FFA for ISIS upgrade

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Collaboration meeting with CSNS

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ISIS Neutron and Muon Source

ISIS upgrade plan: ISIS-II

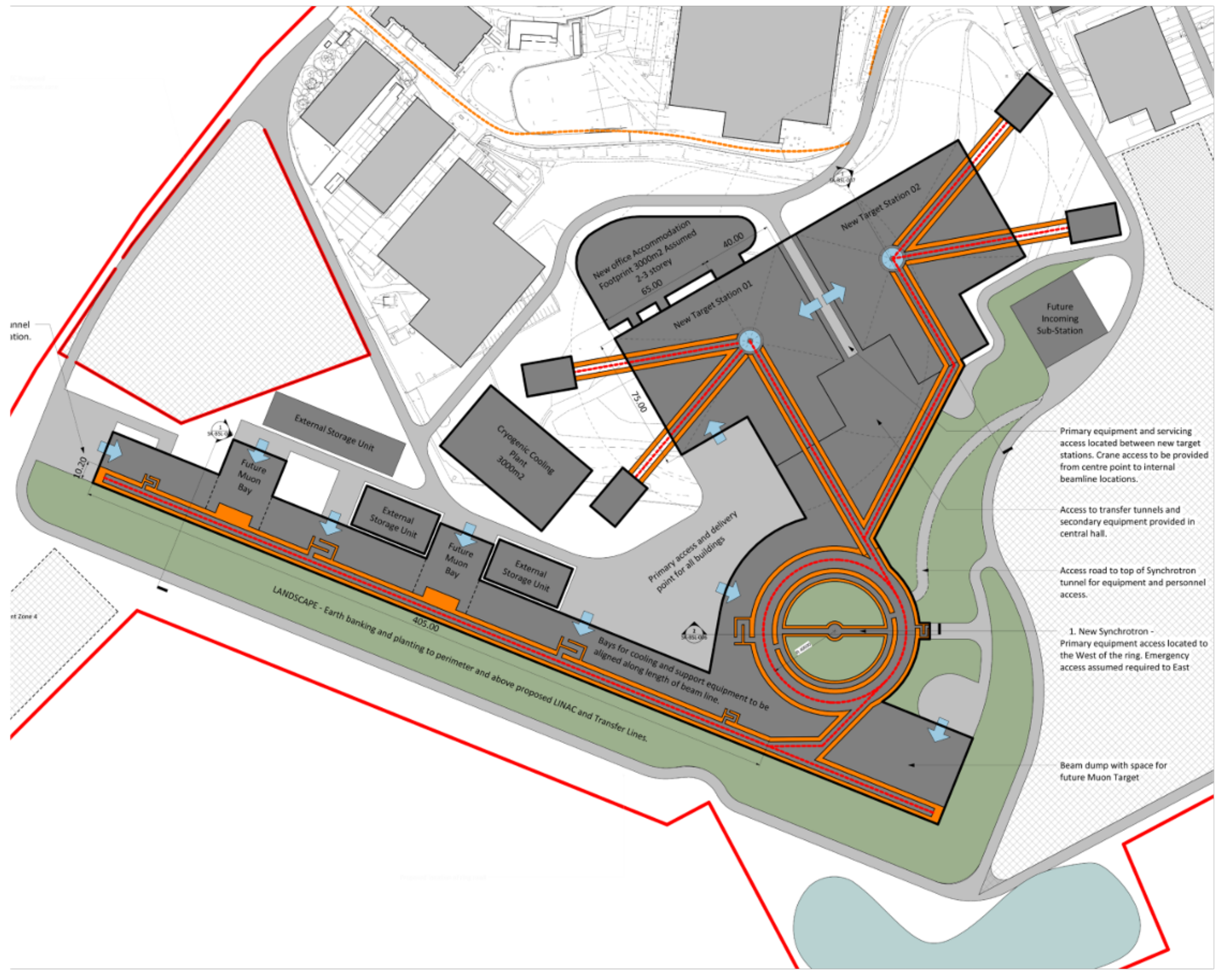
- Choice of the proton driver
  - Rapid Cycling Synchrotron (RCS)
  - Accumulator Ring with a full energy linac (AR)
  - Fixed Frequency Alternating Gradient (FFA)

- Demonstration of a high intensity FFA has to be made
  - A demonstrator FFA ring downstream of Front End Test Stand (FETS-FFA)
  - Named “FETS-FFA”

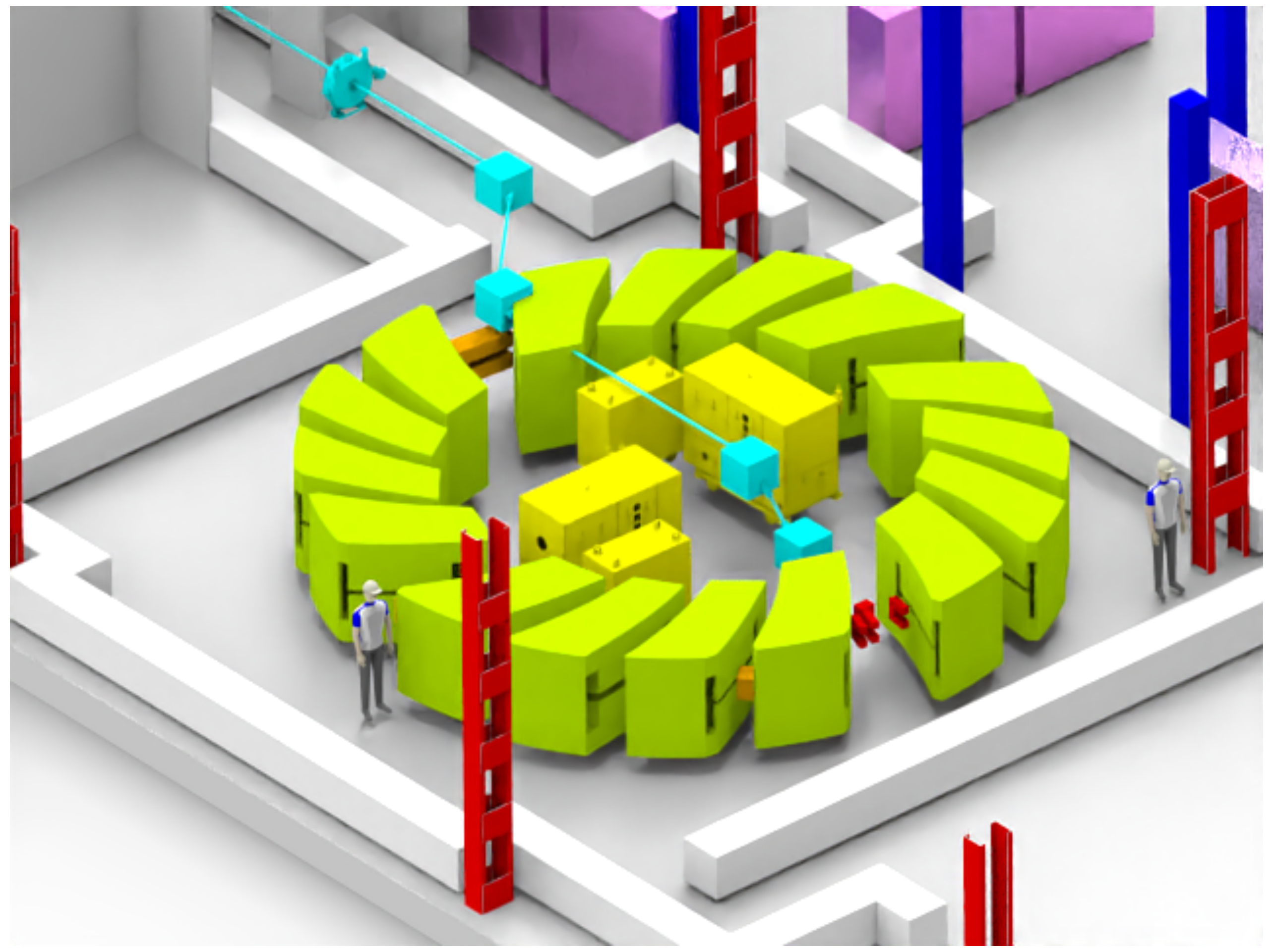
ISIS-II and FETS-FFA, parameters

FETS: Front End Test Stand

	ISIS-II	FETS-FFA
Beam power	**2.4 MW**	32 W (max.)
Kinetic energy	0.4 (0.5) - 1.2 (1.8) GeV	3 - 12 MeV
Repetition	15, 45 Hz	100 Hz (50 pps)
Circumference	150 - 300 m	28 m



RAL site



FETS-FFA ring

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Objectives

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	~ 32 W

- Novel lattice with
  - FD(DF) spiral focusing for **tuneability**, essential for a high intensity accelerator.
  - Superperiod structure to **increase some of straight sections** for injection and extraction.
- Large dynamic aperture.
- Injection painting similar to synchrotron.
- Fix injection radius and move the extraction system if necessary when k-value changes.
- Enough charge current to demonstrate **space charge effects in an FFA**.
- **Beam stacking** for flexible operations.

- Absolute current is low. No issue of coherent instability.

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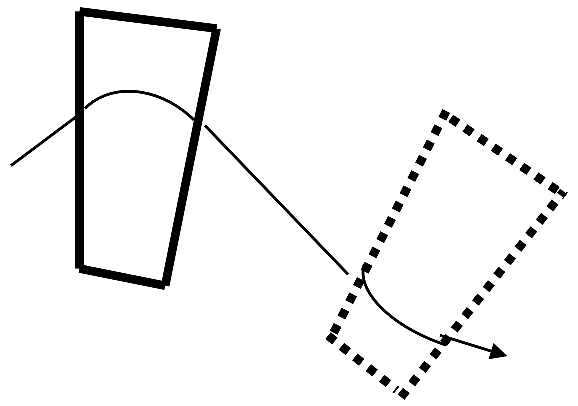
FETS-FFA design

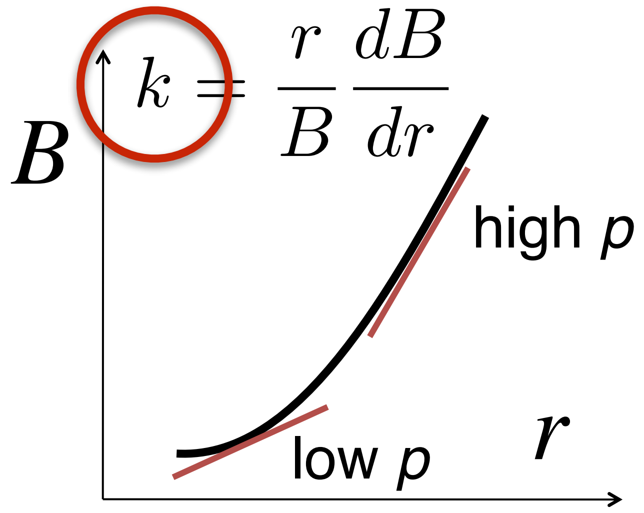
Novel lattice
DF(FD) spiral

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

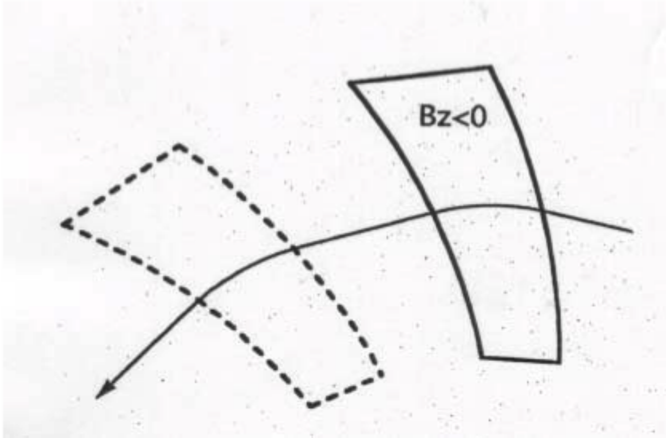
Flexibility of operating point (transverse tune) is essential for high intensity operation (Qh ~ Qv).

