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ISIS upgrade with FFA

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29 September 2022

Overview

- Goal of our project, prototype FFA (FETS-FFA)
- Change of the baseline lattice: vFFA to DFspiral hFFA
- **Dynamic aperture study**
- Summary

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Goal of prototype FFA (FETS-FFA)

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ISIS upgrade, “ISIS-II”

- Specifications of the proton driver

Beam power	1.25 - 2.50 MW
Beam energy	1.2 GeV

You might think it is easy to achieve!

- Beam power is just one of the figure of merits, many others exist, for example …

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Proton driver in the future

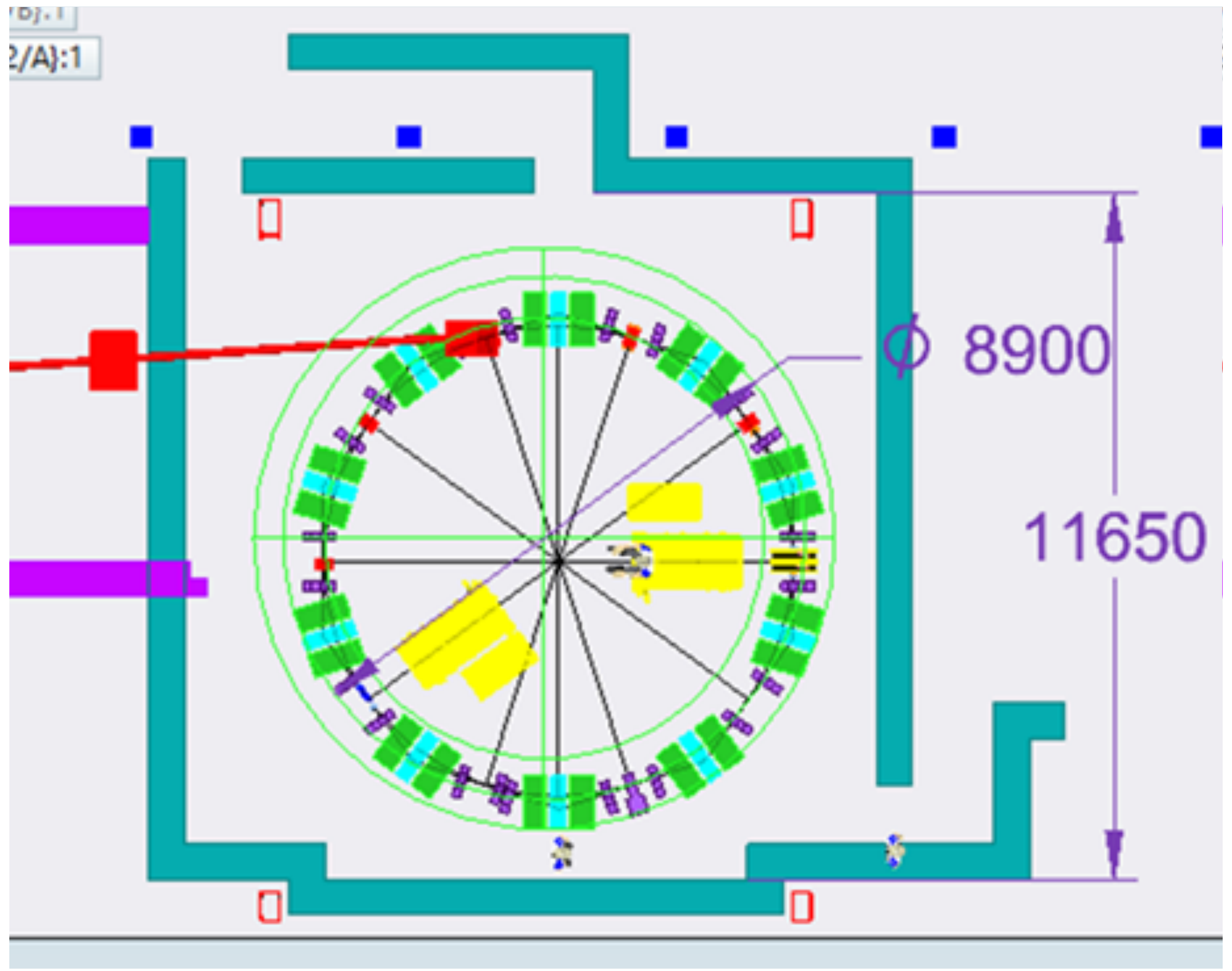
- **Sustainability** seems to be the most important key word. The facility is useless if you cannot operate.
    - Cyclotron is the most energy efficient accelerator.

- **Reliable operation** is also the key factor. If downtime is more than X(90?)%, users go somewhere else.
    - (superconducting) DC magnets are more reliable components.

- As a neutron source facility,
  - "**capacity** (number of experiments, size of community)" and
  - "**capability** (bespoke experiment)" are two key factors.
    - RF gymnastics can make either high peak with low repetition or low peak with high repetition.
    - Time structure of the beam pulse should be flexible.

- Why not **FFA?**
  - However, FFA needs a demonstrator for practical use.
  - Therefore, a prototype FFA, "**FETS-FFA**".

FETS-FFA in R9



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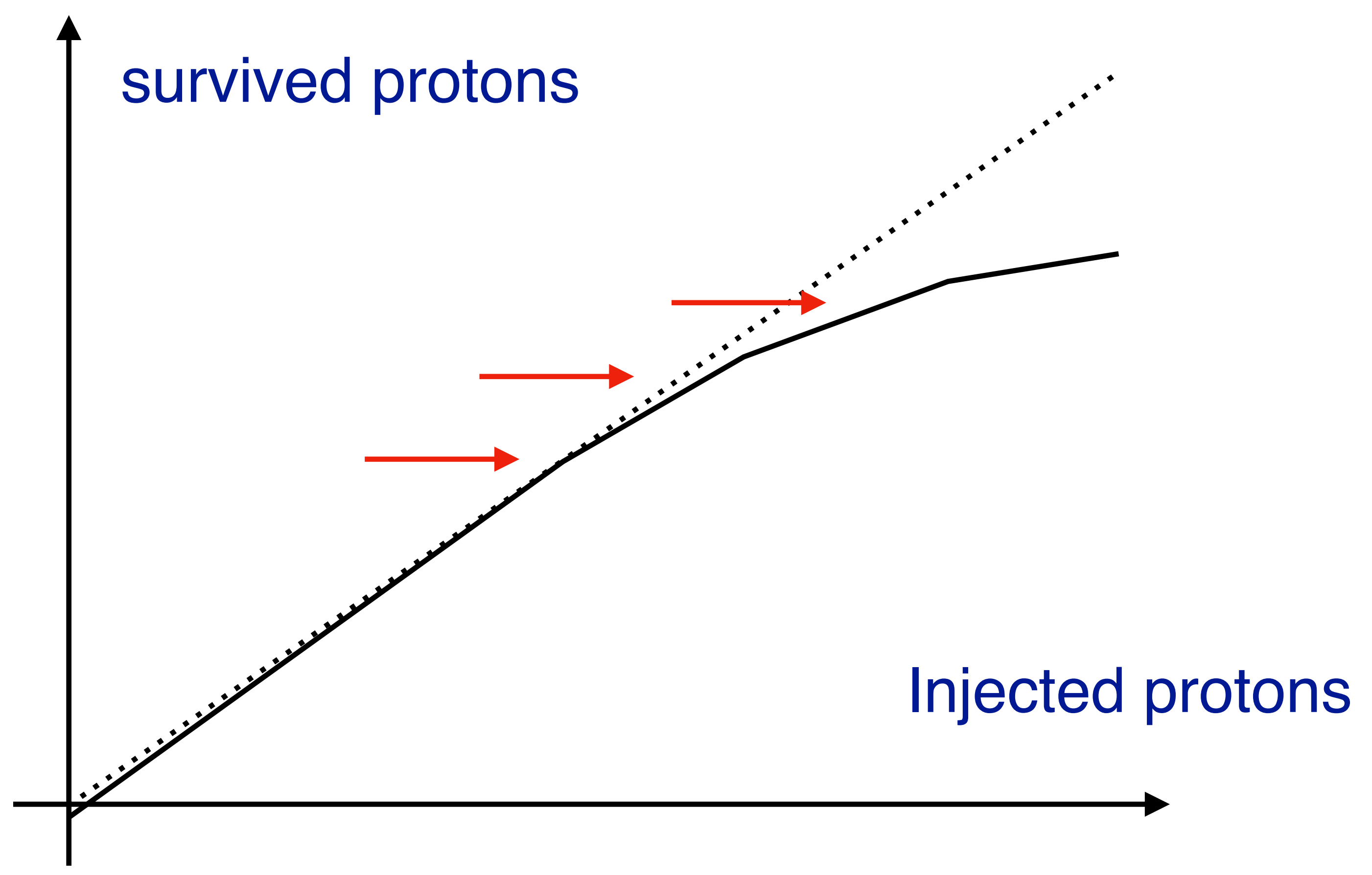
FETS-FFA is to answer …

0. Demonstrate single particle beam dynamics. (for vFFA)

1. How many protons can we **accumulate** “without beam loss” at injection?	2. How many protons can we **accelerate** “without beam loss” to the top energy?
3a. How many protons can we **accumulate** “without beam loss” **by beam stacking** at the top energy?	3b. How many protons can we **capture** and **extract** “without beam loss” **after beam stacking**?



- We need define the meaning of “without beam loss” later (e.g. 5%, 1%, or 0.1%).
- It depends on diagnostics, stability of the hardware, injector (FETS) performance, etc.

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Not just a FFA, but it will be **a high intensity FFA.**

Change of the baseline: from vFFA to DFspiral hFFA

Changed the baseline from vertical FFA to horizontal FFA

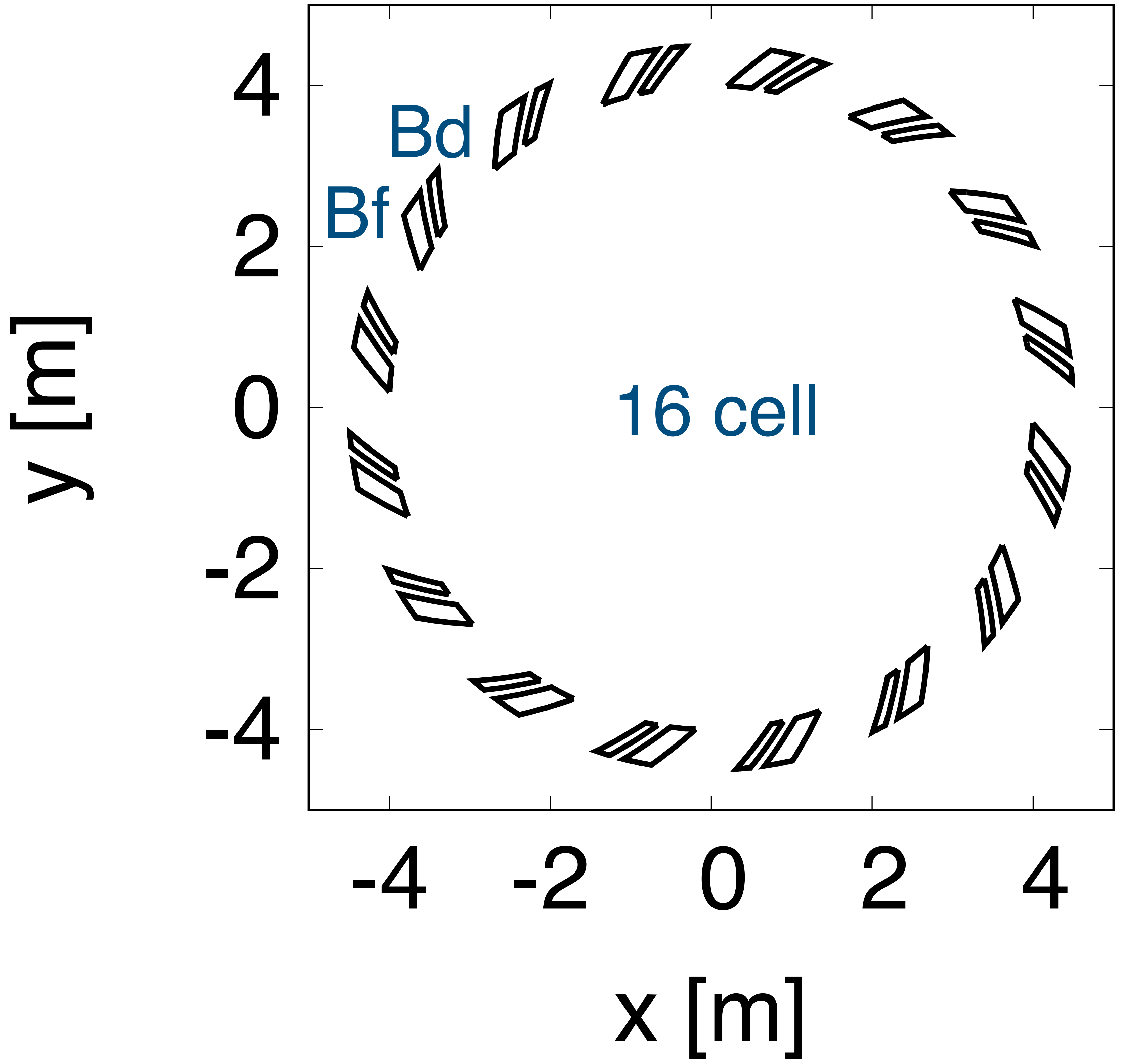
- **Superconducting magnet** development was one of the bottlenecks.
  - It does not fit in our timeline to make a choice of the proton driver for ISIS-II in ~2030.
- **Dynamic aperture** is limited. It was not clear what makes those limitations.

- Prototype FFA, FETS-FFA with radius of ~ 4 m, will be a hFFA.
  - **Scaling FFA** using B ~ r^k magnetic field.
  - Chose a **DFspiral** hFFA design.
  - Combination of radial sector and spiral sector.

- Continue vFFA design and development, especially on magnets.
  - For muon accelerations, for example.

vFFA magnet

DFspiral



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DFspiral design

Strong focusing produced by the gradient variation with azimuth arising from the undulation of the orbit.

$$Q_x^2 \approx 1 + k + \frac{k^2 S^2}{N^2 b_0^2}, \tag{4}$$

$$Q_z^2 \approx -k + \frac{k^2 S^2}{N^2 b_0^2} + \frac{\Phi^2}{b_0^2}(1 + 2\tan^2\delta), \tag{5}$$

Field gradient averaged over the azimuth.

Specific strong focusing due to spiral field shape.

Focusing given by the azimuthal variation of the field, similar to the Thomas focusing in isochronous cyclotrons.

Φ/b_0 ~1 in spiral, ~6 in radial, Inf in two-way
(field flutter)

x: horizontal, z: vertical

$$B_z = B_{z0} \sum_{m=0}^{\infty} b_m e^{imN\theta}$$

and

$$\Phi^2 = 4 \sum_{m=1}^{\infty} |b_m|^2,$$

$$S^2 = 2 \sum_{m=1}^{\infty} \frac{|b_m|^2}{m^2},$$

where N is the total number of cells in the ring lattice. The quantity Φ/b_0 is called the field flutter. The term $2\Phi^2 \tan^2\delta/b_0^2$ is a measure of the specific strong focusing due to the spiral field shape. In short, the vertical tune is a function of the field flutter Φ/b_0 and the spiral angle δ. In a radial sector FFAG, the spiral angle is zero and the tune is dominated by the field flutter. In a spiral sector FFAG, the tune is adjusted by the spiral angle because the field flutter is almost unity since there are only normal bending magnets.

