Science and
Technology
Facilities Council

FFA as high power proton machines

Shinji Machida
UKRI/STFC Rutherford Appleton Laboratory

11 September 2023
FFA school at J-lab

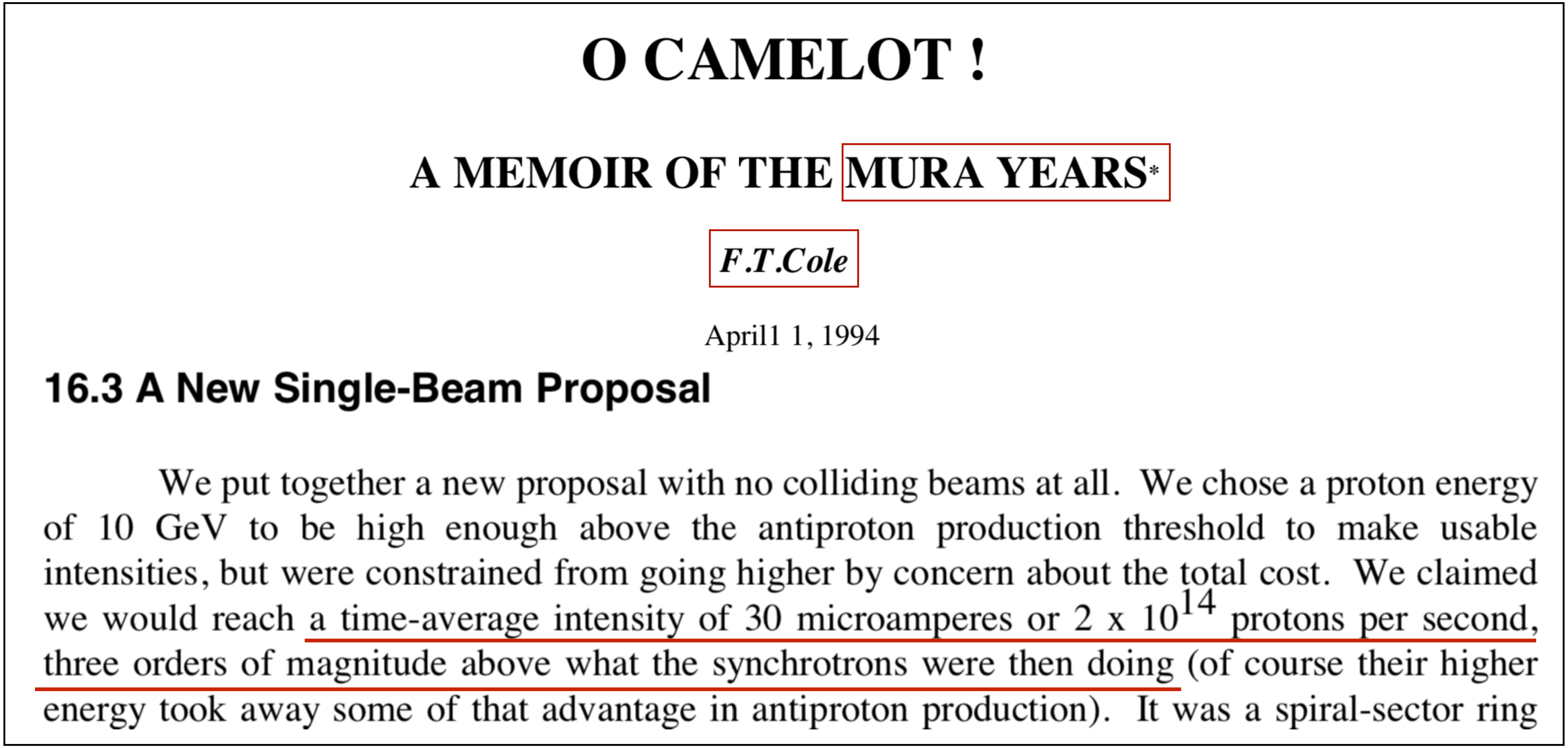
Overview

- A bit of history
  - Midwestern Universities Research Association (MURA)
  - ASPUN at Argonne National Lab
  - Initial ESS project
- Why FFA
  - High power by high repetition
- Some topics
  - Modelling space charge effects
  - Beam stacking
  - (Cyclotron like extraction in a synchrotron (FFA) like ring)
- Summary

A bit of history

MURA

Midwestern Universities Research Association



O CAMELOT !

A MEMOIR OF THE MURA YEARS*

F.T.Cole

April1 1, 1994

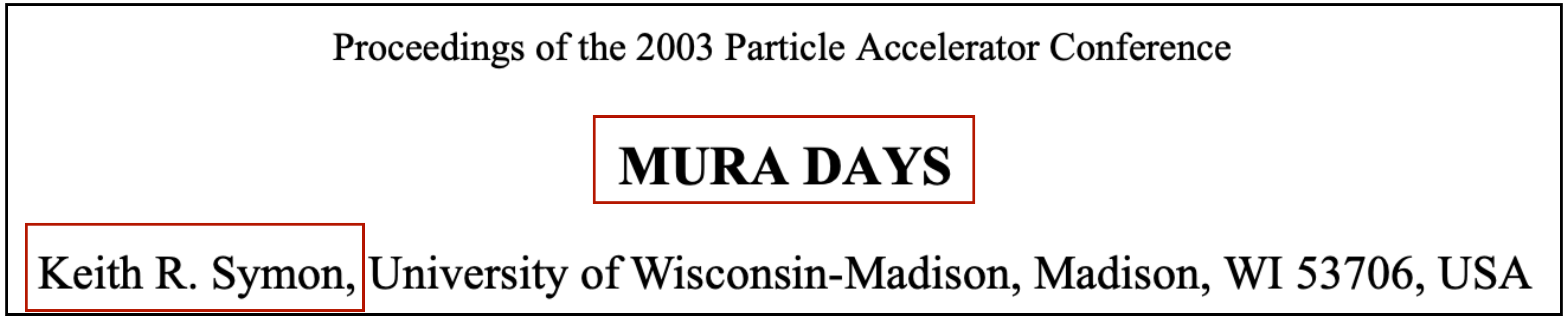
16.3 A New Single-Beam Proposal

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

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

A bit of history

Birth of FFAG accelerator at MURA

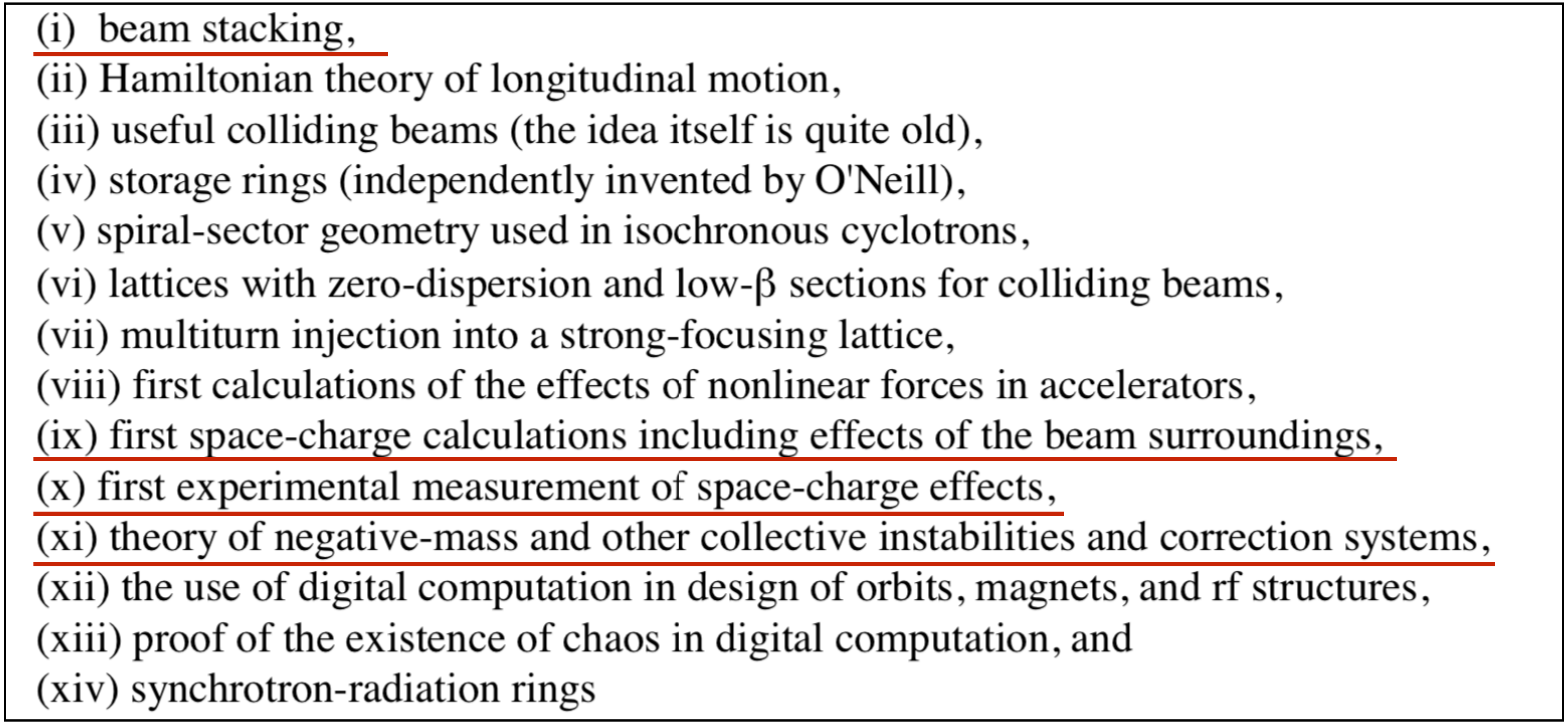


Proceedings of the 2003 Particle Accelerator Conference

MURA DAYS

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

Invited talk at PAC2003

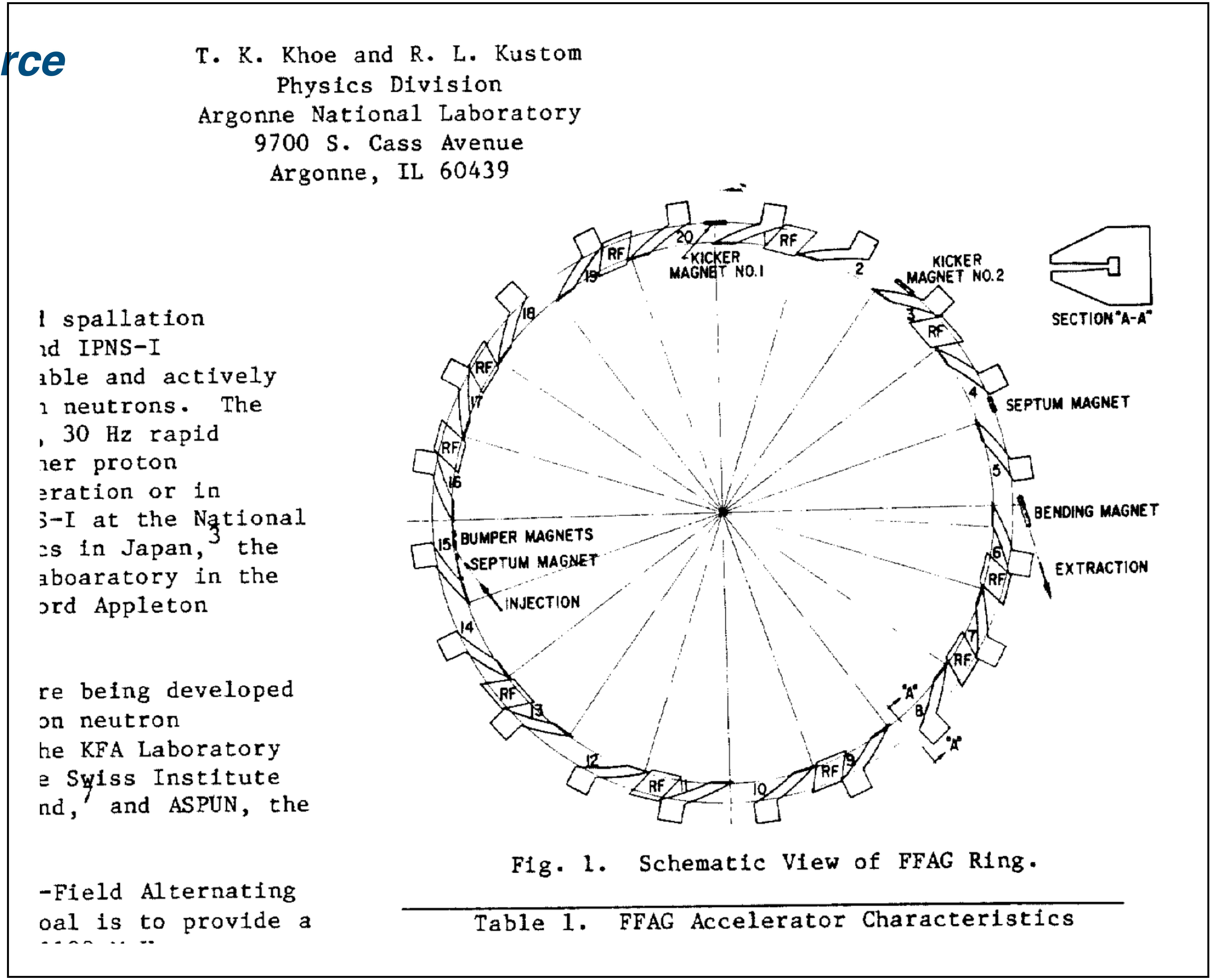


(i) beam stacking,
(ii) Hamiltonian theory of longitudinal motion,
(iii) useful colliding beams (the idea itself is quite old),
(iv) storage rings (independently invented by O'Neill),
(v) spiral-sector geometry used in isochronous cyclotrons,
(vi) lattices with zero-dispersion and low-β sections for 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

As a spallation neutron source

ASPUN, ANL at PAC1983



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

l spallation
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ıer proton
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S-I at the National[3]
cs in Japan, the
aboaratory in the
ord Appleton

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

-Field Alternating
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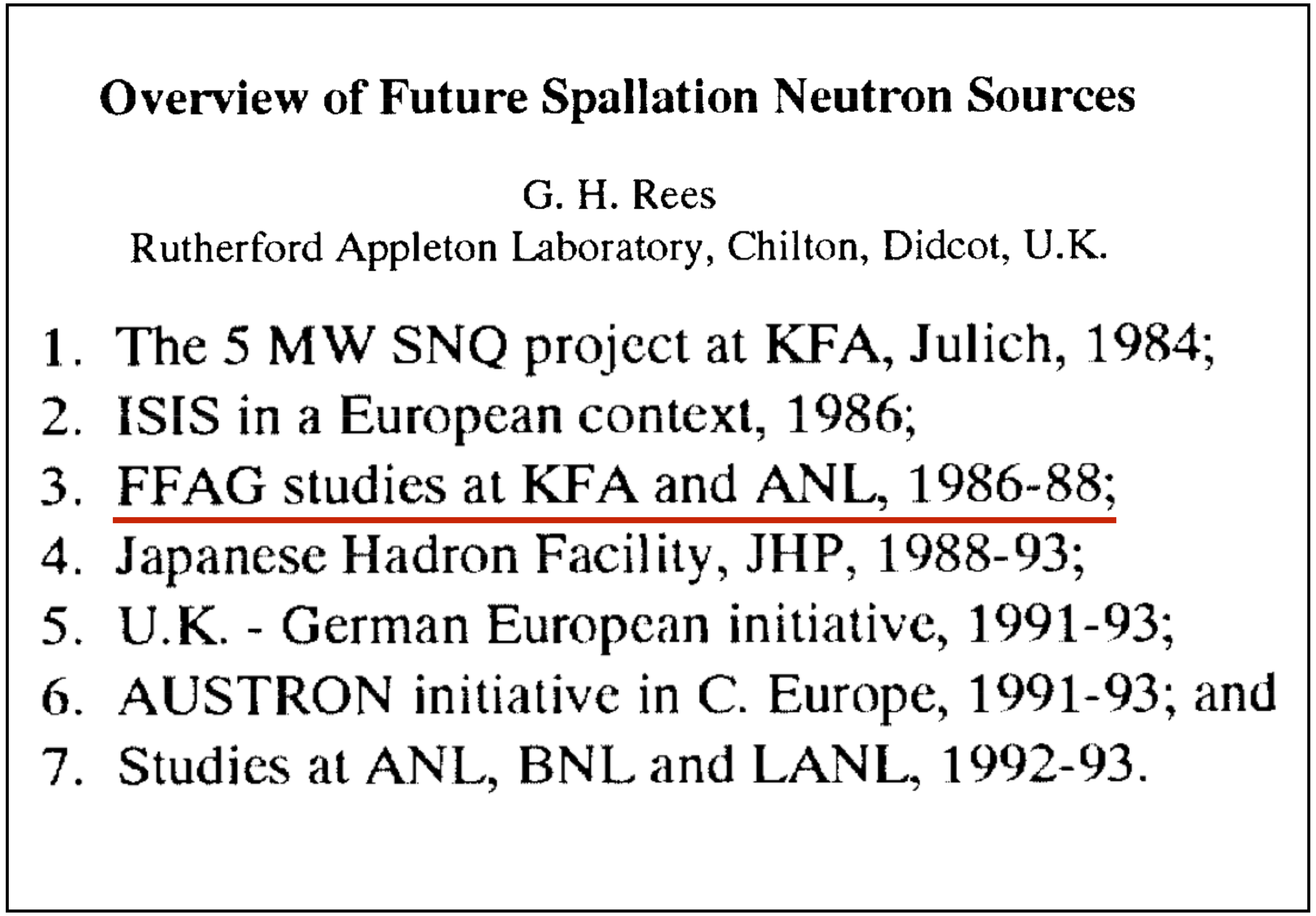
Fig. 1. Schematic View of FFAG Ring.

Table 1. FFAG Accelerator Characteristics

A bit of history

As a spallation neutron source

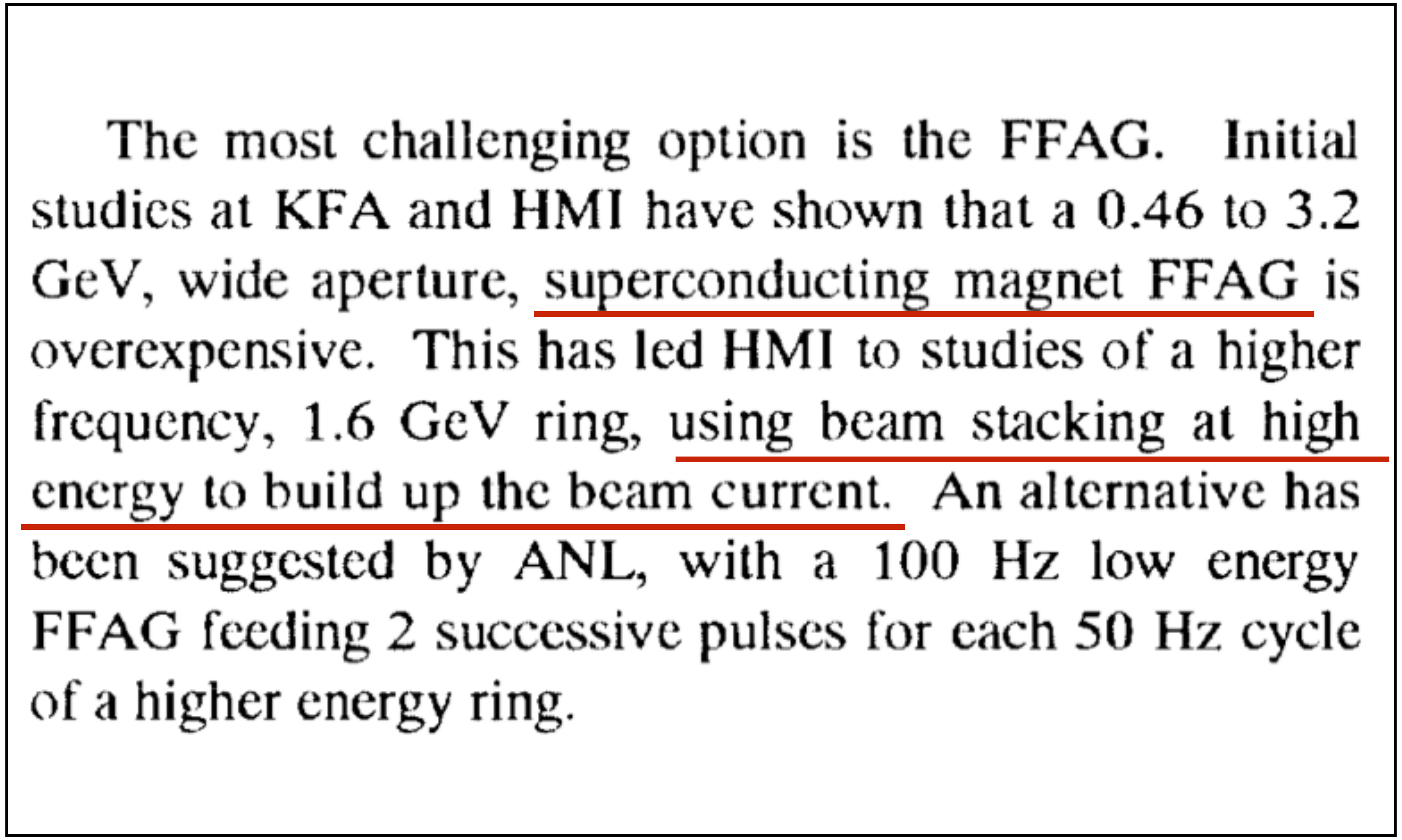
Invited talk at PAC1993



Overview of Future Spallation Neutron Sources

G. H. Rees
Rutherford Appleton Laboratory, Chilton, Didcot, U.K.

1. The 5 MW SNQ project at KFA, Julich, 1984;
2. ISIS in a European context, 1986;
3. FFAG studies at KFA and ANL, 1986-88;
4. Japanese Hadron Facility, JHP, 1988-93;
5. U.K. - German European initiative, 1991-93;
6. AUSTRON initiative in C. Europe, 1991-93; and
7. Studies at ANL, BNL and LANL, 1992-93.



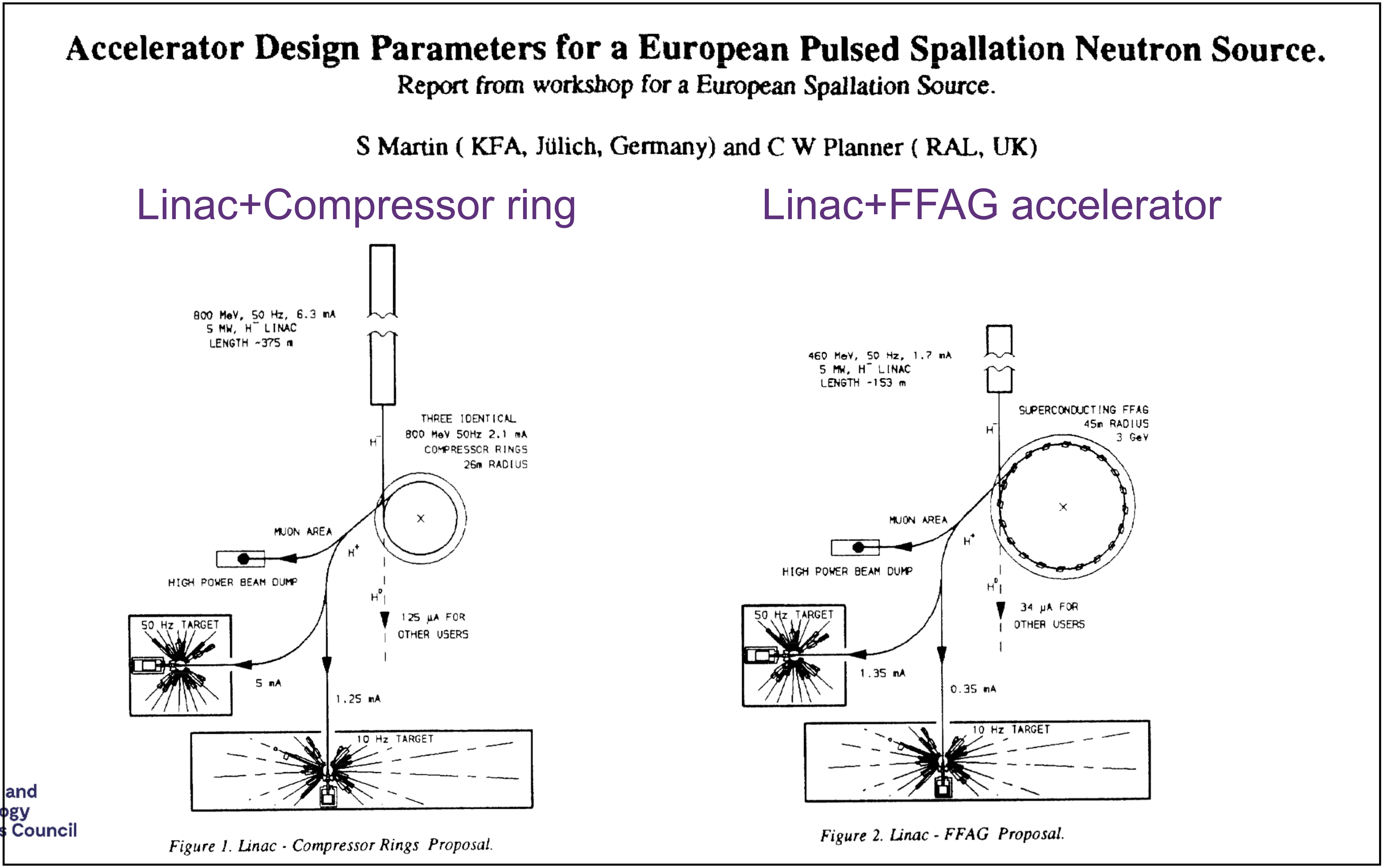
The most challenging option is the FFAG. Initial studies at KFA and HMI have shown that a 0.46 to 3.2 GeV, wide aperture, superconducting magnet FFAG is overexpensive. This has led HMI to studies of a higher frequency, 1.6 GeV ring, using beam stacking at high energy to build up the beam current. An alternative has been suggested by ANL, with a 100 Hz low energy FFAG feeding 2 successive pulses for each 50 Hz cycle of a higher energy ring.

KFA: Nuclear Research Centre Juelich
HMI: Hahn Meitner Institute?

A bit of history

As a spallation neutron source

EPAC1992



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

Linac+FFAG accelerator

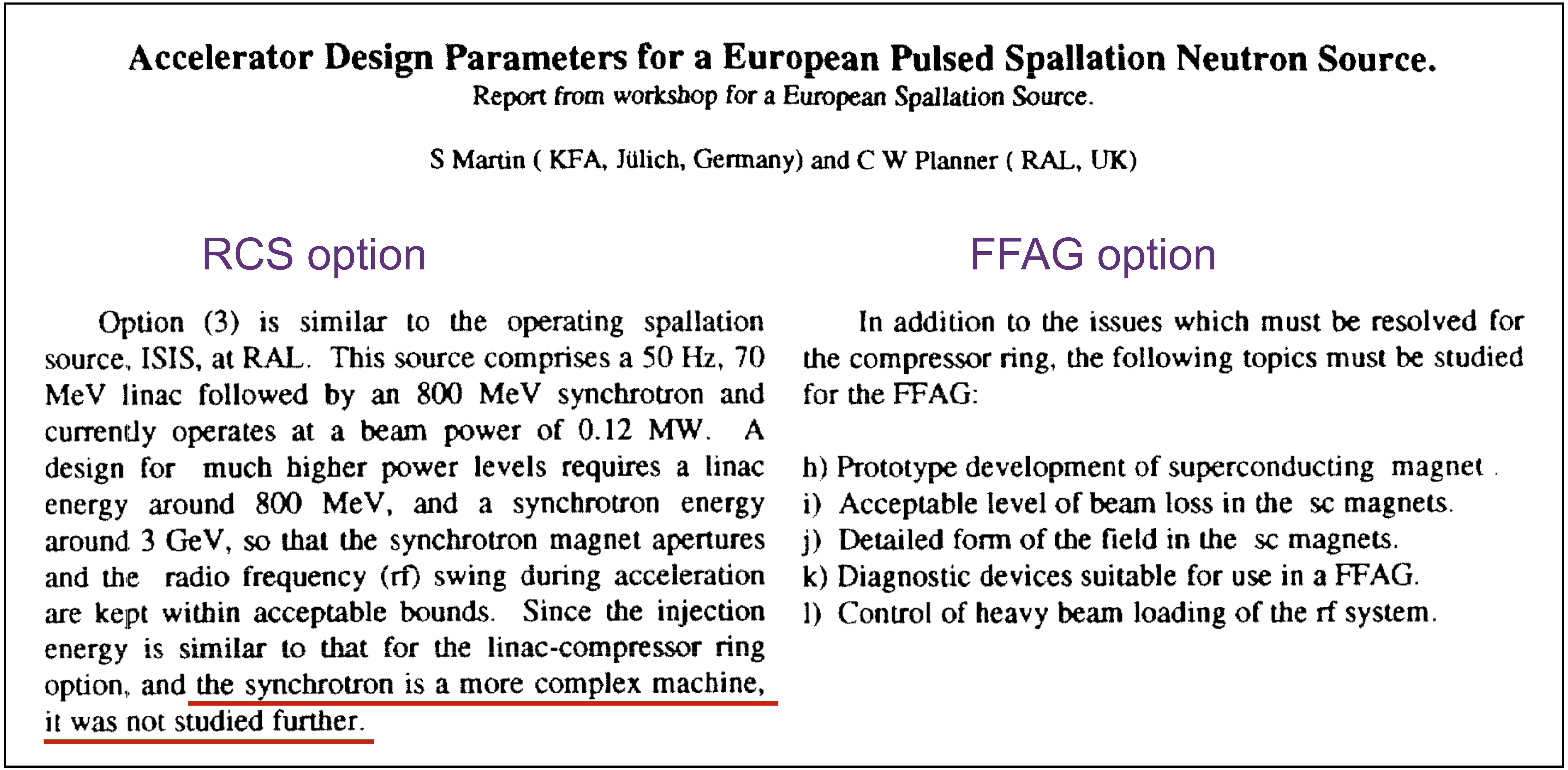
Figure 1. Linac - Compressor Rings Proposal.

Figure 2. Linac - FFAG Proposal.

A bit of history

As a spallation neutron source

EPAC1992



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)

RCS option

Option (3) is similar to the operating spallation source, ISIS, at RAL. This source comprises a 50 Hz, 70 MeV linac followed by an 800 MeV synchrotron and currently operates at a beam power of 0.12 MW. A design for much higher power levels requires a linac energy around 800 MeV, and a synchrotron energy around 3 GeV, so that the synchrotron magnet apertures and the radio frequency (rf) swing during acceleration are kept within acceptable bounds. Since the injection energy is similar to that for the linac-compressor ring option, and the synchrotron is a more complex machine, it was not studied further.

FFAG option

In addition to the issues which must be resolved for the compressor ring, the following topics must be studied for the FFAG:

h) Prototype development of superconducting magnet .
i) Acceptable level of beam loss in the sc magnets.
j) Detailed form of the field in the sc magnets.
k) Diagnostic devices suitable for use in a FFAG.
l) Control of heavy beam loading of the rf system.

Why FFA

High power by high repetition

- Continuous acceleration like a cyclotron is the best way to increase the average beam power (the number of accelerated particles per second).
- When synchrotron was invented, people had to accept the huge reduction of the beam power.

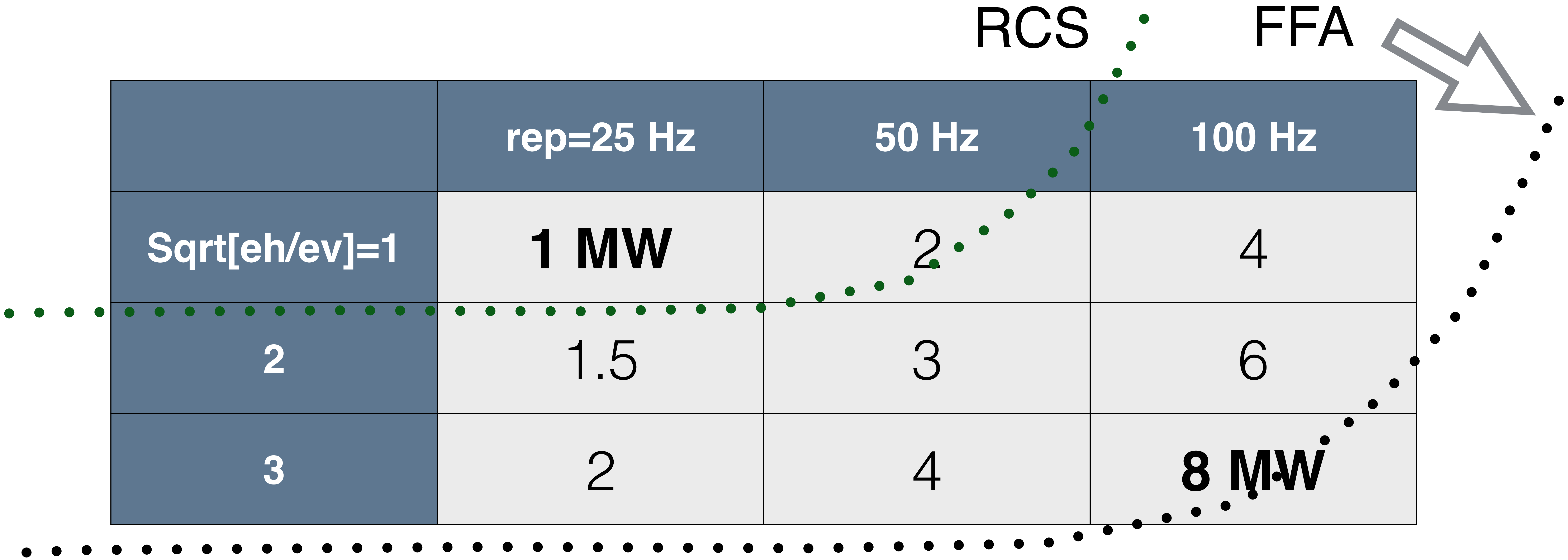
- Can we operate a synchrotron to deliver the DC beams?
  - It is against the principle of a synchrotron where the magnets are synchronised with the beam momentum.

- If the magnets do not have to synchronise with the beam momentum, the repetition of the acceleration cycle can increase.
  - DC magnet with the isochronous condition makes a cyclotron.
  - DC magnet with the zero chromaticity (or constant tune) condition makes a scaling FFA.

Why FFA

Wide horizontal aperture

- Orbit moves horizontally like a cyclotron. Horizontal aperture has to be large, 0.1 ~ 1.0 m.
- Increase horizontal emittance to reduce space charge effects.



	rep=25 Hz	50 Hz	100 Hz
Sqrt[eh/ev]=1	**1 MW**	2	4
2	1.5	3	6
3	2	4	**8 MW**

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

FFA can push the power up to ~10 MW.

