Neutrinos from STORed Muons, nuSTORM

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On behalf of nuSTORM collaboration

Outline

- Overview
- Decay racetrack ring
  - FODO racetrack
  - FFAG racetrack
    - Doublet lattice
    - Triplet lattice
    - Injection
    - FFAG Magnet
- Future improvements

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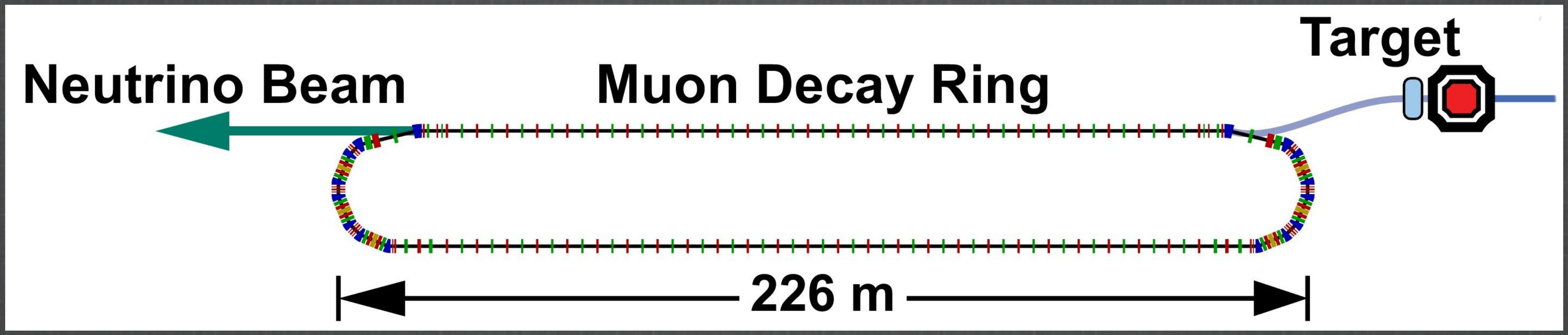
Overview



1. Facility to provide a muon beam for precision neutrino interaction physics (GeV-scale high-statistics ν_e & $\bar{\nu}_e$ data for the first time)

$$\mu^- \longrightarrow e^- + \bar{\nu}_e + \nu_\mu$$
$$\mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

2. Study of sterile neutrinos (appearance & disappearance for ν & $\bar{\nu}$)

$$\pi^- \longrightarrow \mu^- + \bar{\nu}_\mu$$
$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$

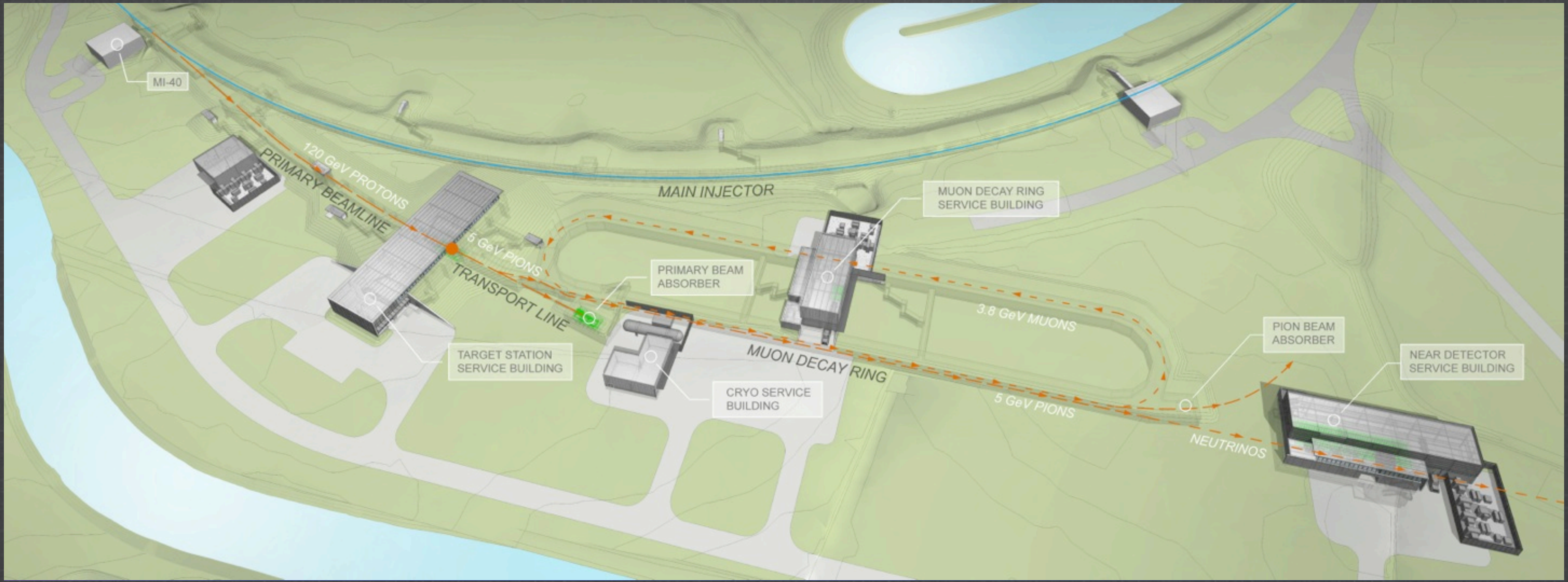
3. Accelerator & Detector technology test bed

