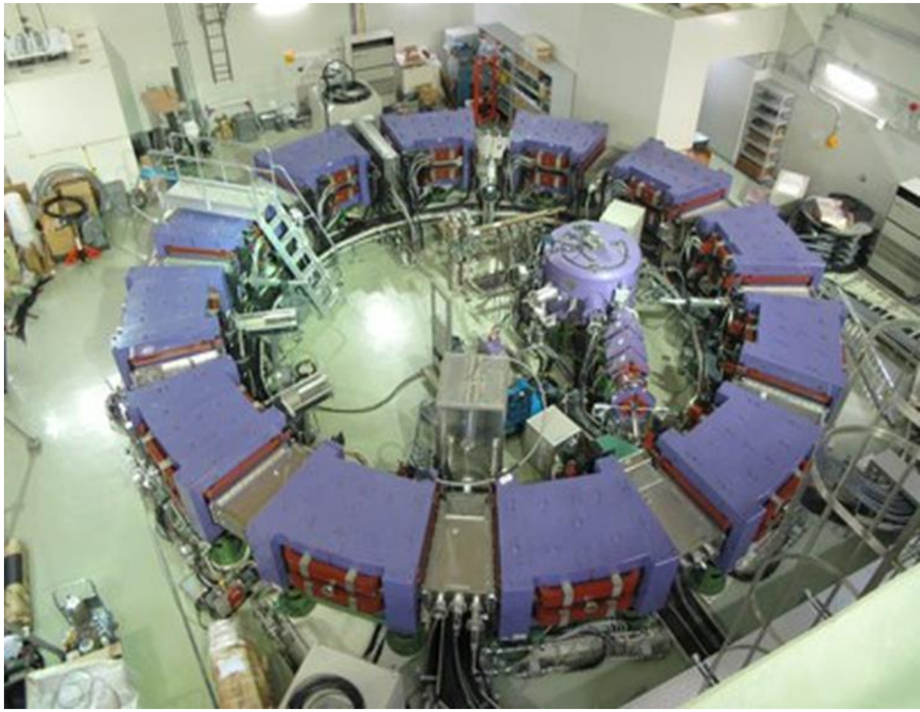
- Prototype of proton FFAG for various applications

- Proton beam

12 MeV ⇒ 150 MeV

at Kyushu University

- Beam commissioning
- Development of components



150 MeV FFAG

Motivation

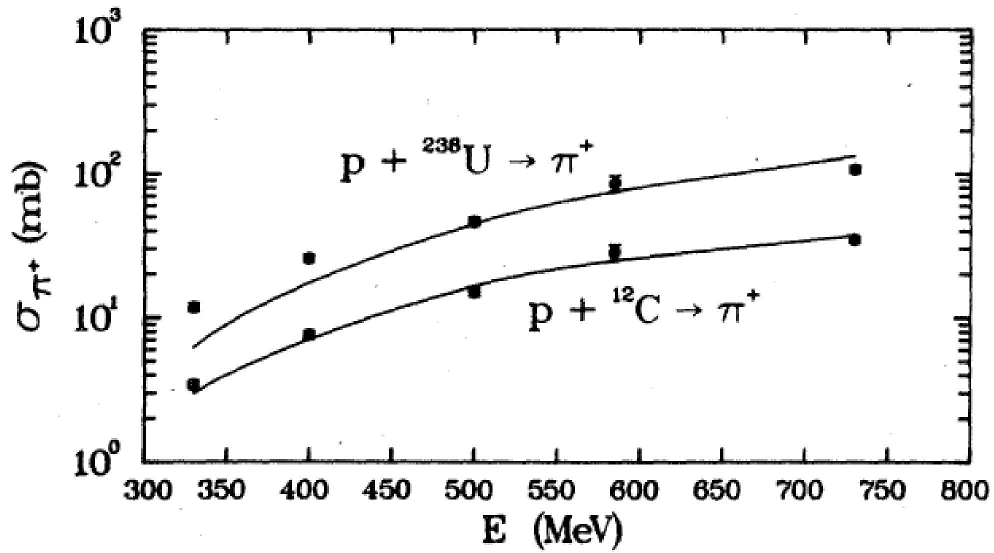
A 300 MeV
or more over proton beam

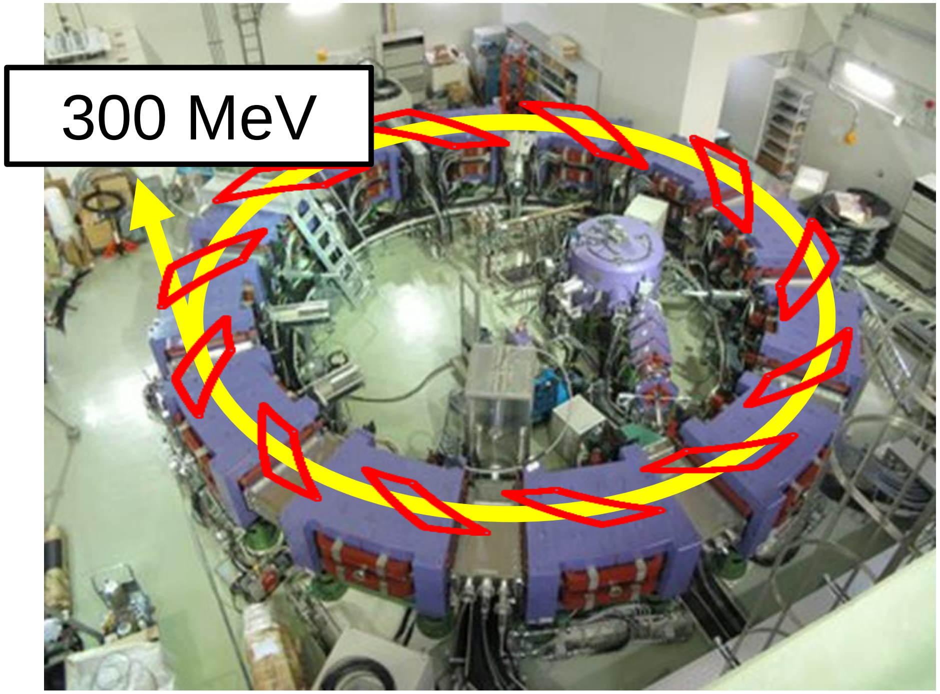
- Particle physics
- Medical (BNCT)
- Material science

Compact Accelerator
Spiral FFAG

150 MeV FFAG
⇒ 300 MeV FFAG

※1





※1 : N. J. DiGiacomo, et ai., Phy. Rev. C 33 988 (1986)

Purpose

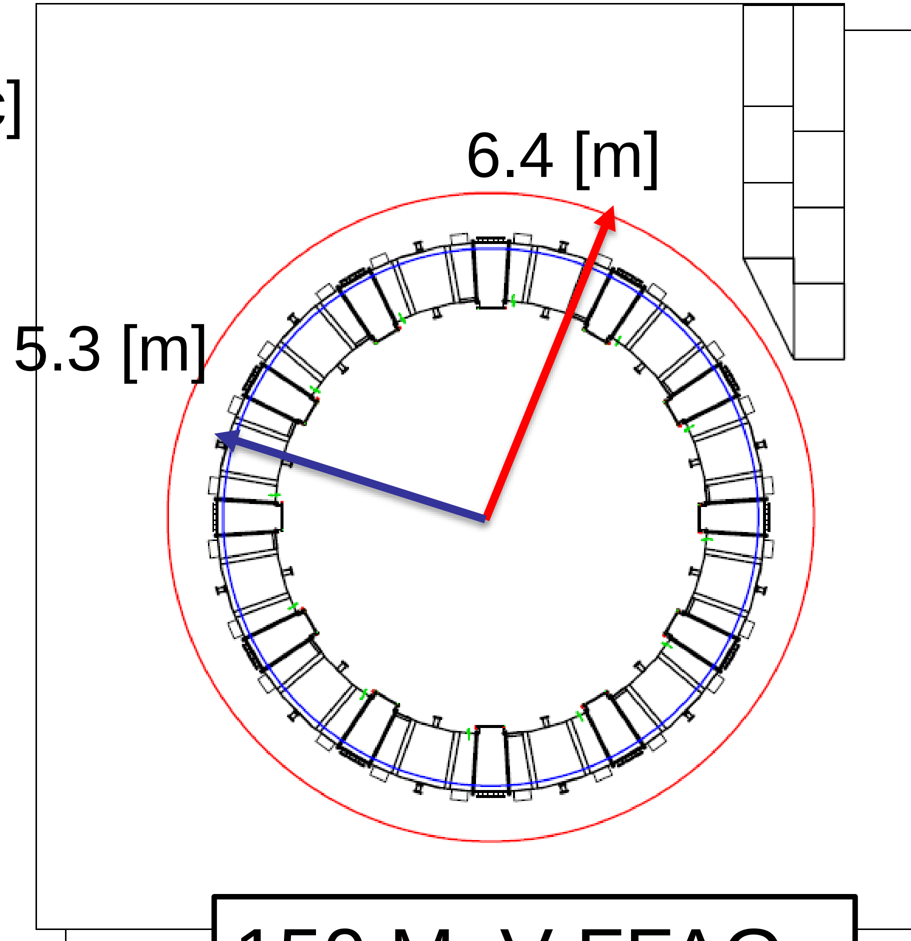
Design of a 300 MeV FFAG

In order to achieve the purpose…

- Lattice parameters search (linear approximation)
- Magnet design with Opera-3D
- Stability study with tracking simulation

Requirements for the accelerator

- Injection momentum:151 [MeV/c] (proton 12 MeV)
- Extraction momentum:808 [MeV/c] (proton 300 MeV)
- Cell Number : 12 (the same number as 150 MeV FFAG)
- Magnetic field : B < 1.6 [T]
- Size of accelerator
Maximum beam radius = 5.30 [m]
- Excursion < 1.40 [m]