radial sector



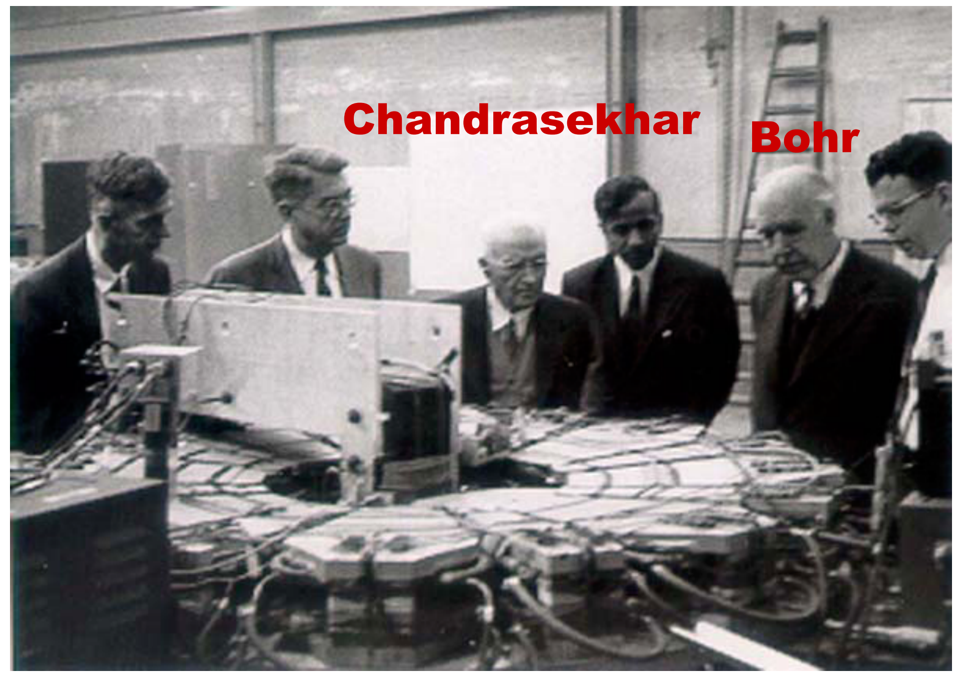


spiral sector

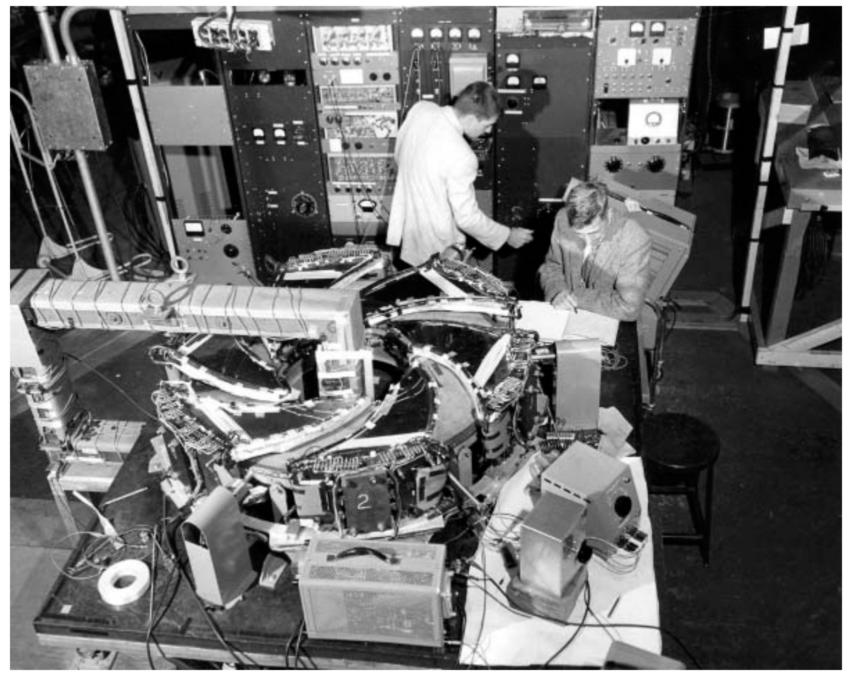


Alternating gradient focusing by focusing (normal bend) and defocusing (reserved bend)

