Racetrack FFAG muon decay ring for νSTORM

JB. Lagrange, J. Pasternak, Y. Mori

Outline

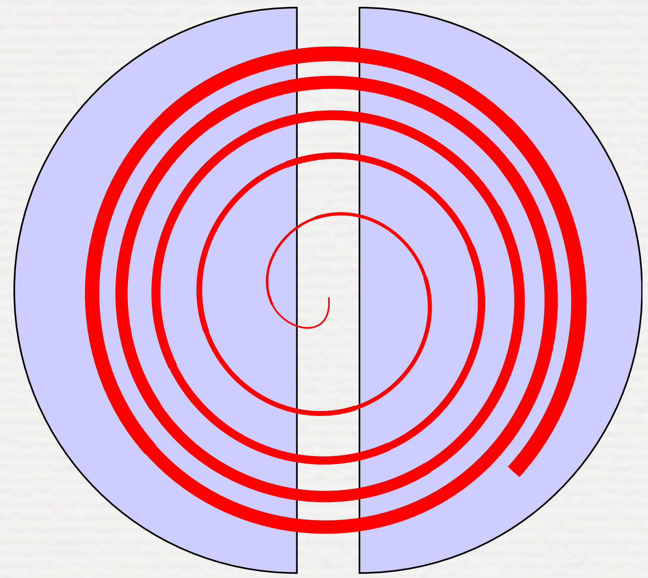
- Zero-chromatic FFAG
- Racetrack FFAG muon decay ring
- Comparison

FFAG accelerator

FIXED FIELD ALTERNATING GRADIENT

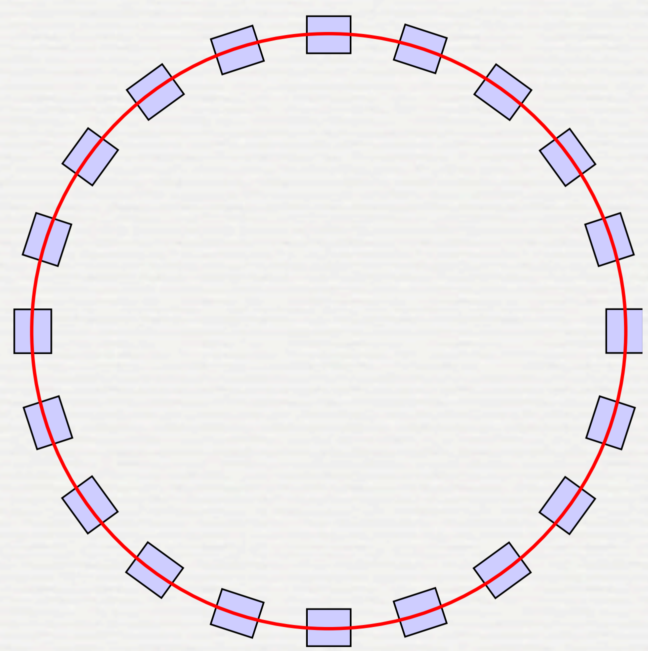
It combines

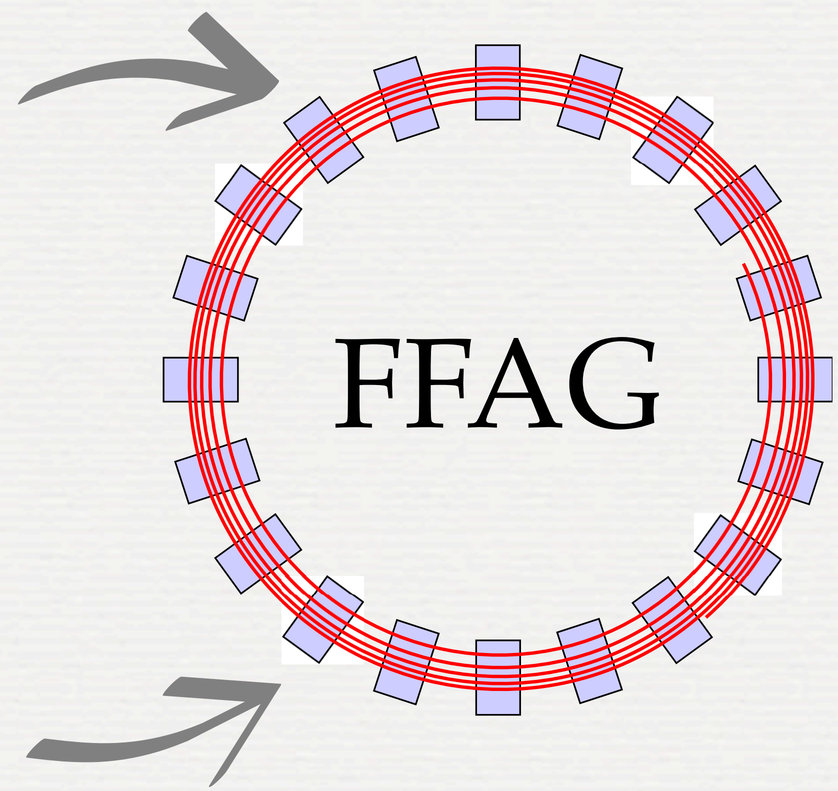
- **a static guide field** like cyclotrons:



AND

- **a strong focusing.** like synchrotrons:

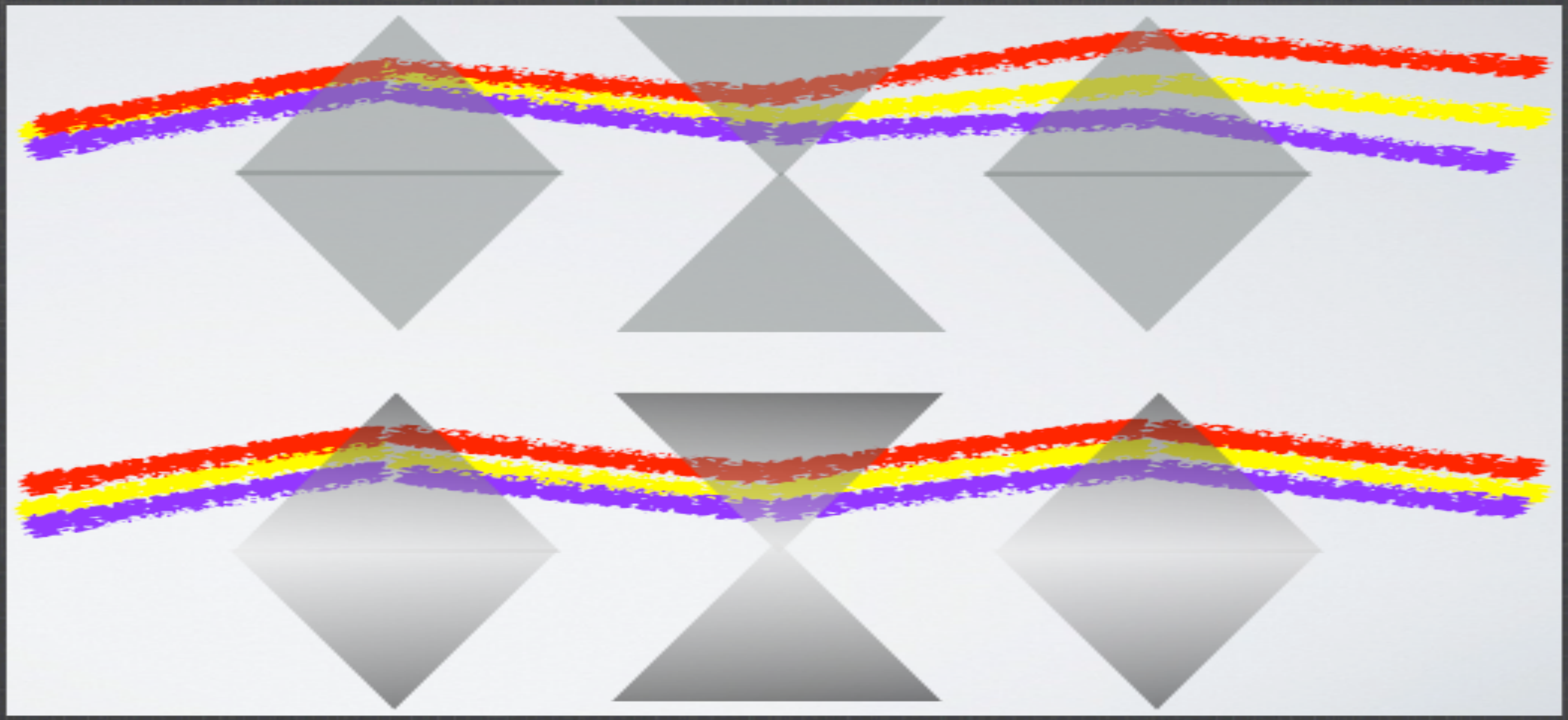




Zero-chromatic FFAG

Advantages:

- stable optics for very large momentum spread.
- allows a good working point with a large acceptance far from harmful resonances.

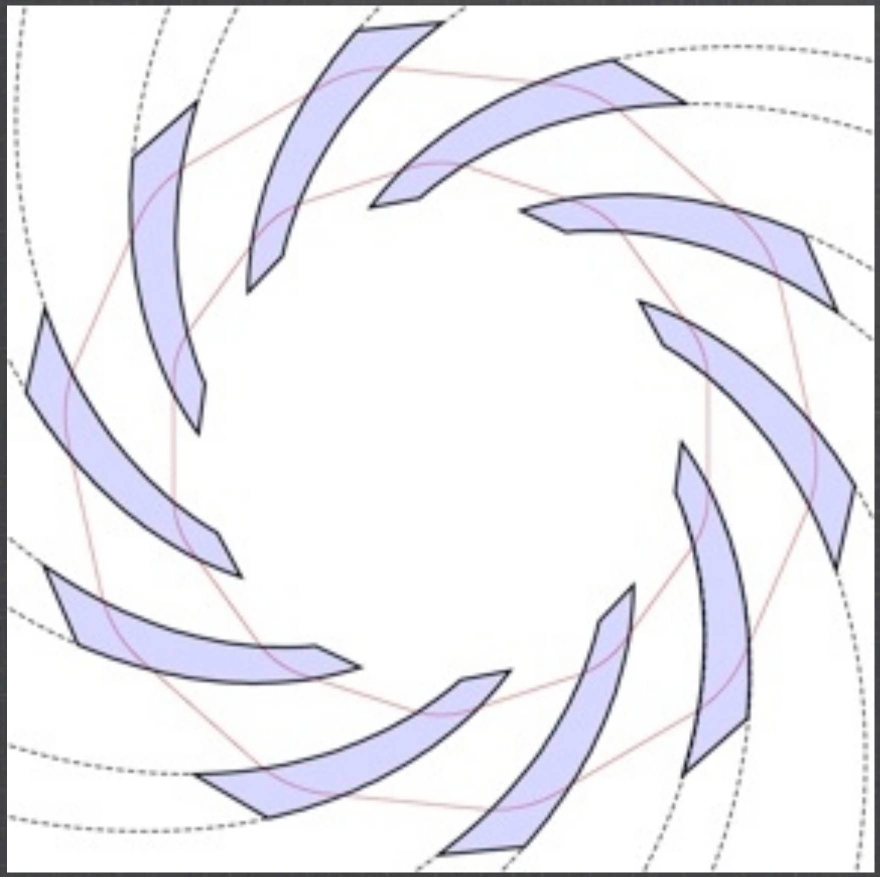


→ Quasi-zero beam loss!

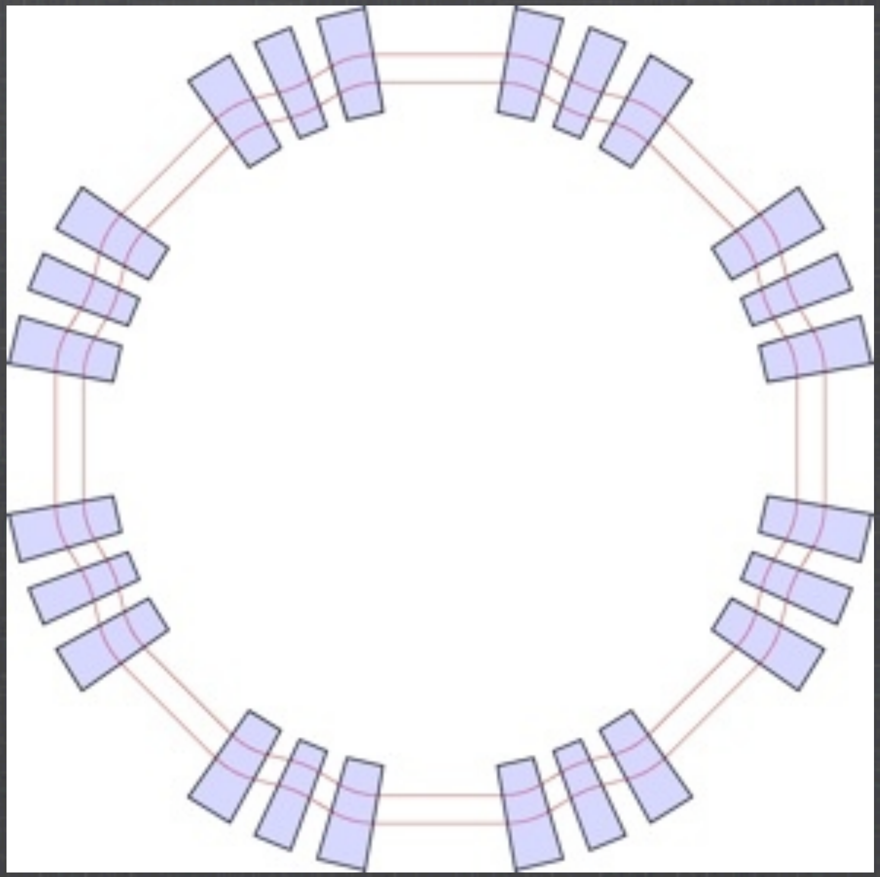
Circular scaling FFAG

Geometrical field index: $k = \frac{R}{\bar{B}}\frac{d\bar{B}}{dR}$

$$\boxed{B(r,\theta) = B_0 \left(\frac{r}{r_0}\right)^k \cdot \mathcal{F}(\theta - \tan\zeta \ln \frac{r}{r_0})}$$