Why FFA

RCS vs FFA

Increase injection energy further increase the beam power.

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

Gain a factor of 3 by increasing from 400 MeV to 800 MeV.

	rep=25 Hz	50 Hz	100 Hz
Sqrt[eh/ev]=1	**3 MW**	6	12
2	4.5	9	18
3	6	12	**24 MW**

Whether we can keep the asymmetry emittance of the high intensity beam is an interesting remaining question!

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Why FFA

Other advantage with DC magnets

- Energy efficient. Wall power is less to produce the same magnetic field compared with AC magnets for RCS.
- Superconducting and permanent magnet design can be made.

- Reliability increases.

- Flexible (bespoke) operation is possible (come back later).

“Sustainable” option!

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A bit of history

Why it did not go further?

Demonstrator

Magnet R&D

FFAG'14 International Workshop on FFAG Accelerators
September 22 – 27, 2014
Brookhaven National Laboratory, New York
(September 23, Tuesday)

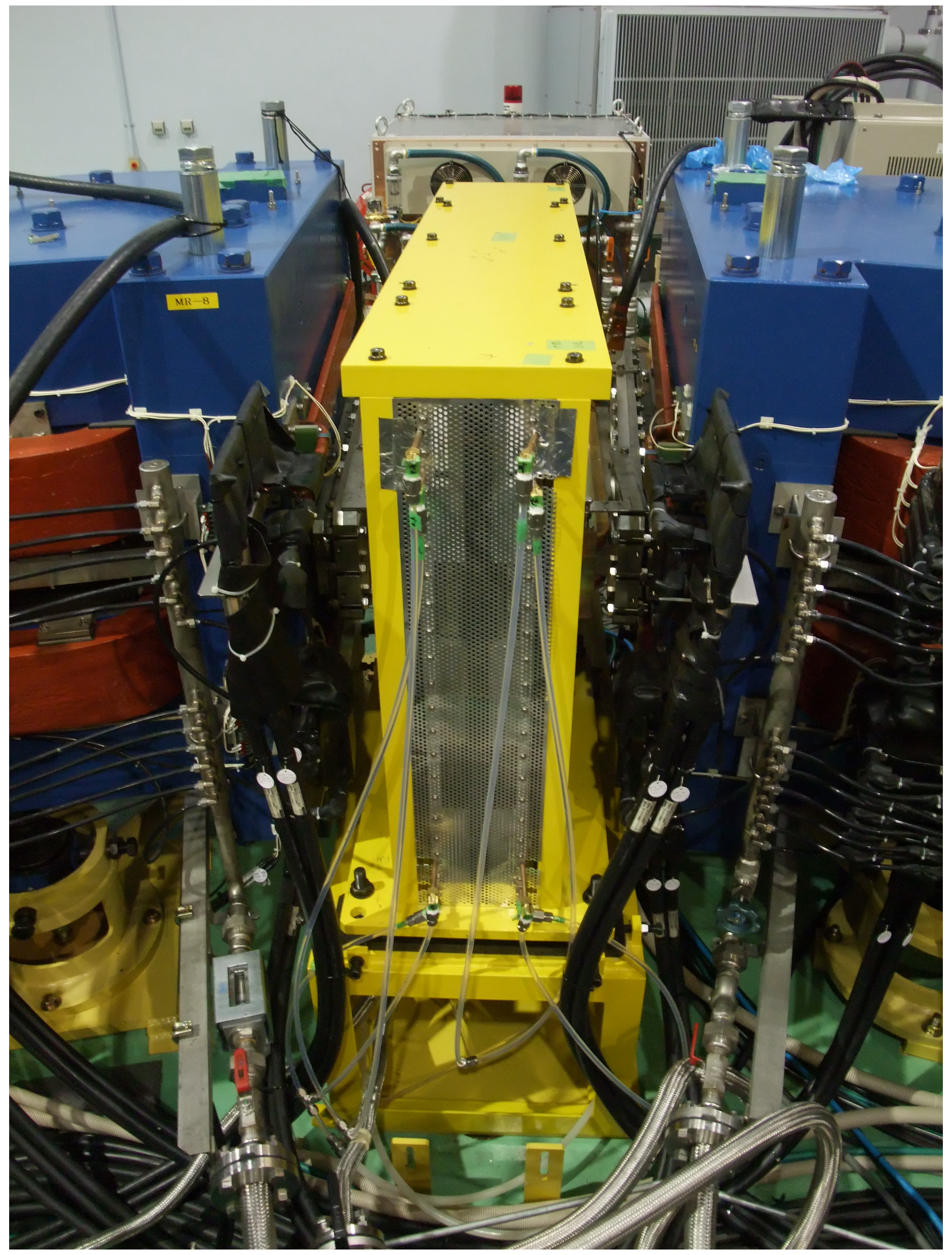
High Temperature Superconductor
Magnet for FFAG Accelerators

N. Amemiya (Kyoto University), T. Ogitsu (KEK)
K. Koyanagi, T. Kurusu (Toshiba)
Y. Mori (Kyoto University)
Y. Iwata, K. Noda (NIRS), M. Yoshimoto (JAEA)

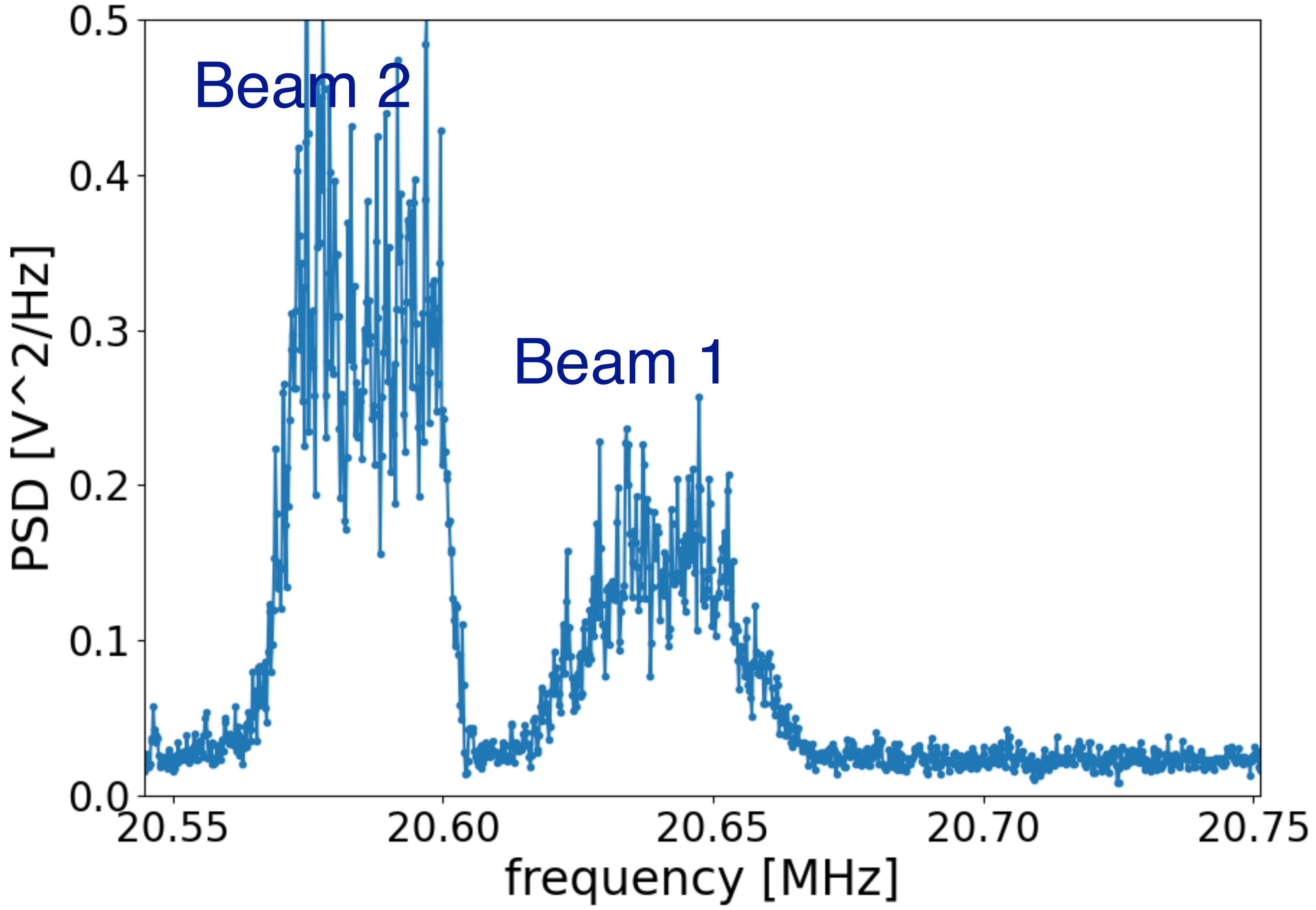
amemiya.naoyuki.6a@Kyoto-u.ac.jp

This work was supported by Japan Science and Technology Agency under Strategic Promotion of Innovative Research and Development Program (S-Innovation Program).

MA RF cavity



Beam stacking



Simply, it was not ready yet.
(Nothing here existed before.)

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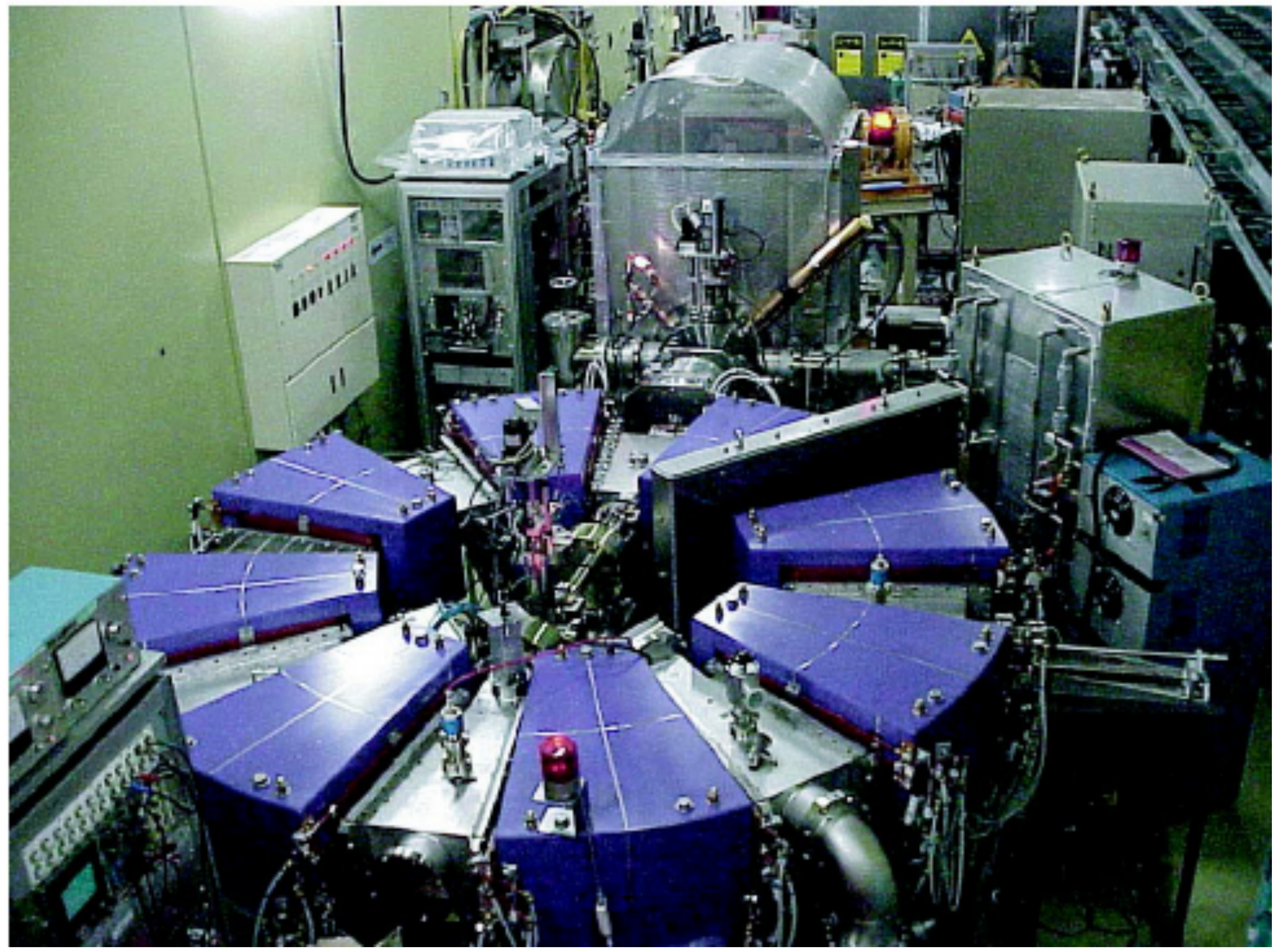
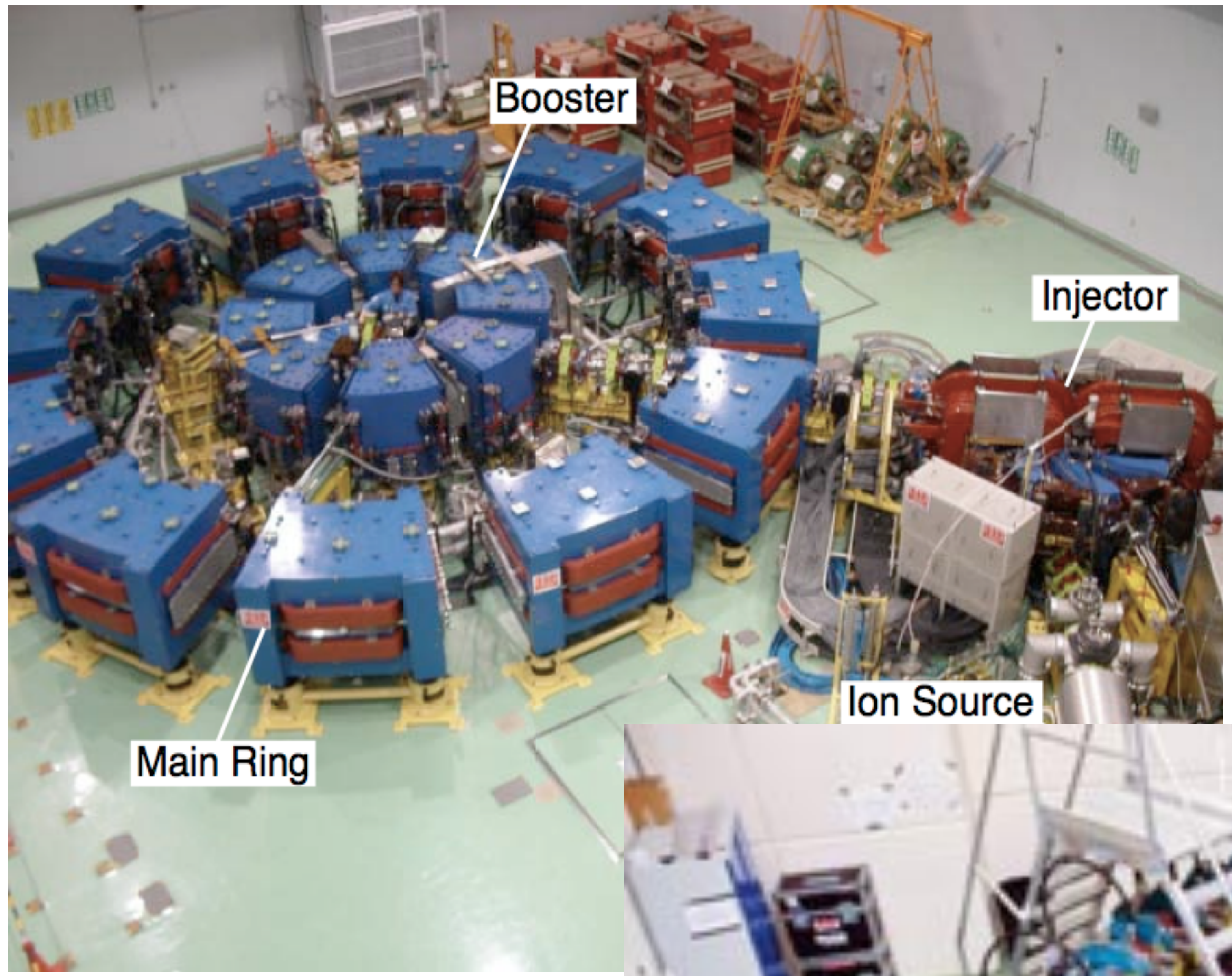
Progress of the last 20 and more years

Rebirth of an FFA

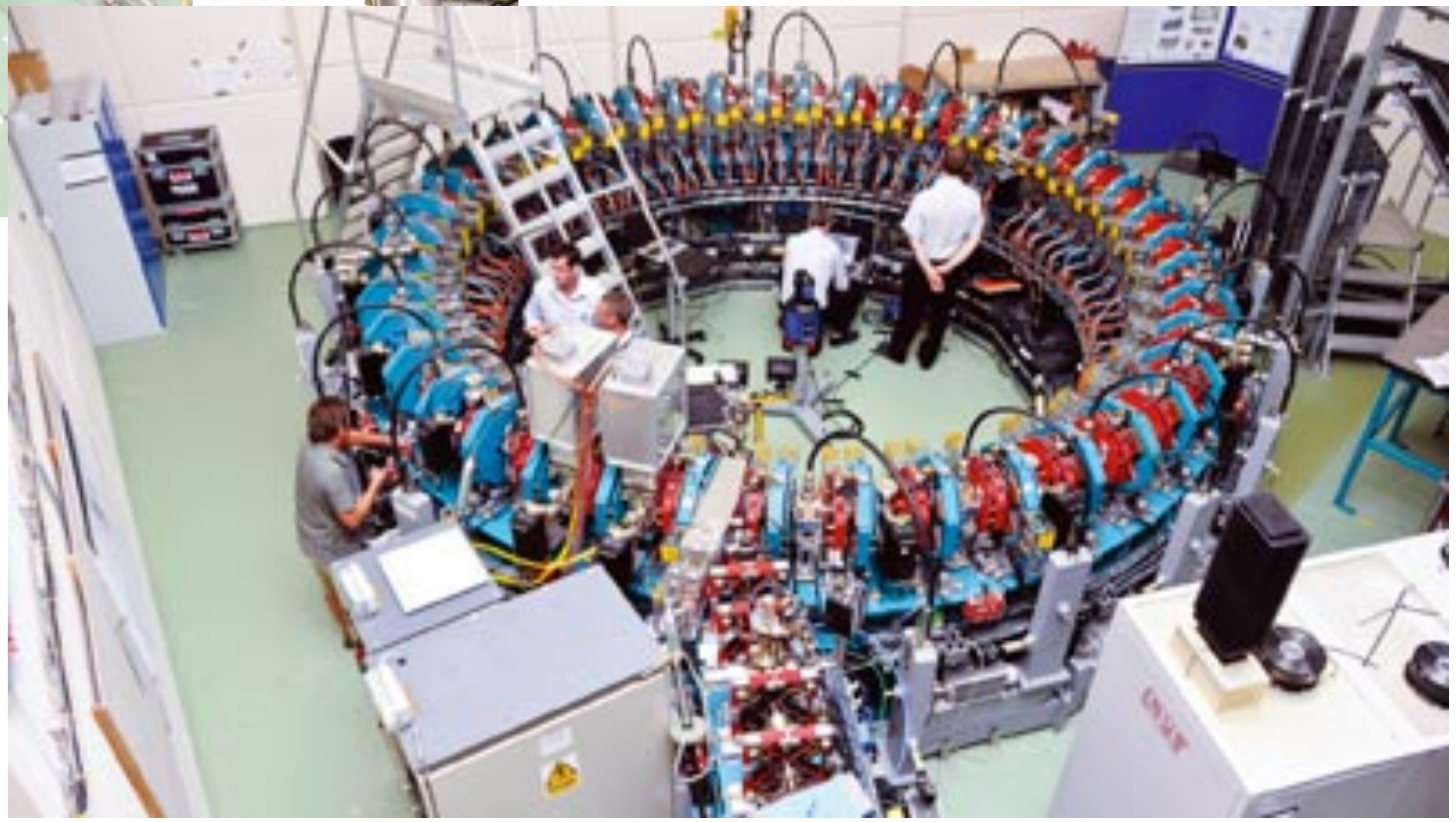
- Repetition of 1 kHz operation at KEK.
- Acc from 50 to 500 keV of protons.



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



- Nonscaling FFA.
- Serpentine channel acceleration.



High beam power operation is still not demonstrated yet.

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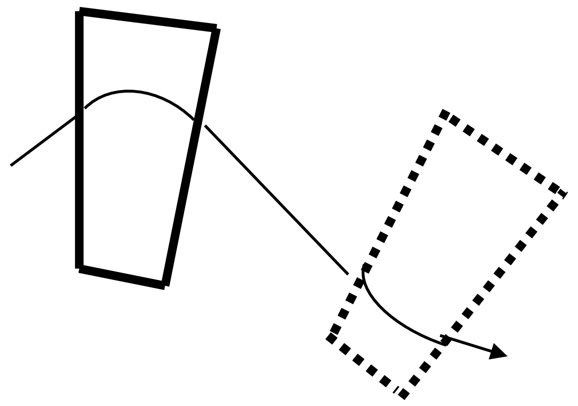
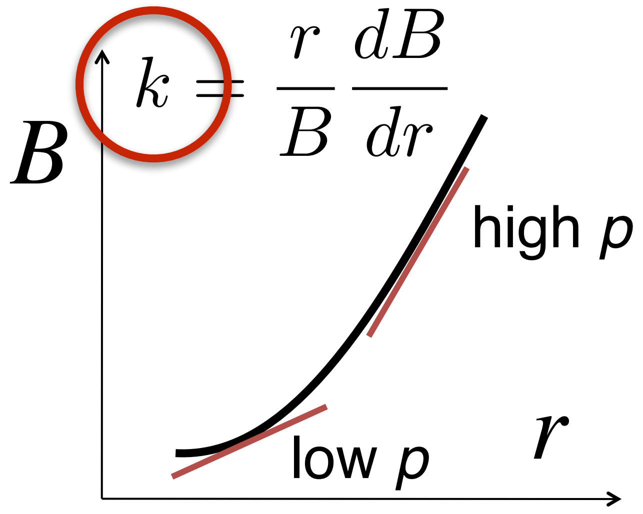
Progress of the last 20 and more years

DF(FD) spiral optics

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

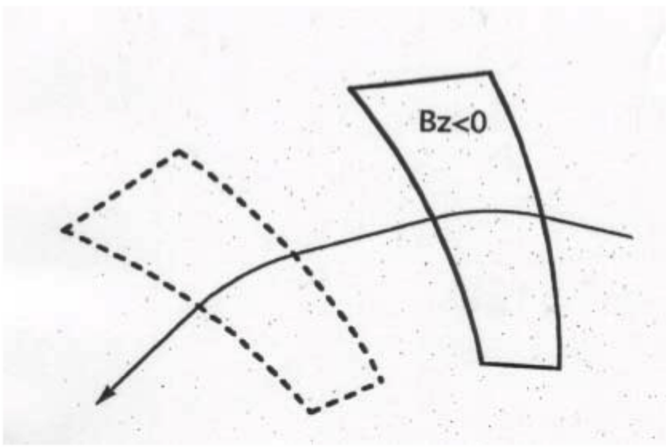
radial sector





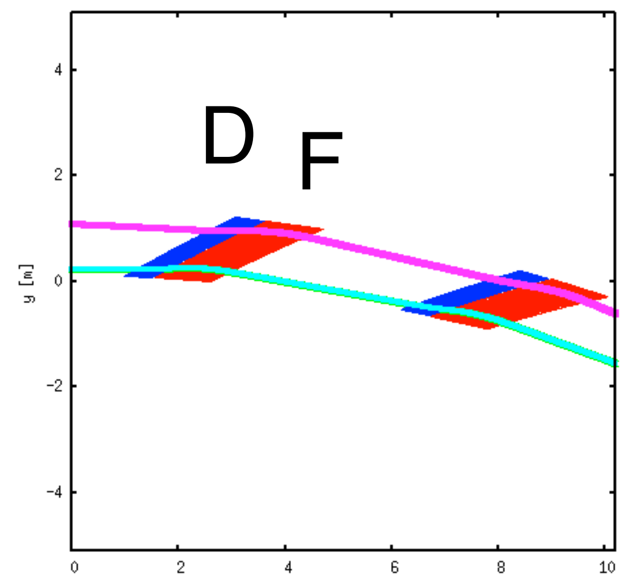
$$k = \frac{r}{B}\frac{dB}{dr}$$

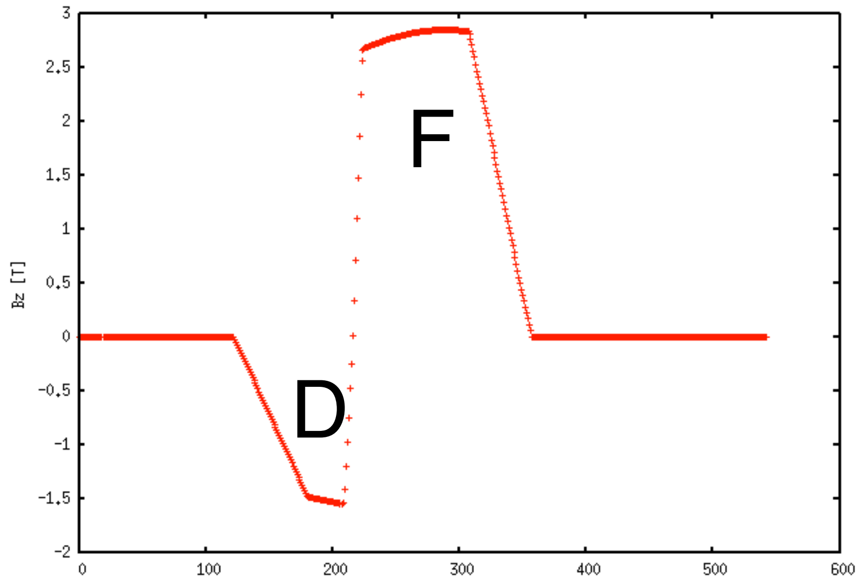
spiral sector

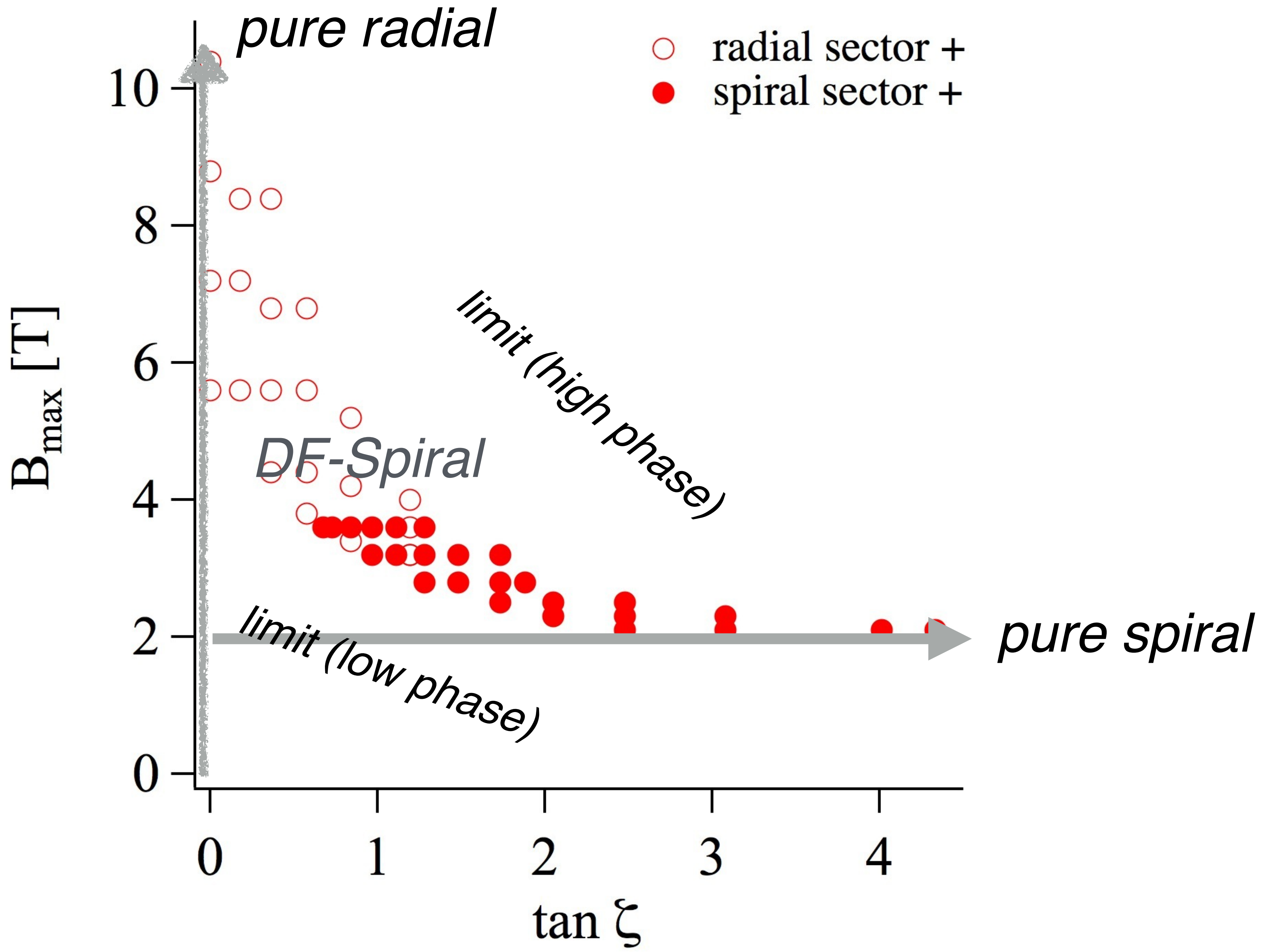


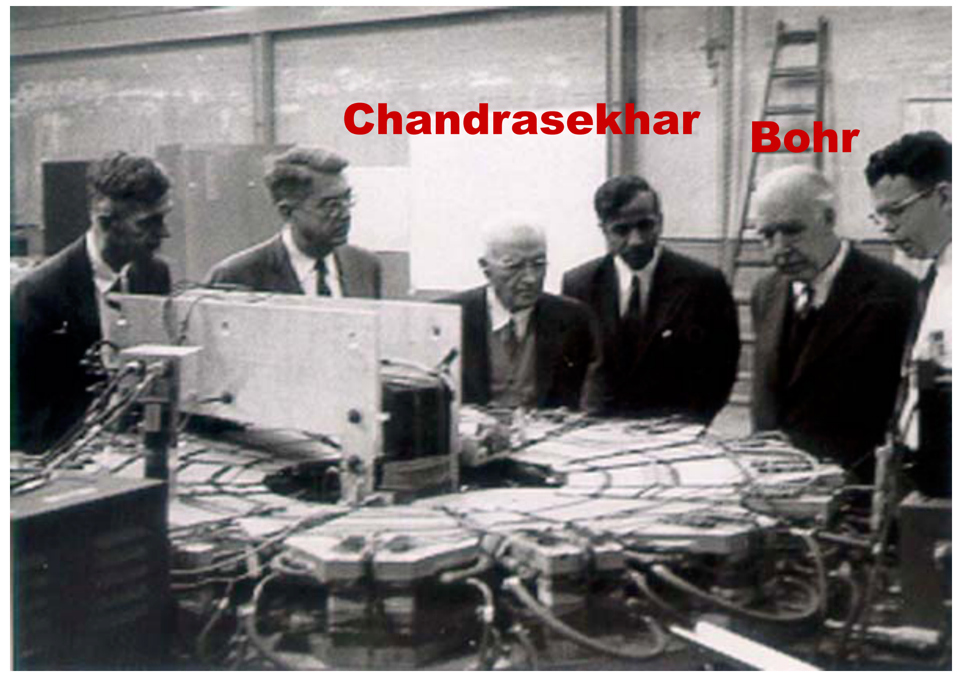
Alternating gradient focusing by focusing (normal bend) and defocusing (reserve bend)

