Design of a fixed field accelerating ring for high power applications

Shinji Machida, STFC/Rutherford Appleton Laboratory

HB2023 at CERN

9 October 2023

UKRI Science and Technology Facilities Council
ISIS Neutron and Muon Source

Outline

- A bit of history
  - Midwestern Universities Research Association (MURA)
  - ASPUN at Argonne National Lab
  - Initial ESS project
- Why Fixed Field Accelerator?
  - High power by high repetition
  - Sustainable option
- Toward high power Fixed Field Accelerator
  - Constant tune
  - FD (DF) spiral sector
  - Superperiodicity
  - Physical and dynamic aperture
  - Collimation
  - Correction by trim coils
- Beam stacking experiment
- (Modelling space charge effects)
- Summary

Fixed Field Accelerating Ring

What is Fixed Field Accelerating Ring?

- Cyclotron
- Synchrocyclotron
- Fixed-Field Alternating-Gradient (FFA, used to be FFAG)

Accelerators I am going to discuss have

- Main lattice with DC magnets
- Alternating gradient focusing
- Non isochronous, RF frequency is modulated
- Zero chromaticity, transverse tune is constant

→ I call it “FFA”

Science and Technology Facilities Council

A bit of history

A bit of history

MURA in 1950s

Midwestern Universities Research Association

O CAMELOT !

A MEMOIR OF THE MURA YEARS*

F.T.Cole

April1 1, 1994

16.3 A New Single-Beam Proposal

We put together a new proposal with no colliding beams at all. We chose a proton energy of 10 GeV to be high enough above the antiproton production threshold to make usable intensities, but were constrained from going higher by concern about the total cost. We claimed we would reach a time-average intensity of 30 microamperes or 2 x 10^{14} protons per second, three orders of magnitude above what the synchrotrons were then doing (of course their higher energy took away some of that advantage in antiproton production). It was a spiral-sector ring

Science and Technology Facilities Council

Must read! https://accelconf.web.cern.ch/c01/cyc2001/extra/Cole.pdf

A bit of history

High current beam studies at MURA

Proceedings of the 2003 Particle Accelerator Conference

MURA DAYS

Keith R. Symon, University of Wisconsin-Madison, Madison, WI 53706, USA

Invited talk at PAC2003

(i) beam stacking,
(ii) Hamiltonian theory of longitudinal motion,
(iii) useful colliding beams (the idea itself is quite old),
(iv) storage rings (independently invented by O'Neill),
(v) spiral-sector geometry used in isochronous cyclotrons,
(vi) lattices with zero-dispersion and low-β sections for colliding beams,
(vii) multiturn injection into a strong-focusing lattice,
(viii) first calculations of the effects of nonlinear forces in accelerators,
(ix) first space-charge calculations including effects of the beam surroundings,
(x) first experimental measurement of space-charge effects,
(xi) theory of negative-mass and other collective instabilities and correction systems,
(xii) the use of digital computation in design of orbits, magnets, and rf structures,
(xiii) proof of the existence of chaos in digital computation, and
(xiv) synchrotron-radiation rings

A bit of history

Spallation neutron source proposal

ASPUN, ANL

T. K. Khoe and R. L. Kustom
Physics Division
Argonne National Laboratory
9700 S. Cass Avenue
Argonne, IL 60439

Proceedings of the 20

Keith R. Symon, University of W

PAC1983

(i) beam stack
(ii) Hamiltonia
(iii) useful coll
(iv) storage ri
(v) spiral-secto
(vi) lattices wi
(vii) multiturn
(viii) first calcu
(ix) first space
(x) first experi
(xi) theory of n
(xii) the use of
(xiii) proof of t
(xiv) synchrotron radiation rings

16.3 A New Single

We put together
of 10 GeV to be high
intensities, but were con
we would reach a time
three orders of magnitude
energy took away some

...gy
...ble
...ed
...nd,
...her
...ng

Must read!

...d spallation
...nd IPNS-I
...able and actively
...n neutrons. The
..., 30 Hz rapid
...her proton
...eration or in
...S-I at the National
...es in Japan,[3] the
...aboaratory in the
...ord Appleton

...re being developed
...on neutron
...he KFA Laboratory
...e Swiss Institute
...nd,[7] and ASPUN, the

...-Field Alternating
...oal is to provide a

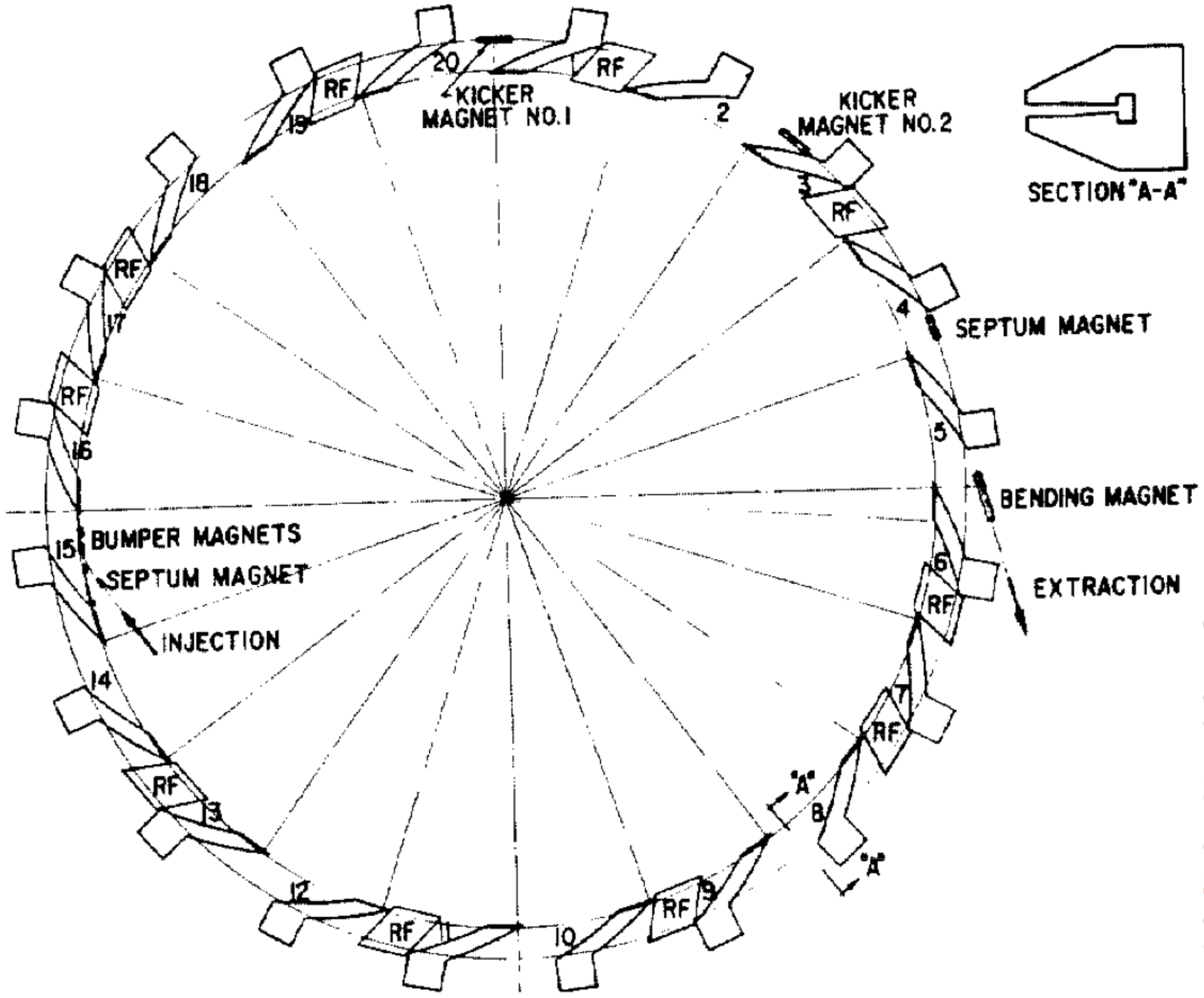


Fig. 1. Schematic View of FFAG Ring.

Table 1. FFAG Accelerator Characteristics

A bit of history

One of two options at (old) ESS Proposal

EPAC1992

T. K. Khoe and R. L. Kustom
Physics Division
Argonne National Laboratory
9700 S. Cass Avenue

Proceedings of the 2003 Particle Accelerator Conference

PAC2003

ASPUN, ANL at PAC1983

Accelerator Design Parameters for a European Pulsed Spallation Neutron Source.

Report from workshop for a European Spallation Source.

S Martin (KFA, Jülich, Germany) and C W Planner (RAL, UK)

Linac+Compressor ring

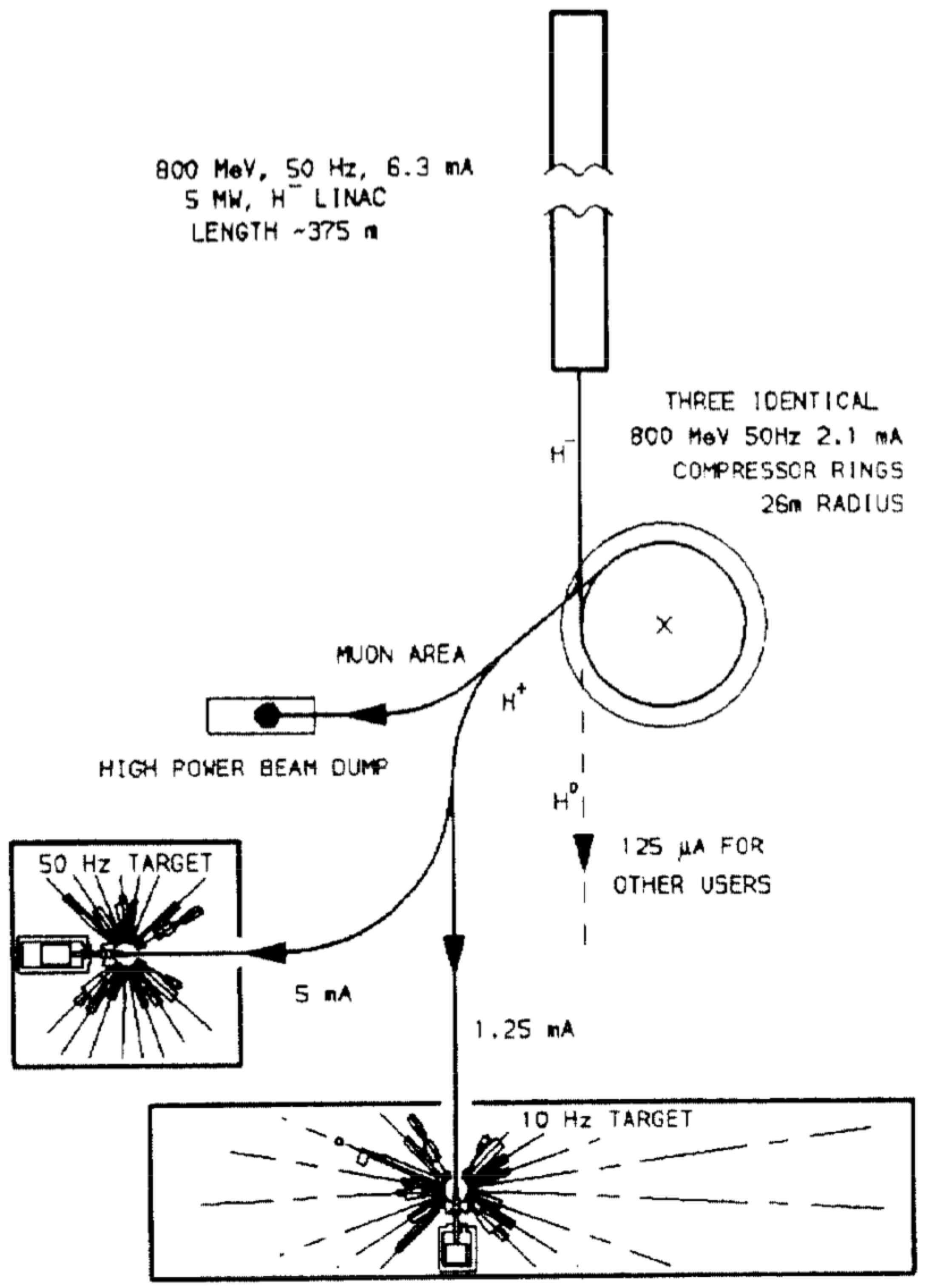


Figure 1. Linac - Compressor Rings Proposal.

Linac+FFAG accelerator

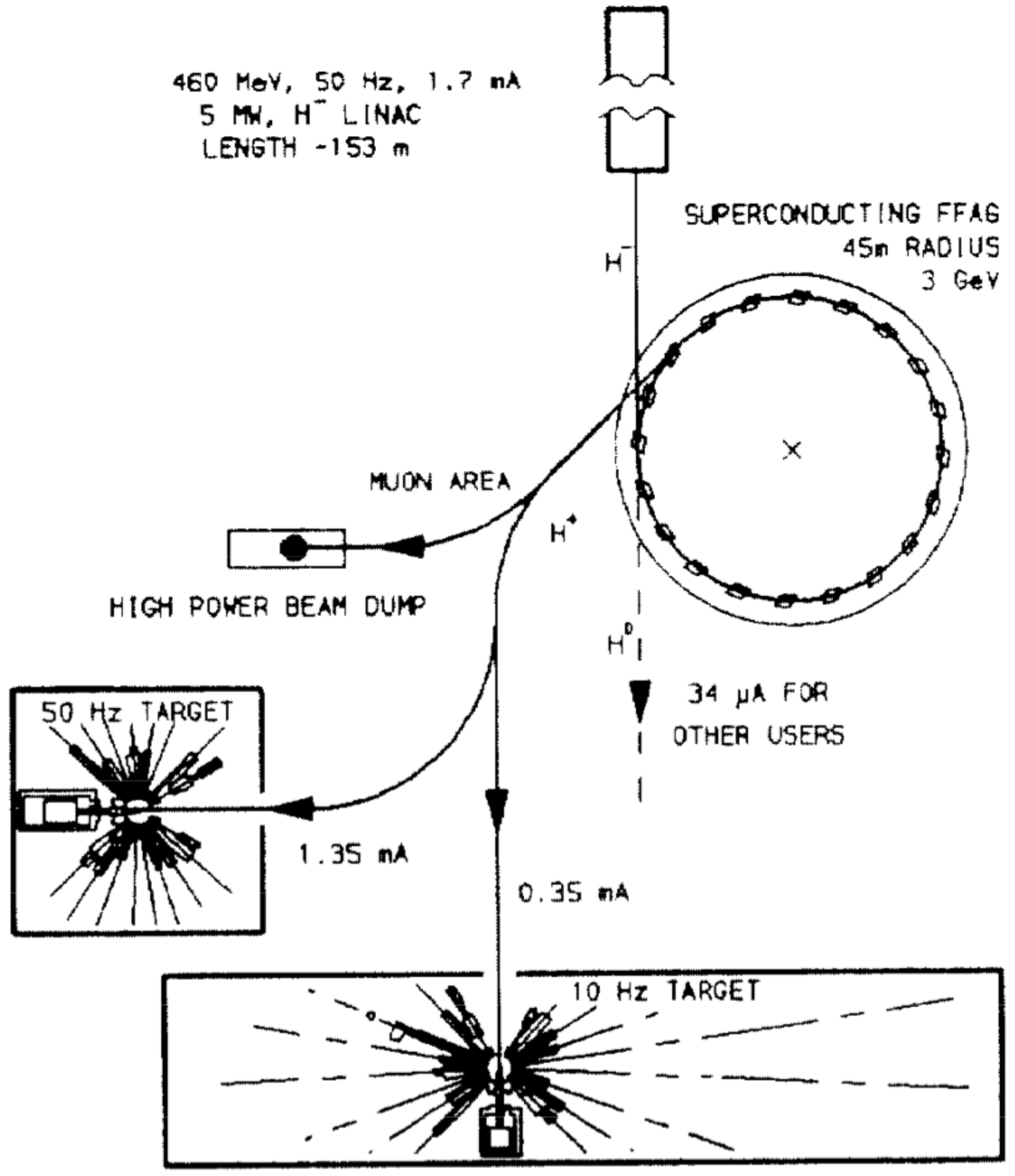


Figure 2. Linac - FFAG Proposal.

Why FFA for high power applications?

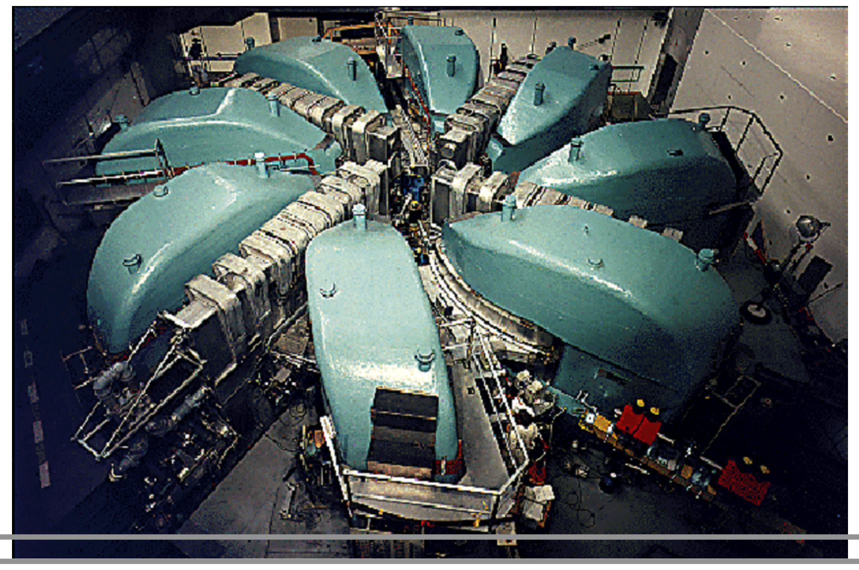
Why we are considering now?

Why FFA for high power applications?

High power by high repetition, but not necessarily low peak current

Continuous acceleration like a cyclotron is the best way to increase the average beam power.

- When synchrotron was invented, people had to accept the huge reduction of the beam current.



PSI cyclotron

ISIS synchrotron

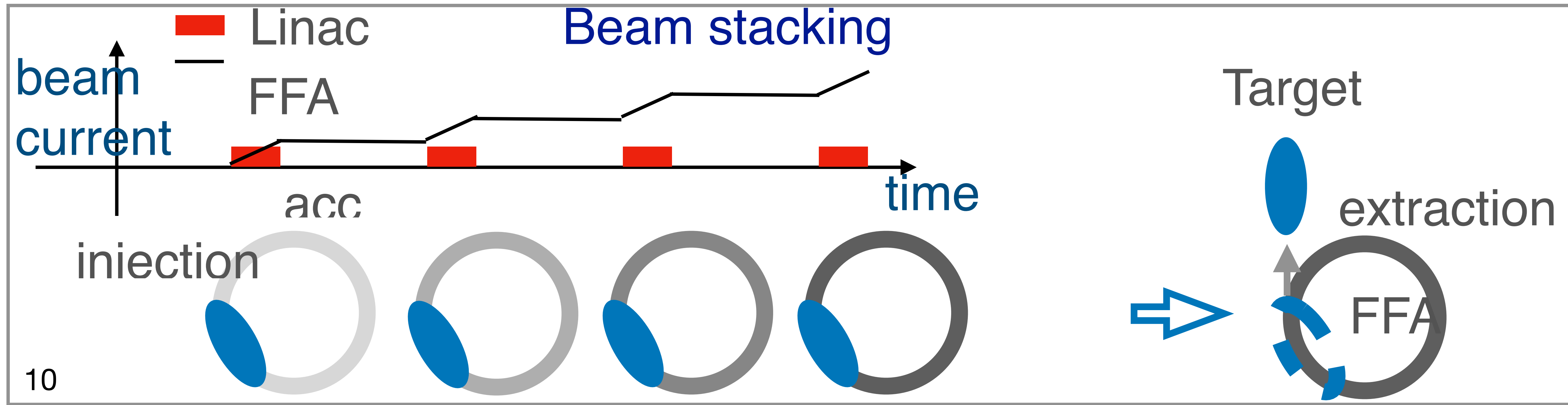
By giving up the isochronous condition, **the accelerator lattice or magnet size can be reduced**.

- This is the reason why a synchrotron took over as a high energy accelerator.

Reduction of the beam current can be **compensated by increasing the repetition rate**. That is possible by fixed field magnets.

- Some high power applications prefer pulsed beam to CW beam.

Kyushu U. FFA



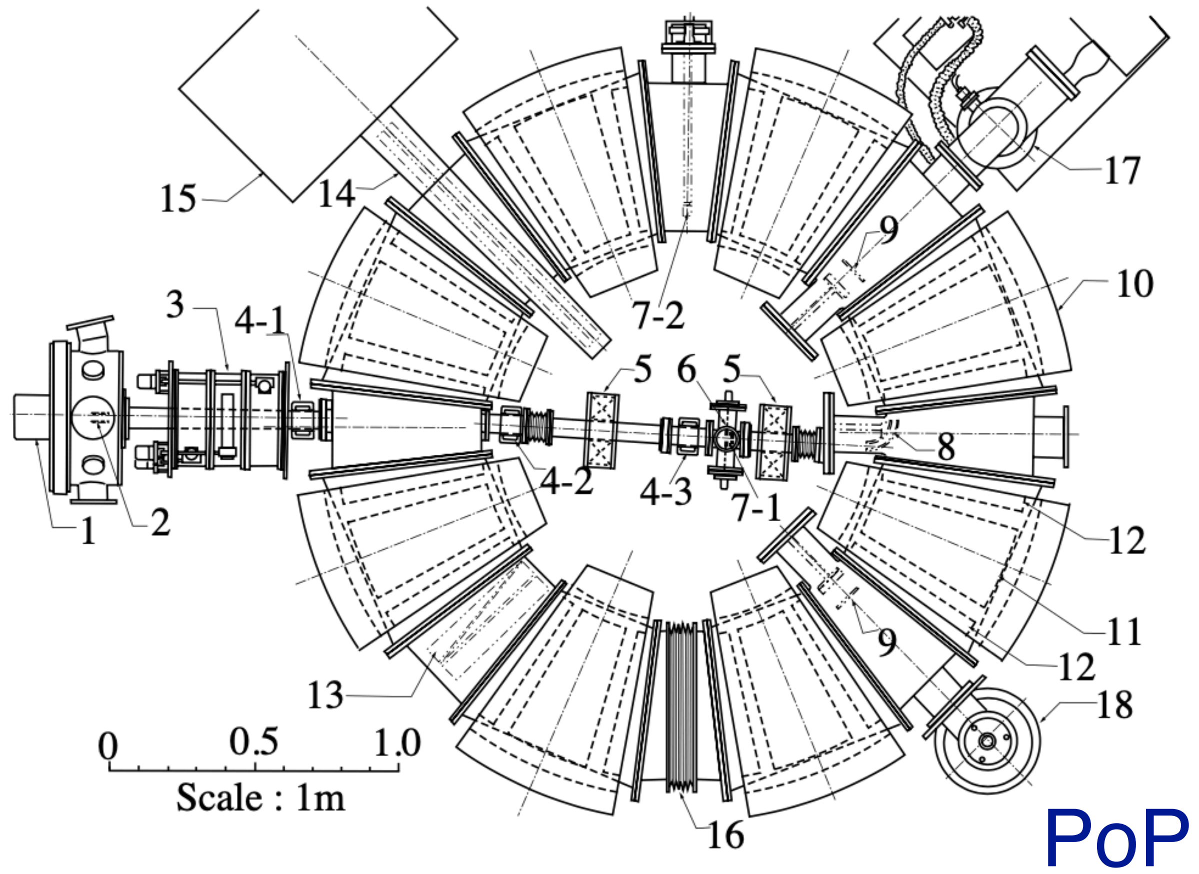
By beam stacking, the pulsed peak current can be increased keeping the average power with a lower repetition rate (~10 Hz).

