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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)

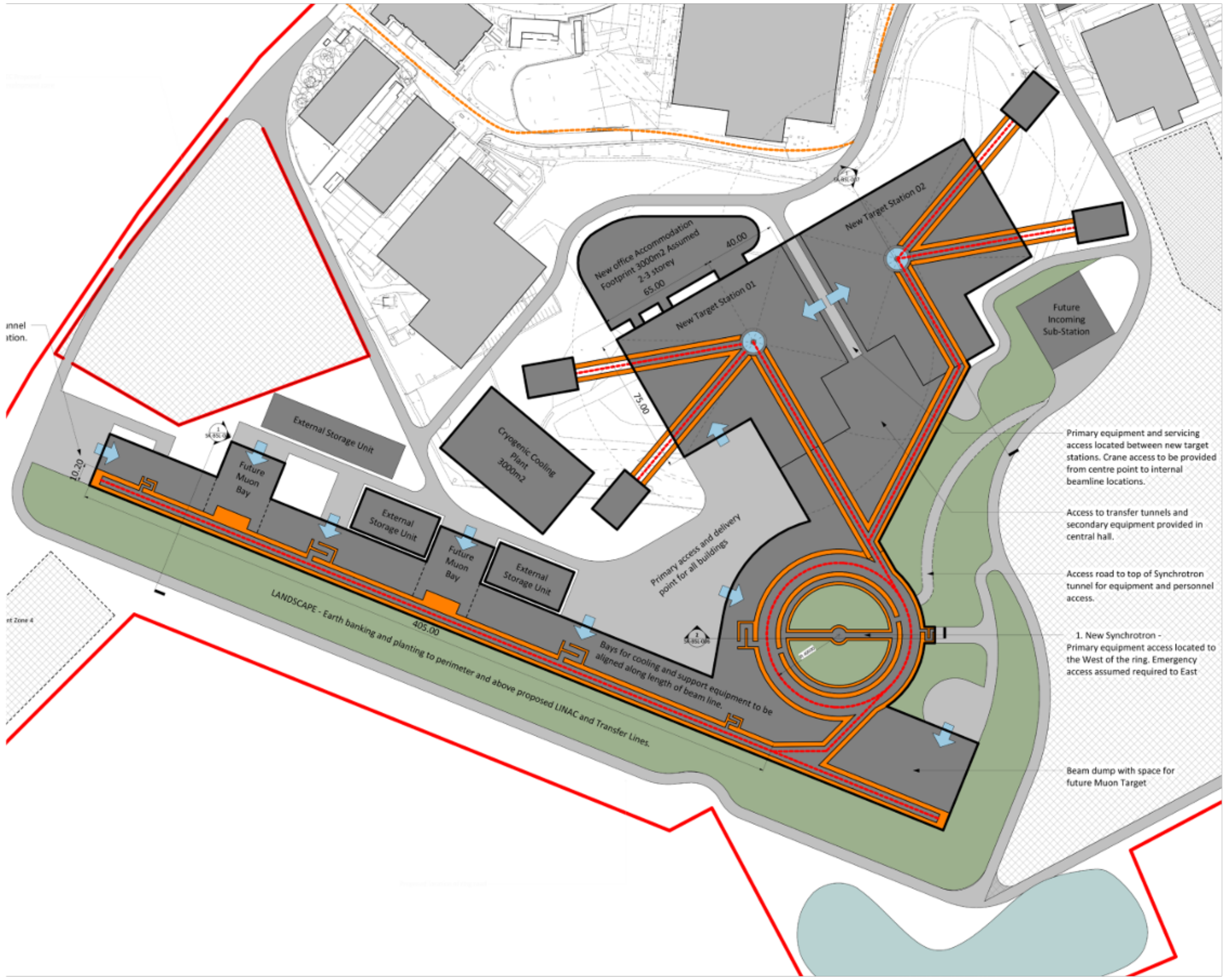
ISIS upgrade, “ISIS-II”

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

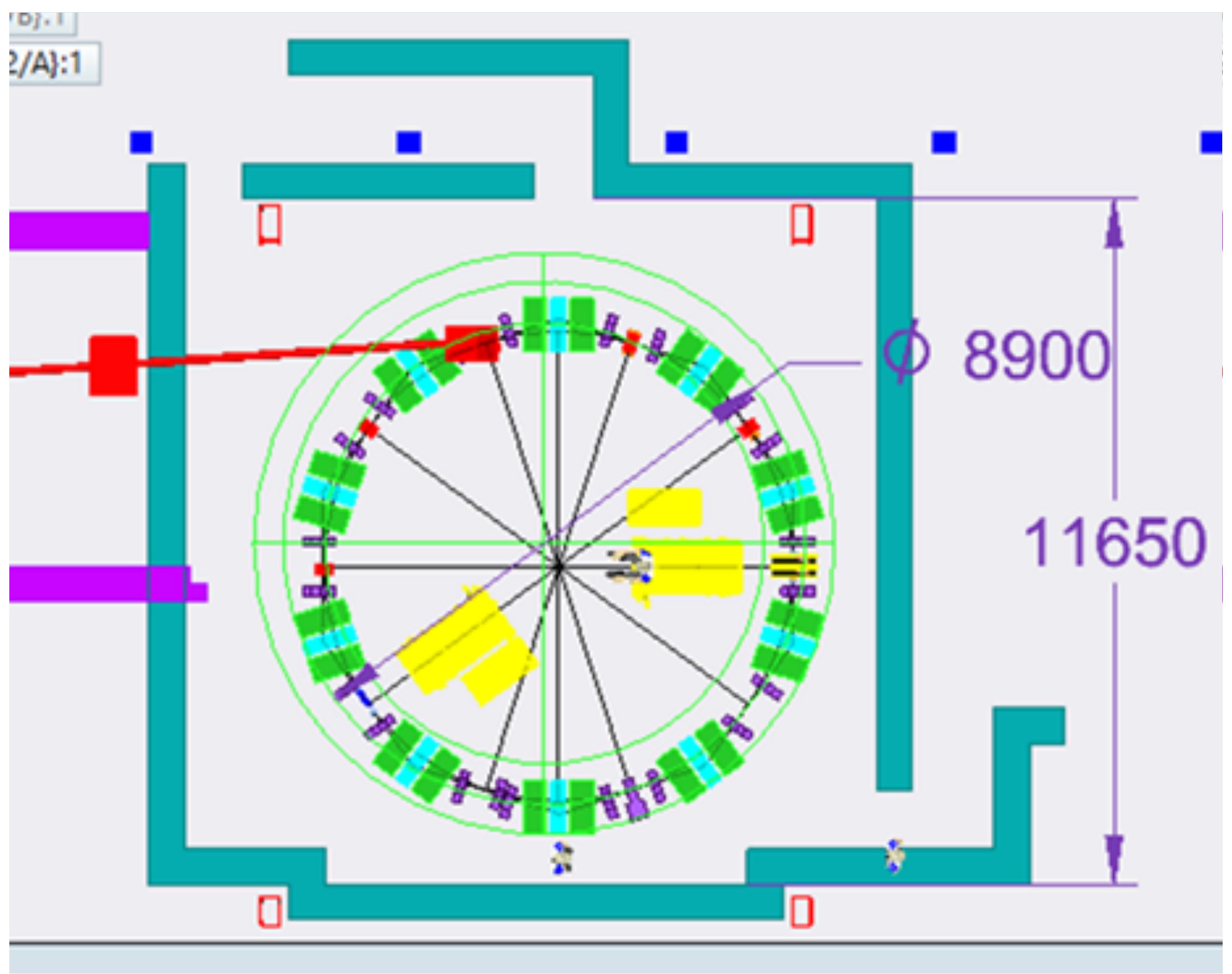
FETS: Front End Test Stand

- 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	3×10^{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

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FD (doublet) spiral lattice

Control of operation tune

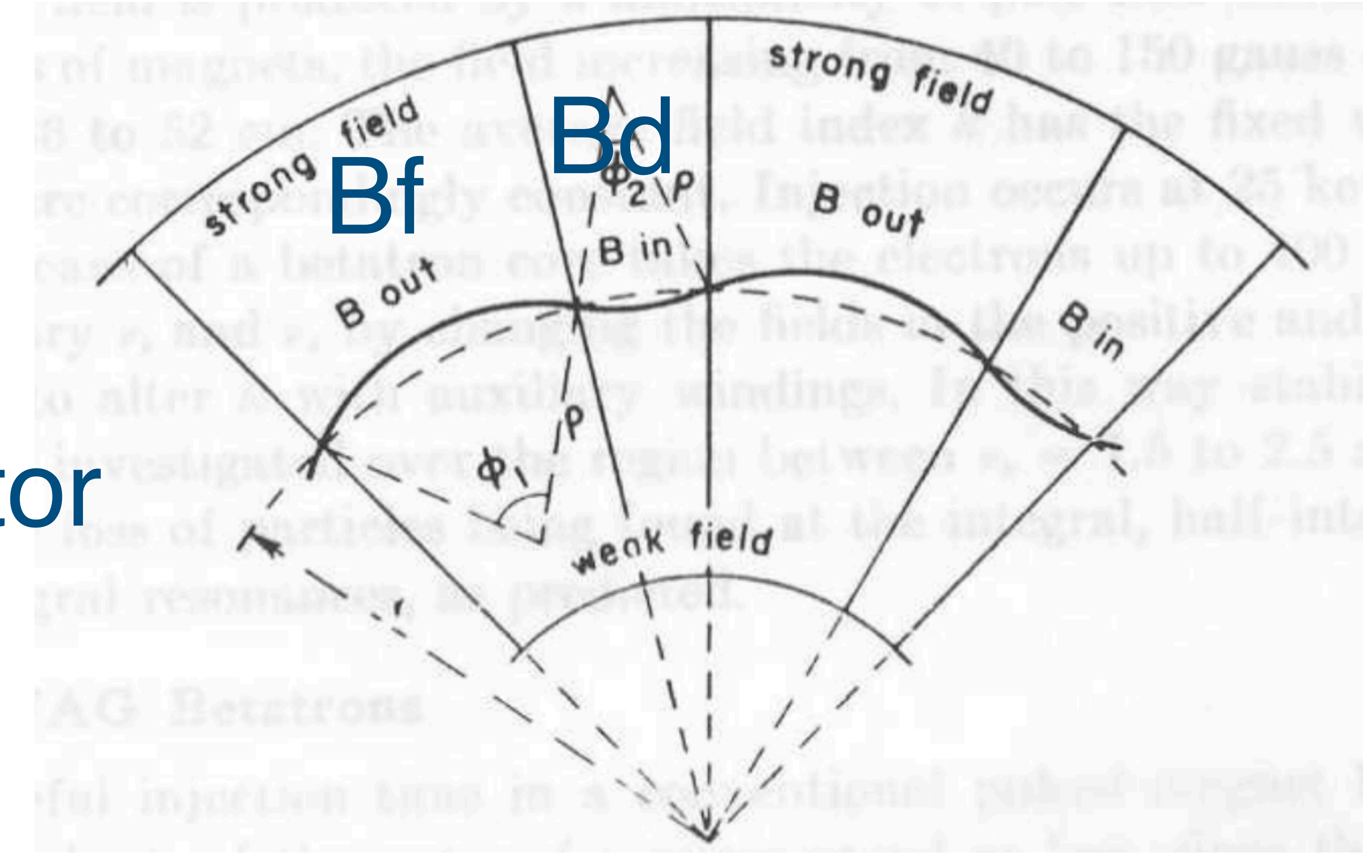
Operation tune should be chosen close to diagonal line, i.e. Qx ~ Qy from experience of SNS and J-PARC.

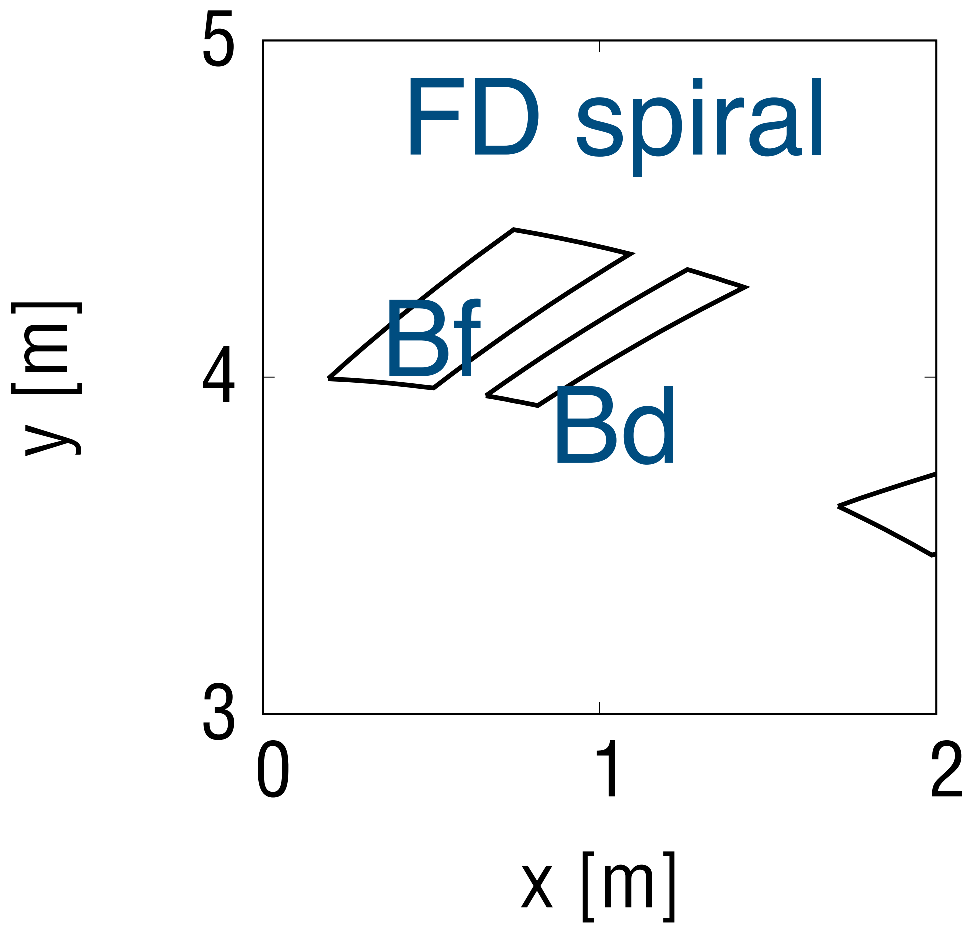
- Field index k and Bd/Bf ratio can adjust operation tune in radial sector FFA. However, a reverse bend Bd enlarges circumference.

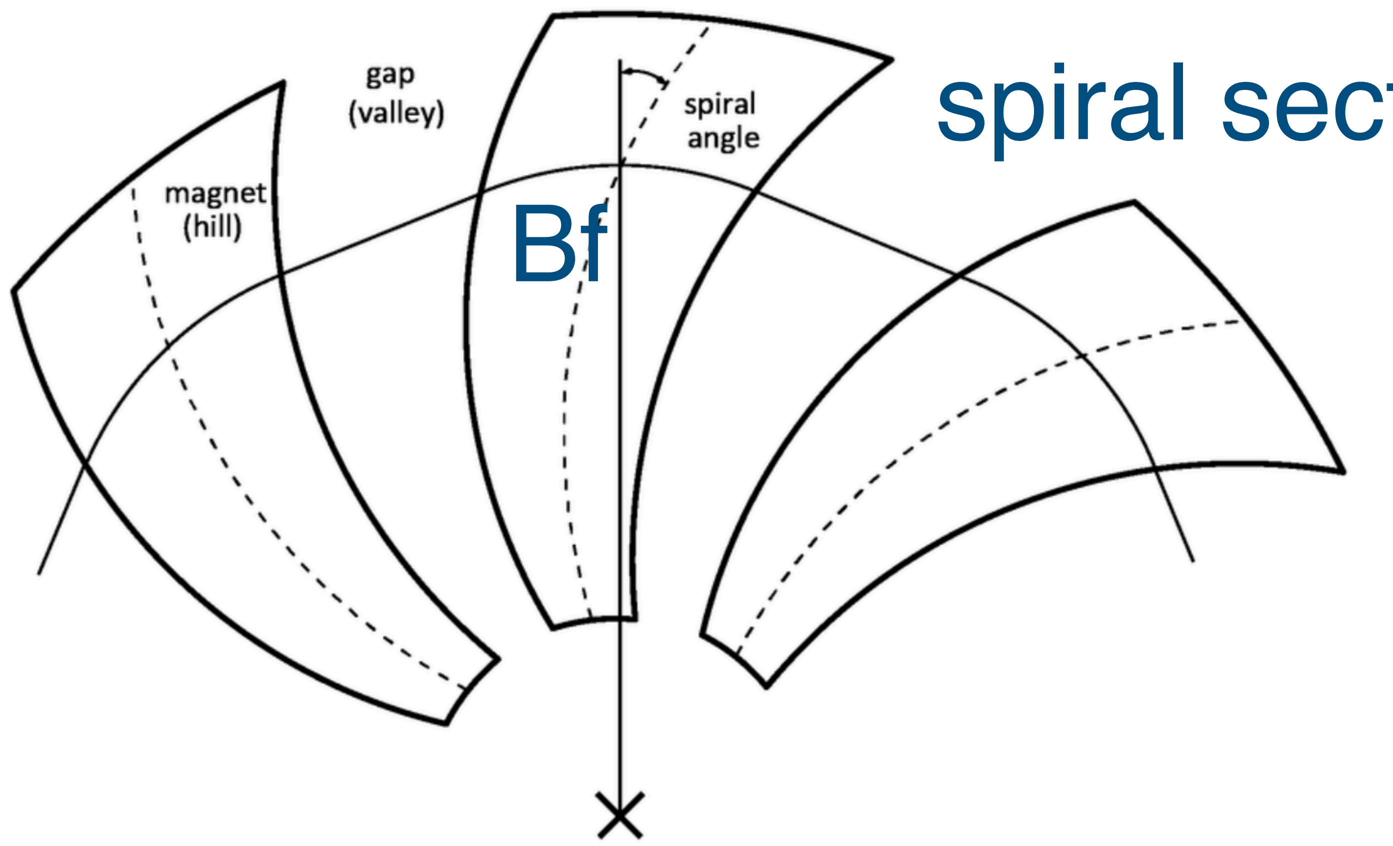
$$k = \frac{r}{B}\frac{\partial B}{\partial r}$$

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

radial sector







spiral 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)