- Potential for intense low energy muon beam
- Enables μ decay ring R&D (instrumentation) & technology demonstration platform
- Provides a neutrino Detector Test Facility
- Test bed for a new type of conventional neutrino beam

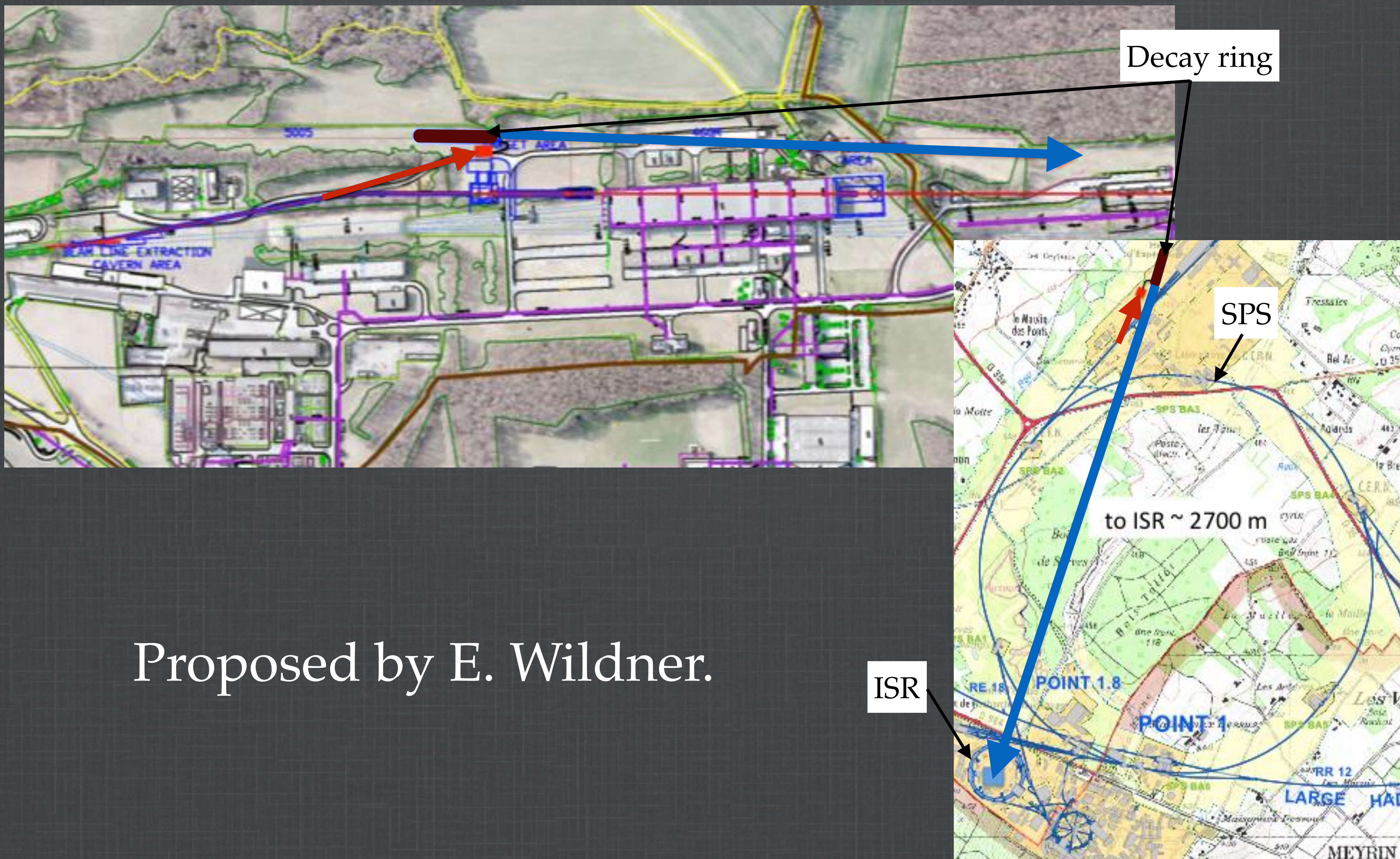
Implementation at FNAL

Implementation at FNAL (2)

Near site view



Implementation at CERN



Proposed by E. Wildner.

Facility

- 100 kW target station (designed for 400 kW)
  - 120 GeV protons from MI (FNAL), or 100 GeV protons from SPS (CERN)
  - Horn to collect pions (π^+ or π^-)
  - Target material Carbon or Inconel
  - 10^{21} protons on target over 4-5 years (3×10^{18} useful muon decays)
- Collection and transport
  - Chicane to select charge of pions
  - Stochastic injection
- Racetrack decay ring
  - large aperture FODO or FFAG.

