Collider arc with skew Q and vFFA

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1st Muon Community Meeting

Two exotic options not discussed in MAP

International
MUON Collider
Collaboration

Collider arc with skew quadrupoles

Vertical excursion FFA for muon acceleration

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Collider arc with skew quadrupoles

Vertical excursion FFA for muon acceleration

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Reasons of skew quadrupole collider arc

- Flexible **momentum compaction factor**
  - Without exciting non-zero harmonic of the dispersion function
  - Without reverse bending

- **Spreading out radiation** due to neutrinos by wiggling (wobbling) orbit in vertical as well as in horizontal.
  - Angle of wiggling orbit is a function of optics, not by mechanical, i.e. easy to adjust different configurations.

- No design of the low-beta insertion yet, but it should be a simple 45 rotation of the conventional one to start.

Excite periodicity of the dispersion close to tune

J-PARC synchrotron

Momentum compaction factor is dominated by non-zero harmonics of the dispersion.

$$\alpha_1 = \frac{1}{L}\int_0^L \frac{D_x}{\rho} ds = \frac{Q_x}{L}\int_0^{2\pi} \frac{\beta_x D_x}{\rho} d\phi$$

$$D_x(s) = \beta_x^{1/2}(s)\, Q_x^2 \sum_k \frac{a_k e^{jk\phi}}{Q_x^2 - k^2}$$

$$a_k = \frac{1}{2\pi}\int_0^{2\pi} \frac{\beta_x^{3/2}}{\rho} e^{-jk\phi} d\phi$$

$$\alpha_1 = \frac{2\pi Q_x^3}{L}\sum_k \frac{|a_k^2|}{Q_x^2 - k^2}$$

$$\sim \frac{1}{Q_x^2} \qquad |a_0^2| = \frac{L}{2\pi Q_x^3}$$

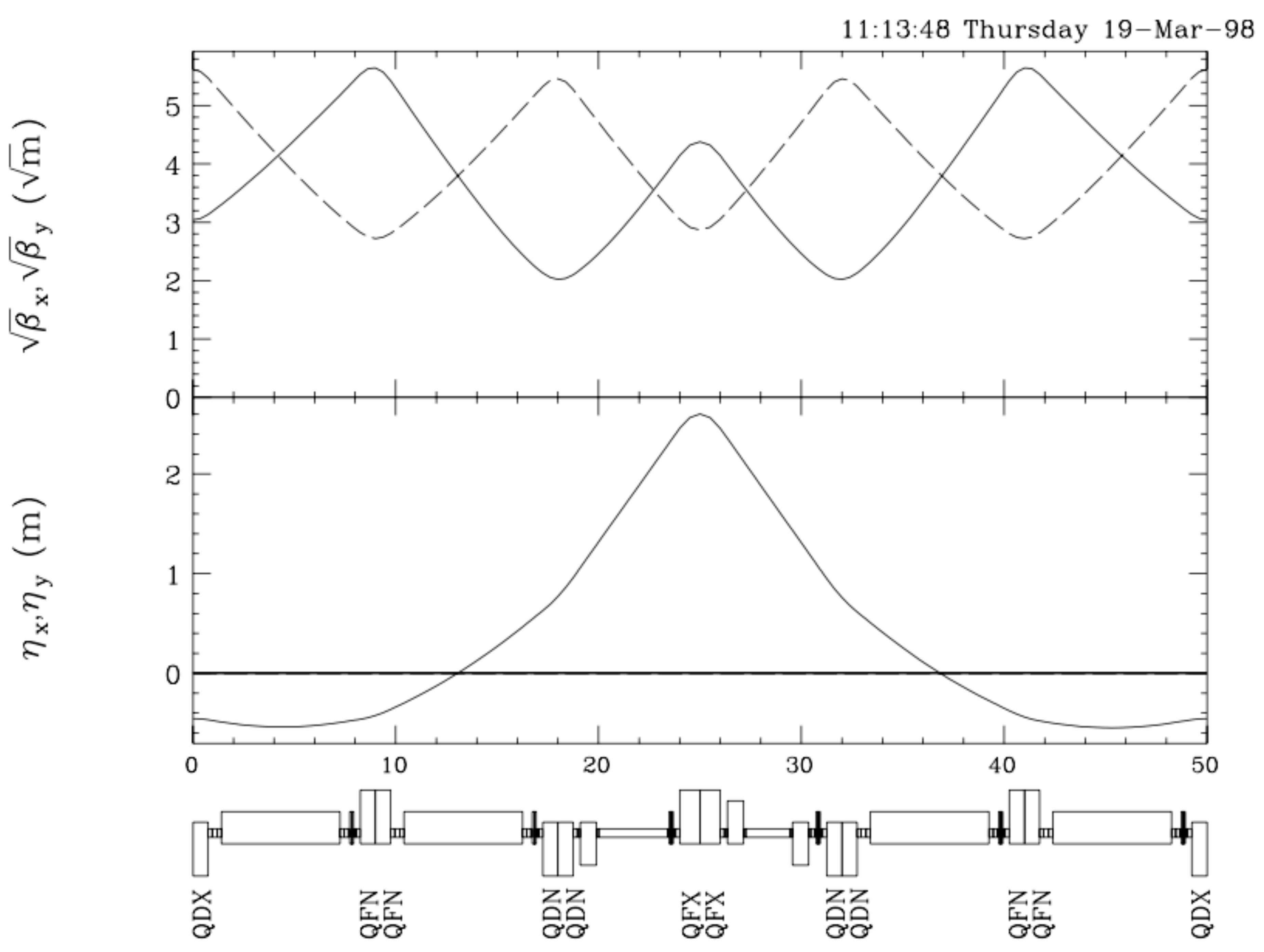

Figure 1: Beam optics functions of the module in arc section of the JHF 50 GeV main ring. $\beta_x^{1/2}$:solid line, $\beta_y^{1/2}$:dashed line.

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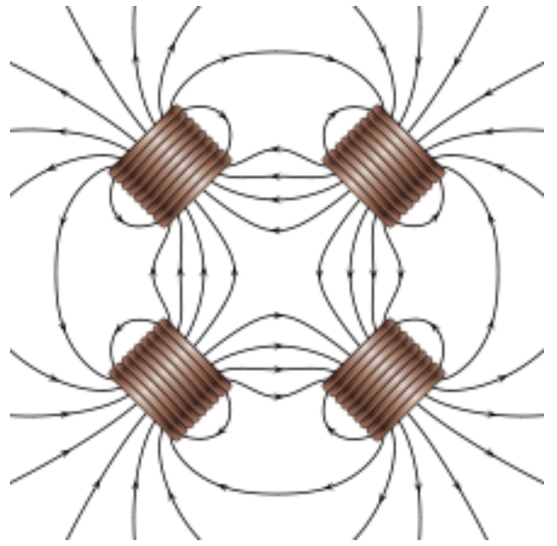
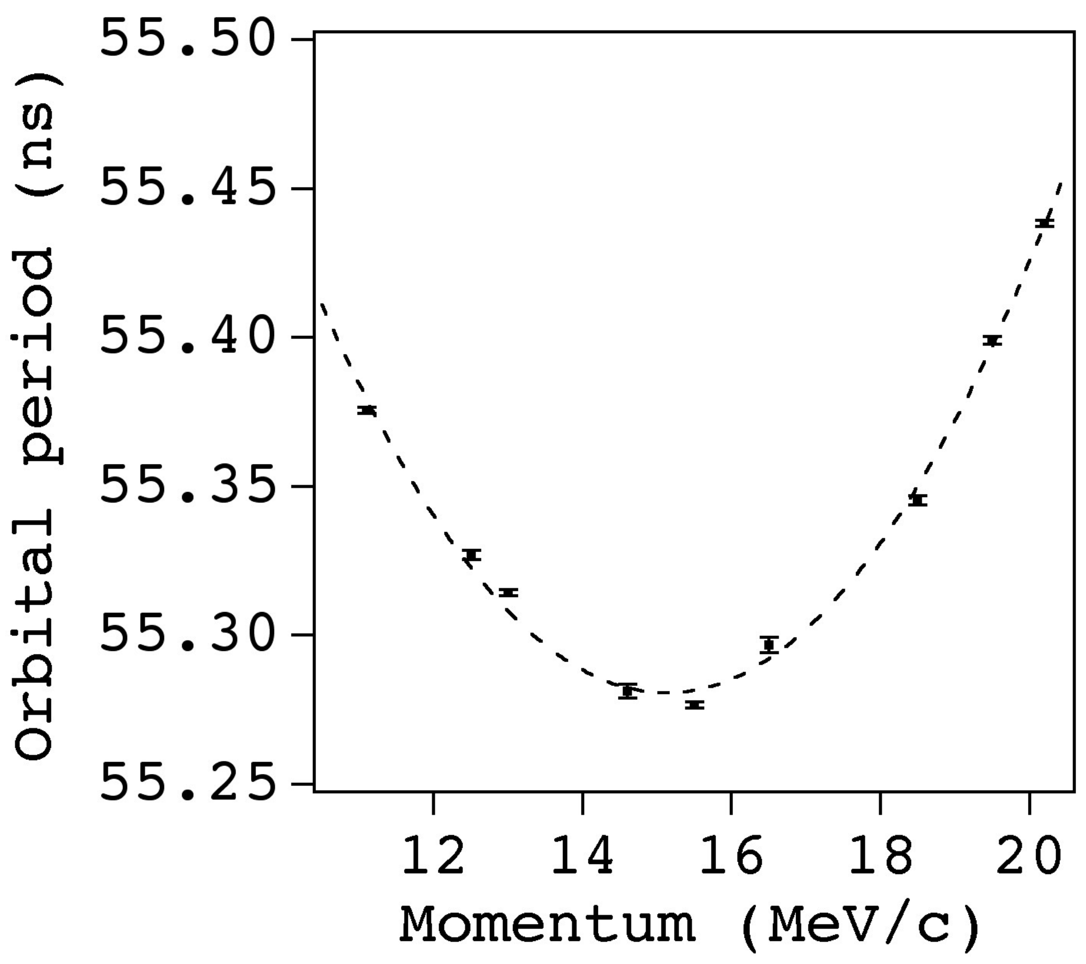
Radial shift of normal quadrupole FODO

non-scaling FFA

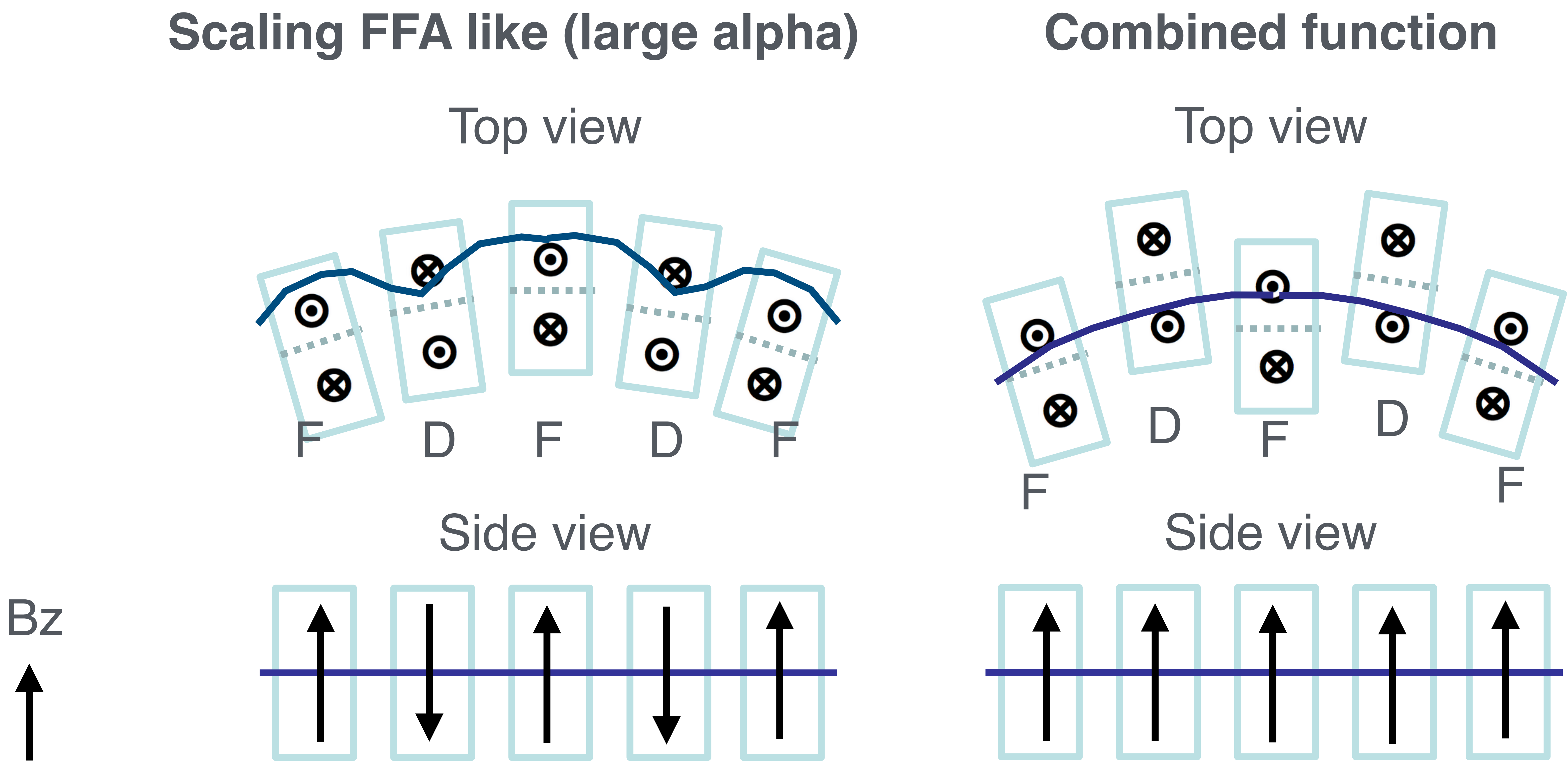
- Dispersion function Dx can be small in ns-FFA lattice configuration.
- **Dispersion action function H** is minimum in ns-FFA so that momentum compaction factor is zero.

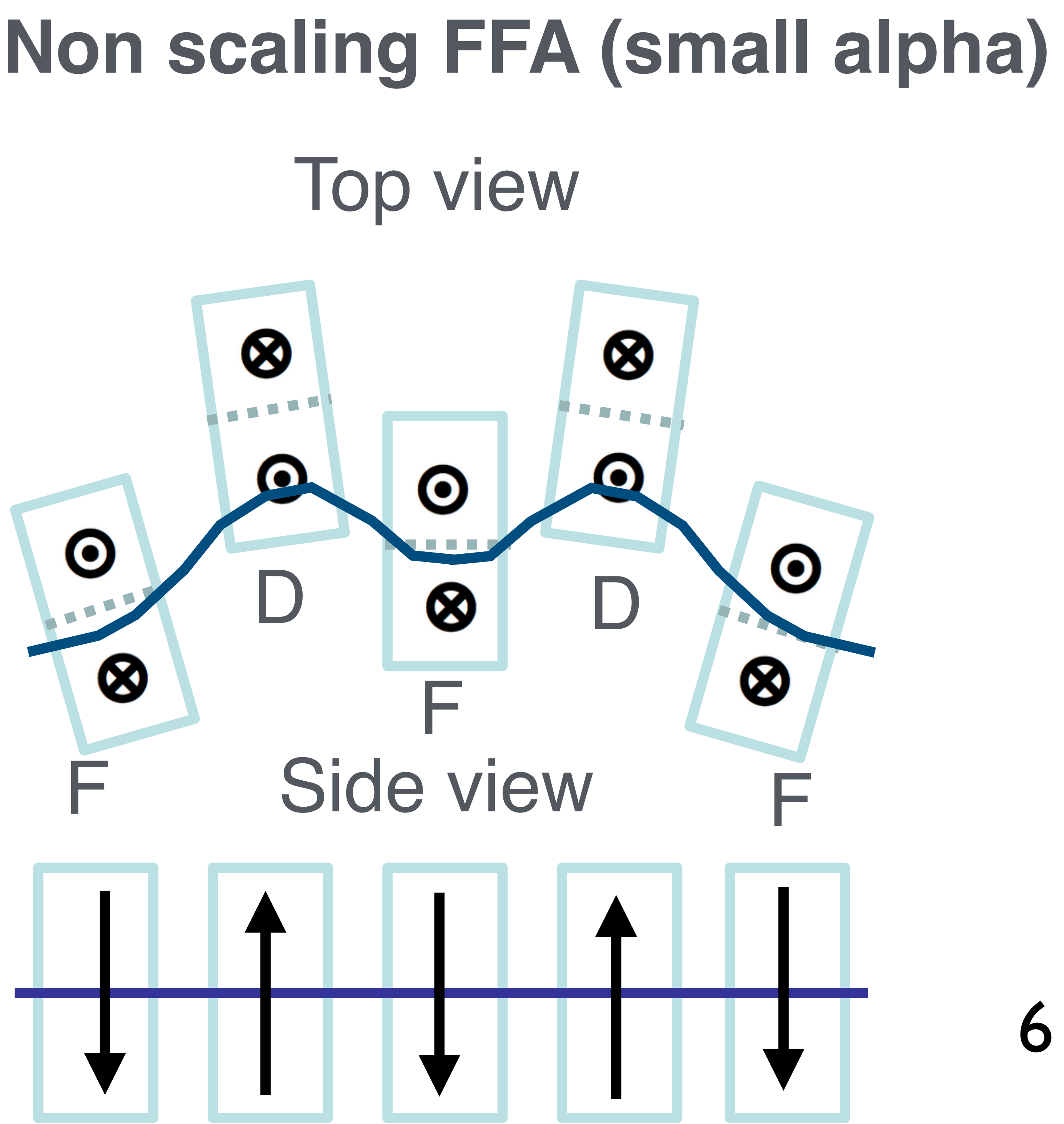
Normal quadrupole





"EMMA comm.", Nature Physics Vol. 8, No. 3 (2012).