150 MeV FFAG

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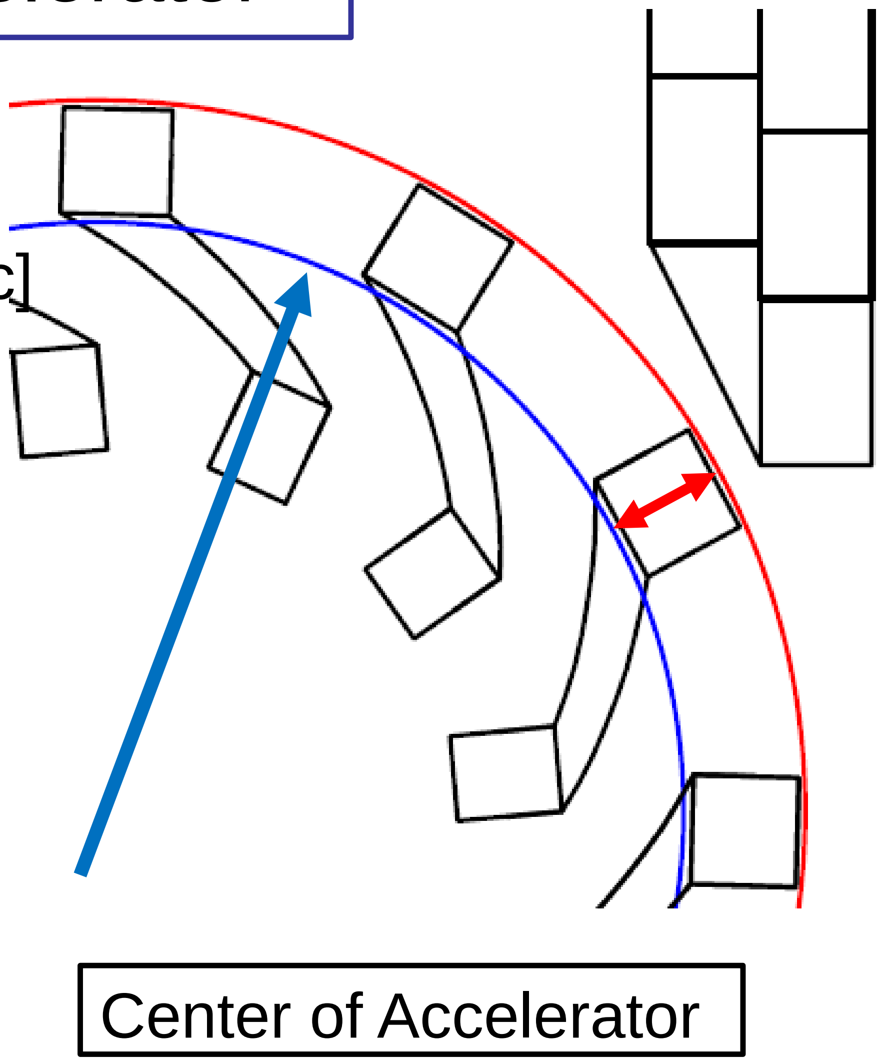
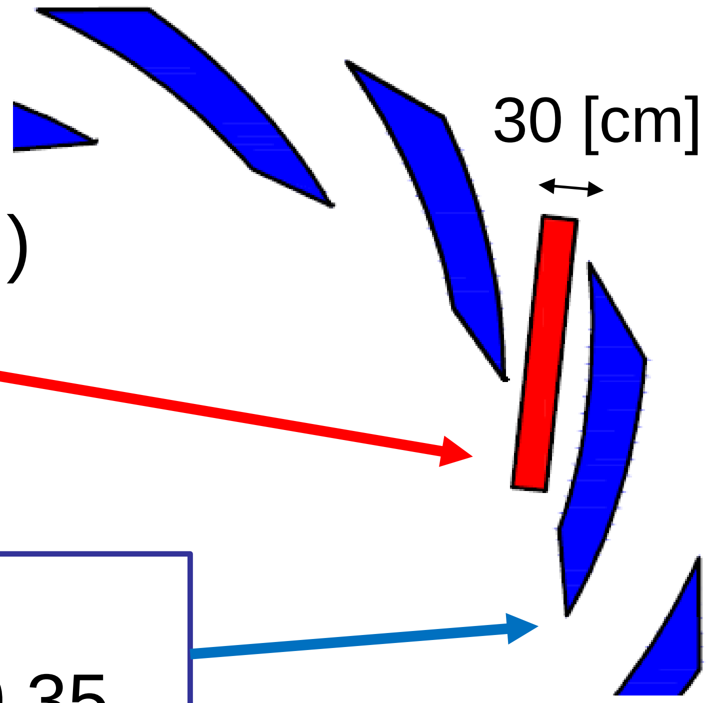


Requirements for the accelerator

- Spiral Angle : $\varsigma < 60$ [deg.]

- Packing Factor : $pf = 0.35$

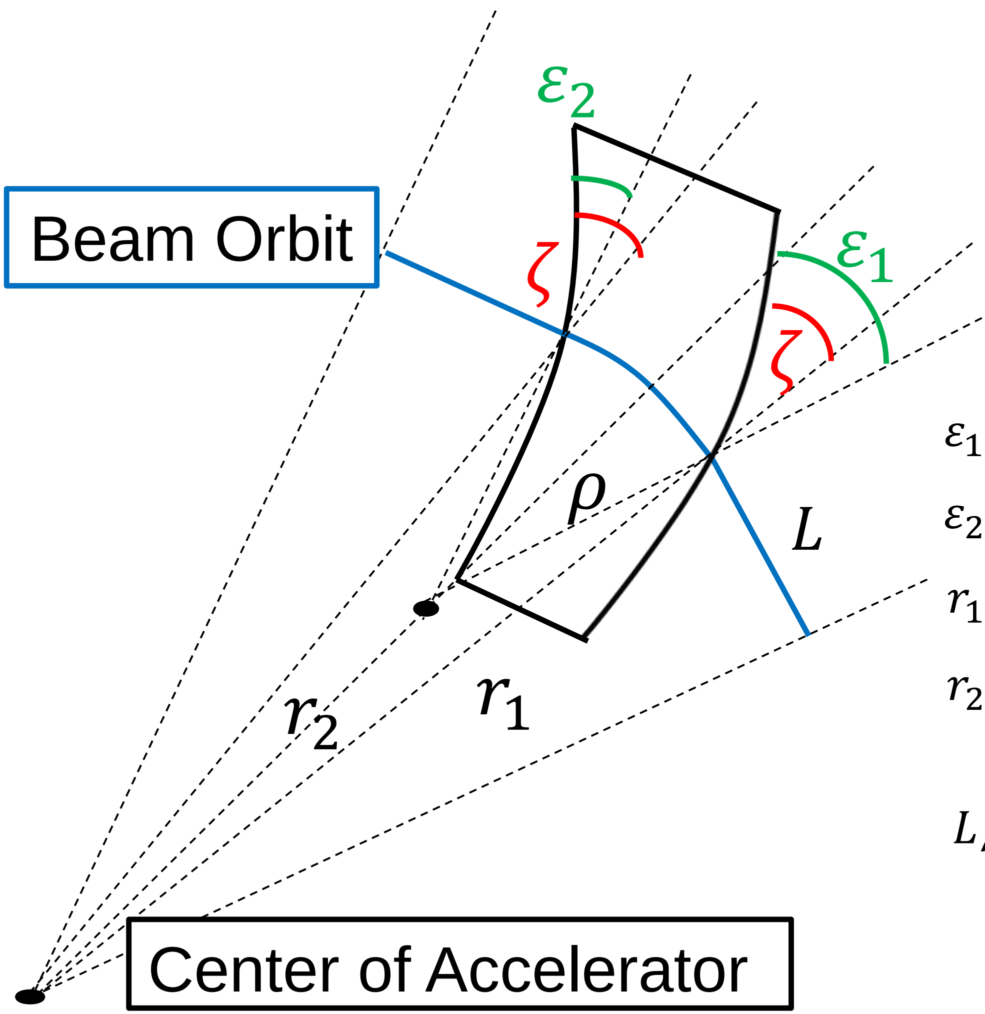
(keep the space of RF cavity, etc.)



Spiral magnet
$\varsigma = 60$ [deg.], $pf = 0.35$

Linear Approximation

Definitions of lattice parameters



L : Length of straight section
ρ : Radius of Curvature
ζ : Spiral Angle
ε : Edge Angle

$$\varepsilon_1 = \pi/N - pf \times \pi/2N - \zeta$$

$$\varepsilon_2 = \pi/N - pf \times \pi/2N + \zeta$$

$$r_1/\rho = \sin(\pi/N)/\sin(pf \times \pi/2N)$$

$$r_2/\rho = 1 + (r_1 - \cos(\pi/N - pf \times \pi/2N)) / \cos(pf \times \pi/2N)$$

$$L/\rho = \sin(\pi/N) \times \sin(\pi/N - pf \times \pi/2N) / \sin(pf \times \pi/2N)$$