Machida, PRL **119**, 064802 (2017)

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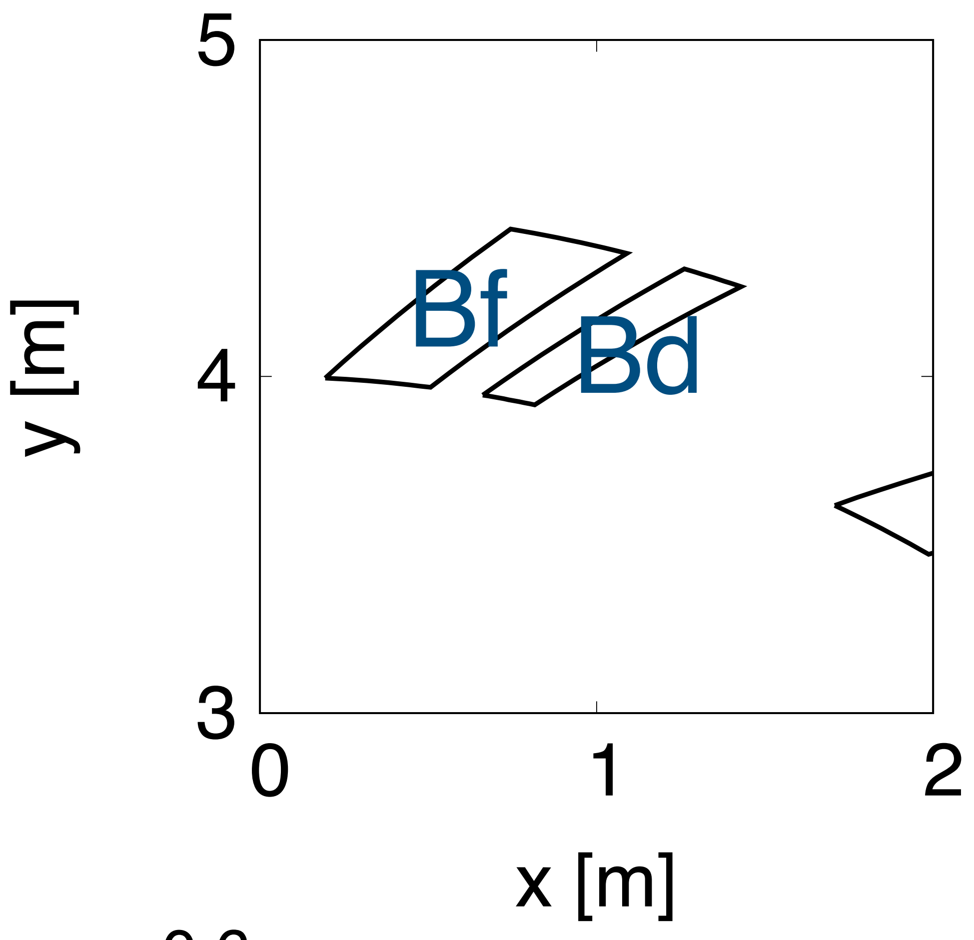
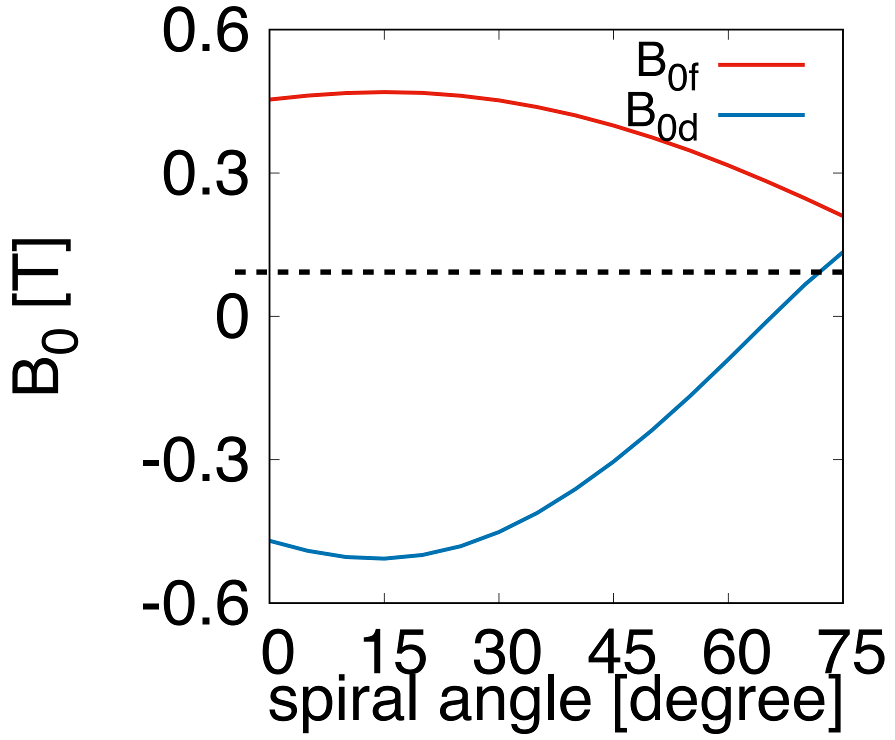
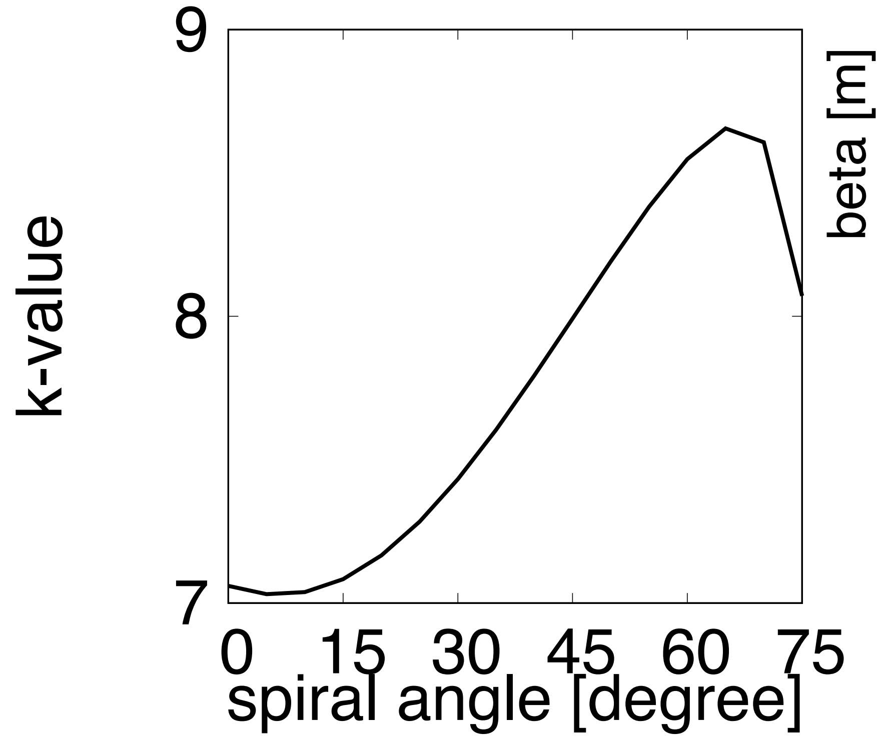
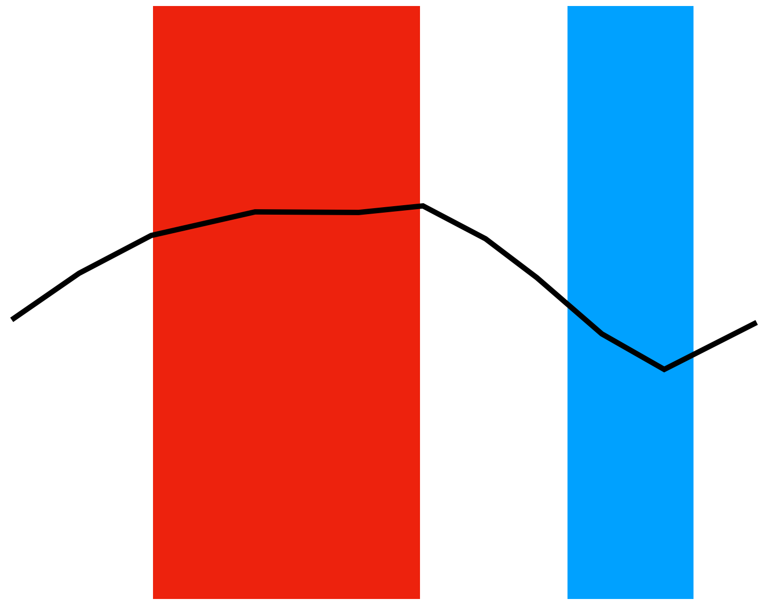
DF(FD)spiral FFA







radial sector

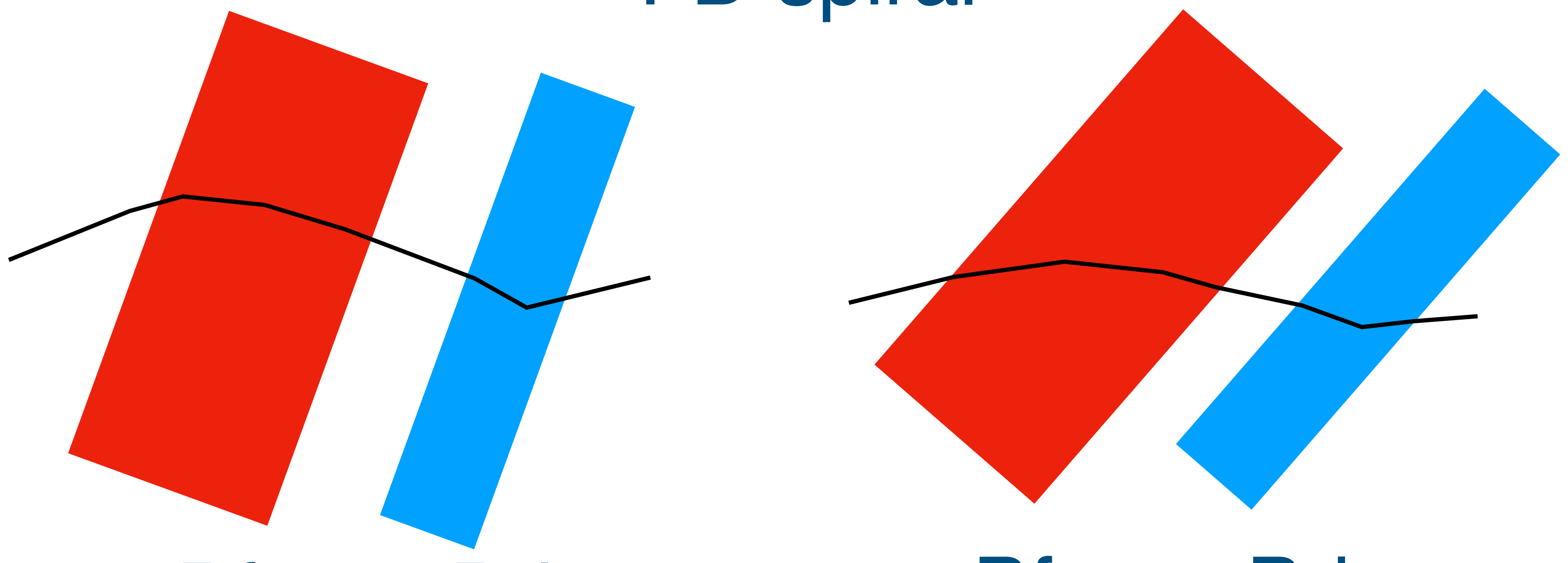


Bf Bd

(DFD) (DDD)

(entrance, body, exit)

FD spiral



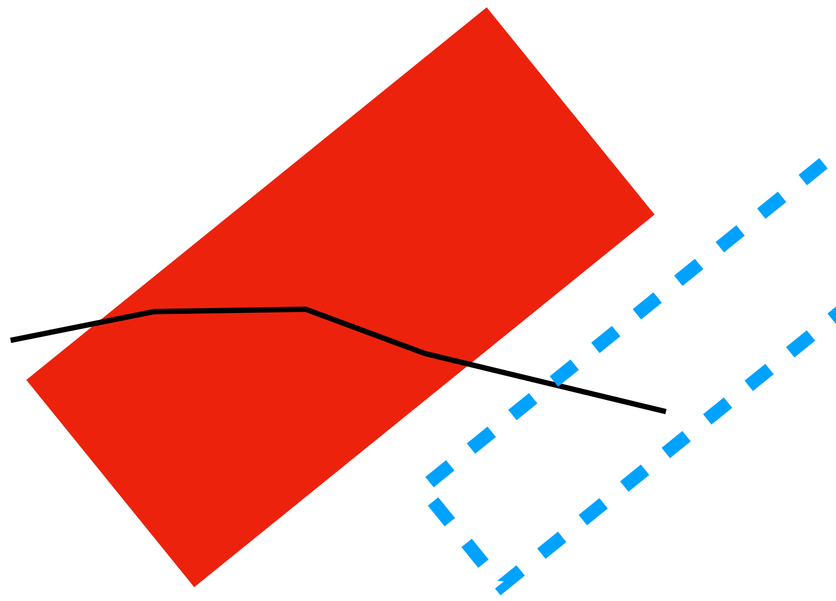
Bf Bd

(DFO) (ODD)

Bf Bd

(DFF) (FDD)

spiral sector

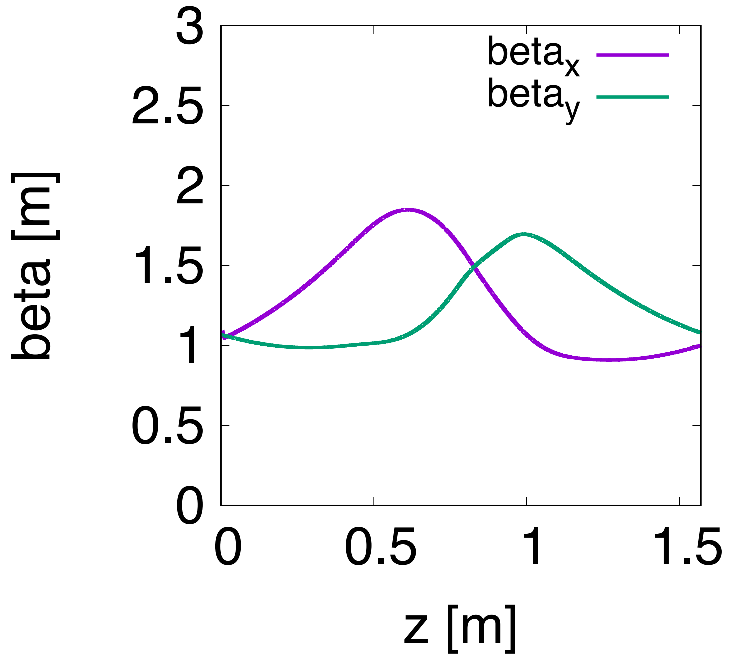


Bf

(DFF)