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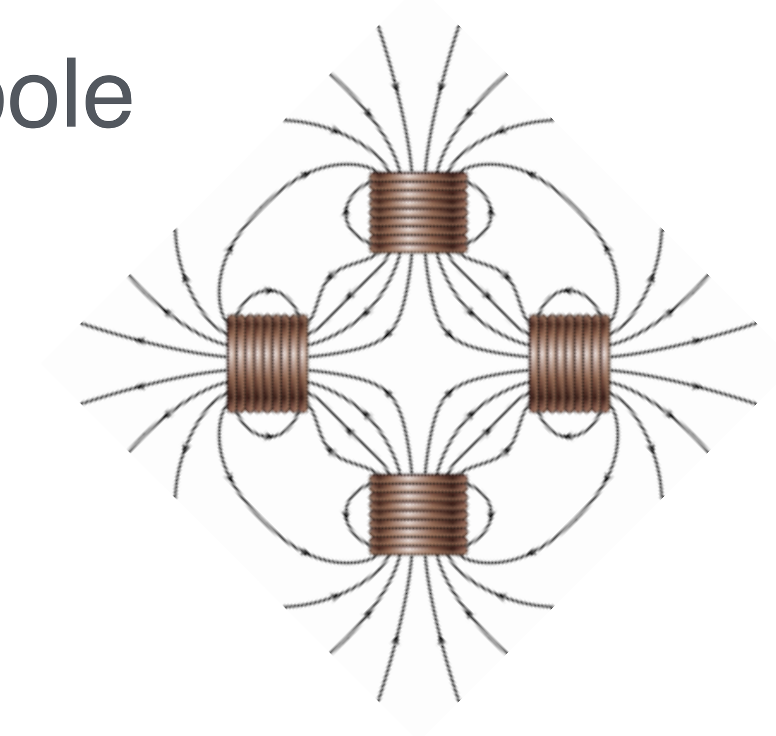
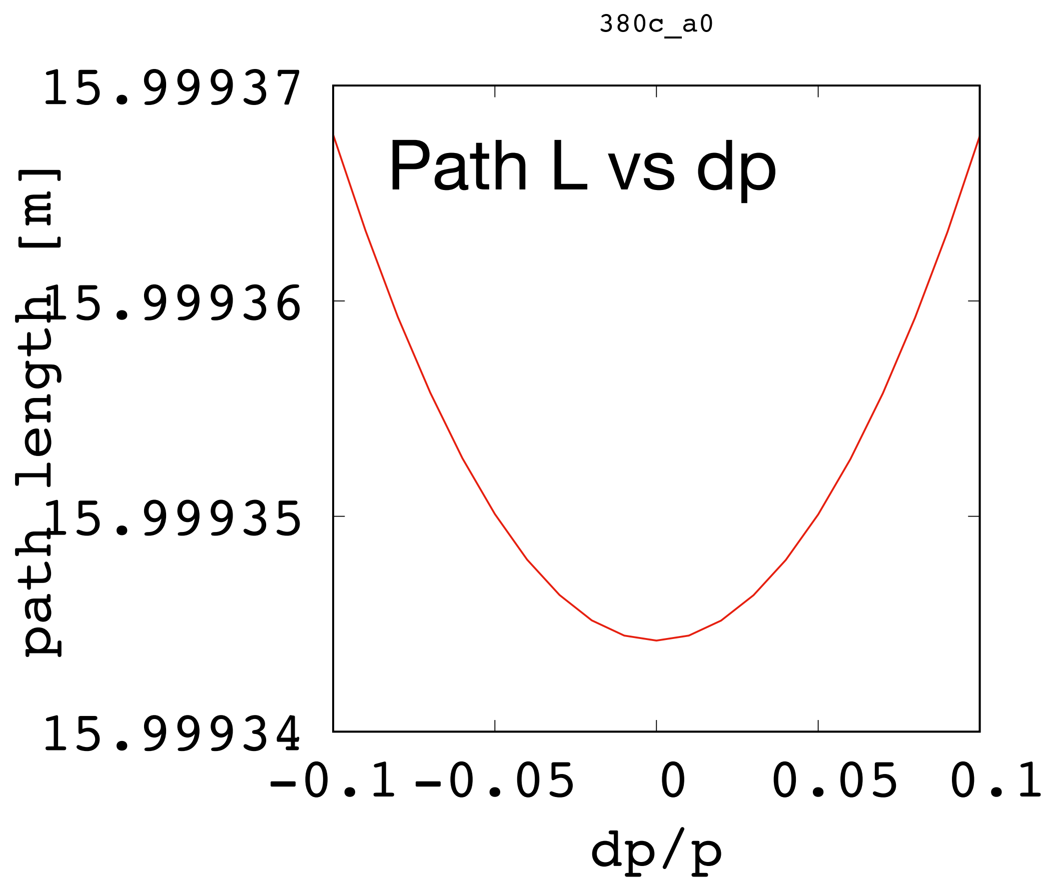
Vertical shift of skew quadrupole FODO

no reverse bending

Skew quadrupole

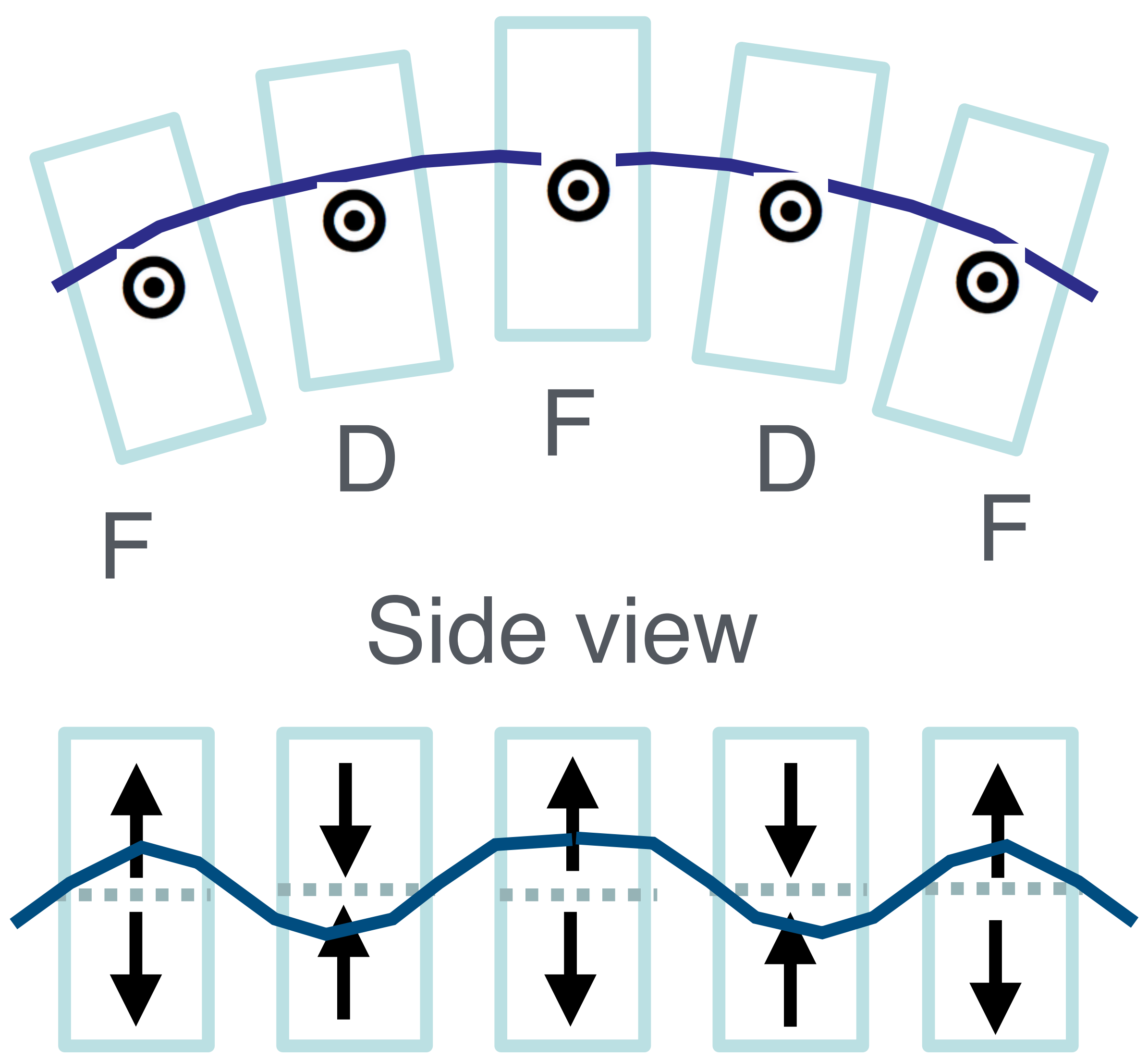




- Vertical bending field changes its sign below or above the mid-plane.
- We can eliminate reverse bend.

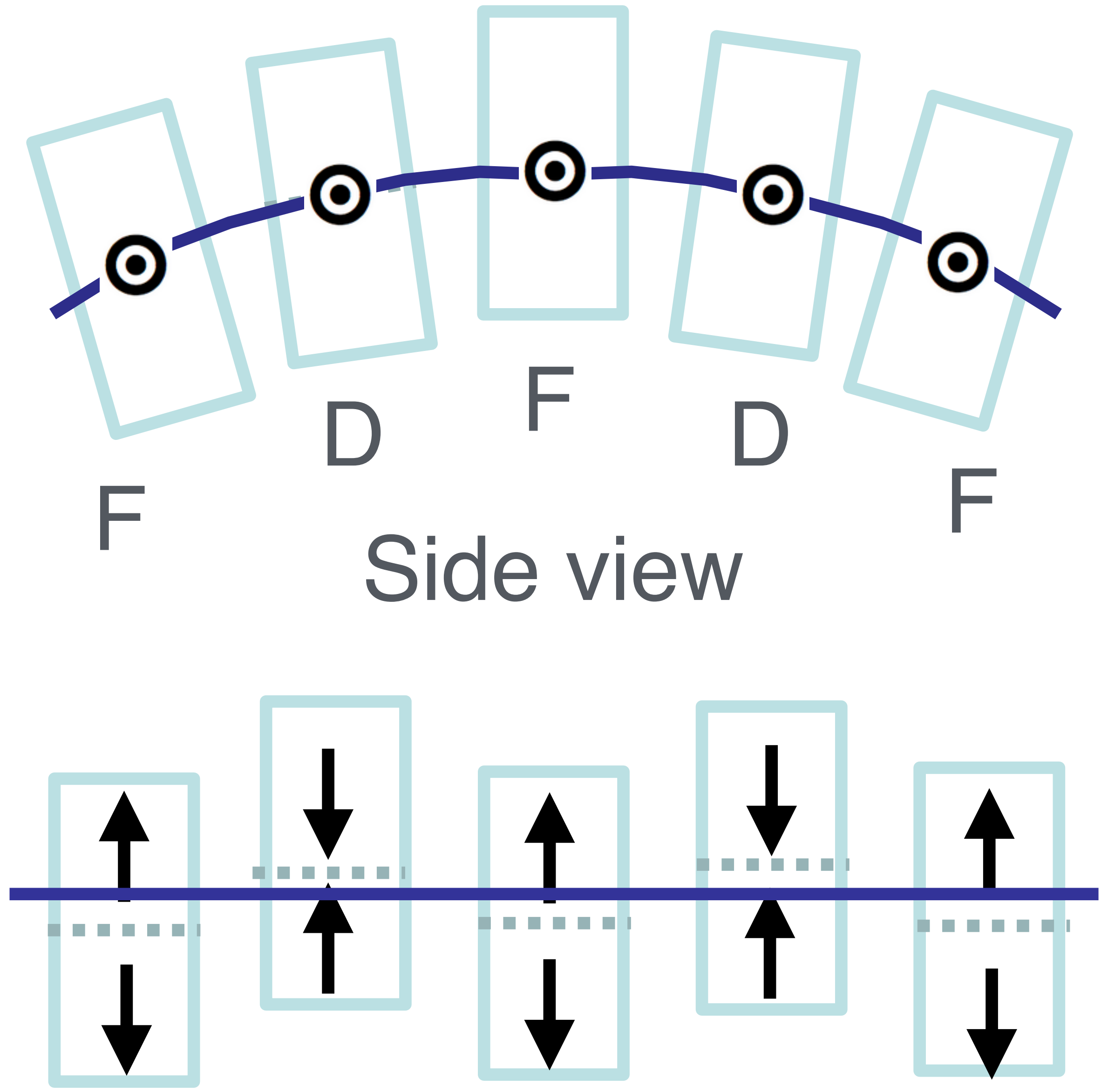
Combined function (large alpha)

Top view



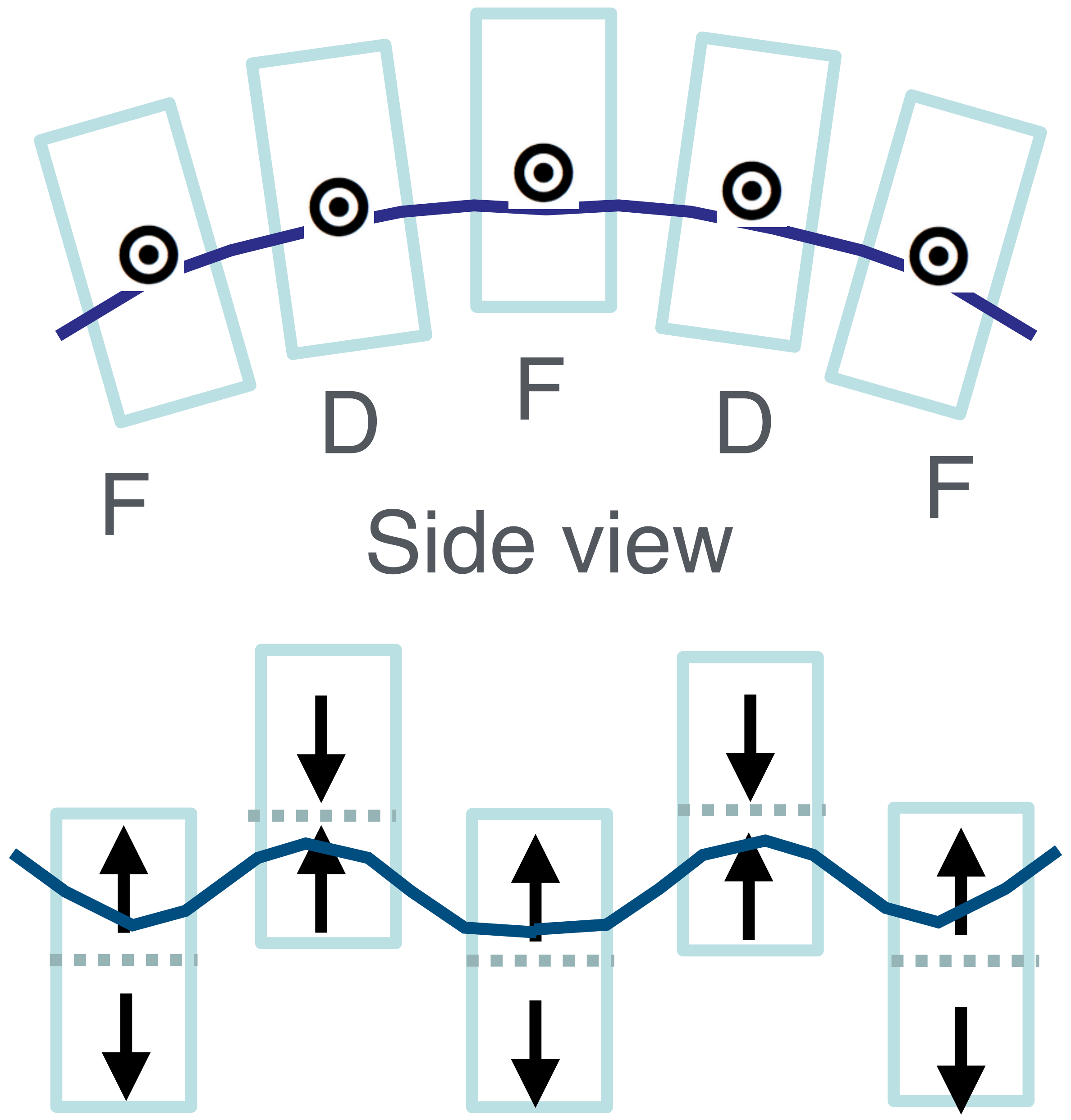
Combined function

Top view

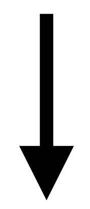


Combined function (small alpha)

