Optics design of a prototype high intensity Fixed Field Alternating Gradient Accelerator (FFA)

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Overview

- Specifications of ISIS-II project and its prototype
- Some design challenges
- Summary

Specification of ISIS-II and goal of prototype FFA (FETS-FFA)

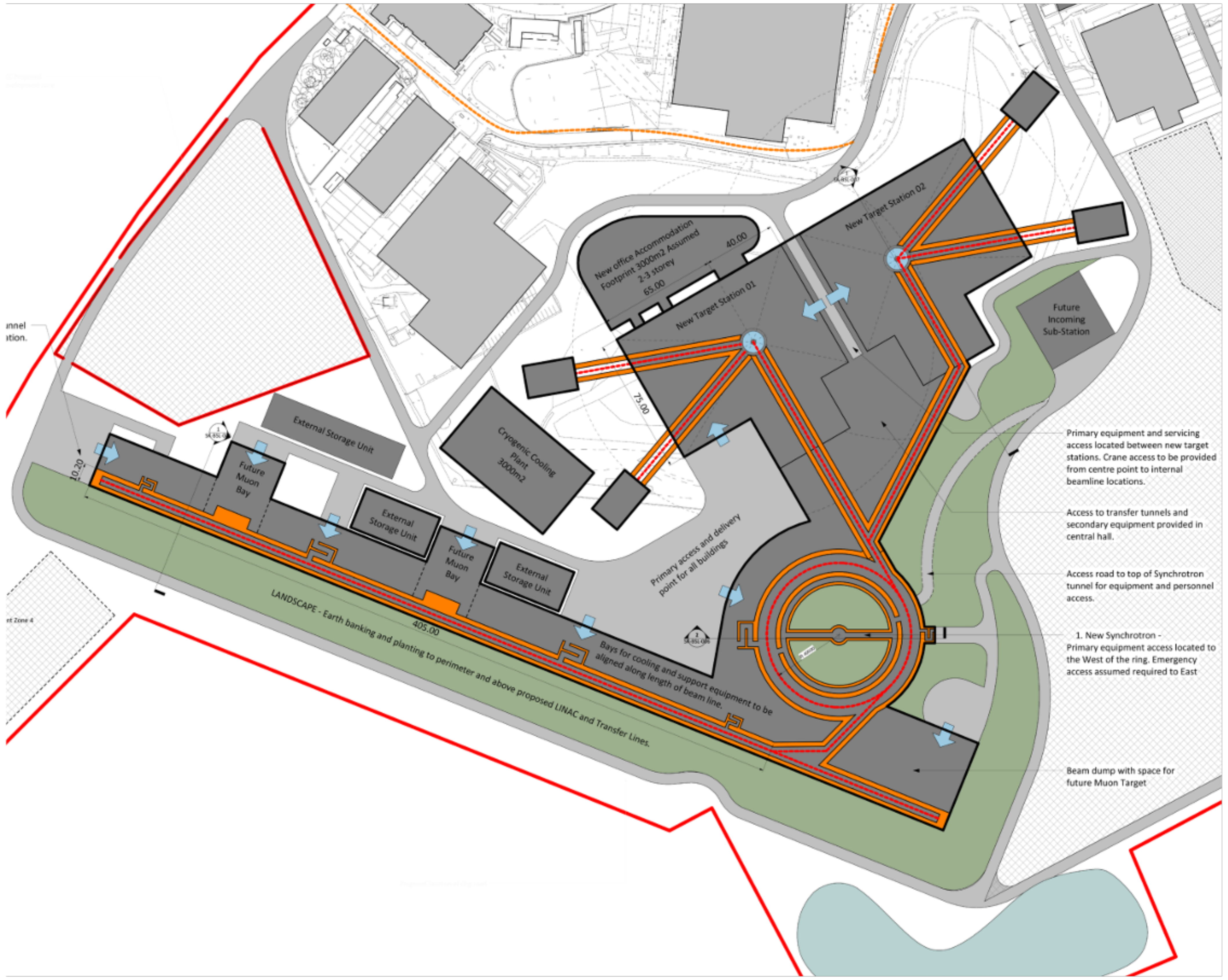
ISIS upgrade, “ISIS-II”

ISIS and ISIS-II is/will be
a pulsed spallation neutron and muon source

- Specifications of the proton driver for ISIS-II

Beam power	1.25 - 2.50 MW
Beam energy	1.2 GeV

It will give the similar beams to SNS and J-PARC.



[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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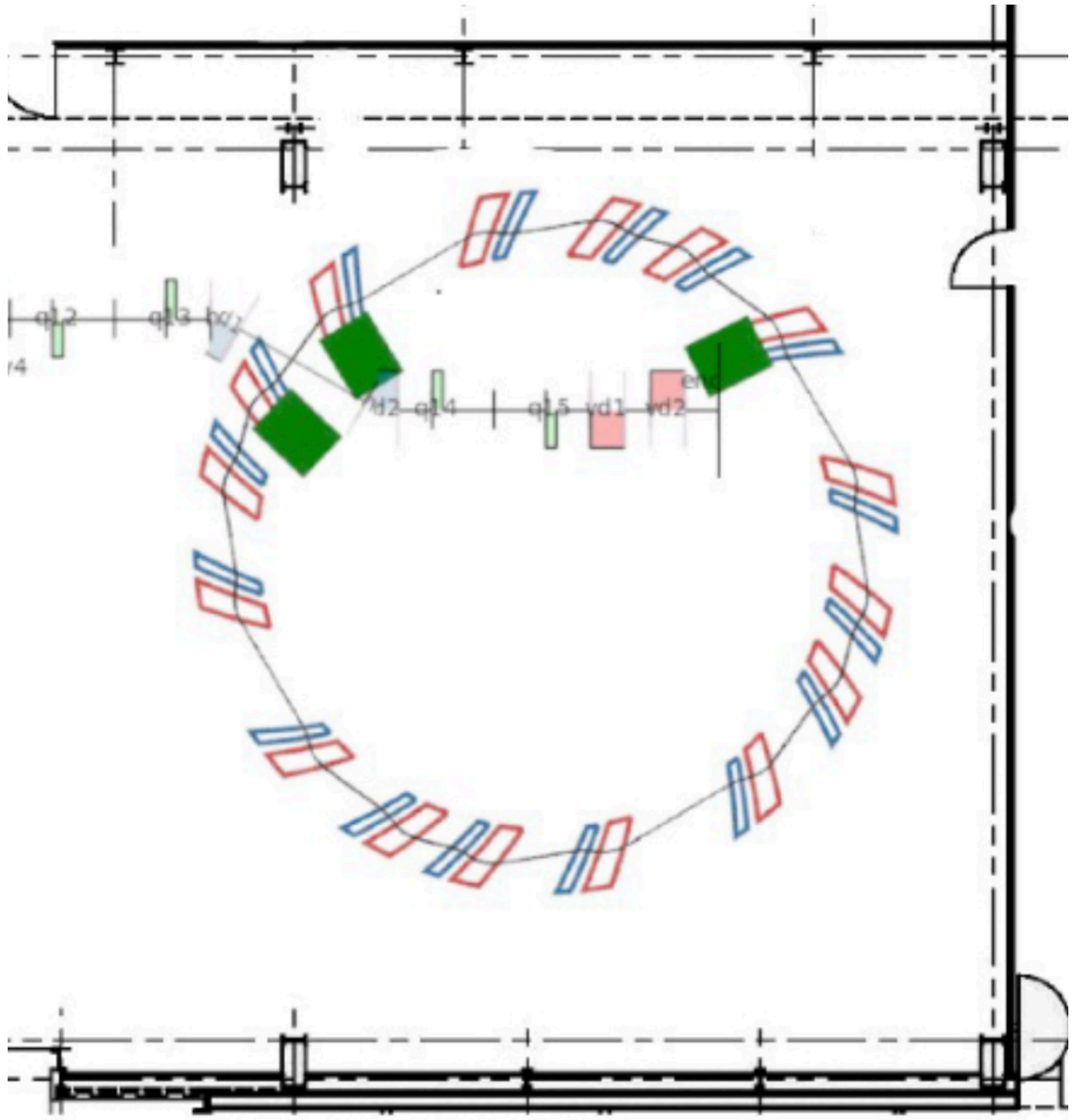
Requirements of future proton drivers

- **Sustainability**.
    - Cyclotron is the most energy efficient accelerator so far.
- **Reliability**
    - DC (superconducting) magnets have a big advantage as a reliable accelerator component.
- **Flexibility**
  - As a pulsed spallation neutron source,
    - “**capacity** (number of experiments, size of community)”
    - “**capability** (bespoke experiments)”

- **FFA option looks attractive, but needs a demonstrator.**

beam energy	3 - 12 MeV
ave. radius	3.6 - 4.2 m
repetition	100 Hz
number of proton per bunch	$3 \times 10^{11}/2$
average current	~ 5 micro A
average beam power	~ 60 W
space charge tune shift	-0.25

FETS-FFA at RAL



FETS=Front End Test Stand

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1. **Superperiod lattice**
2. **FD spiral doublet focusing**
3. **Aperture requirement and dynamic Aperture**
4. **Beam stacking**

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

Lattice with superperiod (Long straight section)

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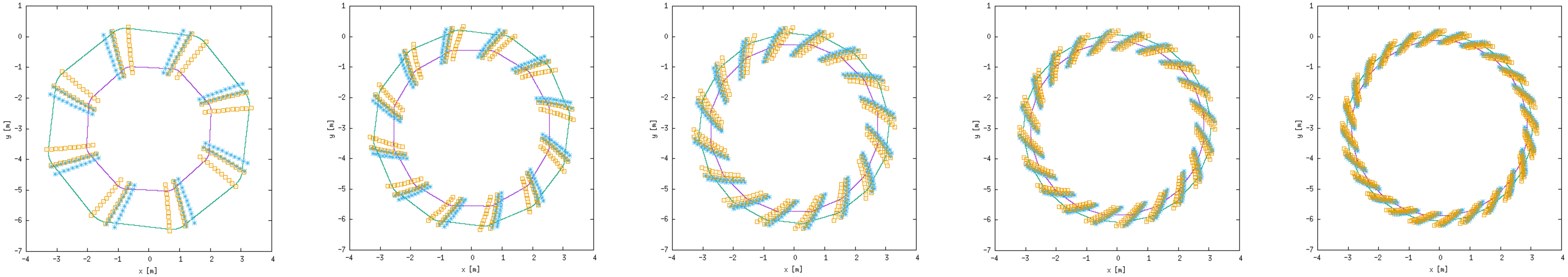
Straight section

- Large number of cells per ring requires **higher field index k**
  - **Small orbit excursion** between injection and extraction.
- Circumference is divided into more number of straight sections.
  - **Each straight section** becomes **shorter.**

field index k

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

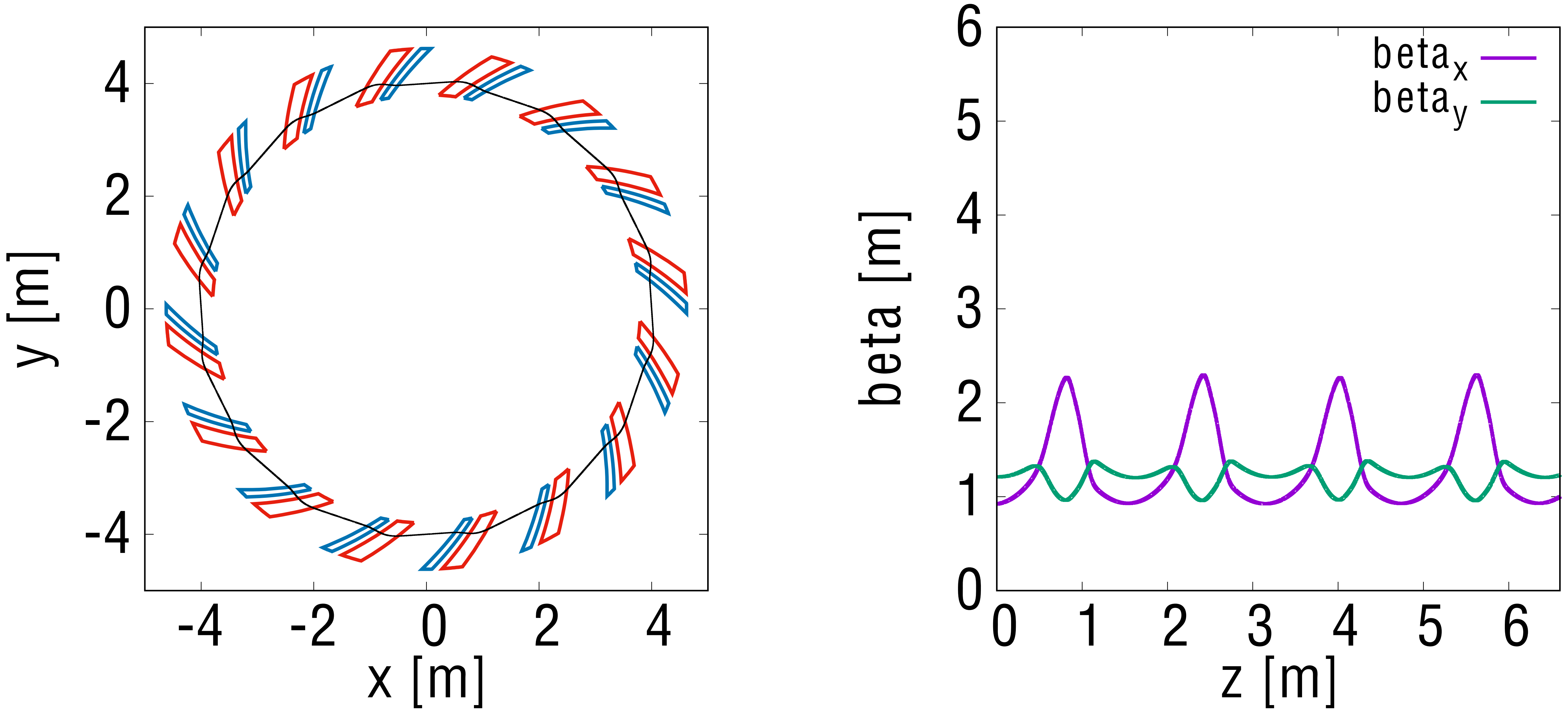


- Let us keep reasonable number of cells, but allocate straight sections unevenly.