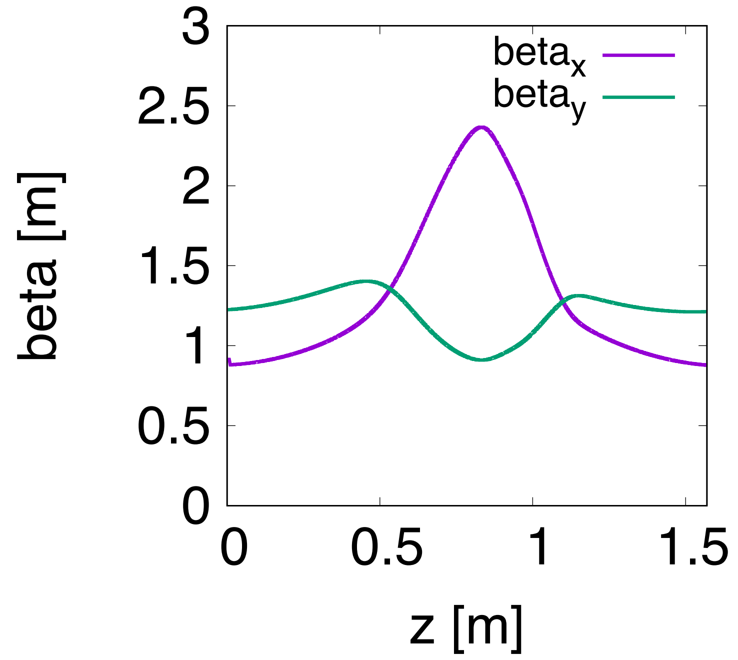
FD

Spiral angle=0 deg

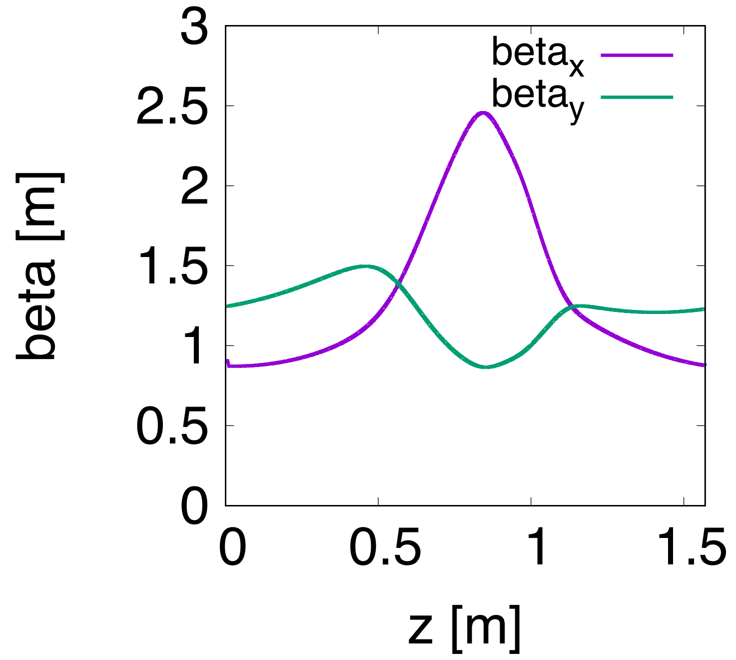


DFD

35 deg

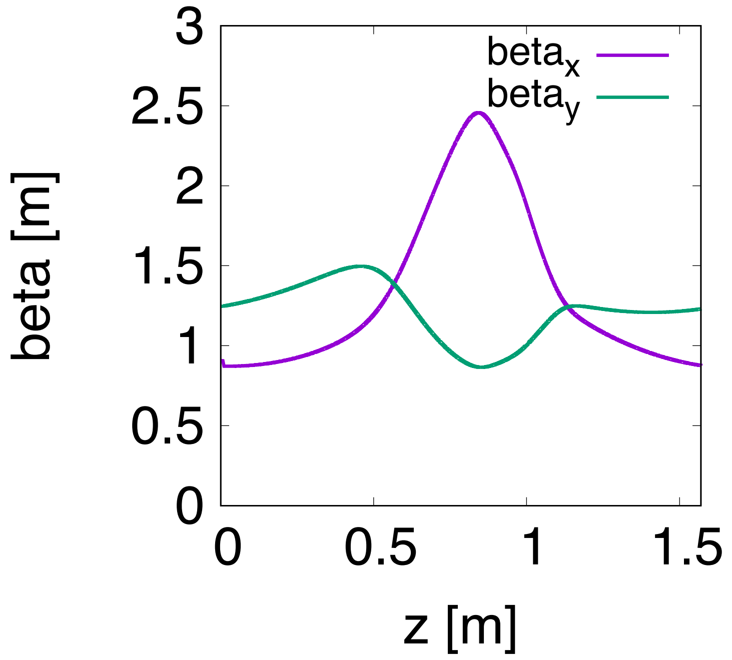


40 deg



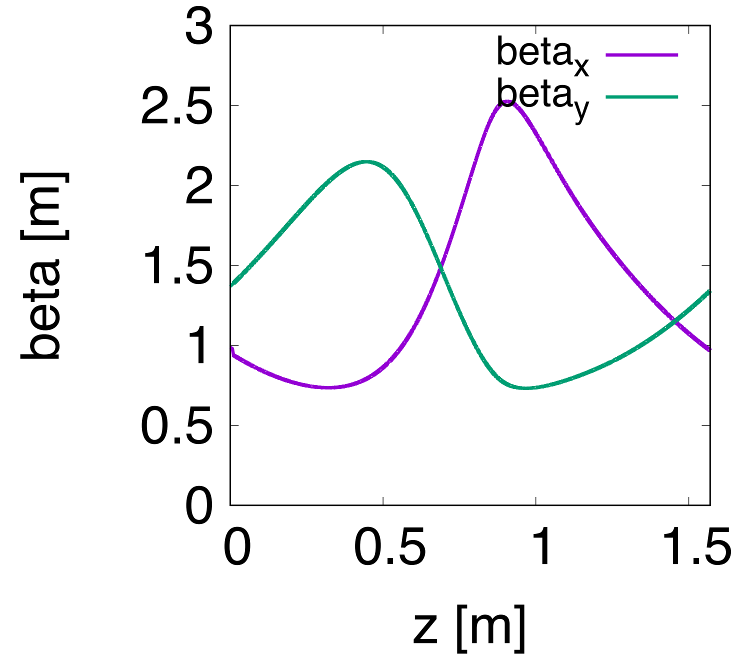
DFD

45 deg



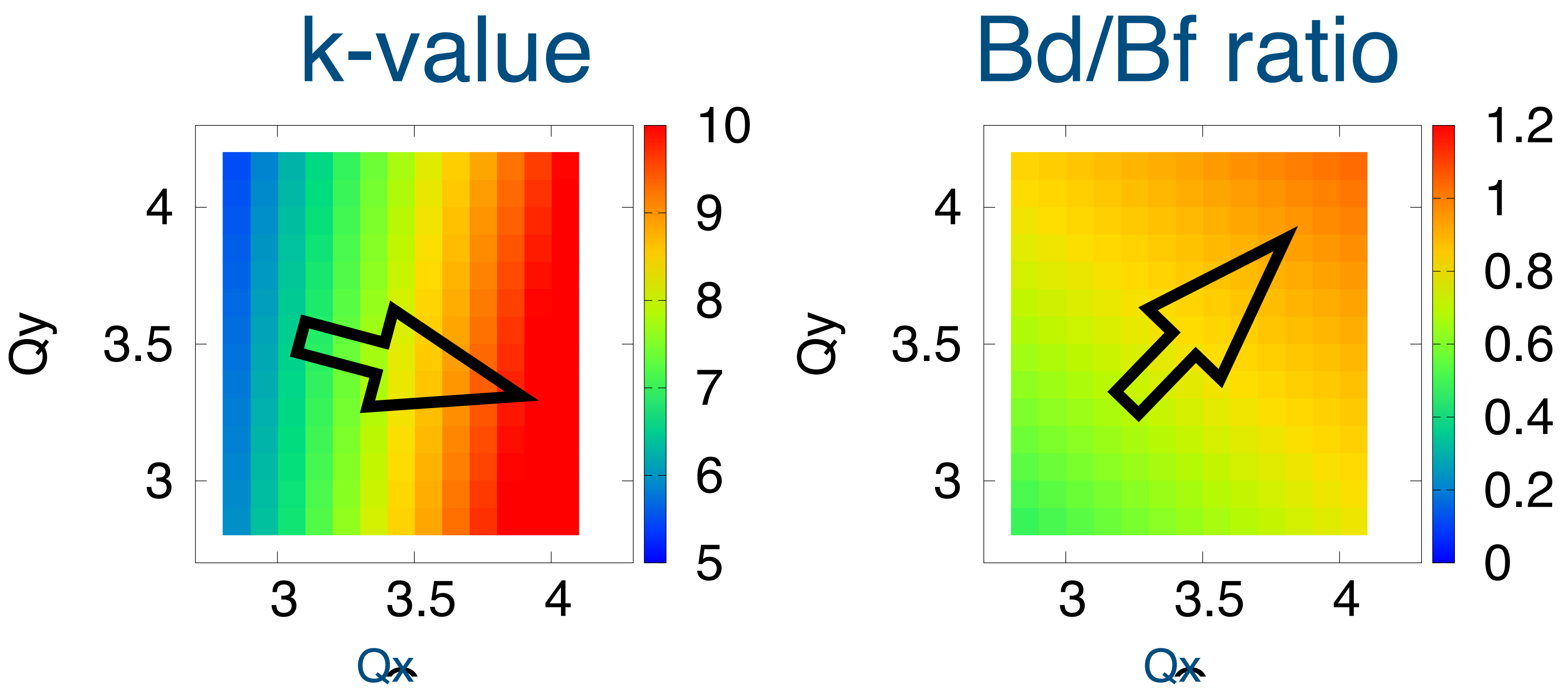
DF

65 deg

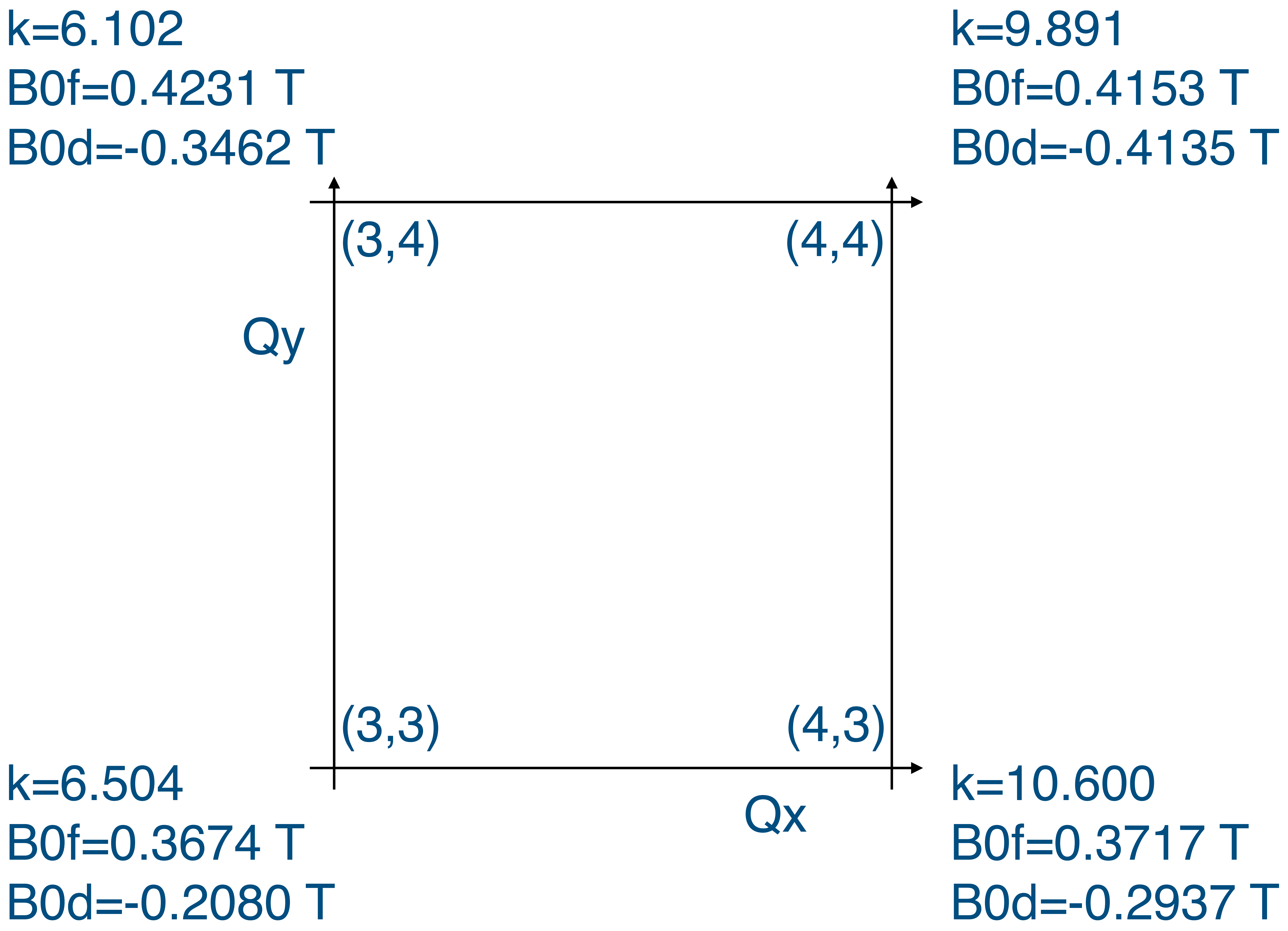


cell tune = (0.213125, 0.213125)

Adjusting Qx and Qy (16 cell, spiral angle=45 deg.)



k-value and Bd/Bf strength ratio are two parameters to adjust tune Qx and Qy.



