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# Developments and Prospects of FFAs at RAL

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Cyclotron 2022

# Overview

- Goal of our project, prototype FFA (FETS-FFA) to demonstrate high intensity operation
- Design issues
- Hardware developments
- Summary

# Goal of prototype FFA (FETS-FFA)

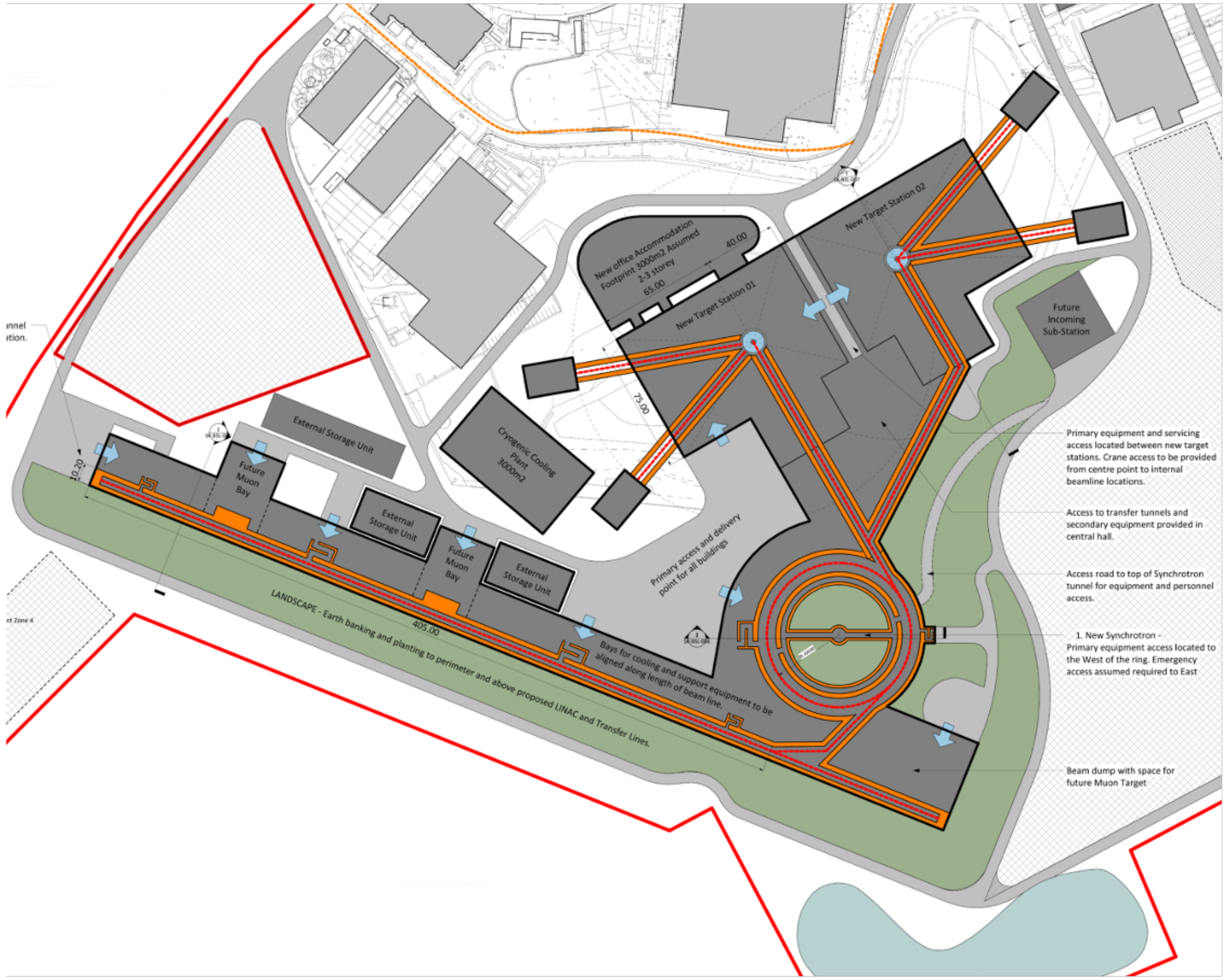
# ISIS upgrade, “ISIS-II”

Pulsed spallation neutron and muon source

- 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!




[From John Thomason at FFA 2022 workshop]

- 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. Facility will be useless if one 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.
    - DC (superconducting) magnets are reliable accelerator components.

- As a pulsed neutron source facility,
    - “**capacity** (number of experiments, size of community)”
        - Enough beam power to produce useful neutrons.
    - “**capability** (bespoke experiment)” must be satisfied.
        - Flexible operation such as high peak current with low repetition or relatively low peak current with relatively high repetition.

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# FFA demonstrator

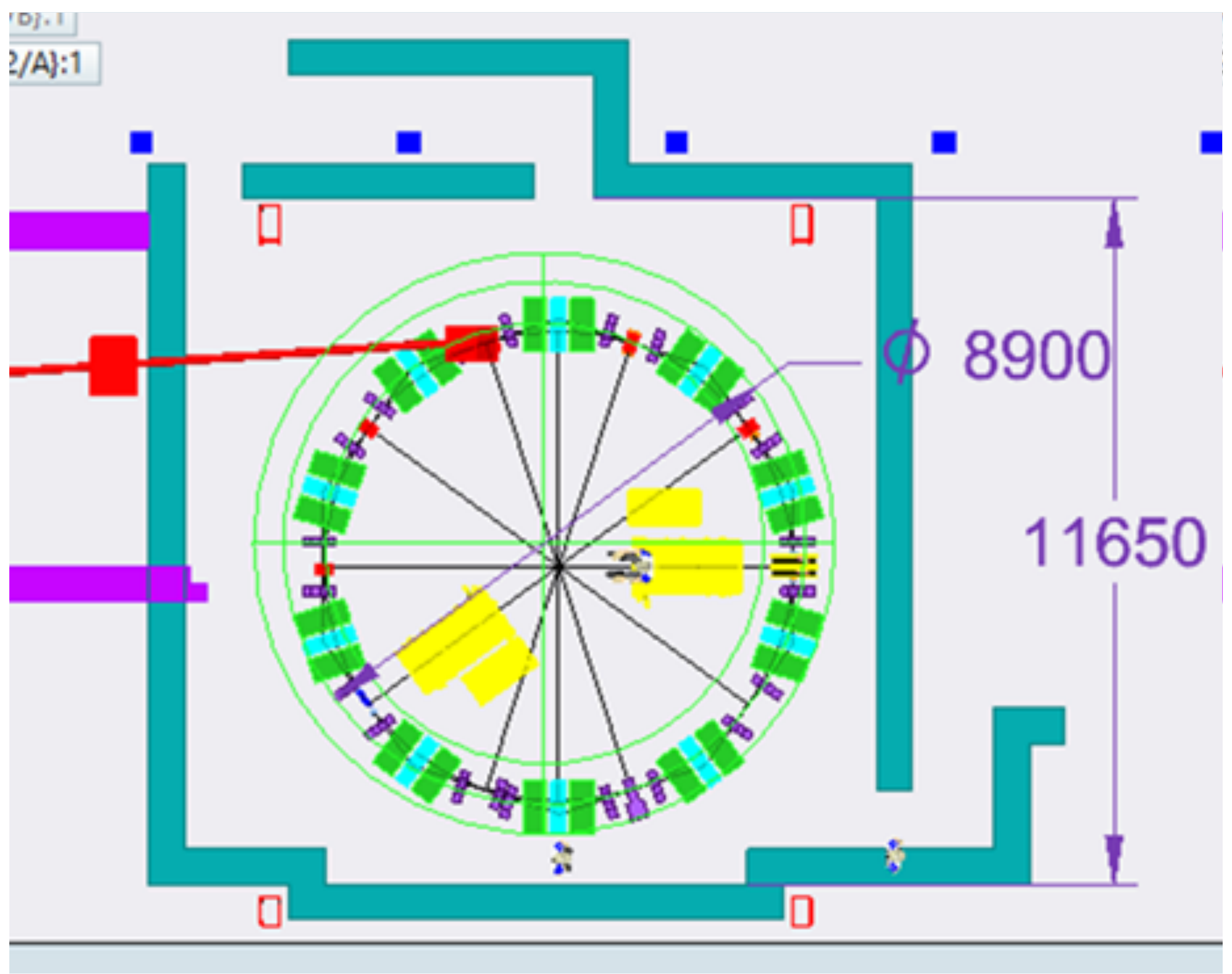
FETS: Front End Test Stand

- Cyclotron is a good candidate. But why not a scaling **FFA?**
  - However, FFA needs a demonstrator of high intensity operation.
  - A prototype FFA, "**FETS-FFA**" as a demonstrator of FFA based ISIS-II proton driver.

- FFA is a pulsed accelerator, like a synchro-cyclotron.
  - A similar challenge as high intensity synchrotron, not like a CW cyclotron.

| | |
|---|---|
| beam energy | 3 - 12 MeV |
| ave. radius | 4 - 4.2 m |
| repetition | 100 Hz |
| number of proton per bunch | $3 \times 10^{11}$ |
| average current | ~ 5 micro A |
| average beam power | ~ 60 W |
| space charge tune shift | -0.25 |

FETS-FFA in R9

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**Tune control, diagonal from experience, FD spiral**
**Superperiod lattice, optimisation**
**(Dynamic) Aperture, control of nonlinearity of fringe field**
**Beam stacking**

**Larger aperture magnet, RF cavity diagnostics**

# FD (doublet) spiral lattice

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# Control of operation tune

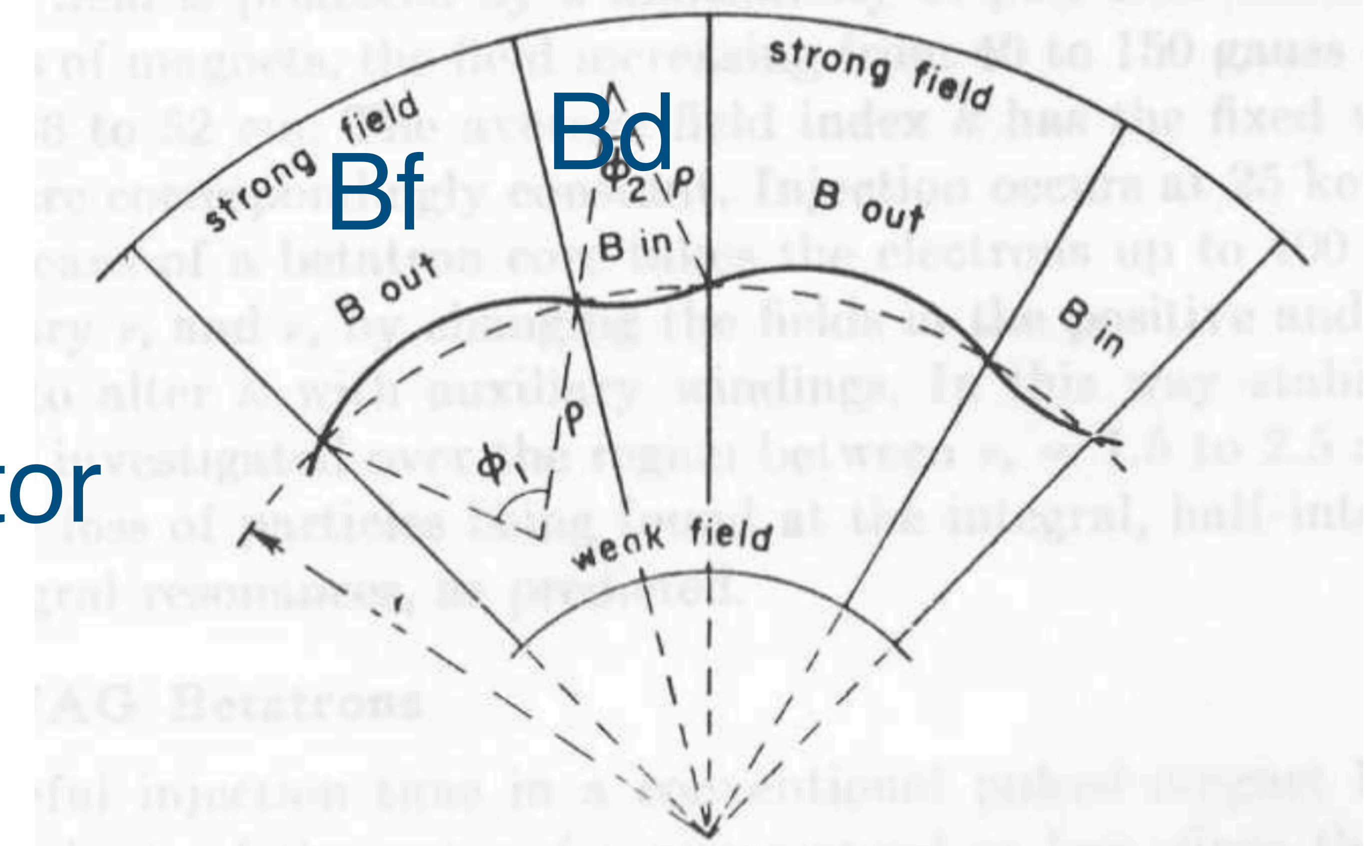
Operation tune should be chosen close to diagonal line, i.e. Qx ~ Qy from experience of SNS and J-PARC.

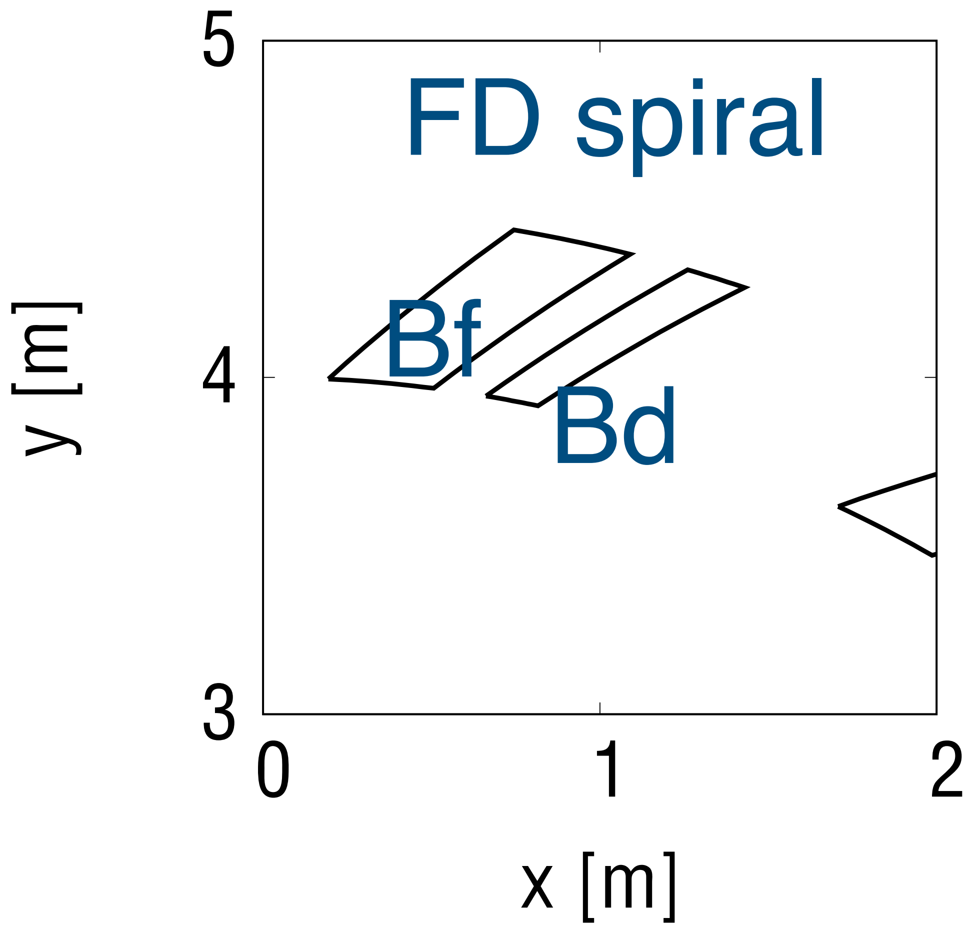
- Field index k and Bd/Bf ratio can adjust operation tune in radial sector FFA. However, a reverse bend Bd enlarges circumference.

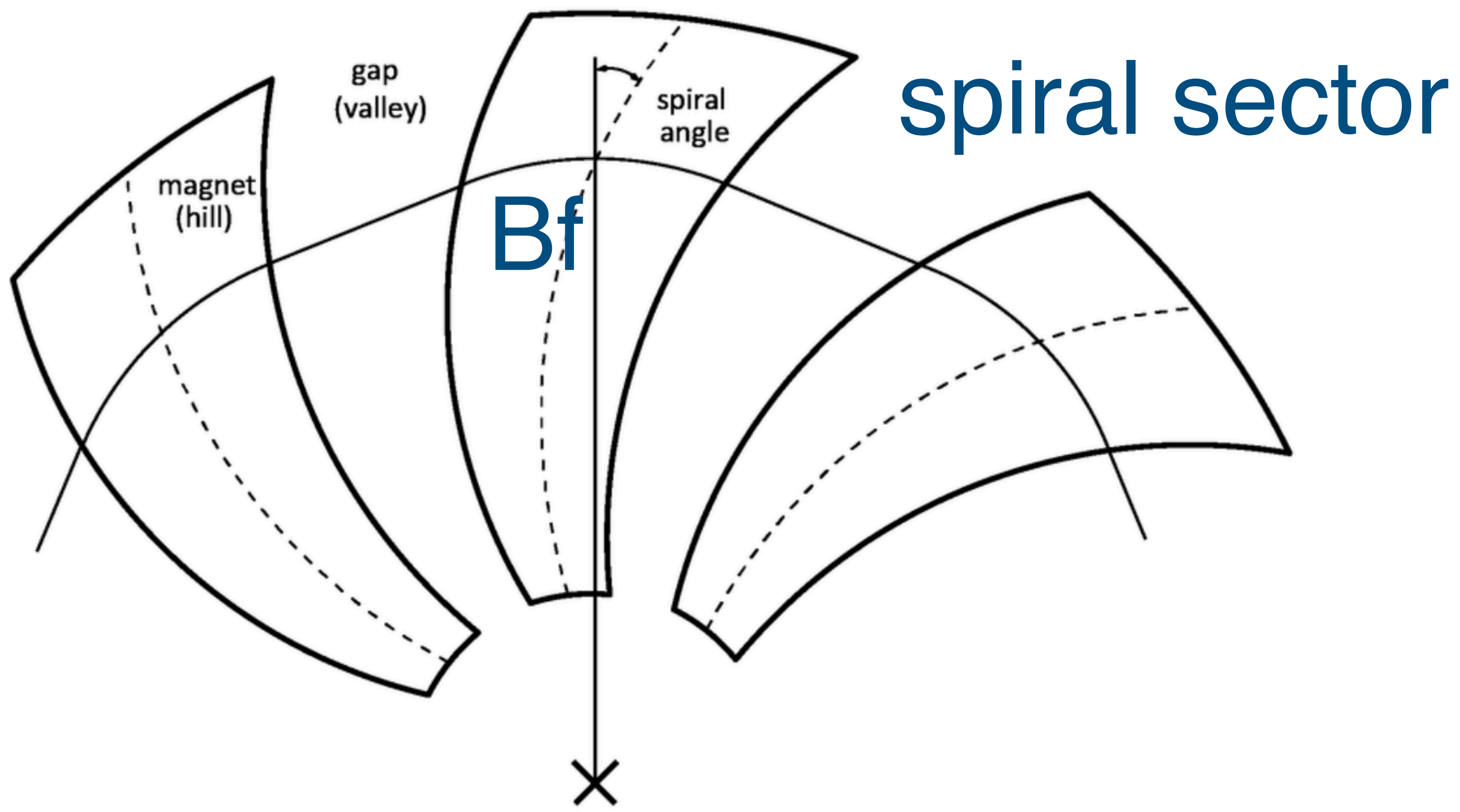
$$k = \frac{r}{B}\frac{\partial B}{\partial r}$$

- Spiral sector FFA does not have full control of tune. Only one control knob, field index k.