- As a proton drive for a muon collider, spallation neutron source, etc.

Why FFA for high power applications?

Other advantage with DC magnets

- Required wall power is less to produce the same magnetic field compared with AC magnets for RCS.
    - **“Sustainability” is the important keyword for future facilities.**
- Main magnet can be superconducting and permanent magnet.
- **Reliability** increases without switched power supply.
- **Flexible (bespoke) operation** by RF gymnastics is possible.



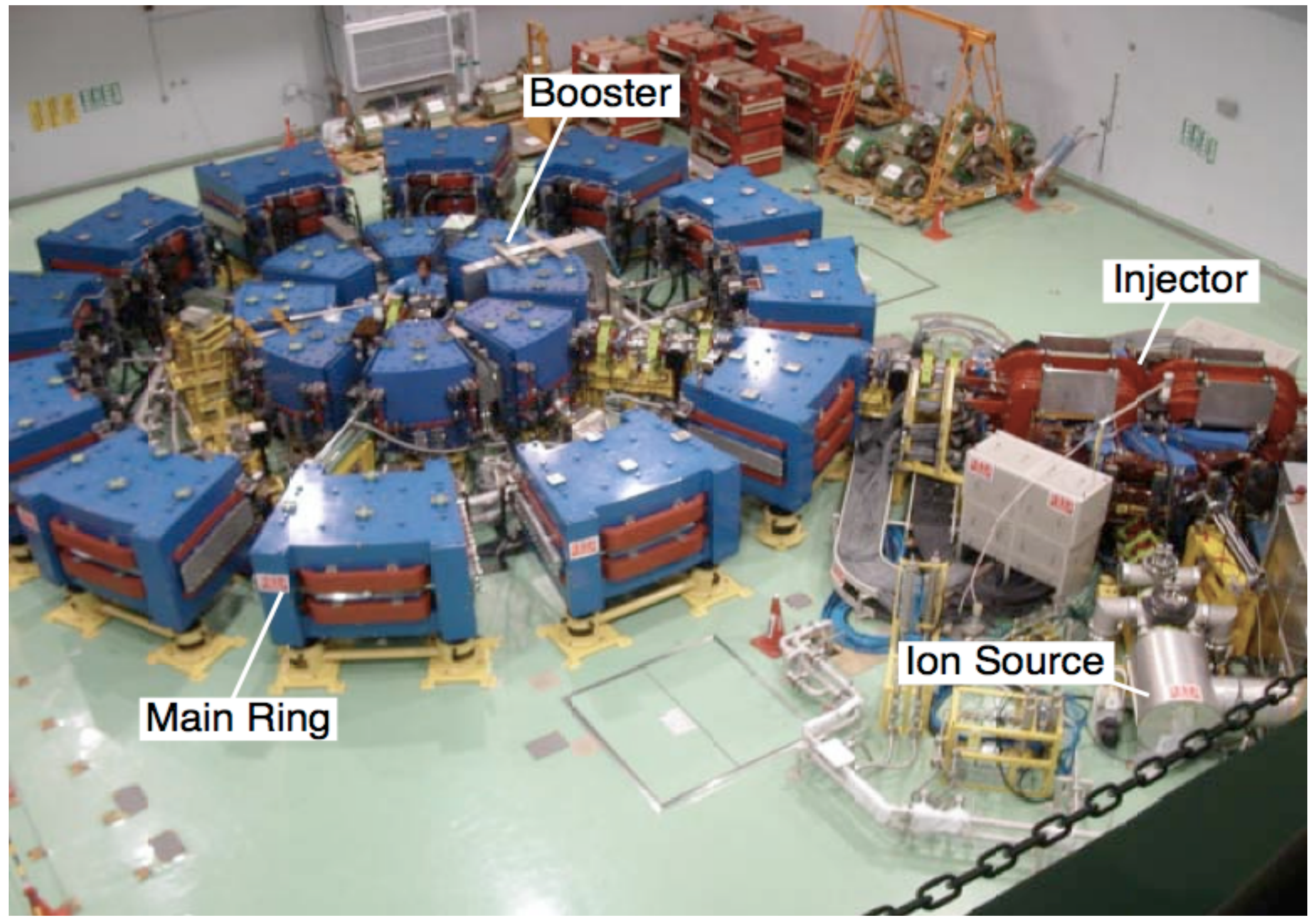
PoP FFA at KEK

17 cell design

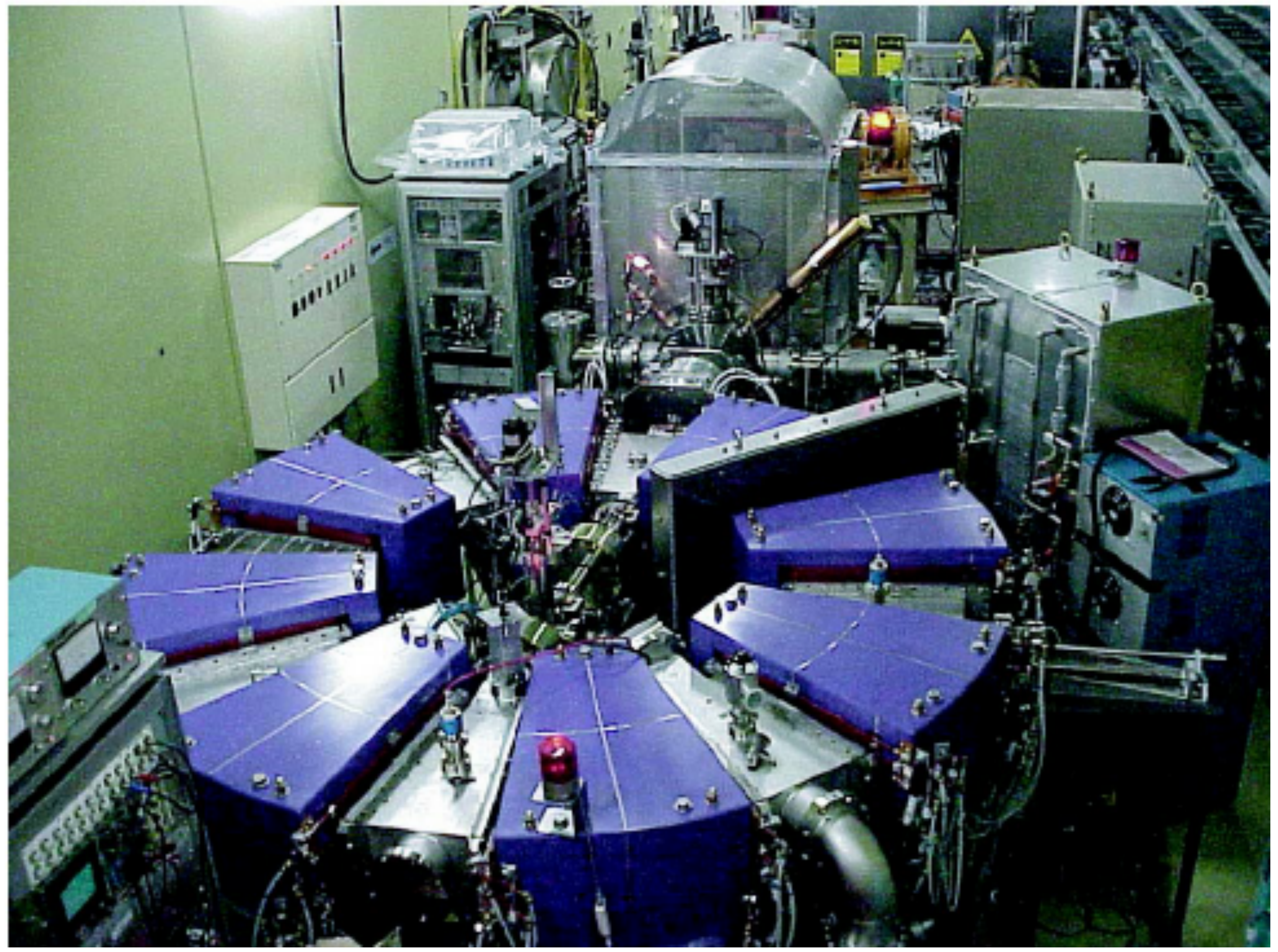
Why we are considering now?

Rebirth of an FFA

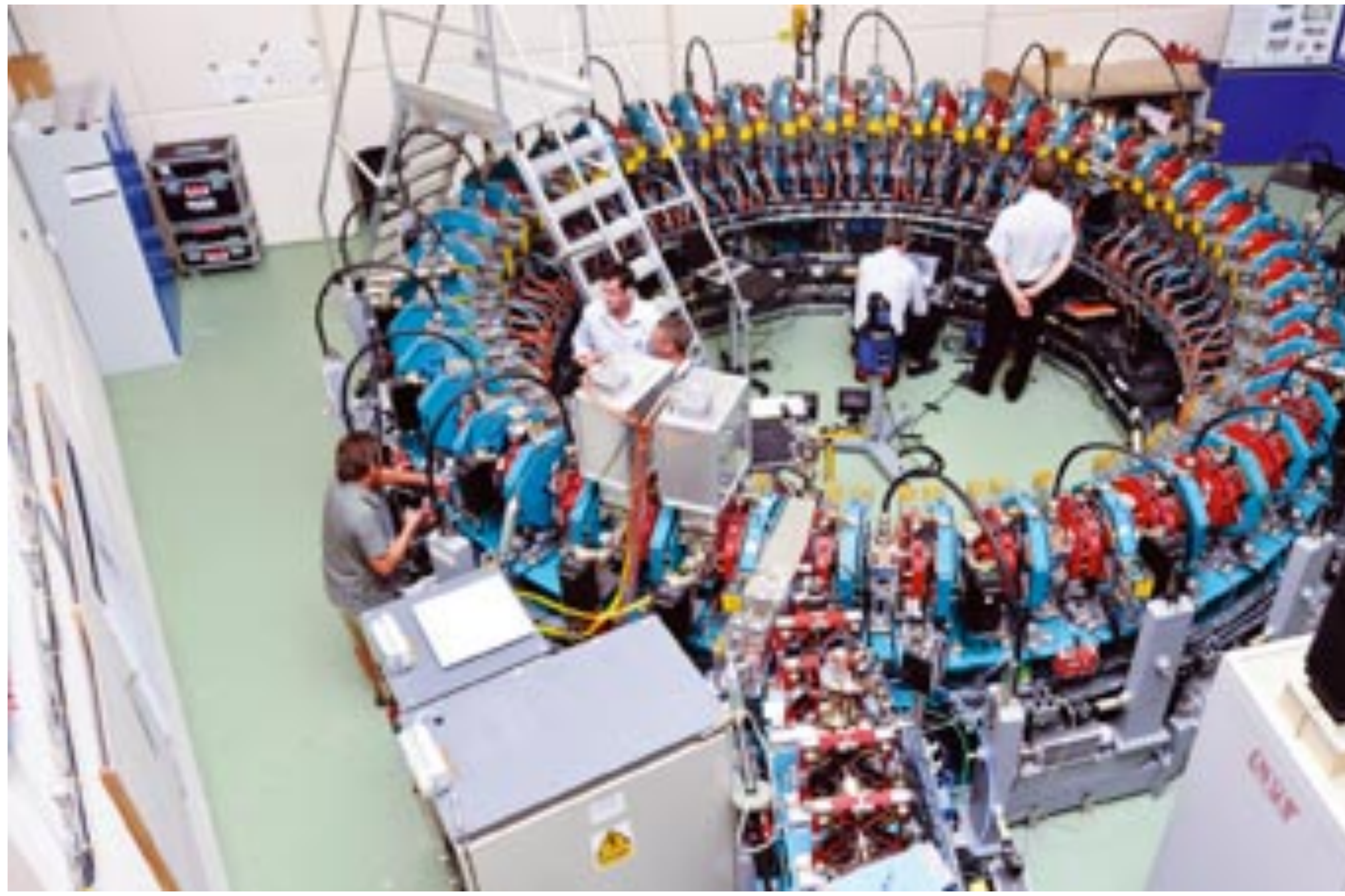
- High energy acceleration to 150 MeV.
- Cascade FFAs.



- Acc from 50 to 500 keV of protons.
- Repetition of 1 kHz operation.



- EMMA: monscaling FFA.
- Serpentine channel acceleration.



No high power FFA yet.

- CBETA: multipass arc of ERL.
- Permanent magnet lattice.

Science and Technology Facilities Council

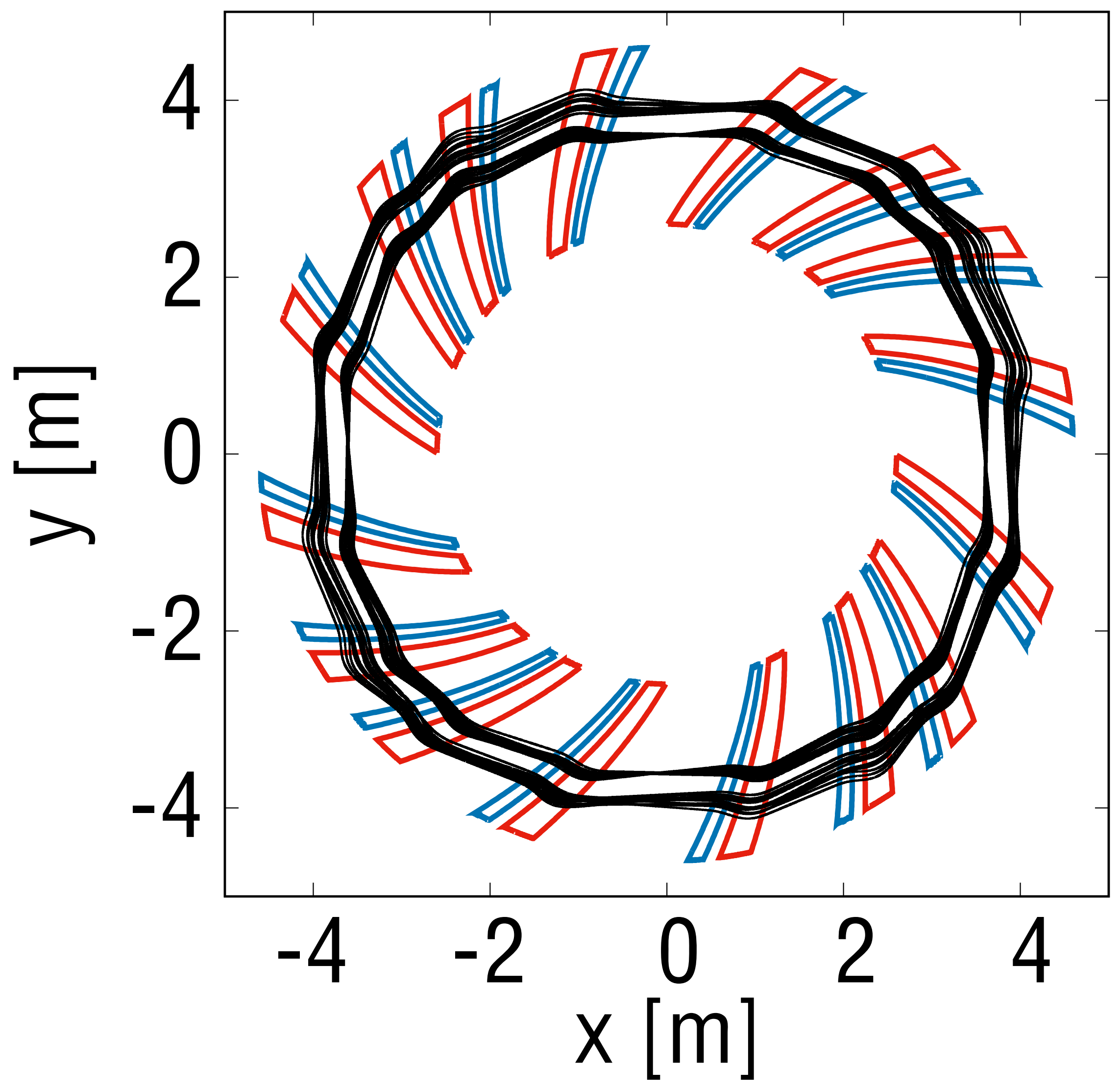
Toward high power FFA

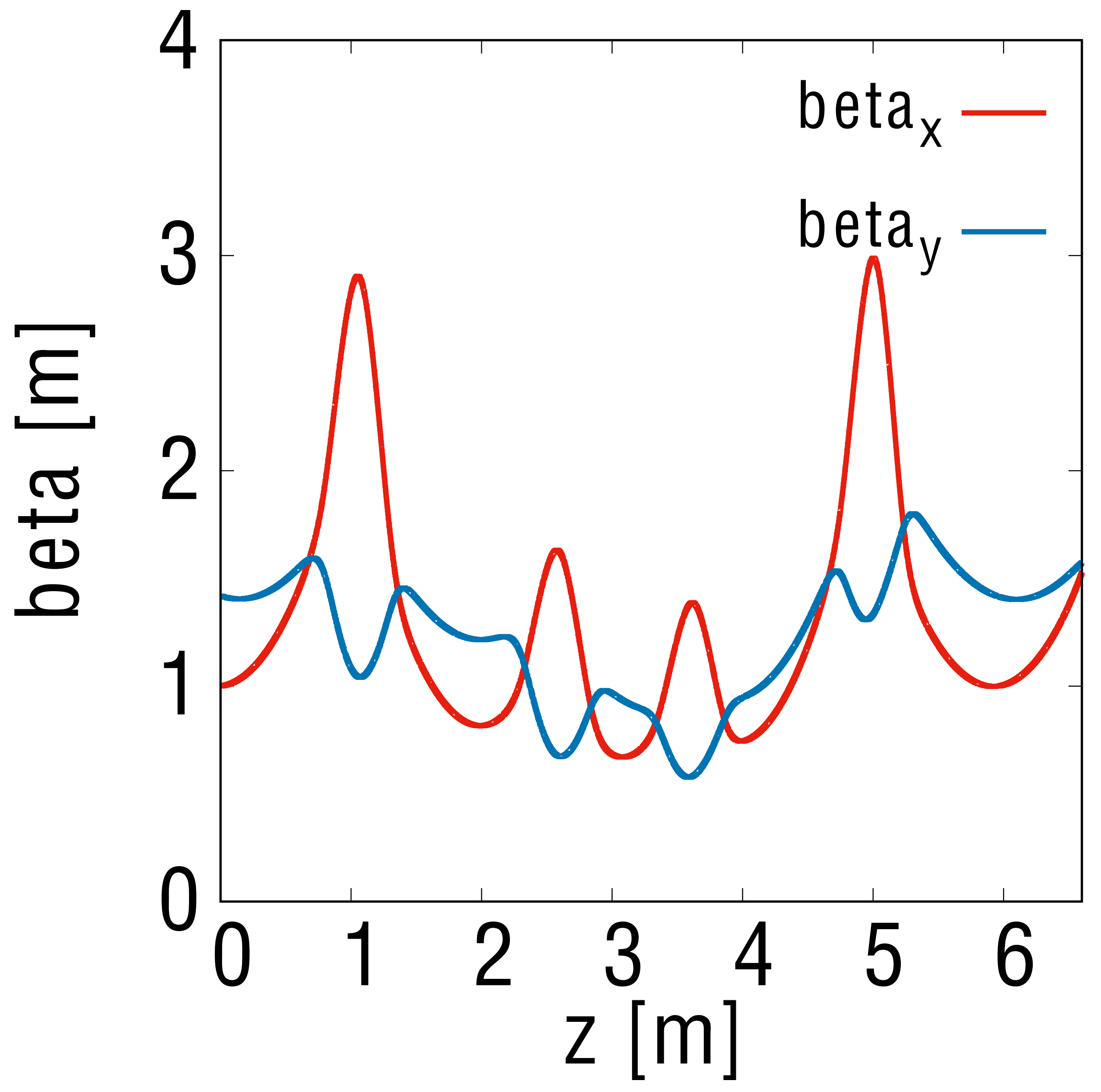
Before we start …

- In the following, I tried to keep the discussion as in general as possible.
- However, I occasionally use specific design parameters where the discussion points become clearer.
- The parameters are based on a demonstrator of high power FFAs which we plan to built at RAL.

Energy	3 - 12 MeV
Minimum radius	3.6 m
Particle	Proton
Maximum intensity	3 x 10^{11}
Emittance (nor.)	10 pi mm mrad
Space charge tune shift	-0.3
Repetition	100 Hz (50 pps)
Average beam power	~ 50 W

FETS-FFA at RAL will be **the first demonstrator FFA** for high intensity operation.





FETS: Front End Test Stand

Science and Technology Facilities Council

DF (FD) spiral sector

Combination of radial and spiral

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

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

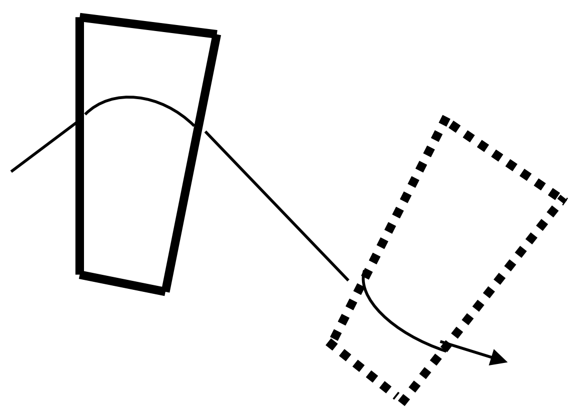
$$Q_x^2 \approx 1 + k + \frac{k^2 S^2}{N^2 b_0^2}, \qquad (4)$$

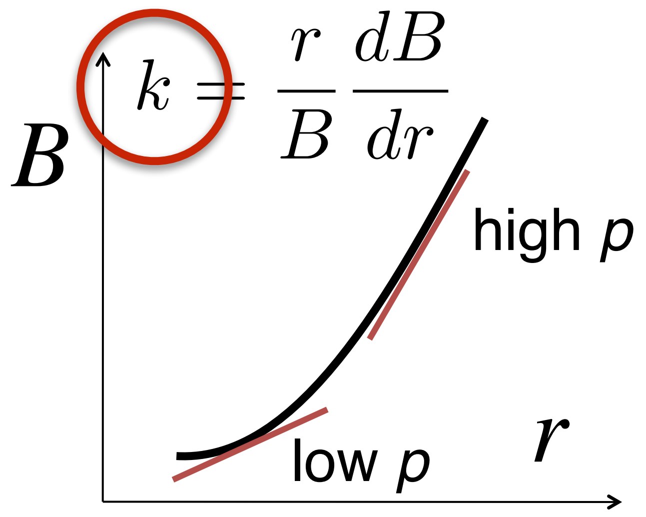
$$Q_z^2 \approx -k + \frac{k^2 S^2}{N^2 b_0^2} + \frac{\Phi^2}{b_0^2}(1 + 2\tan^2\delta), \qquad (5)$$

Field gradient averaged over the azimuth.

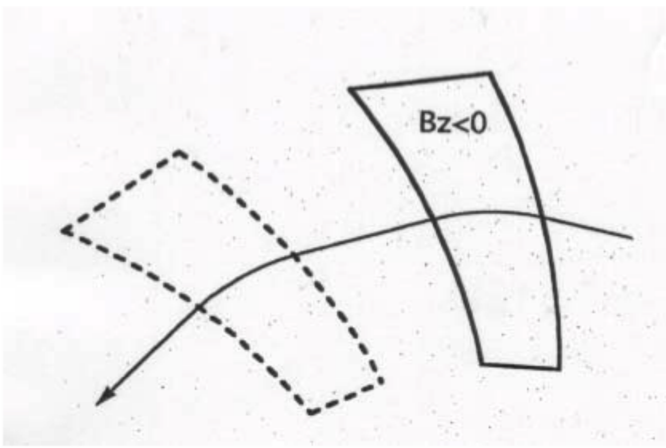
Specific strong focusing due to spiral field shape.