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



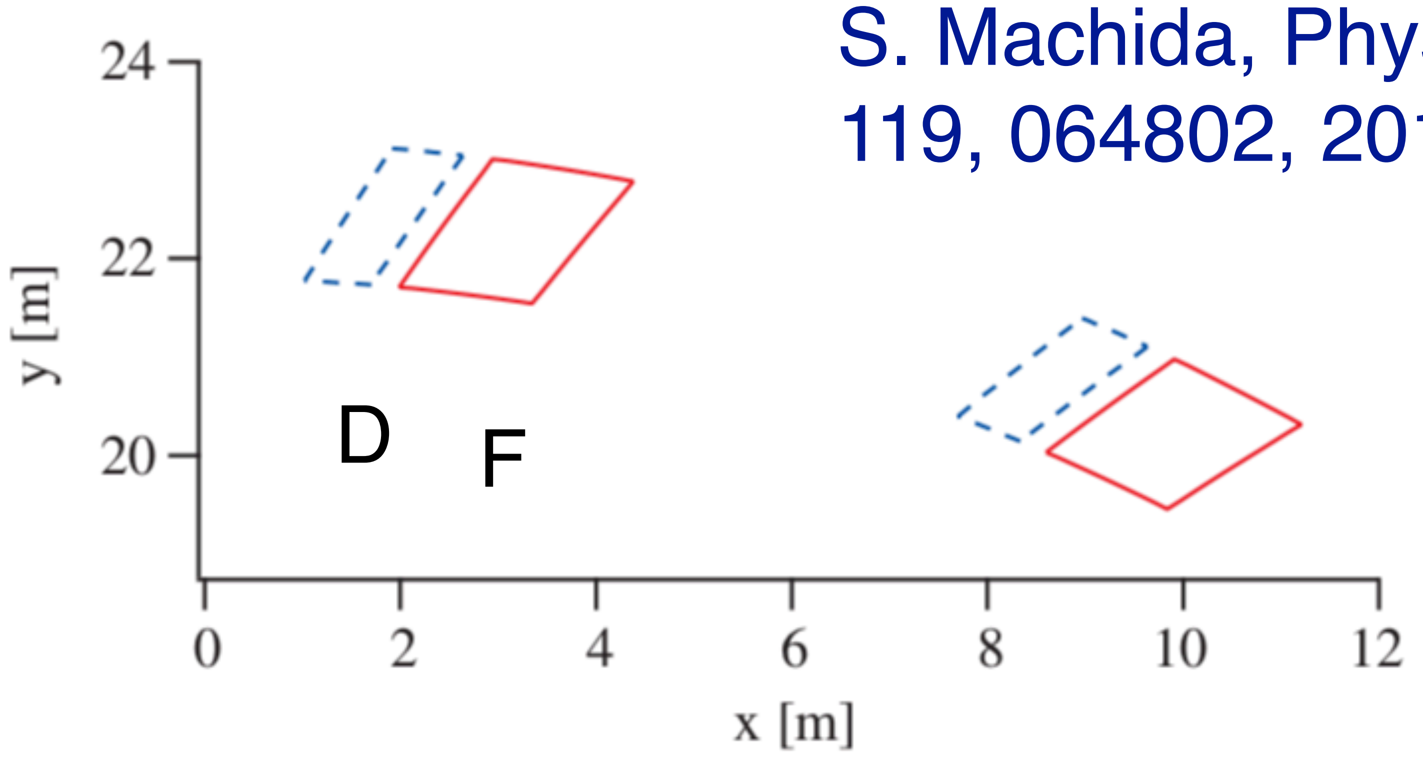
400 keV radial sector



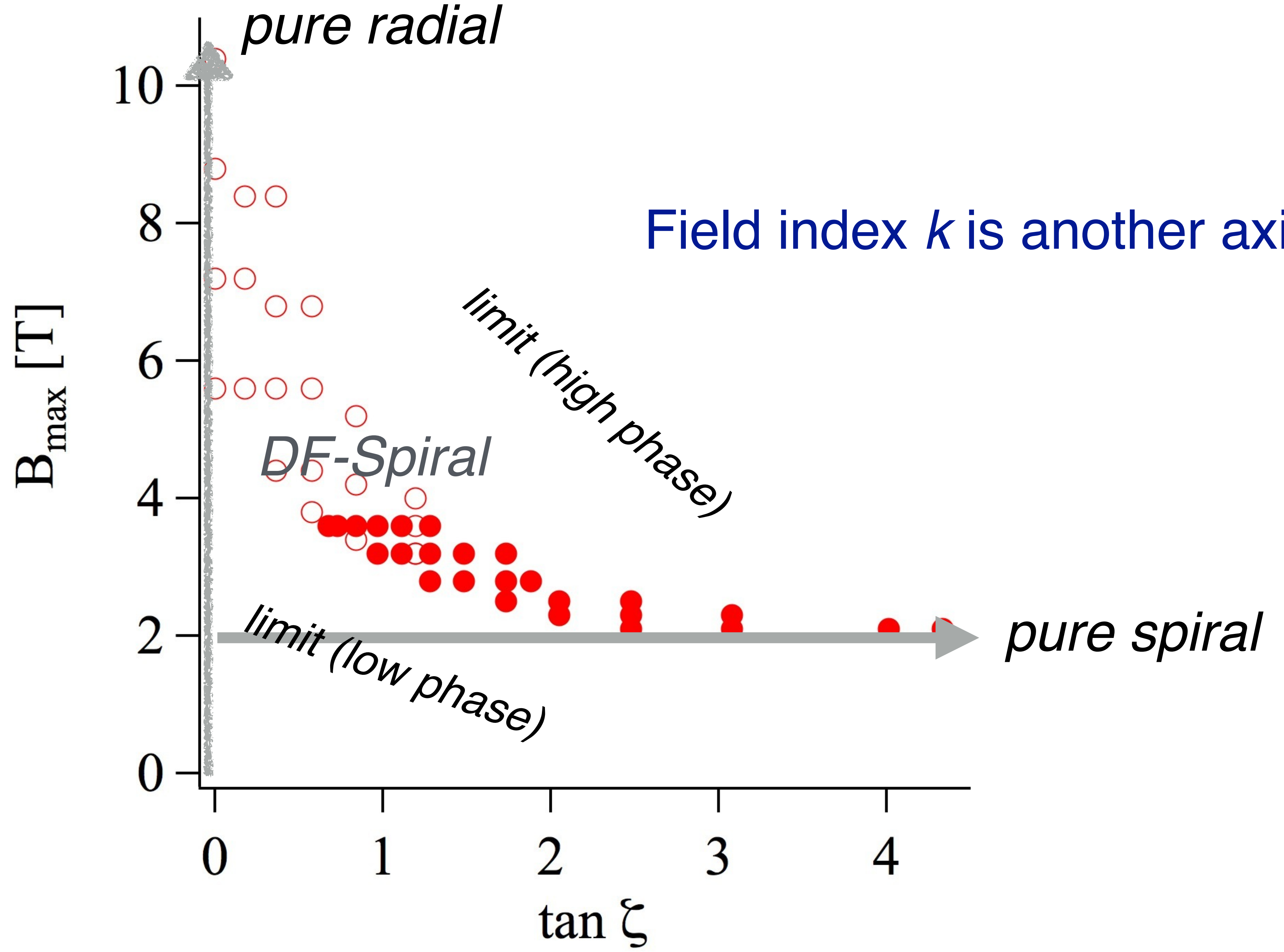
180 keV spiral sector

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

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



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

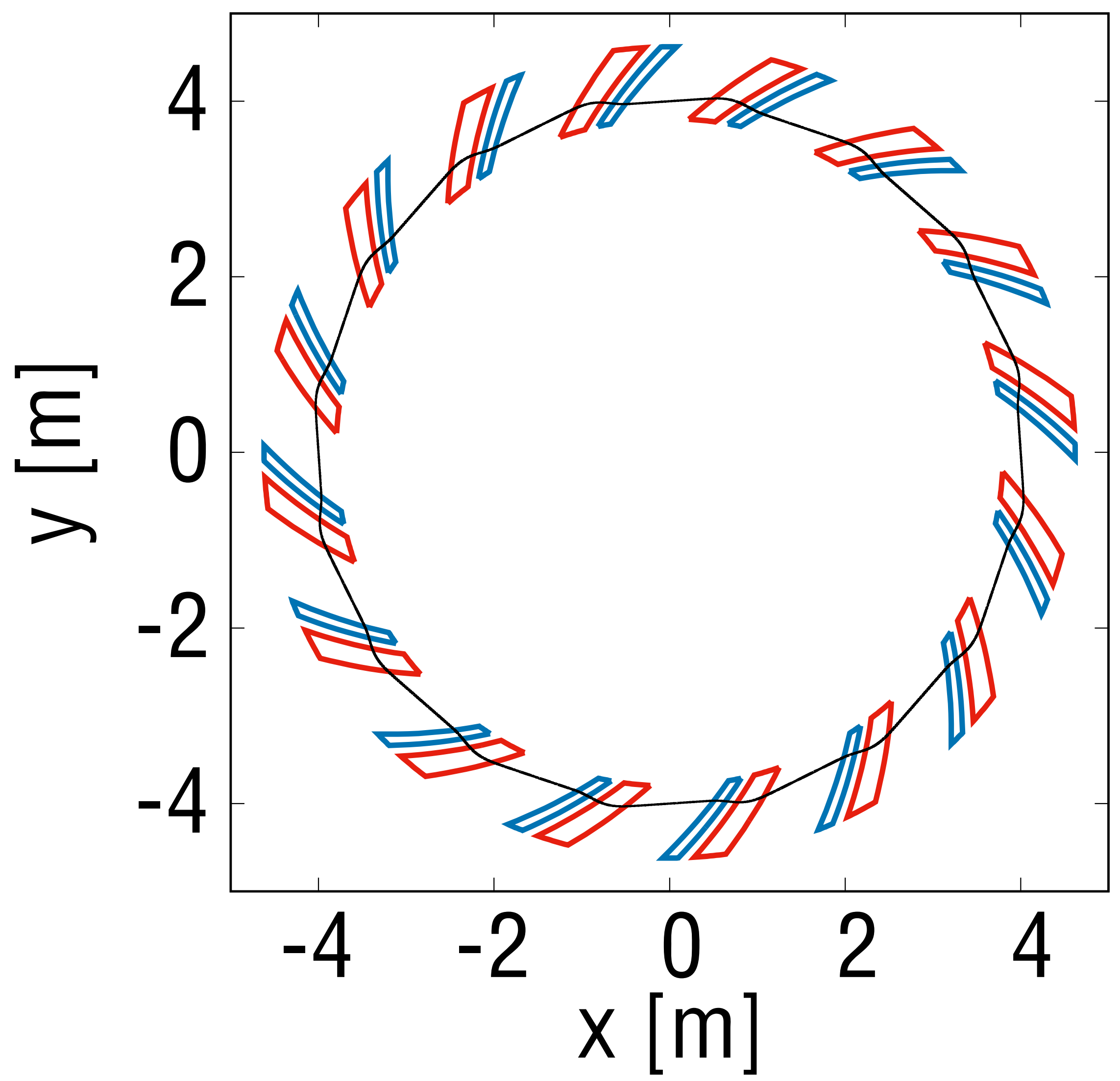


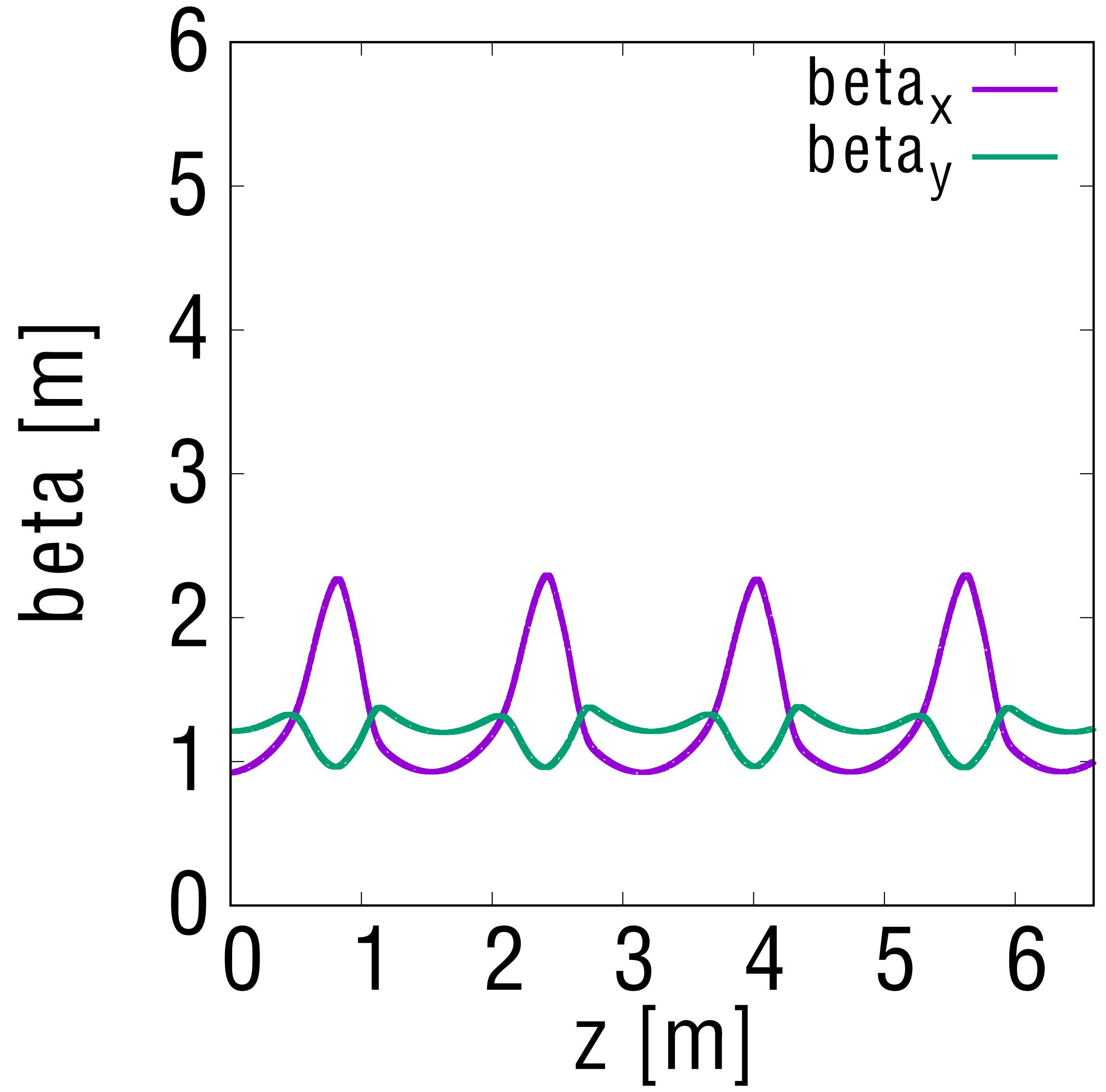
Field index *k* is another axis

Novel lattice

Superperiod structure

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

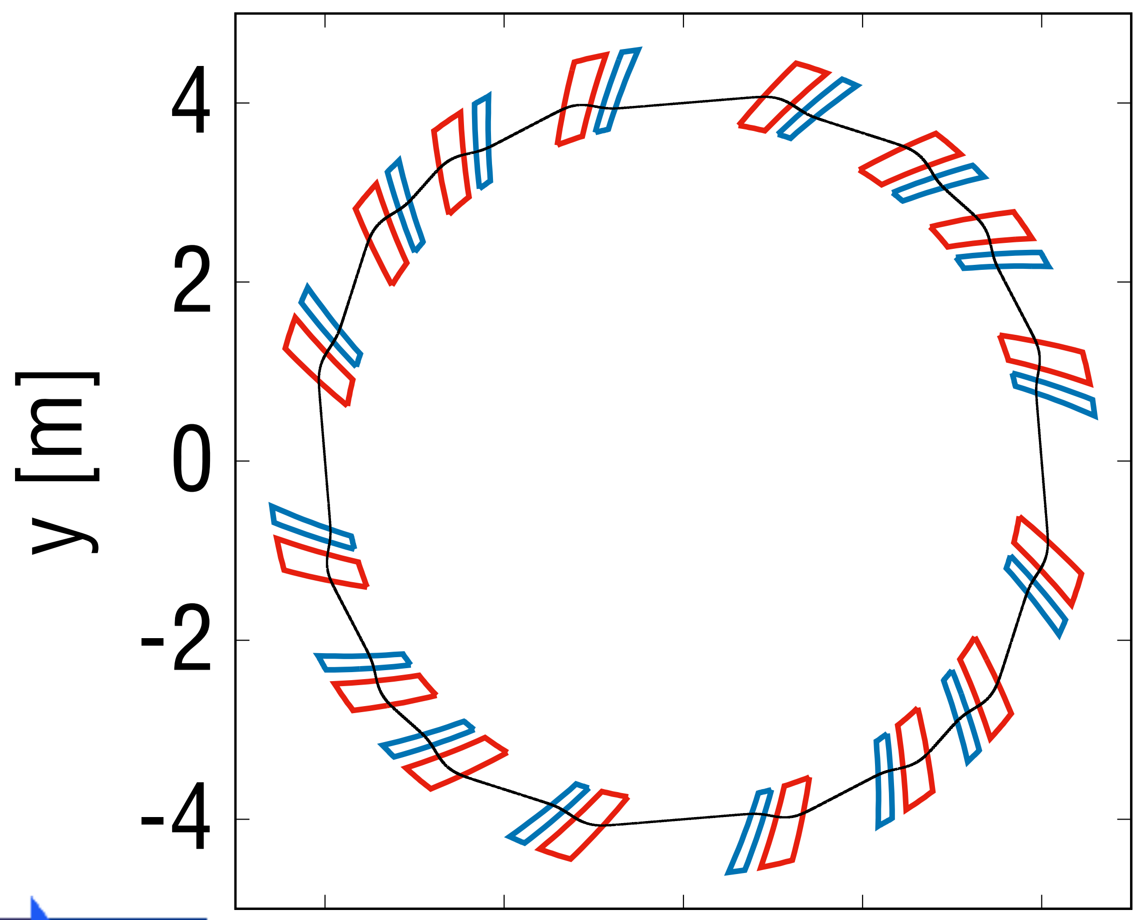