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

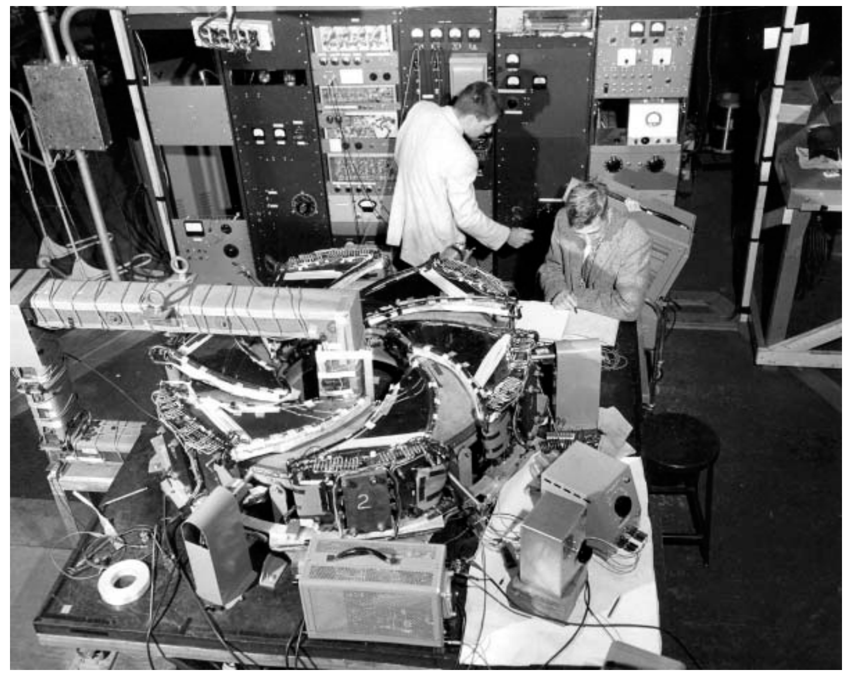








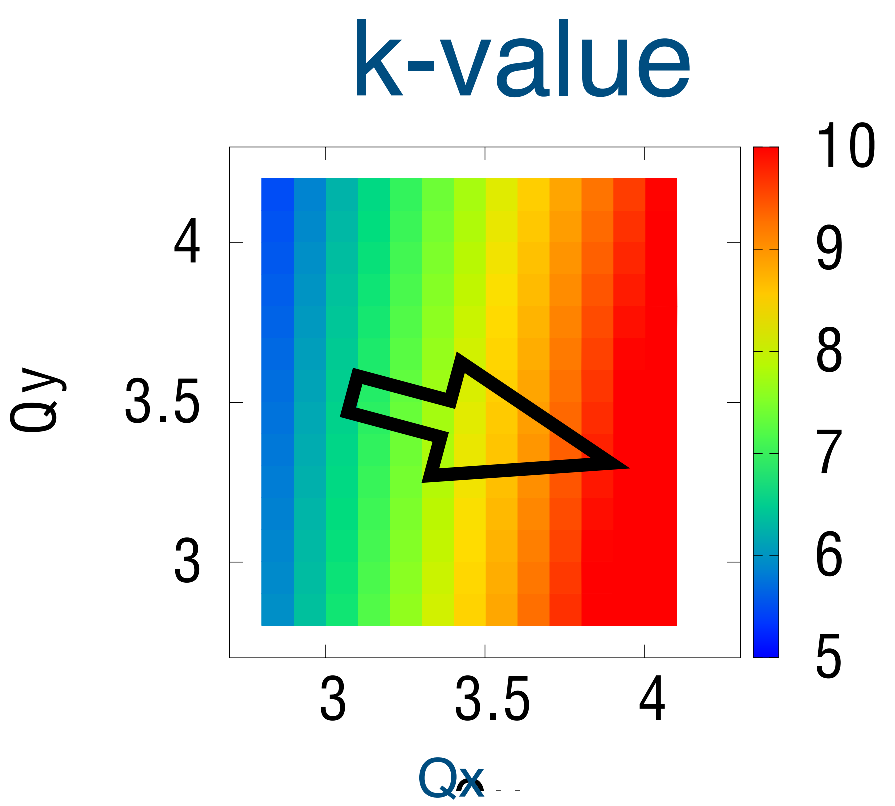
400 keV radial sector

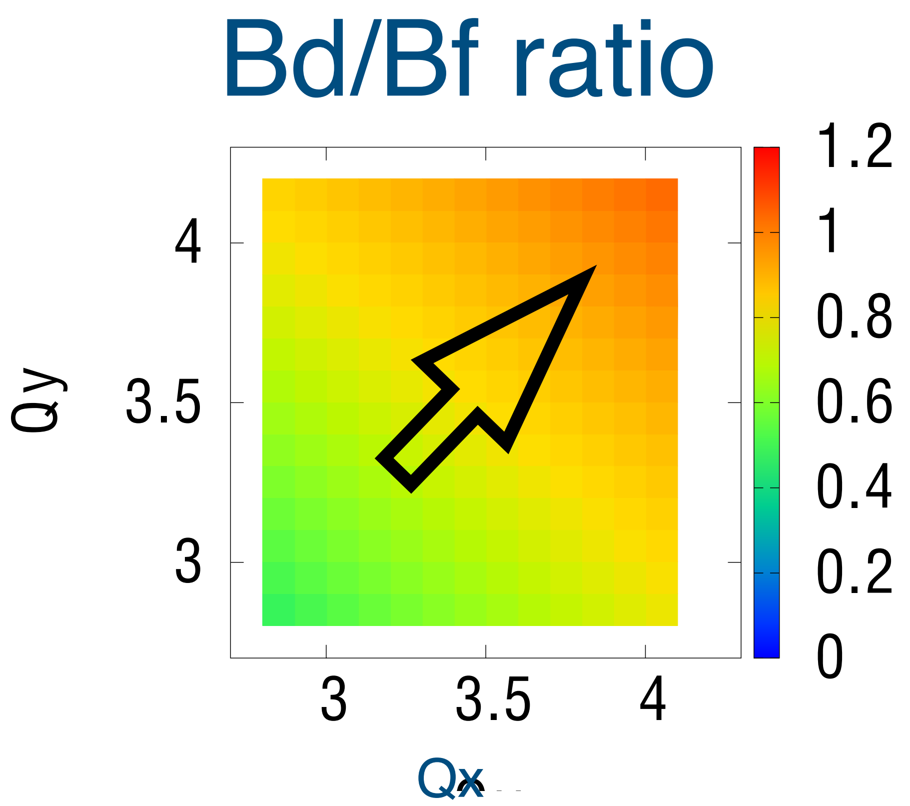


180 keV spiral sector

Progress of the last 20 and more years

Adjusting operating point

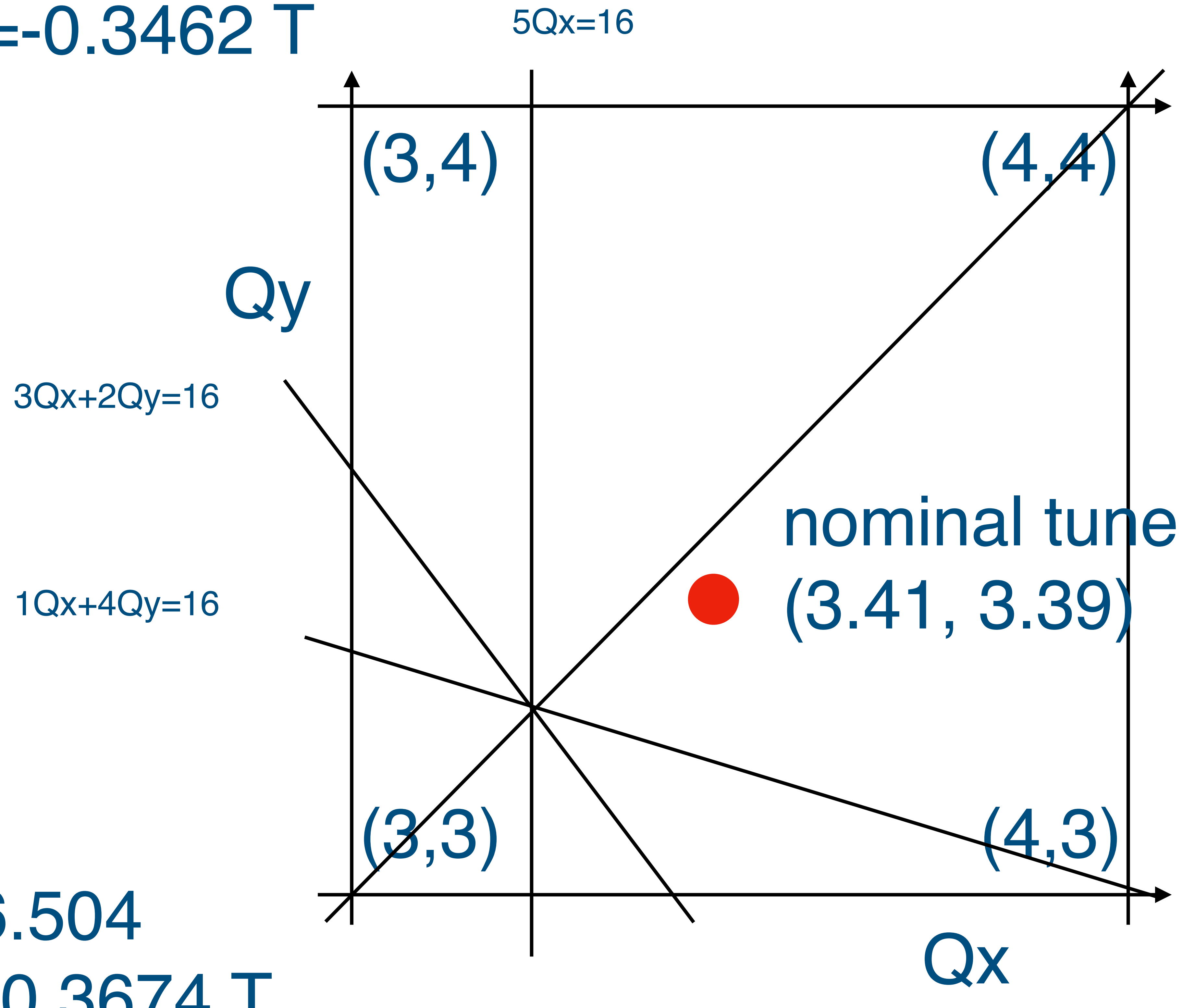




k-value and Bd/Bf strength ratio are two parameters to adjust tune Qx and Qy.

k=6.102
Bf=0.4231 T
Bd=-0.3462 T

k=9.891
Bf=0.4153 T
Bd=-0.4135 T



k=6.504
Bf=0.3674 T
Bd=-0.2080 T

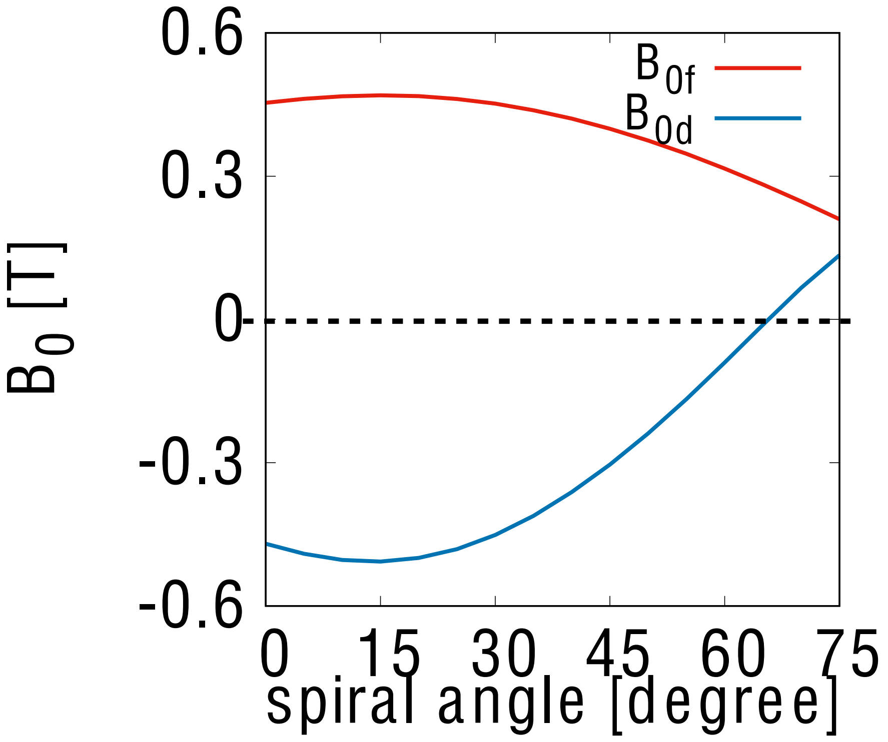
k=10.600
Bf=0.3717 T
Bd=-0.2937 T

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

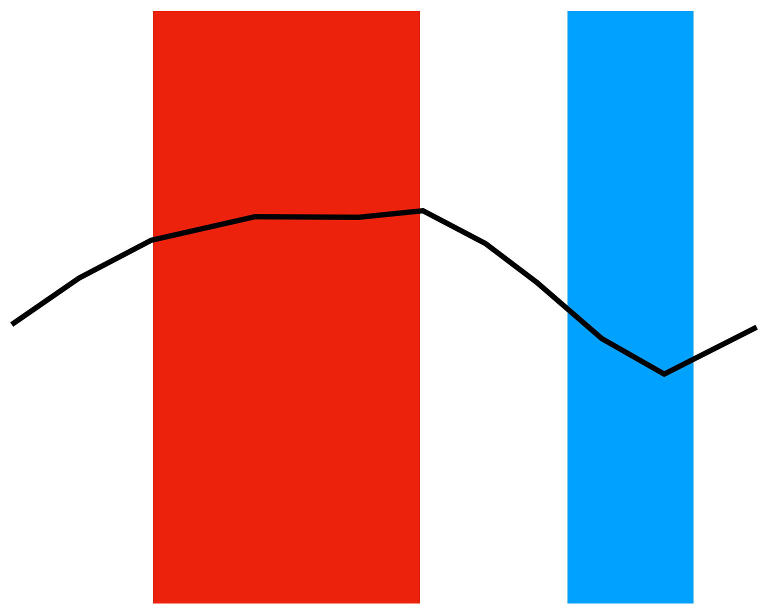
Progress of the last 20 and more years

cell tune is fixed at (0.213125, 0.213125)

Optics



radial sector

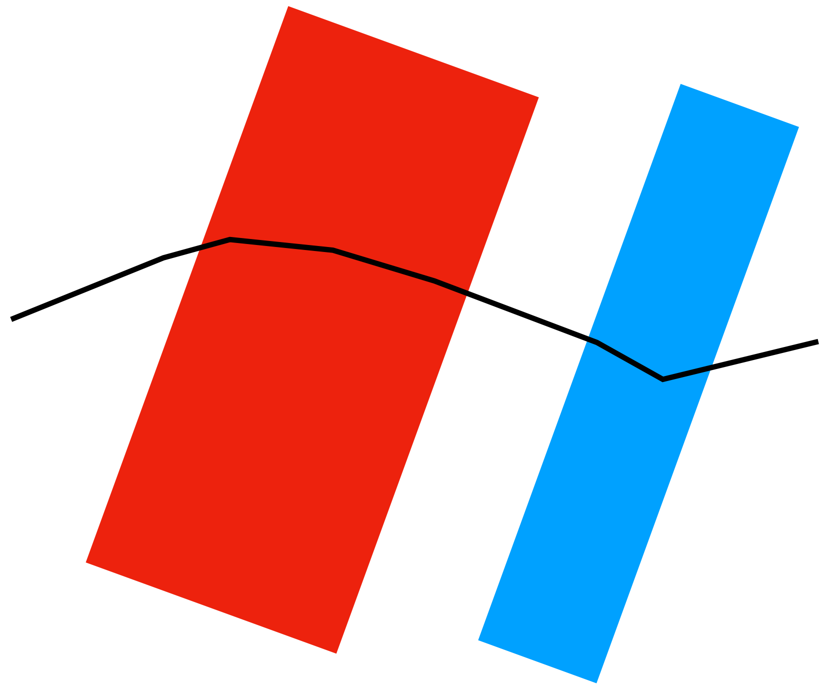


Bf Bd

(DFD) (DDD)

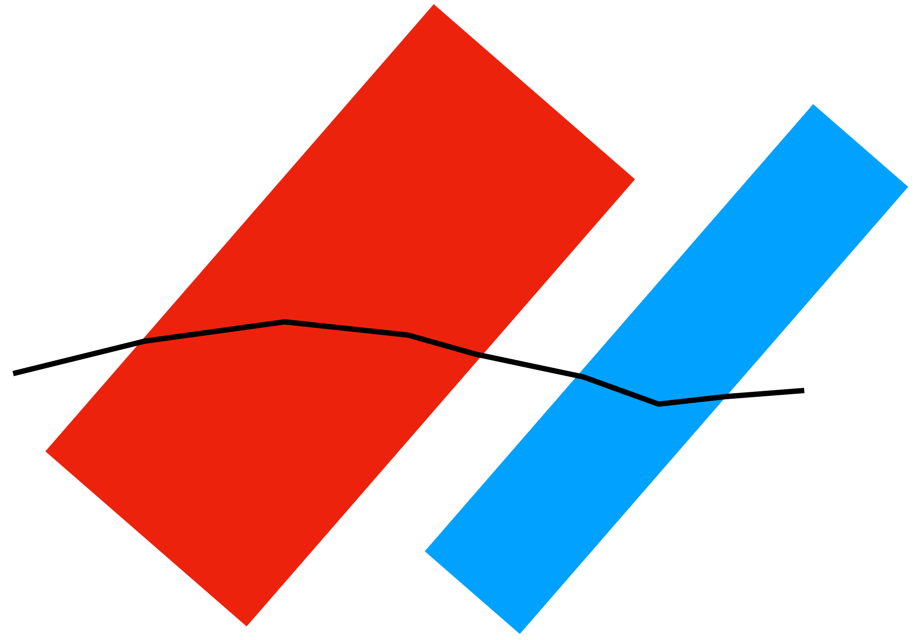
(entrance, body, exit)

FD spiral



Bf Bd

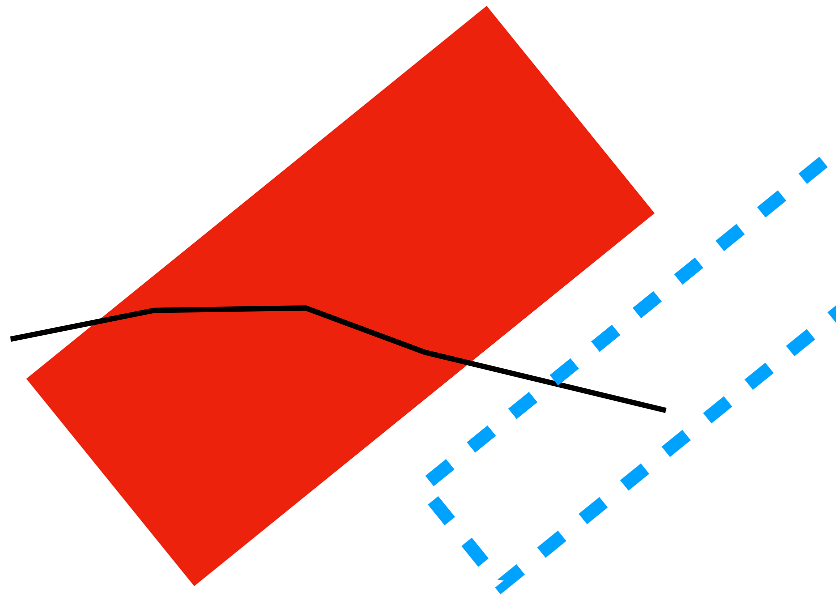
(DFO) (ODD)



Bf Bd

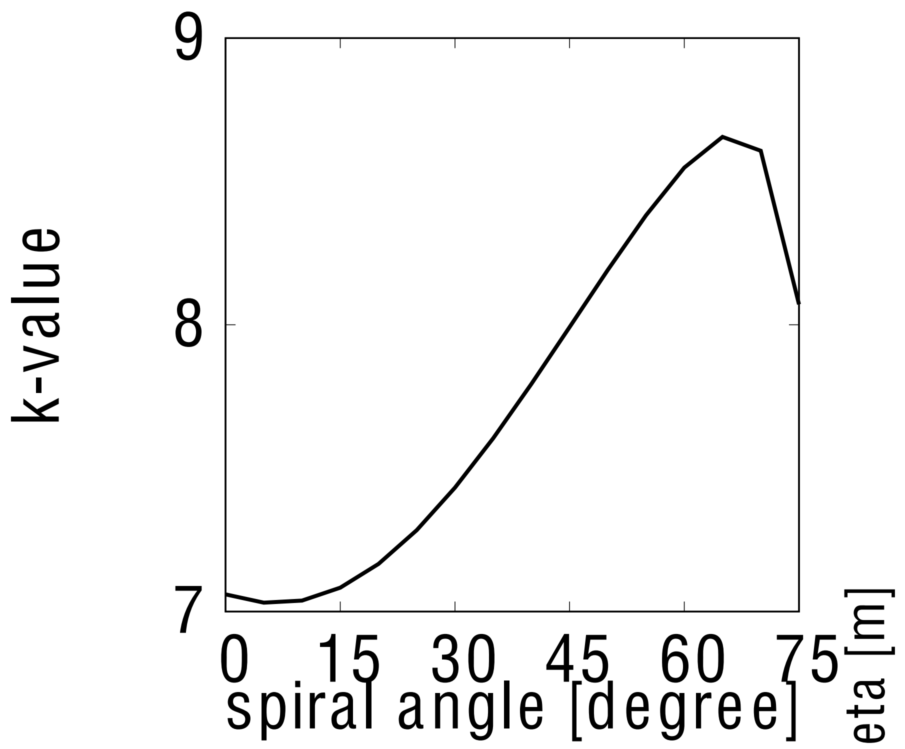
(DFF) (FDD)

spiral sector



Bf

(DFF)



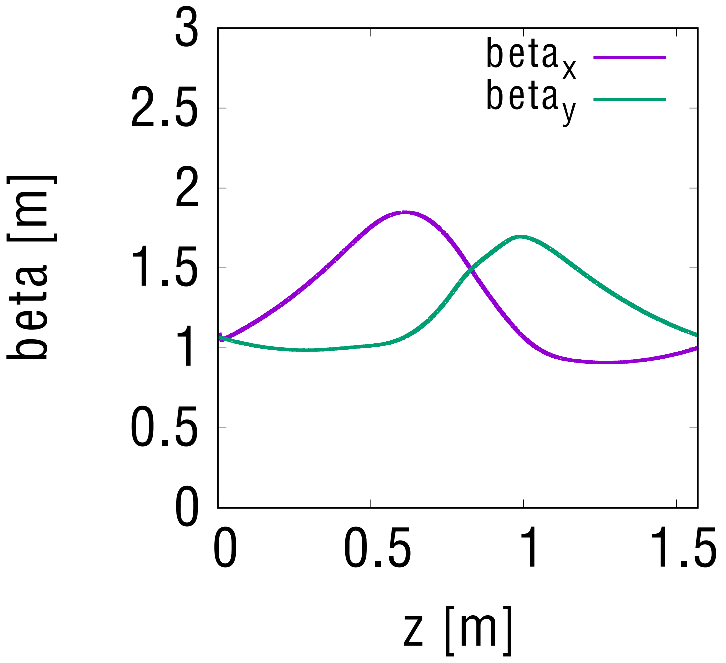
FD

DFD

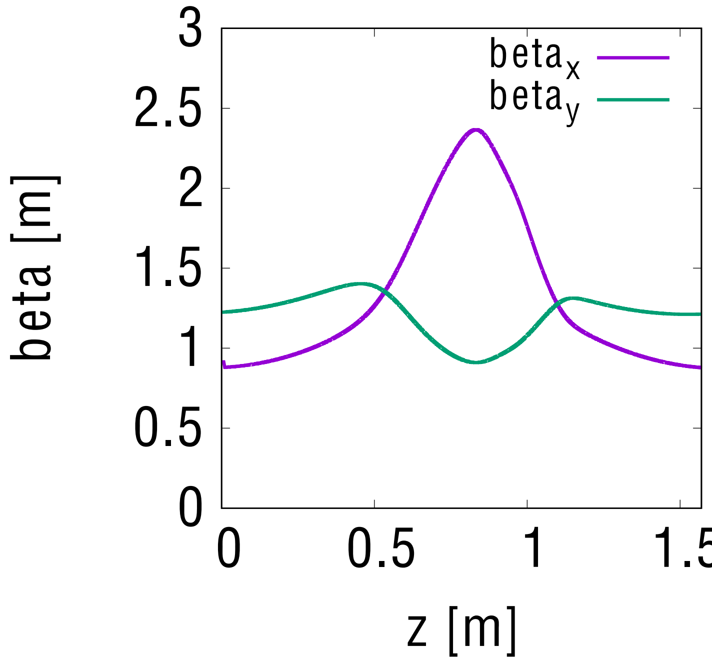
DFD

DF

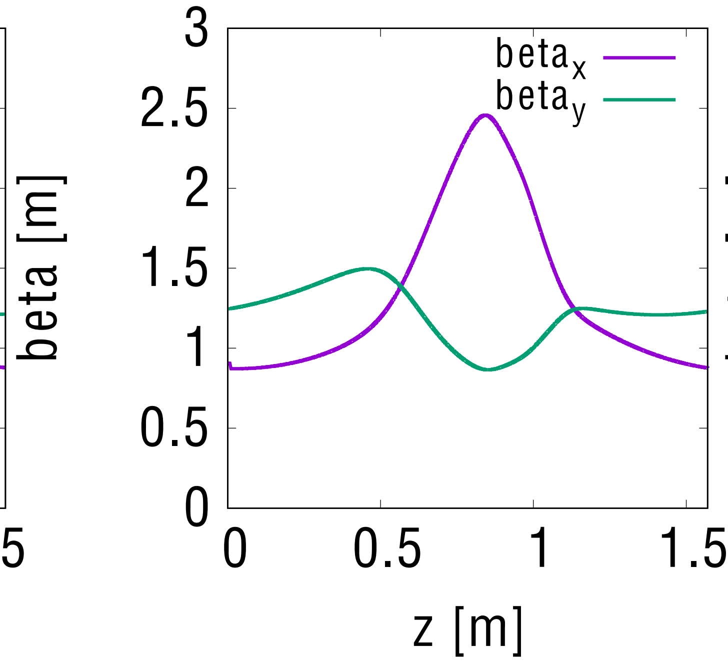
Spiral angle=0 deg



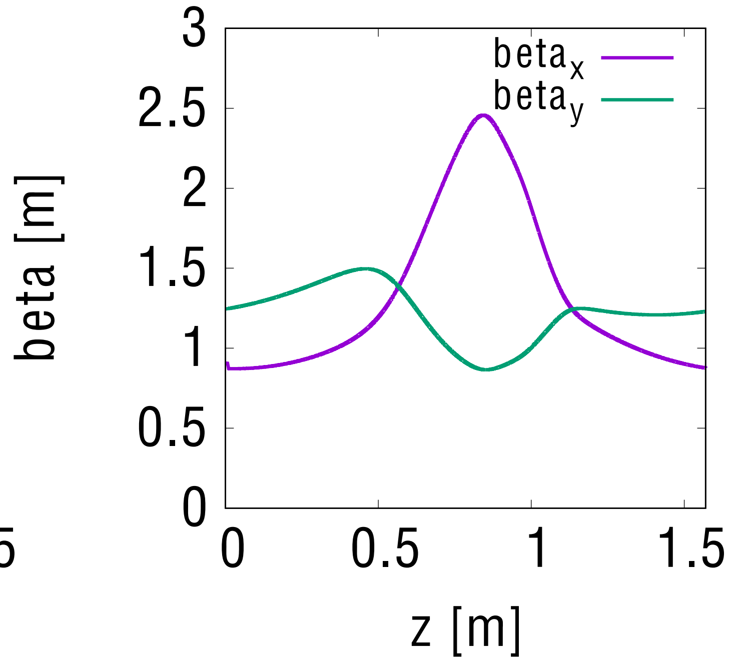
35 deg



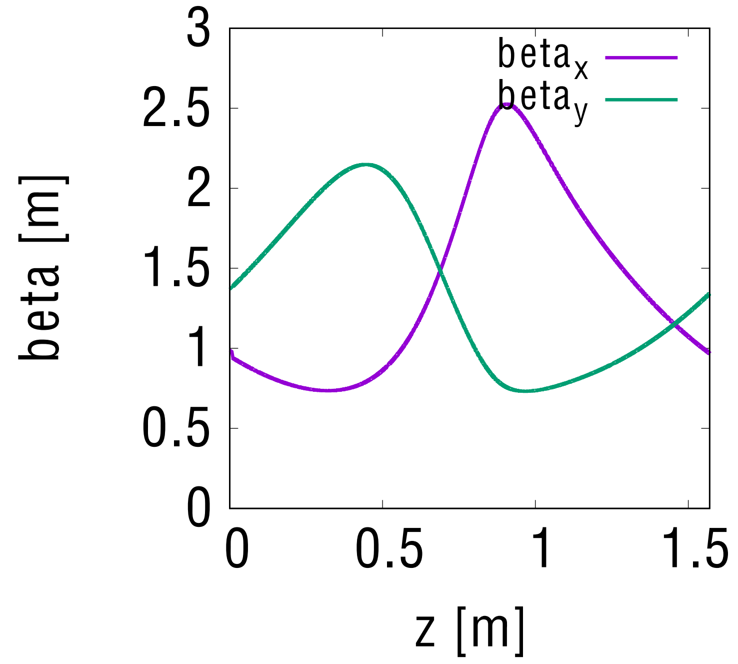
40 deg



45 deg



65 deg

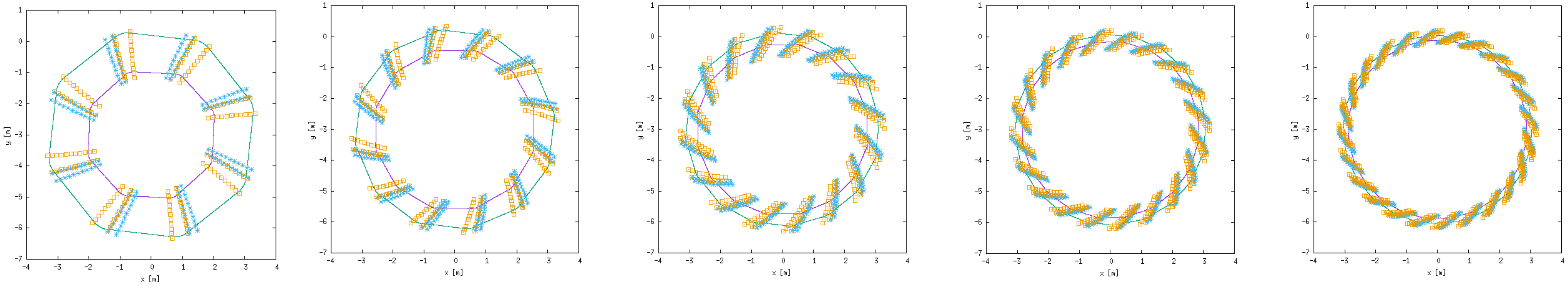


Optics looks like triplet, not doublet

Progress of the last 20 and more years

Orbit excursion vs number of cells

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



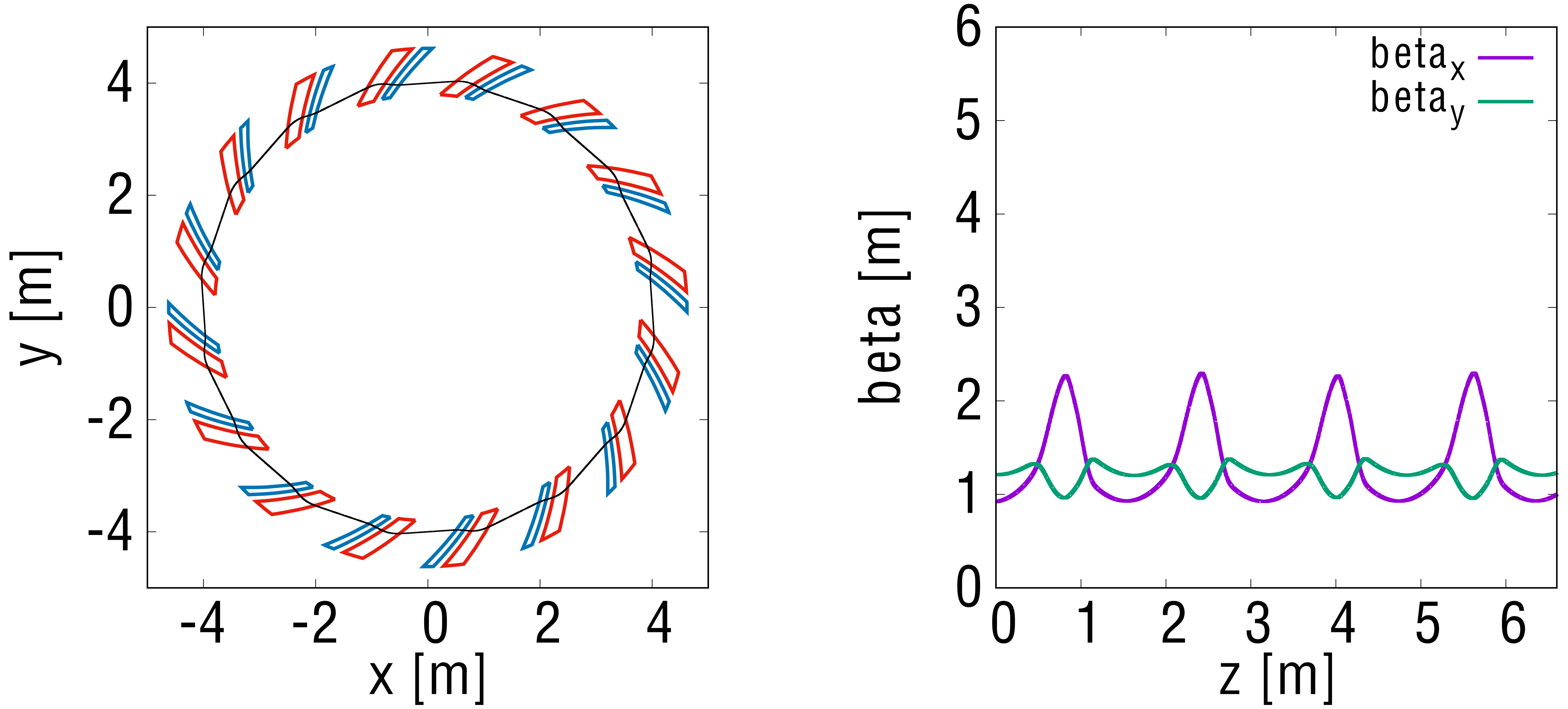
- Let us keep reasonable number of cells, but allocate straight sections unevenly.

Introduction of **superperiod**.