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Dynamic aperture study

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Aperture requirement

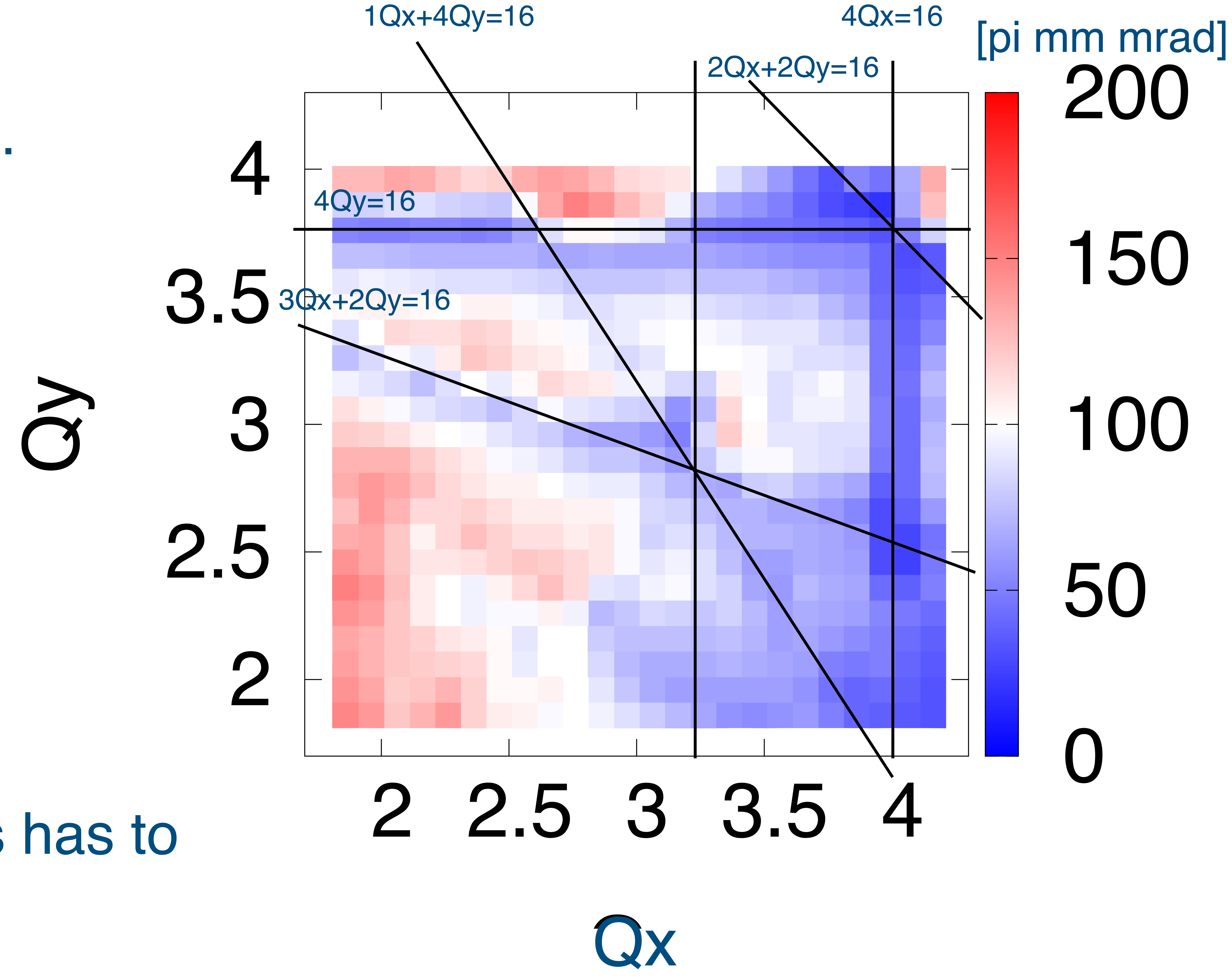
For high intensity operation of FFA, we need large physical aperture and **dynamic aperture larger than physical aperture** to reduce **space charge effects**.

- SNS, J-PARC have ~500 pi mm mrad (geometrical).
- With Qx ~ Qy

- How dynamic aperture depends on the k-value?
- How do we enlarge dynamic aperture?

We have seen a variety of FFA (first order) optics: scaling, nonscaling, novel idea, etc,

- That is not enough!
- As an accelerator for a user facility, nonlinear optics has to be understood well.



dynamic aperture at 3 MeV (normalised)

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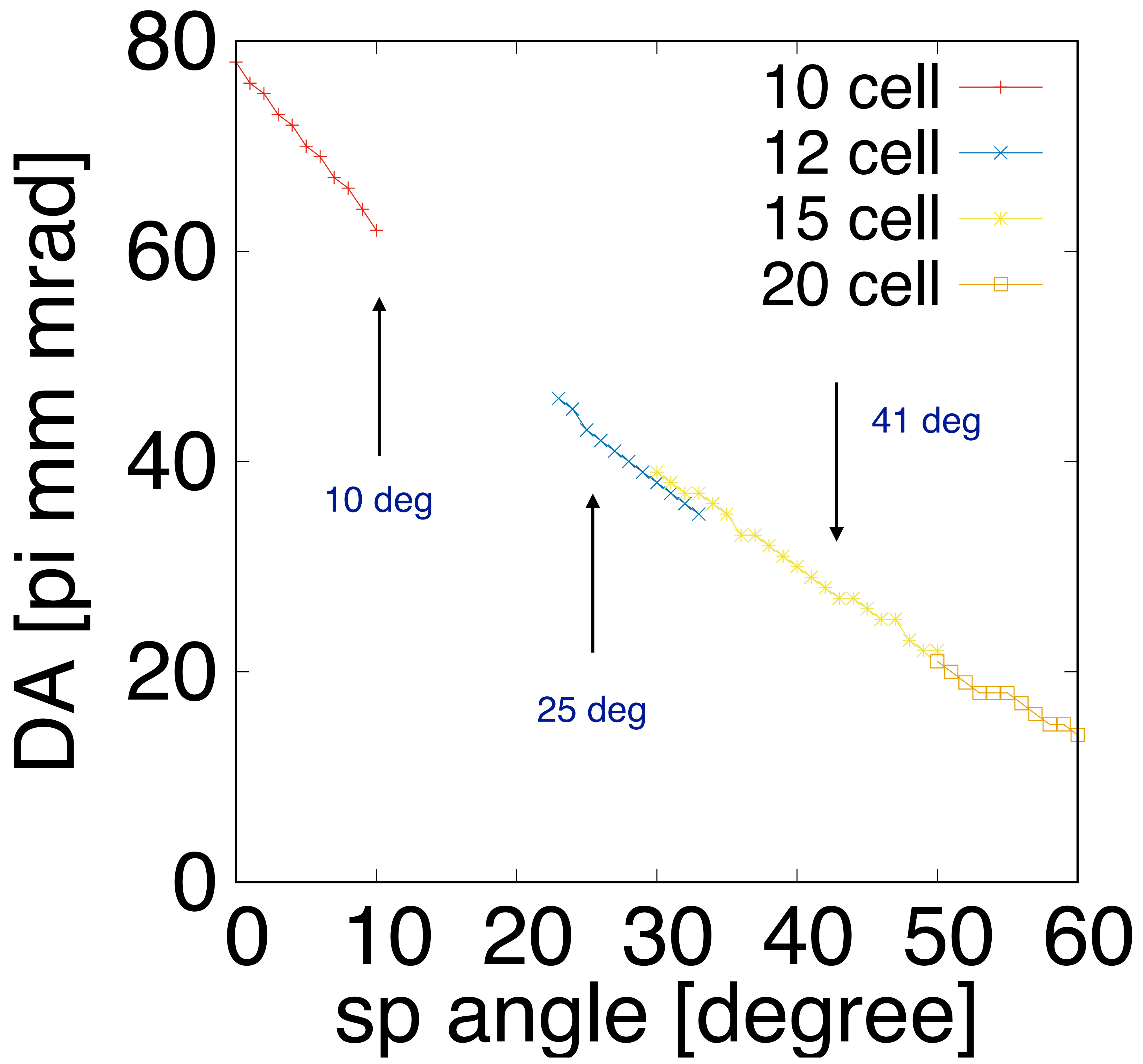
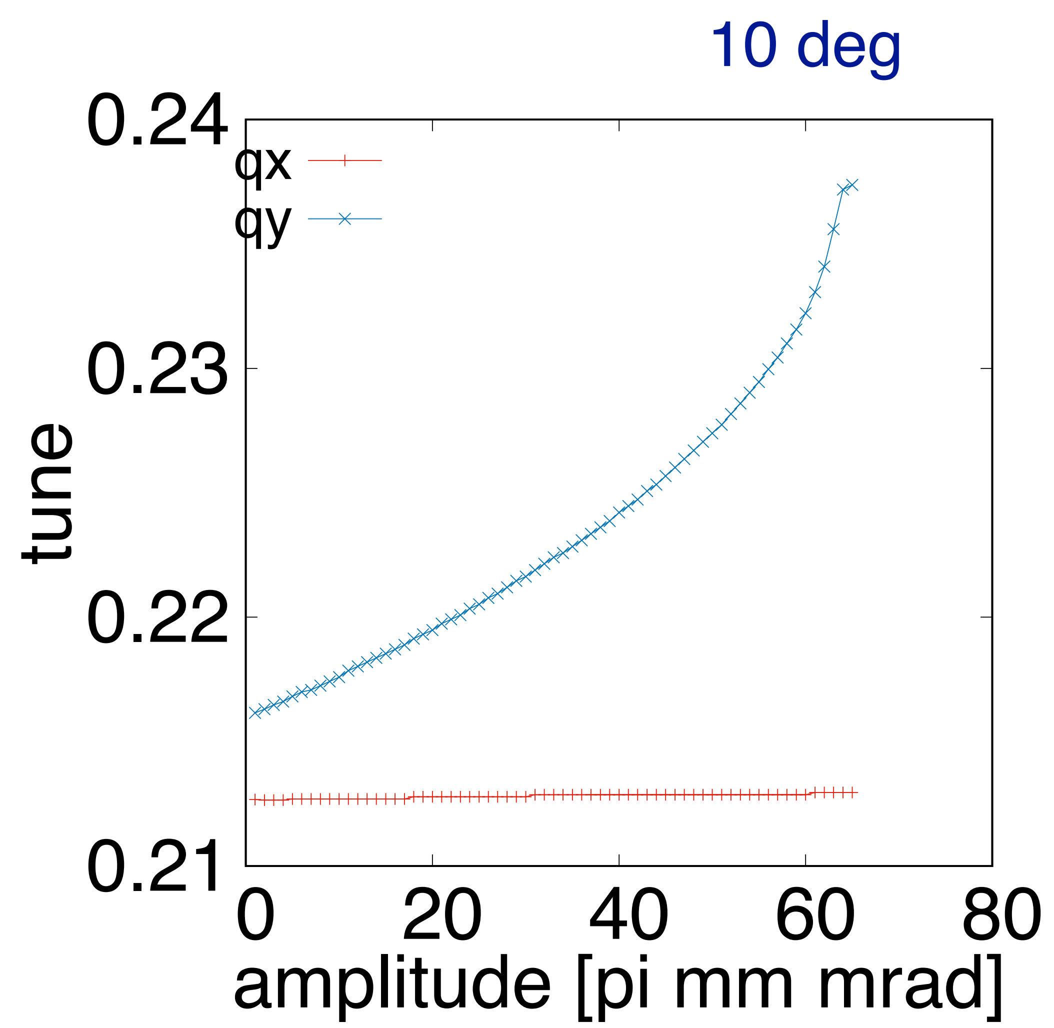
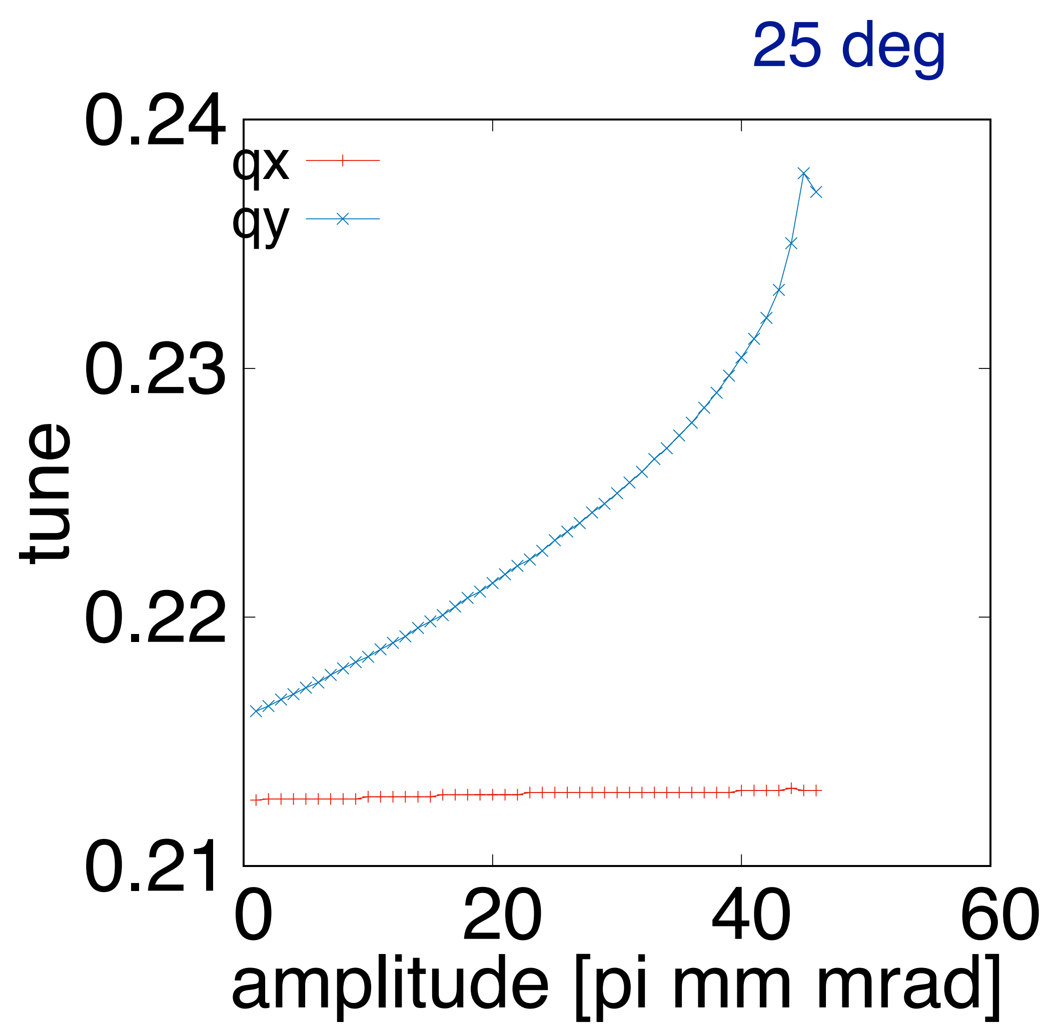
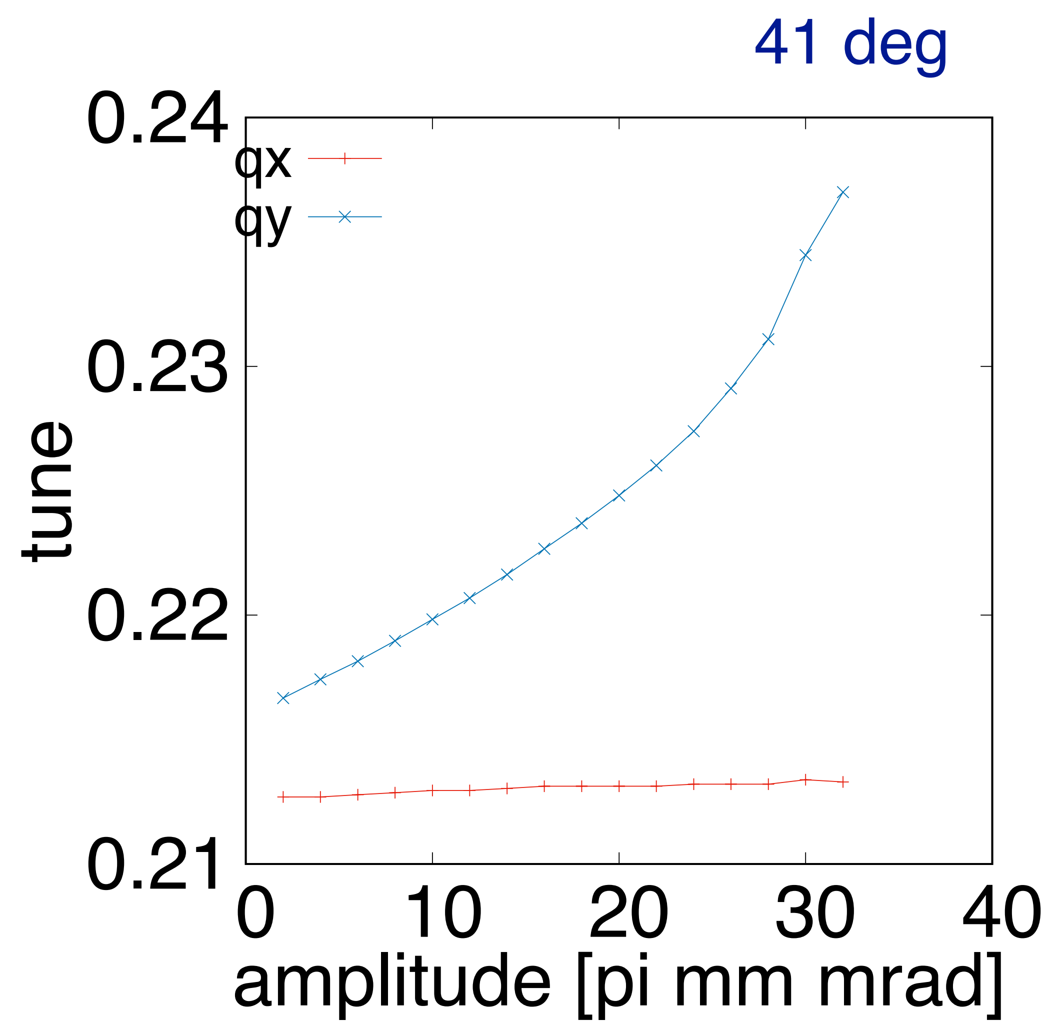
Result 1: Dynamic aperture for different number of cell lattices









Amplitude dependent tune shift is limited at the similar value.