Spiral sector

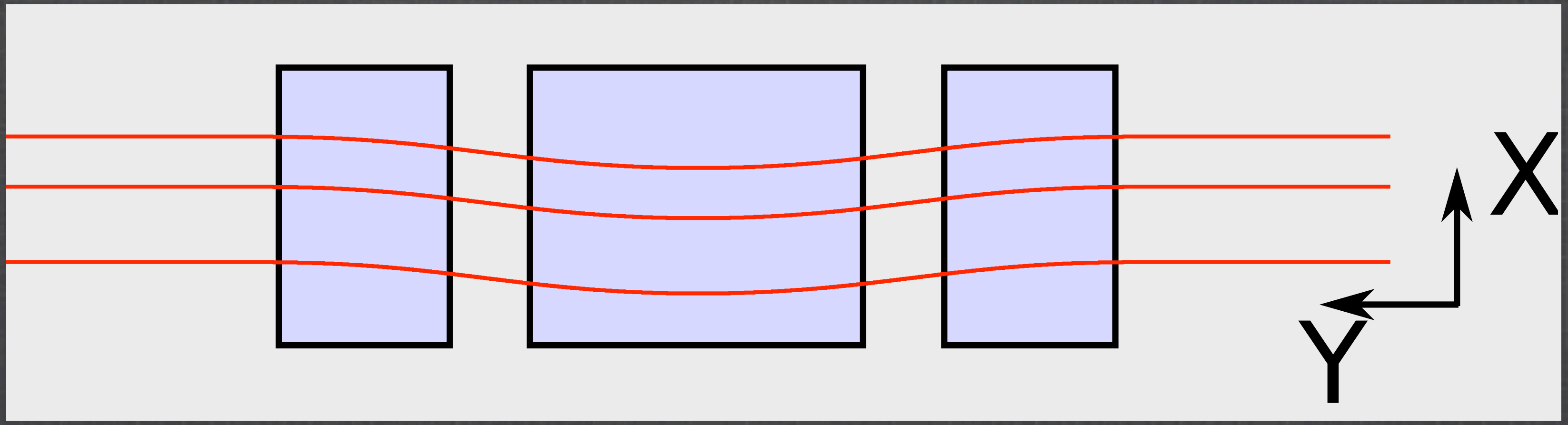


Radial sector

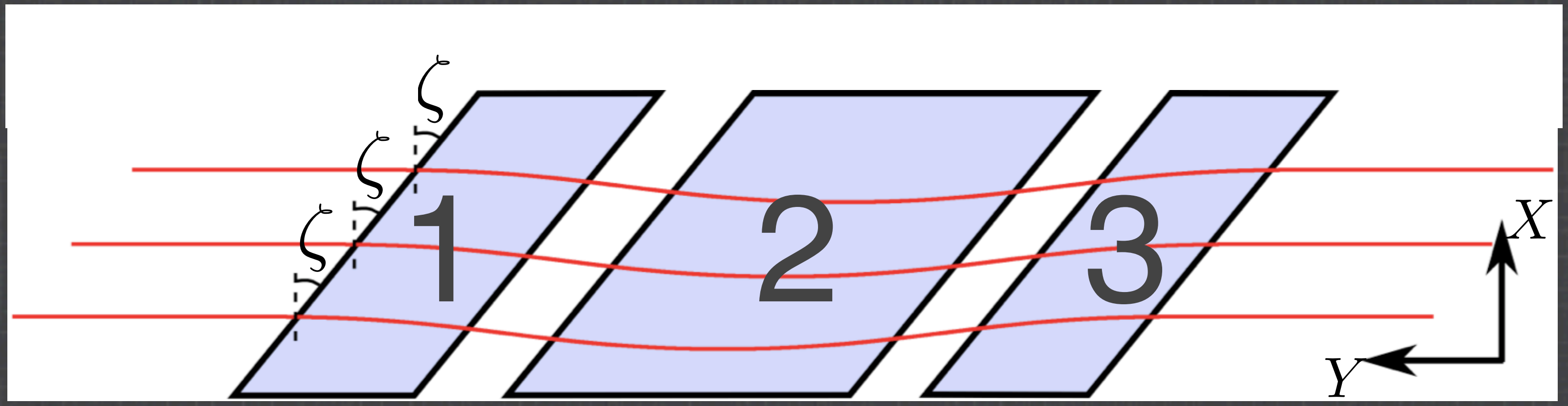
Straight scaling FFAG

Normalized field gradient: $m = \frac{1}{\bar{B}} \frac{d\bar{B}}{d\chi}$

$$B(X,Y) = B_0 e^{m(X-X_0)} \mathcal{F}\left(Y - (X - X_0)\tan\zeta\right)$$

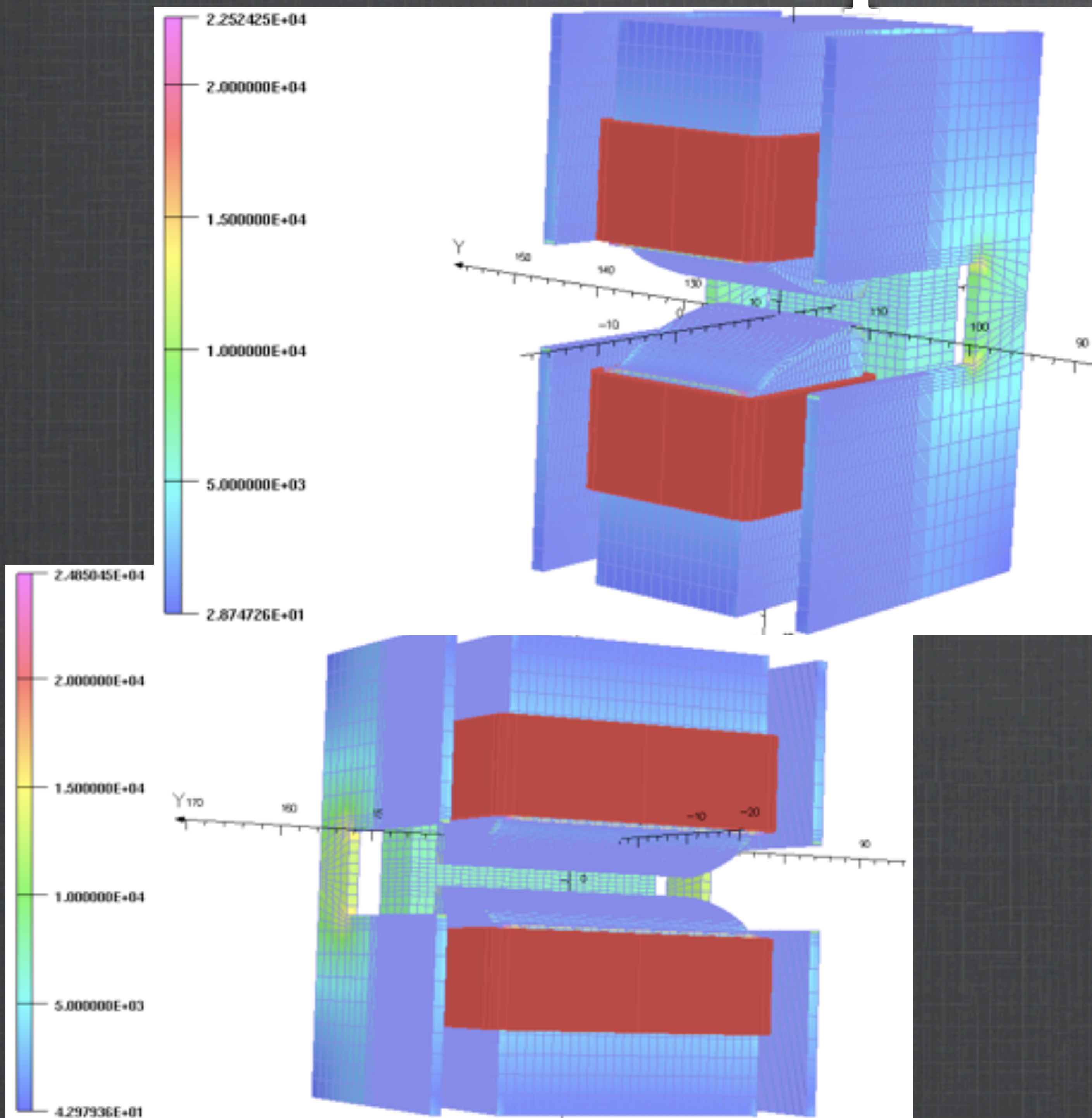


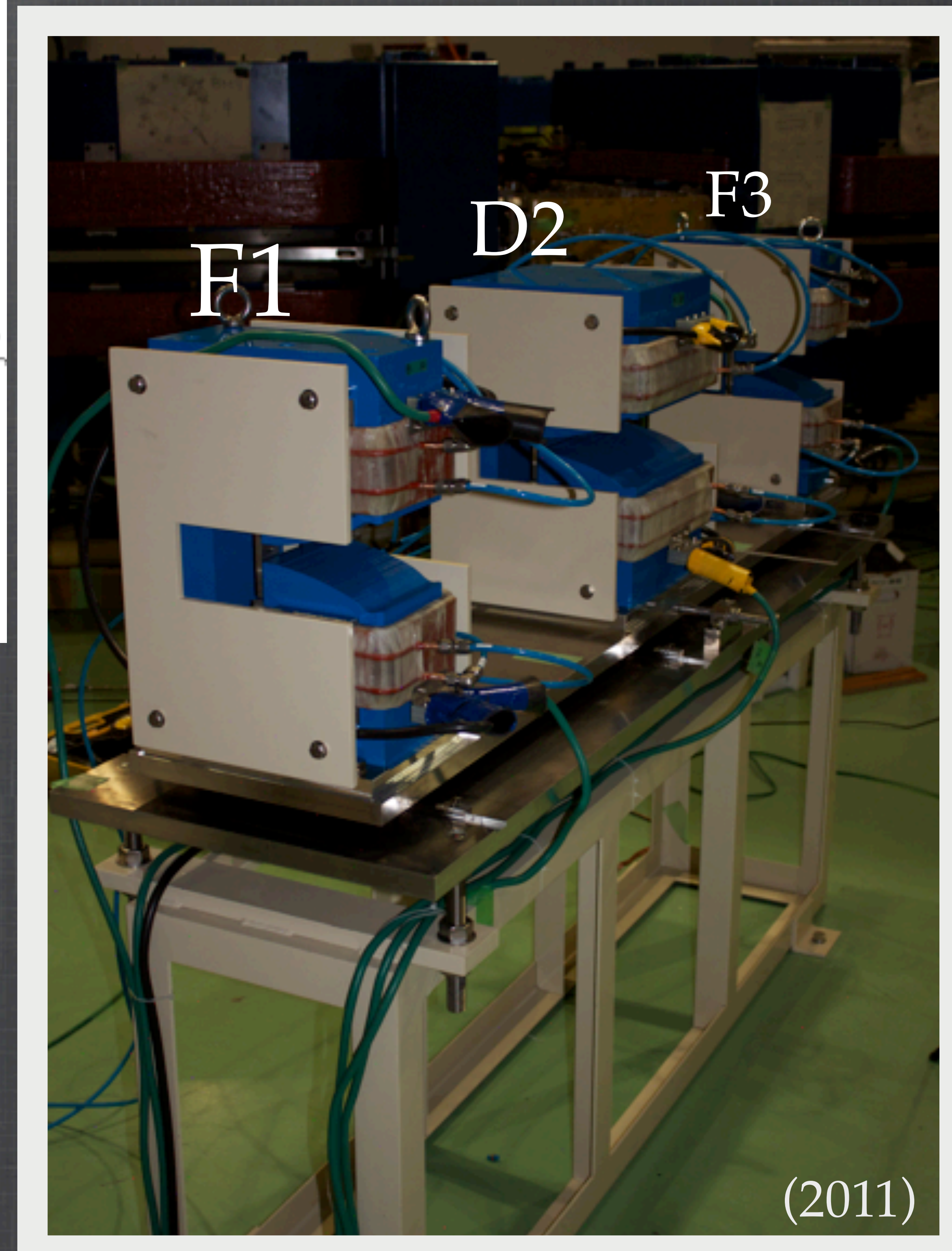
Rectangular case



Tilted straight case

Straight scaling FFAG experiment





JB. Lagrange *et al.*, Straight scaling FFAG beam line, NIM A, vol. 691, pp. 55-63, ISSN 0168-9002 (2012).

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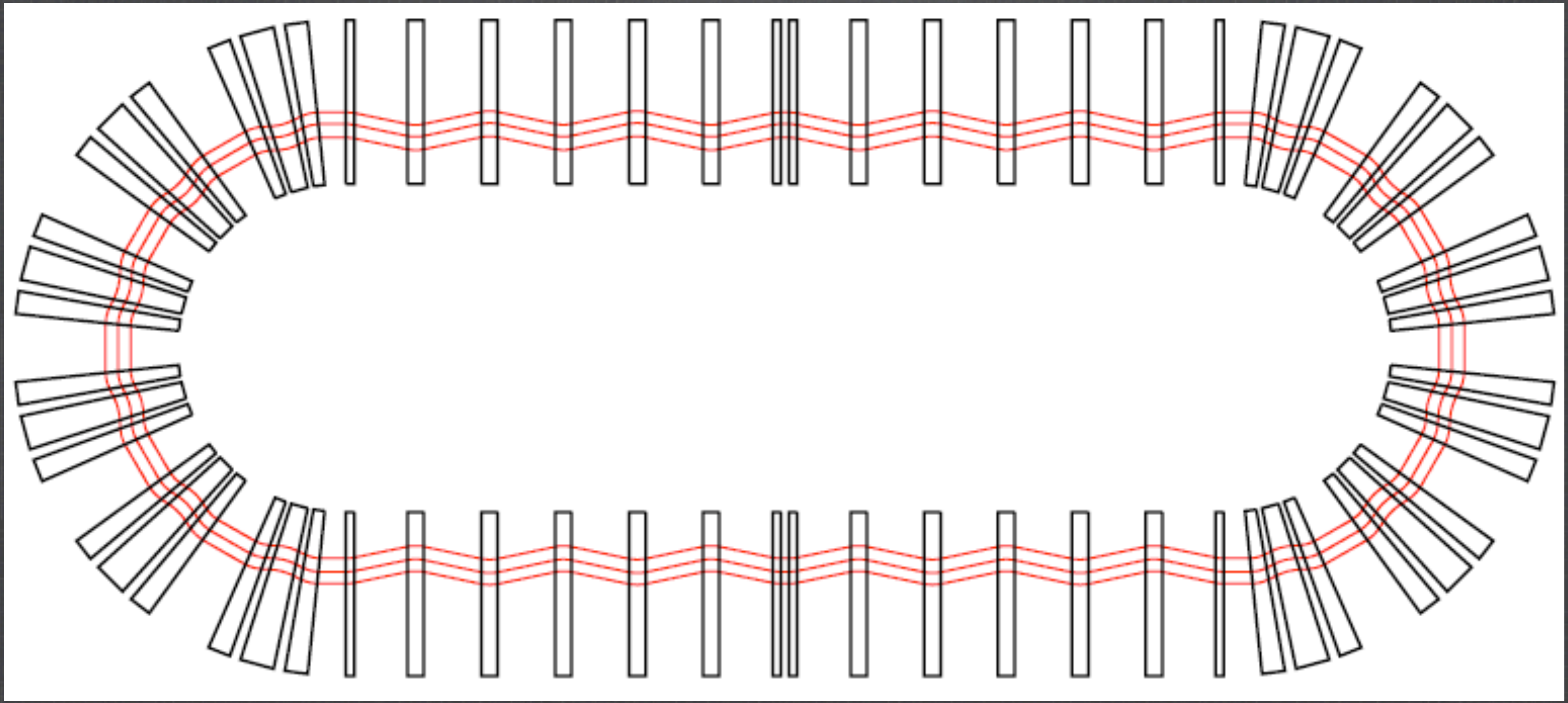
Racetrack FFAG



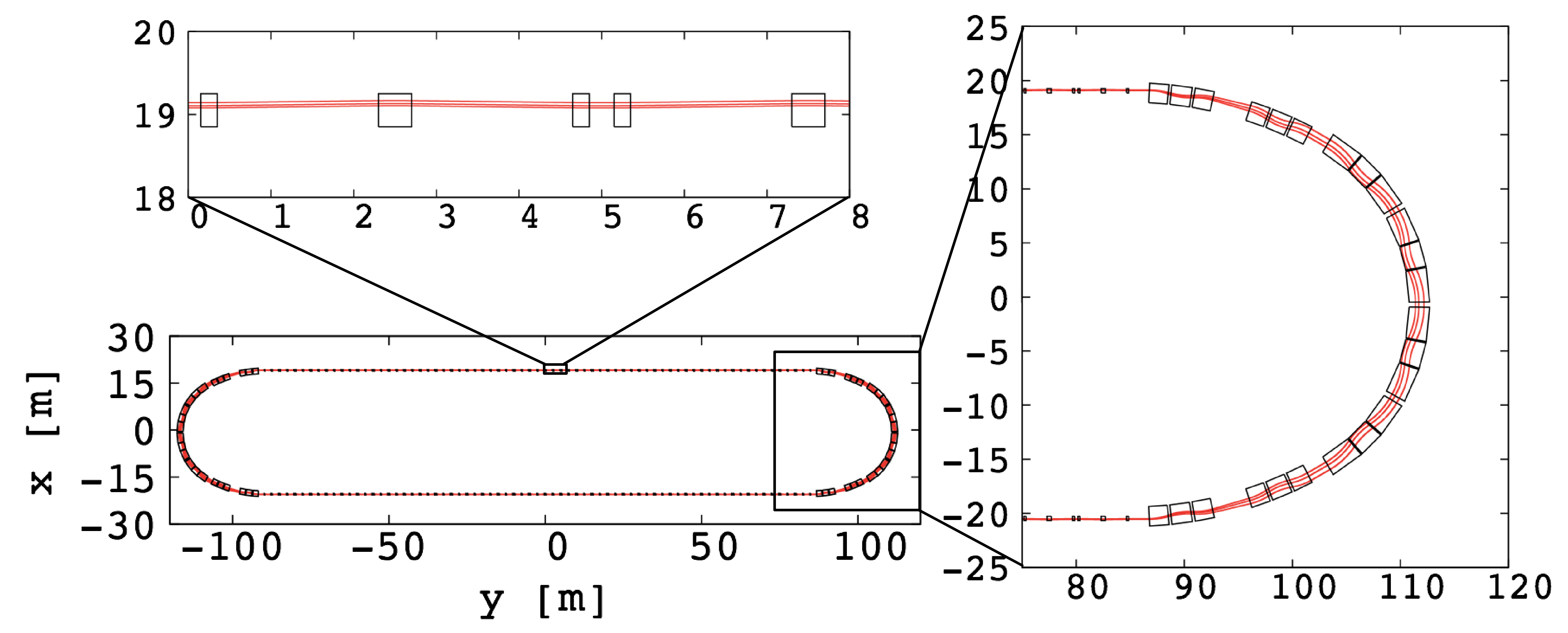
Racetrack FFAG for νSTORM

Constraints:

- in the straight part, the scallop must be as small as possible to keep reasonable the size of the detector. 15 mrad has been chosen as the maximum angle.
- in the dispersion matching section, a drift length of ~2.6 m is necessary for stochastic injection.
- to keep the ring as small as possible, SC magnets (super-ferric, up to 3 T) in the arcs are considered. Normal conducting magnets are used in the straight part.
- large transverse acceptance is needed in both planes (1000π mm.mrad).