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

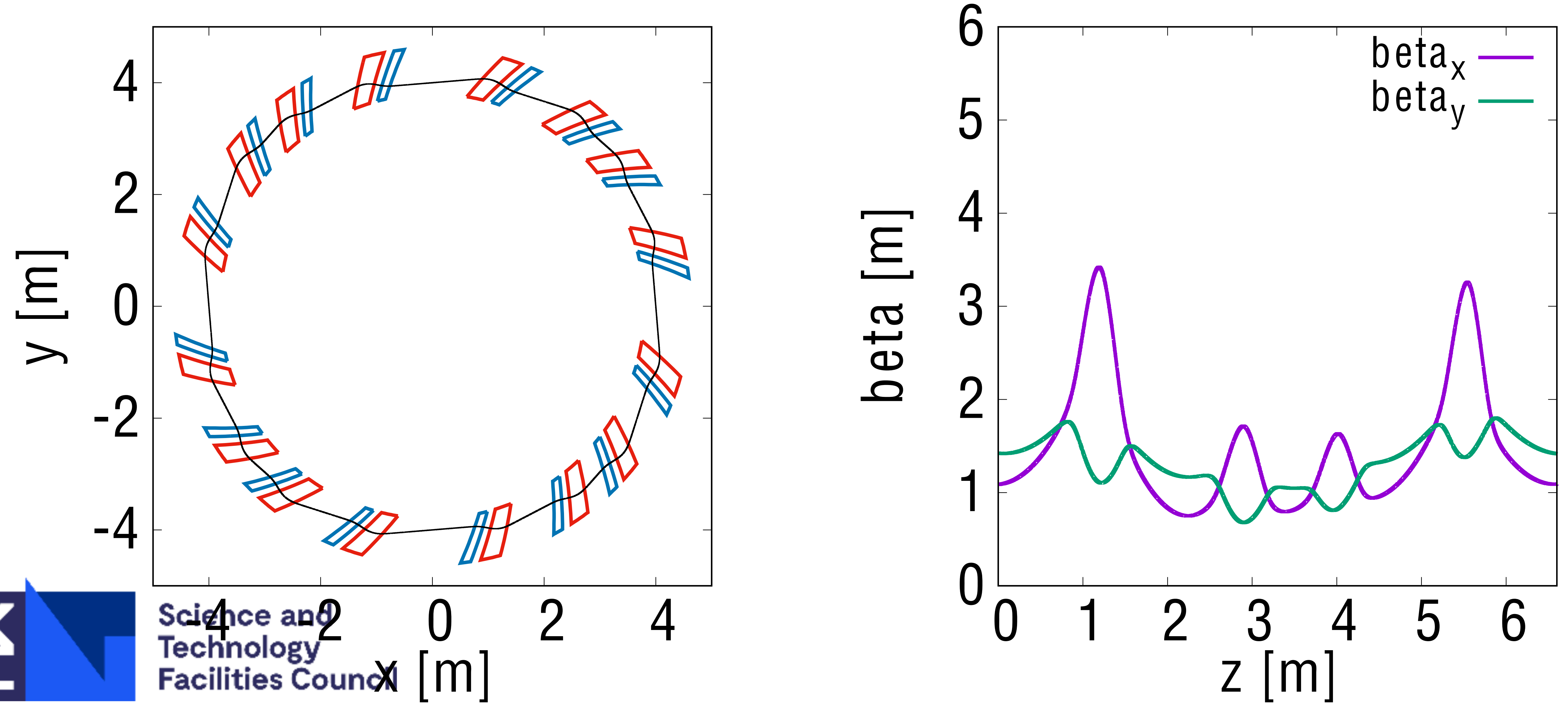
Progress of the last 20 and more years

Superperiod structure



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

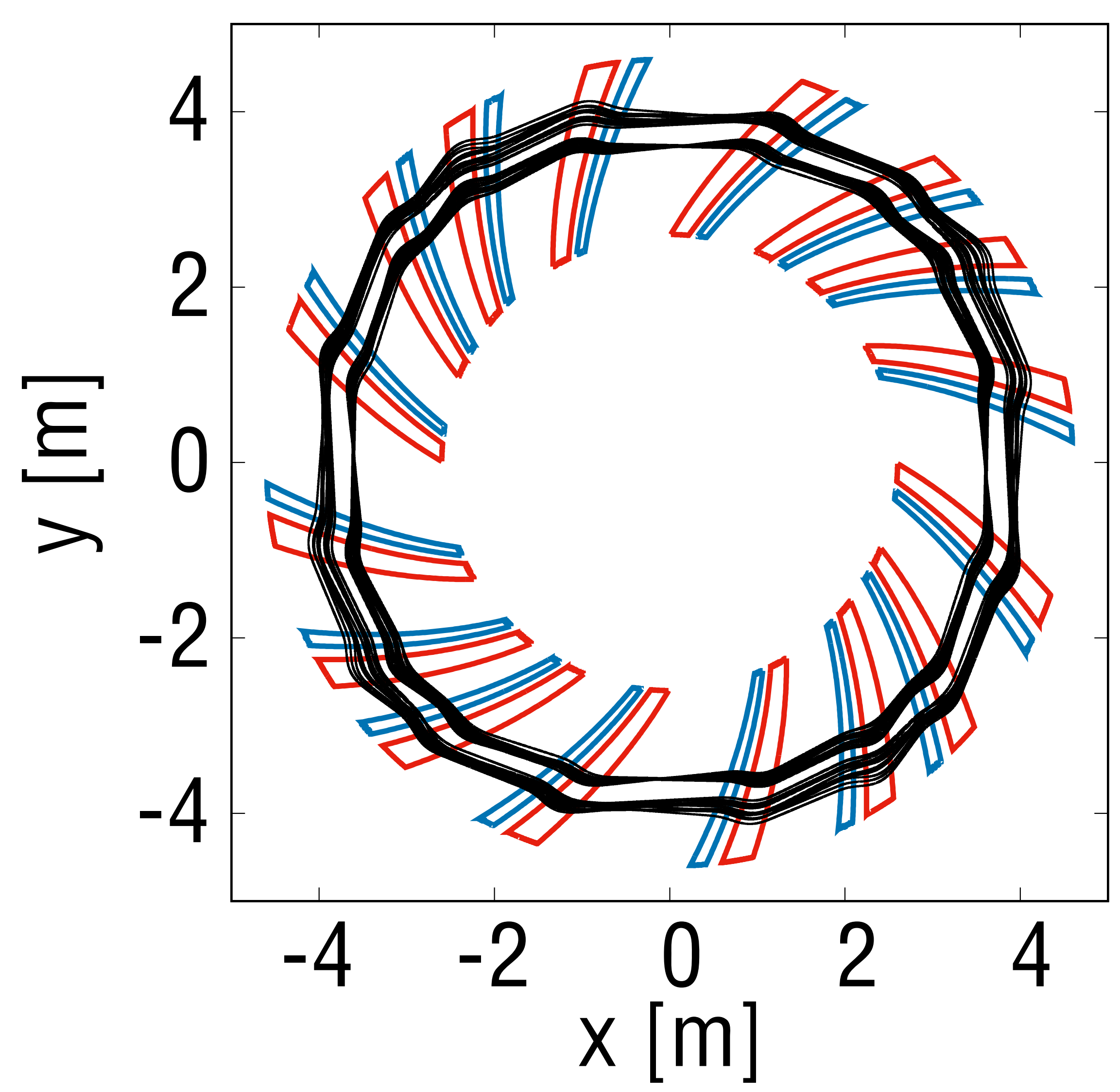
Horizontal beam size is larger.

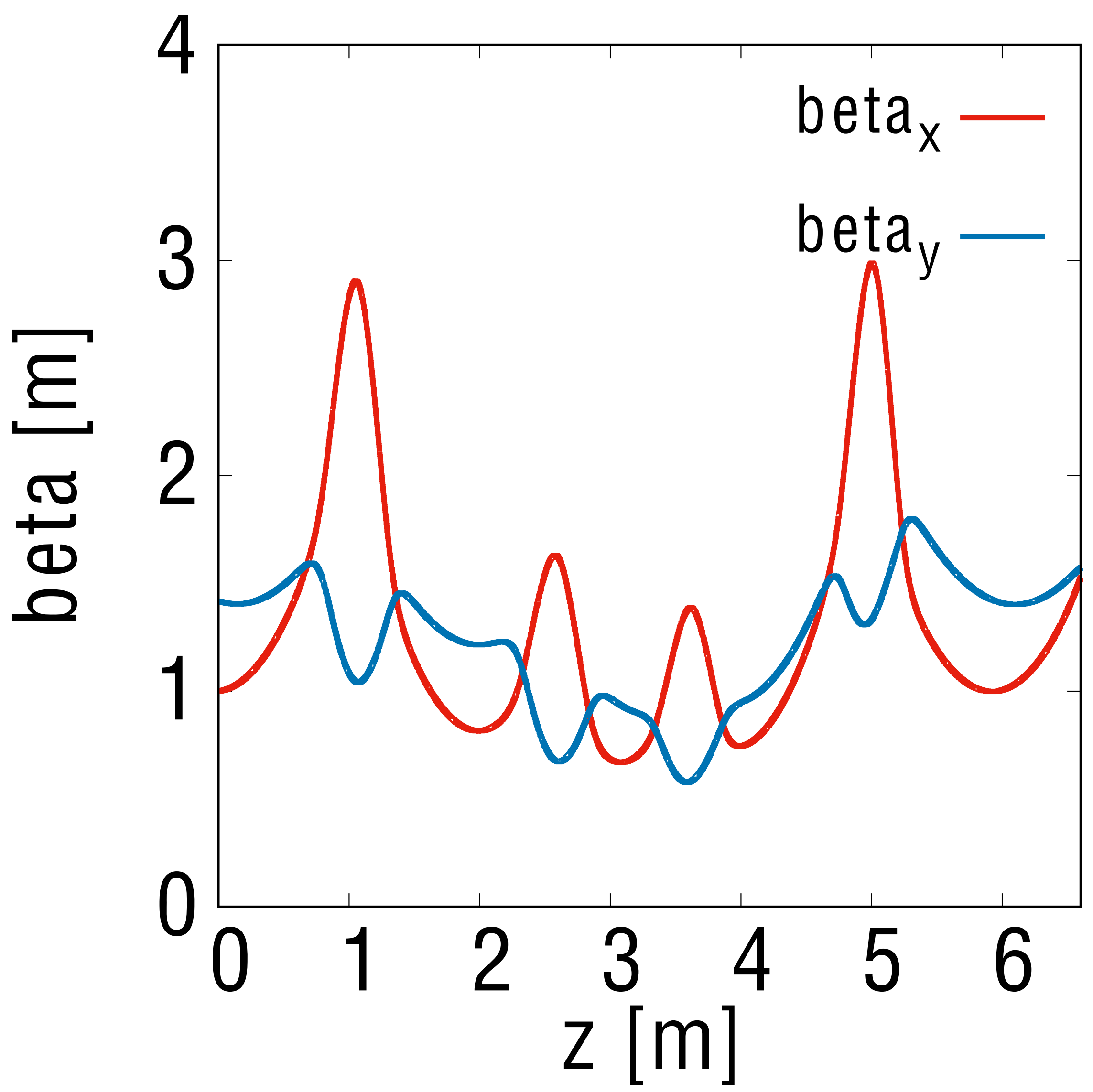
Progress of the last 20 and more years

FETS-FFA proposal at RAL

- 4-fold symmetry lattice with radius of 3.6 m

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





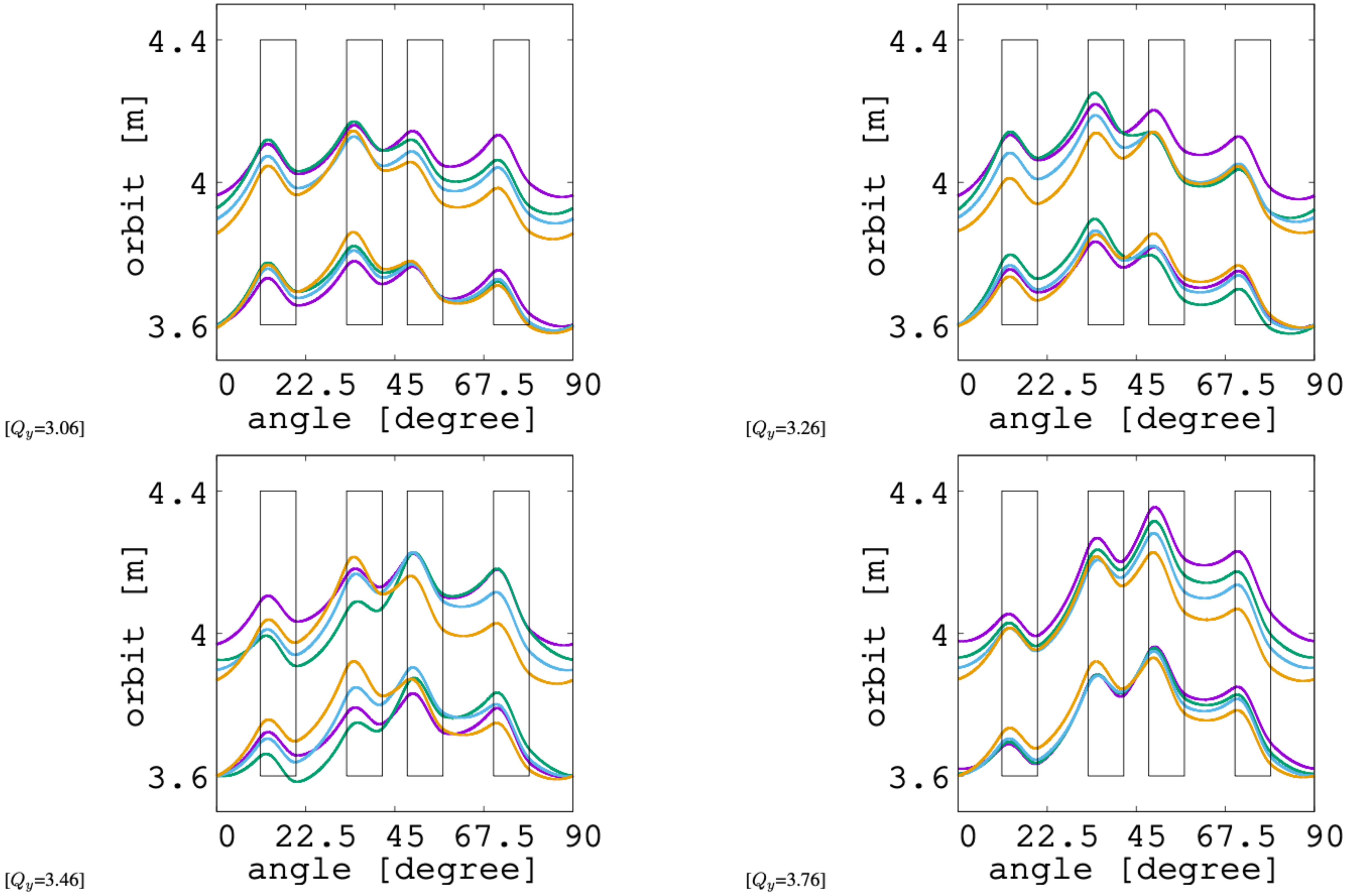


Figure 2.8: 3 MeV and 12 MeV orbits for 16 operating points.

Figures shows injection and extraction orbits which have the momentum ratio of two.

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First demonstrator of a high intensity FFA.

Progress of the last 20 and more years

Physical and dynamic aperture

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 - 80	500 - 1000	+/- (32 - 45) mm

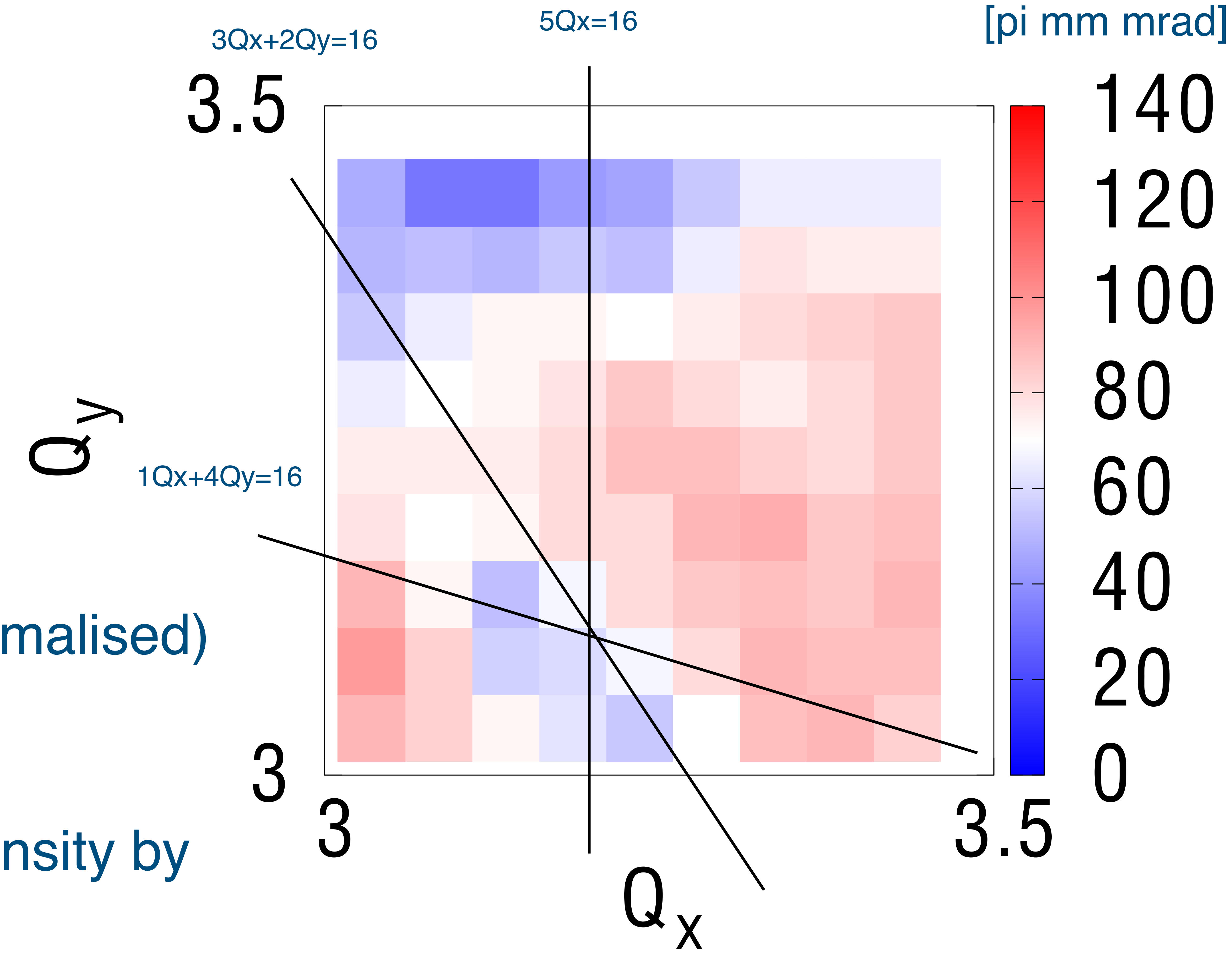
At 3 MeV, uniform beam of 10 pi mm mrad (100%, normalised)

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



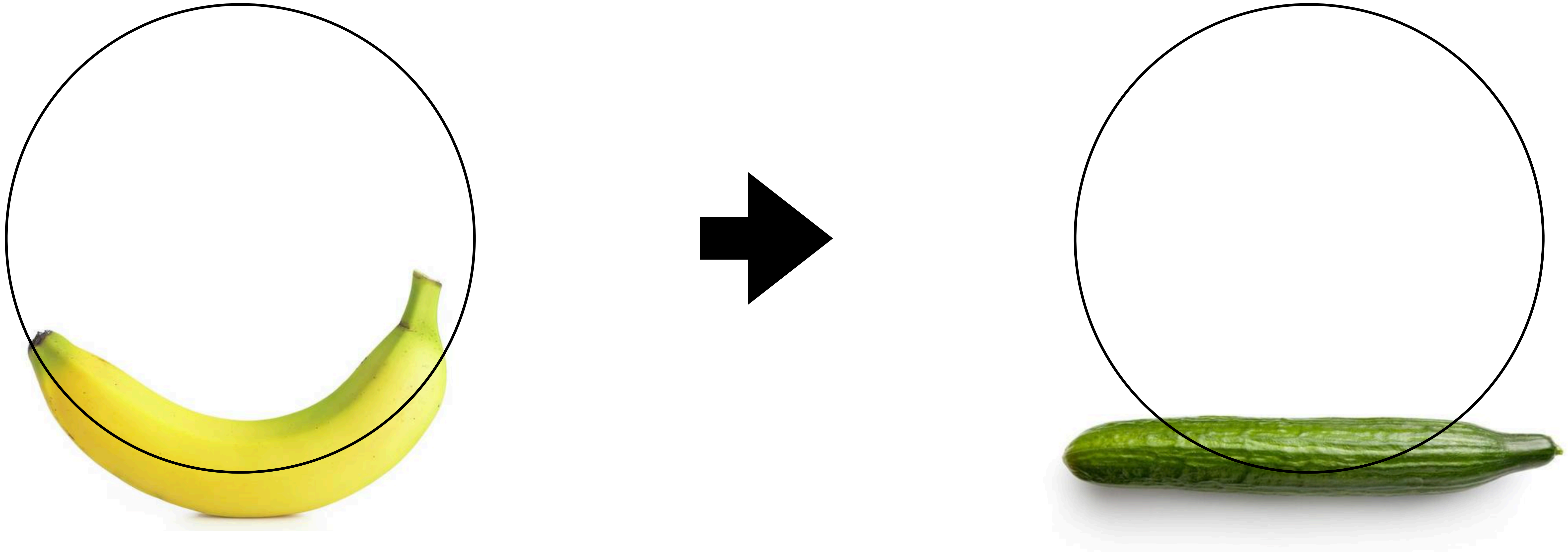
dynamic aperture at 3 MeV (normalised)
4-fold symmetric lattice

Some topics

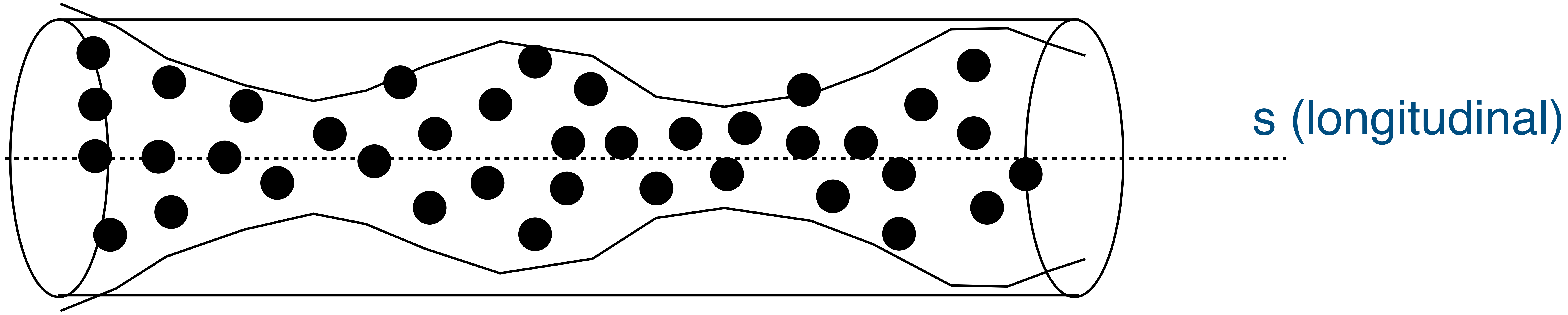
Modelling space charge effects in a FFA

- A FFA does not have a fixed closed orbit.
- The centre of space charge potential is determined by simulation particles, not by design orbit.

Let’s accept the approximation (ignoring bending)



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



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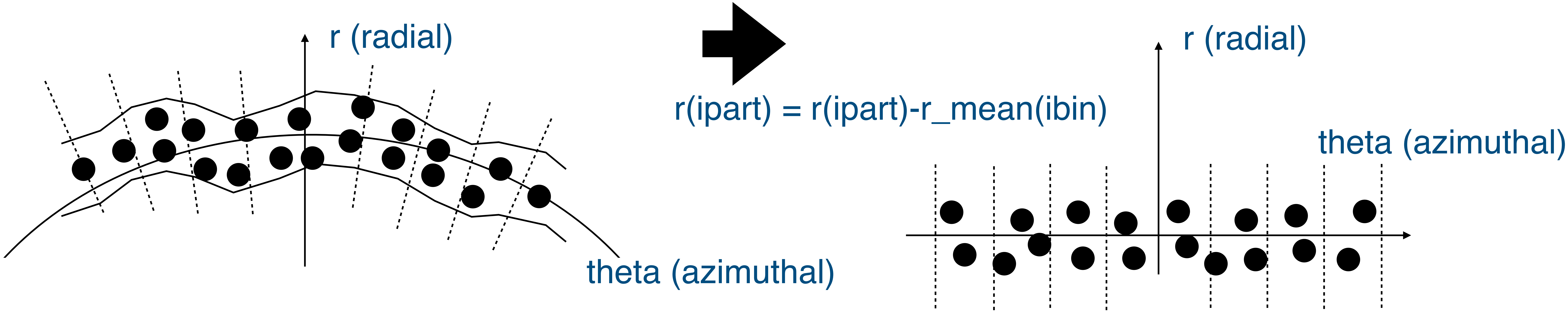
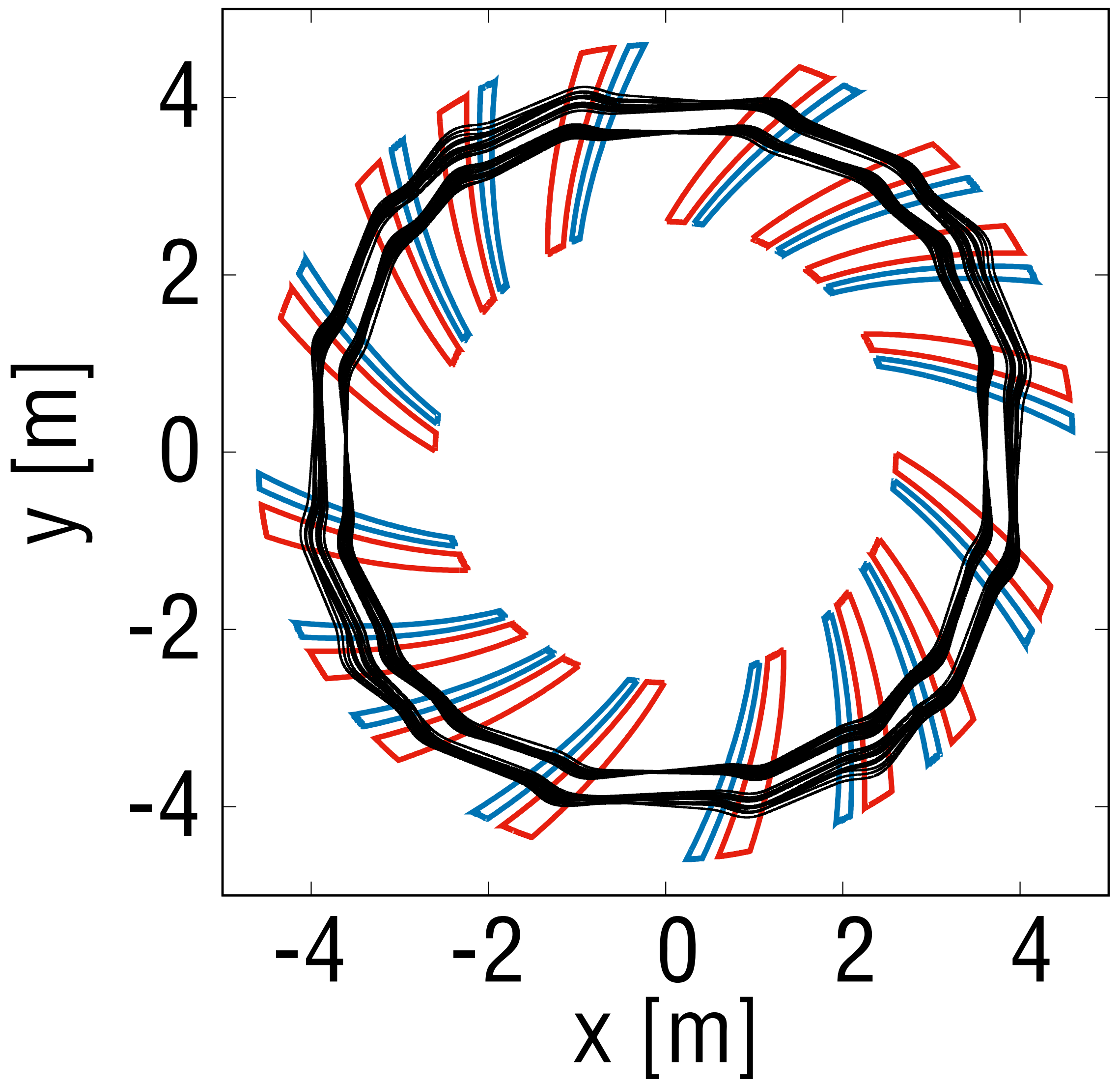
No closed orbit in an FFA

- Particles in global polar coordinate system



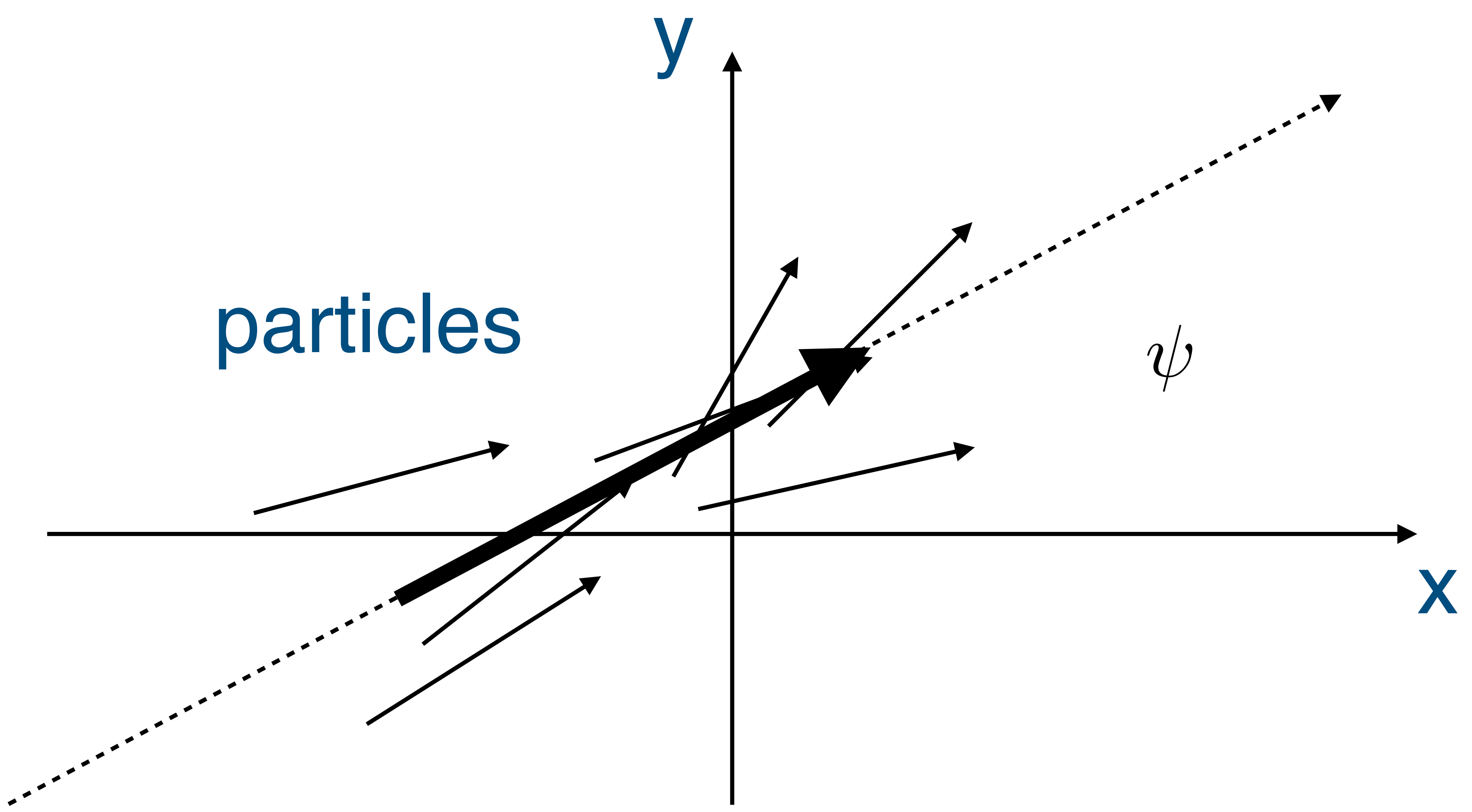
r(ipart) = r(ipart)-r_mean(ibin)



- 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.

Scode, work in progress

- 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

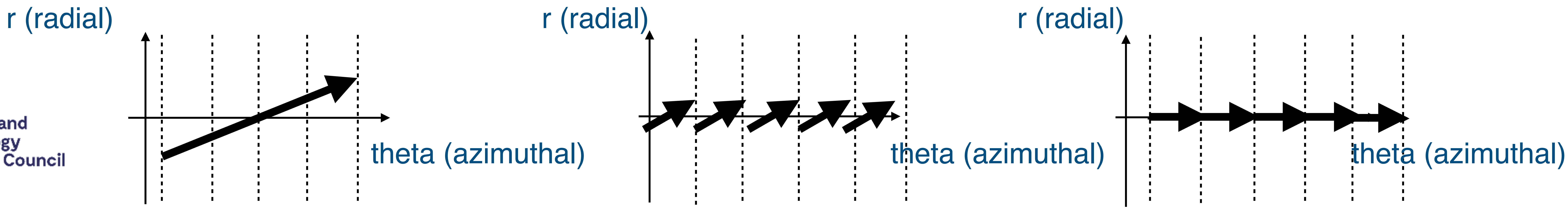
A straight line with a gradient of

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

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.