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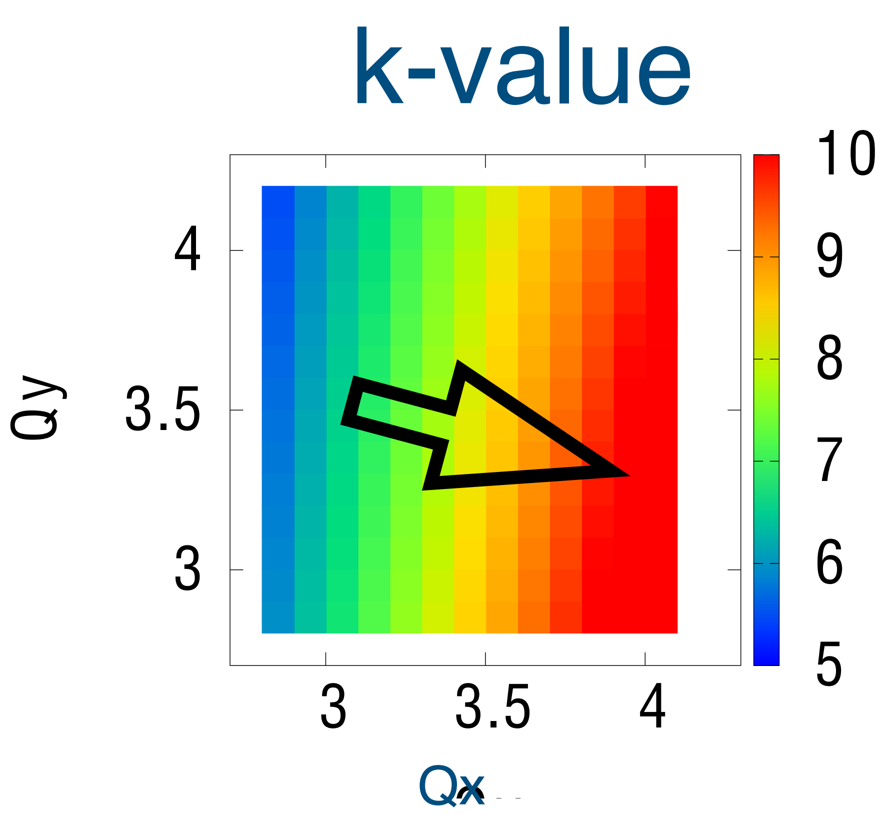
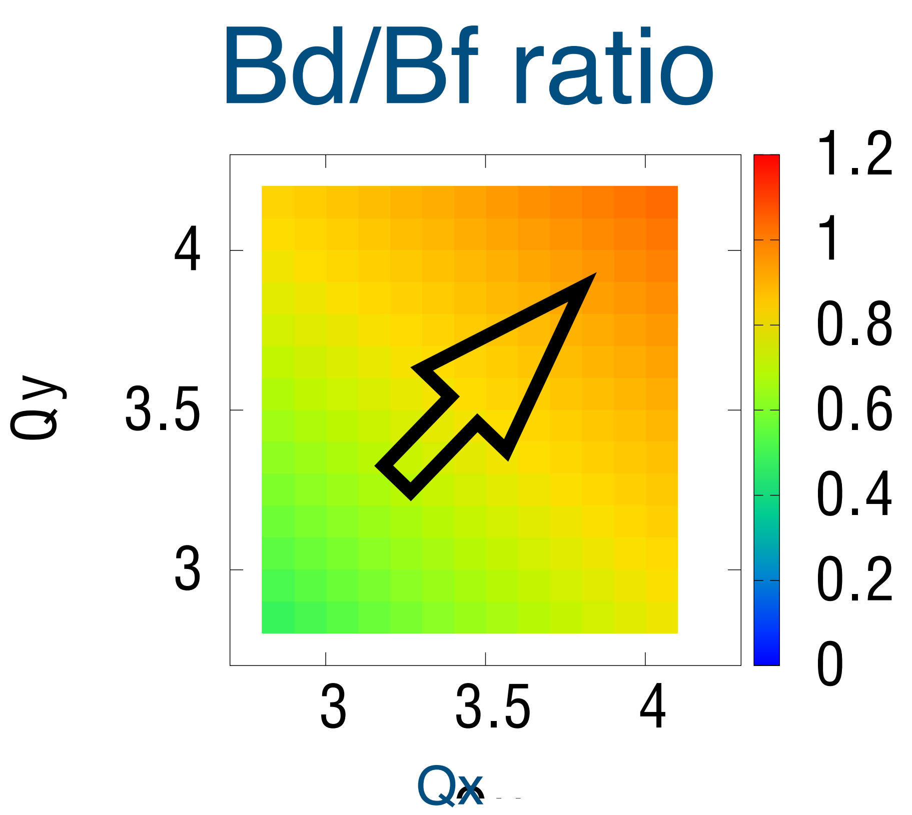
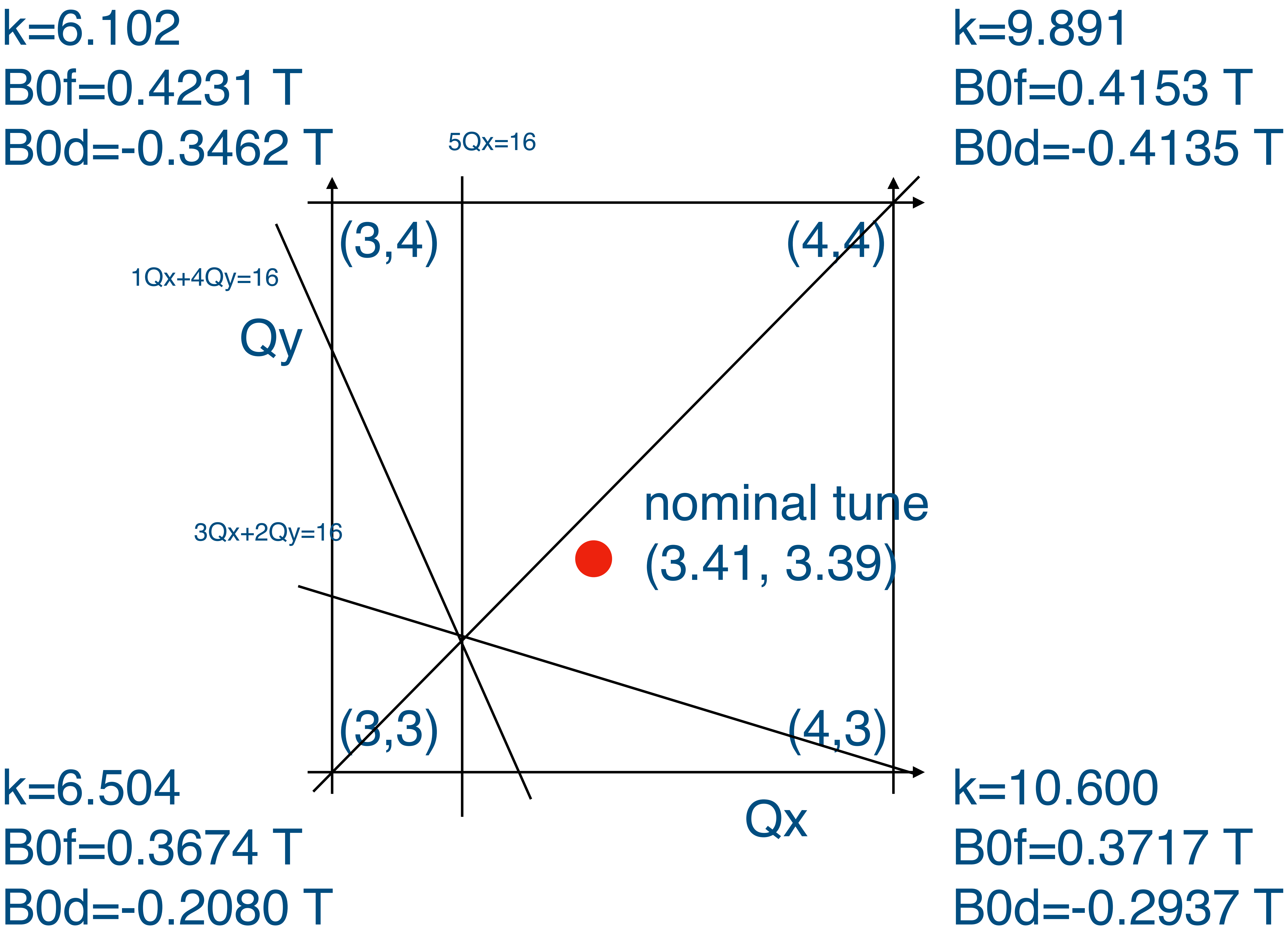
Adjusting Qx and Qy (e.g. 16 cell, spiral angle=45 deg.)





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



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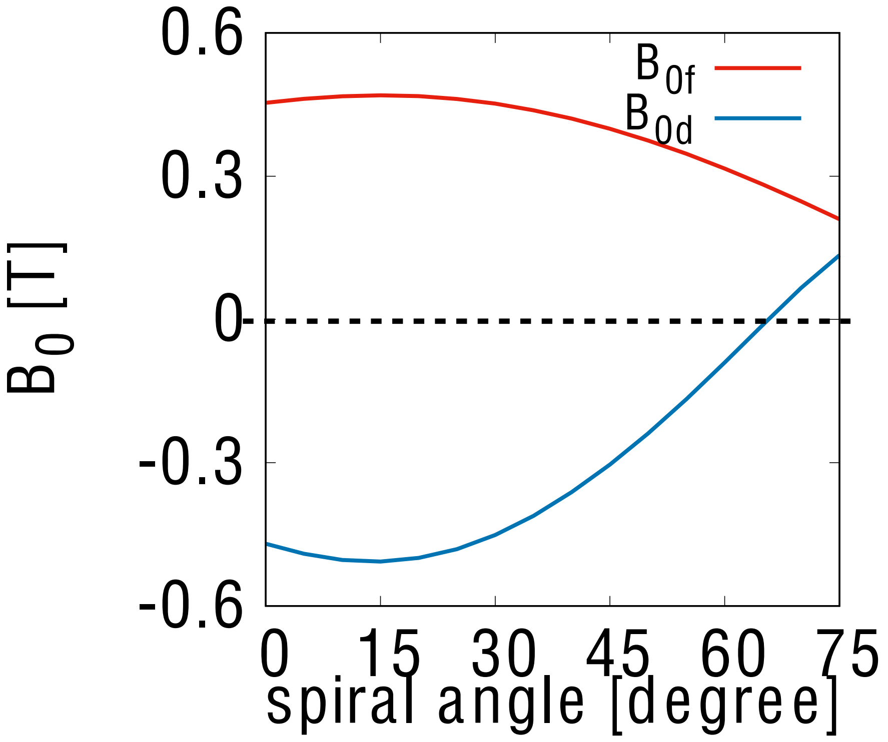
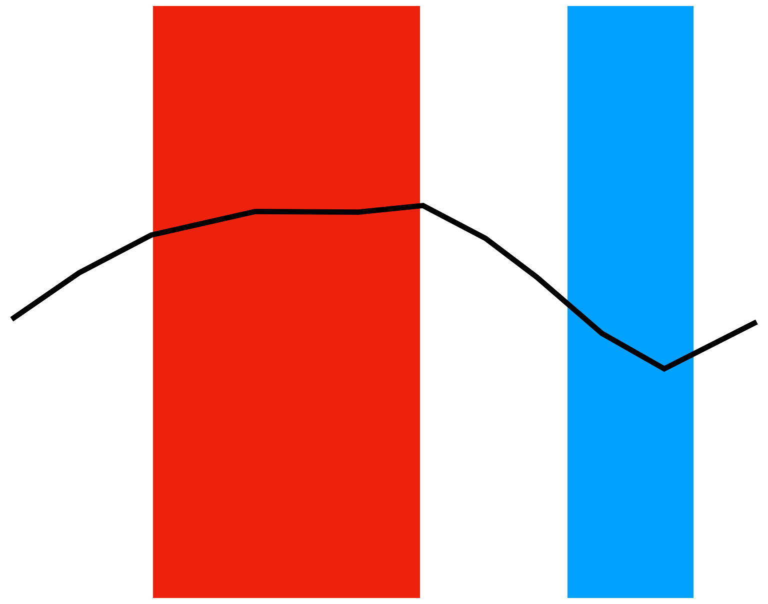
FD spiral FFA



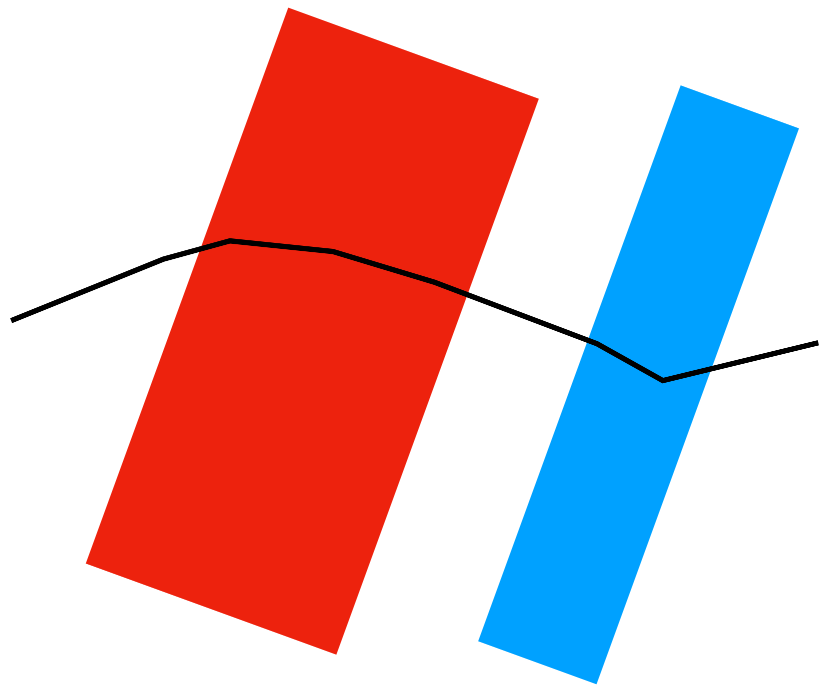
radial sector



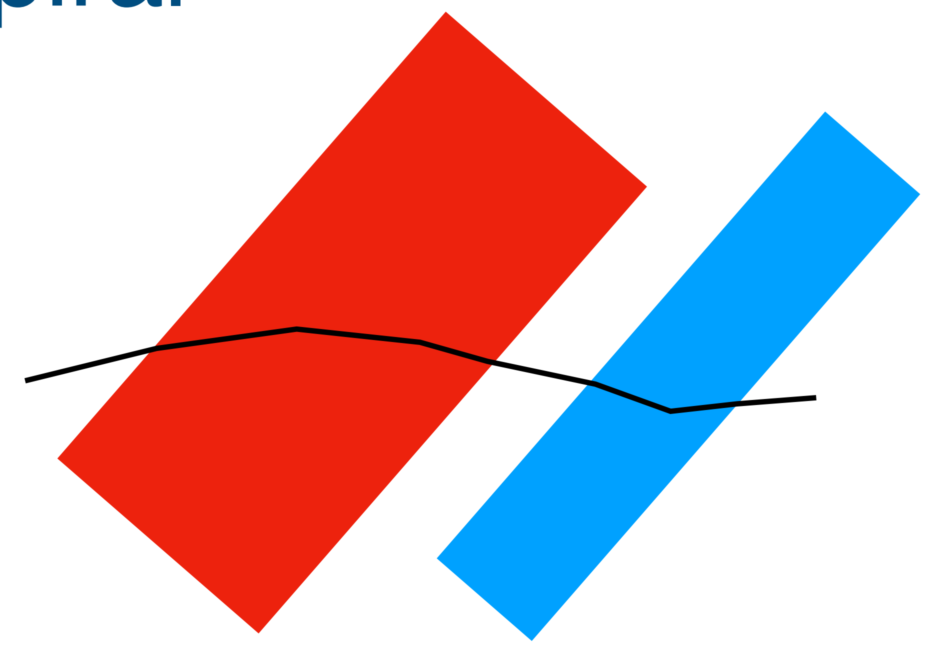
Bf (DFD) Bd (DDD)

(entrance, body, exit)

FD spiral

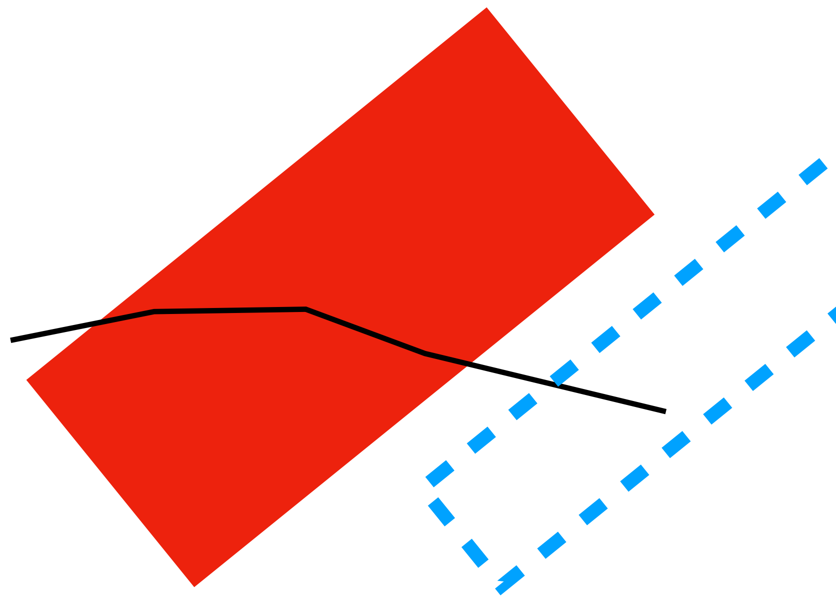


Bf (DFO) Bd (ODD)

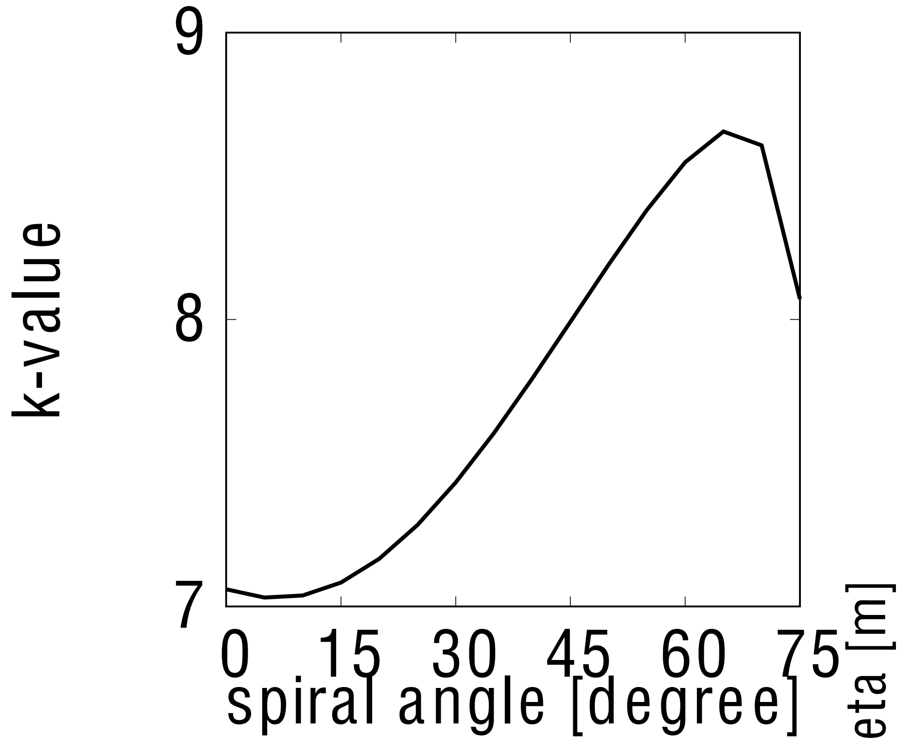


Bf (DFF) Bd (FDD)

spiral sector

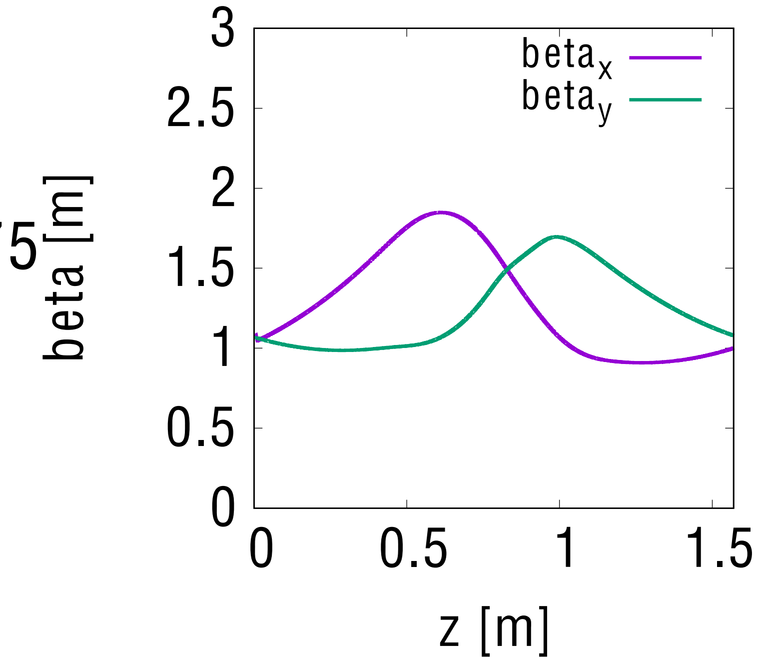


Bf (DFF)