radial sector



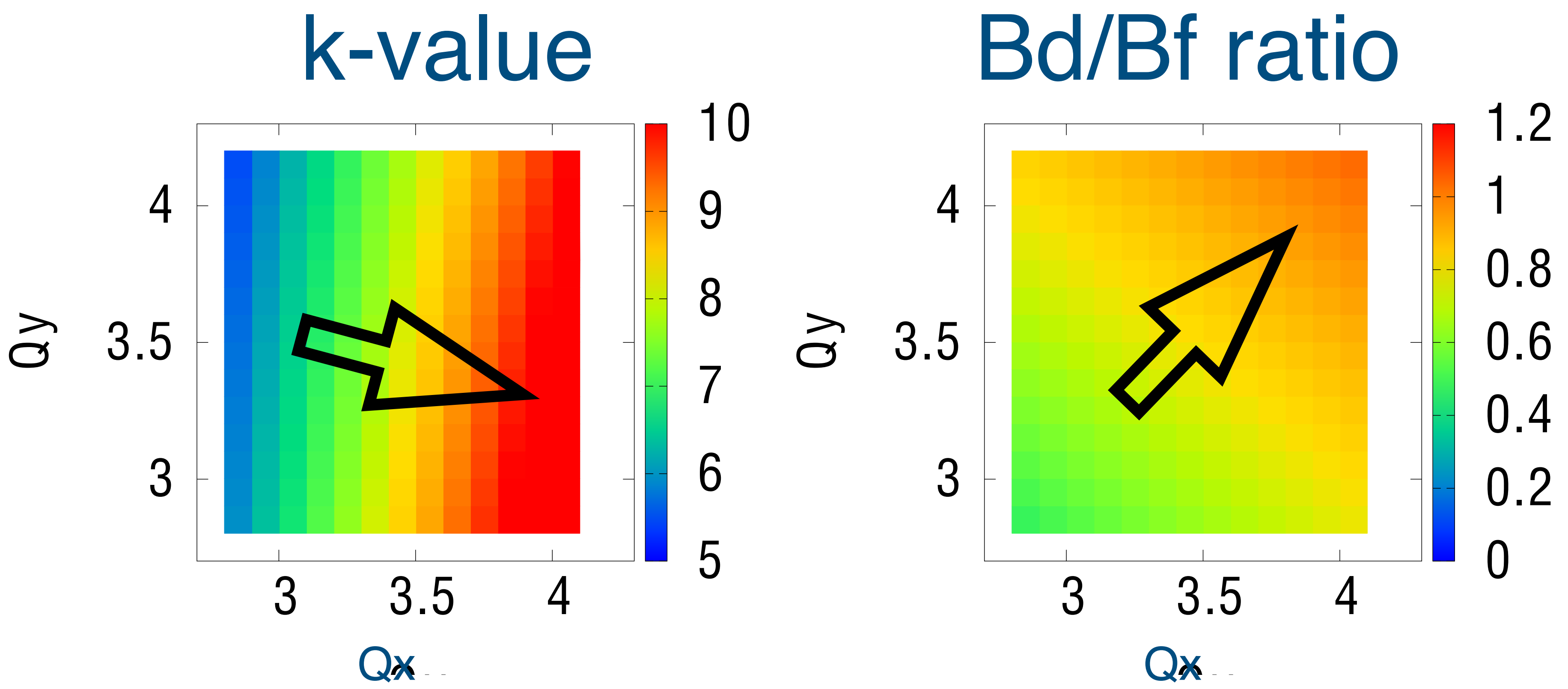



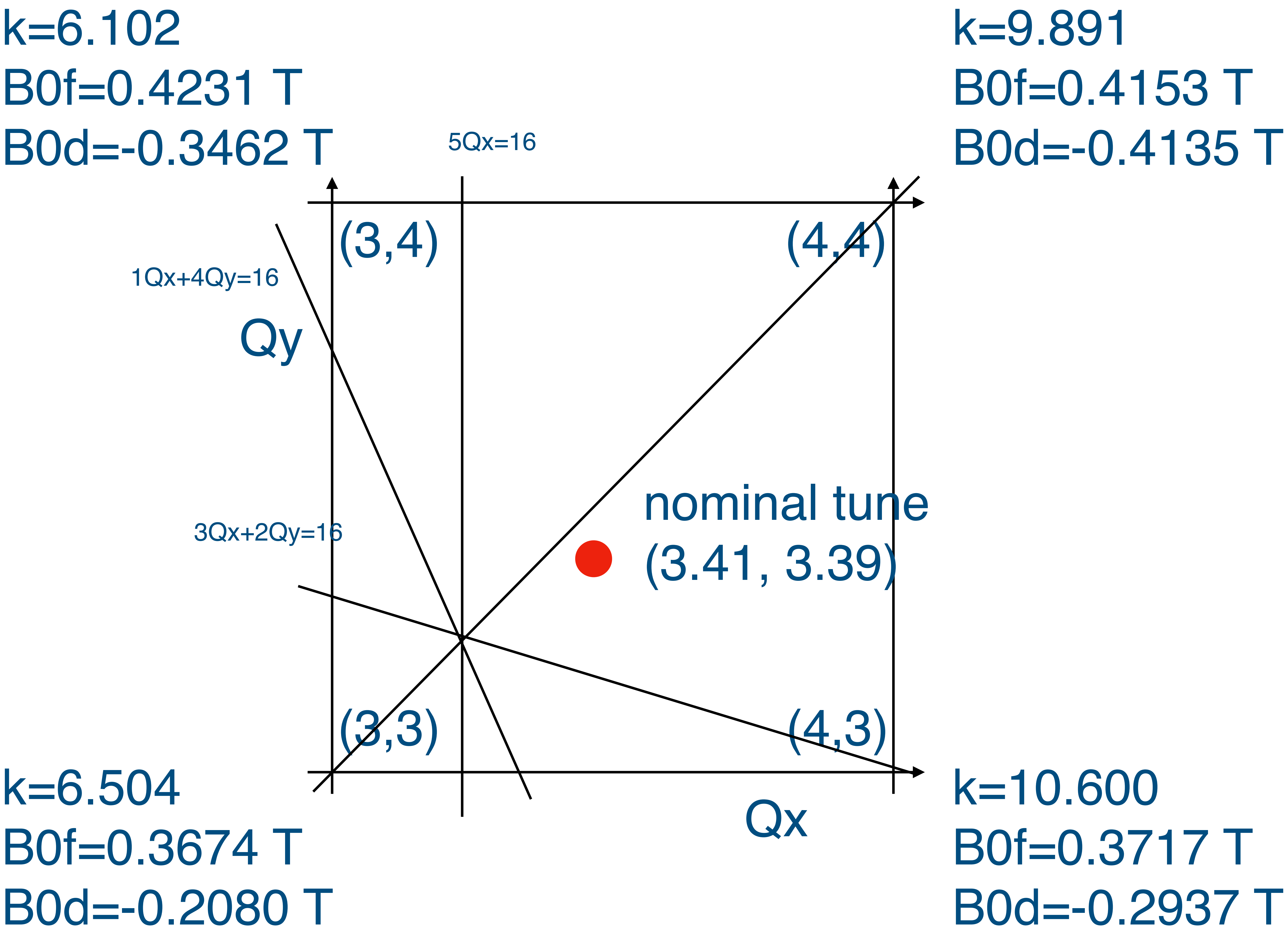

- FD (doublet) spiral sector FFA is a compromise between spiral sector and radial sector FFAs.
  - Two control knobs (field index k and Bd/Bf ratio) to adjust operation tune.
  - Vertical focusing comes from spiral angle as well as reverse bend Bd. Reverse bend can be minimised, hence minimum circumference.

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

# Adjusting Qx and Qy (e.g. 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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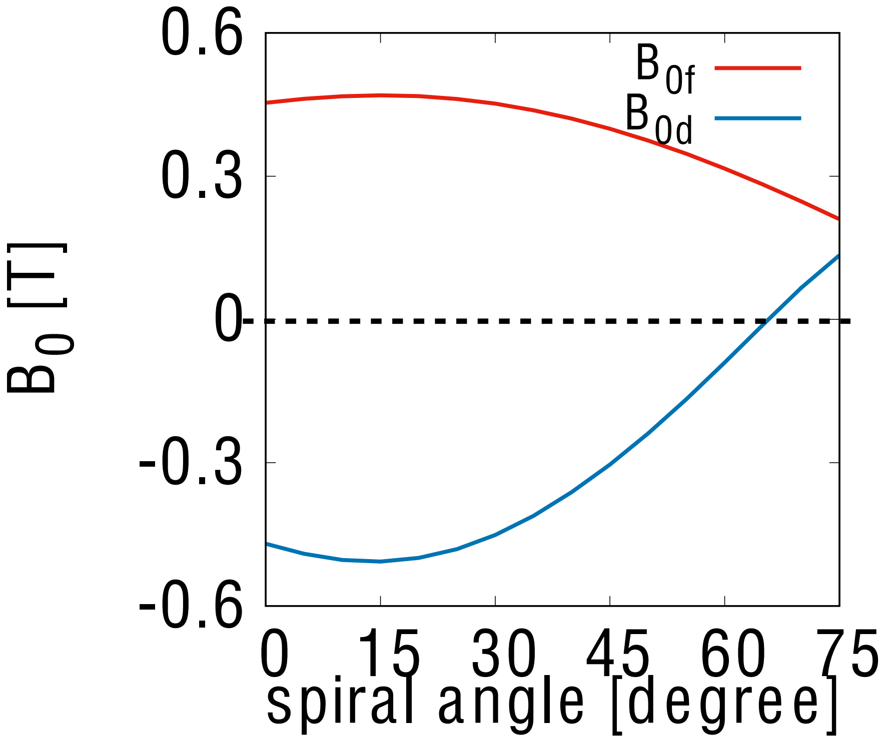
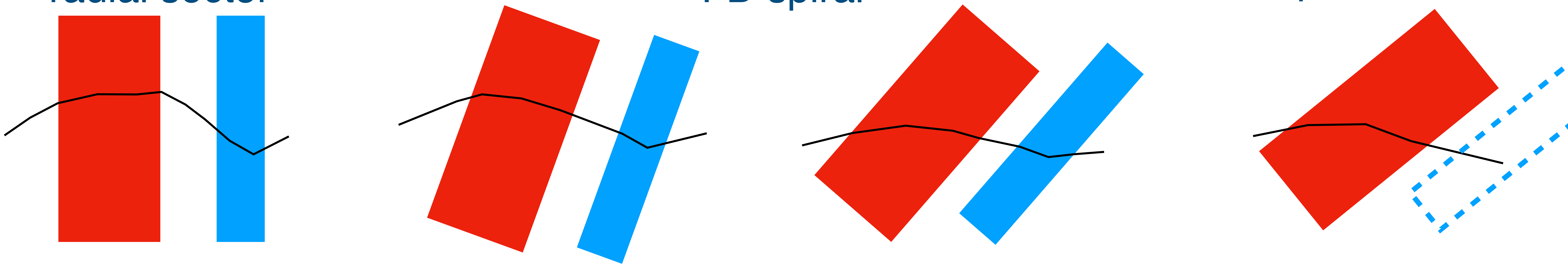
# FD spiral FFA




radial sector | FD spiral | spiral sector

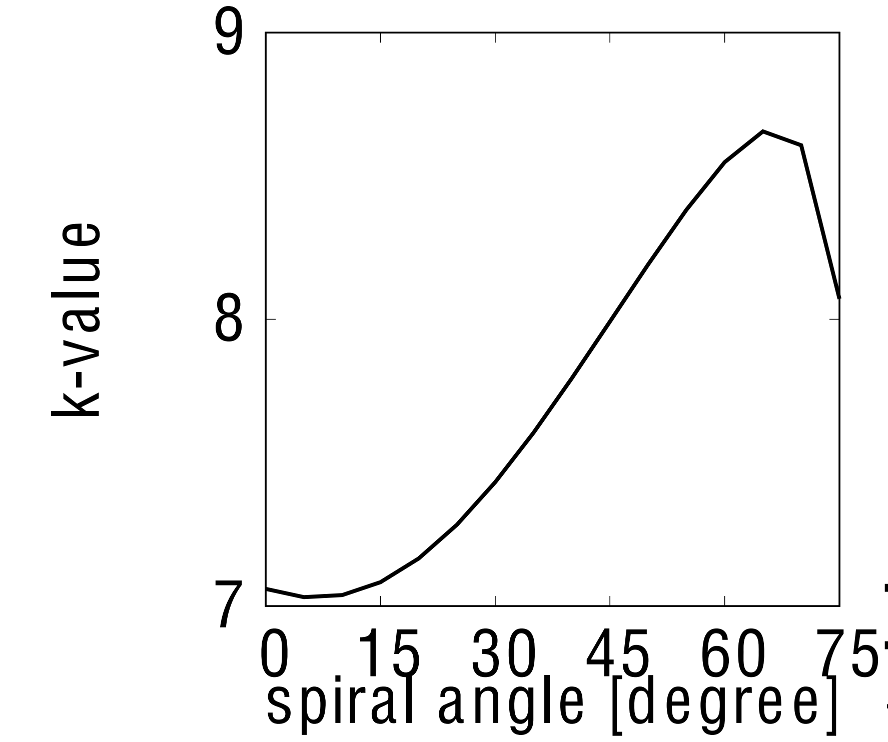


Bf (DFD) | Bd (DDD)
(entrance, body, exit)

Bf (DFO) | Bd (ODD)

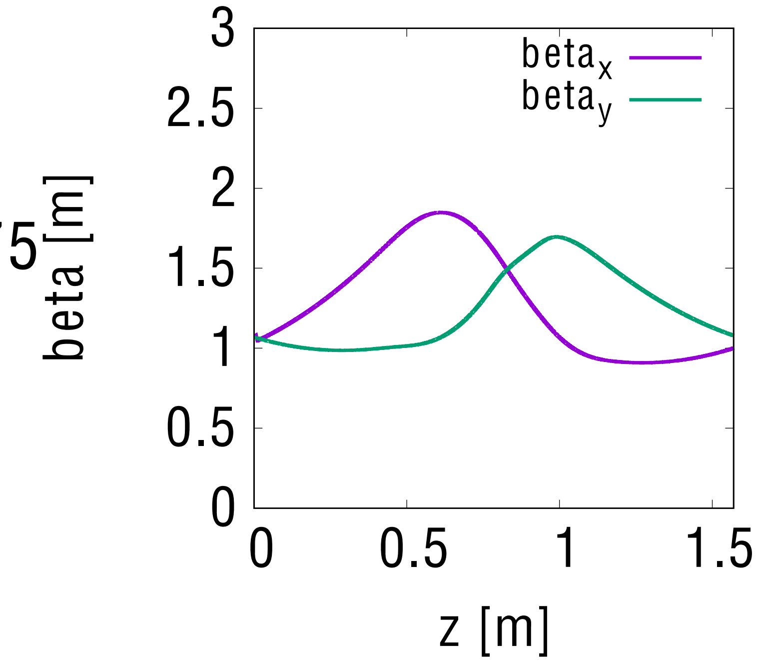
Bf (DFF) | Bd (FDD)

Bf (DFF)

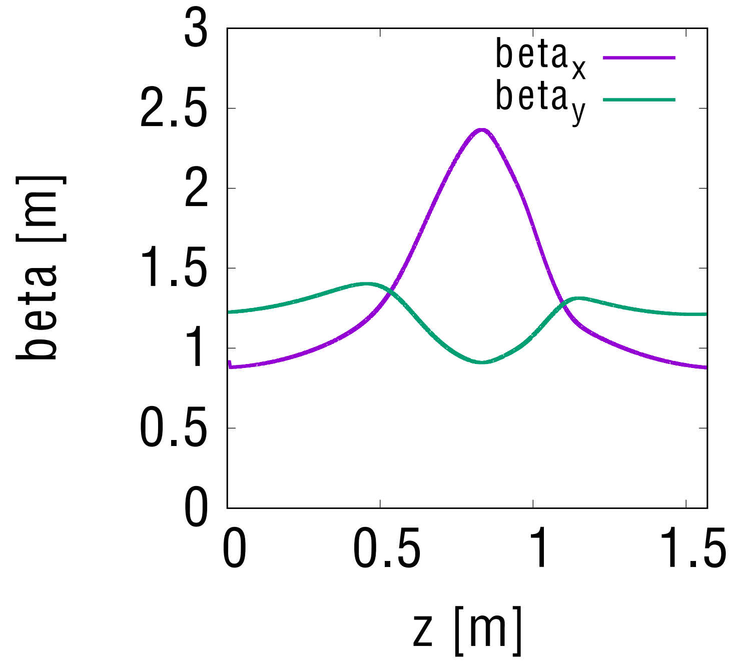



FD | DFD | DFD | DF

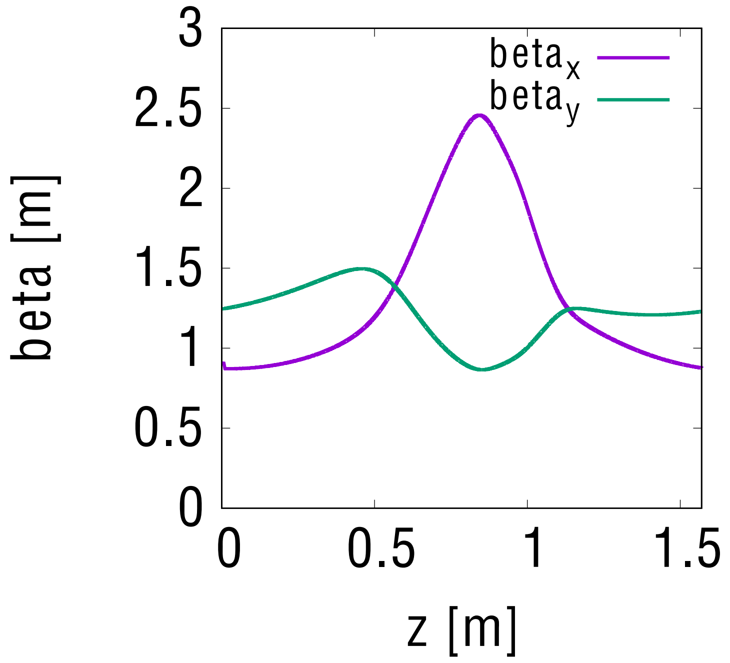
Spiral angle=0 deg



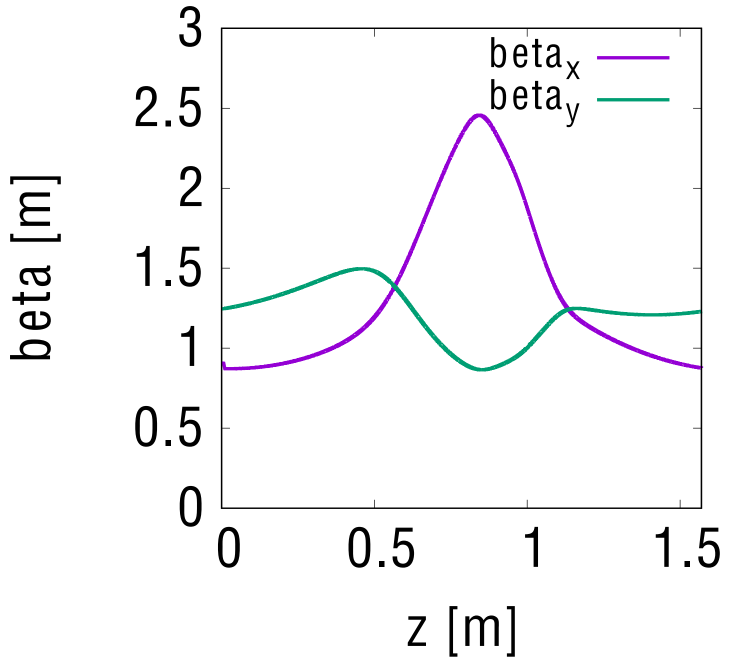

35 deg



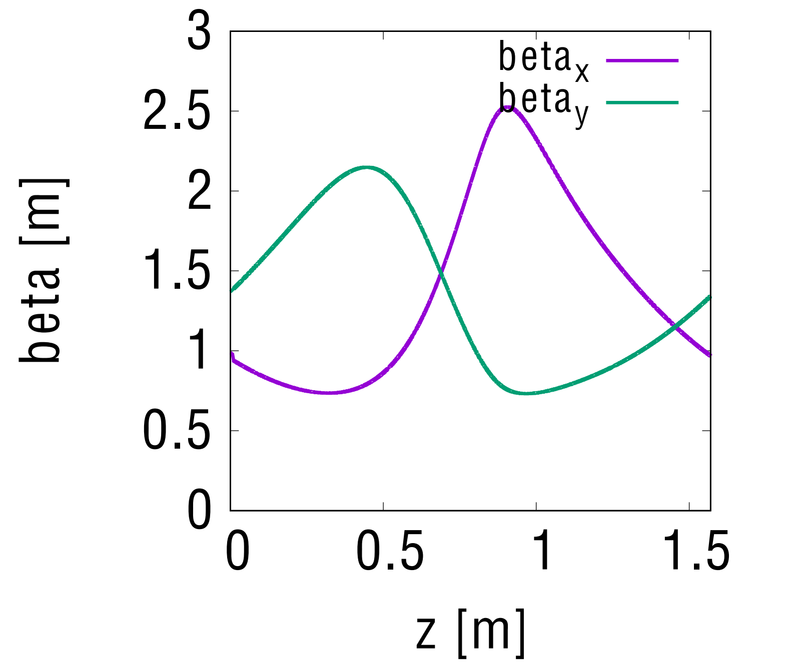

40 deg




45 deg




65 deg

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cell tune = (0.213125, 0.213125)

# Lattice with superperiod (Long straight section)

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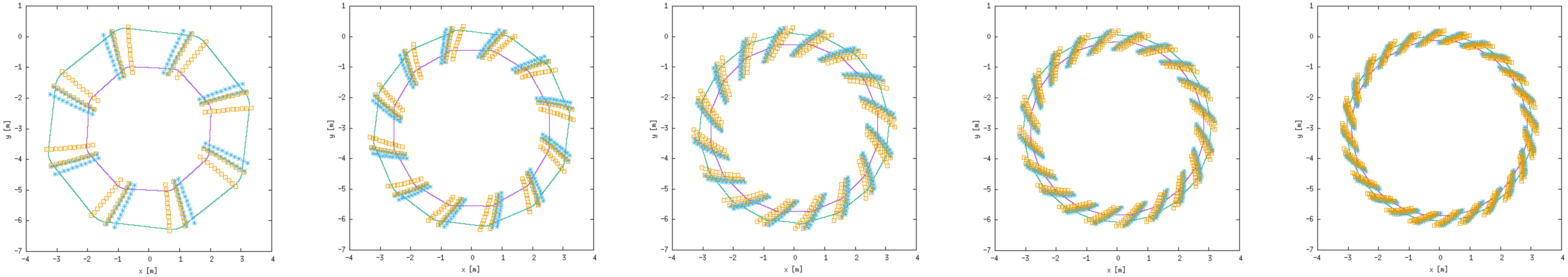
# Straight section

- Increasing the number of cells per ring requires higher field index k, hence small orbit excursion between injection and extraction.
- The total circumference is divided into more number of straight sections. Each straight section becomes shorter.