Requirements for field index : k

Relation between field index : k and excursion

$$\Delta R = \left(1 - 1/(P_{300MeV}/P_{12\,MeV})^{1/(1+k)}\right)R_{max}$$

$P_{300MeV}/P_{12\,MeV}$ = 5.37

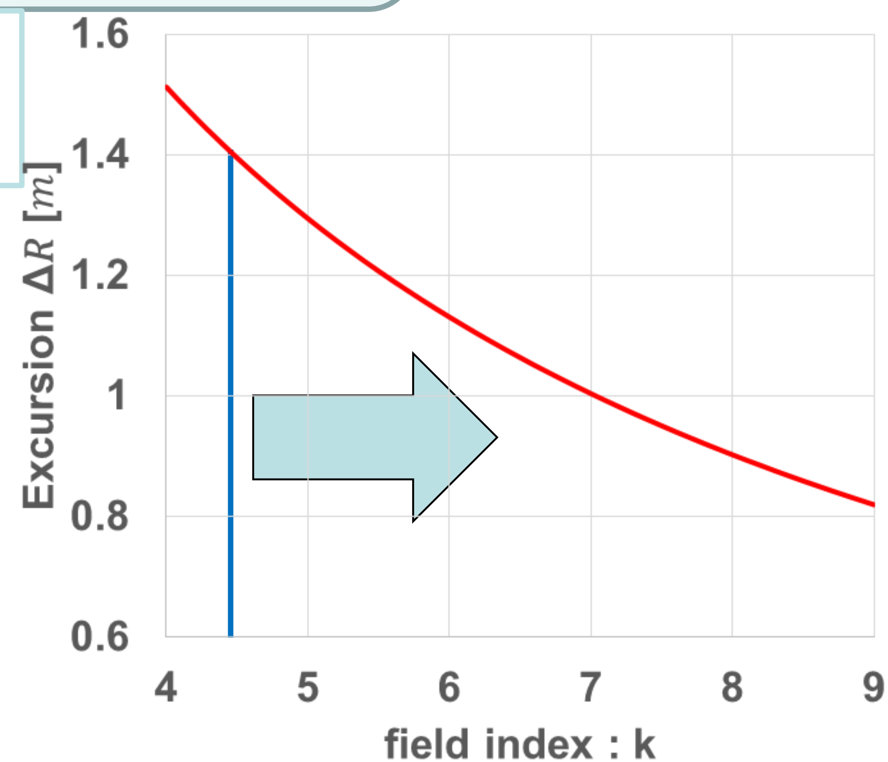
R_{max} = 5.30 [m]

R_{max}: Extraction beam radius

$P_{300MeV}/P_{12\,MeV}$: Momentum ratio

Excursion : $\Delta R < 1.40$ [m]

Field index : k > 4.5



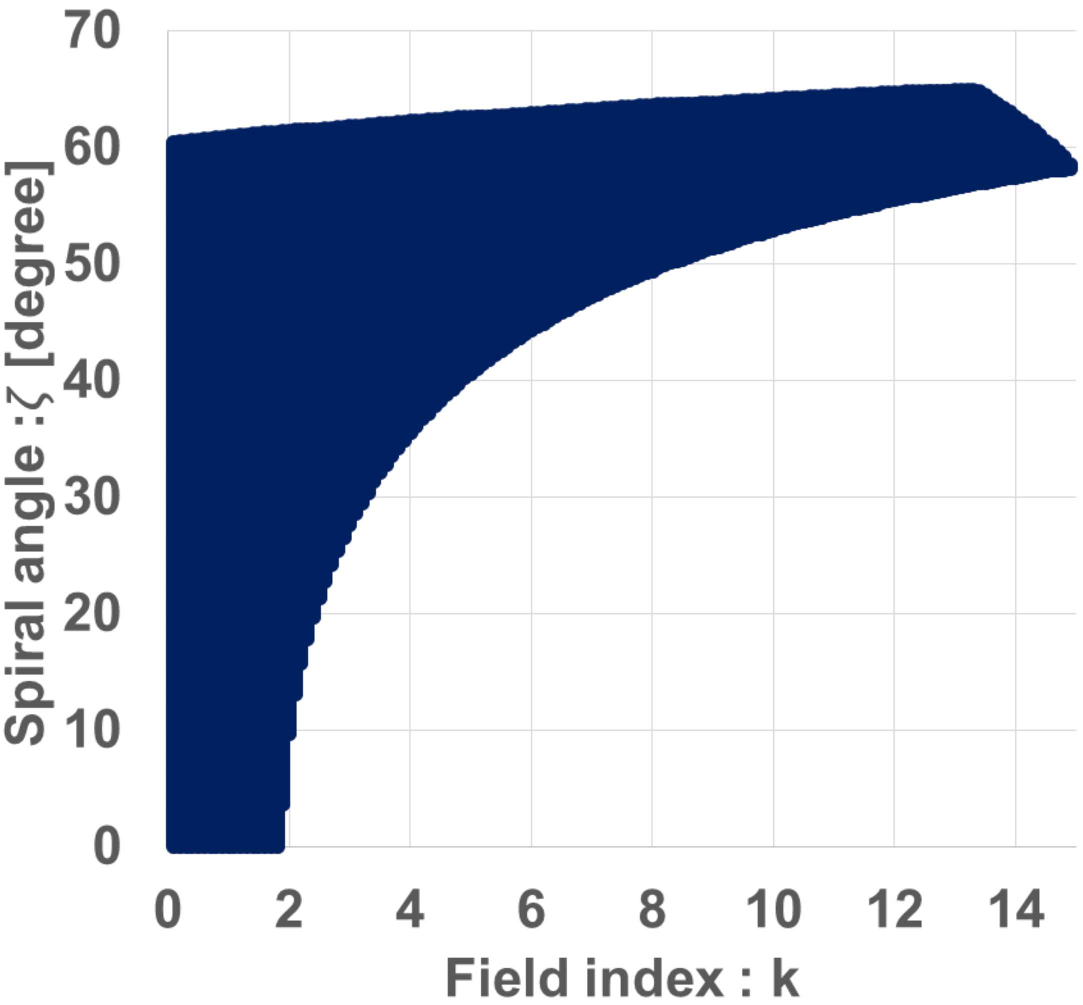
Stability investigation (filed index : k vs spiral angle: ς)

pf = 0.35

Cell number = 12

$B_{inj} = 0.34$ [T]

$B_{ext} = 1.44$ [T]



Stability investigation (filed index : k vs spiral angle: ς)

k>4.5 & ς < 60 [deg]

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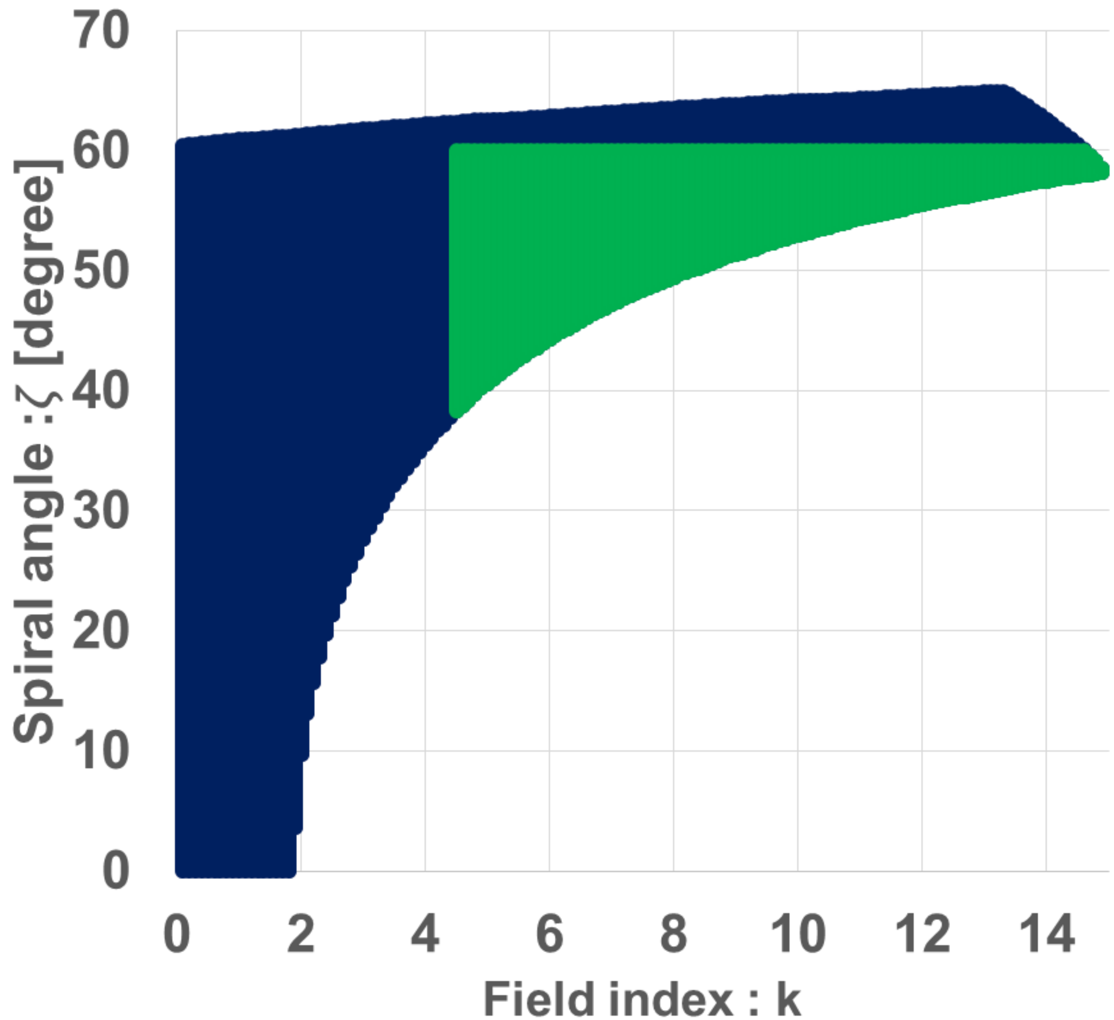


Stability investigation (filed index : k vs spiral angle: ς)

k>4.5 & ς < 60 [deg]