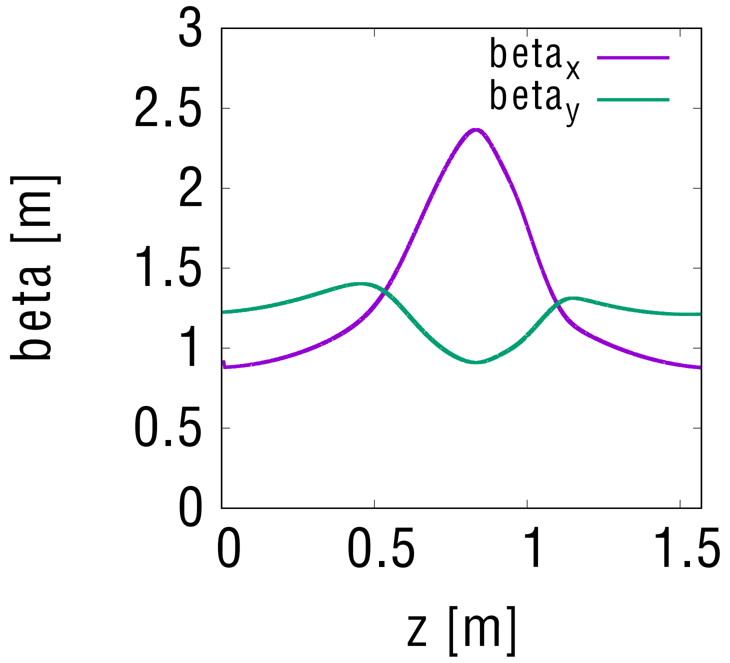
FD

Spiral angle=0 deg

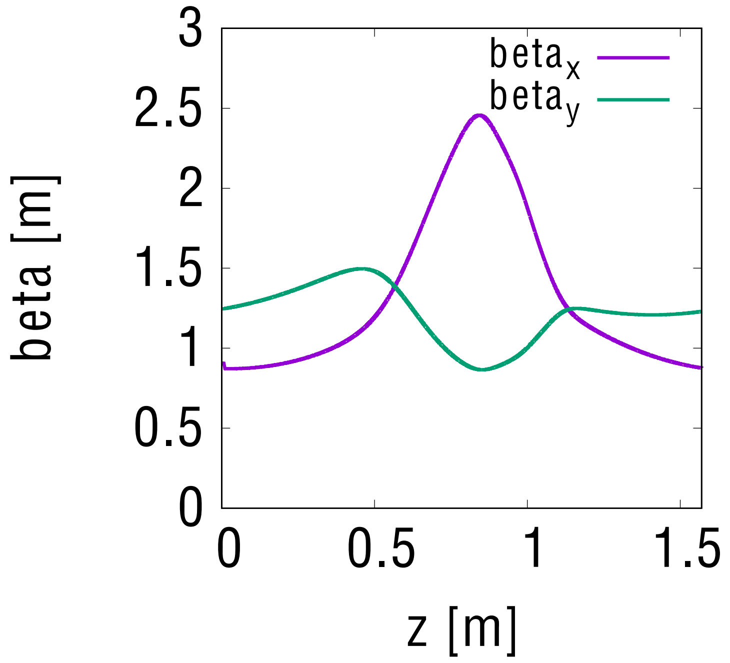


DFD

35 deg

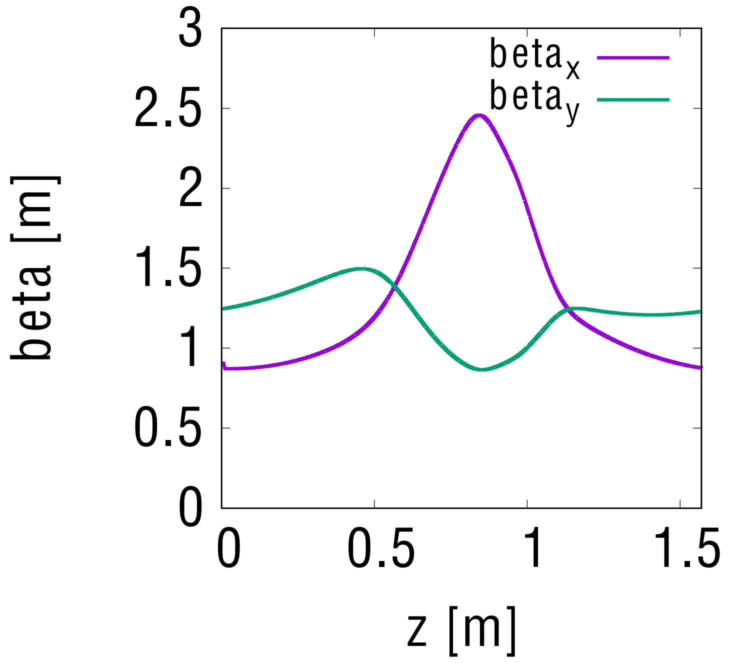


40 deg



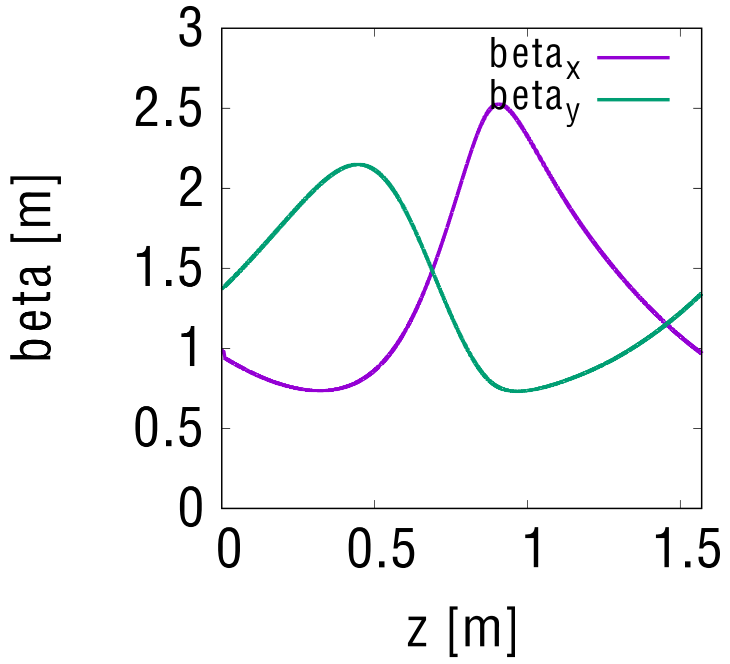
DFD

45 deg



DF

65 deg



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cell tune = (0.213125, 0.213125)

Lattice with superperiod (Long straight section)

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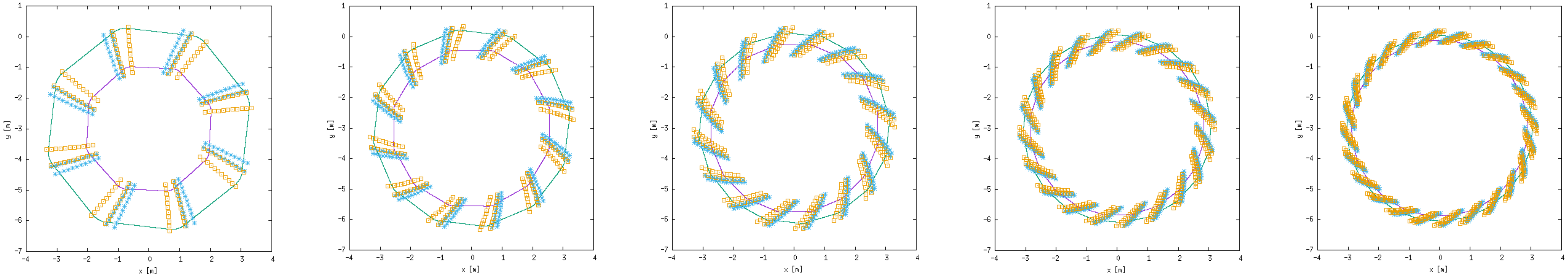
Straight section

- 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.

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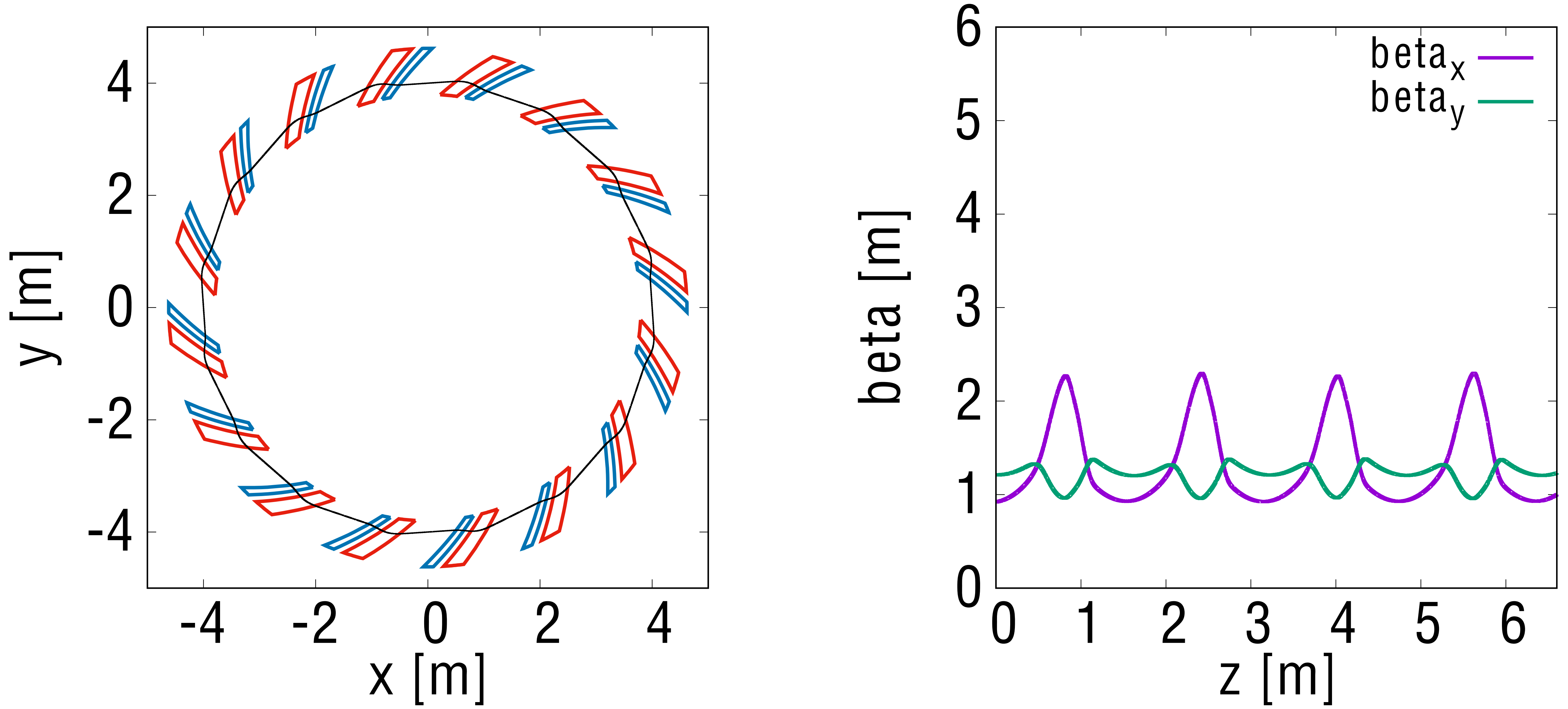
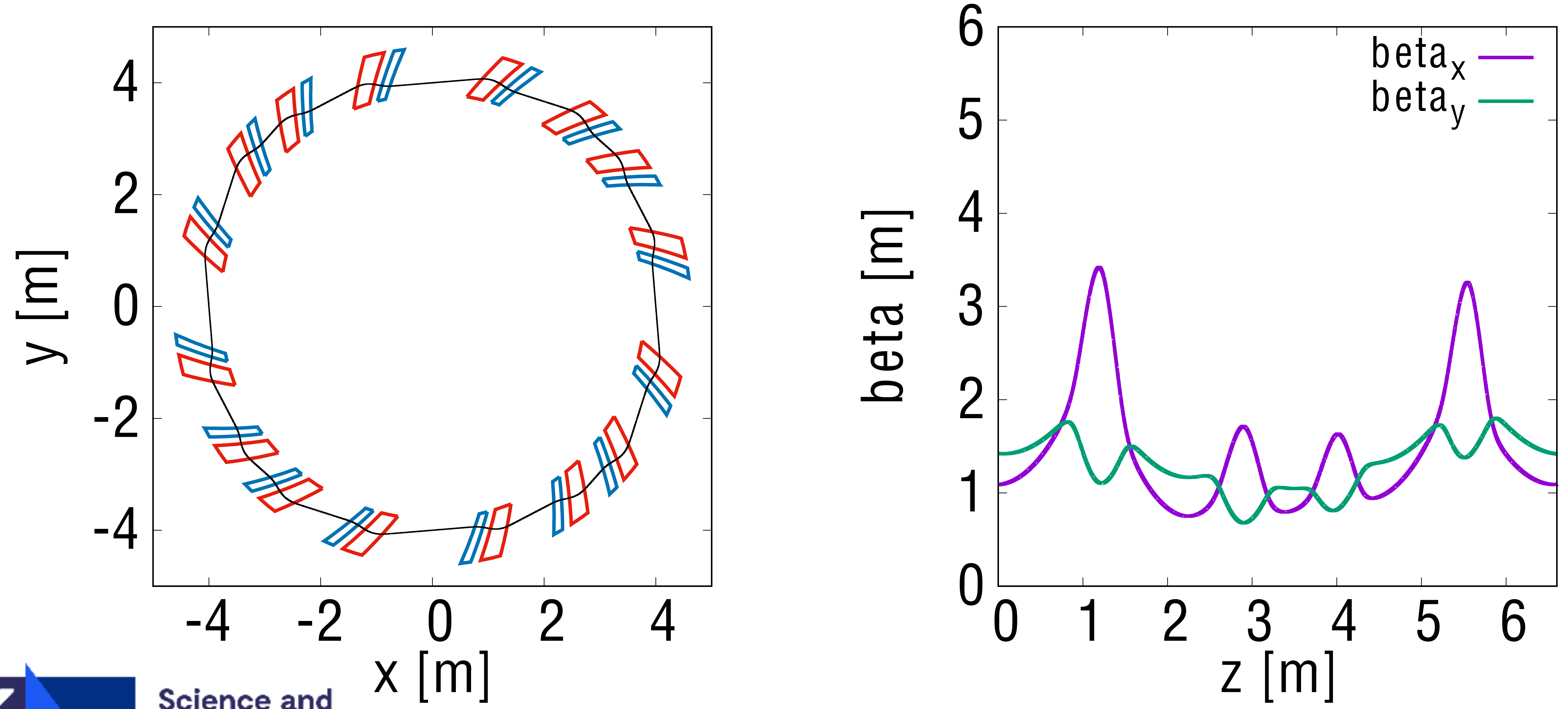
Lattice with superperiodicity



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 4.0	2 k 4.0
3	5 k	1.67 k **3.33**		5.33 k	2.67 k	1.33 k 4.0
4	3.75 k 3.75	1.25 k 3.75		4 k 4.0	2 k 4.0	1 k 4.0
5	3 k 3.0	1 k 3.0		3.2 k 3.2	1.6 k 3.2	0.8 k 3.2, 4.0

red: resonances in the operational tune range.

Dynamic aperture

Aperture requirement

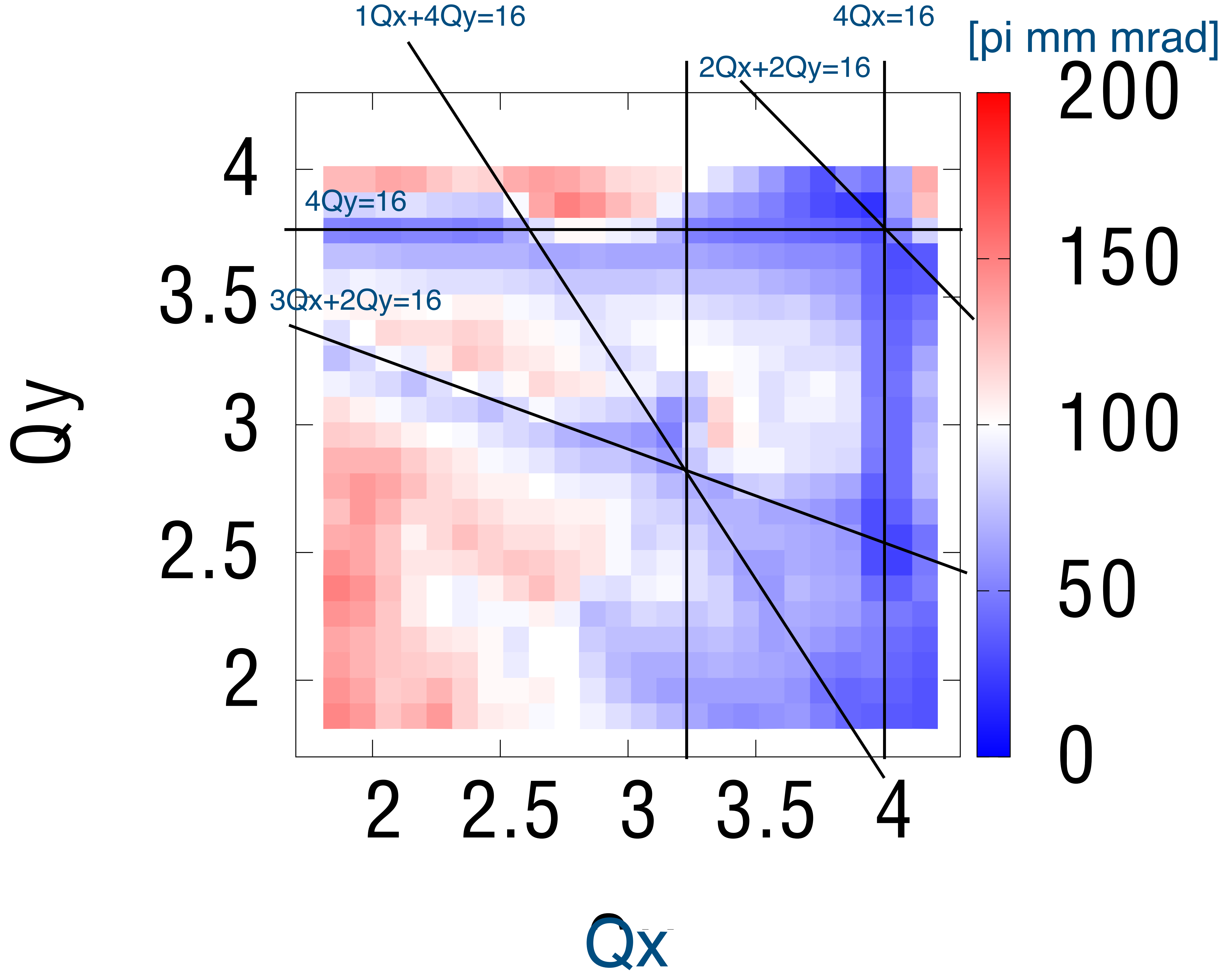
For high intensity operation of FFA, we need large physical aperture and **dynamic aperture larger than physical aperture** to reduce **space charge effects**.