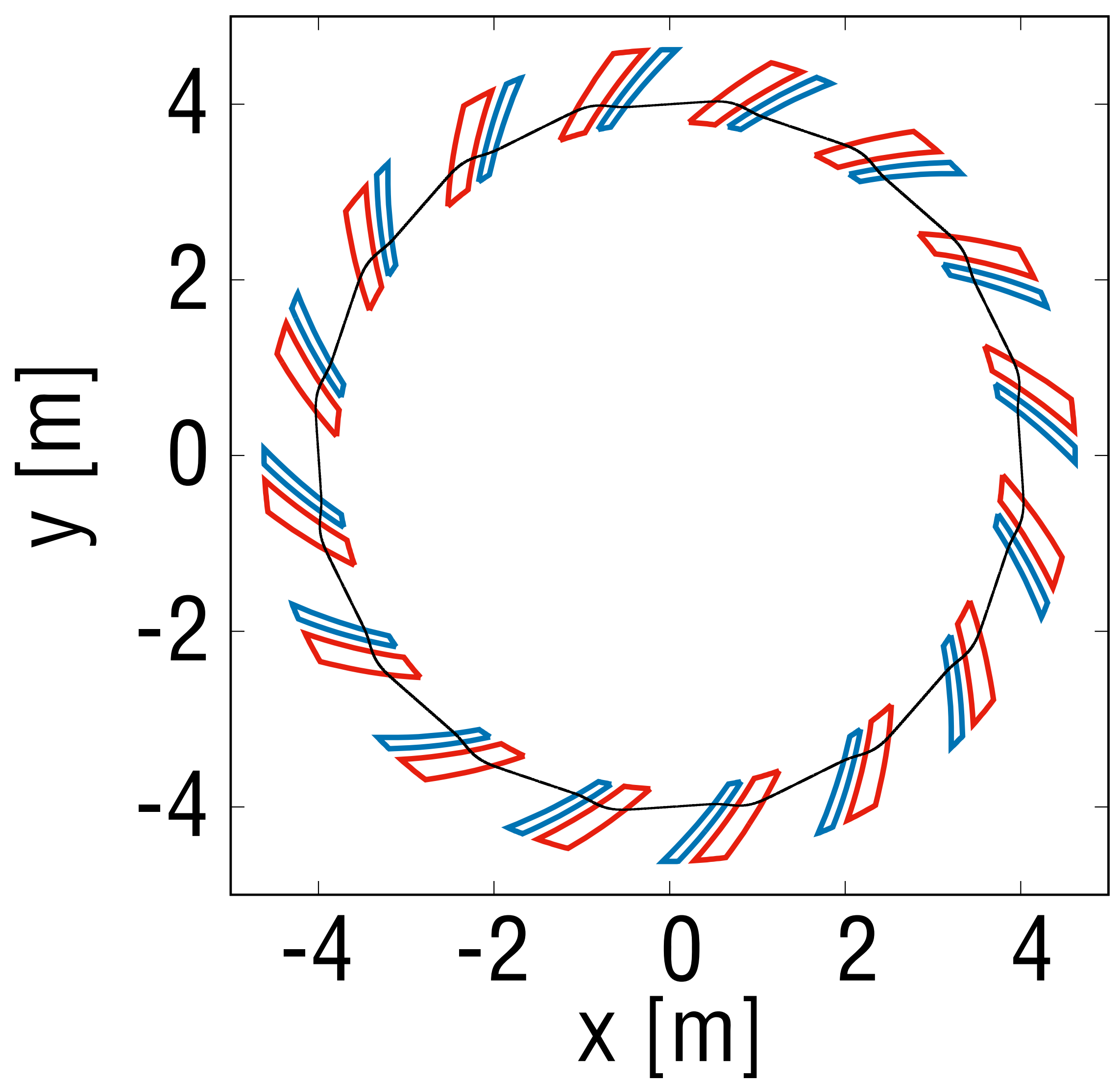


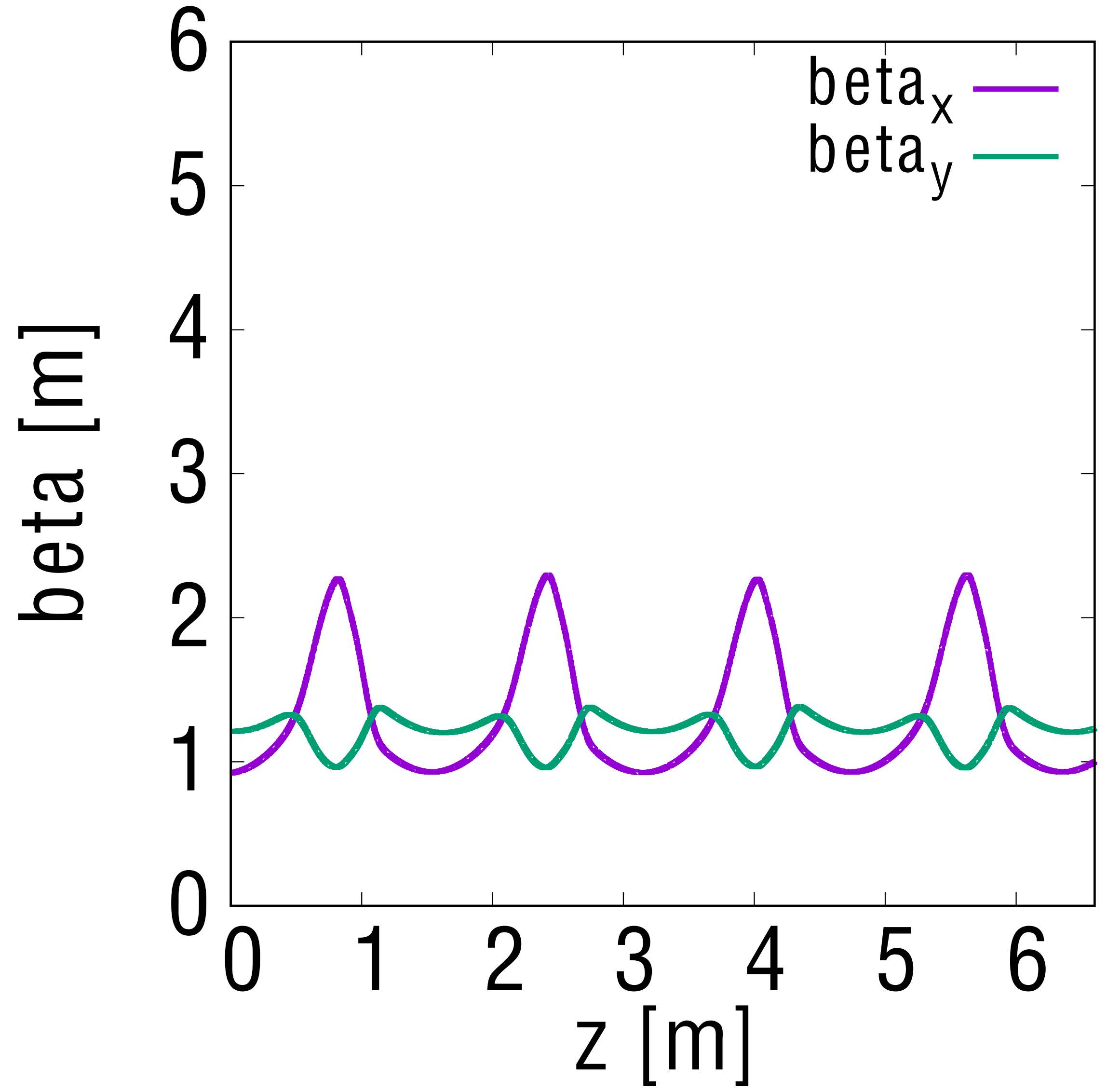
- Let us keep reasonable number of cells, but allocate straight sections unevenly.

Introduction of **superperiod**.

Long straight section is essential for proper handling of the high intensity beams. for injection, extraction, RF cavity, etc.

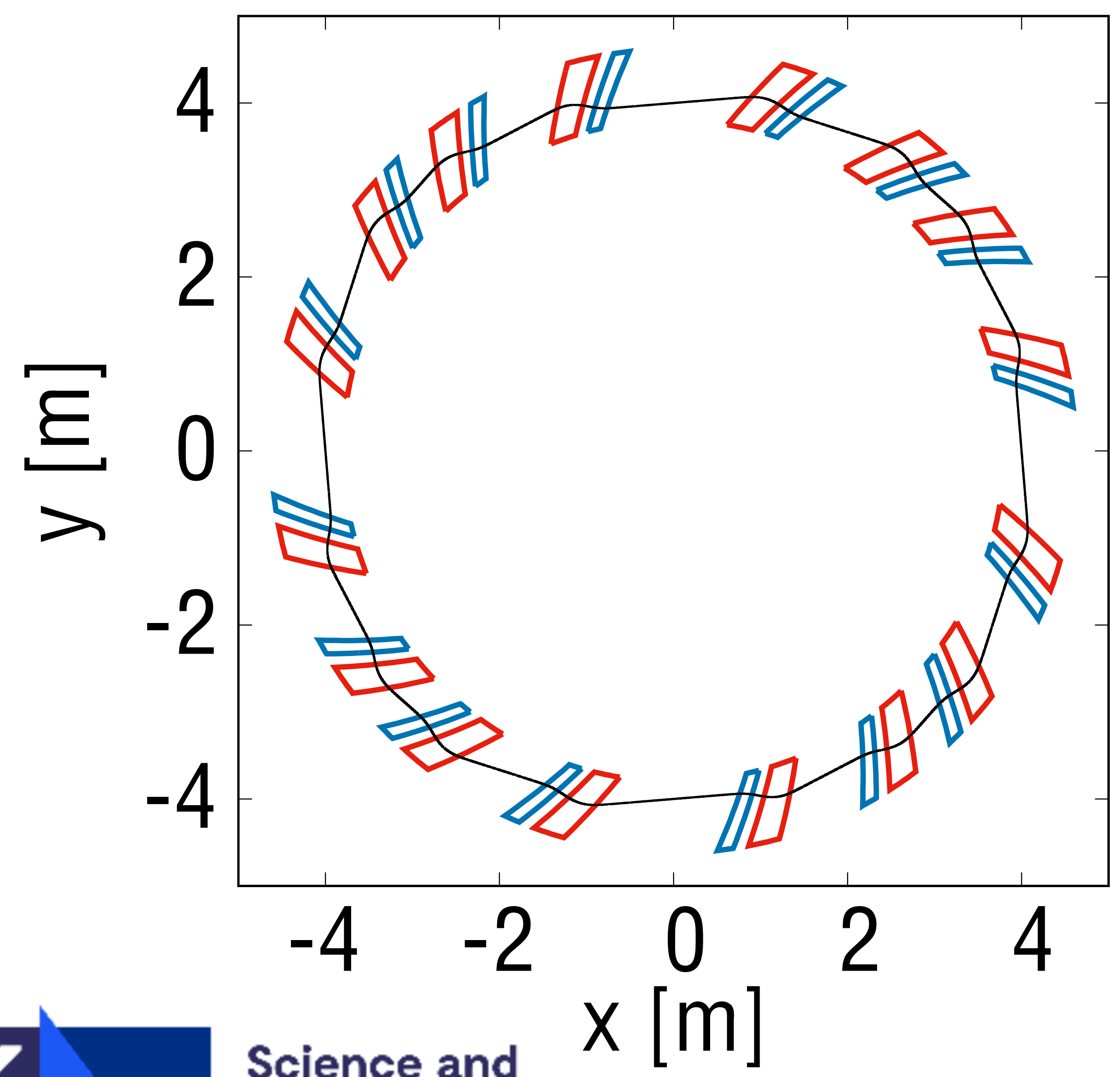
# Lattice with superperiodicity

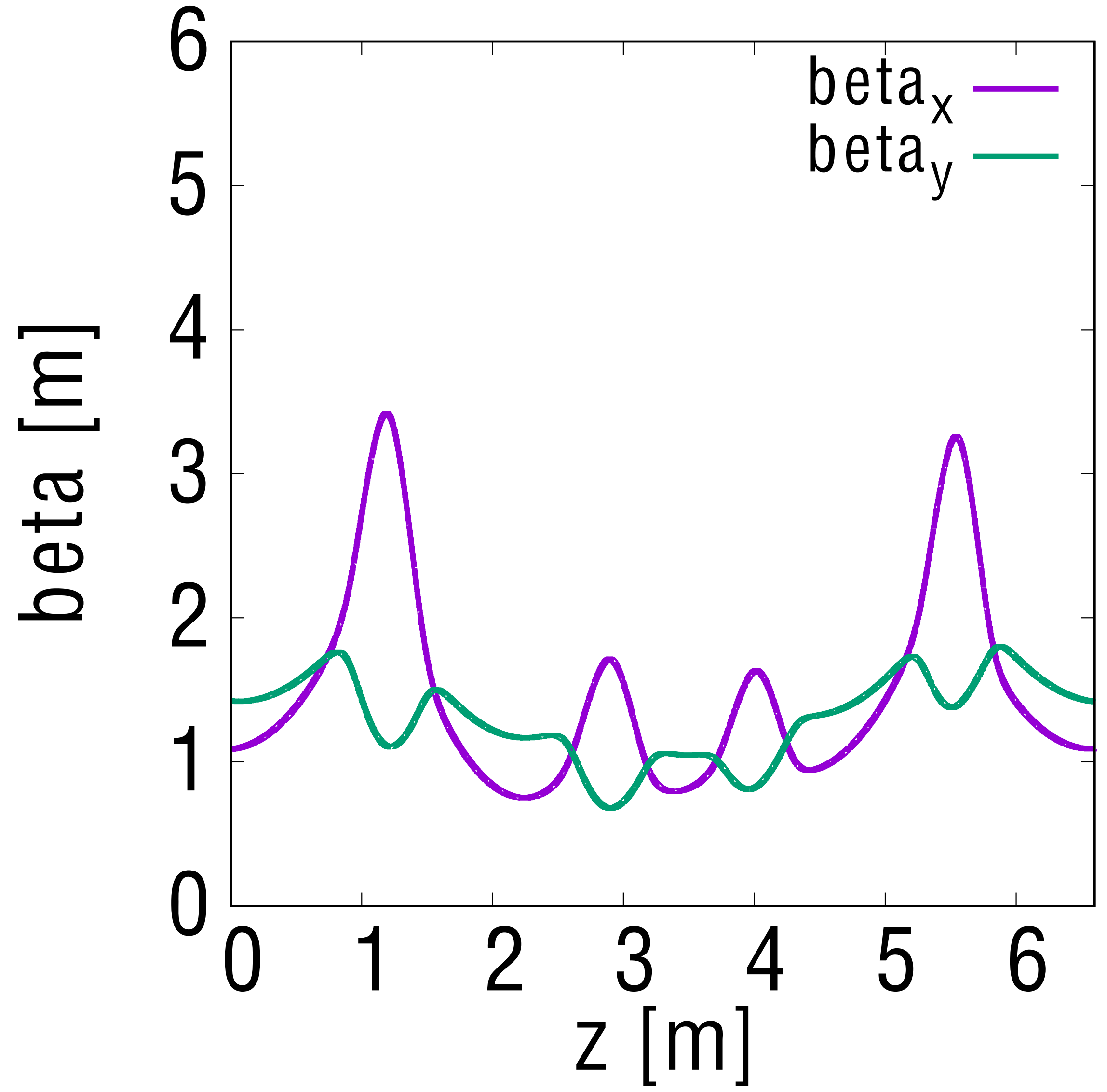



16-fold symmetry

Straight length: 0.95 m
Dynamic aperture: 110 pi mm mrad
Field index k: 8.00
Spiral angle: 45 degree
Magnet family: 2




4-fold symmetry

Straight length: **1.55 m**, 0.90 m, 0.45 m
Dynamic aperture: 80 pi mm mrad
Field index k: 7.40
Spiral angle: 30 degree
Magnet family: 8

Horizontal beam size is larger.

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# Systematic resonance

nQ=pk Q=(p/n)k n: order of resonance, p: periodicity, k: positive integer

| | 15-fold symmetry | 5 (SP) x 3 (FD) | | 16-fold symmetry | 8 (sp) x 2 (FD) | 4 (sp) x 4 (FD) |
|---|---|---|---|---|---|---|
| Q range | 3.0 - 3.75 | 3.0 - 3.75 | | 3.2 - 4.0 | 3.2 - 4.0 | 3.2 - 4.0 |
| n=2 | 7.5 k | 2.5 k | | 8 k | 4 k<br>4.0 | 2 k<br>4.0 |
| 3 | 5 k | 1.67 k<br>**3.33** | | 5.33 k | 2.67 k | 1.33 k<br>4.0 |
| 4 | 3.75 k<br>3.75 | 1.25 k<br>3.75 | | 4 k<br>4.0 | 2 k<br>4.0 | 1 k<br>4.0 |
| 5 | 3 k<br>3.0 | 1 k<br>3.0 | | 3.2 k<br>3.2 | 1.6 k<br>3.2 | 0.8 k<br>3.2, 4.0 |

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red: resonances in the operational tune range.

