Science and Technology Facilities Council

Design study for RAL FETS-FFA

Shinji Machida
UKRI/STFC Rutherford Appleton Laboratory

14 September 2023
FFA workshop at J-lab

Outline

- Goal
- Optics update
- Higher energy extension
- Space charge effects
- RF knock-out and its mitigation
- Hardware
- Summary

Science and
Technology
Facilities Council

Goal

Our project goal

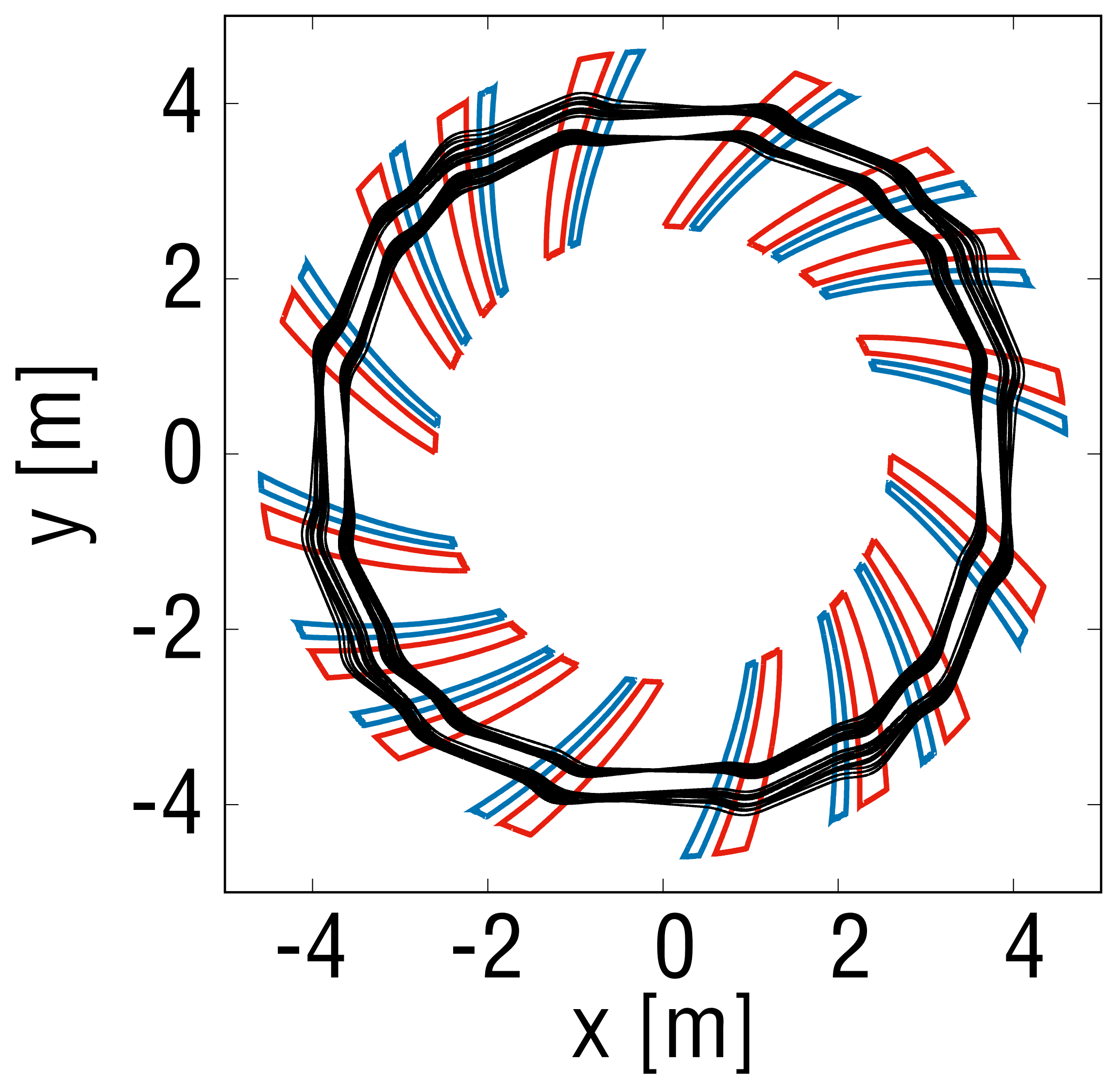
- FETS-FFA at RAL will be **the first demonstrator FFA** for high intensity operation.
- It will not have high current (no instability), but **space charge tune shift** is the same level of SNS and J-PARC.
- **Mitigation of beam loss** is one of the main purpose of the experiment.

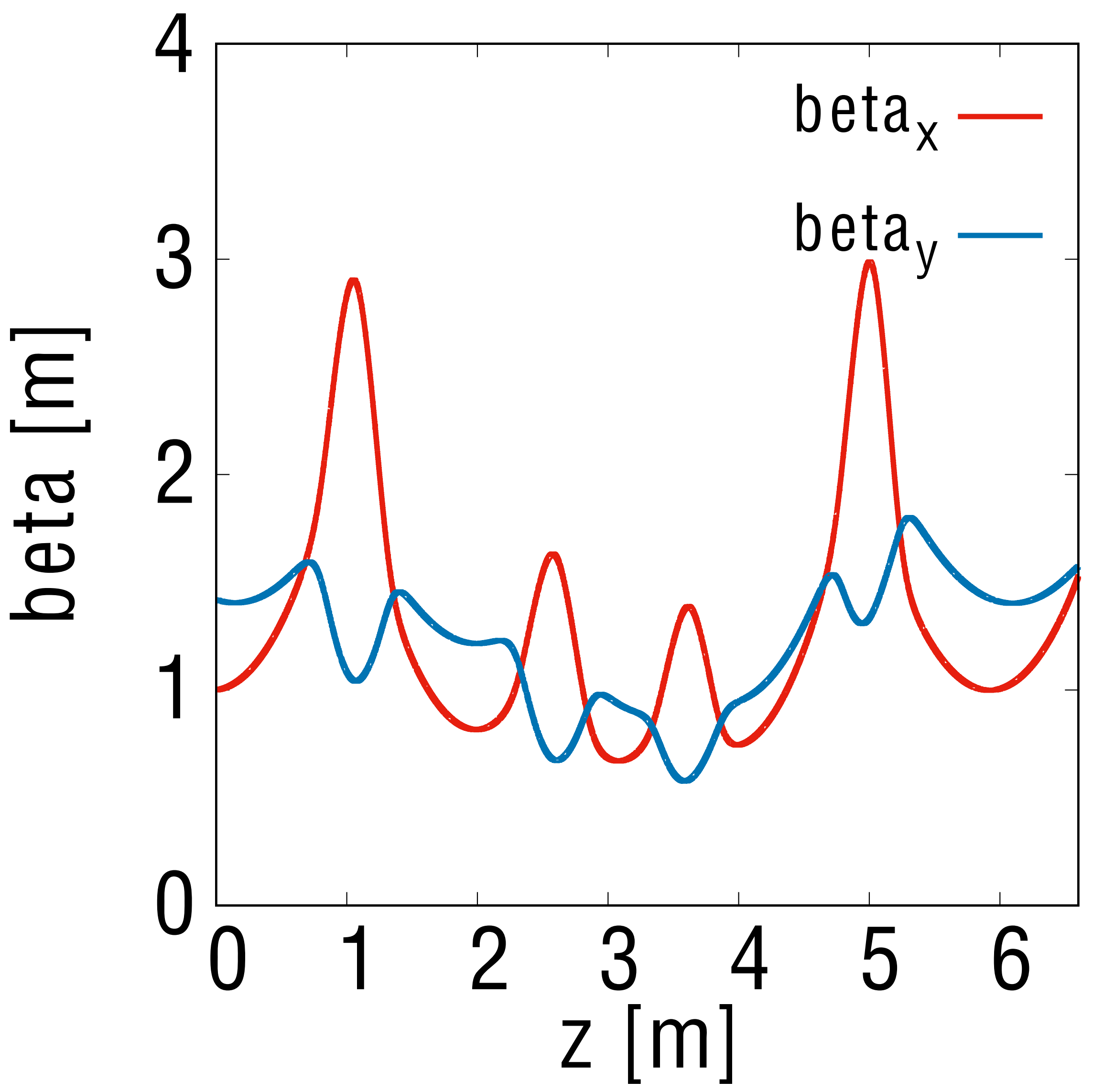
Optics update

Optics baseline fixed

- Novel lattice with
  - FD(DF) spiral
  - Superperiod structure
- Large dynamic aperture

Energy	3 - 12 MeV
Particle	Proton
Intensity	3 x 10^{11}
Space charge tune shift	-0.3
Repetition	100 Hz (50 pps)
Average beam power	~ 50 W





Left figure shows injection and extraction orbits which have the momentum ratio of two. Right figure shows beta functions.

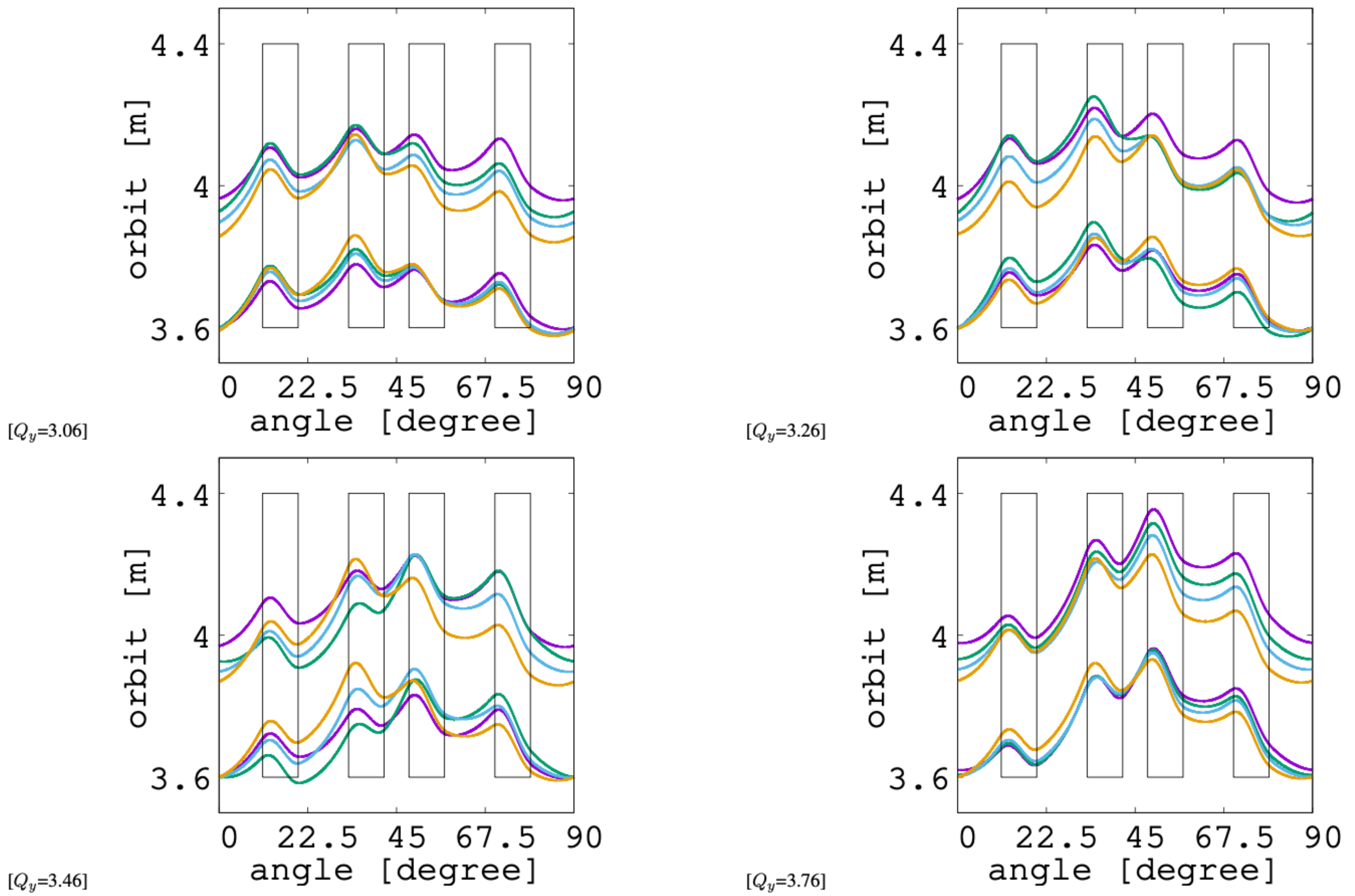


Figure 2.8: 3 MeV and 12 MeV orbits for 16 operating points.

Science and Technology Facilities Council

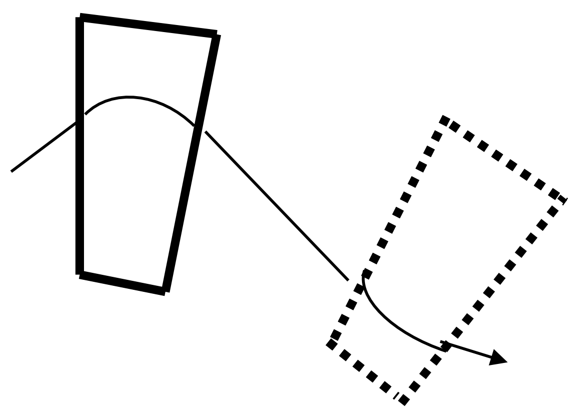
Novel lattice

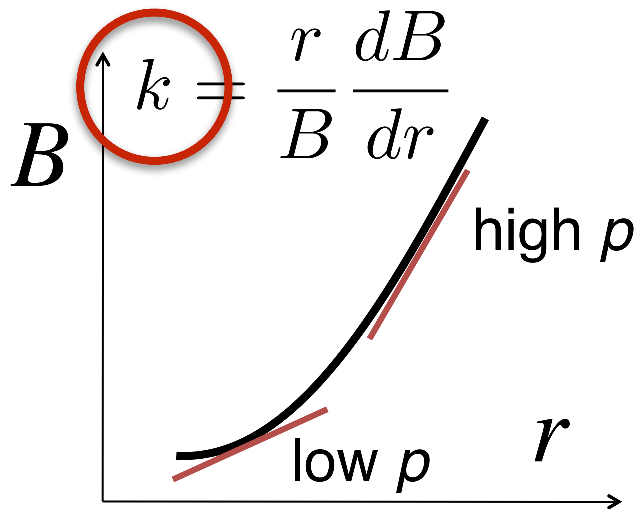
DF(FD) spiral

1) $k = \frac{r}{B}\frac{dB}{dr}$ 2) B_d/B_f 3) $\tan\zeta$

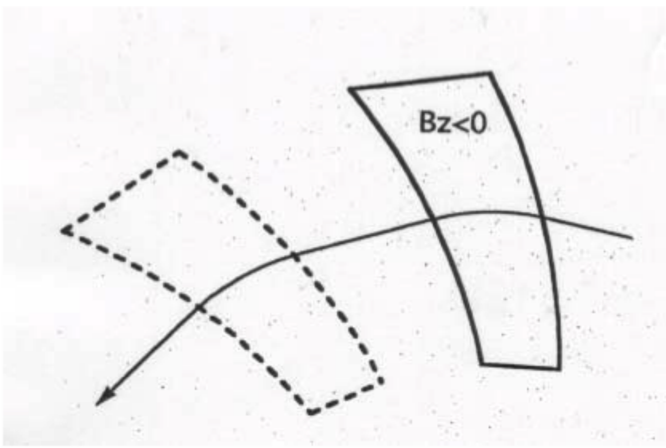
Flexibility of operating point (transverse tune) is essential for high intensity operation (Qh ~ Qv).

radial sector



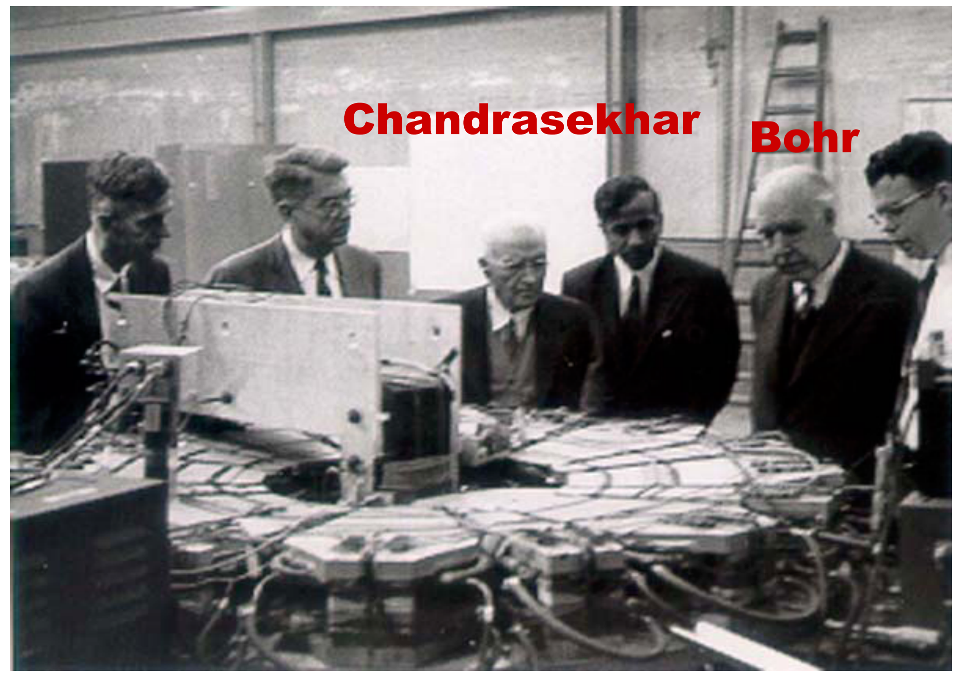


spiral sector

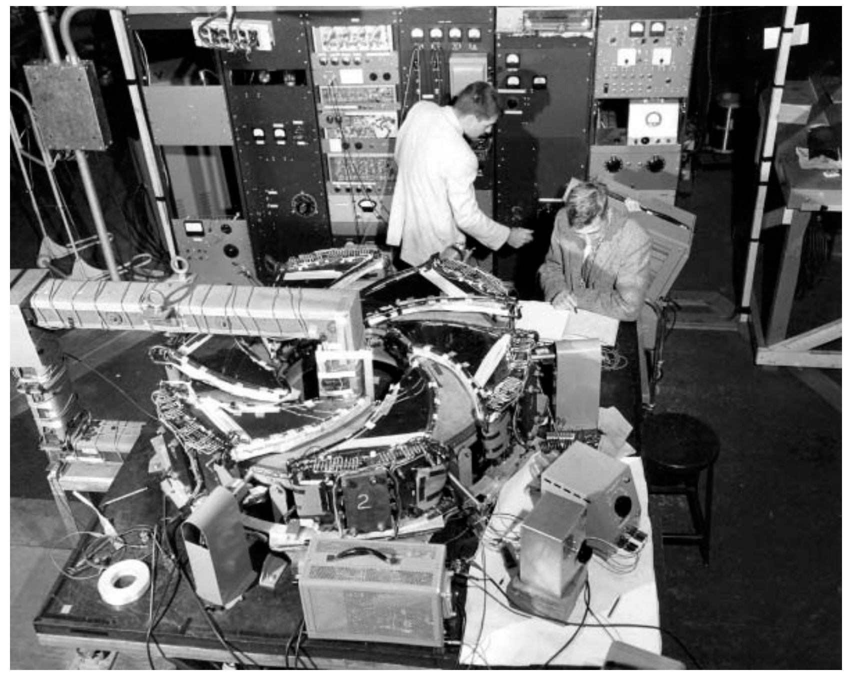


Alternating gradient focusing by focusing (normal bend) and defocusing (reserve bend)

Alternating gradient focusing by focusing (normal bend) and defocusing (edge angle)



400 keV radial sector

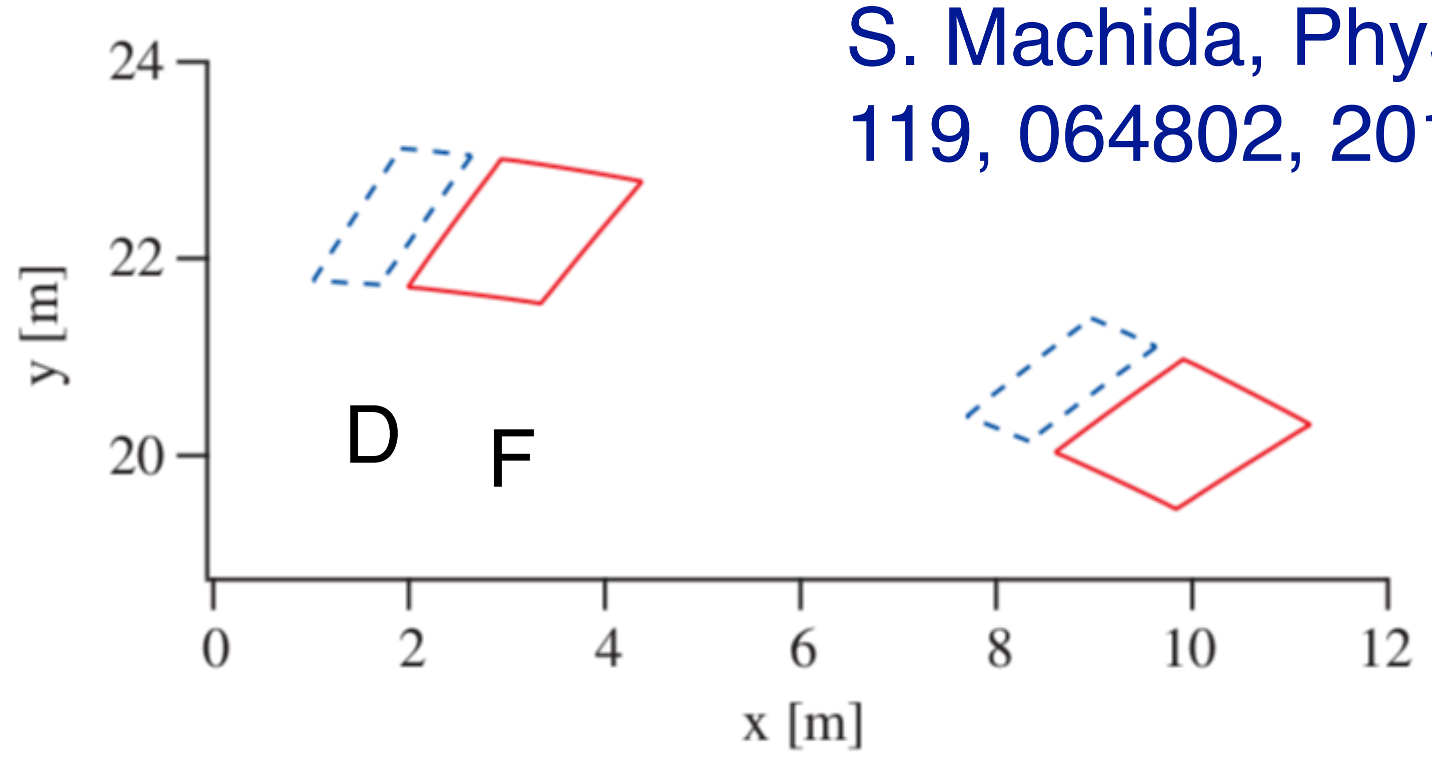


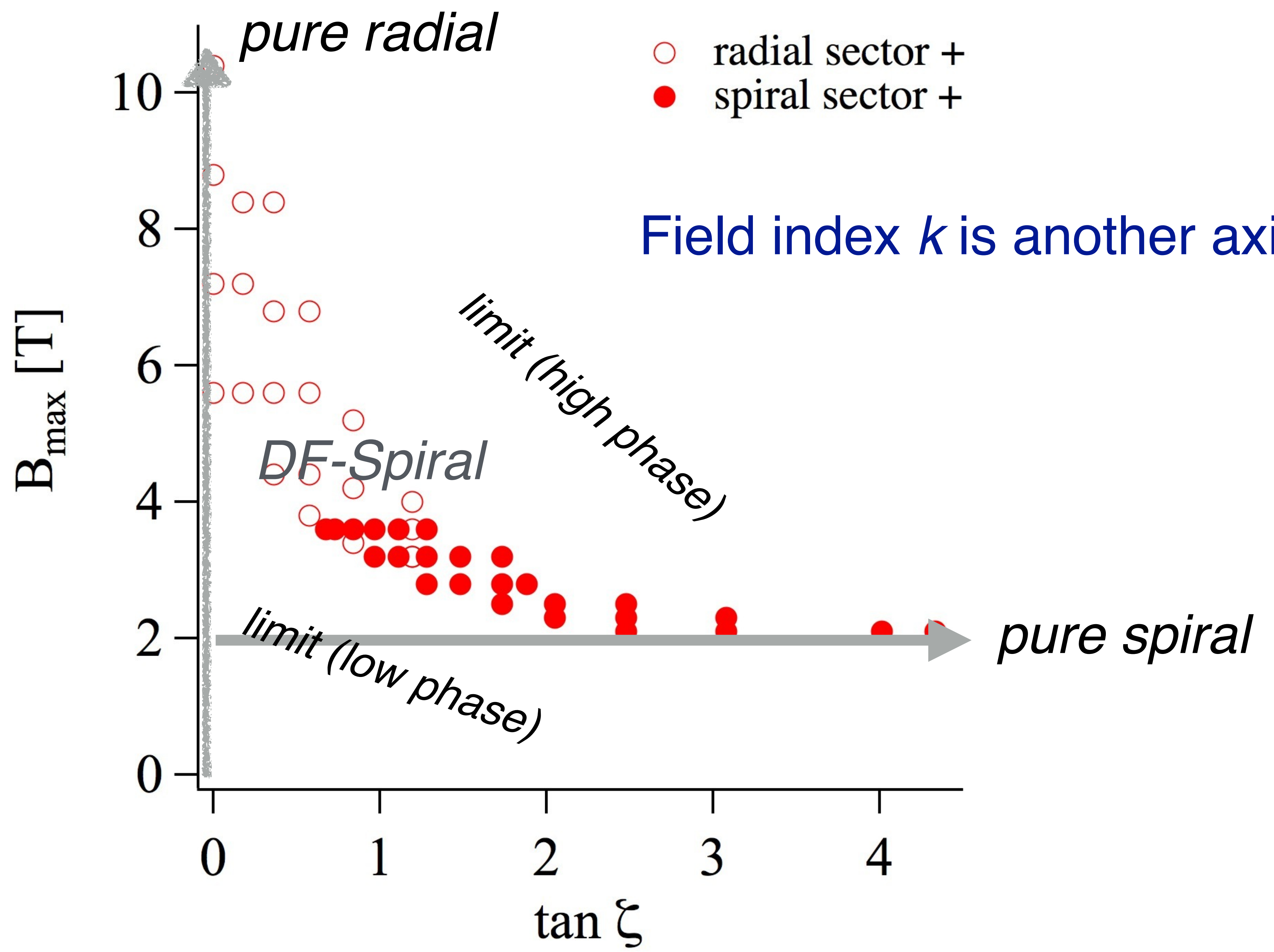
180 keV spiral sector

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

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

S. Machida, Phys. Rev. Lett. 119, 064802, 2017





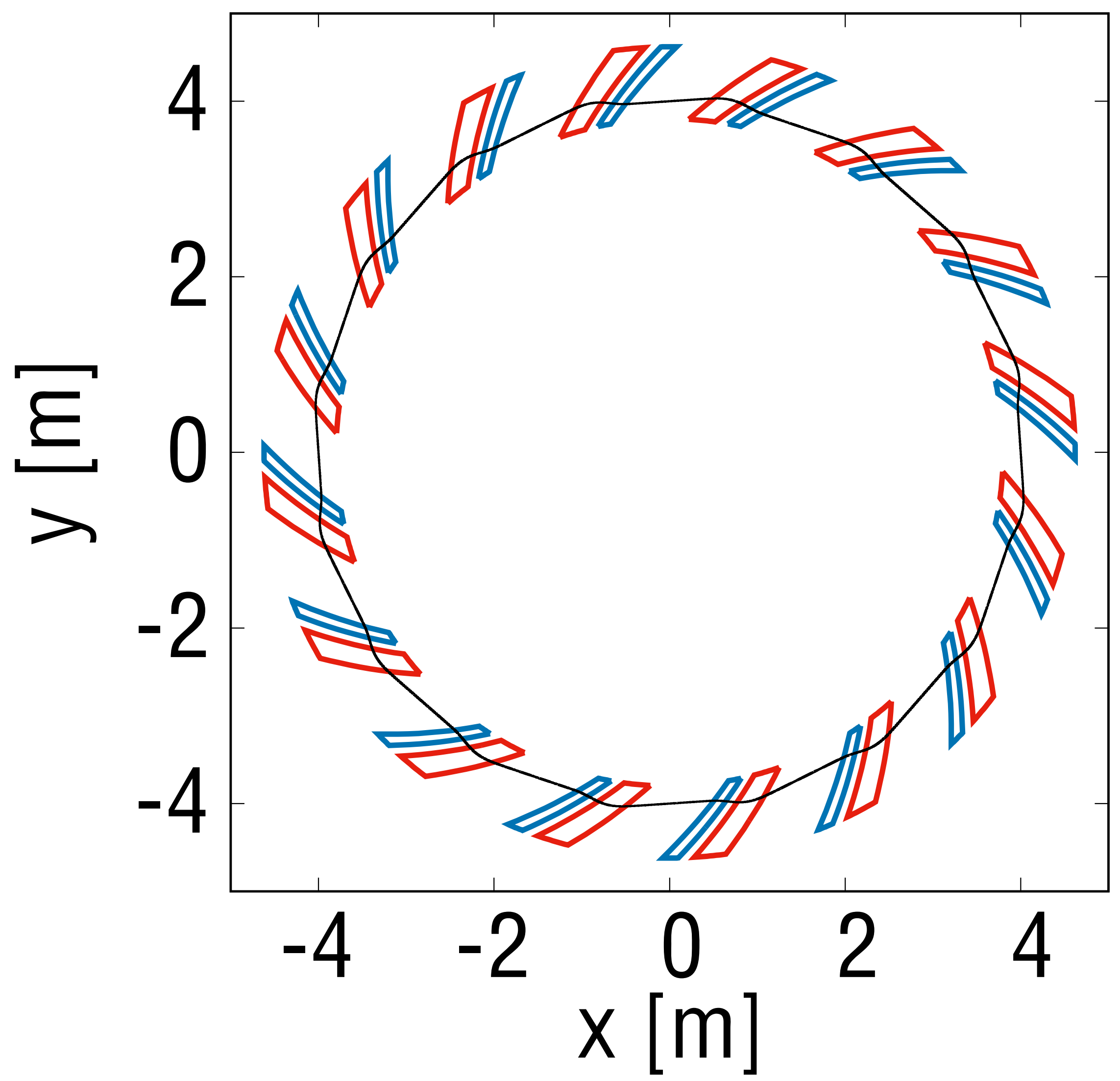
Field index *k* is another axis

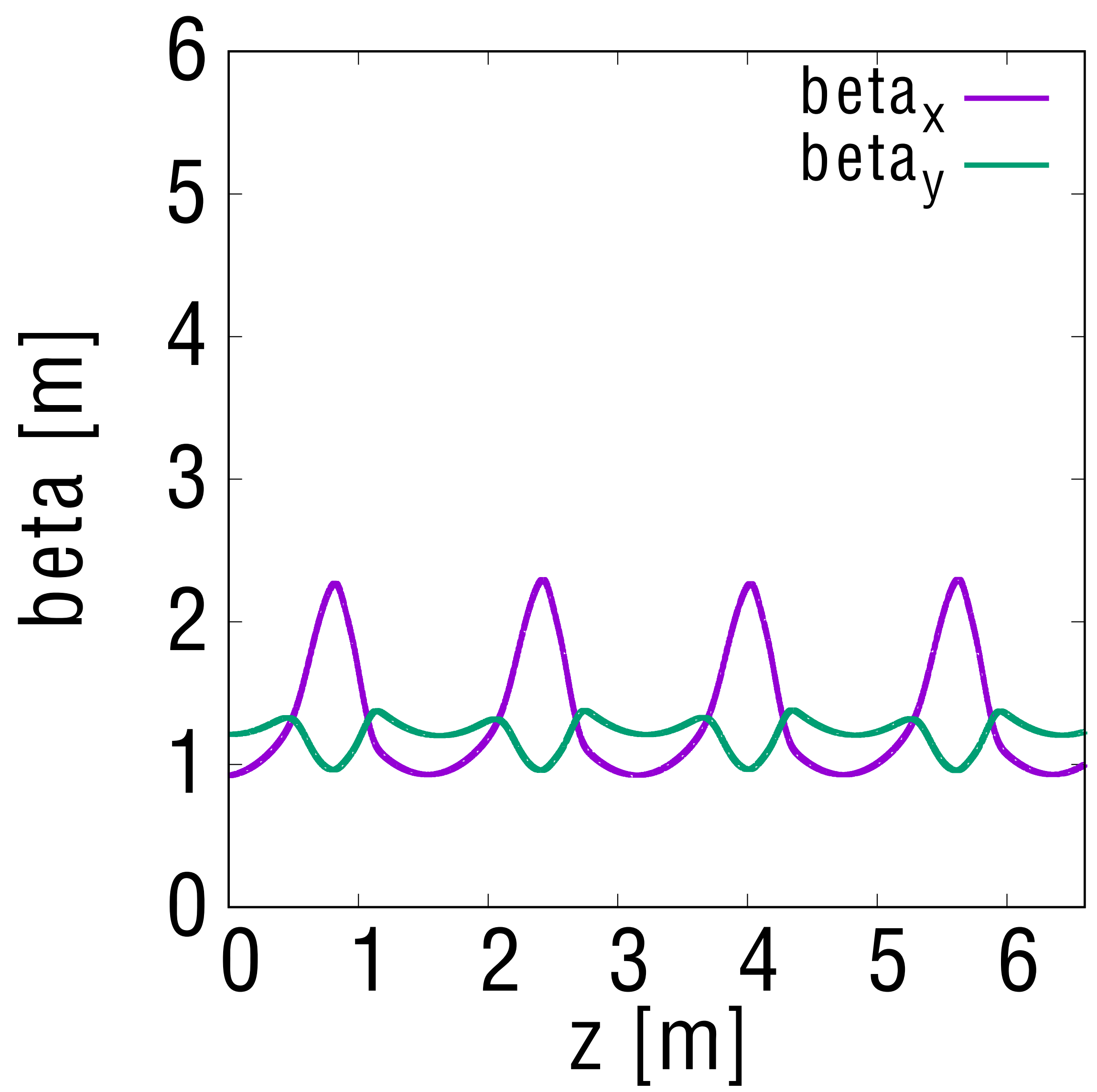
Science and Technology Facilities Council

Novel lattice

Superperiod structure

For high intensity operation, enough space for injection and extraction is essential.