- 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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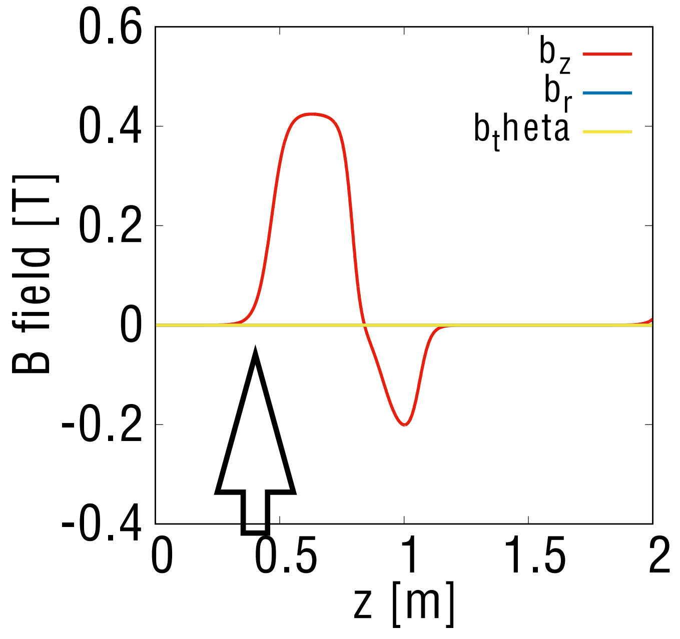
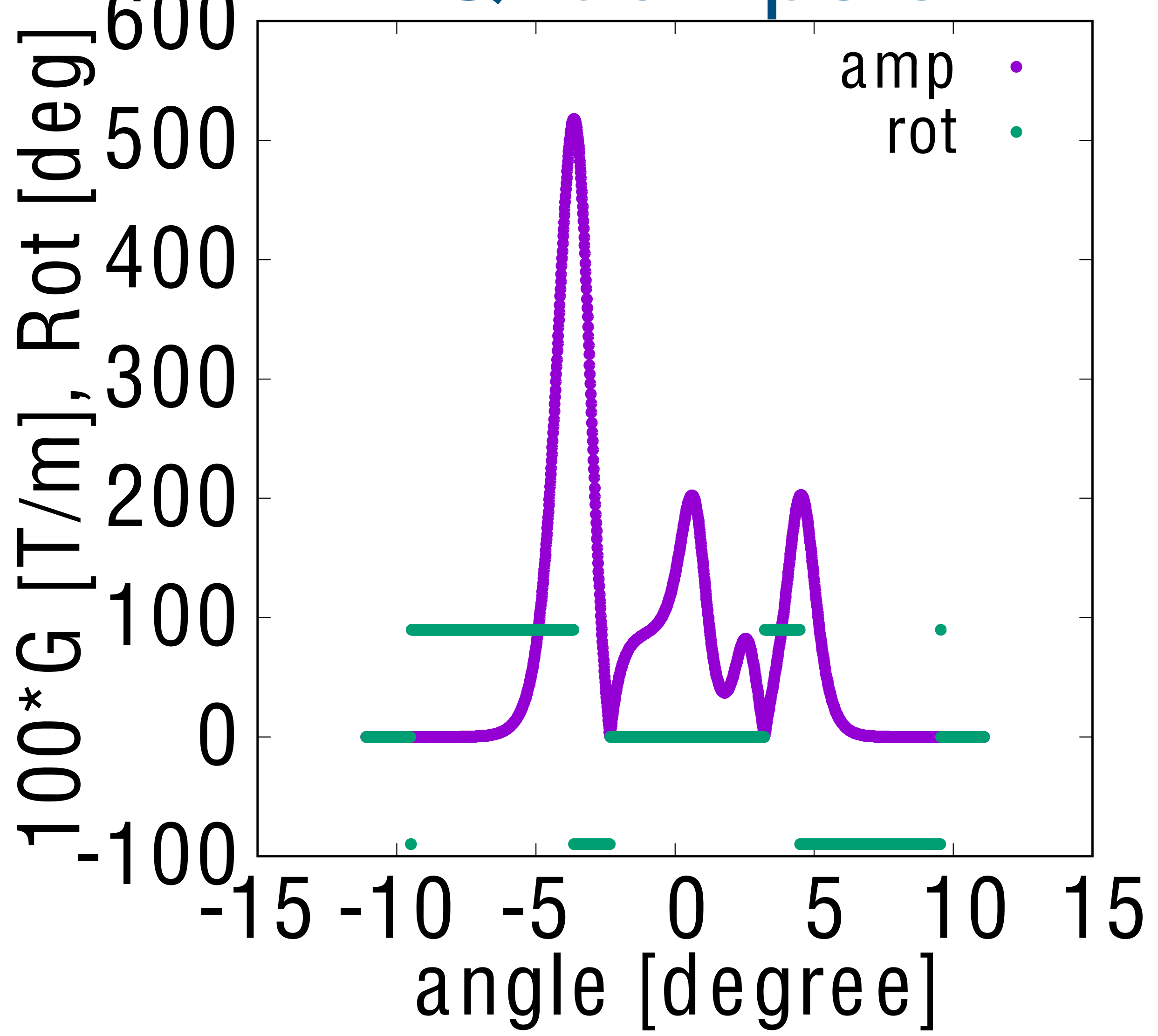
Control of fringe field extent (to be corrected)