Top view



Bz



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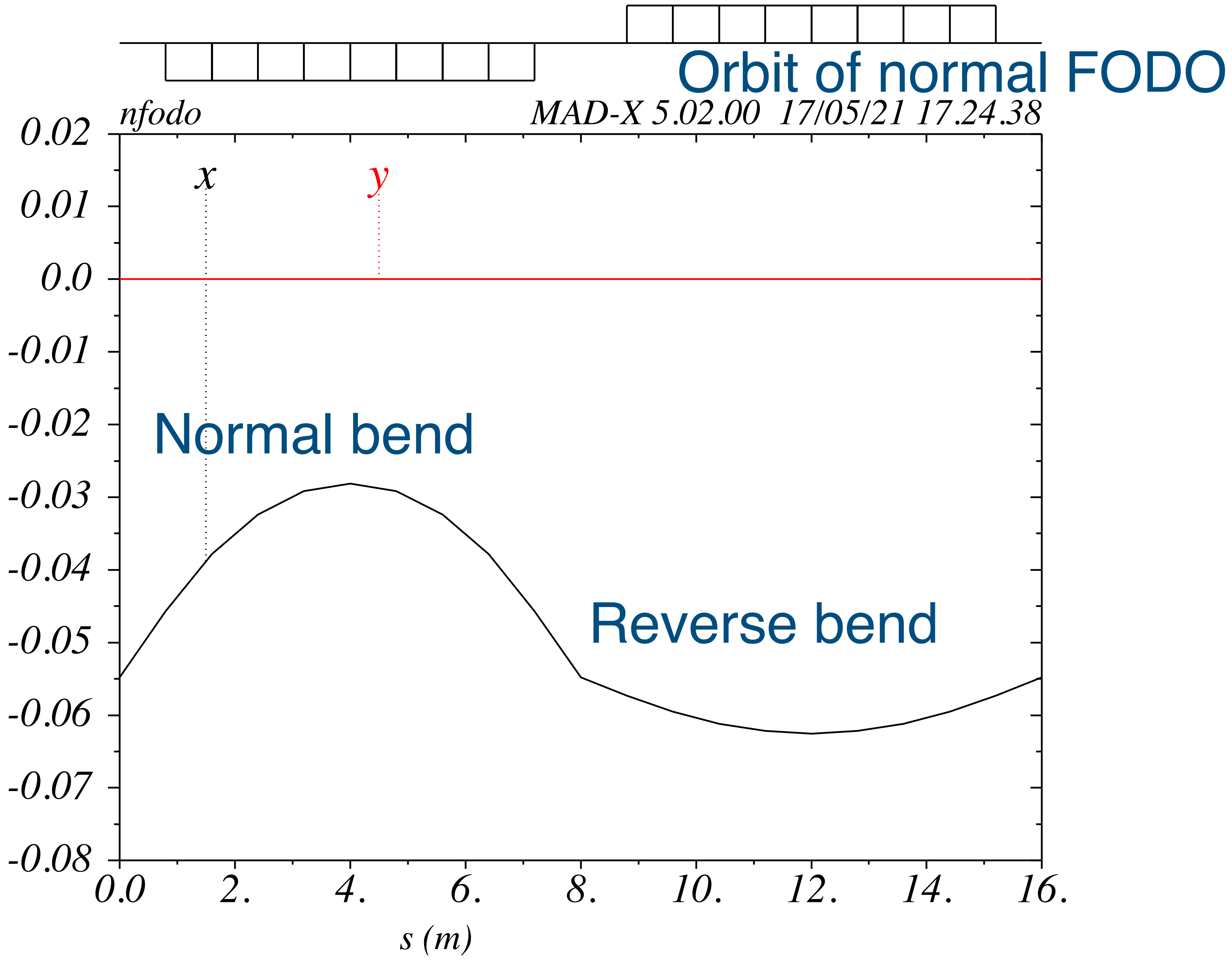
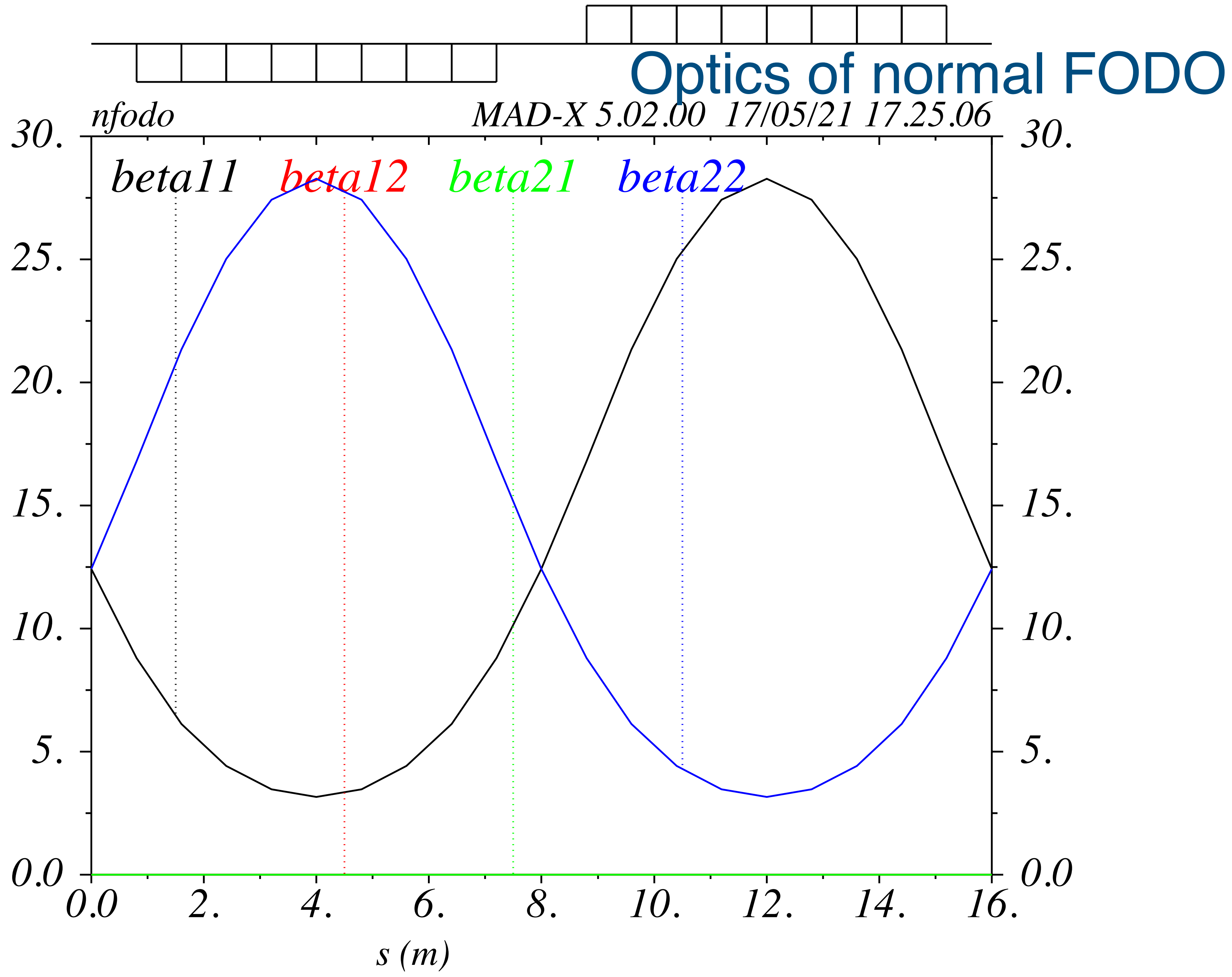
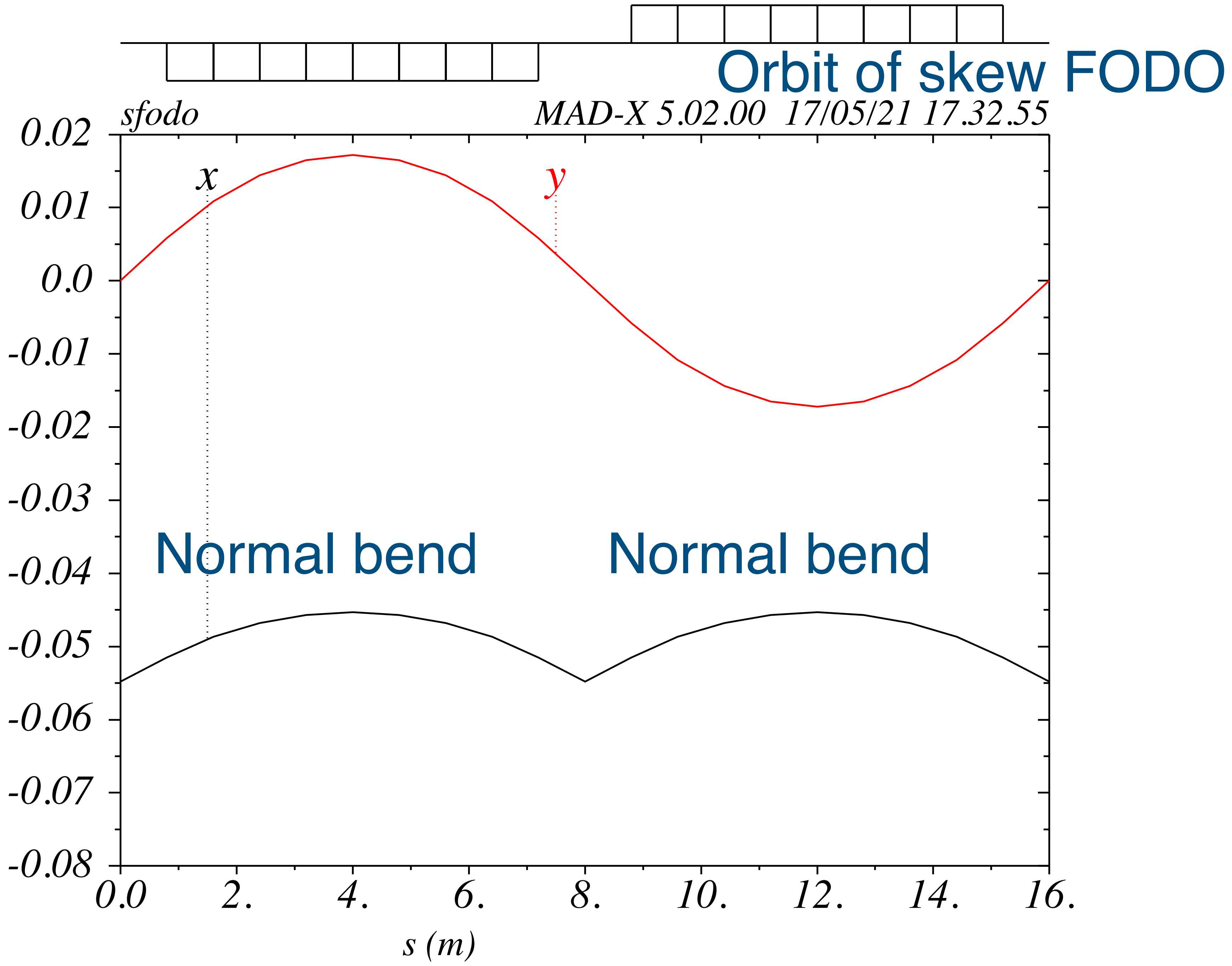
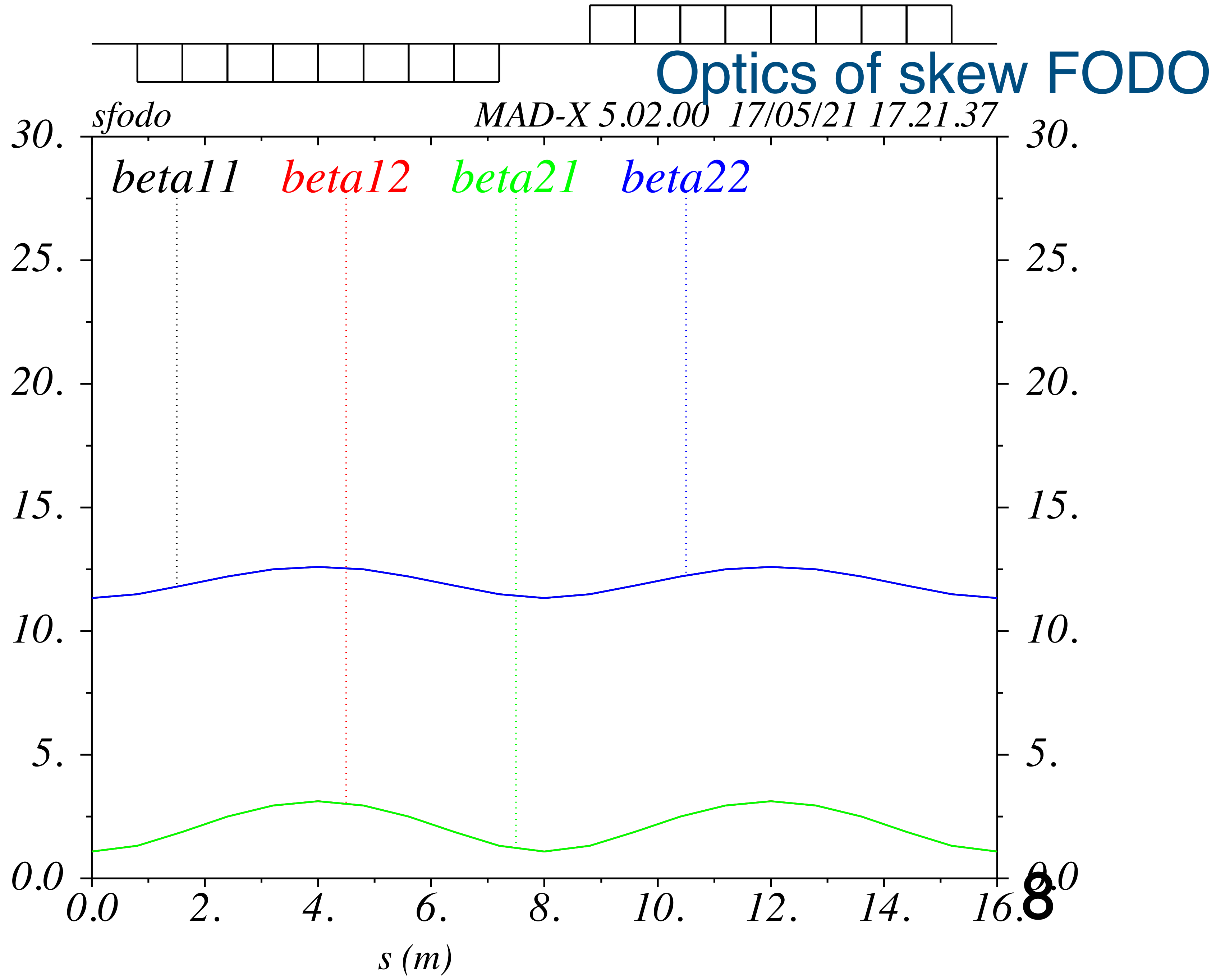
MADX results