# Dynamic aperture

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# Aperture requirement

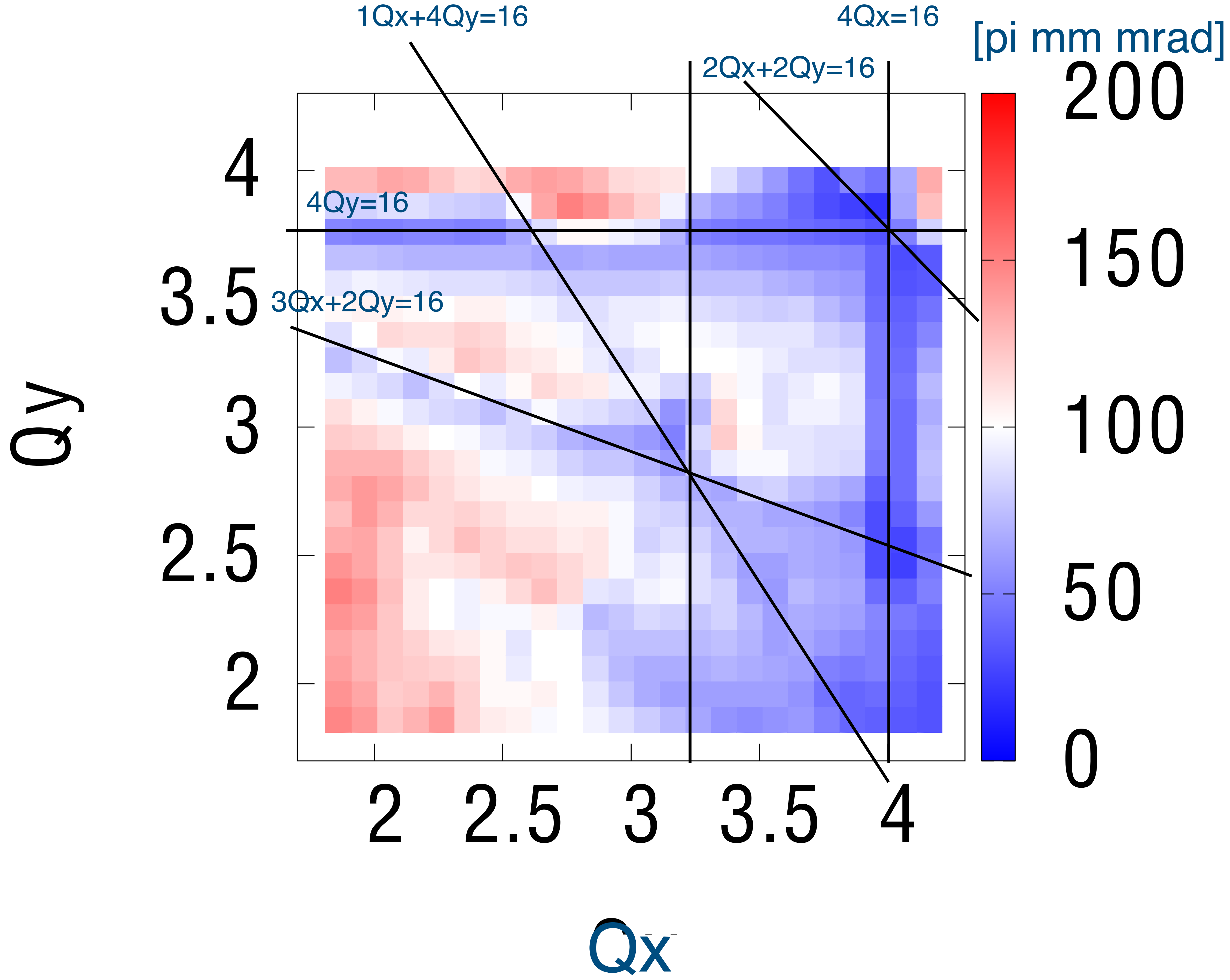
For high intensity operation of FFA, we need large physical aperture and **dynamic aperture larger than physical aperture** to reduce **space charge effects**.

- 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?

Previous study (EPAC2002 by Aiba et al) shows

- Amplitude dependent tune shift due to octupoles is the primary source of the DA limit.
  - Tune gets to a nearby systematic resonance.
- Primary location of octupole is fringe field region.




dynamic aperture at 3 MeV (normalised)
16-fold symmetric lattice

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# Control of fringe field extent (to be corrected)