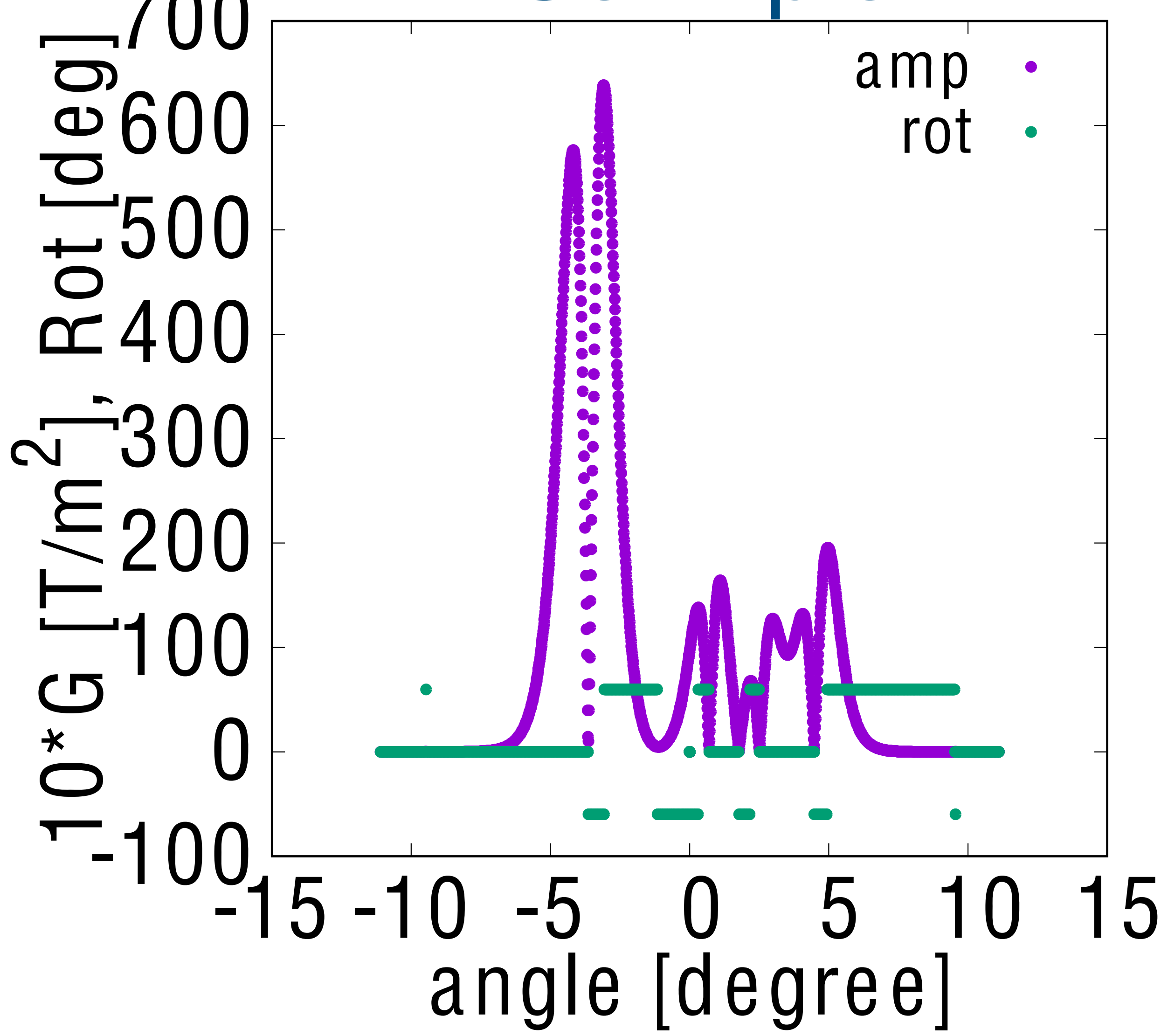
Quadrupole | Sextuple | Octupole

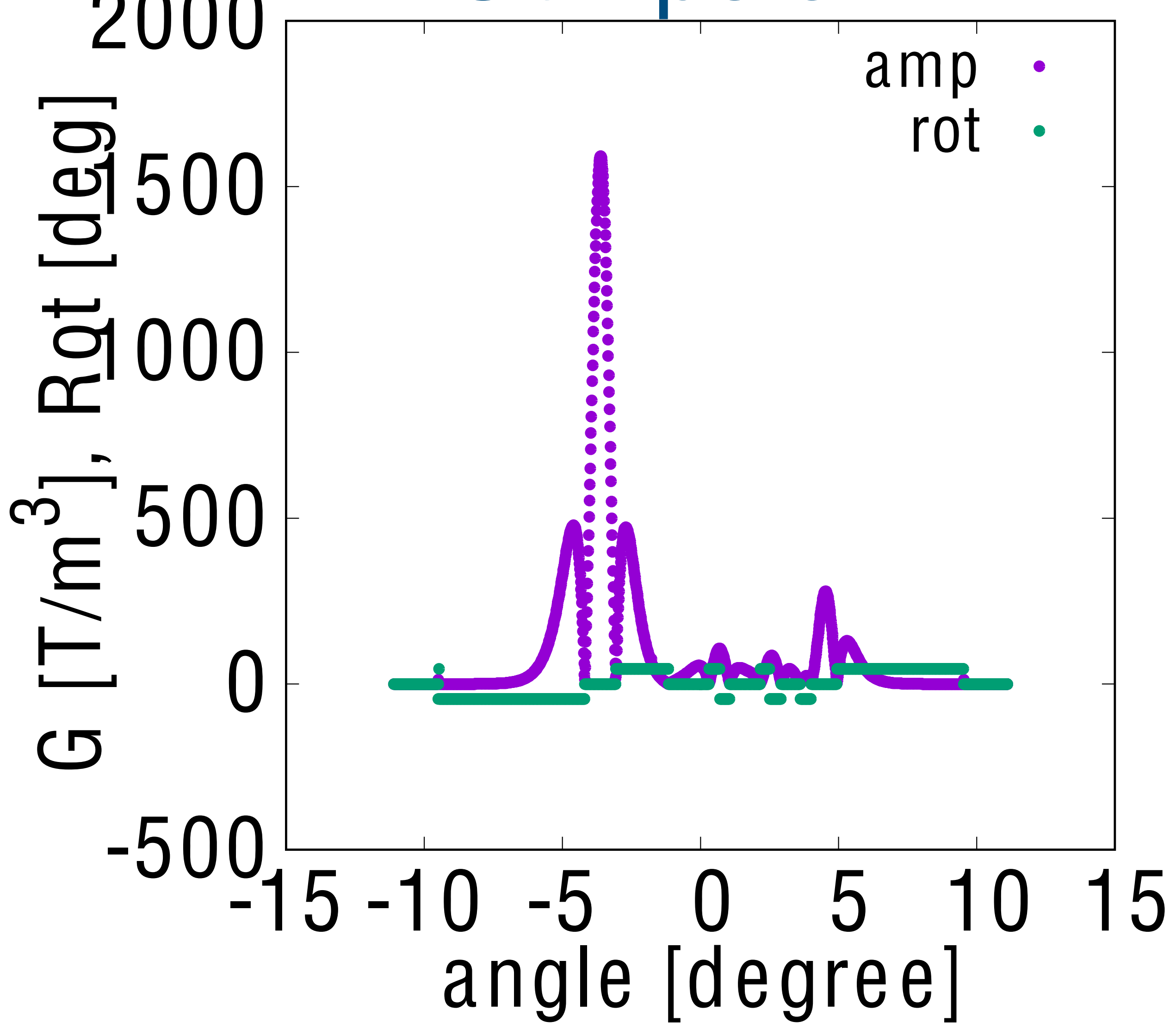
Bf entrance

FFE x 1



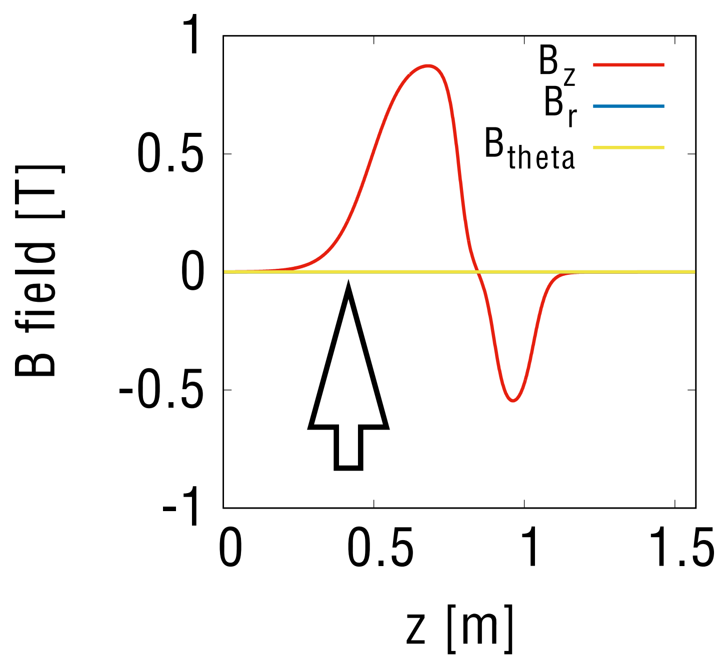


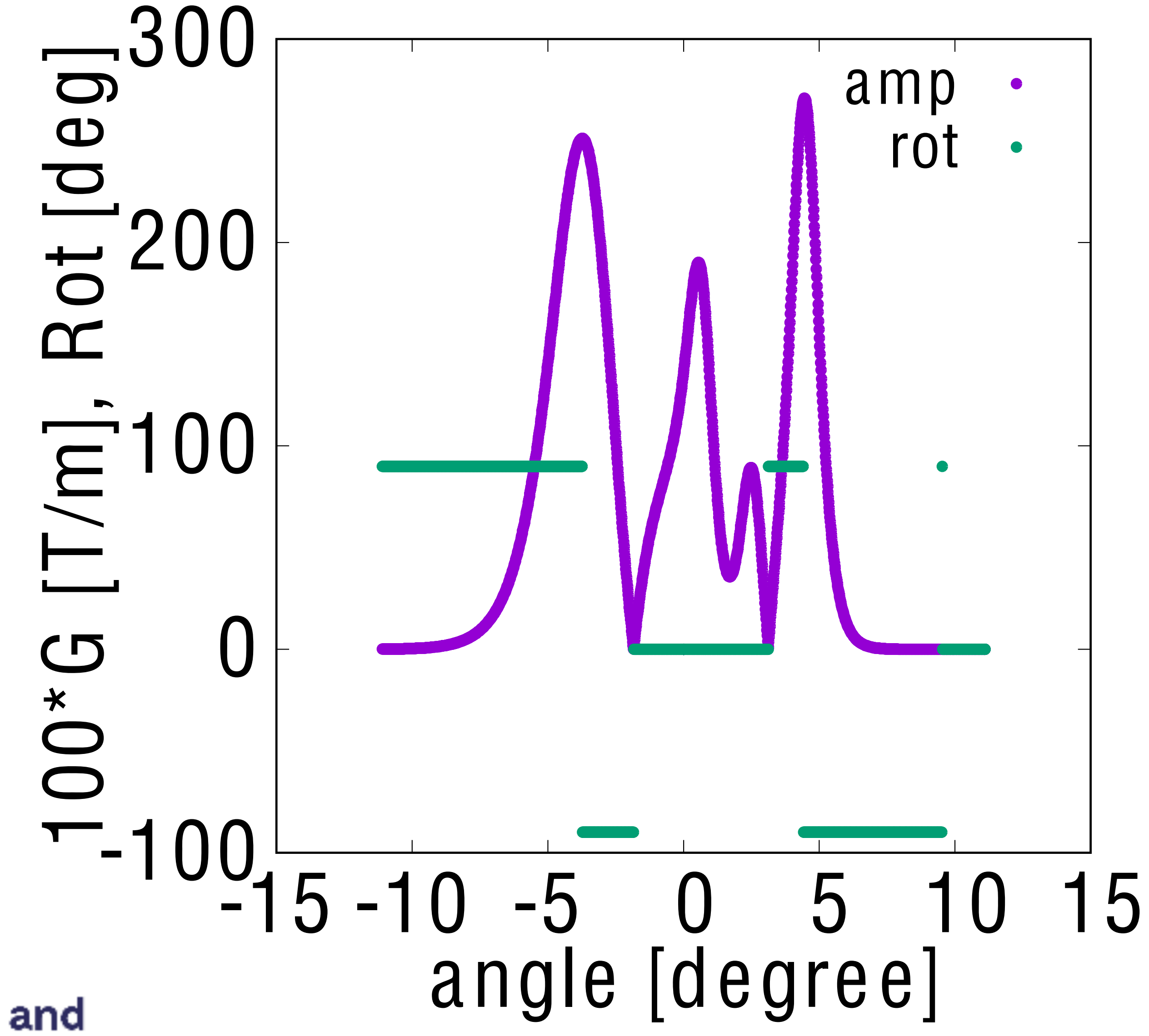


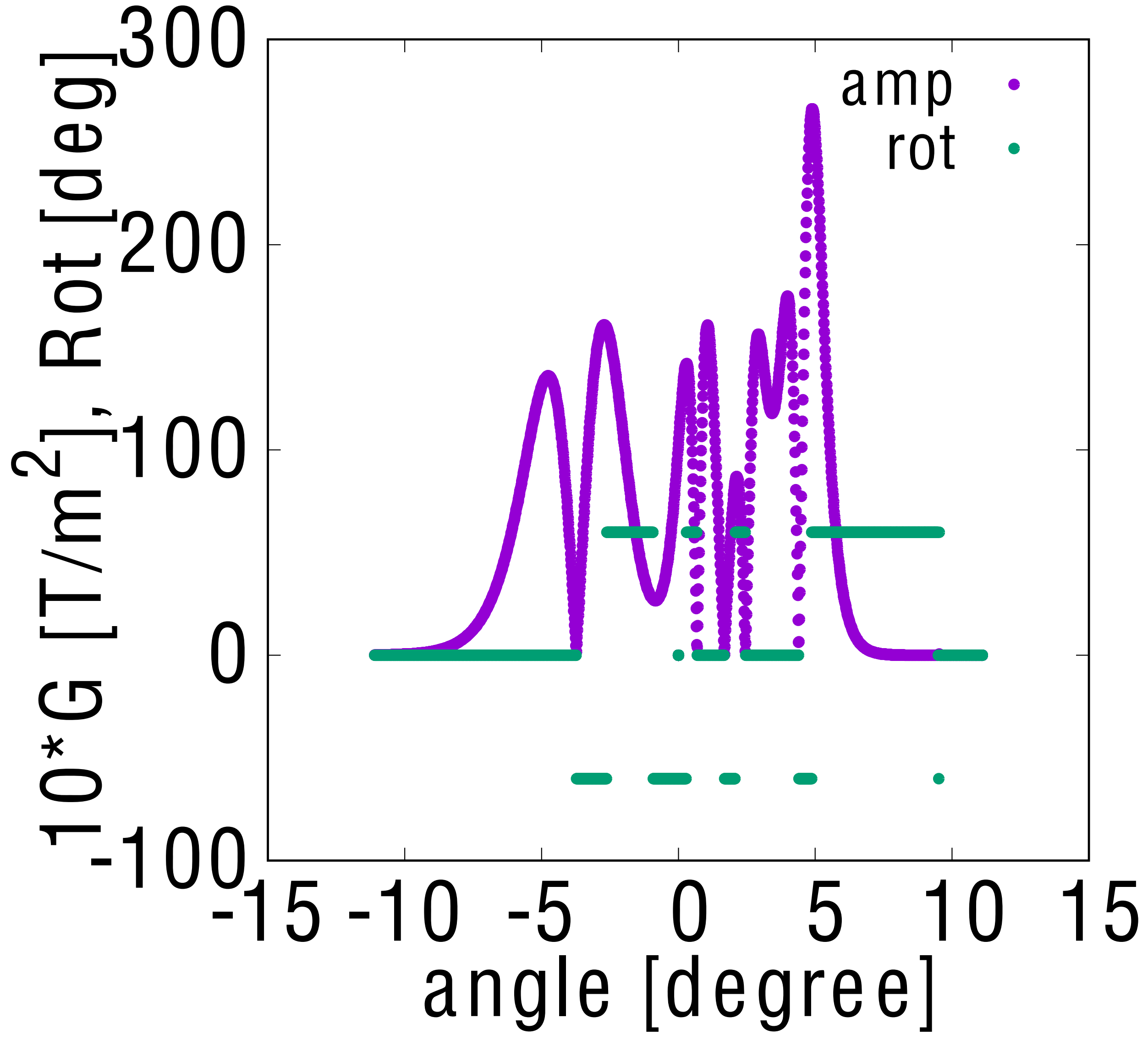


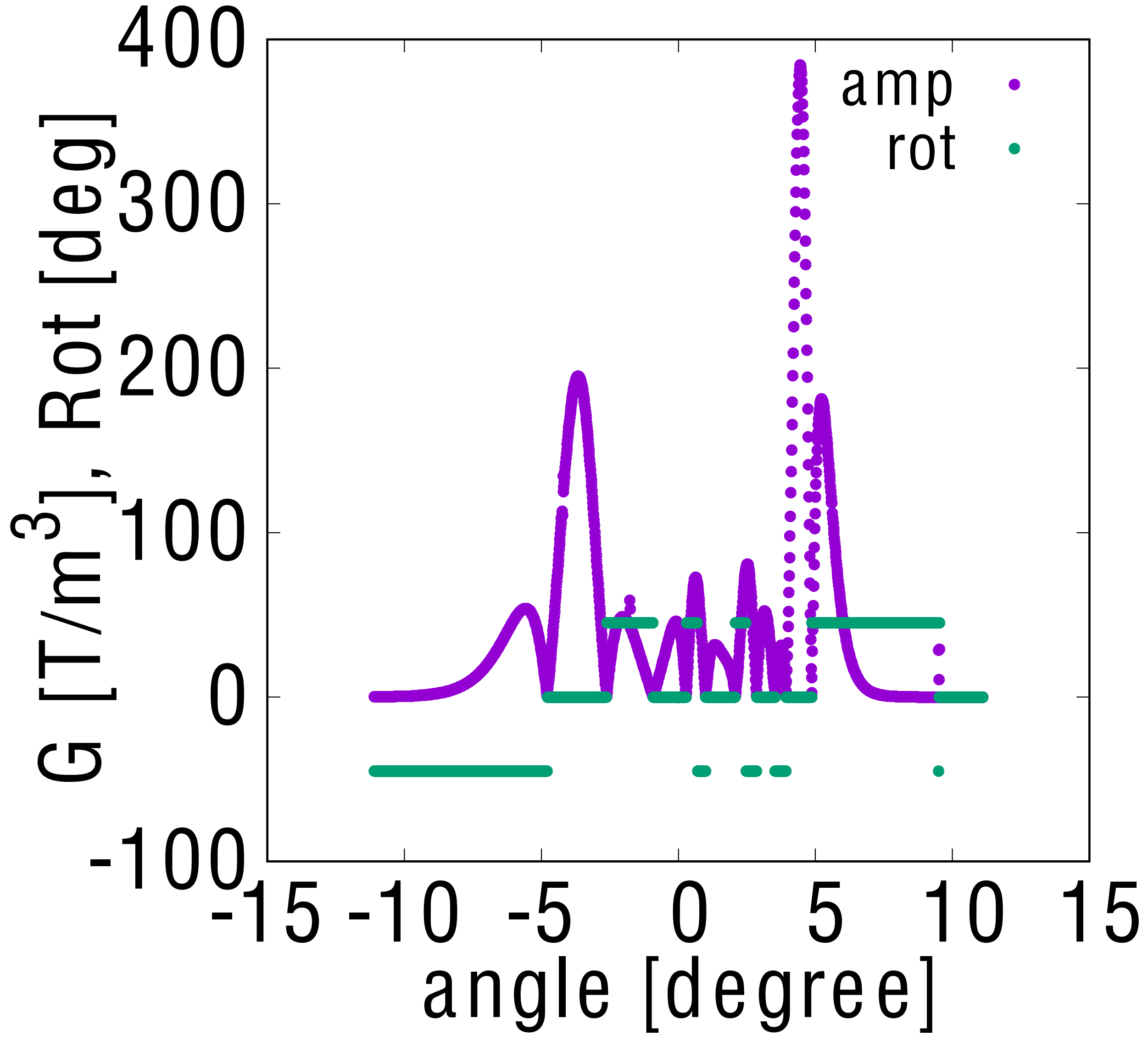
Bf entrance

FFE x 2









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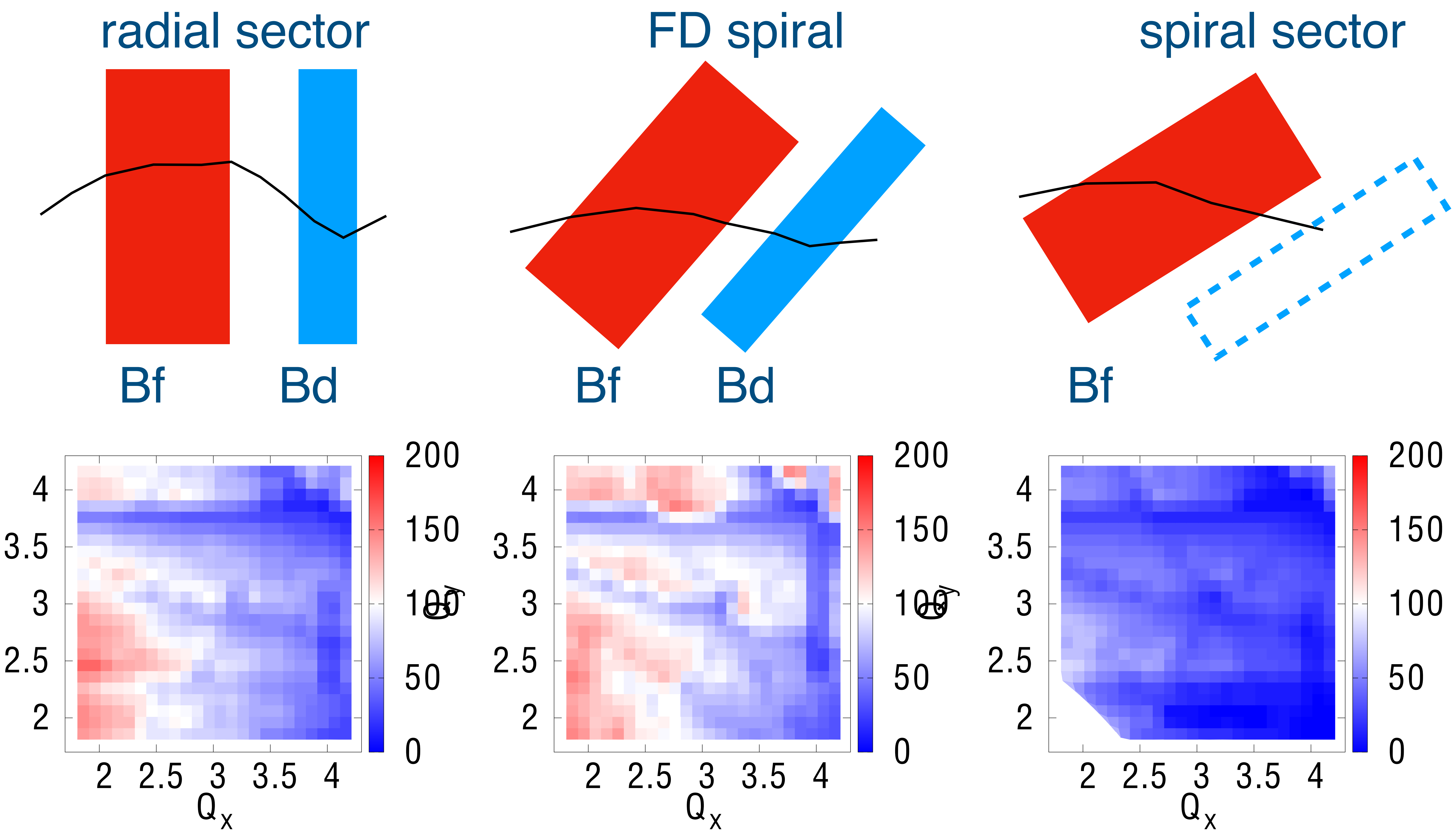
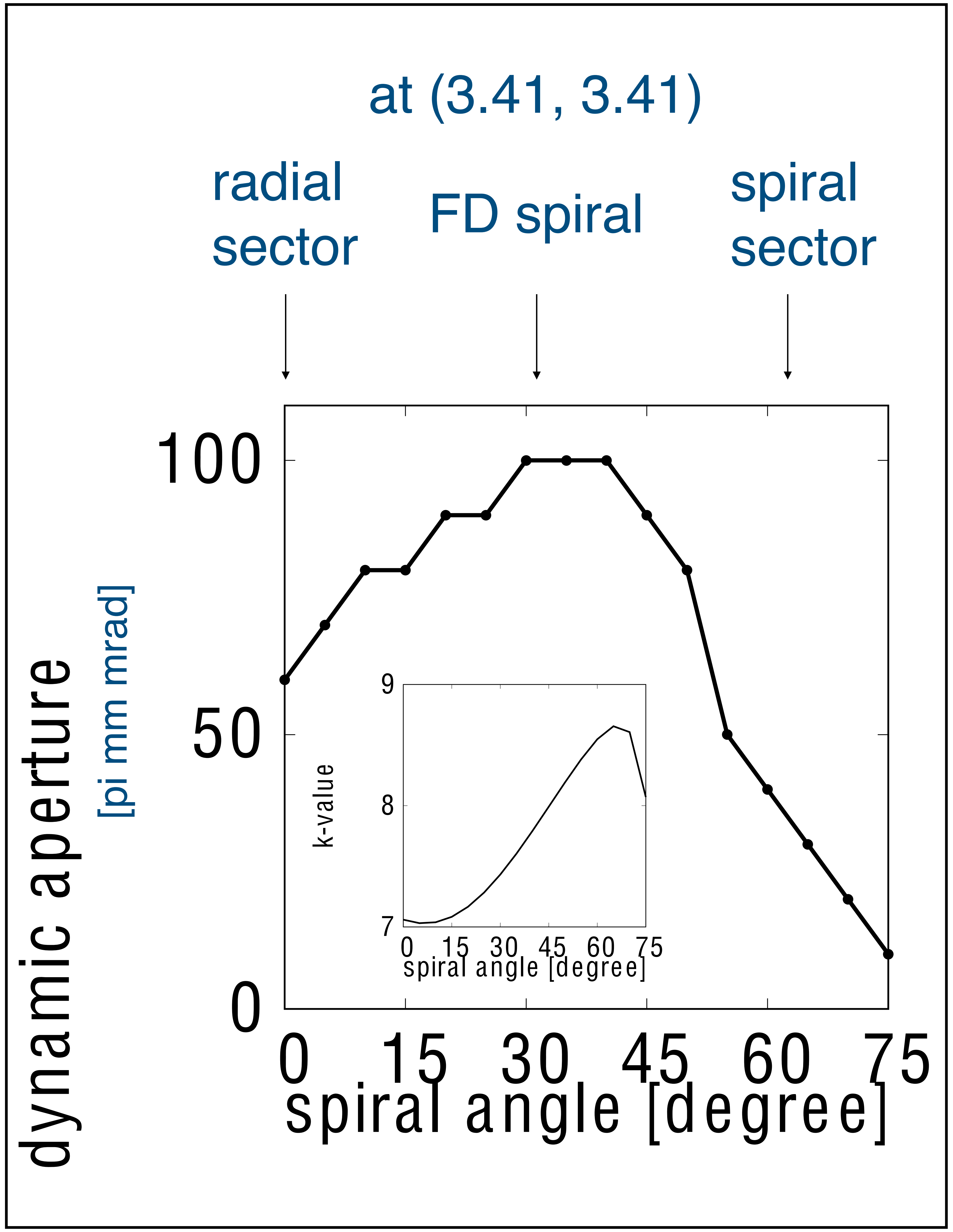
Twice longer FFE makes DA more than double (~ x 2.5).

Dynamic aperture vs spiral angle





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Beam stacking

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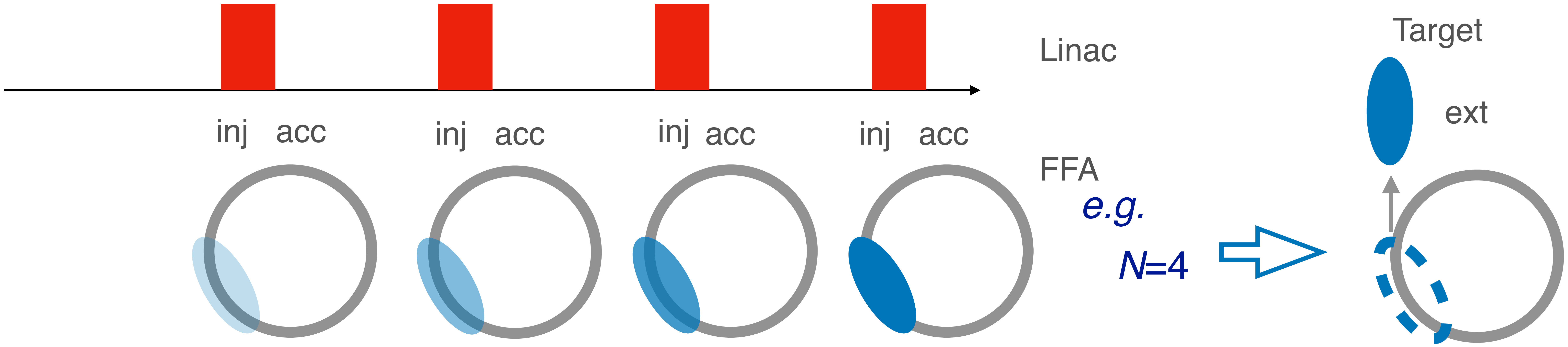
Repetition rate

- 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.