Introduction of **superperiod,** e.g. 4-fold symmetry

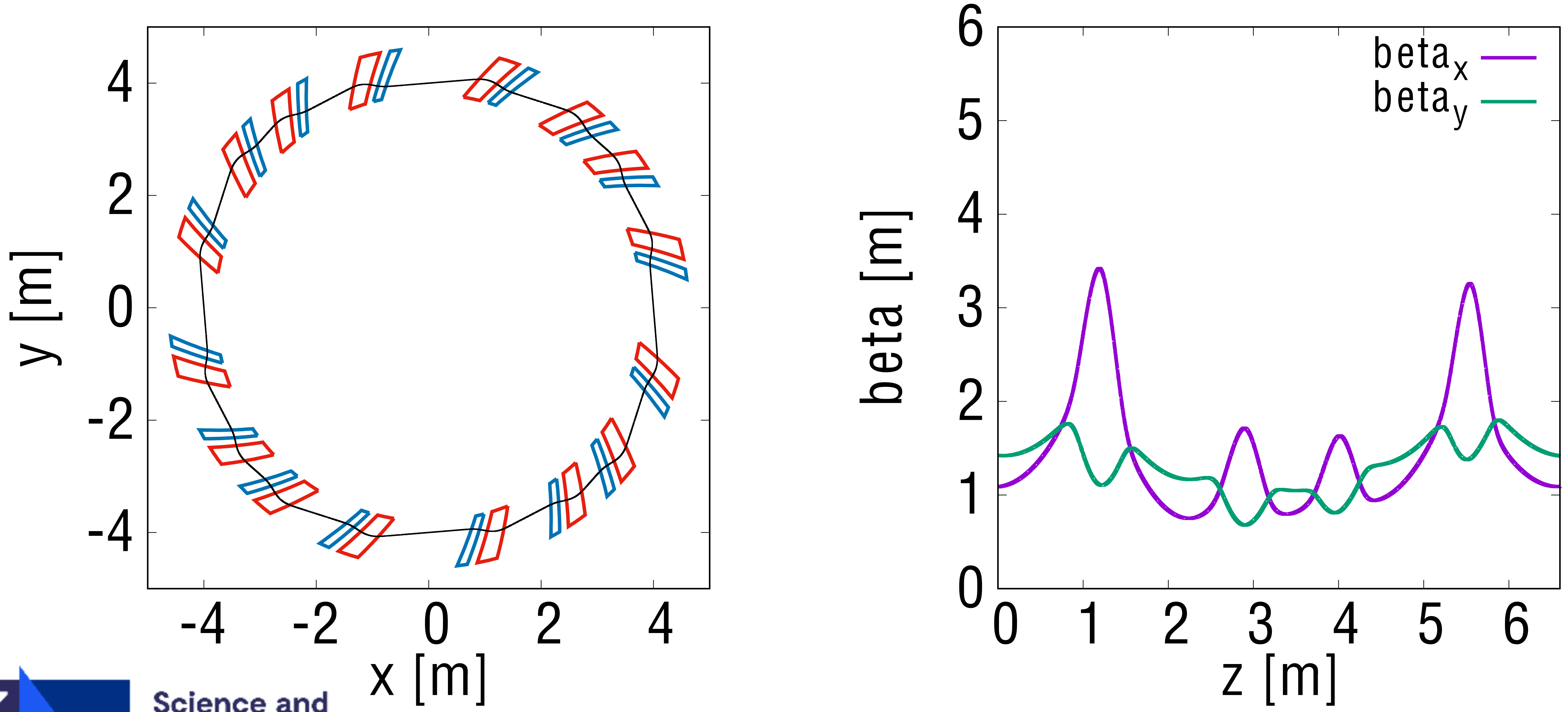
Long straight section is essential for proper handling of the high intensity beams.
injection, extraction, RF cavity, etc.

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 families: 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 families: 8

Horizontal beam size and magnet aperture become larger.

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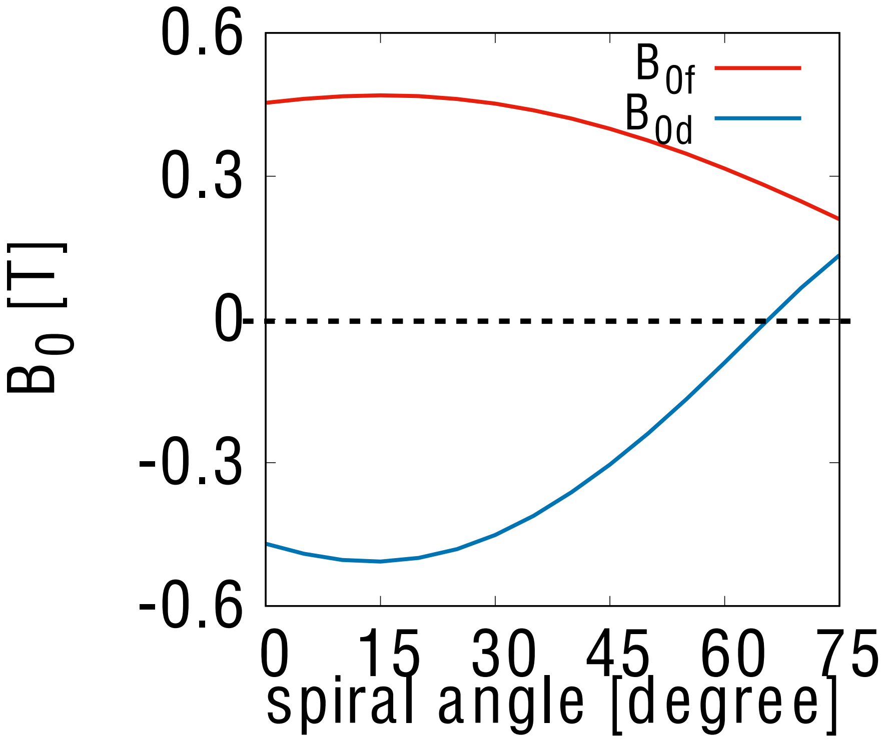
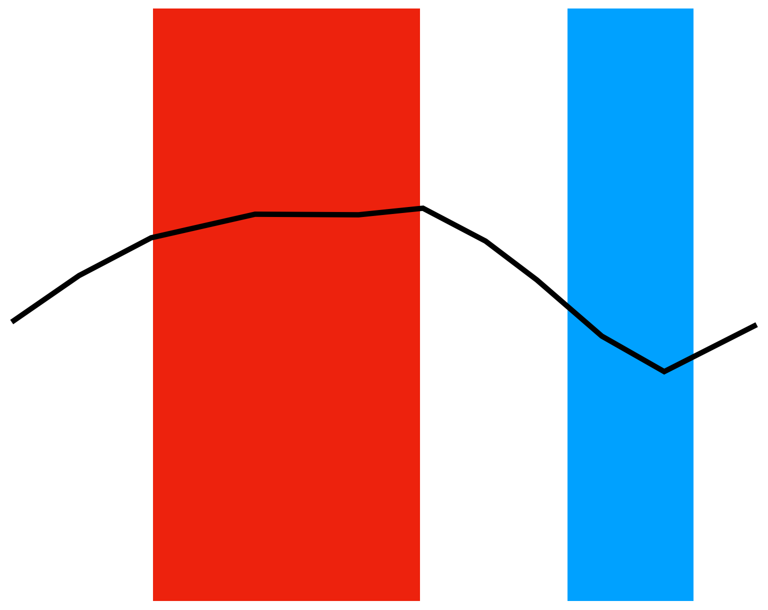
FD spiral doublet

“FD spiral” FFA vs conventional FFA (radial and spiral)



radial sector

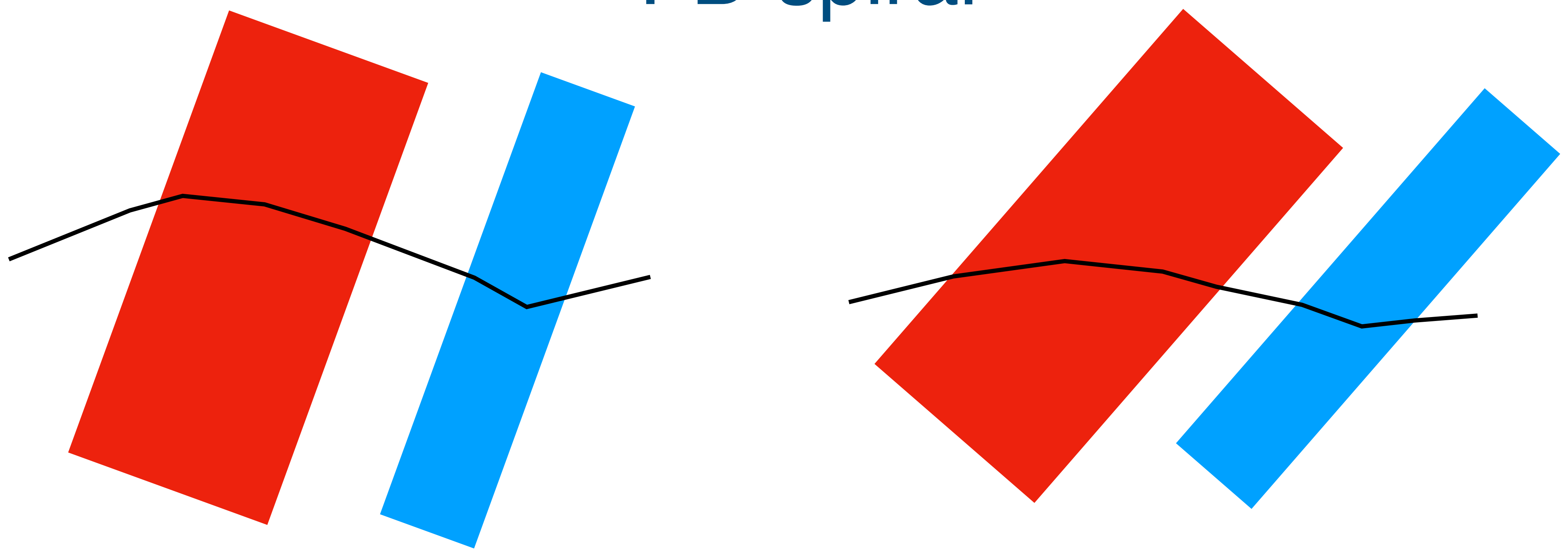


Bf Bd

(DFD) (DDD)

(entrance, body, exit)

FD spiral



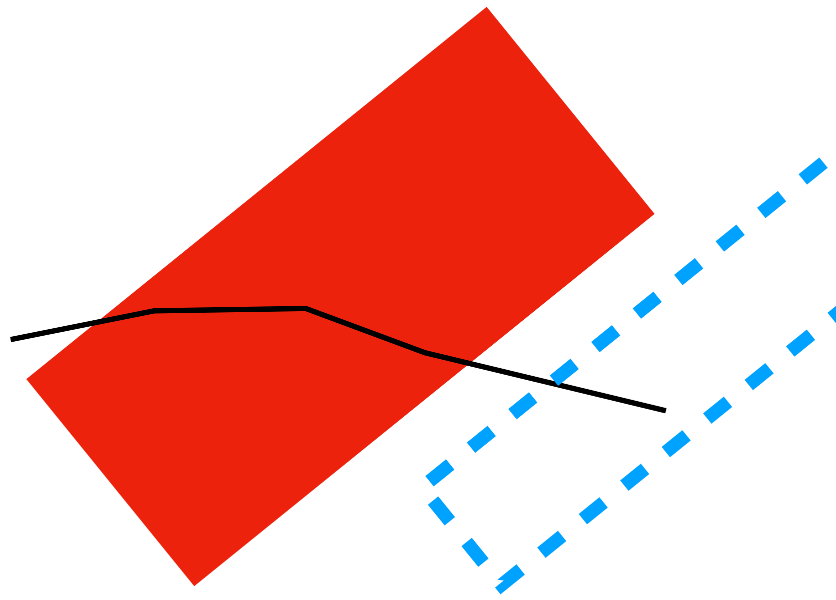
Bf Bd

(DFO) (ODD)

Bf Bd

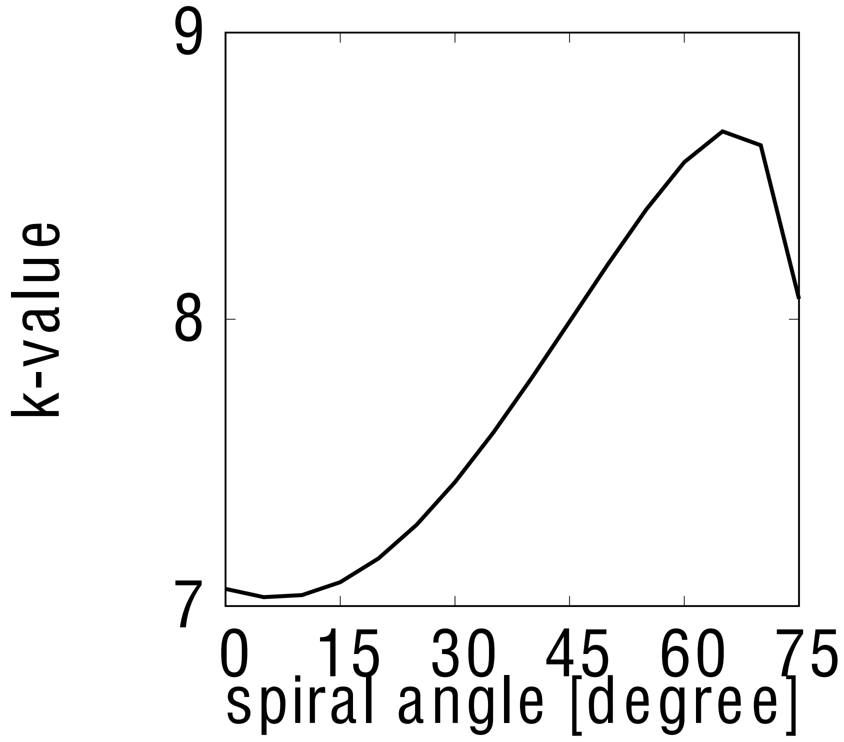
(DFF) (FDD)

spiral sector



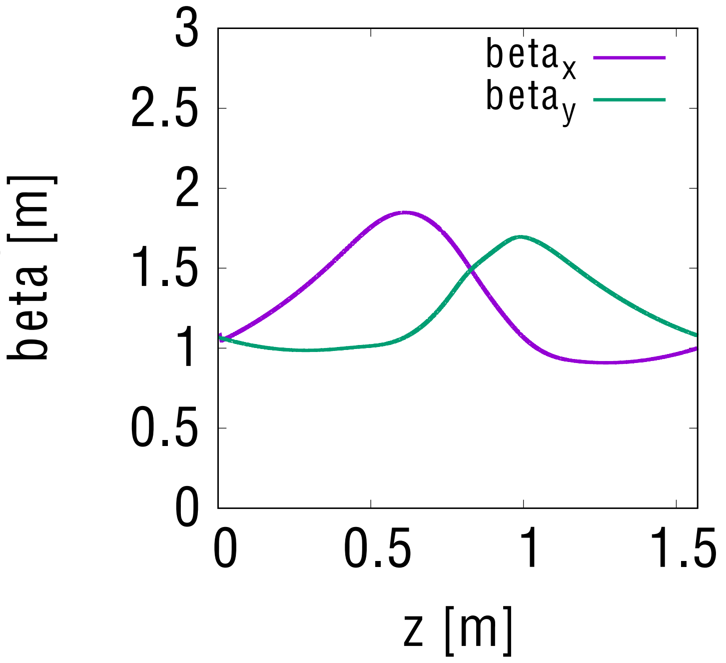
Bf

(DFF)