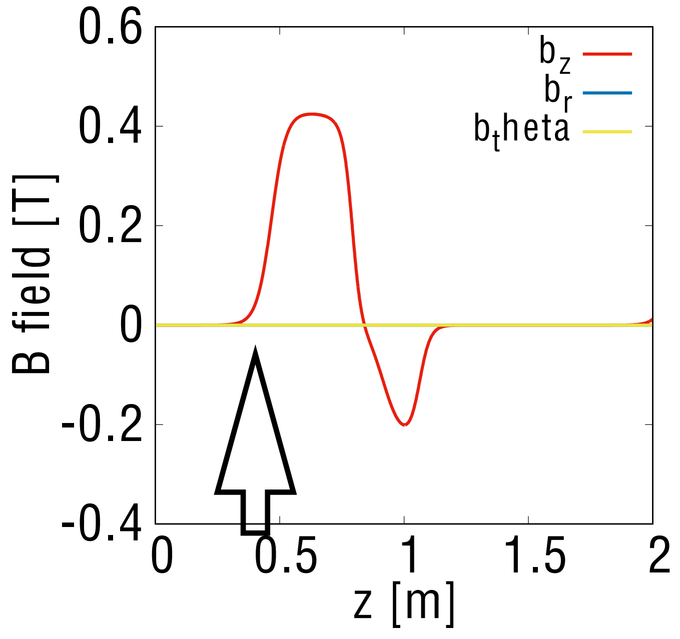
Quadrupole

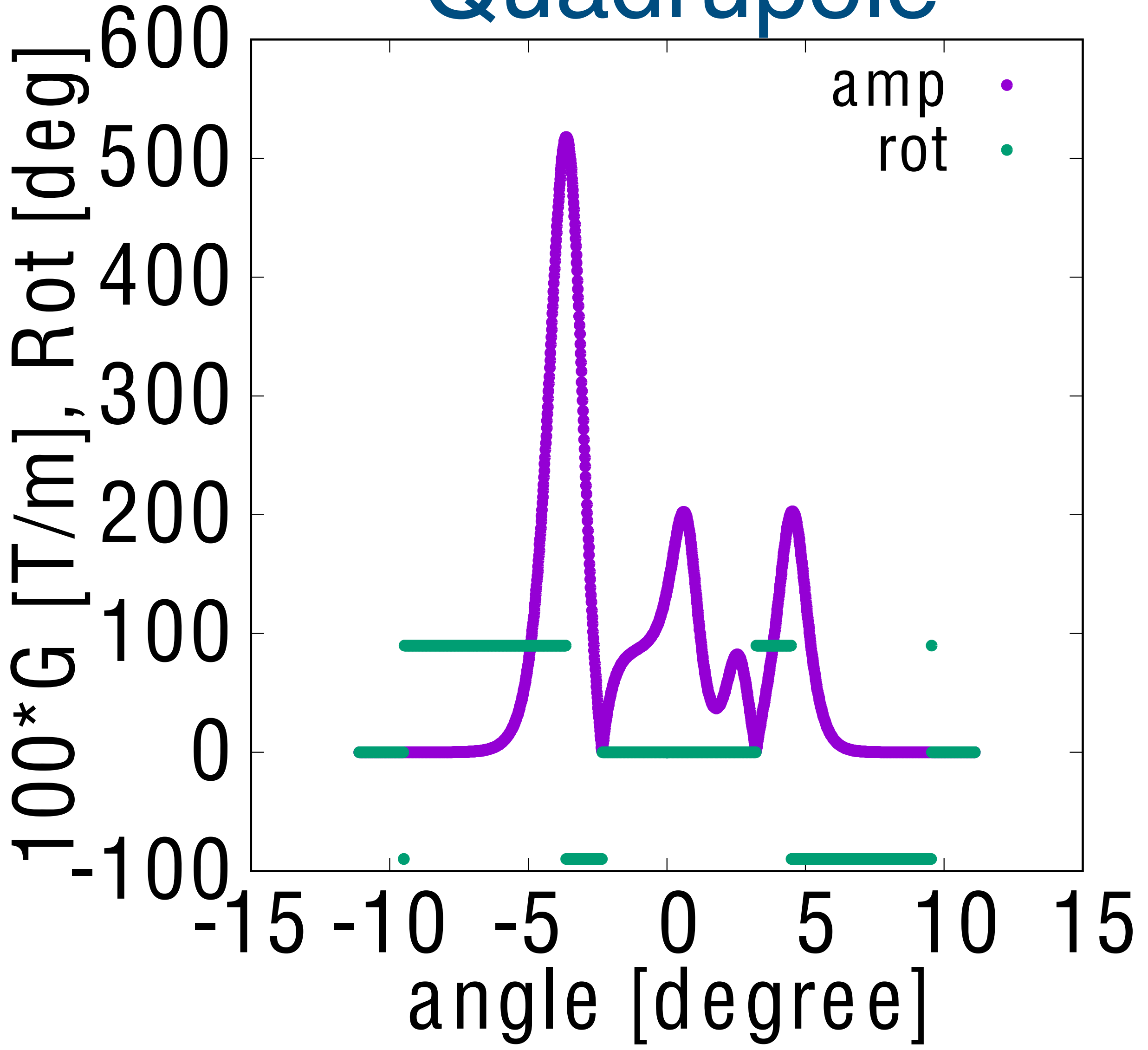
Sextupole

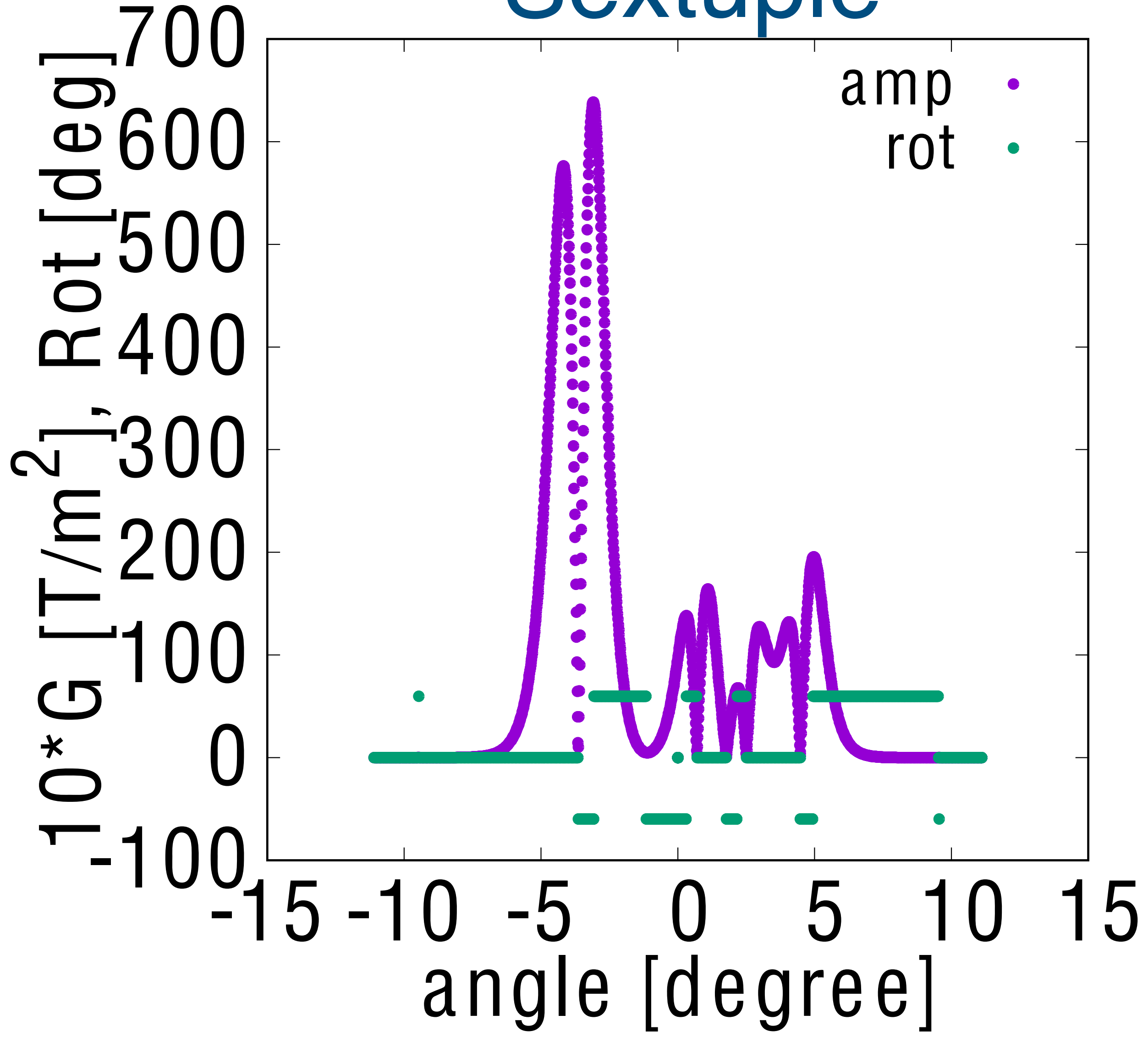
Octupole

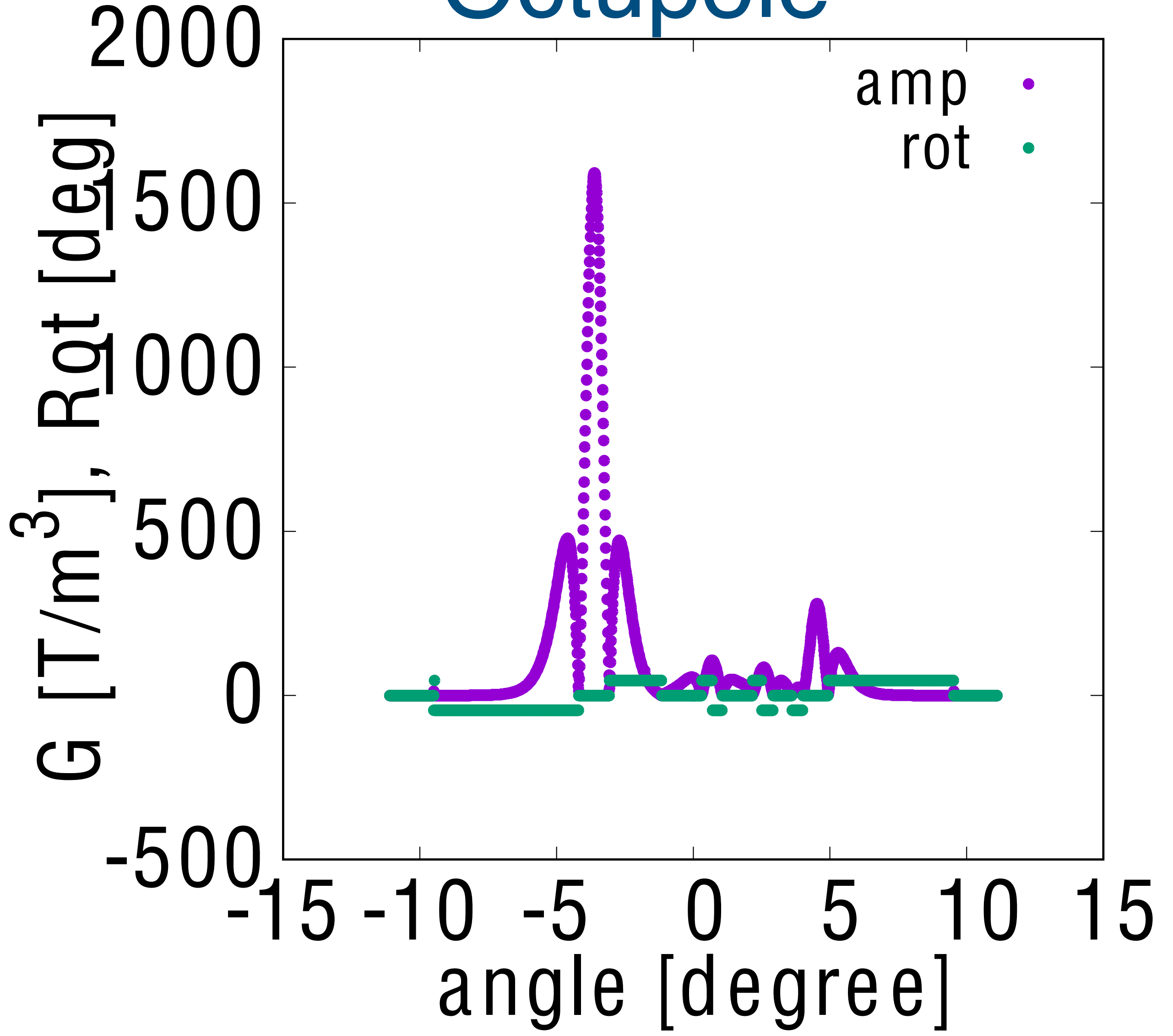
Bf entrance

FFE x 1



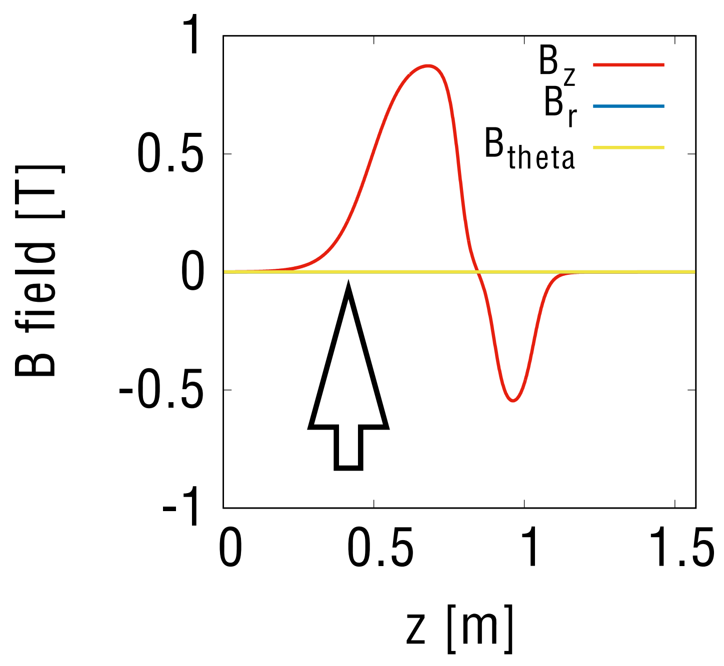



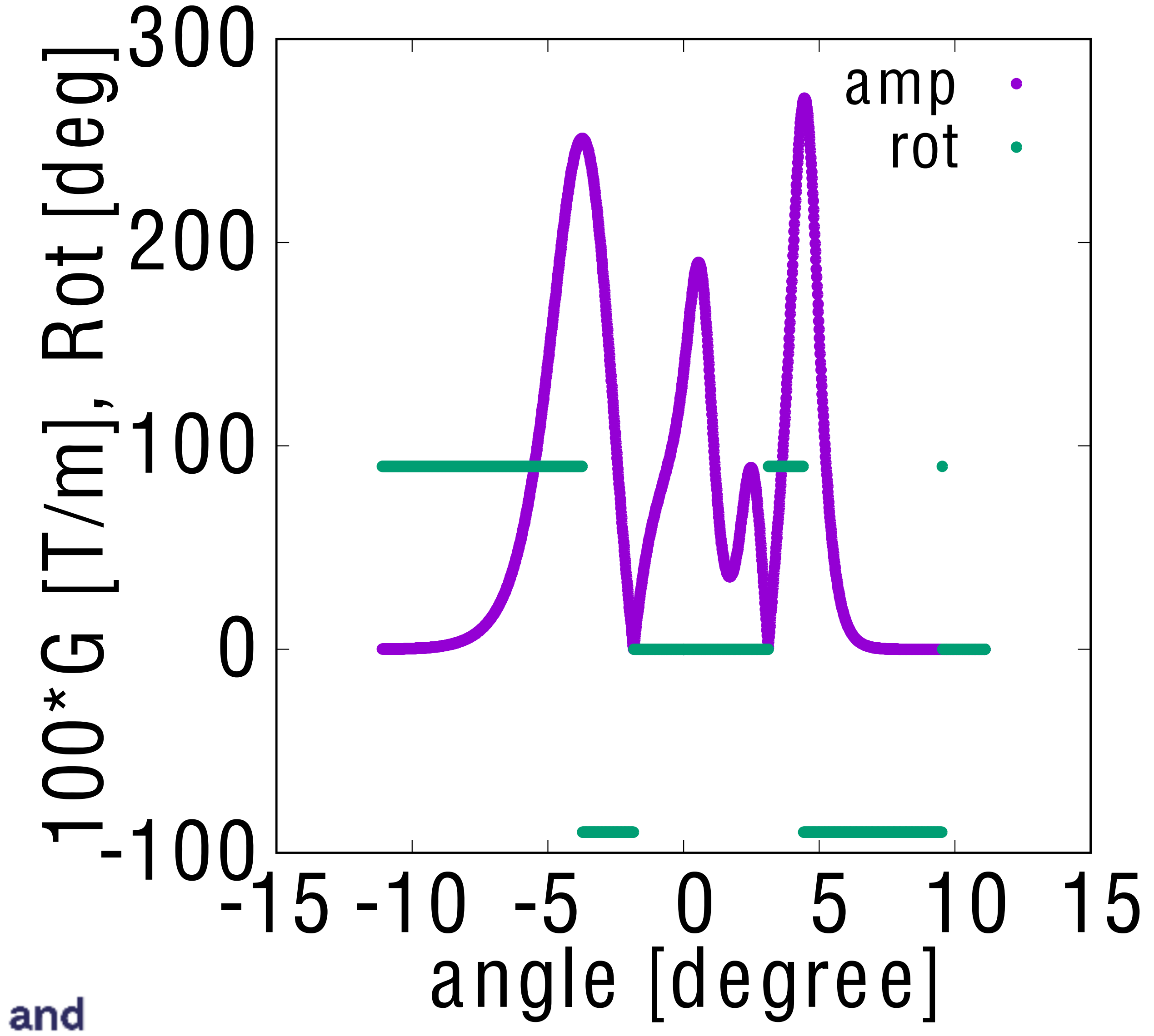



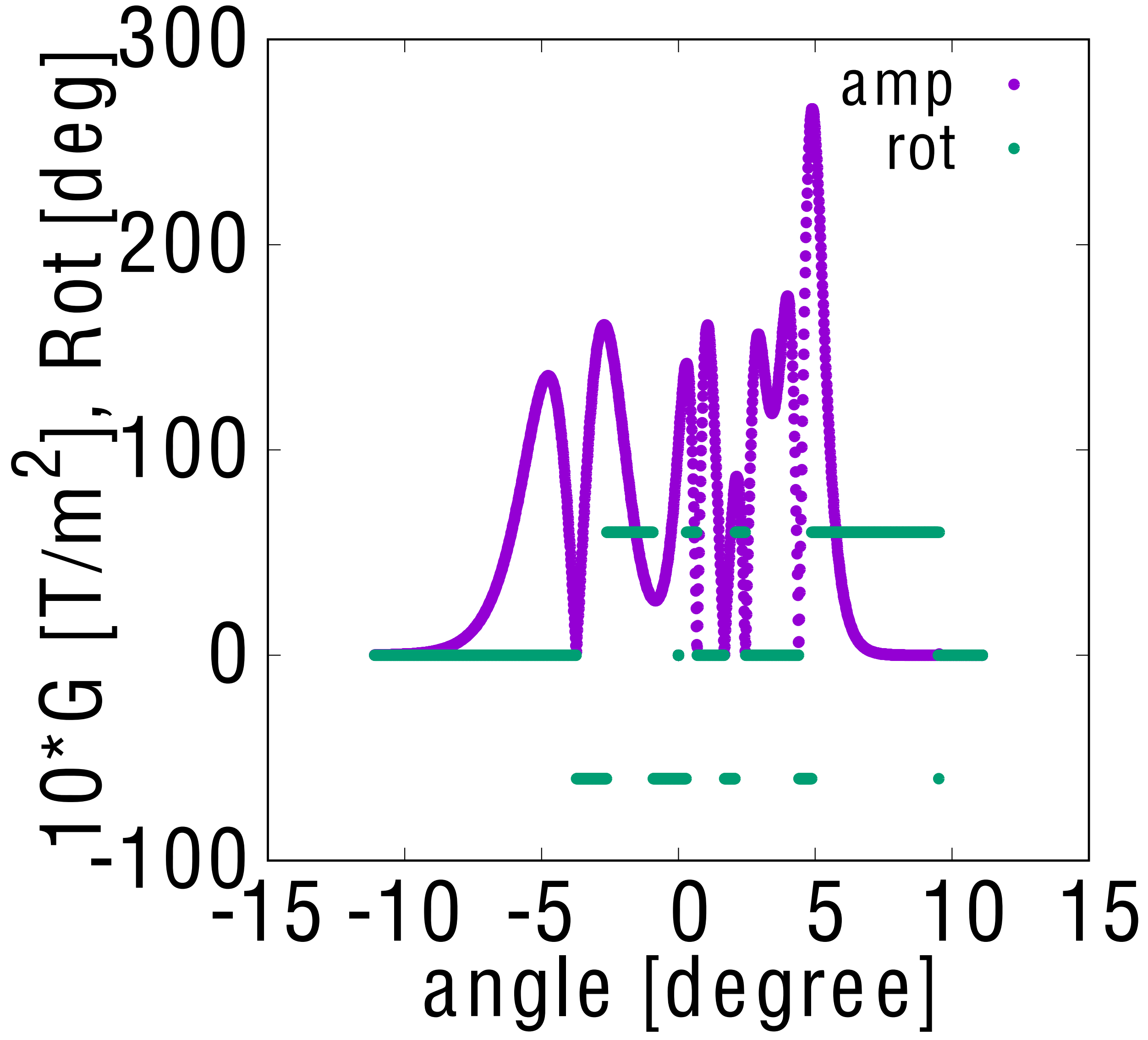



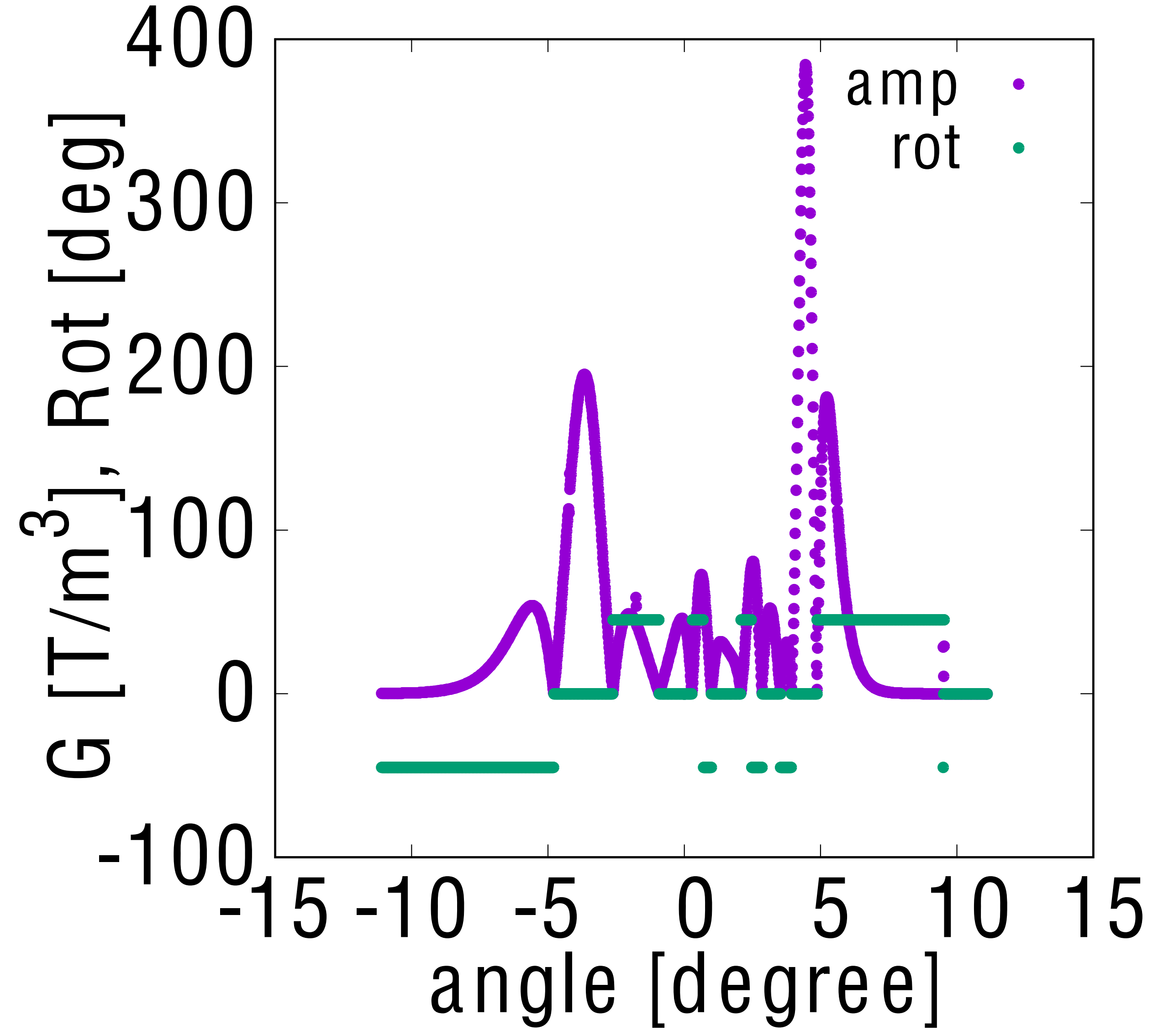

Bf entrance

FFE x 2

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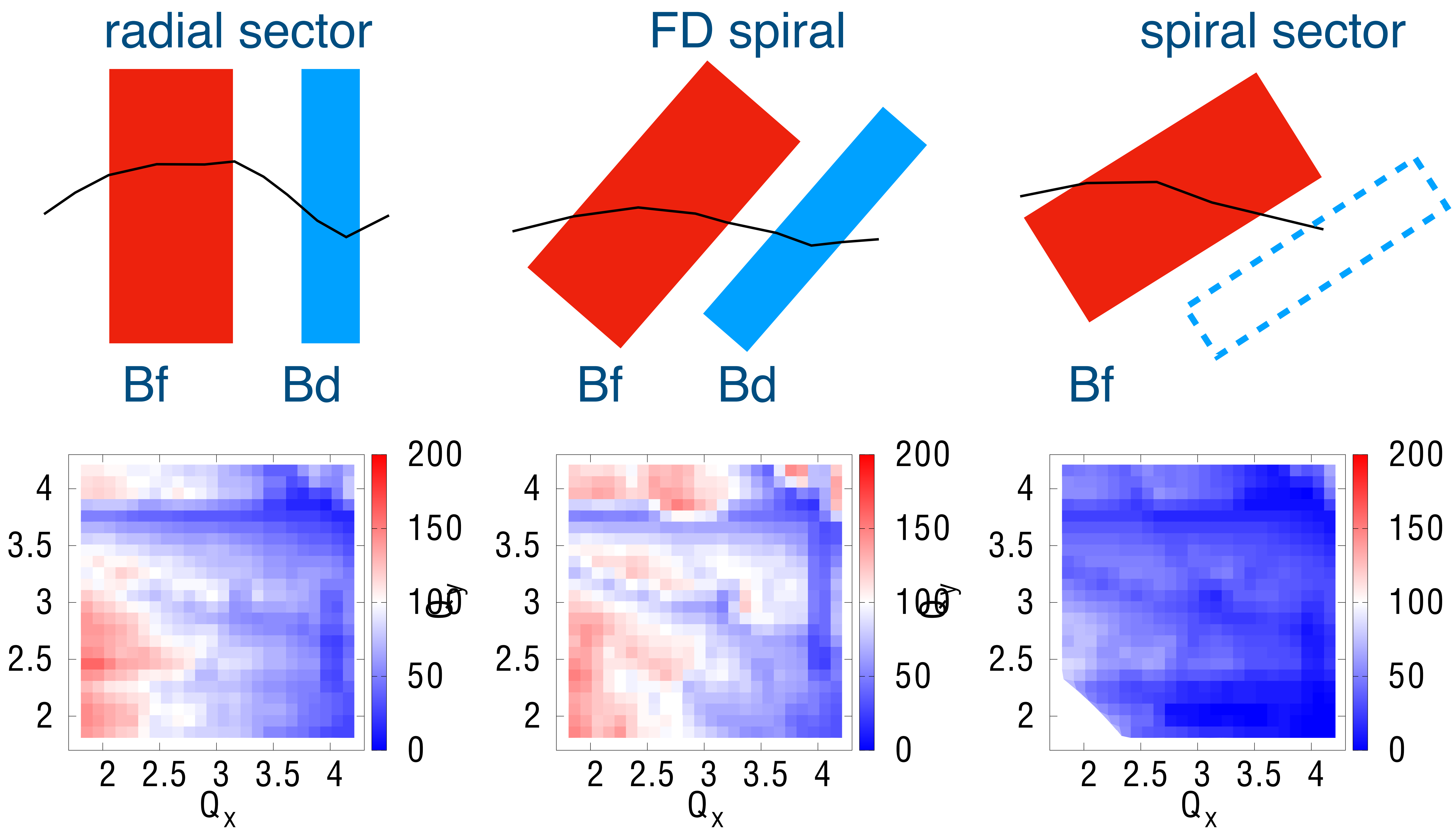
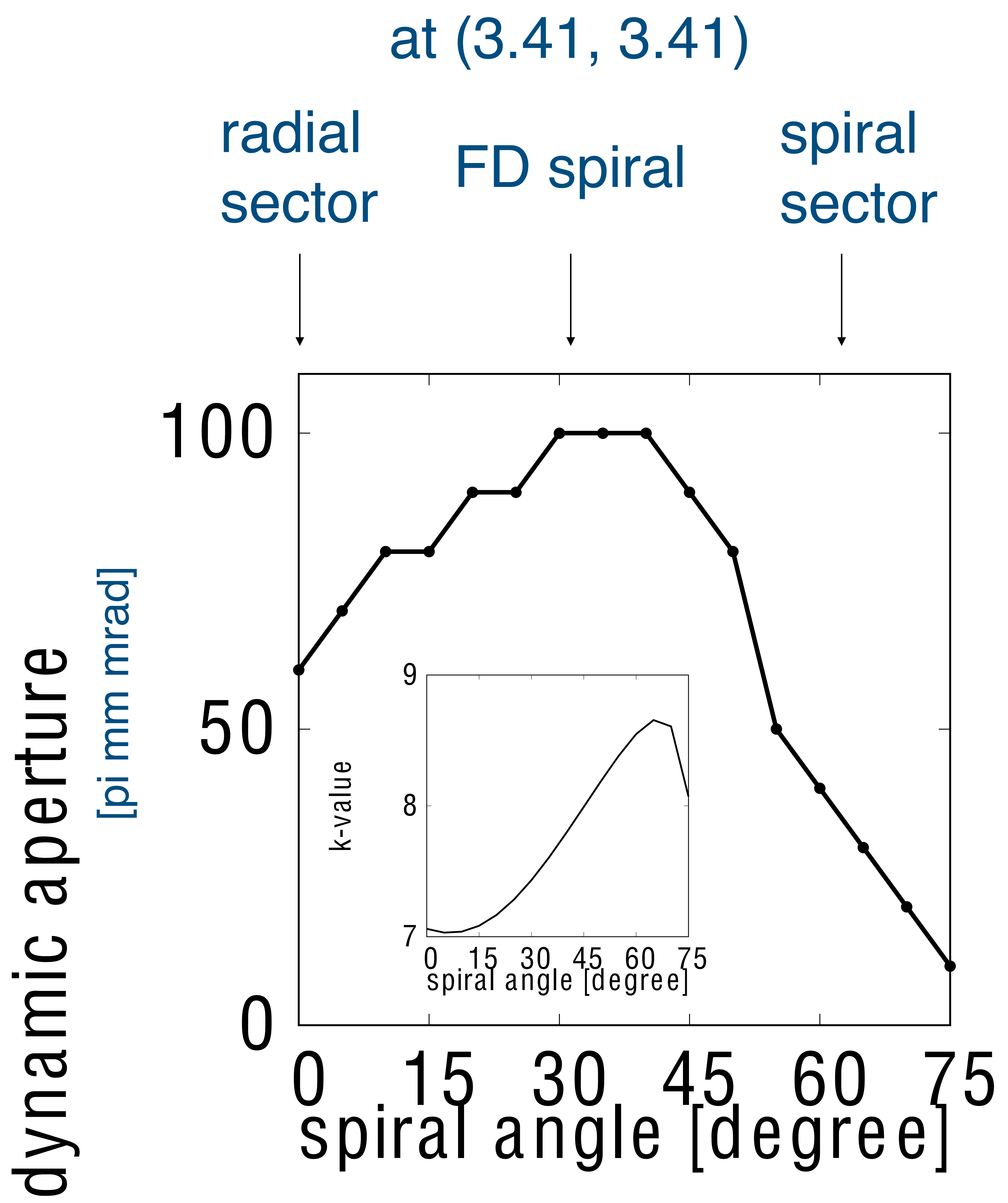
Twice longer FFE makes DA more than double (~ x 2.5).

# Dynamic aperture vs spiral angle

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# Beam stacking

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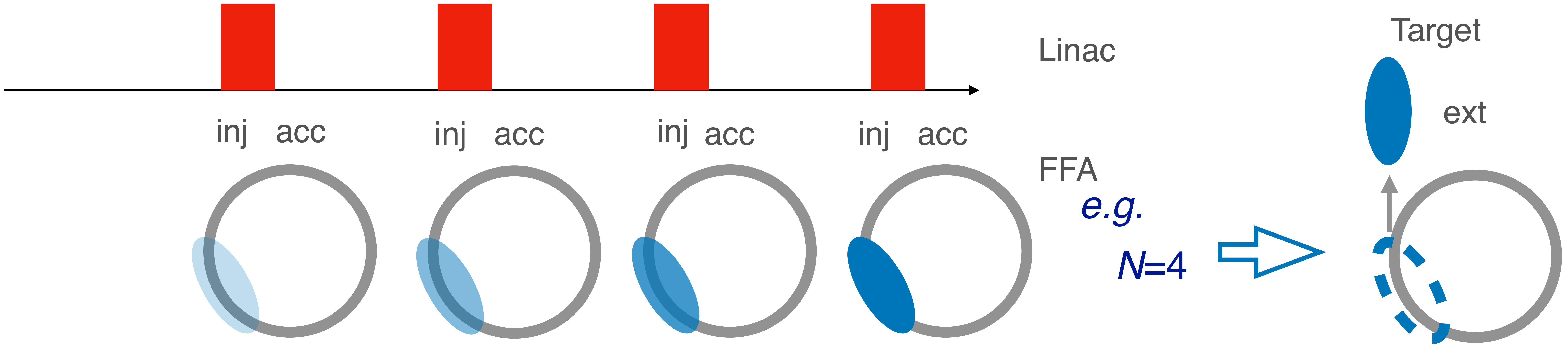
# Repetition rate

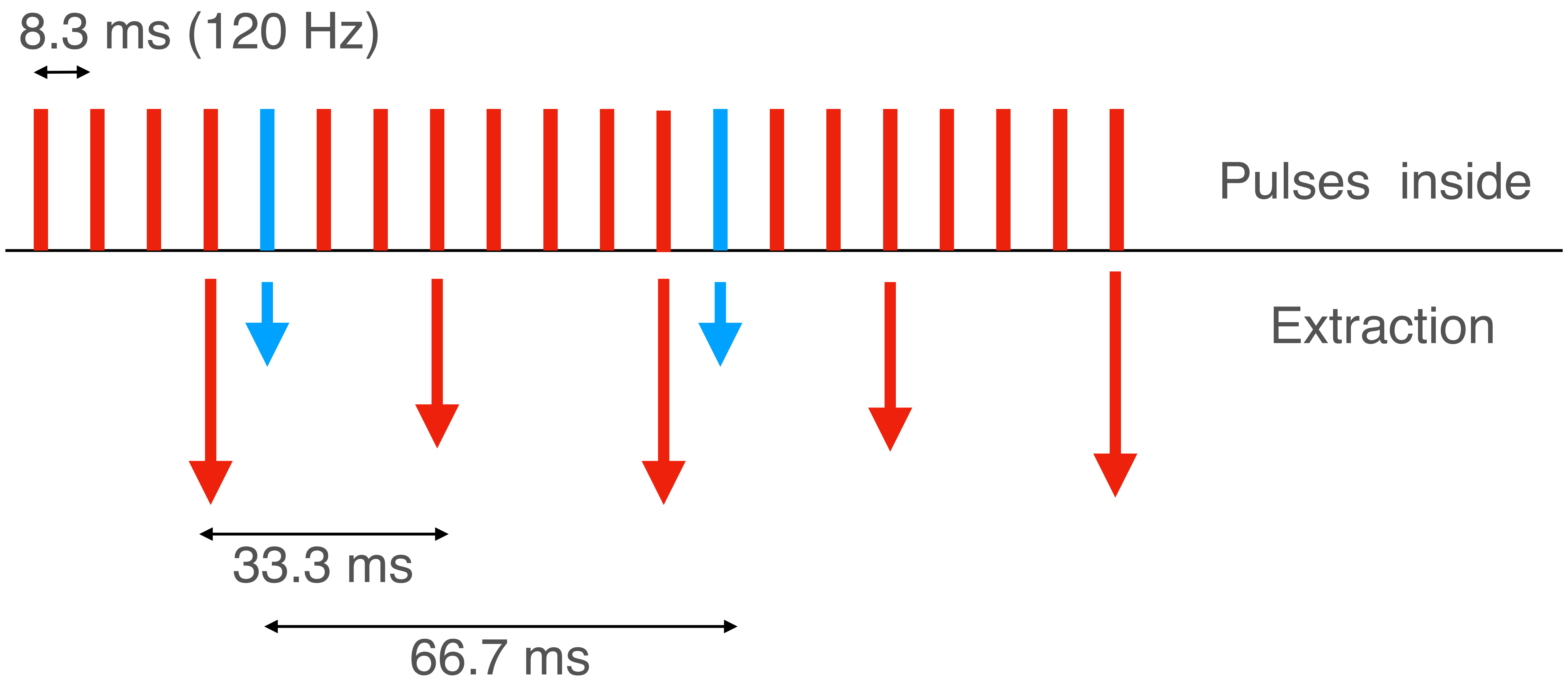
- Higher repetition, or even CW, is the way to increase beam power of accelerators.
  - (Neutron) users prefer lower repetition, eg. 10 Hz, 30 Hz.