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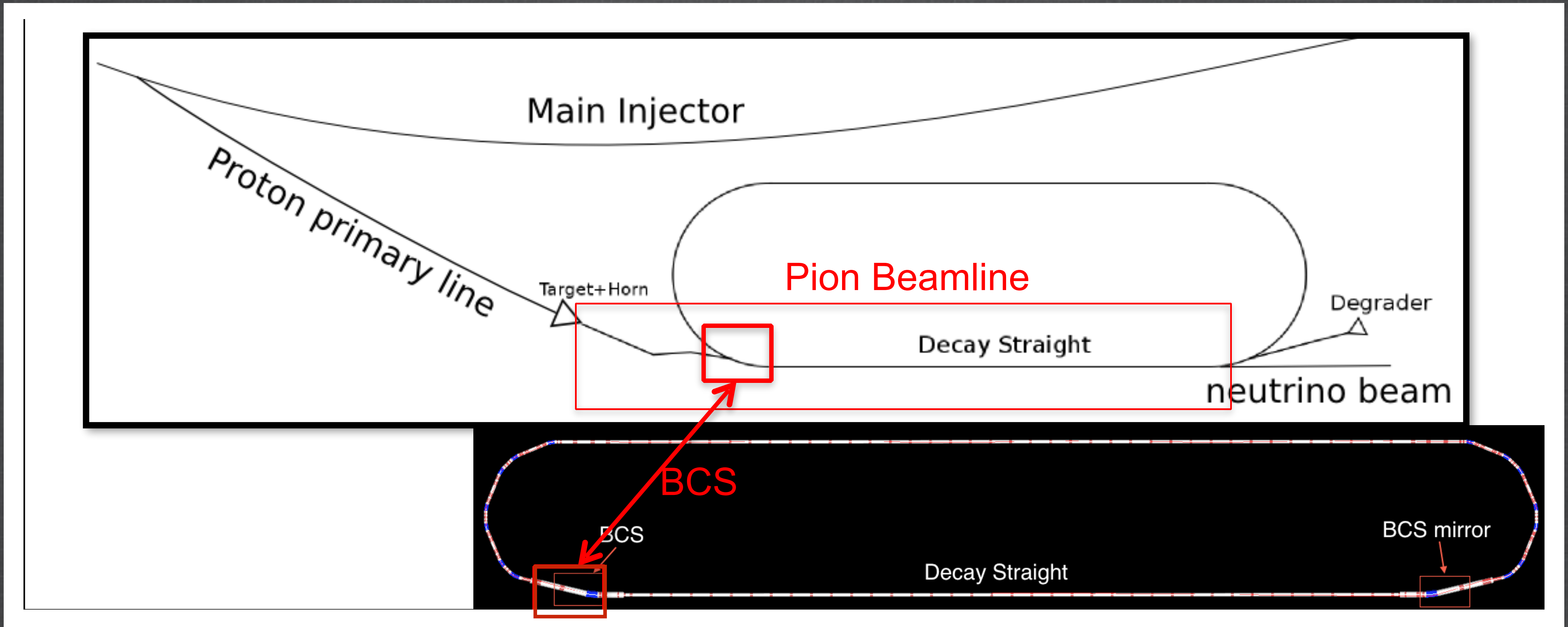
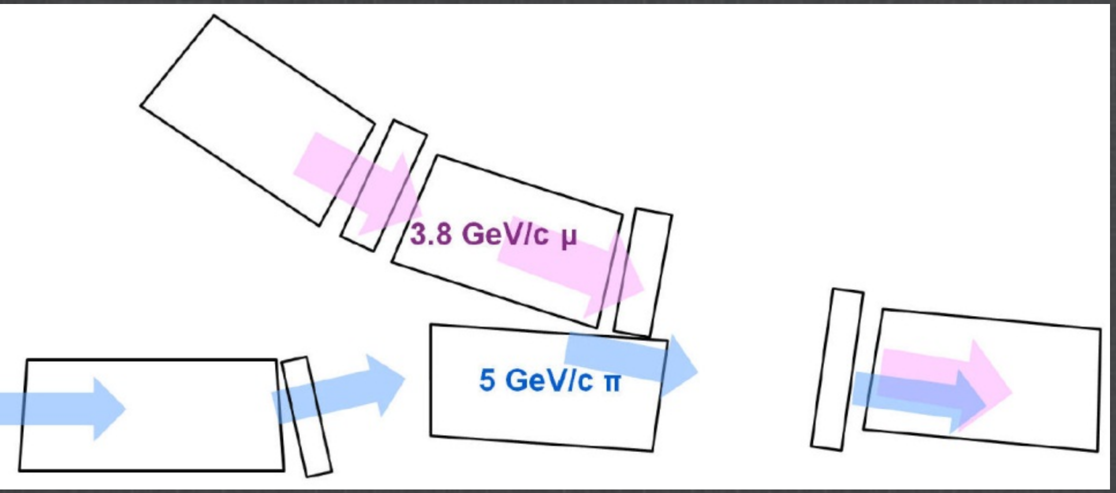
Stochastic injection





- concept from D. Neufer*: injection of pions at the Beam Combination Section (BCS) that decay in the straight section in muons.
- No kicker!