normal Q vs skew Q









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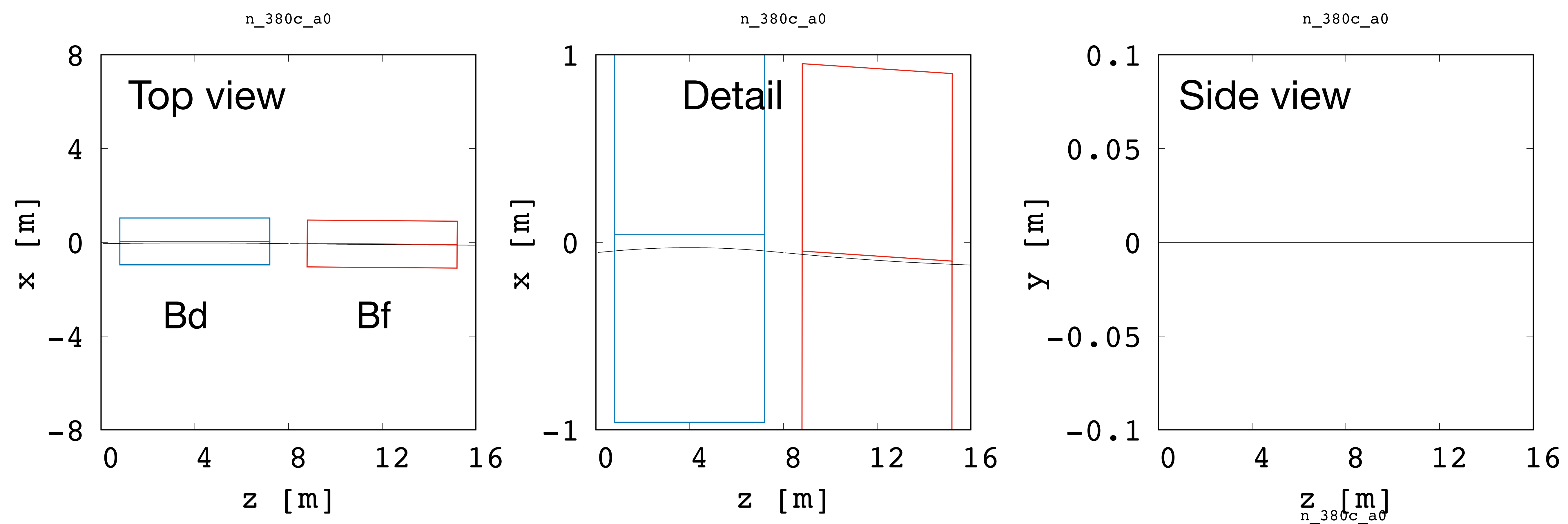
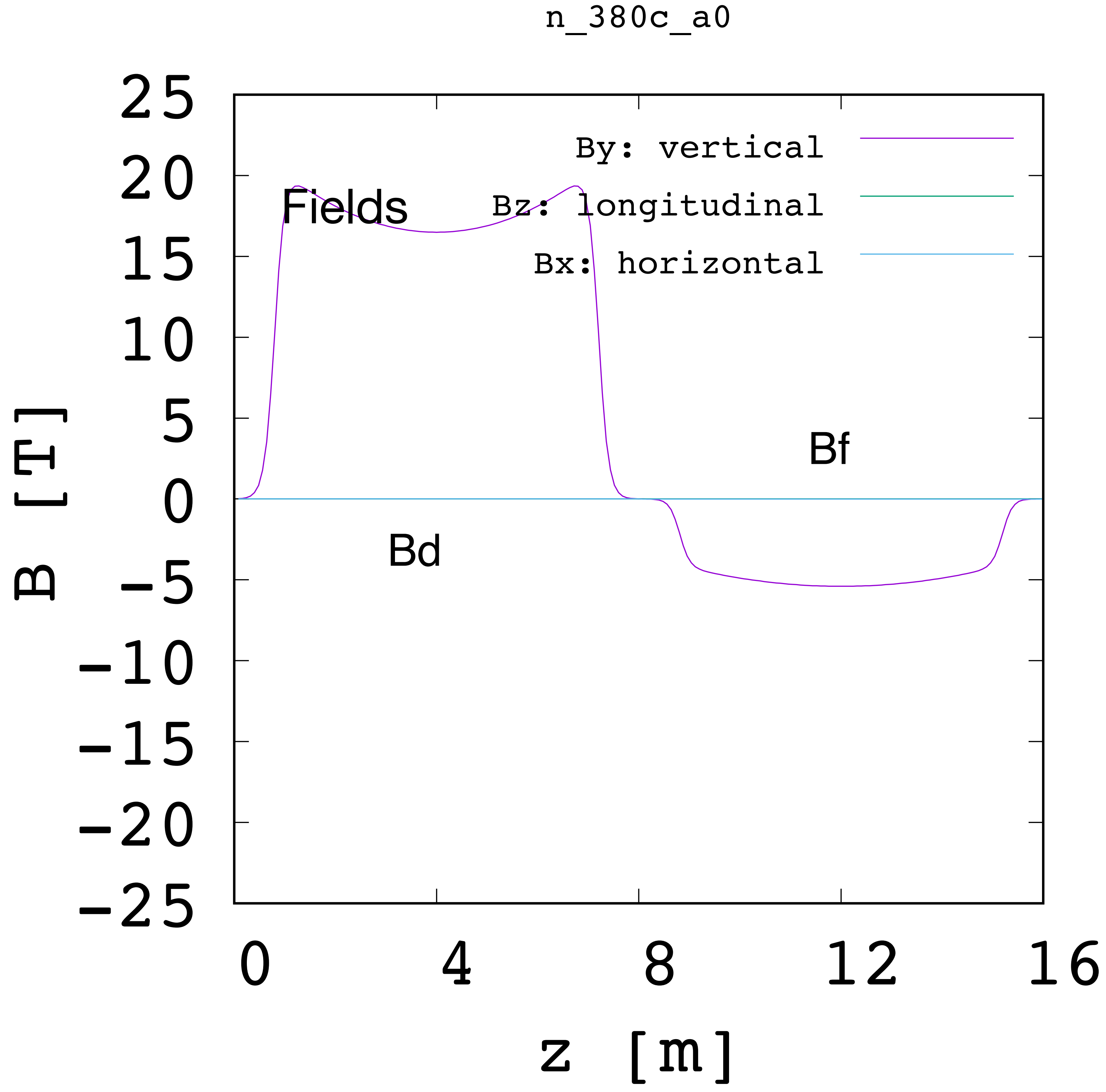
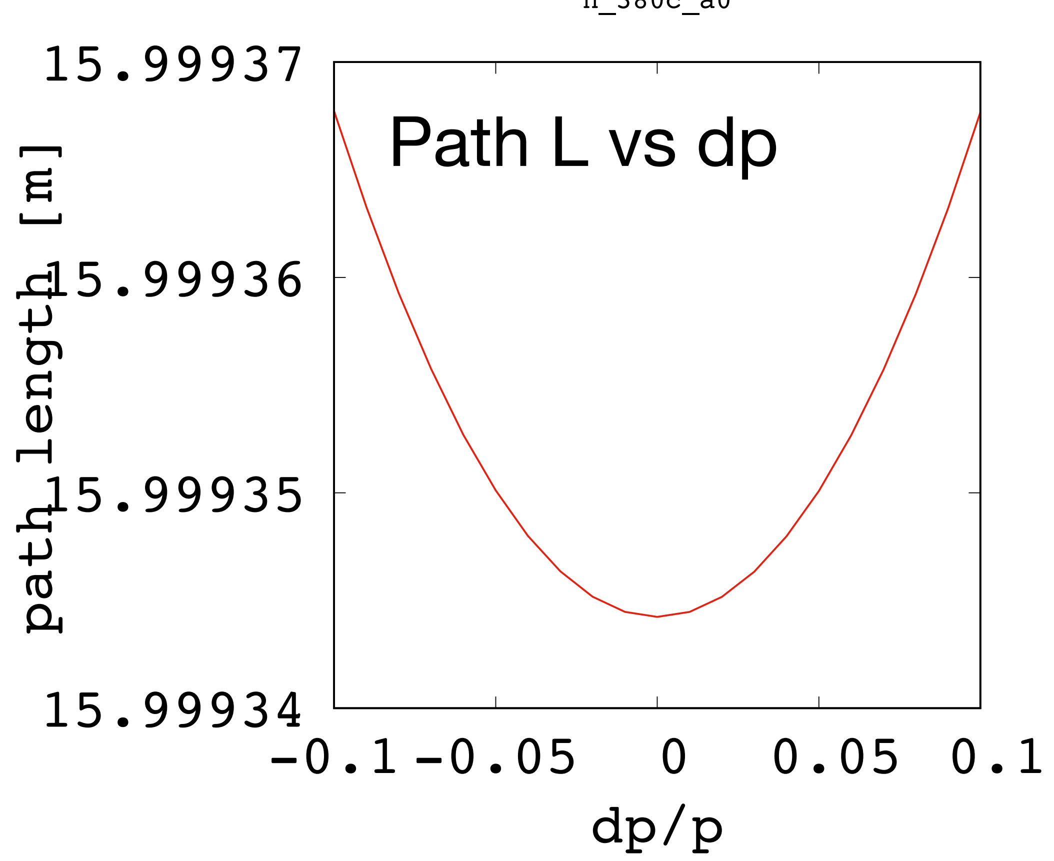
1.5 TeV collider ring

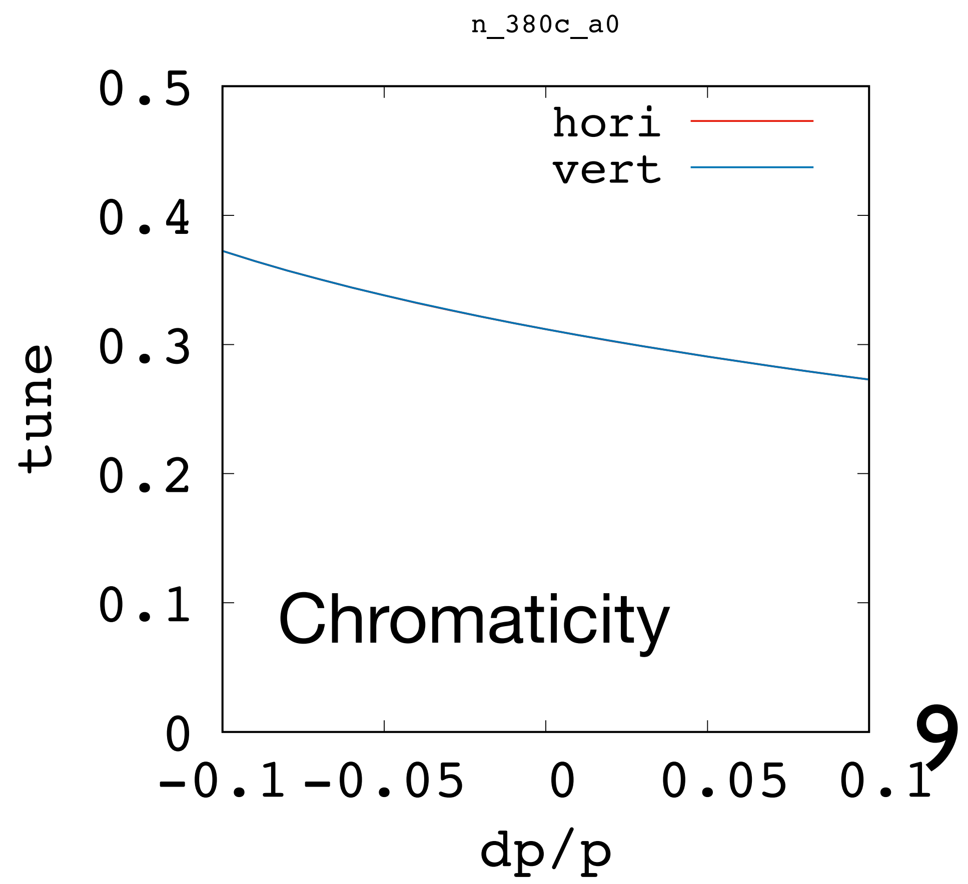
momentum comp=0, arc only

	Normal FODO
Energy	1.5 TeV
Momentum compaction	0
Circumference	6080 m
Cell length	16 m
Magnet length	2 x 6.4 m
# of cell	380
Maximum field	20 T
Field gradient	240 T/m
Cell tune	0.3131 / 0.3131









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1.5 TeV collider ring

momentum comp=0, arc only

	Skew FODO
Energy	1.5 TeV
Momentum compaction	0
Circumference	6080 m
Cell length	16 m
Magnet length	2 x 6.4 m
# of cell	380
Maximum field	14 T
Field gradient	240 T/m
Cell tune	0.3131 / 0.3131