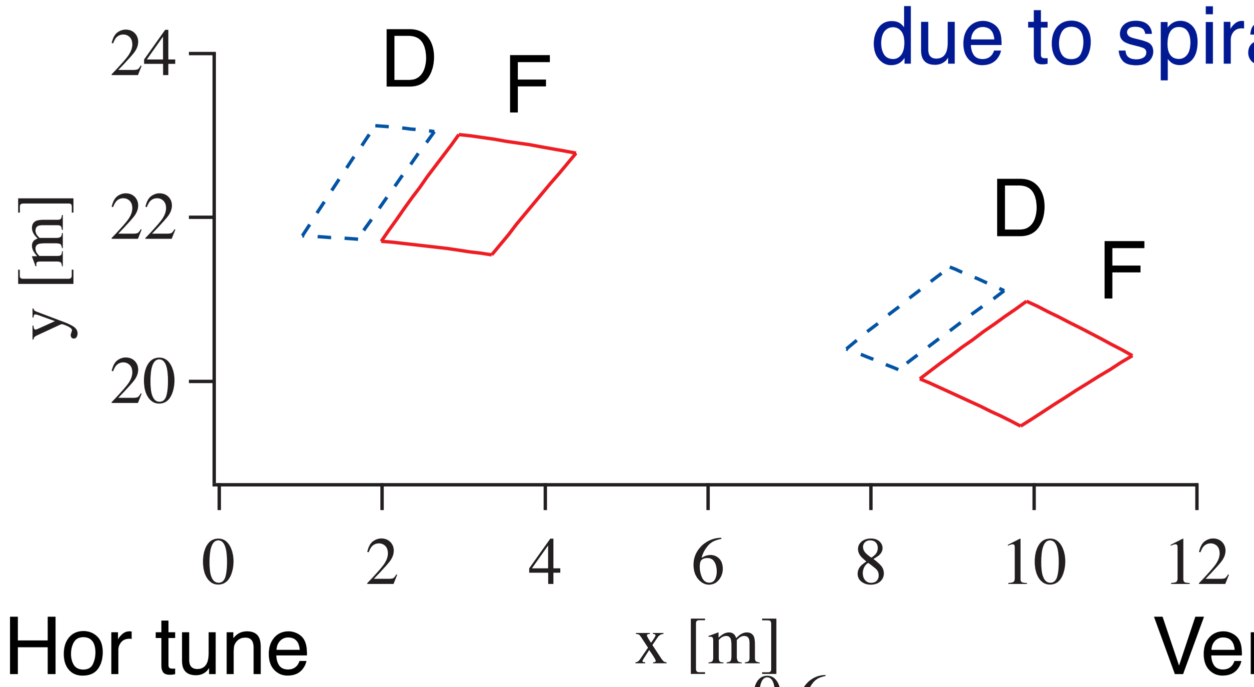
radial sector





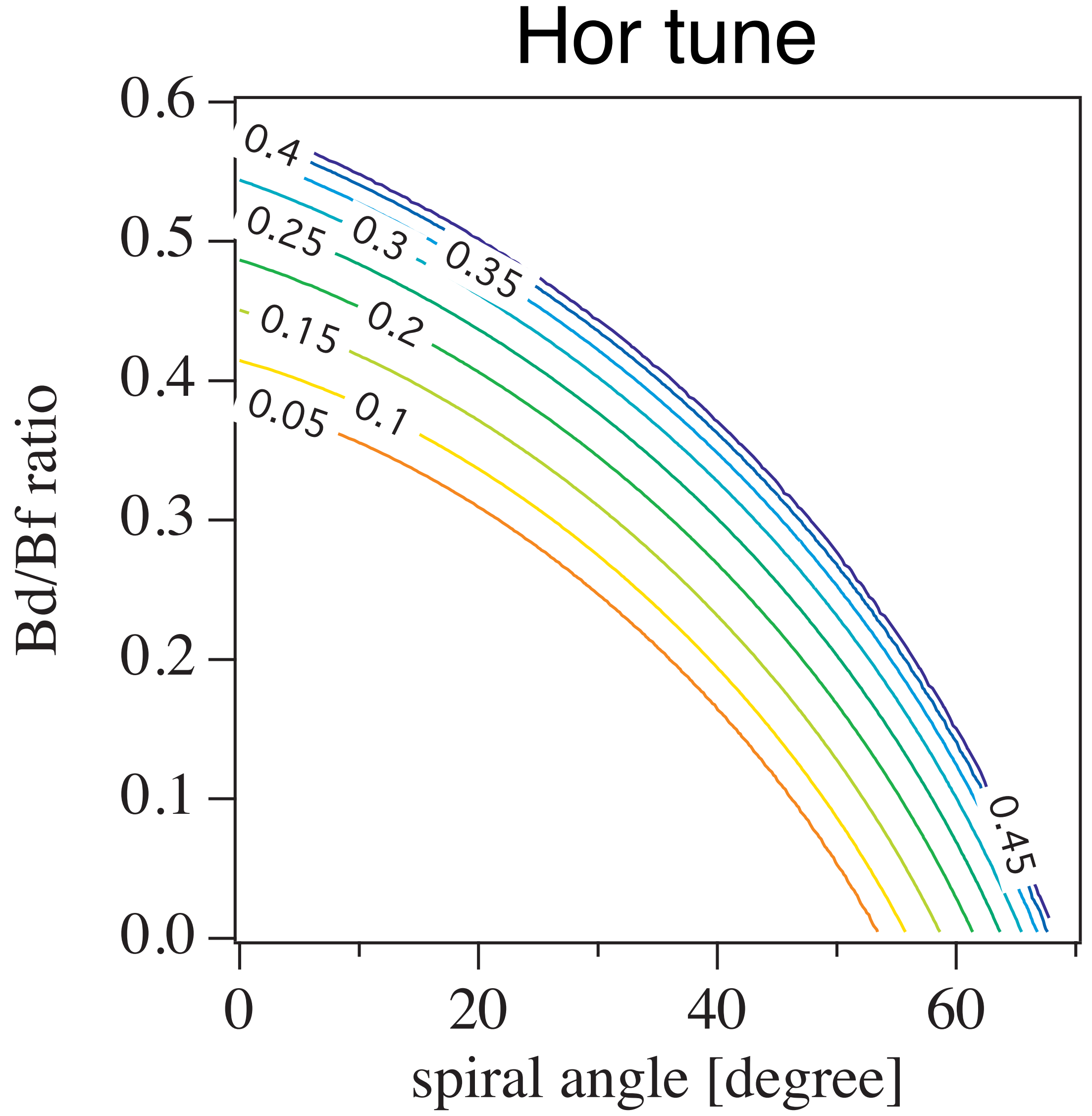
spiral sector

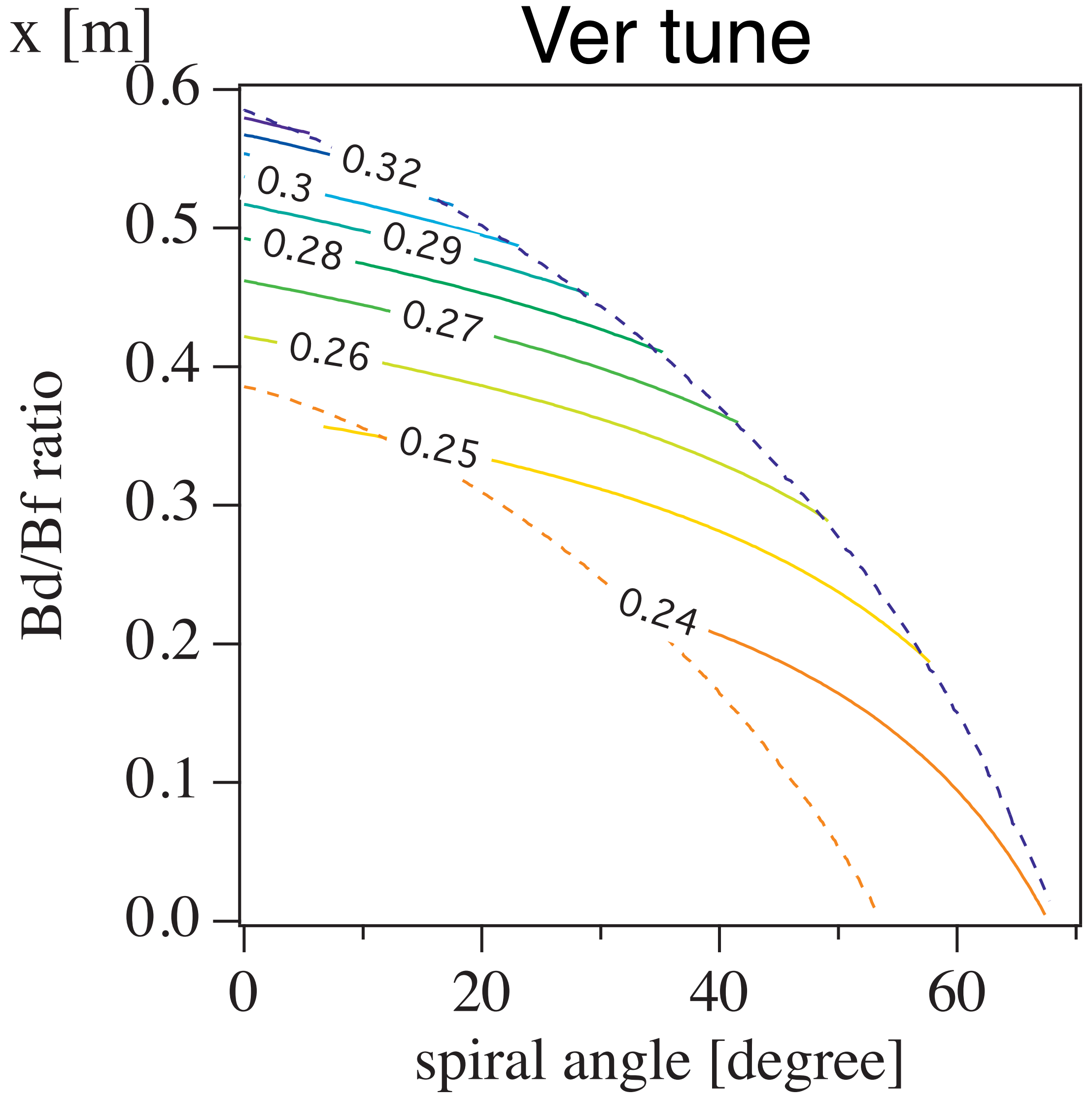


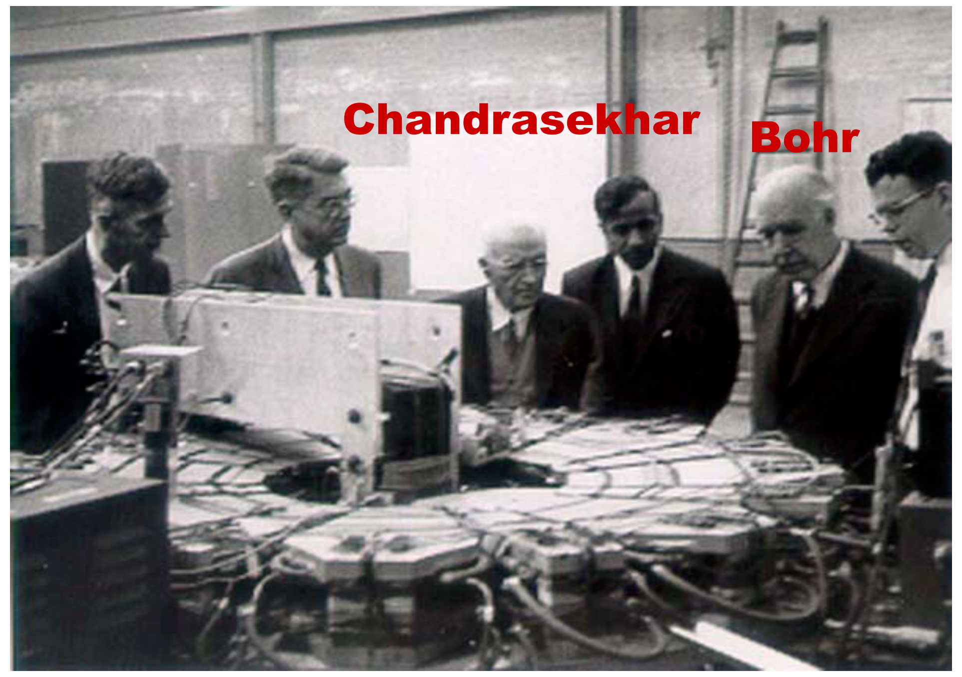


Alternating gradient focusing by focusing (normal bend) and defocusing (reserve bend)

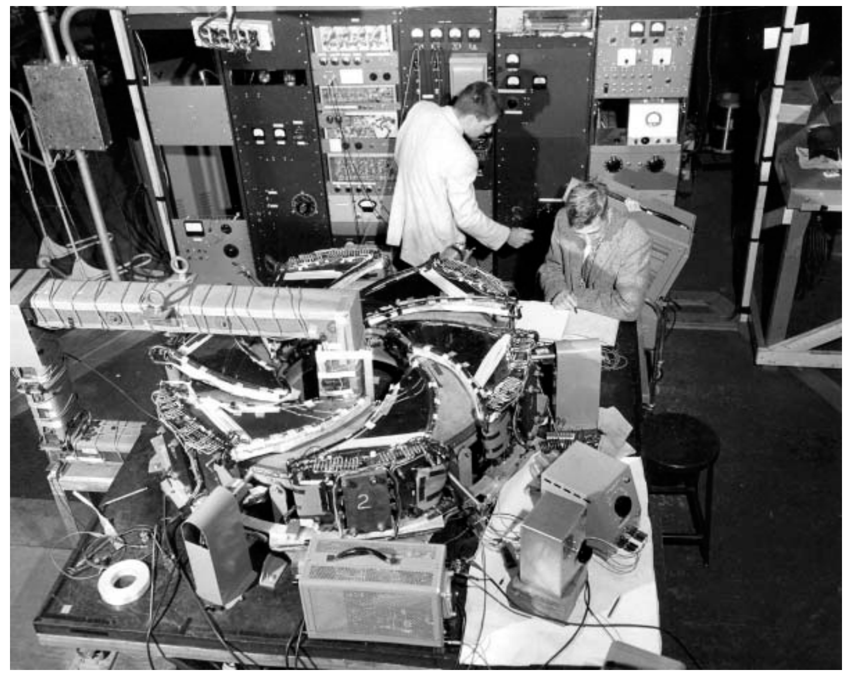
Alternating gradient focusing by focusing (normal bend) and defocusing (edge angle)







400 keV radial sector



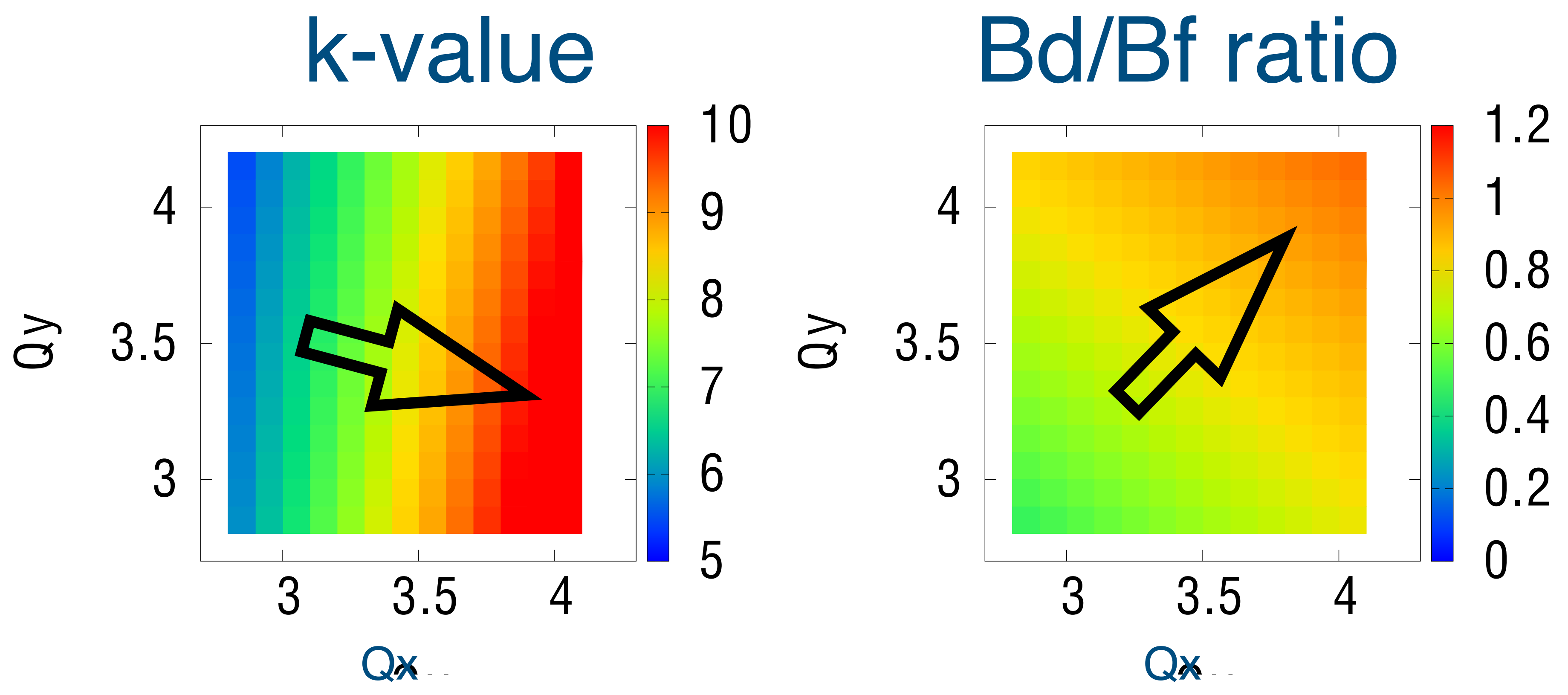
180 keV spiral sector

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

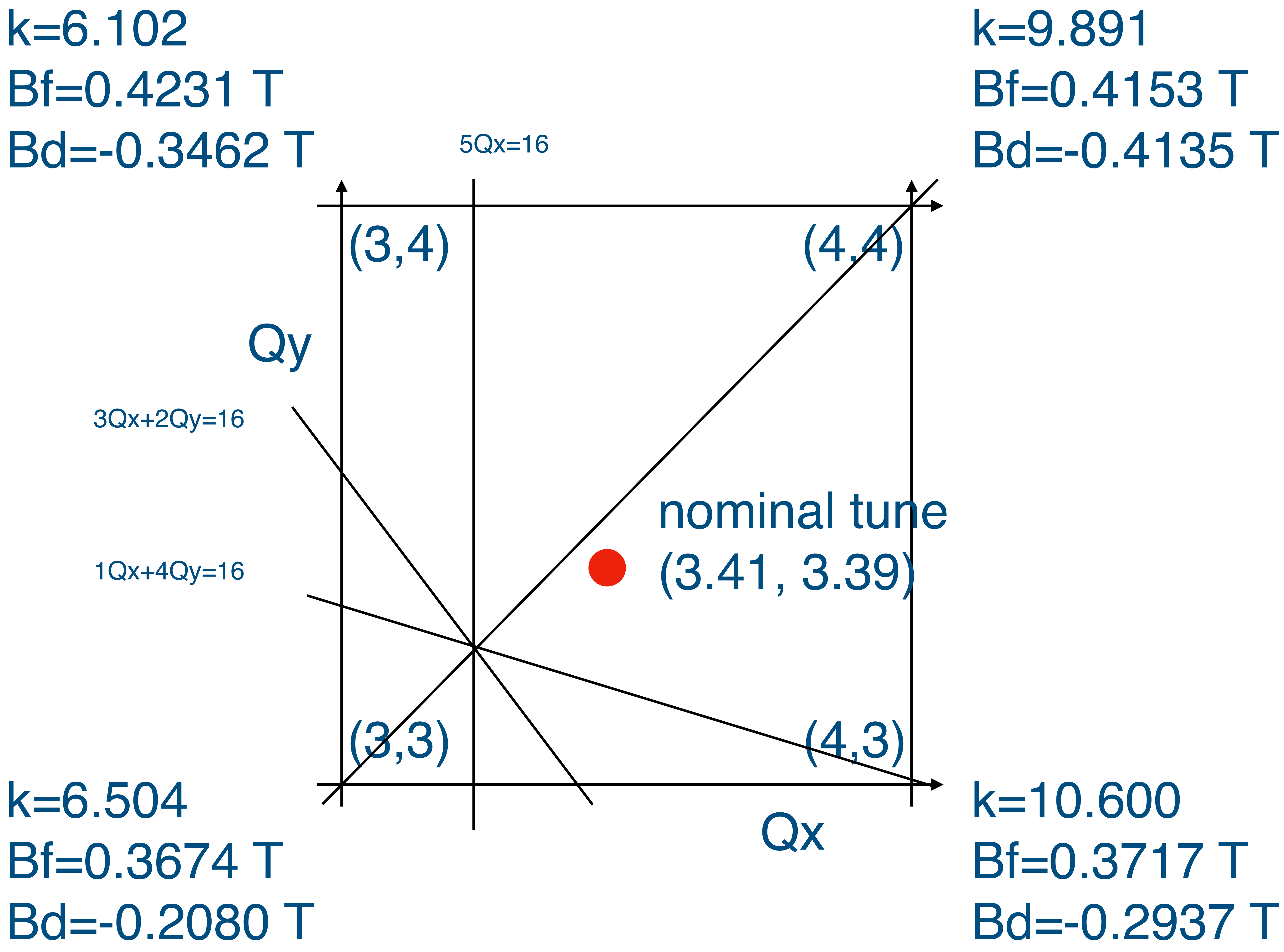
UKRI Science and Technology Facilities Council

DF (FD) spiral sector

Explore wide operating point



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



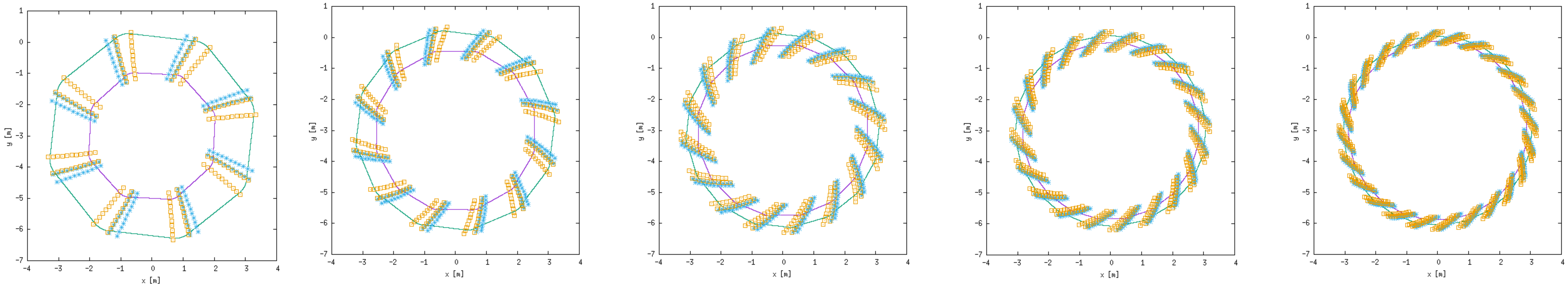
Tune space can be explored without much depending on a reverse bend.

Superperiodicity

Orbit excursion vs number of cells

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

- Increasing the number of cells
  -> higher field index *k* -> small **orbit excursion** (good).
  -> shorter **straight section** (bad).



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

  Introduction of **superperiod** by exciting ***m*** not equal to the number of cell.

  Long straight section is essential for proper handling of the high intensity beams.
  for example, phase space painting with charge exchange injection.