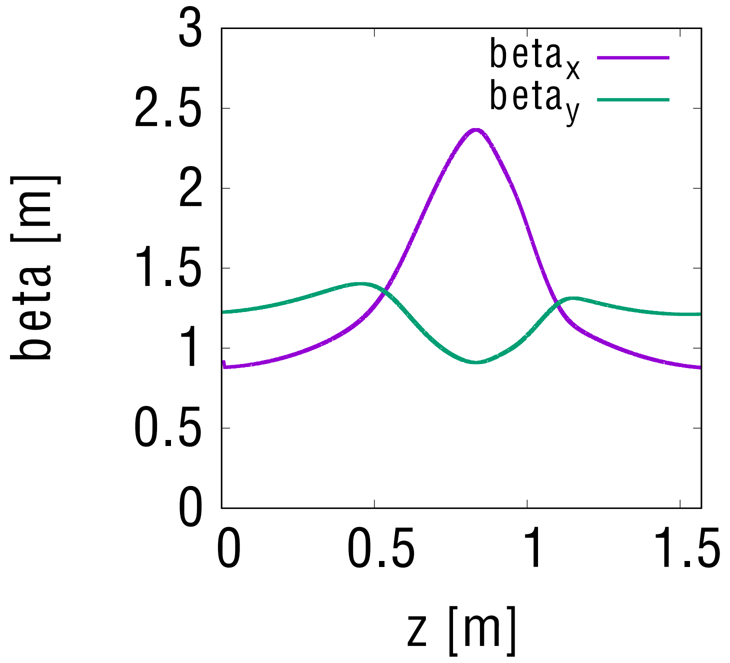
FD

Spiral angle=0 deg

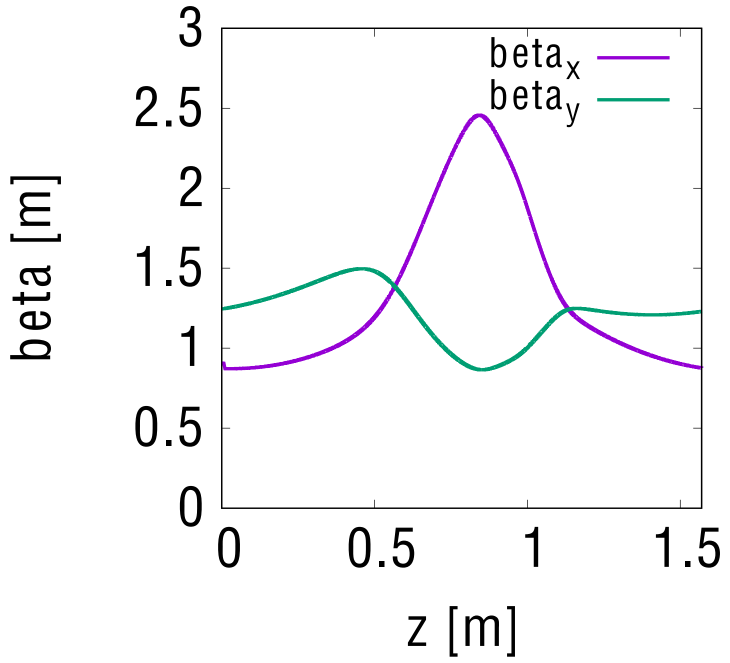


DFD

35 deg

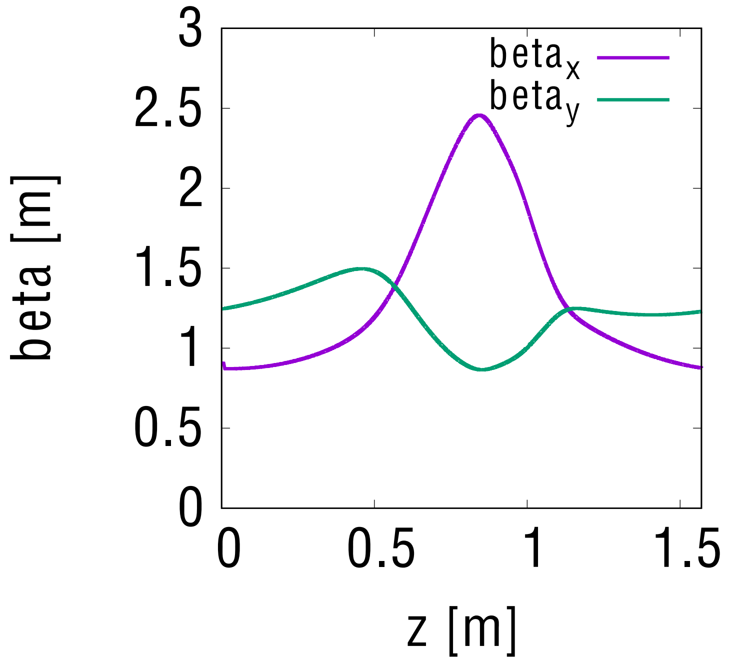


40 deg



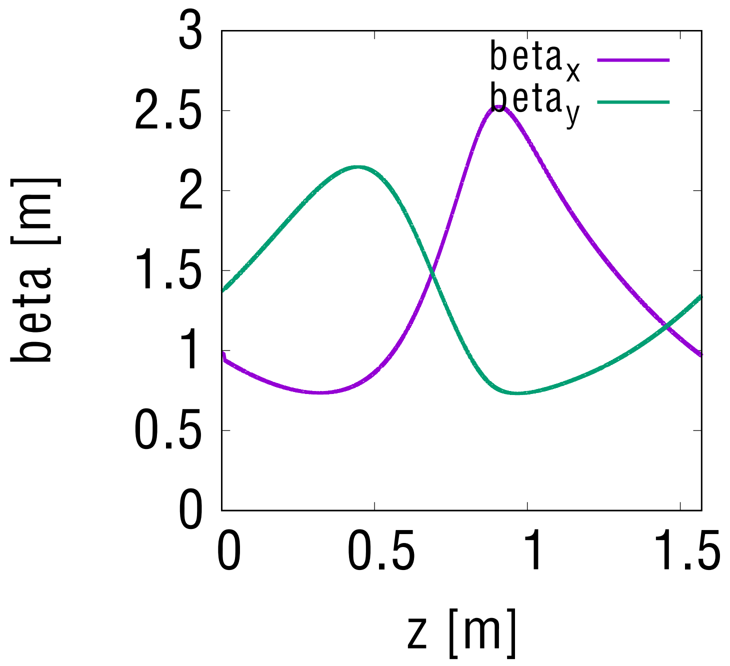
DFD

45 deg



DF

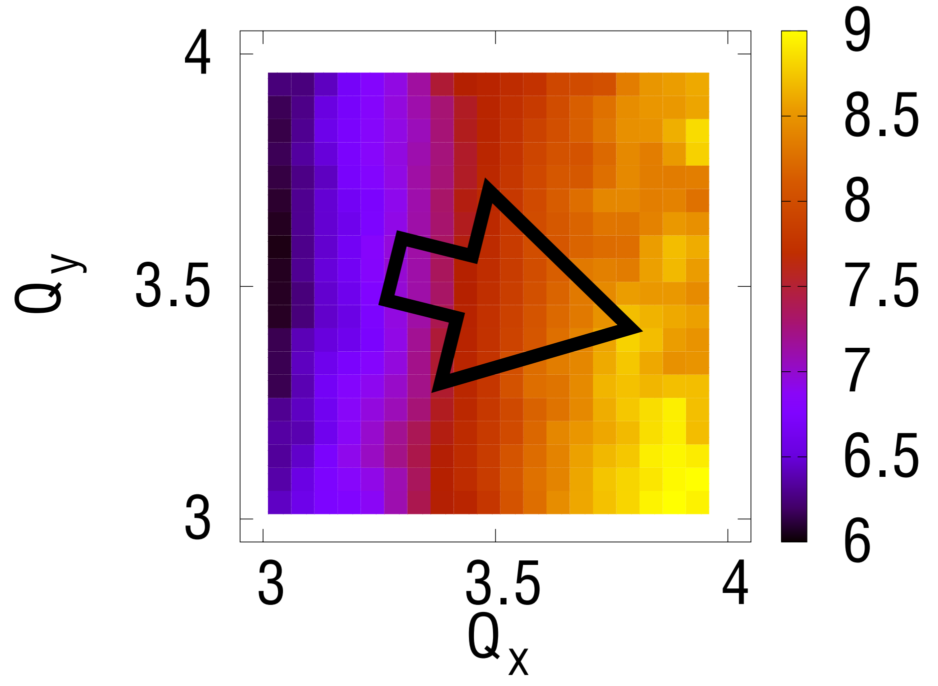
65 deg



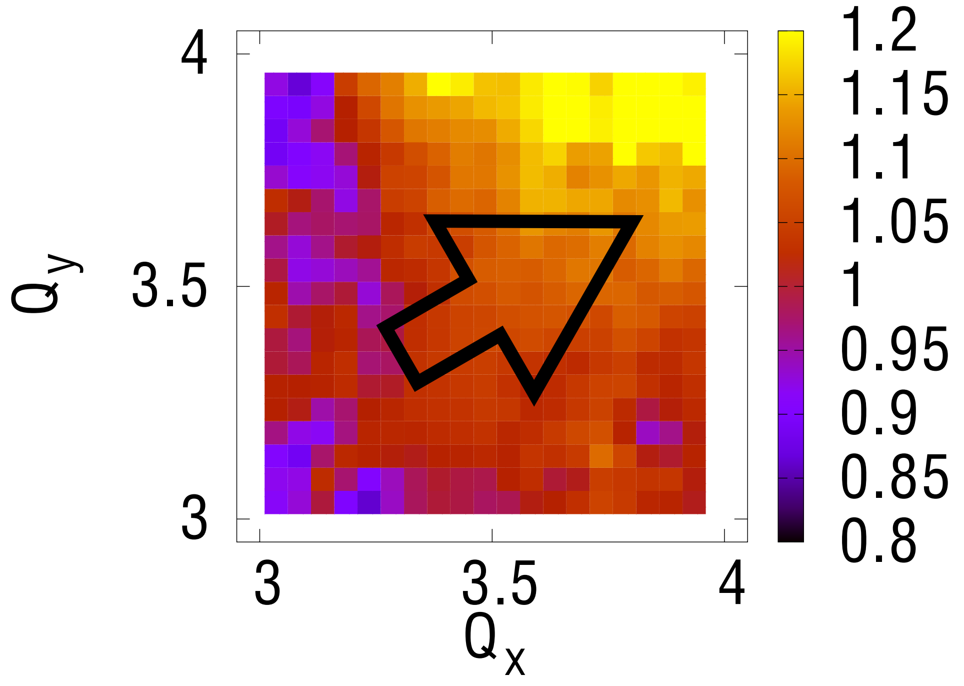
cell tune = (0.213125, 0.213125)

Adjusting Qx and Qy (4-fold superperiod, spiral angle=30 deg.)

k-value

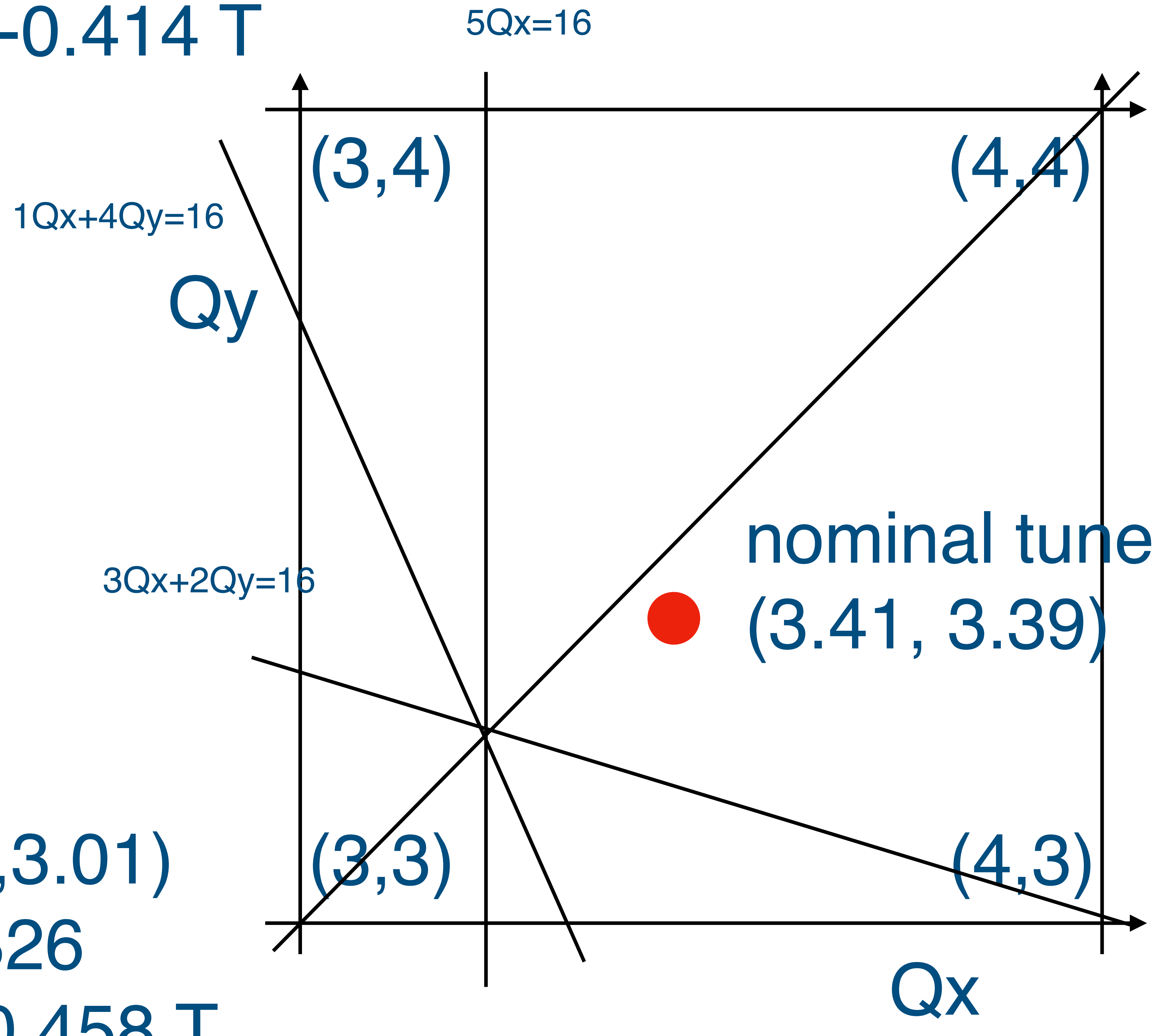


Bd/Bf strength ratio



(3.01,3.96)
k=6.234
B0f=0.385 T
B0d=-0.414 T

(3.96,3.96)
k=8.632
B0f=0.391 T
B0d=-0.471 T



nominal tune
(3.41, 3.39)