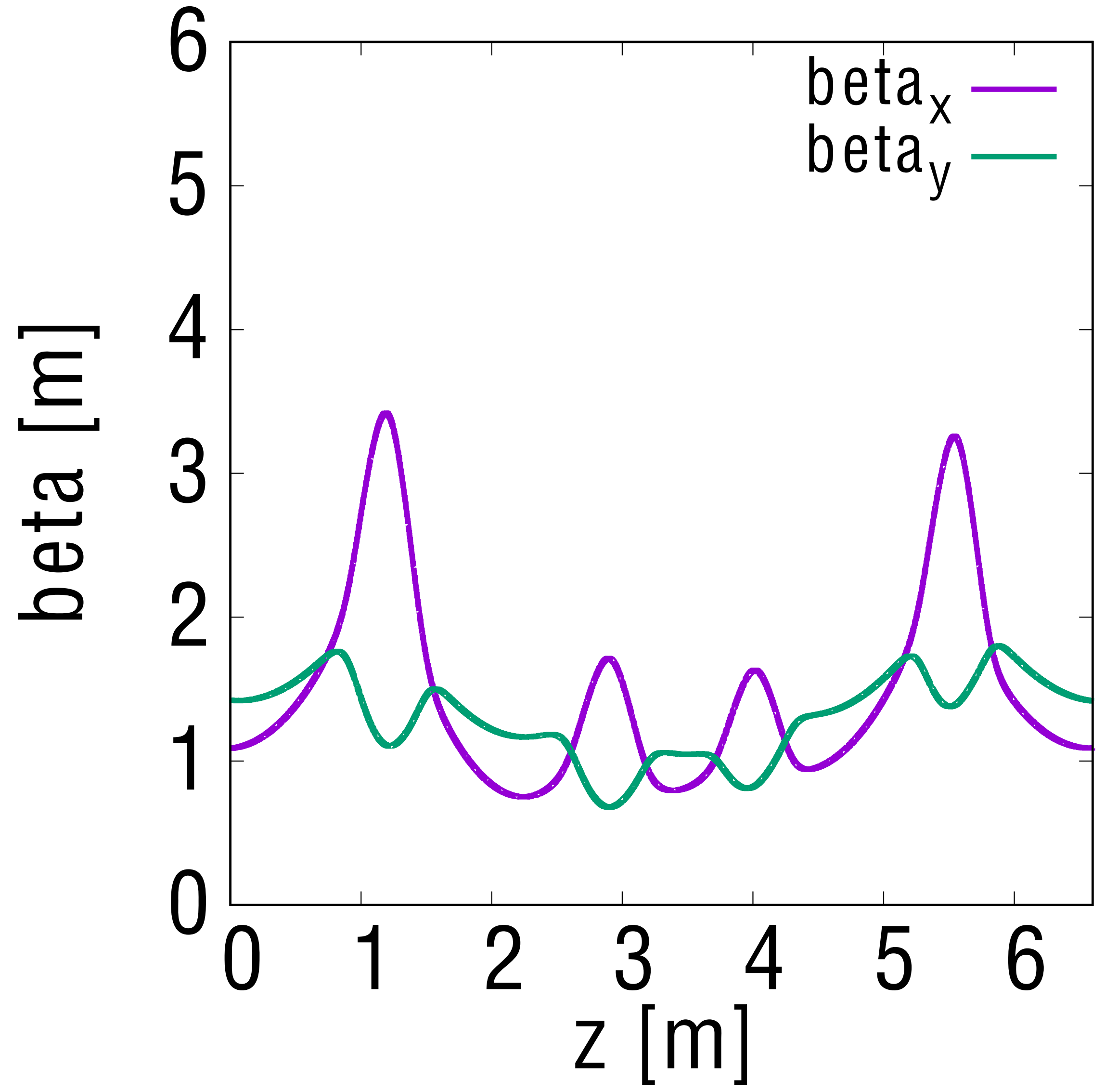


16-fold symmetry

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

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



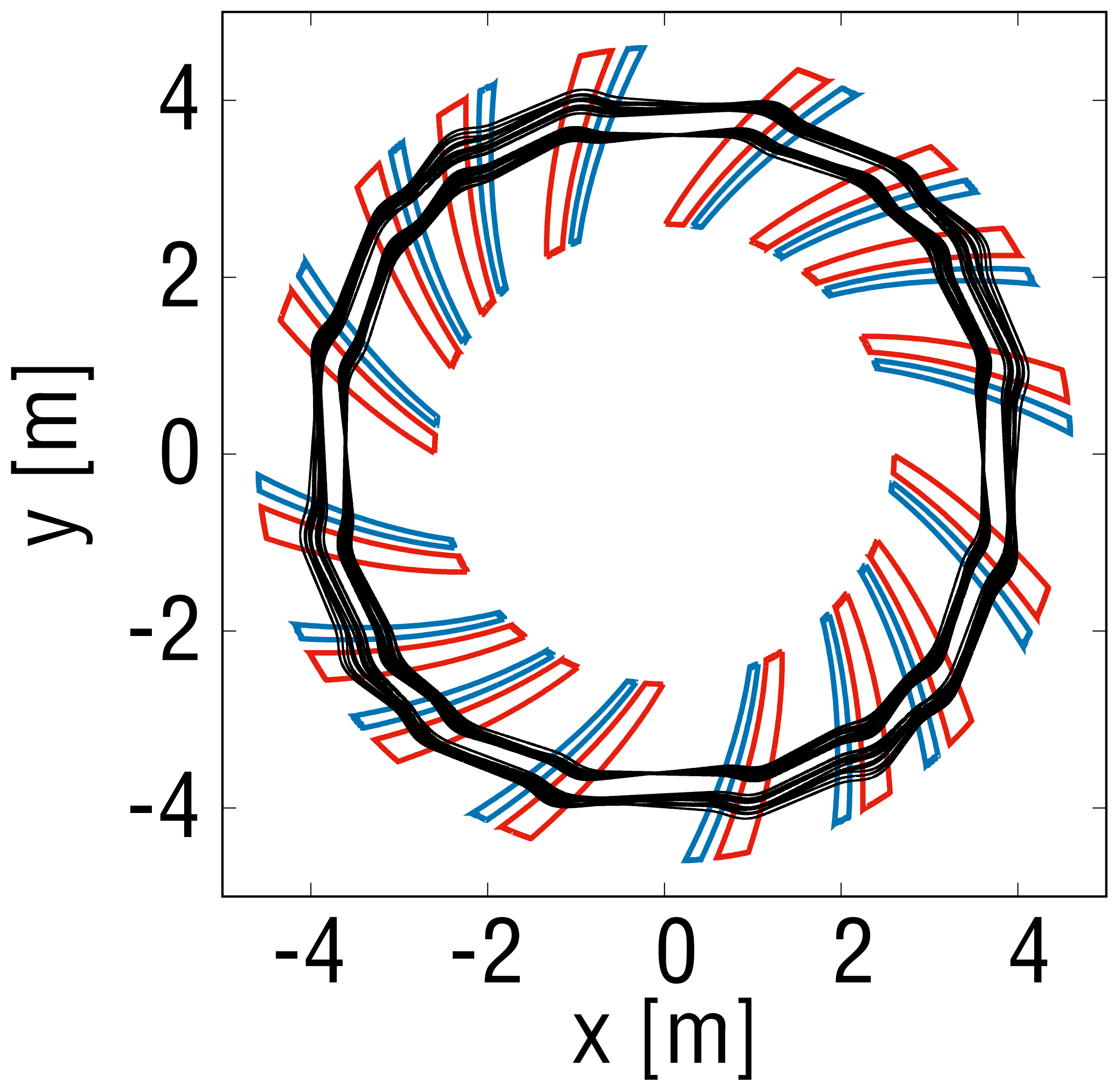


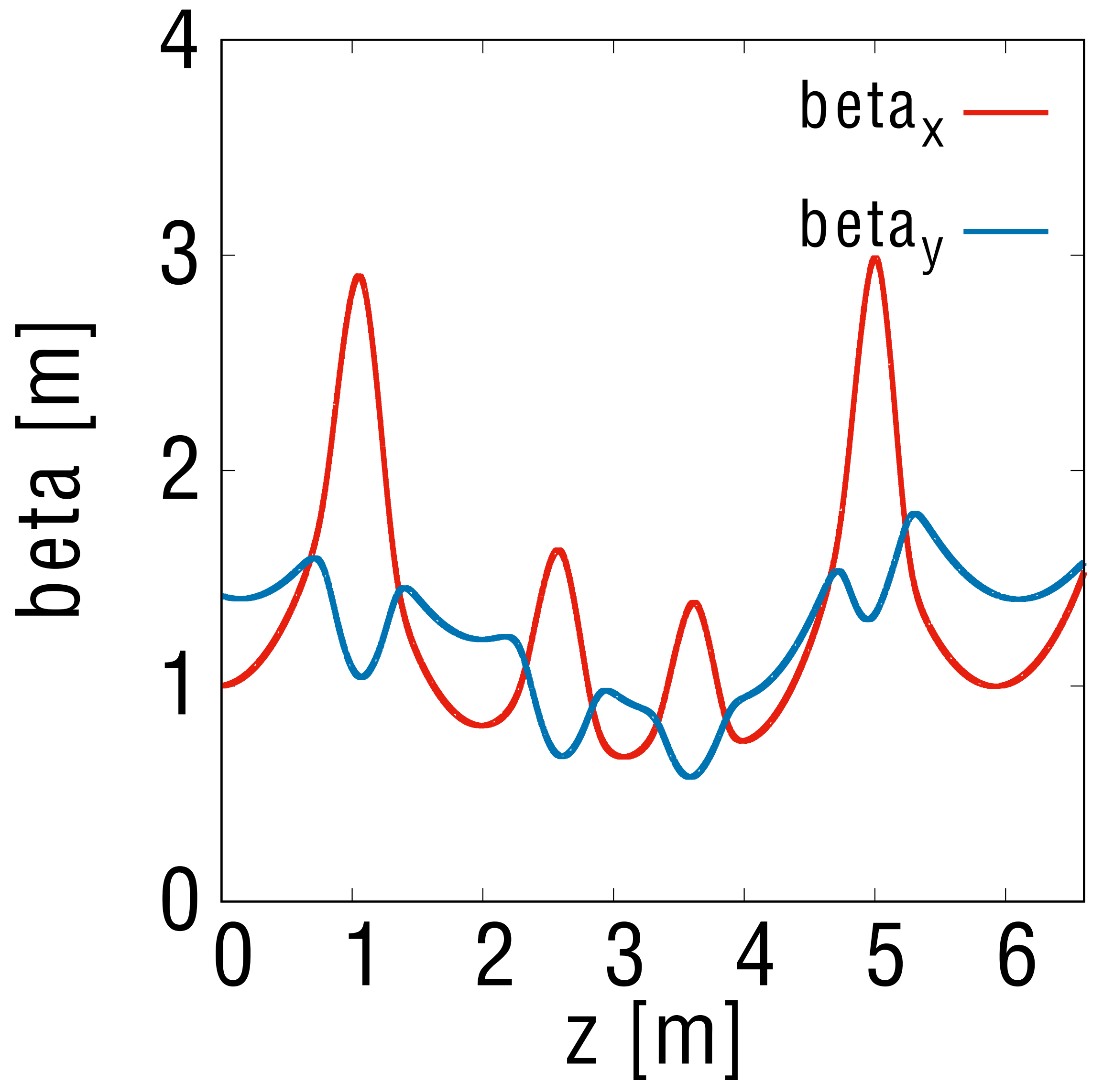
4-fold symmetry

- 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.

Optics baseline





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

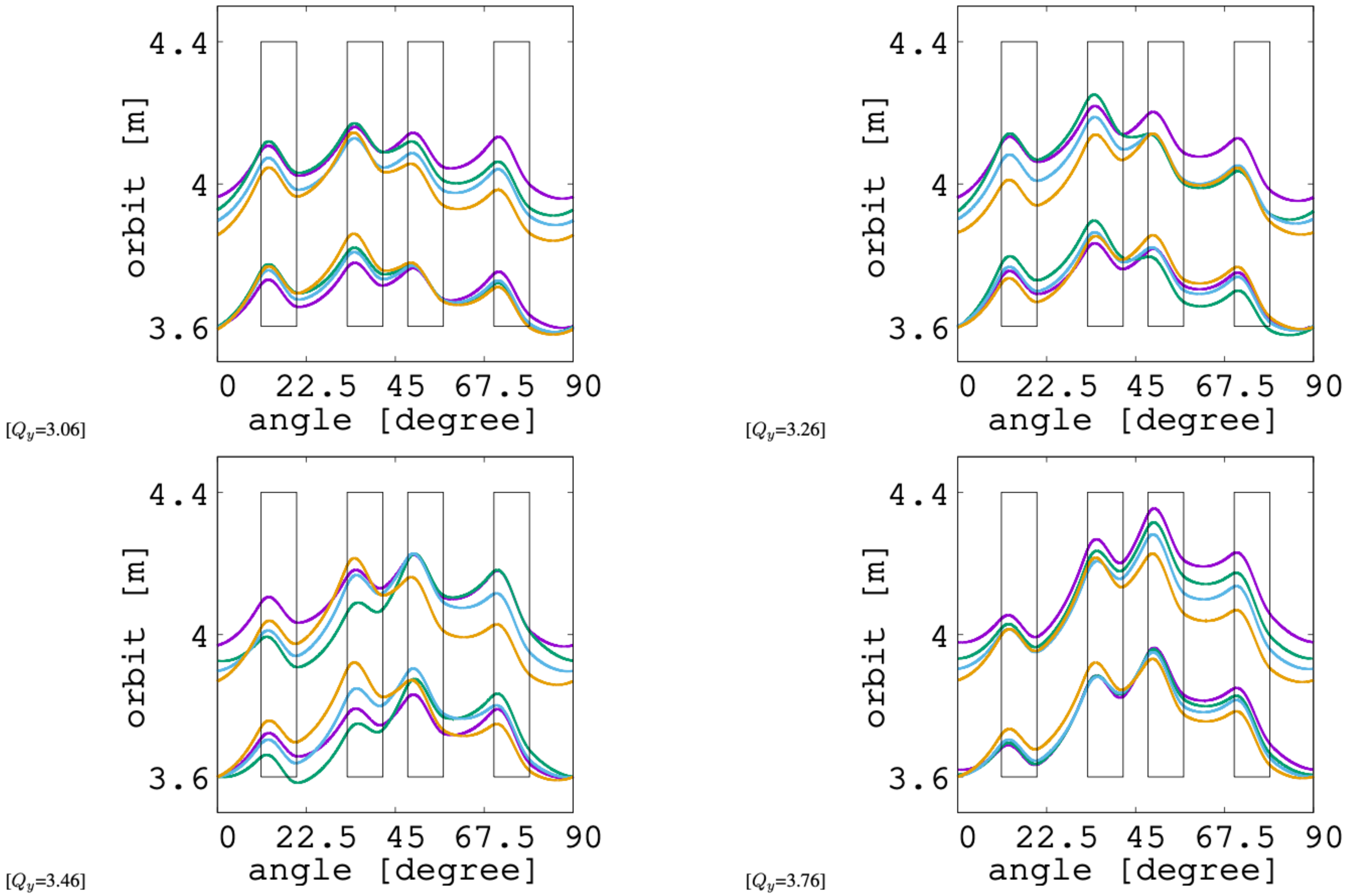


Figure 2.8: 3 MeV and 12 MeV orbits for 16 operating points.

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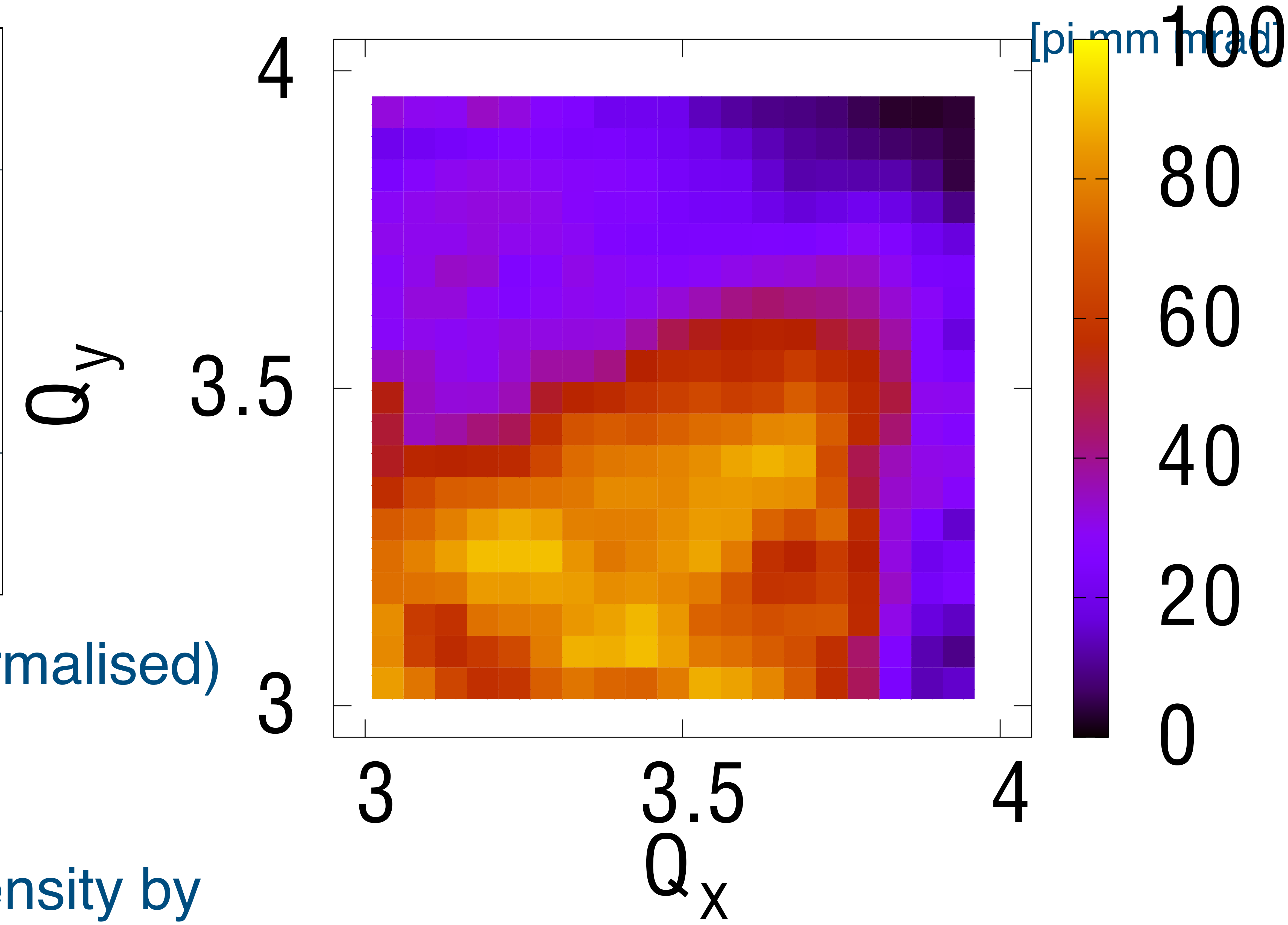
Dynamic aperture