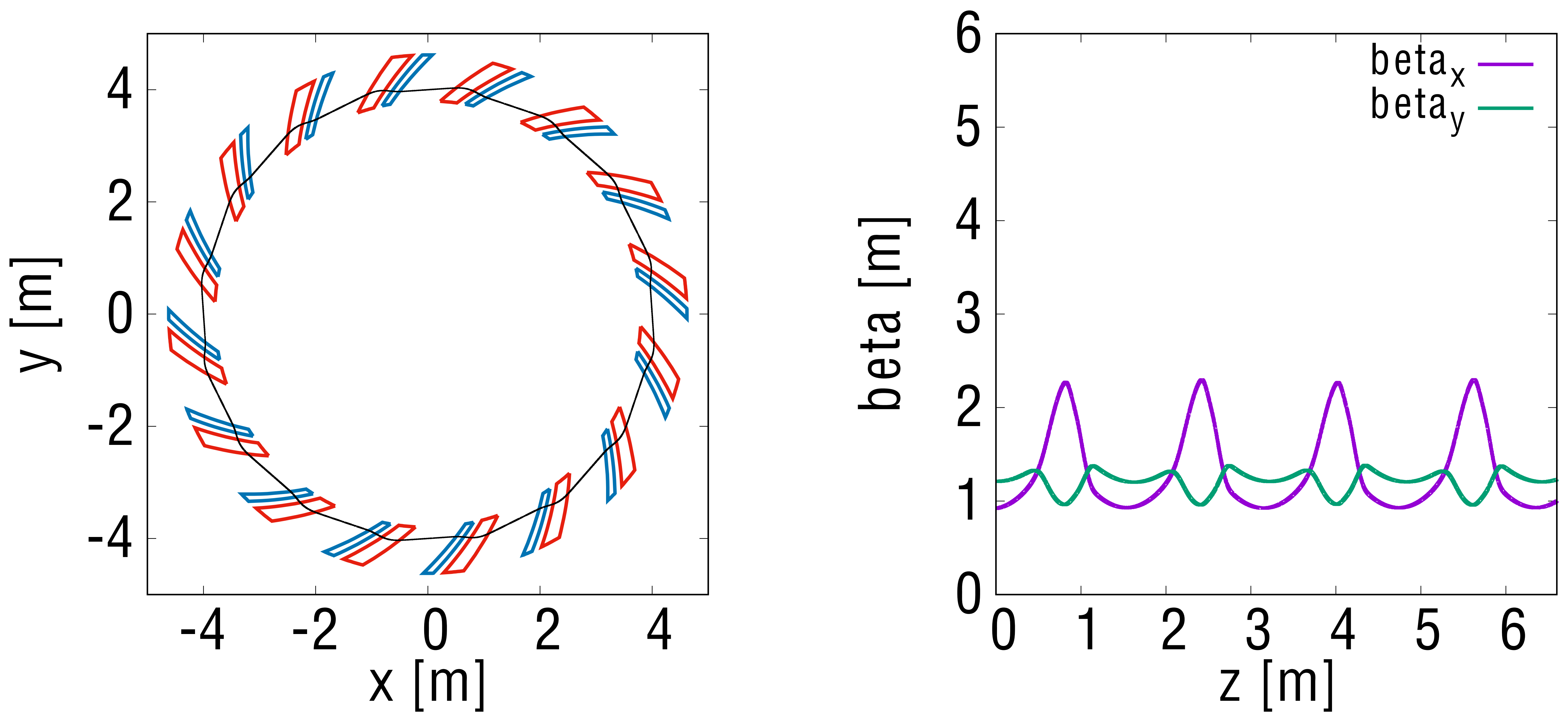
$$F(\theta) = \sum_m f_m \exp(im\theta)$$

Science and Technology Facilities Council

Superperiodicity

Long straight section with zero chromaticity

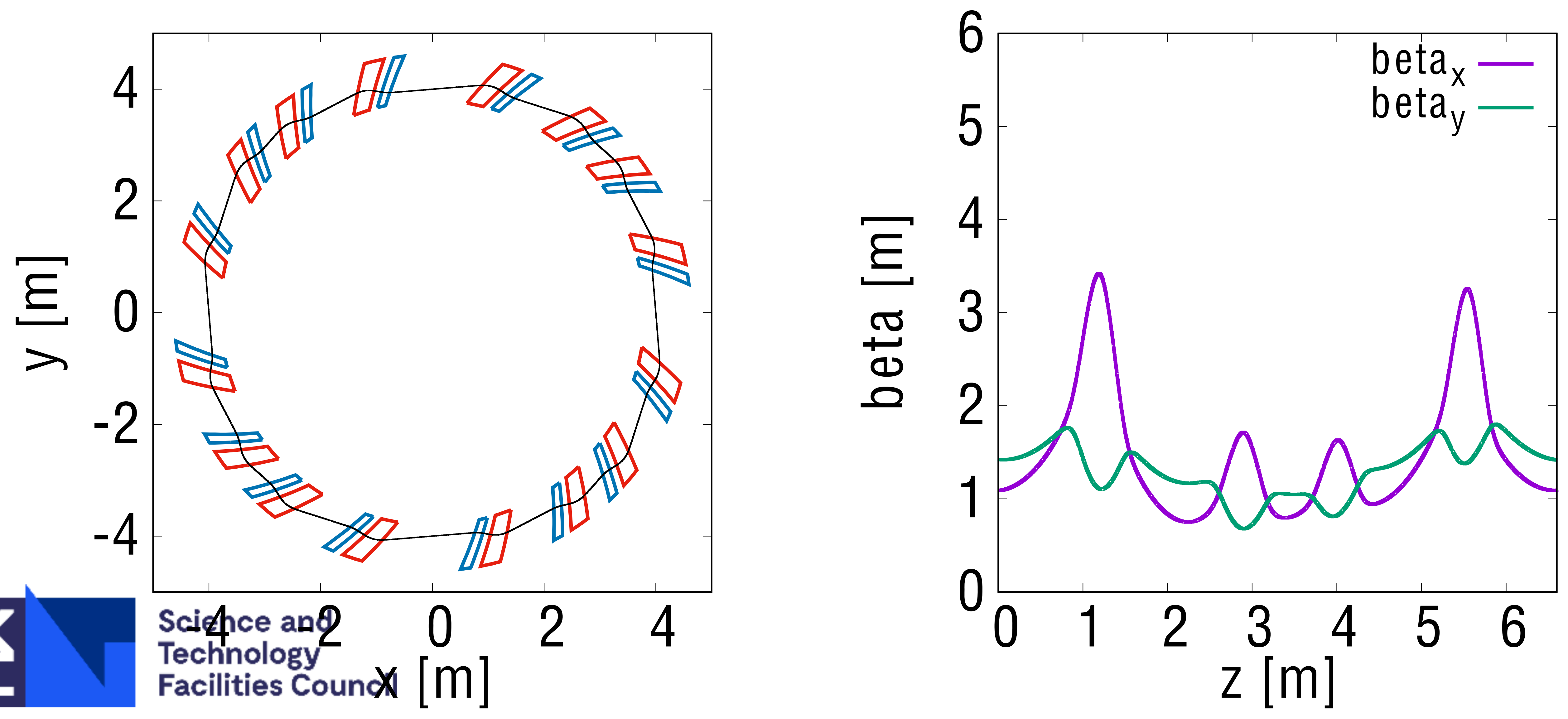
$$B_z(r,\theta) = B_{z0}\left(\frac{r}{r_0}\right)^k F(\theta)$$



16-fold symmetry

$$F(\theta) = f_{16}\exp(i16\theta)$$

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

$$F(\theta) = f_4\exp(i4\theta) + f_{16}\exp(i16\theta)$$

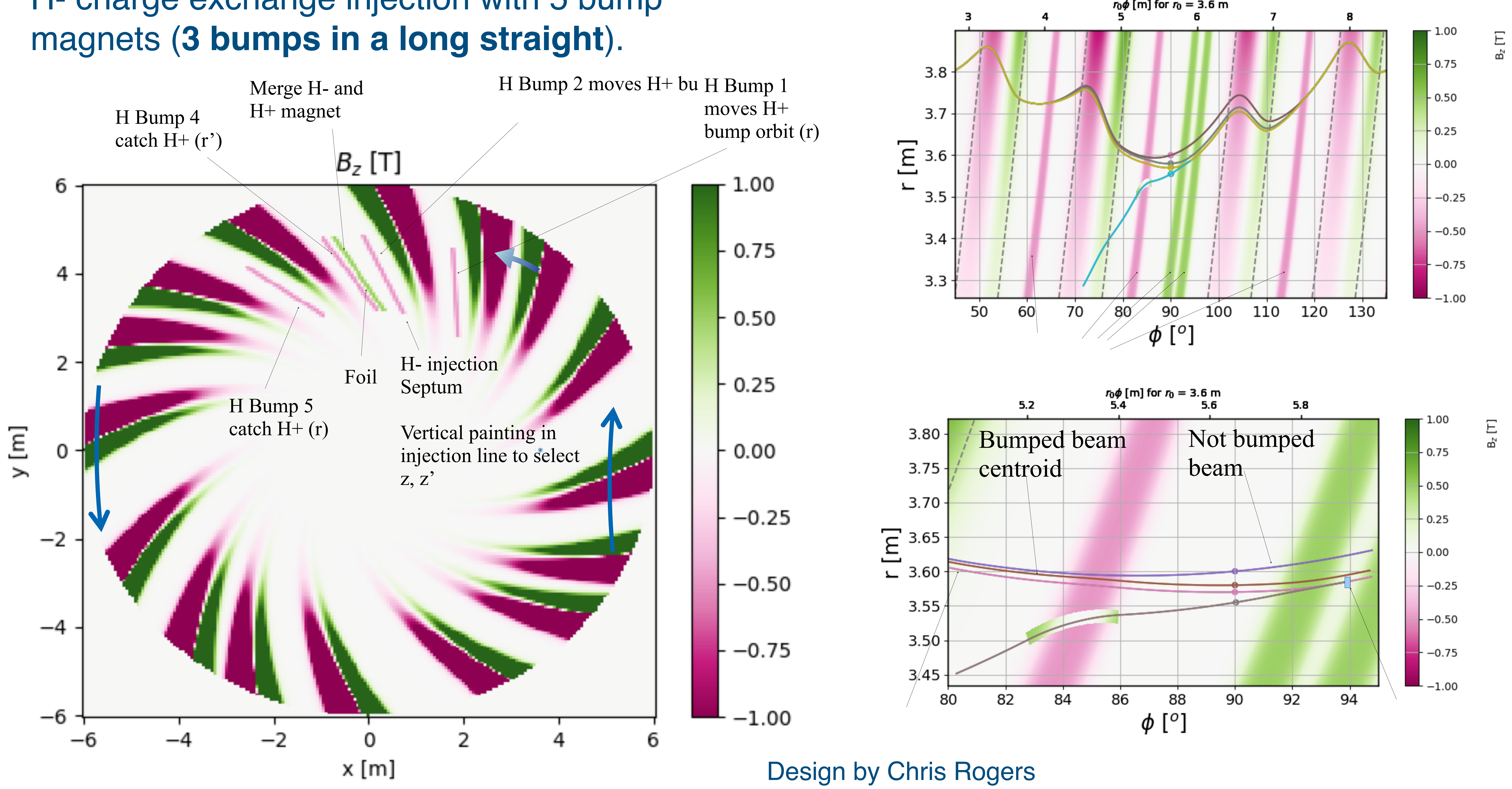
Straight length: **1.55 m**, 0.90 m, 0.45 m
Dynamic aperture: 80 pi mm mrad
Field index k: 7.40
Spiral angle: 30 degree
Magnet families: 8

Note horizontal beam size is larger.

Science and Technology Facilities Council

Injection

H- charge exchange injection with 5 bump magnets (**3 bumps in a long straight**).



Design by Chris Rogers

Physical and dynamic aperture

Large acceptance pays off

Optimise nonlinearity to obtain the same acceptance of SNS/JPARC

	Normalised emittance	Geometrical acceptance	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 Same as SNS/JPARC	+/- 32 mm

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

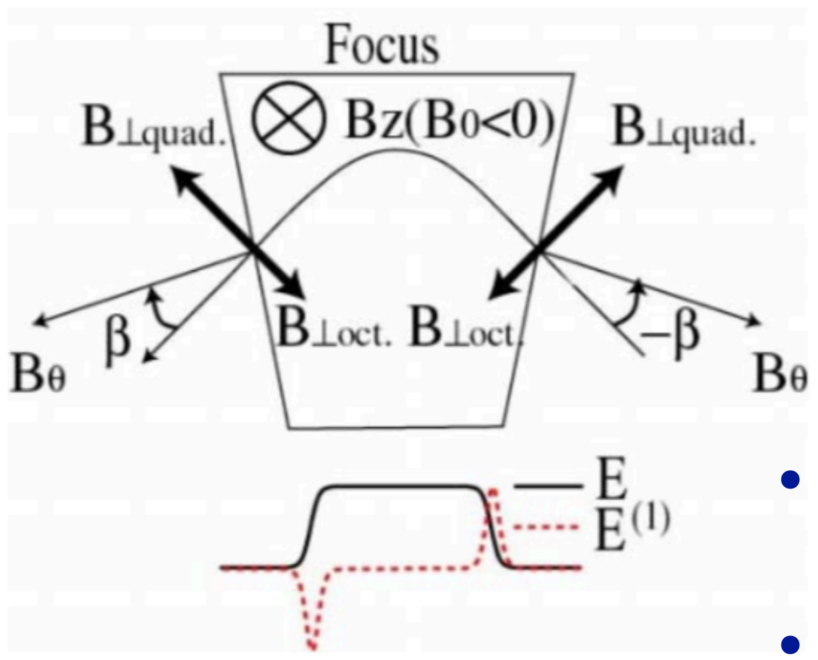
$$\Delta Q = -\frac{r_p n_t}{2\pi\beta\gamma^2\varepsilon_n B_f} = -0.12$$ per 10^{11} protons.

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})

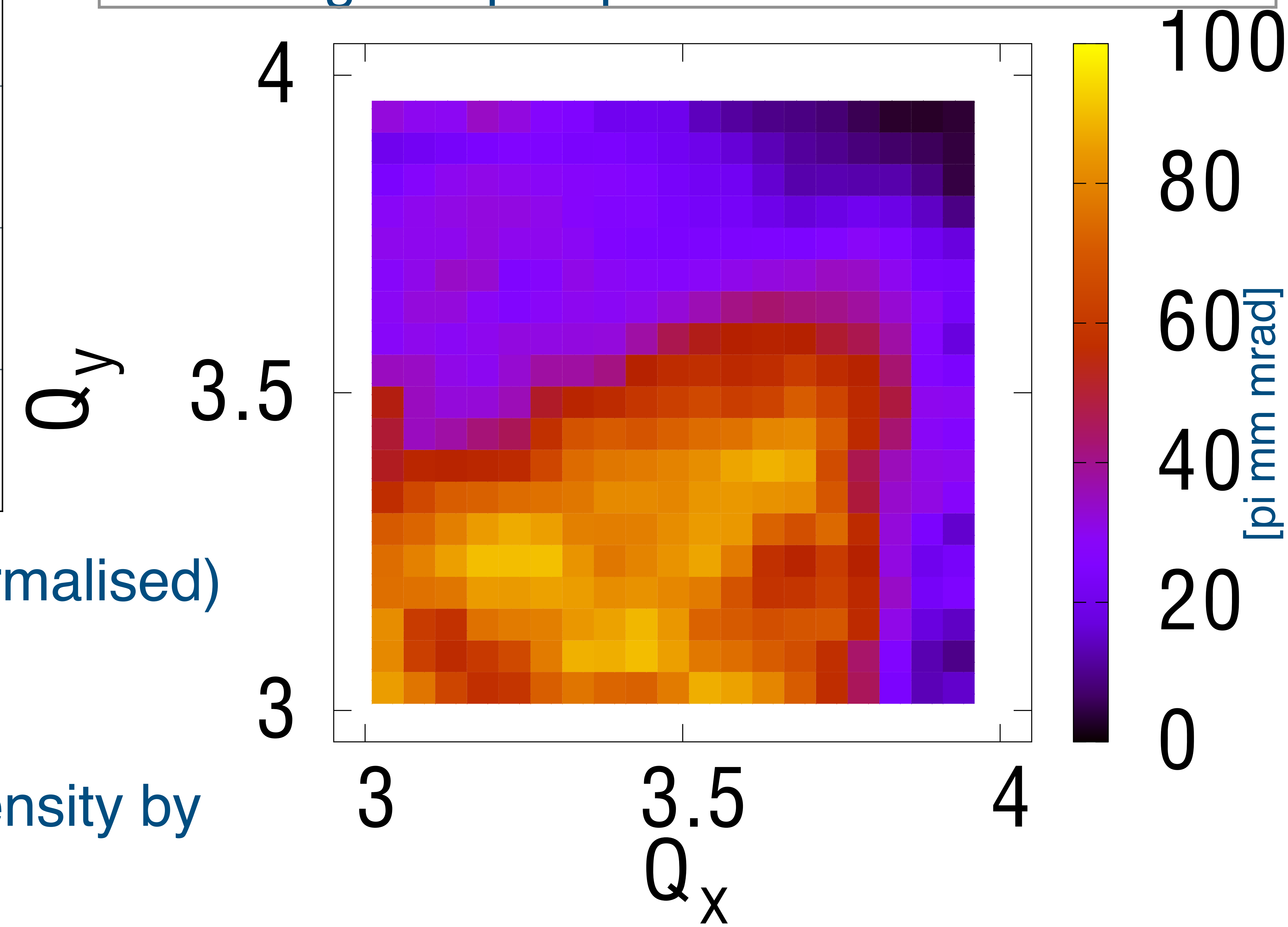
Aiba, et al



$$B_{\perp oct} = -\frac{1}{3!}(E^{(1)}k^2 + E^{(3)})\frac{B_0}{r_0^3}z^3 \sin\beta \cong -\frac{E^{(1)}k^2}{3!}\frac{B_0}{r_0^3}z^3\sin\beta = O(s)z^3 \quad (11)$$

- E(1) is the first derivative of fringe field extent with azimuthal direction.
- Strong octupole at fringe fields.

Large amp dependent tune shift in V



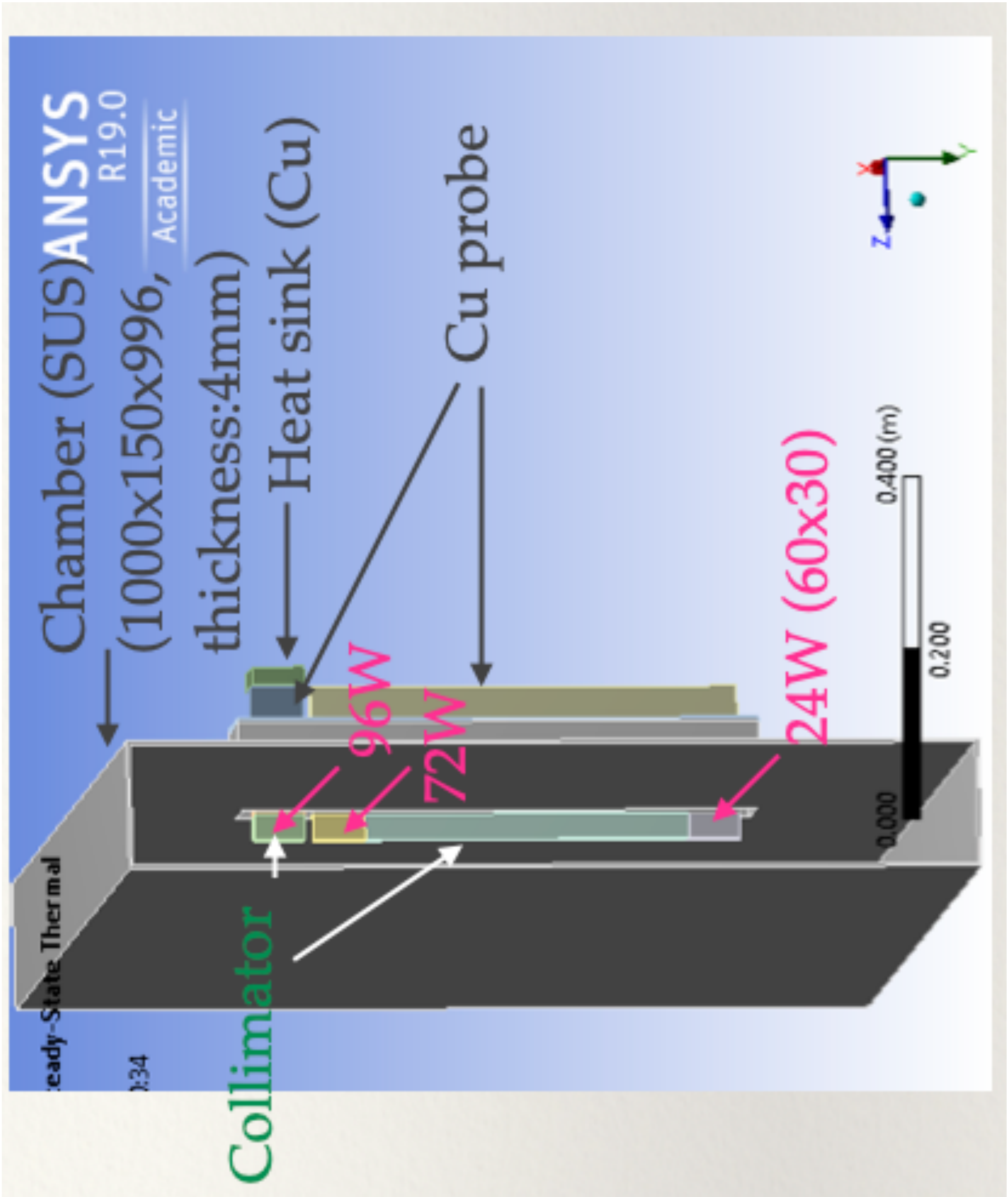
dynamic aperture at 3 MeV (normalised)
4-fold symmetric lattice

Science and Technology Facilities Council

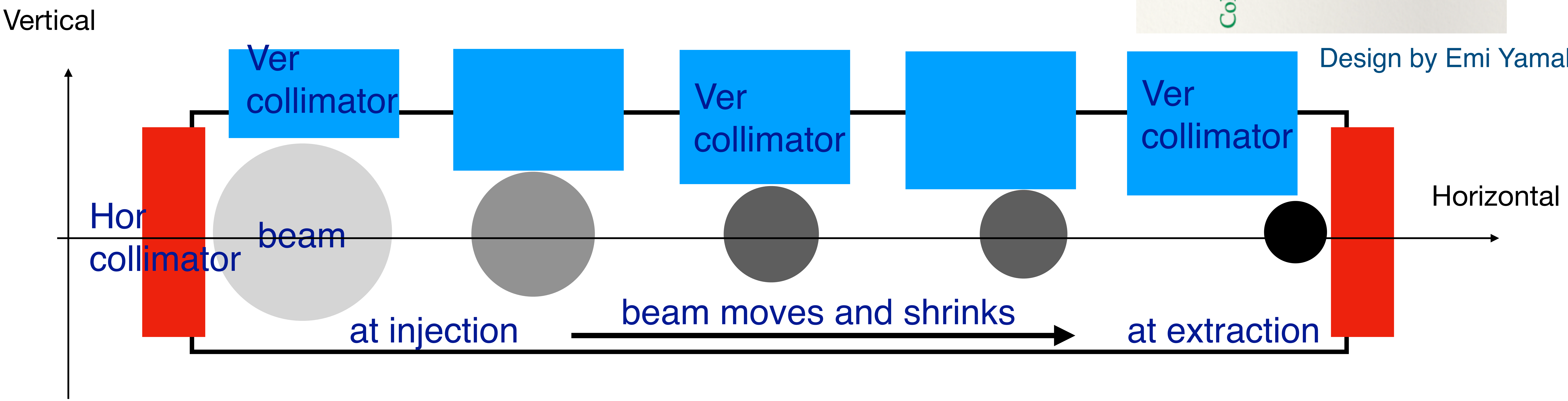
Collimation

For all momentum

- In horizontal
  - Collimator at injection (inner side of the aperture) and at extraction (outer side)
- In vertical
  - Collimator continuously or stepwise for all the momentum