OPTION #1: "FODO-LIKE"

Straight: **175 m**, maximum scallop angle: **12 mrad**



Comparable straight length than FODO lattice

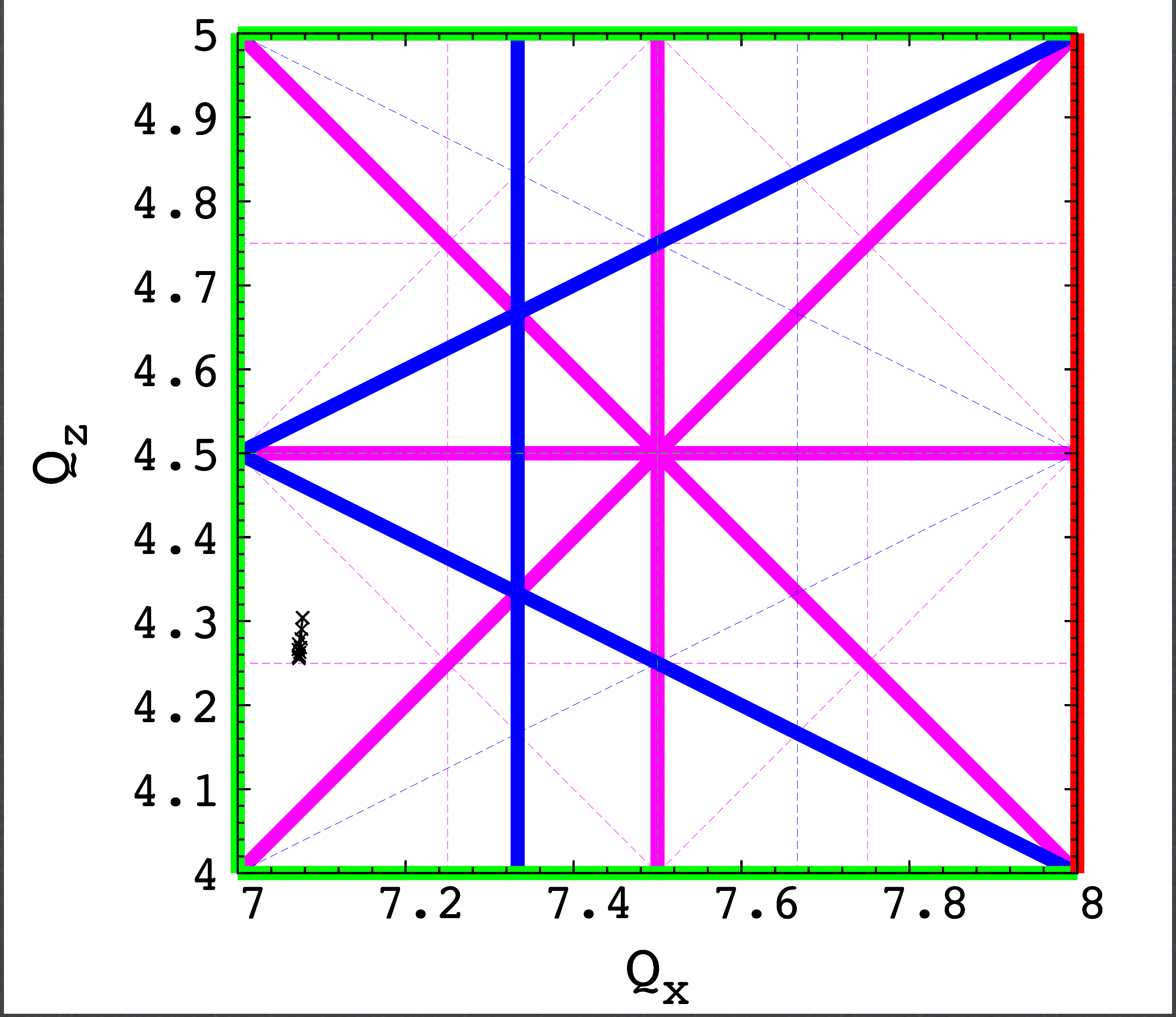
OPTION #1: "FODO-LIKE"

Cell parameters

	Circular Section	Matching Section	Straight Section
Type	FDF	FDF	DFD
Cell radius/length [m]	17.3	36.1	5
Opening angle [deg]	30	15	
k-value/m-value	6.202	26.785	5 m^{-1}
Packing factor	0.92	0.58	0.16
Horizontal phase advance /cell [deg]	90.0	90.0	15.8
Vertical phase advance /cell [deg]	21.1	23.7	16.8
Average dispersion /cell [m]	2.4	1.3	0.2
Number of cells /ring	4×2	4×2	35×2

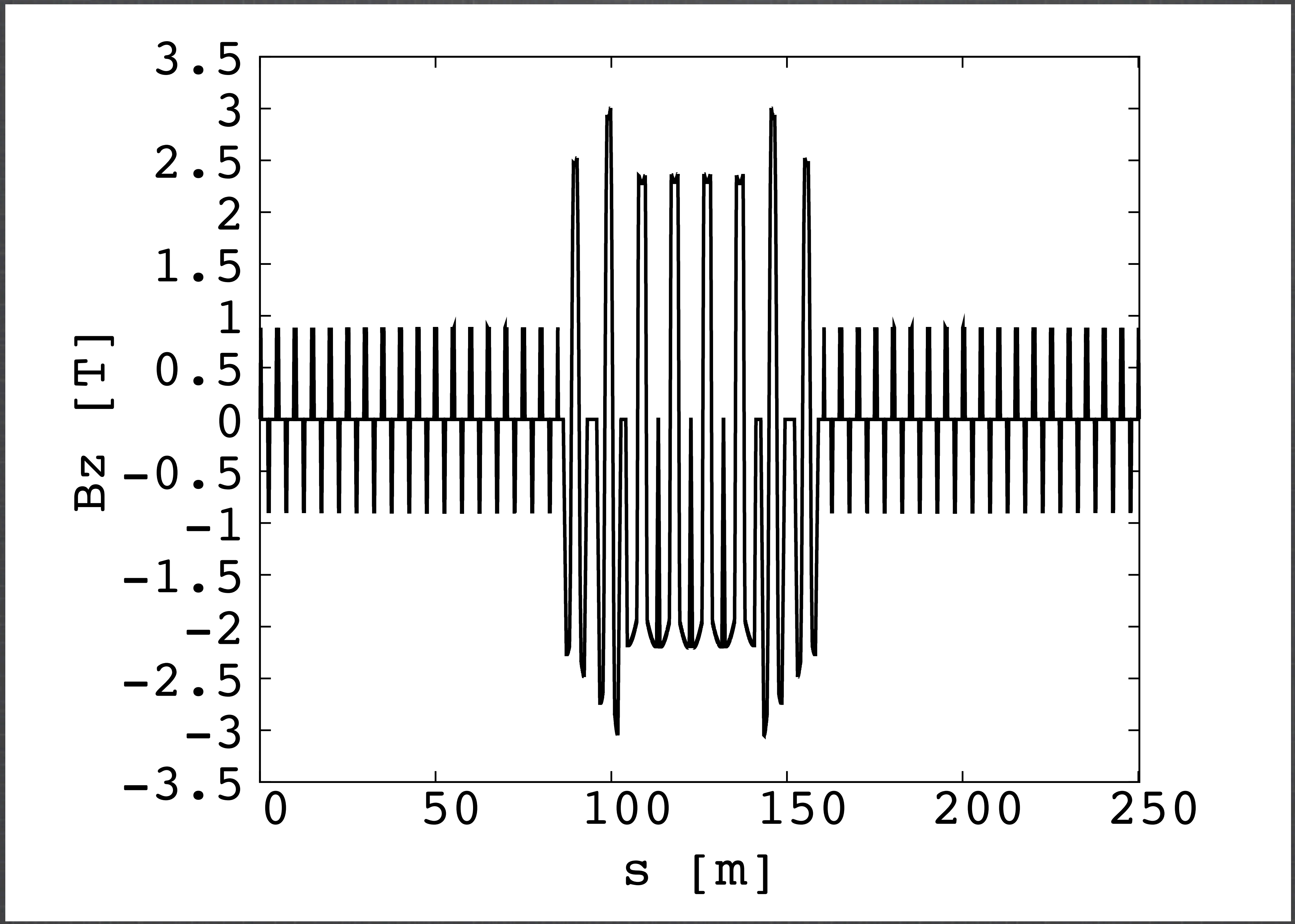
OPTION #1

Tune diagram $\frac{\Delta P}{P} = \pm 16\%$



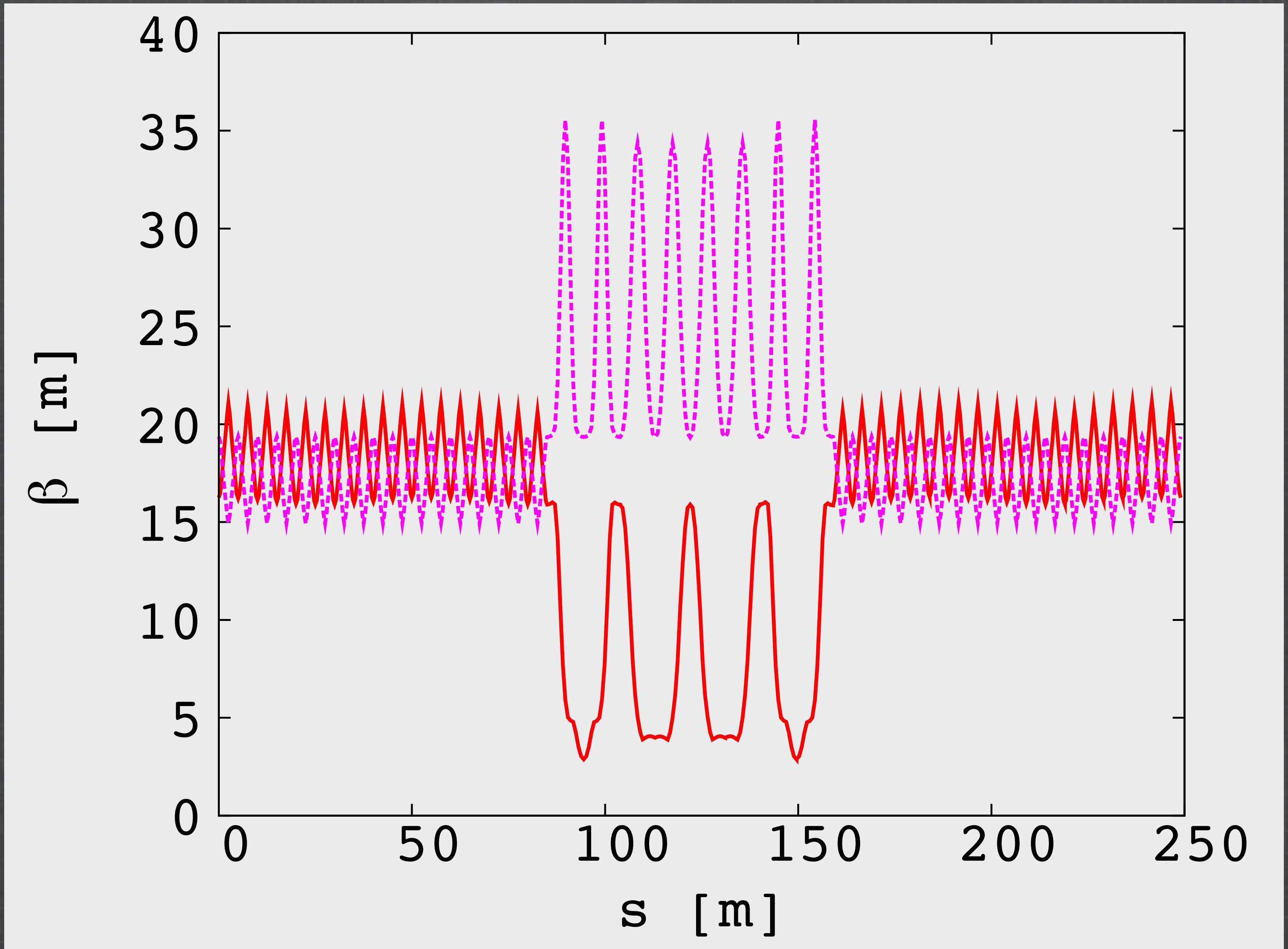
OPTION #1

Magnetic field for P_{max} (+16%)



OPTION #1

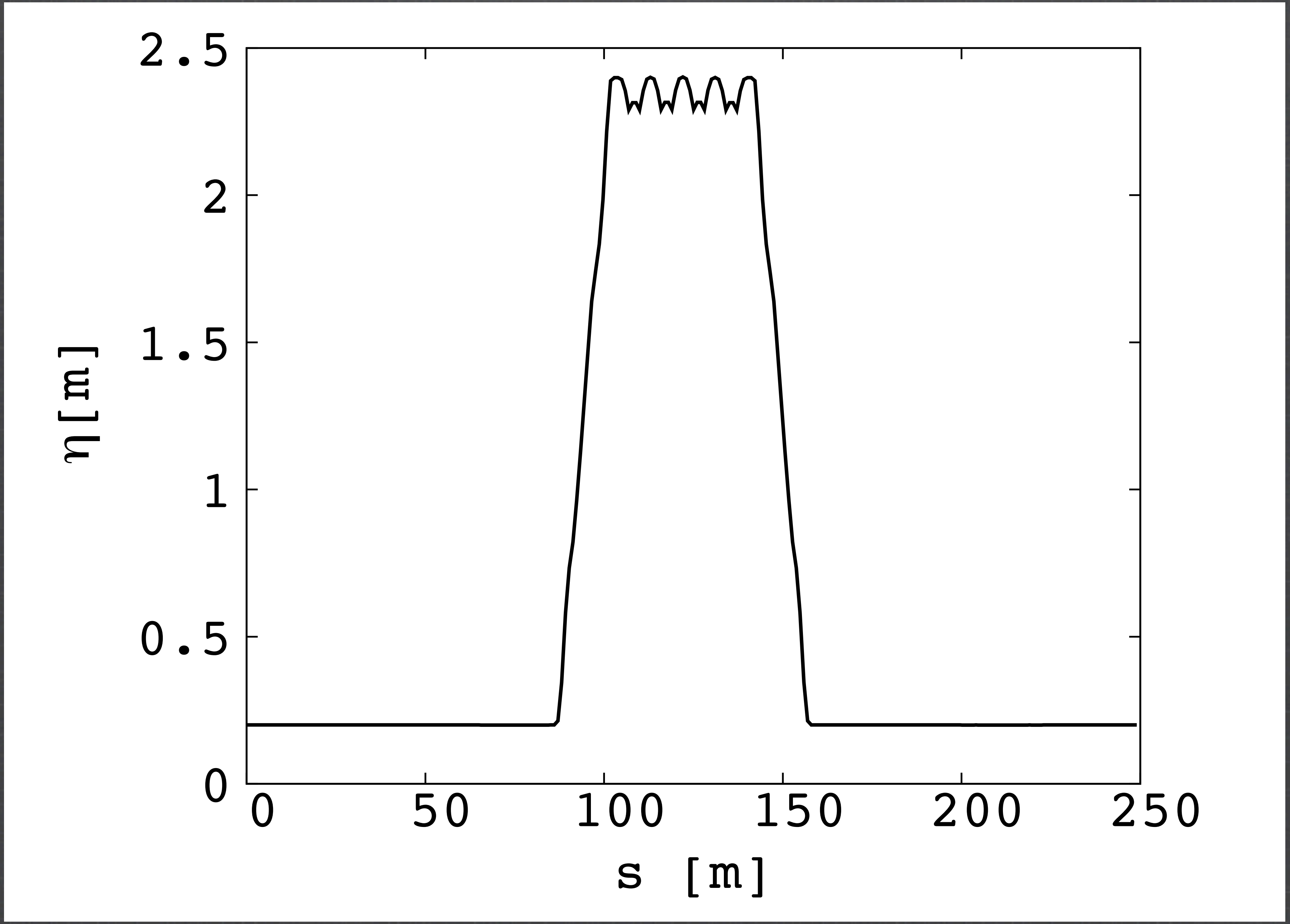
Beta-functions at matching momentum



Horizontal (plain red) and vertical (dotted purple) betafunctions for half of the ring.