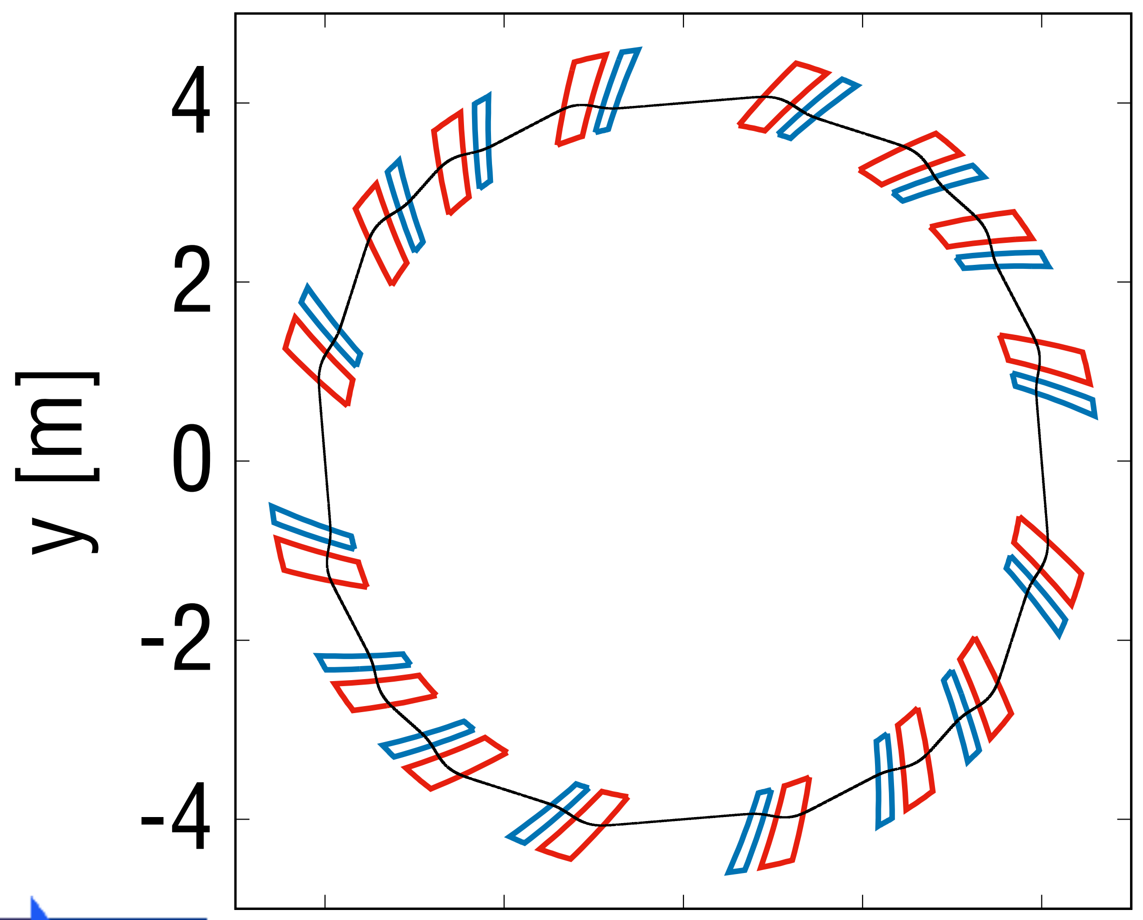


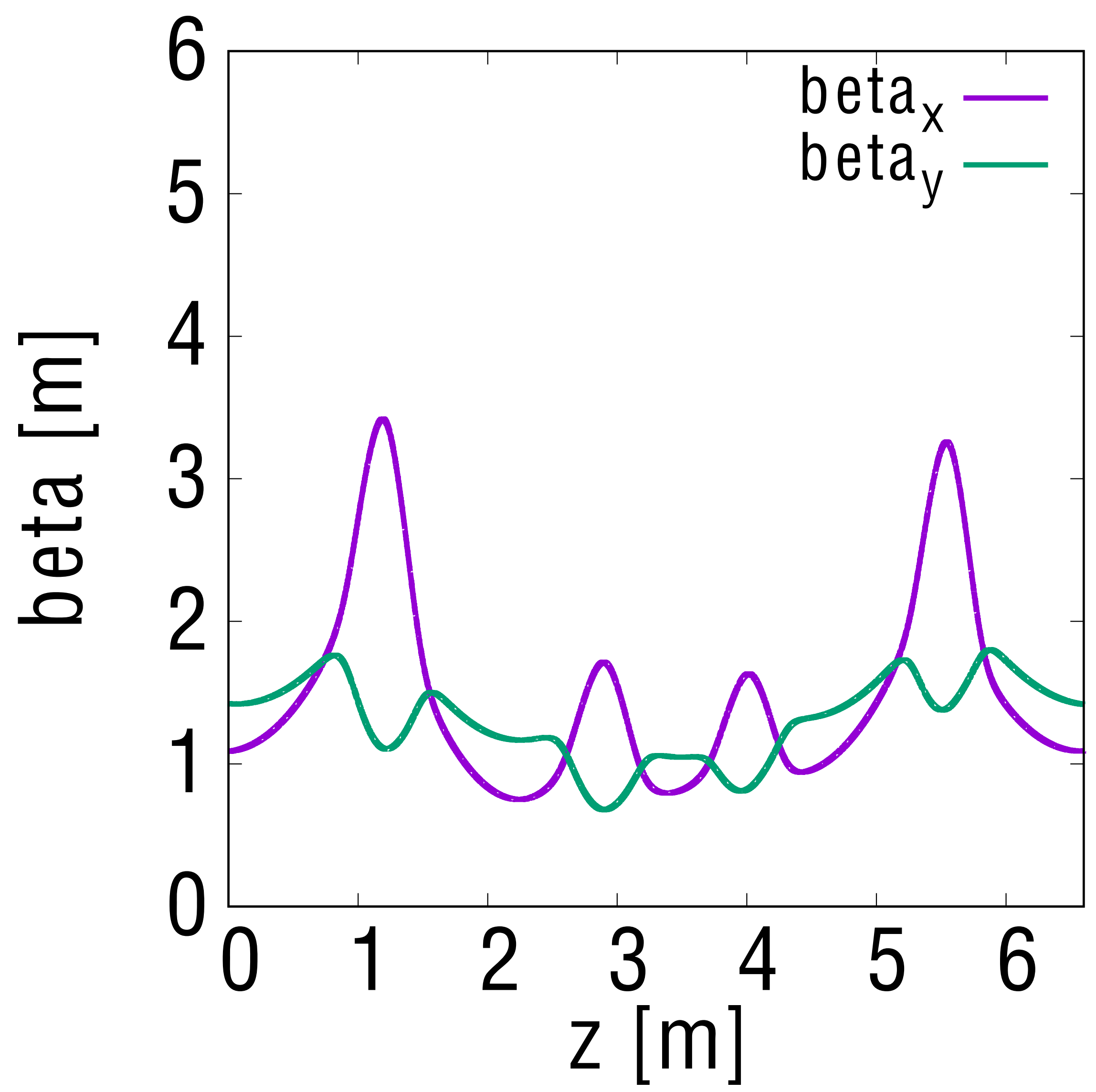


16-fold symmetry

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

keeping $B_z(r, \theta) = B_{z0}\left(\frac{r}{r_0}\right)^k F(\theta)$





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

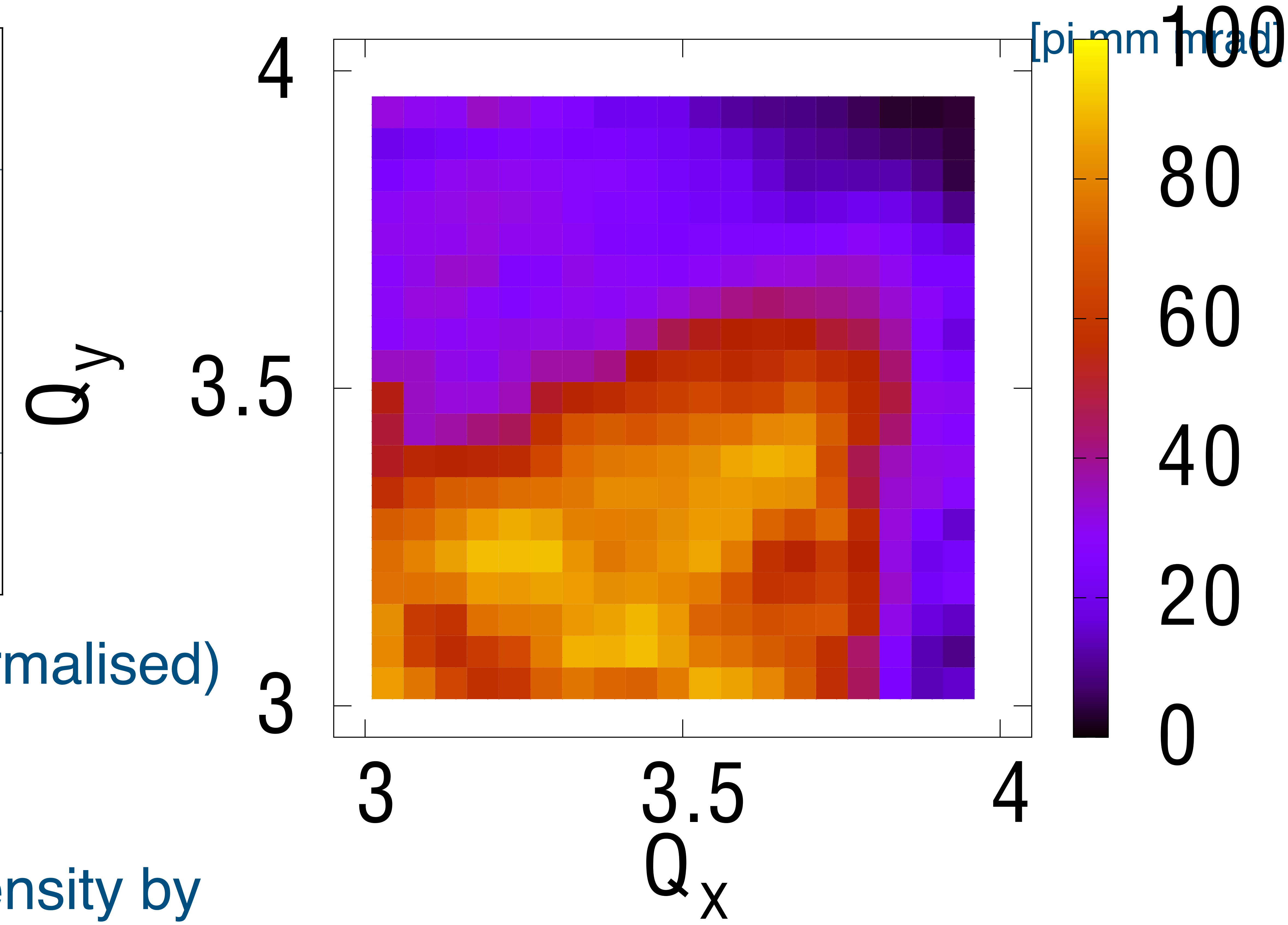
Horizontal beam size is larger.

Dynamic aperture

Same geometrical acceptance as SNS and J-PARC

Dynamic aperture decreases with superperiod structure.
However, still enough margin compared with beam emittance.

	Normalised emittance	Geometrical emittance	Vertical beam size [mm]
Beam core	10 [pi mm mrad]	125 [pi mm mrad]	+/- 16 mm
Collimator acceptance	20	250	+/- 22 mm
Vacuum chamber size	40	500	+/- 32 mm



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

At 3 MeV, uniform beam of 10 pi mm mrad (100%, normalised)

$$\Delta Q = -\frac{r_p n_t}{2\pi\beta\gamma^2\varepsilon_n B_f} = -0.12$$ 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 3×10^{11})

Science and Technology Facilities Council

Aperture specification

Table 2.10: 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

Table 2.11: Vertical aperture

	doublet 1-4
physical acceptance [mm]	±32
closed orbit distortion [mm]	±8
beam stay clear [mm]	±40
vacuum chamber thickness [mm]	10
trim coil thickness [mm]	20
magnet aperture mm]	±70

Orbit excursion: 700~800 mm

Table 2.7: 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 2.8: Horizontal aperture

	doublet 1	doublet 2	doublet 3	doublet 4
orbit radius $_{min}$ [m]	3.5835	3.7143	3.6684	3.5900
orbit radius $_{max}$ [m]	4.1688	4.2695	4.3561	4.2324
orbit excursion [mm]	585	555	688	642
physical acceptance (fixed momentum) [mm]	± 40	± 40	± 40	± 40
closed orbit distortion [mm]	±8	±8	±8	±8
beam stay clear $_{inside}$ [m]	3.5355	3.6663	3.6204	3.5420
beam stay clear $_{outside}$ [m]	4.2168	4.3175	4.4041	4.2804
beam aperture [mm]	681	651	784	738
GFR addition (each for both sides) [mm]	140	140	140	140
iron yoke $_{inside}$ [m]	3.3955	3.5263	3.4804	3.4020
iron yoke $_{outside}$ [m]	4.3568	4.4575	4.5441	4.4204
magnet aperture [mm]	961	931	1064	1018

Table 2.9: Horizontal aperture without operating point of Q_y=3.76

	doublet 1	doublet 2	doublet 3	doublet 4
orbit radius $_{min}$ [m]	3.5835	3.7143	3.6684	3.5900
orbit radius $_{max}$ [m]	4.1433	4.2526	4.2291	4.1831
orbit excursion [mm]	560	538	561	593
physical acceptance (fixed momentum) [mm]	± 40	± 40	± 40	± 40
closed orbit distortion [mm]	±8	±8	±8	±8
beam stay clear $_{inside}$ [m]	3.5355	3.6663	3.6204	3.5420
beam stay clear $_{outside}$ [m]	4.1913	4.3006	4.2771	4.2311
beam aperture [mm]	656	634	657	689
GFR addition (each for both sides) [mm]	140	140	140	140
iron yoke $_{inside}$ [m]	3.3955	3.5263	3.4804	3.4020
iron yoke $_{outside}$ [m]	4.3313	4.4406	4.4171	4.3711
magnet aperture [mm]	936	914	937	969

Why scaling FFA?

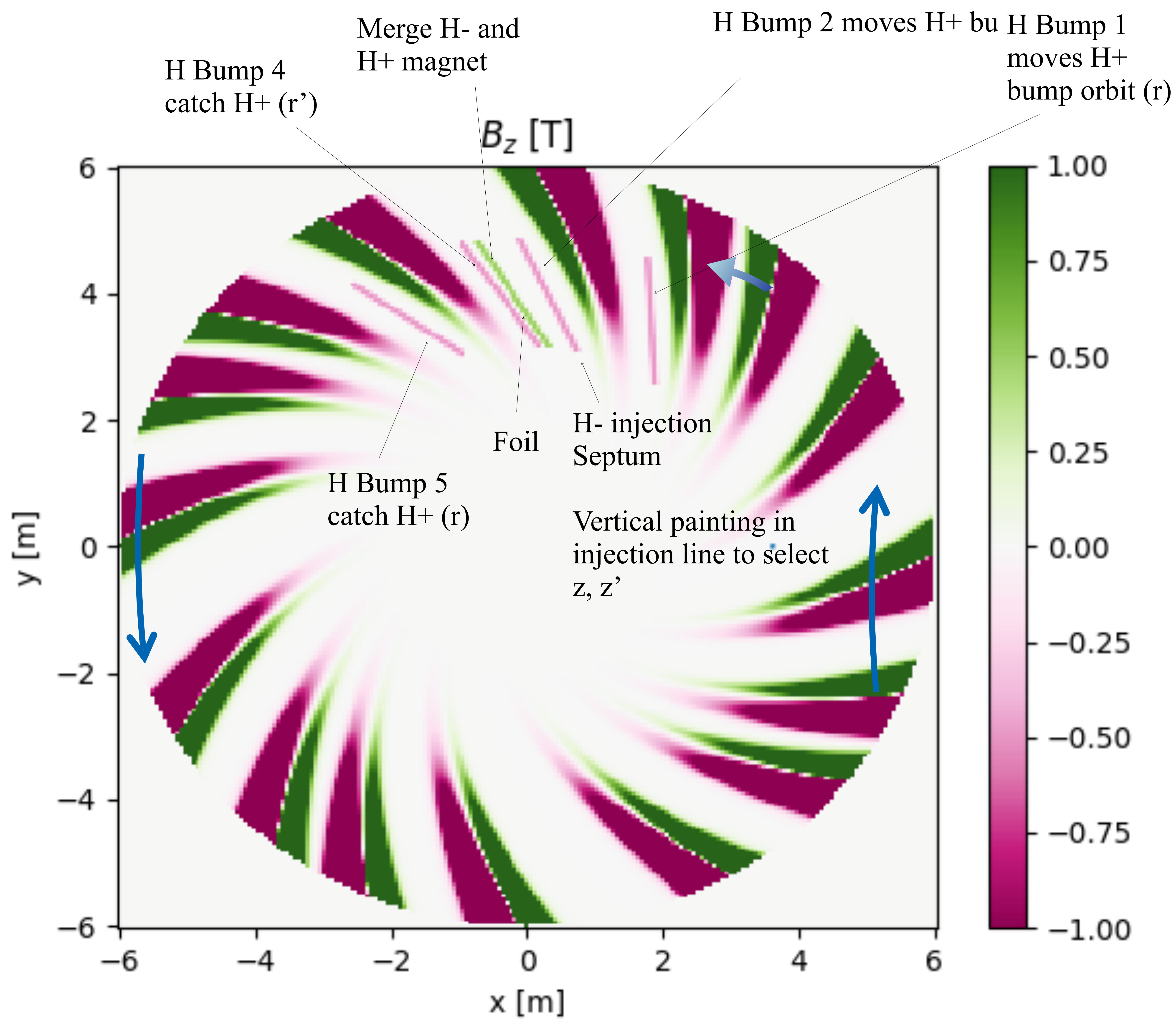
- Primary answer is **dynamic aperture (DA)**.
  - Geometrical DA of ~1000 pi mm mrad (~100 pi mm mrad, normalised) is our target.
- Harder to achieve with a non scaling FFA.
  - Or orbit excursion tends to increase to achieve the target.

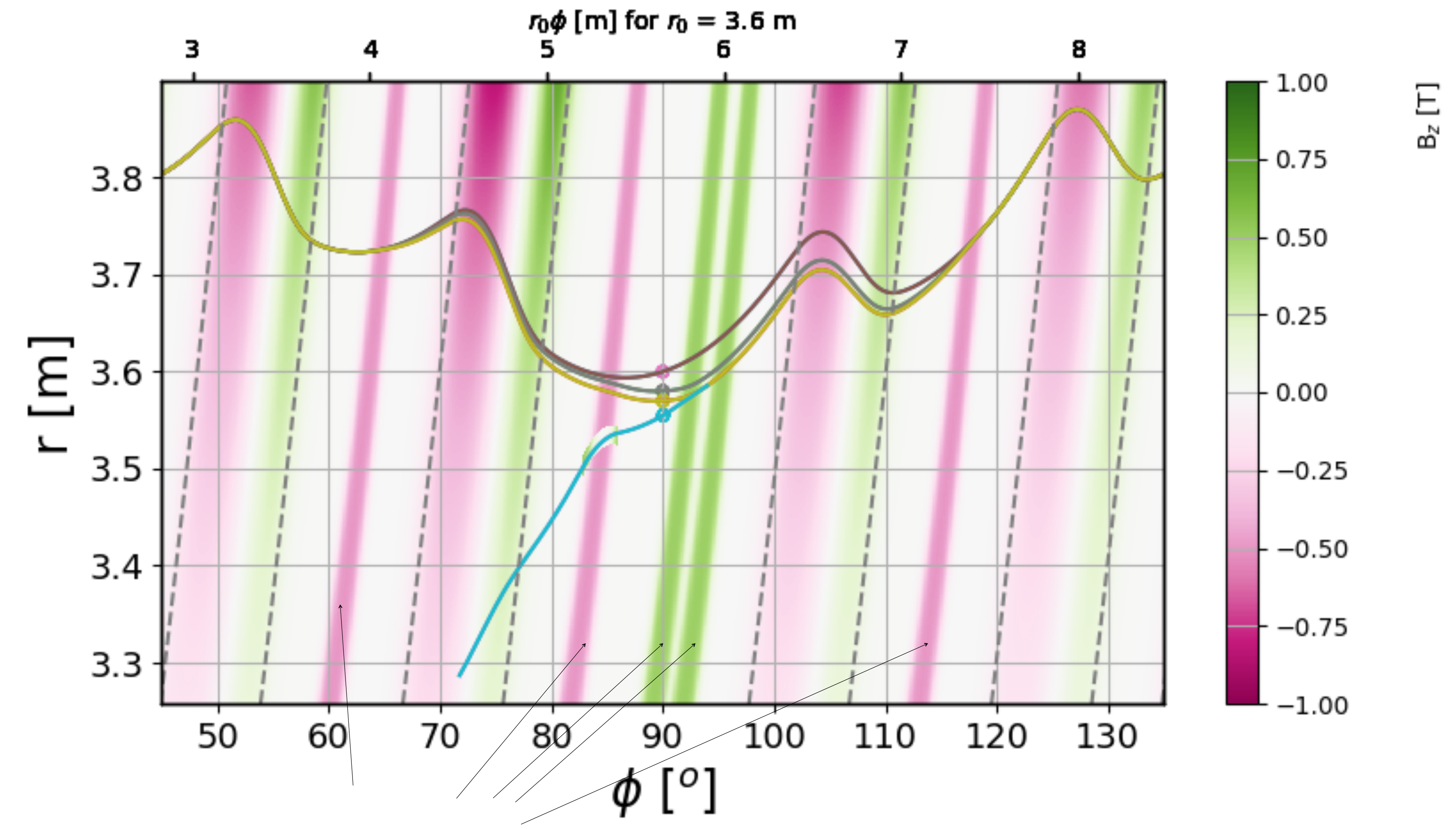
- Scaling law is the guiding principle for **beam commissioning**.

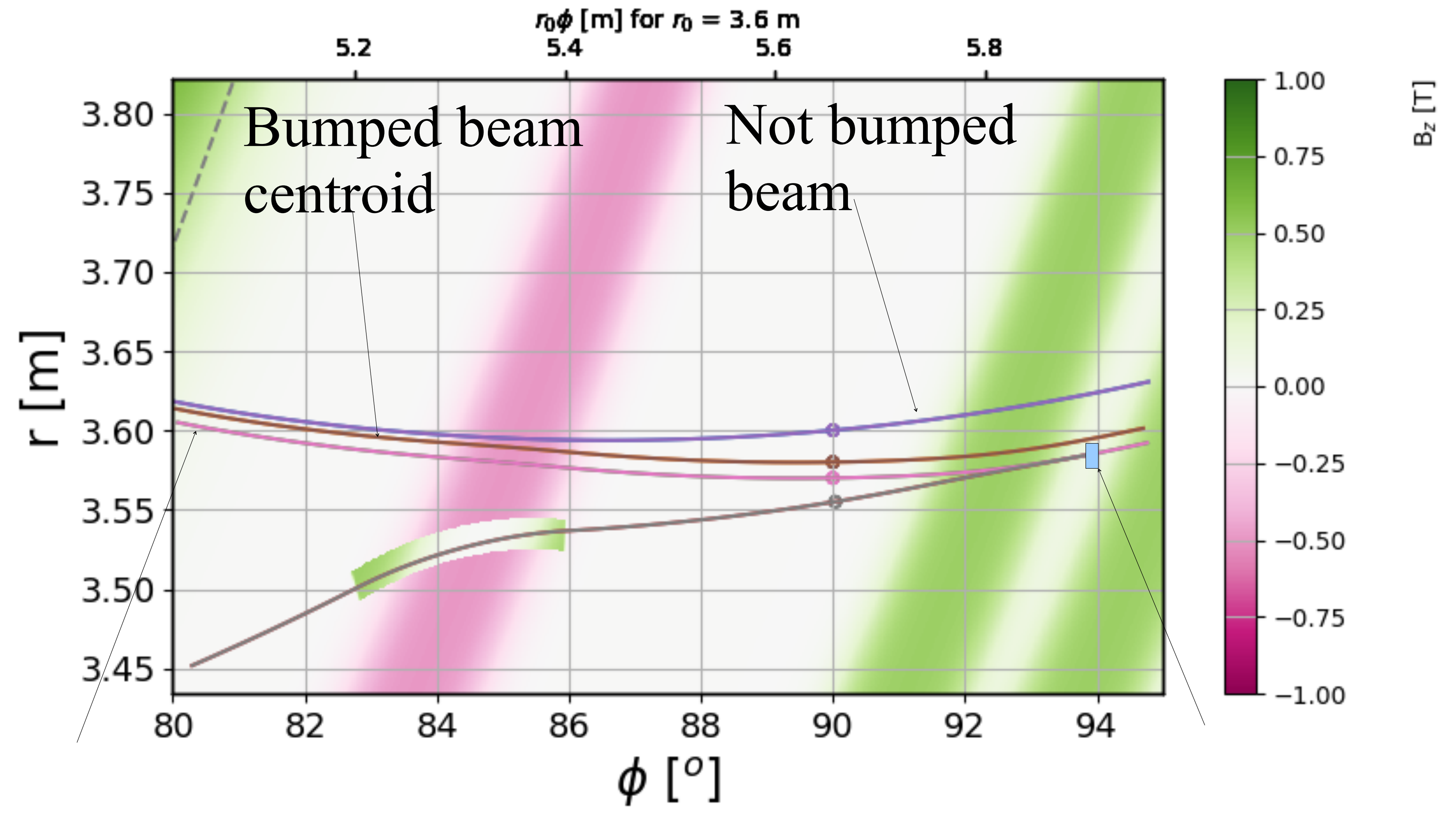
Injection

(Chris Rogers)

H- charge exchange injection with 5 bump magnets.





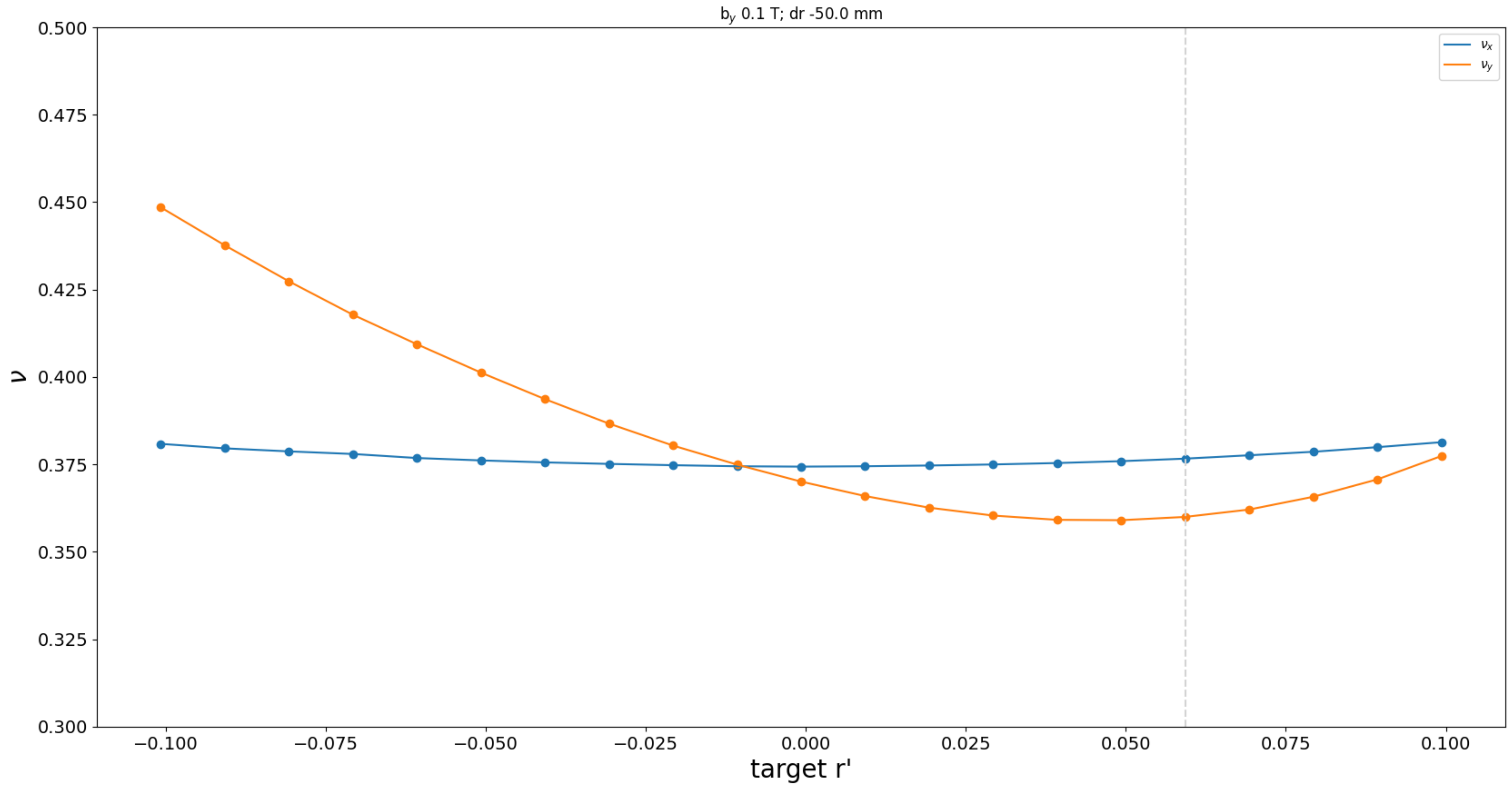


Injection

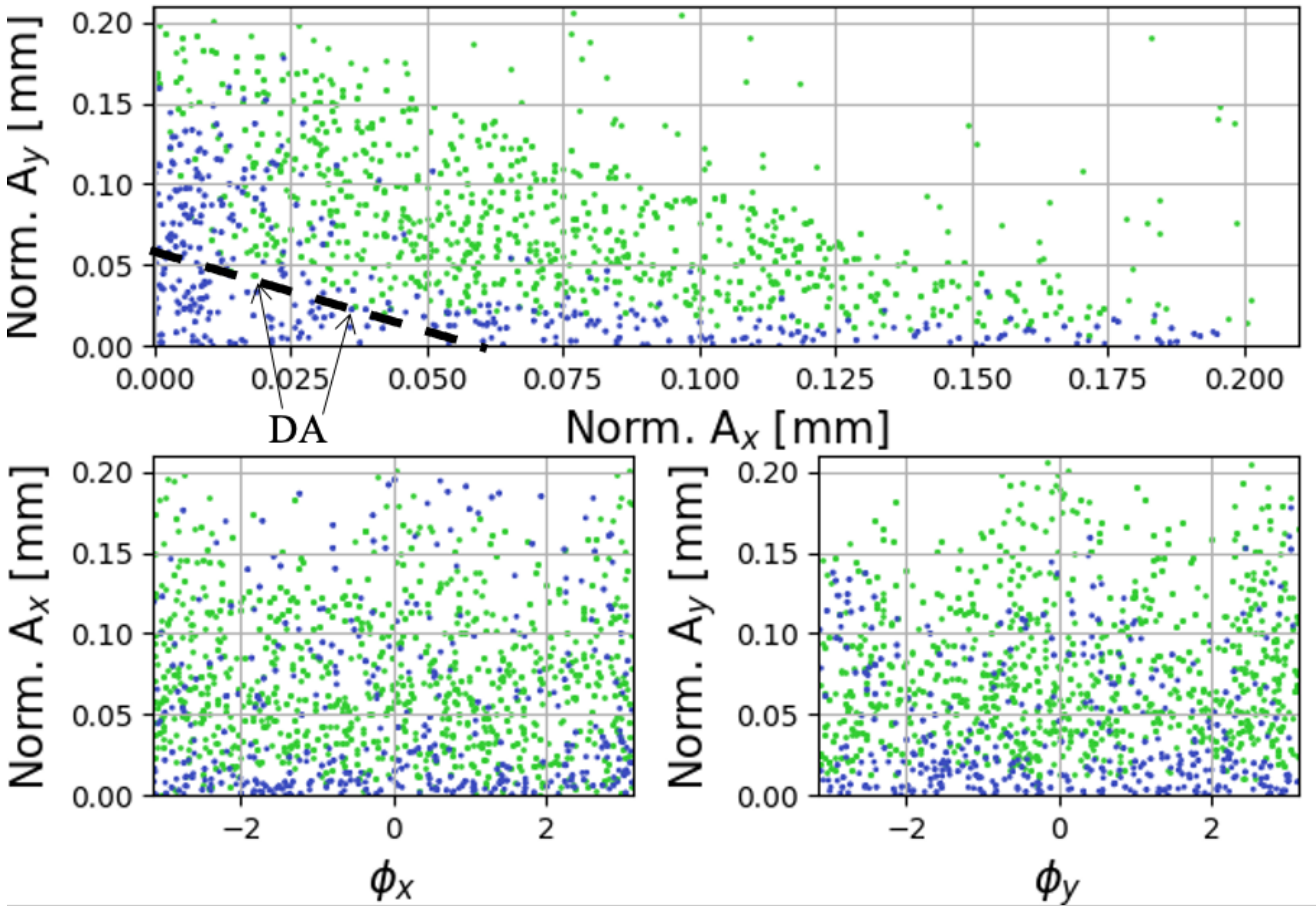
(Chris Rogers)

Orbit distortion will change tune and reduce dynamic aperture.

dQ=0.07 out of Q=3.40



DA > 50 pi mm mrad (normalised)



Science and Technology Facilities Council

Extension to higher energy

5 different ways of operation (FO or FF spiral)

FETS-FFA | Possible ways to extend maximum energy

FETS-FFA					
(3.41, 3.39)	(2.18, 1.05)	(2.87, 1.35)	(1.84, 1.57)	(1.68, 1.77)	(1.48, 1.31)
k=7.49	k=3.59	k=5.07	k=2.04	k=1.55	k=1.06
12 MeV	**19.5 MeV**	**19.7 MeV**	**20.0 MeV**	**20.2 MeV**	**30.9 MeV***

Price we have to pay is the flexibility of transverse tune.