(3.01,3.01)
k=6.326
B0f=0.458 T
B0d=-0.427 T

(3.96,3.01)
k=8.495
B0f=0.450 T
B0d=-0.454 T

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

$$\frac{B_z}{B_{z0}} = \left(\frac{r}{r_0}\right)^k F\left(\theta - \tan\zeta \cdot \log\frac{r}{r_0}\right)$$

ζ : spiral angle

$k = \frac{r}{B}\frac{\partial B}{\partial r}$: mean field index

Aperture requirement and dynamic aperture

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Aperture requirement

At 3 MeV, uniform beam of 10 pi mm mrad (100%, normalised) gives space charge tune shift

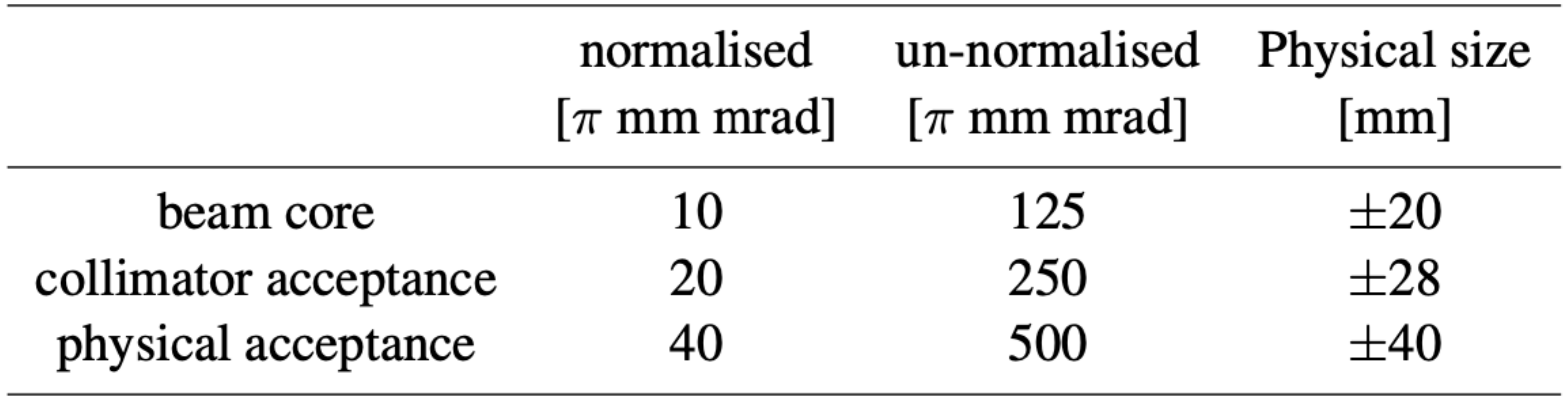
$$\Delta Q = -\frac{r_p n_t}{2\pi\beta\gamma^2\varepsilon_n B_f} = -0.12$$ per 10^{11} protons.

FETS injector will reduce both emittance and peak intensity by more than one order of magnitude.

0.25 pi mm mrad, 60 mA -> 0.02 pi mm mrad, 1 mA (50 turns for $3\text{x}10^{11}$)

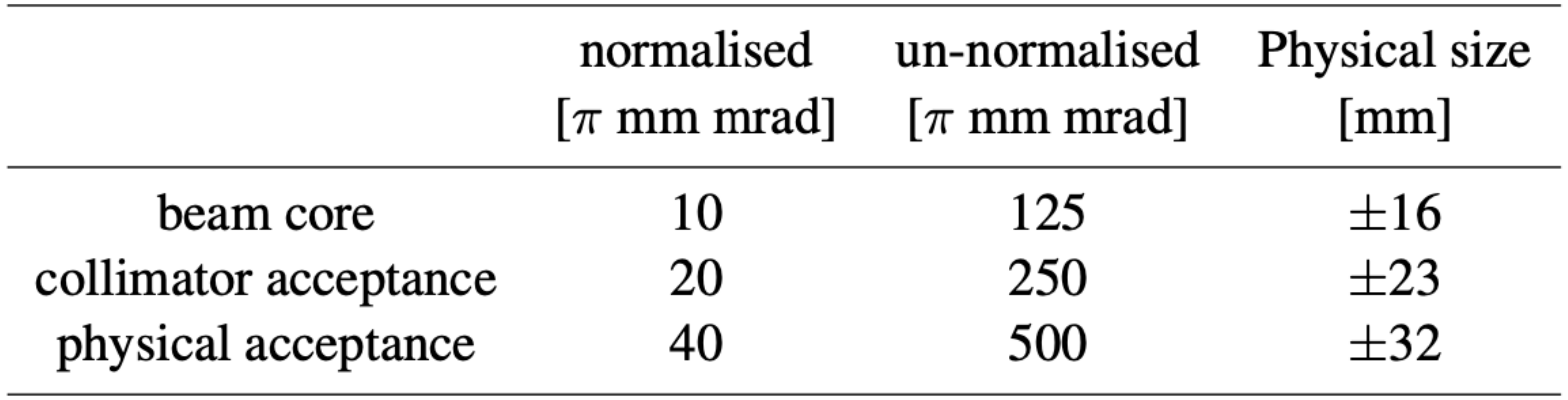
to make multi-turn painting injection.

Table 2.6: Horizontal beam size and acceptance ($\beta_{x,max}$=3.2 m)



	normalised [π mm mrad]	un-normalised [π mm mrad]	Physical size [mm]
beam core	10	125	±20
collimator acceptance	20	250	±28
physical acceptance	40	500	±40

Table 2.9: Vertical beam size and acceptance ($\beta_{y,max}$=2.0 m)



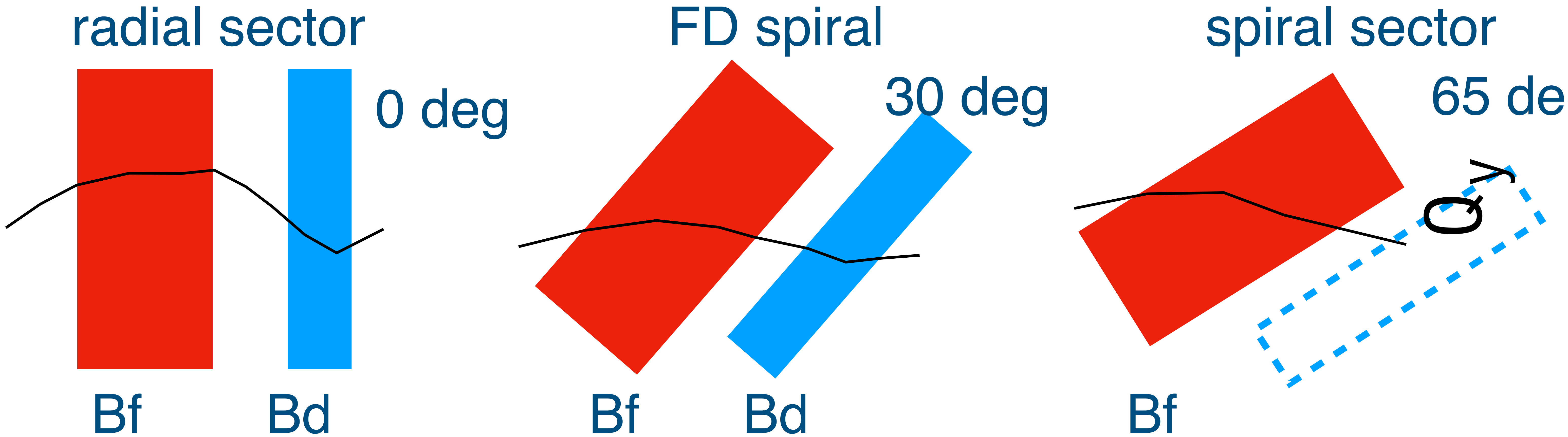
	normalised [π mm mrad]	un-normalised [π mm mrad]	Physical size [mm]
beam core	10	125	±16
collimator acceptance	20	250	±23
physical acceptance	40	500	±32

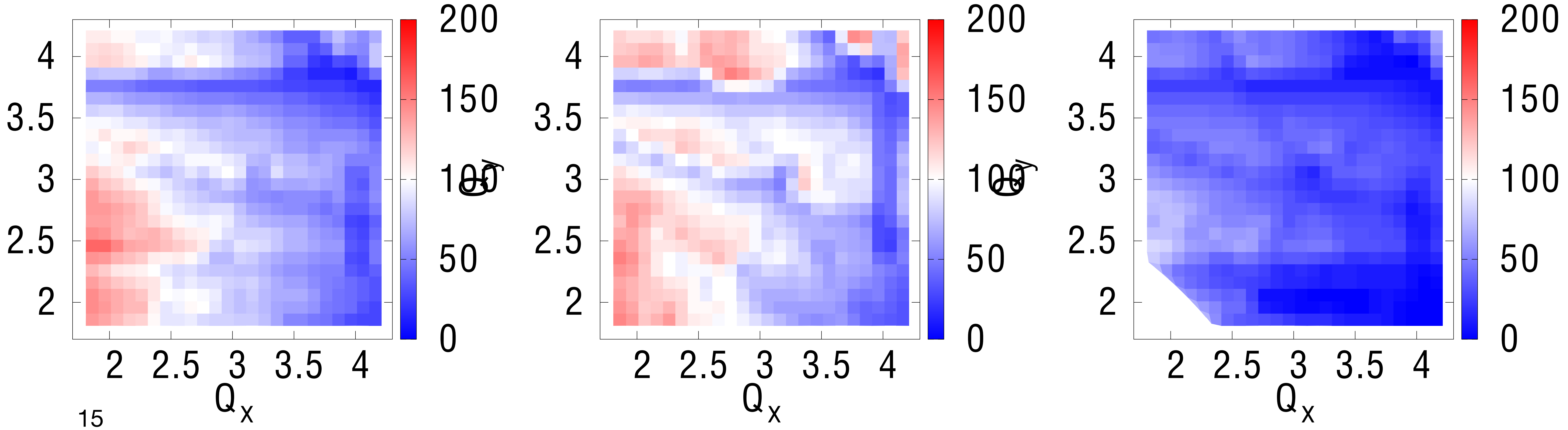
This is the same order of SNS and J-PARC, which has ~500 pi mm mrad (geometrical).

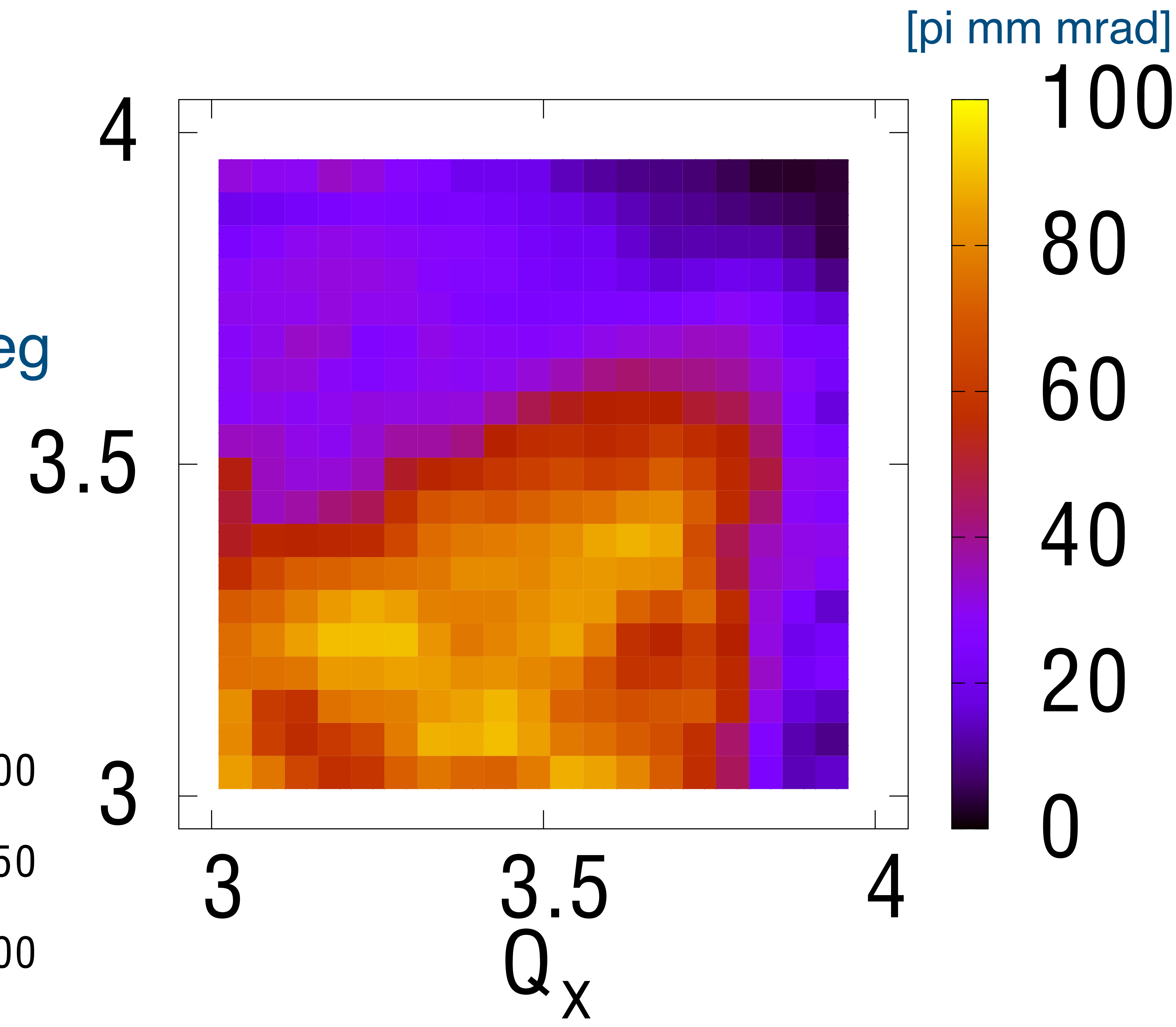
Dynamic aperture calculation

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

- How dynamic aperture depends on various parameters?
- Below shows spiral angle dependence.