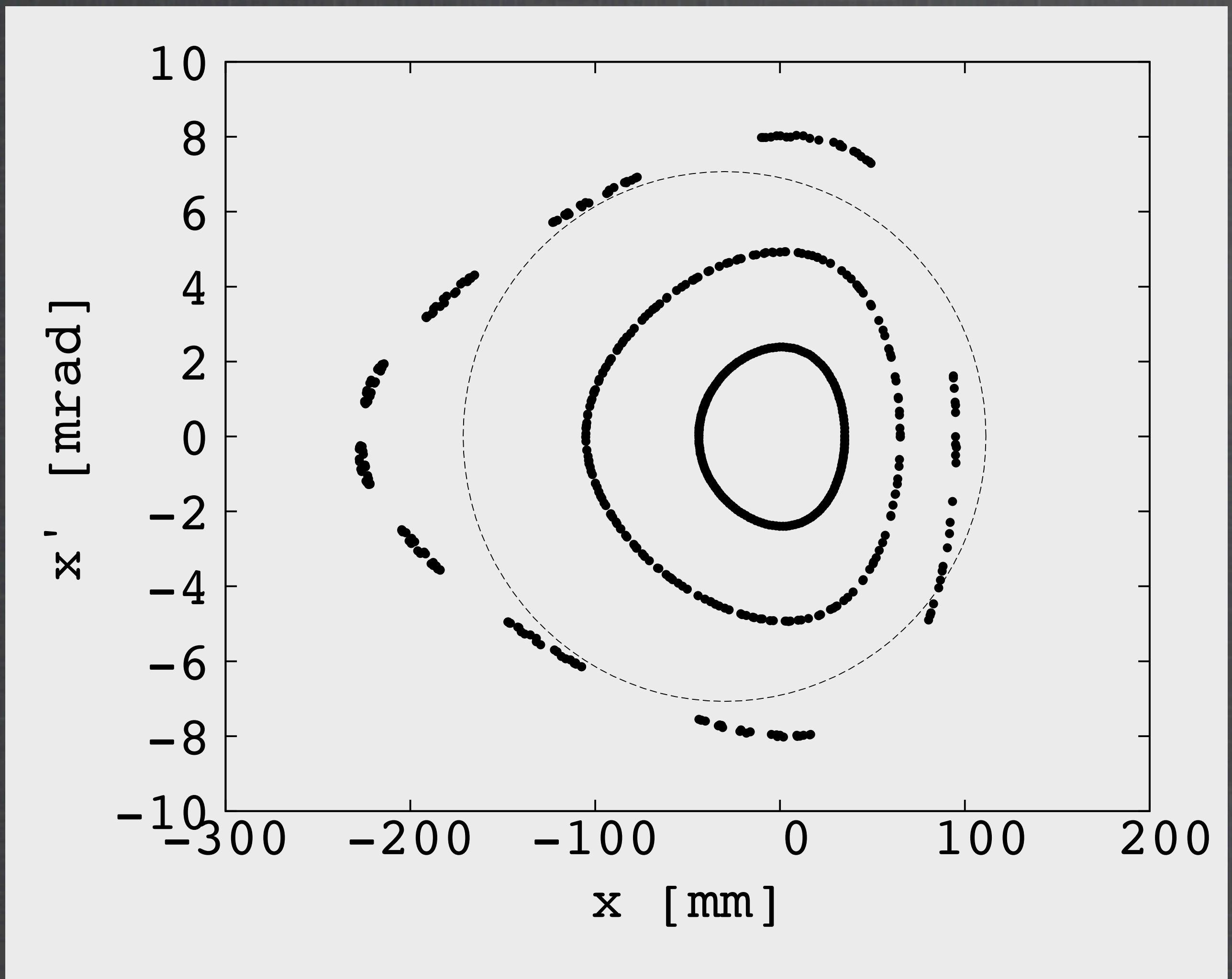
OPTION #1

Dispersion function at matching momentum

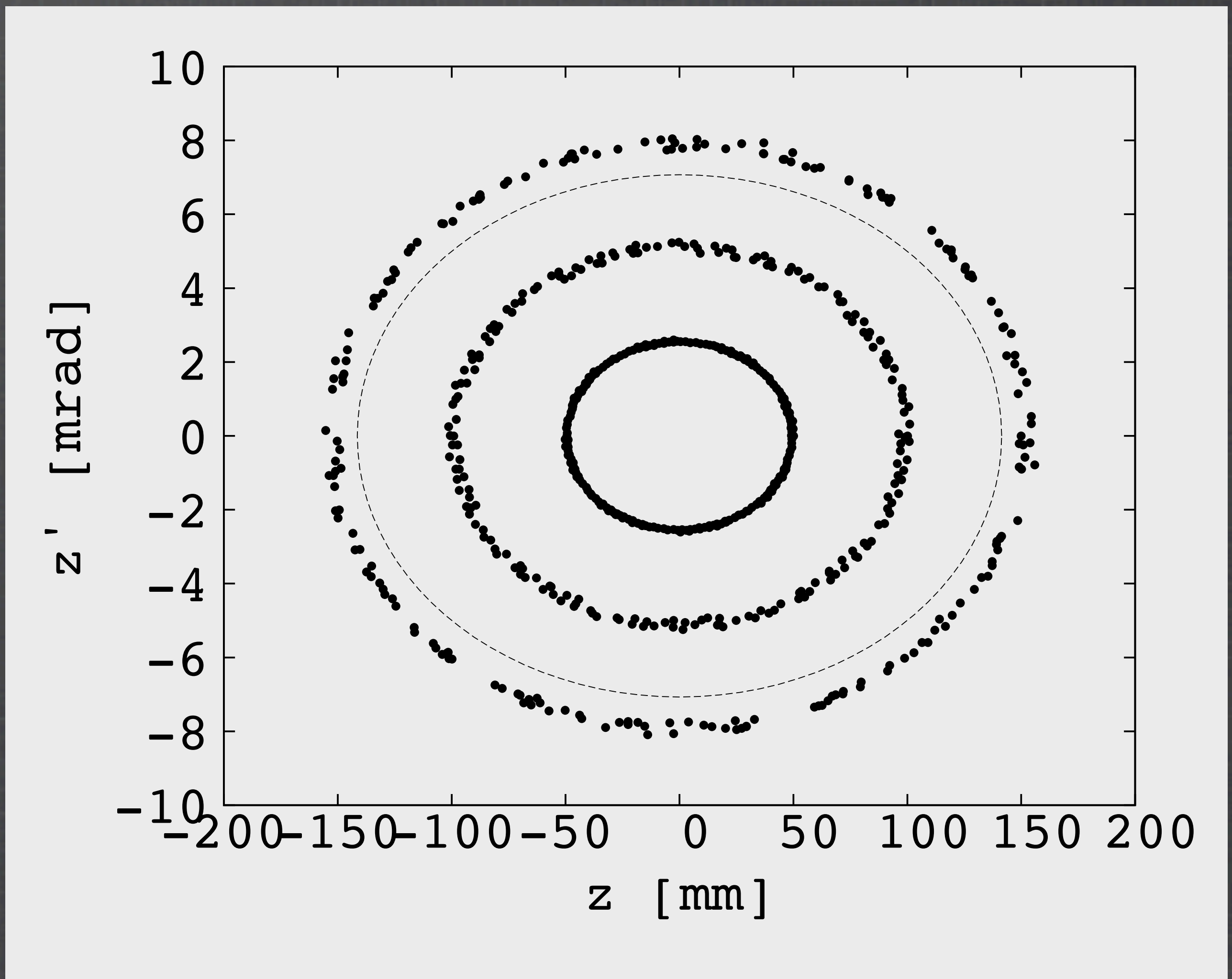


OPTION #1

Transverse acceptance



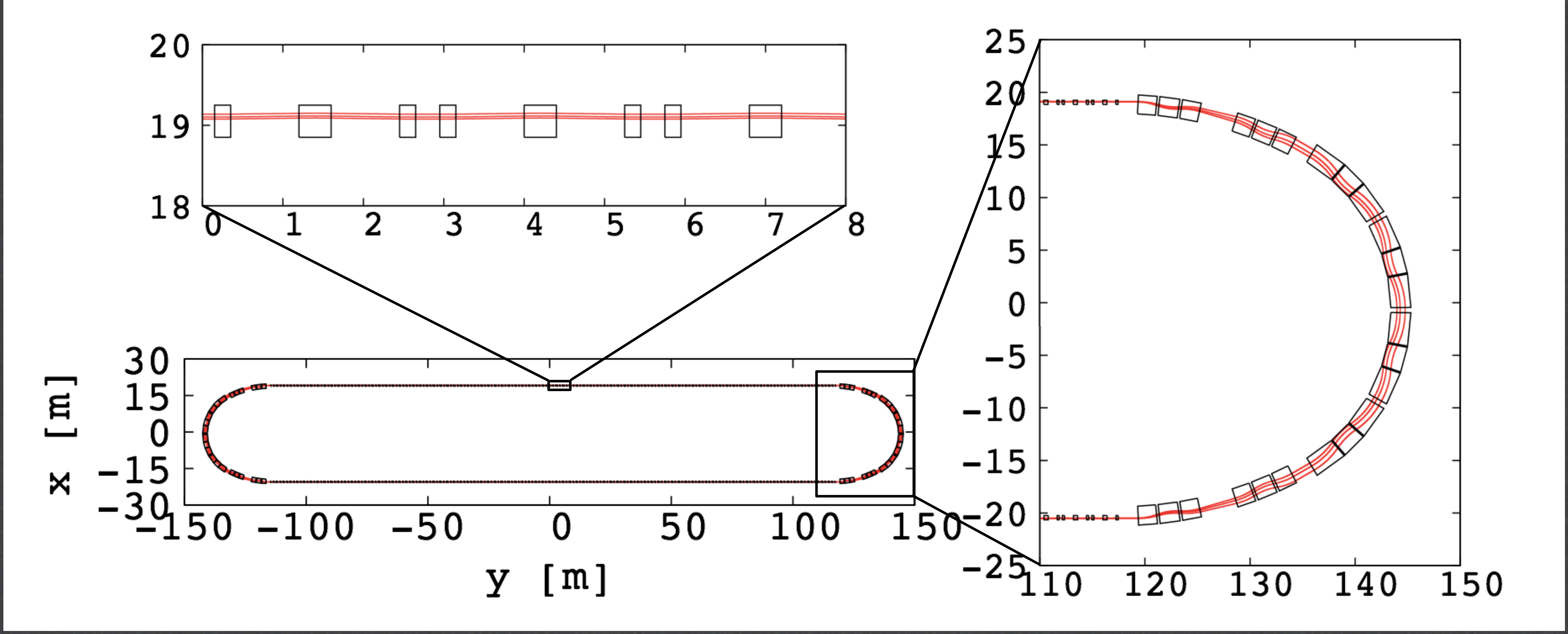
Maximum horizontal stable amplitude over 100 turns



Maximum vertical stable amplitude over 100 turns

OPTION #2: "LONG"

Straight: **230 m**, maximum scallop angle: **12.5 mrad**



Long straight length for a greater number of decayed pions.

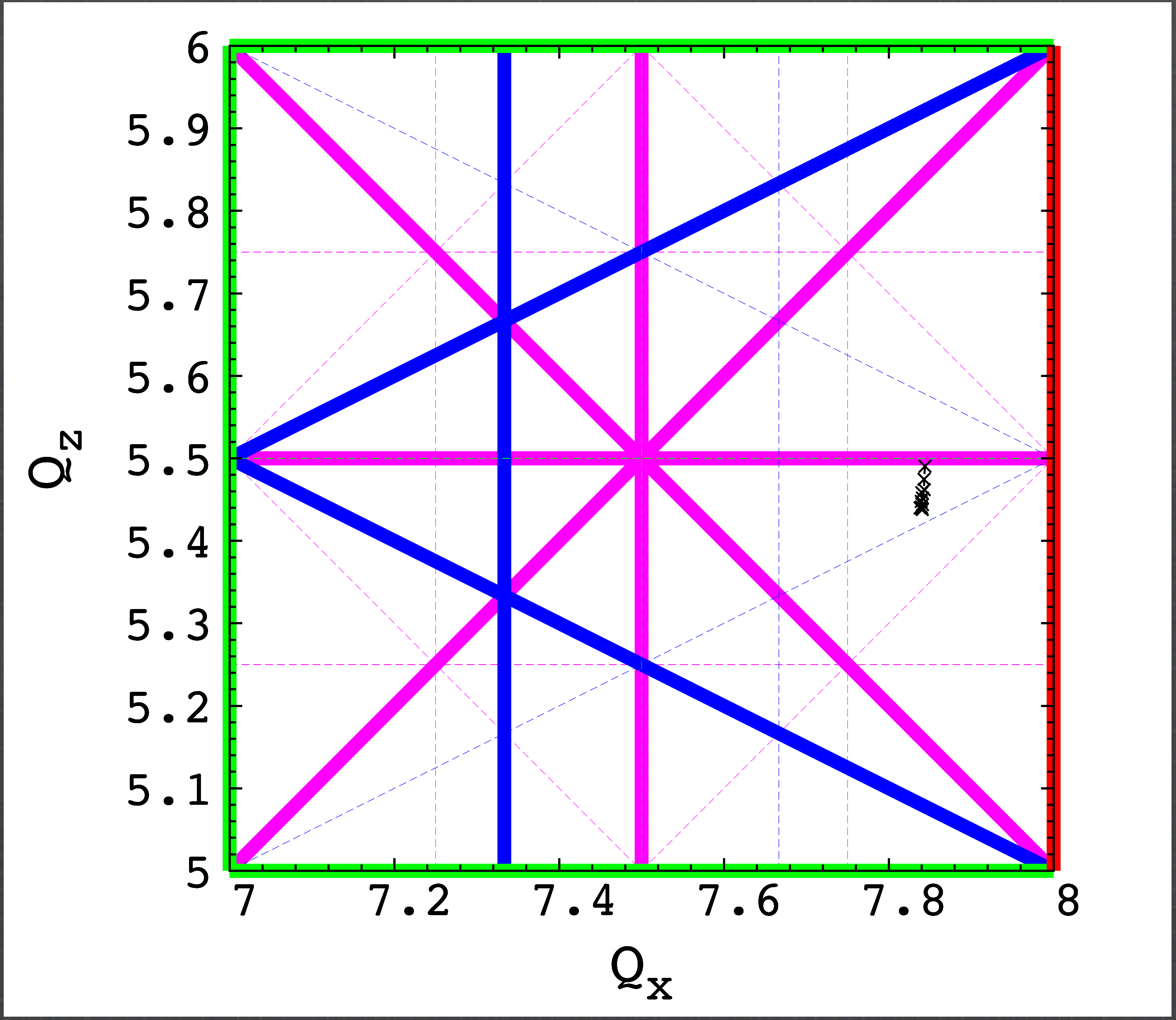
OPTION #2: "LONG"

Cell parameters

	Circular Section	Matching Section	Straight Section
Type	FDF	FDF	DFD
Cell radius/length [m]	17.3	36.1	2.8
Opening angle [deg]	30	15	
k-value/m-value	6.19	26.72	$5\ m^{-1}$
Packing factor	0.92	0.58	0.29
Horizontal phase advance /cell [deg]	90.0	90.0	8.3
Vertical phase advance /cell [deg]	22.6	25.5	9.5
Average dispersion /cell [m]	2.4	1.3	0.2
Number of cells /ring	4×2	4×2	83×2