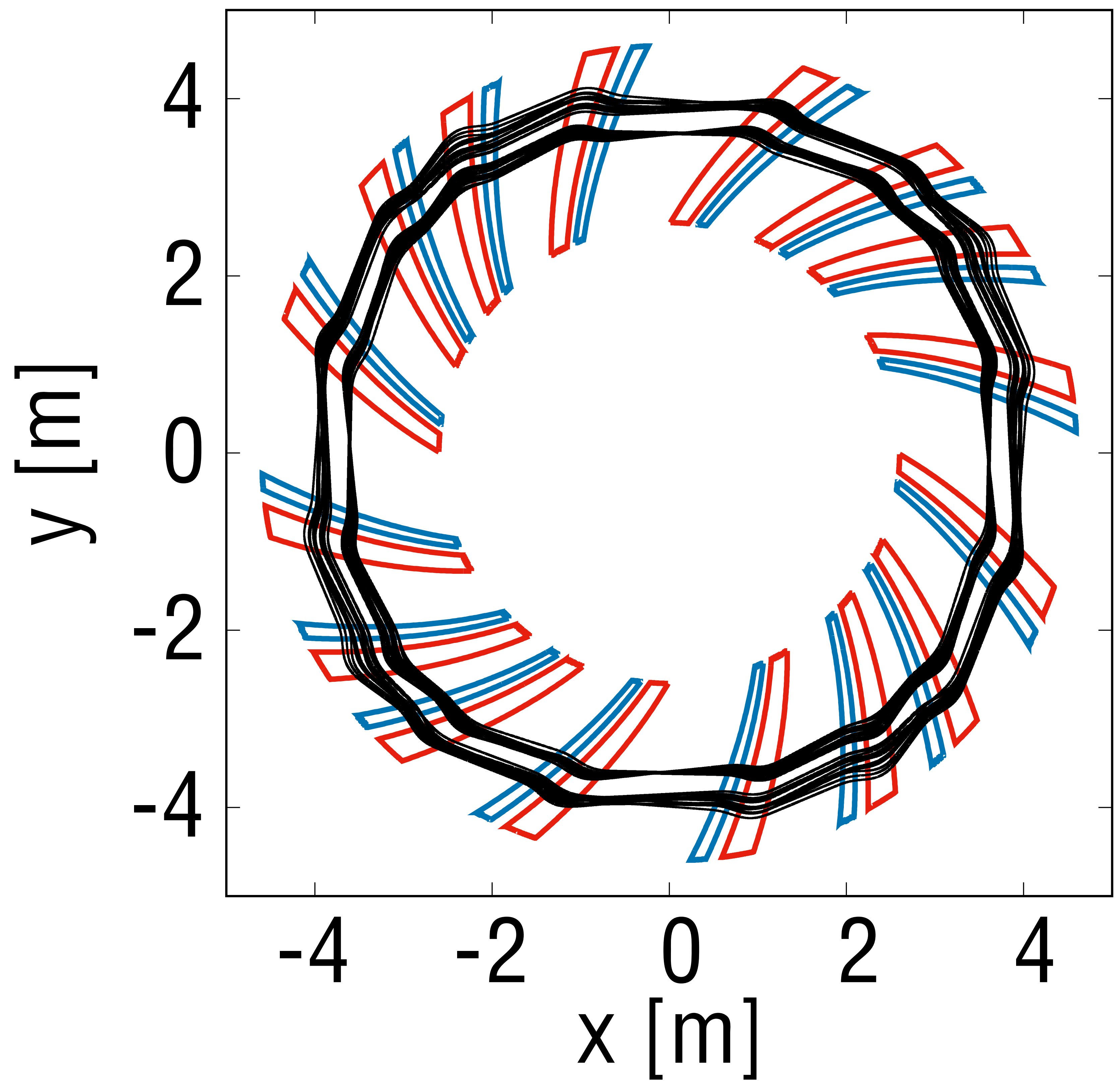
* Injection energy has to be above 20 MeV.

Science and Technology Facilities Council

Space charge effects

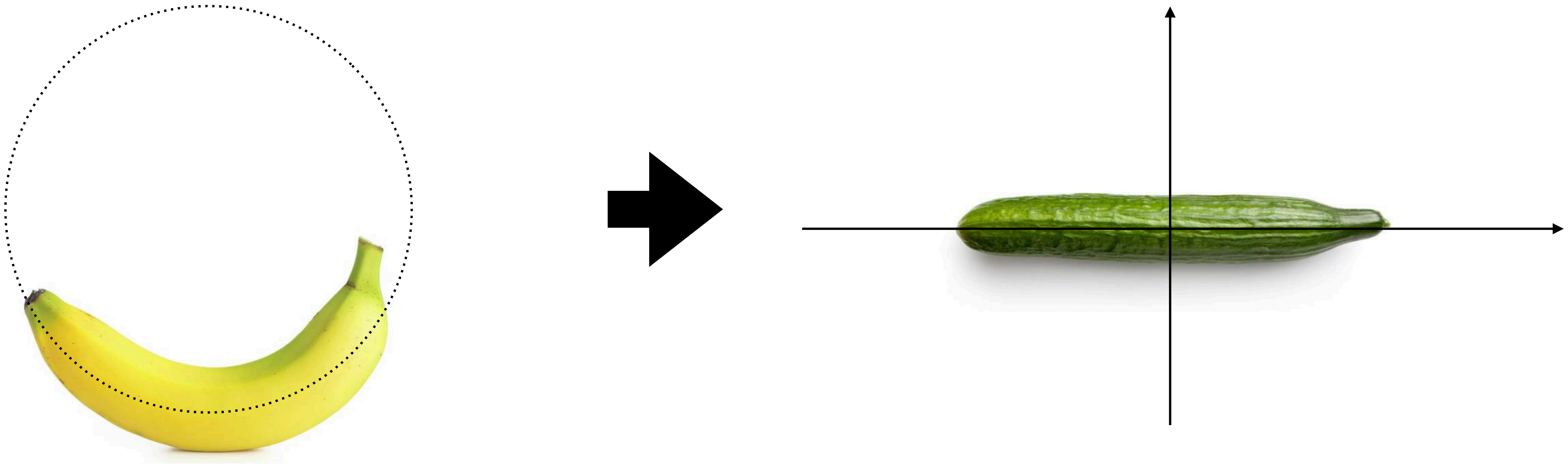
Space charge modelling in an FFA

- Equilibrium orbit is a function of time (momentum) and operating point.
    - Equilibrium orbit is fixed in a synchrotron.
- Important to know where the centre of charge distribution in order to calculate space charge effects.
    - Perturbation to betatron oscillation frequency matters.
- A bunch occupies the large fraction of the circumference, 1/2~1/4. The longitudinal size is much larger than the transverse.
    - A beam size is similar in 3D in a cyclotron.

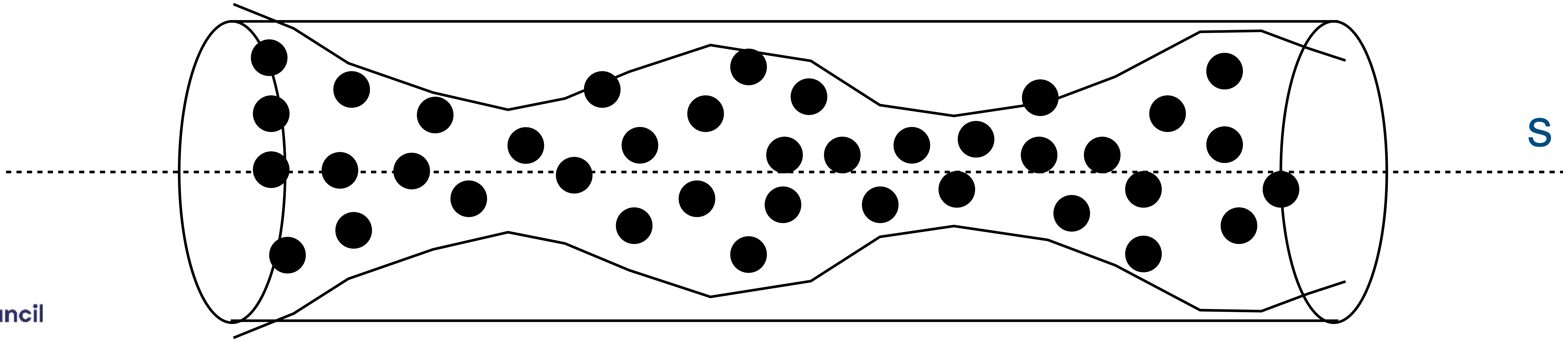


Science and Technology Facilities Council

Let’s make the beam straight in a well defined coordinate



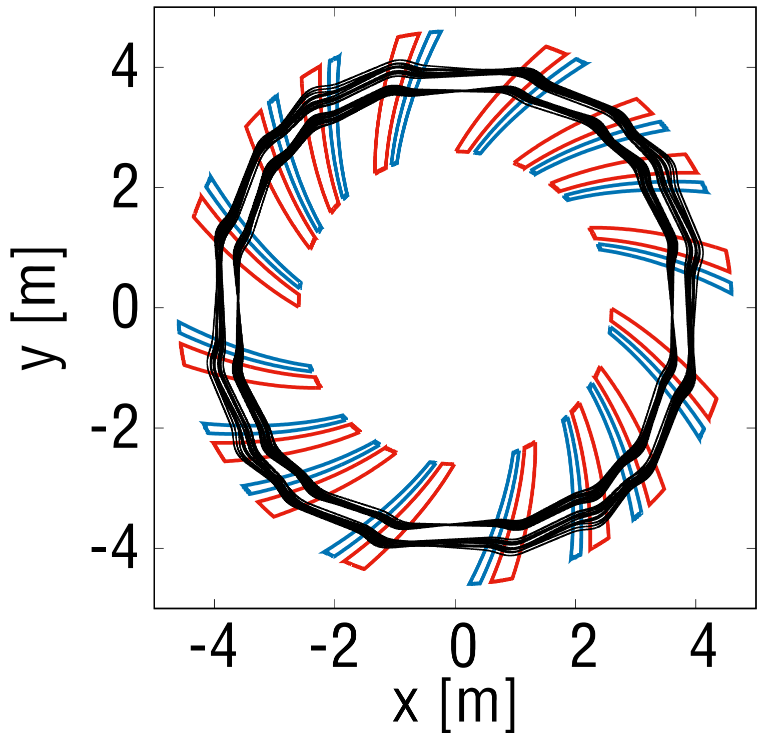
- Then, the next step is how to assign charges in a cylinder.
- We can still keep modulation of beam envelope in s-direction.



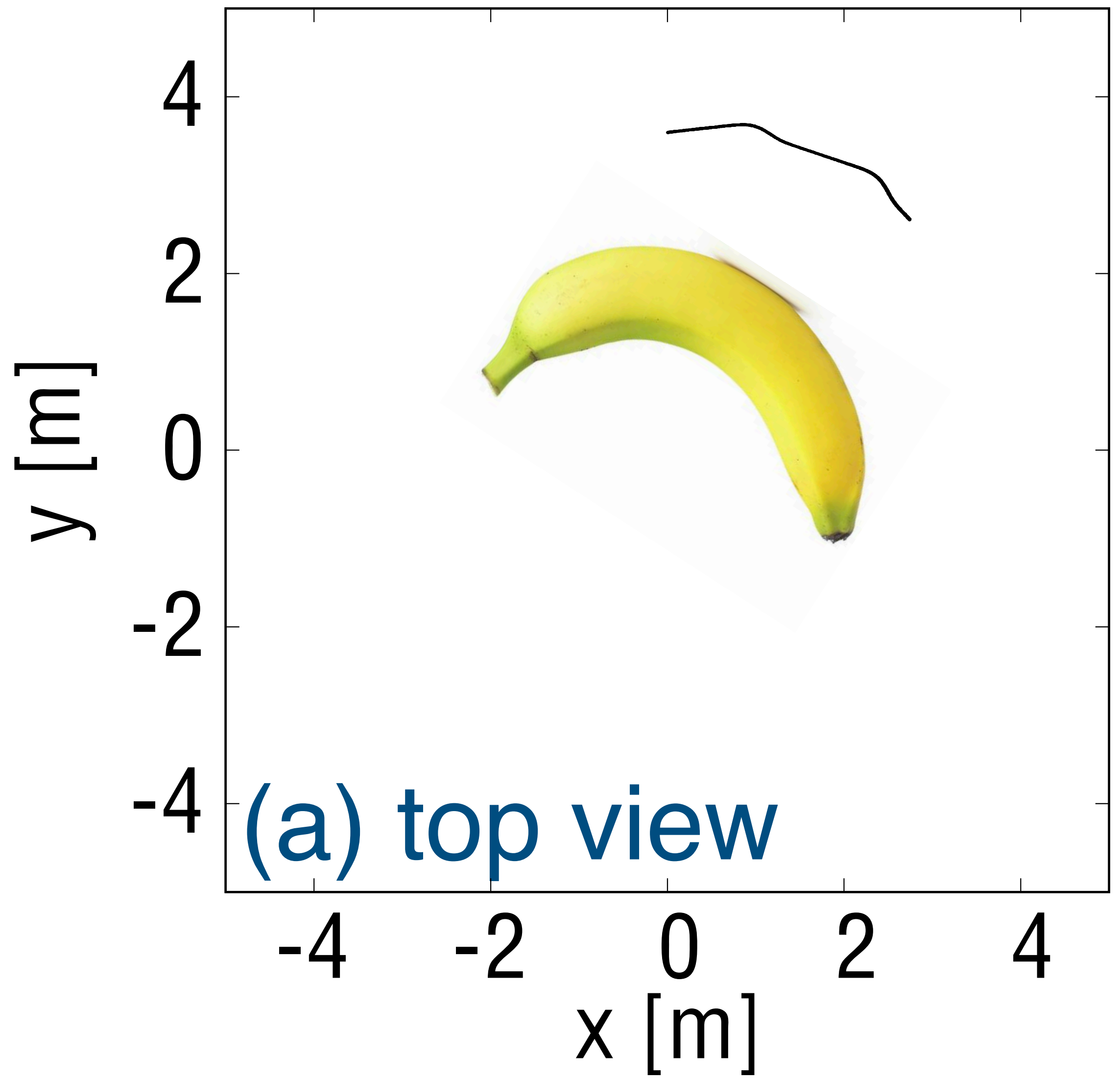
s (longitudinal)

Science and
Technology
Facilities Council

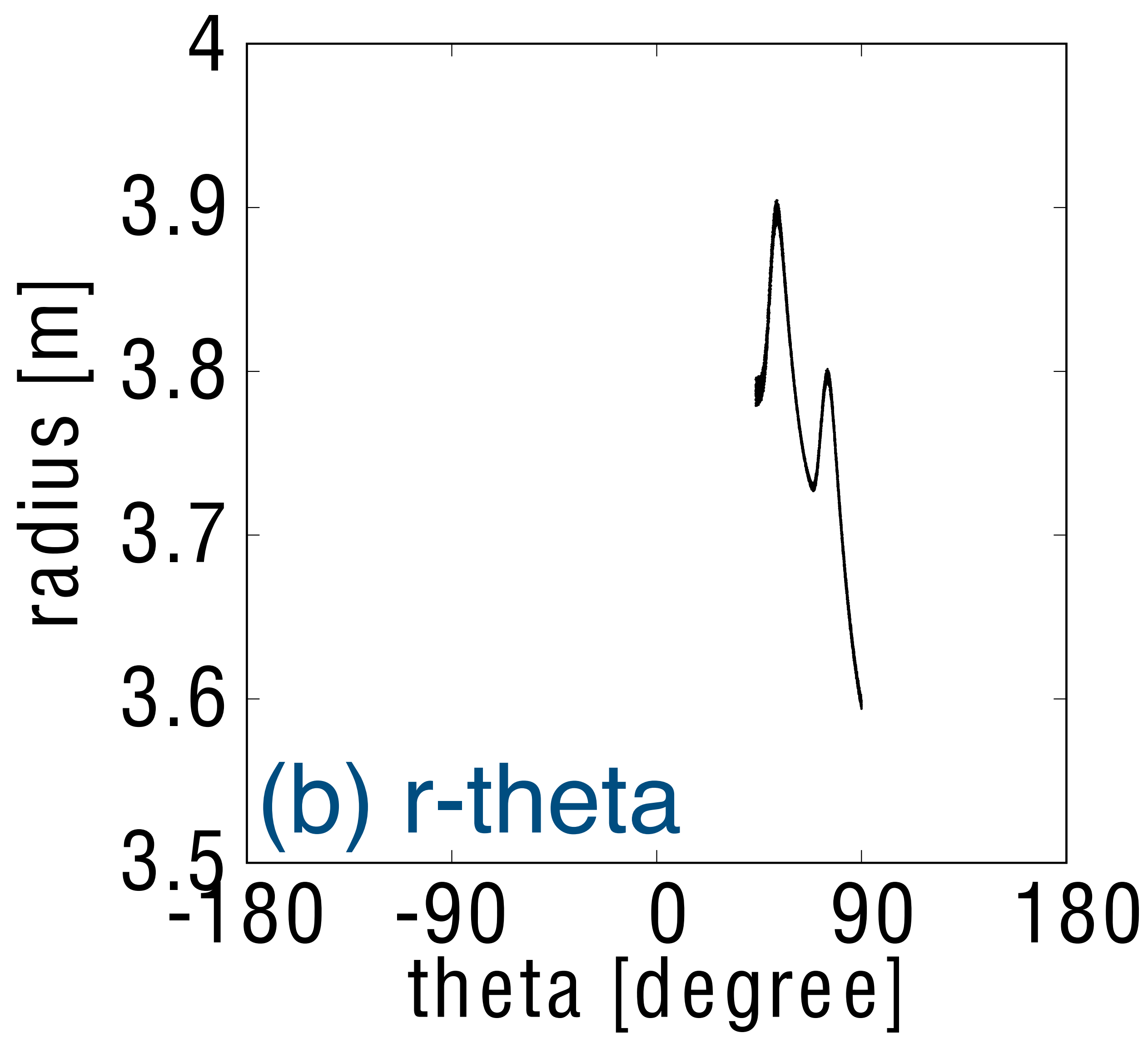
Scode's way of modelling



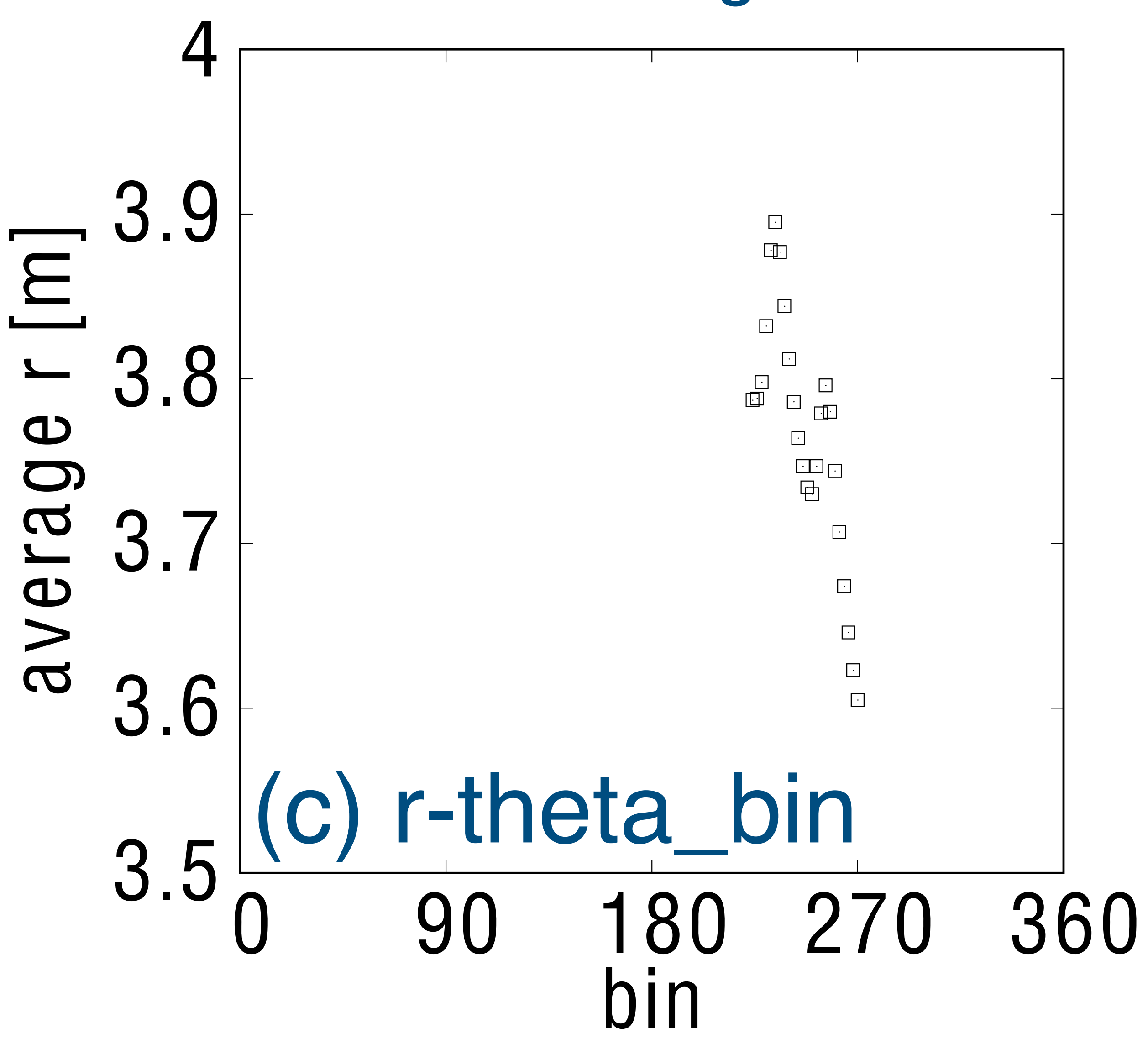
- Beam in arbitrary position.



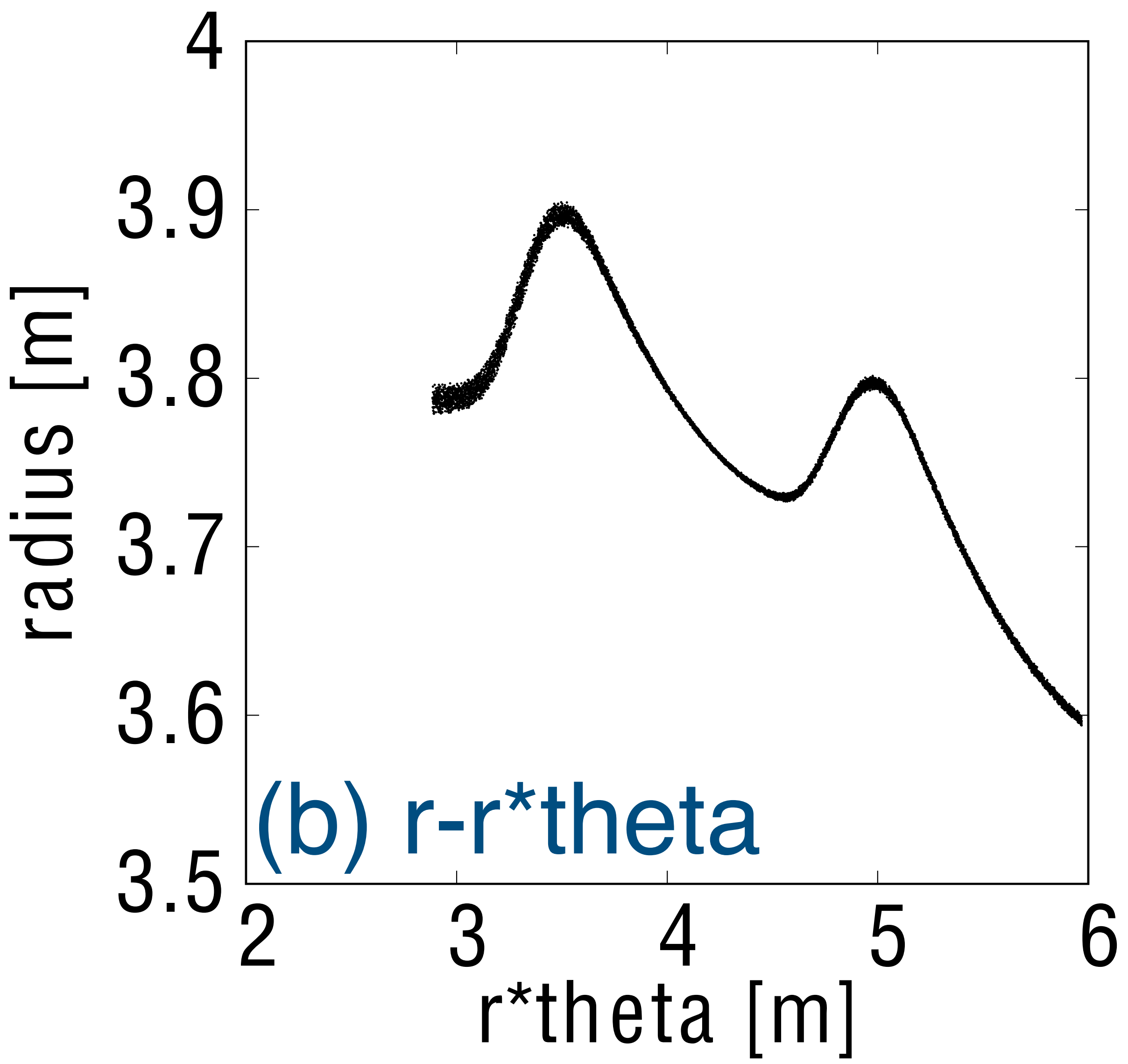
- Convert coordinates to r-theta



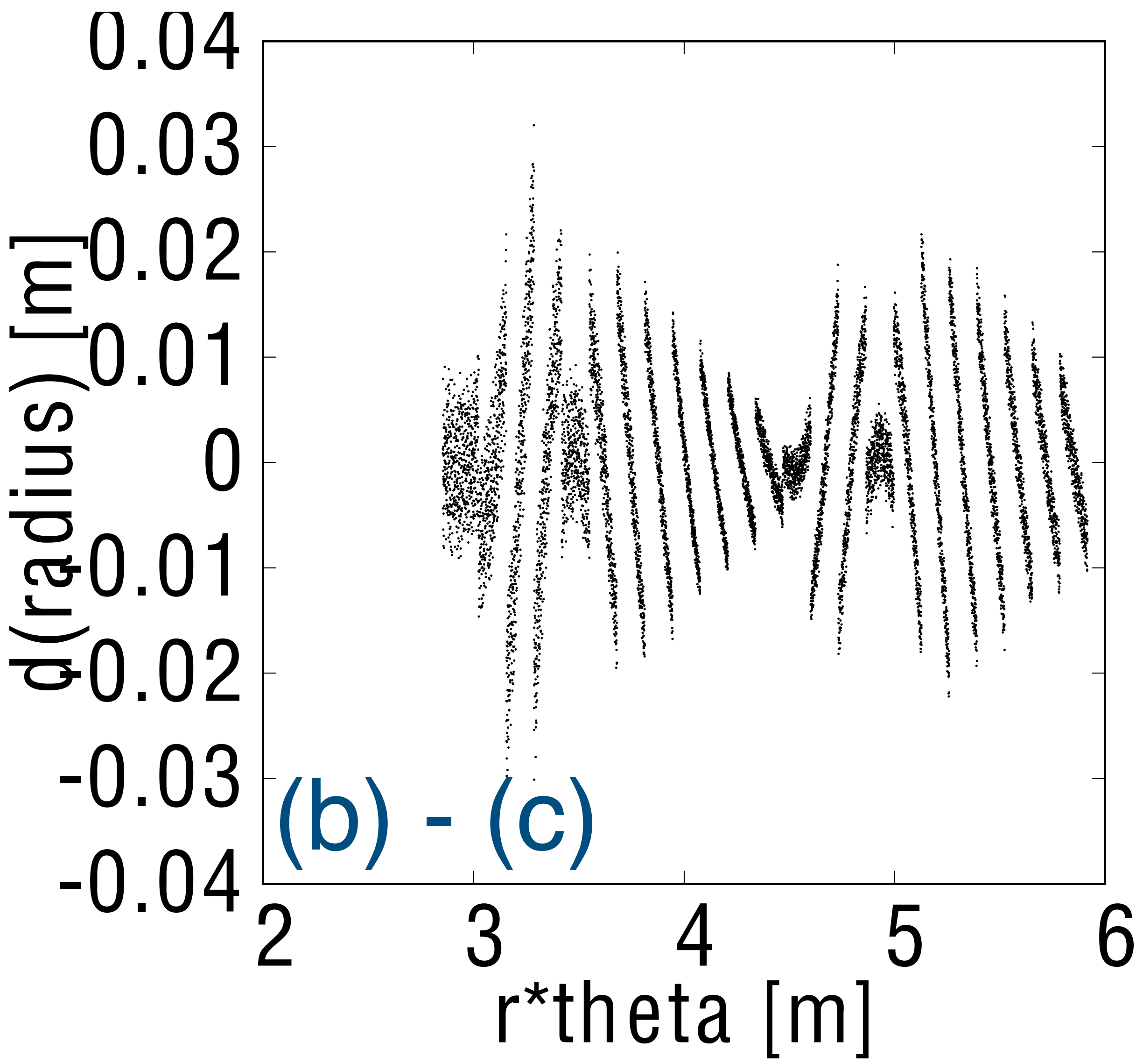
- Binning in theta direction
- Calculate average r in each bin



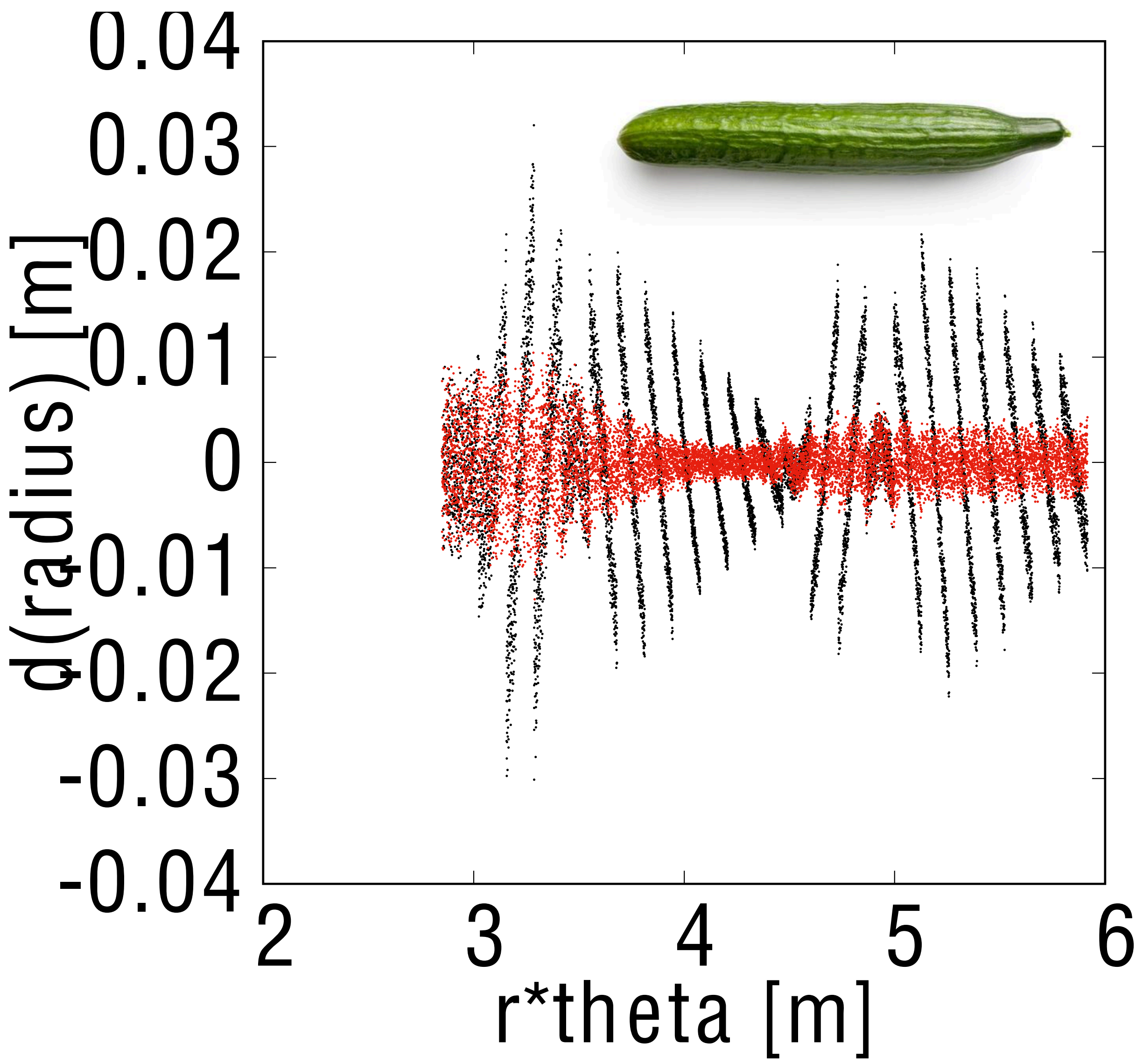
- Same as above



- In each bin, r is measured w.r.t. < r >.