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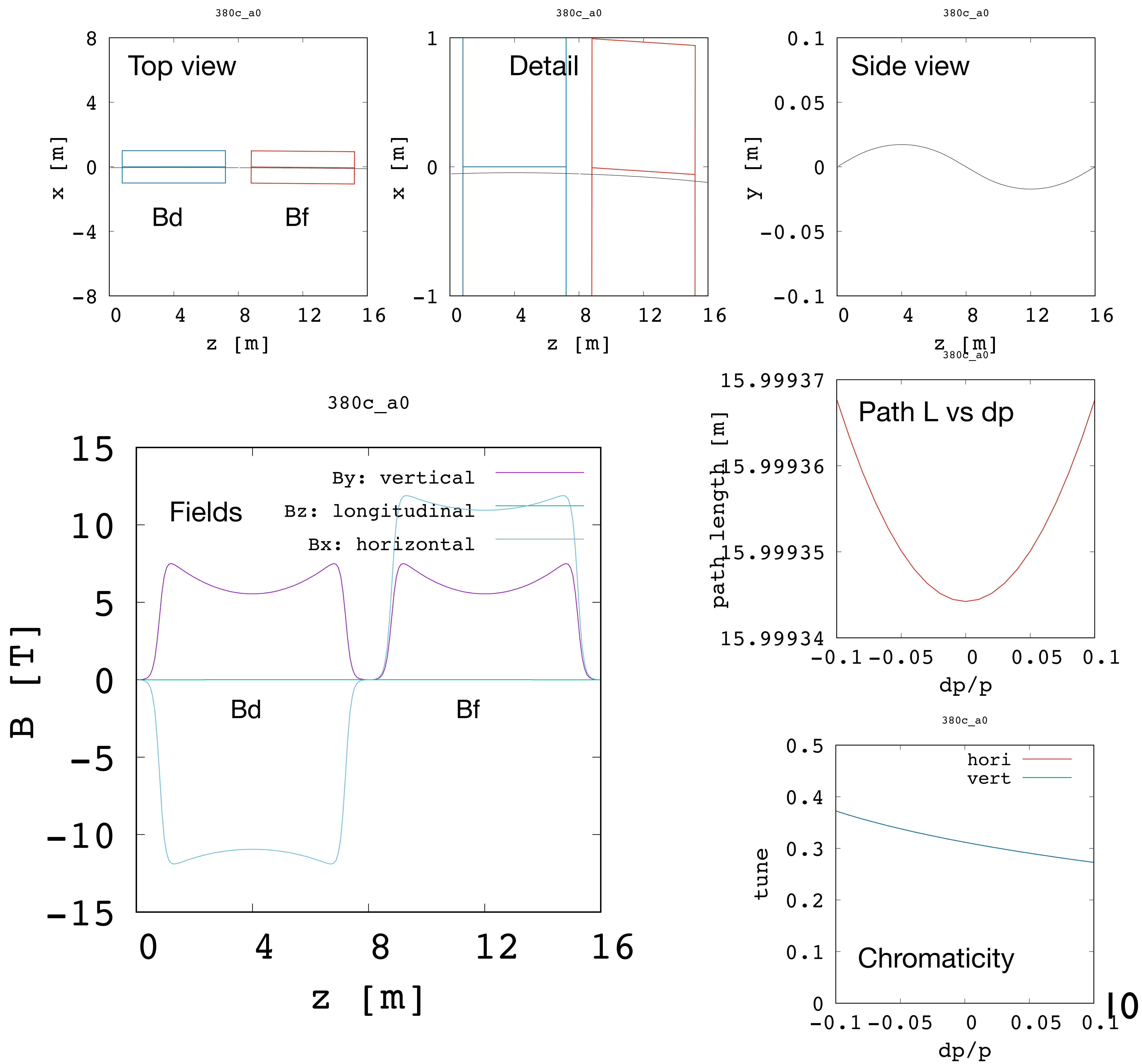
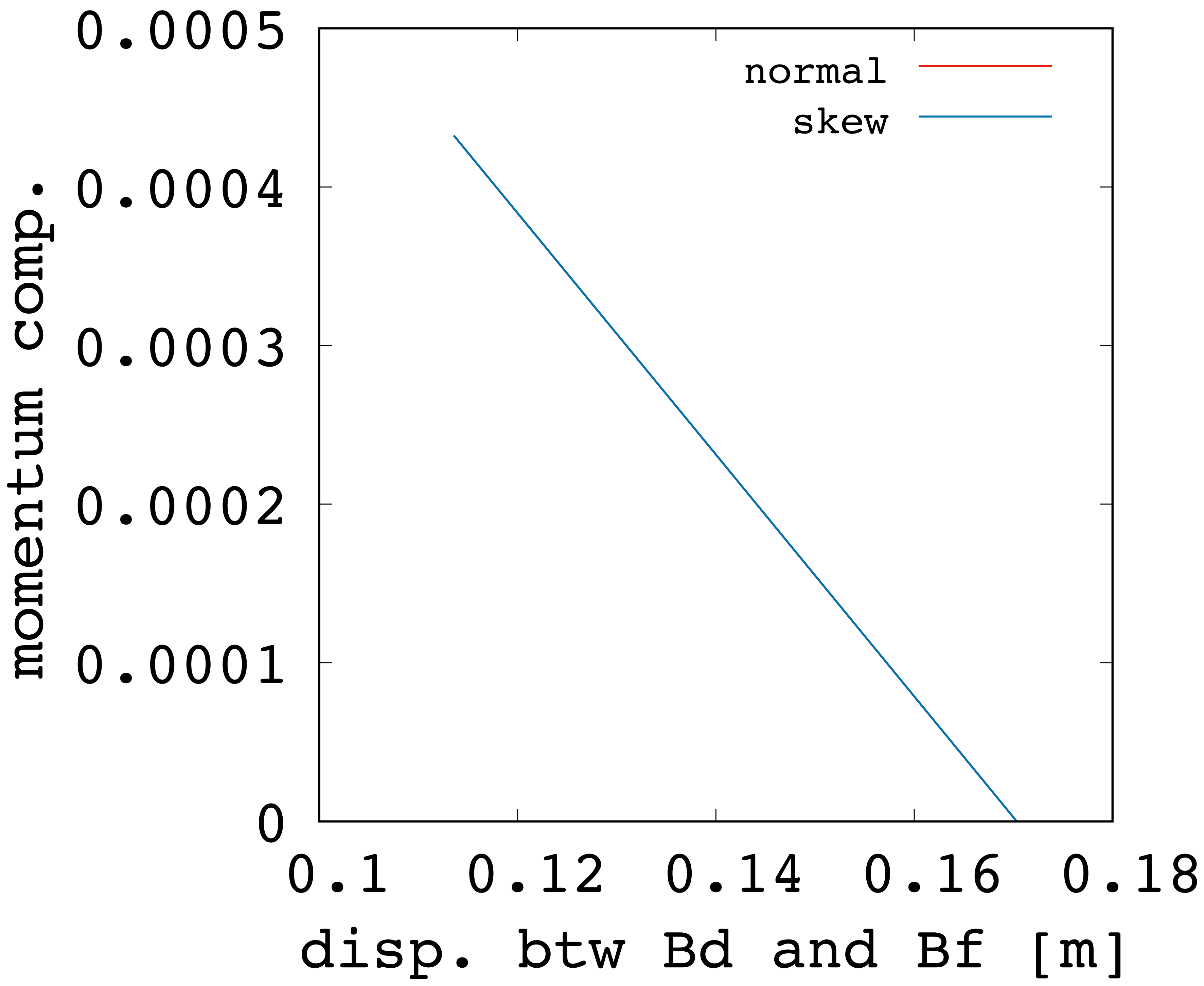
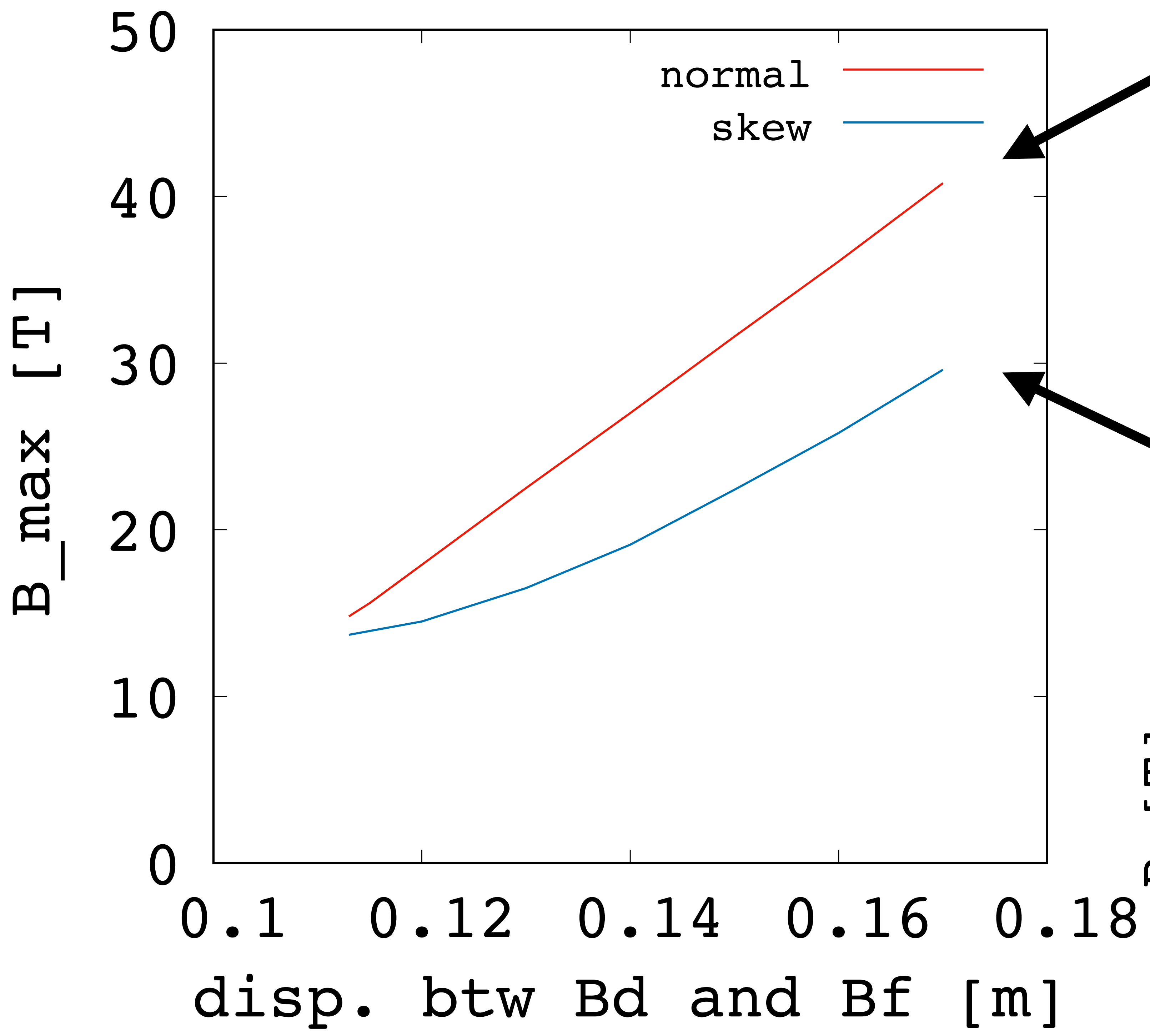
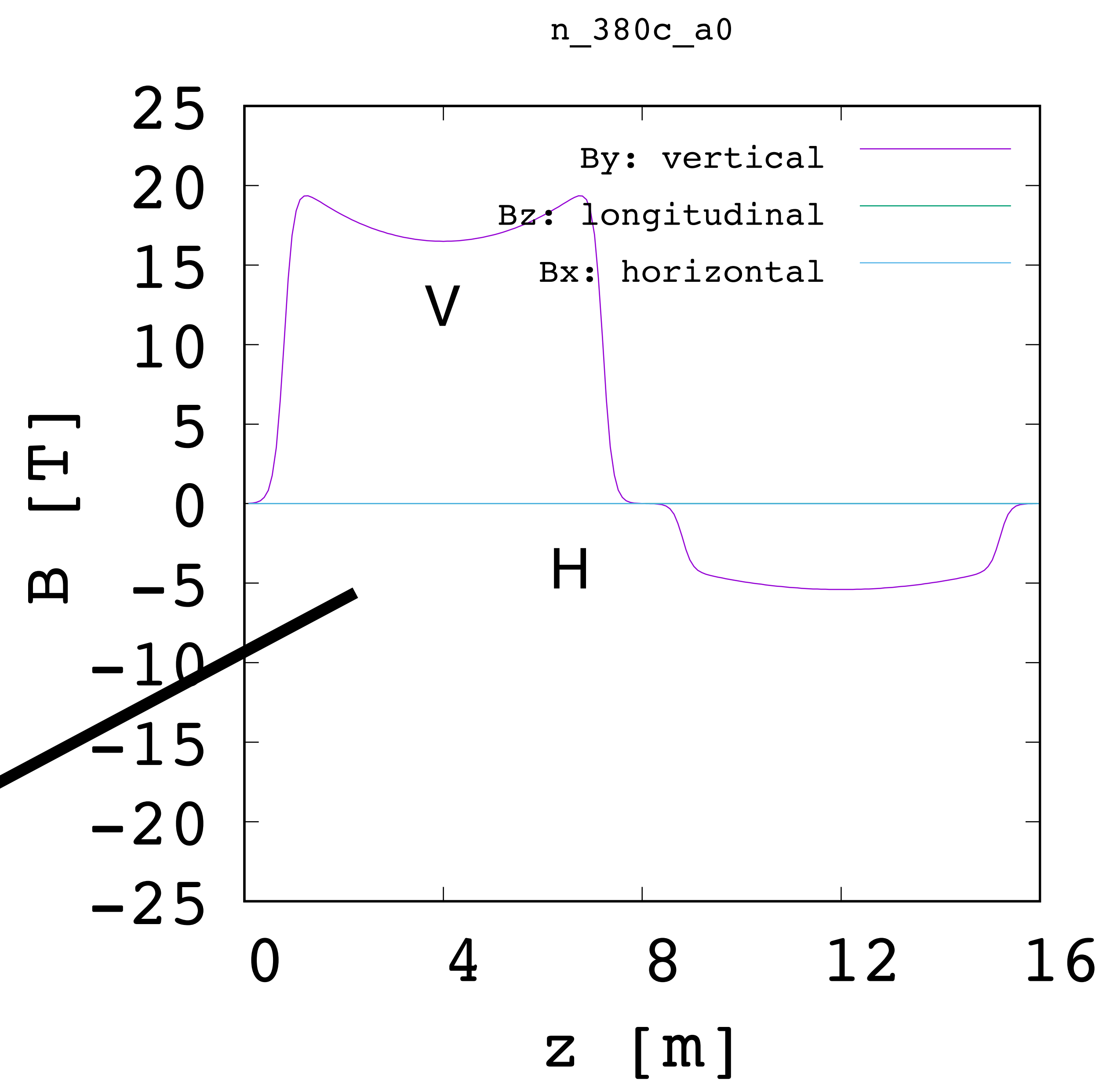