Design by Emi Yamakawa

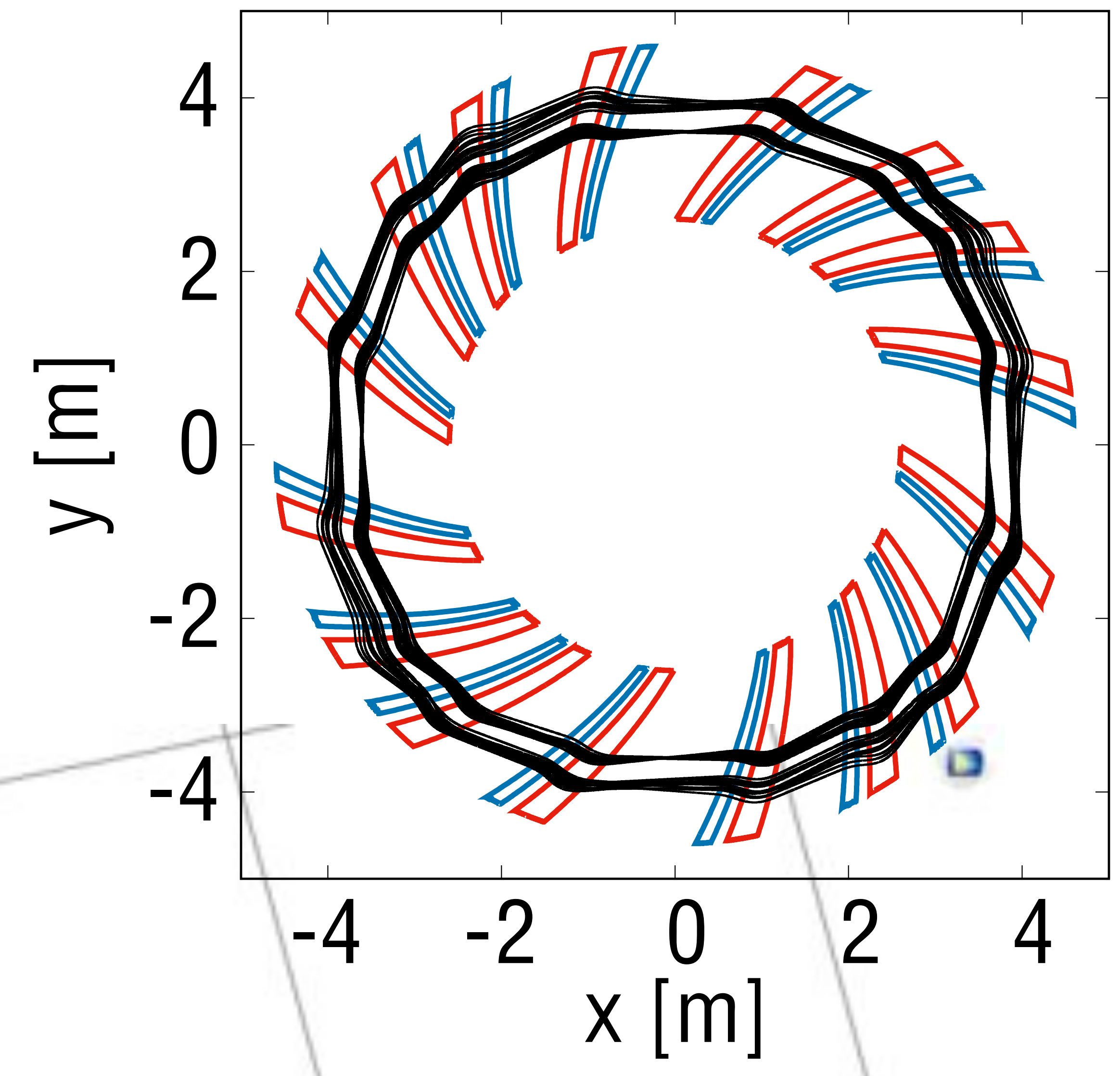


Science and Technology Facilities Council

Collimate beam halos as soon as developed. No need to wait until extraction.

Correction

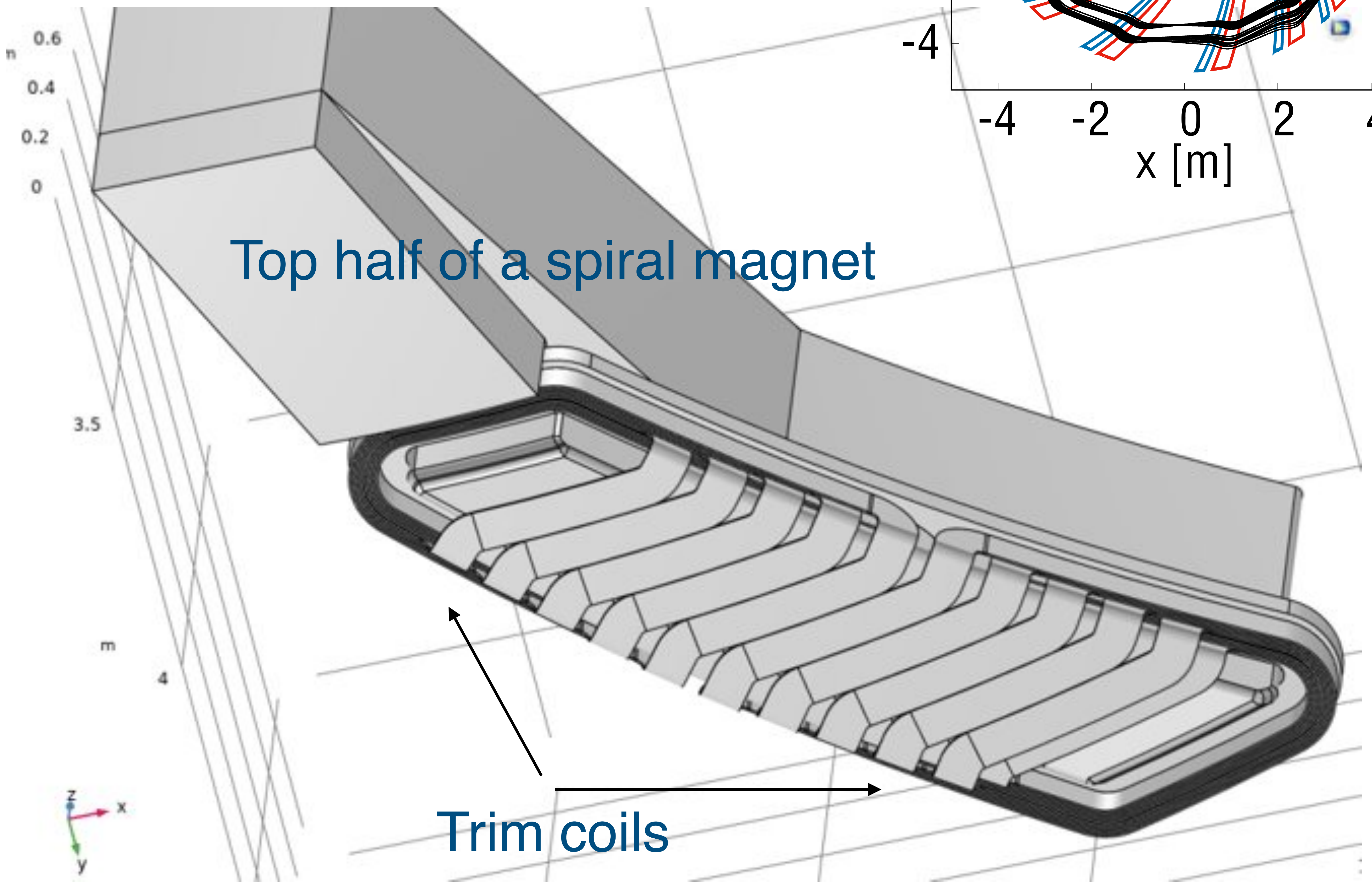
Orbit, optics, nonlinear harmonic



- Each magnet has ~10 trim coil winding on the flat pole.
- **Power supply for each trim coil is independent.**
- Primarily coils are adjusted to make the ideal field.

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

- Additionally small adjustments to excite a harmonic component to correct orbit, optics and nonlinear harmonics.
- How accurately ~10 coils can correct is still a question.

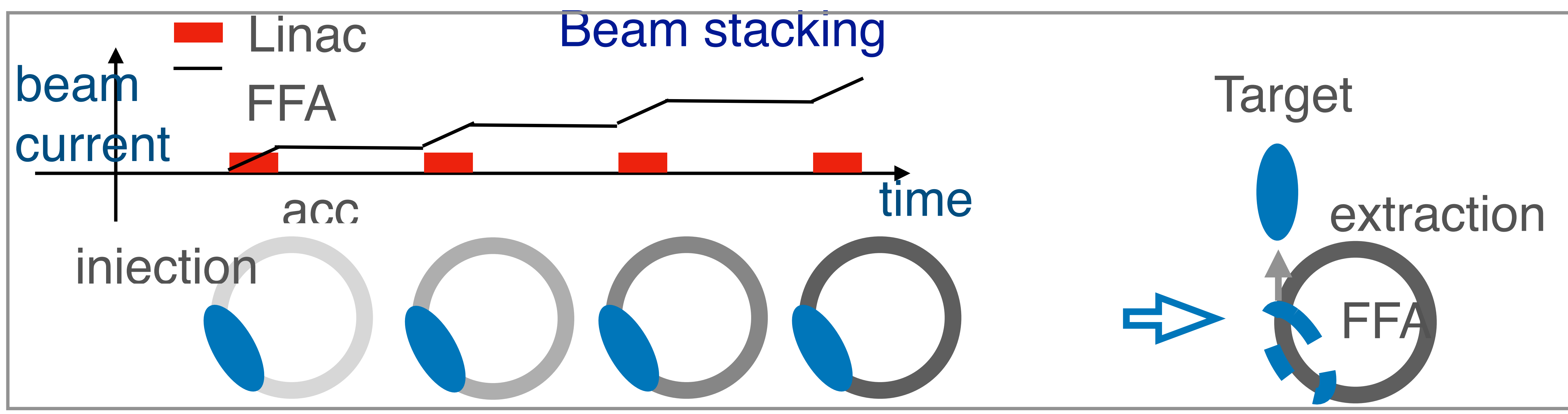


Design by Rodriguez, Kuo and Lagrange

Science and Technology Facilities Council

Poster by Jean-Baptiste Lagrange

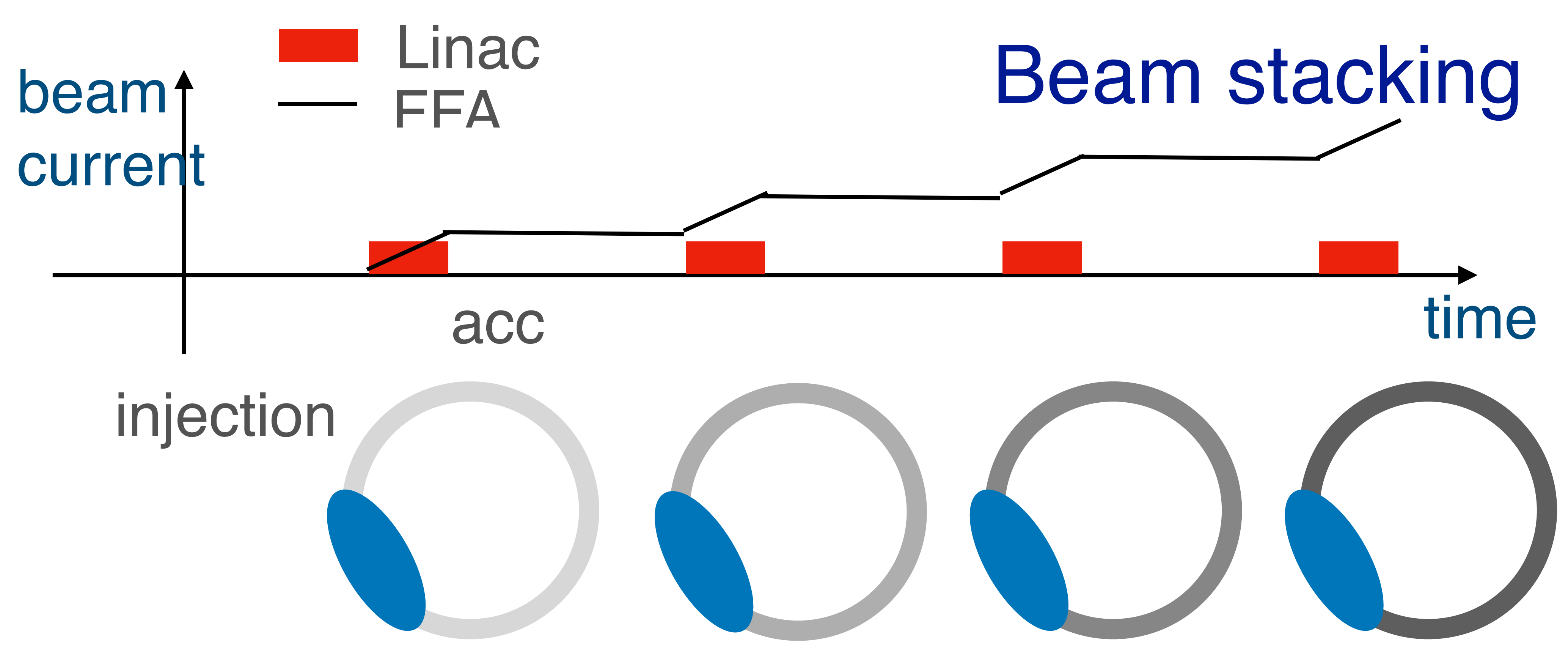
Beam stacking experiment

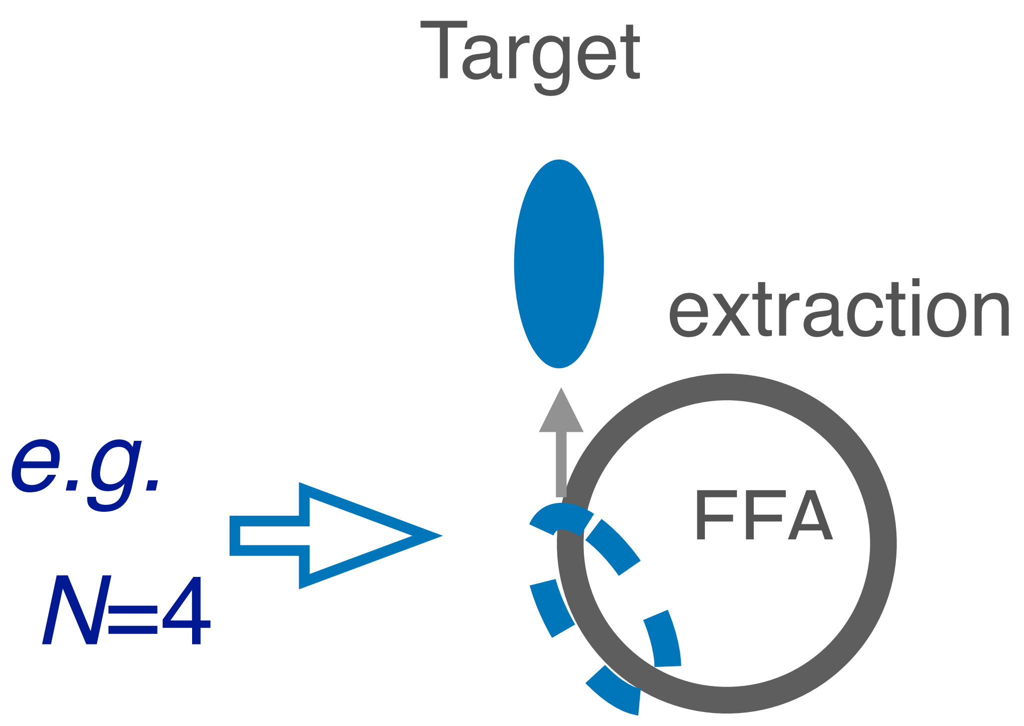


By beam stacking, the pulsed peak current can be increased keeping the average power with a lower repetition rate (~10 Hz).

- As a proton drive for a muon collider, spallation neutron source, etc.

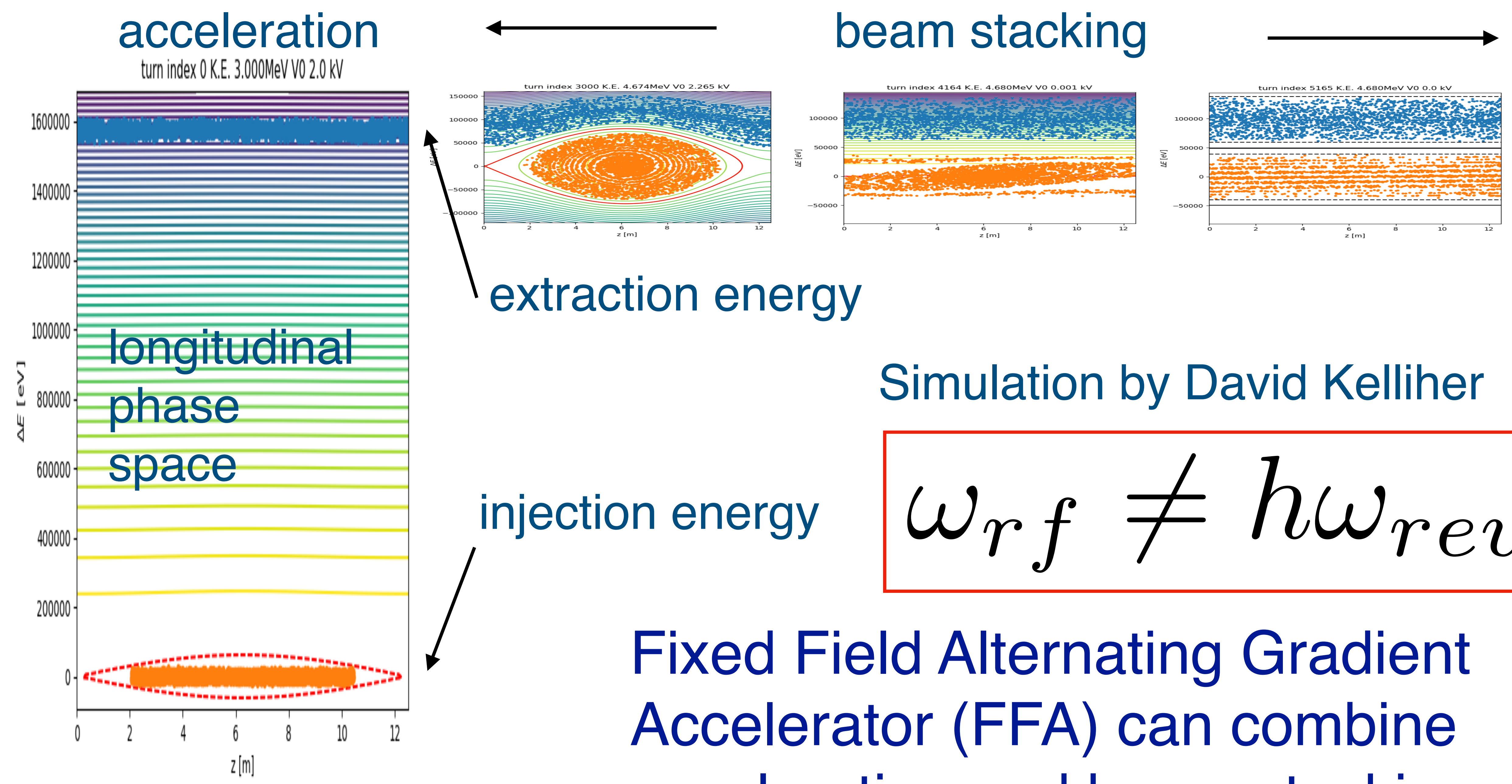
Beam stacking





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**.

Beam stacking is a way to make high peak power with low repetition.

- No other ring accelerators can make that peak power.
- Good as a proton driver for a muon collider, spallation neutron source, etc.

Beam stacking

First experiment at MURA in 1960s

A beam is injected.

A beam is captured and accelerated. Some of particles are not captured.

Repeat 4 times. Momentum spread is larger.