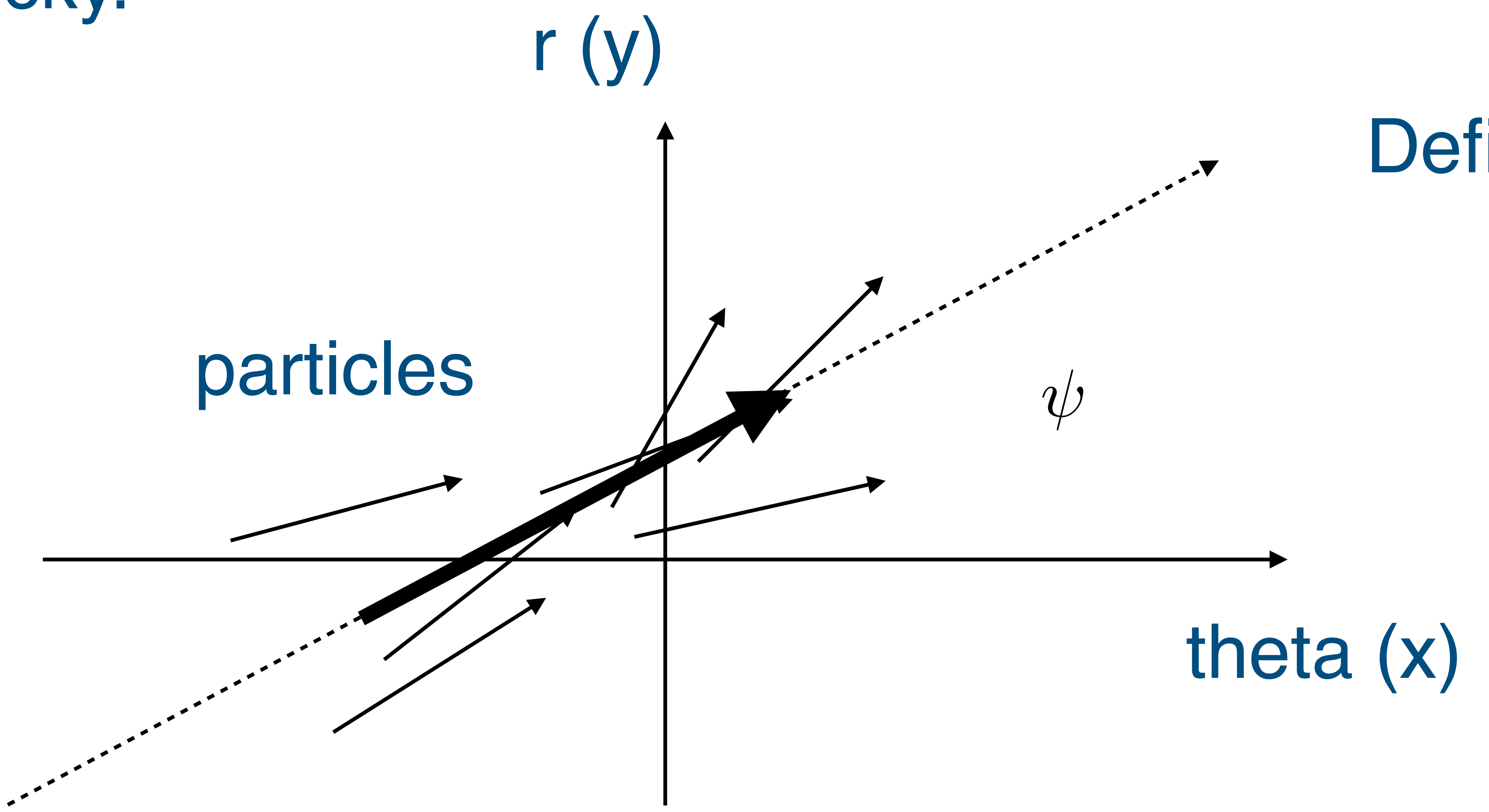
- Last step is explain in the next page.



Science and Technology Facilities Council

Scode's way of modelling

- Ideally, transverse (radial) position is measured from the closed orbit, not from the average position within a bin.
- It may be possible to define the instantaneous closed orbit, but could be tricky.



Define the close orbit within a bin as

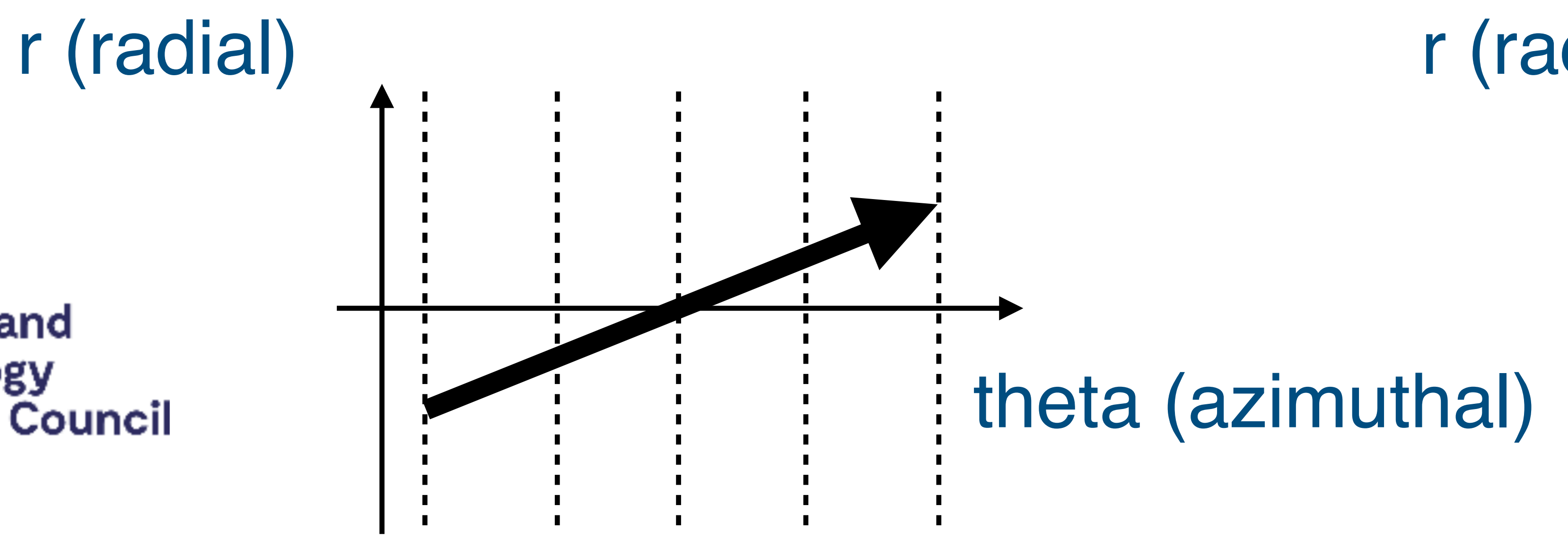
A straight line with a gradient of

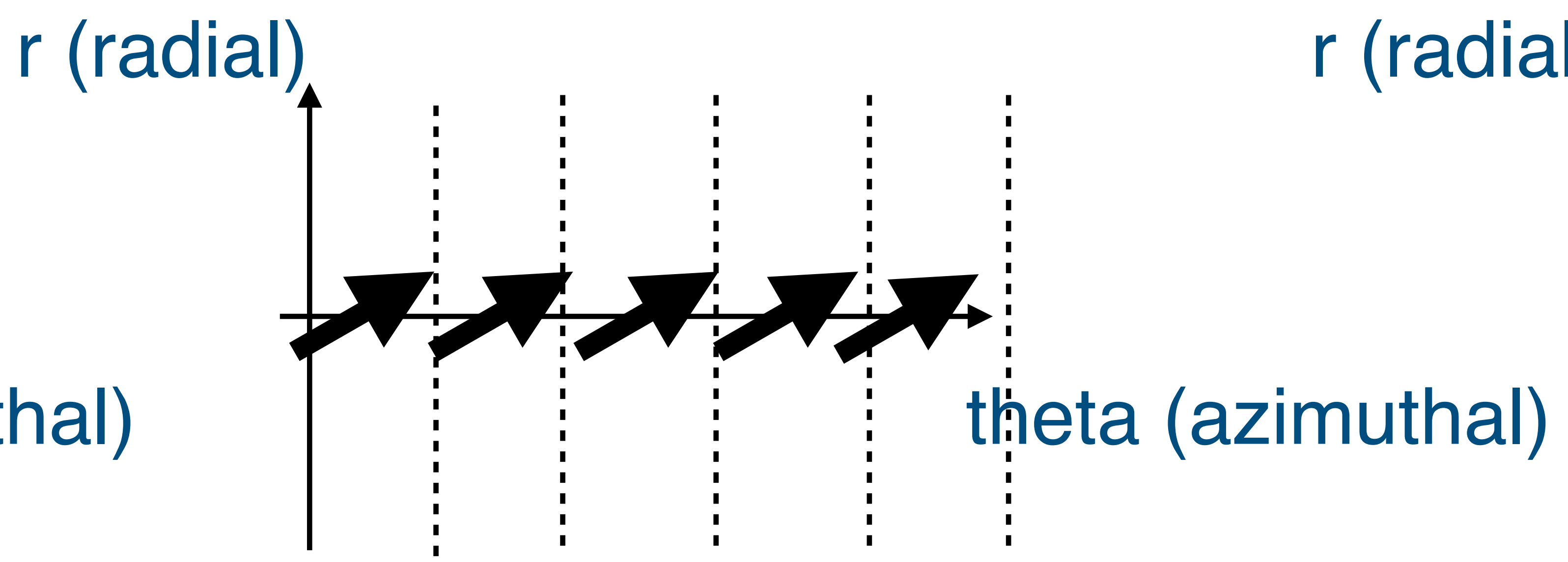
$$\tan(\psi) = \frac{\sum p_{y,i}}{\sum p_{x,i}}$$

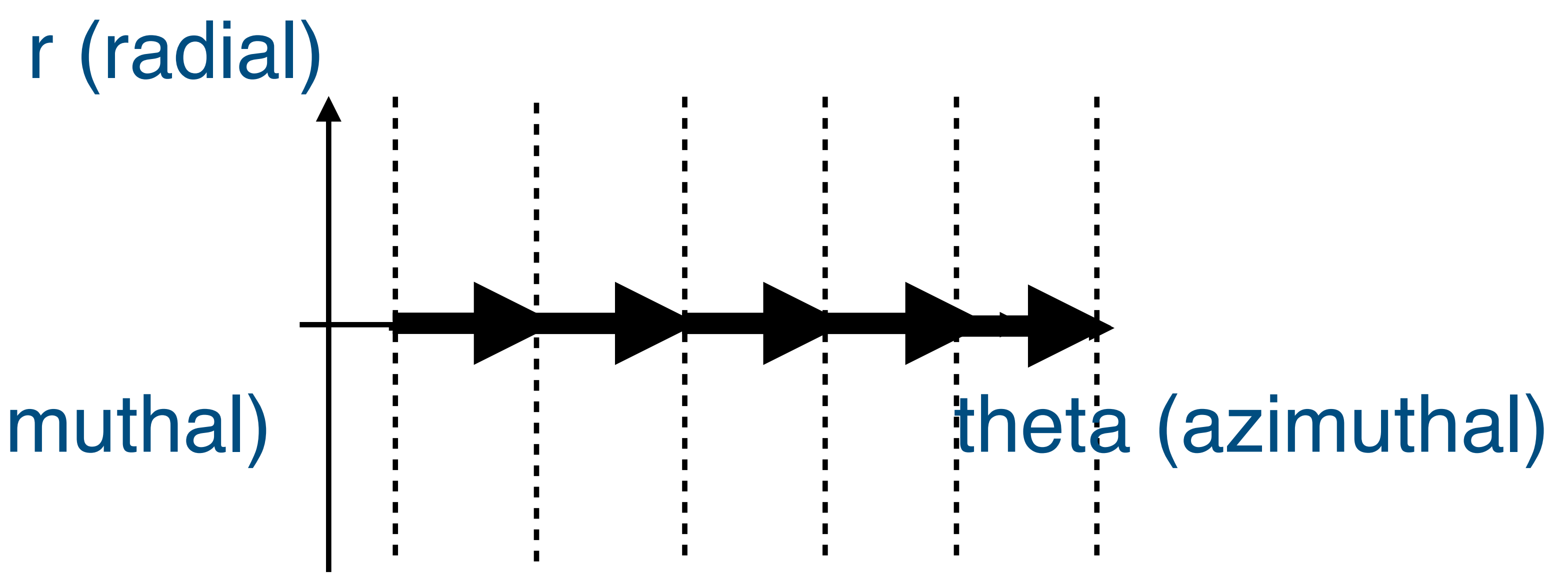
which goes through the point of

$$\left(\frac{\sum x_i}{n}, \frac{\sum y_i}{n}\right)$$

where n is the number of particle and i is index.



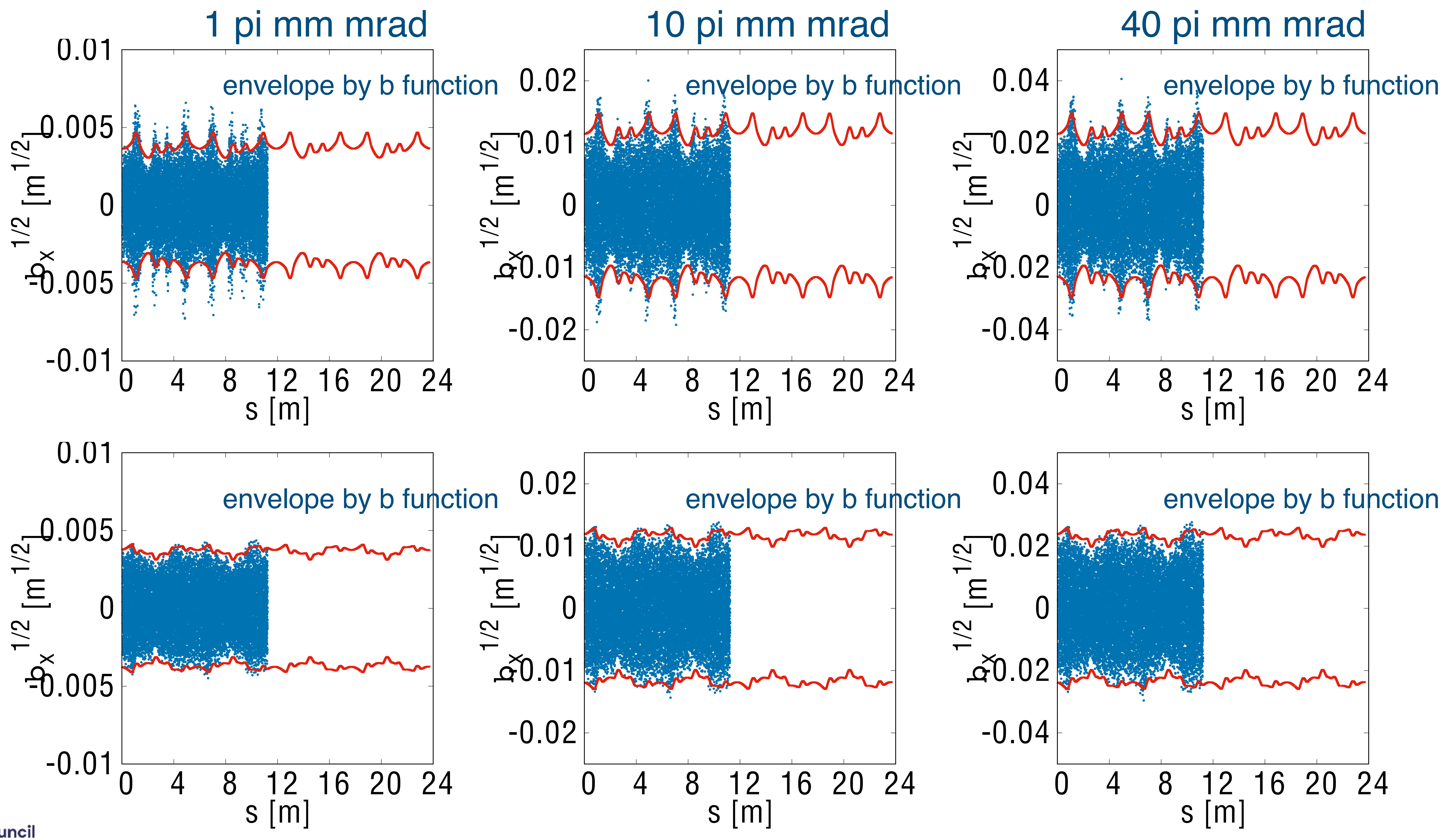




Finally, a curved beam in arbitrary position becomes straight

horizontal

vertical



Science and Technology Facilities Council

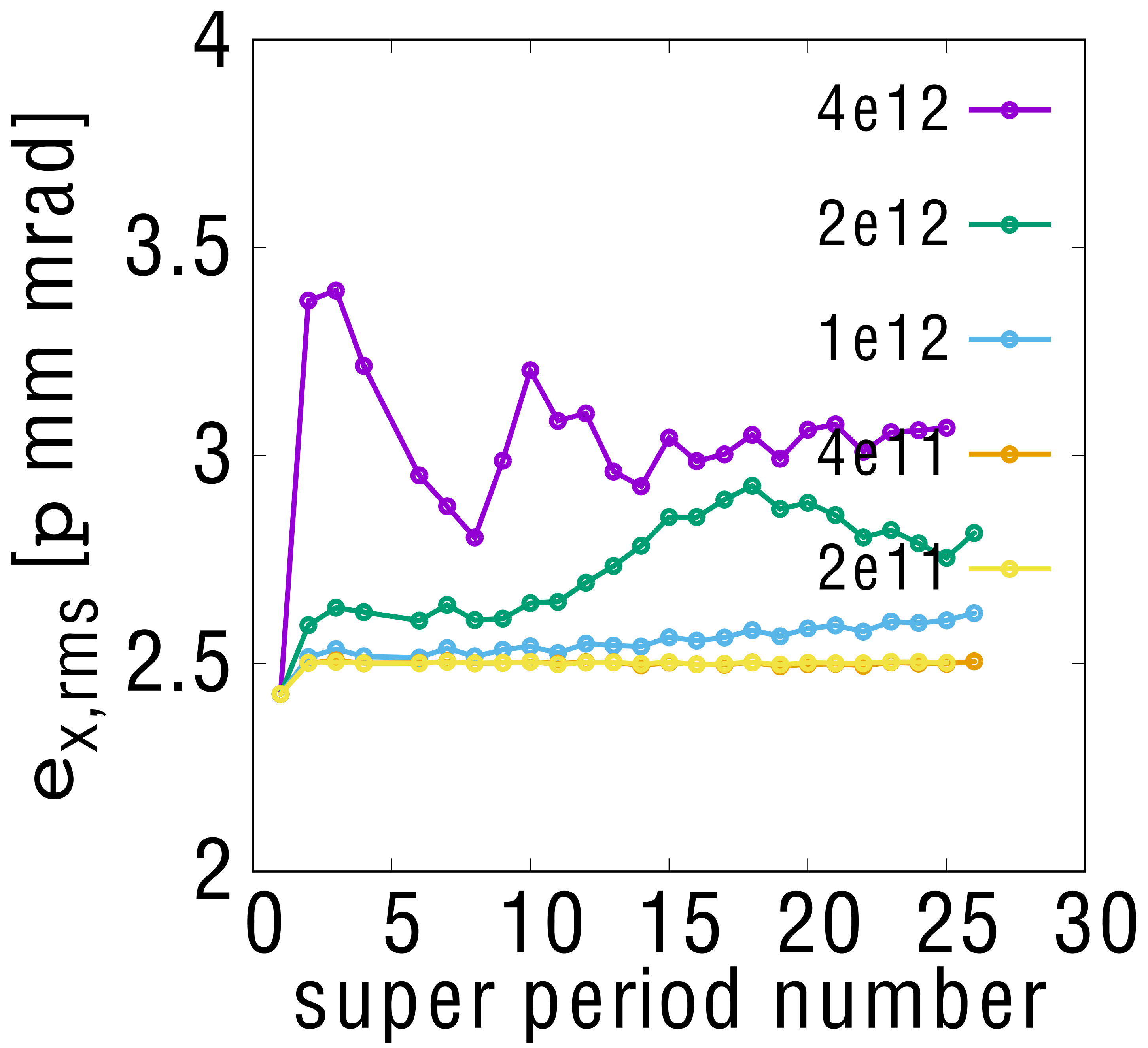
Simulation result (preliminary)

Lattice	FETS-FFA
Circumference	~ 23 m
Energy	3 MeV
Longitudinal distribution	Coasting
Transverse distribution	KV
Emittance (100%)	10 pi mm mrad, normalised
Injection	Single turn
Operating point	(3.26, 3.26)
Longitudinal bin	180 / ring
# of macro particle	10000

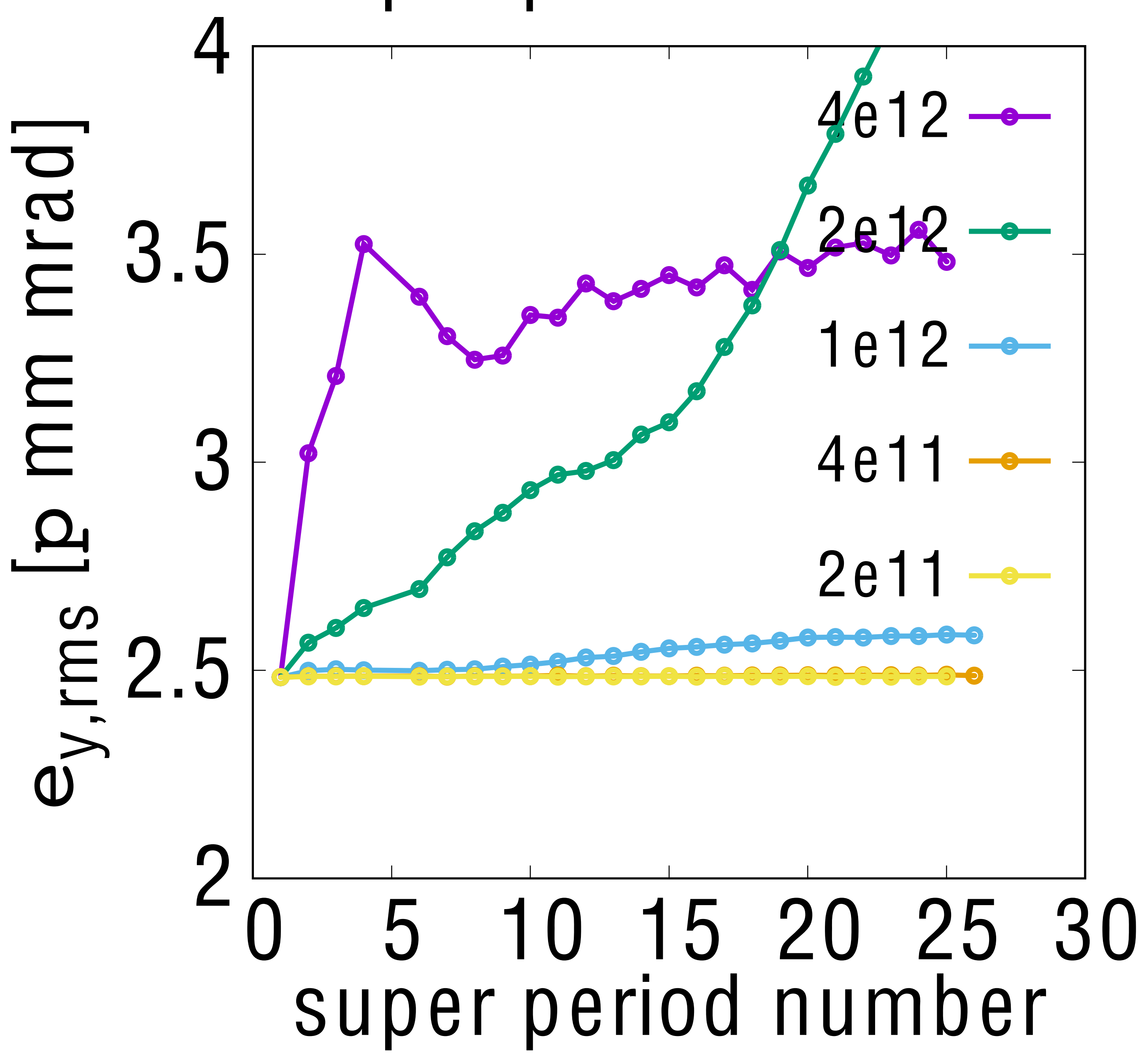
Emittance growth start happening at 1 x 10^{12} and significant one above the intensity of 2 x 10^{12}.

Partially it is due to mismatch.

Hor



Ver



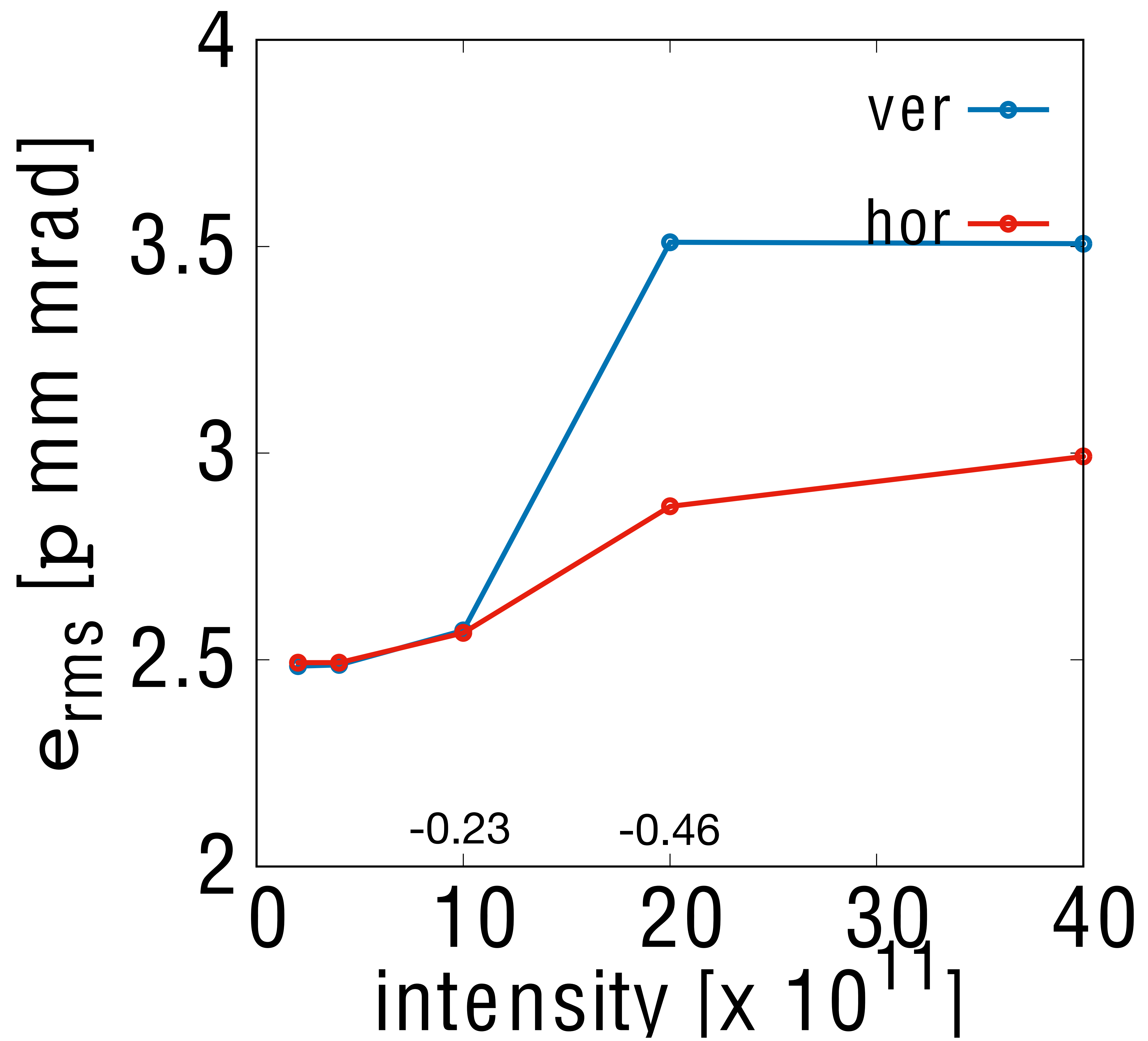
Science and Technology Facilities Council

Simulation result (preliminary)

Space charge incoherent tune shift

$$\Delta Q_v = -\frac{n_t r_p}{\pi \epsilon_v (1 + \sqrt{\epsilon_h/\epsilon_v})\beta^2\gamma^3} \frac{1}{B_f}$$

	Maximum inc. tune shift	RMS inc. tune shift	Coherent tune shift
10 x 10^{11}	-0.304	-0.304	-0.228
20 x 10^{11}	-0.608	-0.608	-0.456



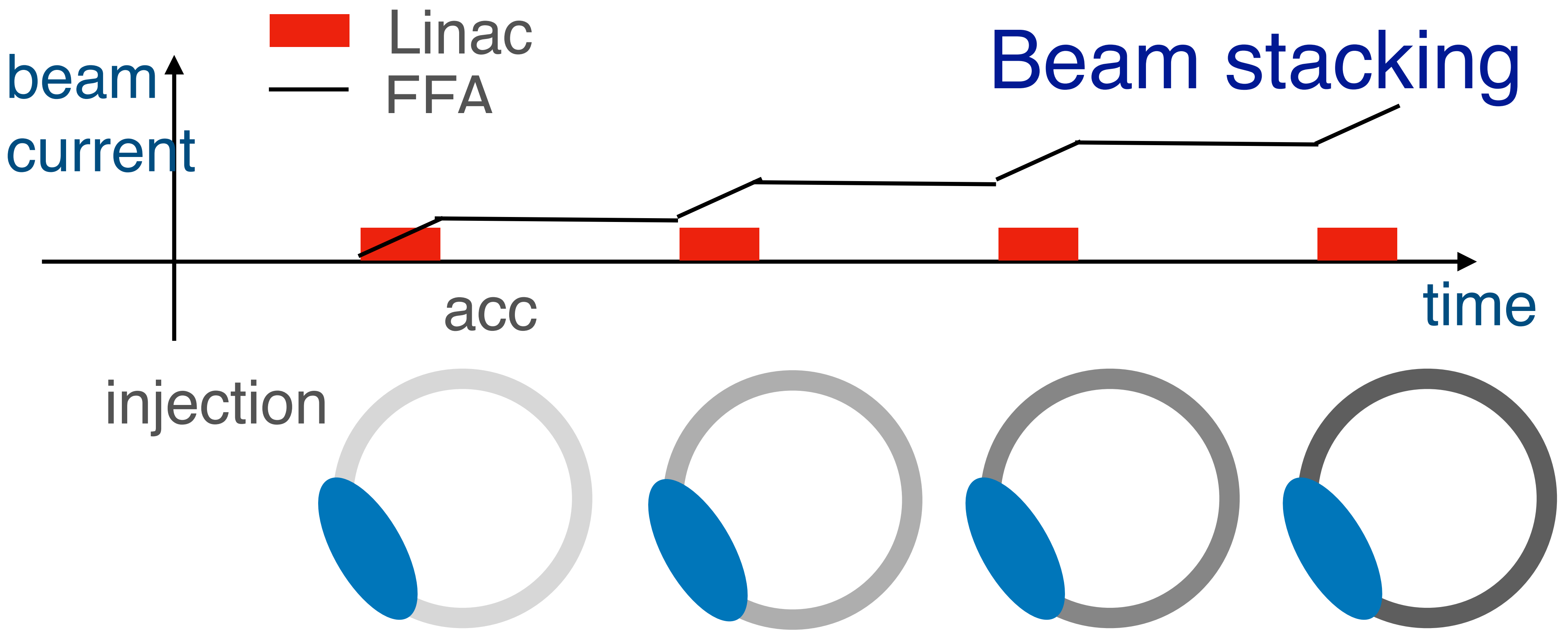
- Distance between operating point (3.26) and nearby resonance (3.00) is 3.26-3.00=0.26.
- Emittance growth starting around 10 x 10^{11} is reasonable **(no surprise!).**

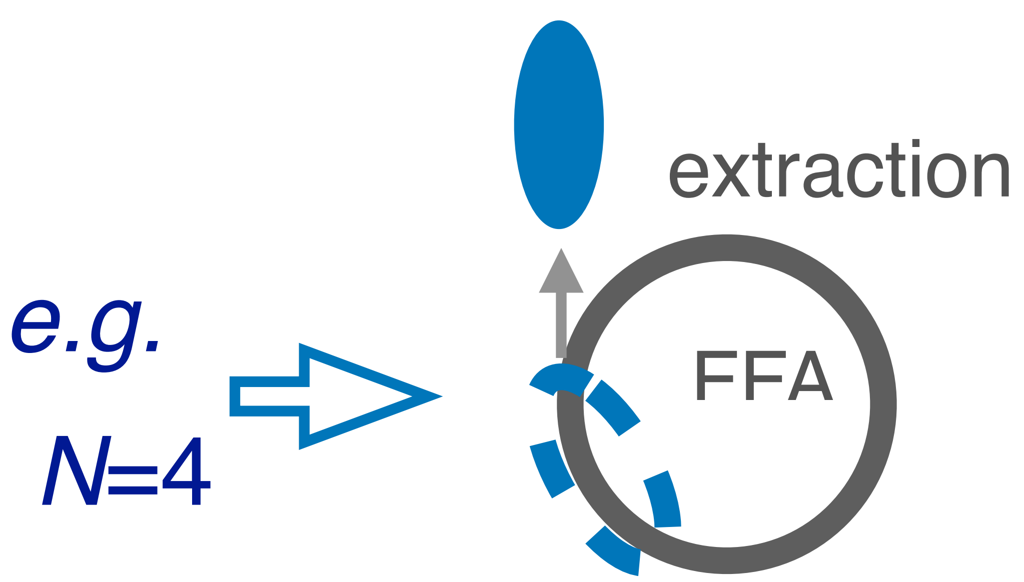
Science and Technology Facilities Council

RF knock-out and its mitigation

Science and
Technology
Facilities Council

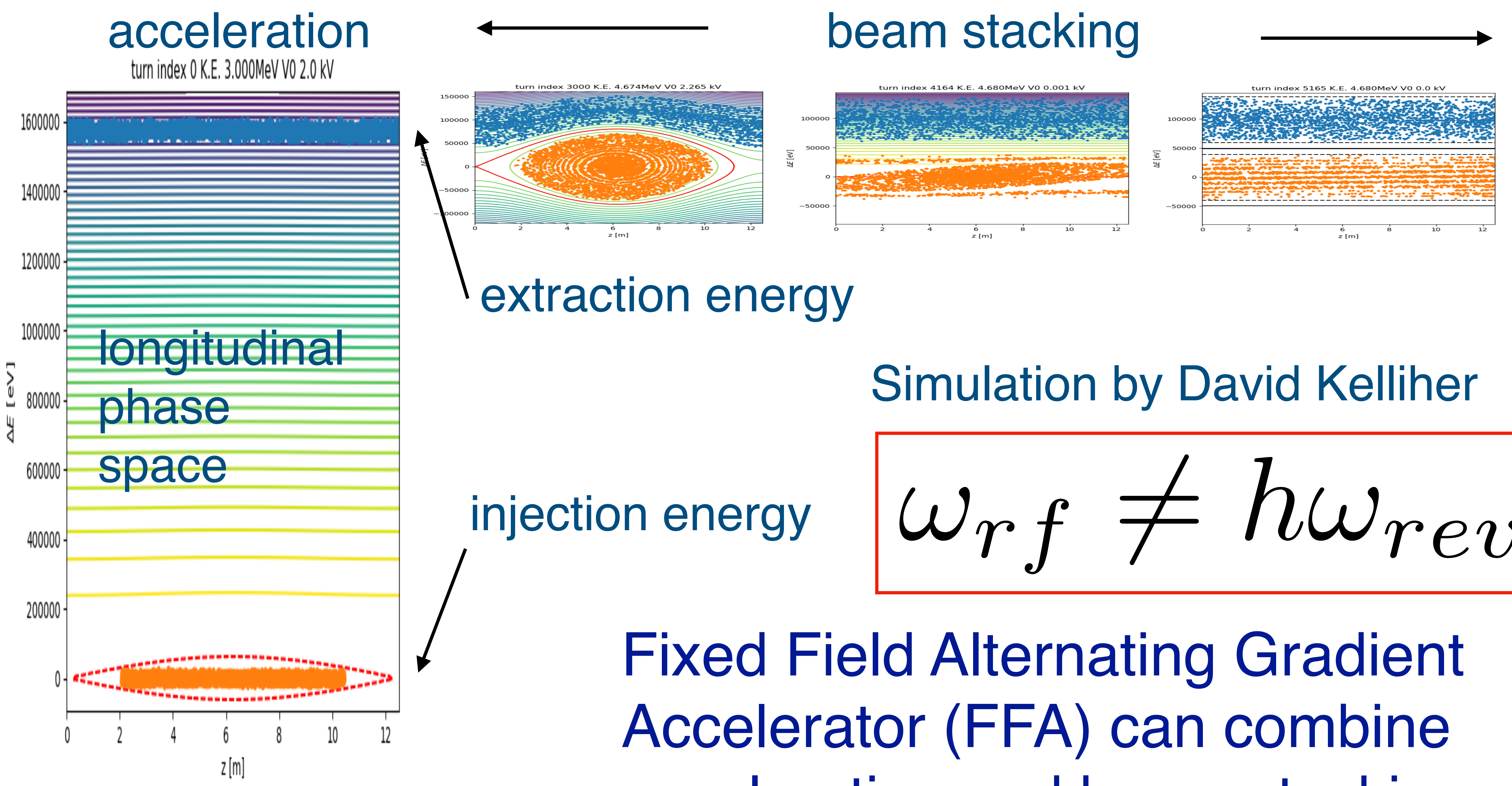
Beam stacking





Benefits

- Bottleneck to achieve high beam power exists at injection energy.
- By beam stacking, beam power is not limited at injection.
- Repetition rate of an accelerator (120 Hz) can be different from that users will see (30 Hz).
- Longitudinal emittance is proportional to # of stacking (or larger).