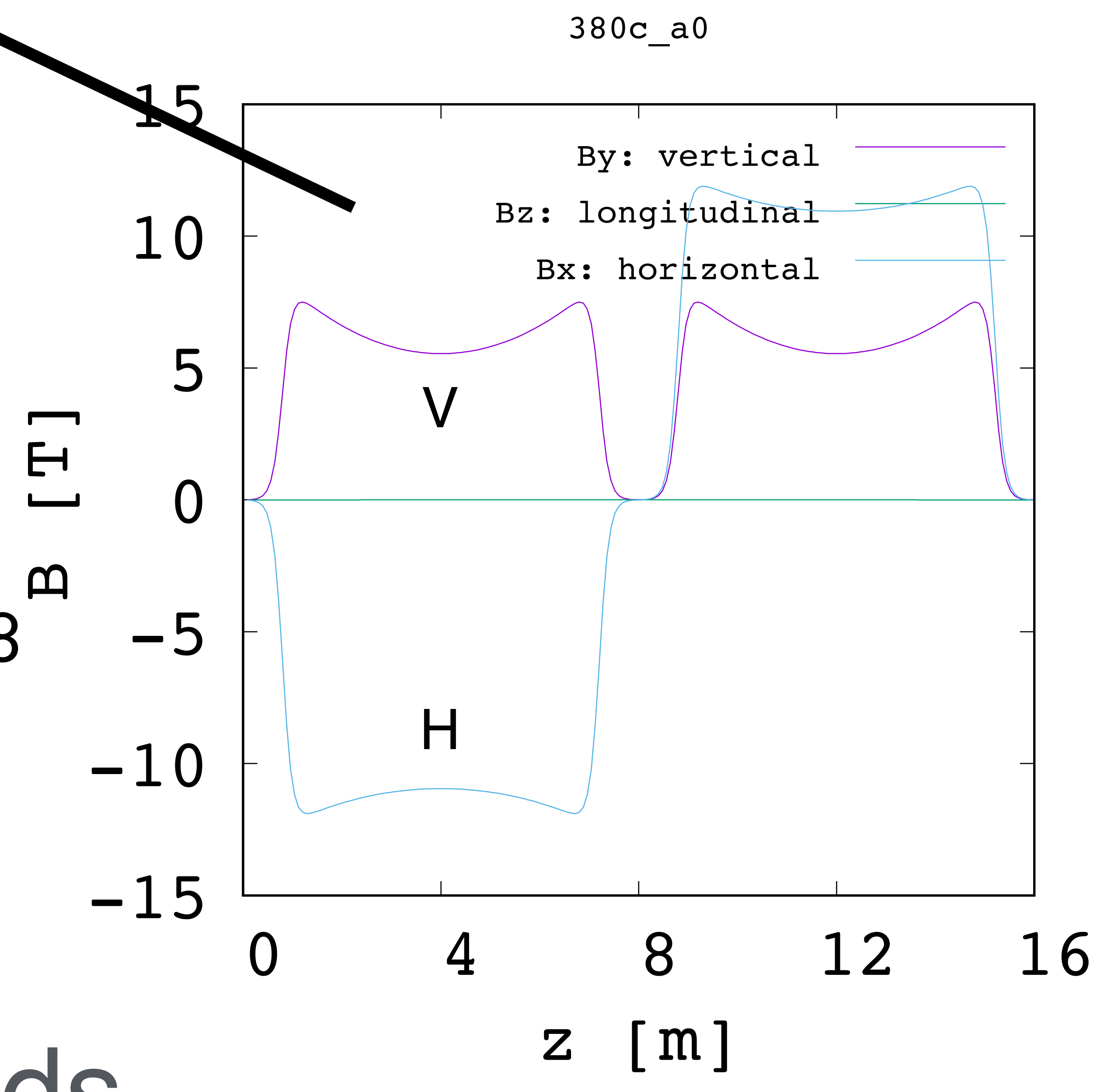
1.5 TeV collider ring

momentum compactor and maximum field strength









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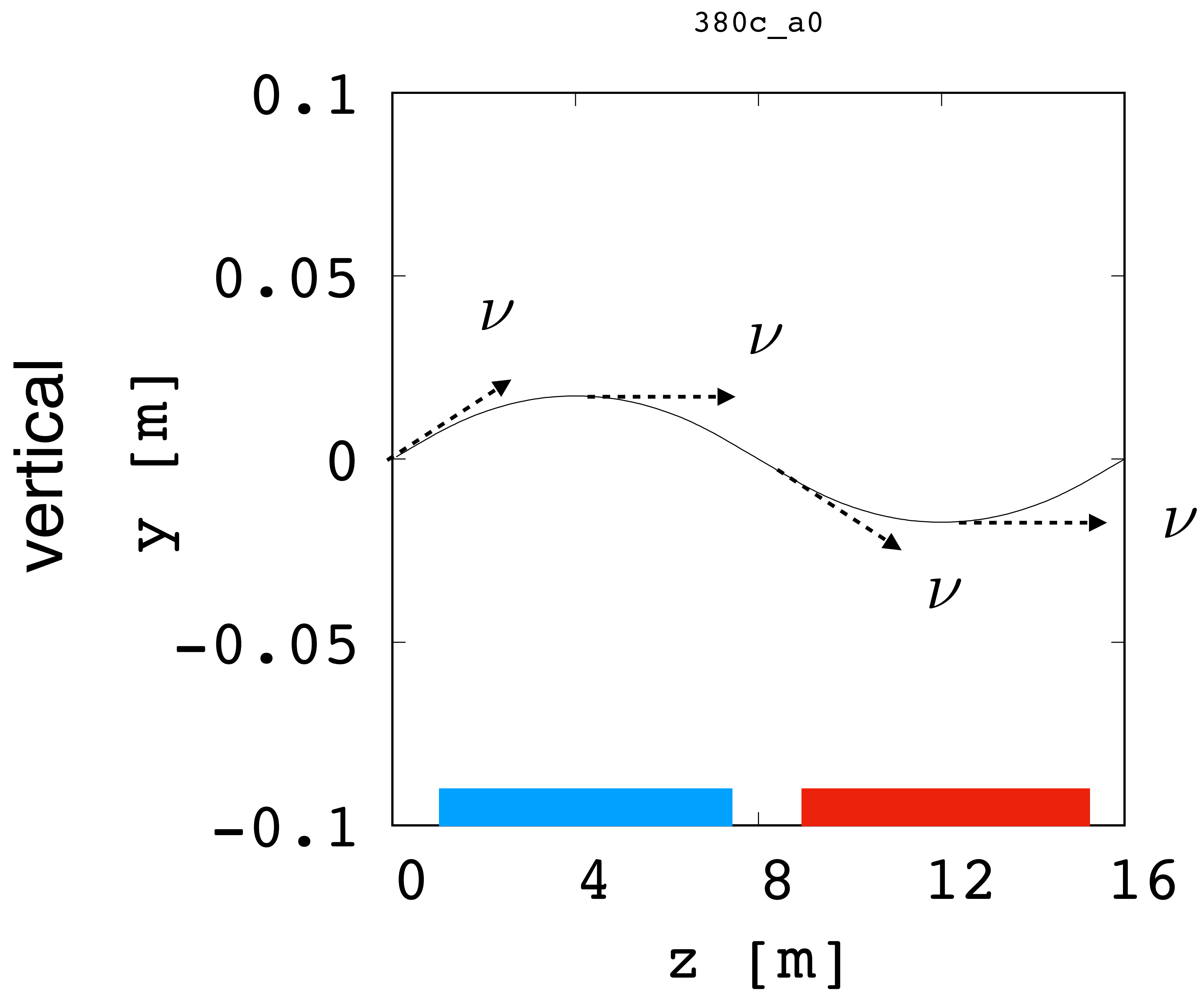
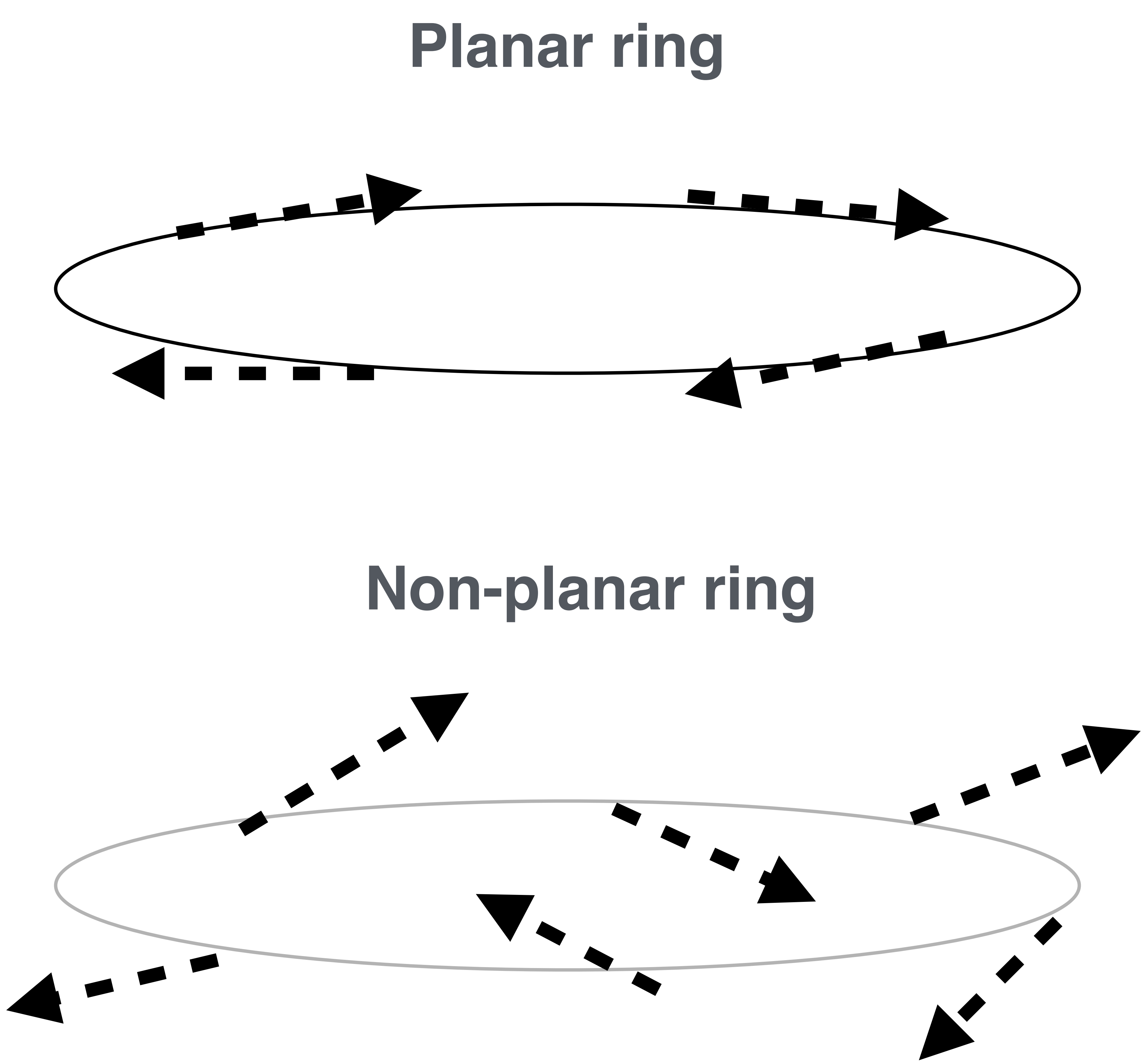
Skew FODO does not need negative bends.

Radiation mitigation

orbit is wiggling in vertical direction by horizontal dipole

- Beam orbit is not constrained on a horizontal plane.
- Vertical wiggling angle is e.g. +/- 8 mrad (see below, but depend on cell length).





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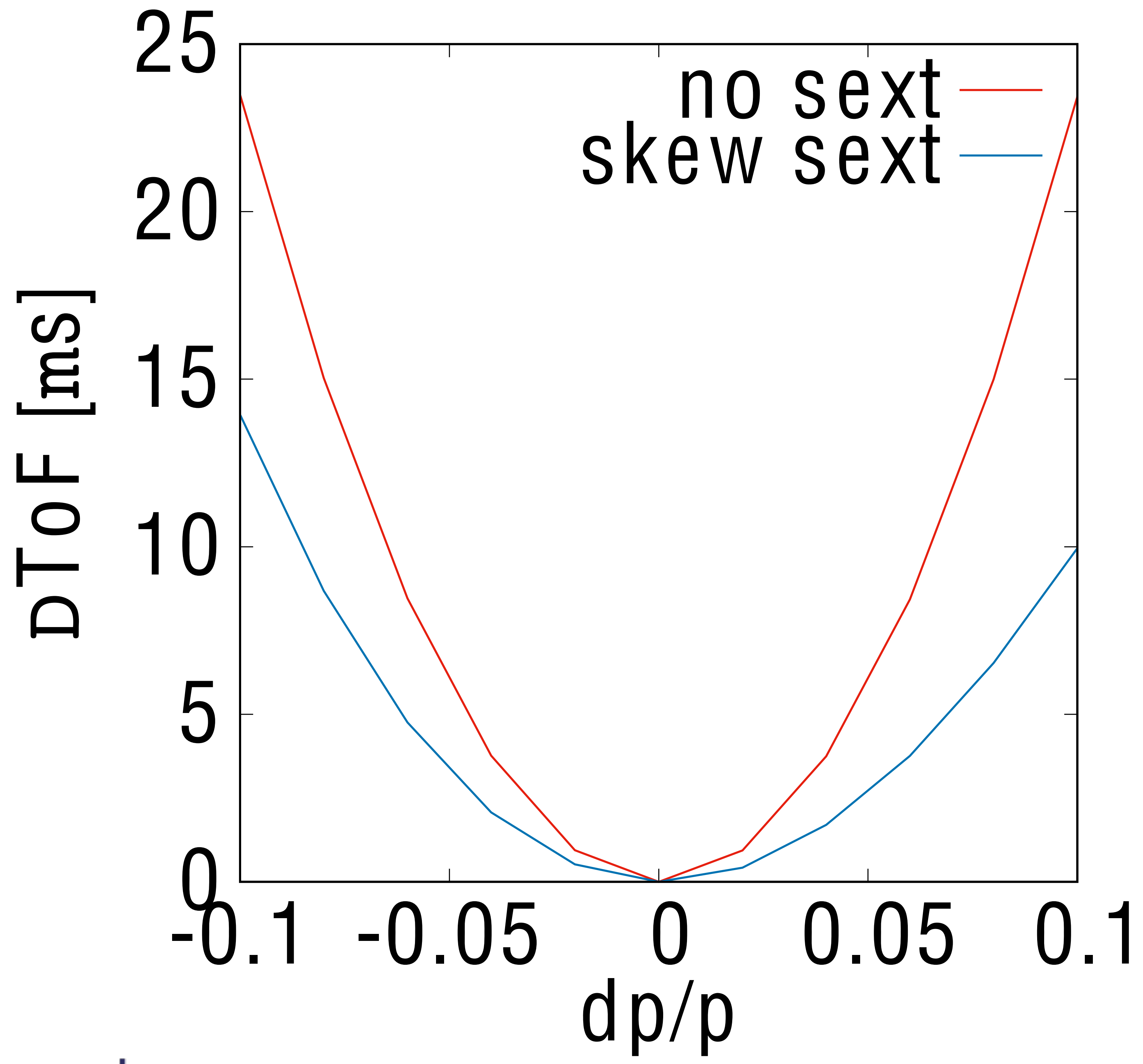
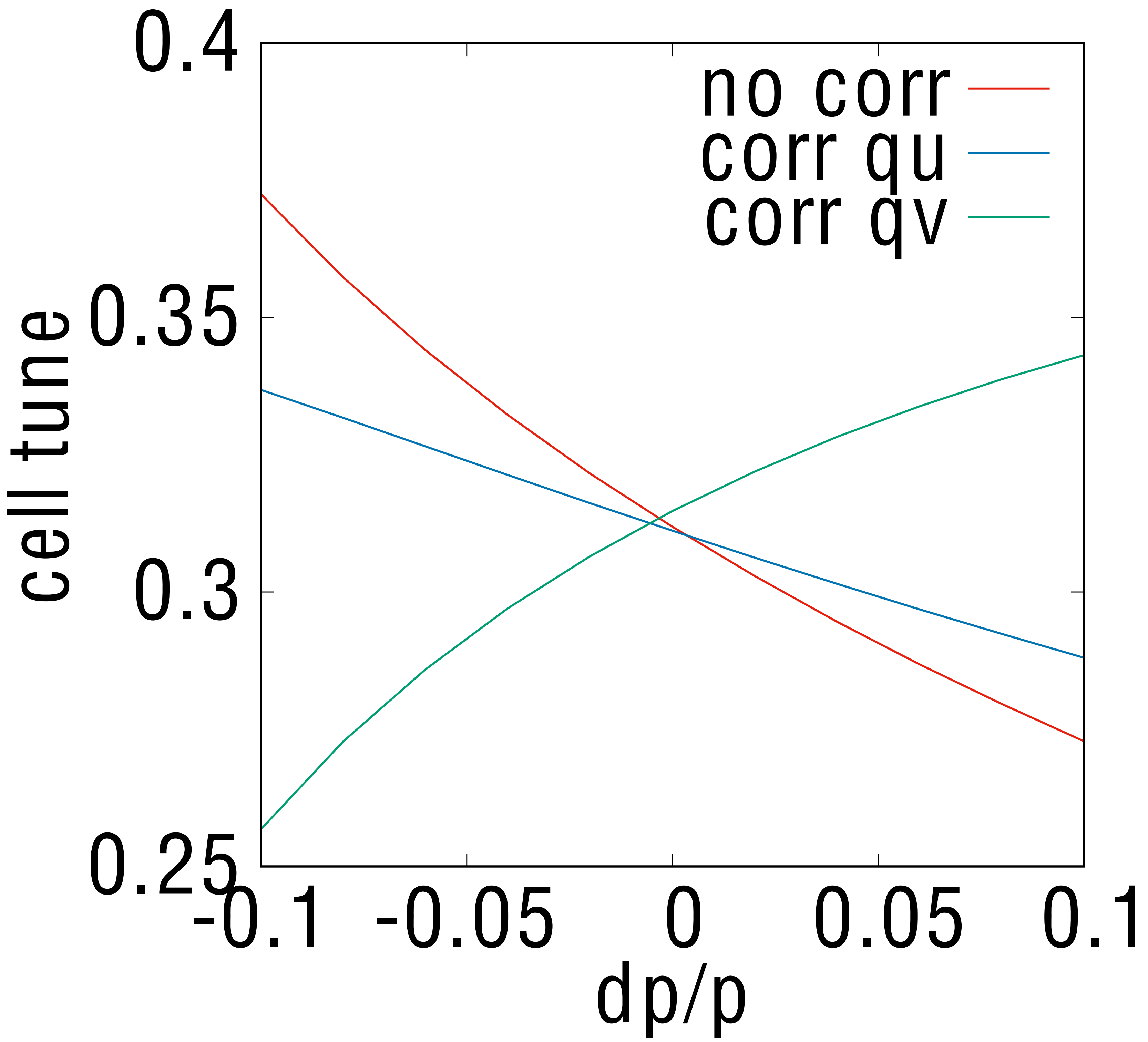
Correction of higher order MC and chromaticity

with skew sextupole

Skew sextupole control higher order momentum compaction factor and chromaticity at the same time.





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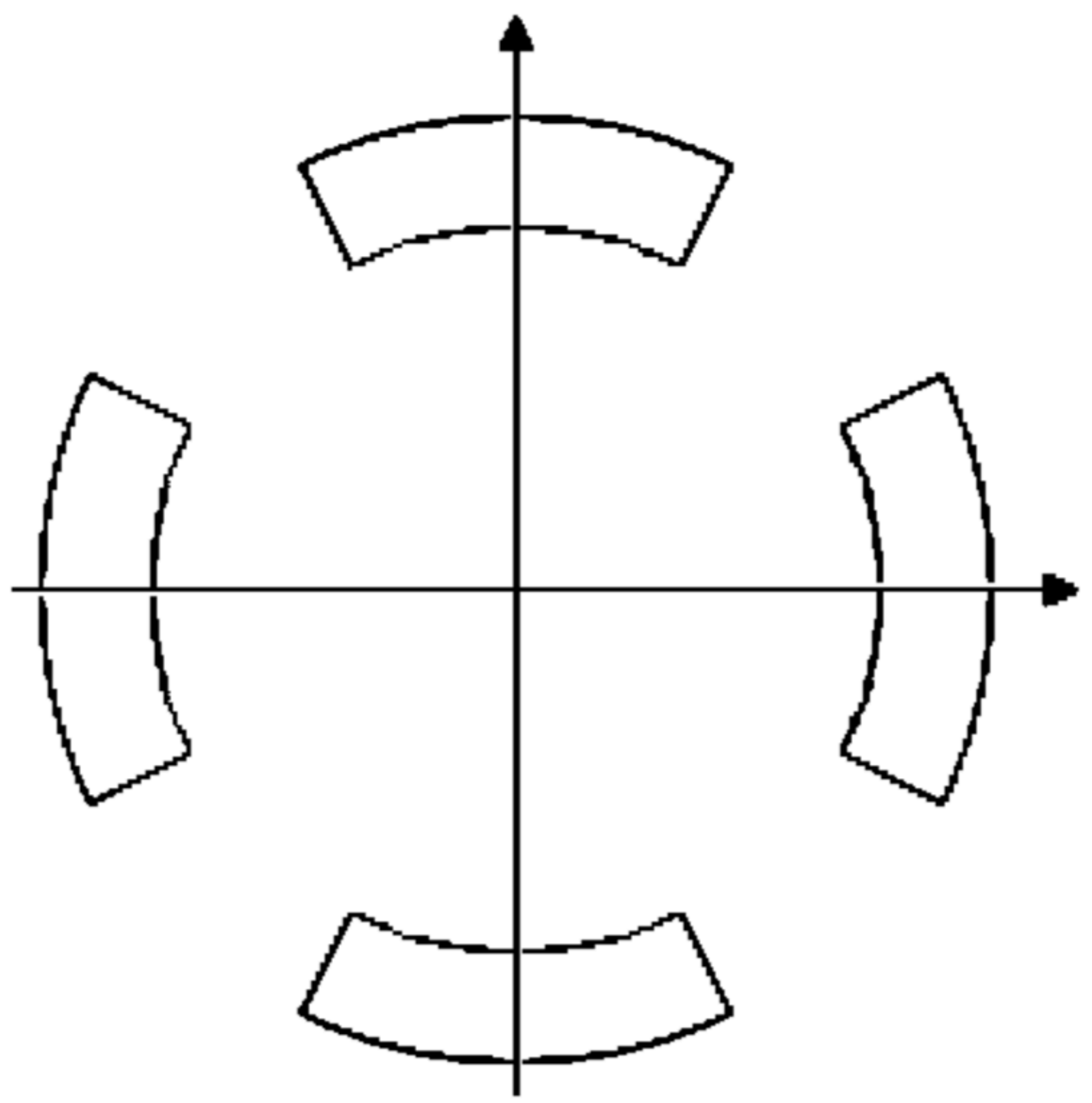
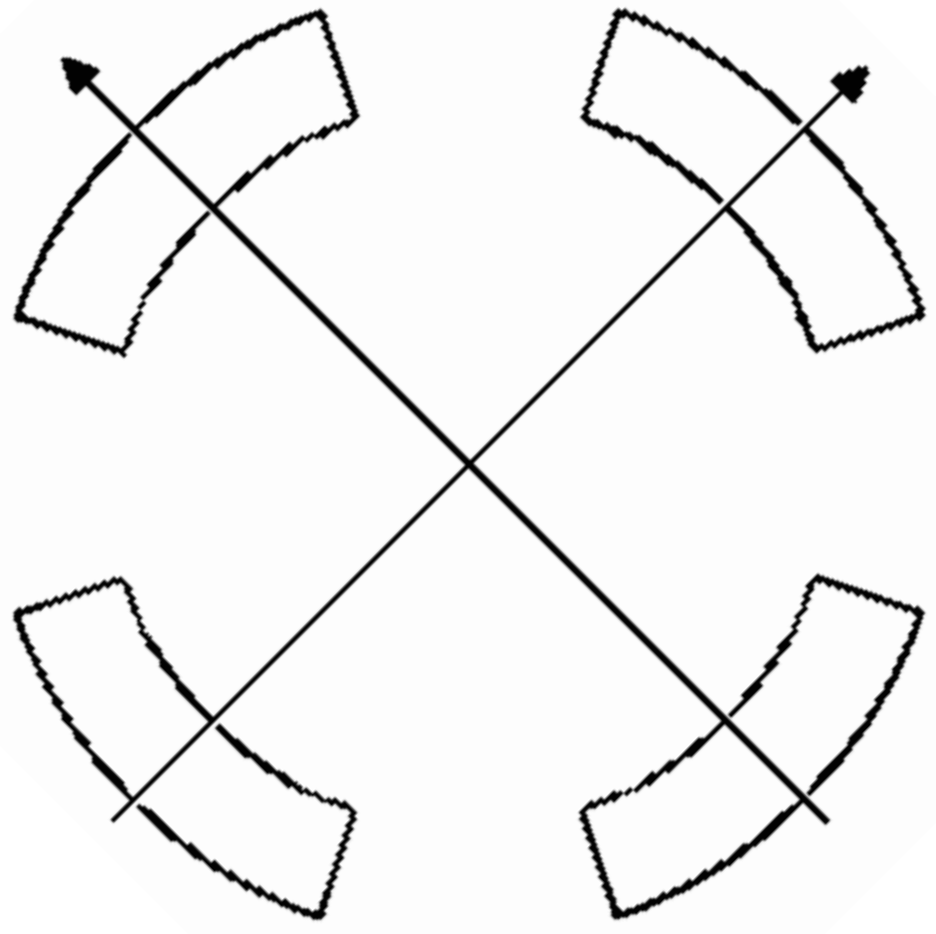
Superconducting coil

Normal quad



Skew quad



Does the gap in horizontal plane (**open mid-plane**) help?