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)

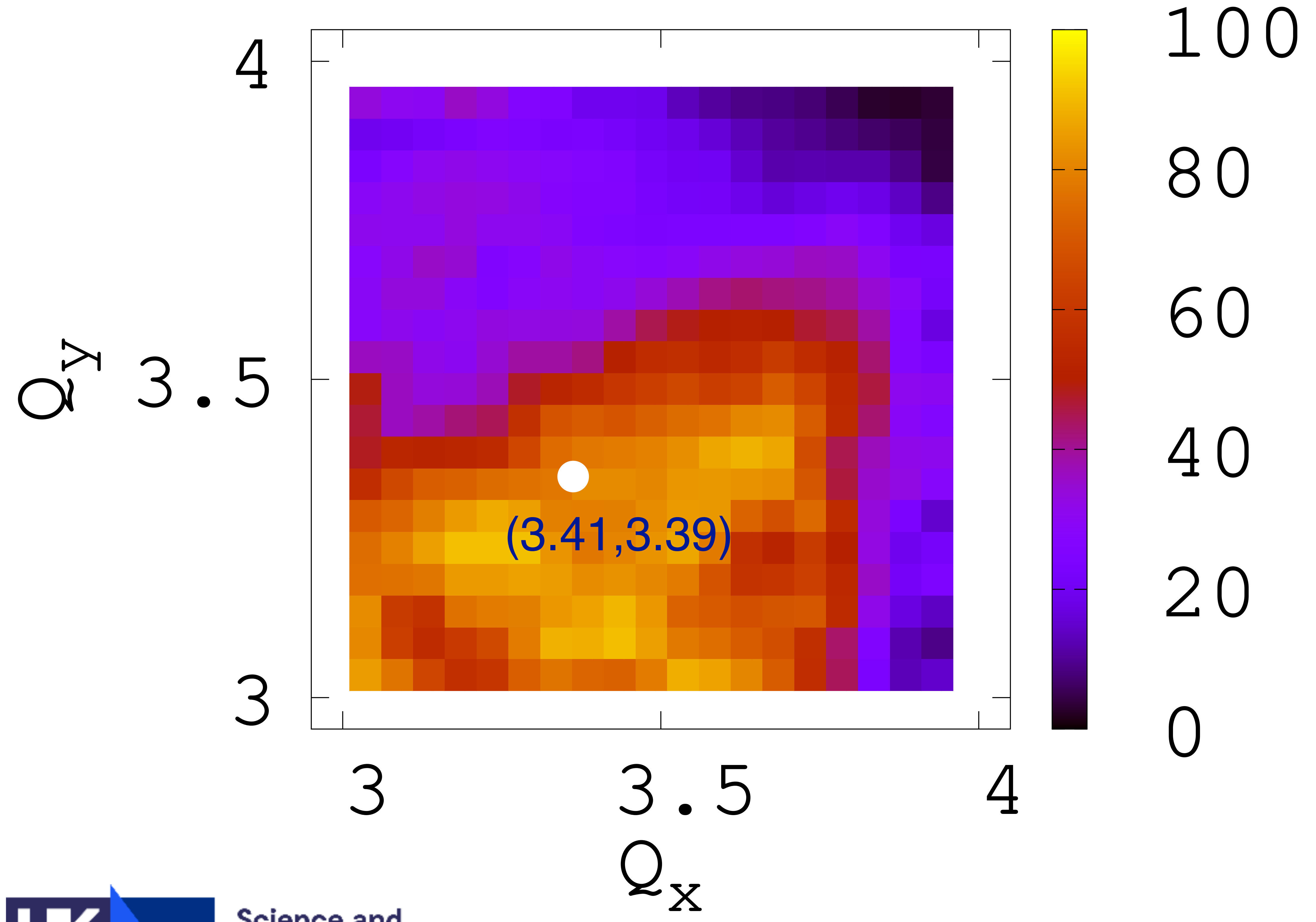
$$\Delta Q = -\frac{r_p n_t}{2\pi\beta\gamma^2\varepsilon_n B_f} = -0.12$$ per 10^{11} protons.

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

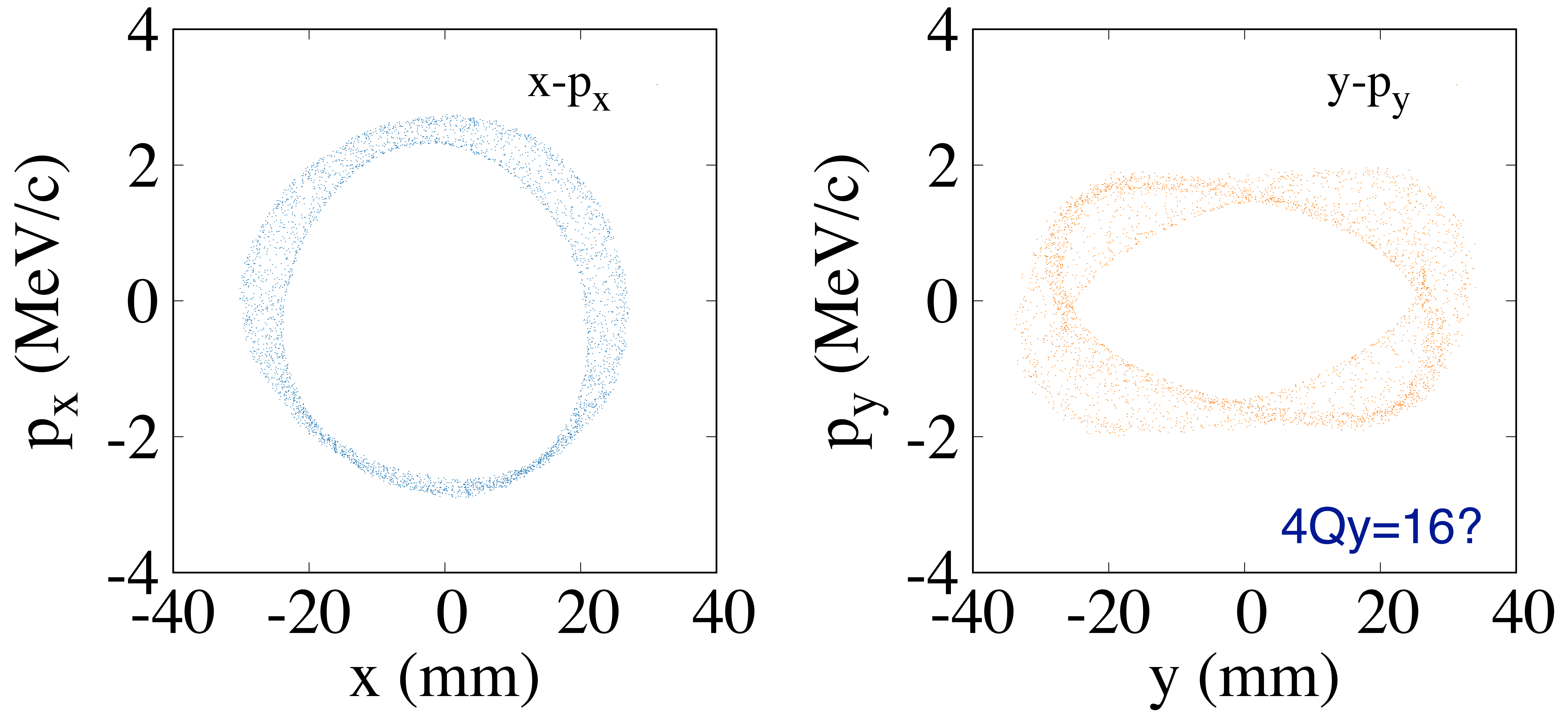
0.25 pi mm mrad, 60 mA
-> 0.02 pi mm mrad, 1 mA (50 turns for 3×10^{11})

Limiting sources of dynamic aperture

- An FFA consists of highly nonlinear magnets.
- Reduction of dynamics aperture would be a concern.
- Identifying the limiting source of dynamic aperture must be done.

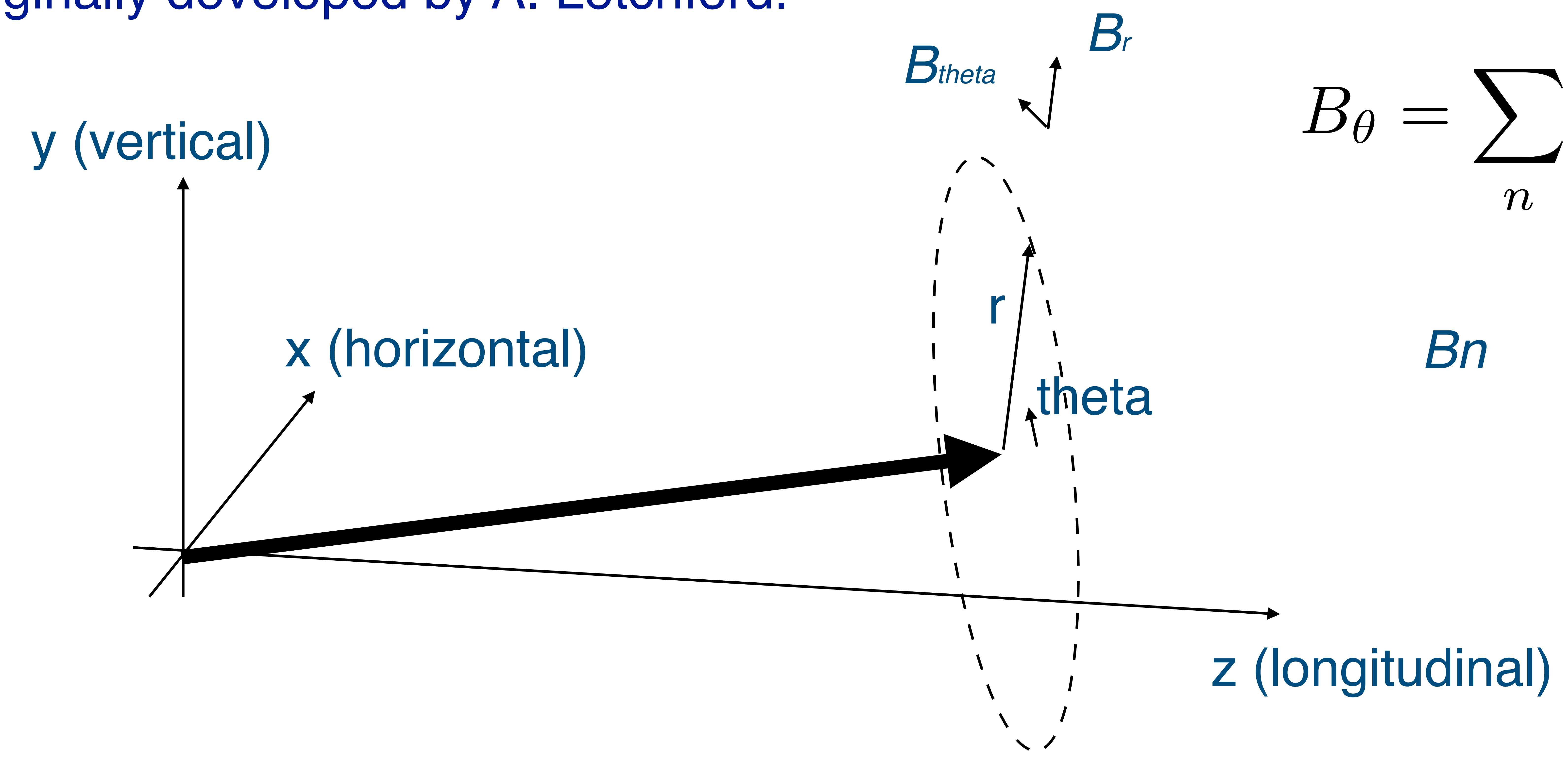


Trajectory of the outer most particle at (3.41,3.39)



Multipole expansion along a closed orbit

- Lumped multipole elements (dipole, quadrupole, or combined function magnet) plus edge focusing give no longer a good optics model.
- Reconstruct optics model by multipoles expansion along the closed orbit.
- Study effects of nonlinearities as well as linear optics.
- Originally developed by A. Letchford.



$$B_\theta = \sum_n B_n \exp\left(in\theta\right)$$

Bn

n=1: dipole
n=2: quadrupole
n=3: sextuple
n=4: octuple
…

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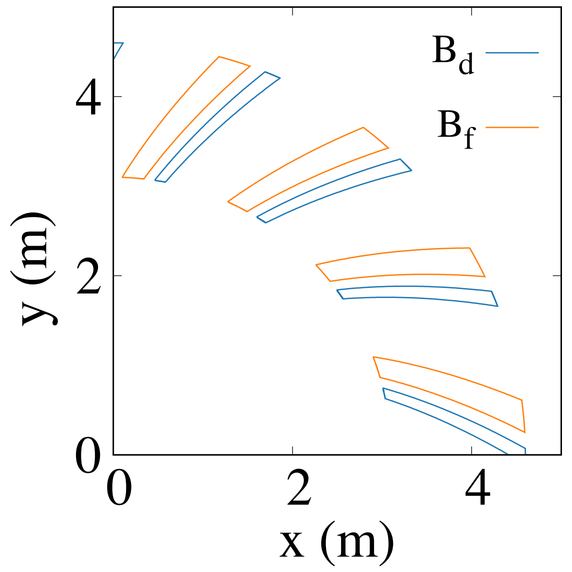
Another approach to understand optics and dynamics.