- Beam stacking is the way to control repetition rate seen by users without decreasing beam power.
  - That can be done only by an accelerator with DC magnets like FFAs.

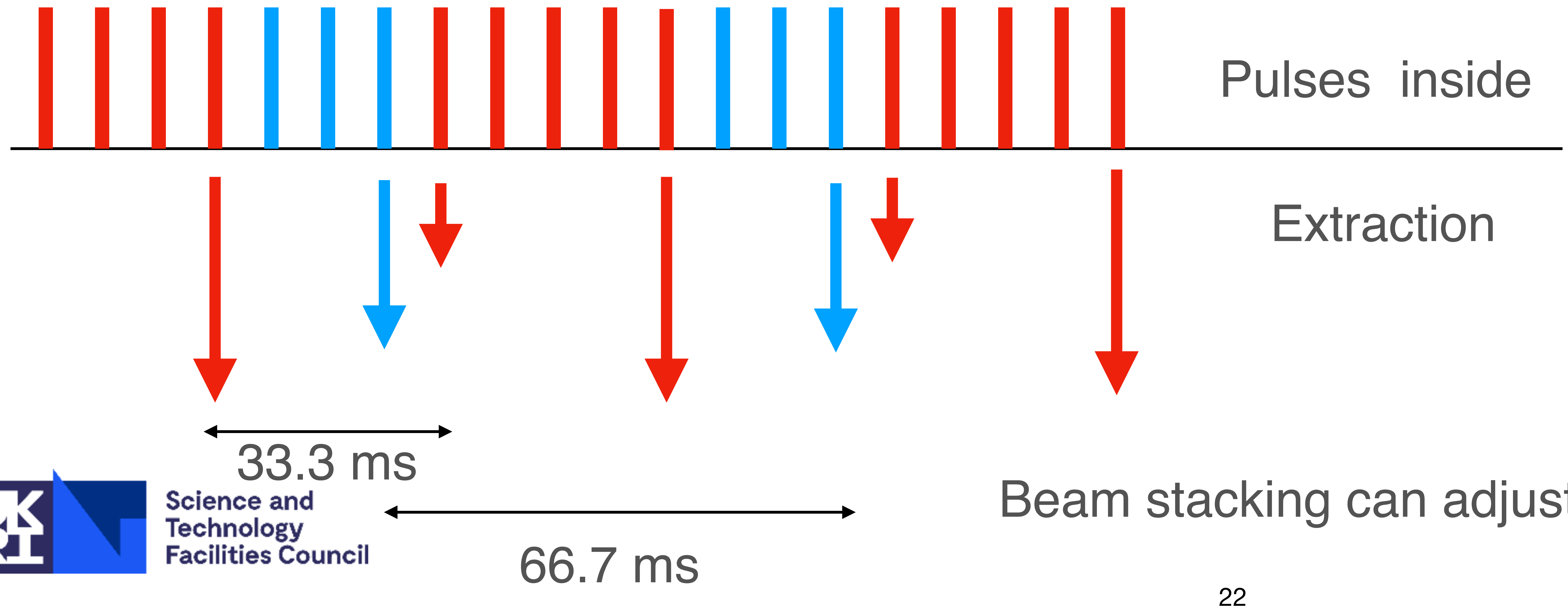
- It is not possible to accumulate N times particles at injection because of space charge effects. This can be done at the top energy because space charge effects are weaker.



# 30/15 Hz by beam stacking




| | TS1 (red) | TS2 (blue) |
|---|---|---|
| Rep. rate | 30 Hz | 15 Hz |
| Power | 2.1 MW | 0.3 MW |




| | TS1 (red) | TS2 (blue) |
|---|---|---|
| Rep. rate | 30 Hz | 15 Hz |
| Power | 1.5 MW | 0.9 MW |

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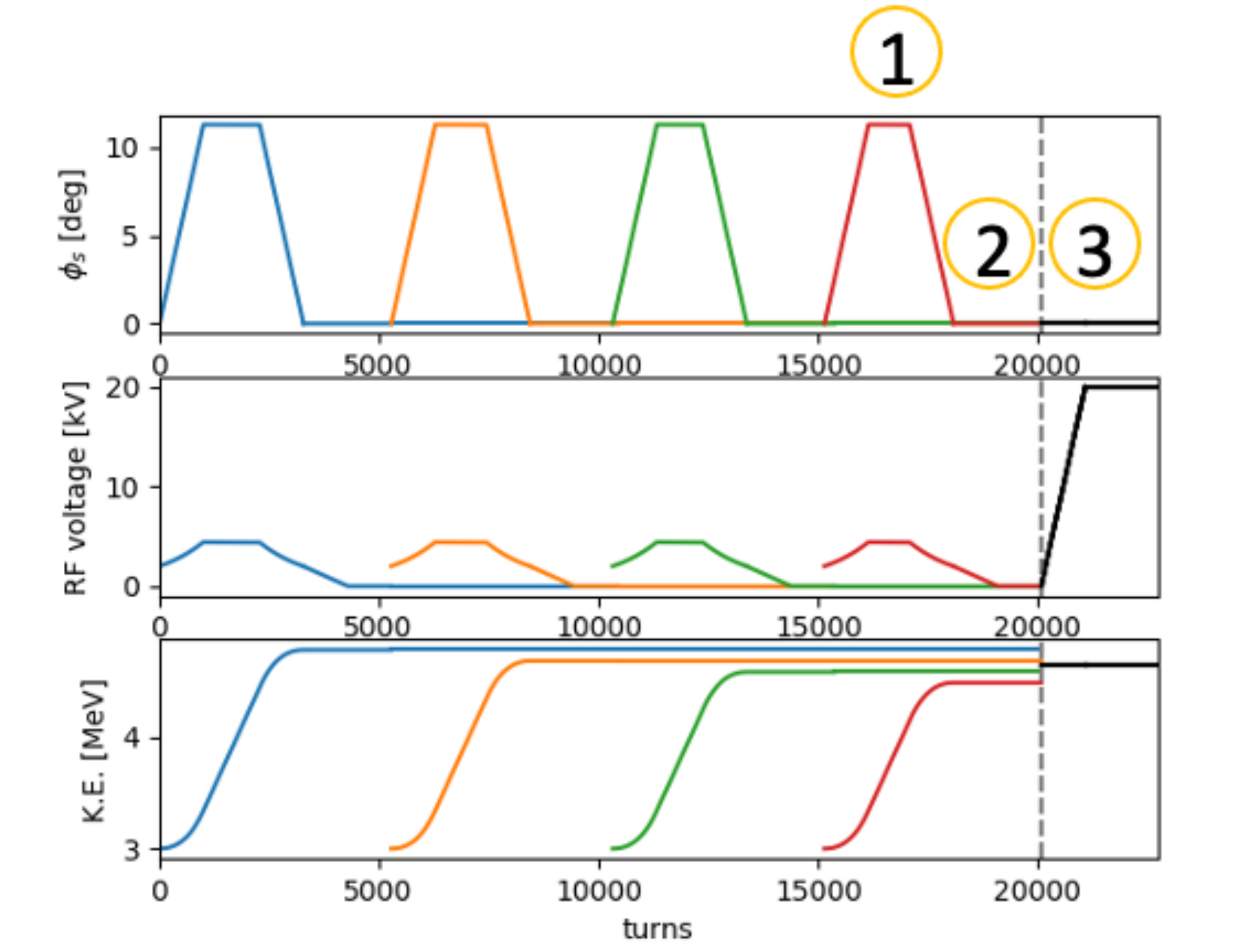
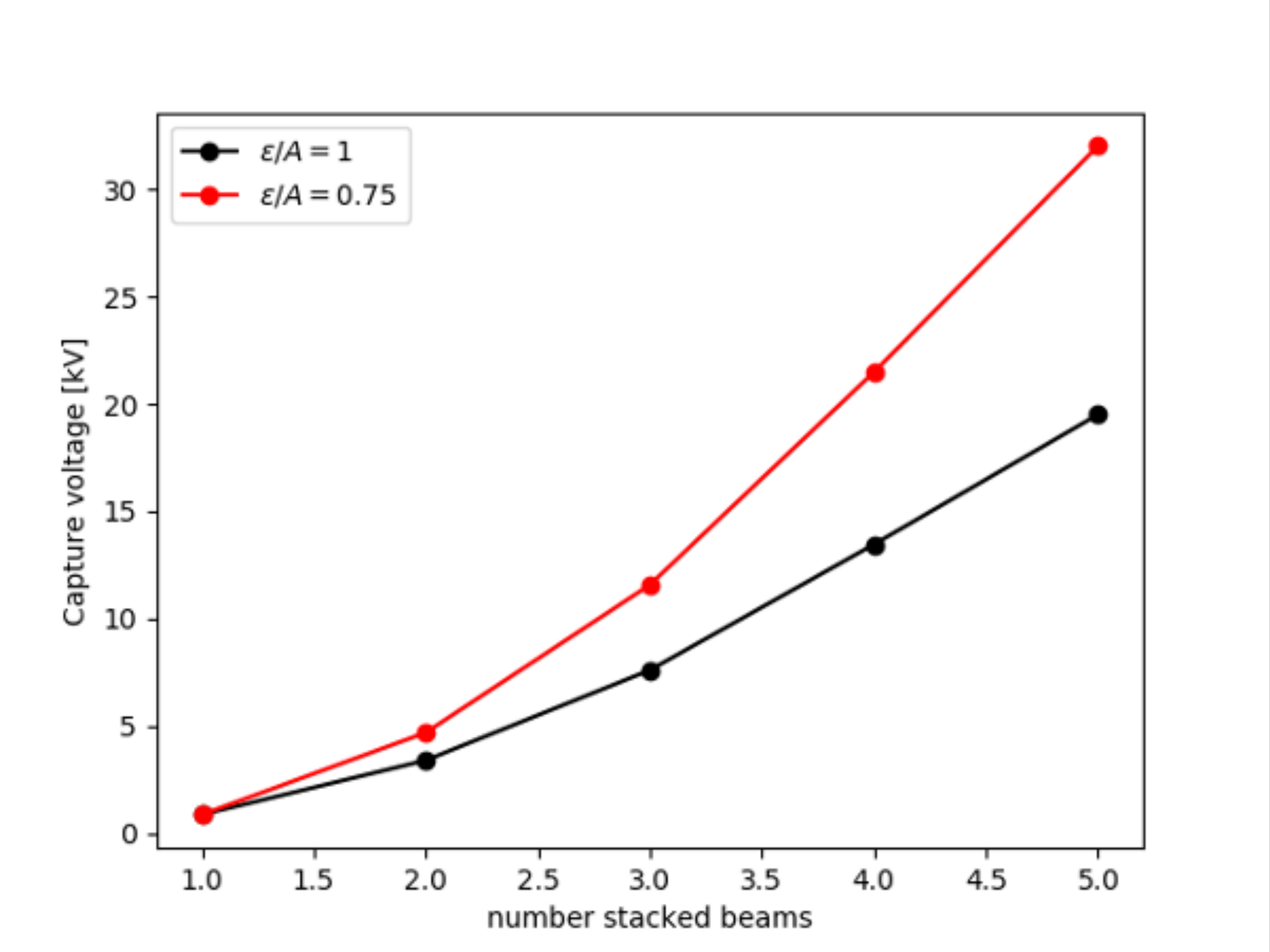
Beam stacking can adjust beam power for TS-1 and TS-2.

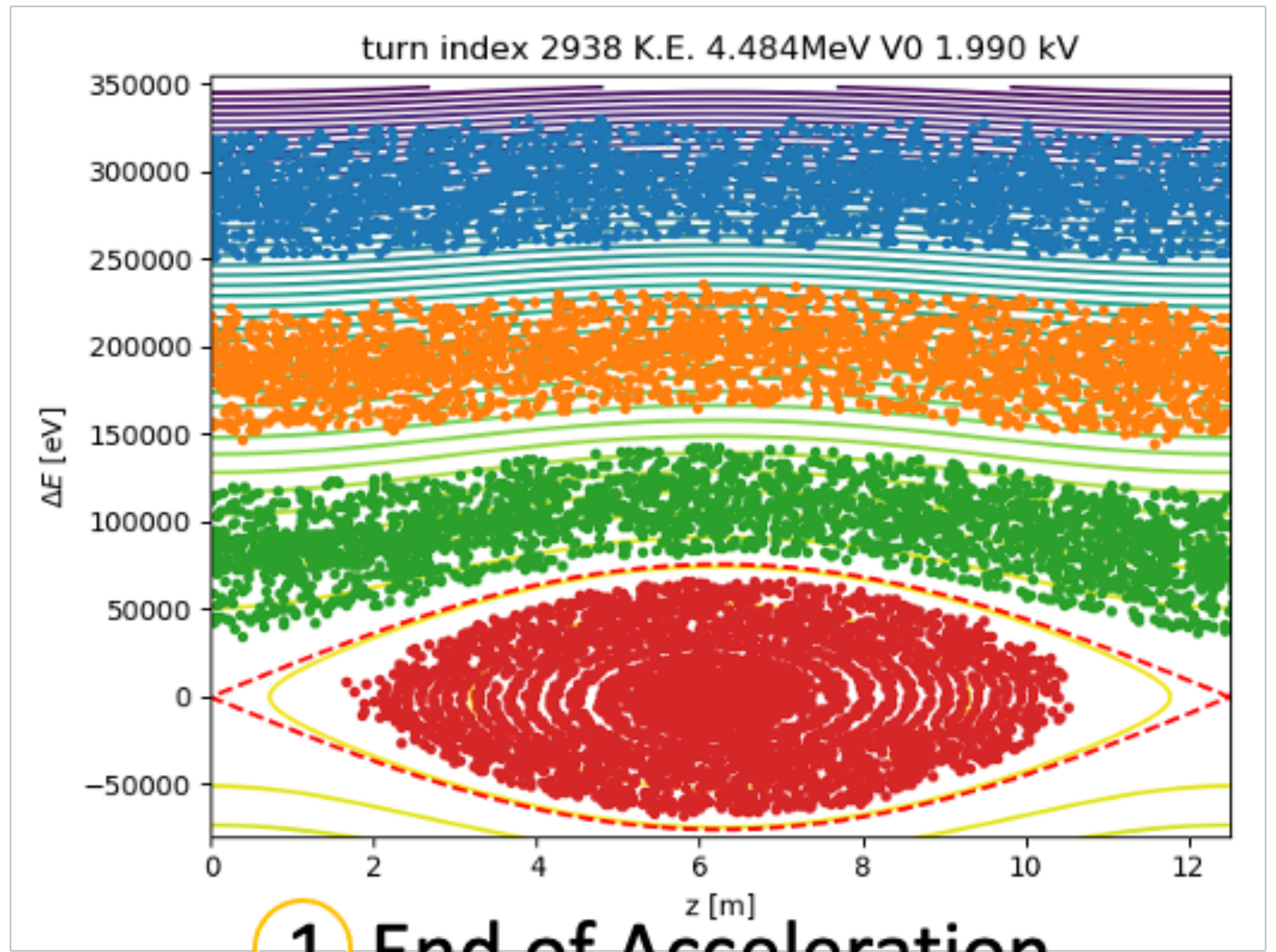
# Required voltage and longitudinal phase space

RF cavity for stacking

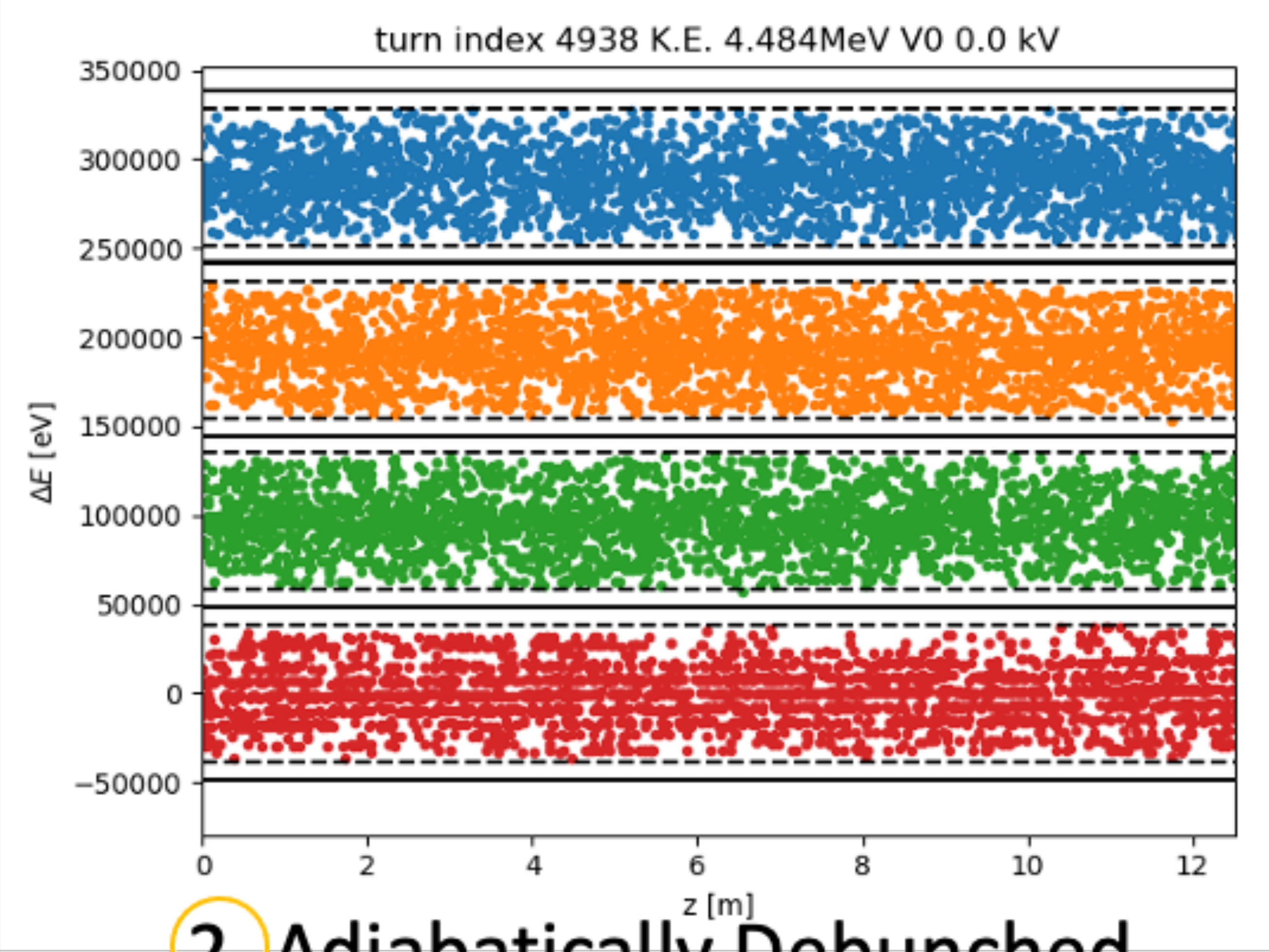
| Parameter | Value |
|---|---|
| RF frequency (h=1, fixed) | ~1 MHz |
| RF peak voltage | 35 kV (stack 5 beams) |