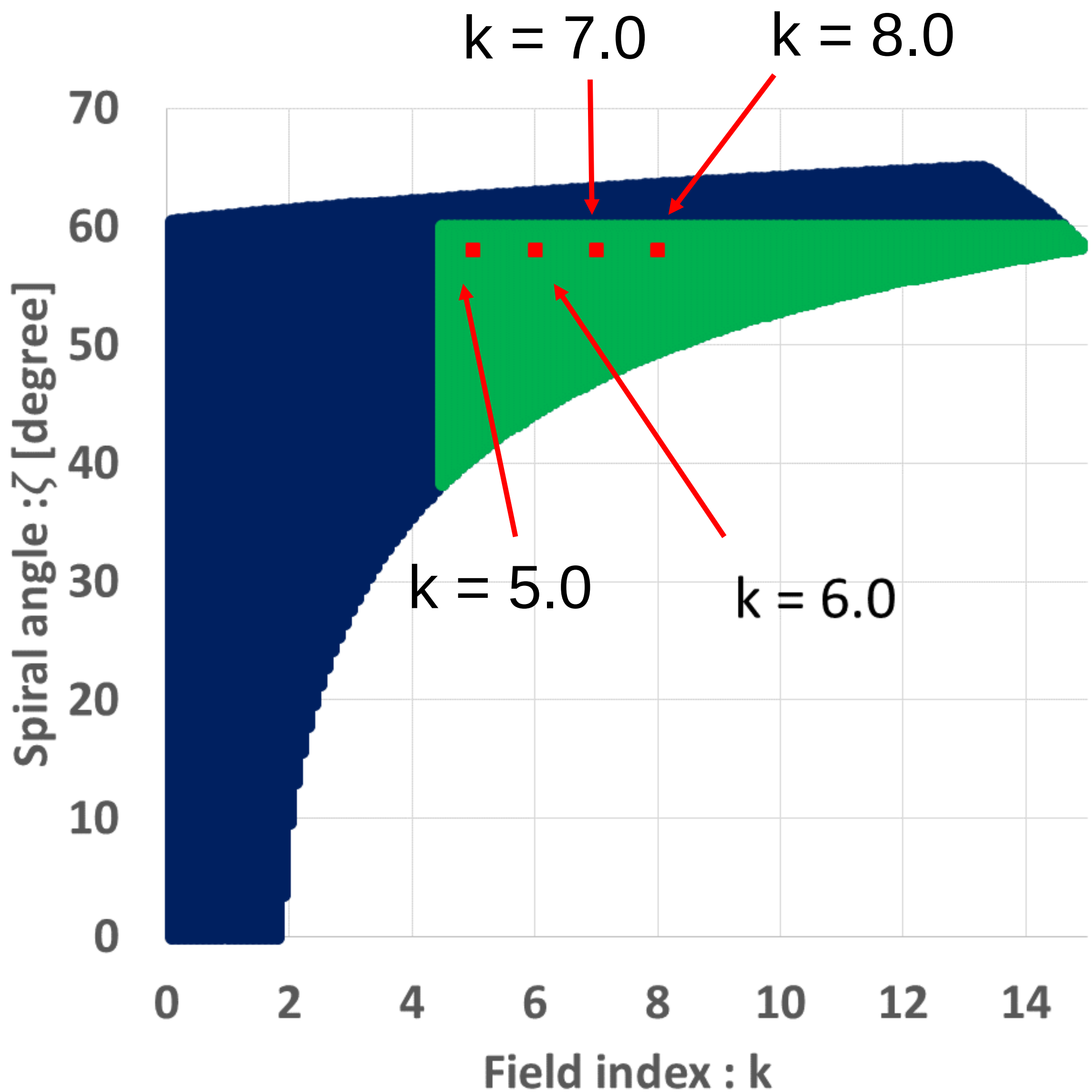
pf = 0.35

Cell number = 12

B_{inj} = 0.34 [T]

B_{ext} = 1.44 [T]

ς = 58.0 [deg]



Result of calculation: linear approximation

$pf = 0.35$

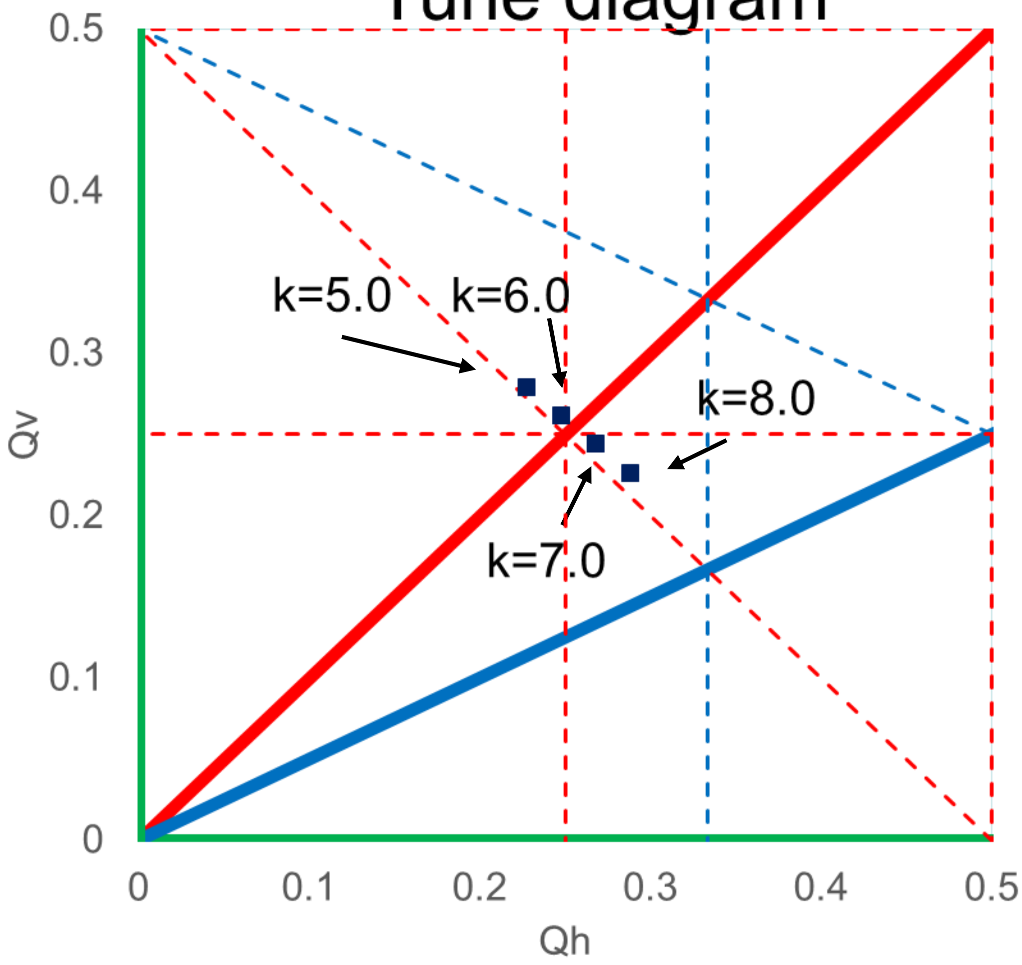
Cell number = 12

$B_{inj} = 0.34$ [T]

$B_{ext} = 1.44$ [T]

$\varsigma = 58.0$ [deg]