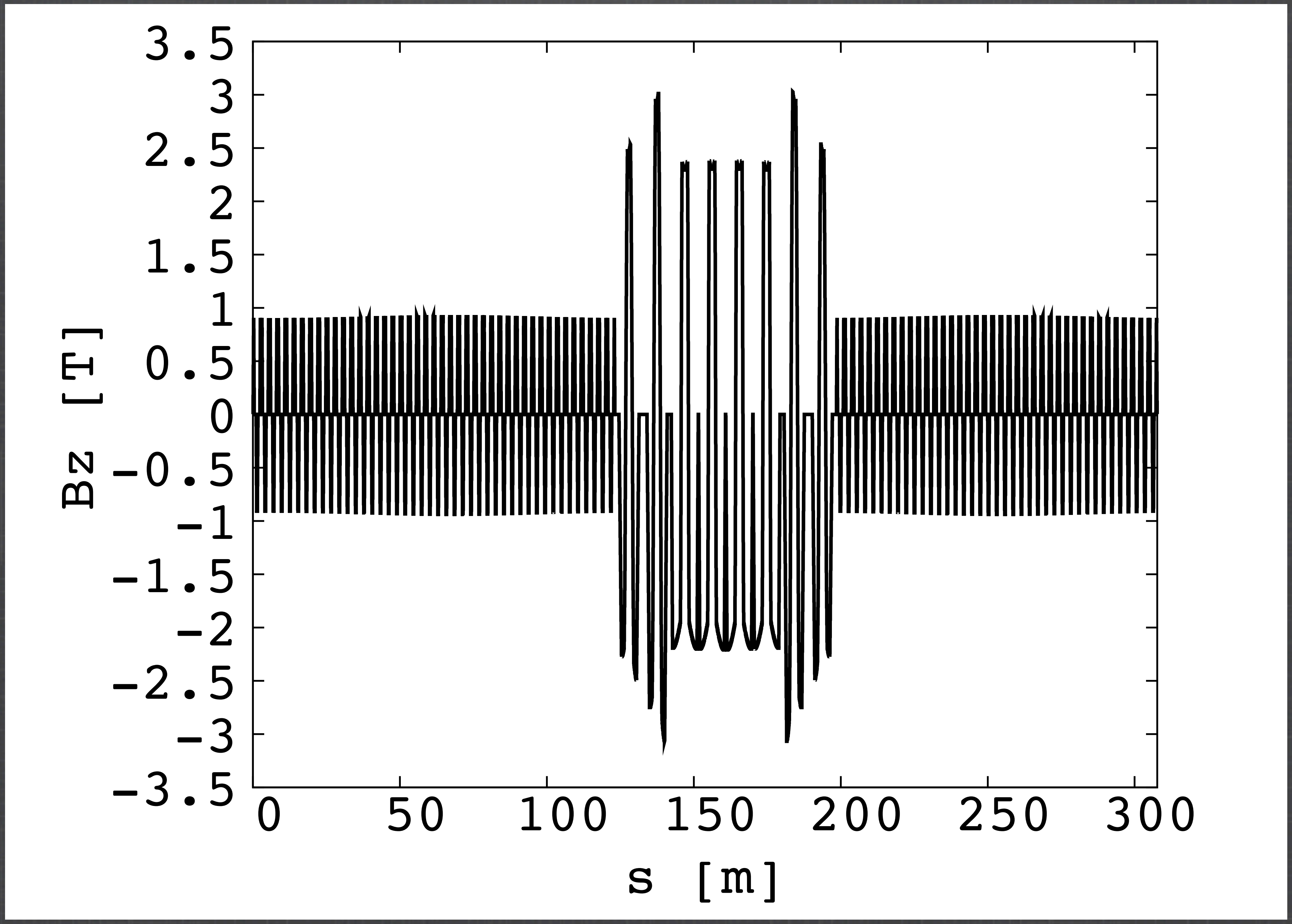
OPTION #2

Tune diagram $\frac{\Delta P}{P} = \pm 16\%$



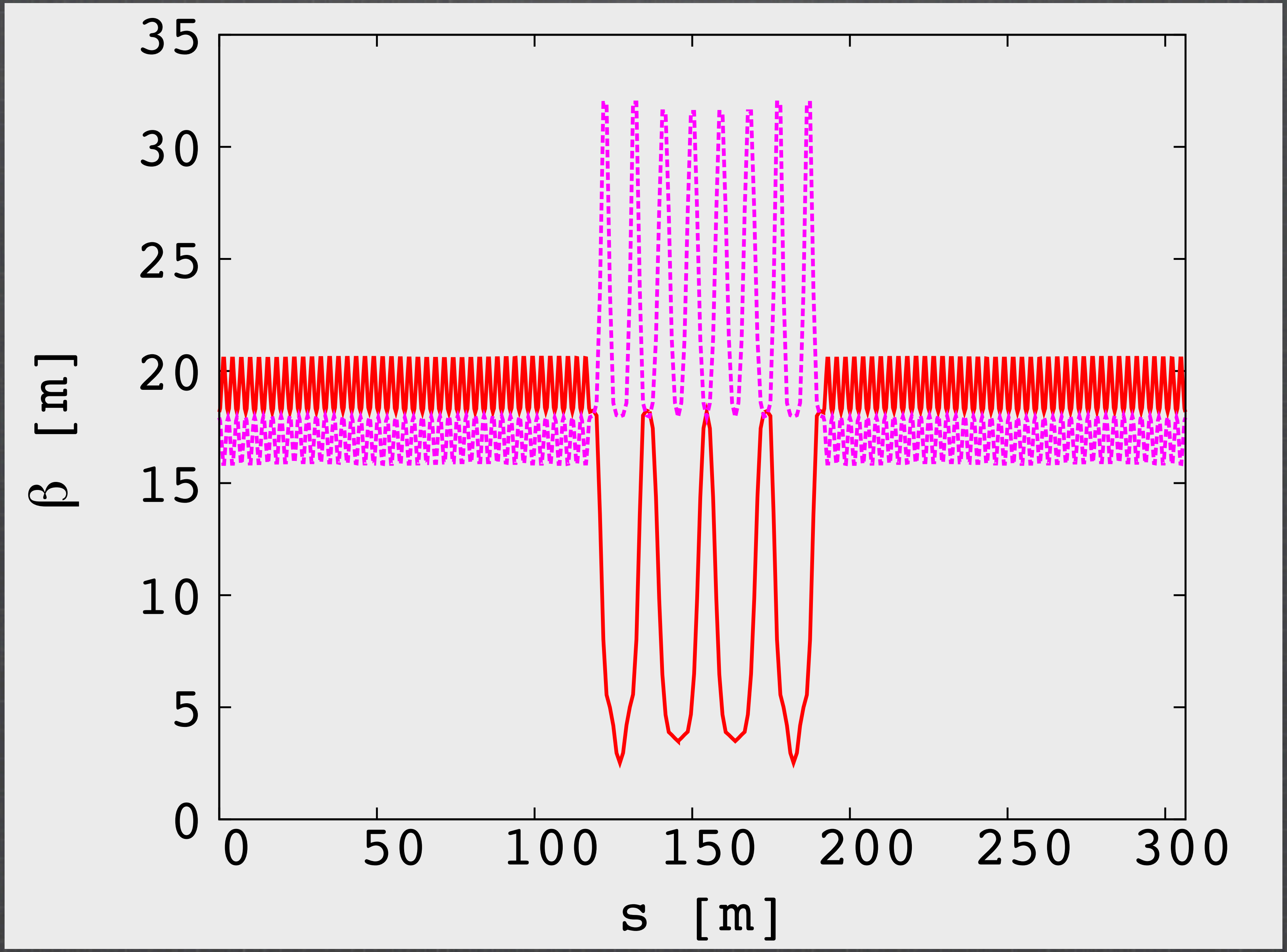
OPTION #2

Magnetic field for P_{max} (+16%)



OPTION #2

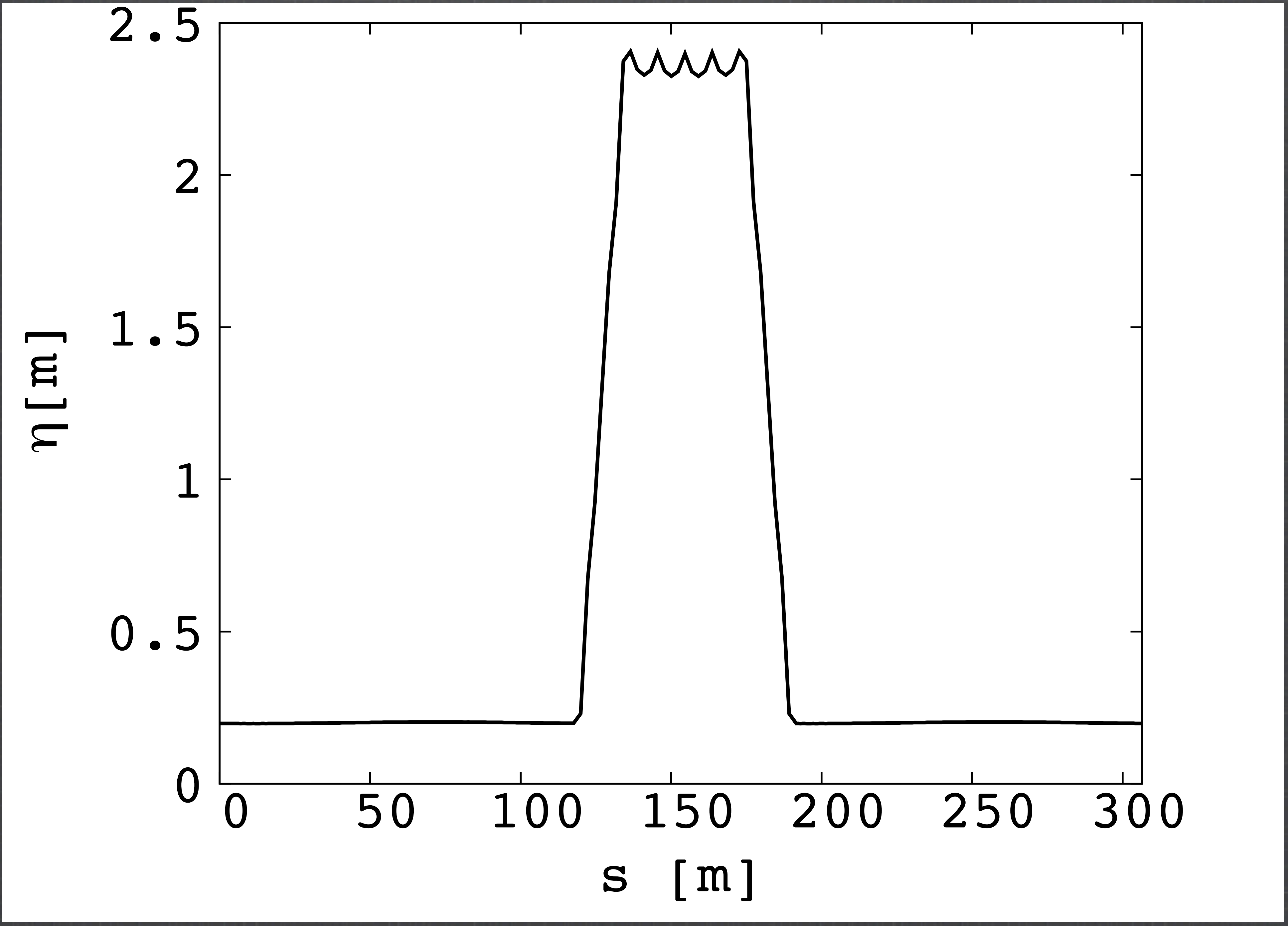
Beta-functions at matching momentum



Horizontal (plain red) and vertical (dotted purple) betafunctions for half of the ring.

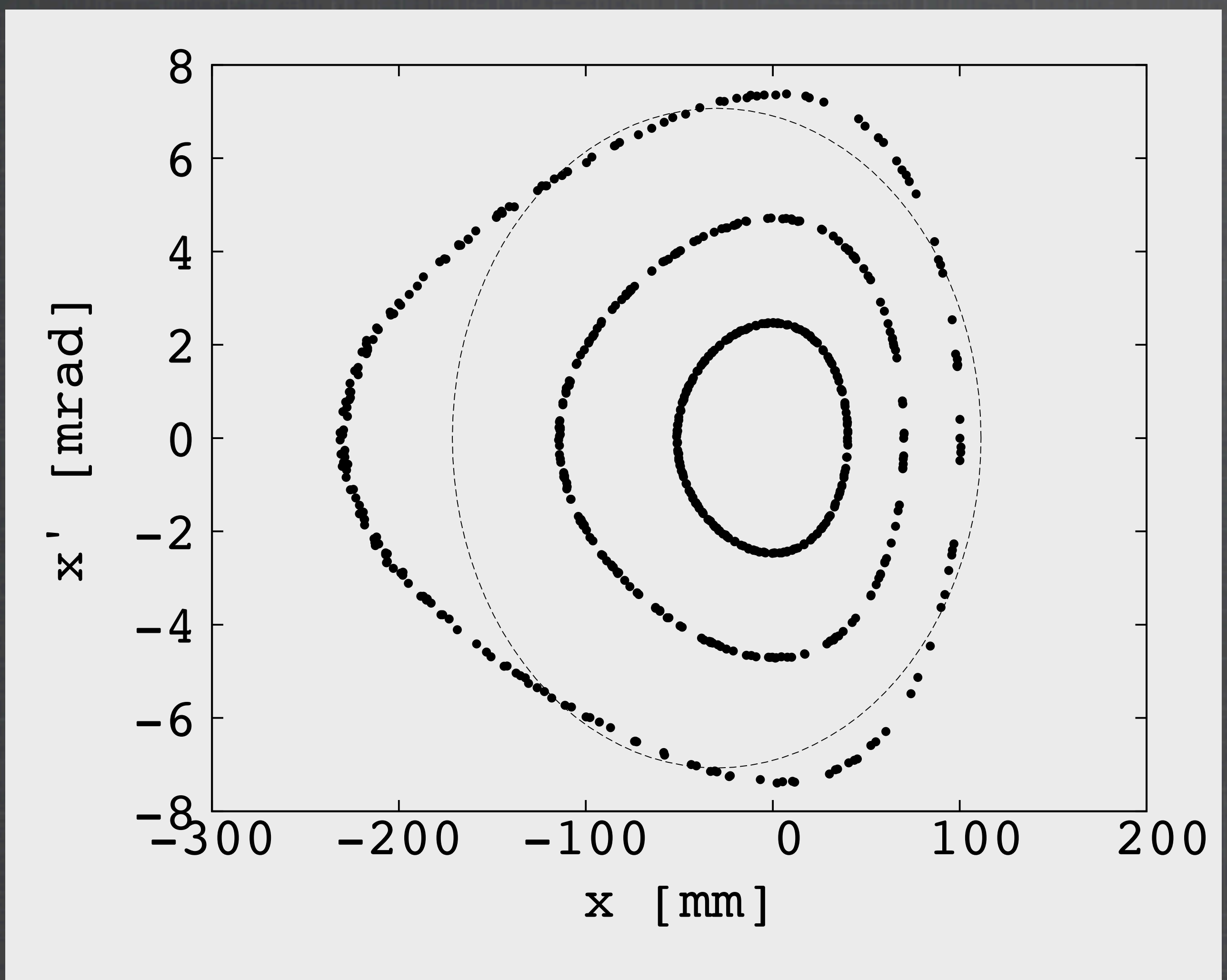
OPTION #2

Dispersion function at matching momentum

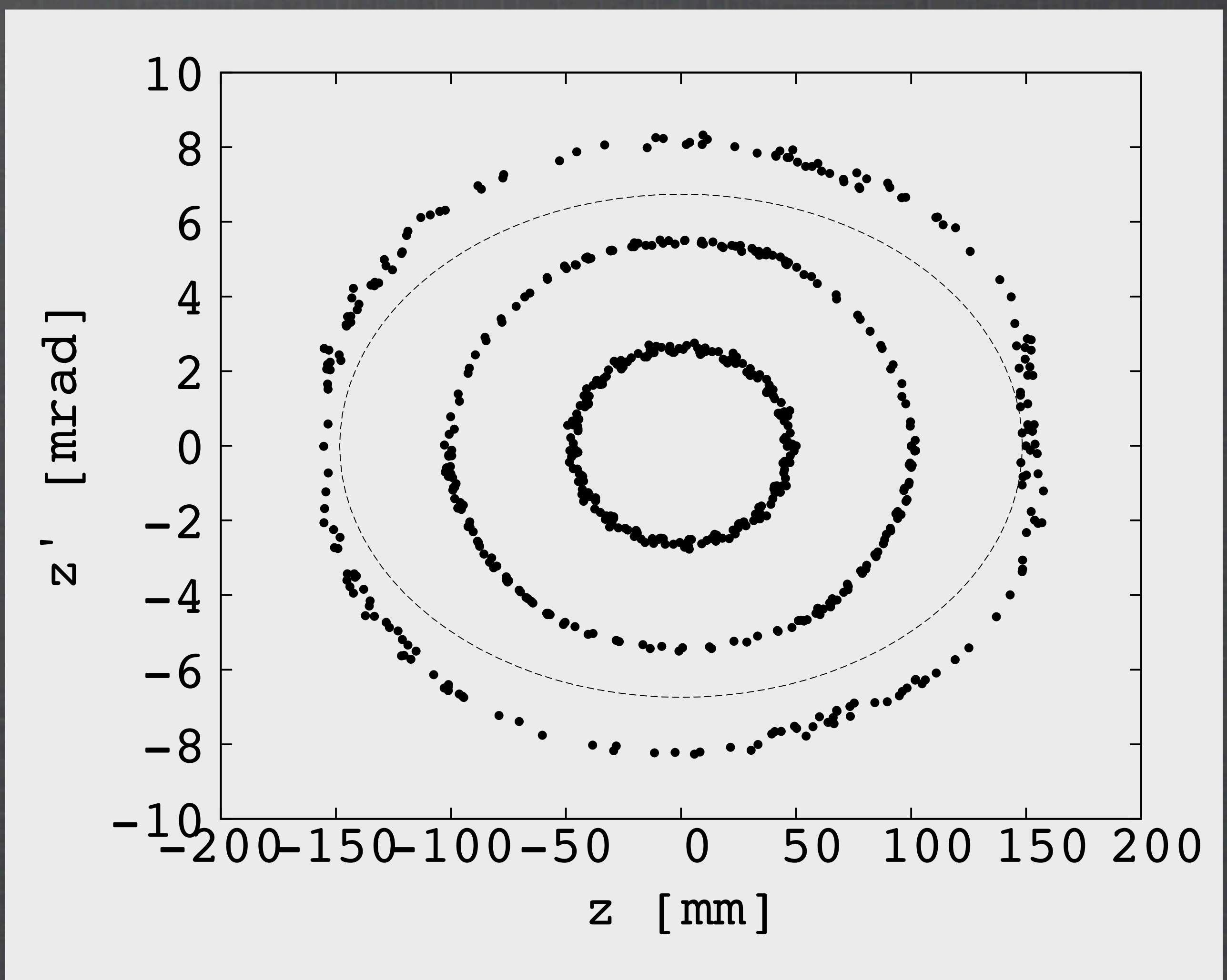


OPTION #2

Transverse acceptance



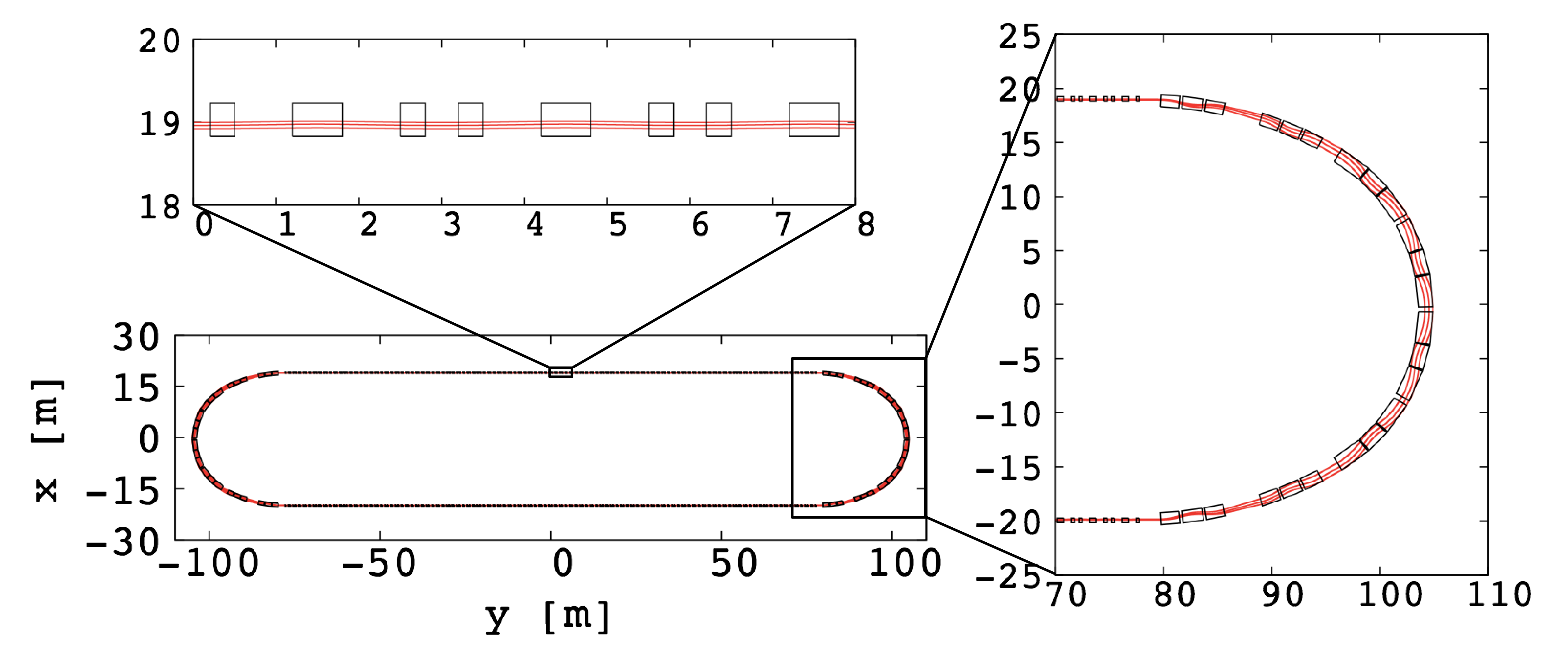
Maximum horizontal stable amplitude over 100 turns



Maximum vertical stable amplitude over 100 turns

OPTION #3: "LOW-COST"

Straight**: 156 m,** maximum scallop angle**: 13.9 mrad**



Short straight length for a cheaper lattice.