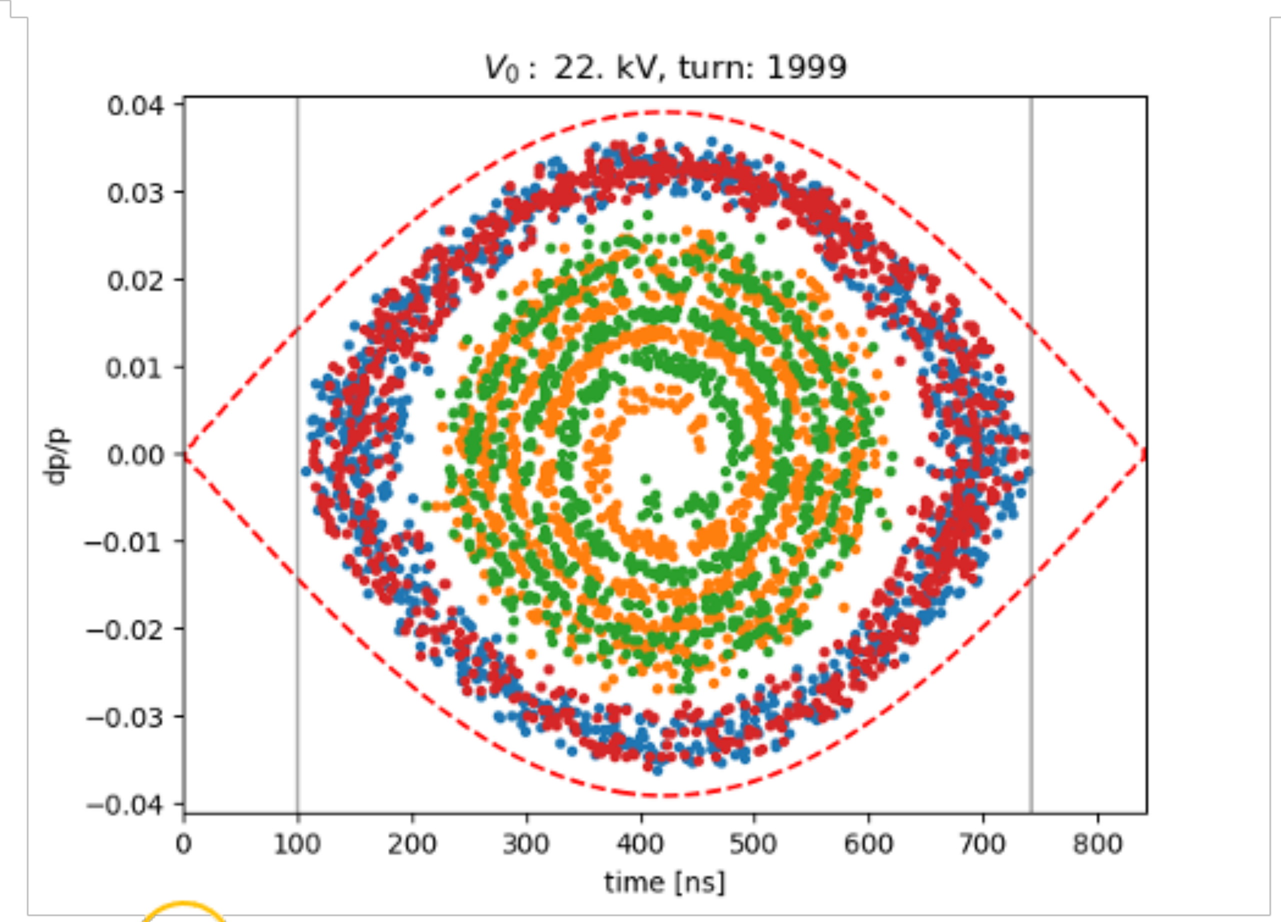




1. End of Acceleration




2. Adiabatically Debunched




3. Adiabatically Captured (200ns beam free)

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# Hardware developments

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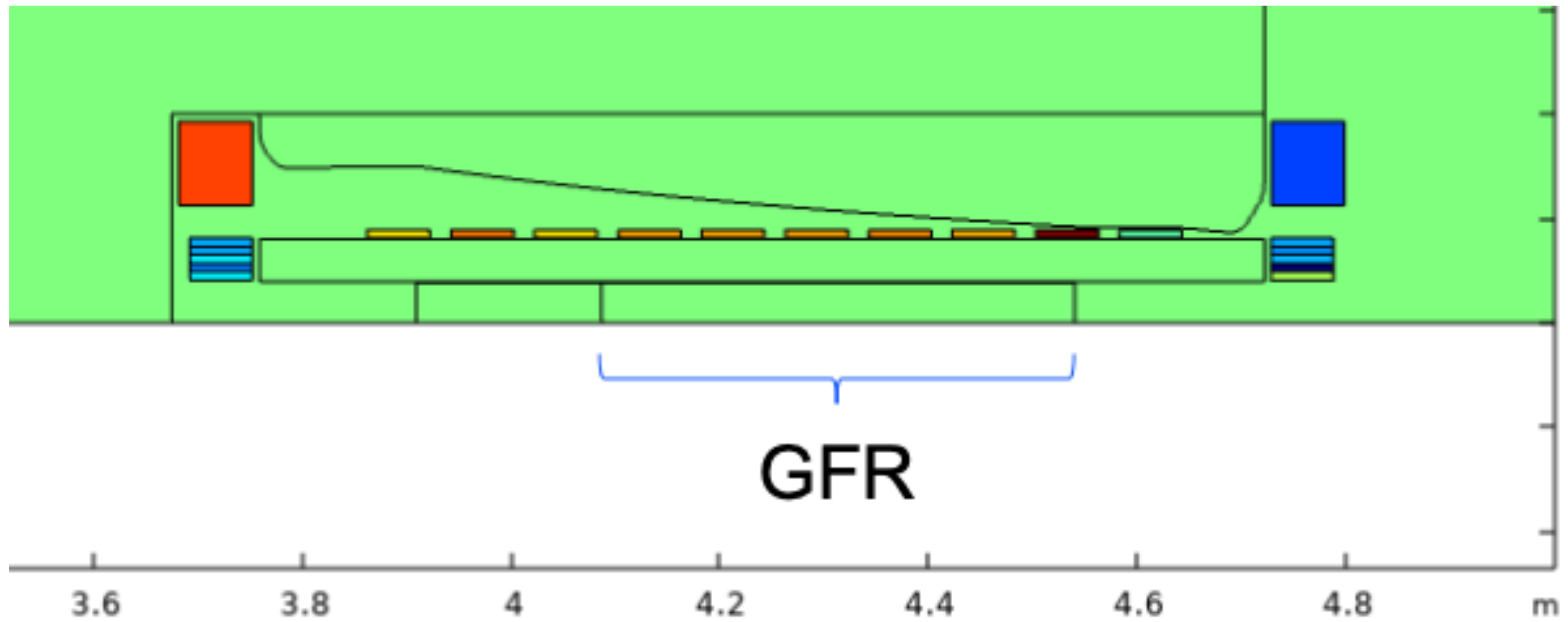
# Magnet prototype

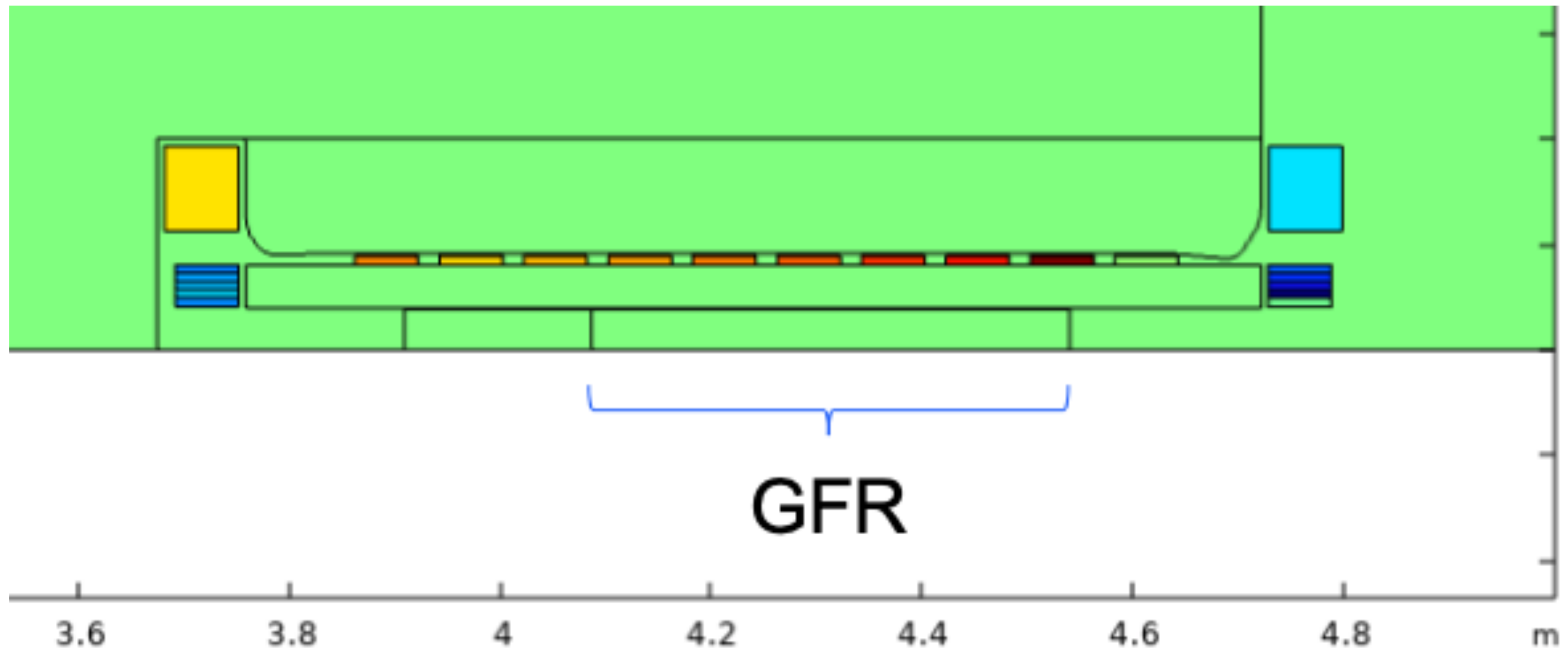
- C-shape magnet because of space constraint.
- Field index $k$ variable from 6 to 11.

Several options were investigated to create field gradient.

$$B(r,\theta) = B_0 \left(\frac{r}{r_0}\right)^k F(\theta) \qquad k = \frac{r}{B}\frac{\partial B}{\partial r}$$

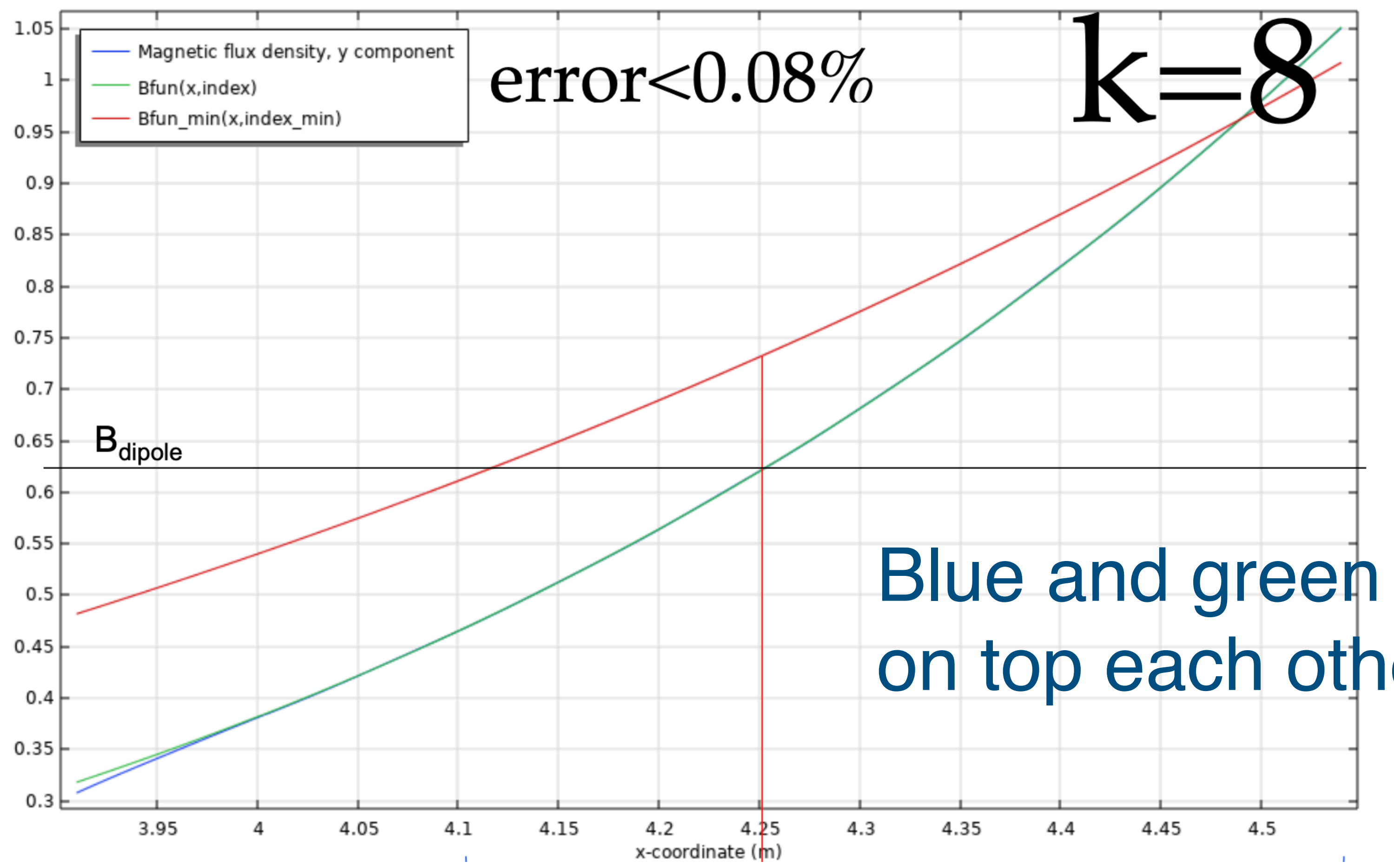
1) gap shaped magnet,
2) parallel pole with trim coils,
3) combined with anisotropic iron plates.



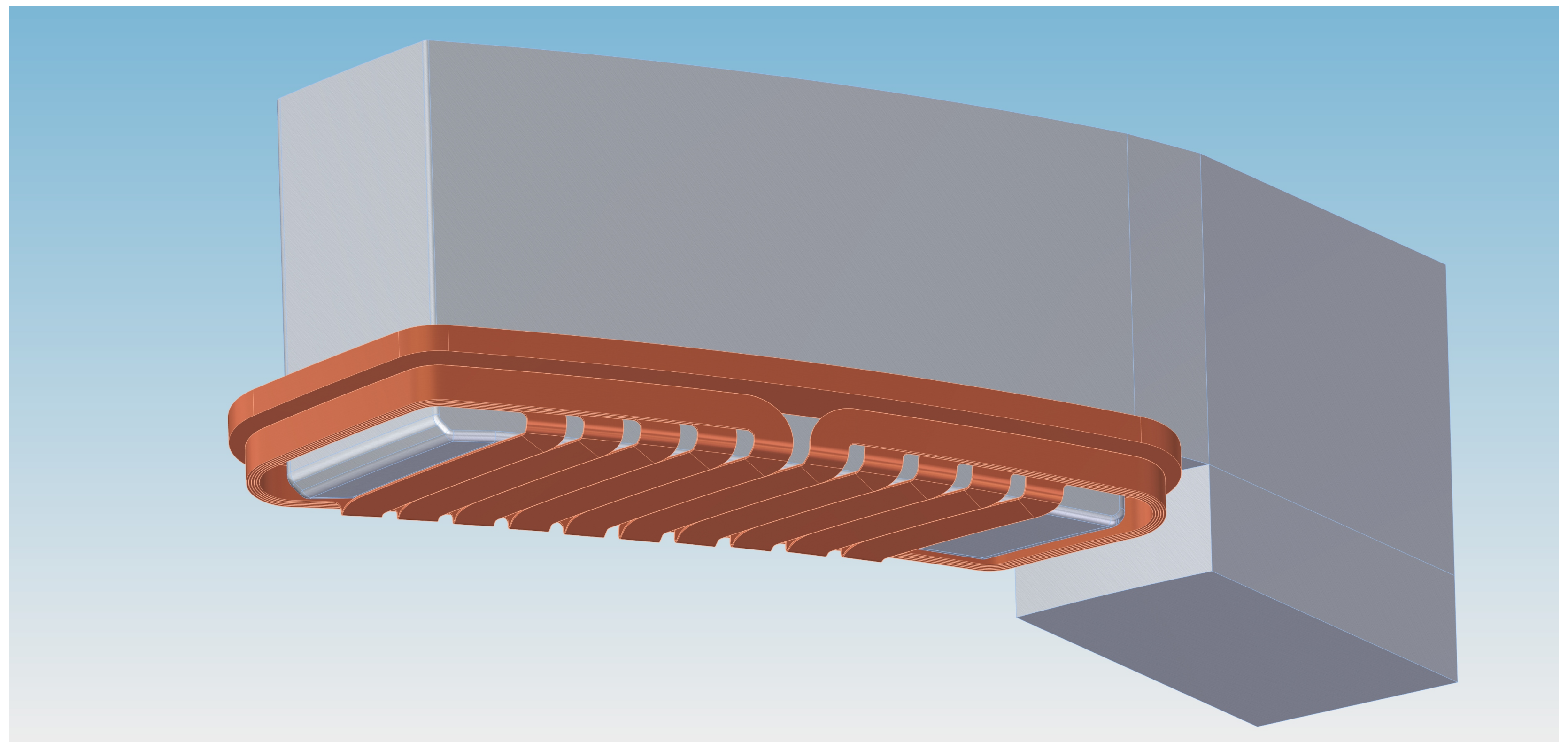

Required power is similar.