Simulation by David Kelliher

$$\omega_{rf} \neq h\omega_{rev}$$

Fixed Field Alternating Gradient Accelerator (FFA) can combine acceleration and beam stacking in **a single ring**.

Proton driver with beam stacking makes ISIS-II a unique spallation neutron source.

Experimental demonstration (2 beams)

- Is the total **momentum spread dp/p** 2 times dp/p of each beam?
- Is the total **number of particles** is 2 times that of each beam?

Science and Technology Facilities Council

Frequency component during beam stacking

The beam sees RF voltage at a cavity location

$$V_{gap} = V_0 \cos \omega_{rf} t \sum_{n=0}^{\infty} \delta\left(t - nT_{rev}\right)$$
$$= V_0 \sum_{n=0}^{\infty} \cos \omega_{rf} n T_{rev} = V_0 \sum_{n=0}^{\infty} \cos 2\pi n \frac{\omega_{rf}}{\omega_{rev}}$$

when \omega_rf << \omega_ref

$$V_{gap}\,(\text{envelope}) = \boxed{V_0 \cos \omega_{rf} t}$$

when \omega_rf ~ \omega_ref

$$V_{gap}\,(\text{envelope}) = \boxed{V_0 \cos\left(\omega_{rev} - \omega_{rf}\right) t}$$

(aliasing, beat, …)

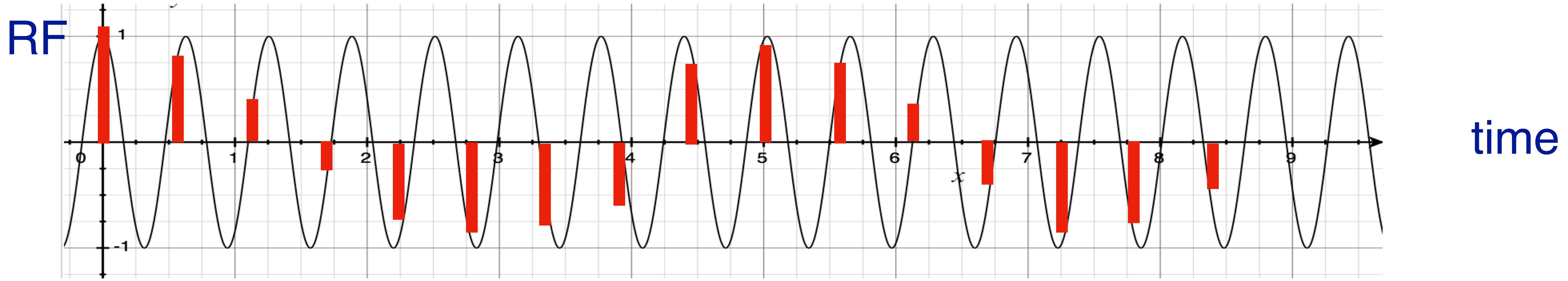
$V_{gap}\,(\text{envelope})$ means the lowest frequency component of RF voltage seen by the beam.

Requirement in the longitudinal direction imposes

\omega_rf > (1/2) \omega_rev

RF voltage seen by the coasting beam

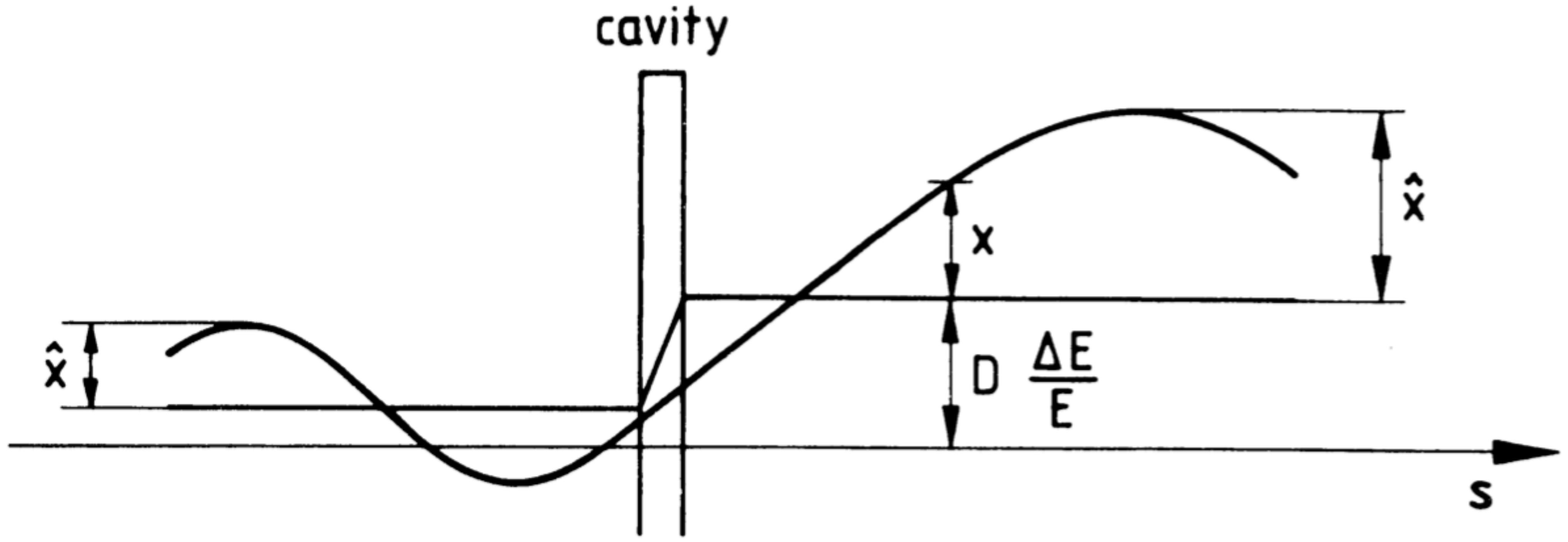
f_rf < f_rev



Similarity to synchro-beta resonance

When the RF cavity is located at the finite dispersion point D_x, energy gain induces horizontal displacement.

In a bunched beam, energy gain or induced horizontal displacement has a frequency of synchrotron oscillation and its higher harmonics.



from CERN-87-03

$$\delta x = -D_x \frac{dp}{p} = -\frac{D_x}{2}\frac{dT}{T} = -\frac{\pi D_x V_0 a_s}{T\lambda}\cos(\omega_s t)$$

For the stacked (coasting) beam,

$$\delta x = -D_x \frac{dp}{p} = -\frac{D_x}{2}\frac{dT}{T} = -\frac{D_x V_0}{T}\cos(\omega_{rev} - \omega_{rf})\, t$$

When it becomes the same frequency of (horizontal) betatron oscillations, **resonance occurs**.

$$\frac{\omega_{rev} - \omega_{rf}}{\omega_{rev}} = \frac{\omega_{\beta,h}}{\omega_{rev}} \quad \text{or} \quad 1 - \frac{\omega_{\beta,h}}{\omega_{rev}} \qquad \text{where} \quad \frac{\omega_{\beta,h}}{\omega_{rev}} = Q_{\beta,h}$$

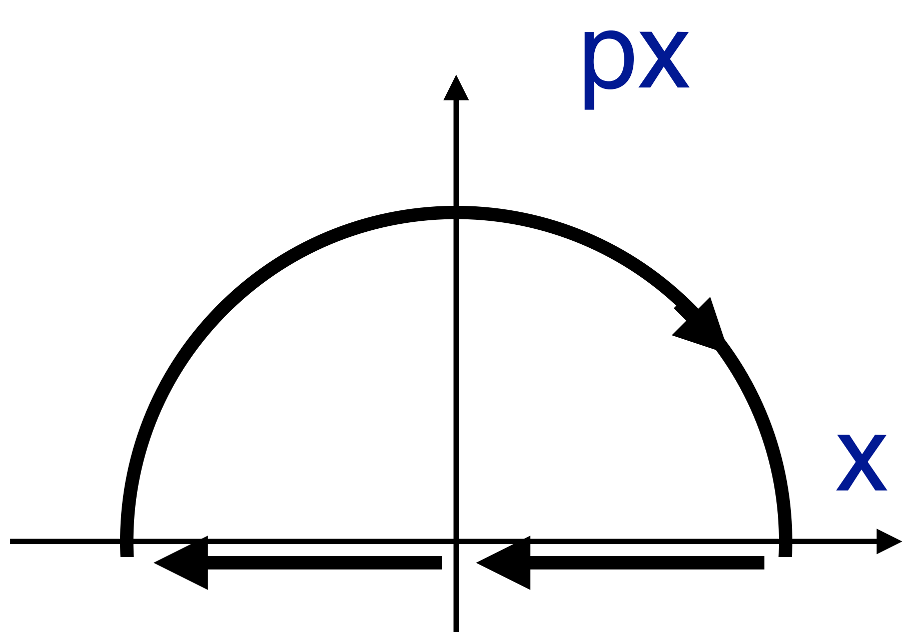
Science and Technology Facilities Council

Proposed mitigation methods (from MURA papers)

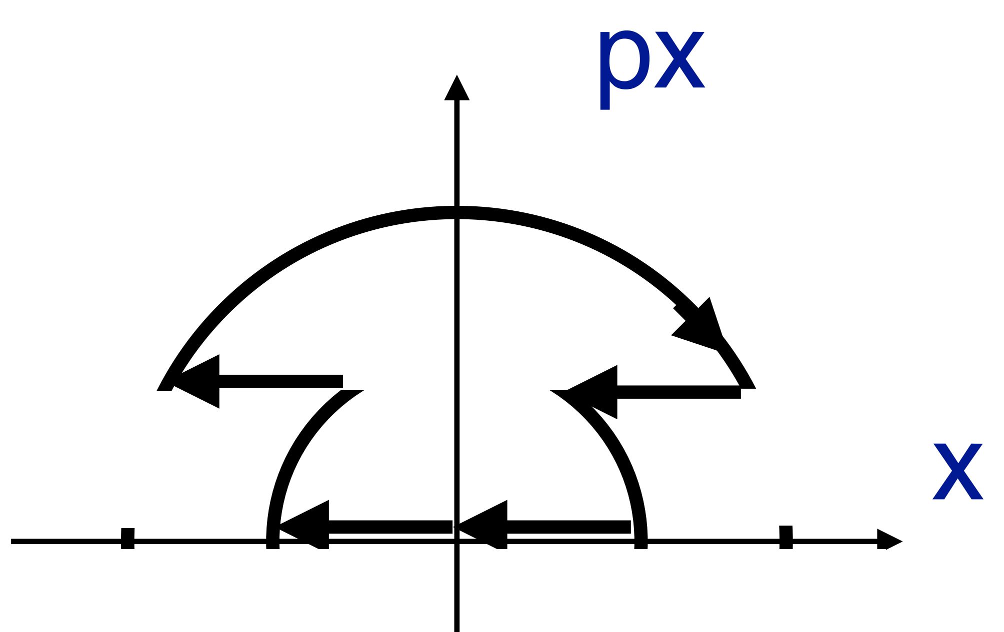
- For a ring with single RF cavity
  - Reduce voltage around resonance
  - Control betatron phase around resonance by changing tune for short time (like a jump around transition energy crossing).

- For a ring with two RF cavities
  - **Choose a proper betatron phase advance between two cavities**
  - Tipped RF cavities to cancel transverse fields

- For a ring with multiple RF cavities
  - Place cavities with equal spacing.



When phase advance btw 2 cavities is pi.



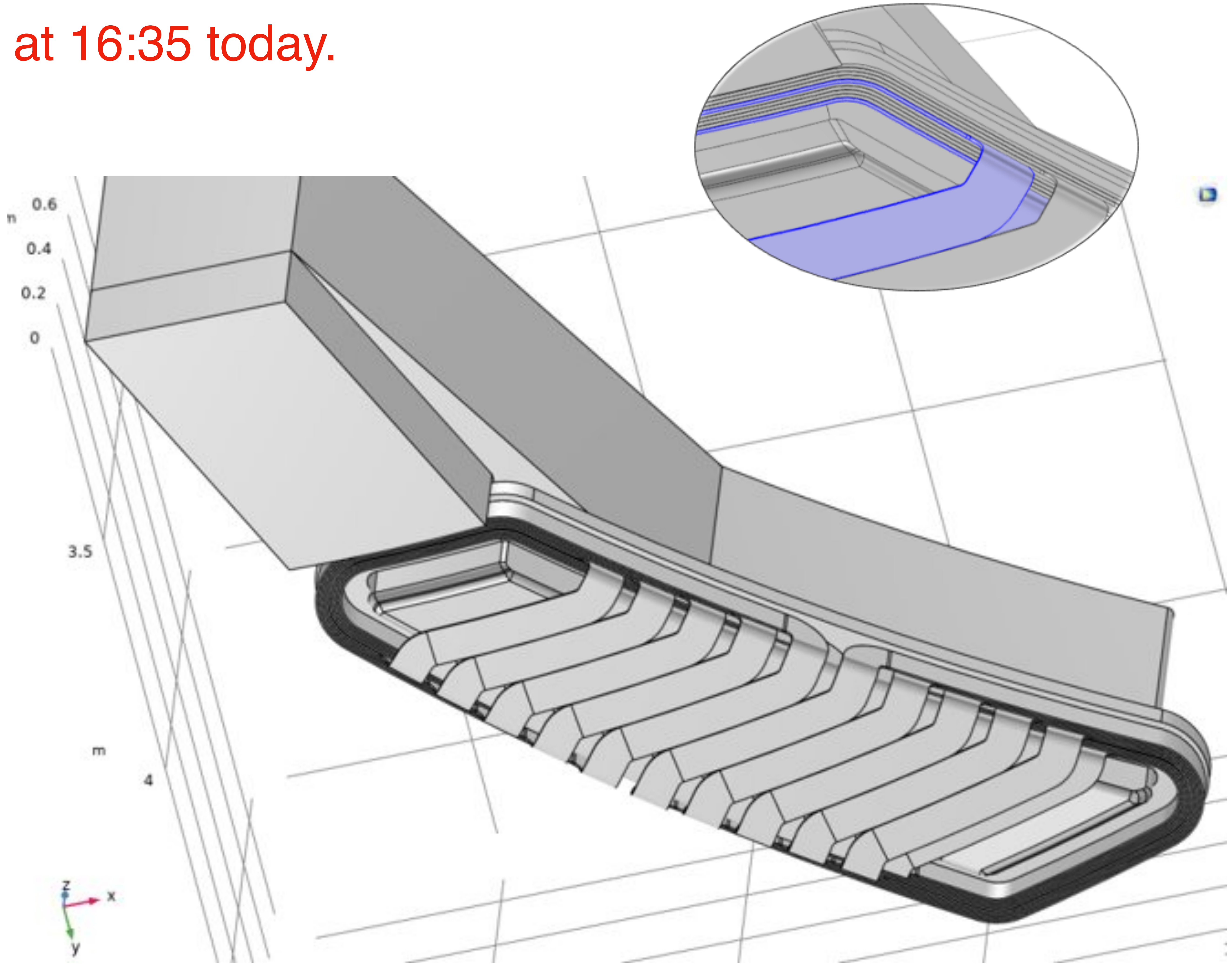
When phase advance per cavity is not pi.

Science and Technology Facilities Council

Hardware R&D status

Hardware
magnet prototype

- Ta-Jen Kao' s talk at 16:35 today.

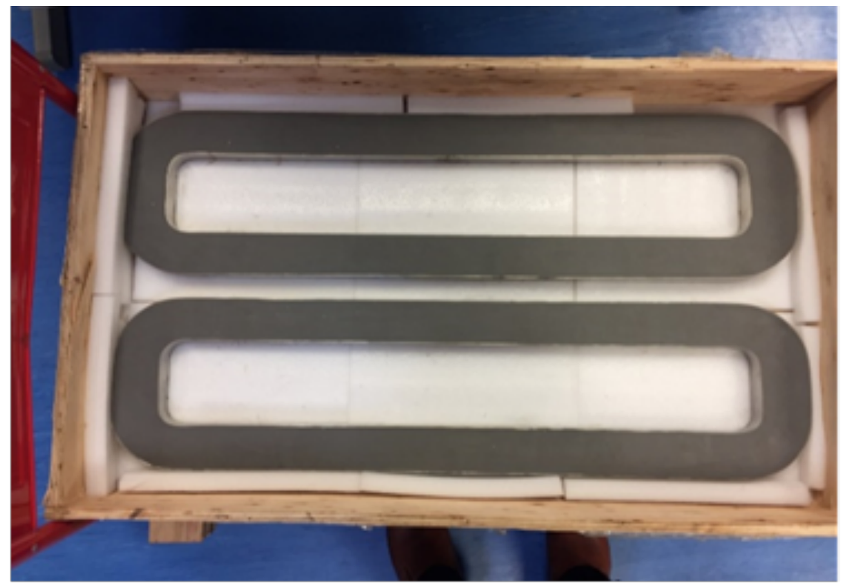


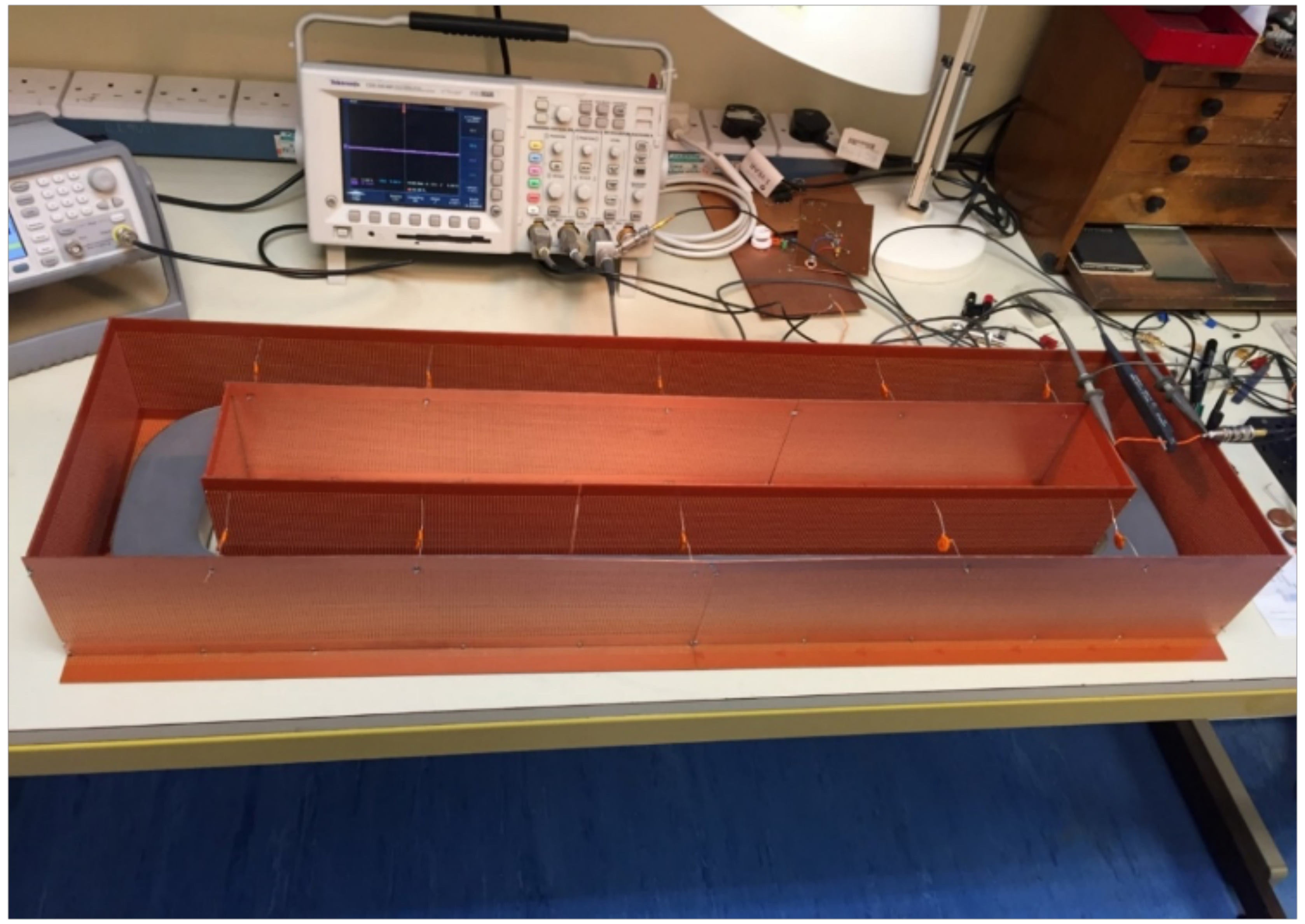
Science and Technology Facilities Council

Hardware

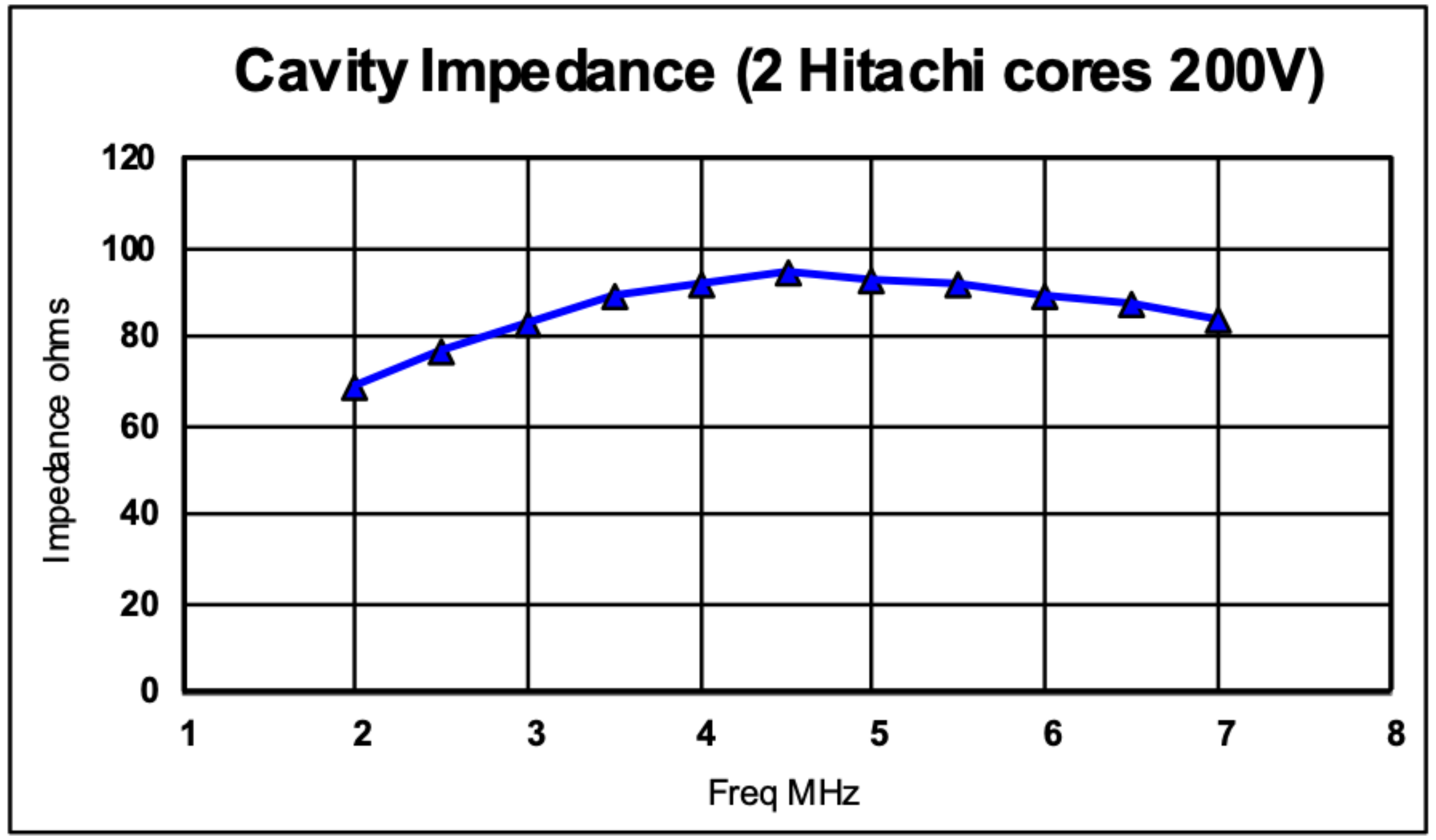
RF cavity update

- MA as well as ferrite cavity R&D.





Hitachi FT3L Core Measurements

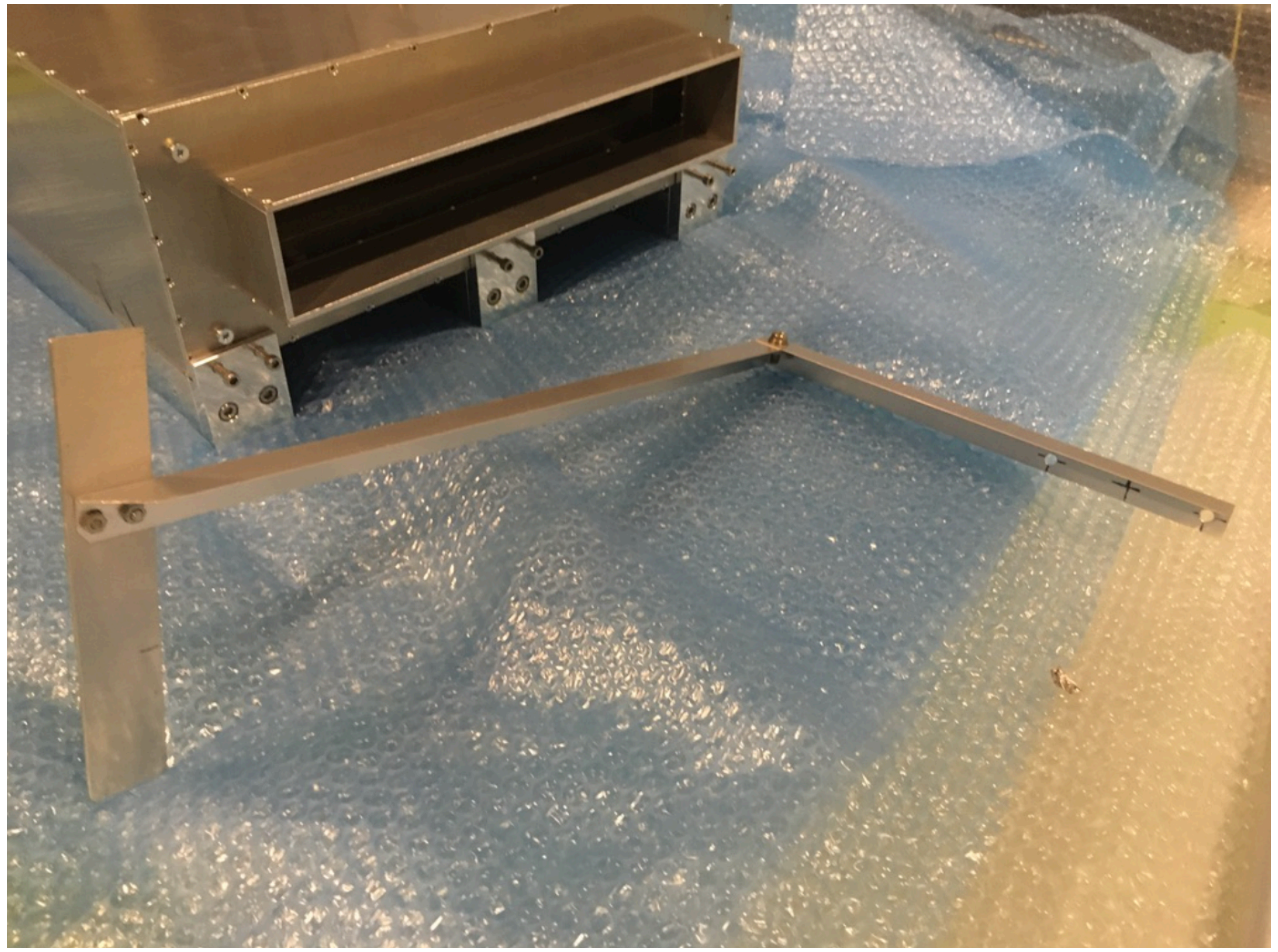


- Measured with 100 V peak per core
- Power for 8 core cavity at 6 kV peak 50 - 65 kW
- Consider using 2 cavities at ½ voltage ~16 kW each, meaning no Tuning system and wideband for fast modulations

Hardware

diagnostics

- Beam position monitor
- DC current monitor
- Beam loss monitor
- Wall current monitor
- …



A half size BPM and scraper

Summary

- Our goal is demonstration of the high intensity FFA
- Baseline lattice is fixed
  - FD spiral
  - Superperiod with 4-fold symmetry
  - Large dynamic aperture
- Possible option to be a higher energy accelerator was studied
- Space charge effects are similar to synchrotron
- Found RF knock-out is one of known issues during beam stacking and mitigation is considered
- Hardware prototype is under development based on the baseline lattice parameters

Thank you for your attention

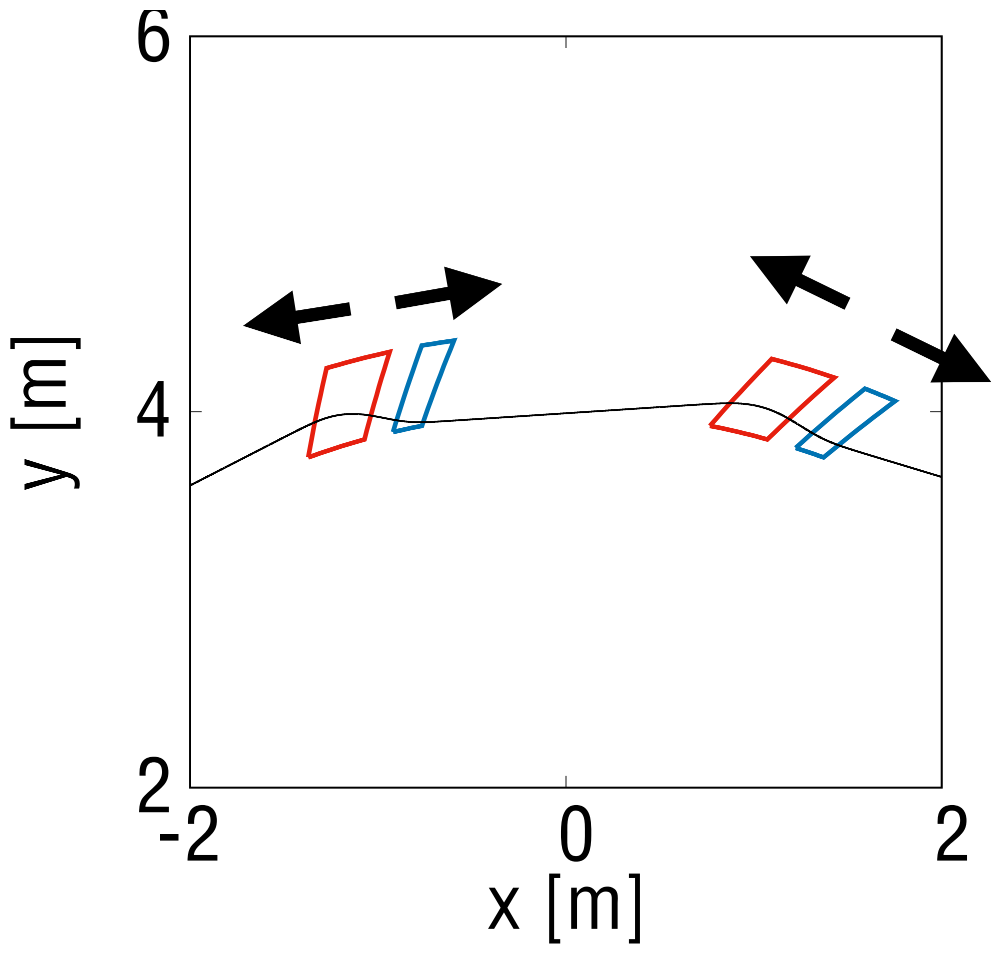
Science and
Technology
Facilities Council