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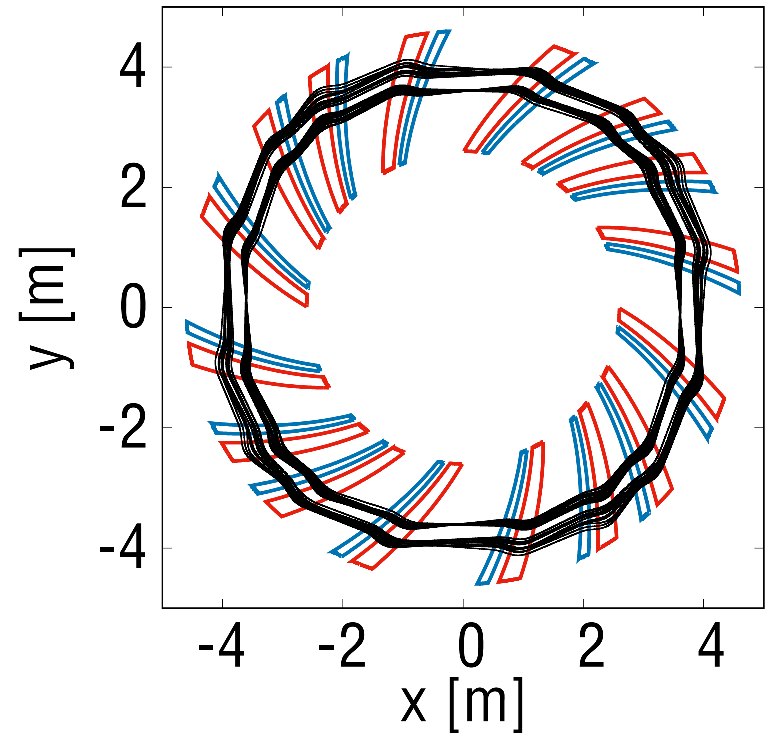
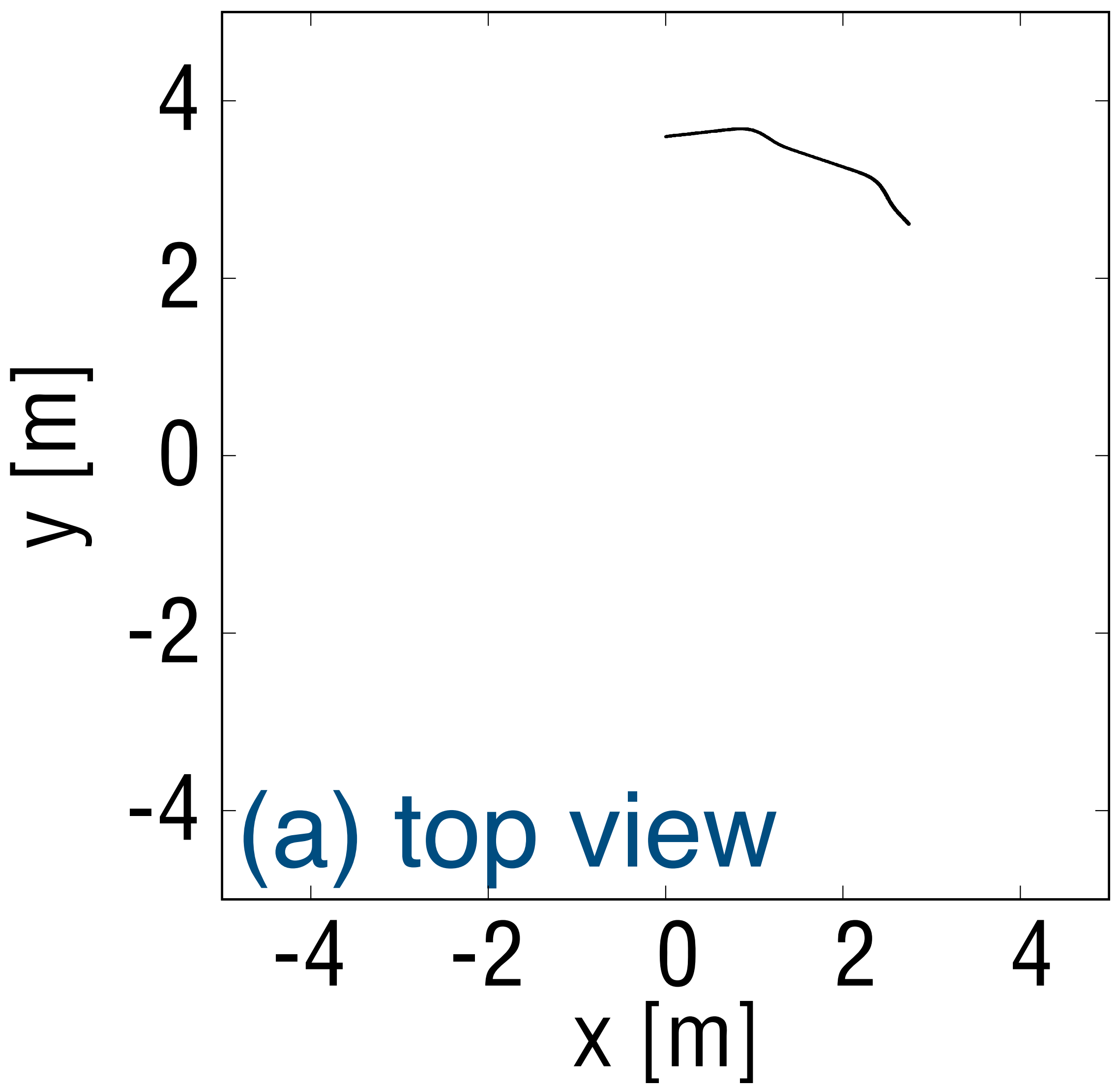
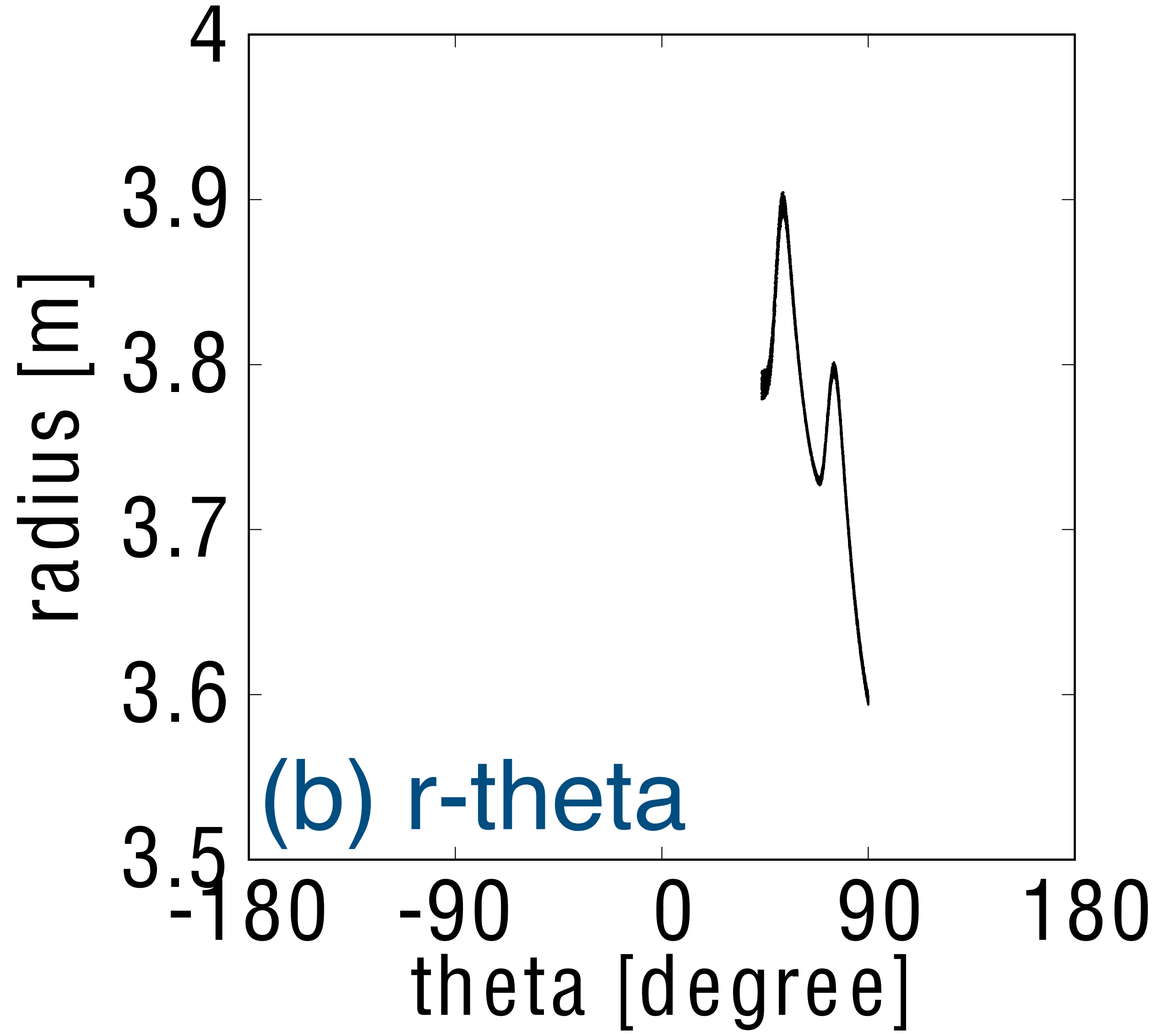
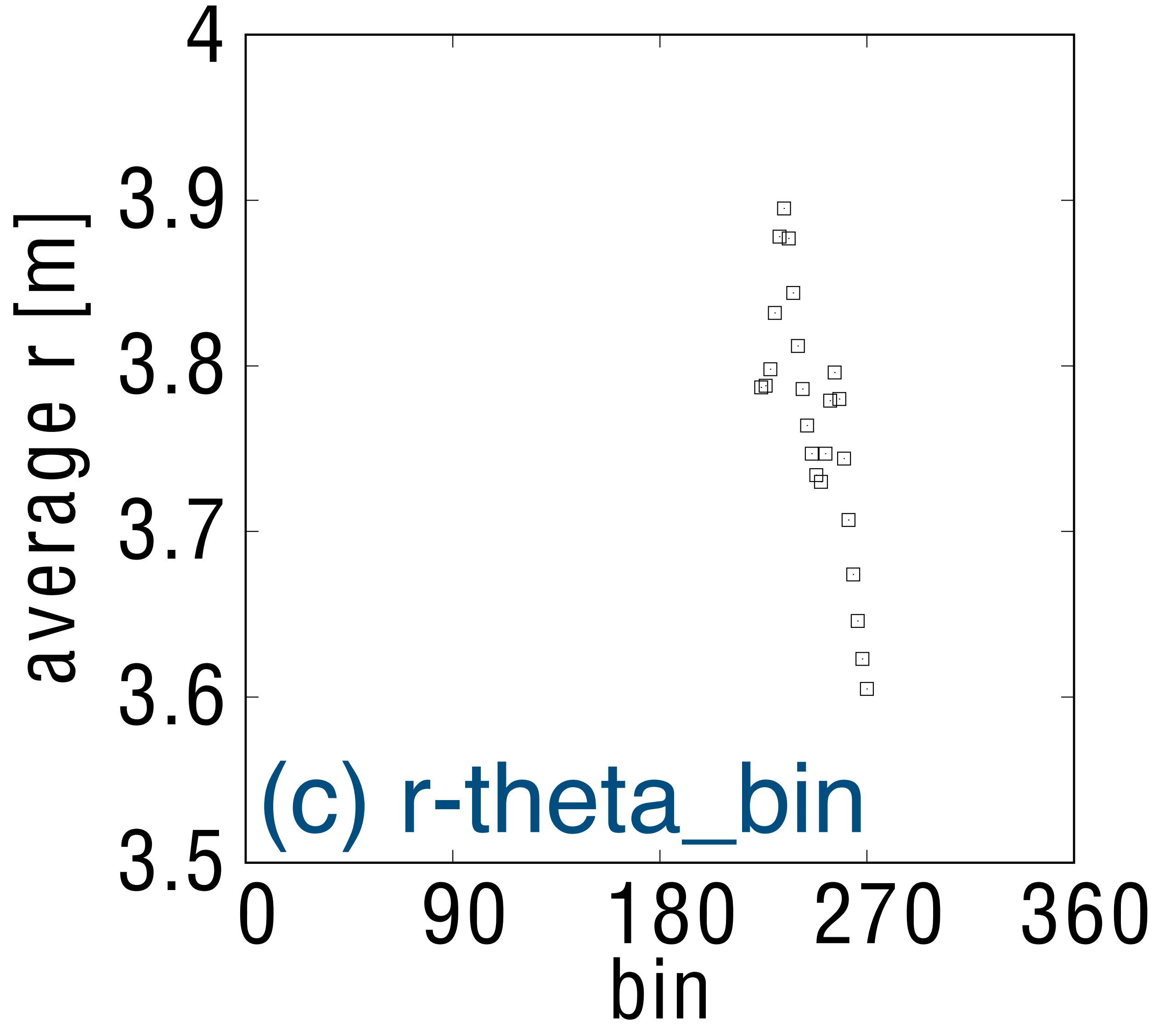
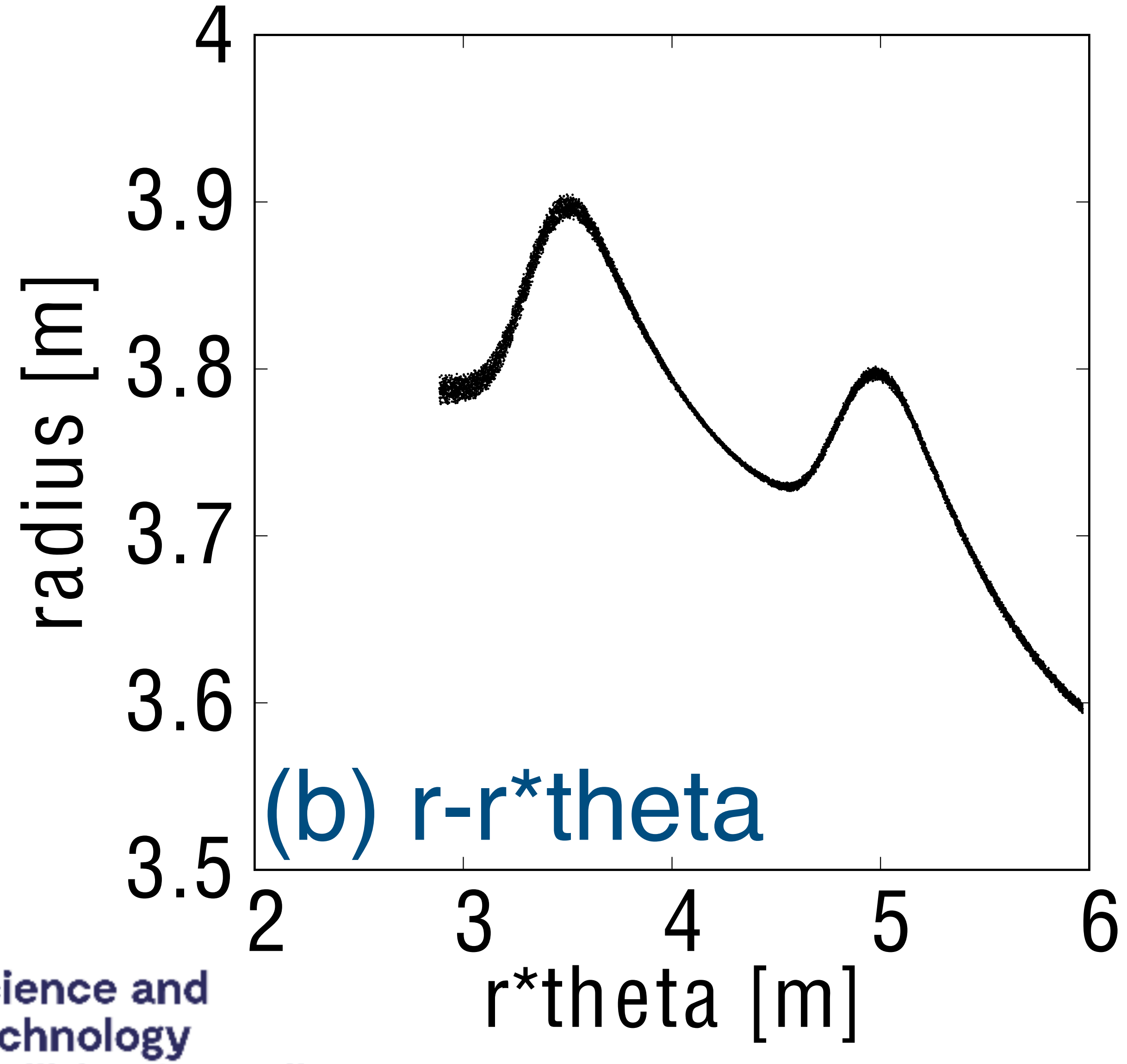
Scode, work in progress

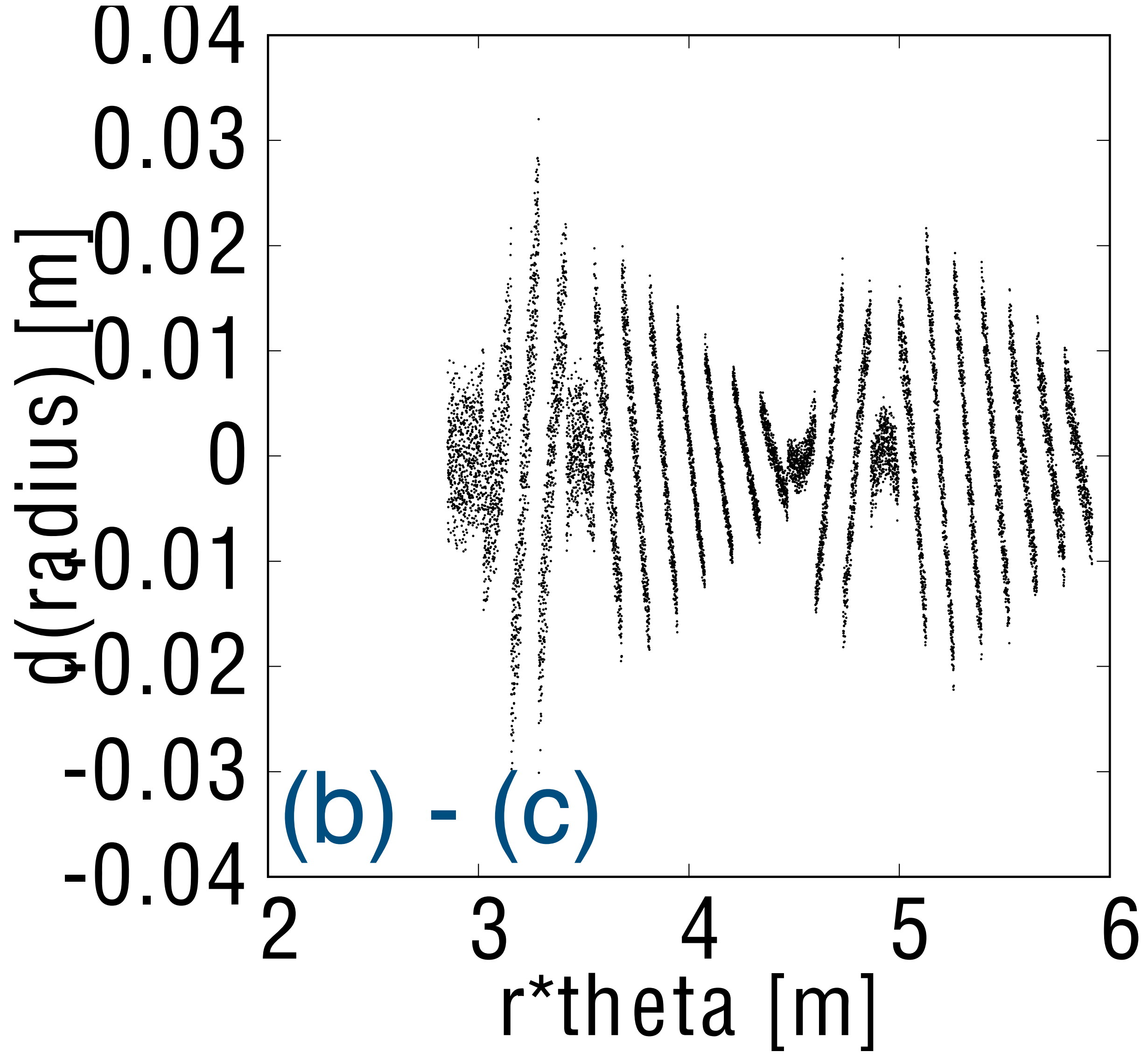


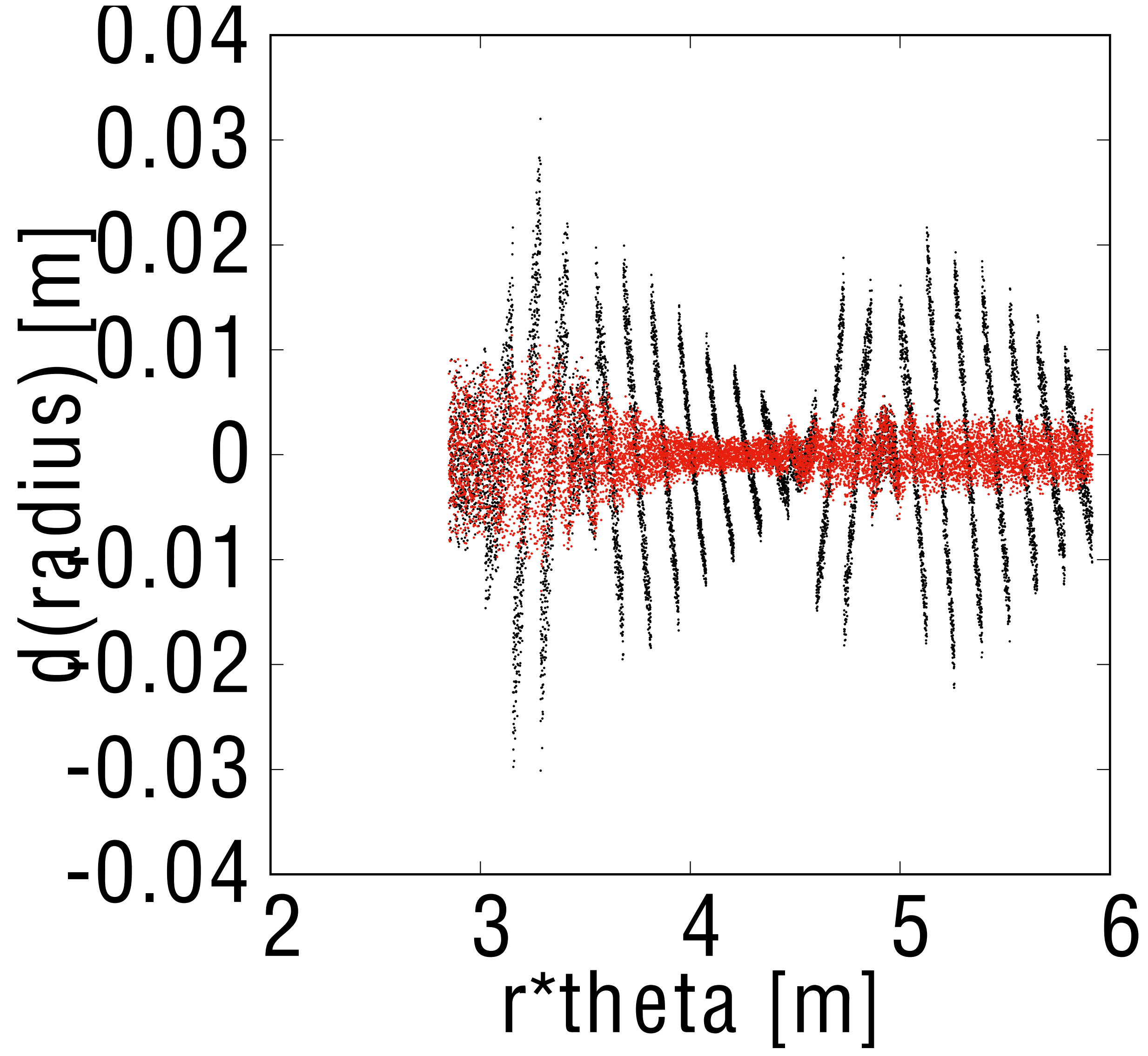




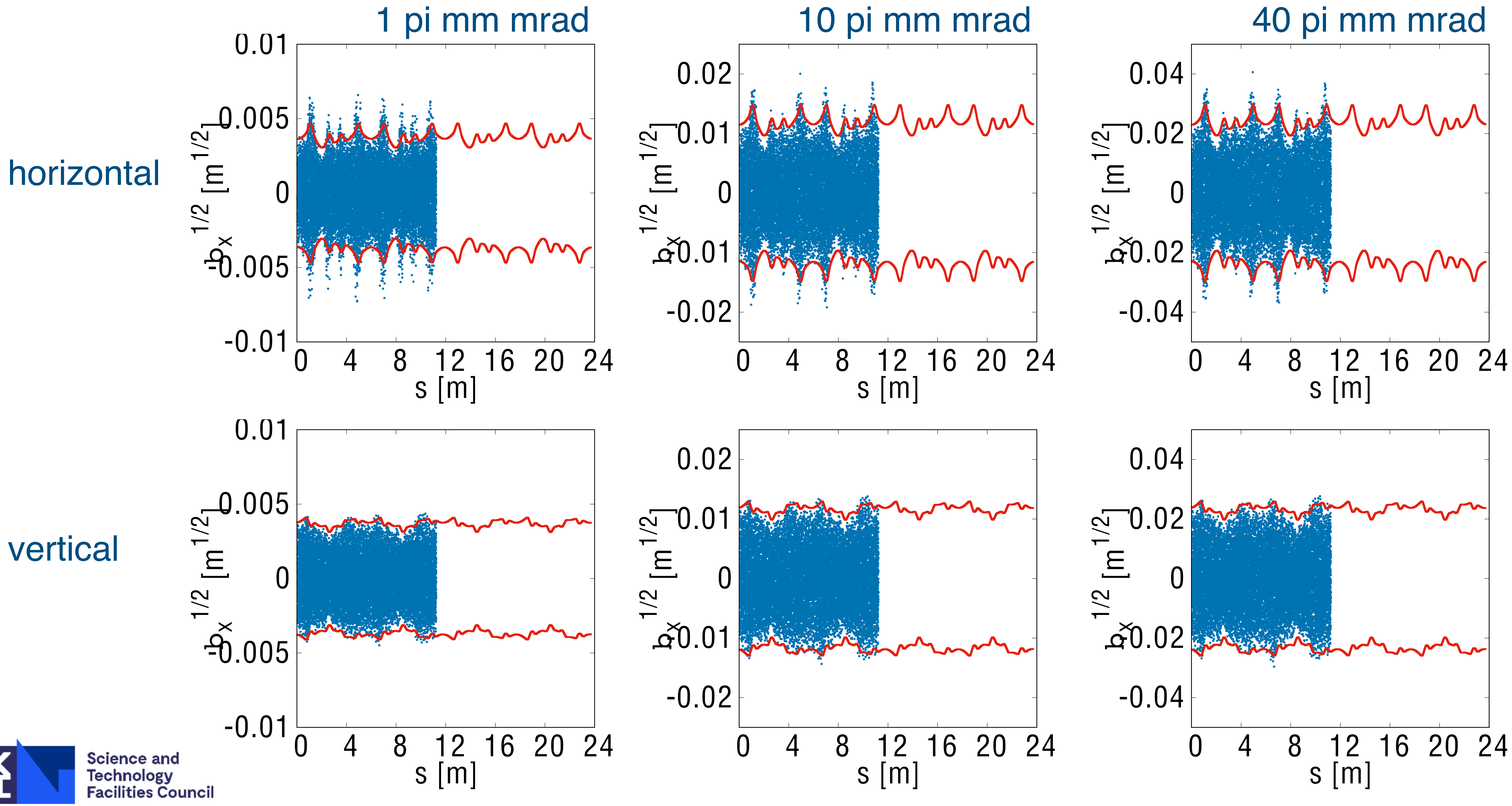








Finally, a curved beam becomes straight

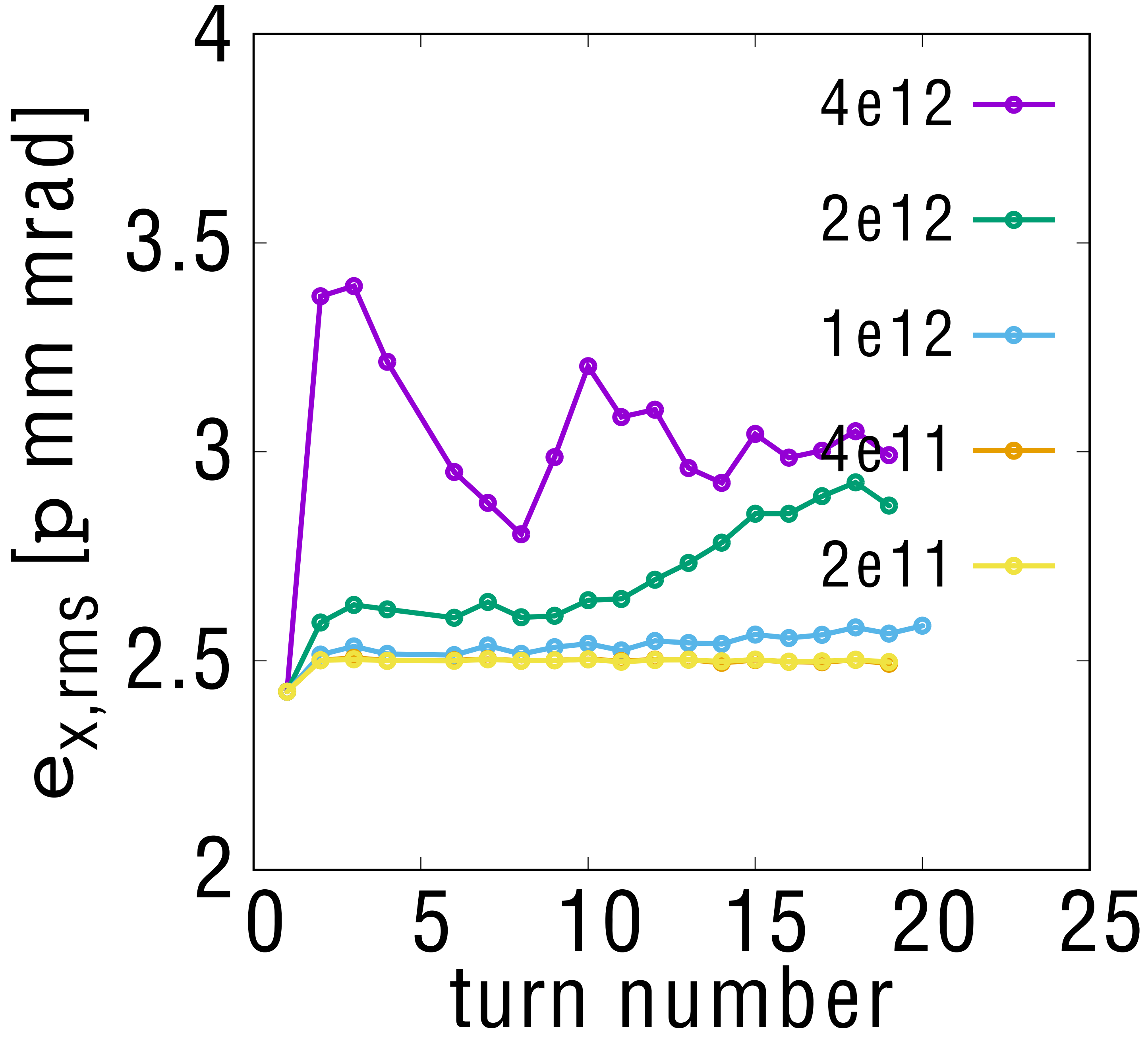


For space charge calculation, it is good enough.

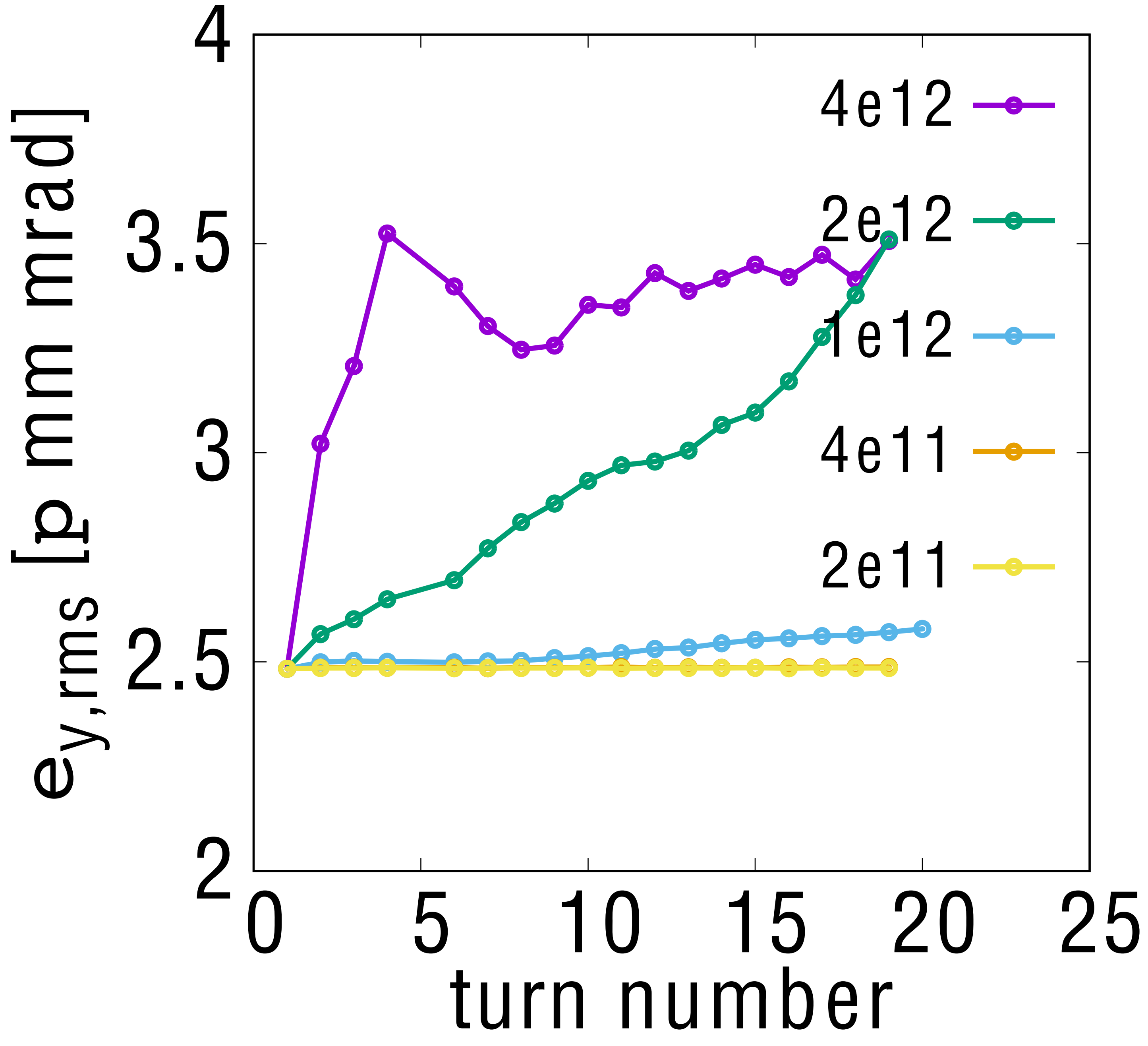
Simulation result (preliminary)

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)

Hor



Ver



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

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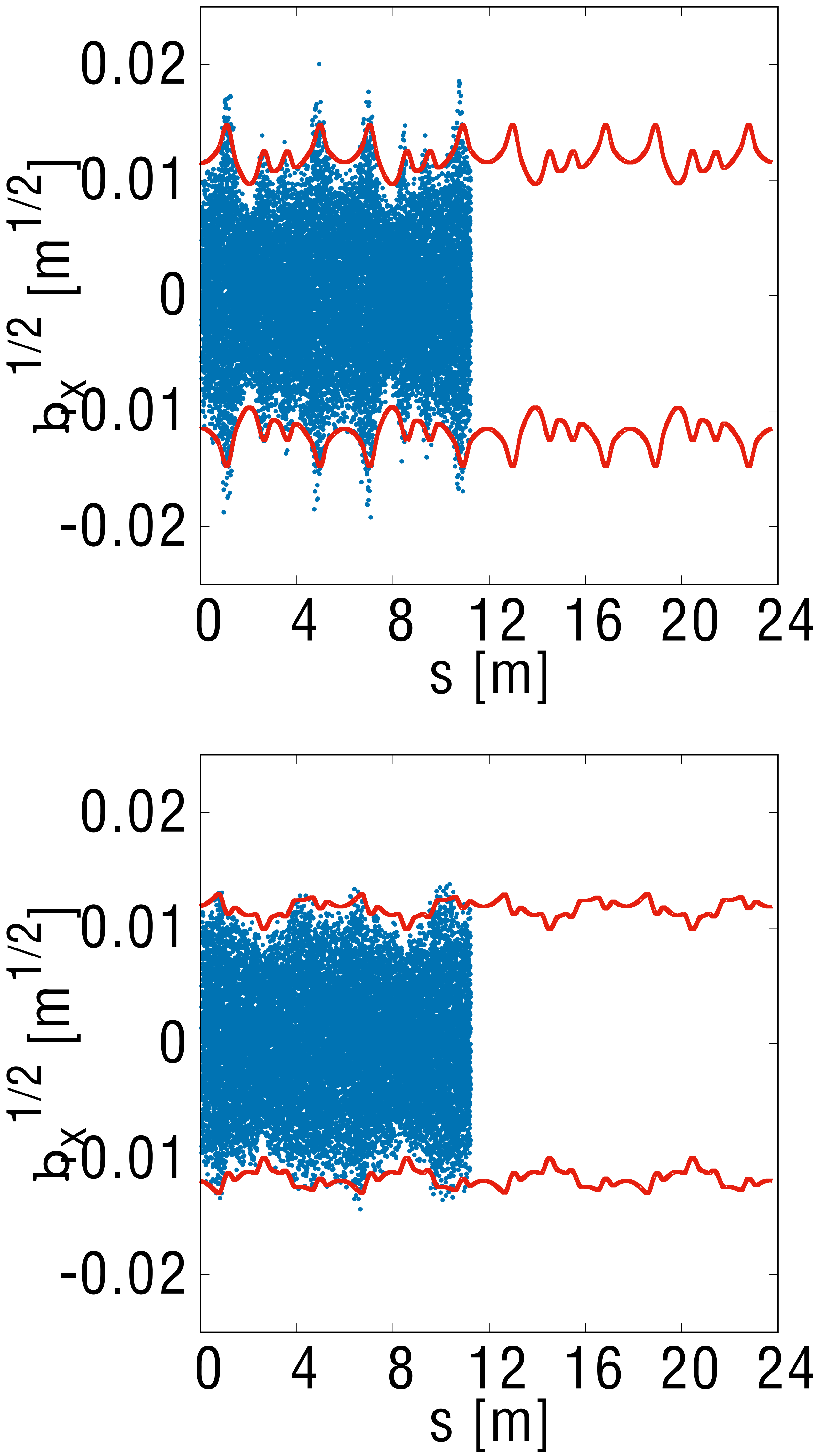
Simulation result (preliminary)

Initial beam envelope.