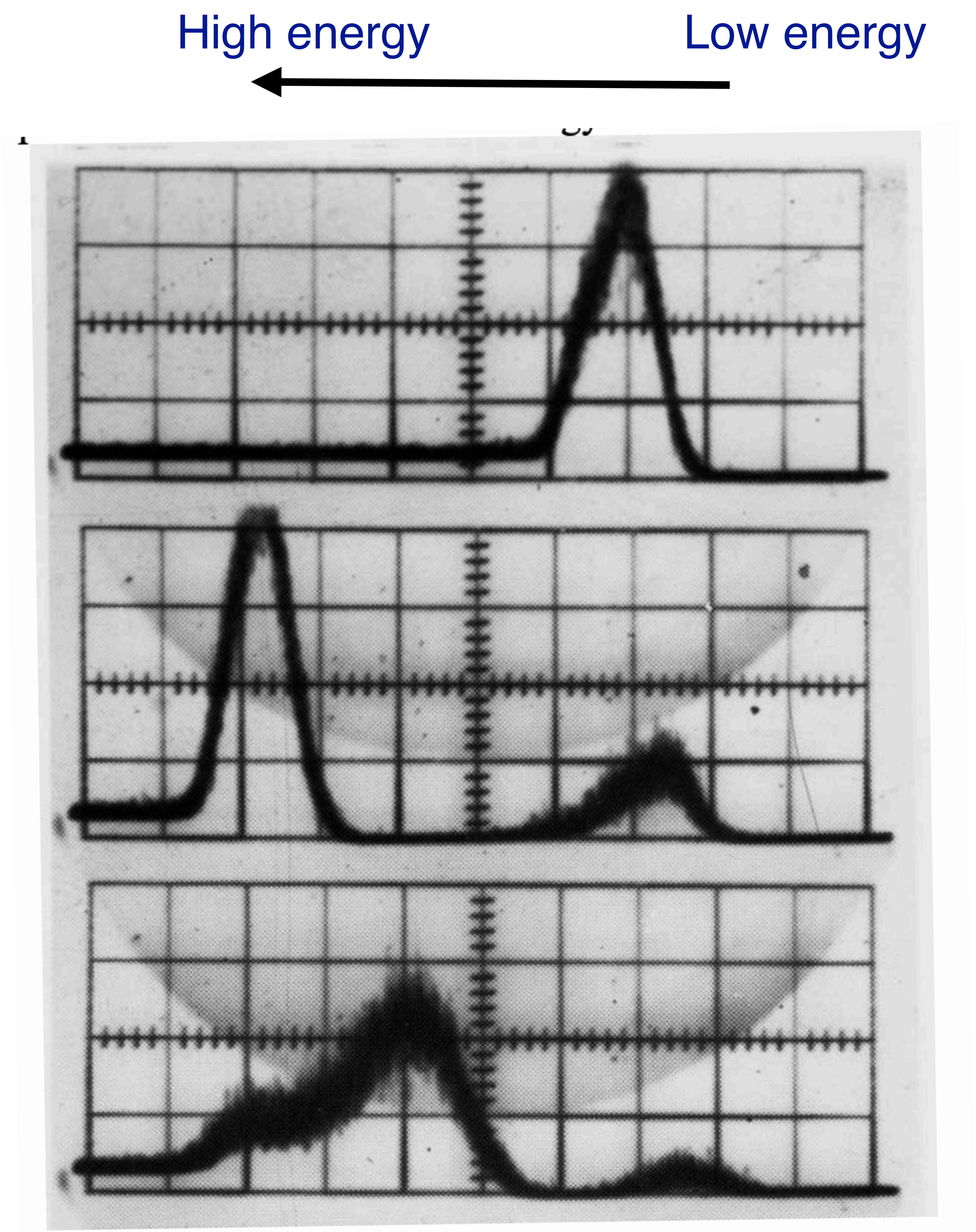


Figure 6: Beam Stacking Experiment

Beam stacking

New experiment this year

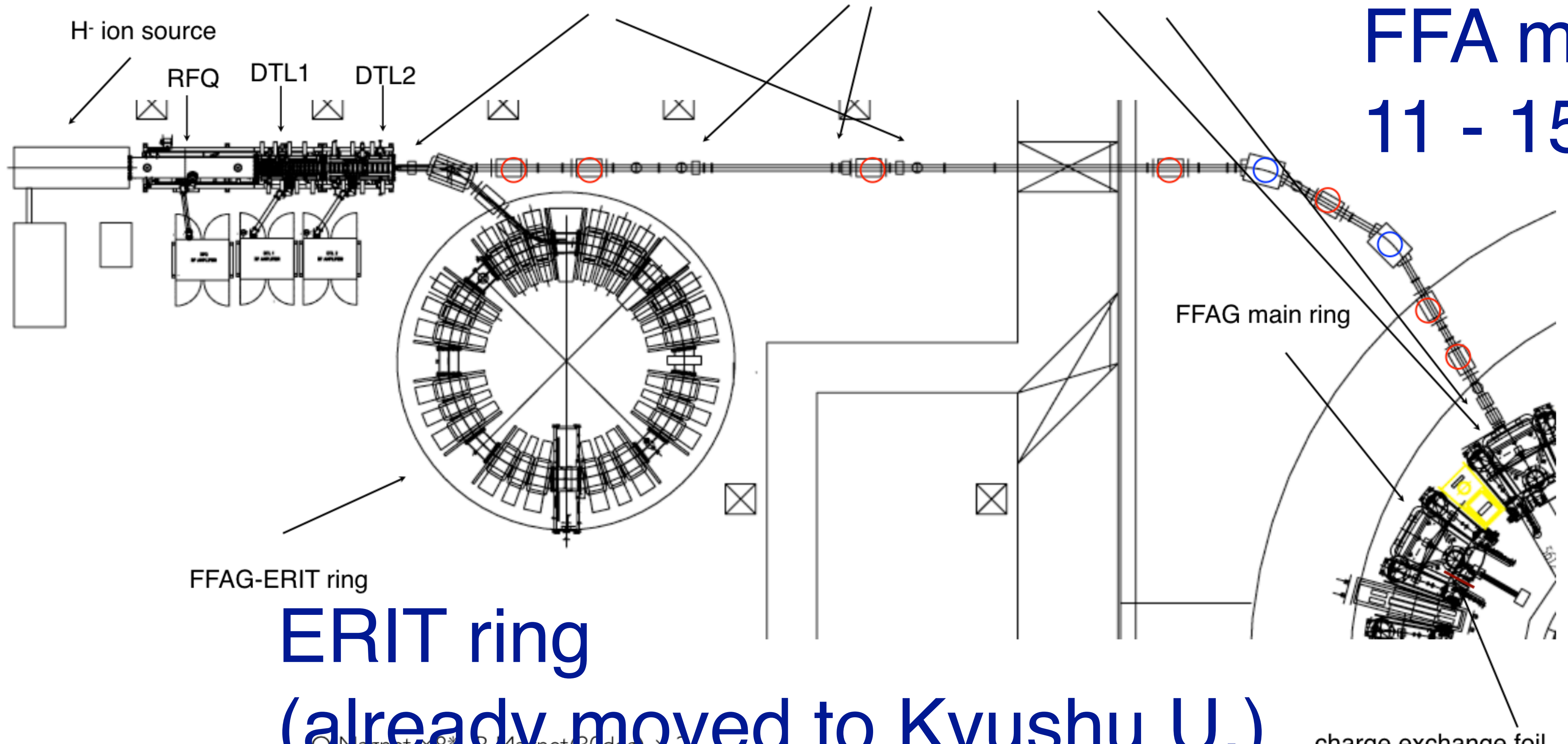
Experimental demonstration (of 2 beams)

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

KURNS FFA accelerator complex at Kyoto Univ.

11 MeV H- linac

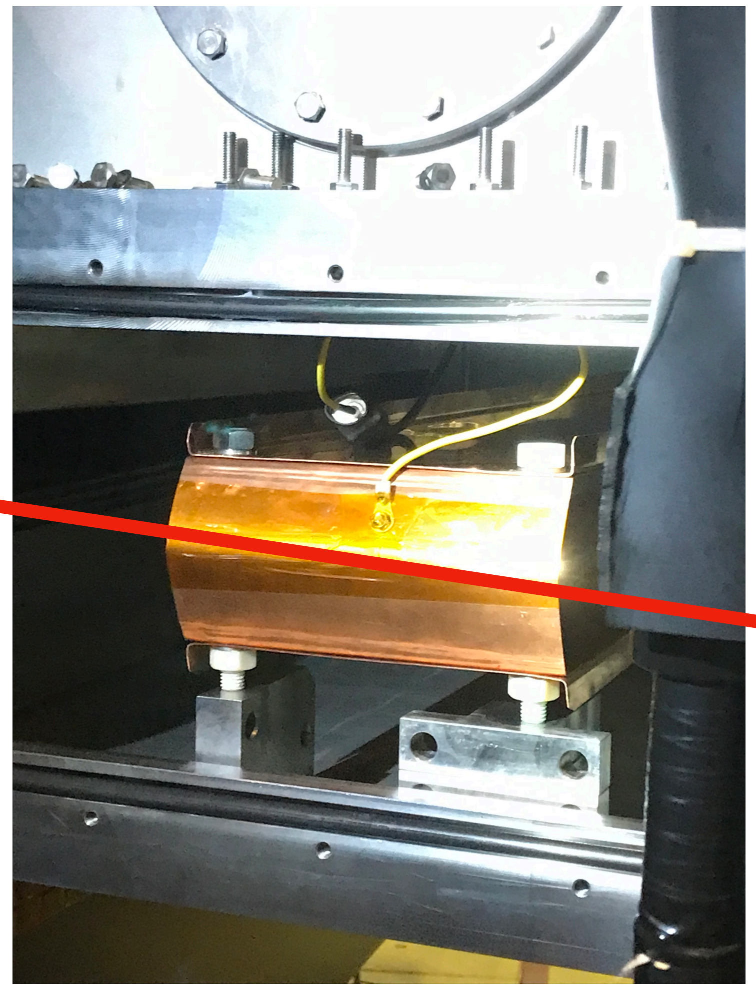
FFA main ring
11 - 150 MeV



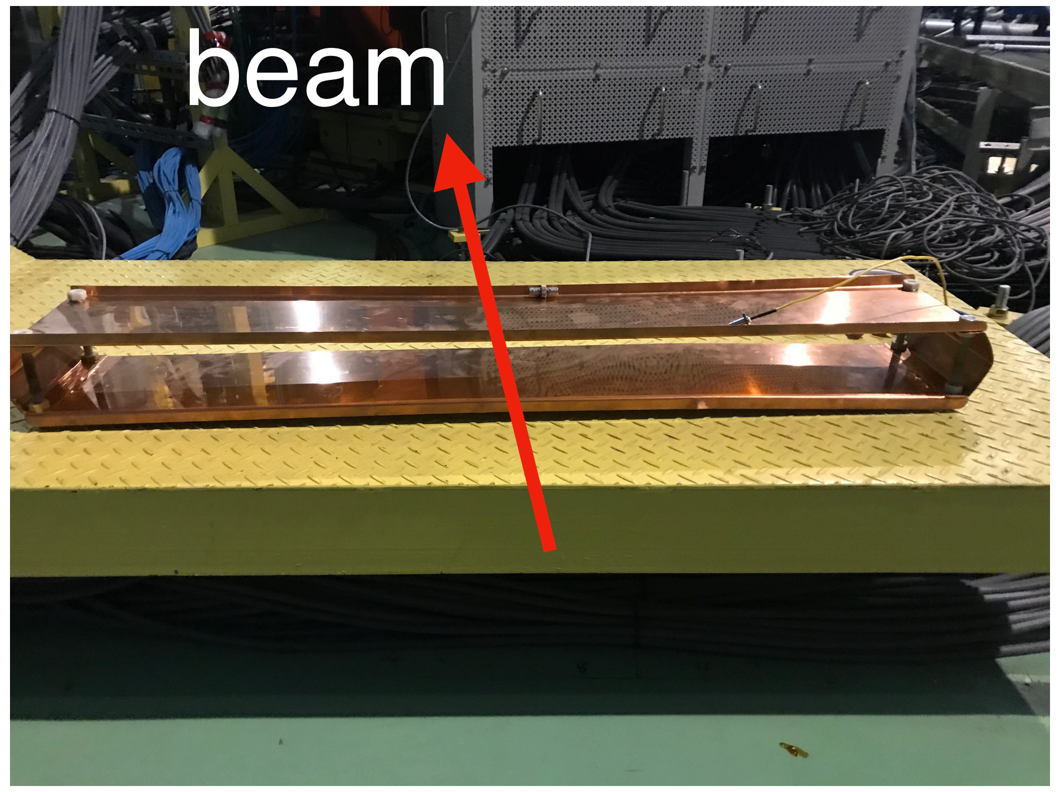
ERIT ring
(already moved to Kyushu U.)

Full Aperture Bunch (FAB) monitor

- Pickup bunch structure.
- Signal is amplified to the scope.



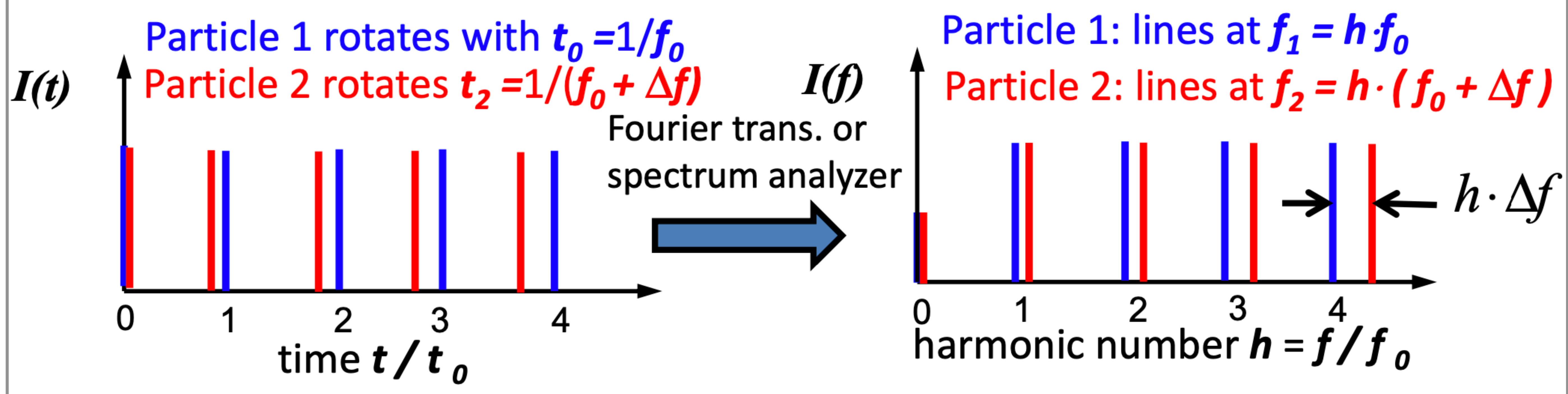
beam



Schottky signal analysis

A Beam consists of finite number of particles

IBIC 2017, Peter Forck



- Momentum spread is seen by different revolution time.
- Spread of frequency spectrum at each harmonic h can be measured

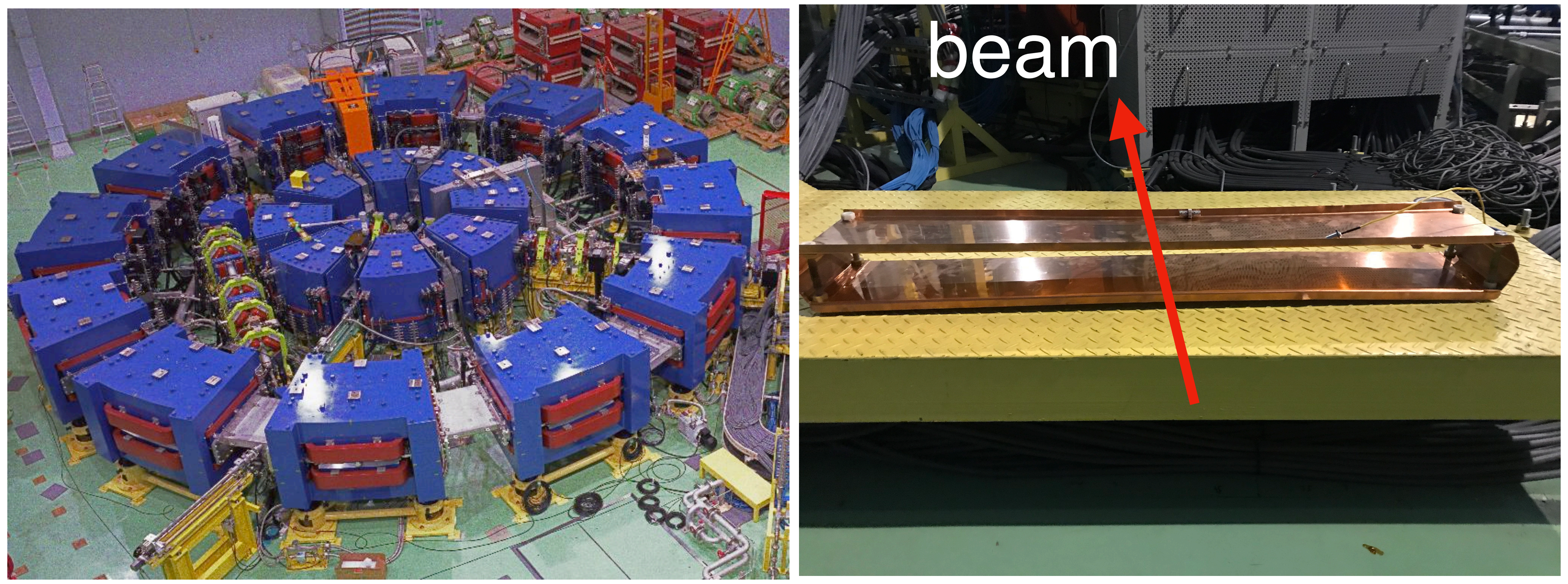
$$\frac{dp}{p} = \frac{1}{h\eta}\frac{df}{f}$$

η : slippage factor

- This is an incoherent signal.
- Sum of frequency spectrum (more precisely PSD) is proportional to the number of particles

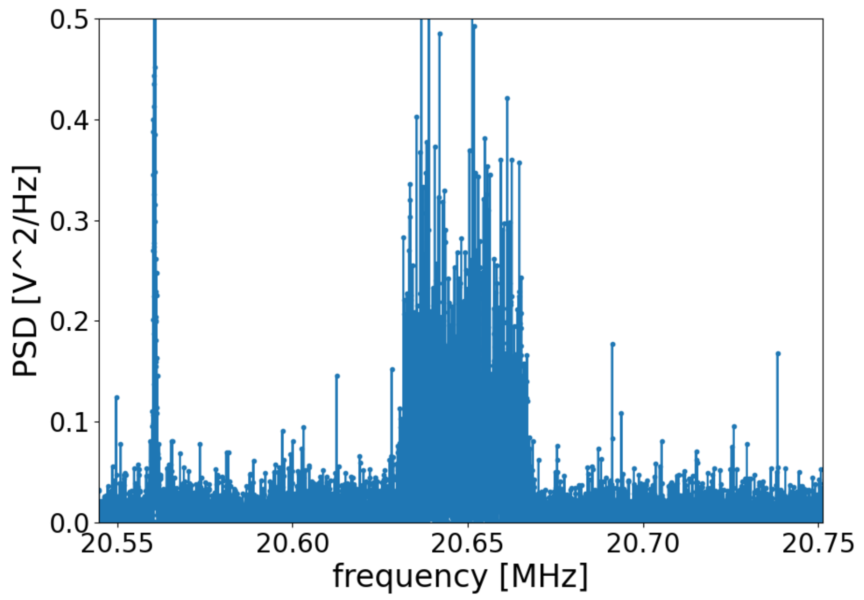
$$\int \left(\frac{dP}{df}\right) df = 2 Z_t e^2 f_0^2 \int \left(\frac{dN}{df}\right) df$$

Z_t: transfer impedance



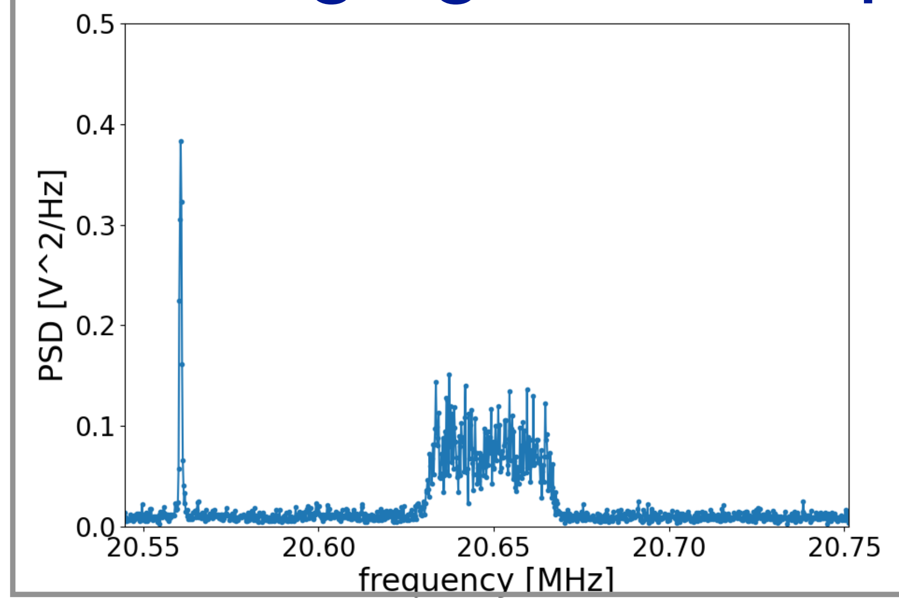
Schottky signal and PSD as an output tells 1) beam intensity and 2) momentum spread

Power Spectrum Density (PSD)

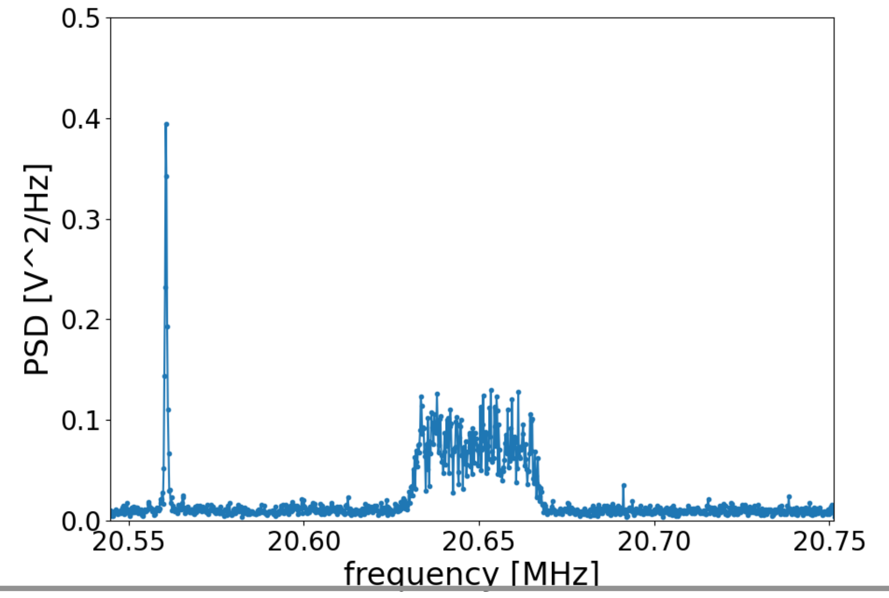


FFA spectrum
(Vertical axis is power V^2)

averaging over freq

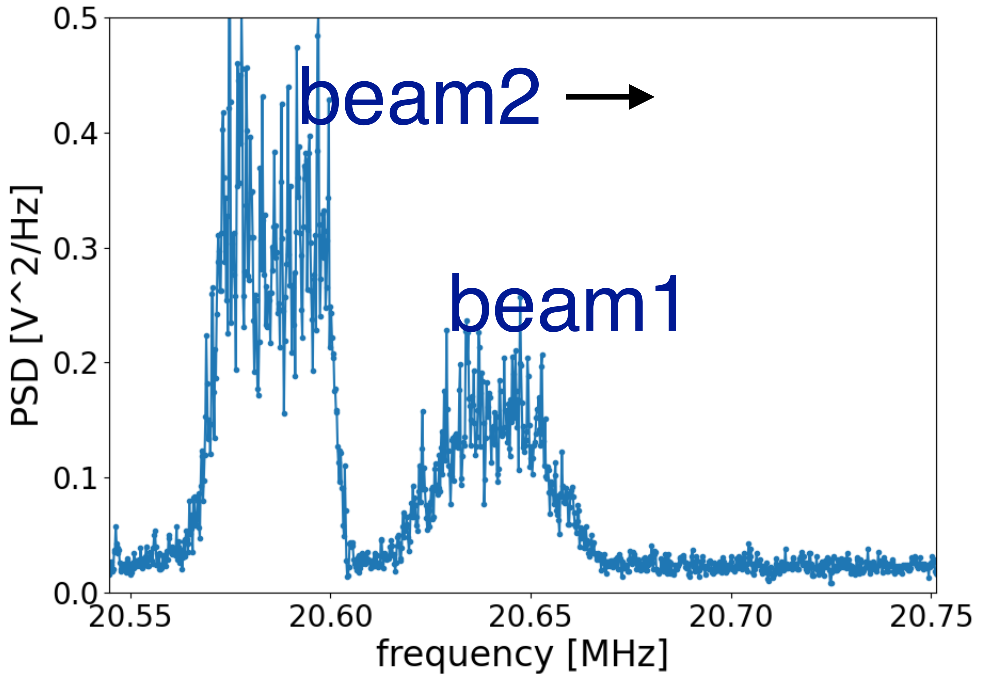


averaging over time
“Bartlett” or “Welch”



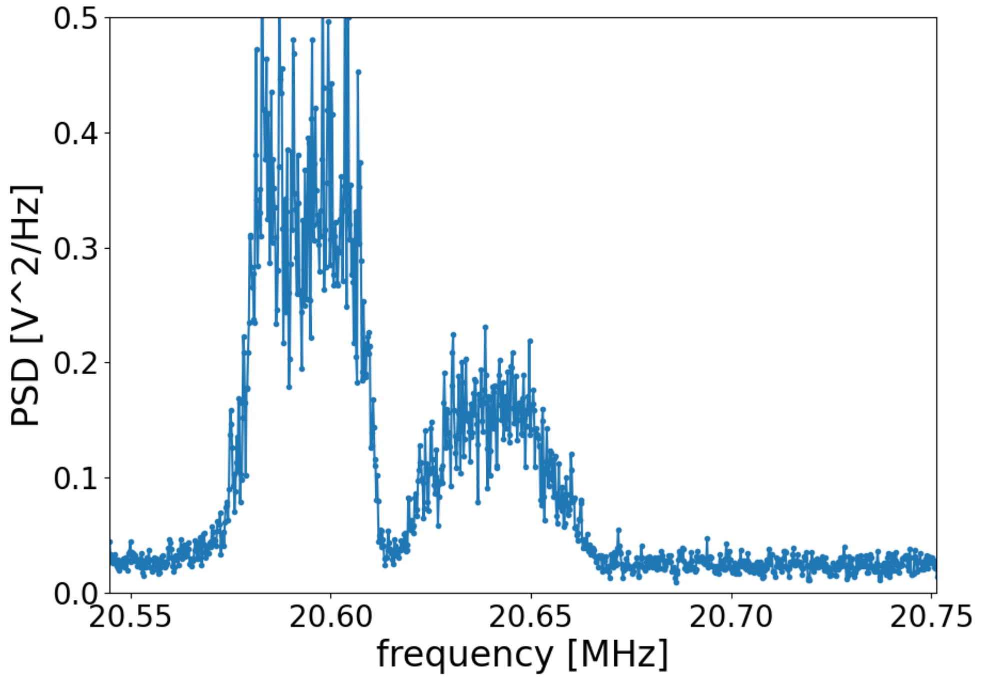
Science and Technology Facilities Council

Schottky signal as a function of the final energy of beam 2.