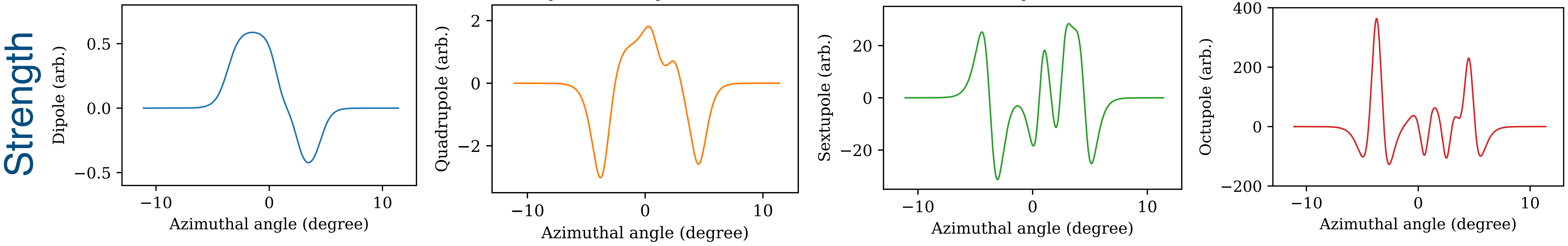
Multipole expansion of one doublet cell

- All the multipole varies continuously along a closed orbit.
- Compare multipoles when the spiral angle is +30 and -30 degrees.

+30 degrees

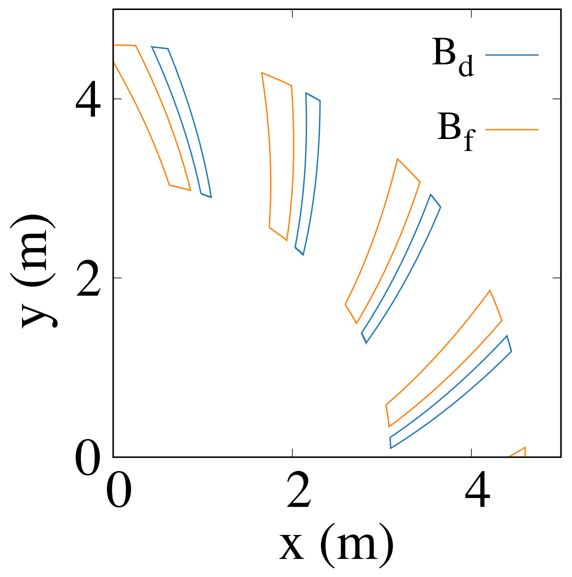
dipole quadrupole sextupole octupole

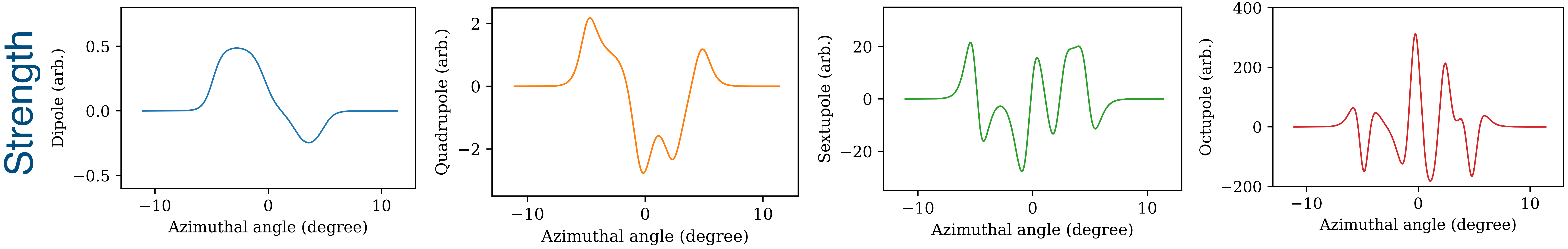




-30 degrees

Path length (degree)





Path length (degree)

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Reconstruct optics from dipole and quadrupole components

- Dipole and quadrupole components (not magnets) is a continuous function of path length.
- Optics can be reconstructed.