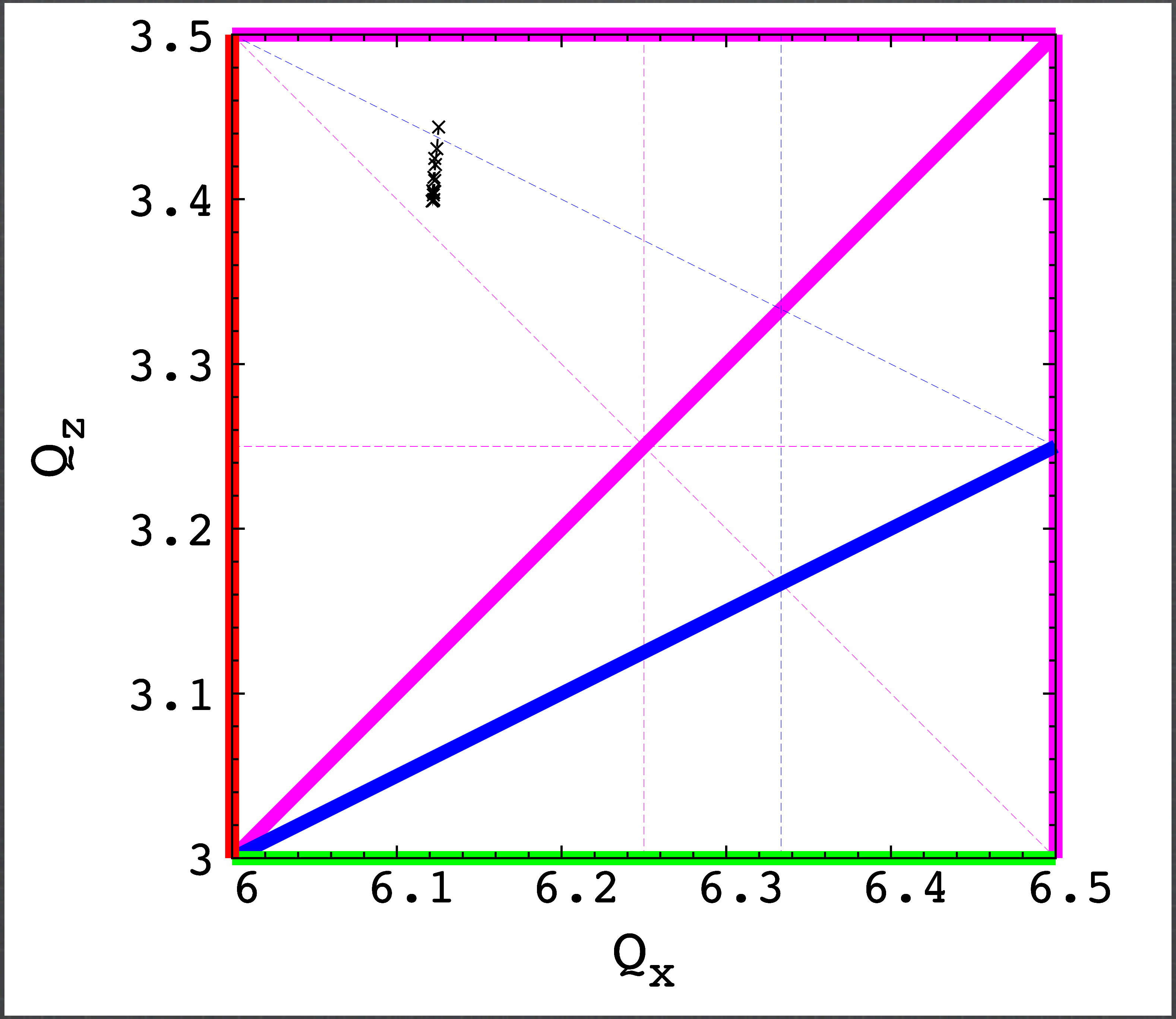
OPTION #3: "LOW-COST"

Cell parameters

	Circular Section	Matching Section	Straight Section
Type	FDF	FDF	DFD
Cell radius/length [m]	17	36.15	3
Opening angle [deg]	30	15	
k-value/m-value	6.21	26.83	$4\ m^{-1}$
Packing factor	0.92	0.58	0.4
Horizontal phase advance /cell [deg]	90.0	90.0	7.3
Vertical phase advance /cell [deg]	19.1	21.9	8.6
Average dispersion /cell [m]	2.4	1.3	0.25
Number of cells /ring	4×2	4×2	52×2

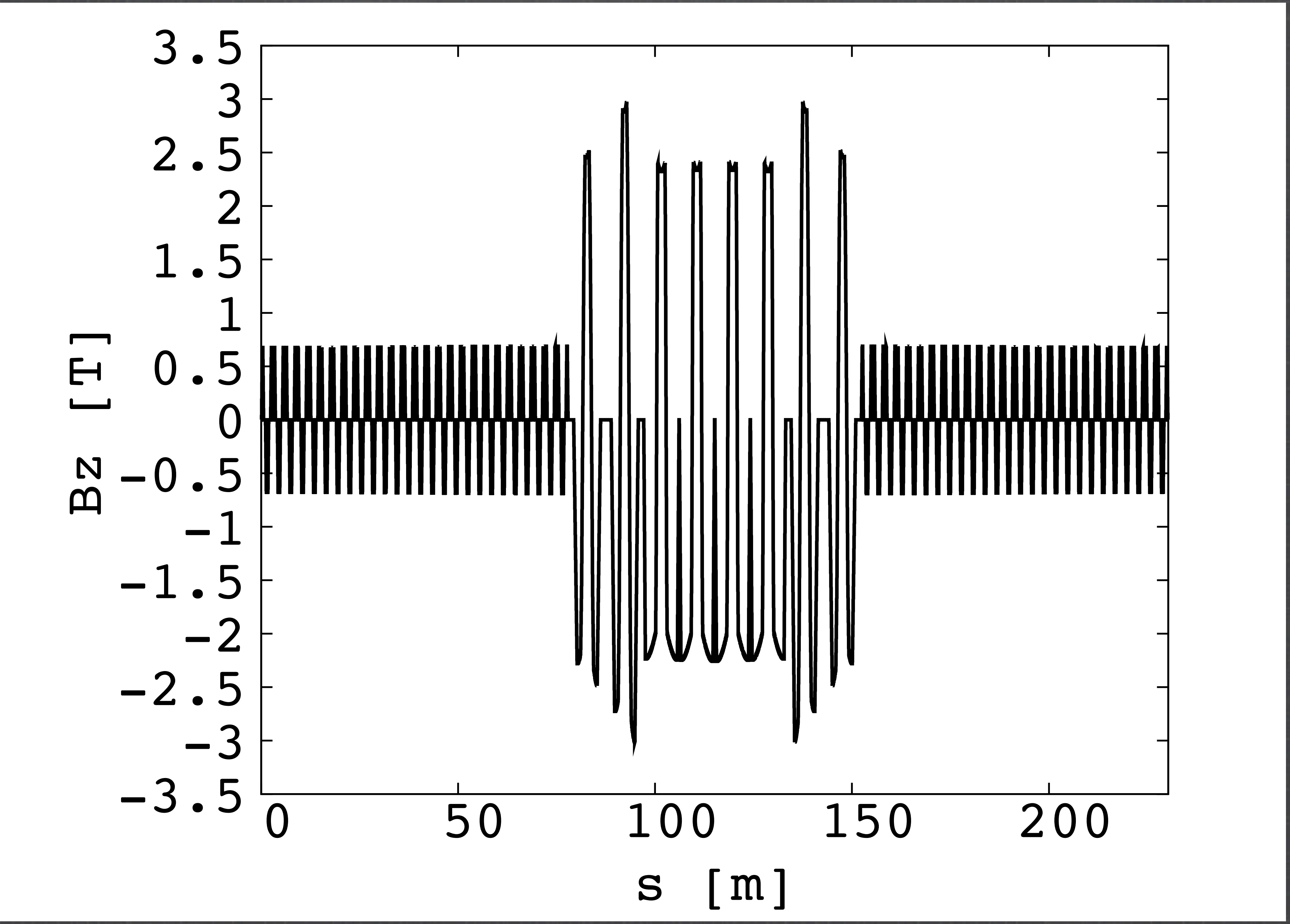
OPTION #3

Tune diagram $\frac{\Delta P}{P} = \pm 16\%$



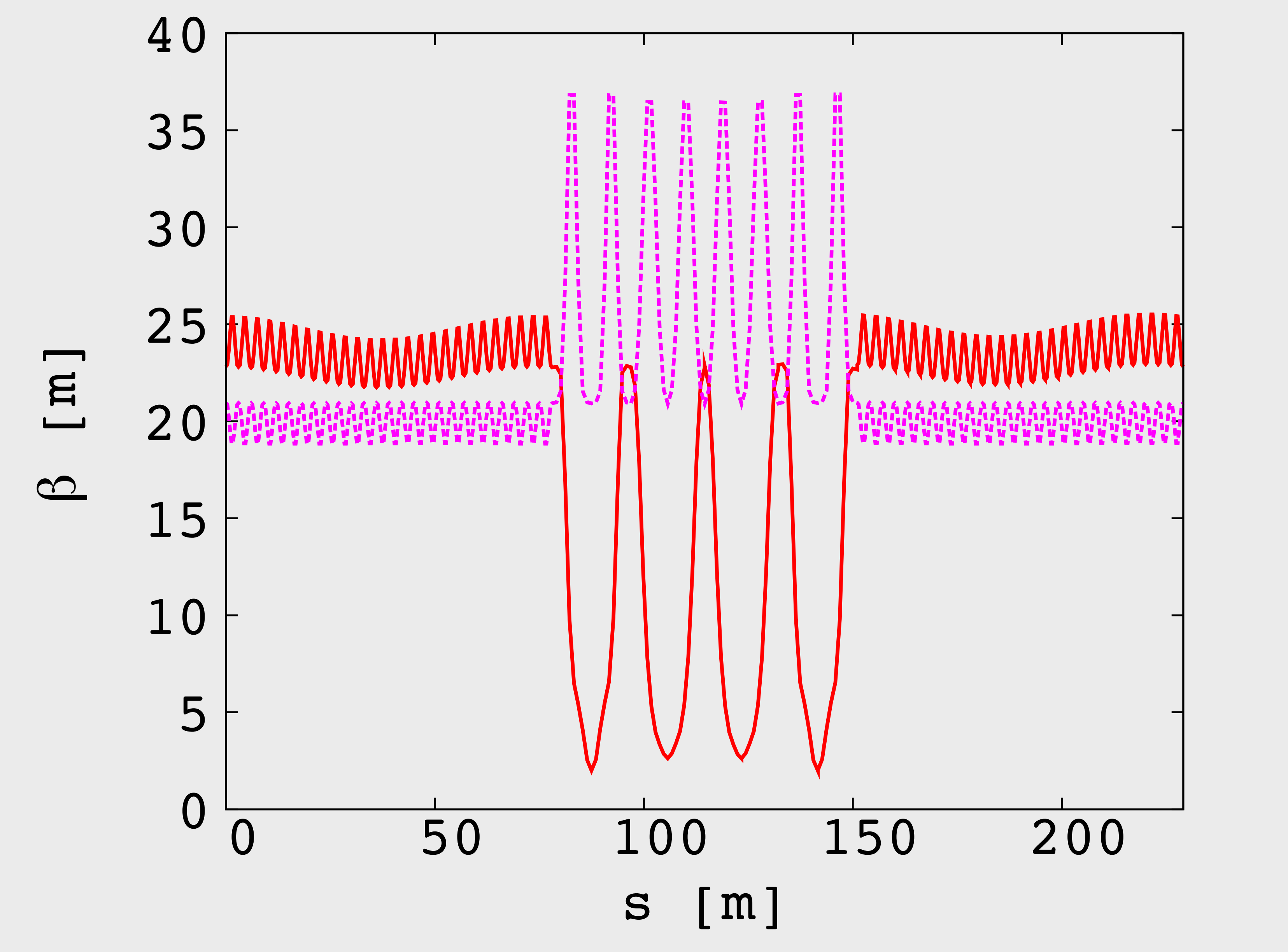
OPTION #3

Magnetic field for P_{max} (+16%)



OPTION #3

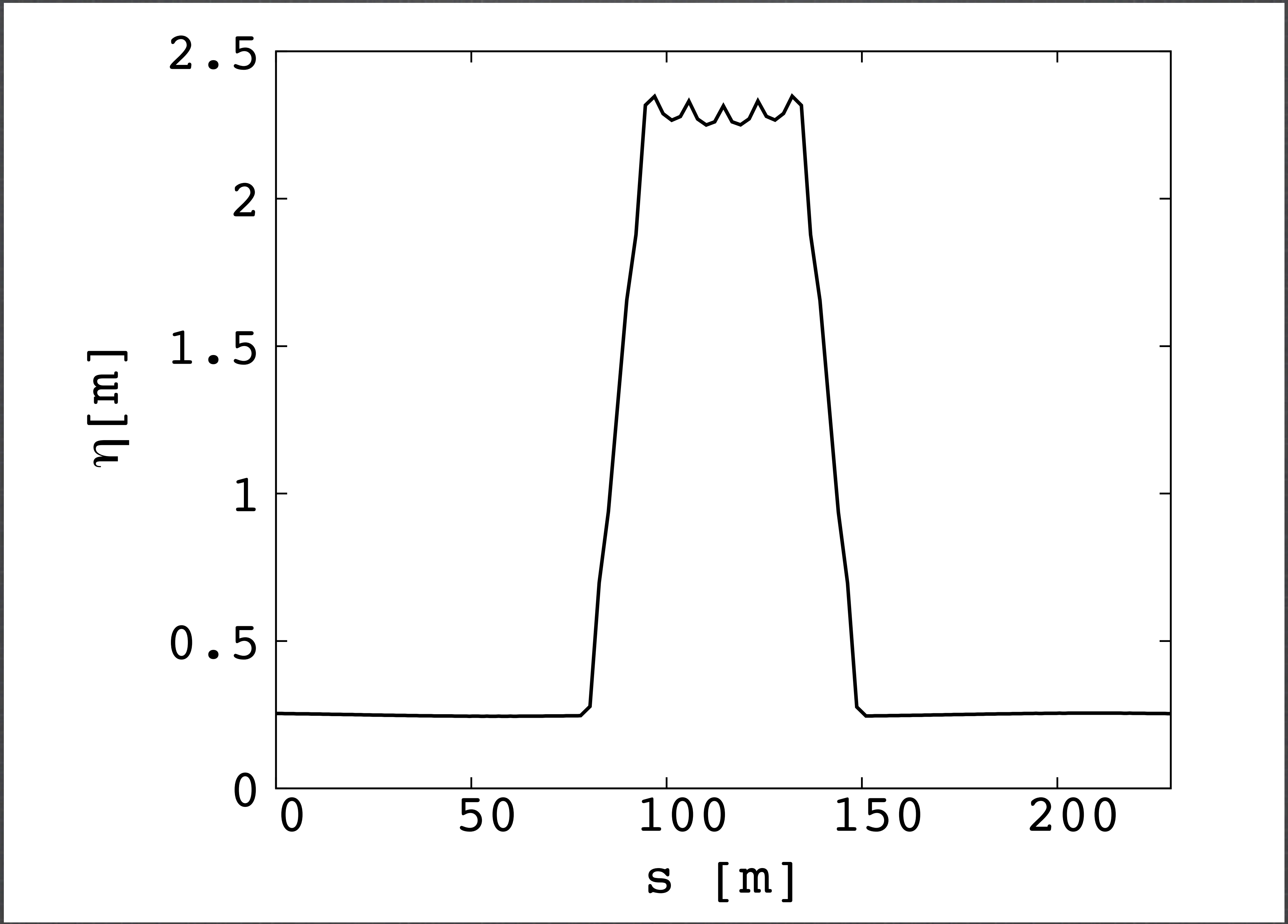
Beta-functions at matching momentum



Horizontal (plain red) and vertical (dotted purple) betafunctions for half of the ring.