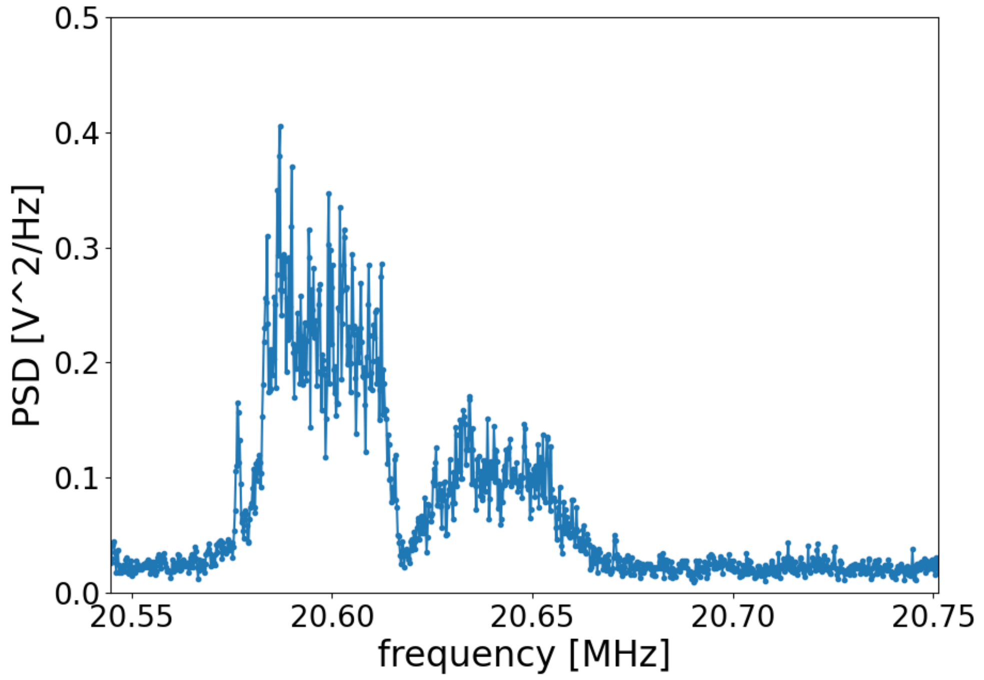
-235.4 keV

beam2



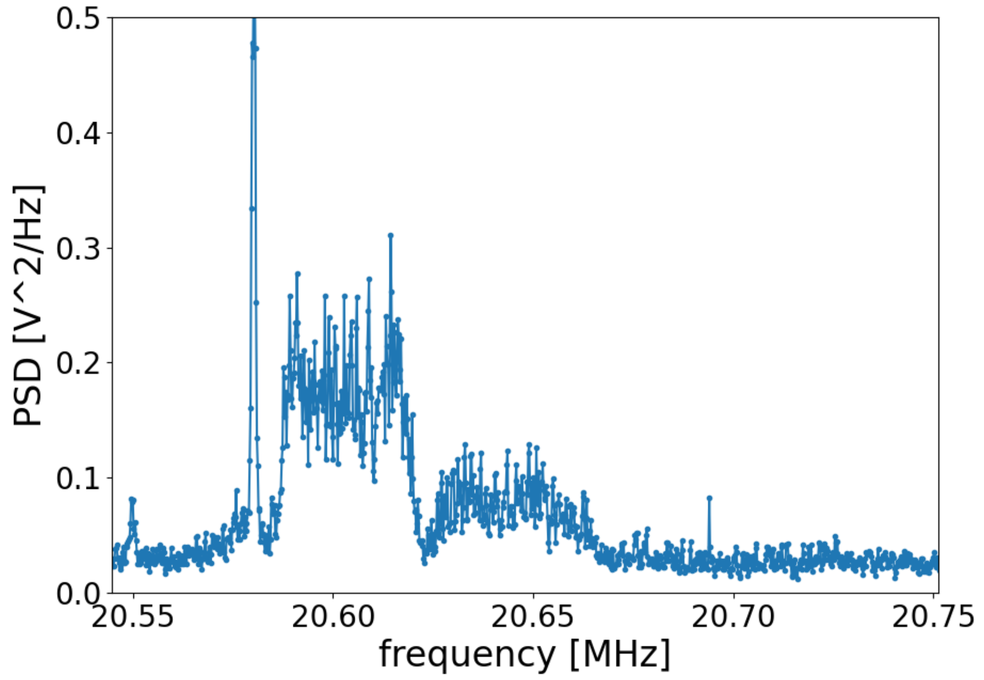
-200.6 keV

beam2



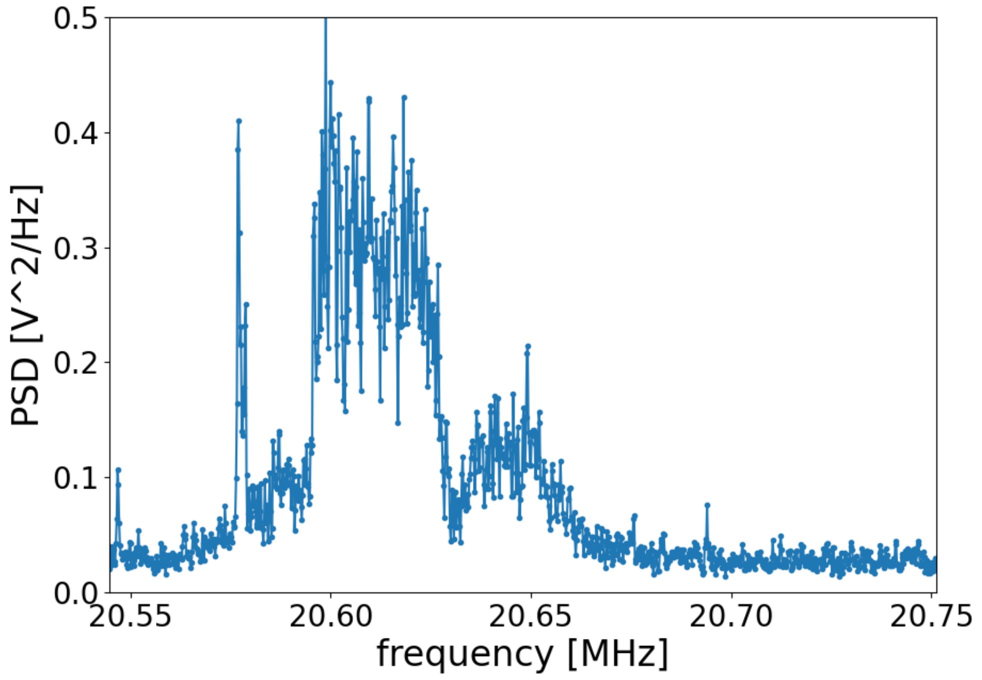
-182.5 keV

beam2



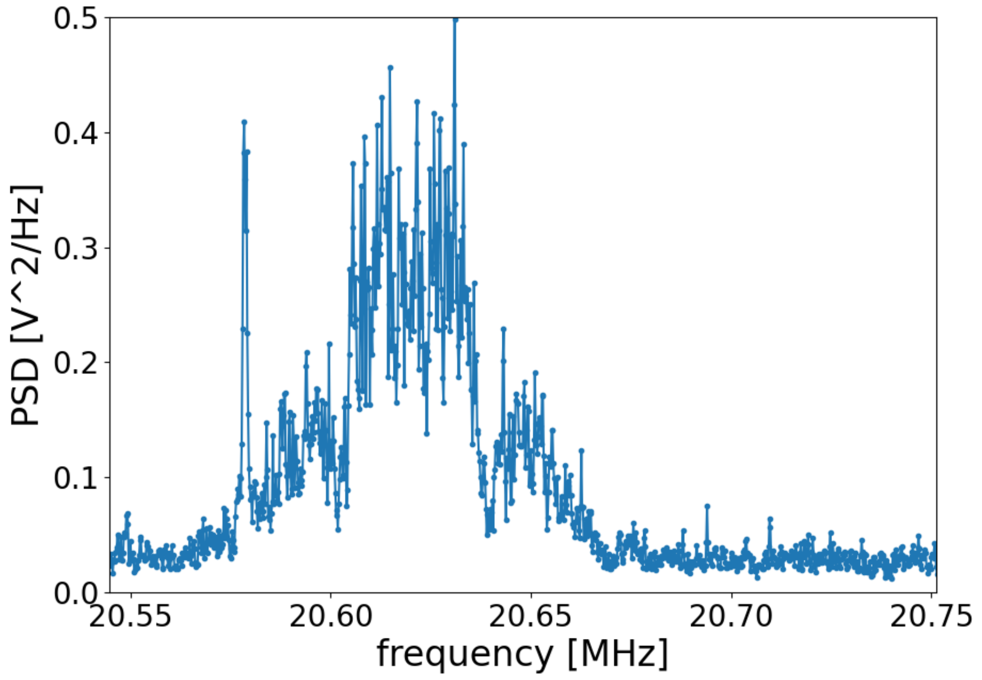
-165.0 keV

beam2



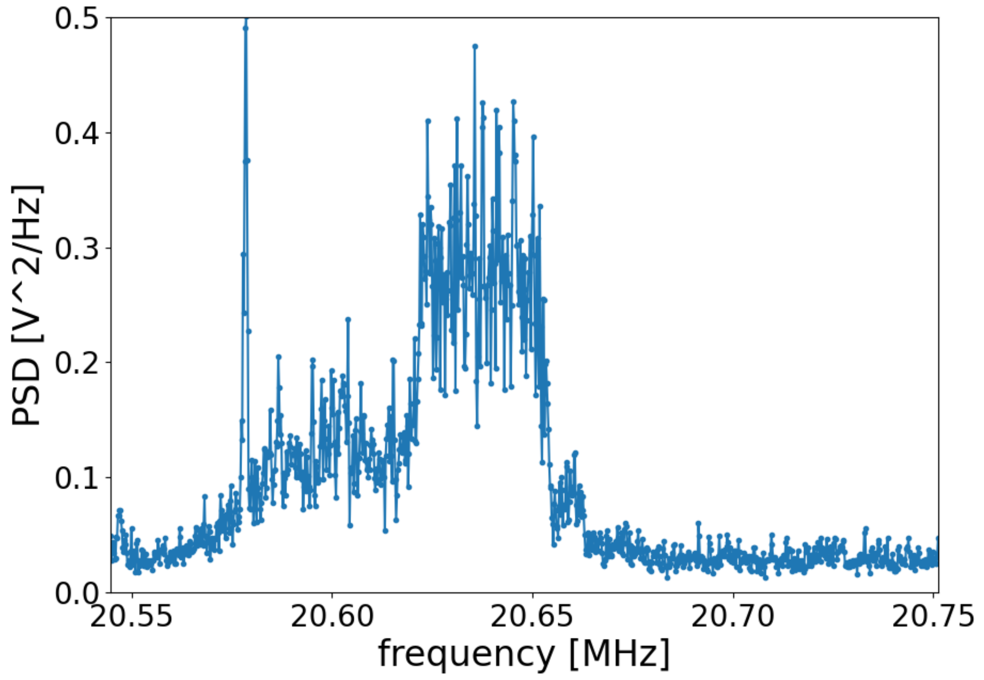
-129.7 keV

beam2

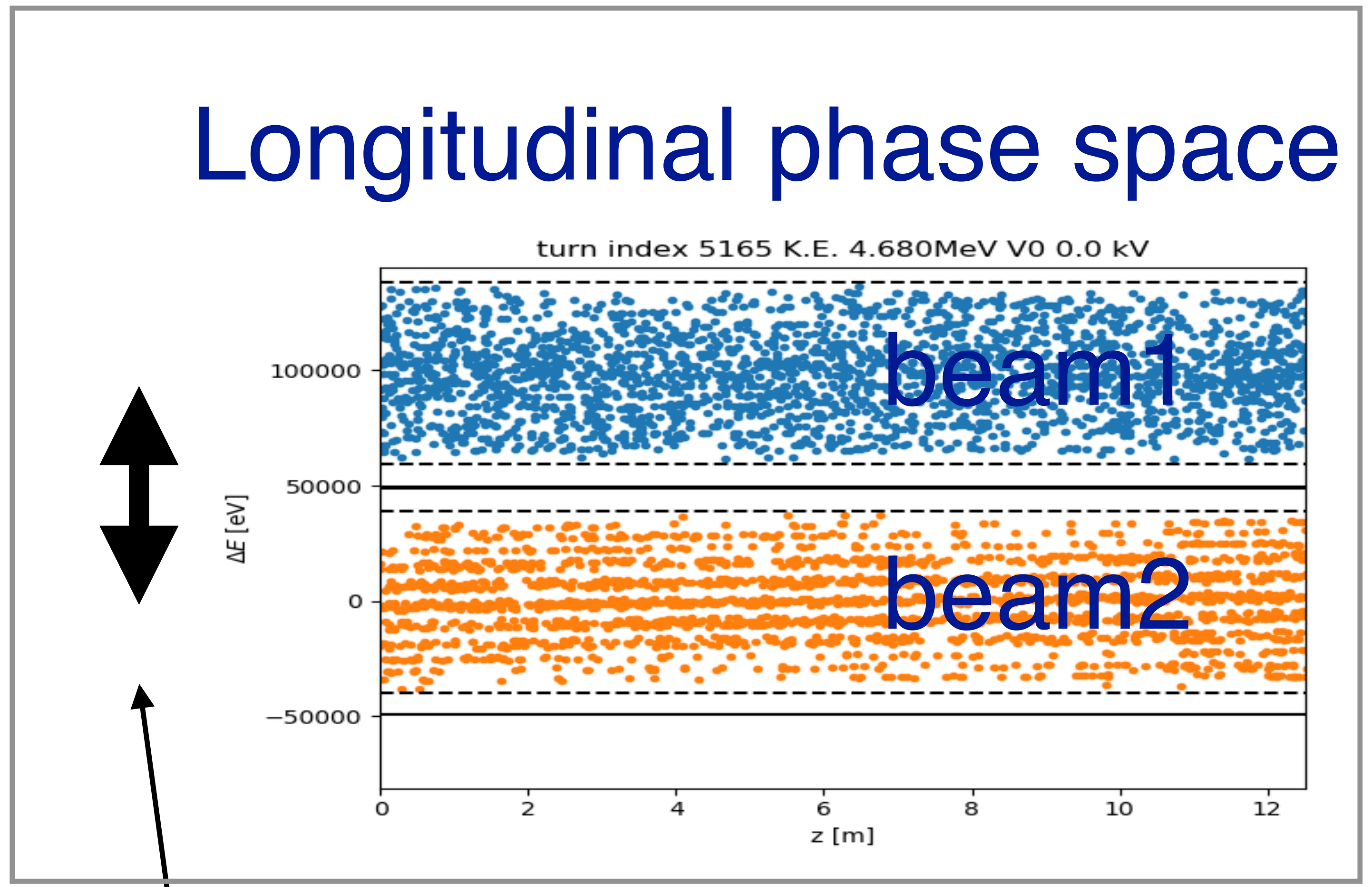


-94.4 keV

beam2



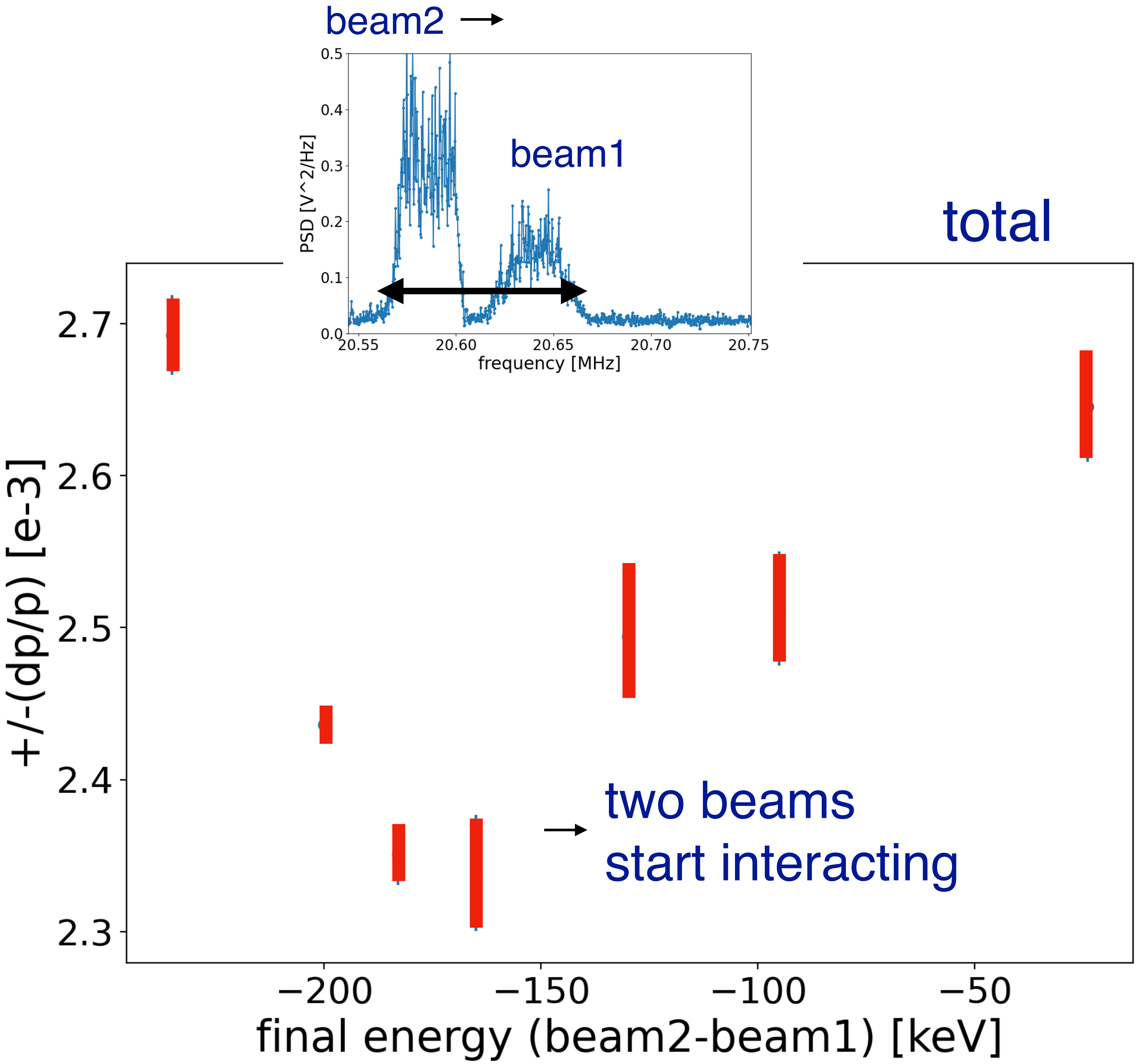
-23.8 keV

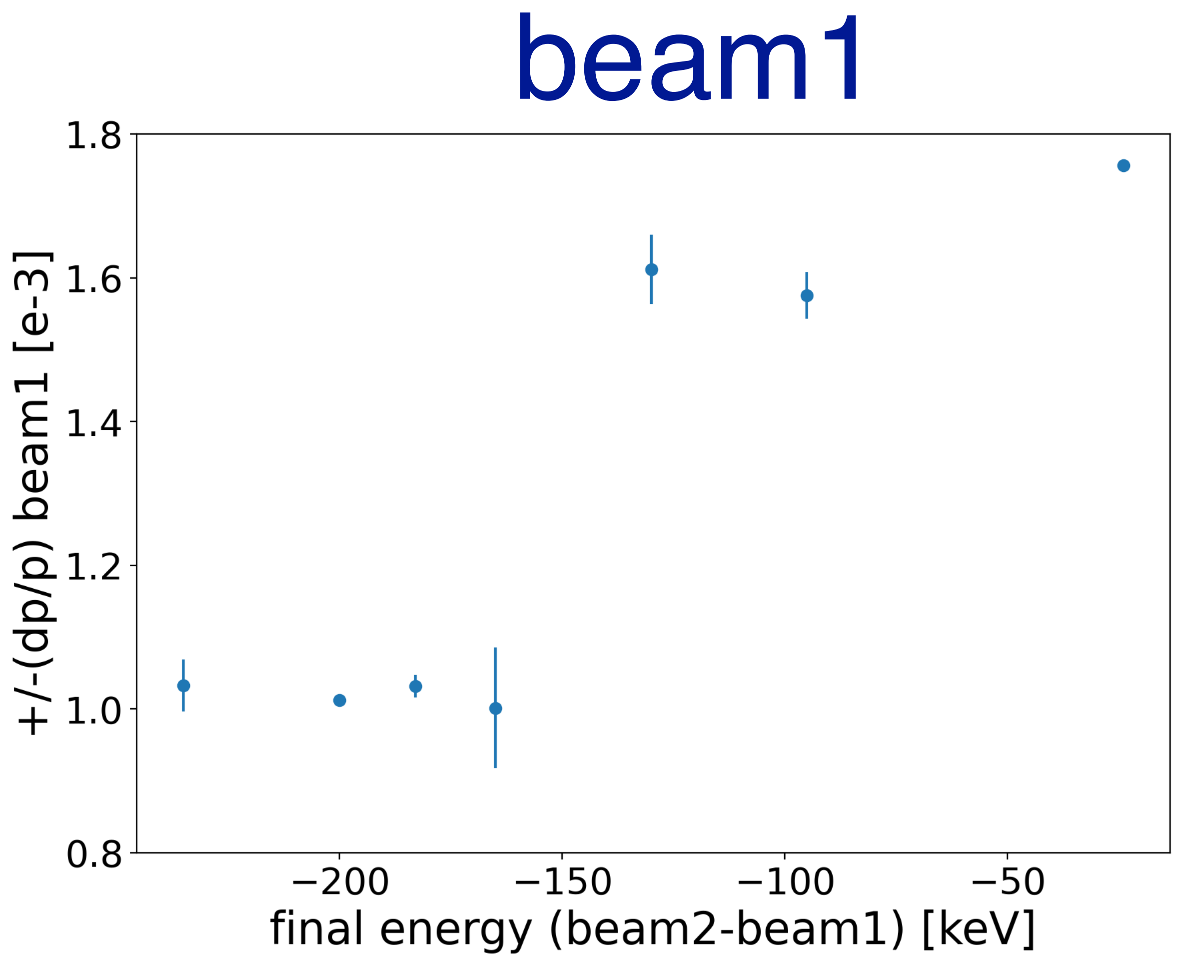


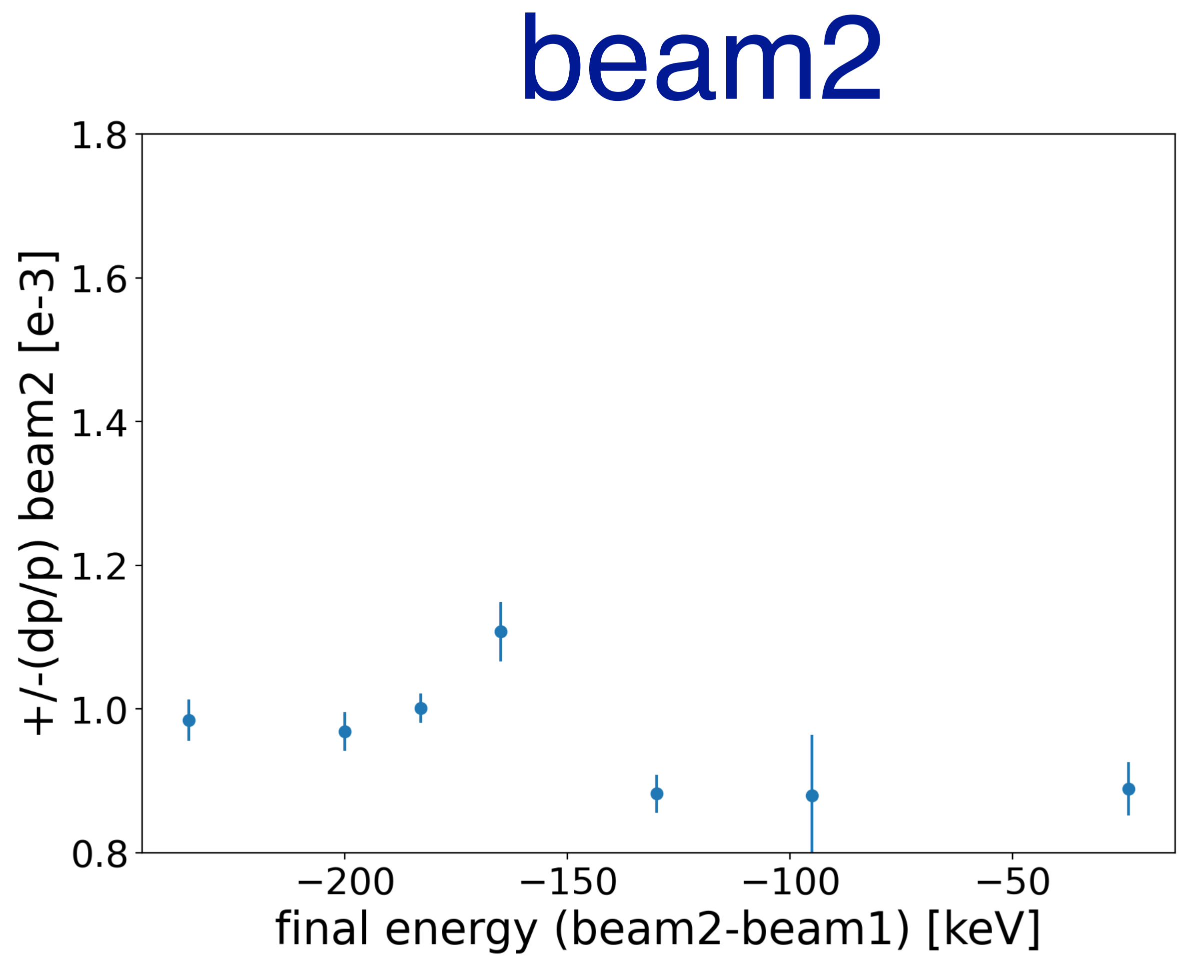
Energy separation (beam2-beam1)