Hor

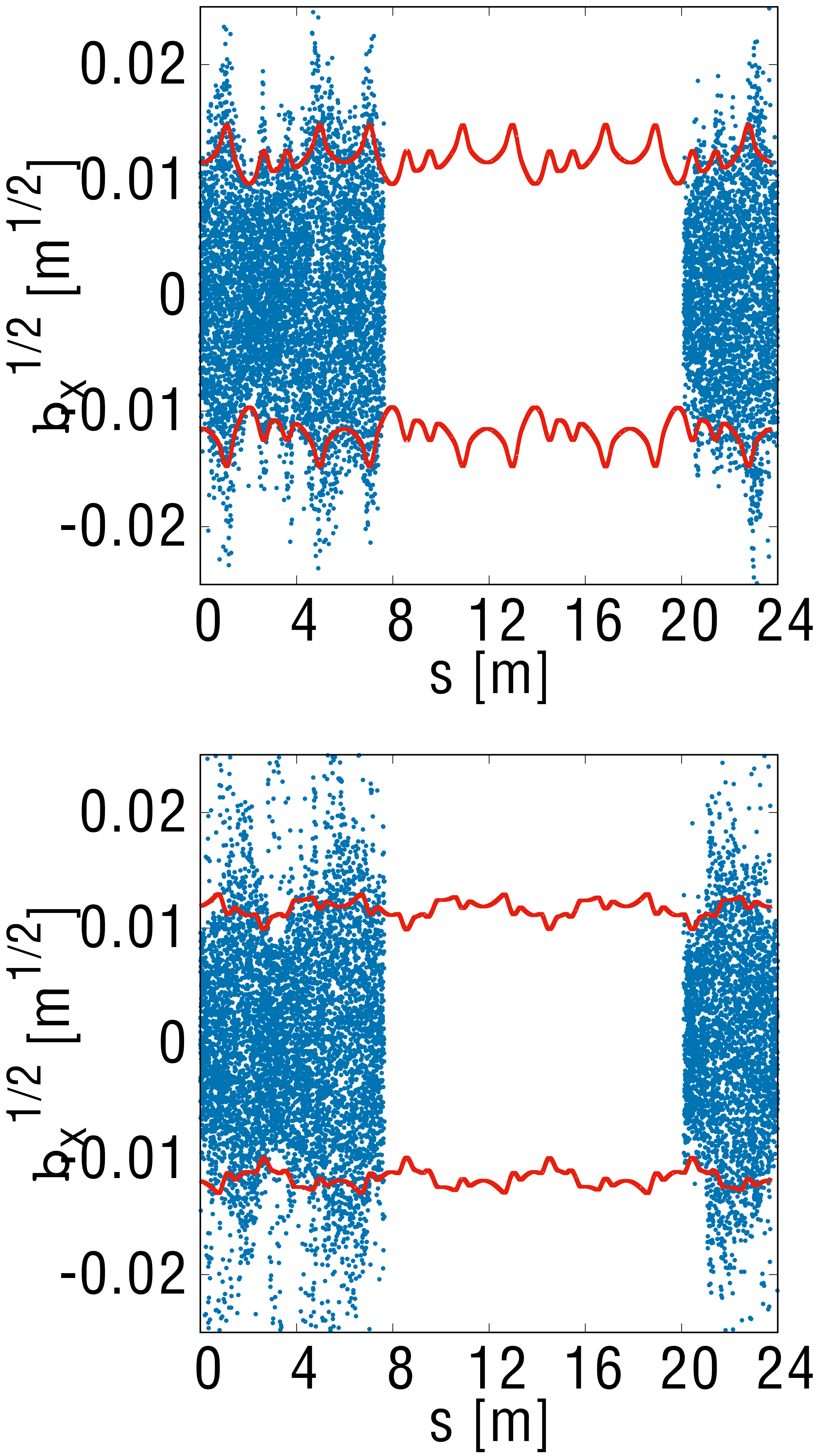
Ver



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

Hor

Ver

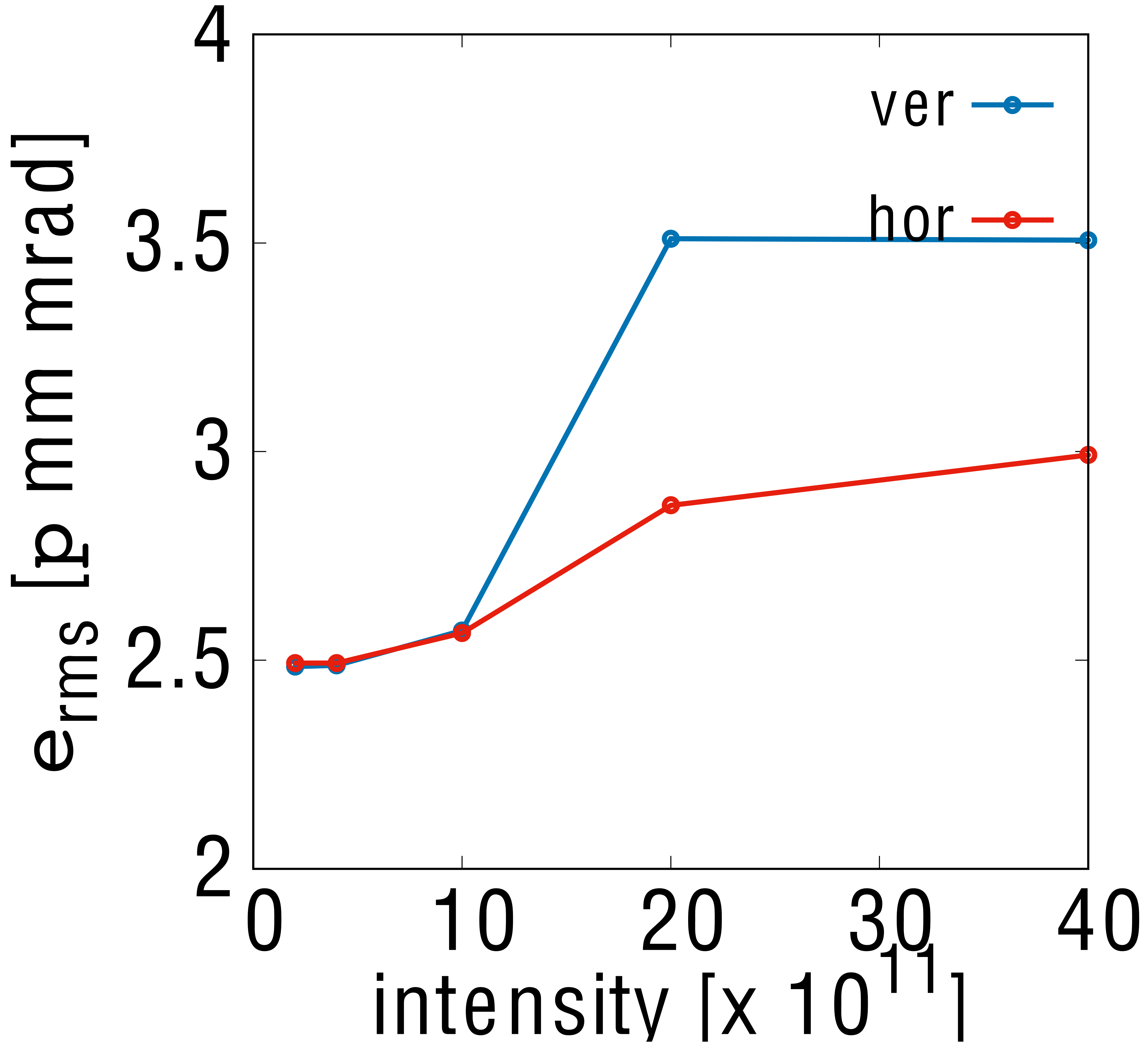


Simulation result (preliminary)

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 0.26.
- **Emittance growth starting around 10 x 10^{11} is reasonable.**

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Some topics

Beam stacking

- 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).

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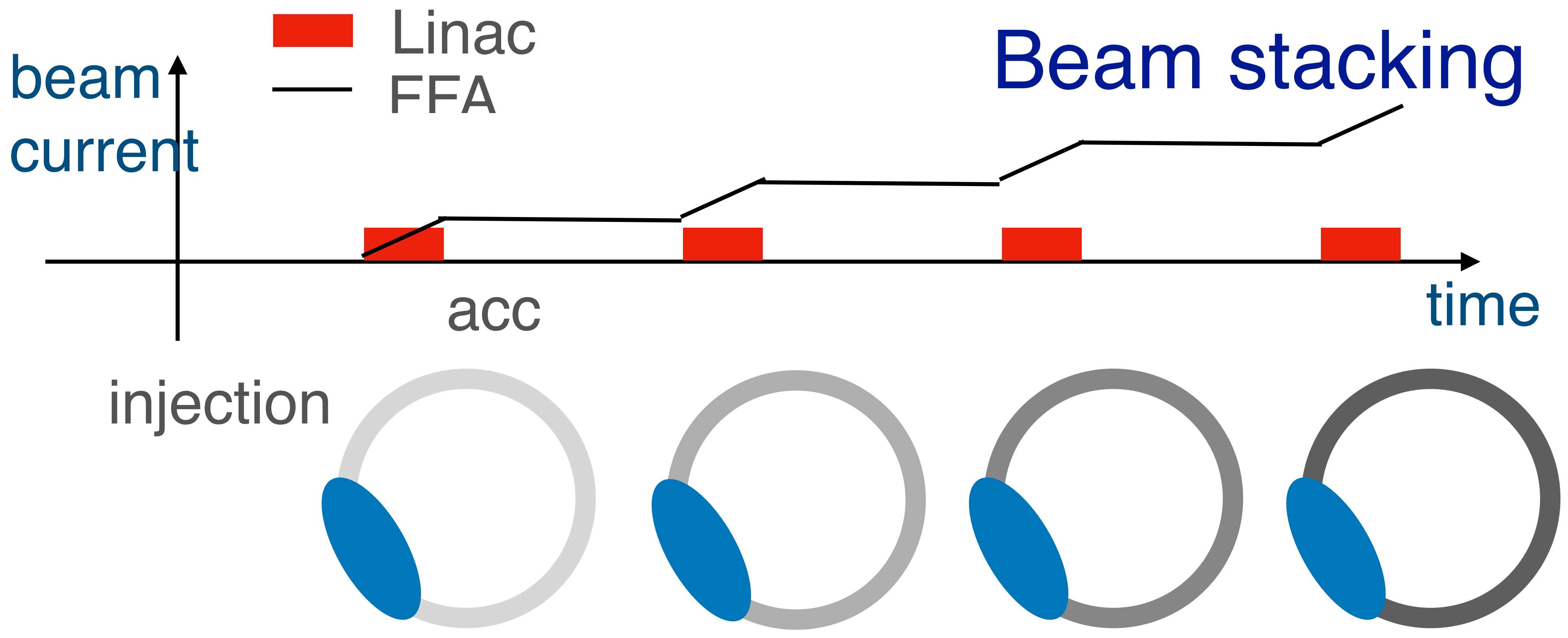
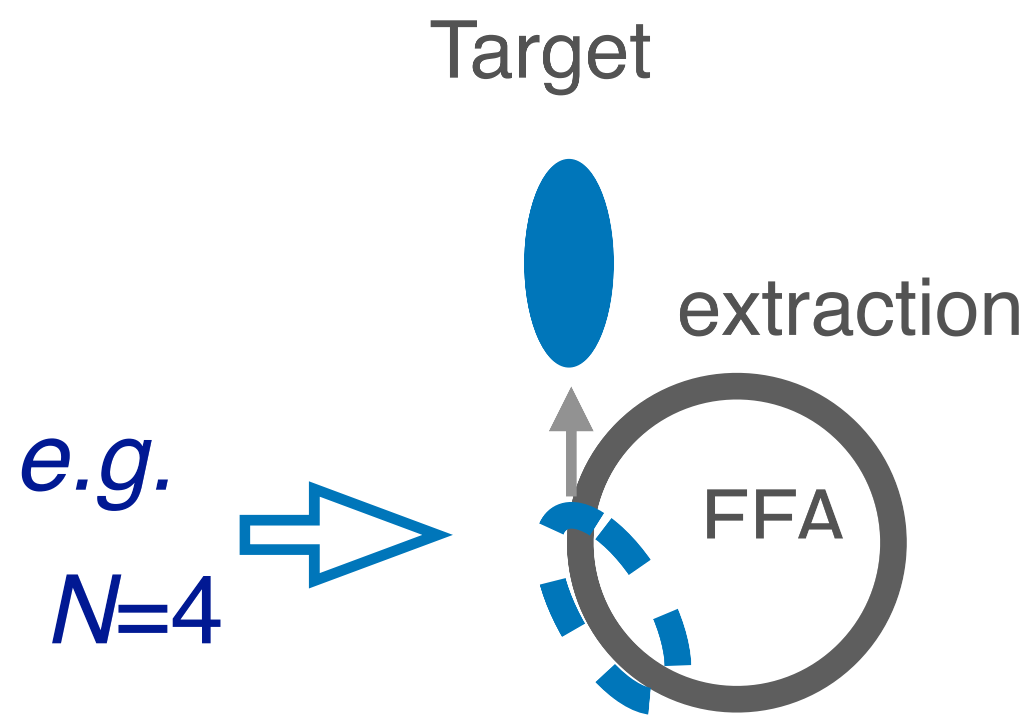
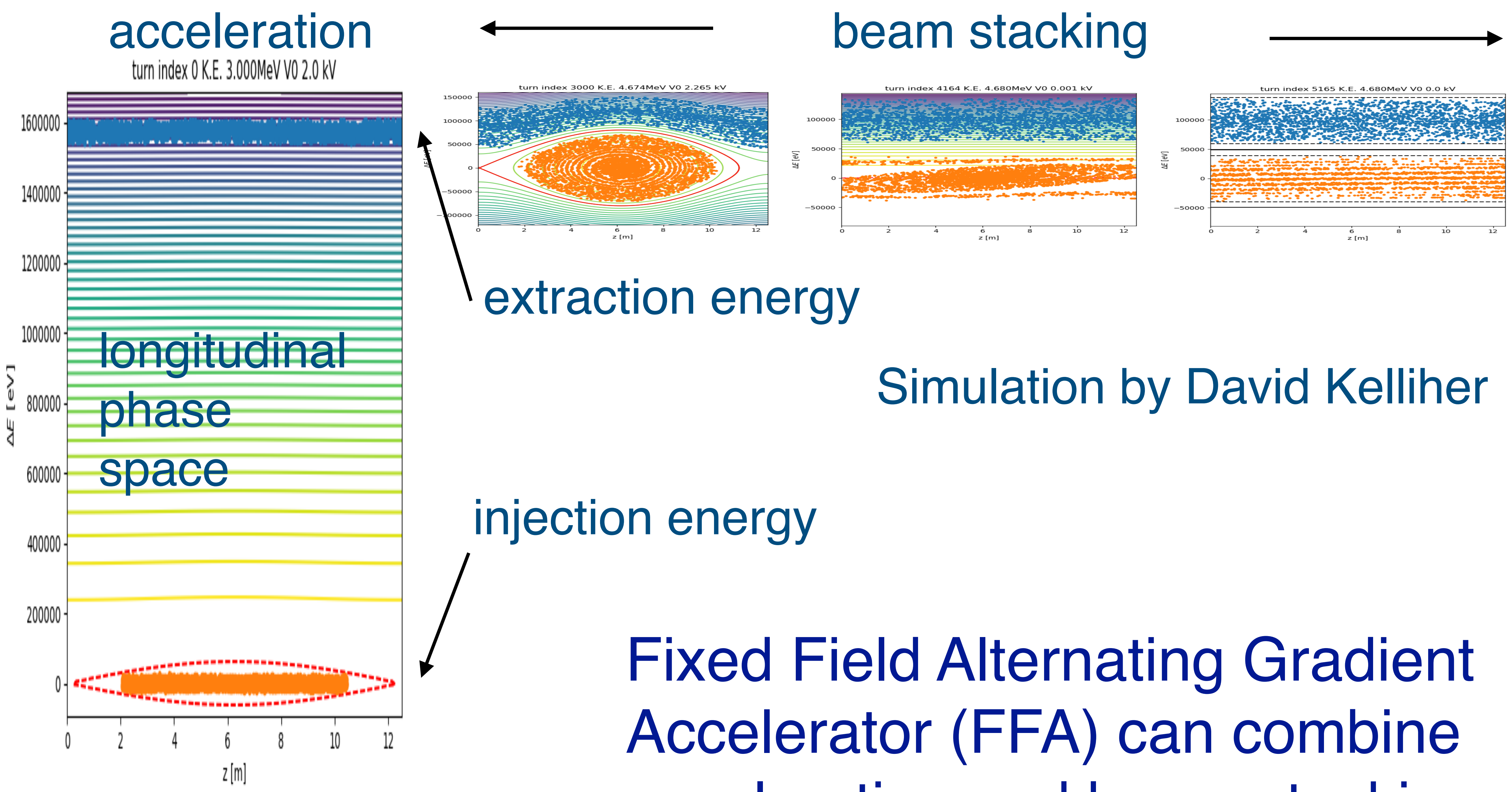
Beam stacking





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

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?

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Space charge tune shift

- Tune shift is inversely proportional to beta^2 gamma^3.
- Space charge effects are strong at injection, but decrease quickly with acceleration.

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

- If all the particles are injected at the same time, the peak beam power is limited at injection.
- It is possible to combine more number of particles at extraction to increase the peak power.

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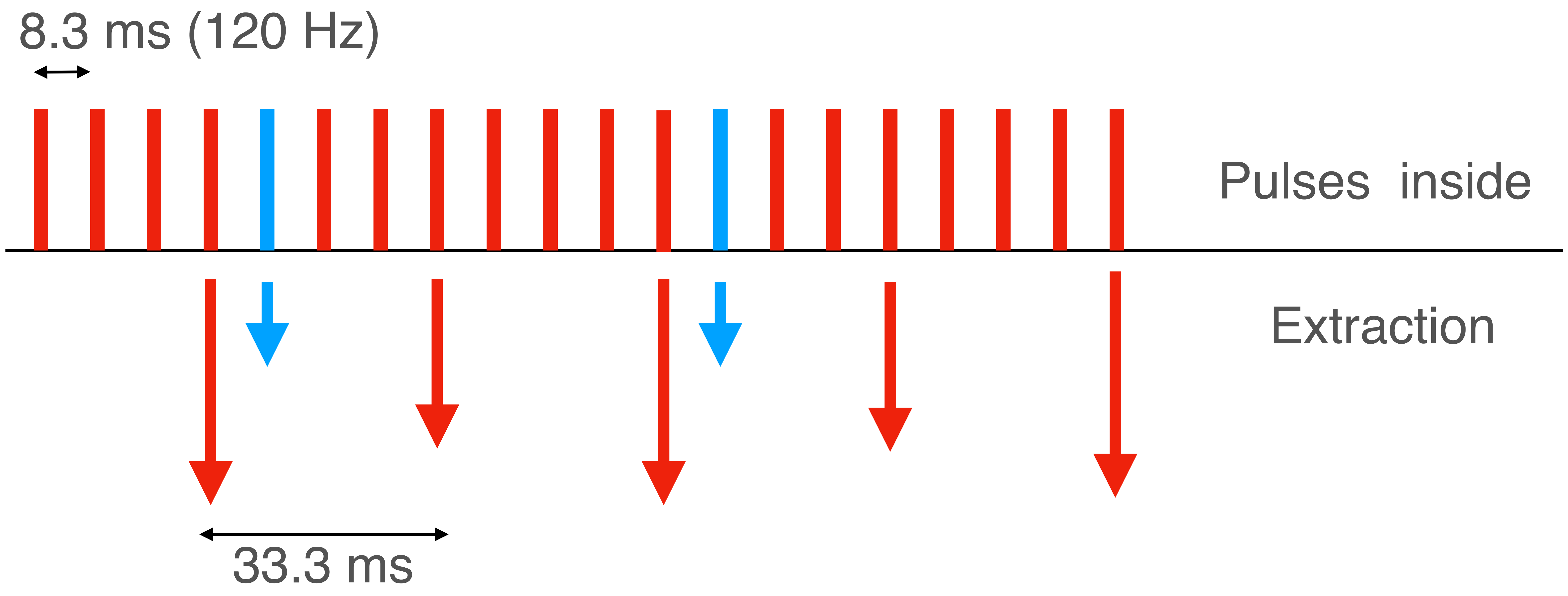
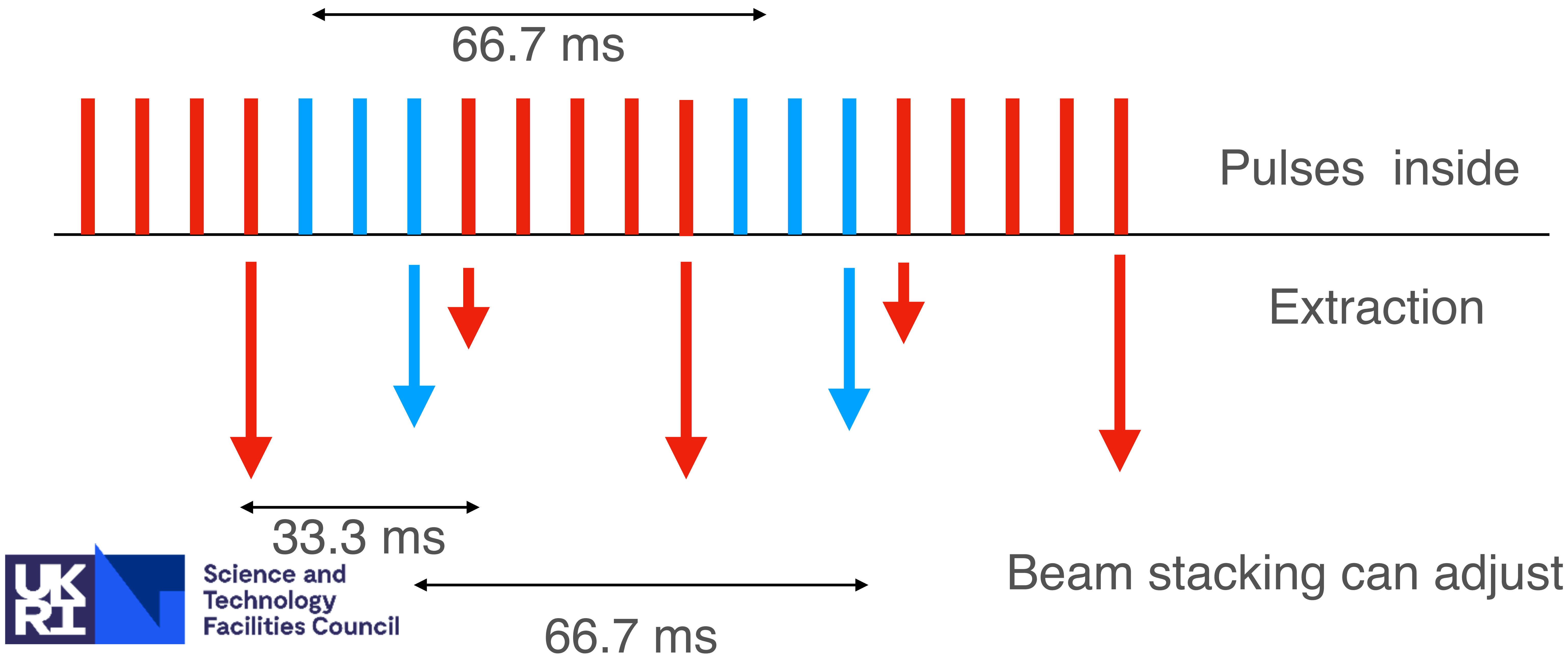
30/15 Hz user cycle by beam stacking from 120 Hz accelerator



	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

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

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Beam stacking experiment at MURA

High energy

Low energy

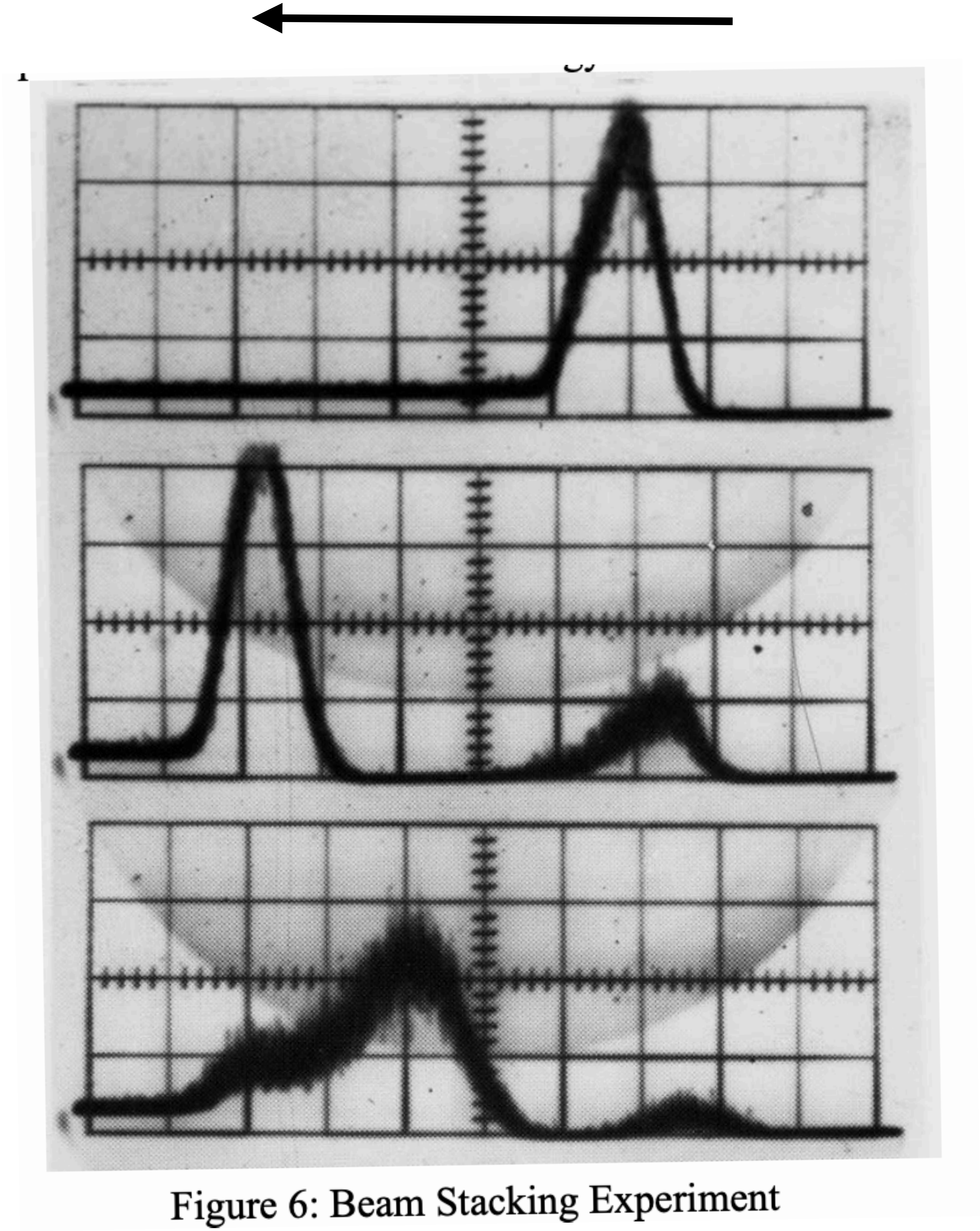


Figure 6: Beam Stacking Experiment

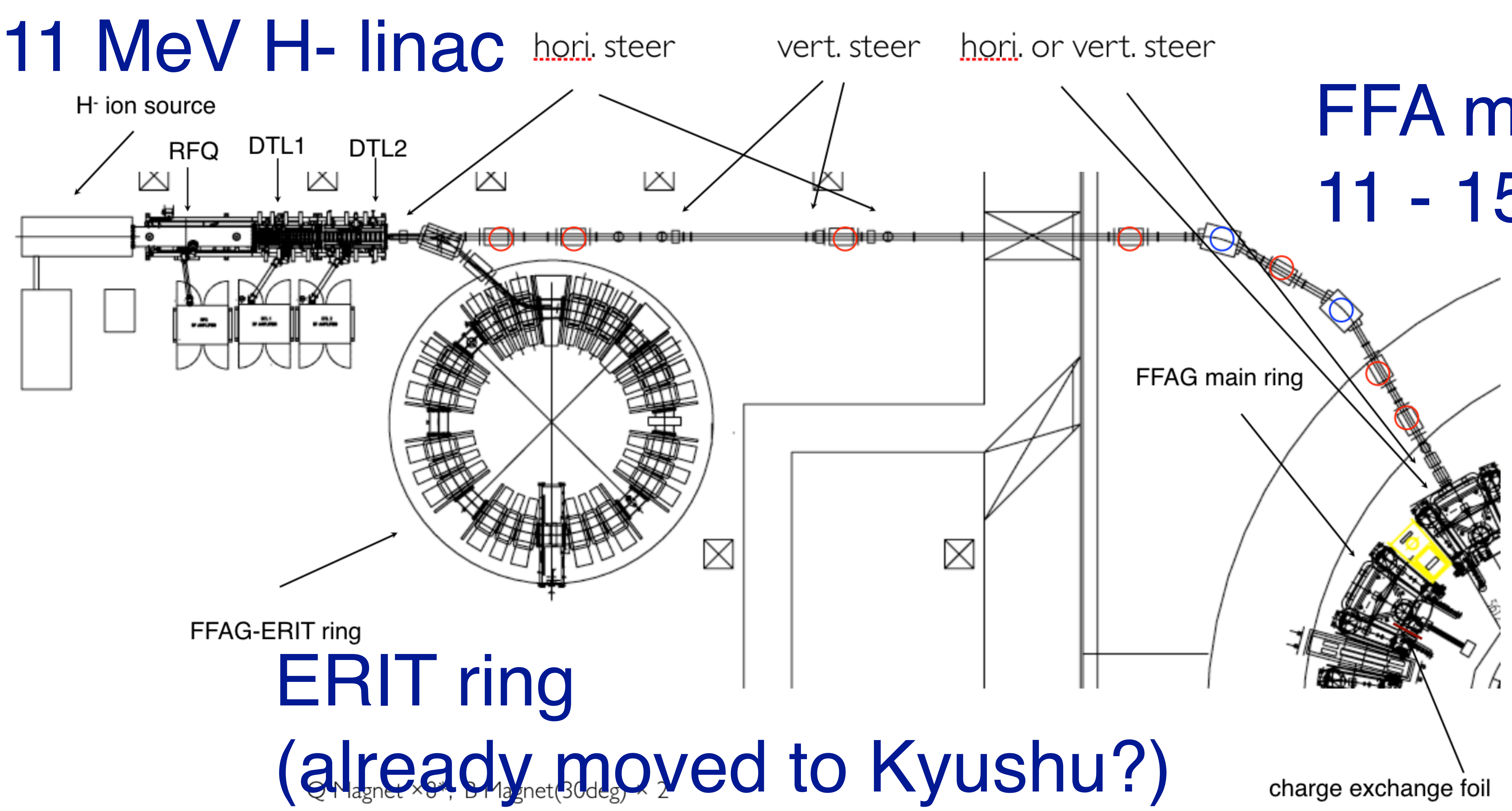
A beam is injected.

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

Repeat 4 times. Momentum spread is larger.

FFA ring and diagnostics

KURNS FFA accelerator complex at Kyoto Univ.