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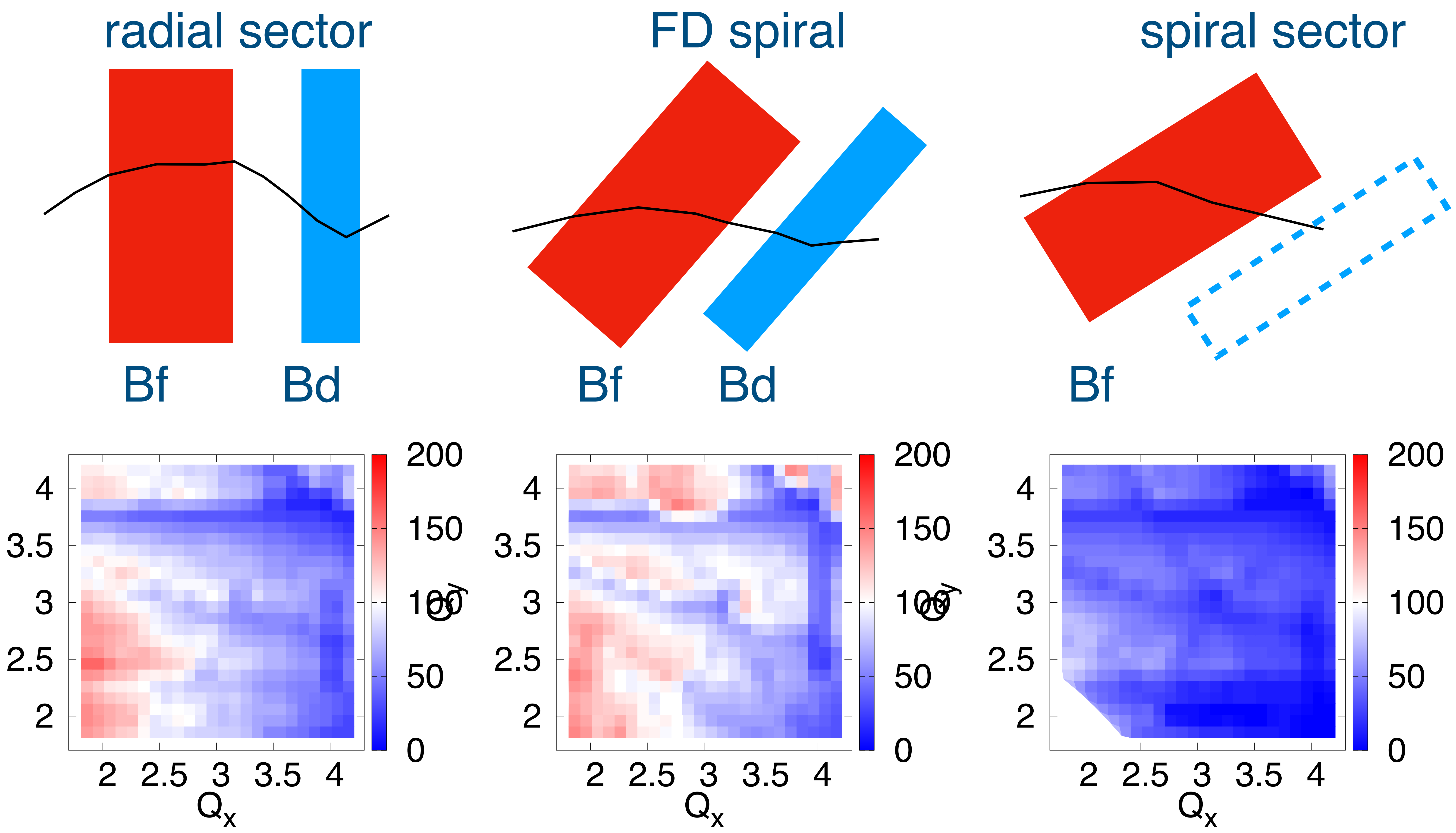
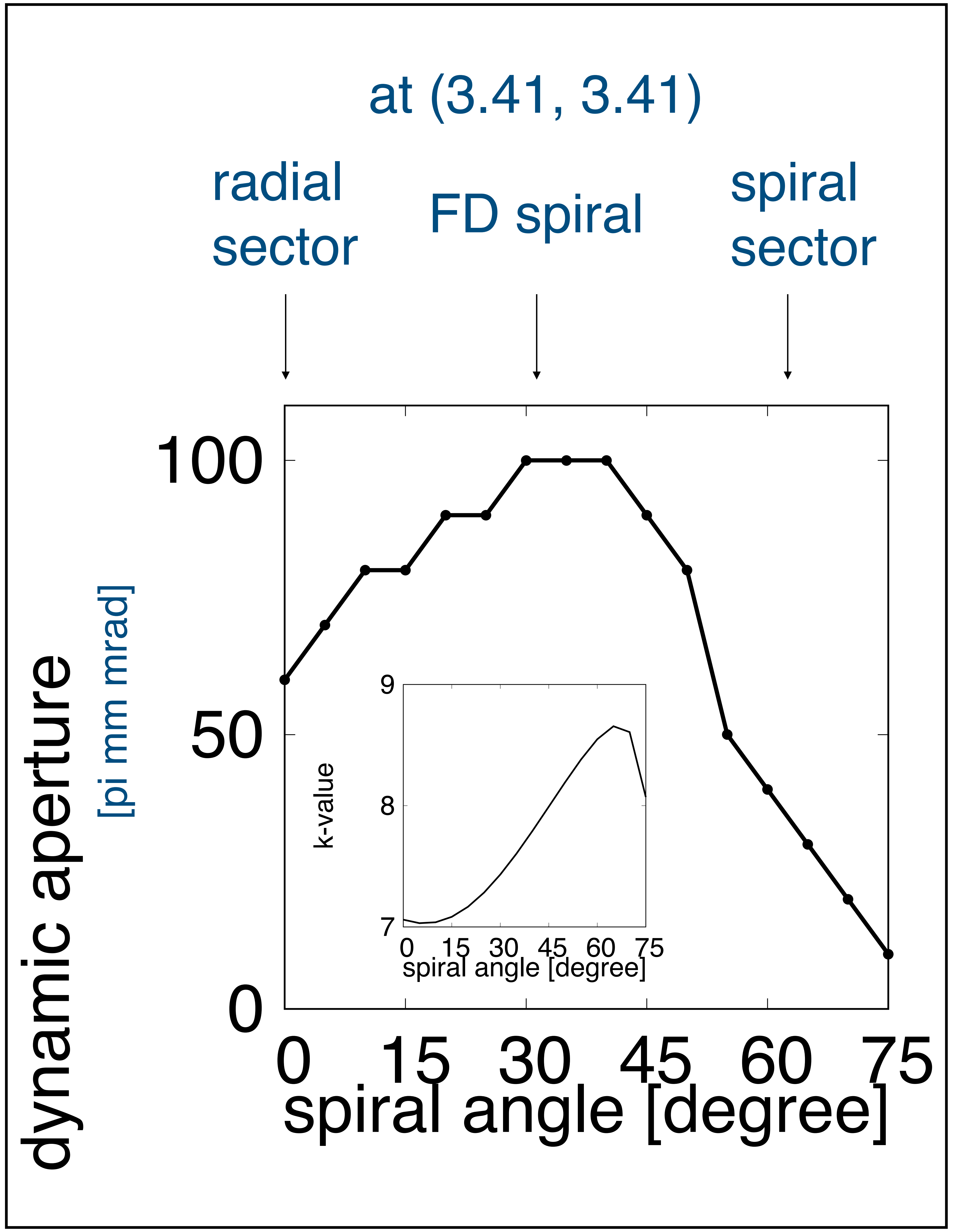
Result 2: Dynamic aperture for 16 cell lattice





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Previous work by Aiba, et al.

Proceedings of EPAC 2002, Paris, France

STUDY OF ACCEPTANCE OF FFAG ACCELERATOR

M. Aiba, S. Machida, Y. Mori, A. Mutoh, J. Nakano, C. Ohmori, I. Sakai, Y. Sato, M. Sugaya, A. Takagi, T. Uesugi, R. Ueno, T. Yokoi, Y. Yonemura, M. Yoshii, M. Yoshimoto, A.Yamazaki, Y. Yuasa (KEK), K. Koba (FNAL)

Abstract

The aim of this study is to establish the generalized procedure to design a FFAG accelerator having large transverse acceptance. Due to the large momentum and transverse acceptance, it is considered that the FFAG accelerator is quite appropriate for a phase rotator or a secondary particle accelerator [1]. Some analytical ways and tracking simulations were performed to study the problem of non-linear motion in FFAG accelerator.

enhances the higher order components of the guiding field, which causes the tune shift. Here, B_z show the vertical component of the field, B_0 is the field strength at the radius r_0 and k is the k value. In this study, positive k value is assumed.

$$B_z = B_0\left(\frac{r}{r_0}\right)^k = B_0 + B_0\frac{k}{r_0}x + B_0\frac{k(k-1)}{2!r_0}x^2 + \cdots \quad (1)$$

$$(\textit{Taylor Expansion around } r_0, r = r_0 + x)$$

$$\textit{orbit excursion} = r_{inj}\left(A^{\frac{1}{k+1}} - 1\right) \quad (2)$$

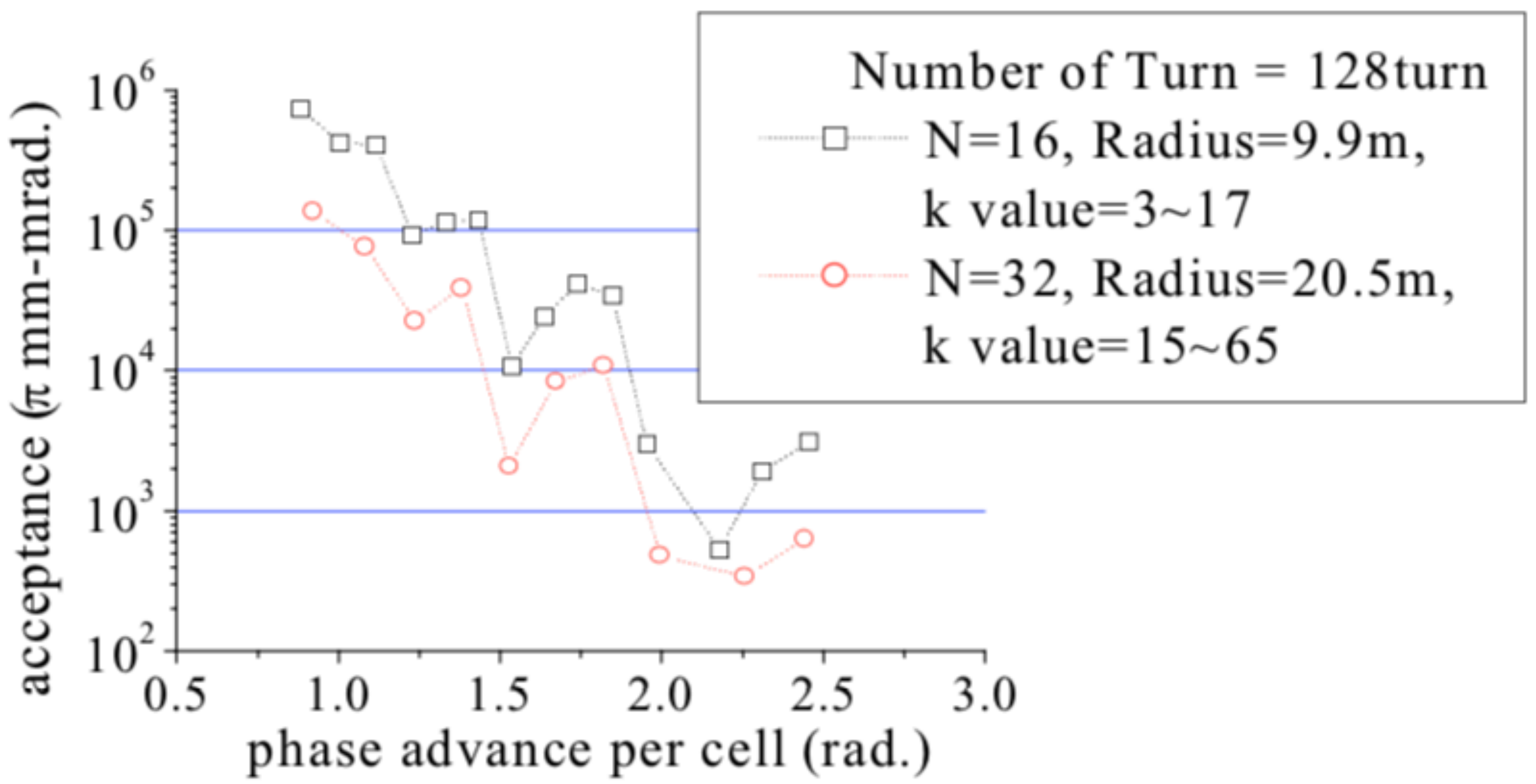

FIGURE 1. Acceptance vs. Phase Advance

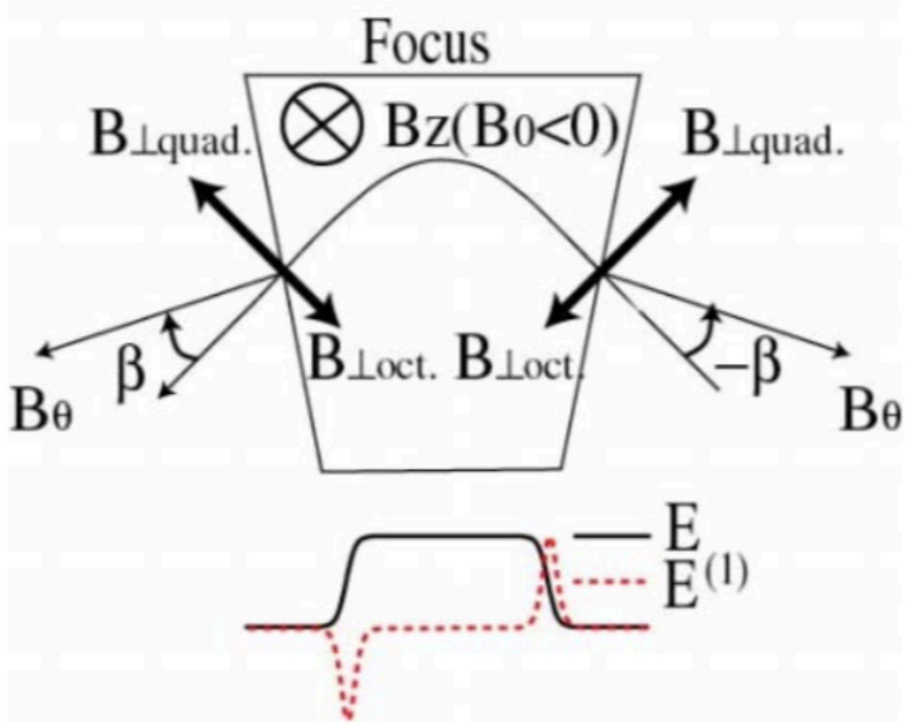

FIGURE 3. Octupole Component in Edge Focus

$$B_{\perp oct} = -\frac{1}{3!}\left(E^{(1)}k^2 + E^{(3)}\right)\frac{B_0}{r_0^{\,3}}z^3 \sin\beta$$

$$\cong -\frac{E^{(1)}k^2}{3!}\frac{B_0}{r_0^{\,3}}z^3 \sin\beta = O(s)z^3$$

- E(1) is the first derivative of fringe field extent with azimuthal direction.
- E(3) is the third derivative of …