Science and Technology Facilities Council

Result 1: Momentum spread dp/p







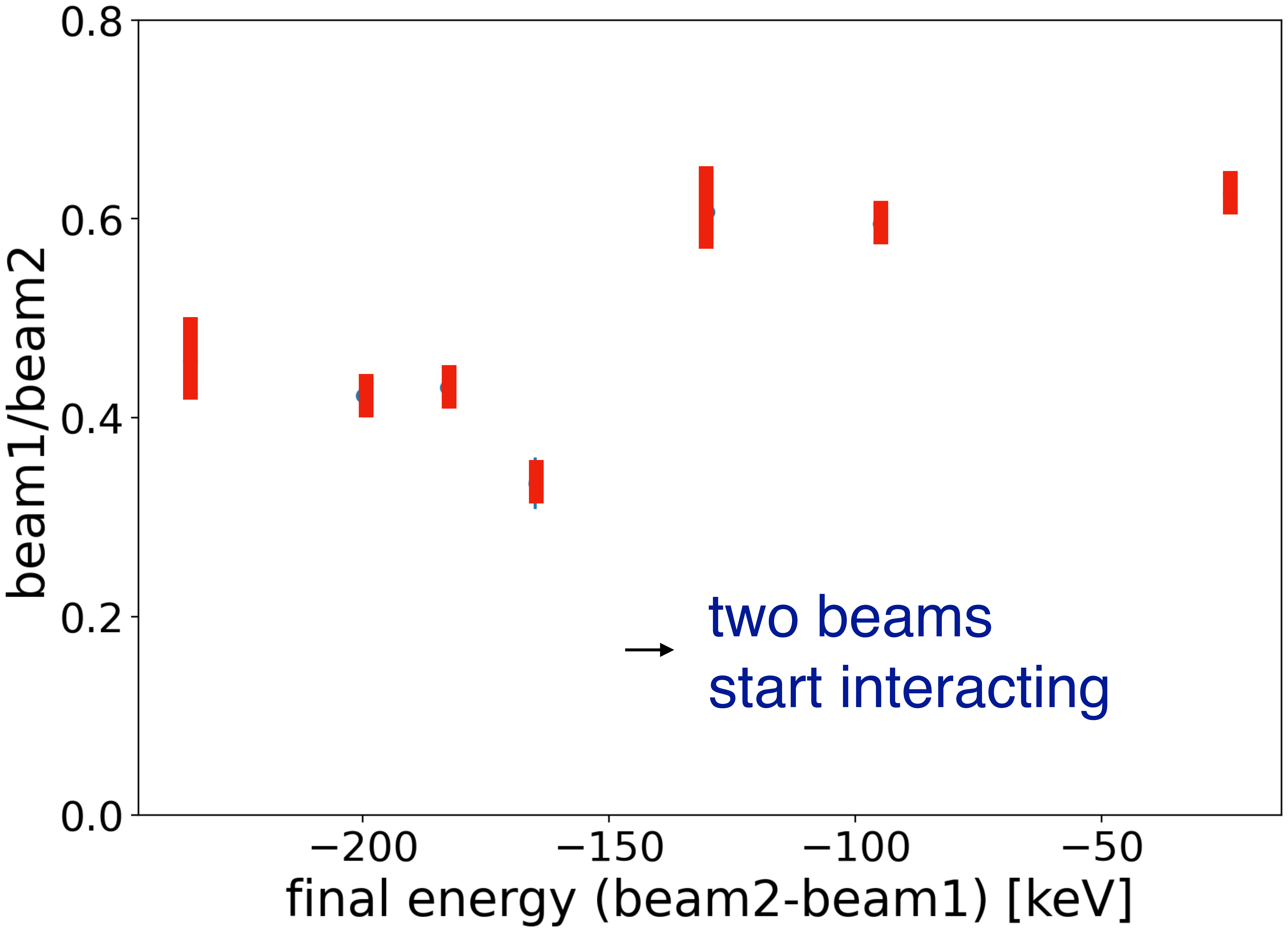
- **Total dp/p becomes minimum** just at the point where two beams start interacting.

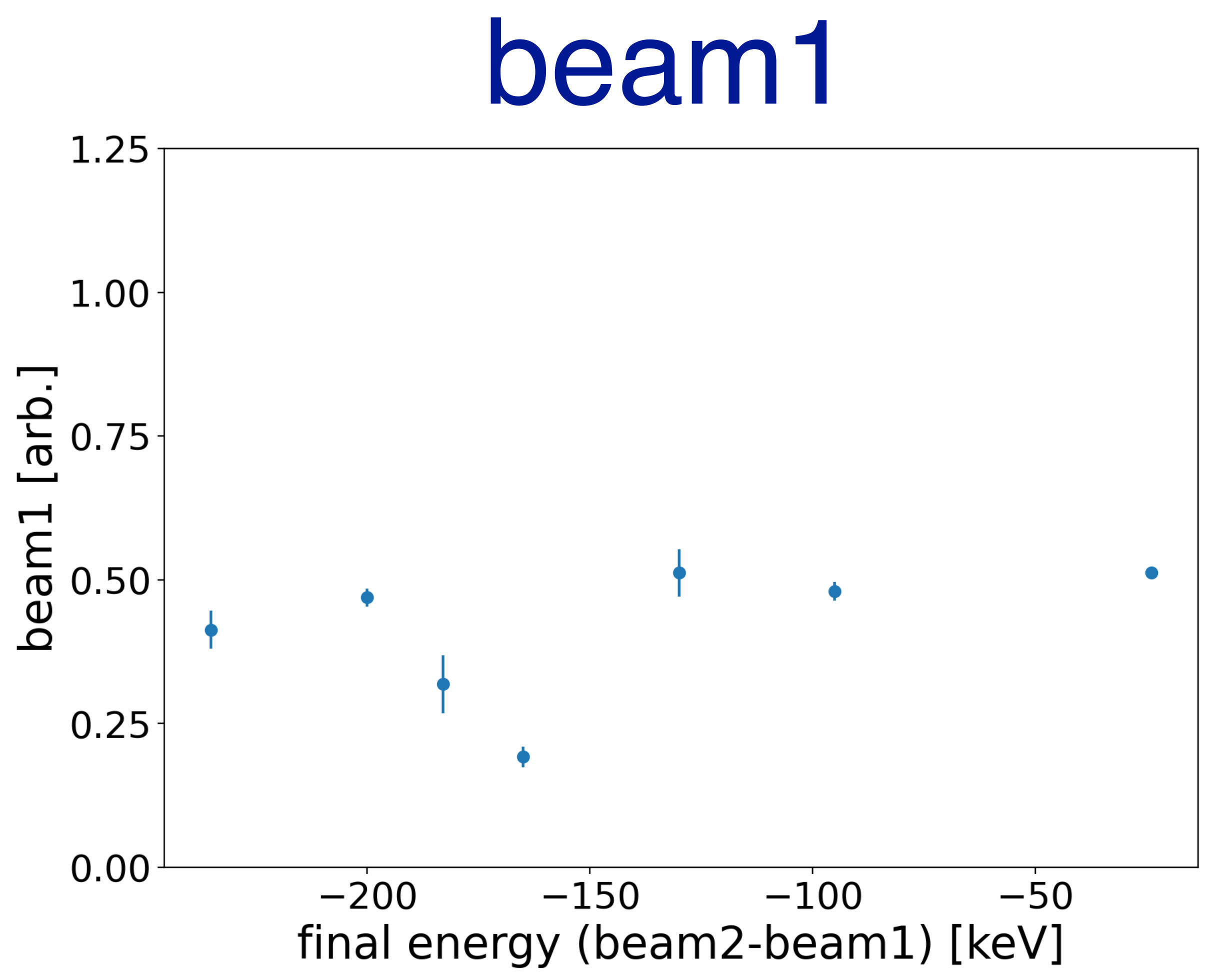
- Once two beams interact each other, total dp/p is larger than twice of dp/p of each beam.
- dp/p of each beam is unchanged until two beams start interacting.

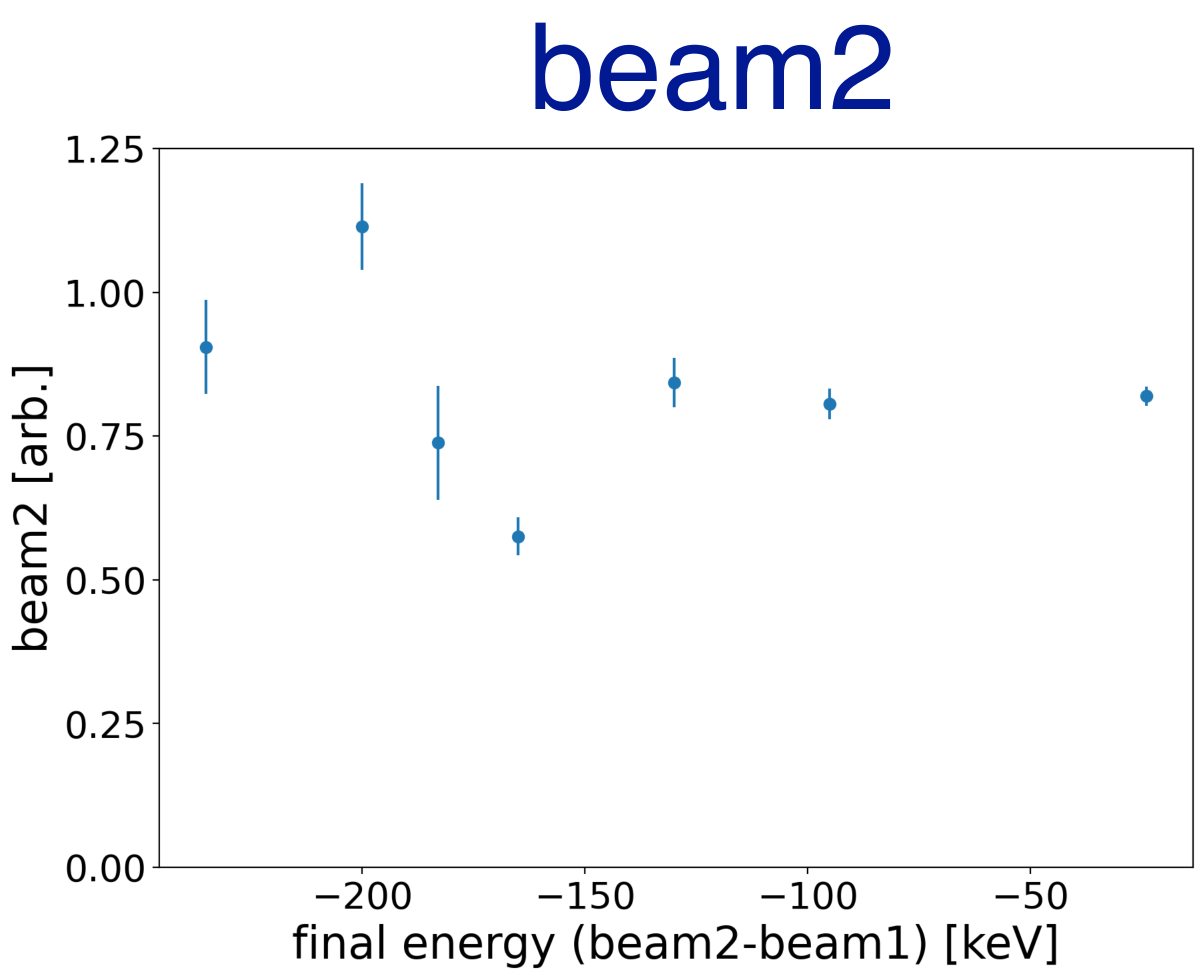
Science and Technology Facilities Council

Total dp/p after stacking is slightly (~15%) more than twice of dp/p of each beam.

Result 2: Beam intensity







- Until two beams start interacting, **the ratio of beam 1 and beam 2 is about 40%** independent of final energy of beam 2.
- Ratio of beam 1 and beam 2 looks higher with interaction, but it depends on the definition of beam 1 intensity. In this analysis, beam 1 includes intensity of both sides of beam 2.

Science and Technology Facilities Council

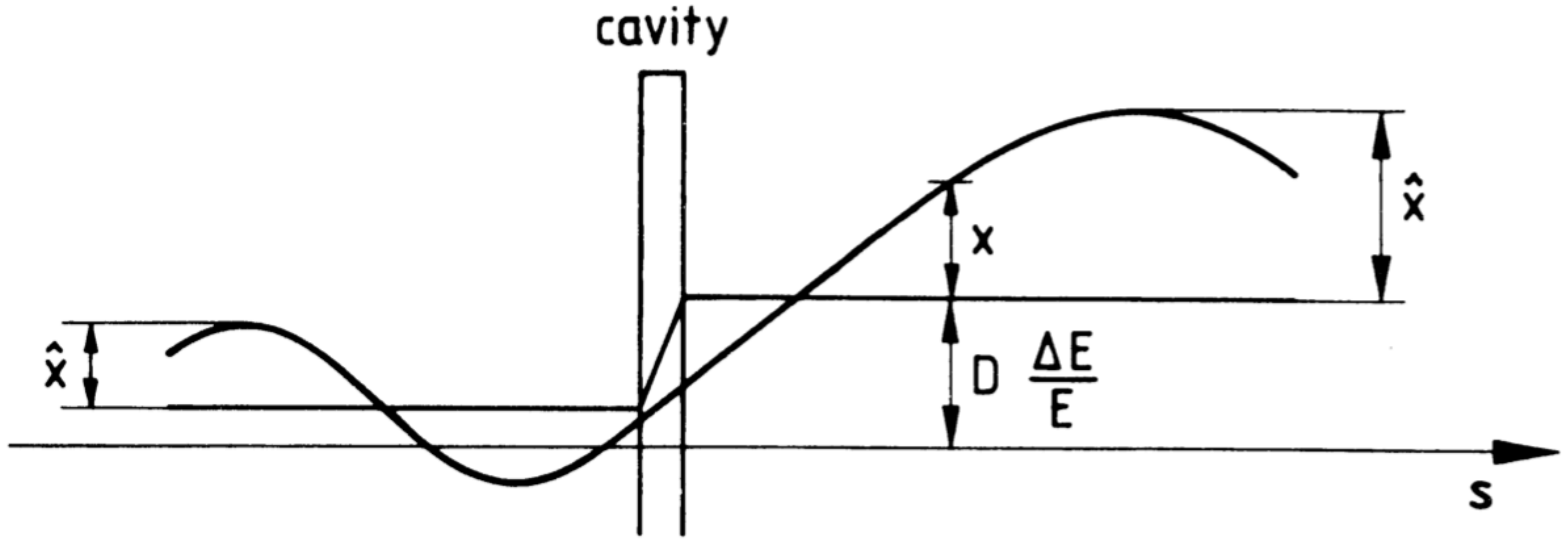
Intensity of beam1 (waiting at top energy) is significantly reduced.

RF knock out

Similar 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

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

For the stacked (coasting) beam,

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

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

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

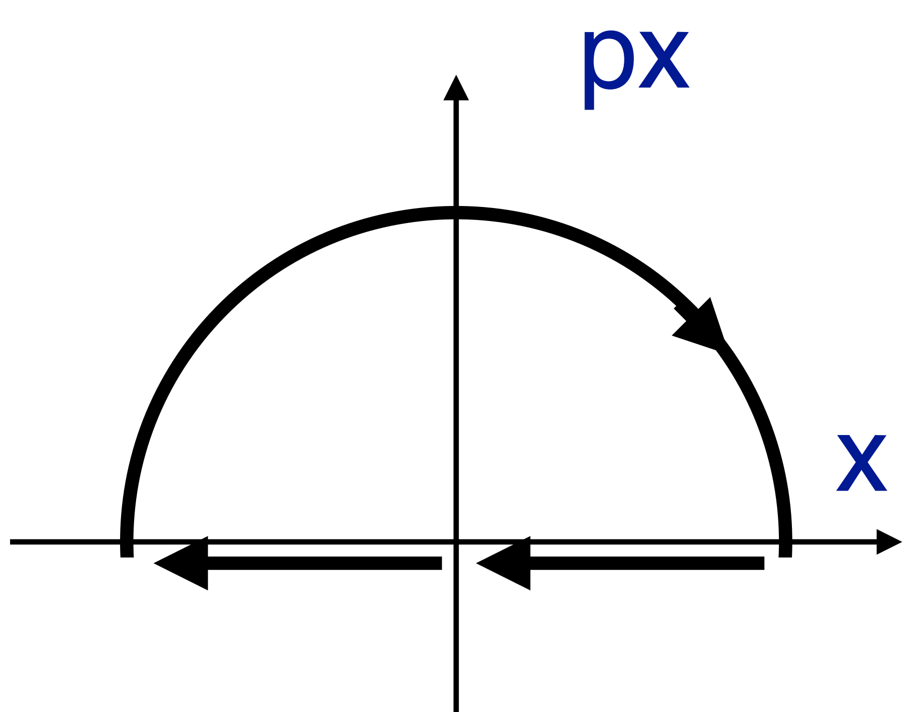
Science and Technology Facilities Council

Proposed mitigation methods (from MURA papers)

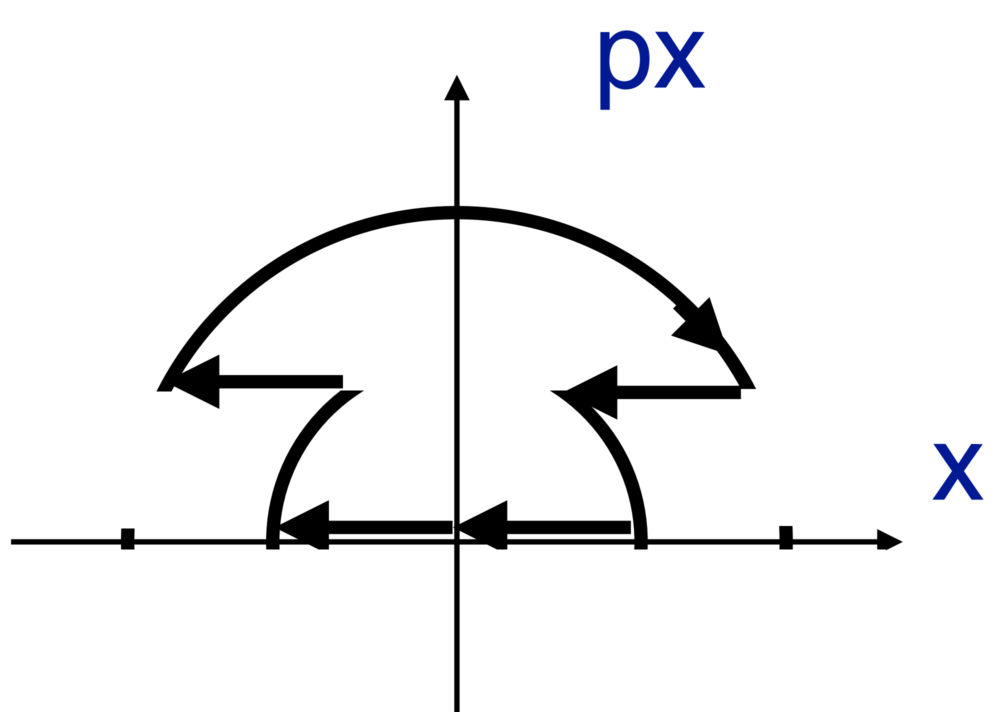
- For a ring with single RF cavity
  - Reduce voltage around resonance
  - Control betatron phase around resonance by changing tune for short time (like a jump around transition energy crossing).

- 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.
  - Place cavities with proper phase.



When phase advance btw 2 cavities is pi.



When phase advance per cavity is not pi.

Science and Technology Facilities Council

Before summary
Many studies to be done

- **Impedance** calculation of a wide window shape vacuum chamber, even irregular shape at some points.
- **Instability and its mitigation**
  - Acceleration is fast.
  - Beam stacking requires the stability of high current coasting beams for long time.

- Zero chromaticity for the entire energy to keep the tune constant.
- Chromaticity is not a knobs to control instabilities.

- Full of systematic multiples and large amplitude dependent tune shift.
- Does it help?

Summary

- High intensity is the primary goal of the Fixed Field Accelerator development at the start.
- Many ideas and proposals existed, but hardware was not ready until recently.

- Now time to revisit the initial idea with the state of the art equipment and new technique.
- It has a potential to give the highest peak power without sacrificing the average current.
- Prototype construction of a high intensity Fixed Field Accelerator is the next step.
    - First, beam loss handling with the same space charge level of SNS/JPARC.
    - Second, study beam instability and its mitigation.

Thank you for your attention

Science and Technology Facilities Council

ISIS Neutron and Muon Source

www.isis.stfc.ac.uk

@isisneutronmuon

uk.linkedin.com/showcase/isis-neutron-and-muon-source