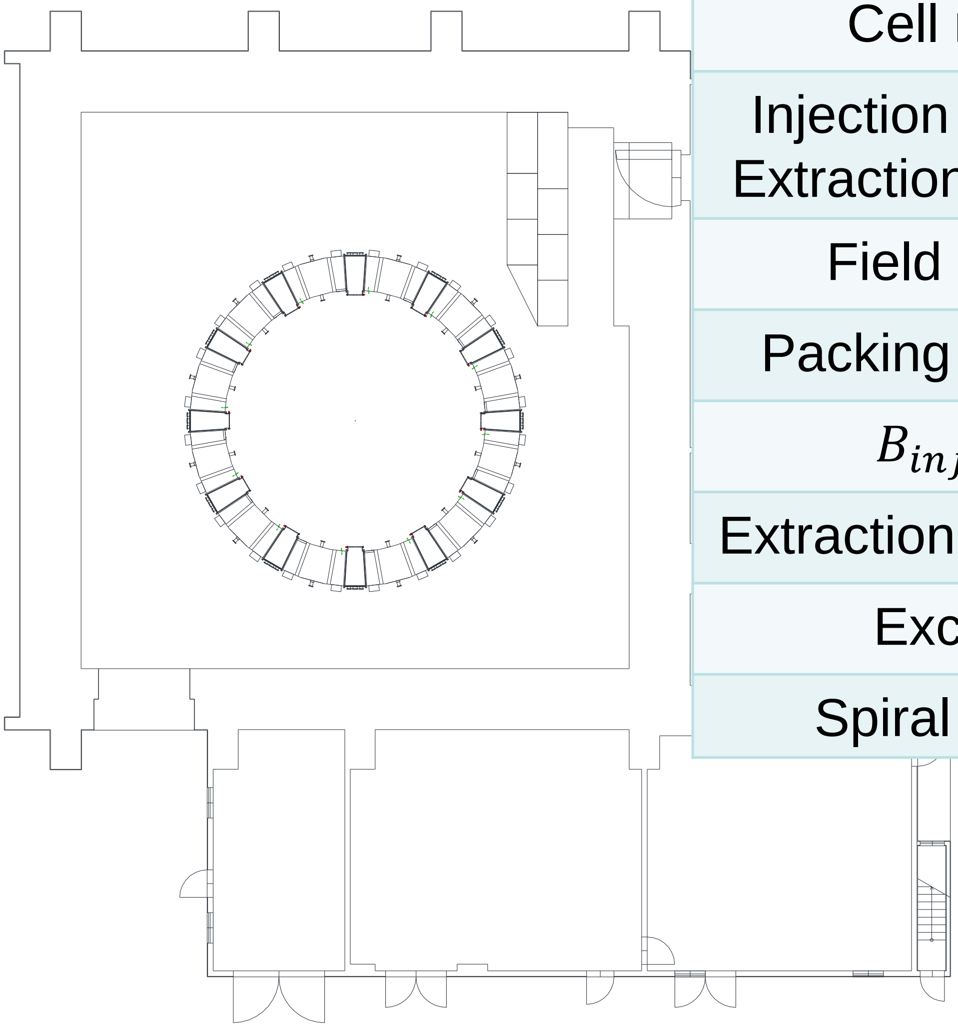
Tune diagram



Bold line
Structure resonance

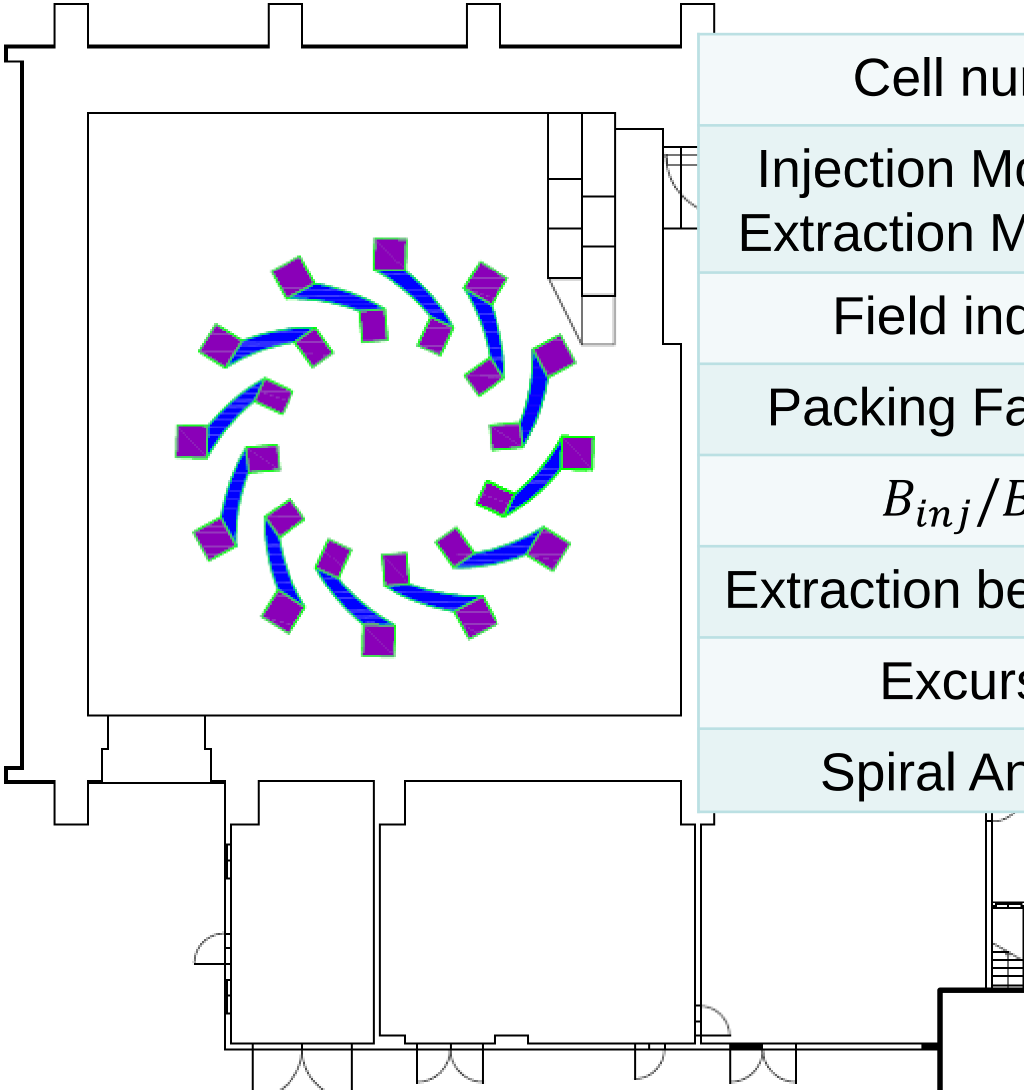
k ~ 6.0 : horizontal phase advice per cell ~ 90 [deg]

Lattice Parameters



Cell number	12
Injection Momentum Extraction Momentum	151 [MeV/c] 808 [MeV/c]
Field index : k	5.0 ~ 8.0
Packing Factor : pf	0.35
B_{inj}/B_{ext}	0.34 [T] / 1.44 [T]
Extraction beam radius	5.30 [m]
Excursion	0.88 [m] ~ 1.38 [m]
Spiral Angle : ζ	58.0 [deg]

Lattice Parameters



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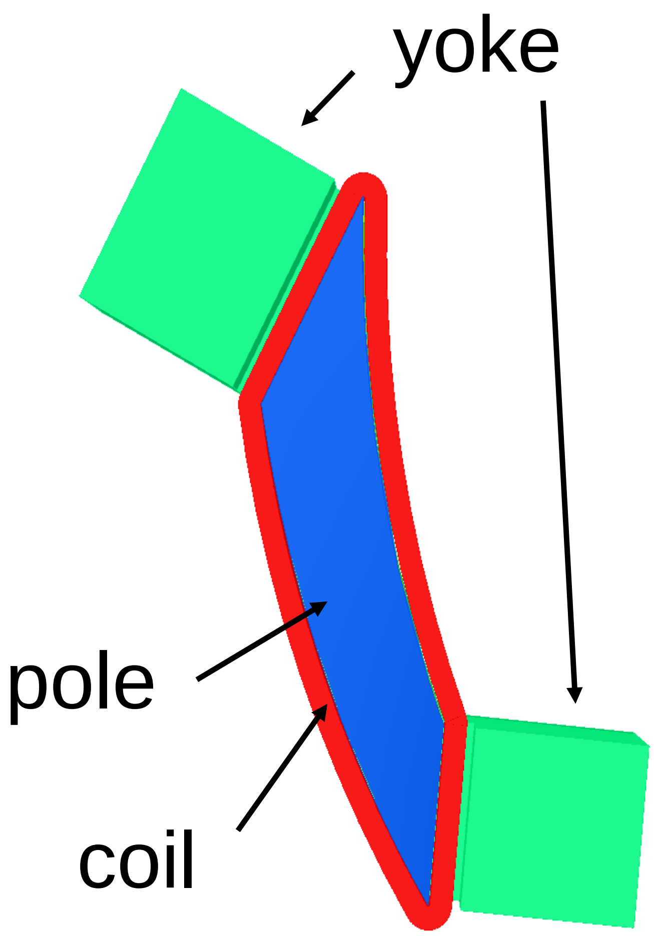
Spiral Angle : ζ	58.0 [deg]

Magnet Design

Magnet Design with Opera-3D

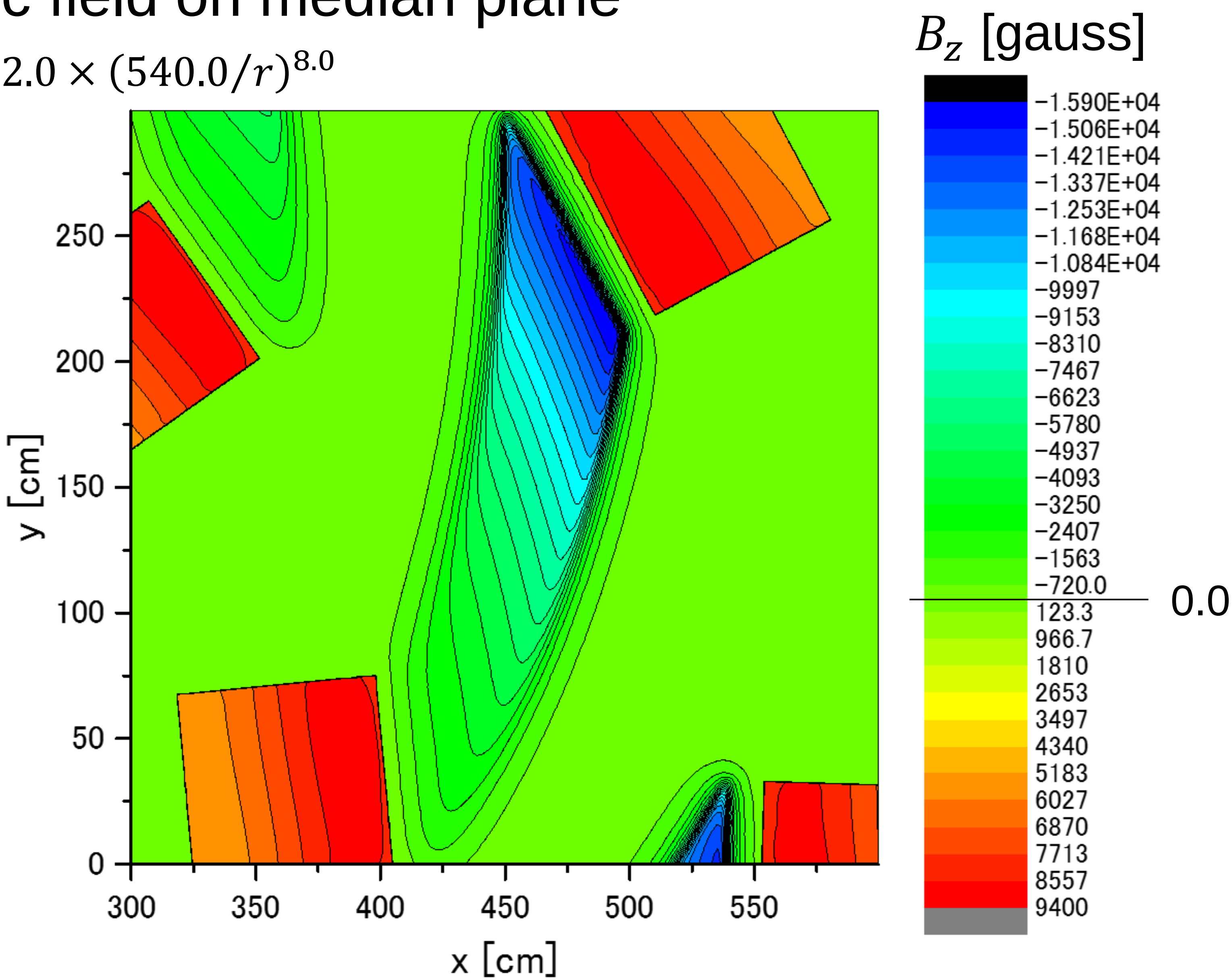
Cell	12
Field index : k	5.0 ~ 8.0
Packing Factor	0.35
Spiral Angle	58 [deg.]
Pole shape	Half gap $\propto \left(\frac{r}{r_0}\right)^{-k}$
half gap	2.0 [cm] @ r = 5.3 [m]
B @ r=5.3 [m]	1.45 [T]
Coil current density	1.20 [A/mm^2]
Coil cross section	100mm×200mm