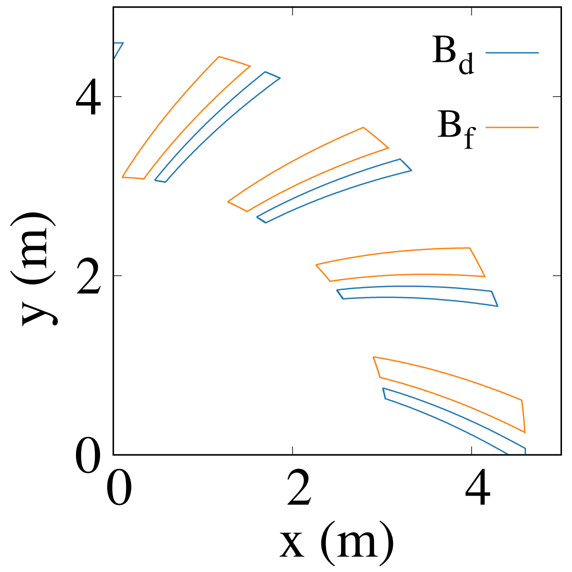
+30 degrees

From multipole

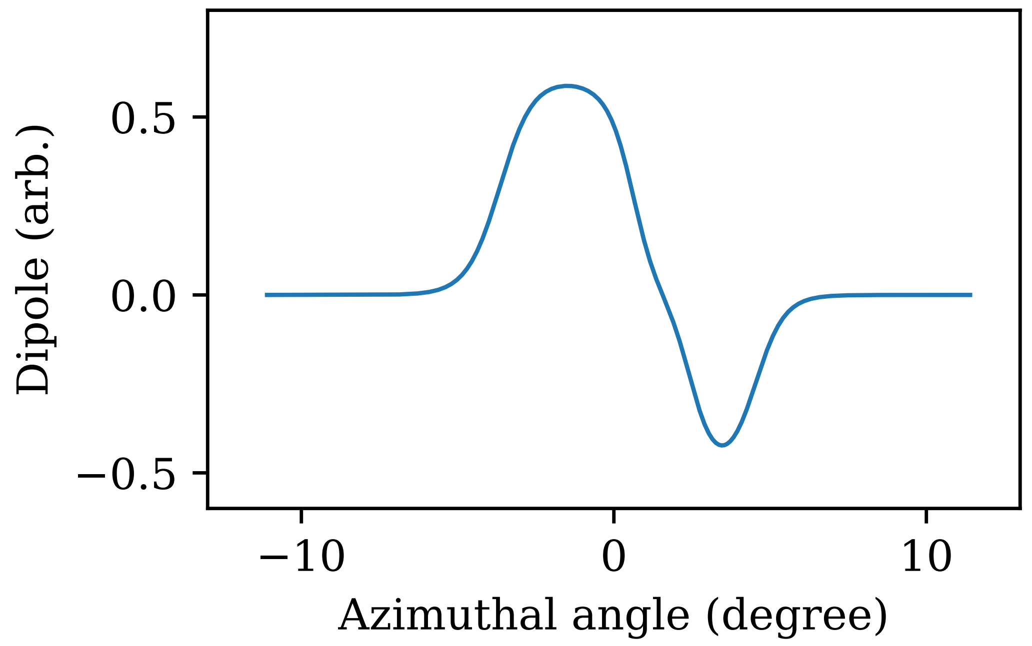
dipole

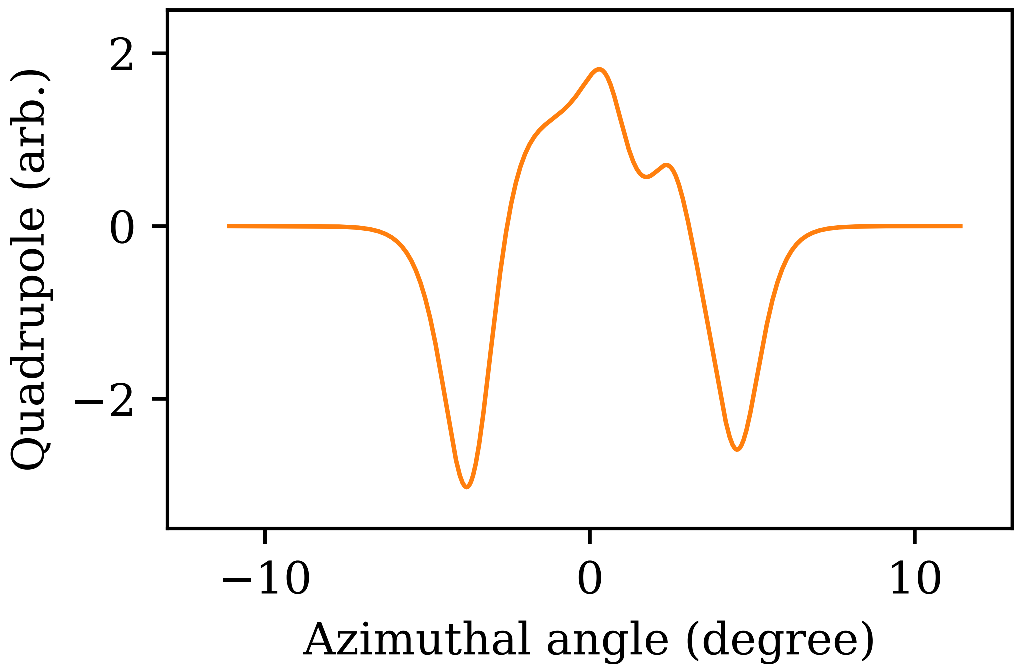
quadrupole

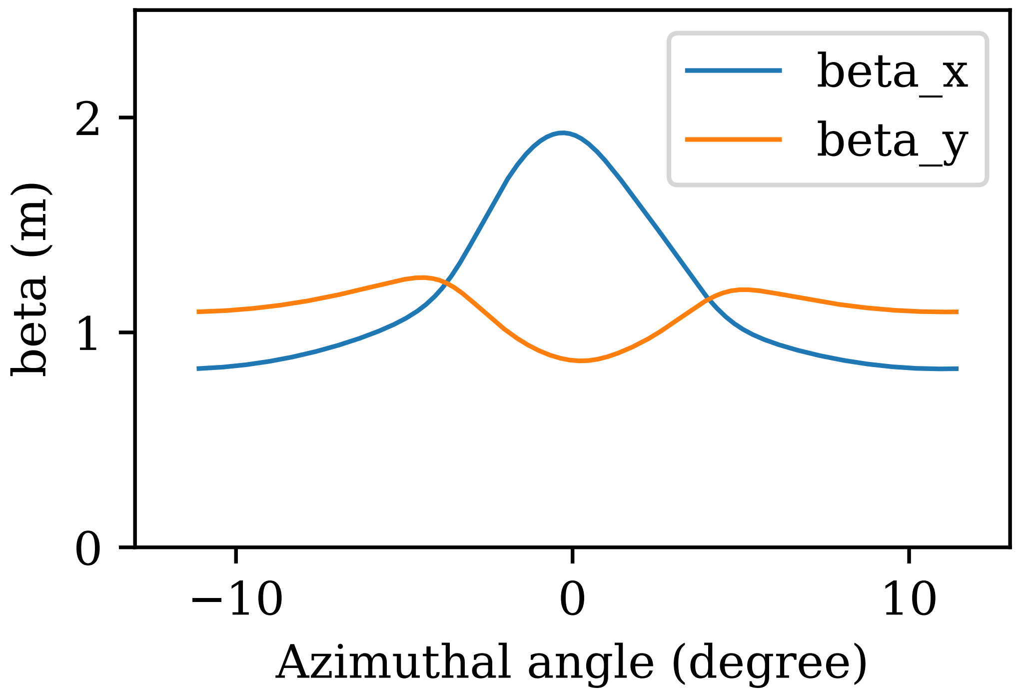
From matrix

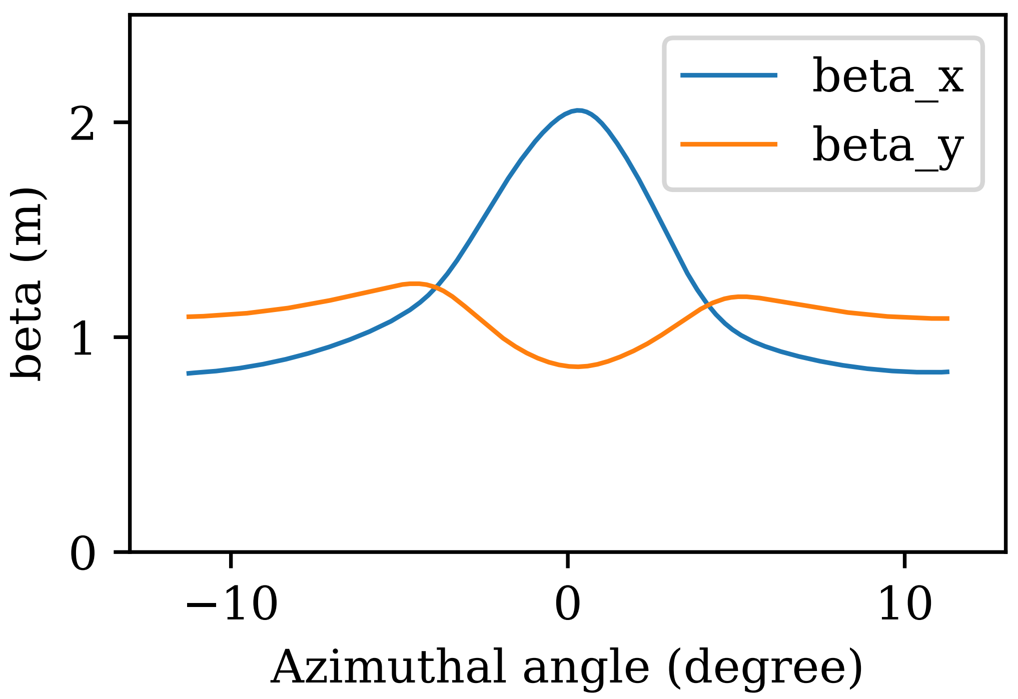


Strength



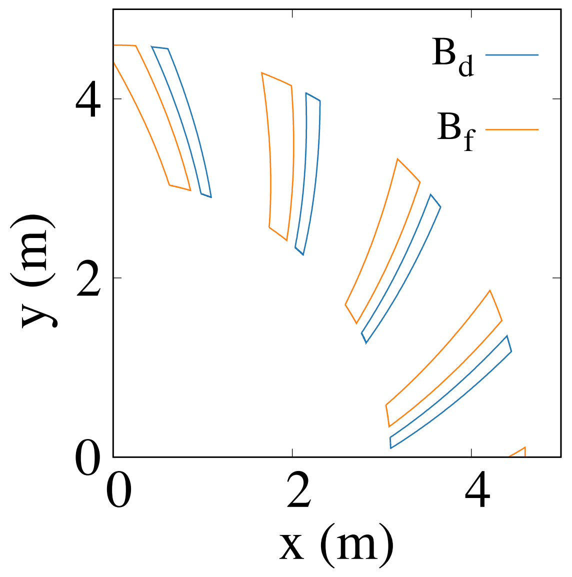




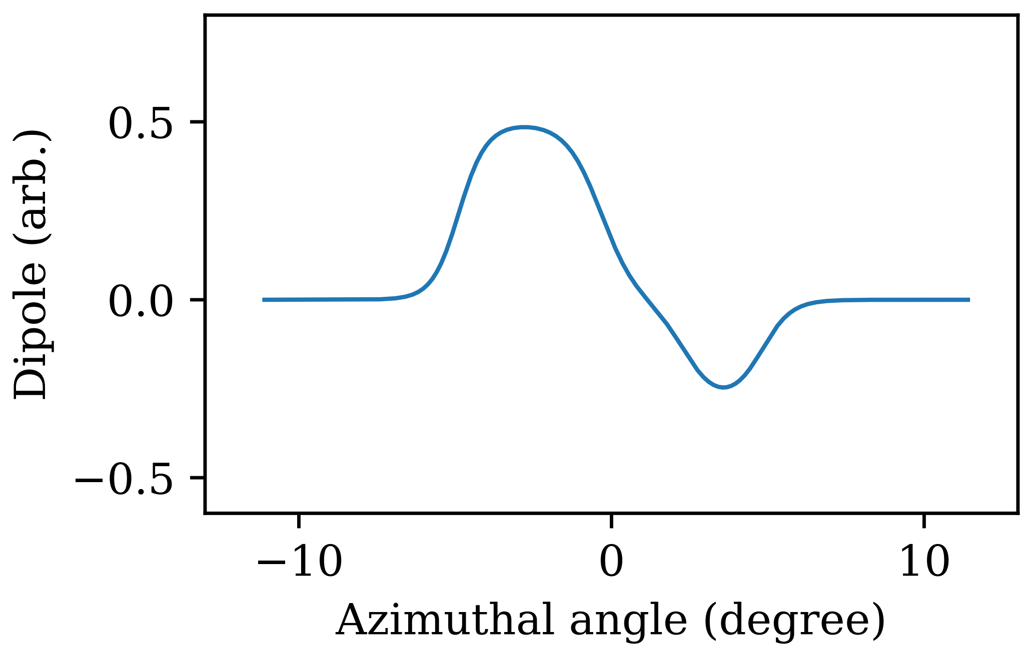


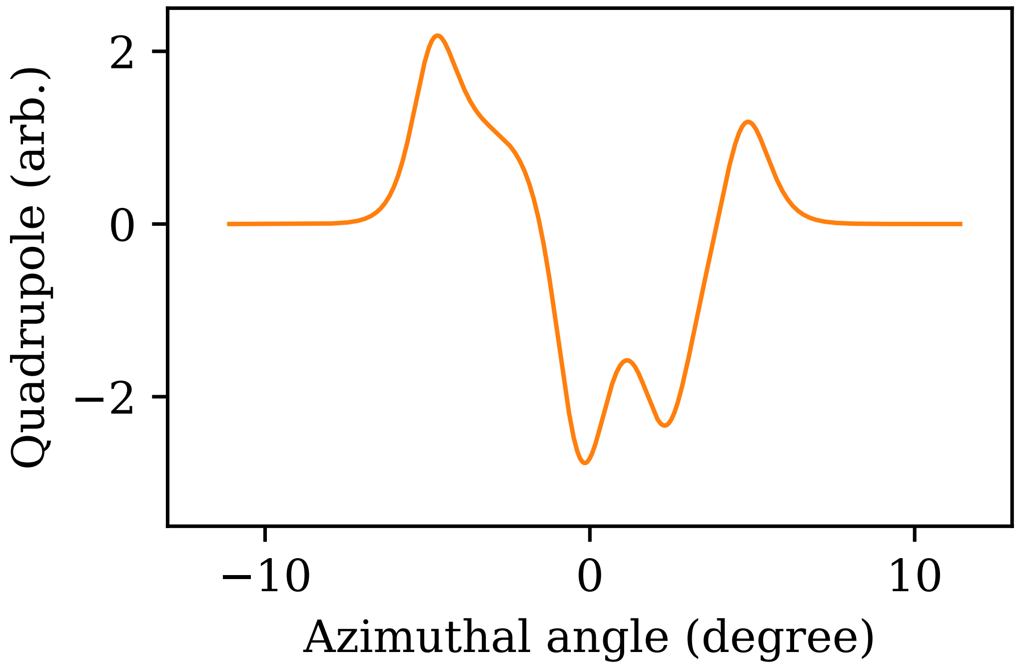
Path length (degree)

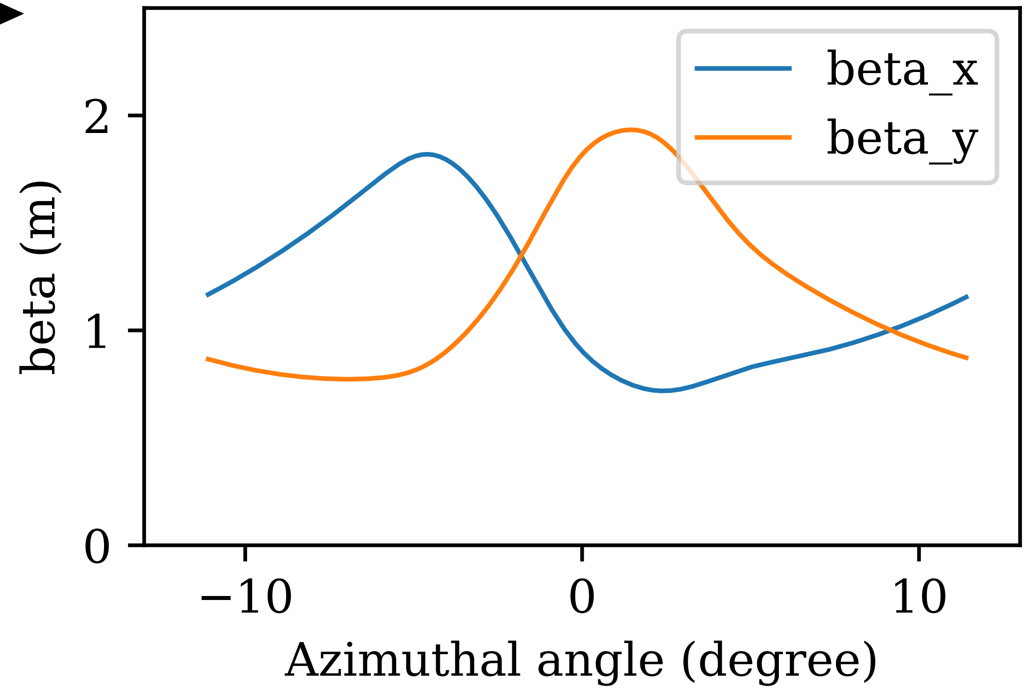
-30 degrees

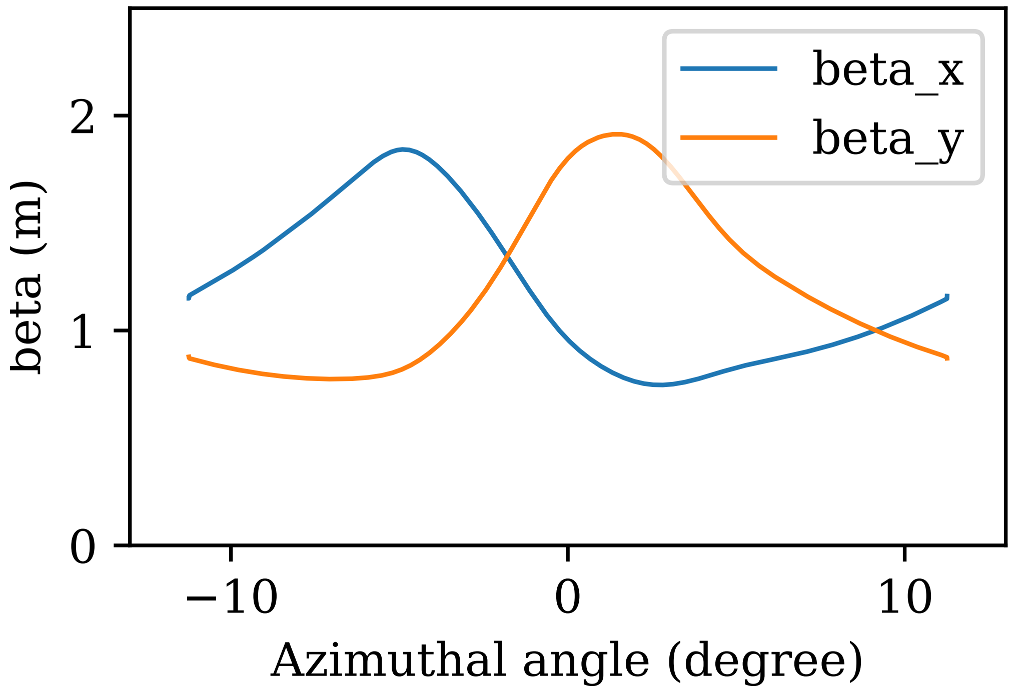


Strength









Path length (degree)