*Telmark Conference on neutrino mass, 1980

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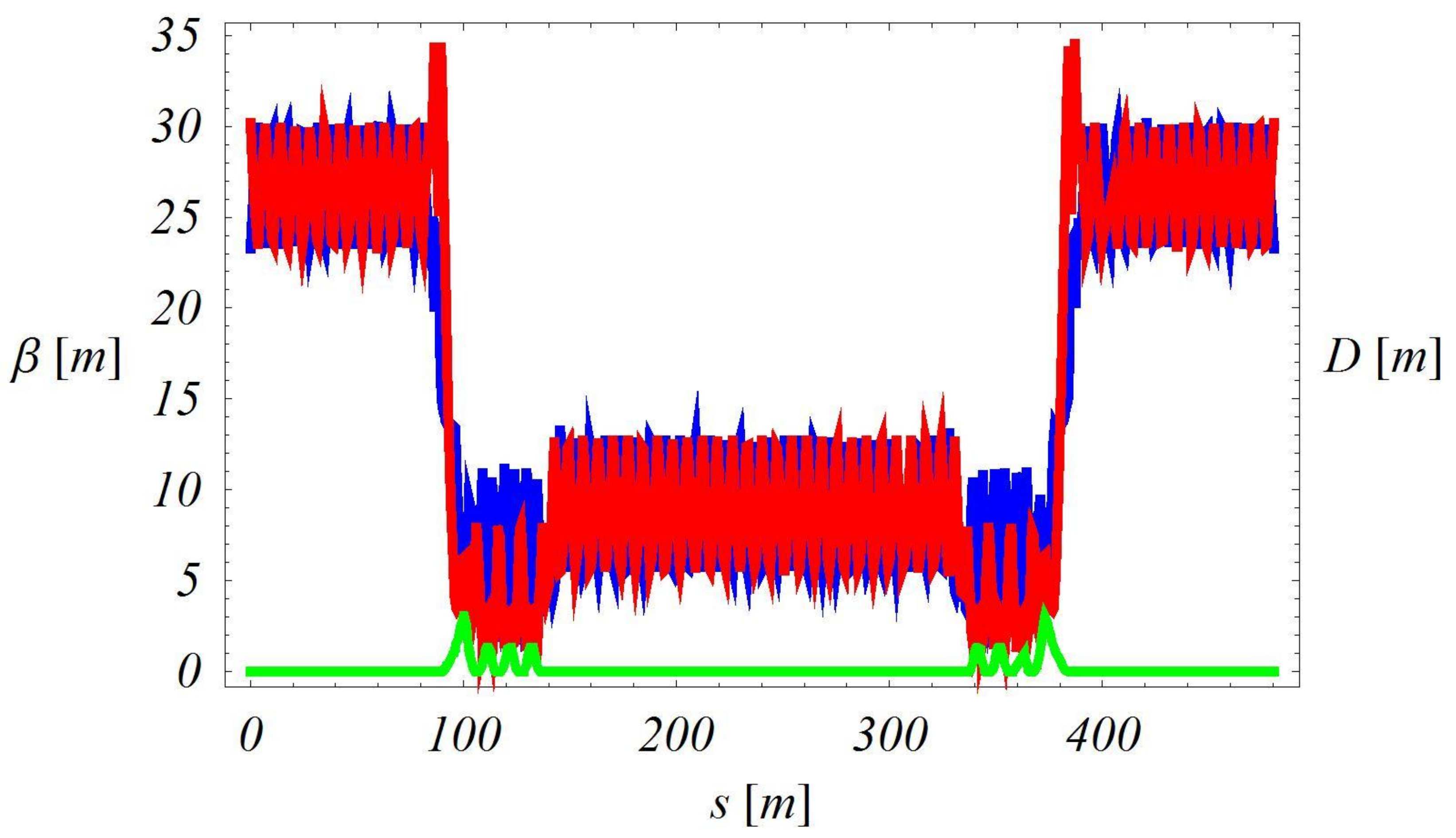
Decay ring: FODO

muon 3.8 GeV/c ± 10% (no chromatic correction)
Circumference: 480 m, straight section length: 180 m

- FODO ring based on SC separated function magnets in the arcs.
- Only quadrupoles in the straight sections.
- zero dispersion kept in the straight section.