- DA decreases with phase advance.
    - Higher k-value means stronger nonlinearity.
- Several dips appear when a systematic resonance occurs.
    - All order of multipoles exist.
- Amplitude dependent tune shift due to octupoles is the primary source of the DA limit.
    - Tune gets to a nearby systematic resonance.

vFFA design, lessons learned

- Any circular accelerator should have
  - Fixed point in phase space (equilibrium orbit) and
  - It should be stable (stable optics).

- Cyclotron
  - Pseudo**-** equilibrium orbit and pseudo**-** stable optics
  - As long as the total number of turns are small (a few 100s turn), it does not make a problem.

- Synchrotron
  - Equilibrium orbit is **defined by design**, by positioning magnets.
  - Stable optics can be obtained by exciting magnets proportional to momentum.

- FFA
  - Equilibrium orbit **moves** (in all the 3D directions for vFFA).
  - Stable optics is **determined along the (p dependent) equilibrium orbit** and time independent.
  - **Fringe fields** are essential components.

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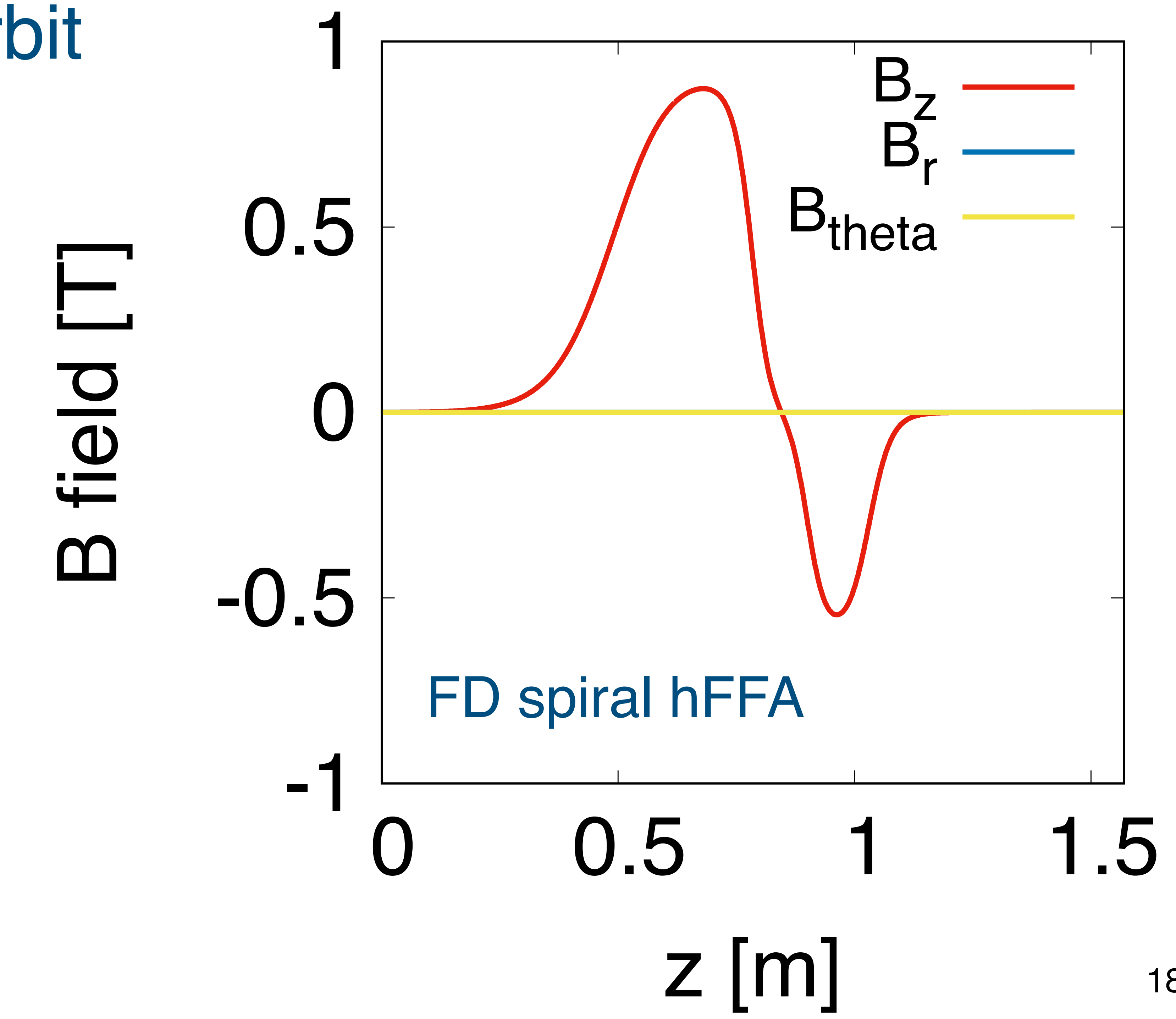
Scaling FFA

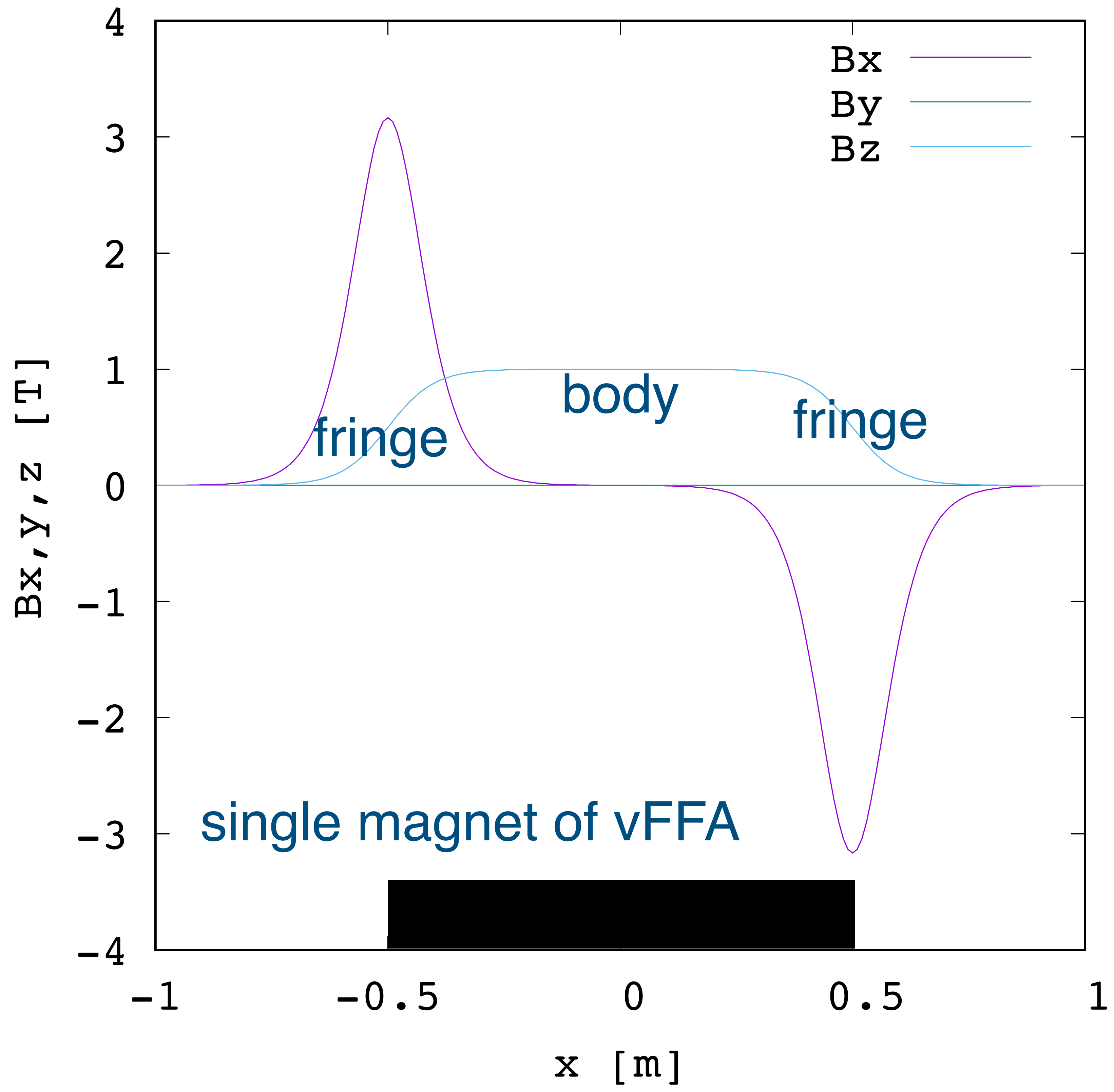
- **exp(mr) field** in vertical or **r^k field** in horizontal can satisfy the condition.
  - It is a remarkable finding (idea of scaling FFA)!
  - Not only focusing strength (quadrupole), all the multipoles scale with momentum (Chris Rogers).

- However, this is only a part of the whole story.
  - Fringe fields plays the essential role.

- Unlike synchrotron, we do not know multipoles strength along the orbit until we find the orbit.

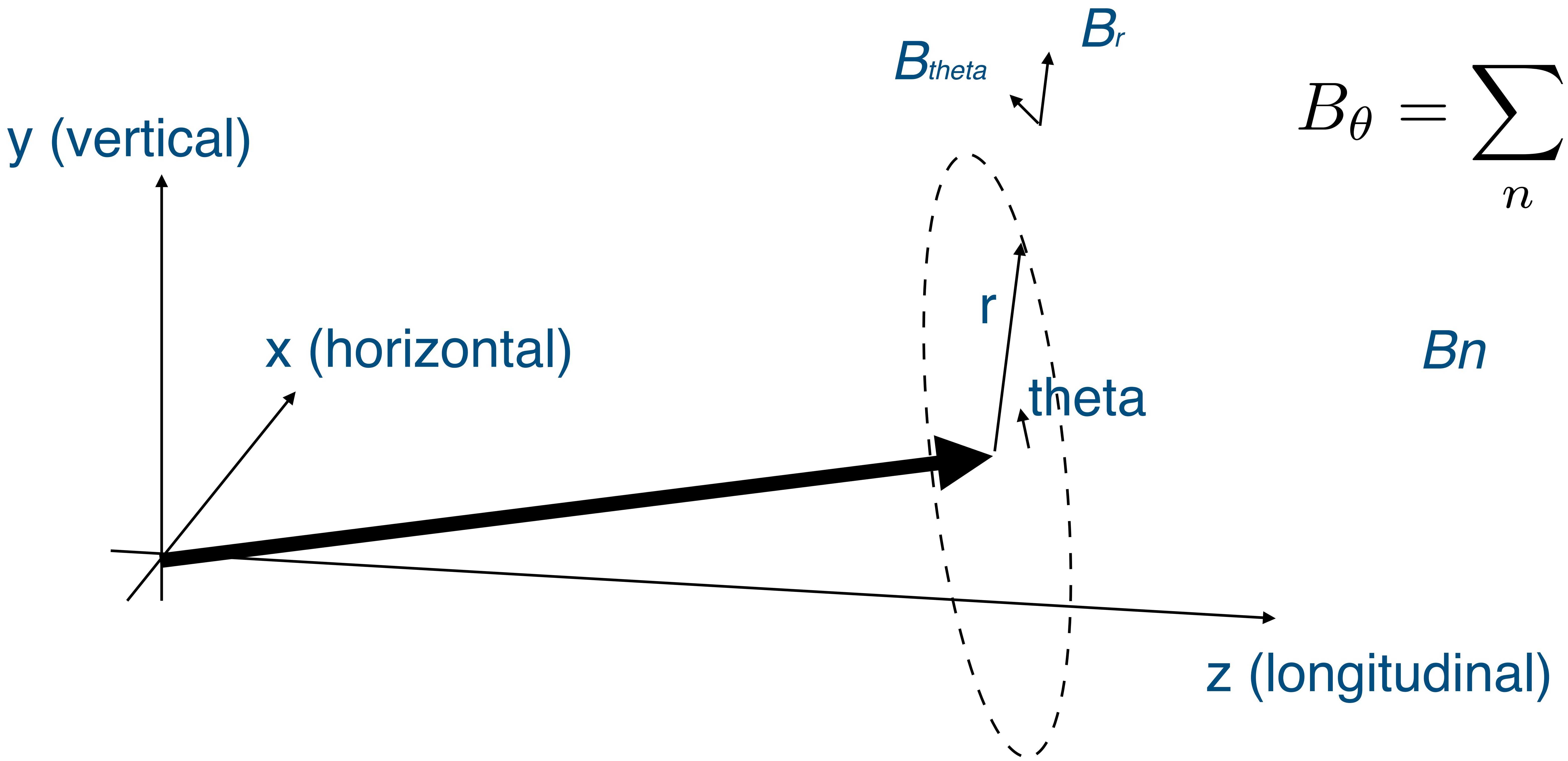


x: longitudinal, y: horizontal, z: vertical



Harmonic analysis (proposed by Alan Letchford)

- Multipole expansion of the transverse fields along the equilibrium orbit.