Cross sectionnal view of magnet

Magnetic field on median plane

Half gap $= 2.0 \times (540.0/r)^{8.0}$

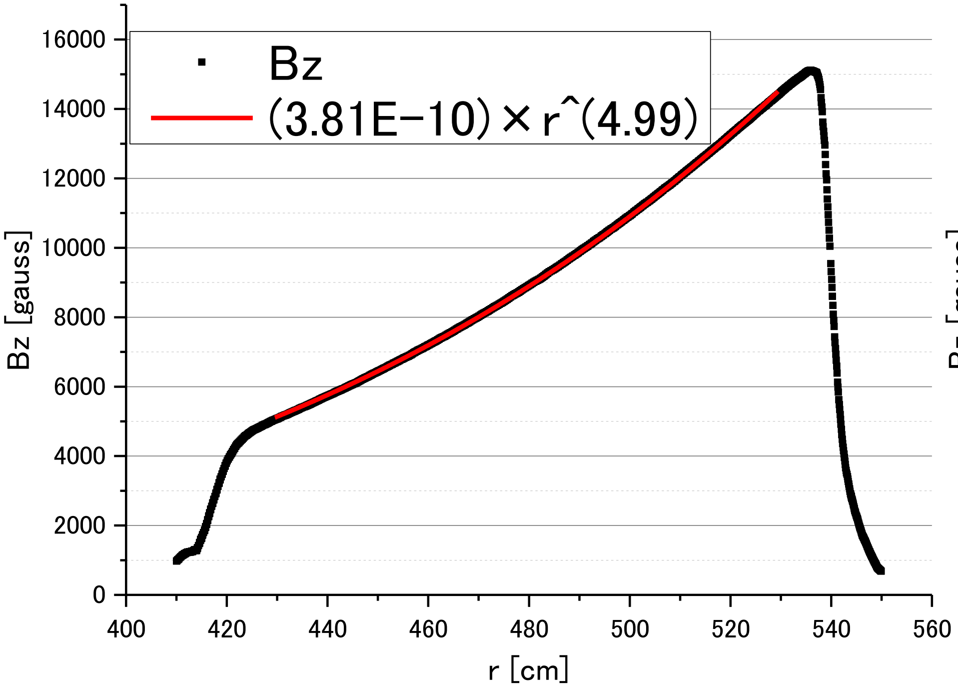


Magnetic field with Opera 3D (field index : k)

Magnetic field of center of the spiral magnet on median plane

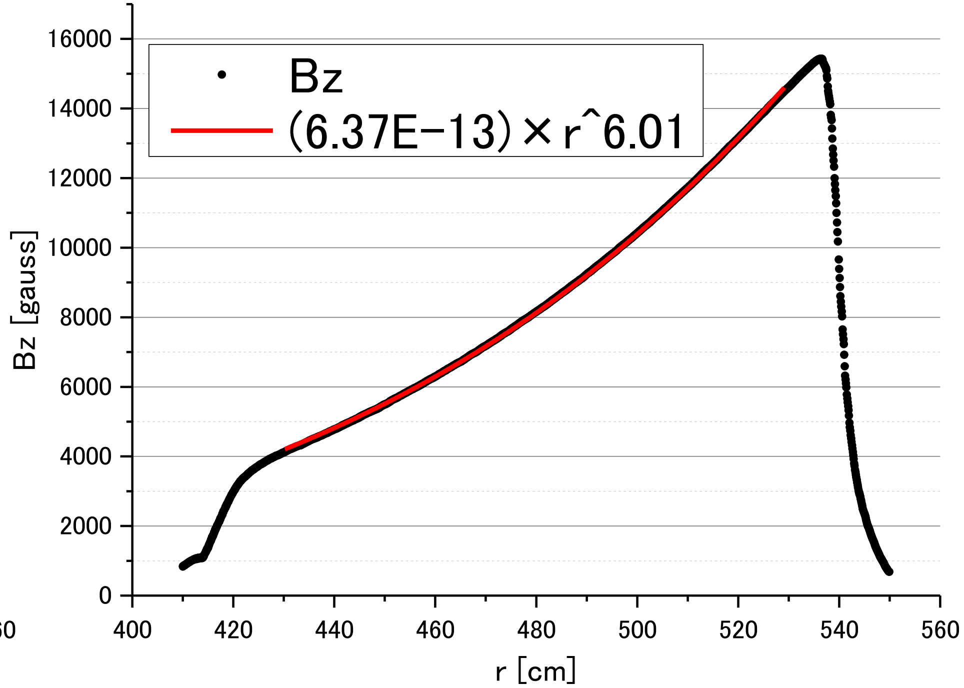
$$Bz = Ax^k$$

Half gap $= 2.0 \times (530.0/r)^{5.0}$



Effective : k = 4.99

Half gap $= 2.0 \times (530.0/r)^{6.0}$

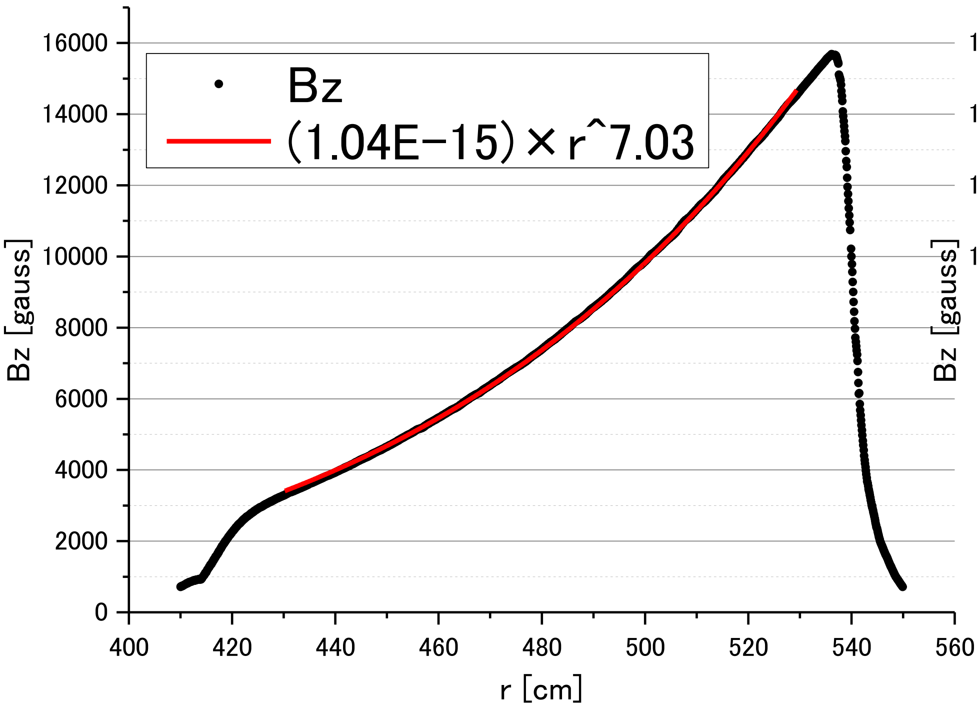


Effective : k = 6.01

Magnetic field with Opera 3D (field index : k)

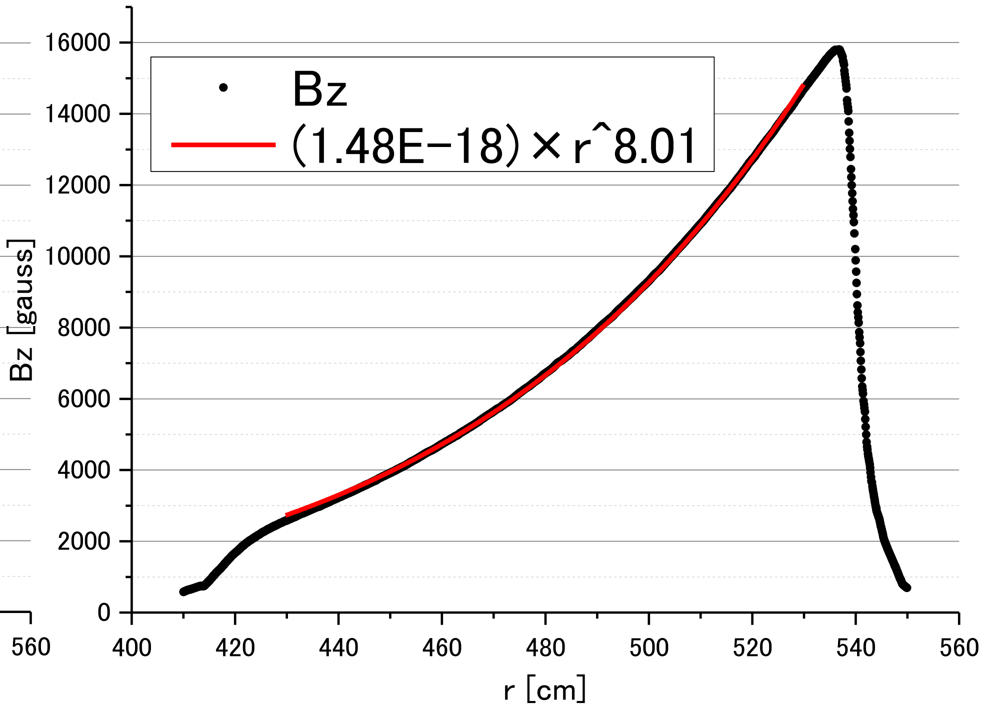
Magnetic field of center of the spiral magnet on median plane