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

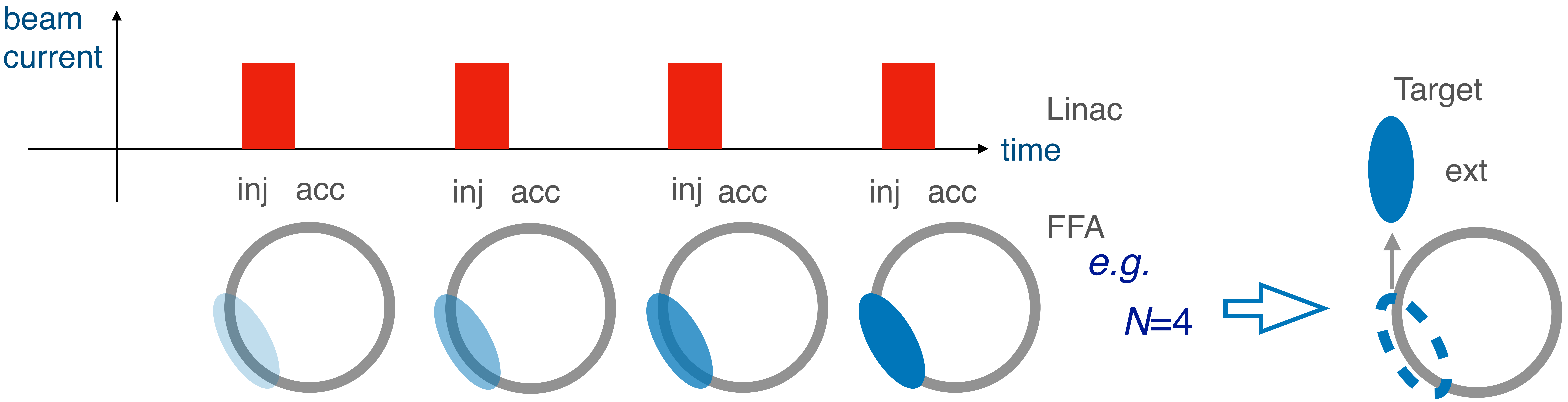
Beam stacking

Repetition rate and space charge mitigation

- 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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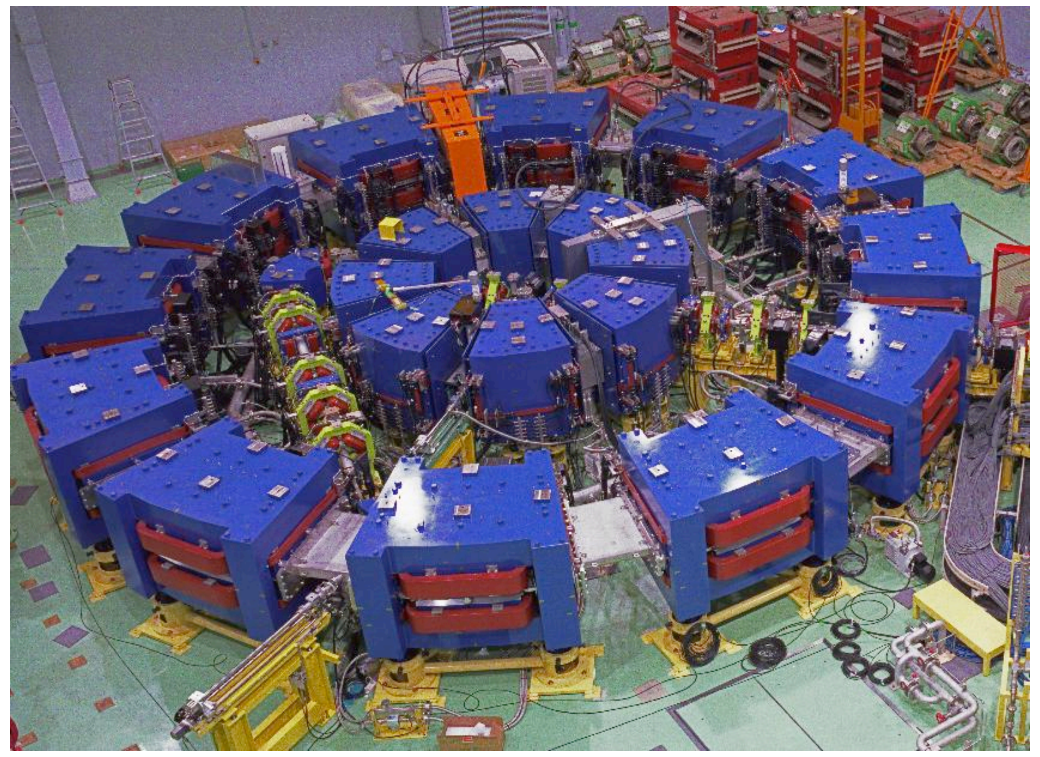
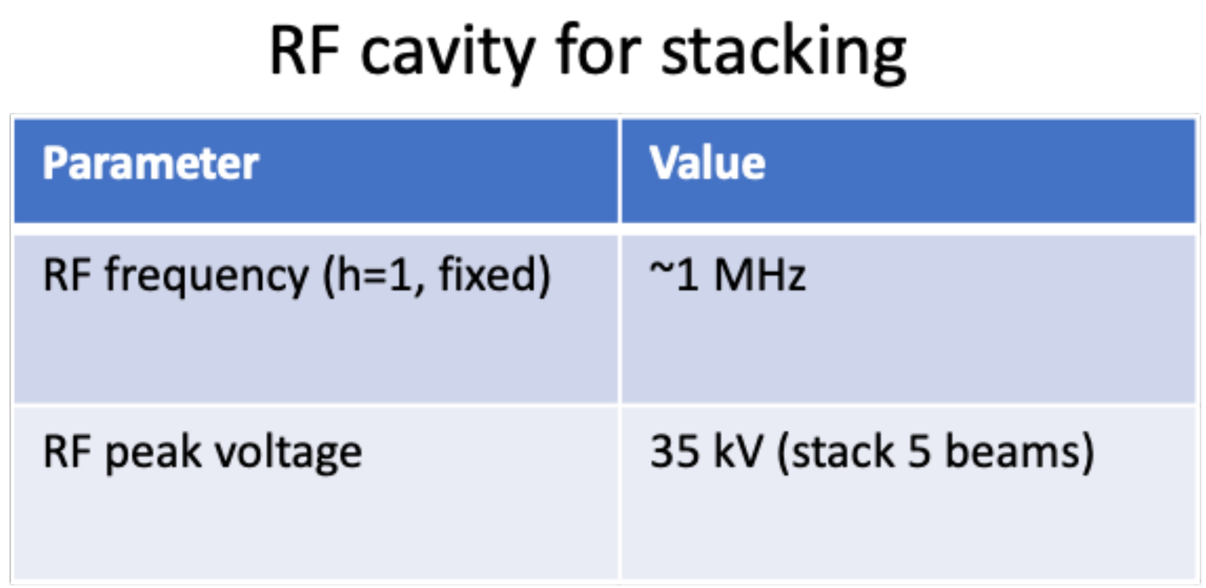
Experiment at KURNS (Kyoto Univ.) in March 2023

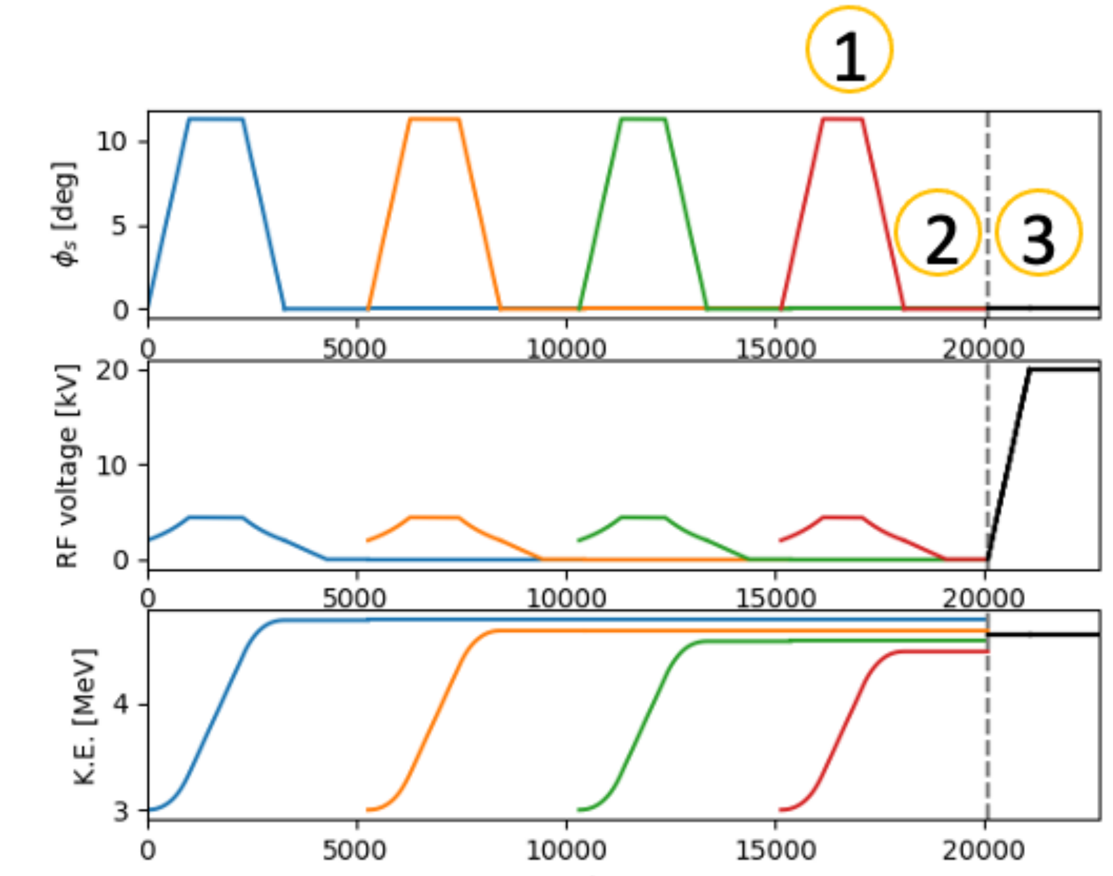


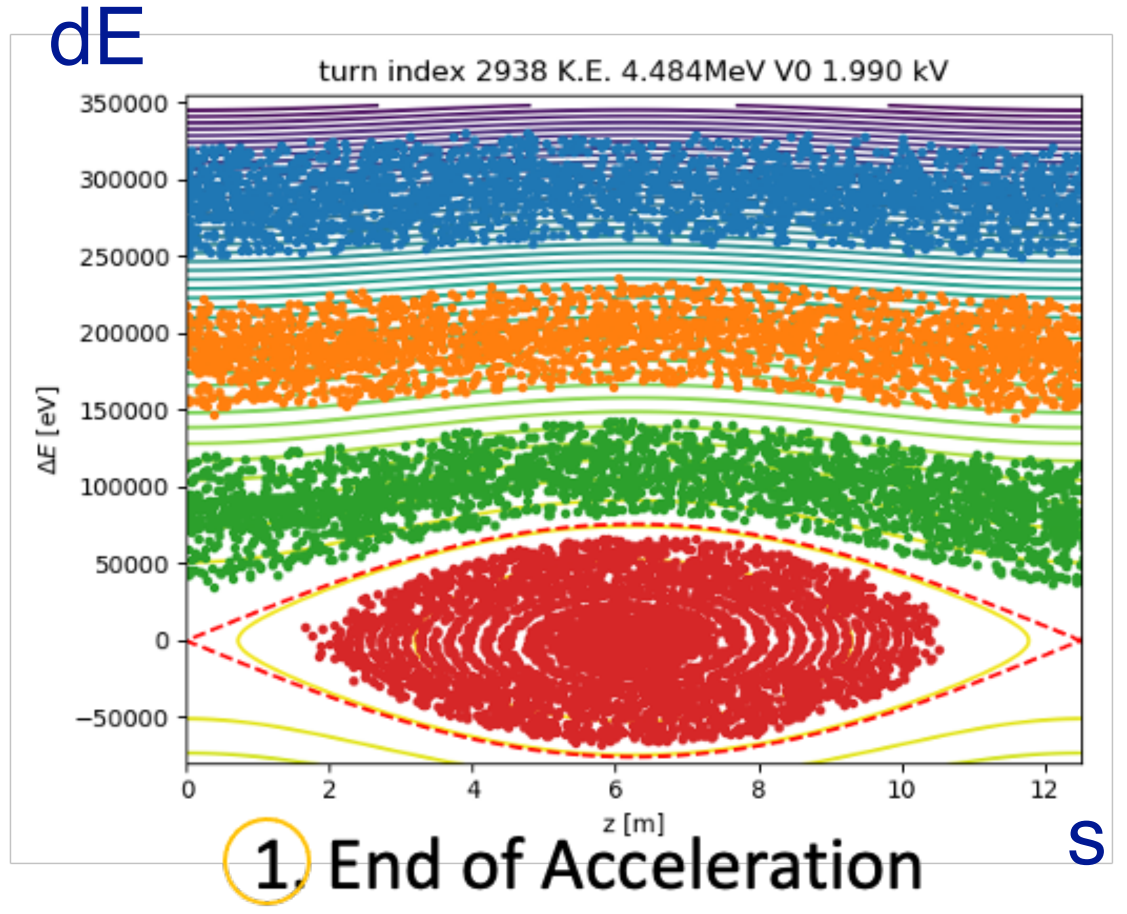
- Stack 2 beams in longitudinal phase space (example below shows 4 beams).
  - Total momentum spread dp/p is *n* times dp/p of each beam?
  - Total number of particles is *n* time that of each beam?