11 MeV H- linac

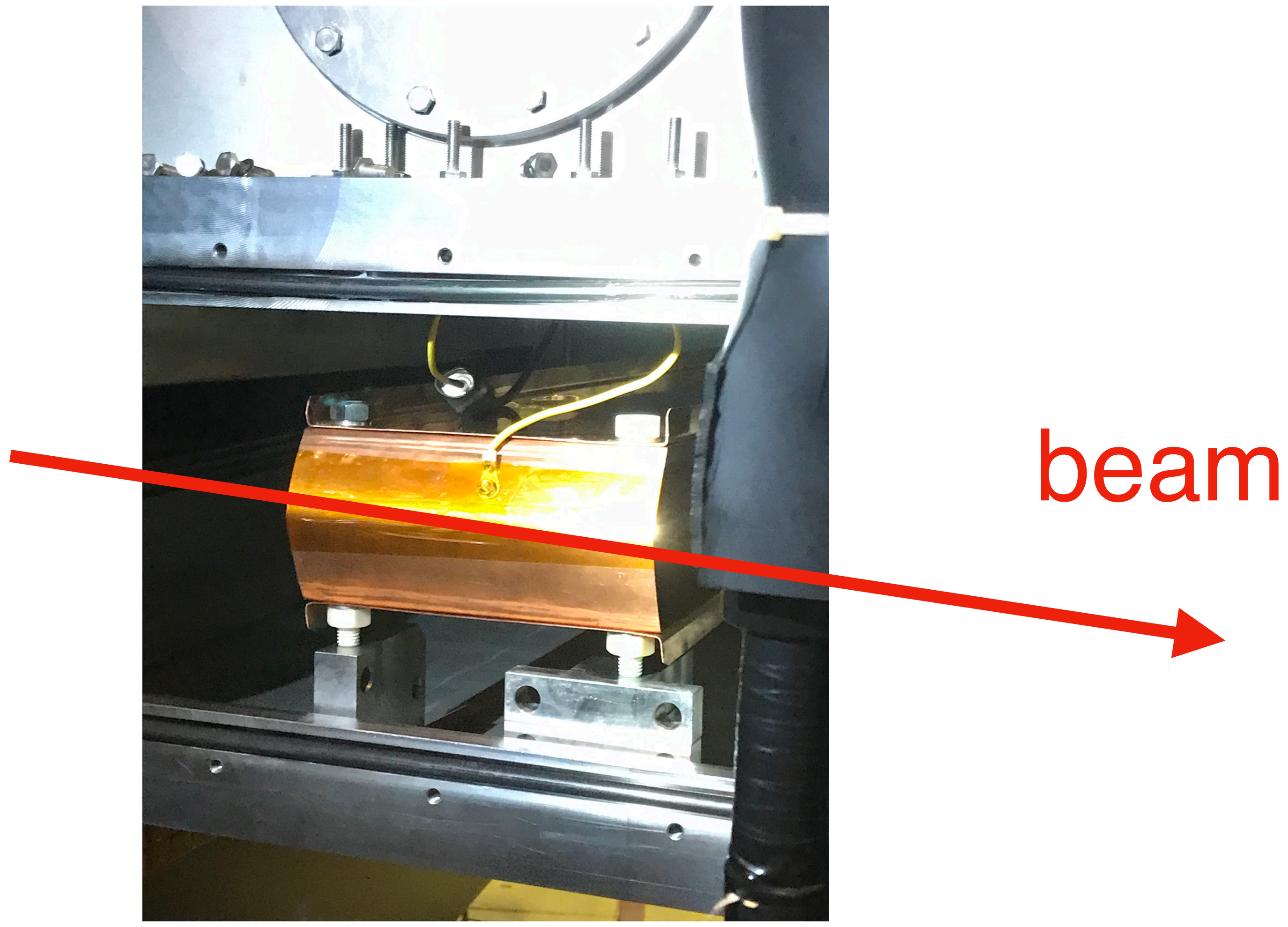
FFA main ring
11 - 150 MeV

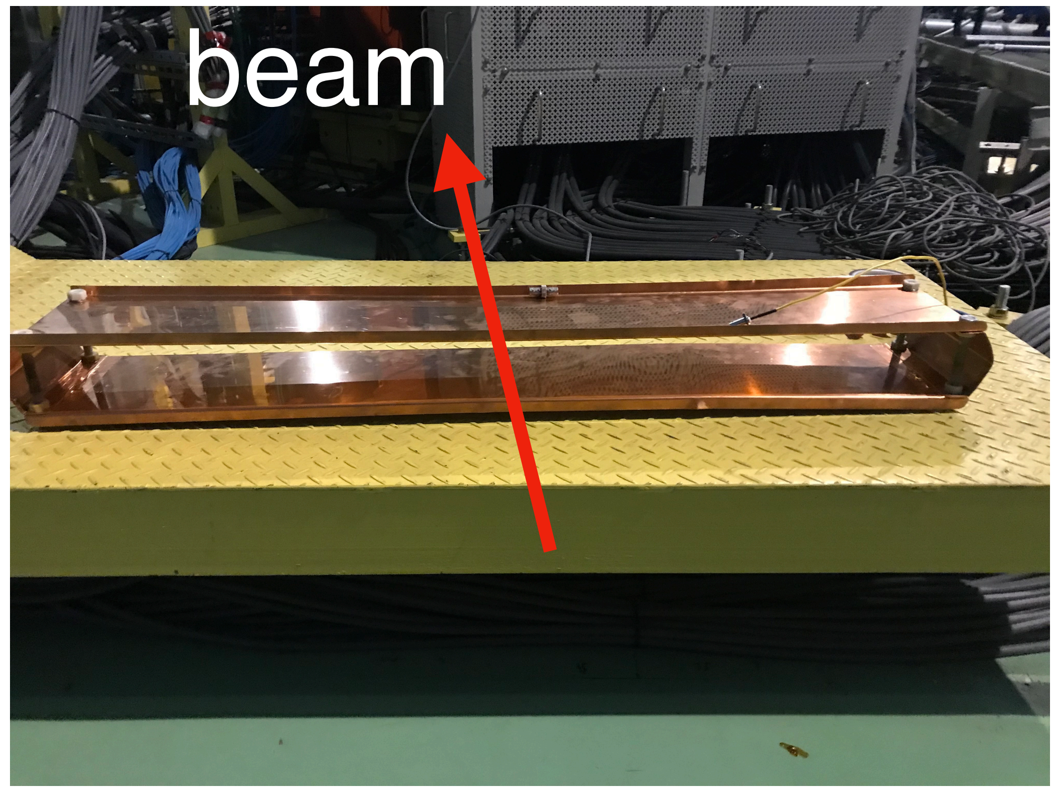
ERIT ring
(already moved to Kyushu?)

- H- charge exchange injection without bump magnets.
- No painting, inject into the closed orbit.
- No chopper in the injection line.
- Capture by moving bucket with phis=20 degree, voltage=4 kV.
- The beams move radially for a few 10 cm as accelerated.

Full Aperture Bunch (FAB) monitor

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

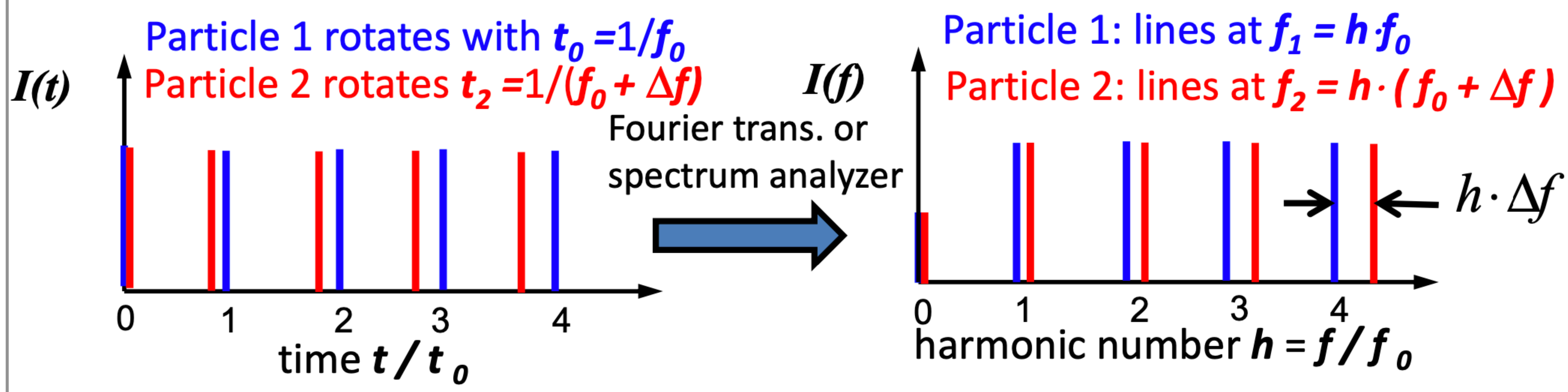




Schottky signal analysis

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

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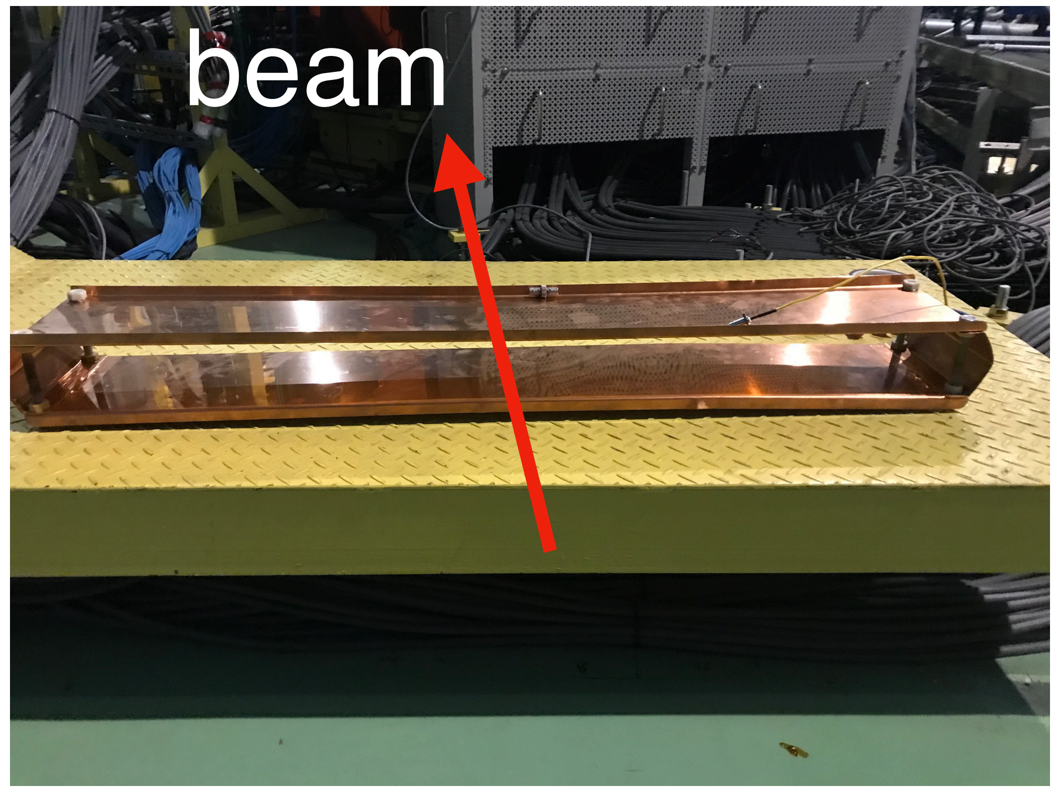
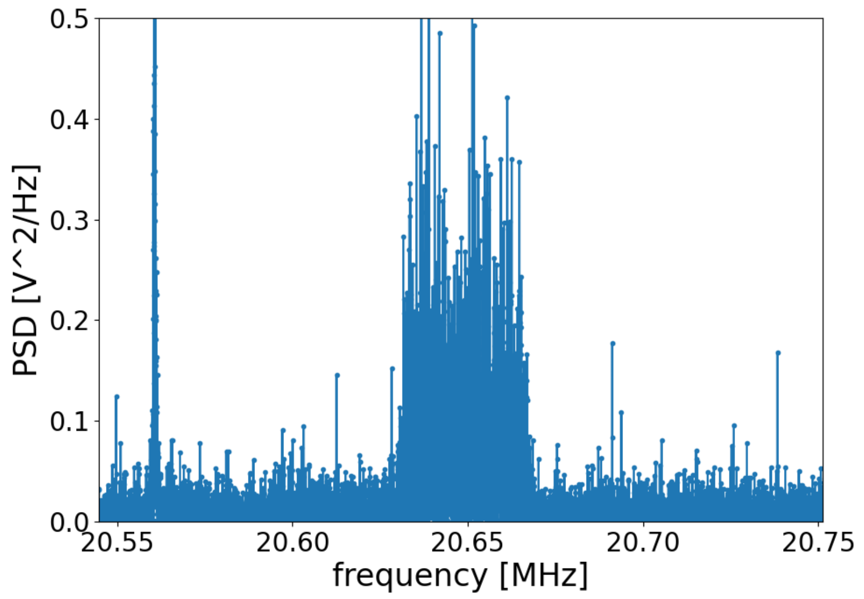


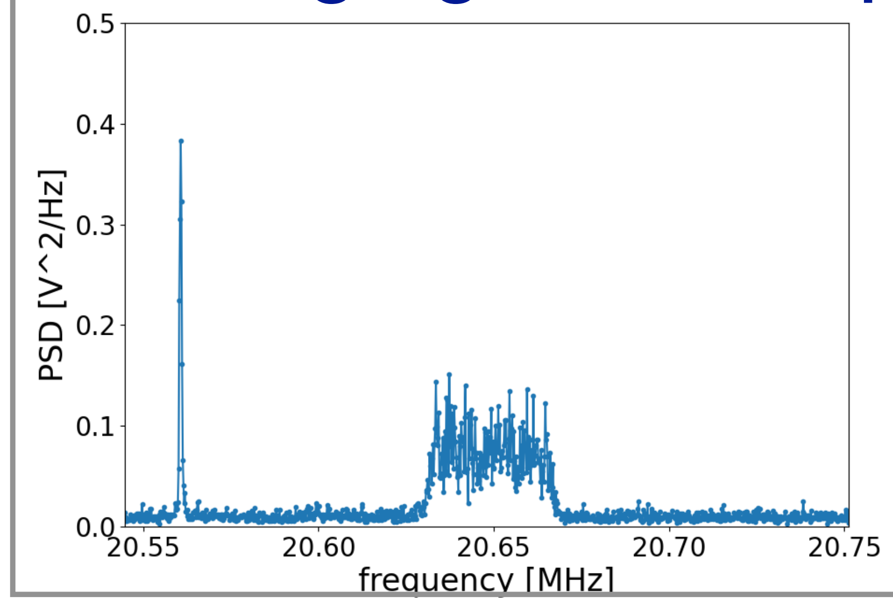
Schottky signal and PSD as an output tells 1) beam intensity and 2) momentum spread

Power Spectrum Density (PSD)

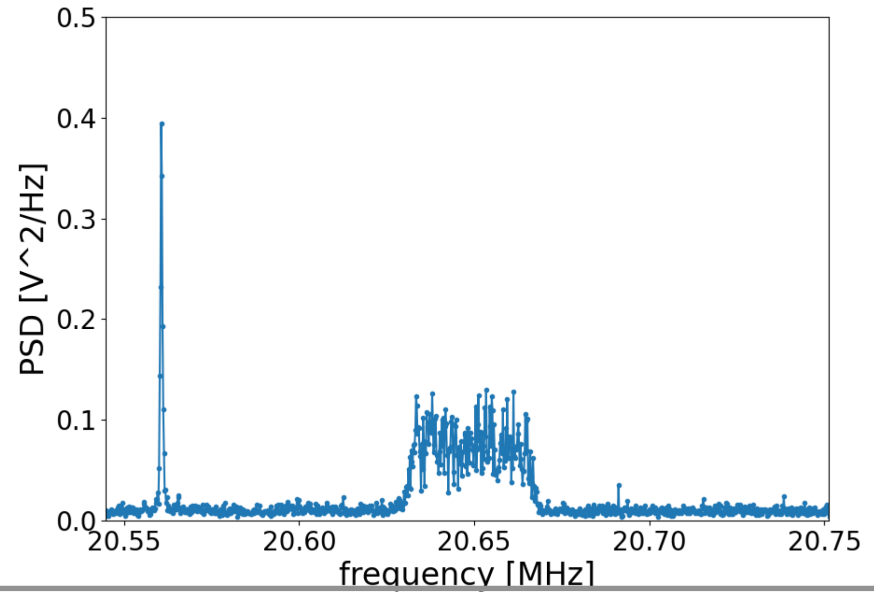


FFA spectrum
(Vertical axis is power V^2)

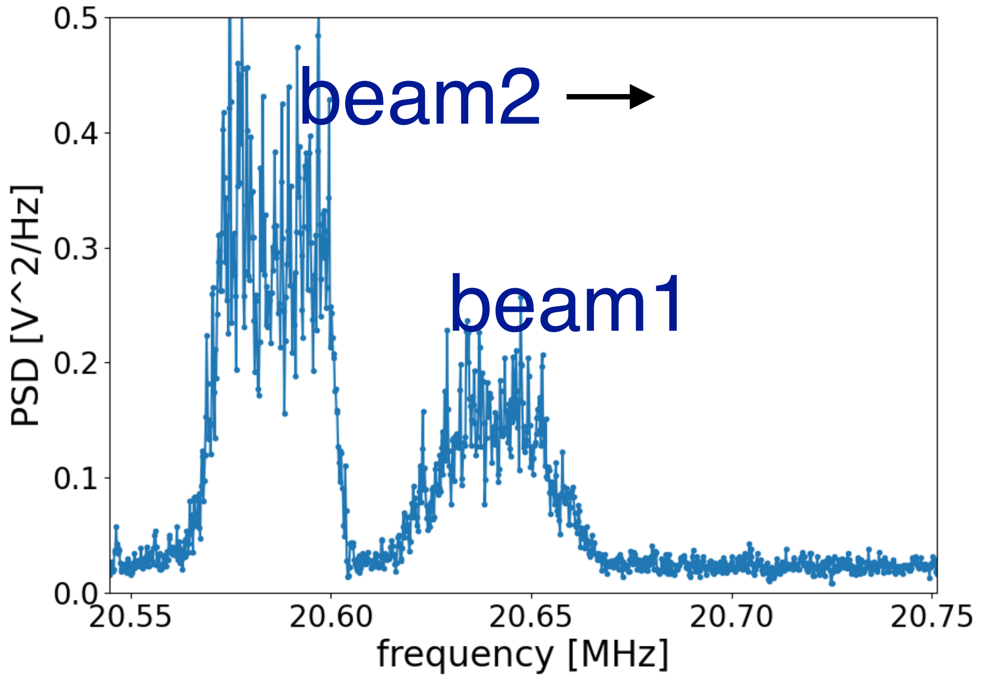
averaging over freq



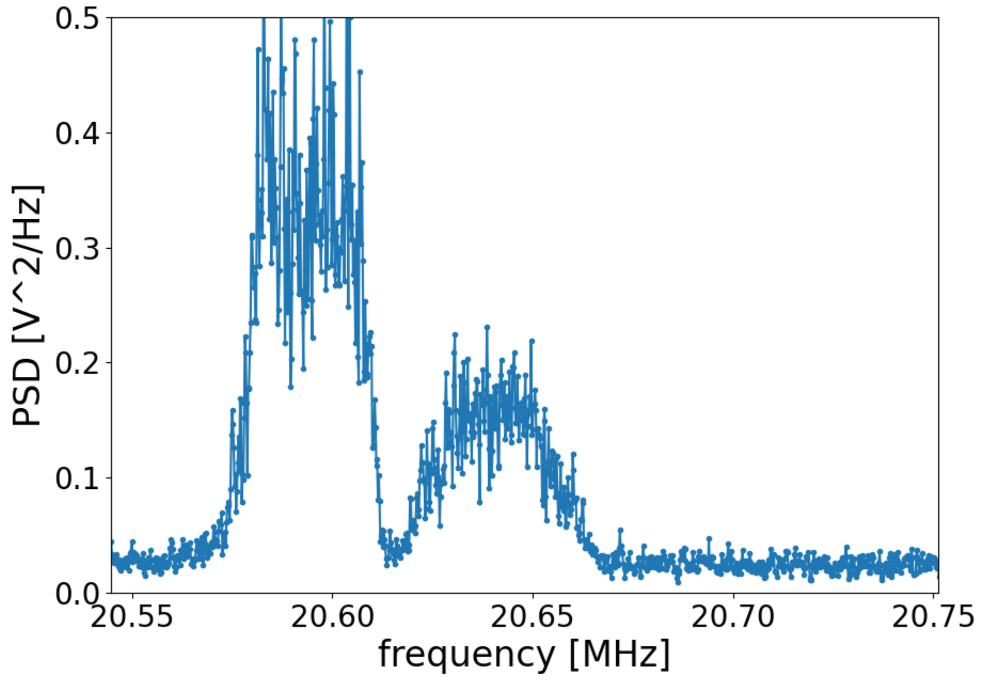
averaging over time
“Bartlett” or “Welch”



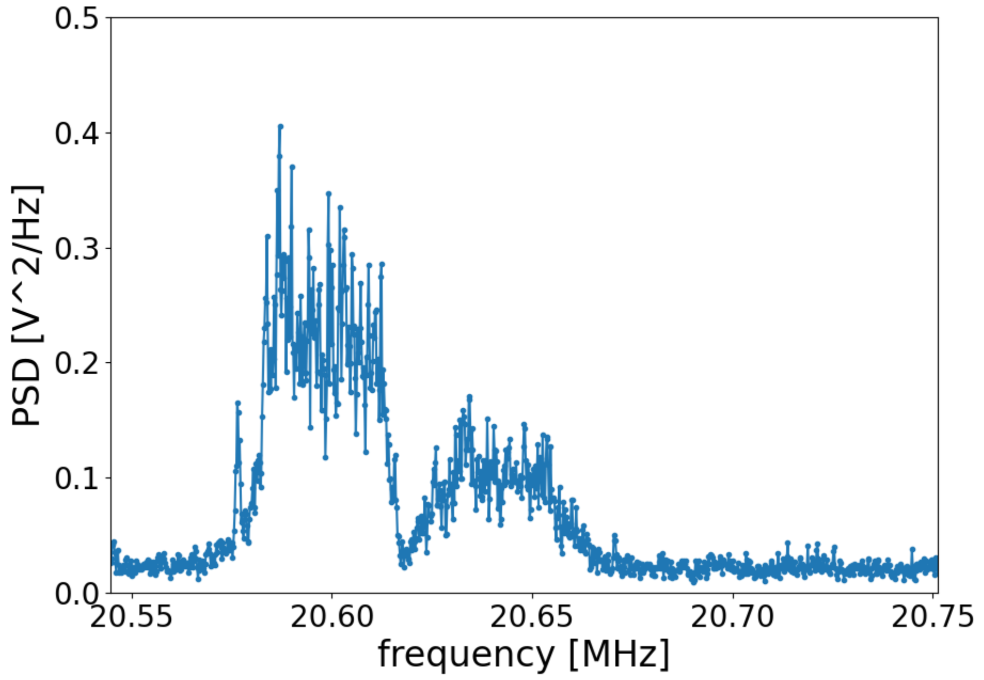
Schottky signal as a function of the final energy of beam 2.



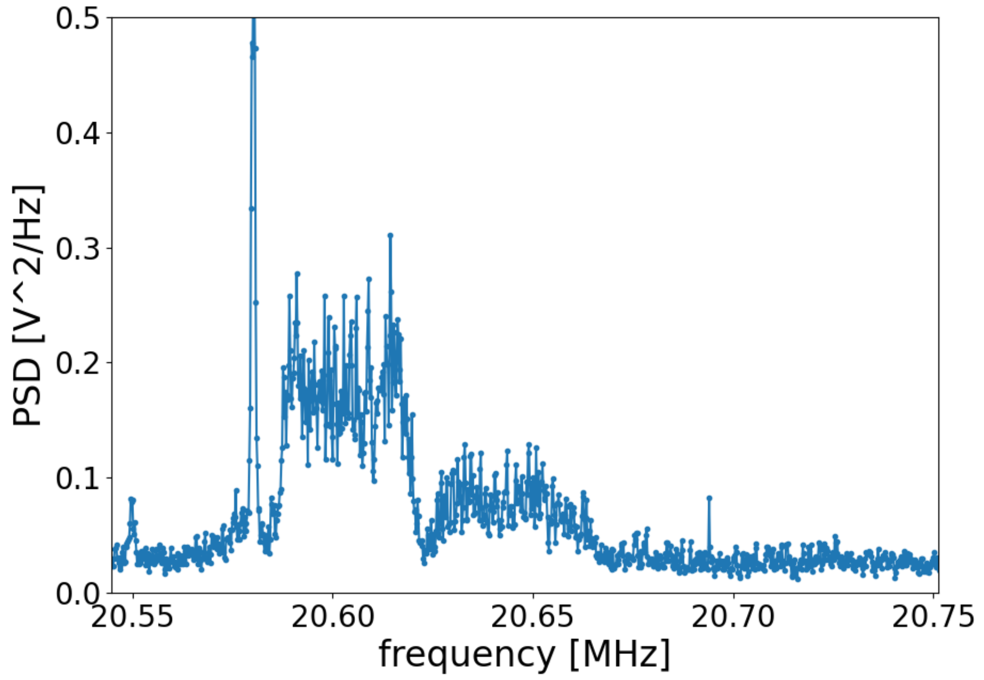
6.96 ms, -235.4 keV



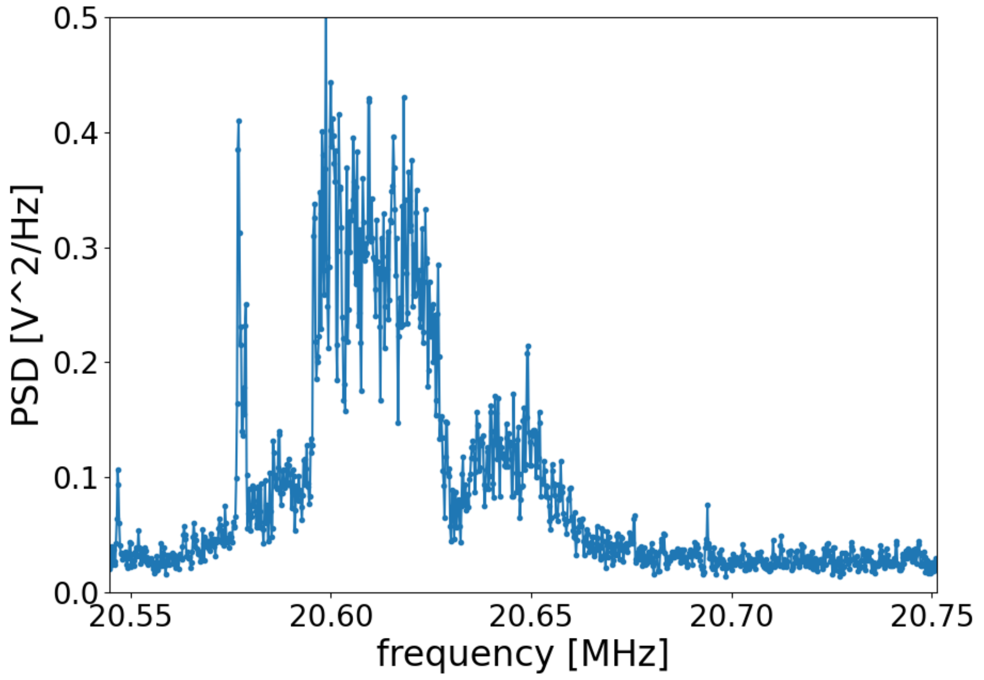
6.97 ms, -200.6 keV



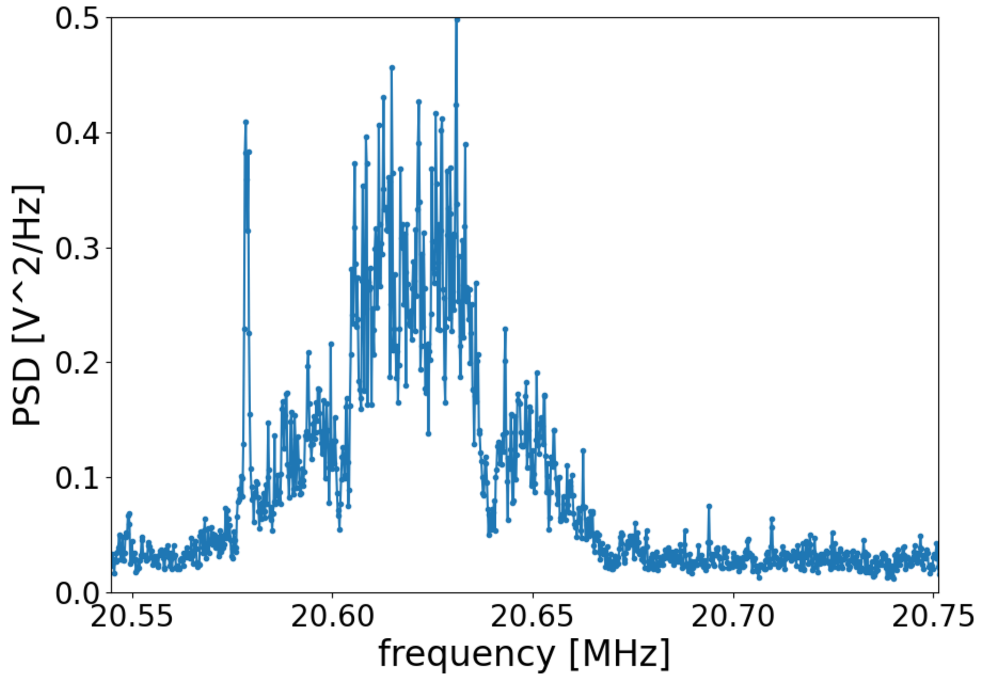
6.975 ms, -182.5 keV



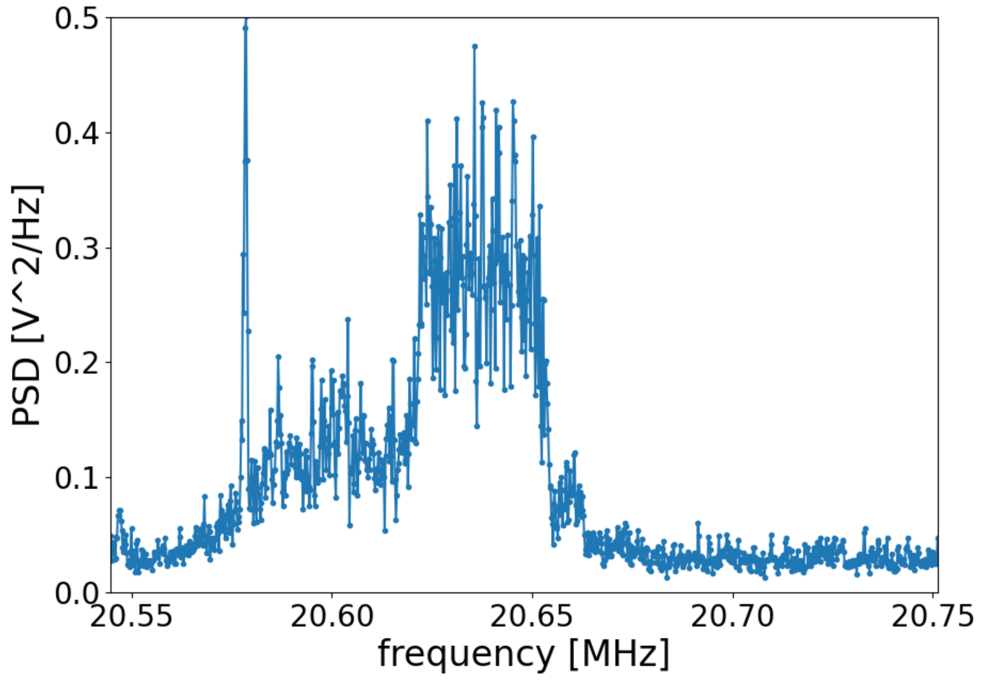
6.98 ms, -165.0 keV



6.99 ms, -129.7 keV



7.00 ms, -94.4 keV



7.02 ms, -23.8 keV

Acceleration time of beam2

Energy separation (beam2-beam1)