Half gap = $2.0 \times (530.0/r)^{7.0}$



Effective : k =7.03

Half gap = $2.0 \times (530.0/r)^{8.0}$



Effective : k = 8.01

Result of tracking simulation : tune variation

Tune variation (k=4.99)

$$\Delta Q_H = 0.03$$
$$\Delta Q_V = 0.12$$

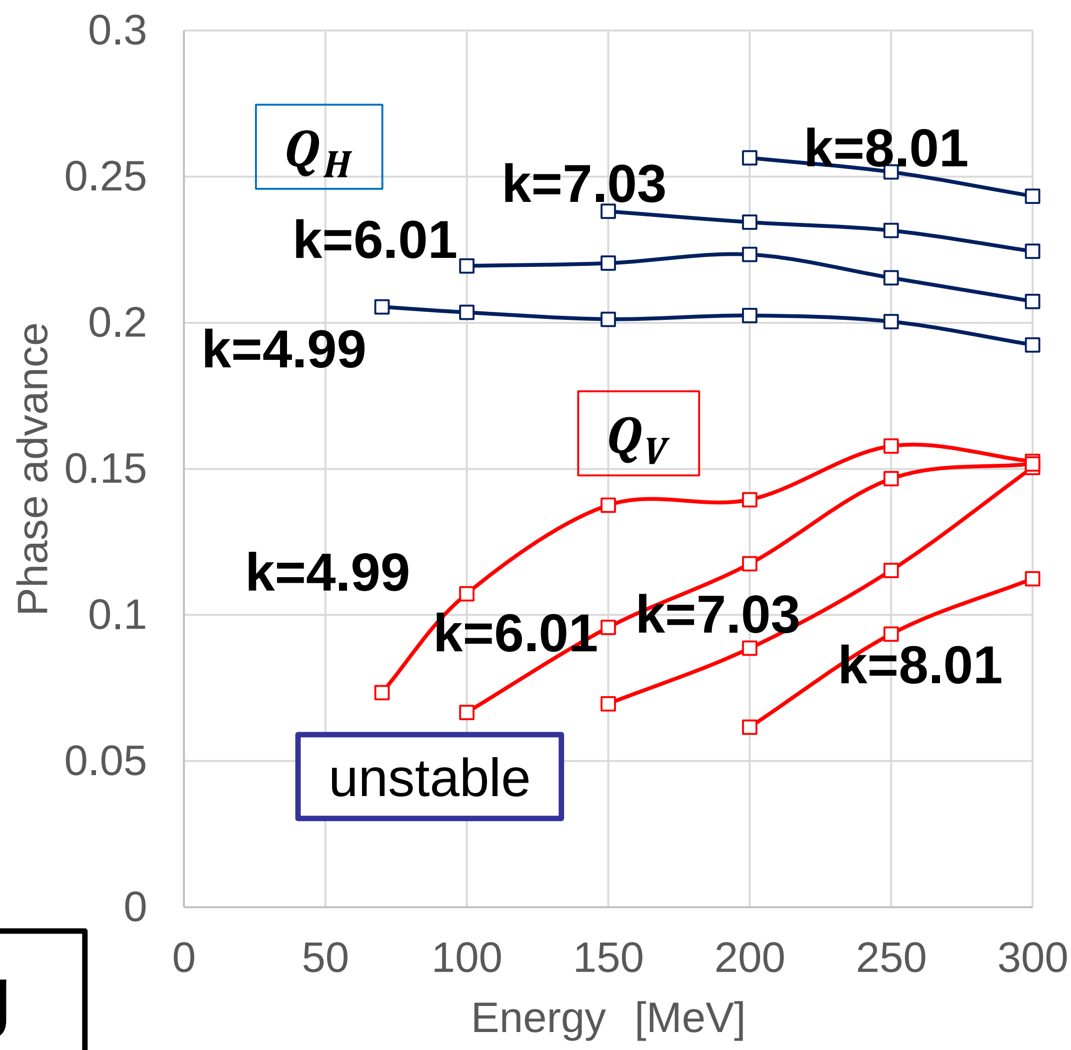
Large vertical tune variation

$$Q_H \approx \sqrt{k+1}$$

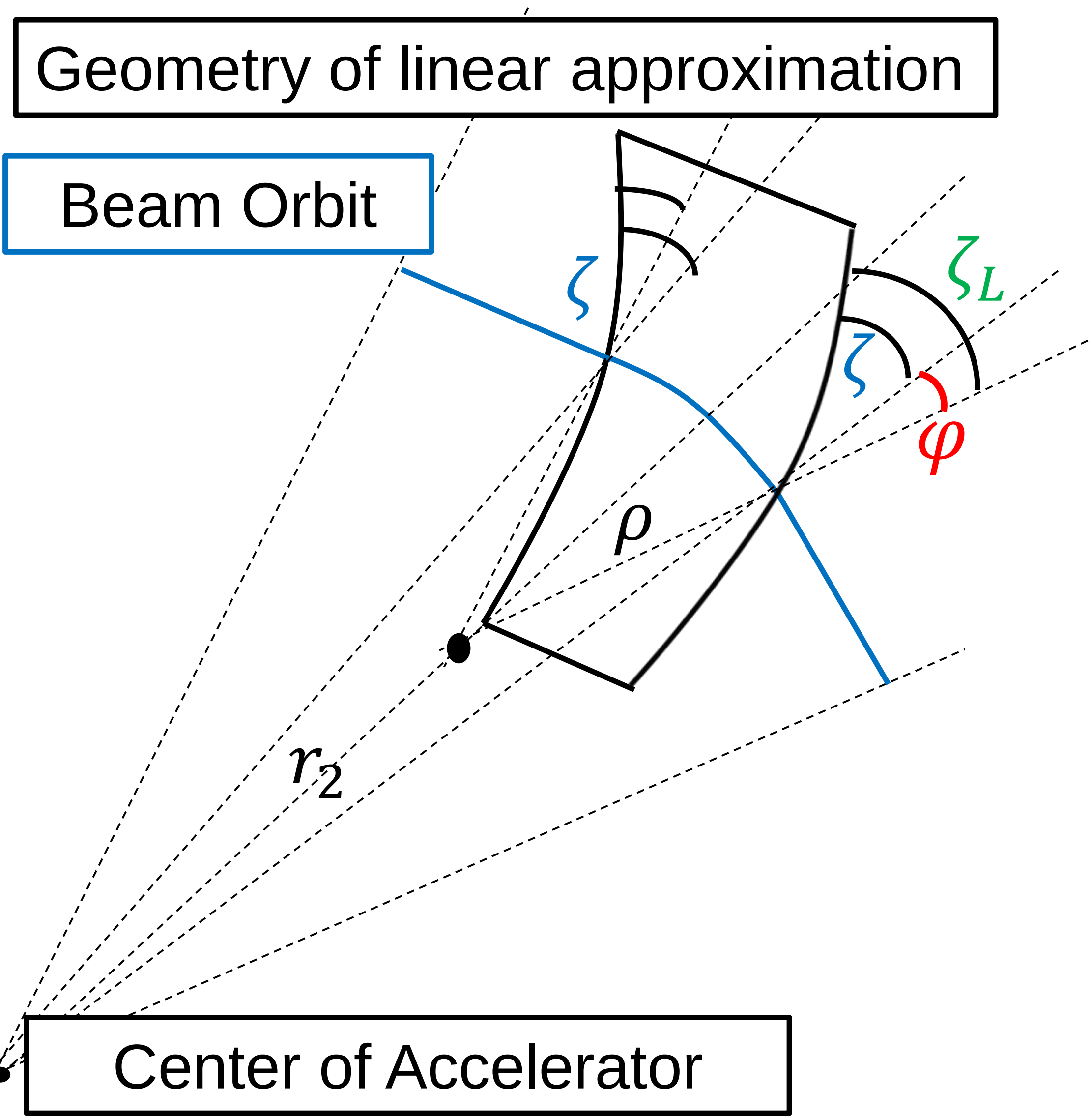
$$Q_V \approx \sqrt{-k + f(1 + 2\tan^2\zeta)}$$

$(f: flutter\ factor)$

ζ or f varied during acceleration ?