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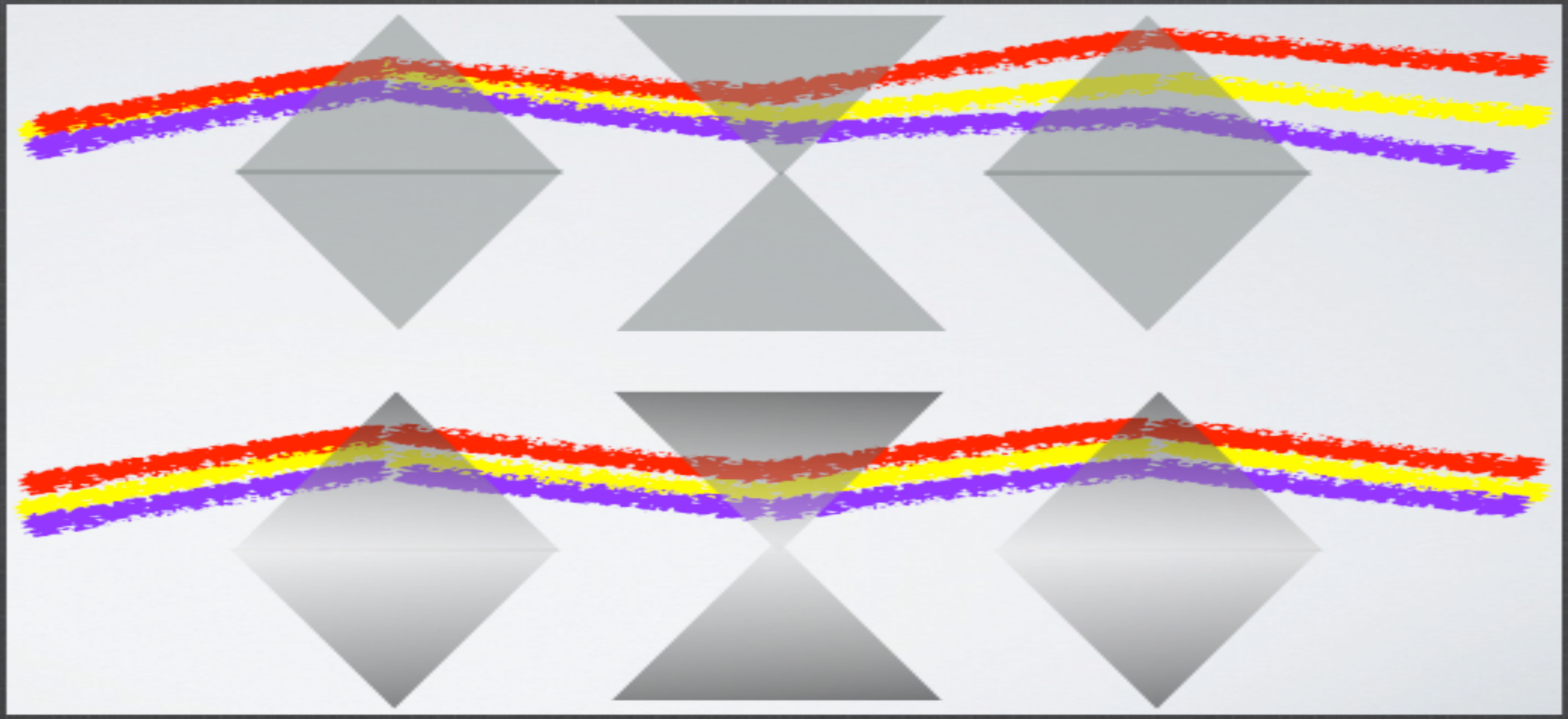
Zero-chromatic FFAG

Advantages:

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

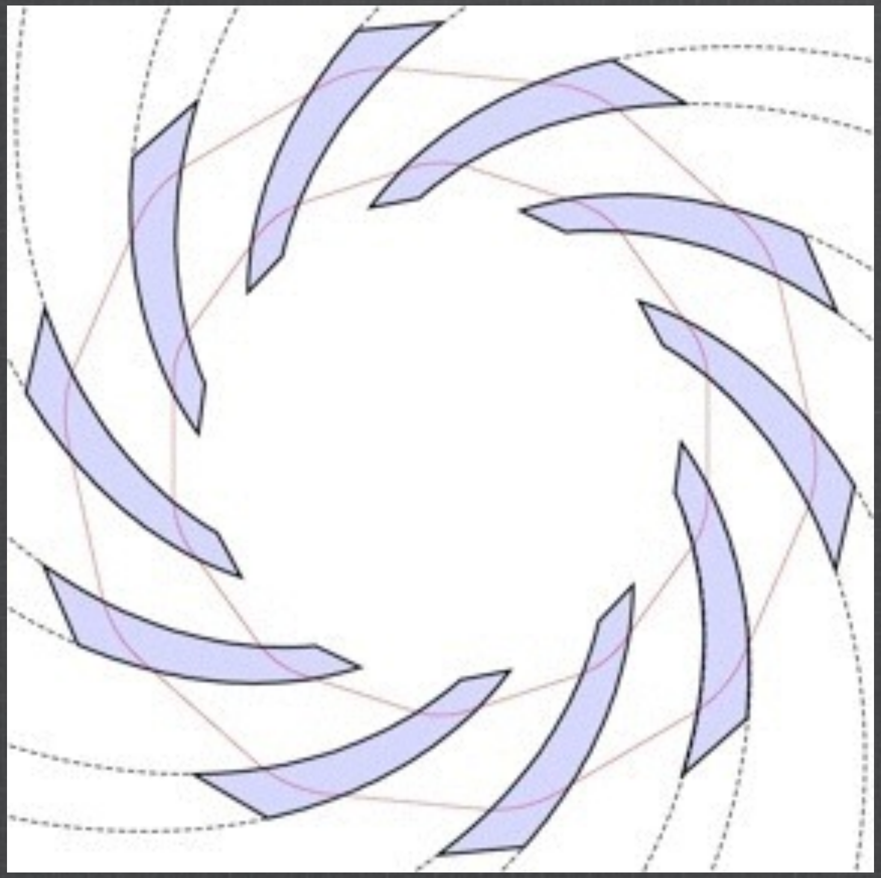


→ Quasi-zero beam loss!