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R&D proposal

- **Full collider arc optics design with combined skew quadrupole magnets**
  - Control of the momentum compaction factor and mitigation of radiation due to neutrino decaying from muons can be achieved by a lattice whose main elements are skew quadrupoles with vertical displacement.
  - It is a promising novel design concept, but needs more investigation on the effects of nonlinear components, tuneability of the orbit and optics.
  - Low beta section is not designed which to be compatible with the arc. Simple 45 rotated low beta is a good start.
  - R&D aims for the completion of conceptual design in 2025.

Two exotic options not discussed in MAP

International MUON Collider Collaboration

Collider arc with skew quadrupoles

Vertical excursion FFA for muon acceleration

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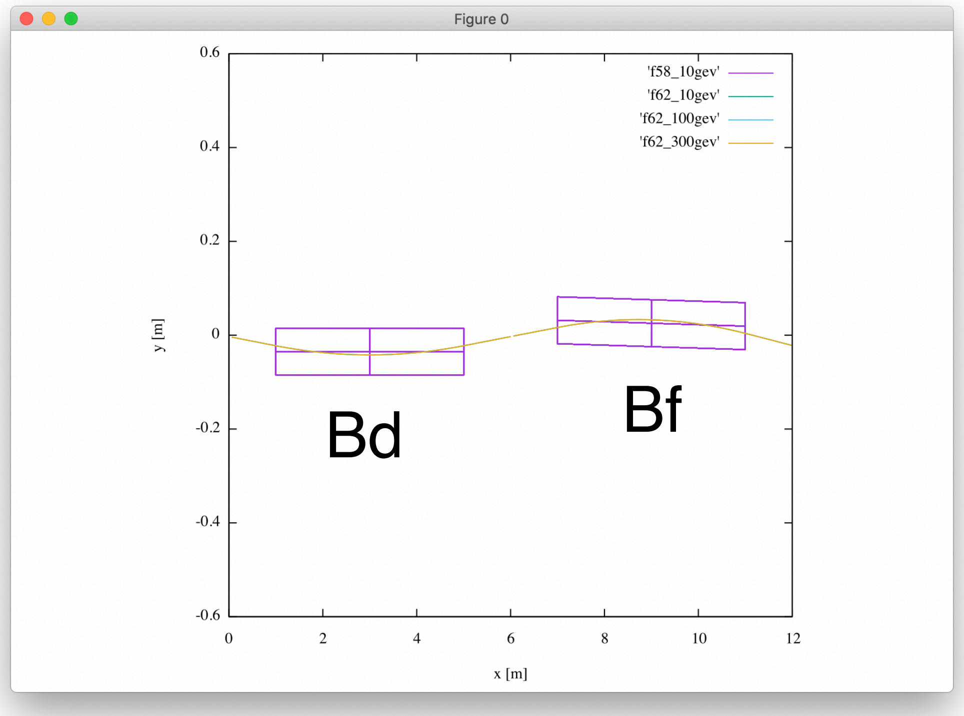
Reasons for vertical excursion FFA (vFFA)

- **DC magnet**: no need to ramp according to the beam momentum.
- **Isochronous operation**: no need to modulate RF frequency according to the beam momentum.
- The beam orbit moves up when the beams are accelerated.

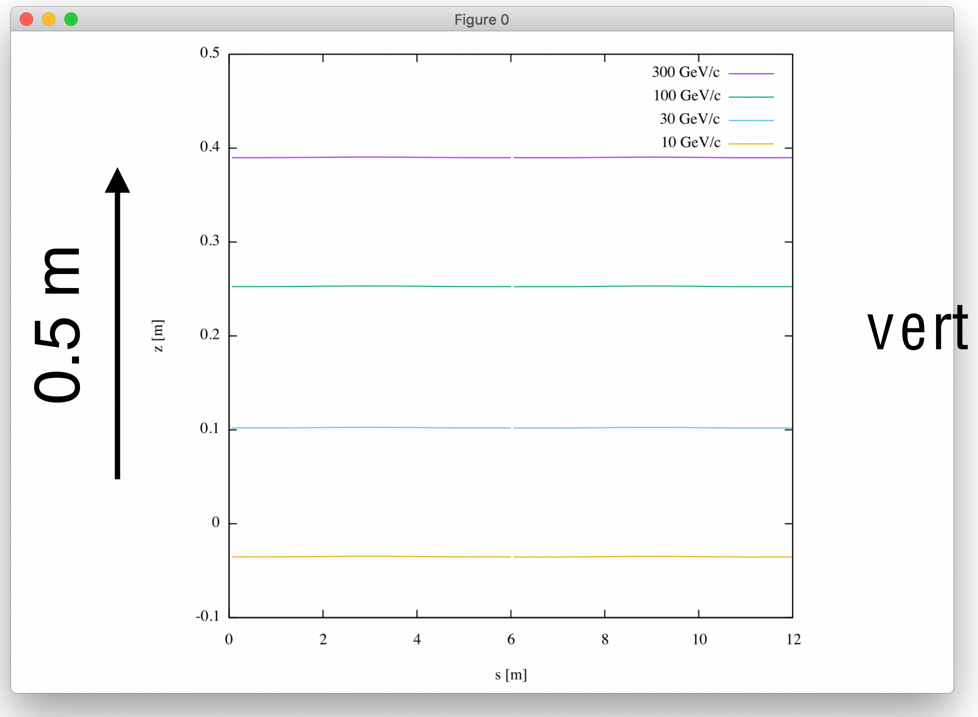
$$B = B_0 \exp(my)$$

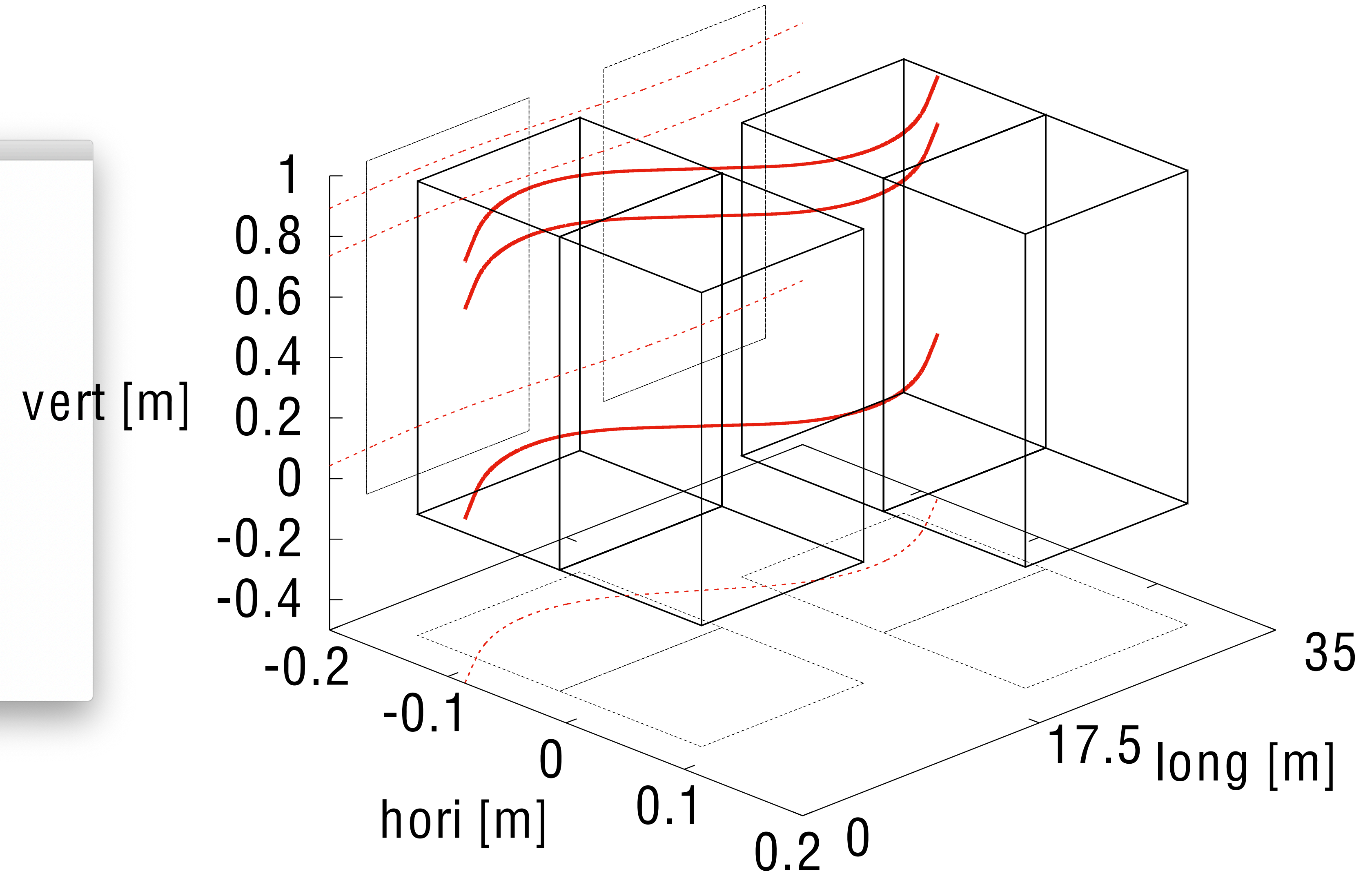
m : field index
y : vertical

Top view



Side view





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Example: 1.5 TeV accelerator in similar size of LHC tunnel

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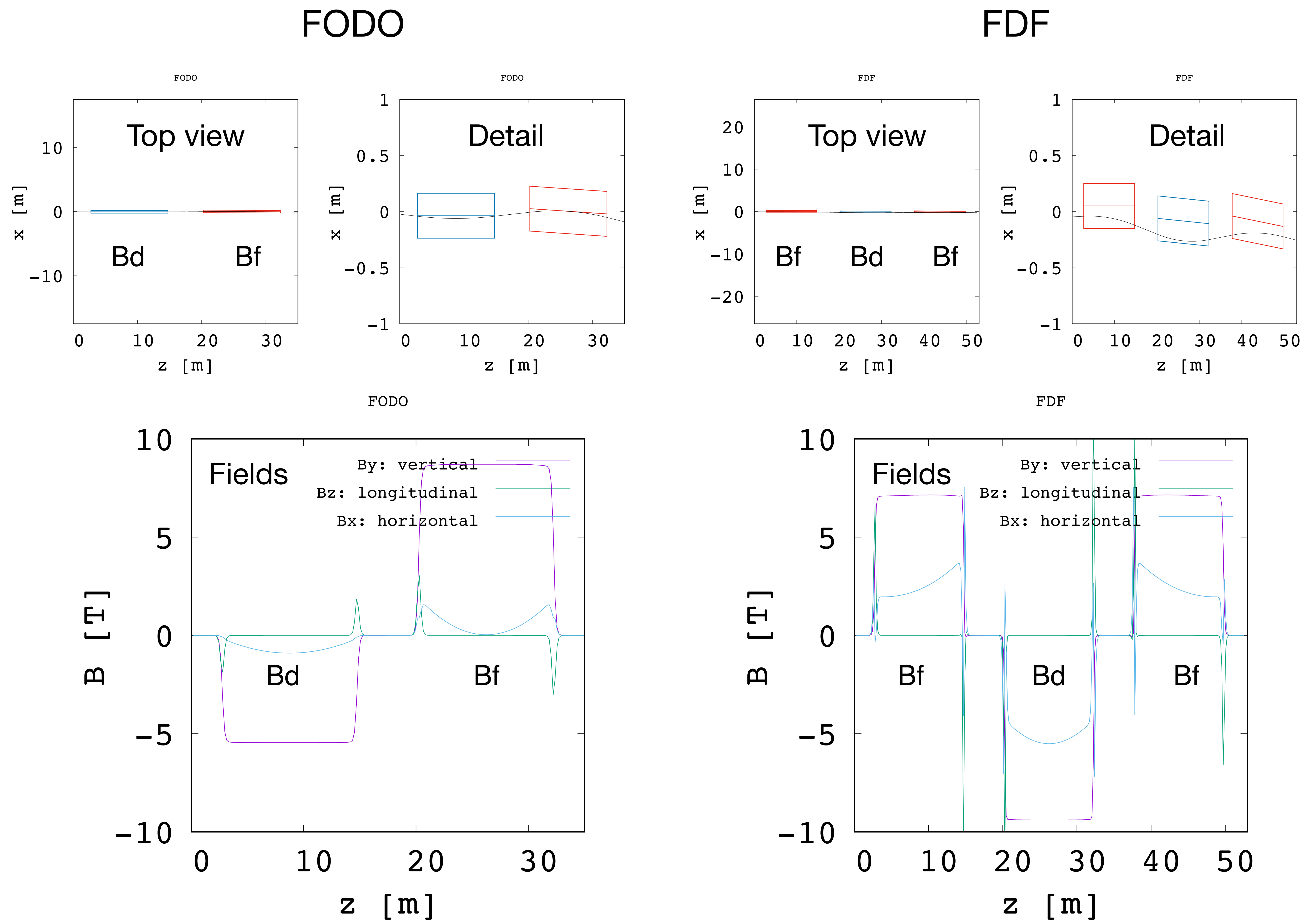
	FODO	FDF
Energy	50 GeV to 1.5 TeV	50 GeV to 1.5 TeV
Cell length	35 m	52.5 m
Magnet length	2 x 15 m	3 x 15 m
# of cell	810	540
Maximum field	8.7 T	10.6 T
Field index m	6.8	3.0
Orbit excursion	0.50 m	1.13 m
Cell tune	0.3957 / 0.0861	0.3510 / 0.1515