$$B_\theta = \sum_n B_n \exp\left(in\theta\right)$$

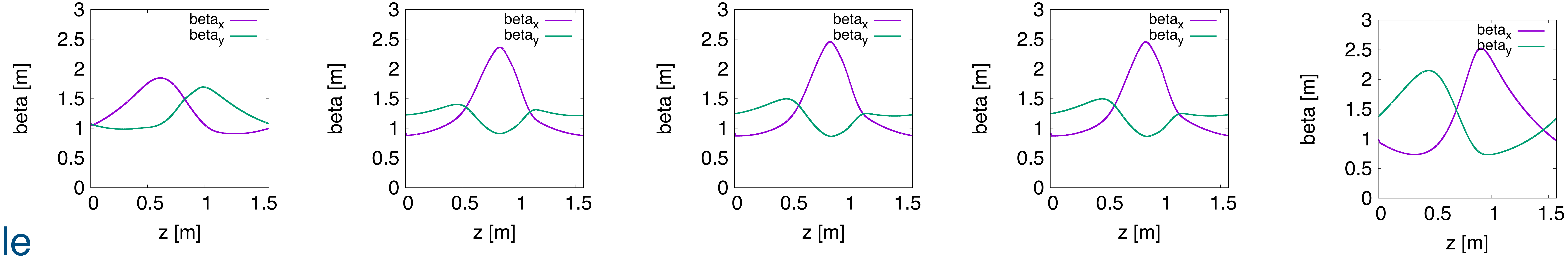
Bn

n=1: dipole
n=2: quadrupole
n=3: sextuple
n=4: octuple
…

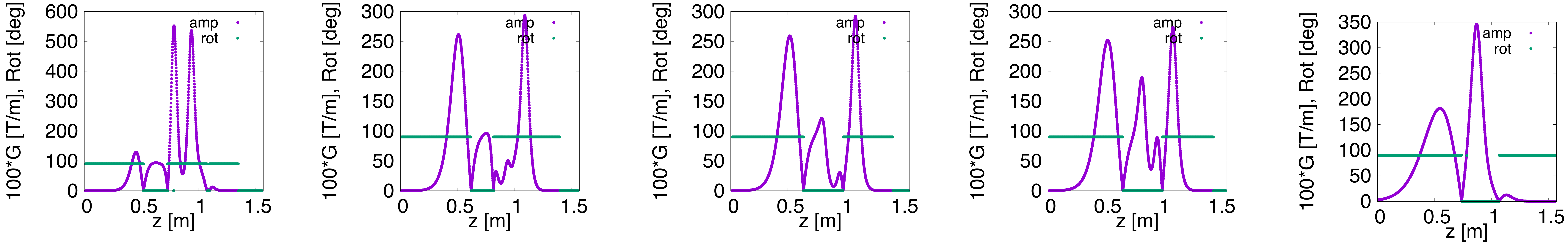
Multipoles along the orbits

spiral angle = 0 deg | 35 deg | 40 deg | 45 deg | 65 deg

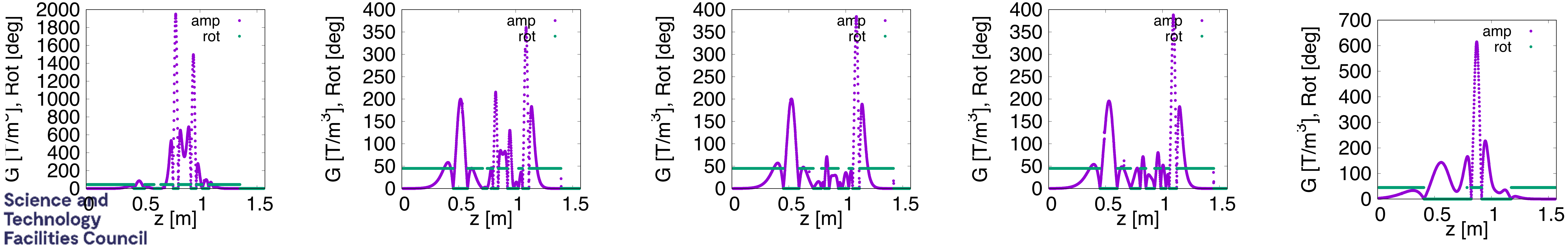
beta function



quadrupole



octupole



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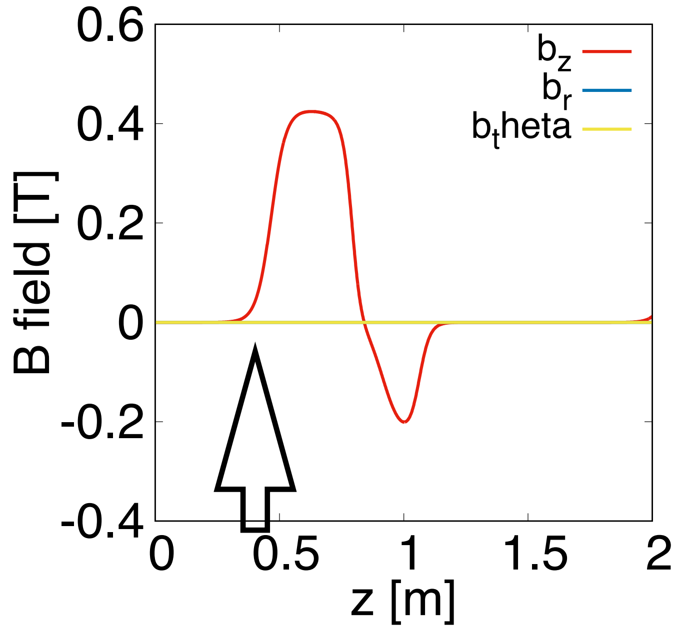
Correlation between Octupole and DA