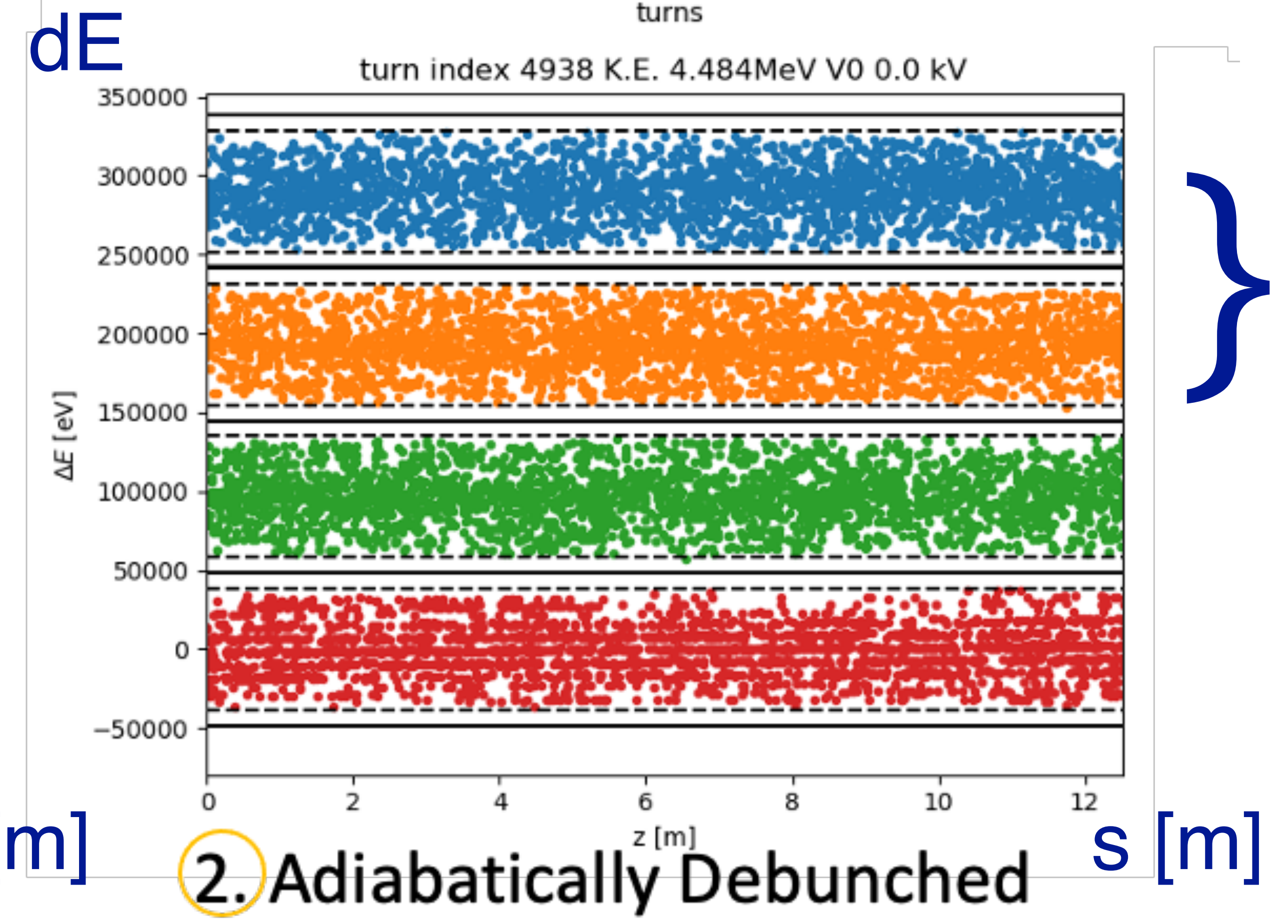
RF cavity for stacking

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





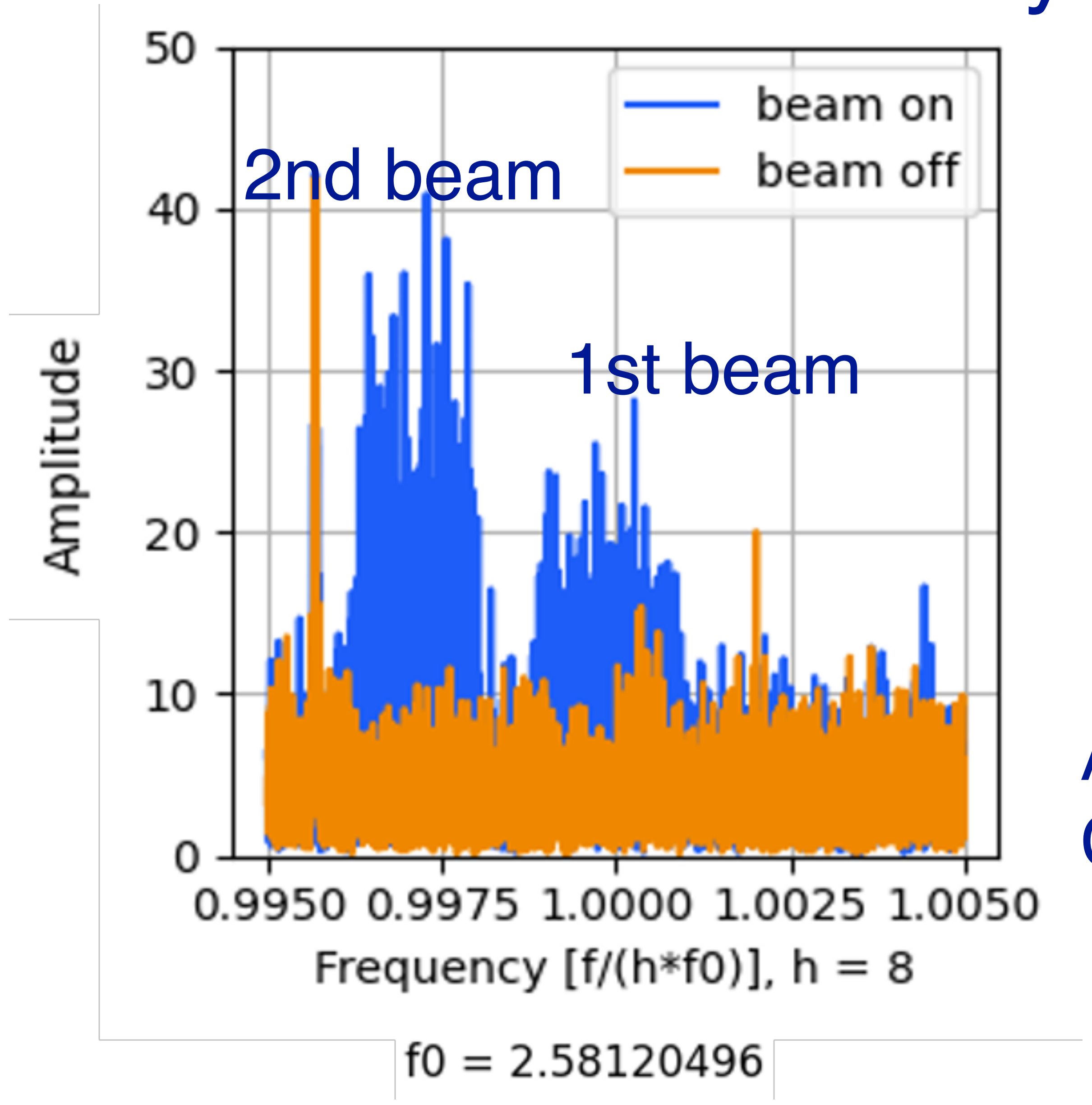
① End of Acceleration



② Adiabatically Debunched

Simulation by David Kelliher

Schottky signal after stacking 2 beams
Preliminary!



Analysed by Carl Jolly

- Total momentum is under control.
- There is unexpected beam loss.
  - Data analysis continues.

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Summary

Summary

- Our goal is to demonstrate high intensity operation of a FFA.
  - with a scaling FFA.

- From physics design point of view
  - Superperiod lattice to give space for beam handling
  - Proper lattice structure ready for high intensity operation with enough parameters
  - 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
  - Experimental demonstration with FFA at Kyoto Univ. gives confirmation of the idea as well as a bit of surprise.

Thank you for your attention

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Backups

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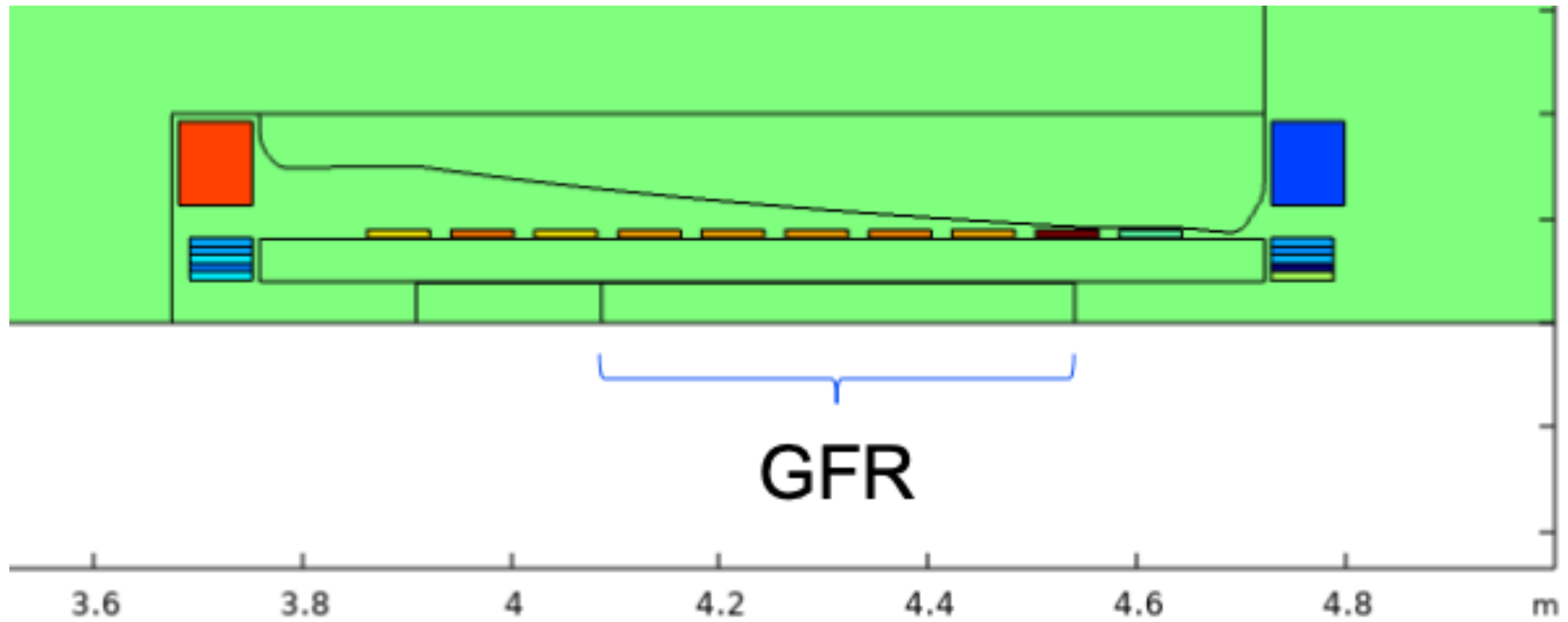
Magnet prototype

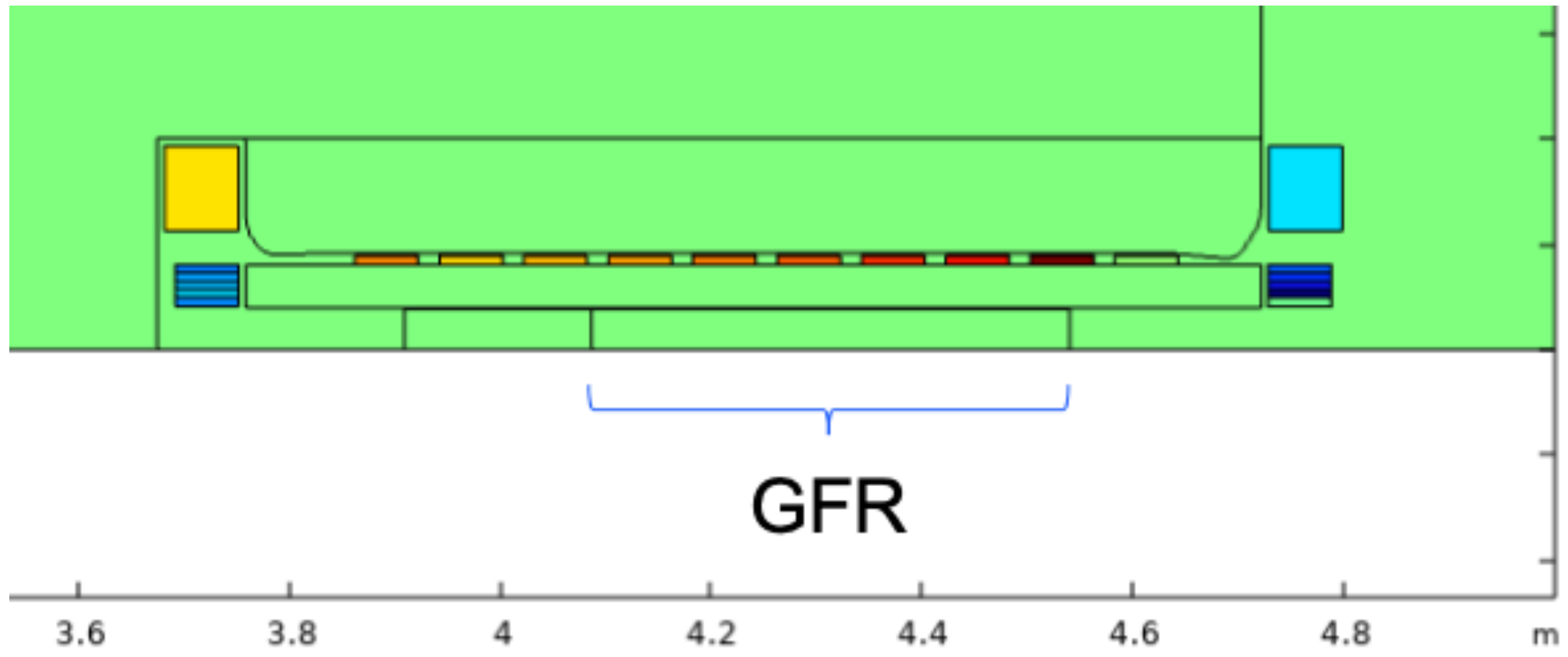
- C-shape magnet because of space constraint.
- Field index *k* variable from 6 to 11.