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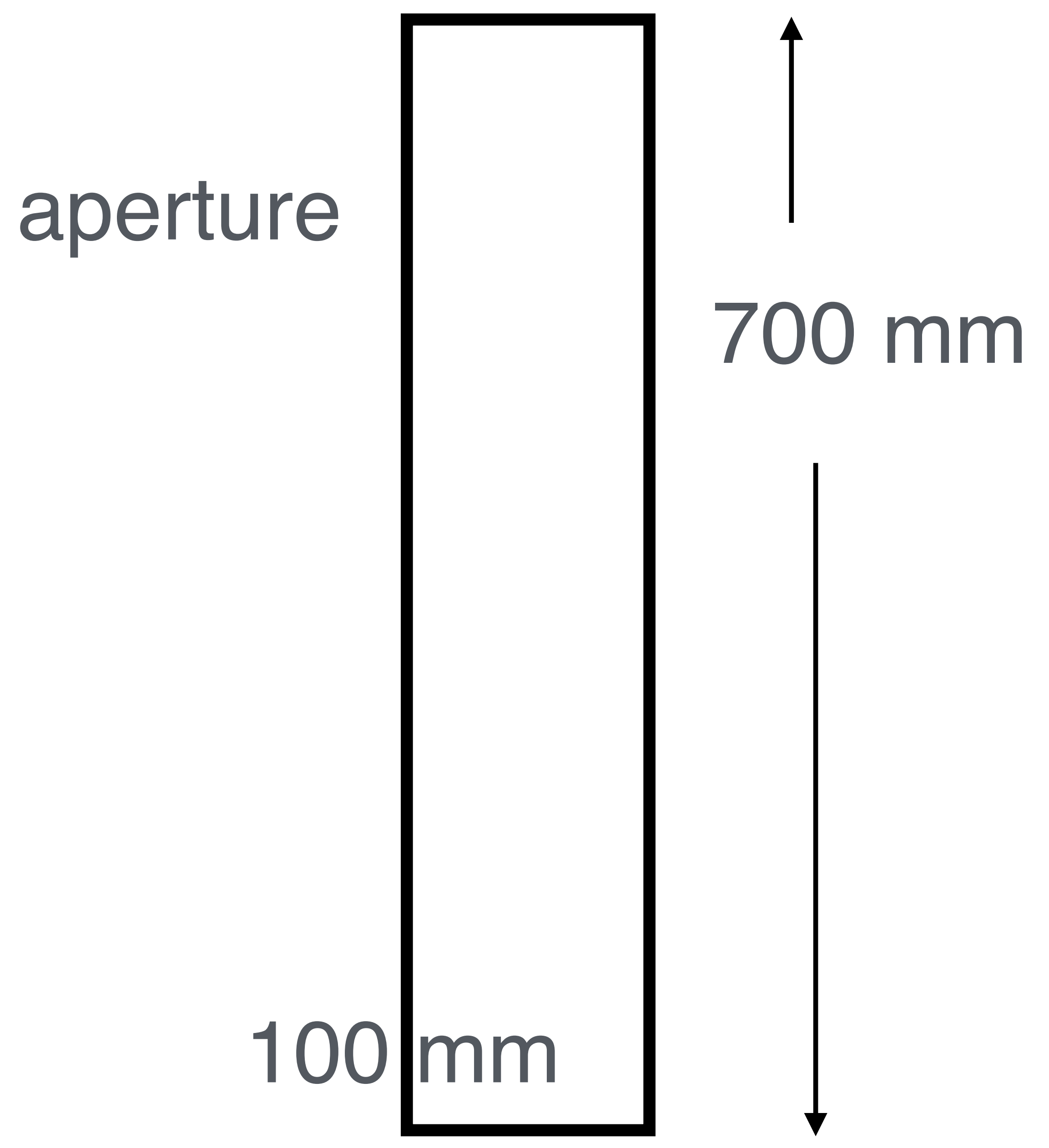
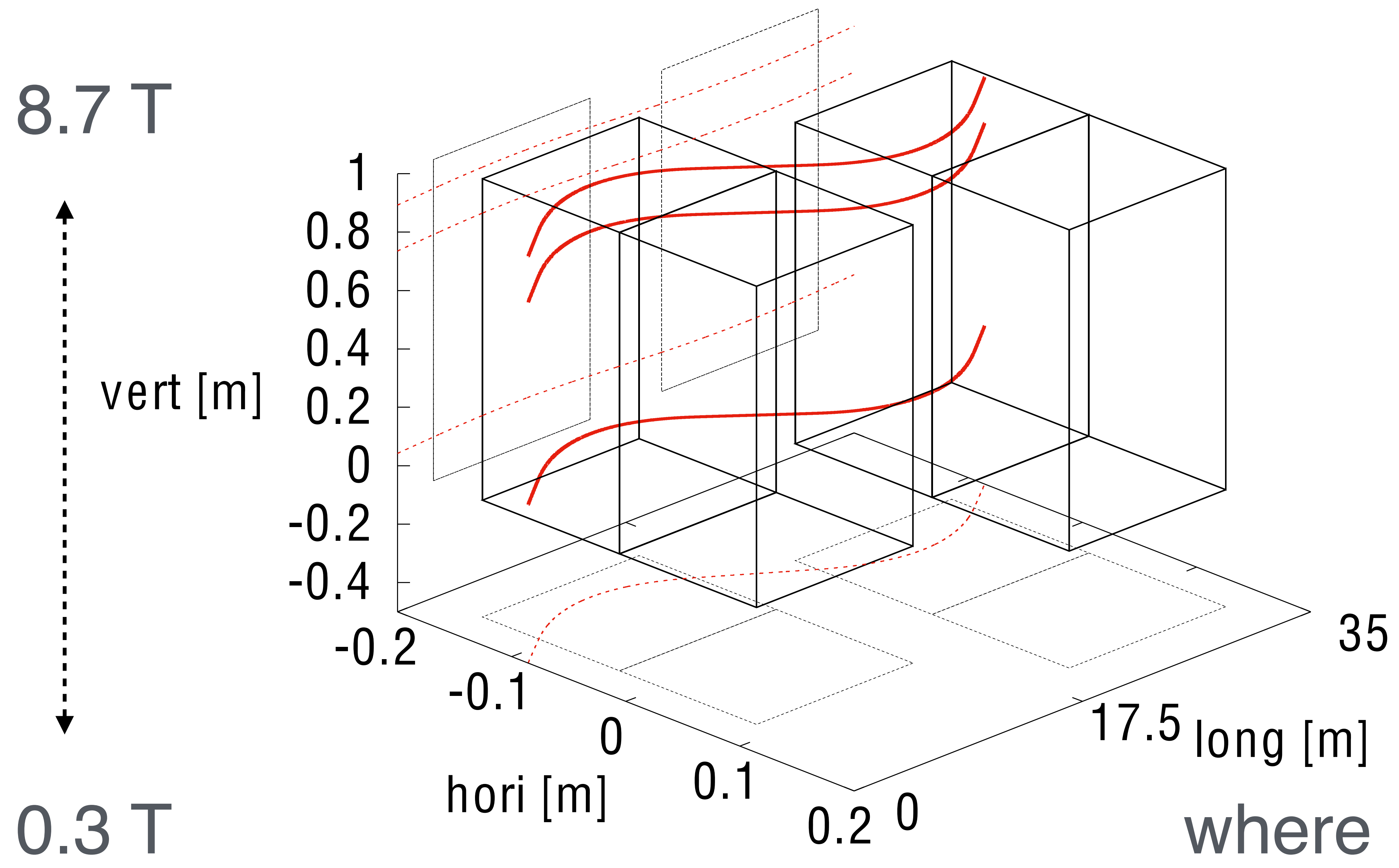
- Reduction of reverse bending is one of optimisation targets.

Critical issues (1)

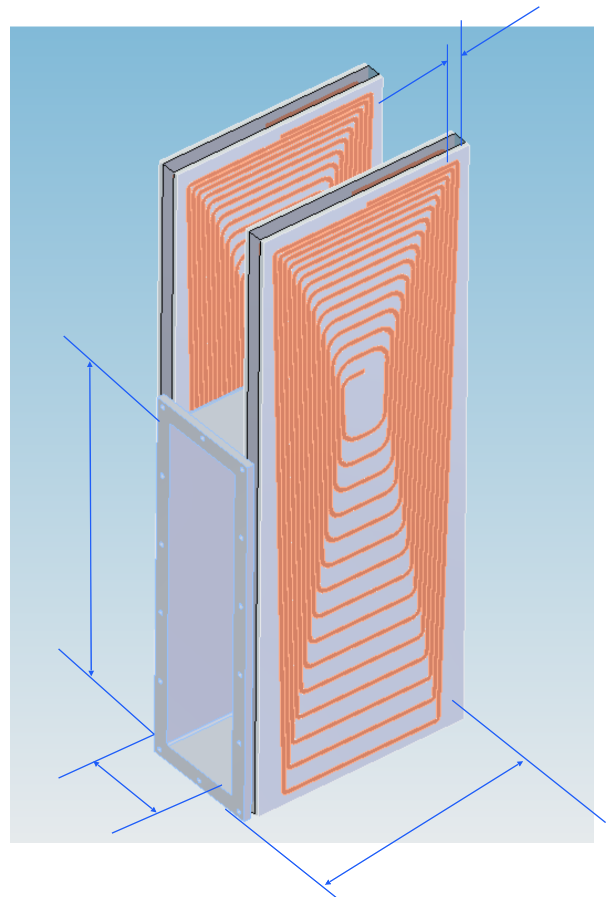
orbit excursion makes a large aperture

- DC but large aperture (in vertical only) magnet.





Prototype at STFC/RAL



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- 3D magnetic field increase exponentially.

$$B_x(x,y,z) = B_0 \exp(my) \sum_{i=0}^{N} b_{xi}(z) x^i,$$

$$B_y(x,y,z) = B_0 \exp(my) \sum_{i=0}^{N} b_{yi}(z) x^i,$$

$$B_z(x,y,z) = B_0 \exp(my) \sum_{i=0}^{N} b_{zi}(z) x^i.$$

where $m = (1/B)(\partial B/\partial y)$

$$b_{x0}(z) = 0, \quad b_{y0}(z) = g(z), \quad b_{z0}(z) = \frac{1}{m}\frac{dg}{dz},$$

$$b_{x,i+1}(z) = -\frac{1}{i+1}\left(m b_{yi} + \frac{db_{zi}}{dz}\right),$$

$$b_{y,i+2}(z) = \frac{m}{i+2} b_{x,i+1},$$

$$b_{z,i+2}(z) = \frac{1}{i+2}\frac{db_{x,i+1}}{dz}.$$

Critical issues (2)

reverse bend

- The present lattice design has large fraction of reverse bending field which increases the overall circumference of the ring.
- Reduction of reverse bend is the high priority item of vFFA optics.
  - e.g. **vFFA without reverse bend** magnets (replaced by edge focusing).

STEPHEN BROOKS

Phys. Rev. ST Accel. Beams 16, 084001 (2013)

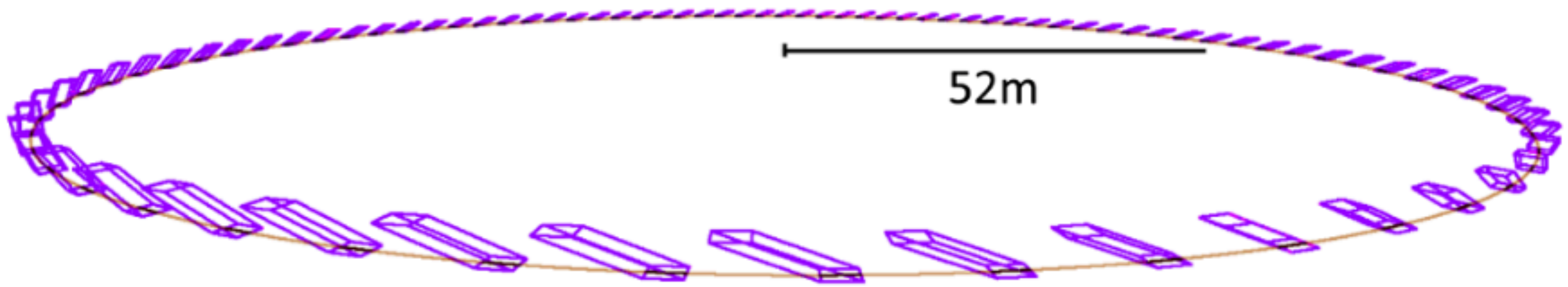

FIG. 8. Perspective view of the 12 GeV ring.

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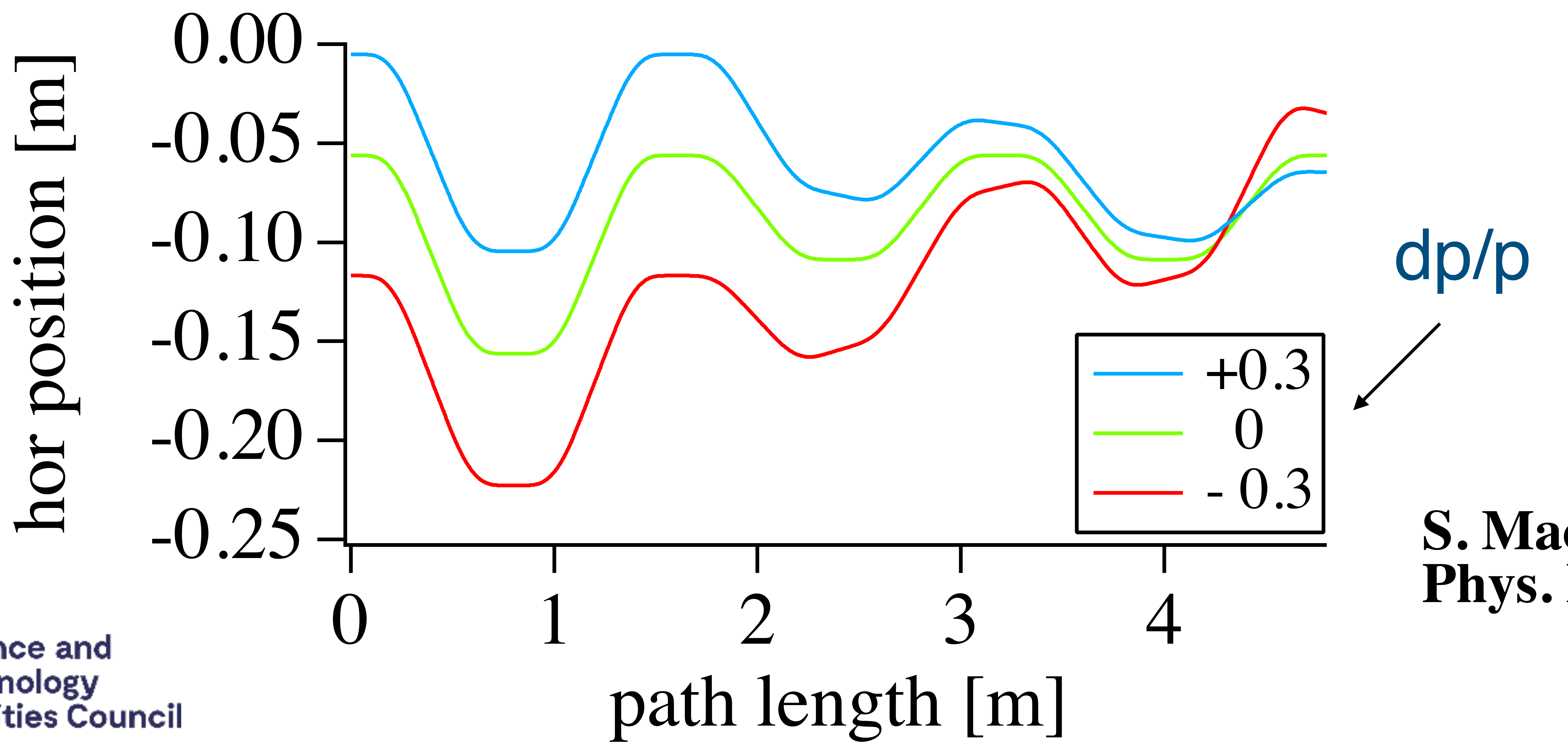
Critical issues (3)

orbit excursion at RF cavity

- High frequency RF (1.3 GHz) does not have a wide enough aperture (~ 0.5 m) to accommodate orbit excursion of high and low momentum beams.
- Conventional FFA has a way to **reduce the dispersion function locally**, which makes the orbit excursion small or zero locally.
- The same technique is under investigation in vFFA.



S. Machida, R. Fenning
Phys. Rev. ST Accel. Beams 13, 084001

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R&D proposal

International MUON Collider Collaboration

- **Optimisation of vFFA accelerator lattice**
  - DC magnet and isochronous operation are the main reasons to consider a vFFA for muon acceleration.
  - Relatively large circumference and orbit excursion of the order of ~ meter are two main issues of the vFFA based muon accelerator.
  - Reverse bend could be reduced or eliminated, for example, by edge focusing. Dispersion suppressor could be considered which was successful designed in a conventional horizontal excursion FFA.
  - R&D aims for the completion of conceptual design in 2025.

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Thank you for your attention

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Summary

	Normal FODO		Skew FODO	
Energy	1.5 TeV	1.5 TeV	1.5 TeV	1.5 TeV
Momentum compaction	4.32×10^{-4} →	0	4.32×10^{-4} →	0
Circumference	2880 m →	6080 m	2880 m →	6080 m
Cell length	16 m	16 m	16 m	16 m
Magnet length	2 x 6.4 m	2 x 6.4 m	2 x 6.4 m	2 x 6.4 m
# of cell	180	380	180	380
Maximum field	14 T →	20 T	14 T →	14 T
Field gradient	240 T/m	240 T/m	240 T/m	240 T/m
Cell tune	0.3119 / 0.3119	0.3131 / 0.3131	0.3119 / 0.3119	0.3131 / 0.3131

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Low beta insertion will be with skew quadrupoles even with up and down straight section.