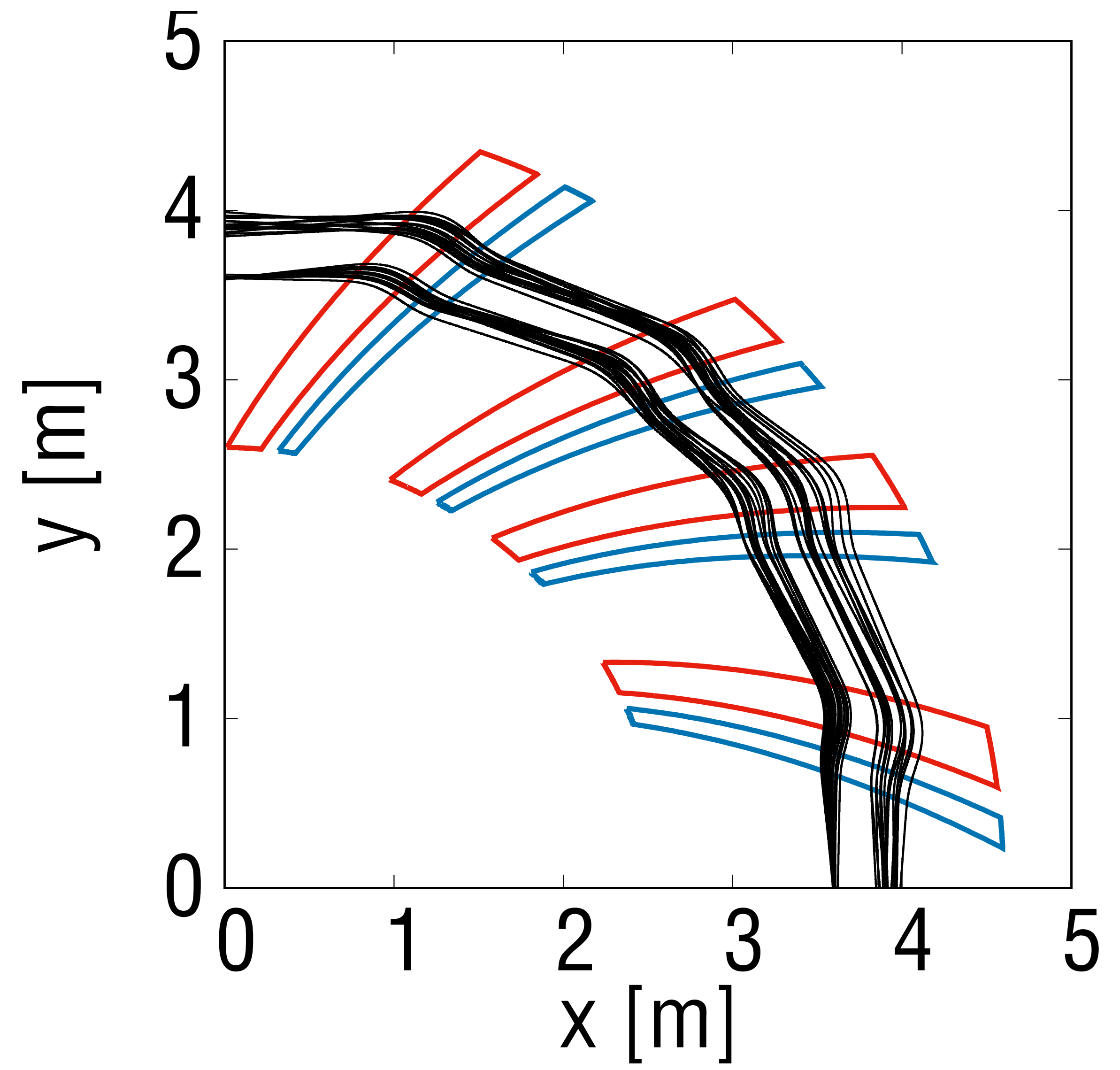
Robustness of optics

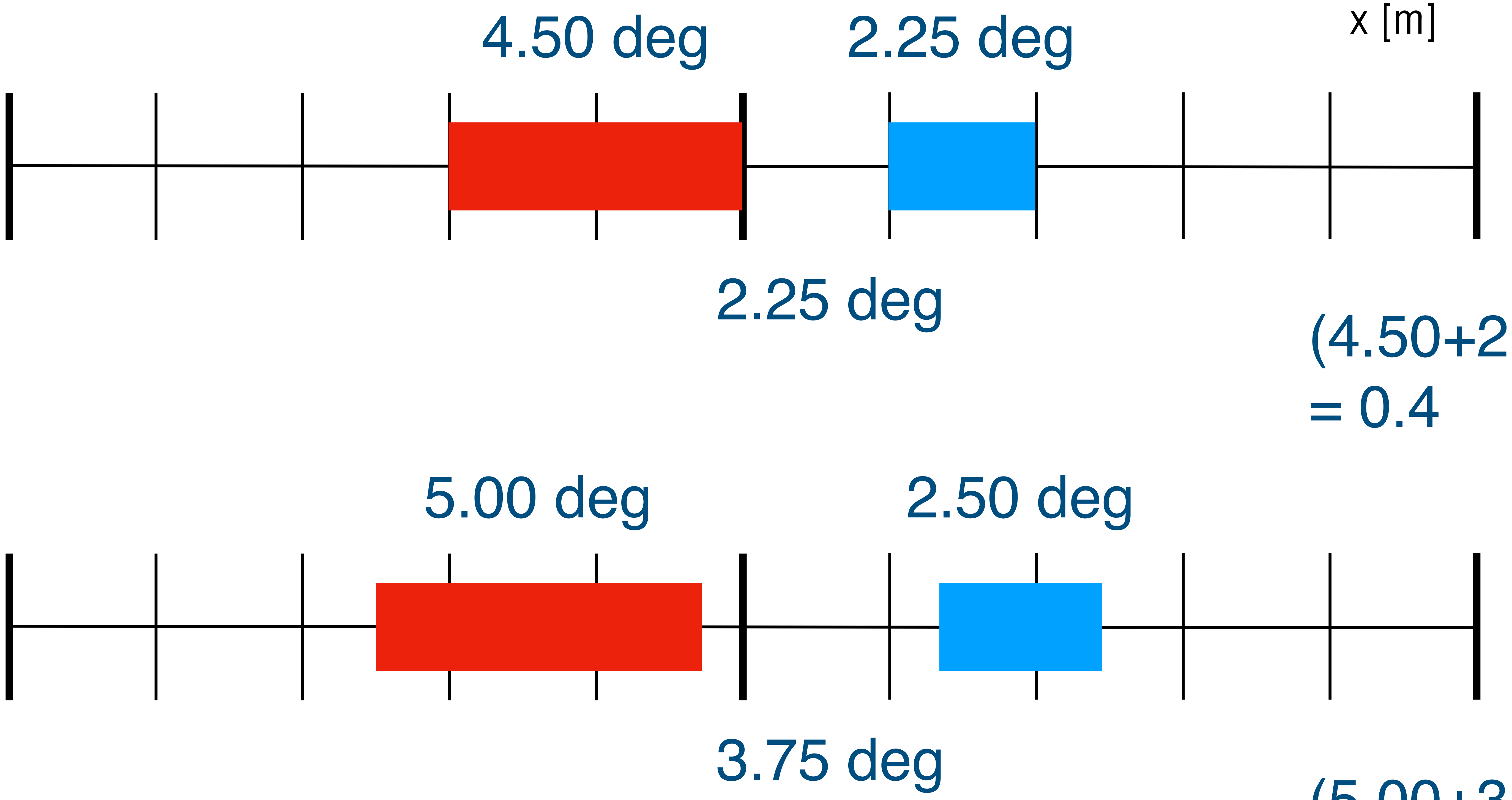
Practical adjustment of doublet magnet specification

- Magnetic field is now up to ~1.4 T.
- There is not much space between Bf ad Bd.

- Keeping the centre of each doublet at the same position
  - increase the gap between Bf and Bd.
  - increase magnet length.







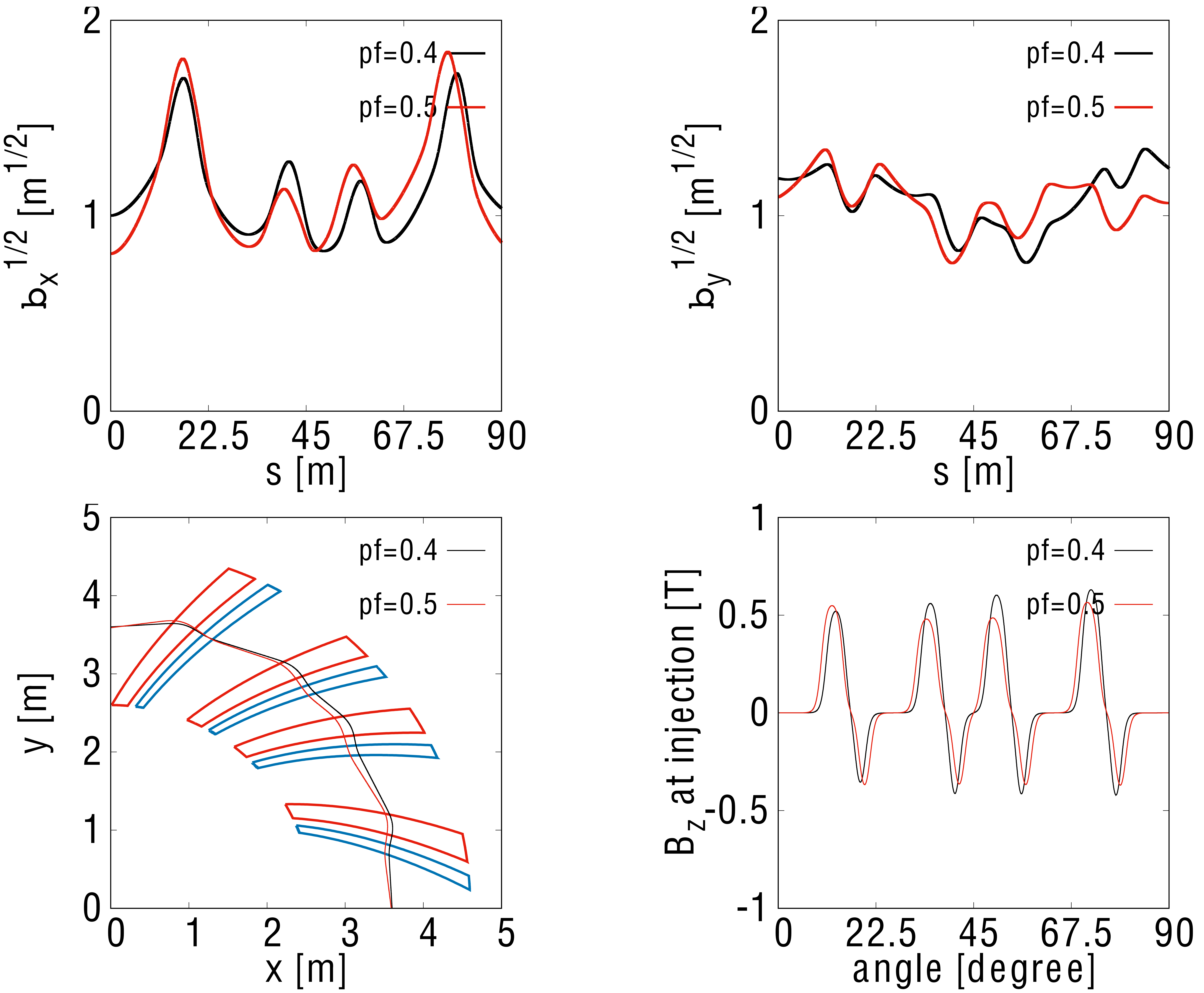
(4.50+2.25+2.25)/22.5 = 0.4

(5.00+3.75+2.50)/22.5 = 0.5

2.25 deg = 141 mm

Science and Technology Facilities Council

Packing factor 0.5



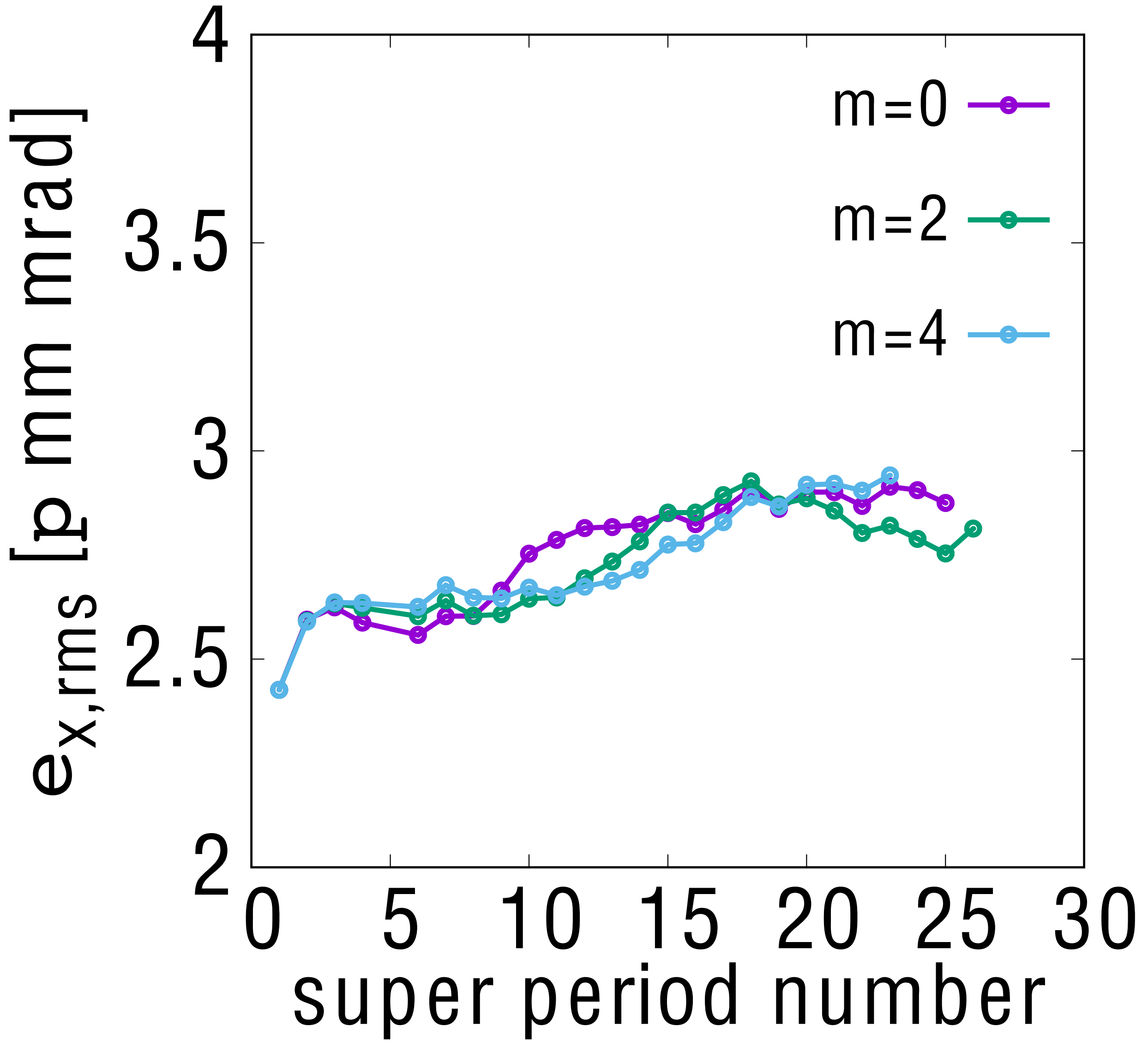
- Reduction of field by ~10%.
- Short straight is 0.257 m.

Science and Technology Facilities Council

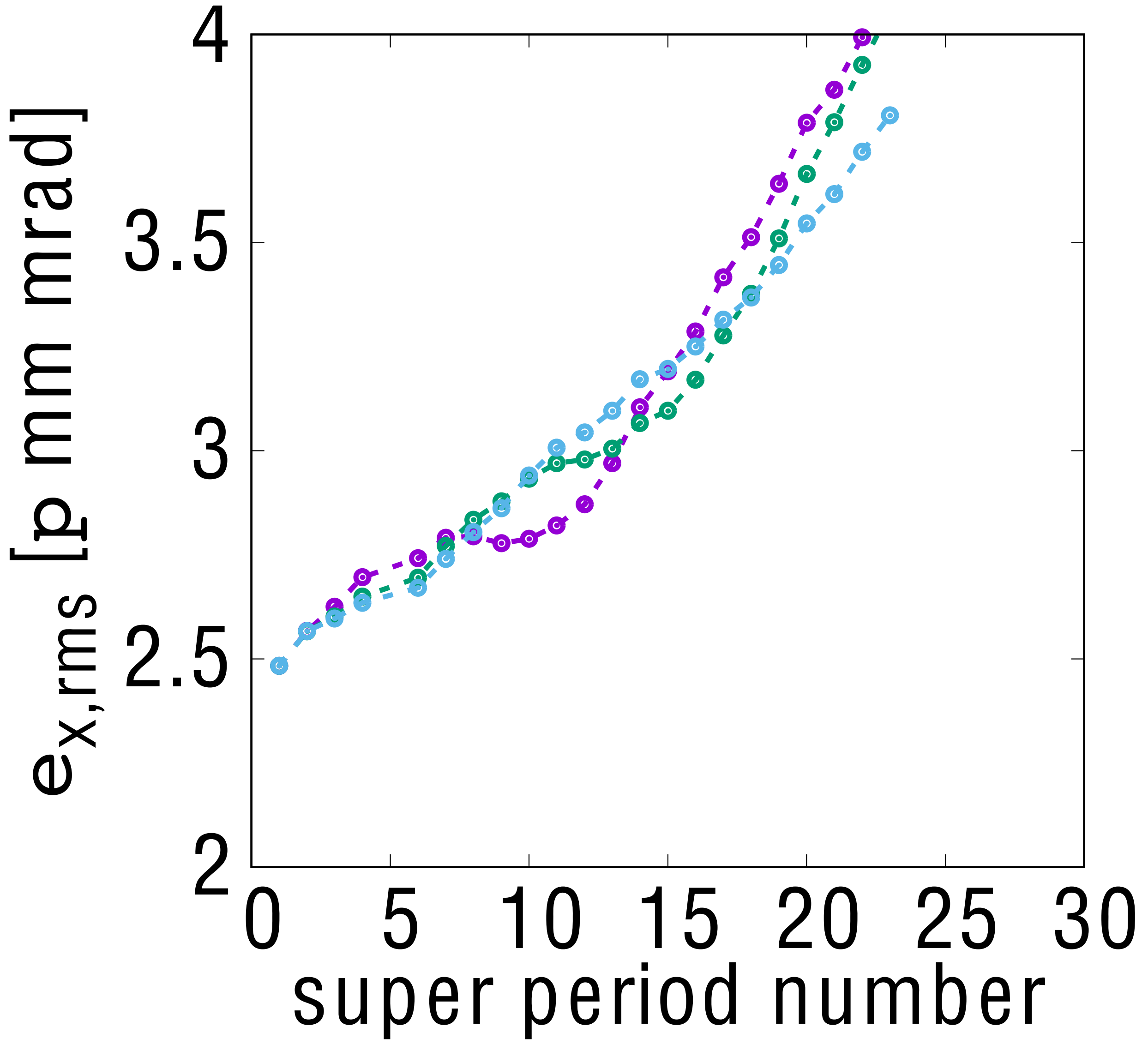
Parameter dependence

Mode number (macro part=10000)

Hor

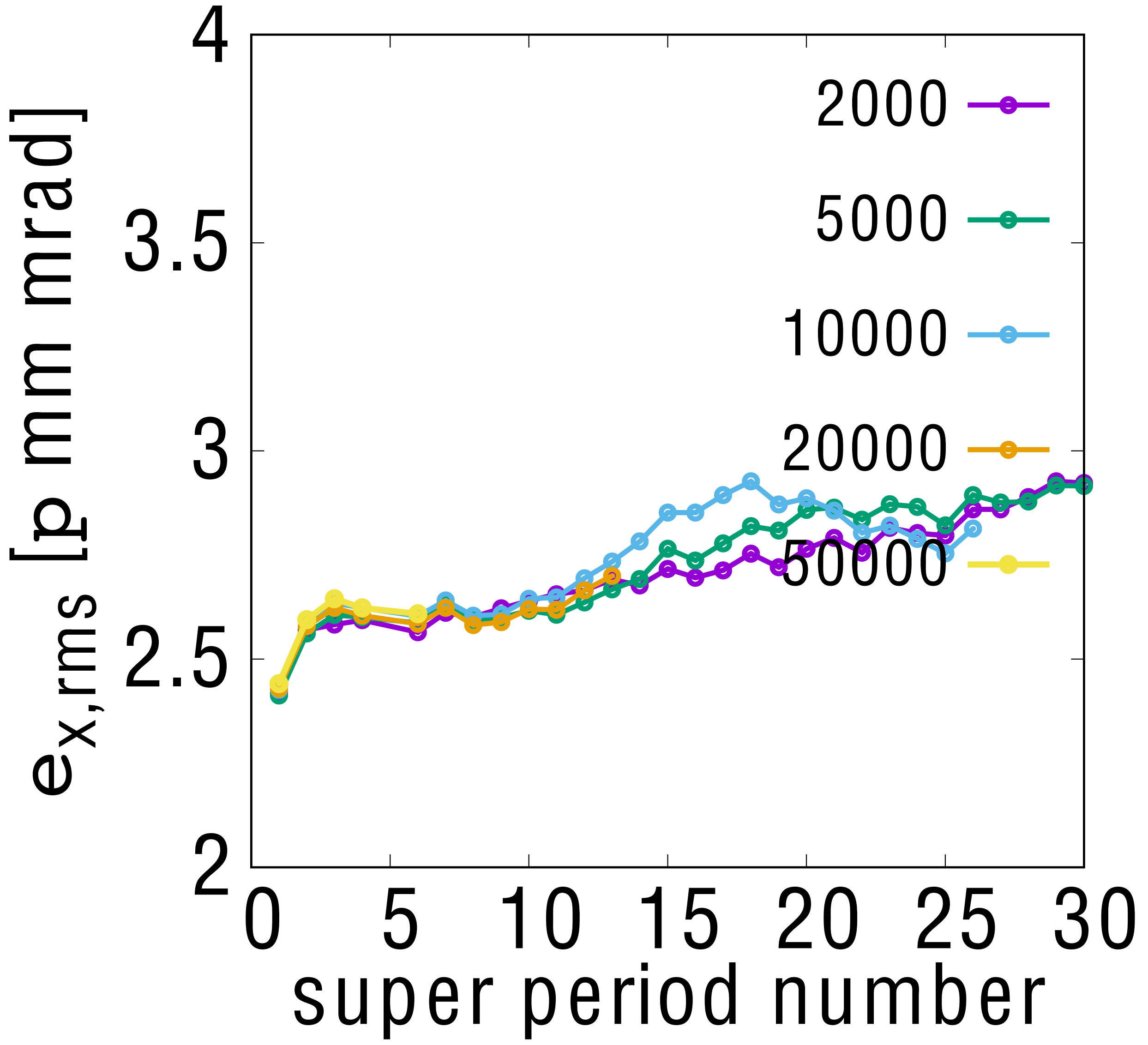


Ver

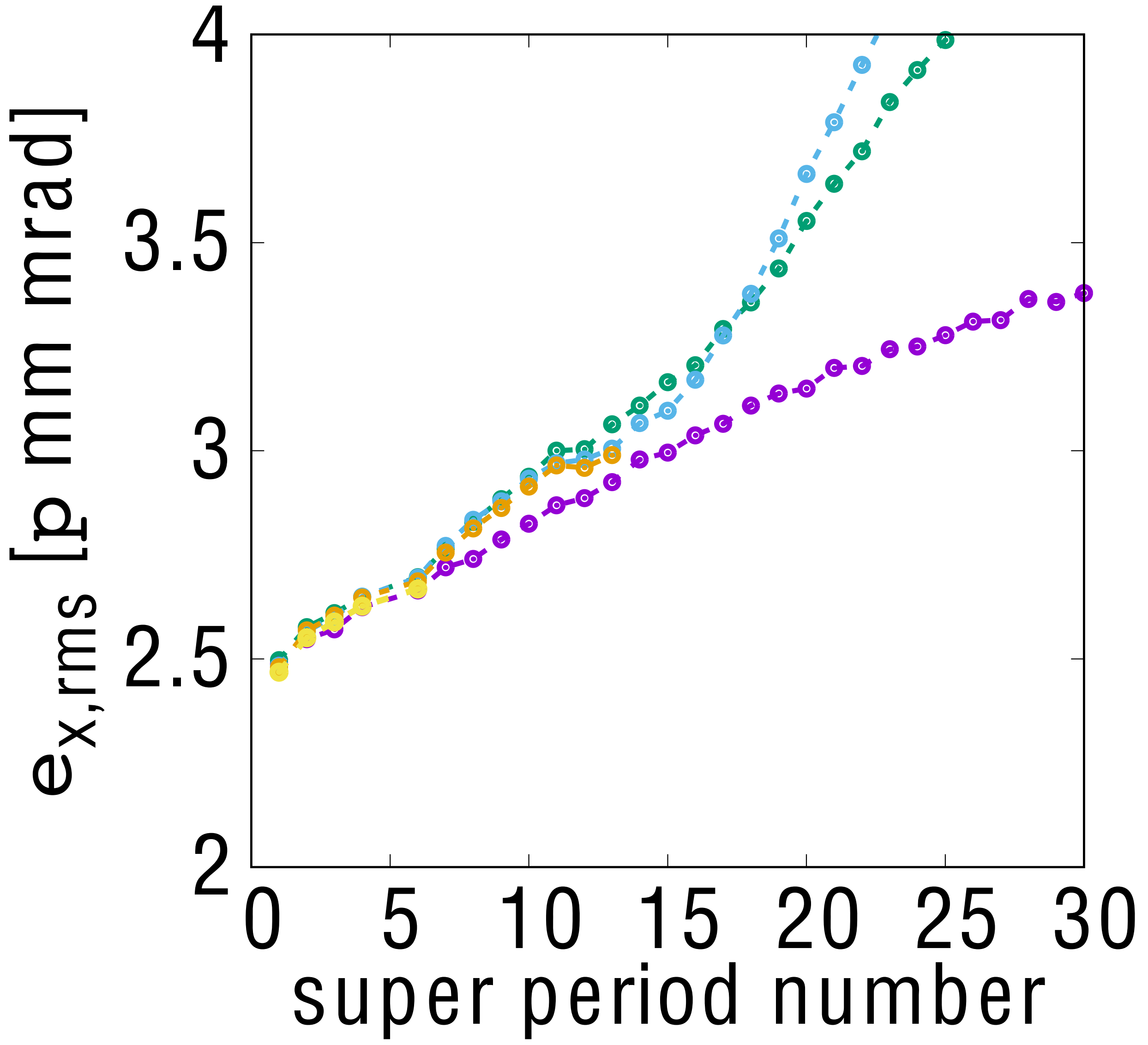


Macro particles (mode number=2)

Hor



Ver

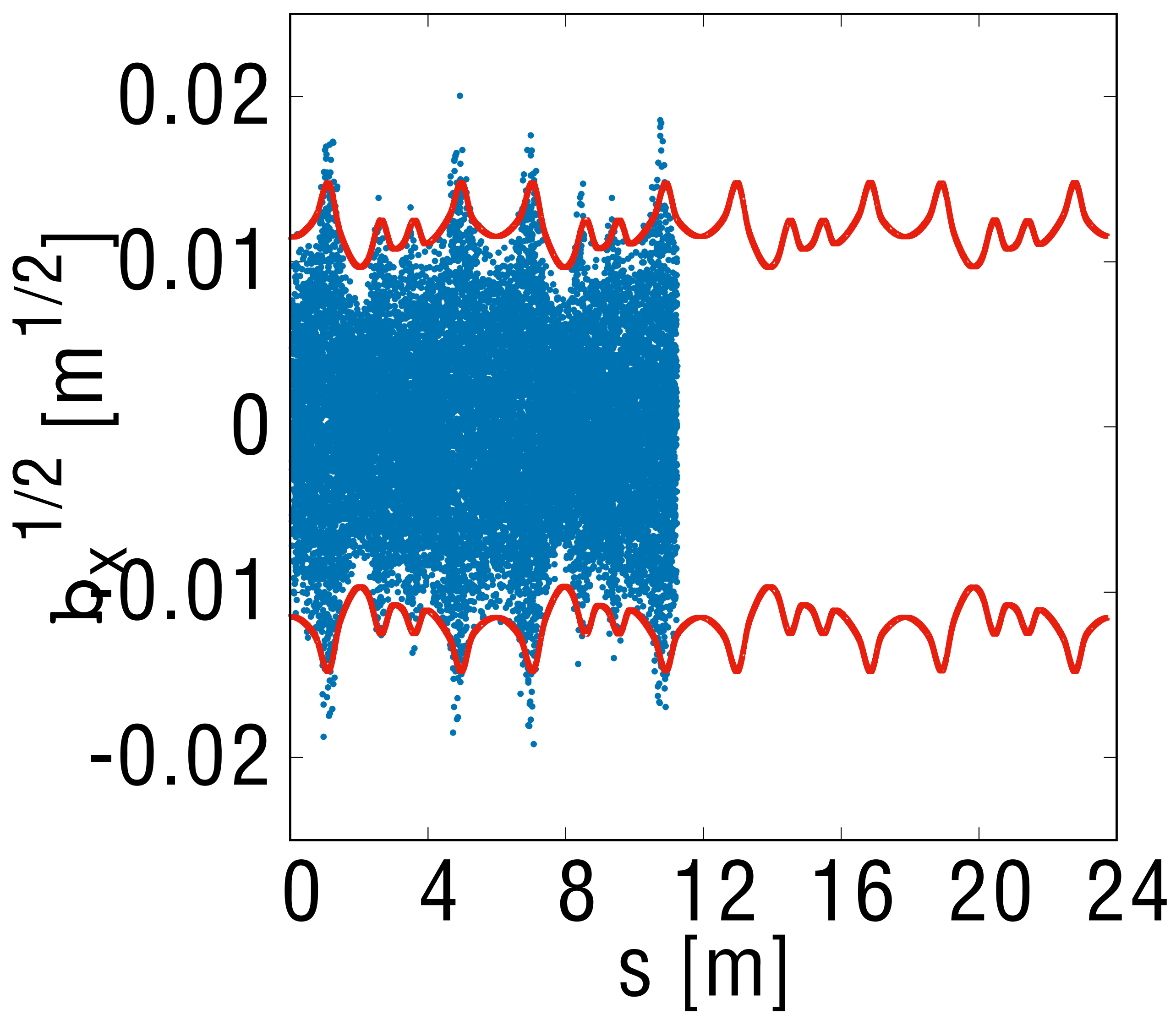


Simulation result (preliminary)

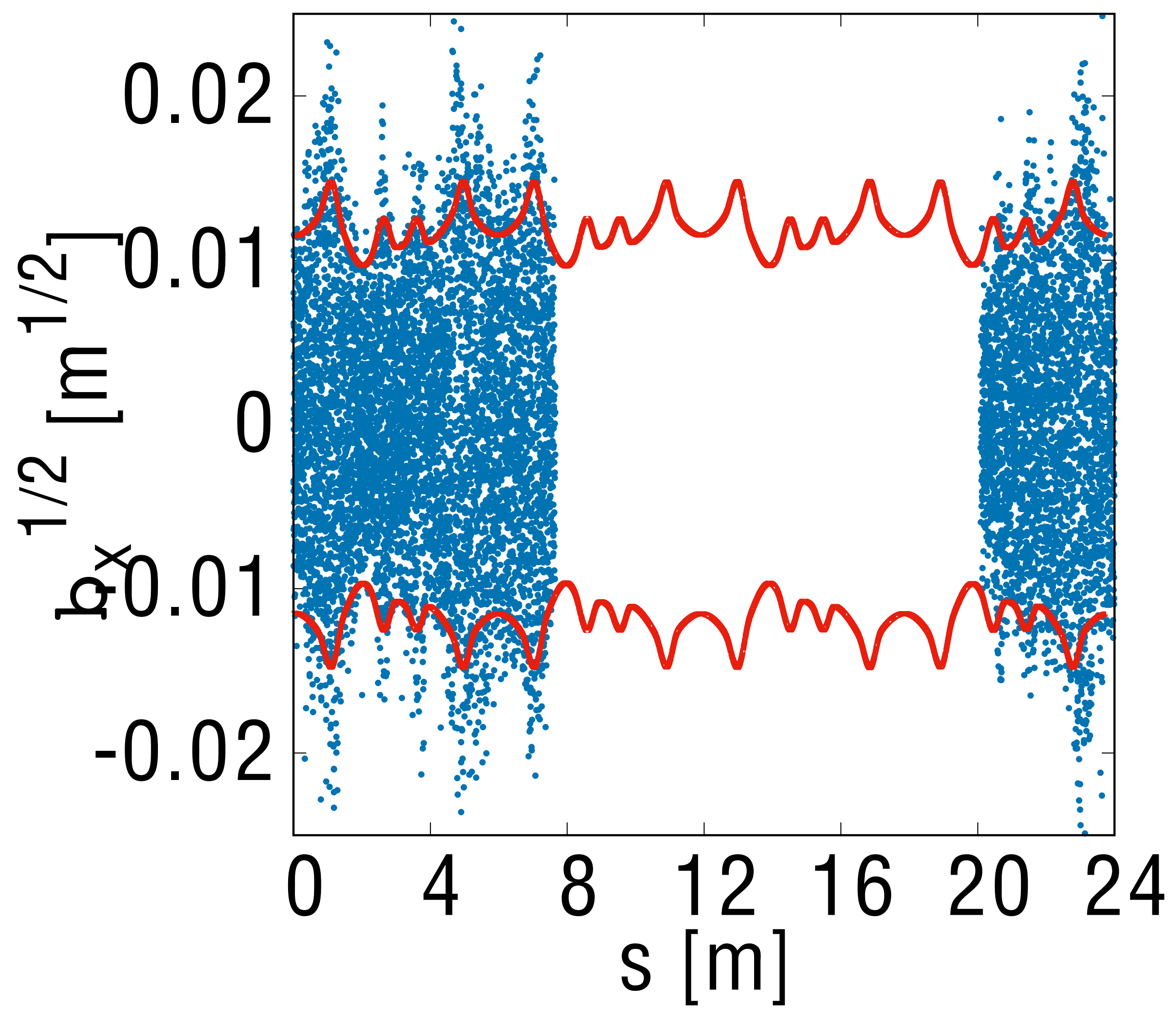
Initial beam envelope.

Beam envelope at 19th turn with 20 x 10^{11}.