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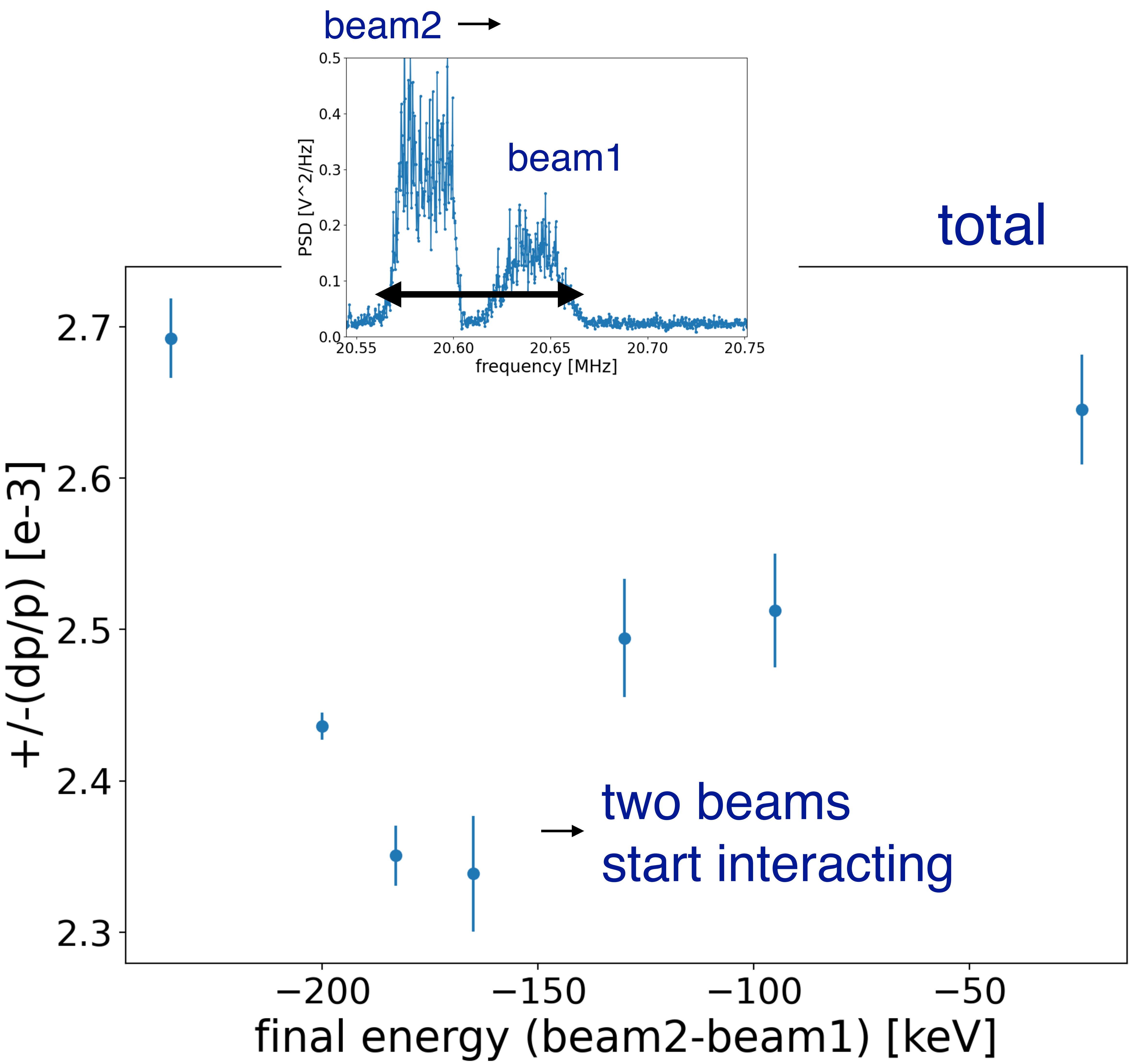
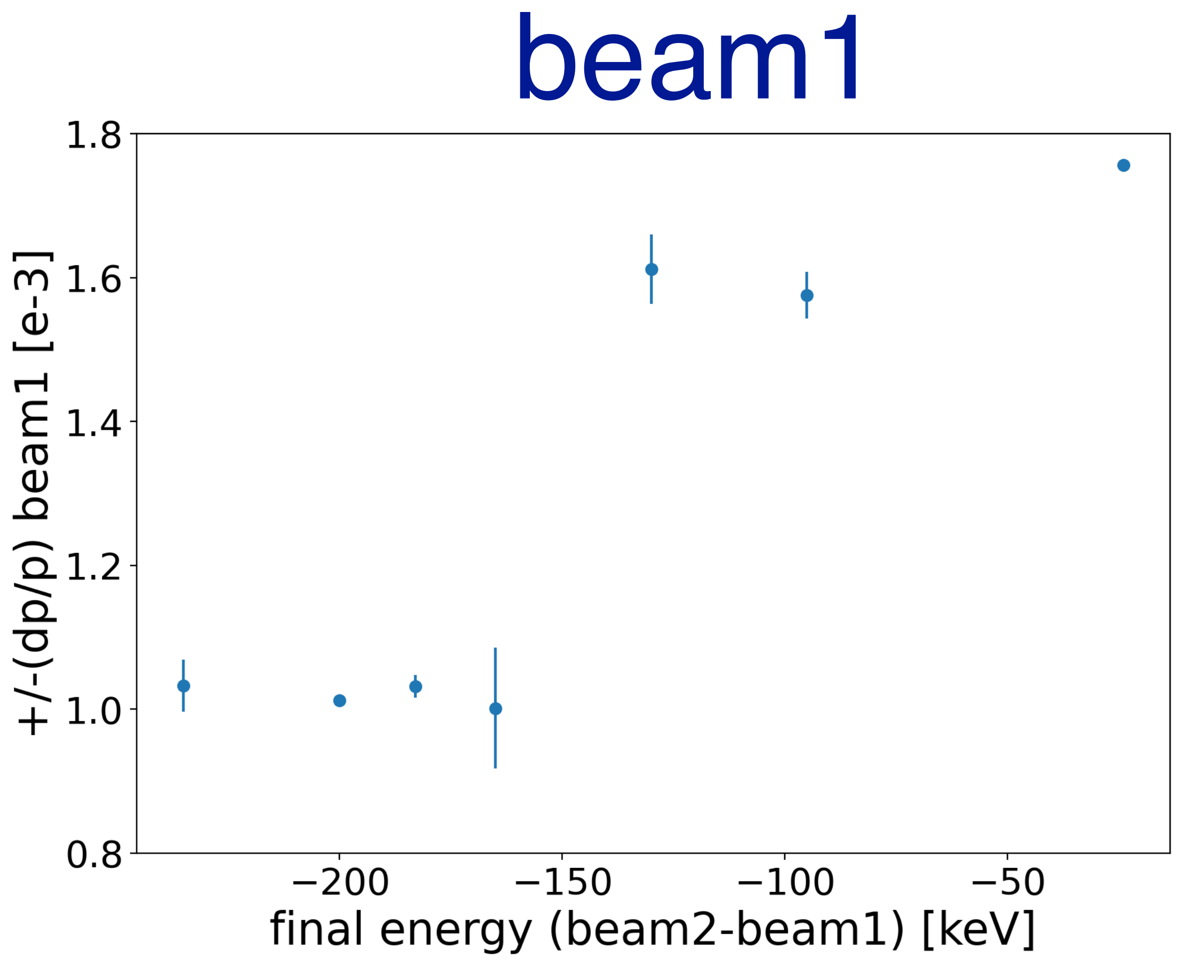
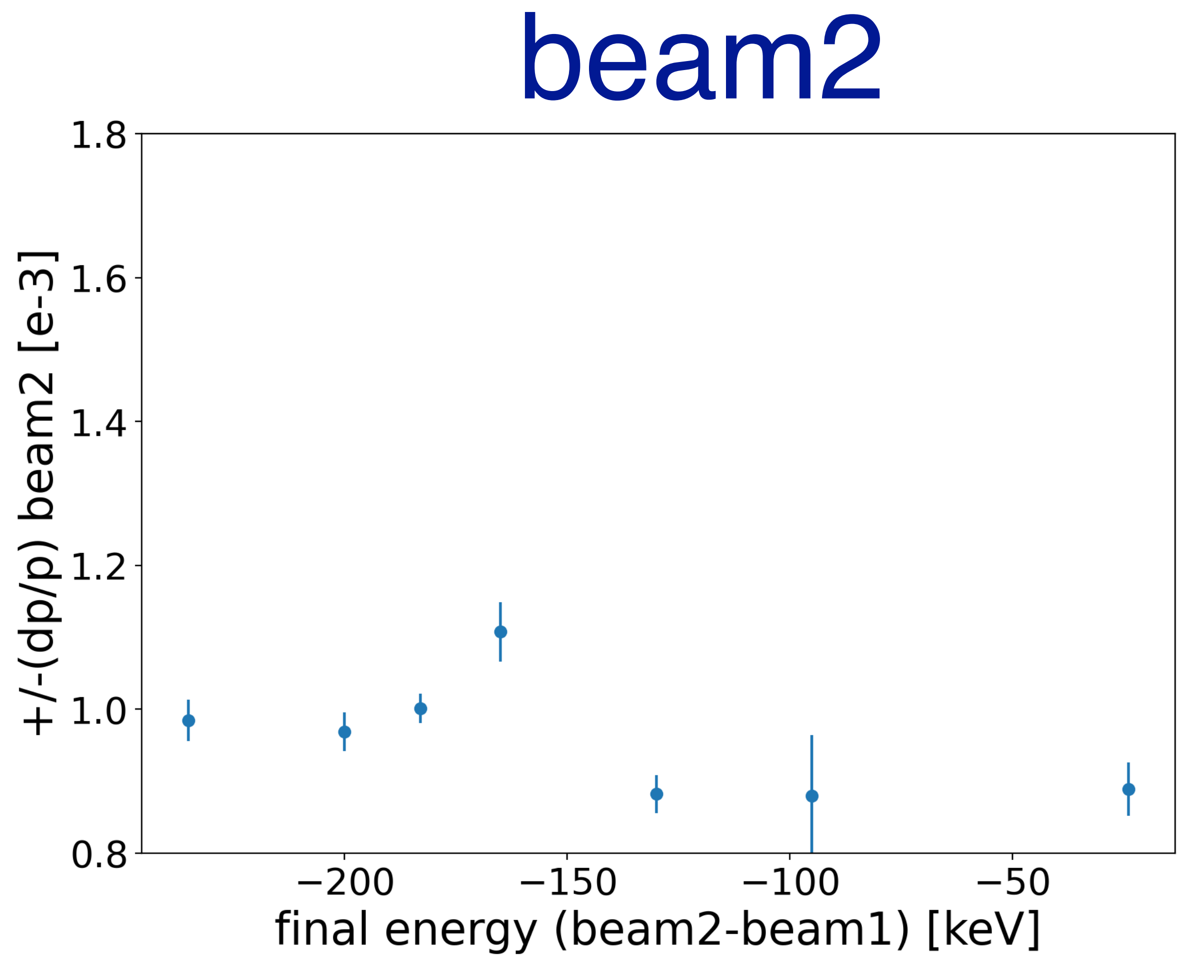
Result 1: Momentum spread dp/p







- 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.

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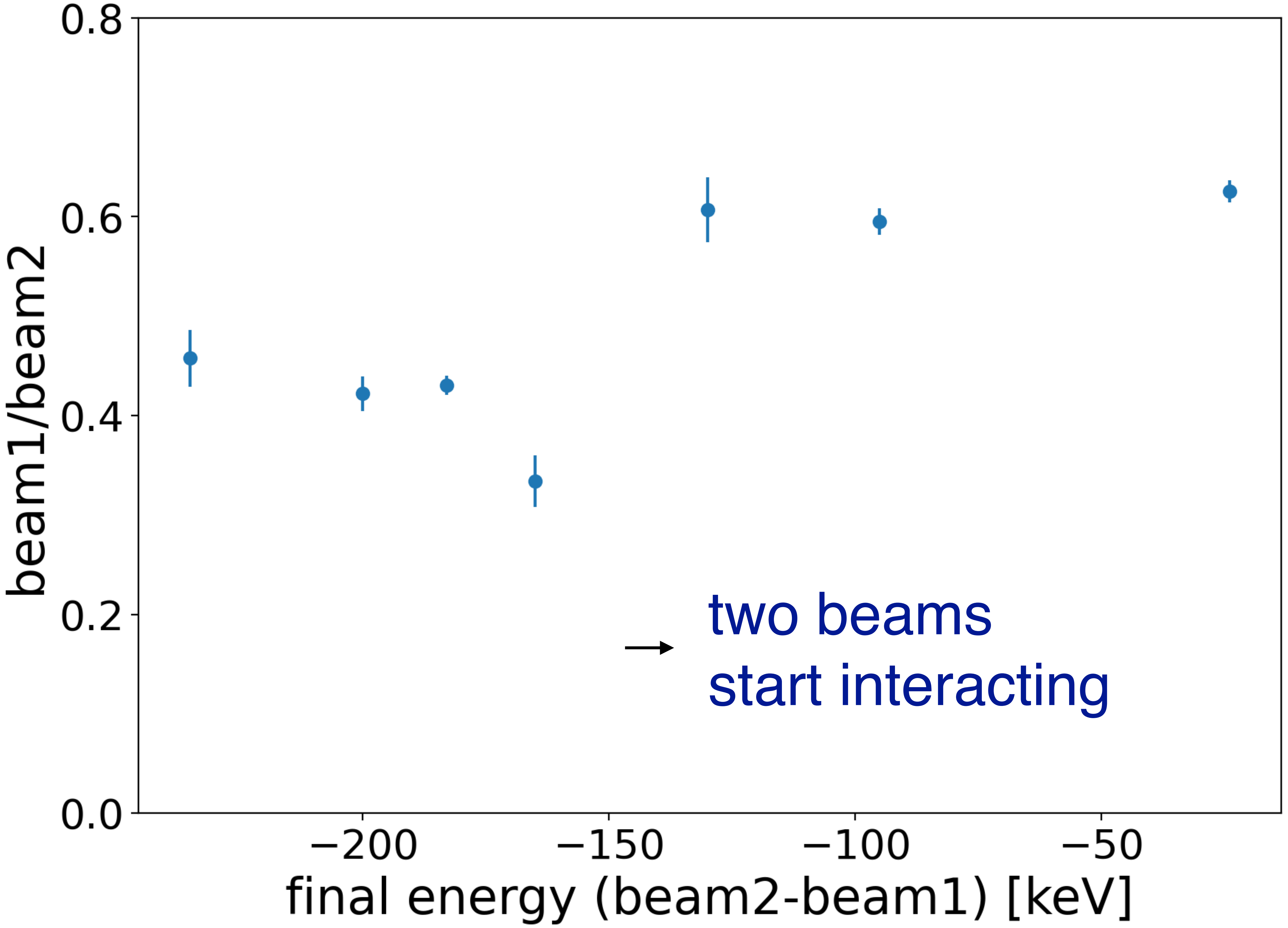
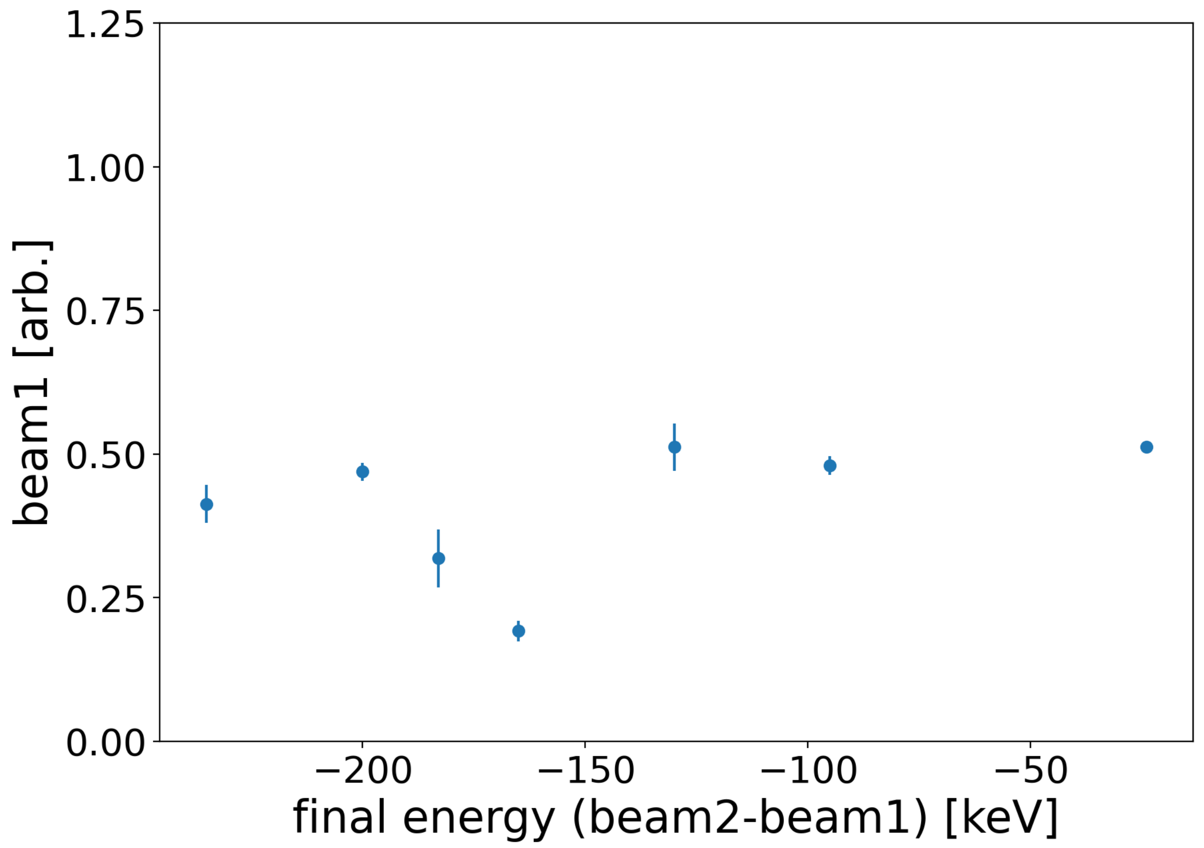
Total dp/p after stacking is slightly (~15%) more than twice of dp/p of each beam.

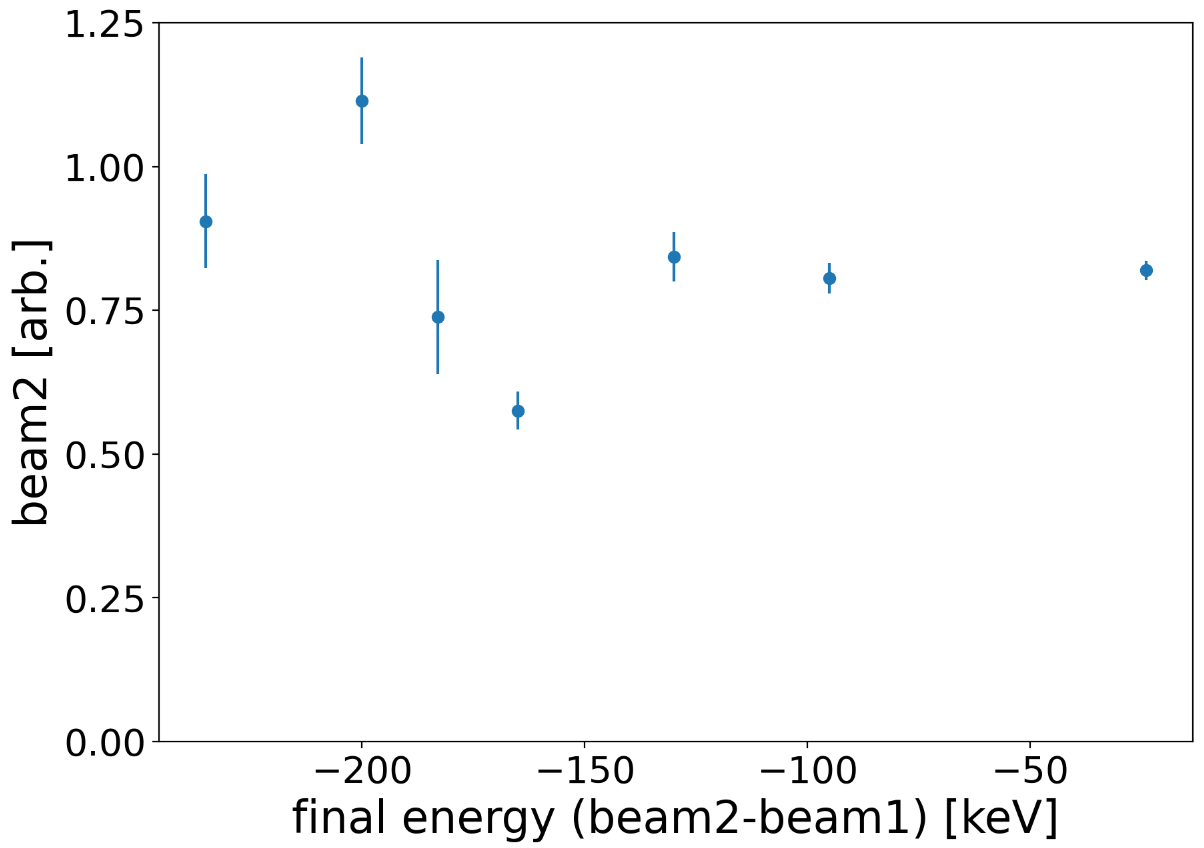
Result 2: Beam intensity



beam1



beam2

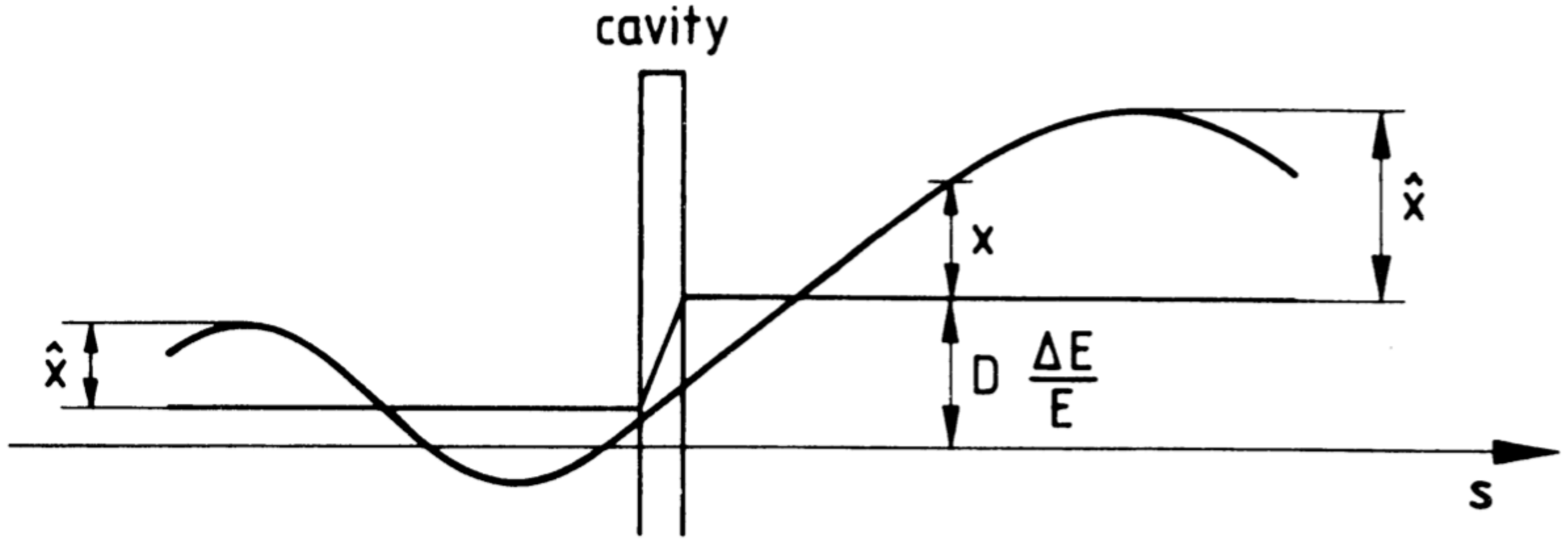


- Until two beams start interacting, the ratio of beam 1 and beam 2 is about 40% independent of final energy of beam 2.
- This is independent of beam intensity fluctuation, namely, when beam 2 is low, beam 1 is low as well giving the similar ratio.
- Ratio of beam 1 and beam 2 looks higher with interaction, but it depends on the definition of beam 1 intensity. In this analysis, beam 1 includes intensity of both sides of beam 2.

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

Similarity to synchro-beta resonance

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



from CERN-87-03

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

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

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.

$$\frac{\omega_{rev} - \omega_{RF}}{\omega_{rev}} = Q_h \text{ or } 1 - Q_h$$

Frequency component

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

$$V_{gap} \left(\mathrm{envelope} \right) = \boxed{V_0 \cos \omega_{rf} t}$$

when \omega_rf ~ \omega_ref

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

(aliasing, beat, …)

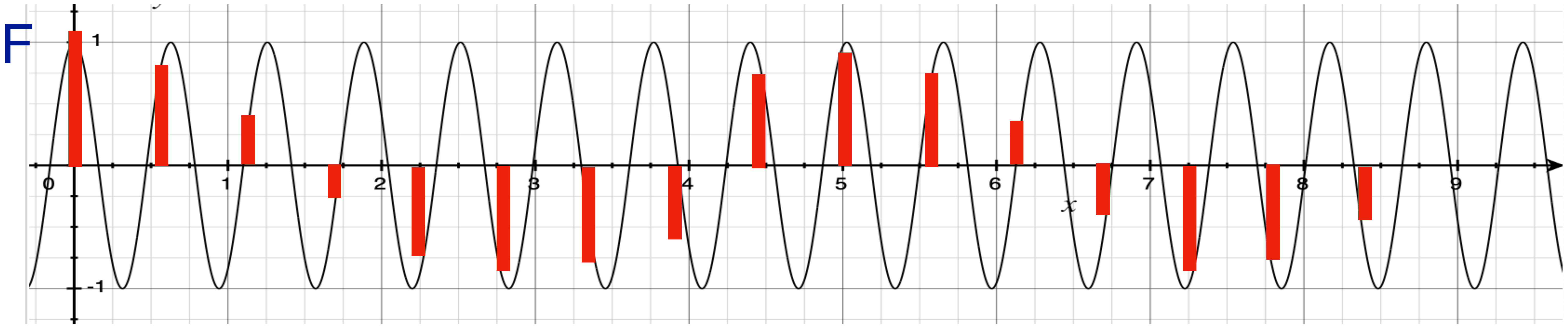
$V_{gap} \left(\mathrm{envelope} \right)$ means the lowest frequency component of RF voltage seen by the beam.

Requirement in the longitudinal direction imposes

\omega_rf > (1/2) \omega_rev

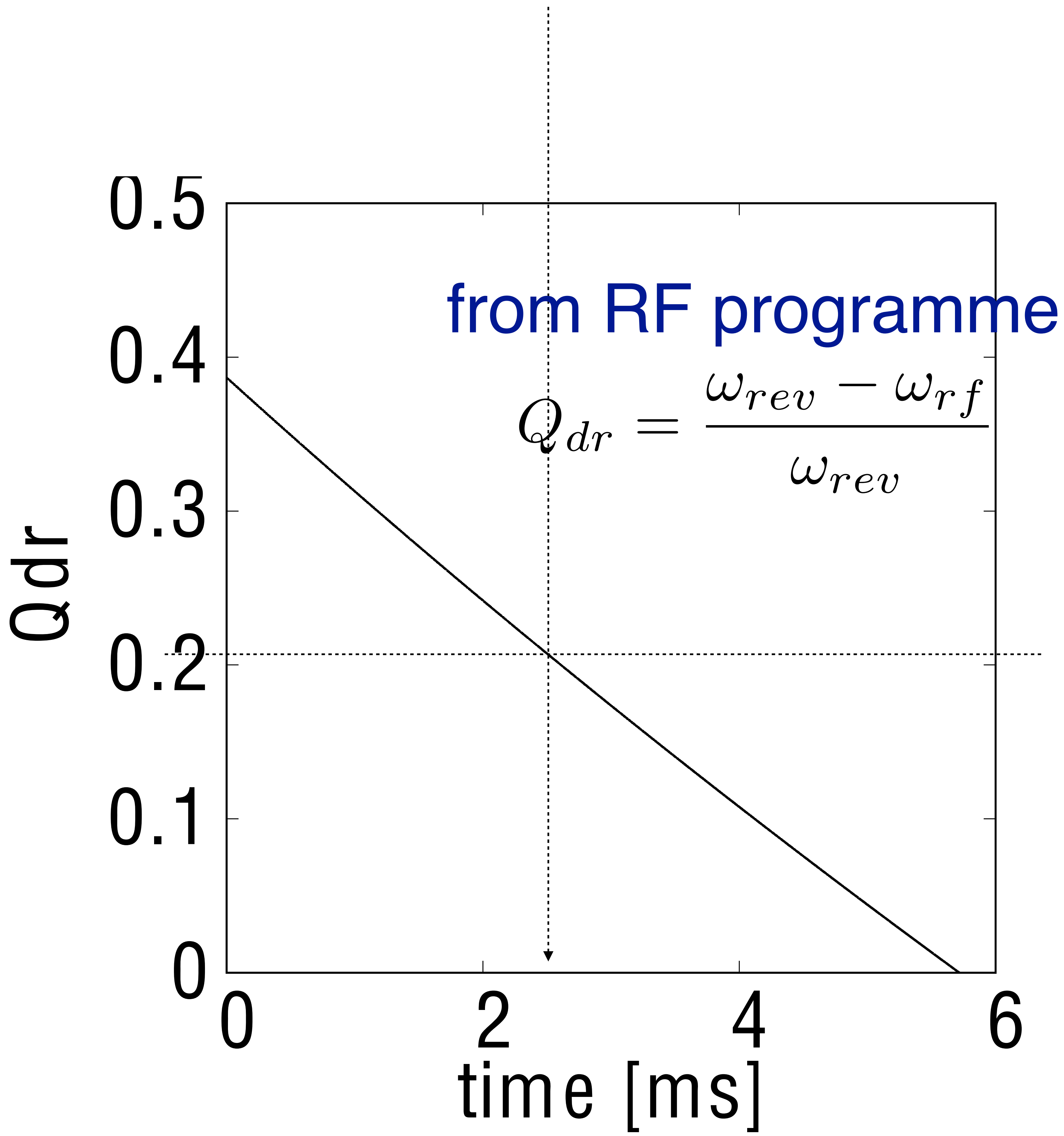
RF voltage seen by the coasting beam

f_rf < f_rev



Simulation with KURNS 3D field map

Qh = 0.79   or 1-Qh = 0.21

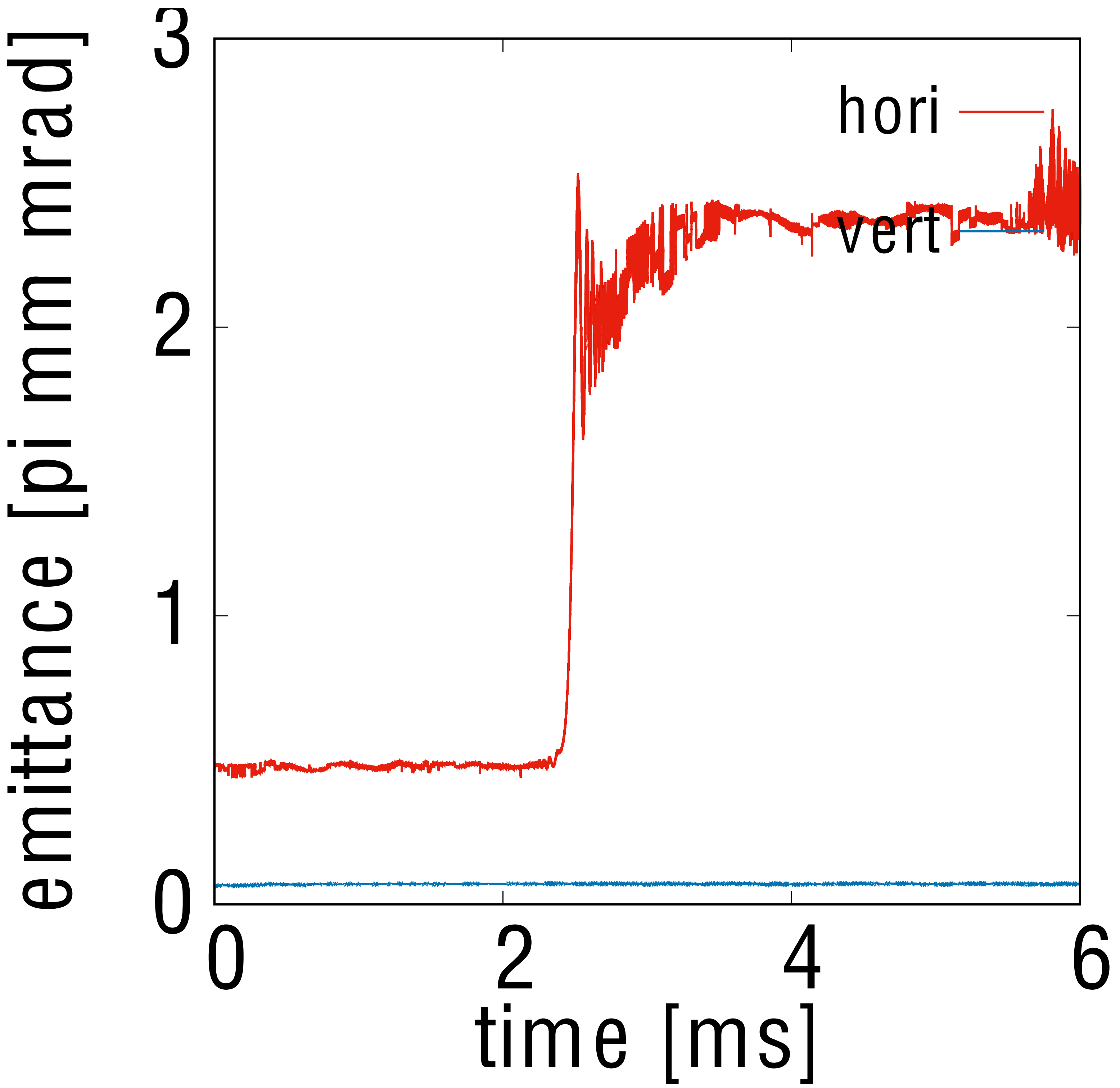


from RF programme

$$Q_{dr} = \frac{\omega_{rev} - \omega_{rf}}{\omega_{rev}}$$

We should see something at ~2.5 ms

horizontal emittance growth
at ~2.5 ms.

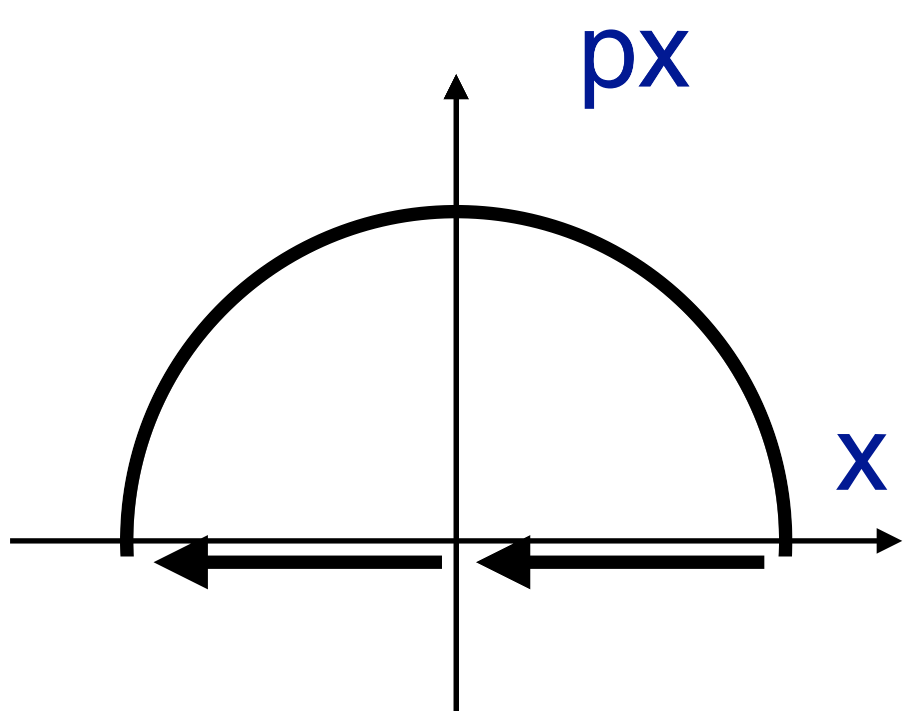


Proposed mitigation methods (from MURA papers)

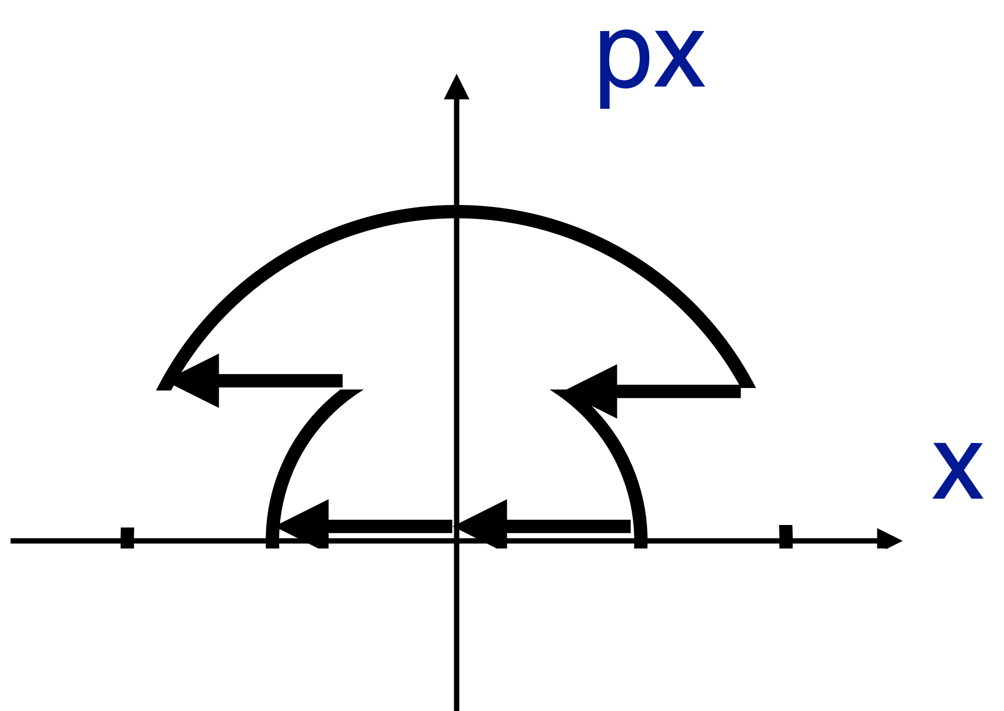
- For a ring with single RF cavity
  - Reduce voltage around resonance
  - Control betatron phase around resonance by changing tune for short time (like a jump around transition energy crossing).

- 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.

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Summary

- High intensity is the primary goal of the FFA development at the start.
- Many ideas were there, but hardware was not enough 50 years ago.
- Rebirth of an FFA provides the necessary hardware to achieve the initial goal.
- Now time to revisit the initial idea with the state of the art equipement.
- Demonstration of a high intensity FFA is the immediate next step.