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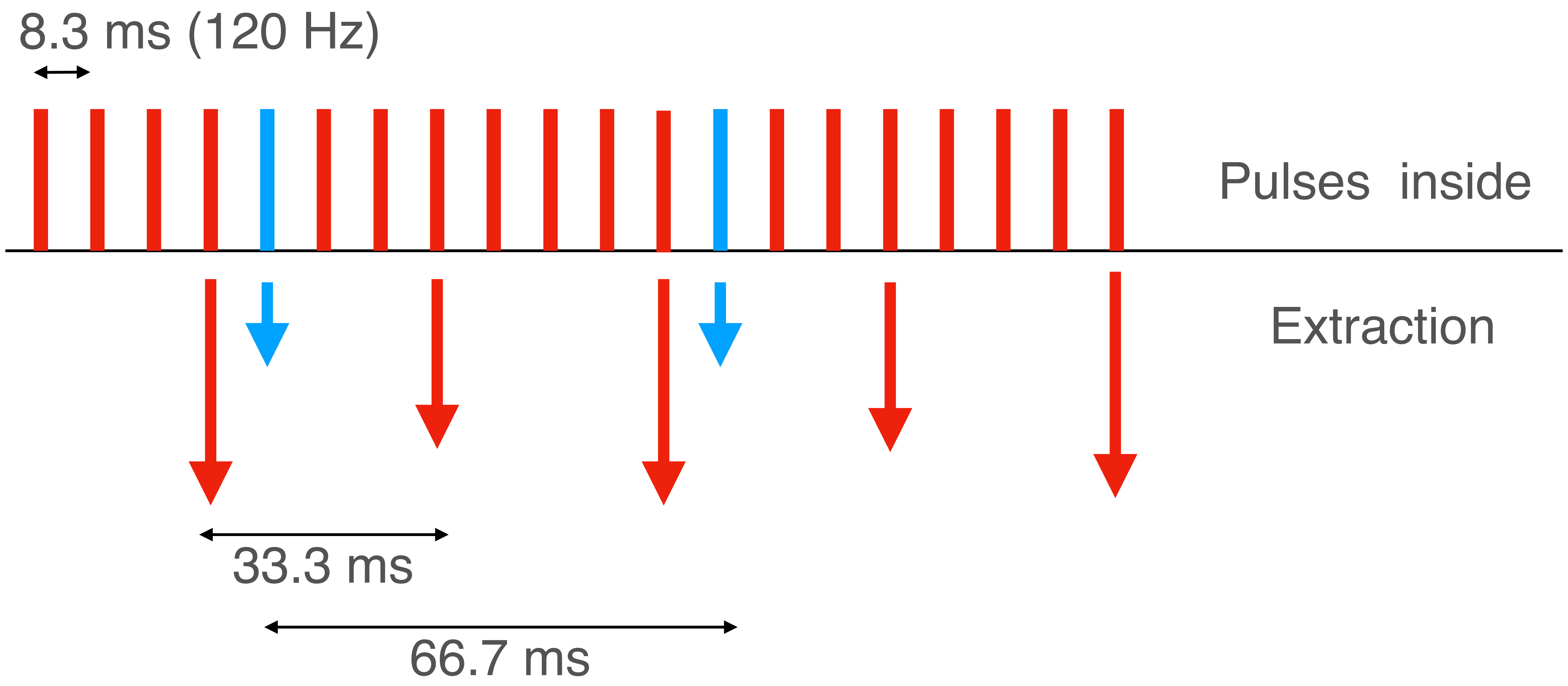
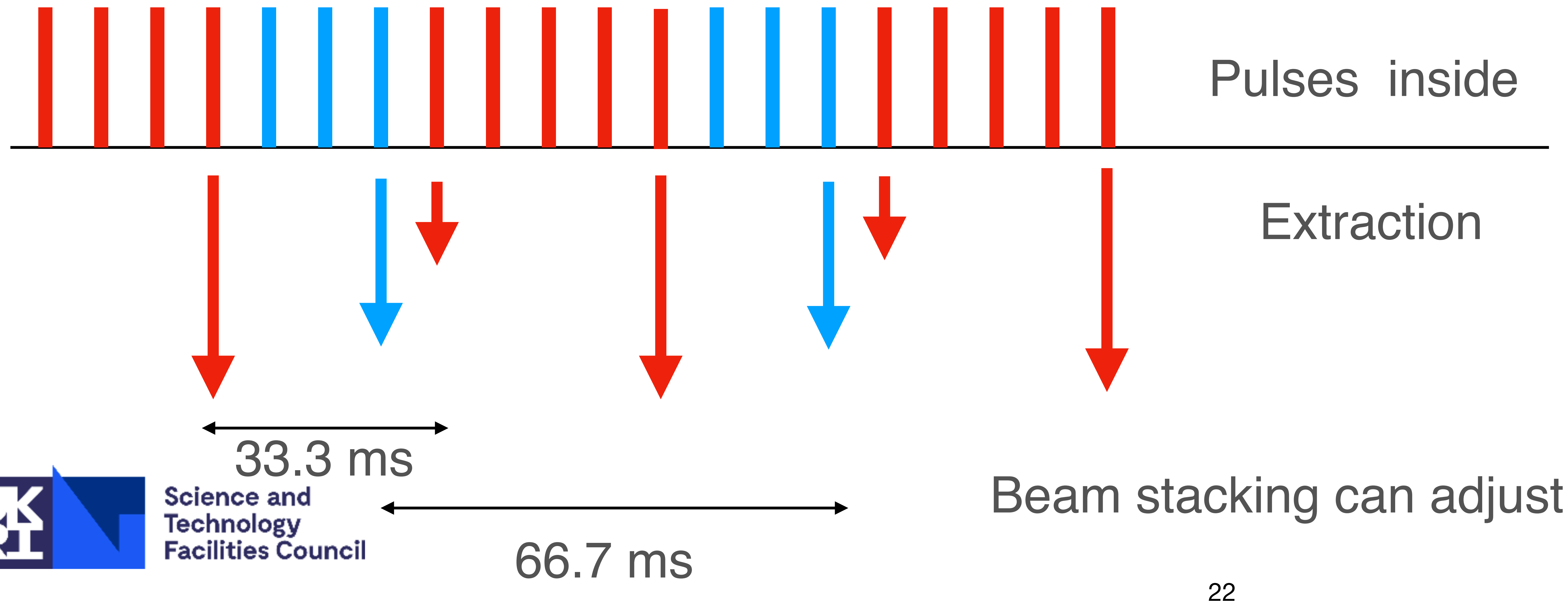
30/15 Hz by beam stacking



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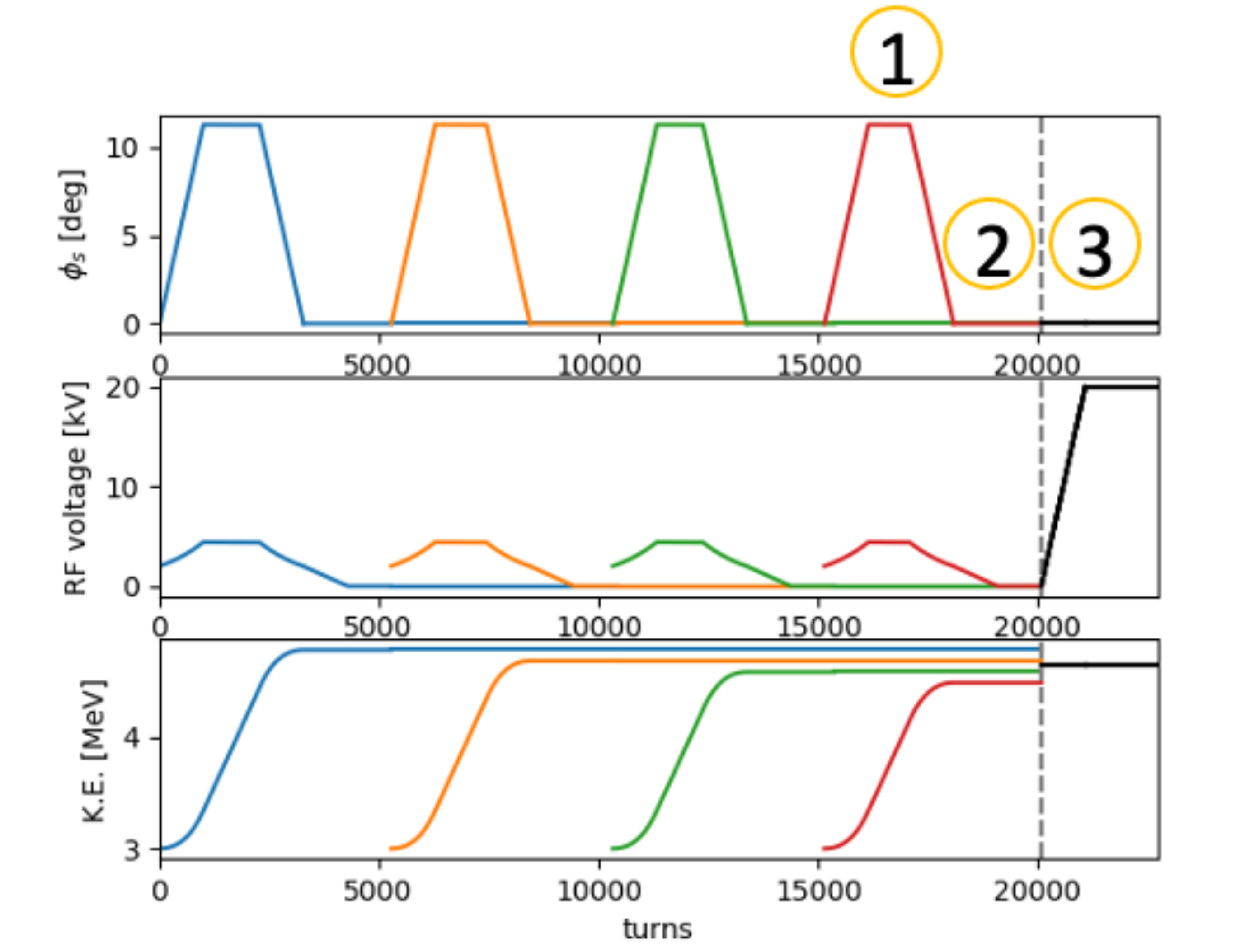
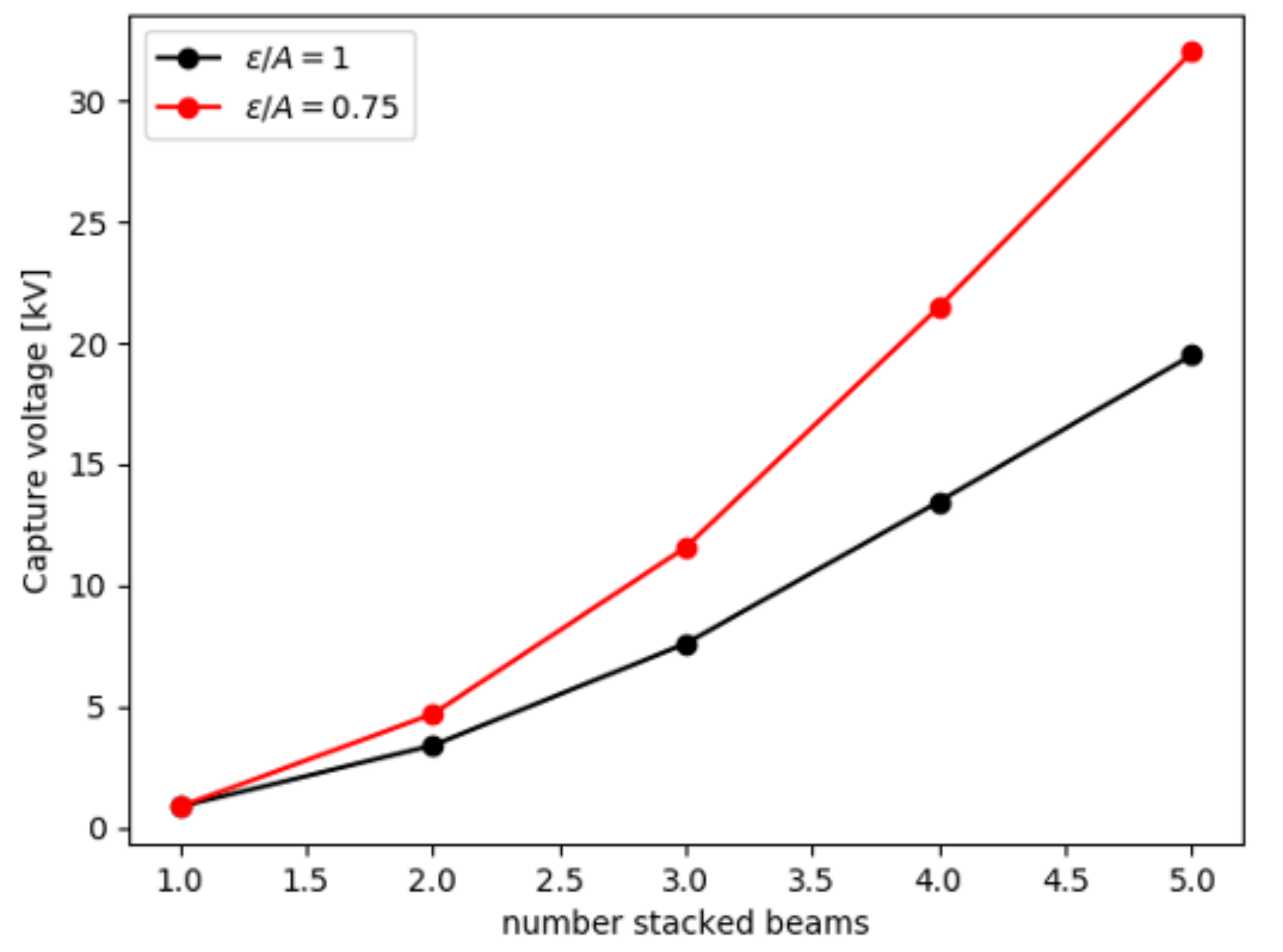
Beam stacking can adjust beam power for TS-1 and TS-2.

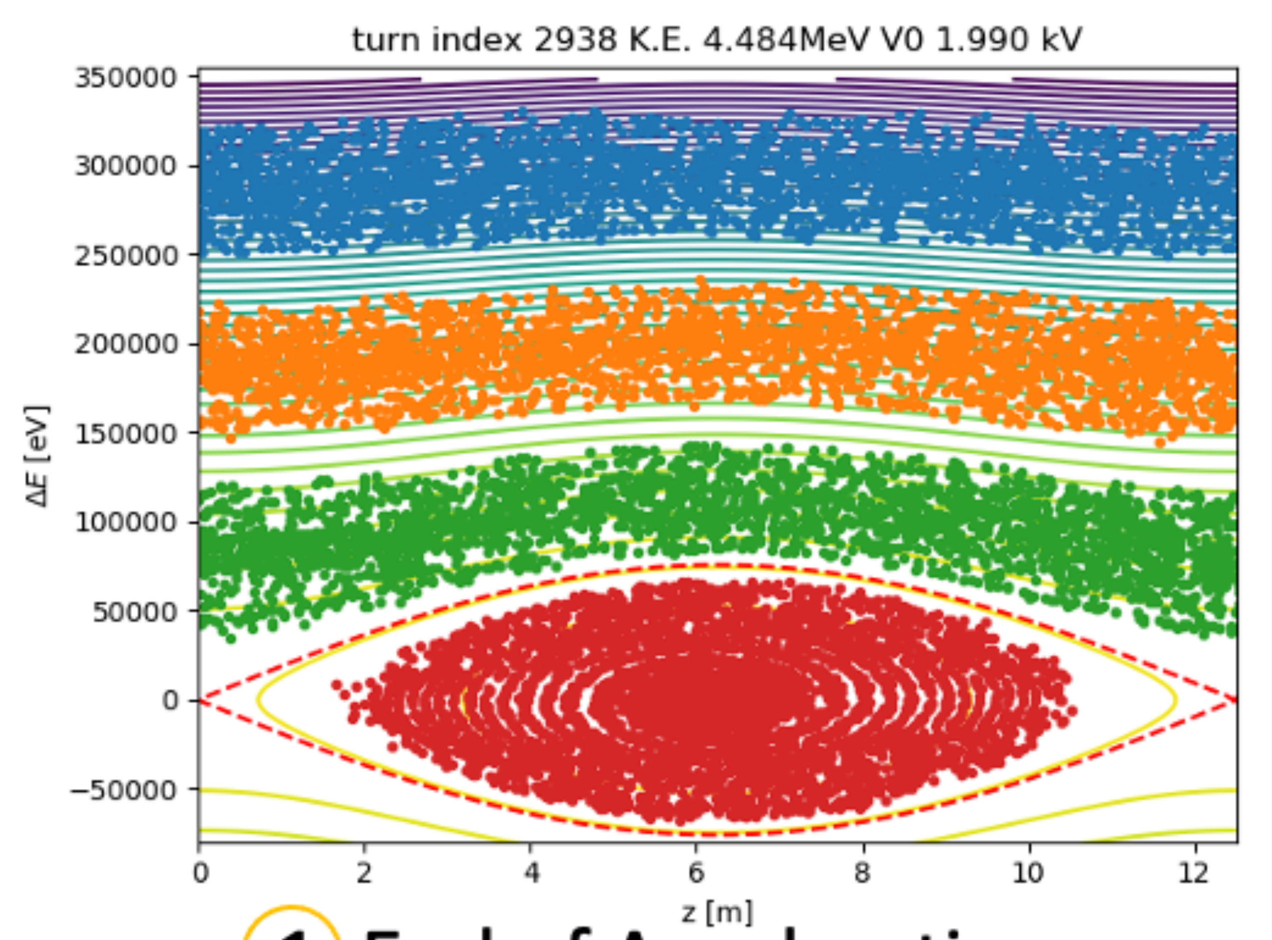
Required voltage and longitudinal phase space

RF cavity for stacking

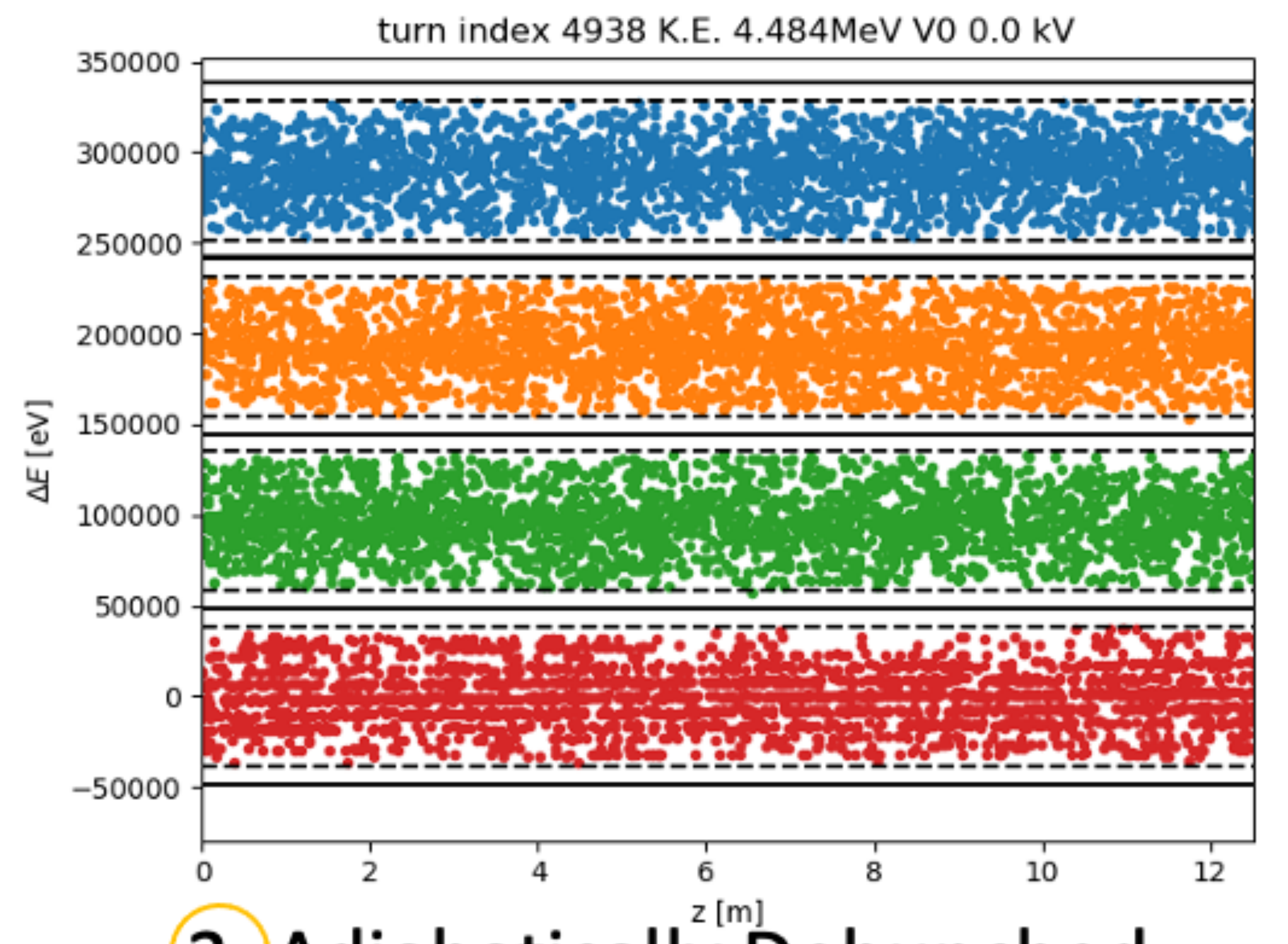
Parameter	Value
RF frequency (h=1, fixed)	~1 MHz
RF peak voltage	35 kV (stack 5 beams)