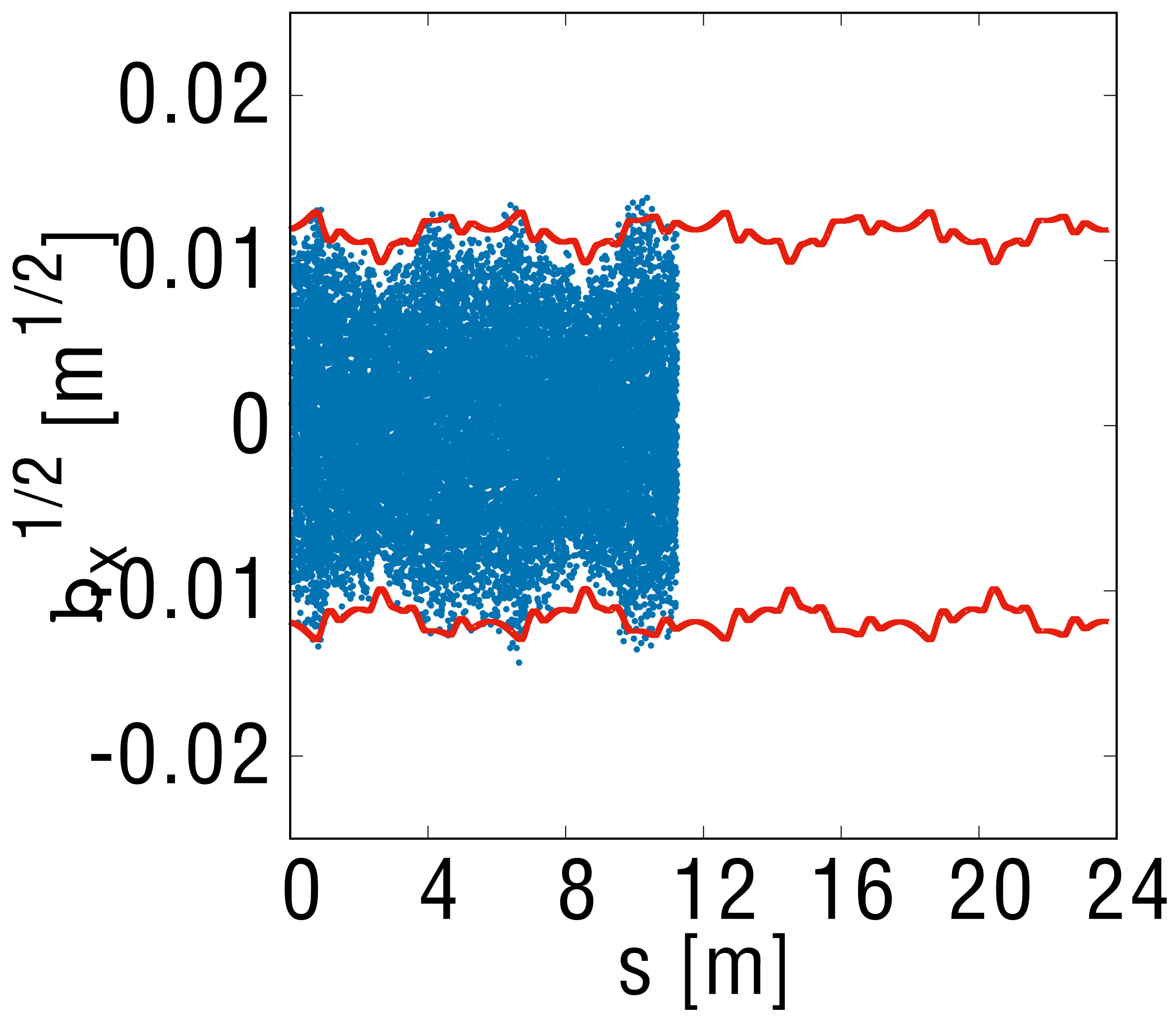
Hor



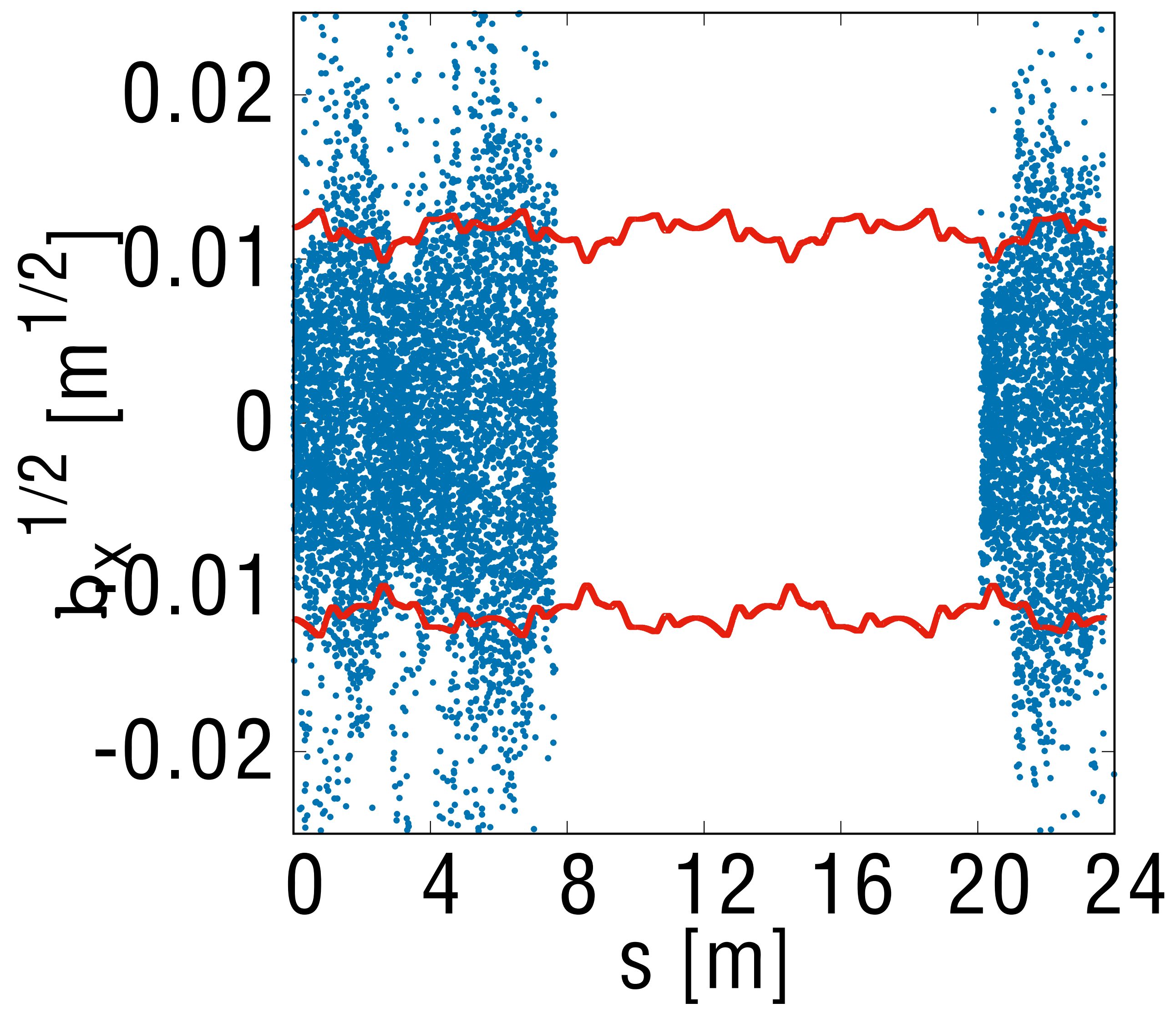
Hor



Ver

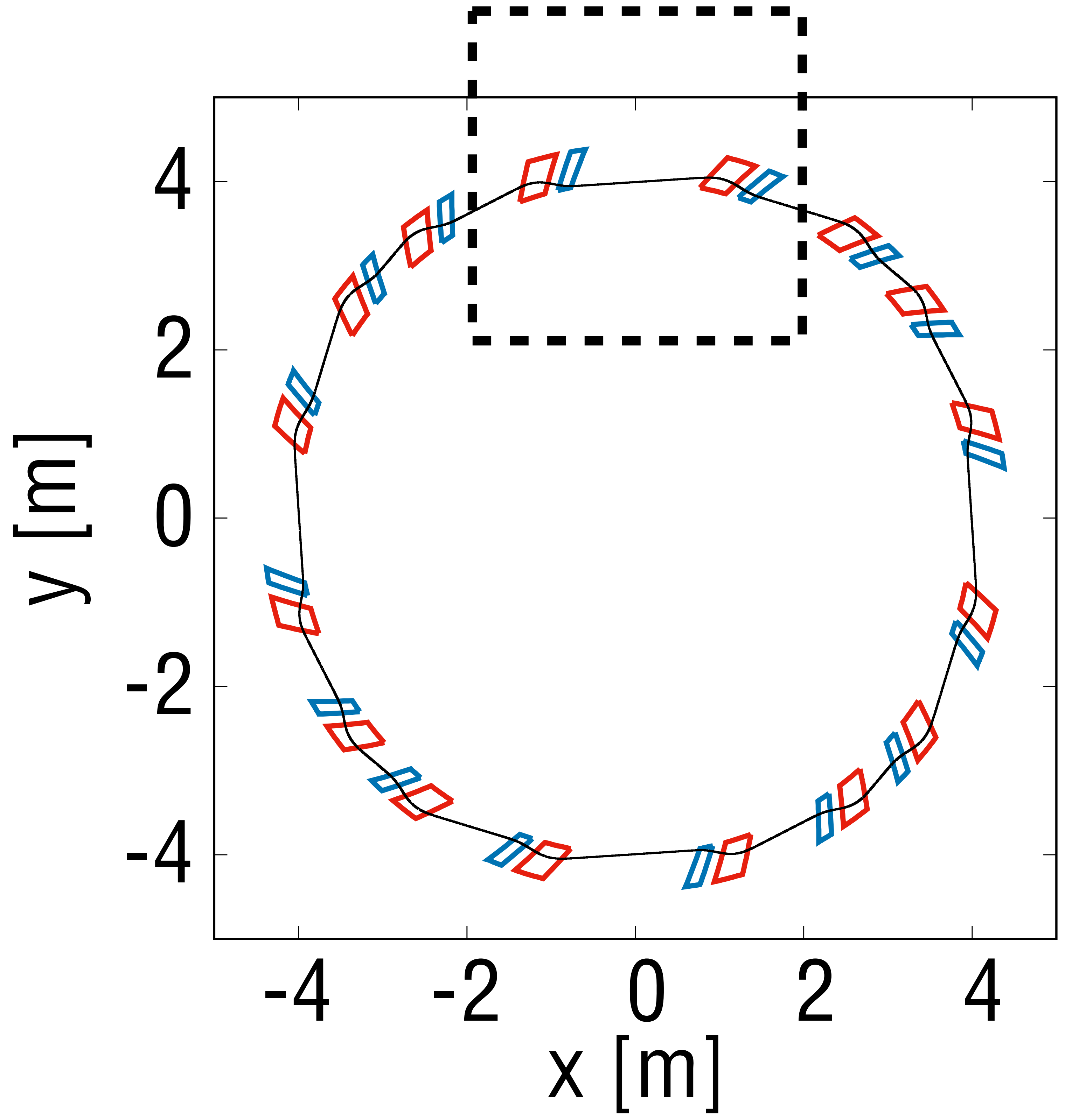


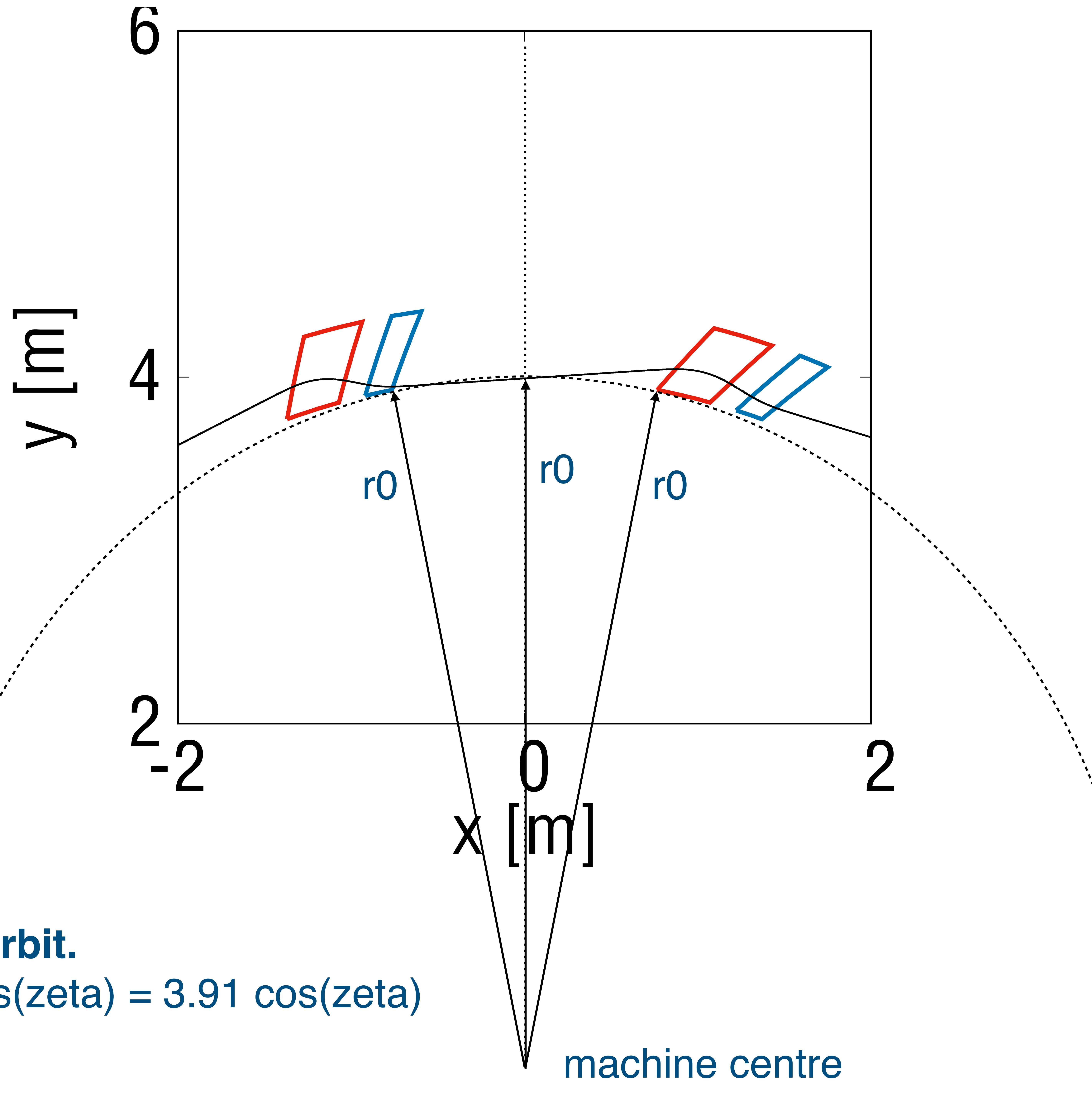
Ver



Science and Technology Facilities Council

Layout, coordinate system





- C-shape magnet
- **r0 = 3.6 m for 3 MeV orbit.**
- Tanh fringe, c1=c10 cos(zeta) = 3.91 cos(zeta) = 3.38616 at r=4.0 m.

Multipole expansion

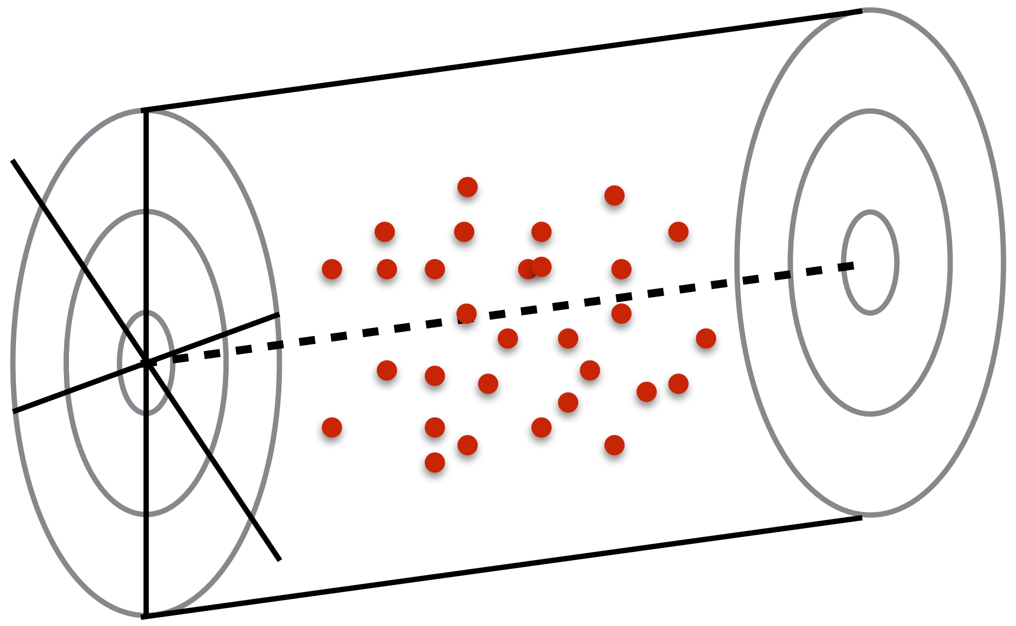
- Scode uses multipole expansion to calculate space charge potential.

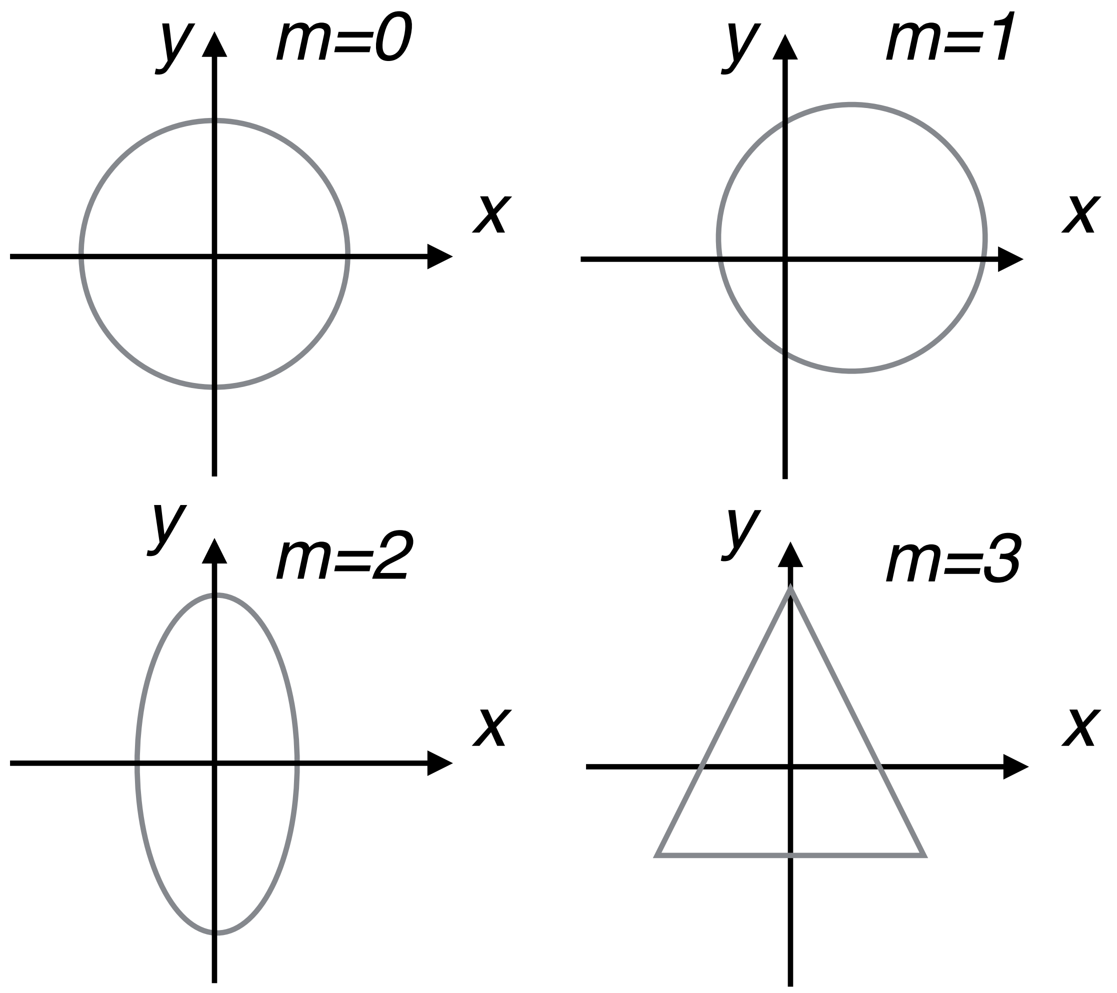
$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial}{\partial r}\phi\right)+\frac{1}{r^2}\frac{\partial^2}{\partial\varphi^2}\phi+\frac{\partial^2}{\partial z^2}\phi-\epsilon_0\mu_0\frac{\partial^2\phi}{\partial t^2}=-\frac{\rho}{\epsilon_0}$$

- Fourier decompose in azimuthal direction

$$\phi\left(r,z,\varphi\right)=\sum_{m=-\infty}^{\infty}\phi_m\left(r,z\right)\exp\left(im\varphi\right),$$

$$-\frac{\rho}{\epsilon_0}\left(\equiv n\left(r,z,\varphi\right)\right)=\sum_{m=-\infty}^{\infty}n_m\left(r,z\right)\exp\left(im\varphi\right).$$





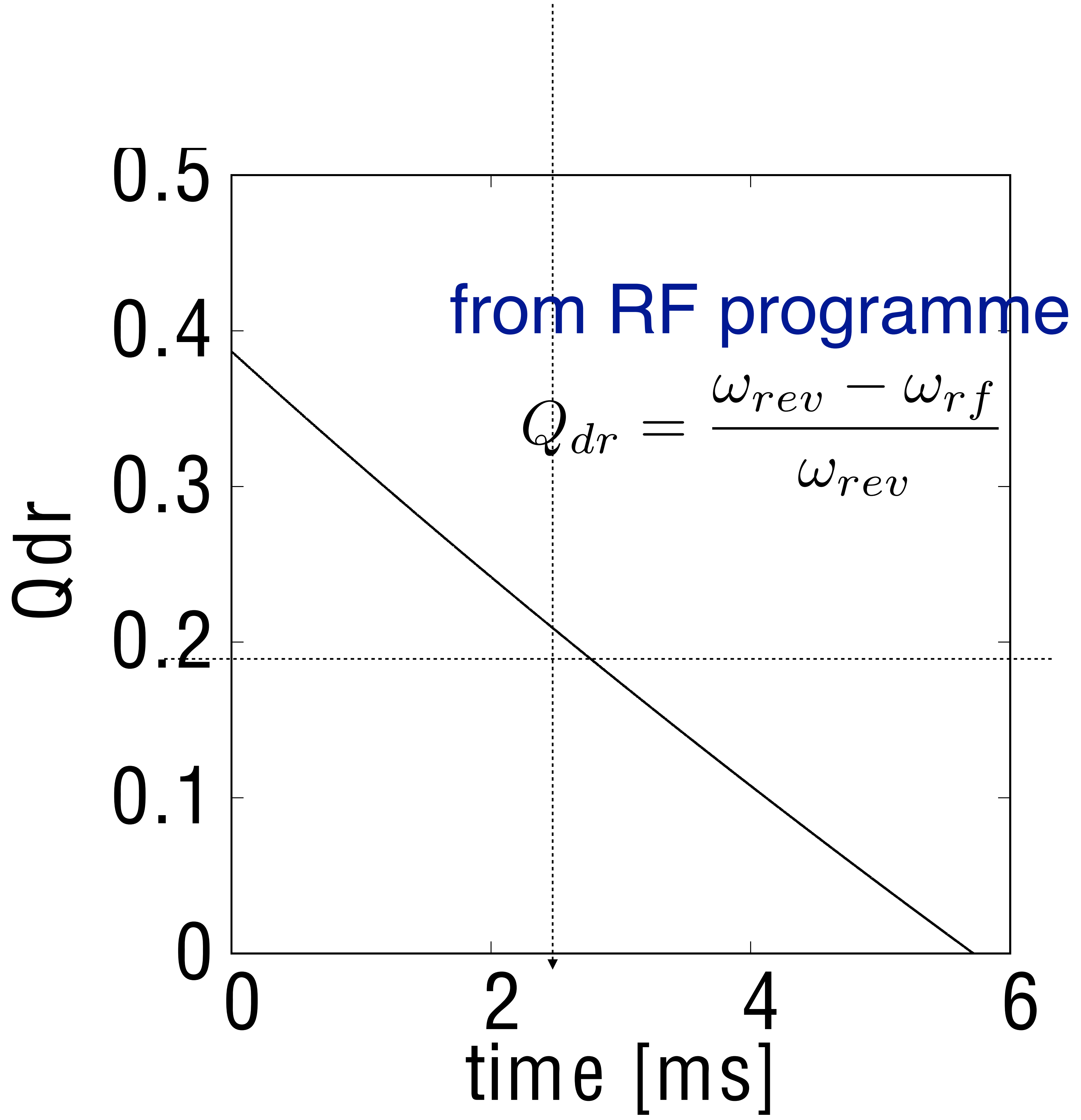
- Potential is solved in each multipole m separately

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial}{\partial r}\phi_m\left(r,z\right)\right)-\frac{m^2}{r^2}\phi_m\left(r,z\right)=n_m\left(r,z\right)$$

- Needs to define the expansion centre.
  - It is a closed orbit in a synchrotron.
  - Define expansion centre as the average position of all the macro particles.

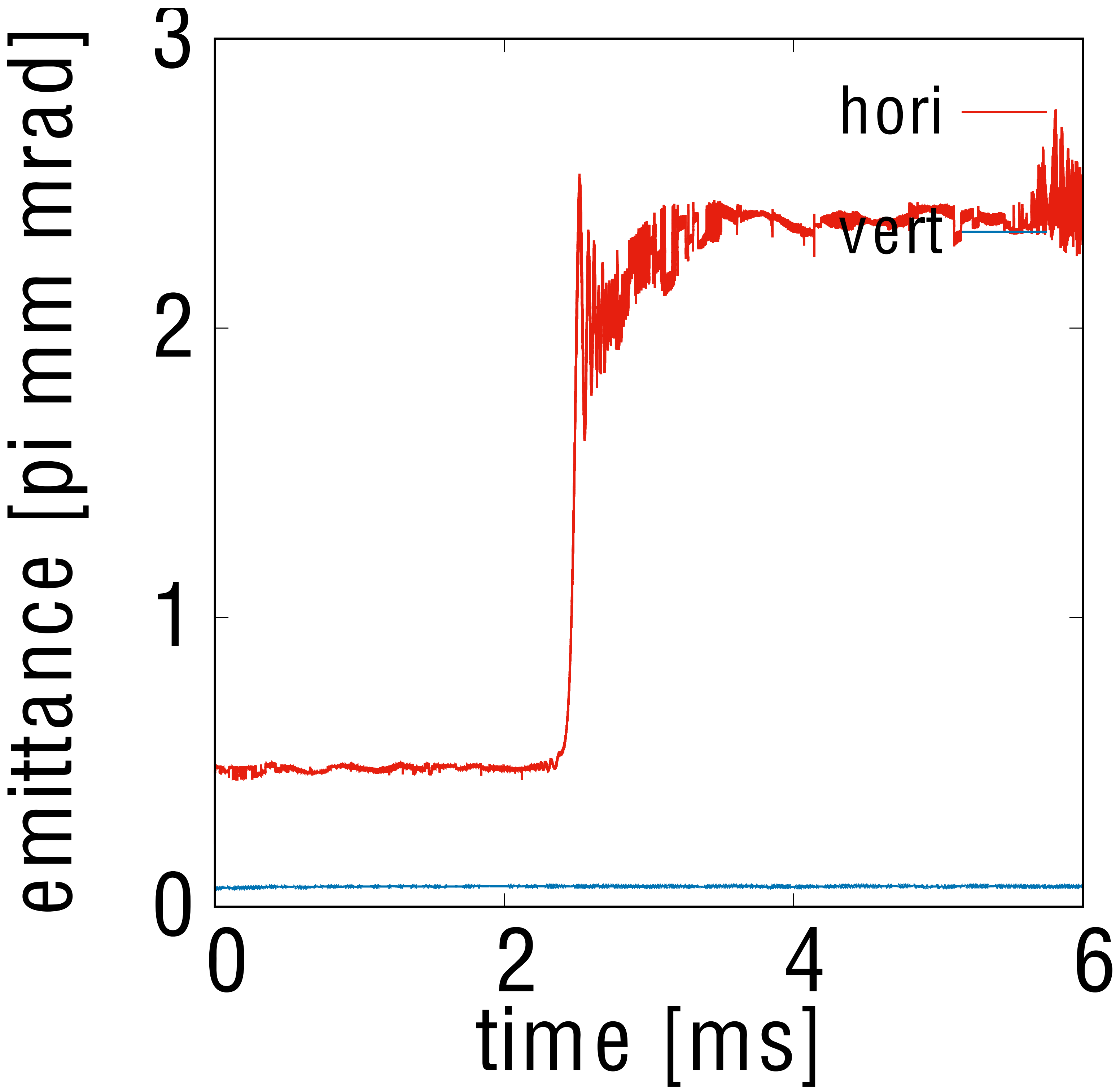
Simulation with KURNS 3D field map

Qh = 0.79 or 1-Qh = 0.21



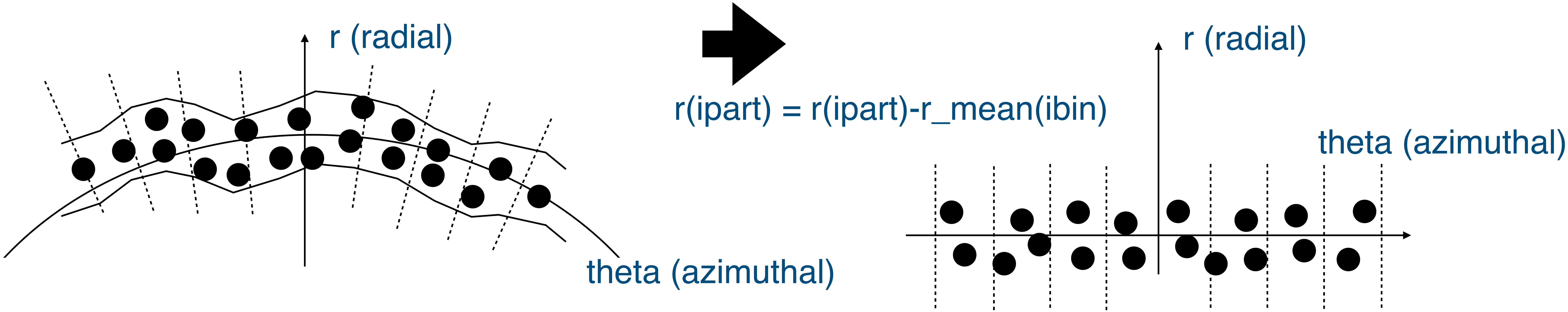
We should see something at ~2.5 ms

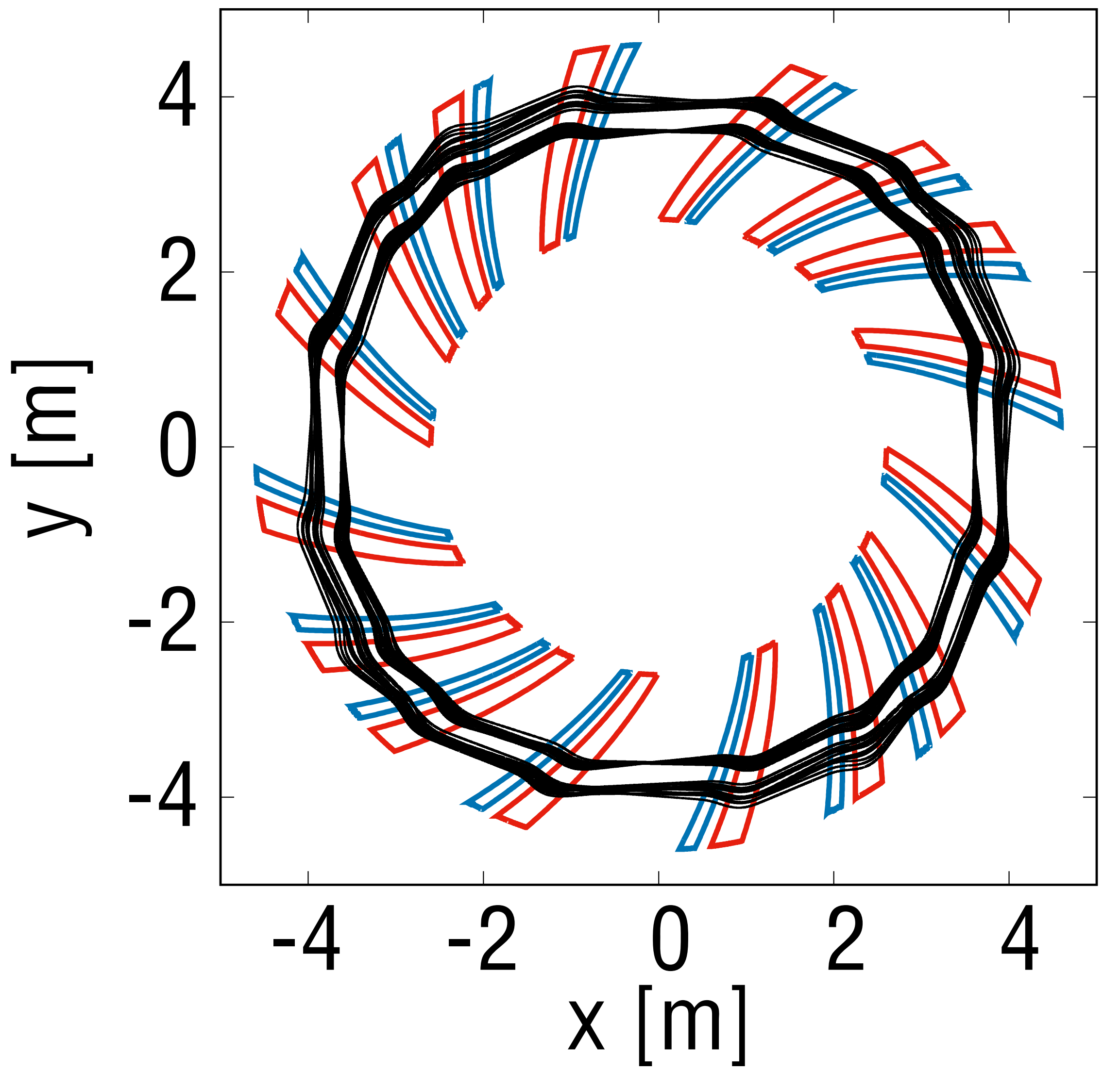
horizontal emittance growth at ~2.5 ms.