Several options were investigated to create field gradient.

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

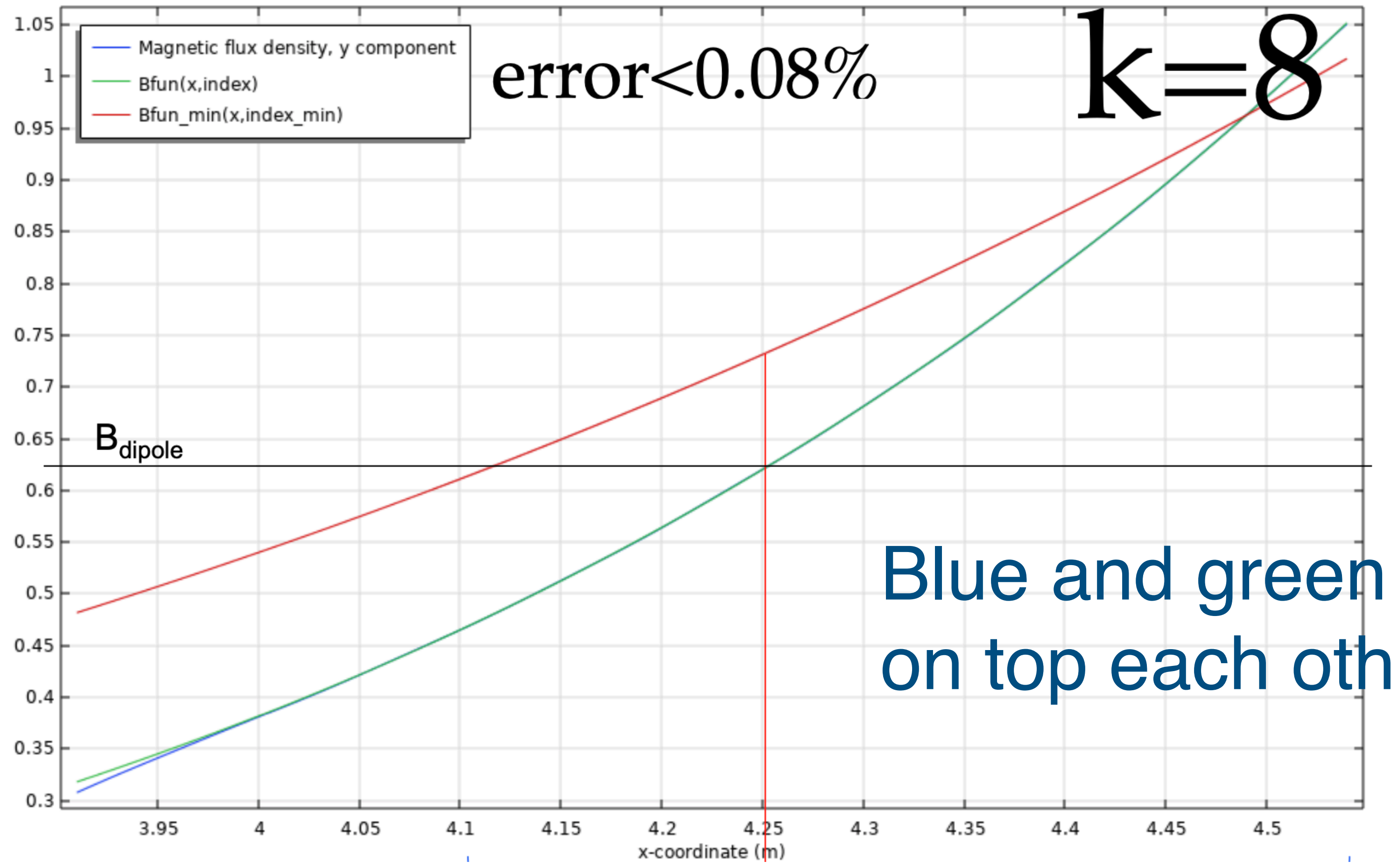
1) gap shaped magnet,
2) parallel pole with trim coils,
3) combined with anisotropic iron plates.





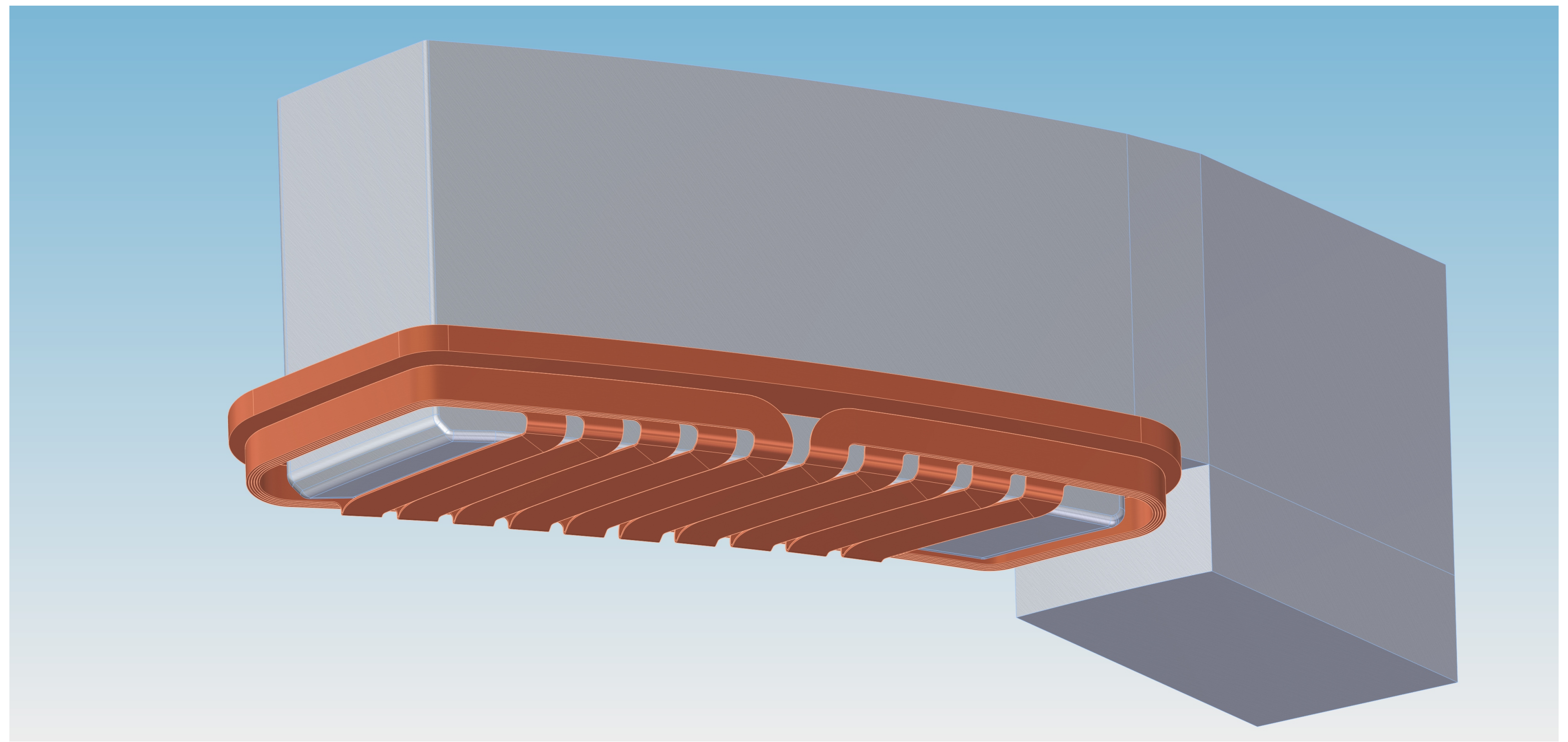
Required power is similar.

Optimisation of 2D model



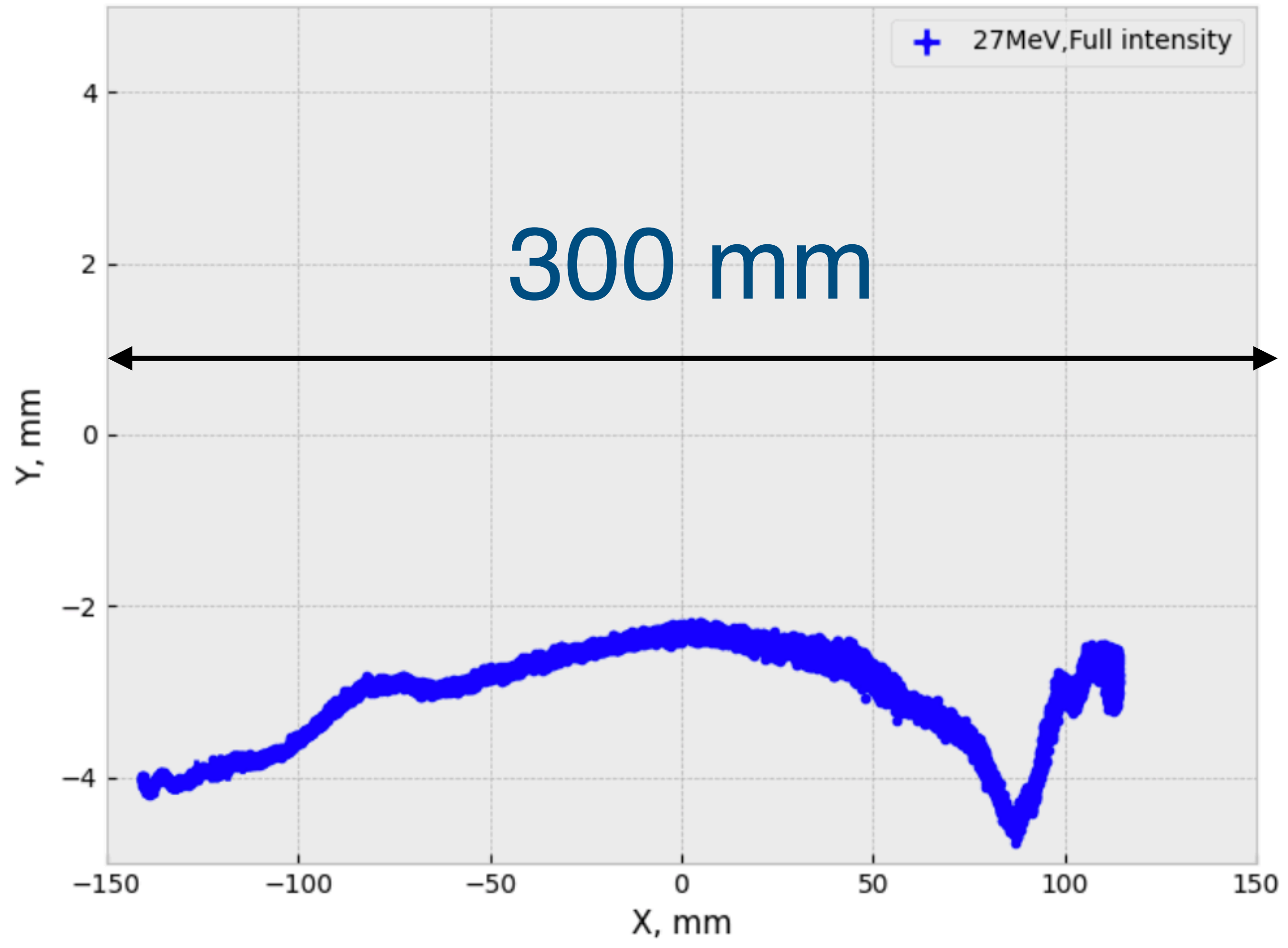
Blue and green lines are on top each other.