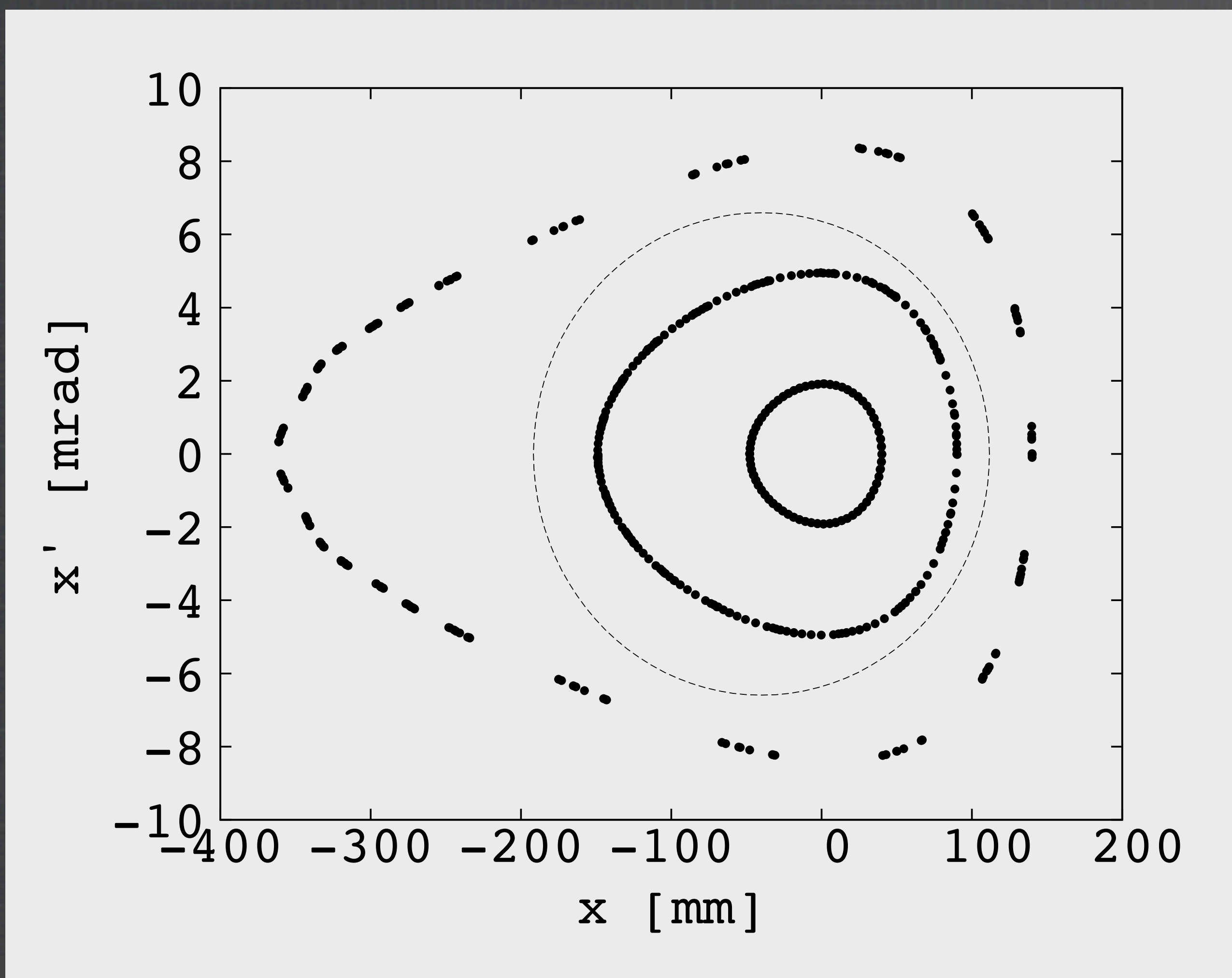
OPTION #3

Dispersion function at matching momentum

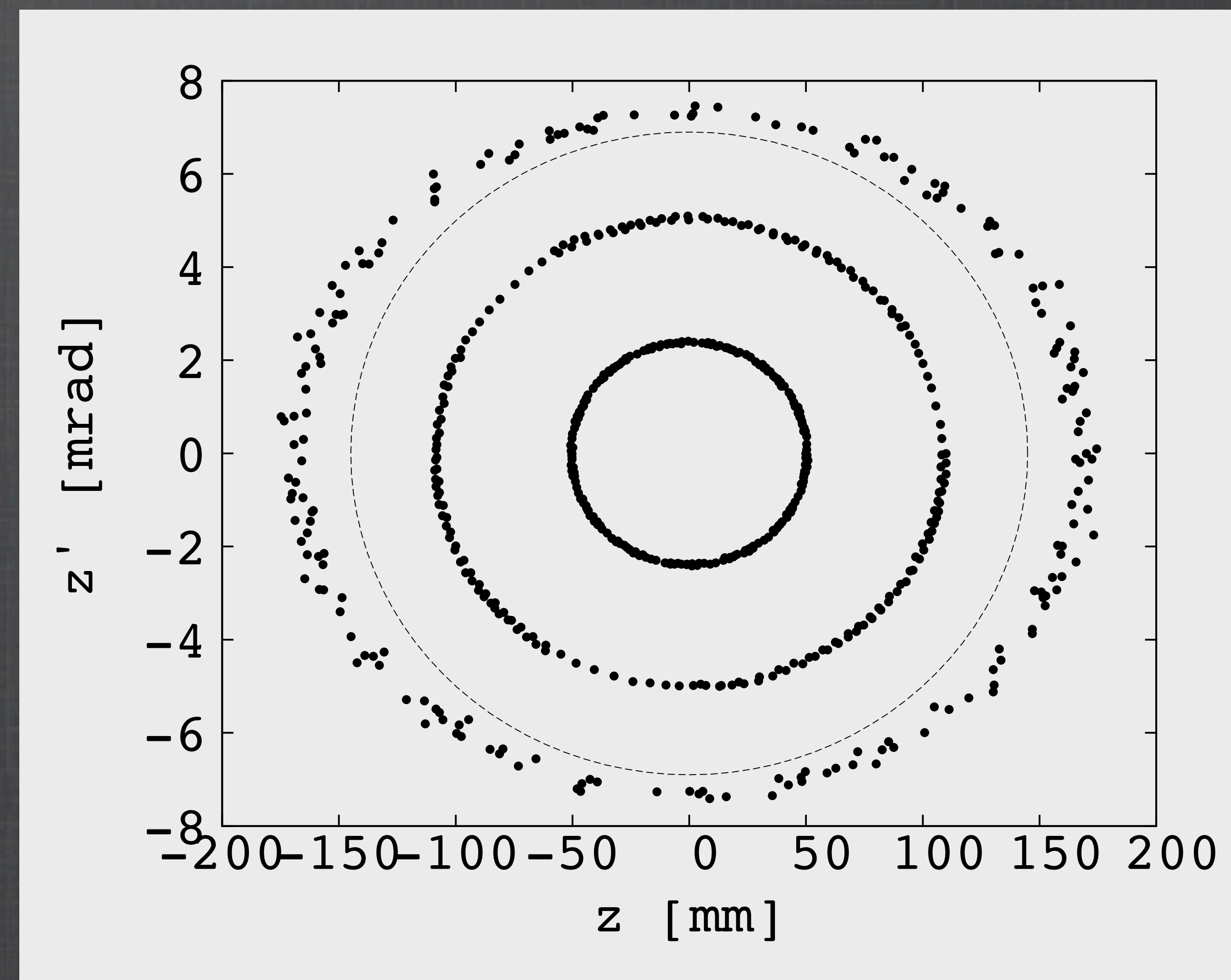


OPTION #3

Transverse acceptance



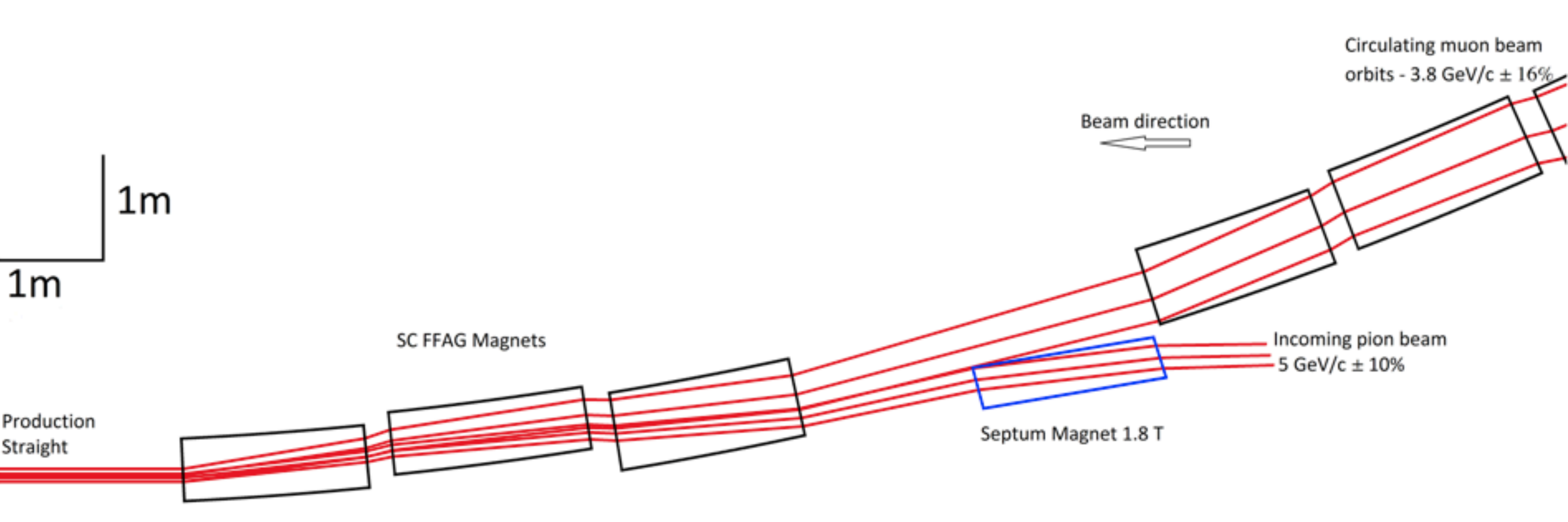
Maximum horizontal stable amplitude over 100 turns



Maximum vertical stable amplitude over 100 turns

Stochastic Injection

Preliminary results



Stochastic injection principle (J. Pasternak)

Outline

- Zero-chromatic FFAG
- Racetrack FFAG muon decay ring
- Comparison

Comparison

Parameters	FODO (Jun. 2013)	RFFAG "FODO-like"	RFFAG "long"	RFFAG "low-cost"
$L_{straight}$ [m]	185	175	230	156
Circumference [m]	480	500	613	460
Dynamical acceptance A_{dyn}	0.6	0.95	0.95	0.95
Momentum acceptance	±10%	±16%	±16%	±16%
π/POT within momentum acceptance	0.094	0.171	0.171	0.171
Fraction of π decay in one straight (F_s)	0.48	0.47	0.56	0.43
Straight-circumference ratio (Ω)	0.39	0.35	0.38	0.34
A_{dyn} x π/POT x F_s x Ω	**0.011**	**0.027**	**0.035**	**0.024**

4T magnet option

4T magnet (PAMELA type) would give several advantages:

- shrink the arc part of about 25 m,
- increase the straight/circumference ratio,
- better dispersion matching ($\eta_{max} < 2$ m),
- smaller excursion.

→
- Cheaper!
- Better performance!

Summary

- Promising results for racetrack FFAG ring as a muon decay ring for NuSTORM.
- Quite flexible regarding the circumference.
- Large 6D acceptance compared with FODO lattice.
- Cost may not be higher than FODO solution.
- Larger momentum acceptance (±25% achieved previously) for wider magnets.

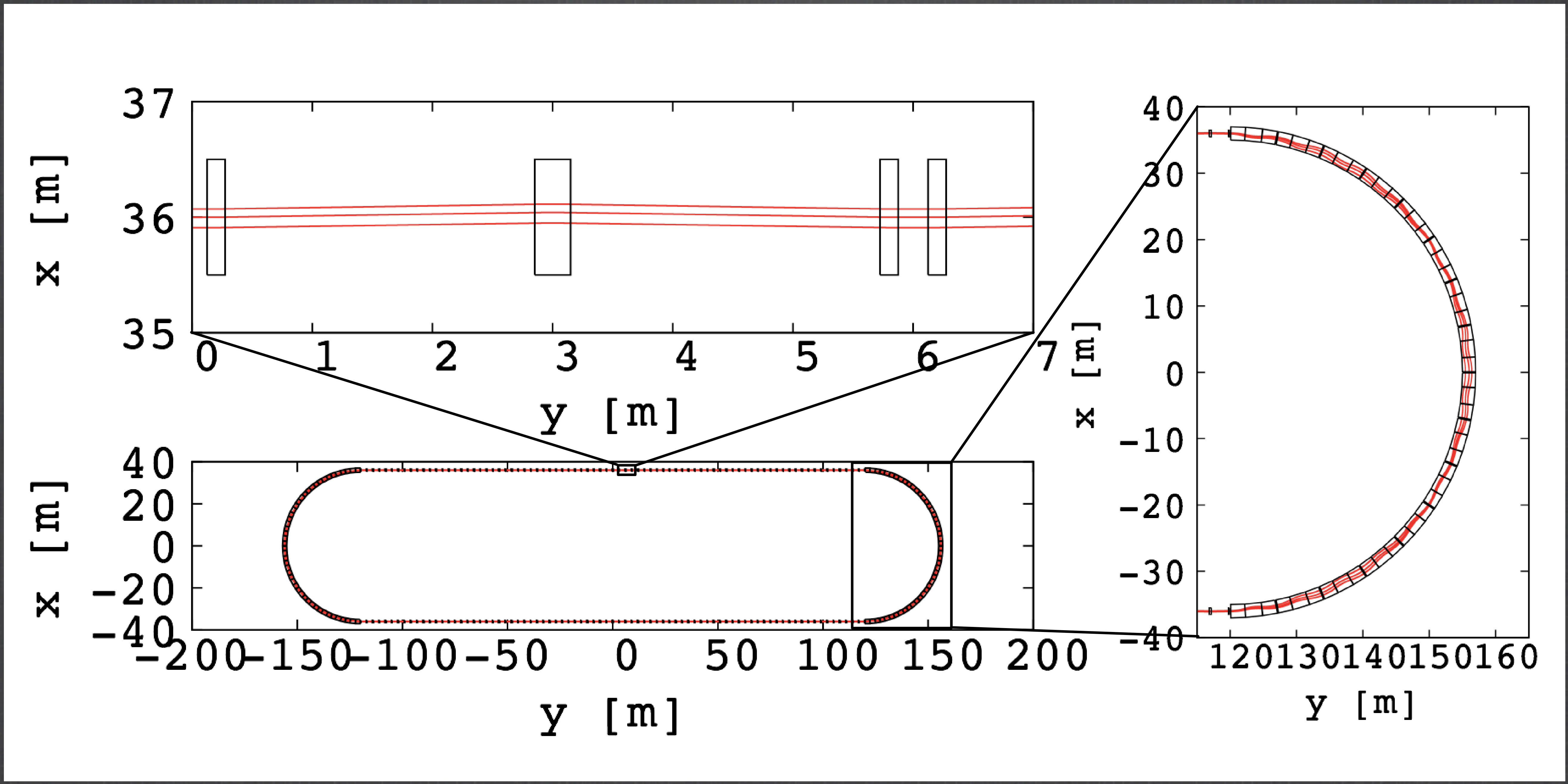
Thank you for your attention

Back-up slides

Normal conducting arcs

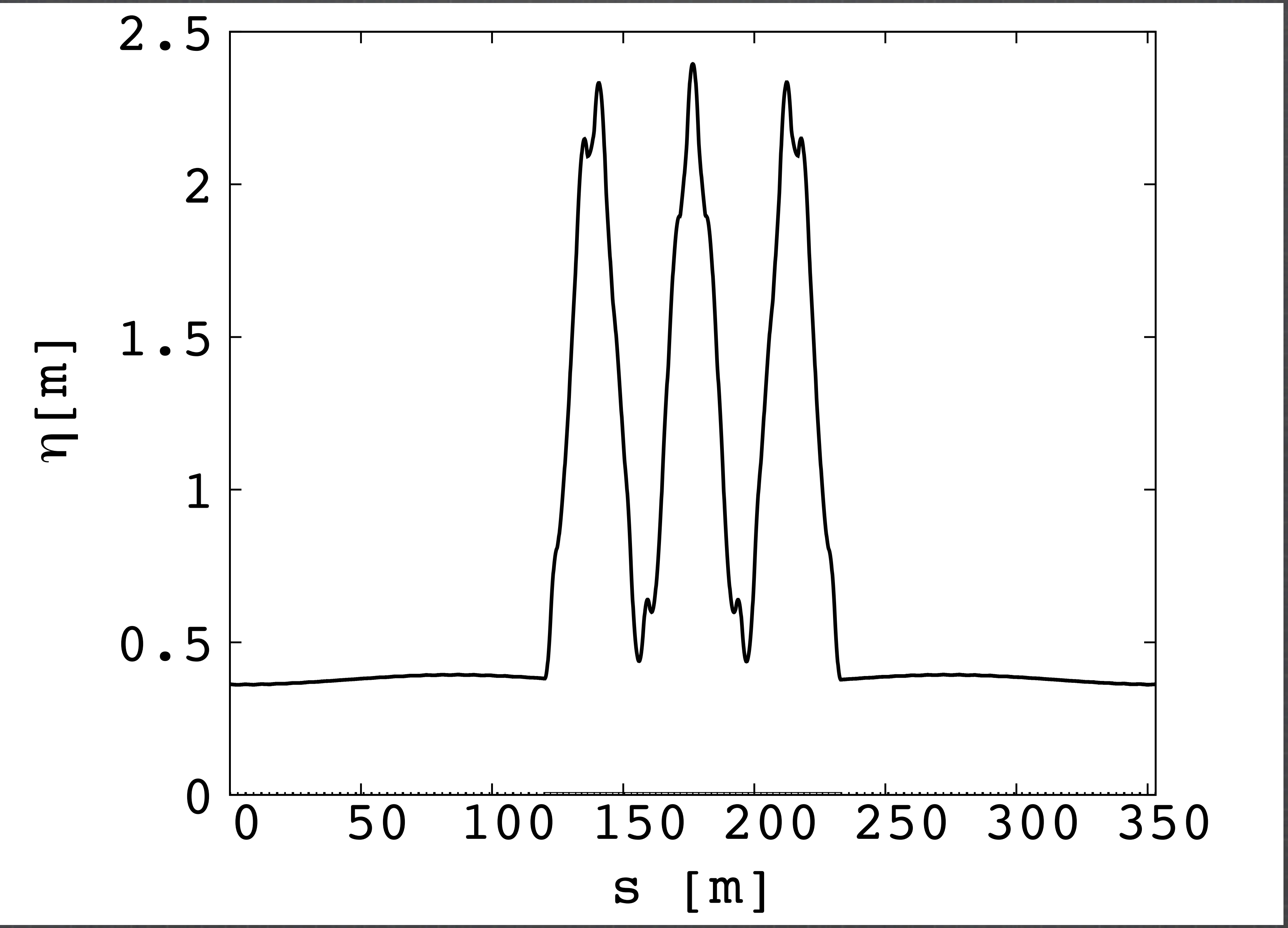
	Circular Section	**Straight Section**
Type	FDF	DFD
Cell radius [m]/opening angle [deg] or Length [m]	36/11.25	6
k-value or m-value	24.95	$2.65\ m^{-1}$
Packing factor	0.96	0.10
Horizontal phase advance /cell [deg]	67.5	13.1
Vertical phase advance /cell [deg]	11.25	16.7
Average dispersion /cell [m]	1.39	0.38
Number of cells /ring	16×2	40×2