No closed orbit in an FFA

- Particles in global polar coordinate system





- It is still an approximation because design orbit is not along the constant radius.
- It could be improved later. For the time being, let’s try.

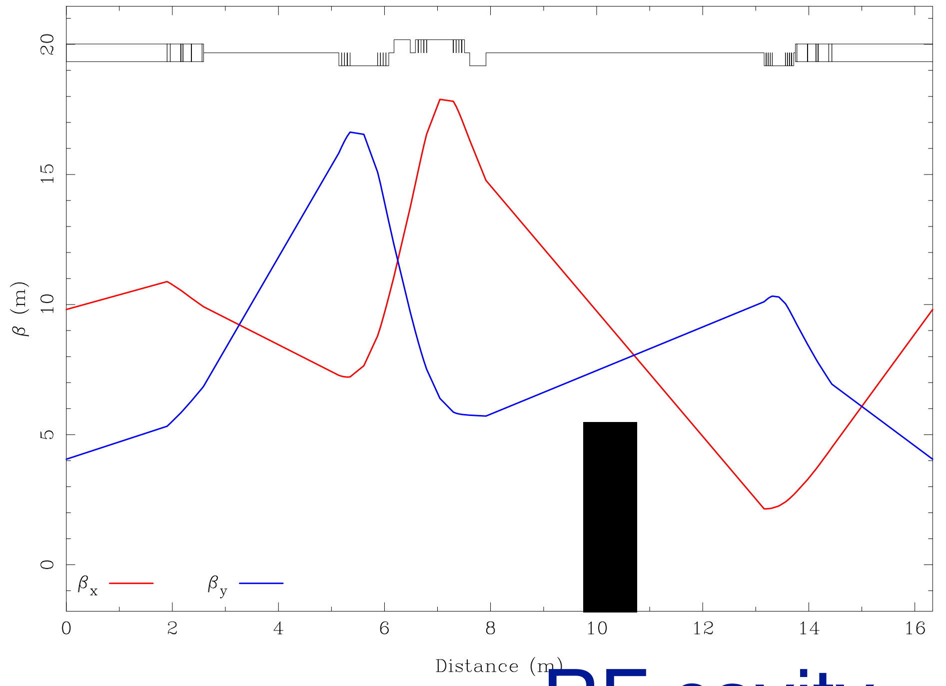
Parameters necessary for back of the envelope calculation

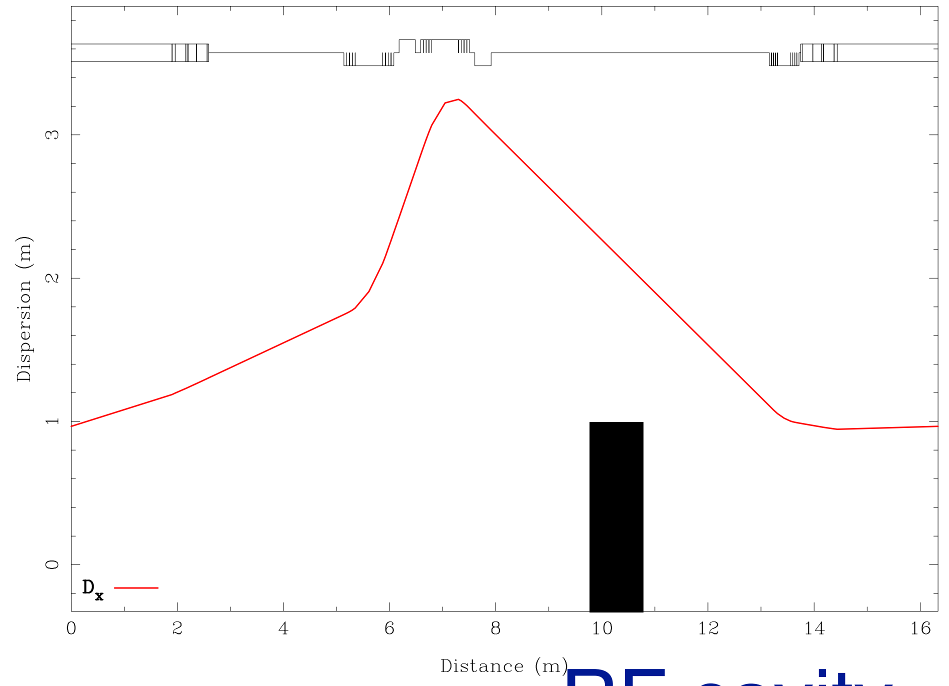
ISIS RF parameters I assumed (from catalogue of HEAs, 1989)

injection energy	70.4 MeV
beta, gamma	0.367040, 1.075032
ring diameter	52 m
revolution time	1.484635 micro s
harmonic number	2
RF frequency	1.34 to 3.06 MHz*
RF voltage	14 kV per cavity
transverse tune	(4.31, 3.83)

*df/dt = (3.06 - 1.34) MHz/ 0.010 s = 172 MHz/s at least

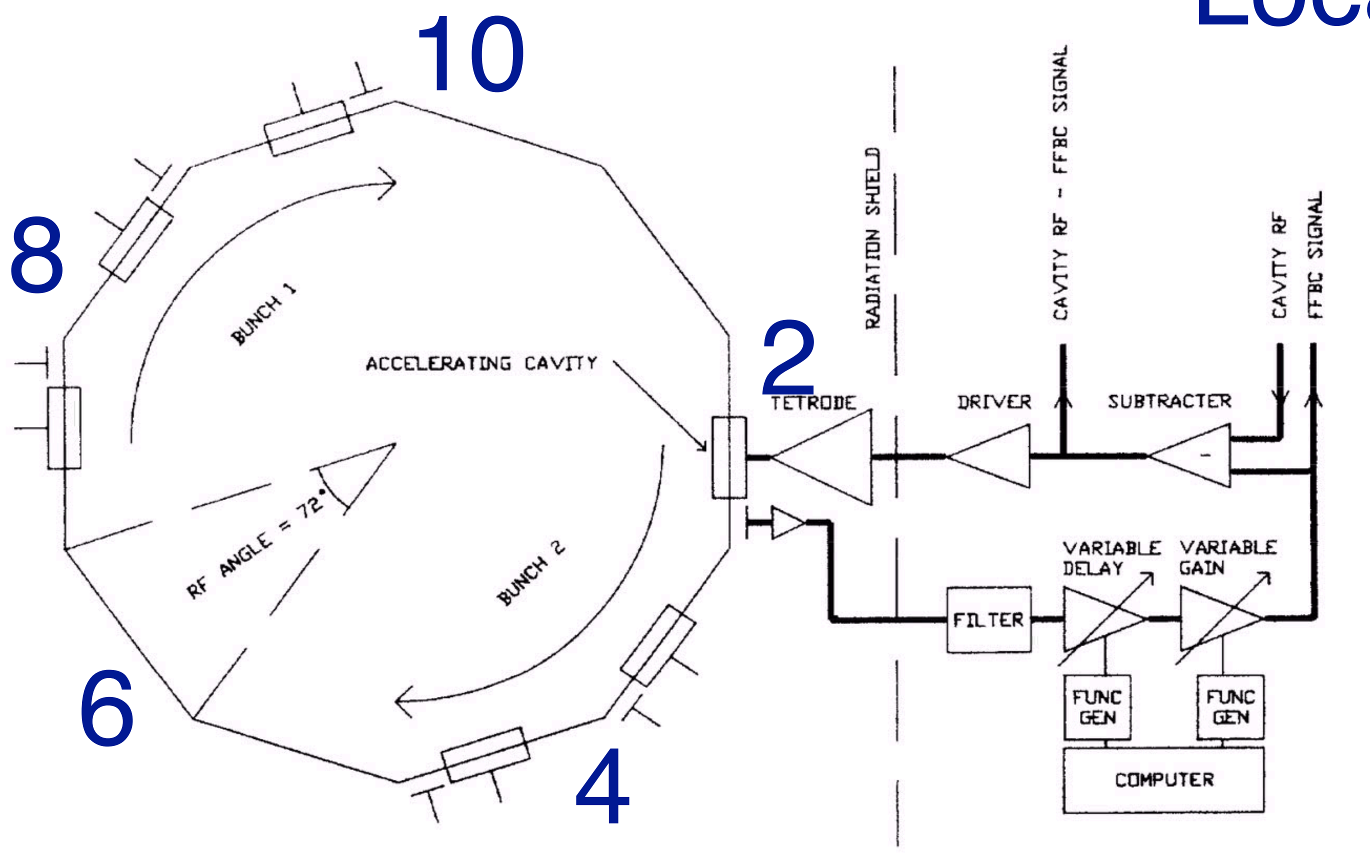
Optics parameters at cavity (from C. Prior)





beta_x, y	(4 m, 6 m)
alpha_x, y	(2, -1)
Dx, Dx’	2 m, -0.4
transverse tune	(4.31, 3.83)

Location of RF cavities

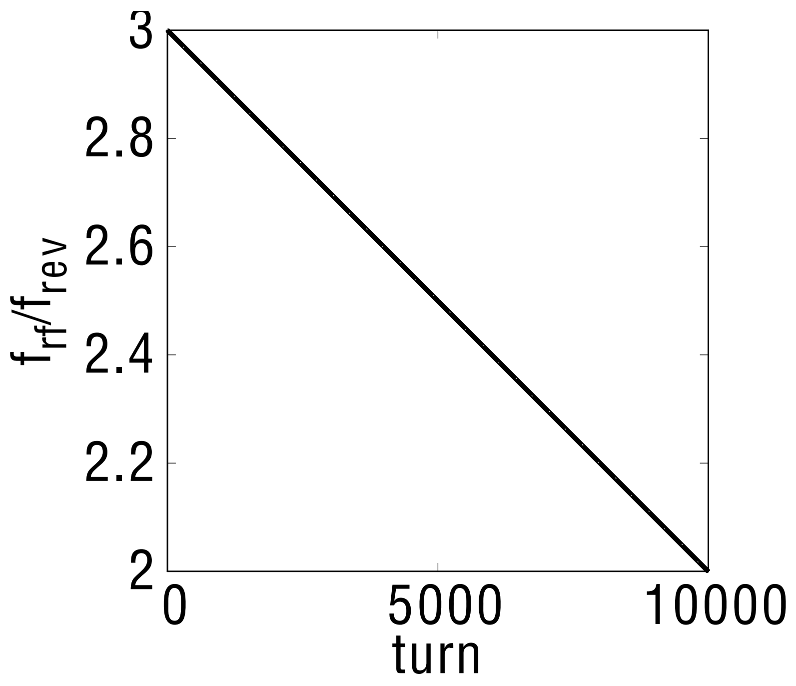


h=2 cavities	Long straight section 2,3,4,7,8,9*
h=4 cavities	Long straight section 5,6
	Short straight section 4,5

*phase advance between 2 cavities could be = 0.431 x 1, 2, 3, 4, 5

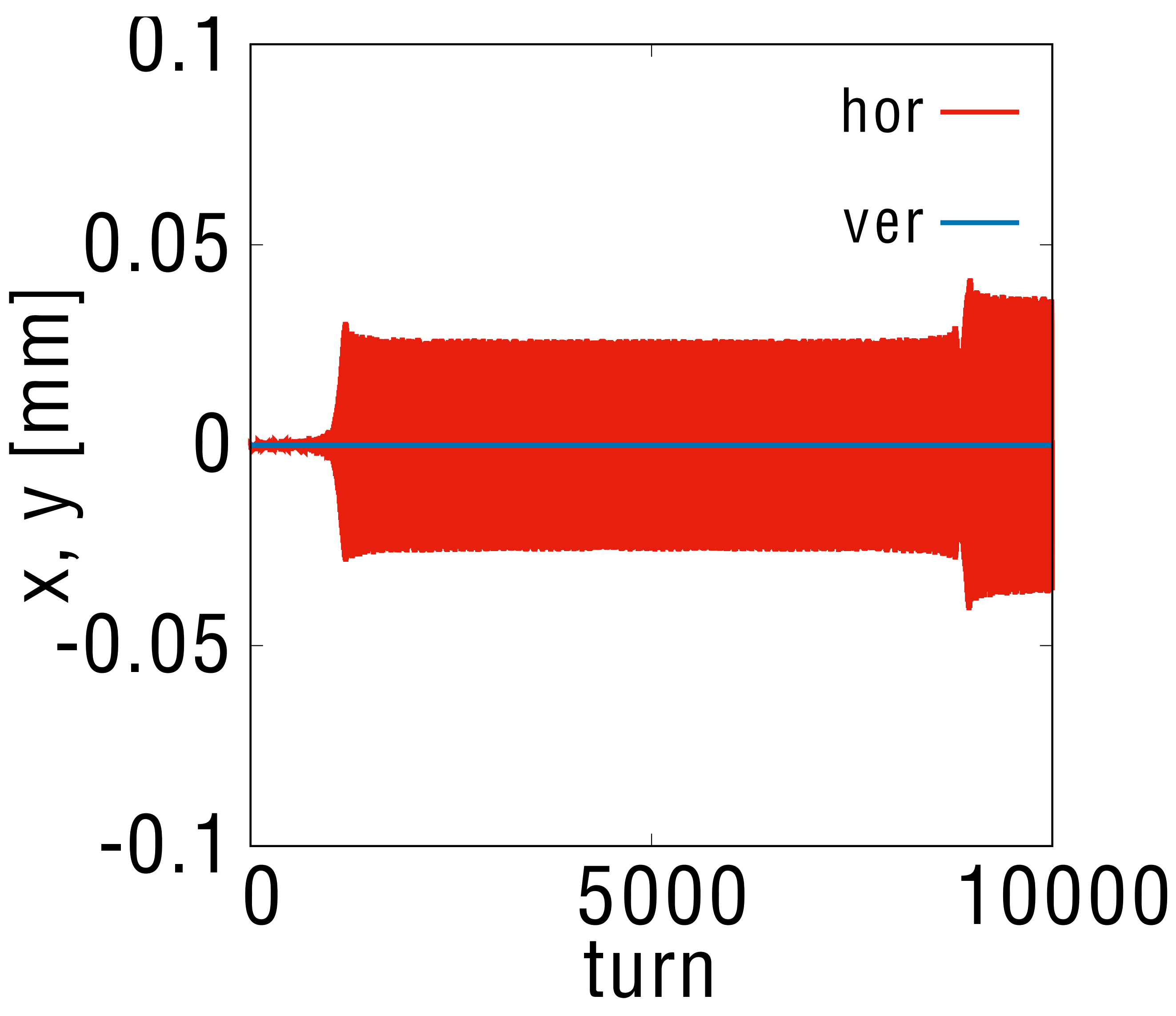
We want to change the RF phase difference between two cavities arbitrarily, not necessarily according to synchronised particles.

Simulation results

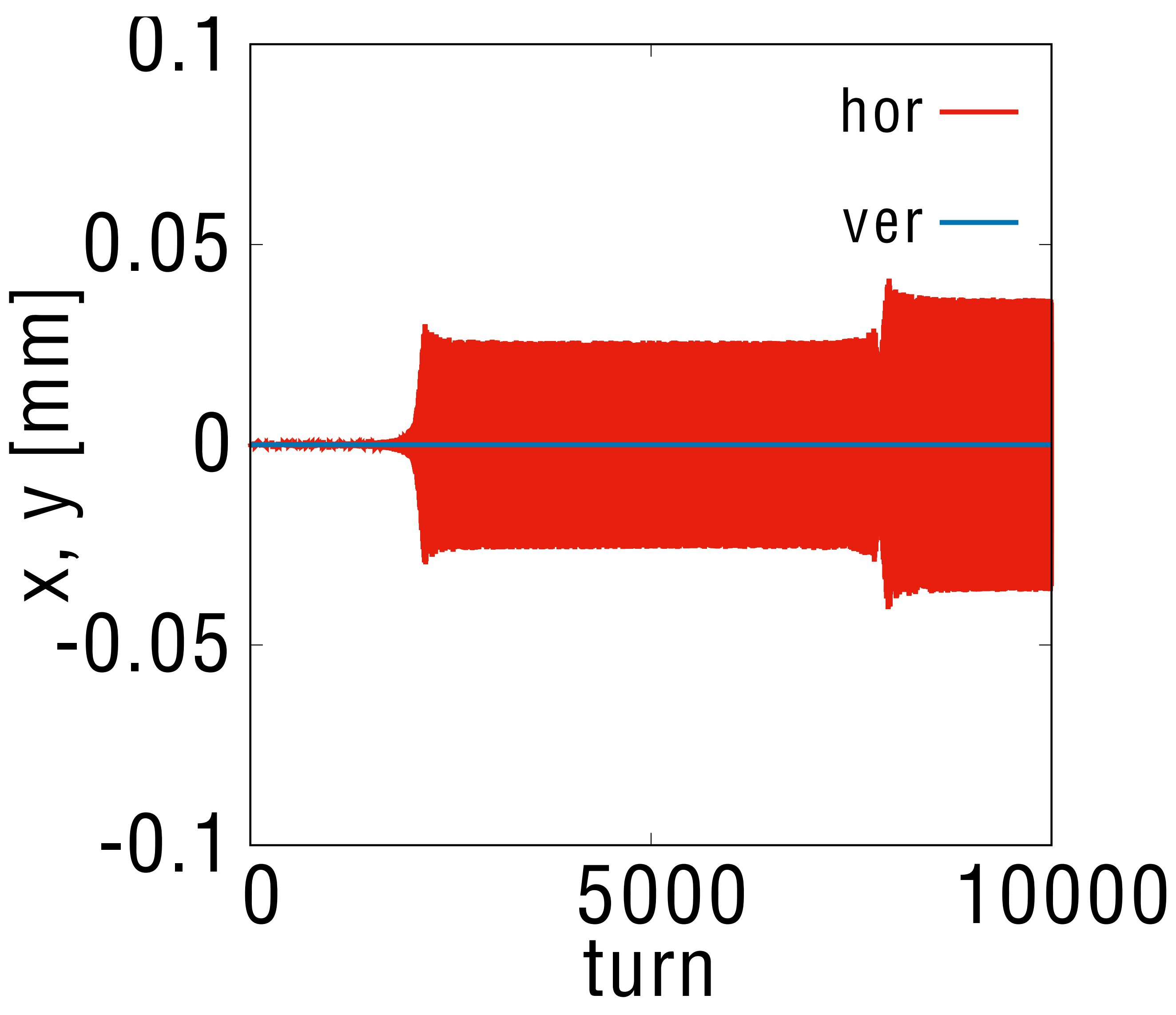


*df/dt = 45 MHz/s

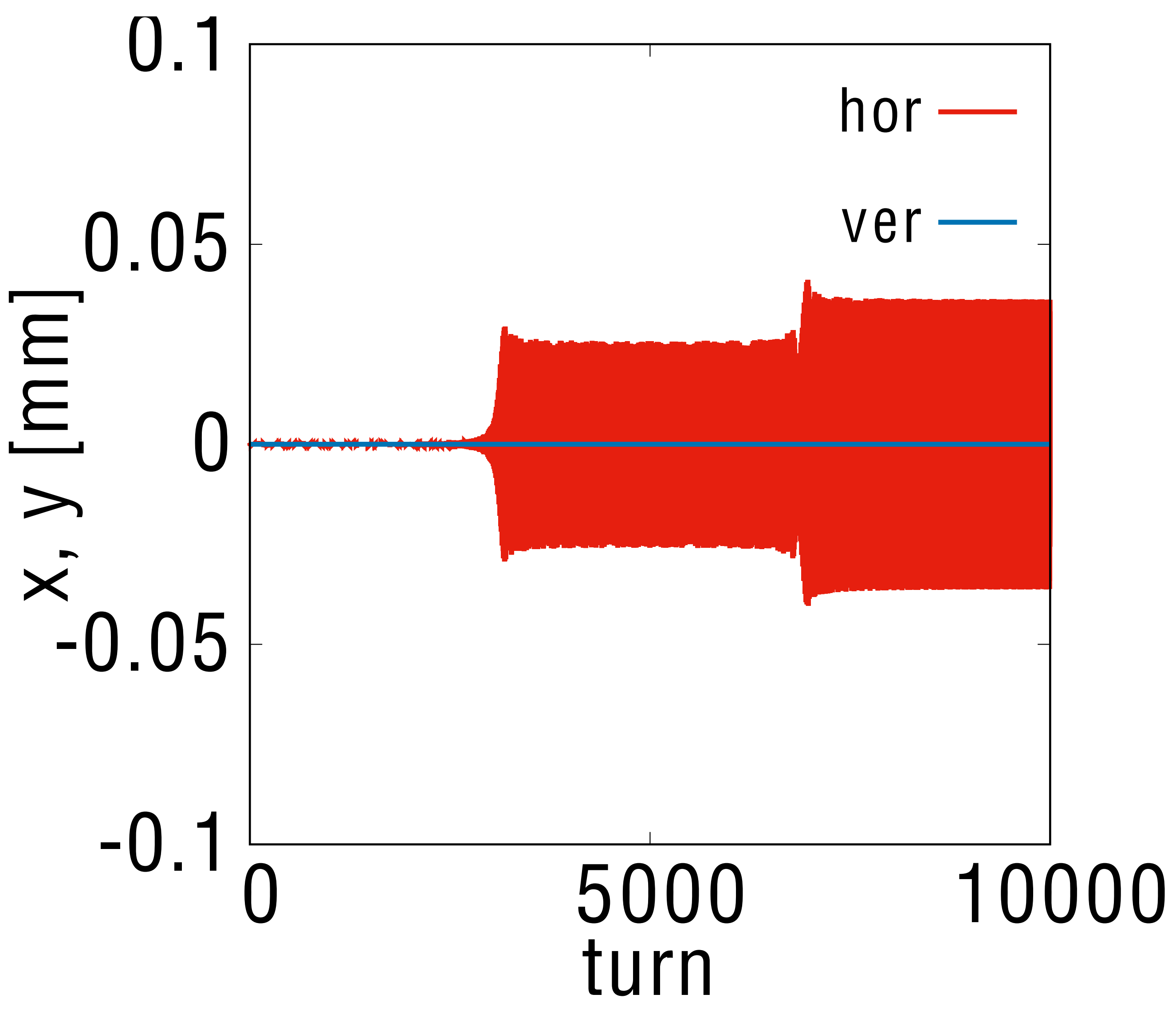
Qh=4.11



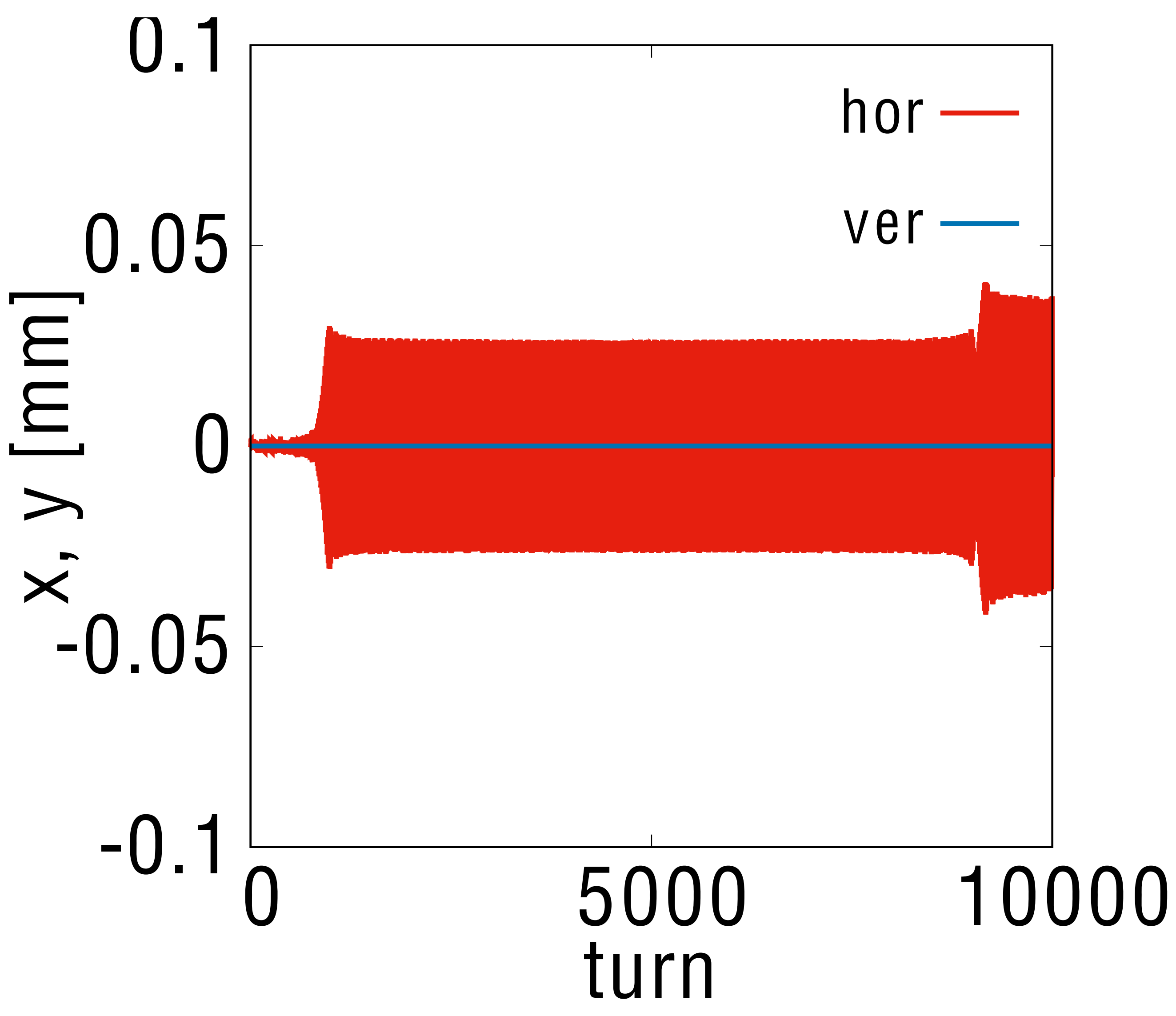
Qh=4.21



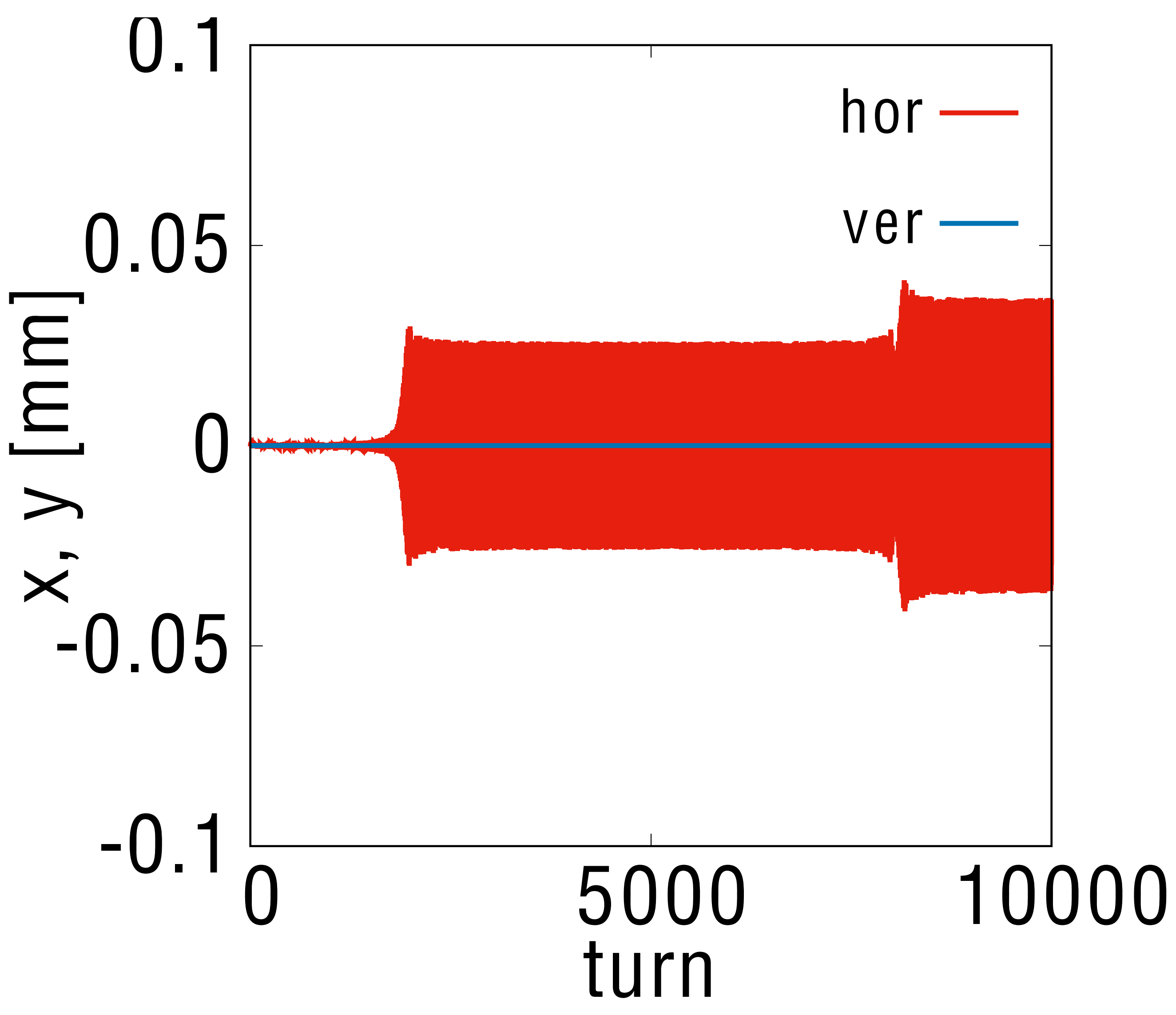
Qh=4.31



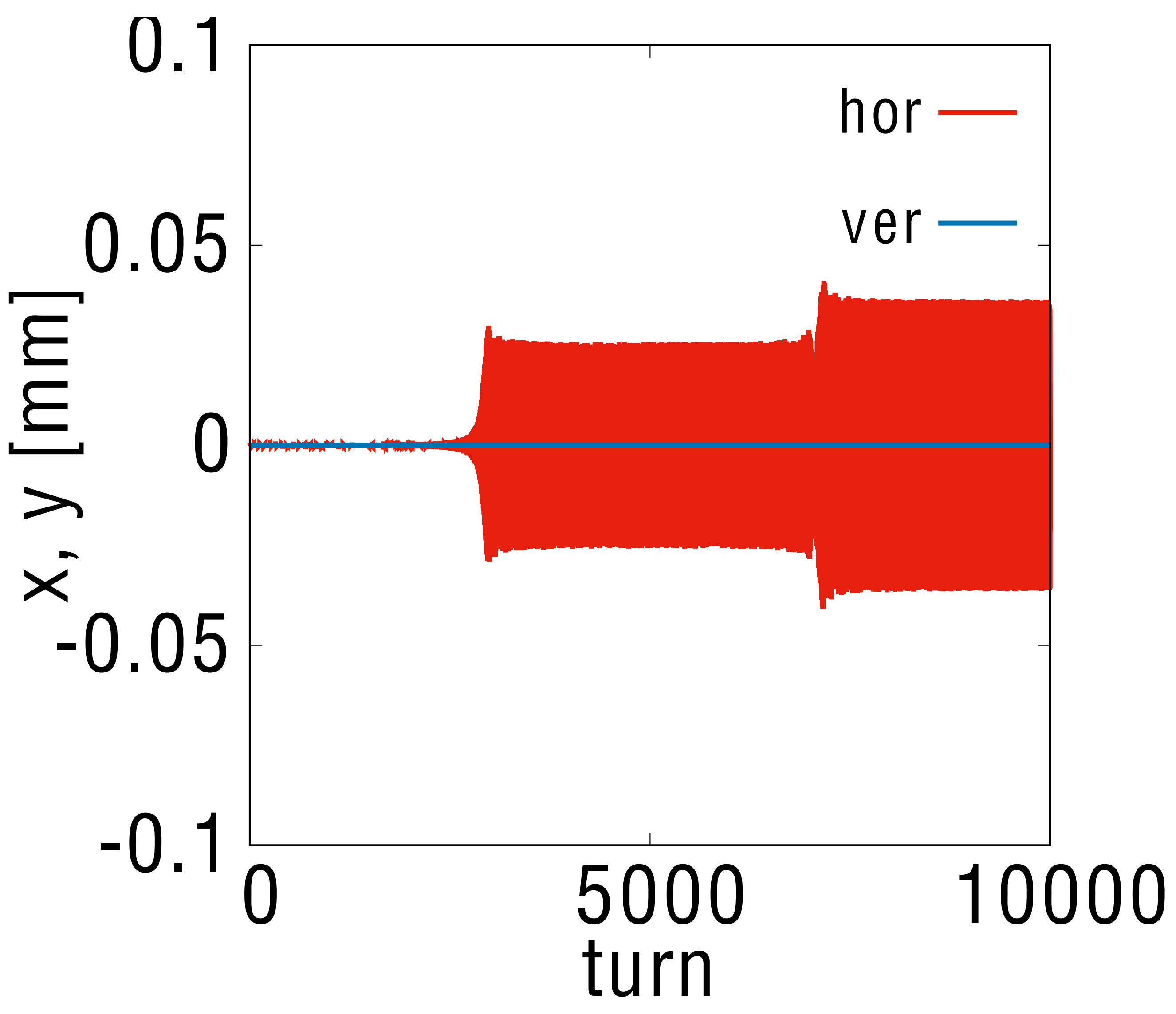
Qh=4.91



Qh=4.81



Qh=4.71



Proposed beam experiment at ISIS

Procedure

- Storage mode at injection energy.
- Inject the beam and let it debunch to become the coasting beam.
    - Measure momentum spread by Schottky signal and beam intensity.
- Excite one or two RF cavities with below 3*f_rev. It does not disturb the coasting beam.
- Change RF frequency from 3*f_rev to 2*f_rev linearly.
    - Measure momentum spread by Schottky signal and beam intensity in the process.

Measurement

- DC current monitor
- Beam size
- Schottky signal

Parameters we will scan

- Speed of RF frequency change.
- RF voltage
- Phase difference of two cavities.

Goals

- Reproduce beam loss during the beam stacking process.
- Verify if mitigation measures work.