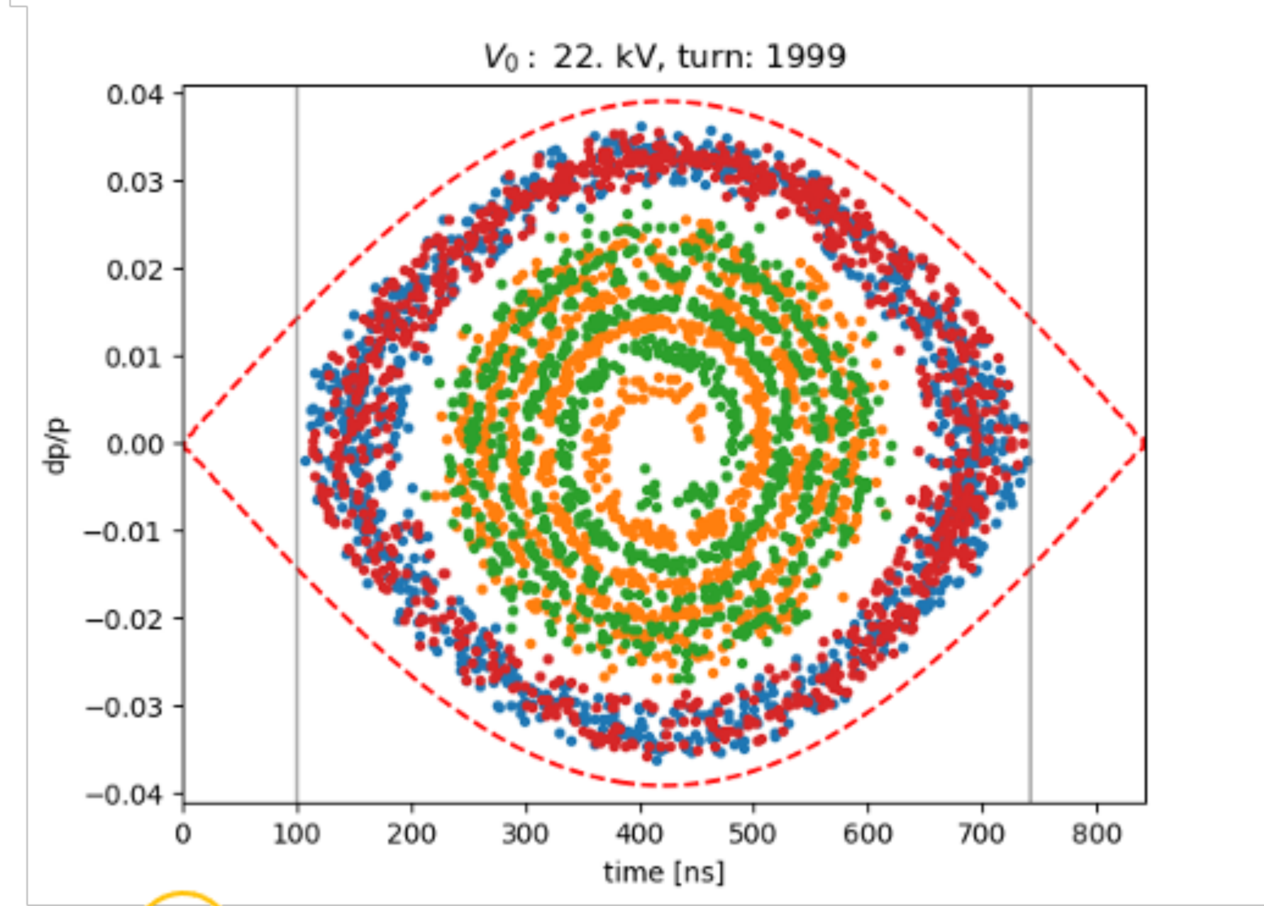




1. End of Acceleration



2. Adiabatically Debunched



3. Adiabatically Captured (200ns beam free)

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Hardware developments

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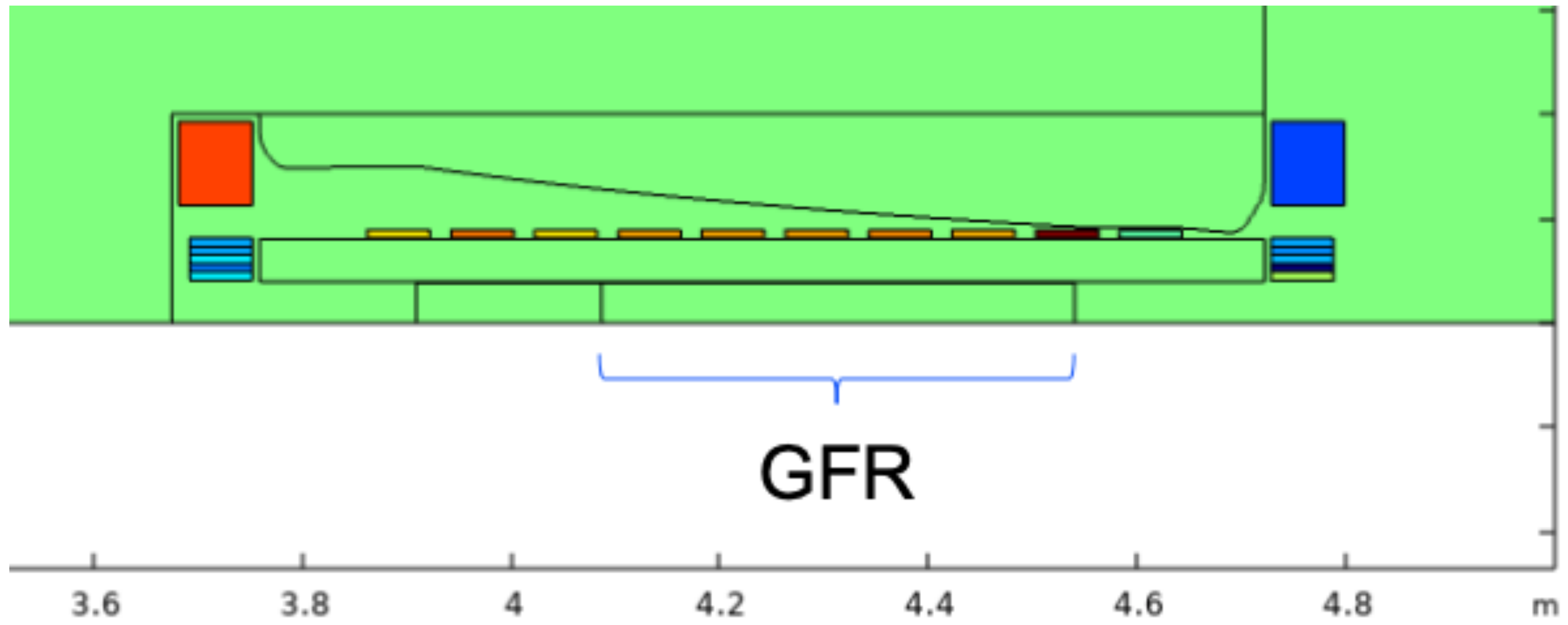
Magnet prototype

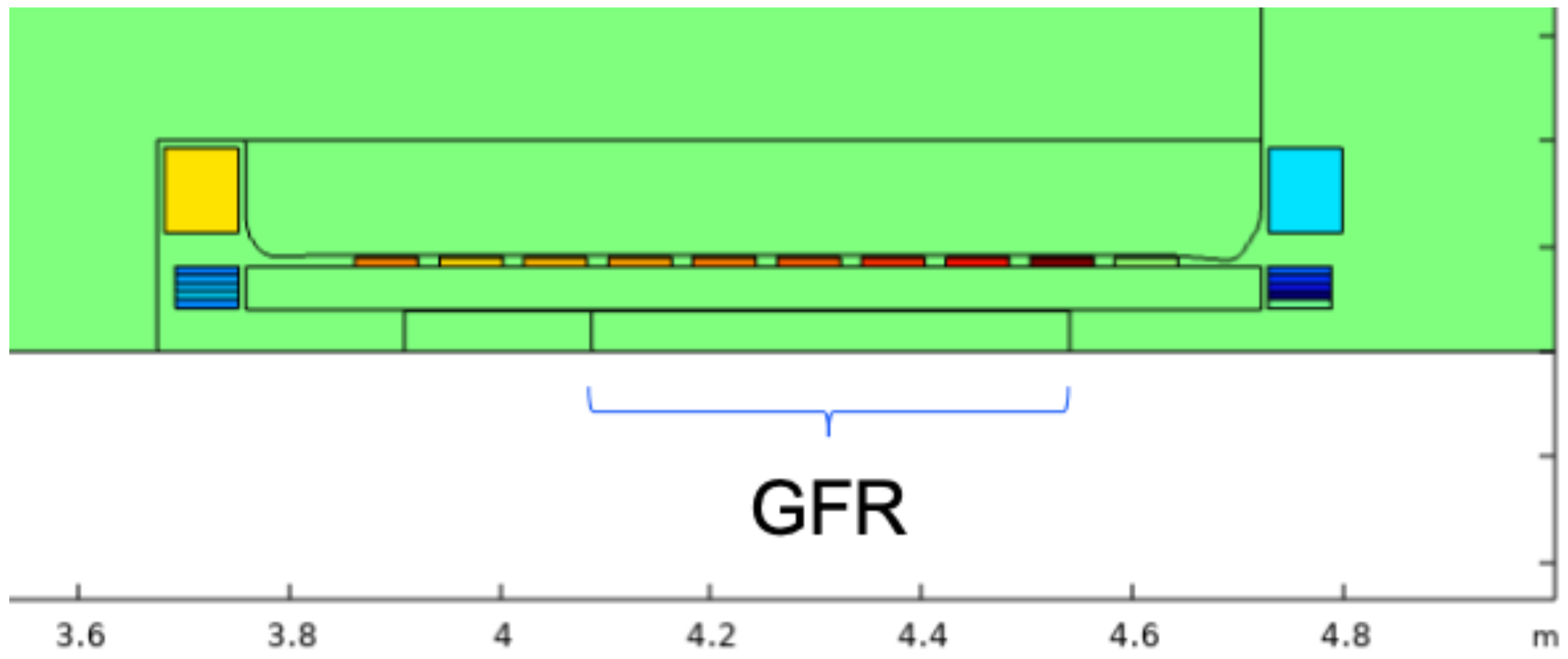
- C-shape magnet because of space constraint.
- Field index k variable from 6 to 11.

Several options were investigated to create field gradient.

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

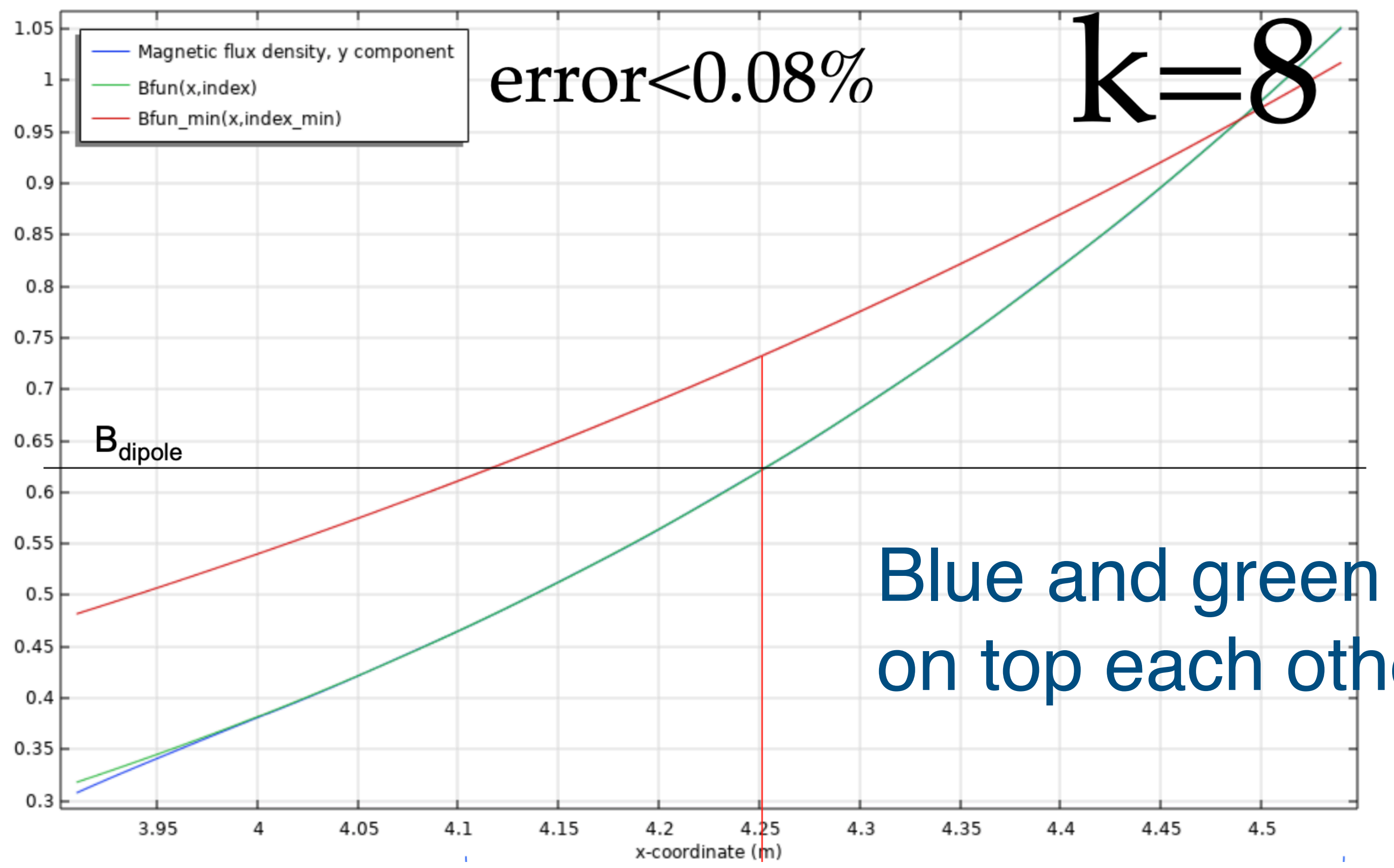
1) gap shaped magnet,
2) parallel pole with trim coils,
3) combined with anisotropic iron plates.





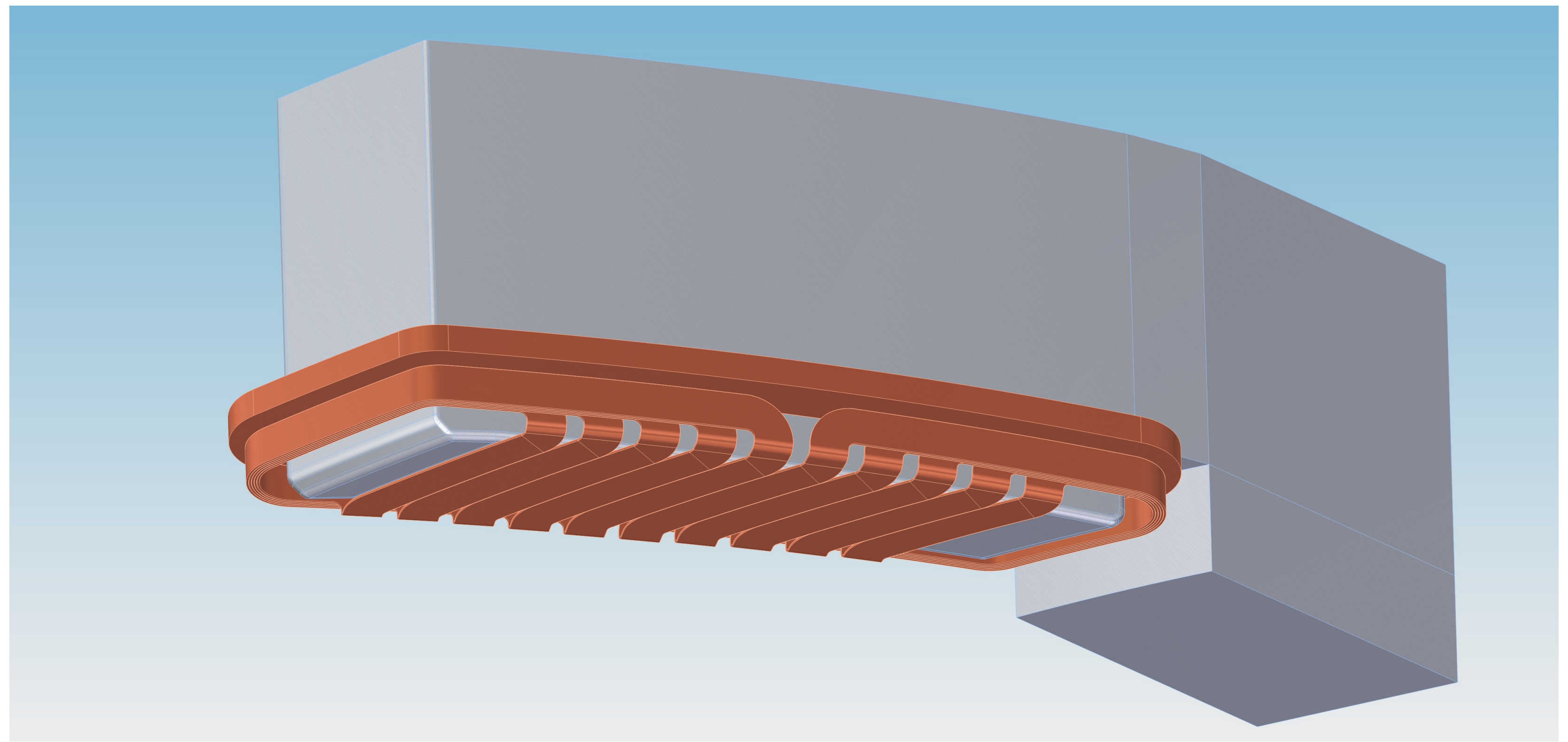
Required power is similar.