Normal conducting arcs



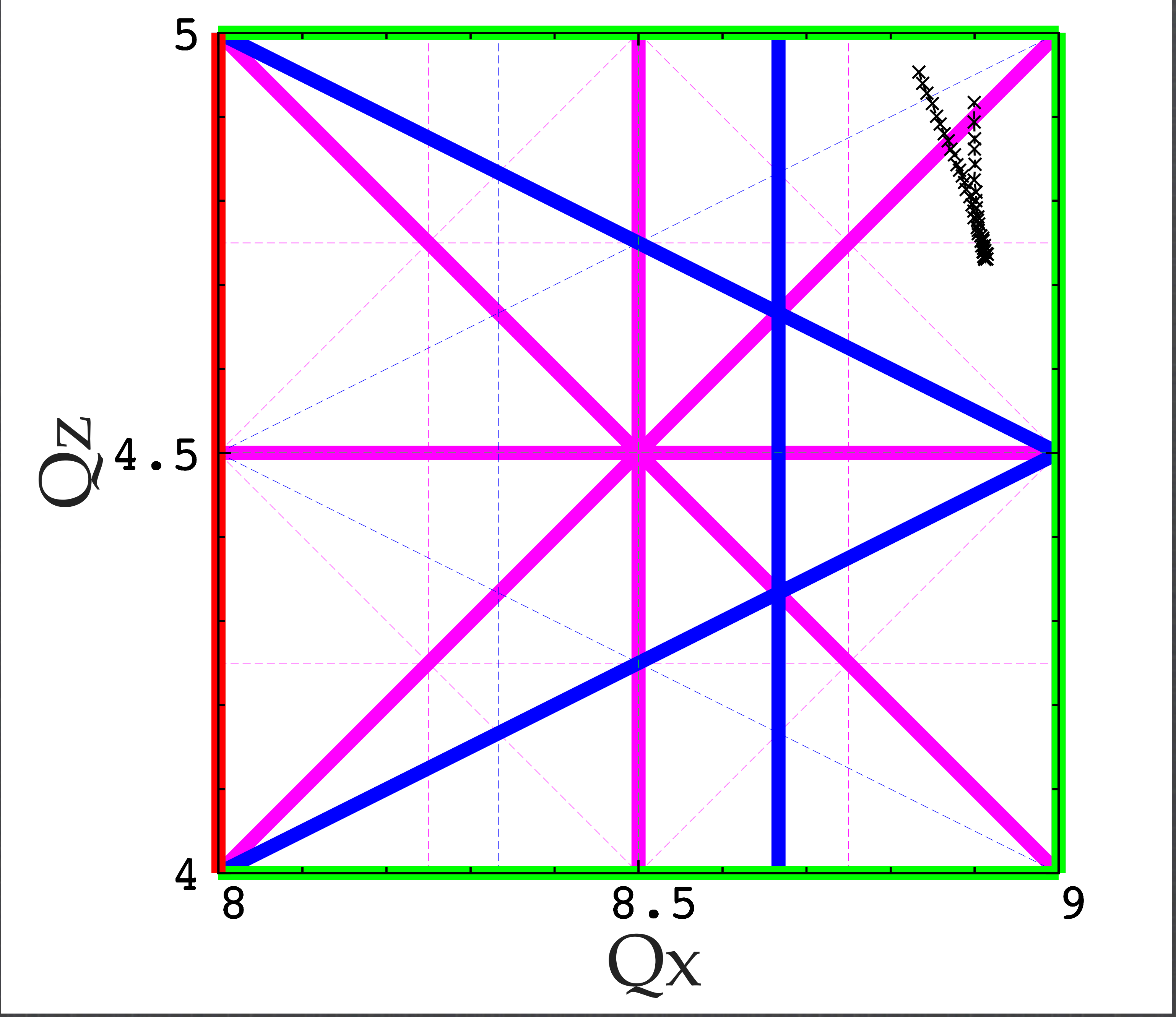
Normal conducting arcs

Dispersion function



Normal conducting arcs

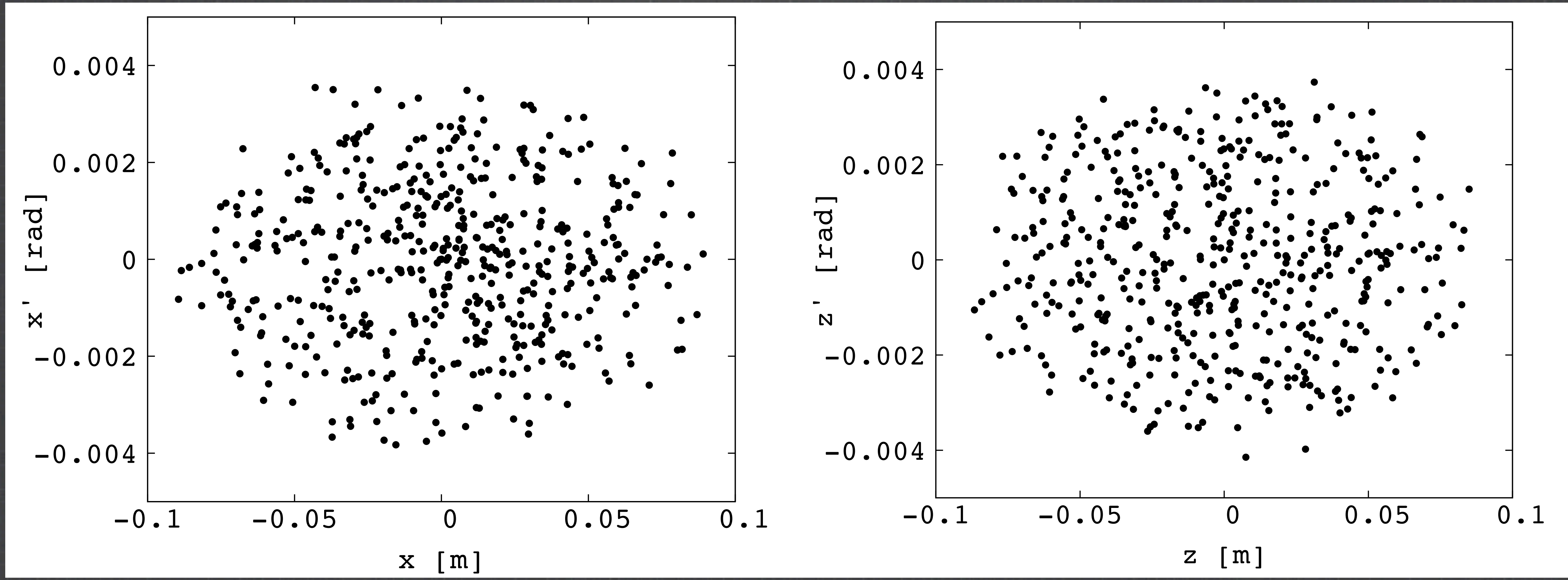
Tune diagram $\frac{\Delta P}{P} = \pm 26\%$



Normal conducting arcs

Multi-particle tracking **without dispersion matching.**

500 particles with a Waterbag distribution. Unnormalized emittances are $400\ \pi\ mm.mrad$ in transverse planes. Momentum uniformly distributed around 3.8 GeV/c **±16%**.



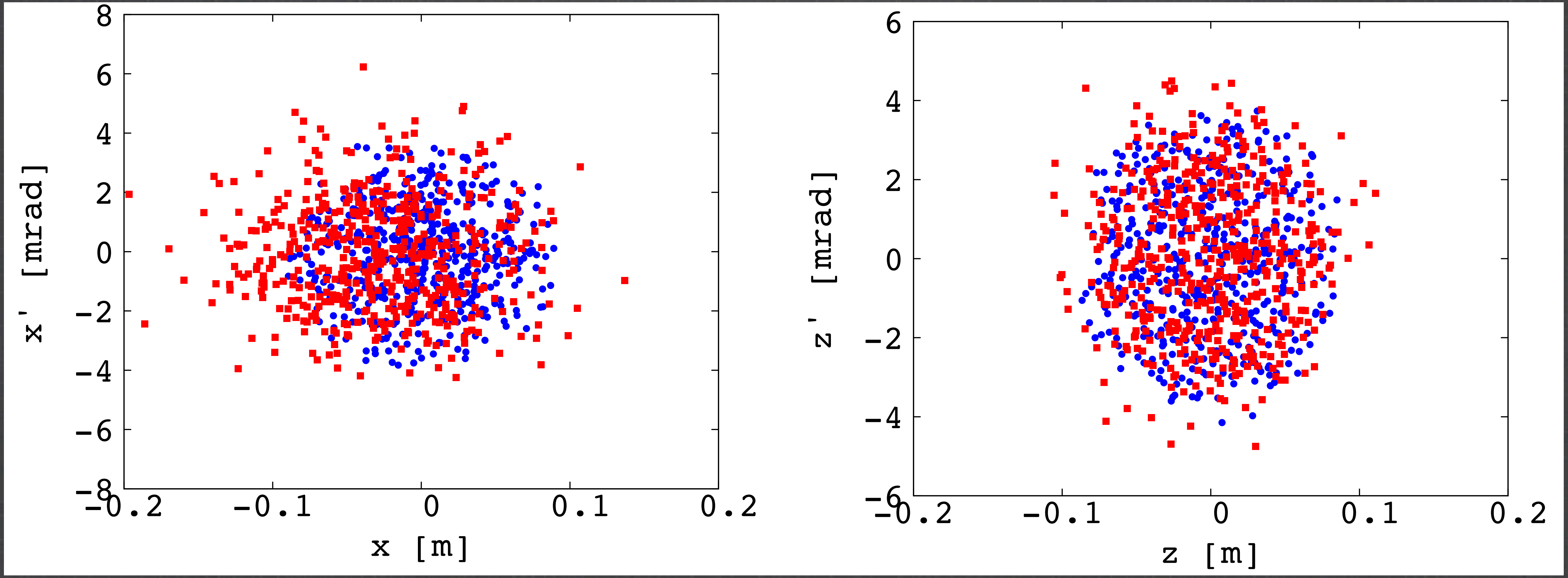
Injected Beam in the horizontal (left) and vertical (right) phase spaces

Normal conducting arcs

Multi-particle tracking **without dispersion matching.**

After 60 turns → no particle lost.

(no muon decay implemented in the simulation).



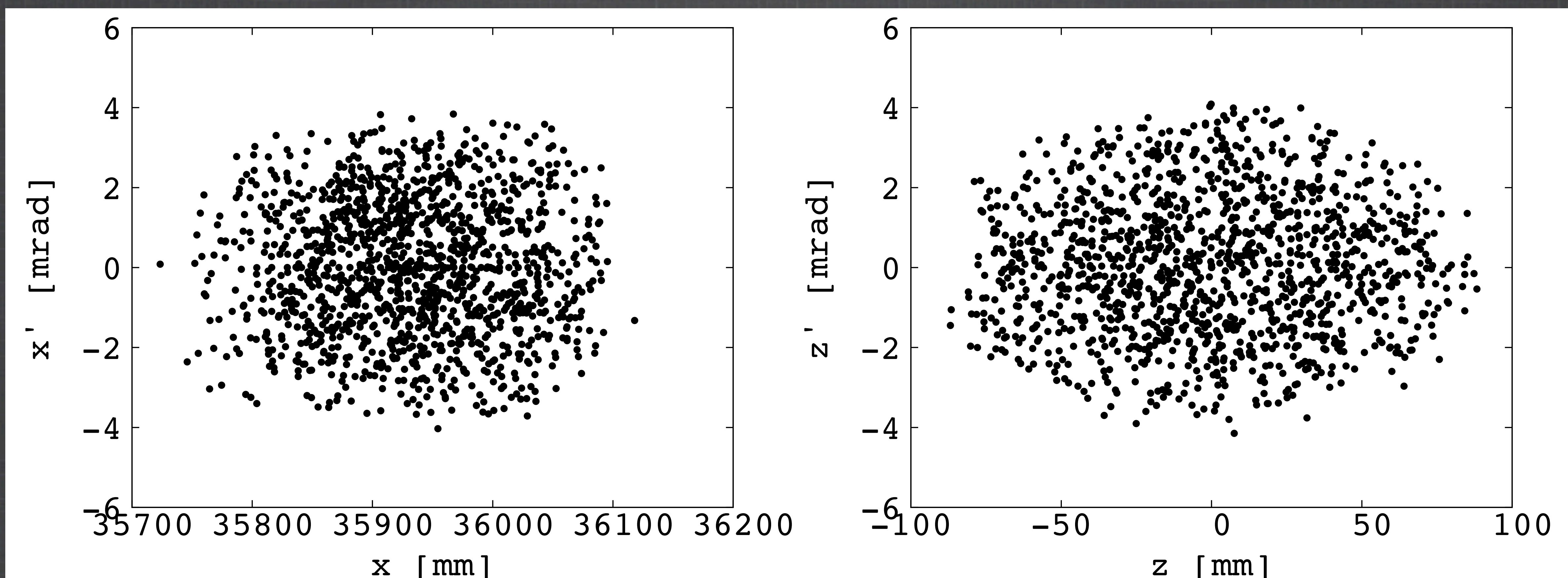
Results in the horizontal (left) and vertical (right) phase spaces

extraction
injection

Normal conducting arcs

Multi-particle tracking **with dispersion matching.**

1350 particles with a Waterbag distribution. Unnormalized emittances are $400\ \pi\ mm.mrad$ in transverse planes. Momentum uniformly distributed around 3.8 GeV/c **±26%**.



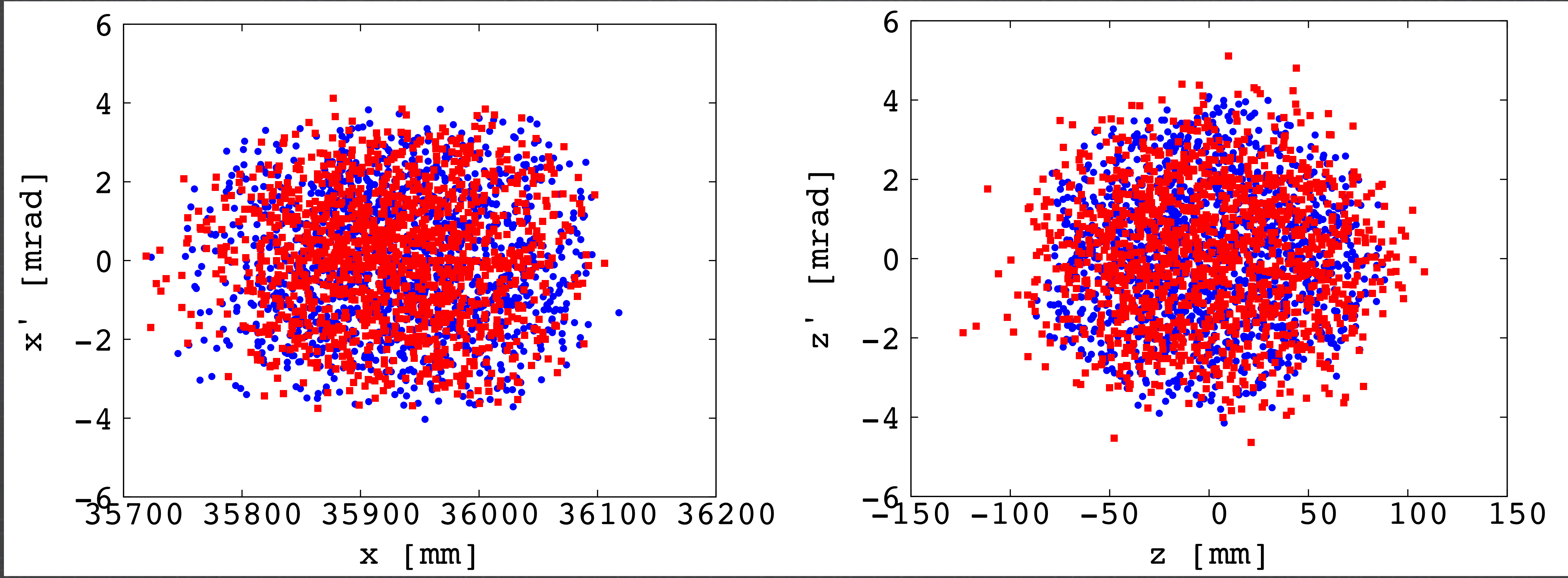
Injected Beam in the horizontal (left) and vertical (right) phase spaces

Normal conducting arcs

Multi-particle tracking **with dispersion matching.**

After 60 turns → 10 particles (0.7%) lost

(no muon decay implemented in the simulation).



Results in the horizontal (left) and vertical (right) phase spaces

■ extraction
● injection