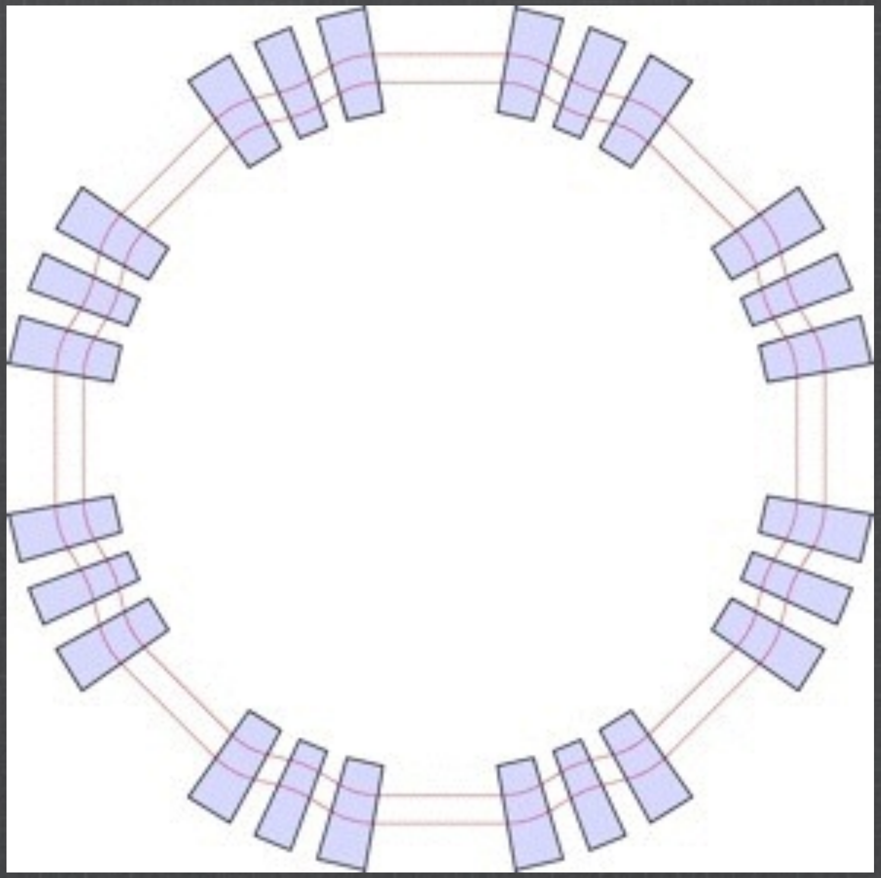
Circular scaling FFAG

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

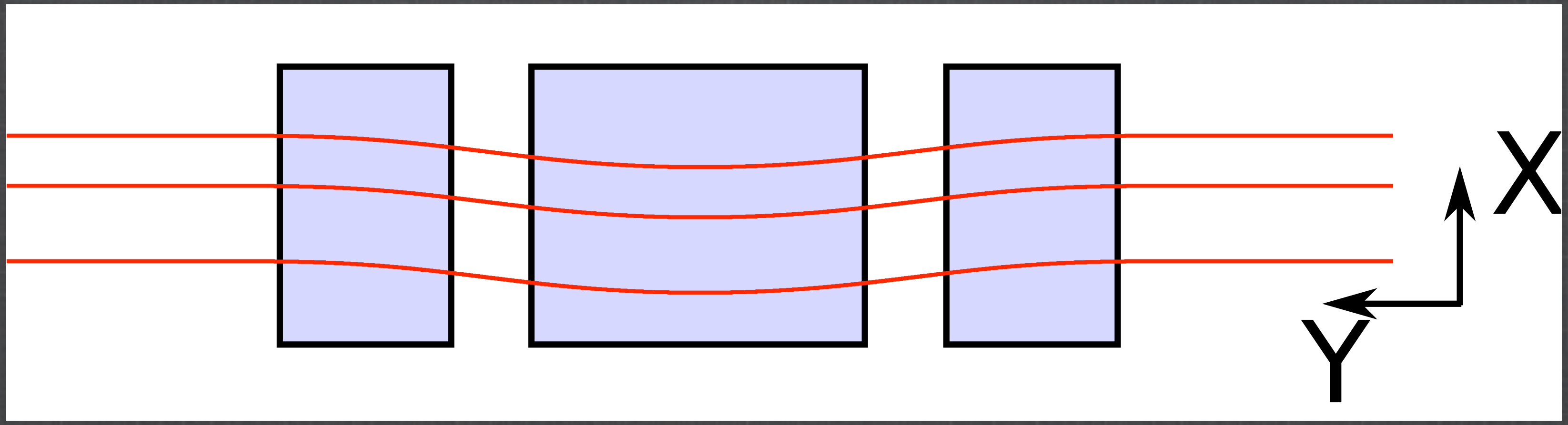


Radial sector