Optimisation of 2D model



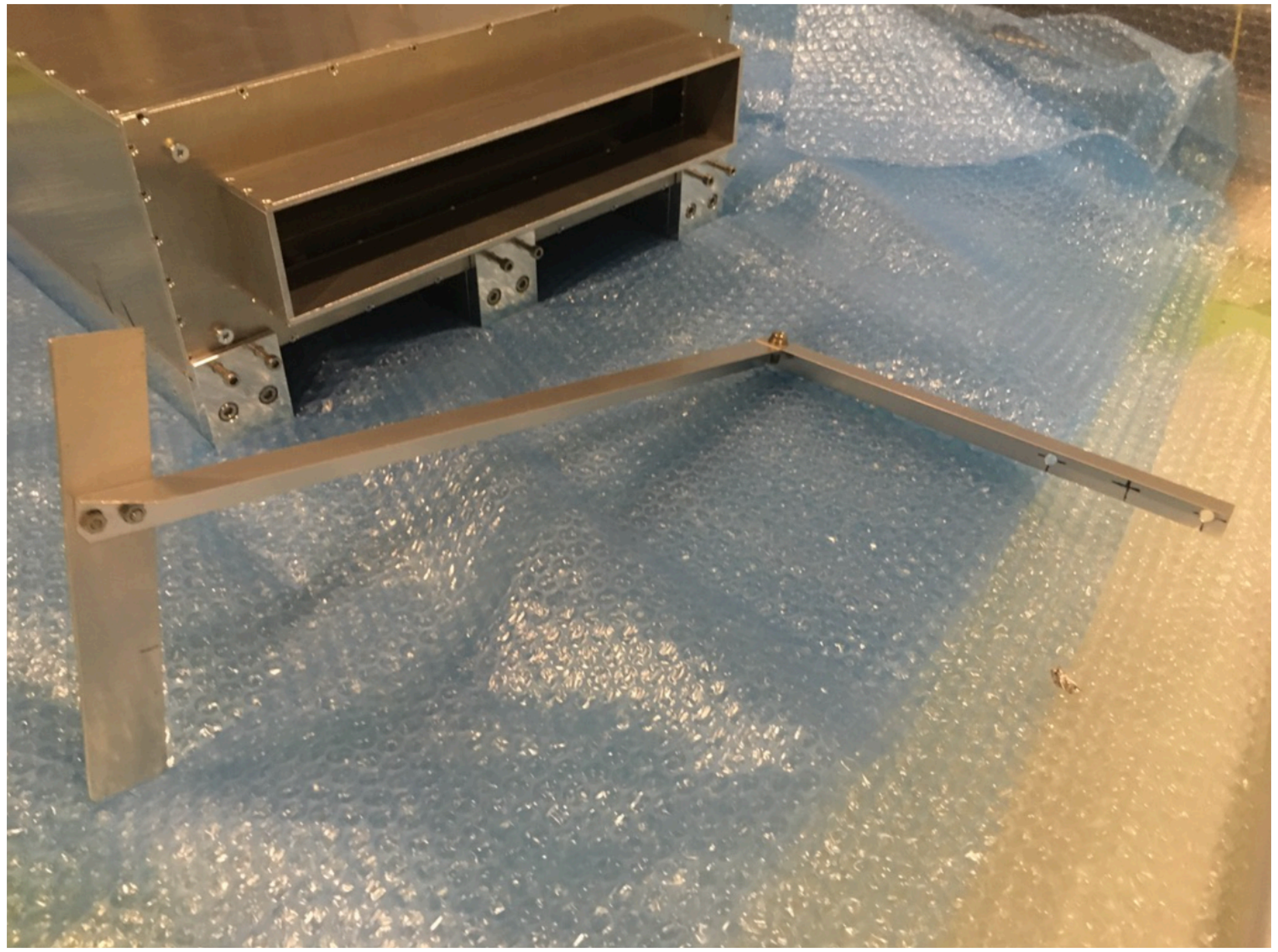
Blue and green lines are on top each other.

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

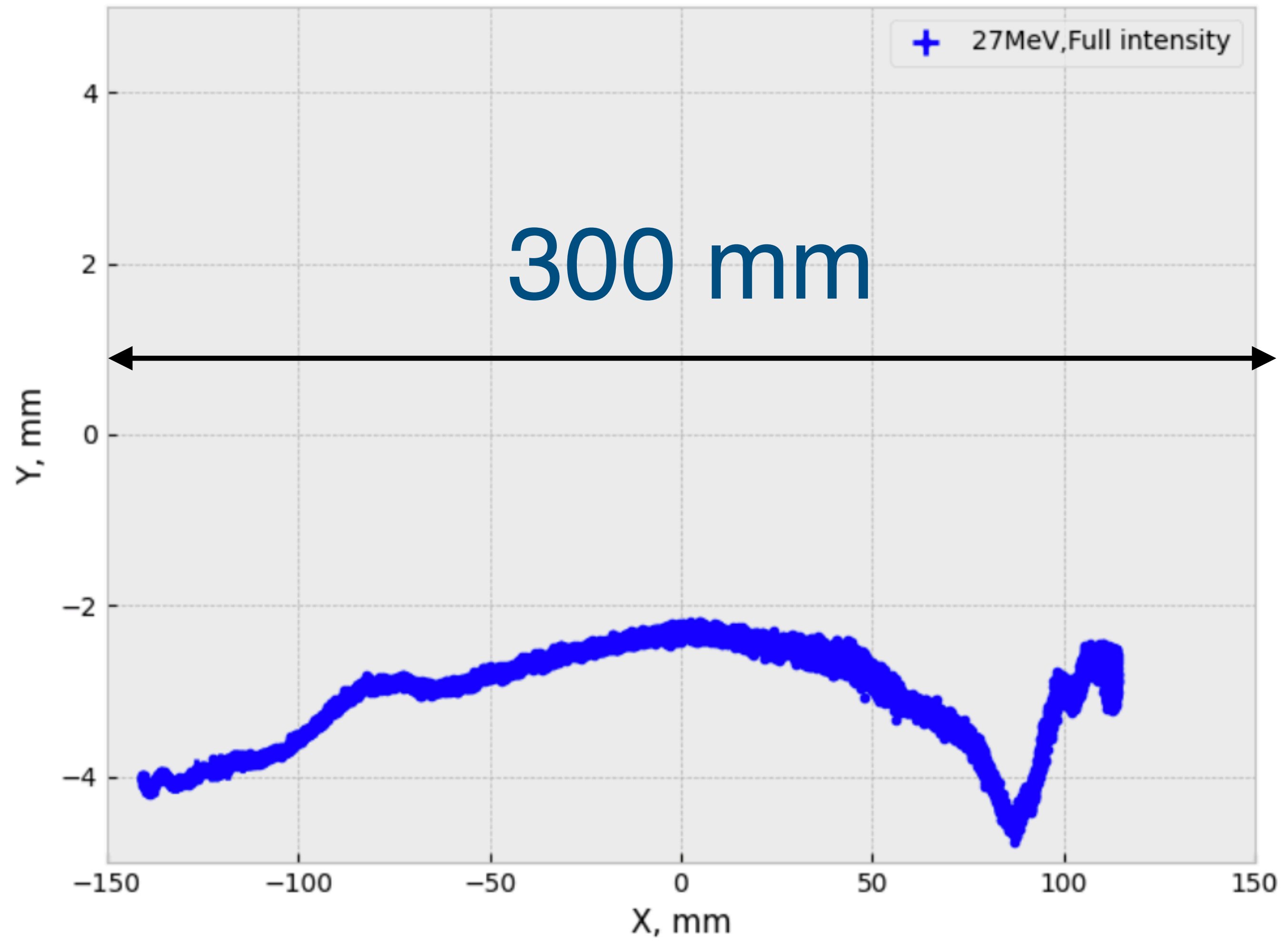


Beam Position Monitor (BPM) prototype

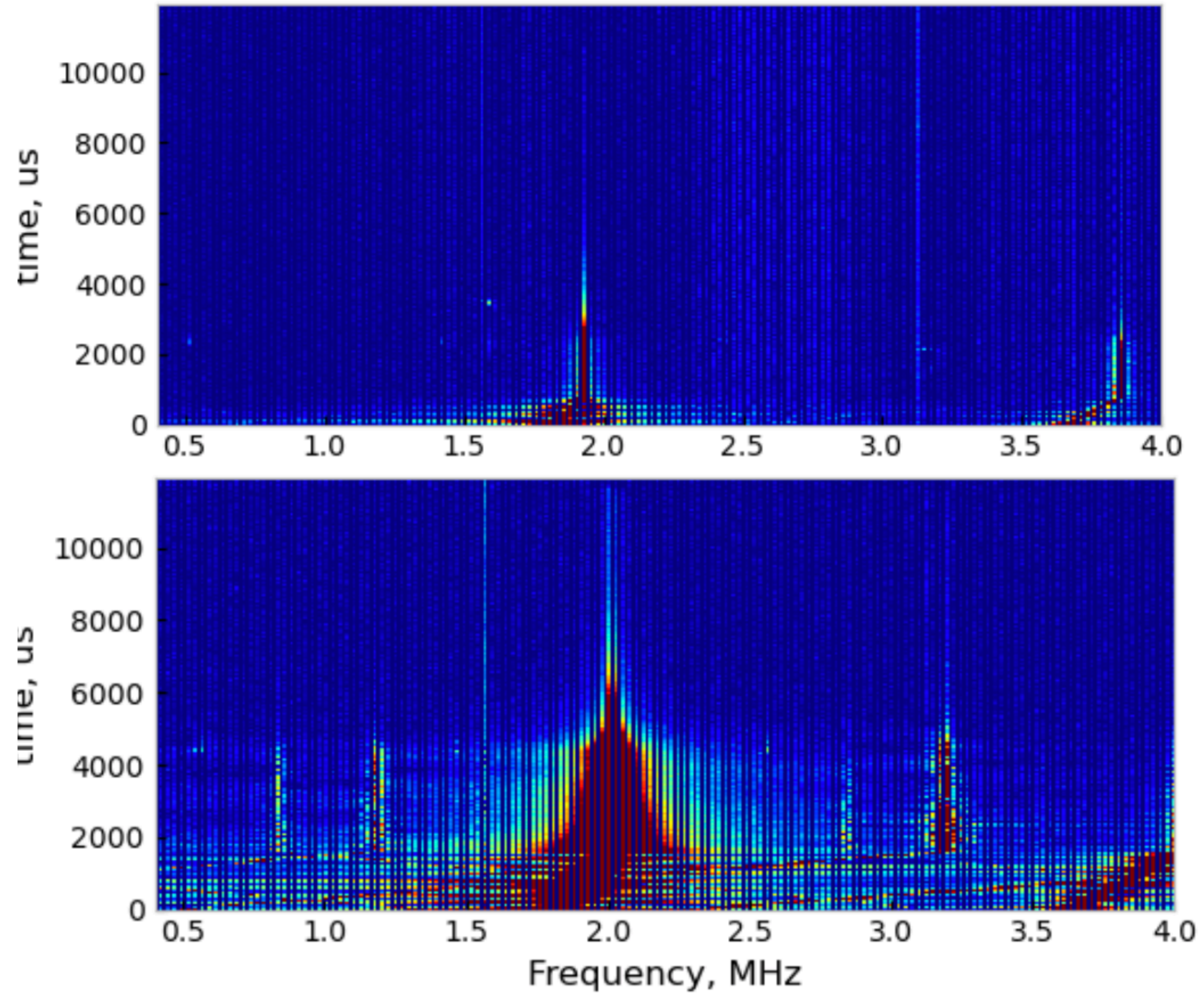
- A half size (horizontal) BPM prototype is made and tested in the FFA at Kyoto Univ. (KURNS).
- Turn by turn position measurement and tune measurement have been done.



A half size BPM and scraper



Hor. and Ver. beam position evolution during acceleration.



Frequency spectrum to measure tune.

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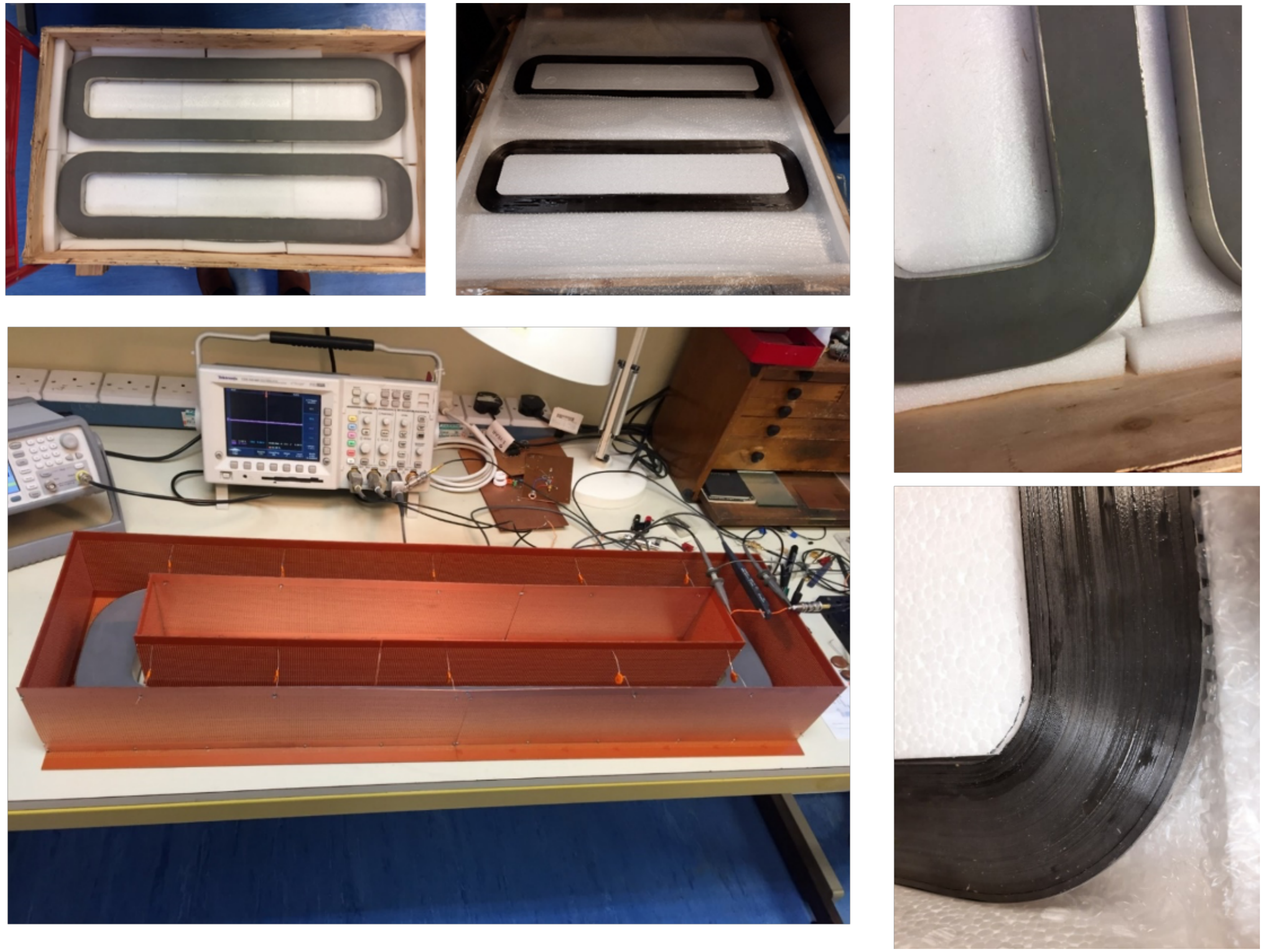
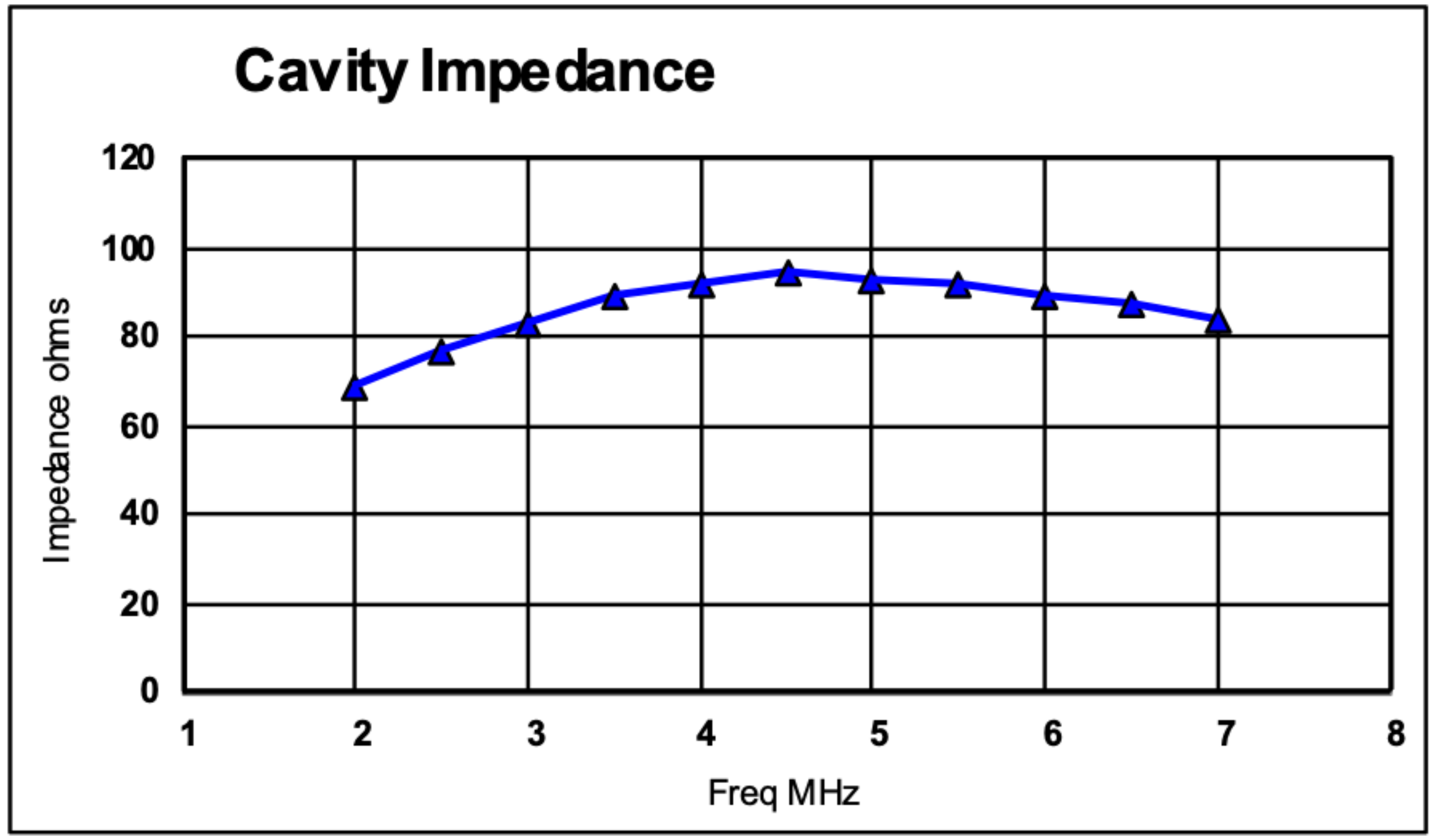
RF cavity, Ferrite or Magnetic Alloy (MA)

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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