## Optimisation of 2D model



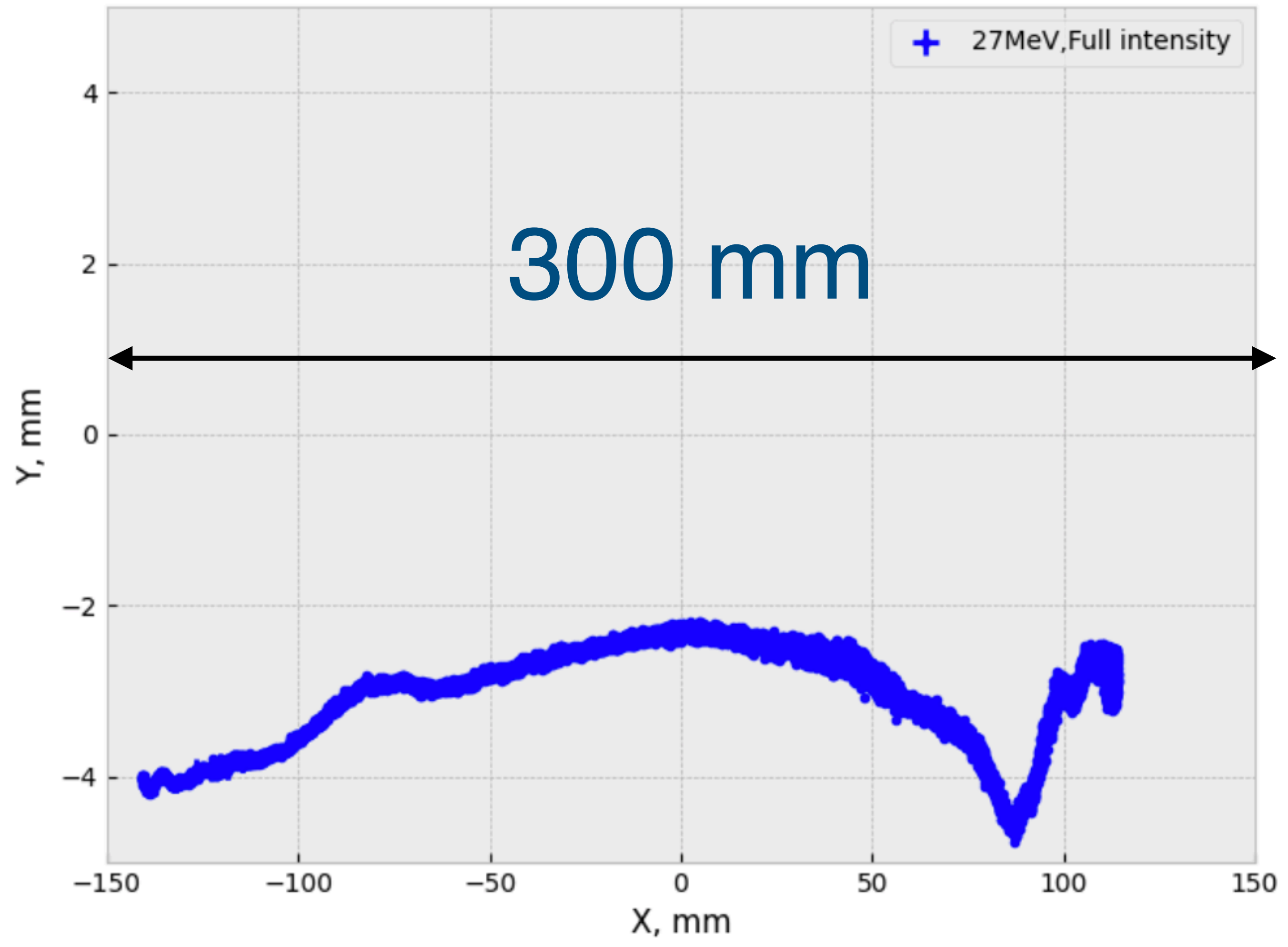

Blue and green lines are on top each other.

- Just started 3D modelling.
  - Single magnet has both Bf and Bd.

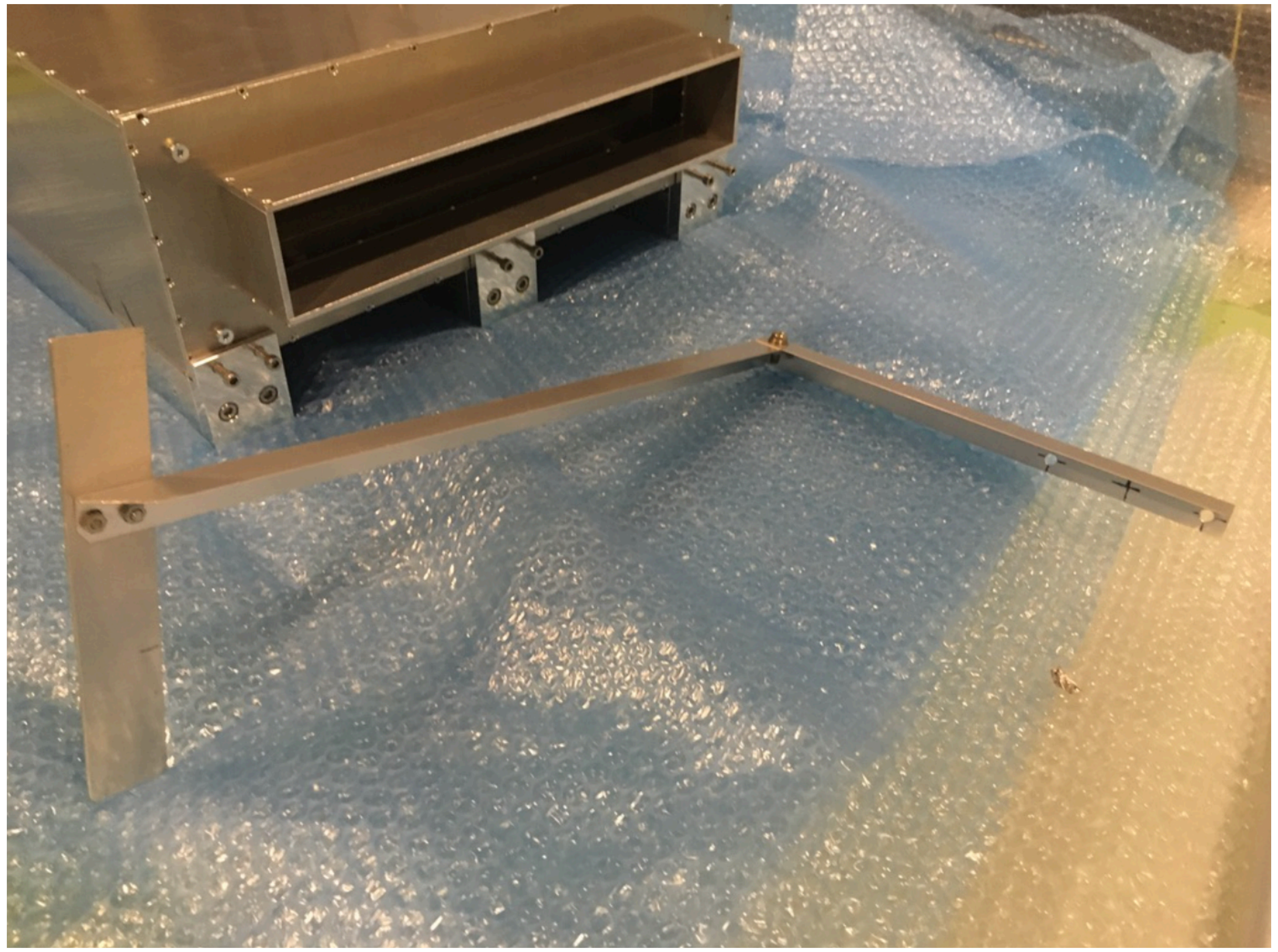


# Beam Position Monitor (BPM) prototype

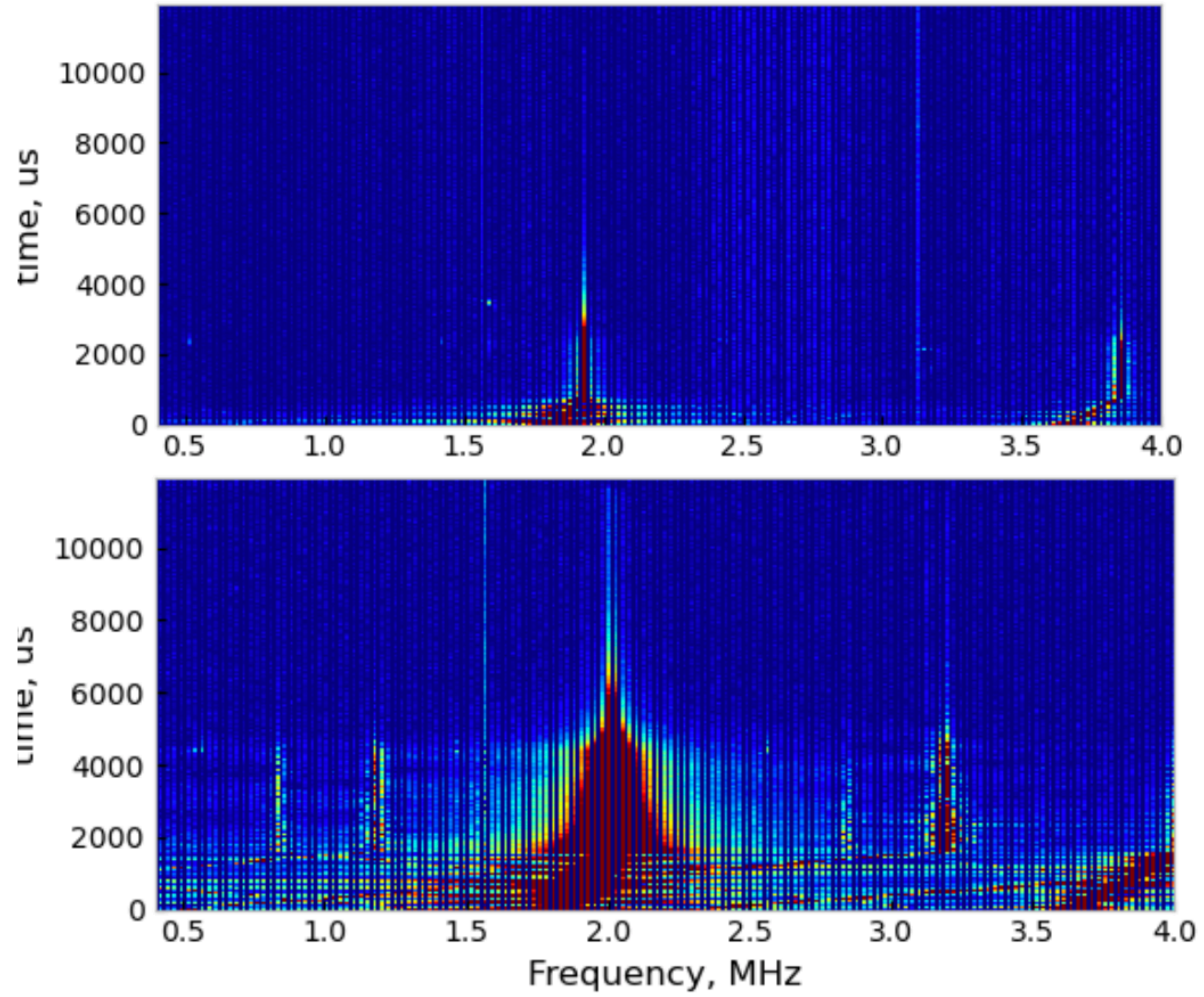
- A half size (horizontal) BPM prototype is made and tested in the FFA at Kyoto Univ. (KURNS).
- Turn by turn position measurement and tune measurement have been done.




Hor. and Ver. beam position evolution during acceleration.



A half size BPM and scraper




Frequency spectrum to measure tune.

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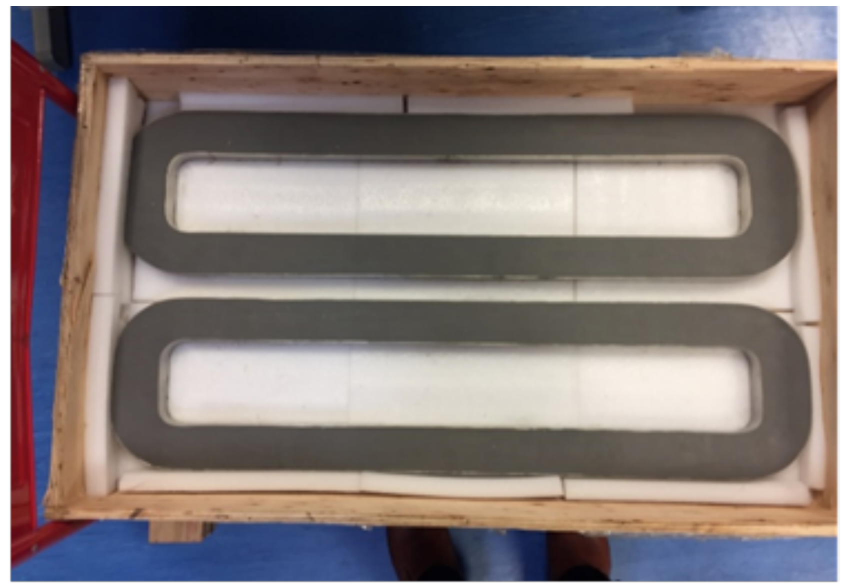
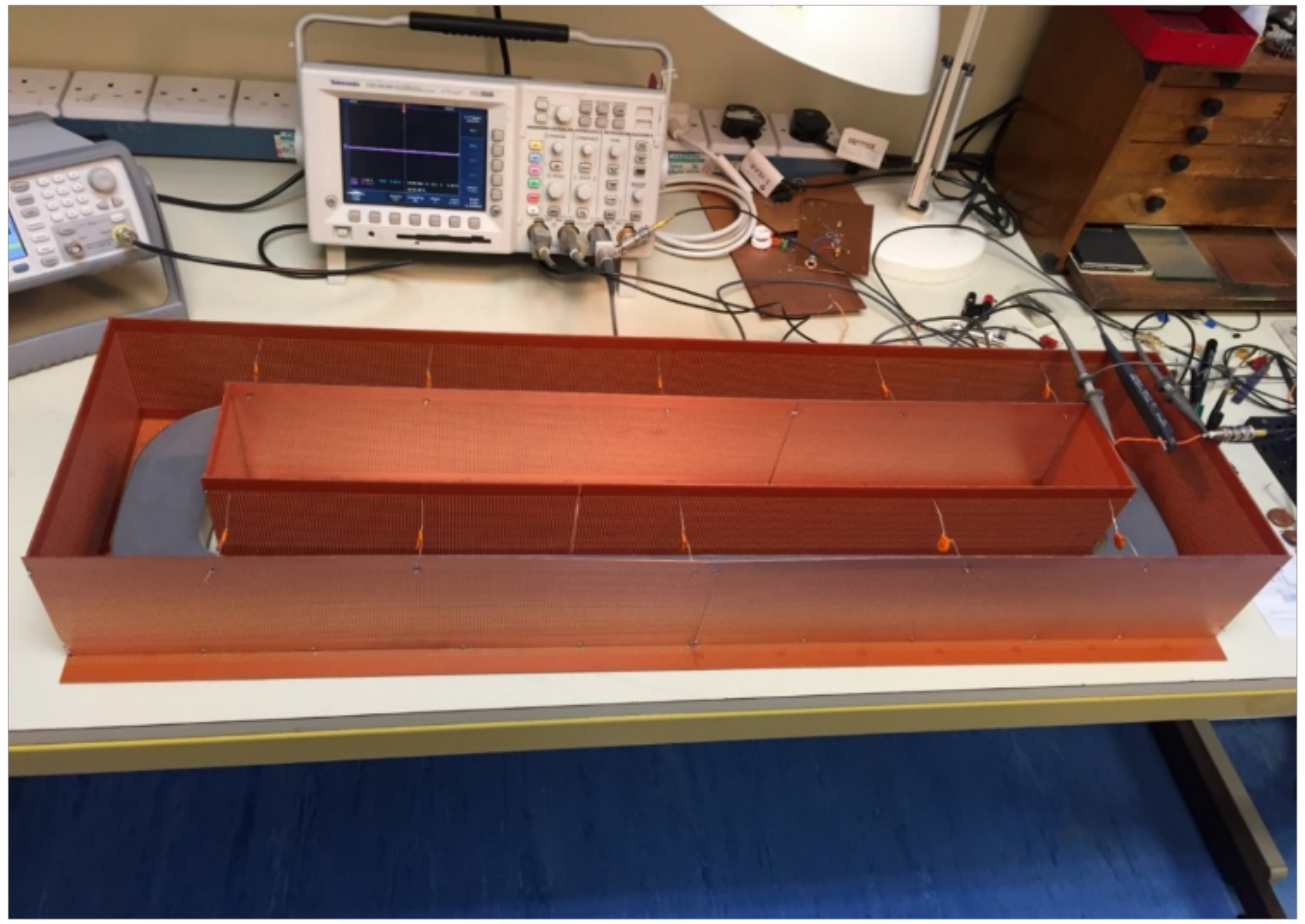
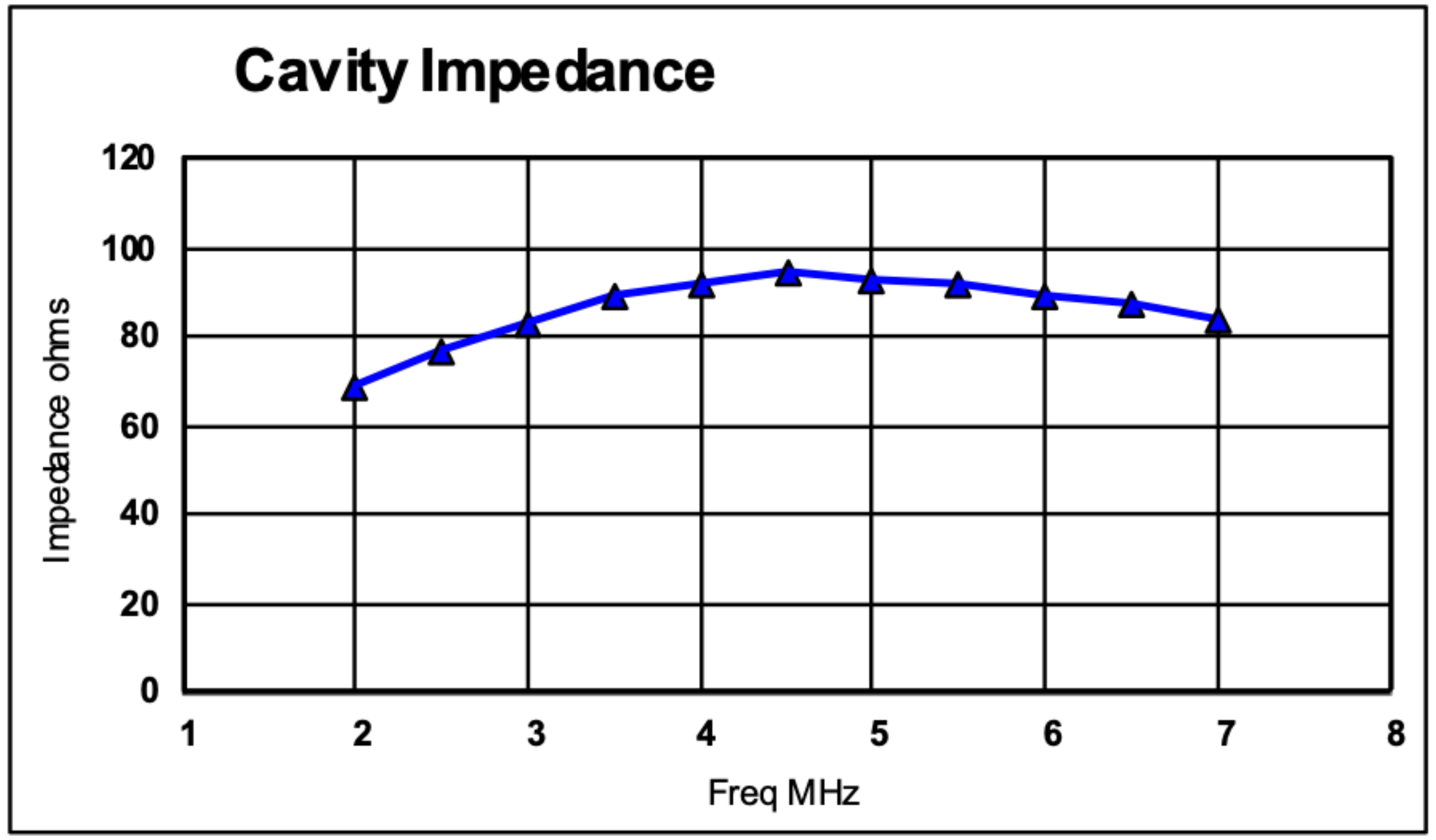
# RF cavity, Ferrite or Magnetic Alloy (MA)

## Measure shunt impedance of MA core.





## Preliminary result




- Measured with 100 V peak per core
- Power for 8 core cavity at 6 kV peak 50 - 65 kW
- Consider using 2 cavities at ½ voltage ~16 kW each, meaning no Tuning system and wideband for fast modulations

# Summary

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# Summary

- Our goal is to demonstrate high intensity operation of a FFA.
    - with a scaling FFA.
- From physics design point of view
    - Proper lattice structure ready for high intensity operation
    - Superperiod lattice to give space for beam handling
    - Enlarge dynamics aperture to accommodate large number of particles
- From operational point of view
    - Consider beam stacking to produce either high peak with low rep or low peak with high rep.
- Hardware design and prototyping has started.

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# Thank you for your attention

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