Calculation of local ζ in tracking simulation



local ζ = ζ_L = $\zeta + \varphi$

In case of linear approximation

$$\zeta_L = \text{constant}$$

Result of calculation of local ζ

Normalized angle $= \zeta'_L = \dfrac{\zeta_L}{\zeta_{L(300MeV)}}$

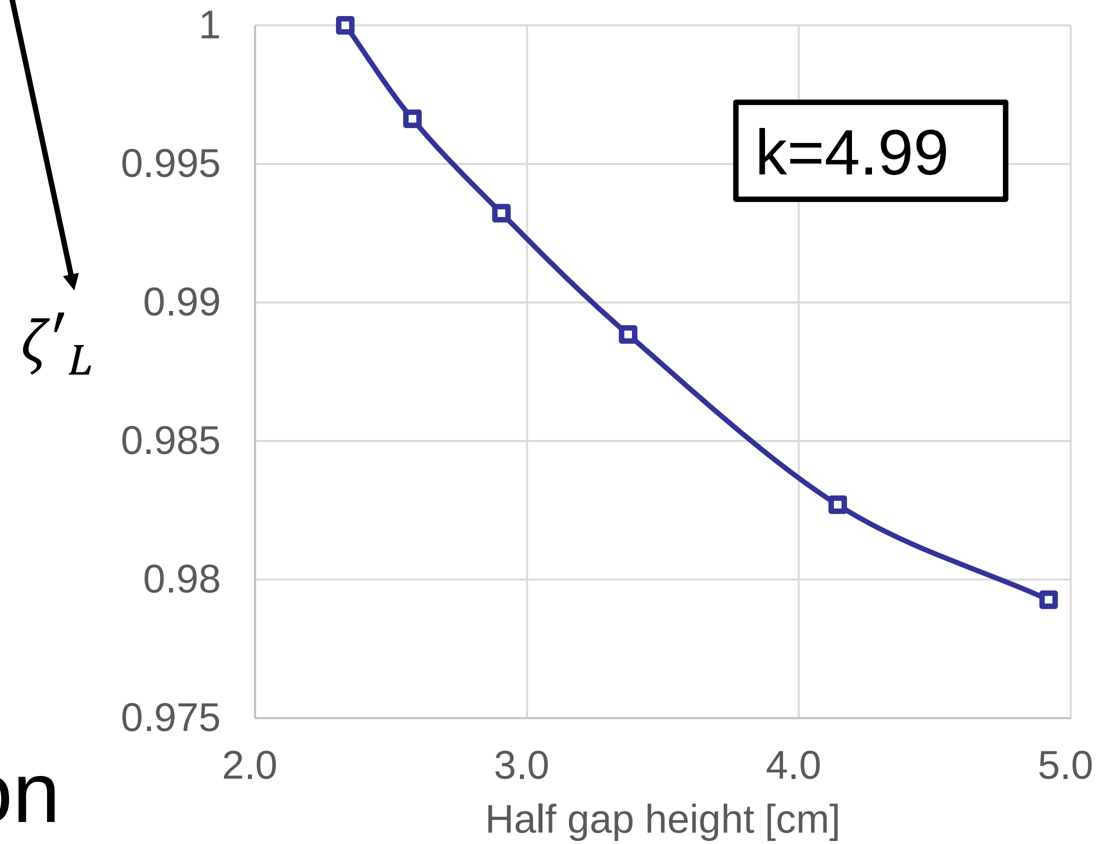
Gap height ⇒ large

⇓

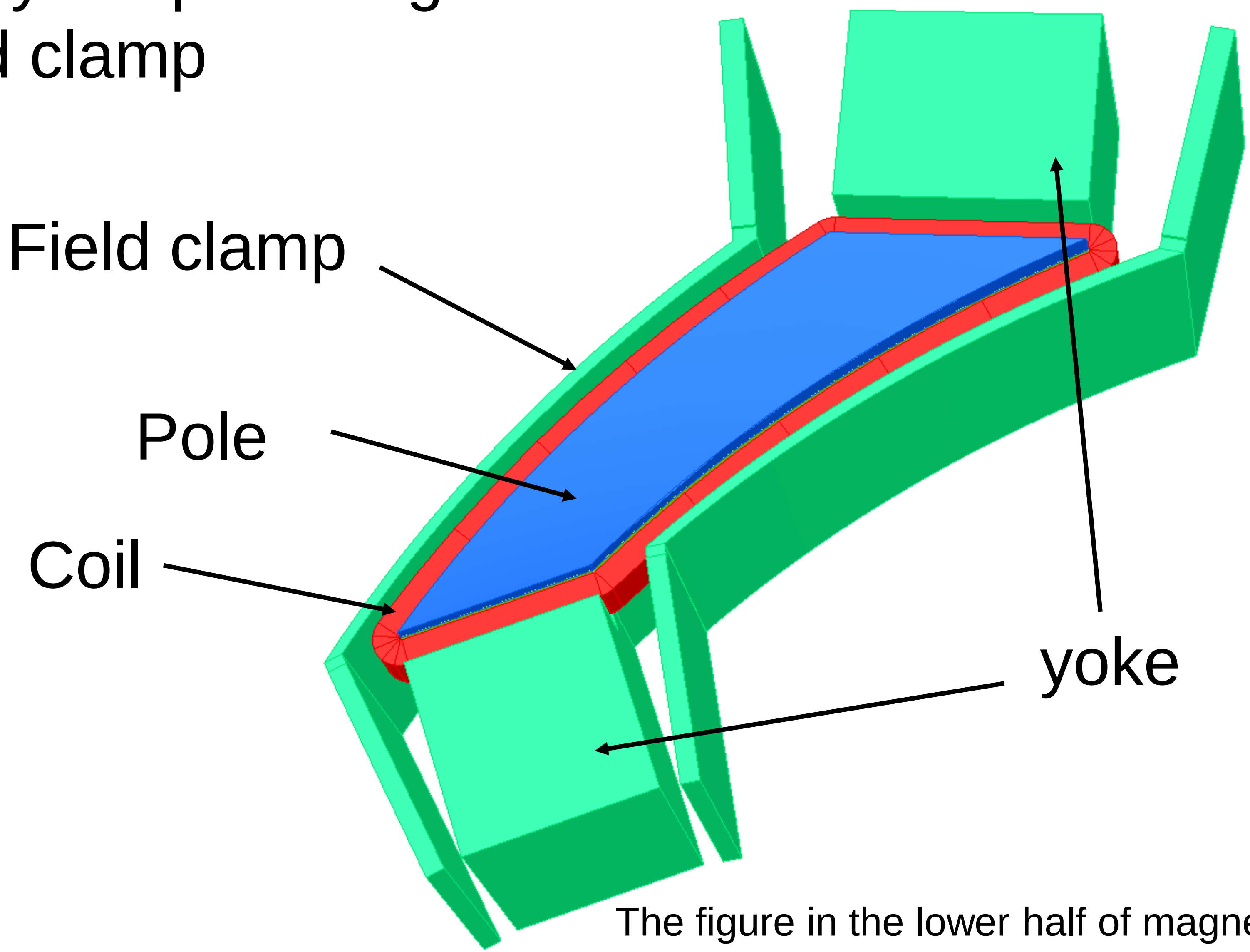
ζ_L ⇒ small

⇓

Vertical tune variation

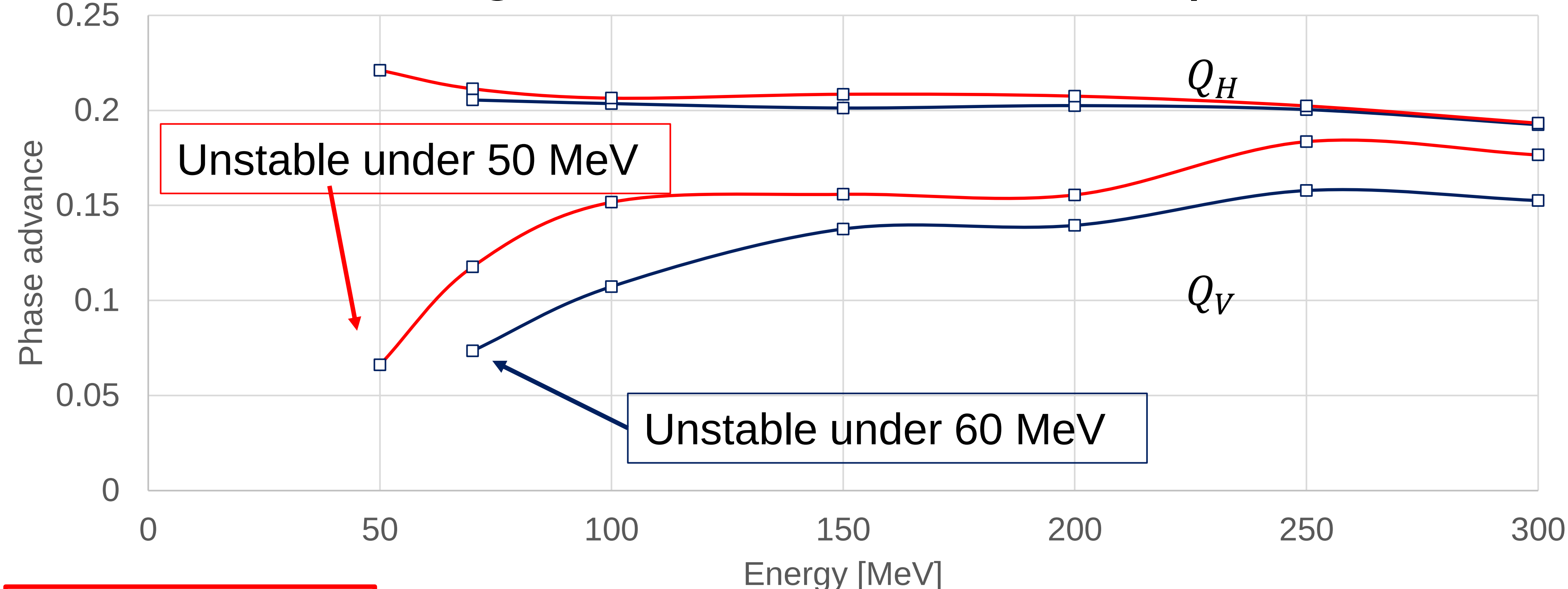


Geometry of spiral magnet with field clamp



The figure in the lower half of magnetic

Result of tracking simulation : Field clamp k=4.99



with field clamp

without field clamp

field clamp

⇩

Vertical tune variation control in low energy region

Extension of stable region ⇒ 50 MeV

Summary

Design of a 300 MeV FFAG

・Definition of lattice parameters of 300 MeV spiral FFAG with linear approximation

・Magnet design with Opera-3D
⇒ Accurate effective field index k

・Optimization of magnet (field clamp)
⇒control of vertical tune variation in low energy region
⇒extension of stable region ⇒ 50 MeV

・Further improvement

・Examination of other optics (ex. FDF triplet type of radial sector)

Thank you for your attention