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

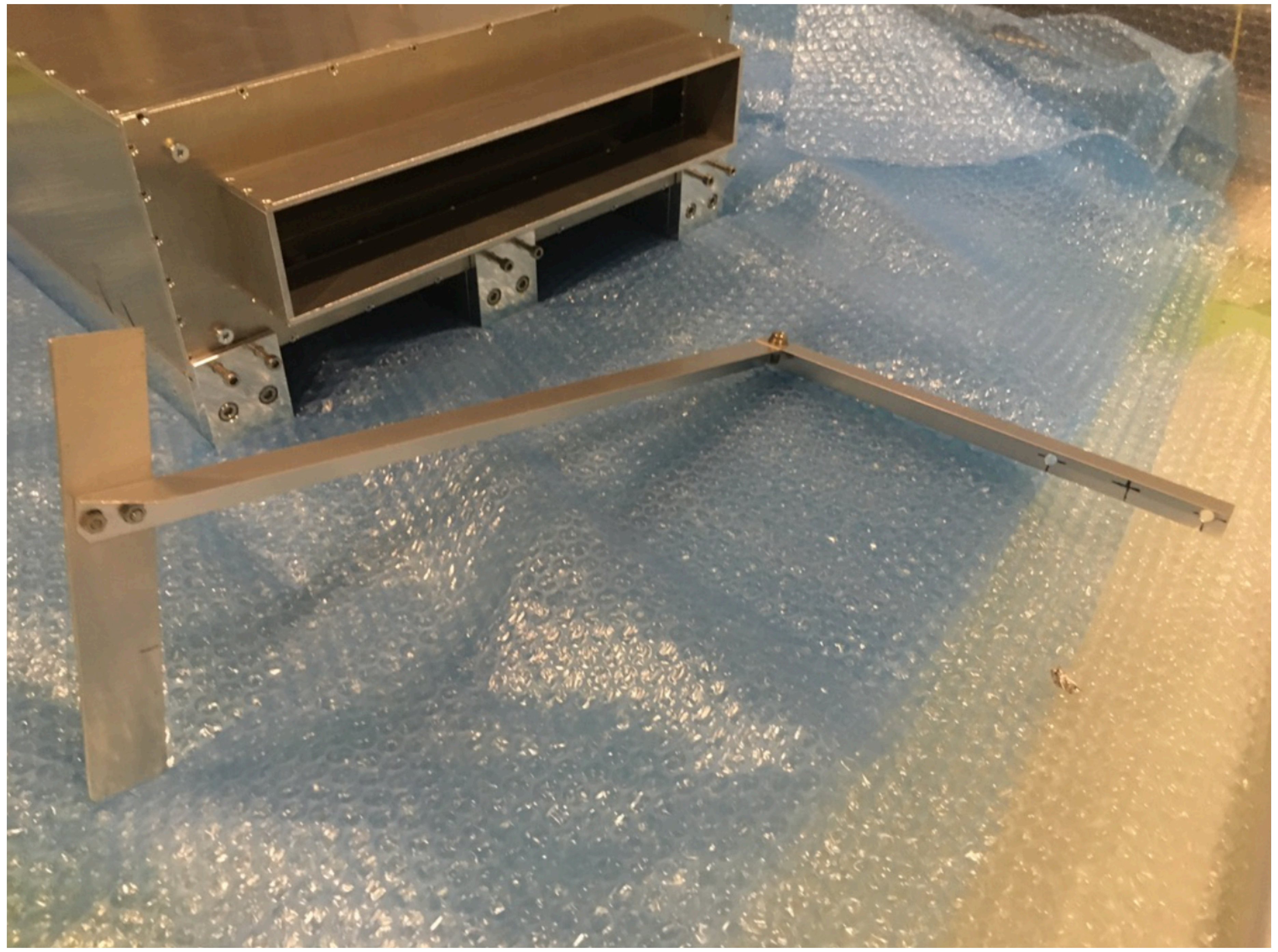


Beam Position Monitor (BPM) prototype

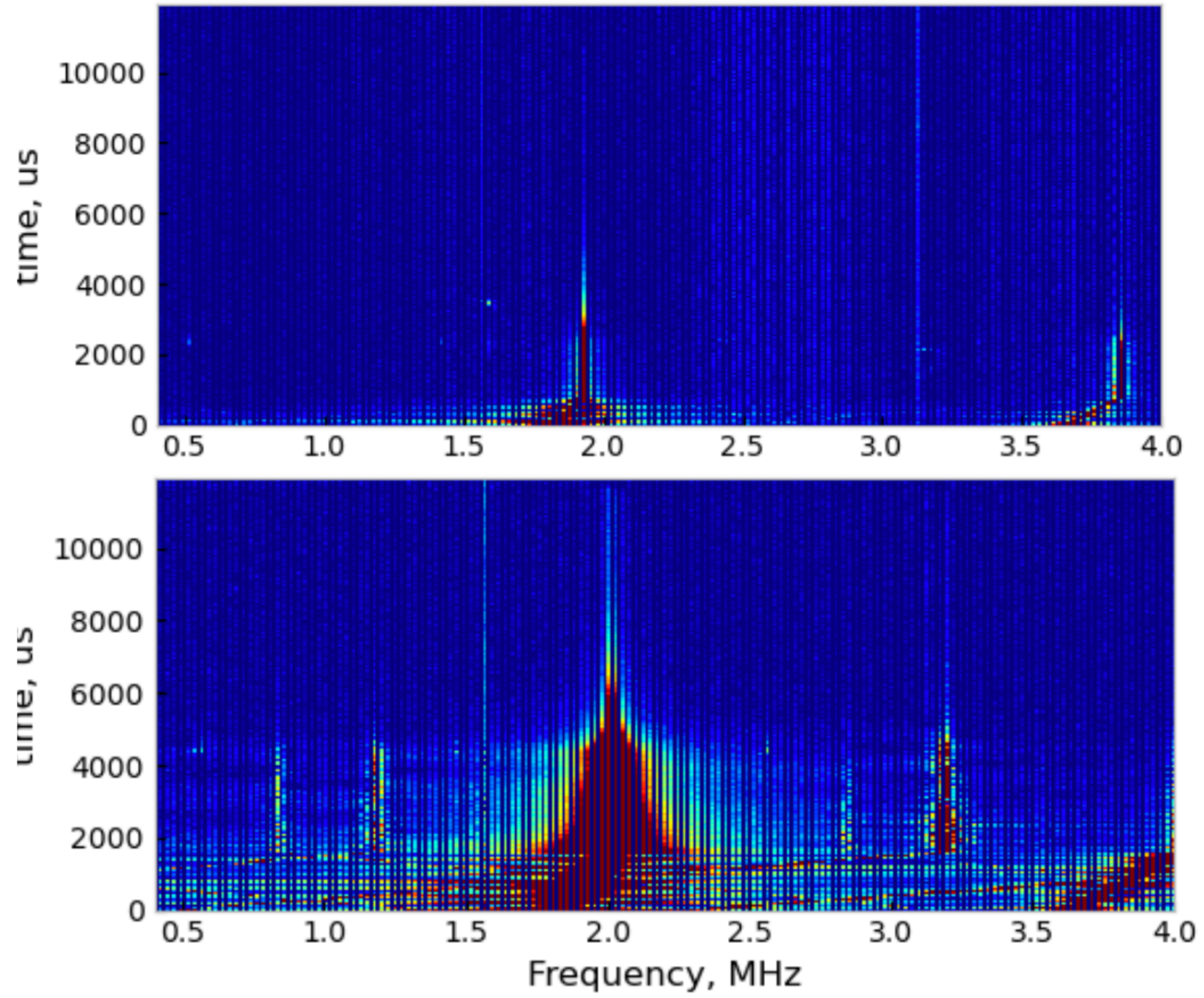
- A half size (horizontal) BPM prototype is made and tested in the FFA at Kyoto Univ. (KURNS).
- Turn by turn position measurement and tune measurement have been done.



Hor. and Ver. beam position evolution during acceleration.



A half size BPM and scraper



Frequency spectrum to measure tune.

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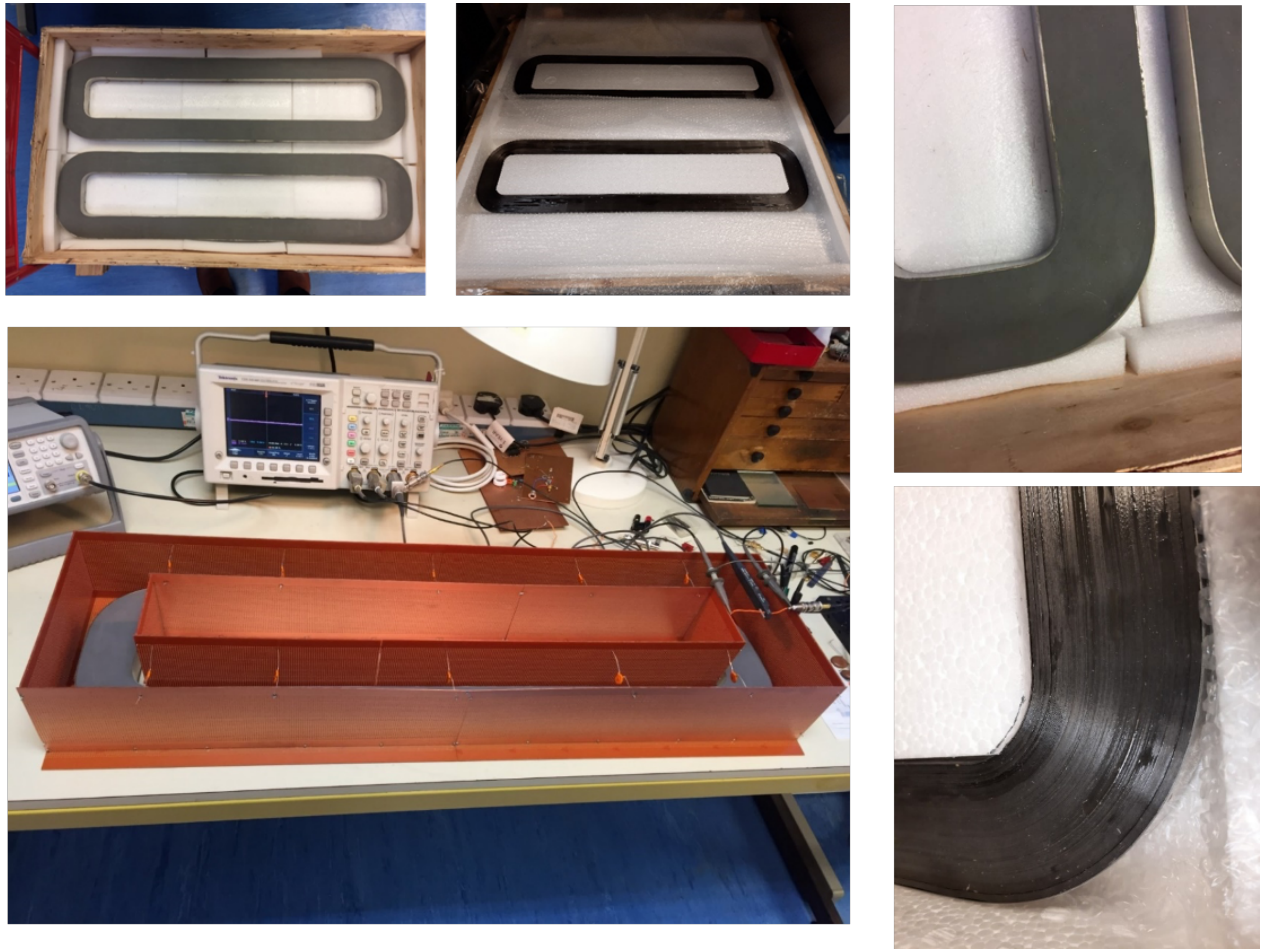
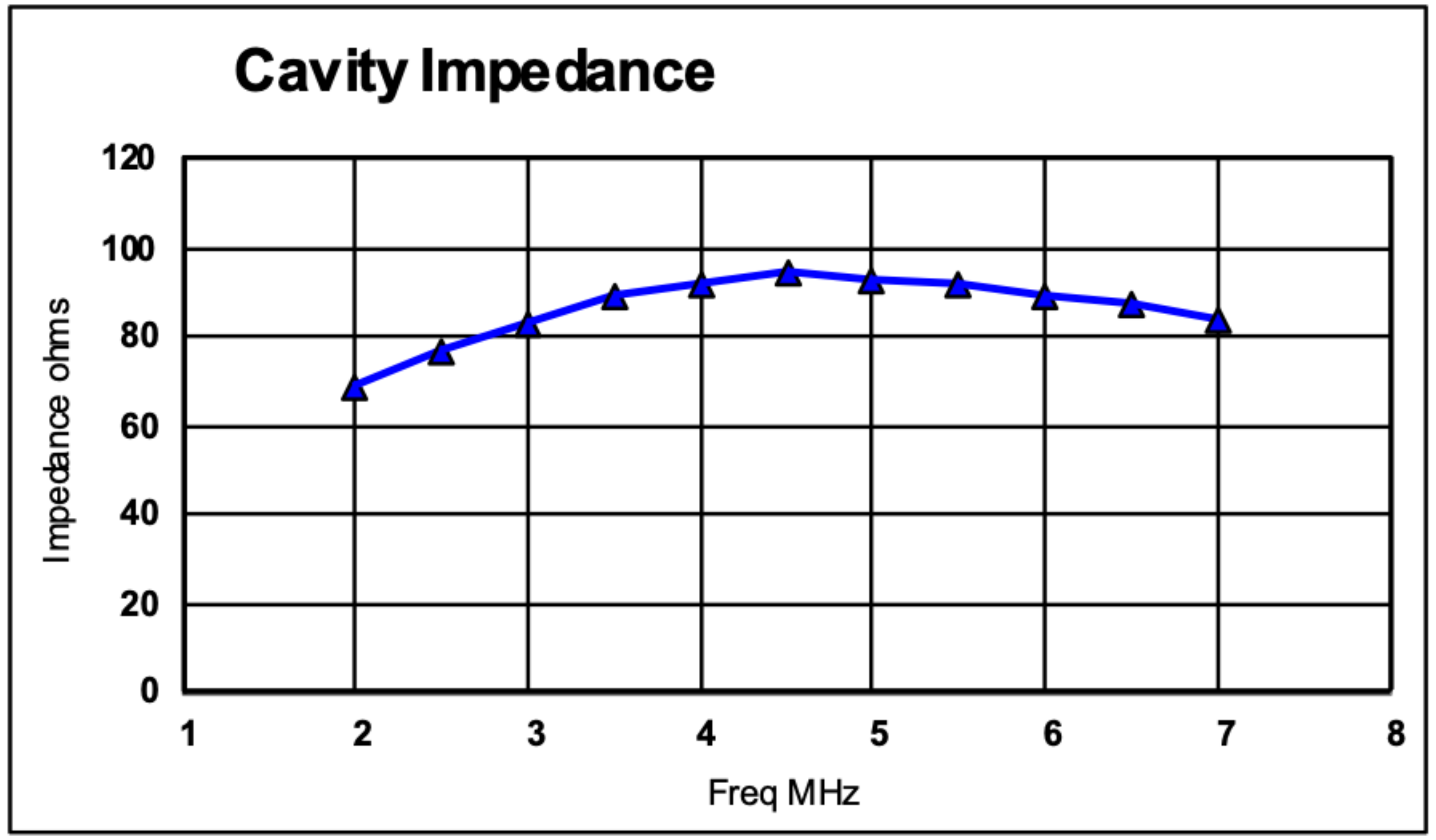
RF cavity, Ferrite or Magnetic Alloy (MA)

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