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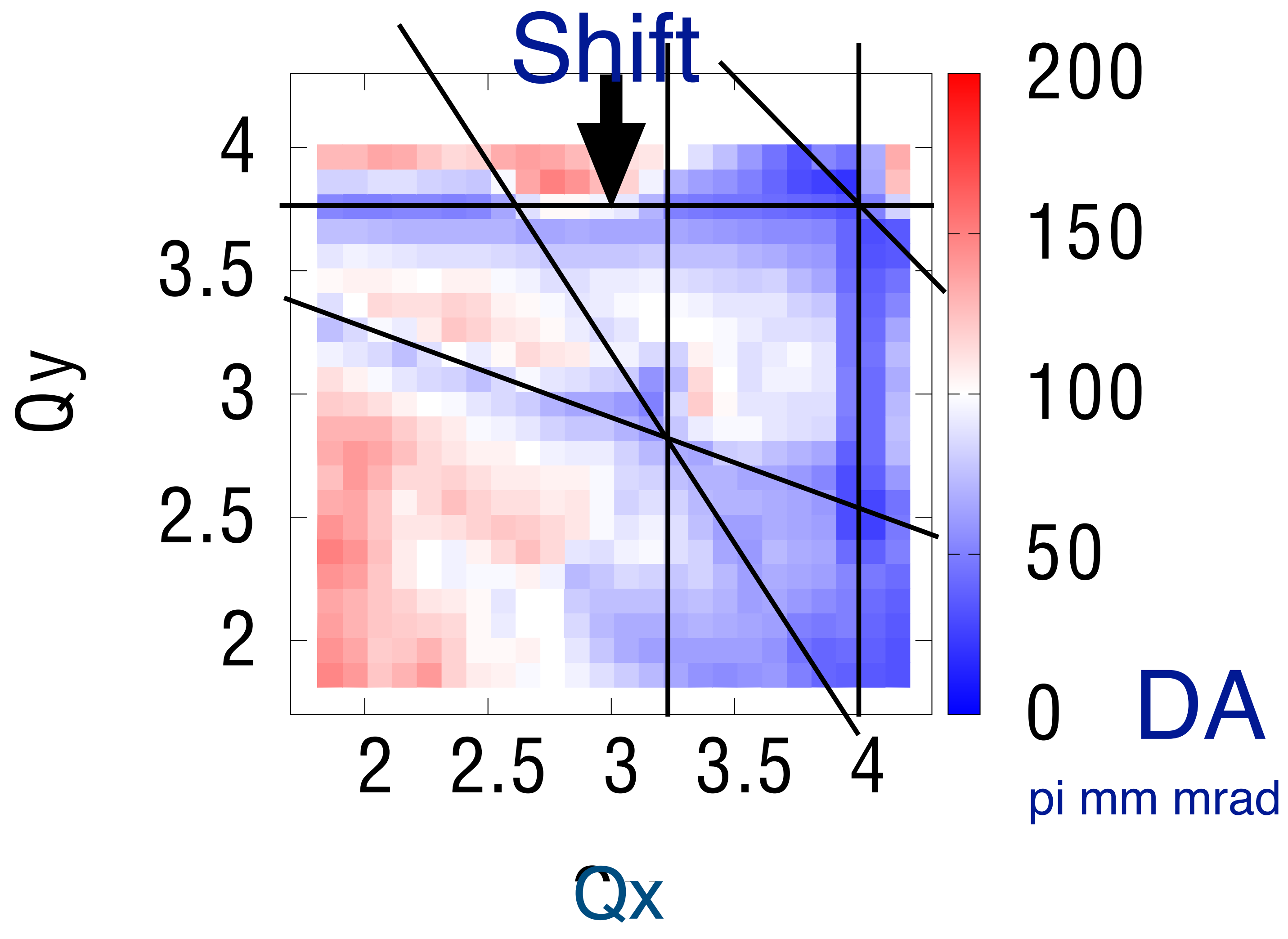
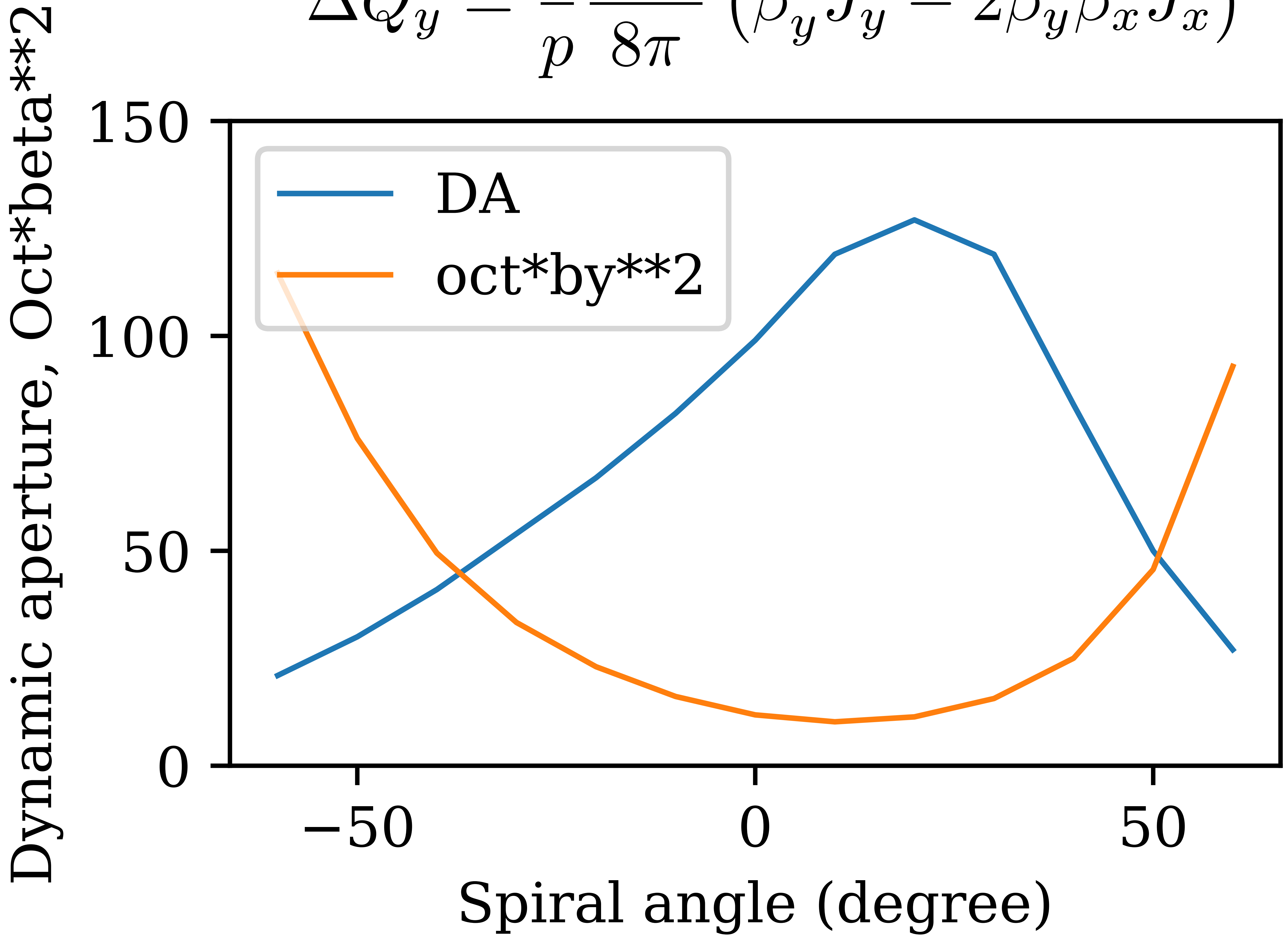
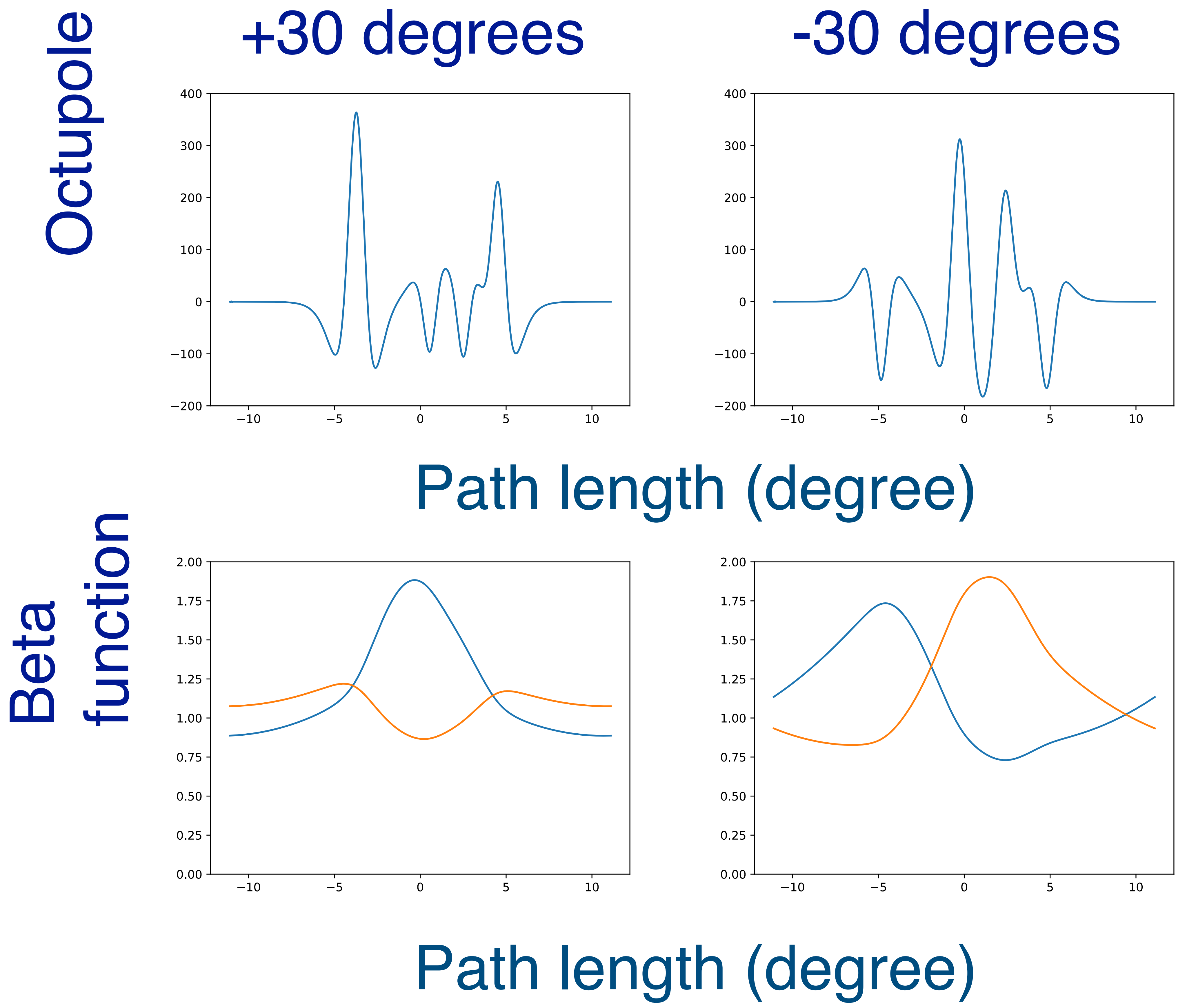
Dynamic aperture of 16 cell lattice



- Dynamic aperture (DA) is limited by amplitude dependent tune shift.
- Octupole component with beta functions explains asymmetry of DA with spiral angle.

$$\Delta Q_y = \frac{q}{p}\frac{3B_4}{8\pi}\left(\beta_y^2 J_y - 2\beta_y\beta_x J_x\right)$$

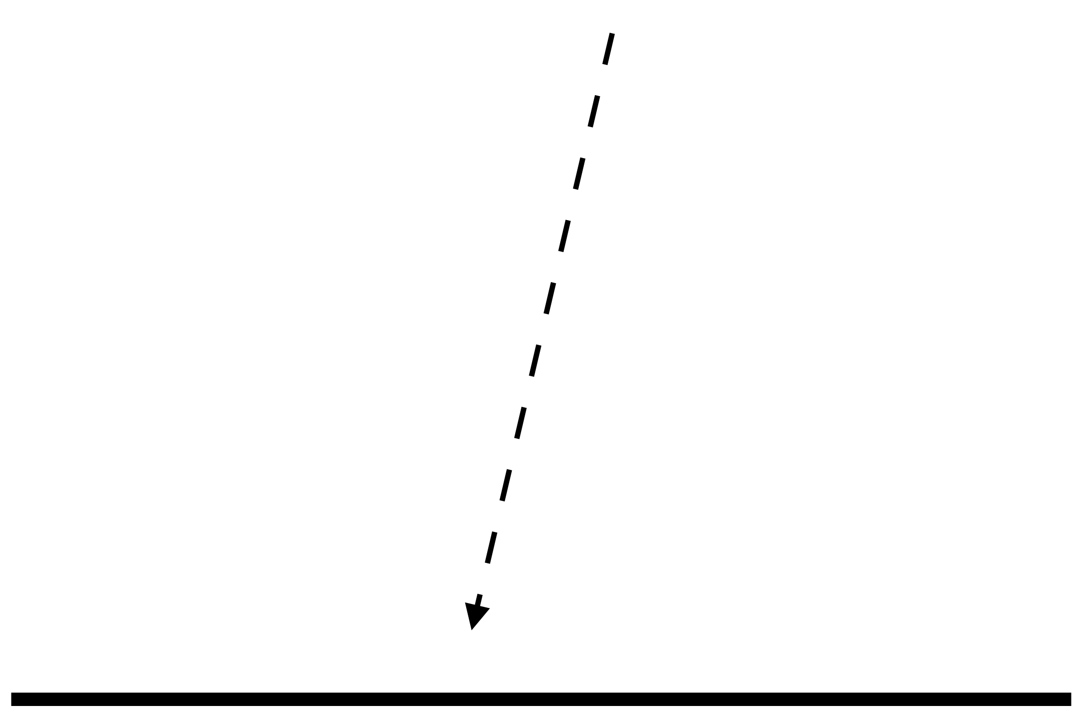




Mitigation

- Amplitude dependent tune shift is a function of nonlinearities and beta function.
    - Spiral angle changes distribution of both factors.
    - In principle, we can add correction magnets to reduce the overall tune shift.

- Compensation of resonances.
    - Larger COD reduces dynamic aperture likely because non systematic resonances are appearing more significantly.
    - Correction of COD and optics by trim coils.
    - Correction of nonlinear resonance driving term may not be feasible by trim coils.



Summary

- 4 fold symmetry FD doublet spiral lattice was designed for FETS-FFA, a demonstrator of a high intensity FFA.
- Dynamic aperture was studied and amplitude dependent tune shift is calculated as a source of limitation.

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Thank you for your attention

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