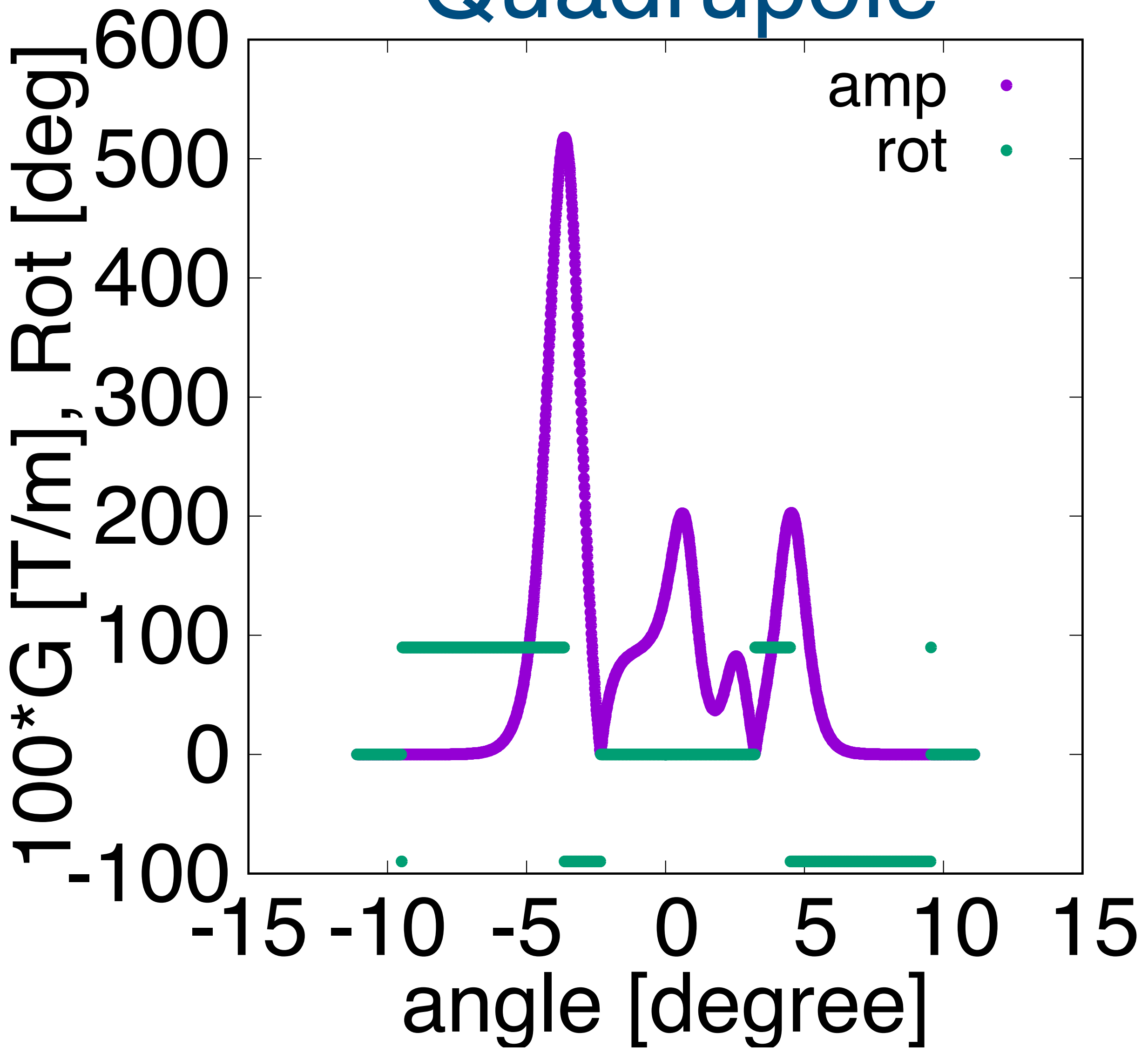
Fringe field extent

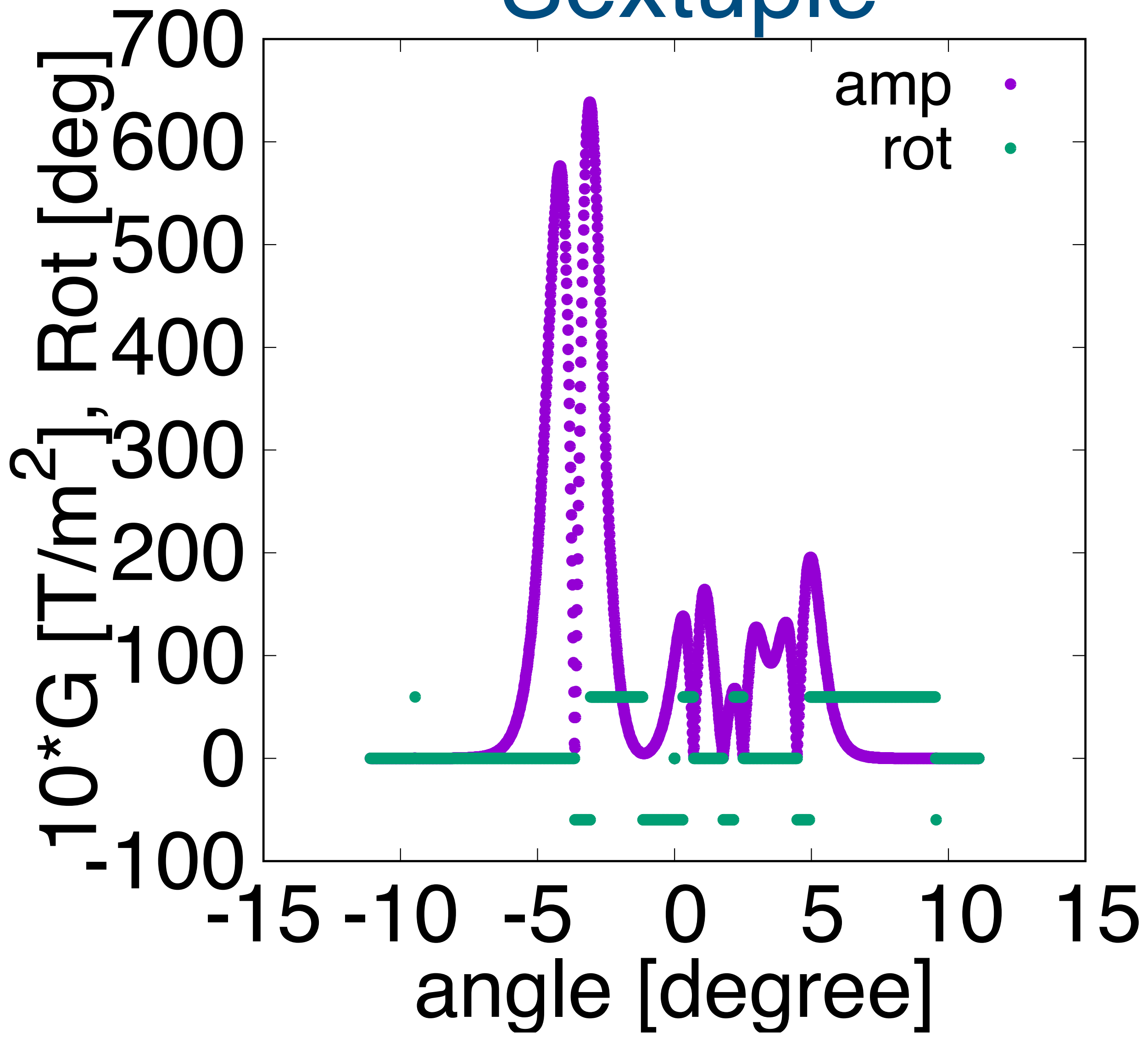
	Quadrupole	Sextuple	Octupole

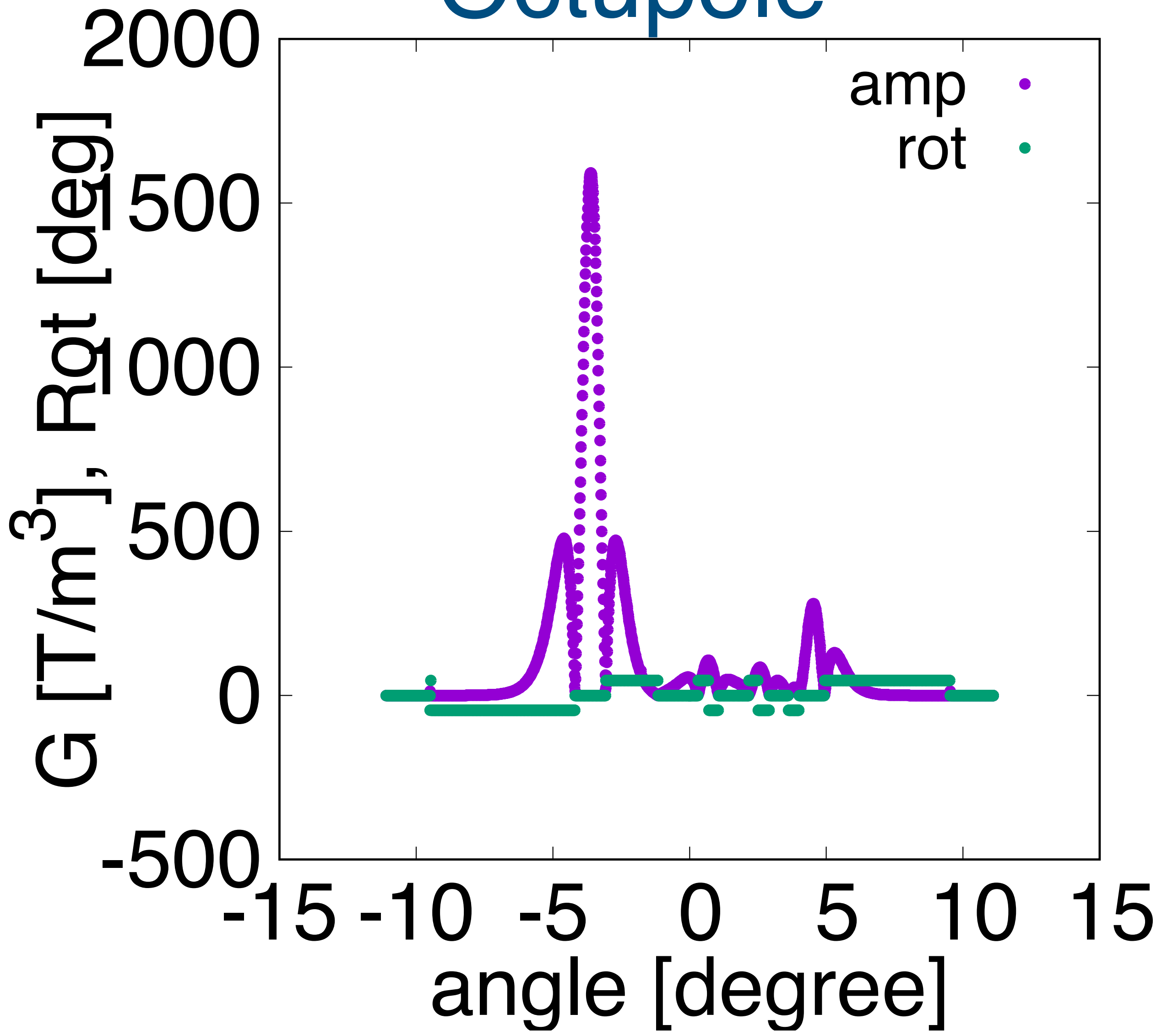
Bf entrance

FFE x 1



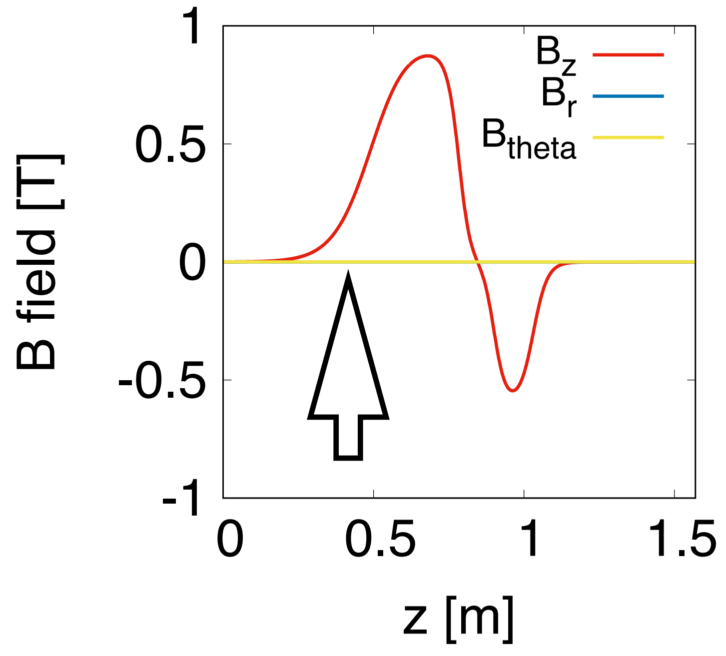


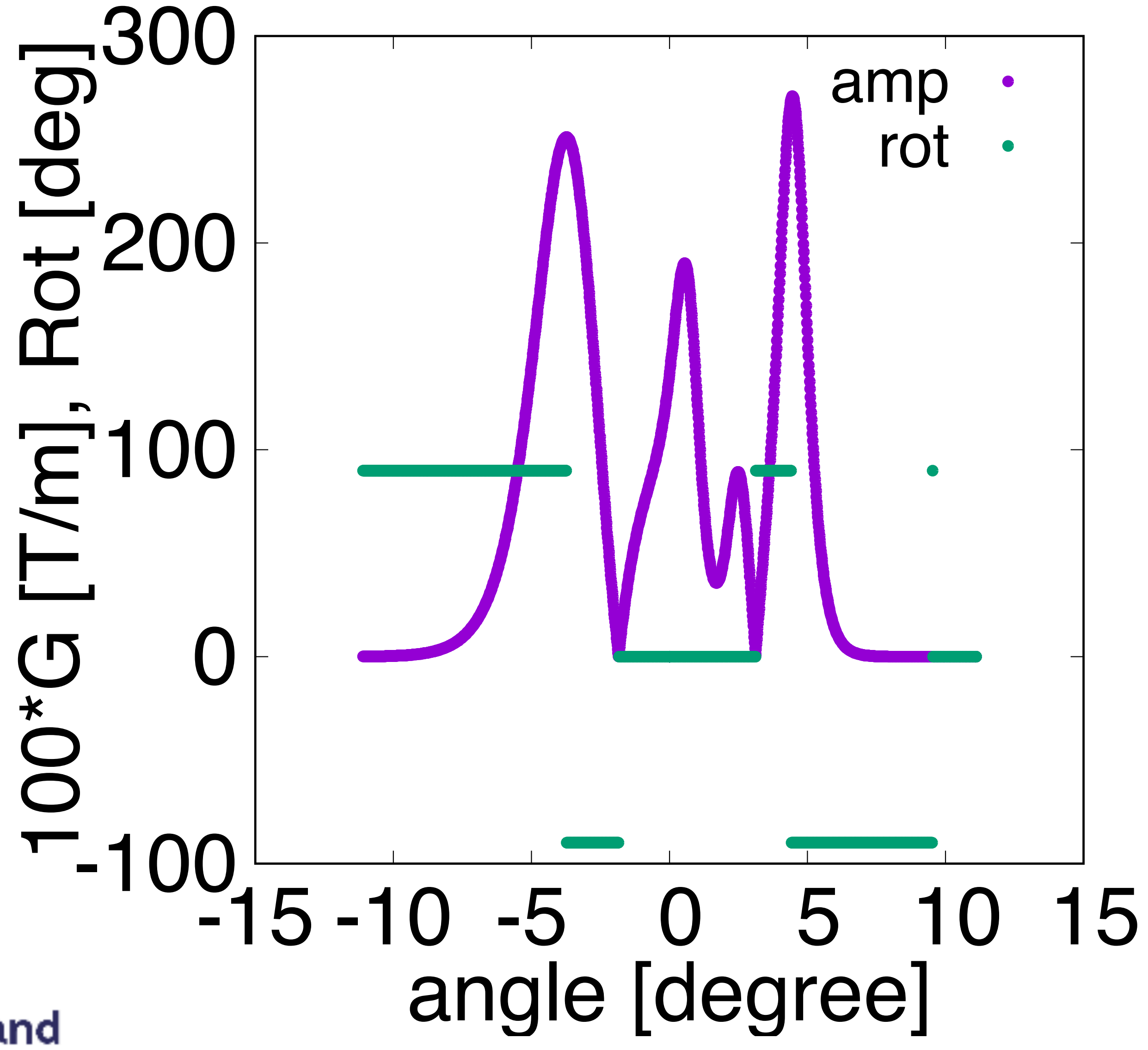


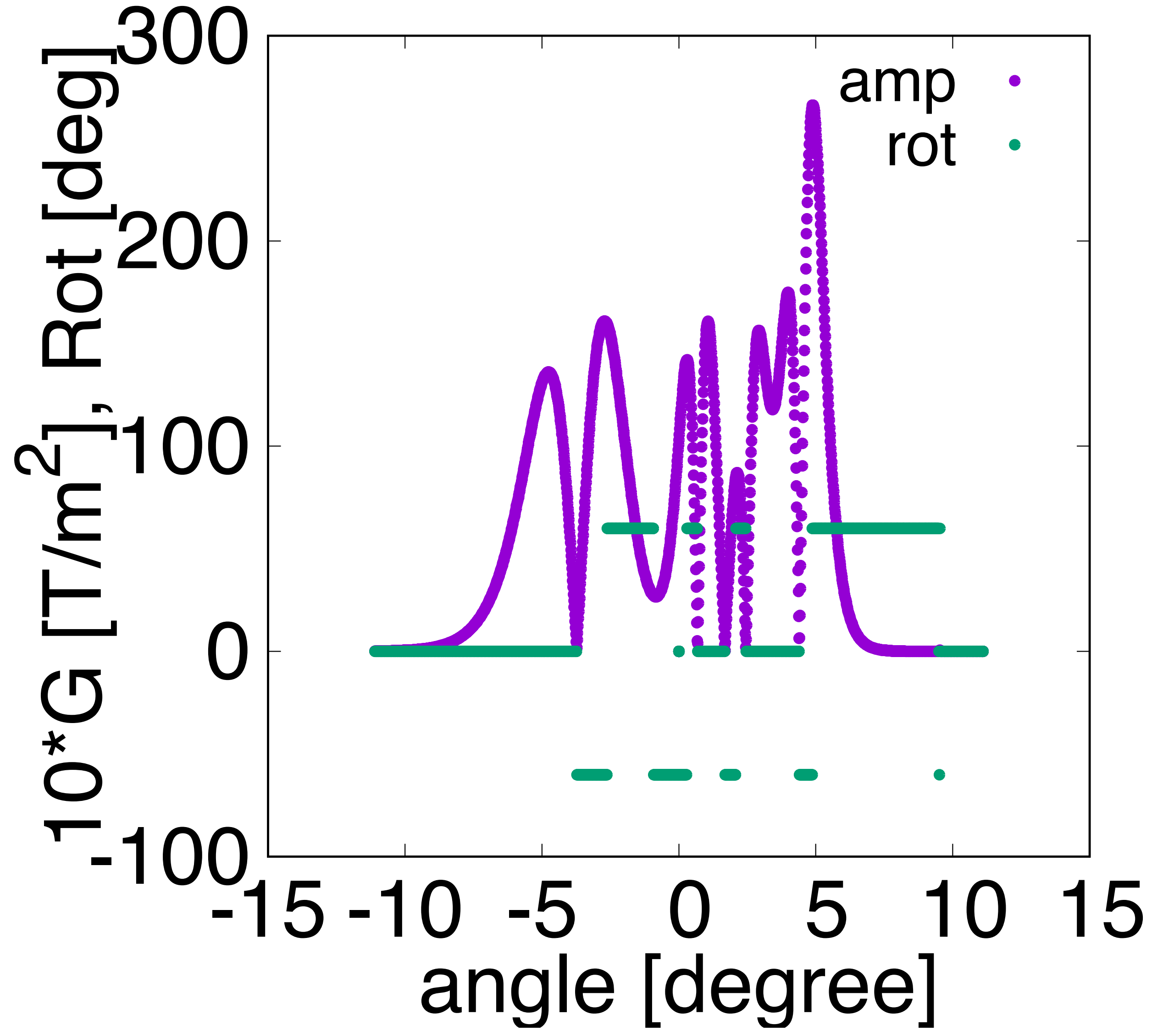


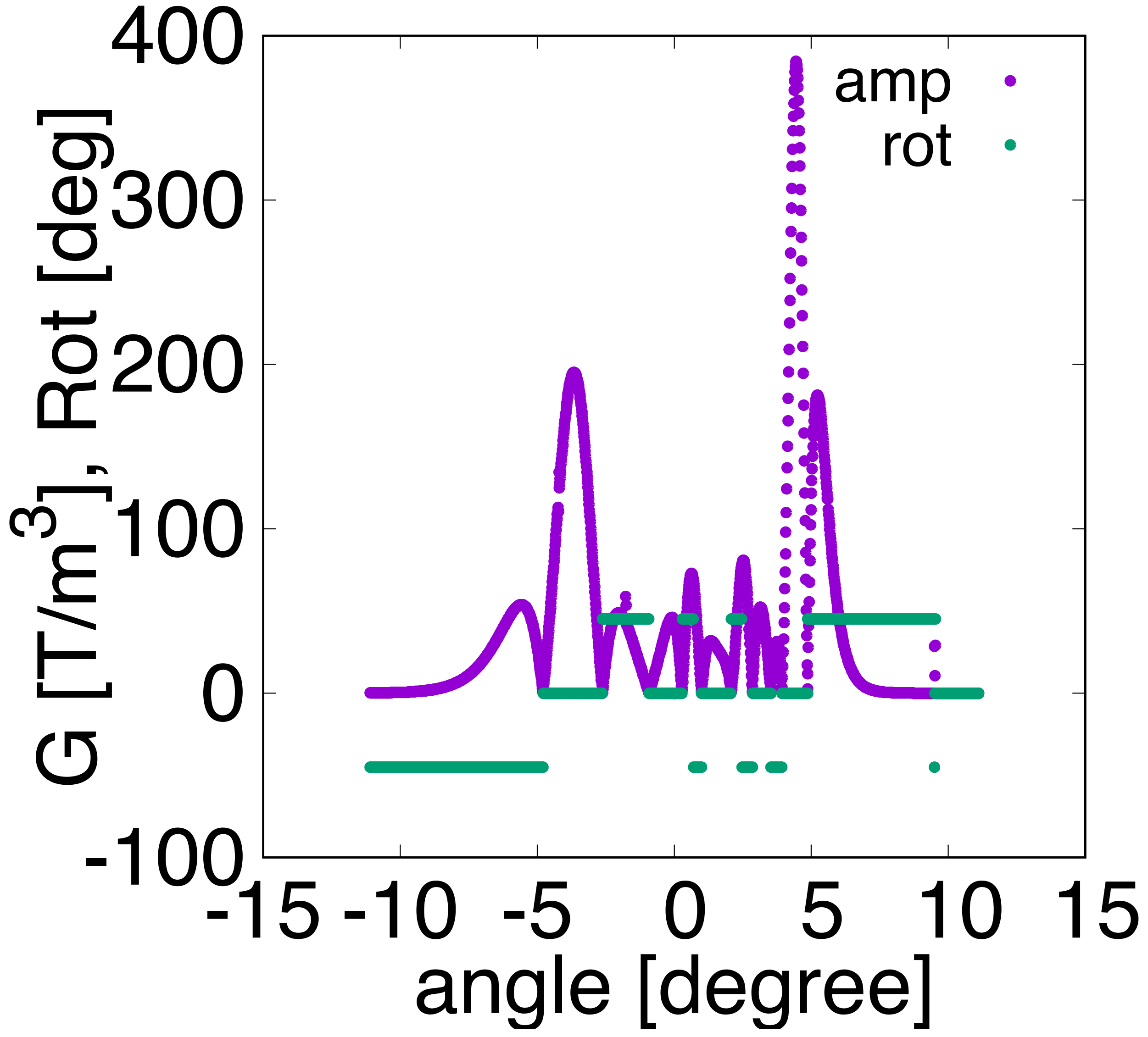
Bf entrance

FFE x 2









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Twice longer FFE makes DA more than double (~ x 2.5).

Summary

Summary

- Our design goal is to demonstrate high intensity operation of a FFA.
    - with conventional scaling FFA.
- Changed the baseline lattice from vFFA to DFspiral hFFA.
- Understanding nonlinear optics is essential.
    - to enlarge dynamic aperture.
    - to establish COD correction, beta beating correction, nonlinear resonance correction.
- Developed a tool to numerically evaluate multipole component along the orbit.
- Dynamic aperture: FDspiral > radial sector > spiral sector.

Thank you for your attention

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