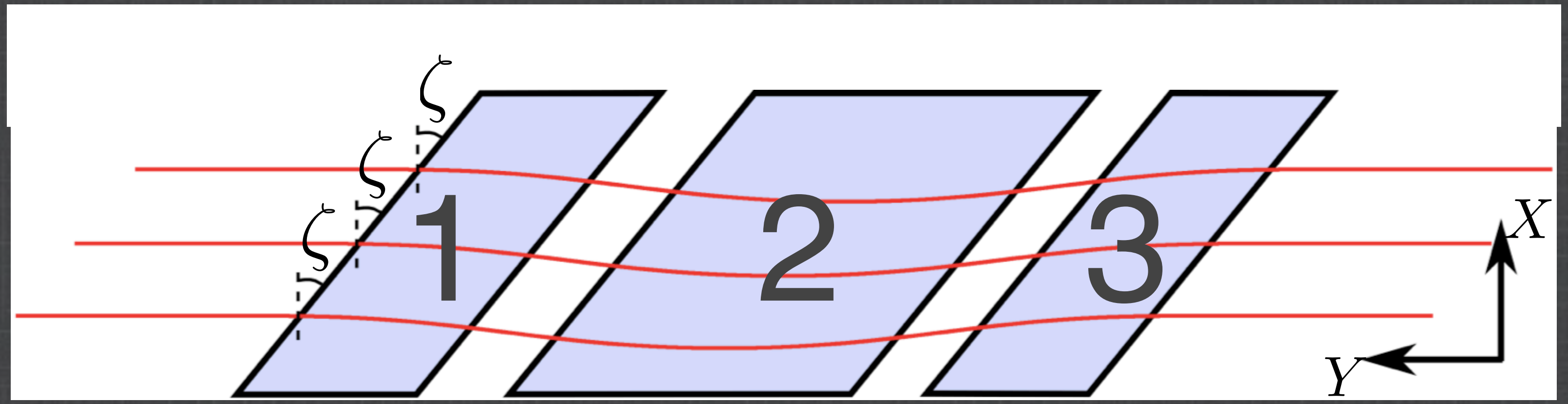
Straight scaling FFAG

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

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

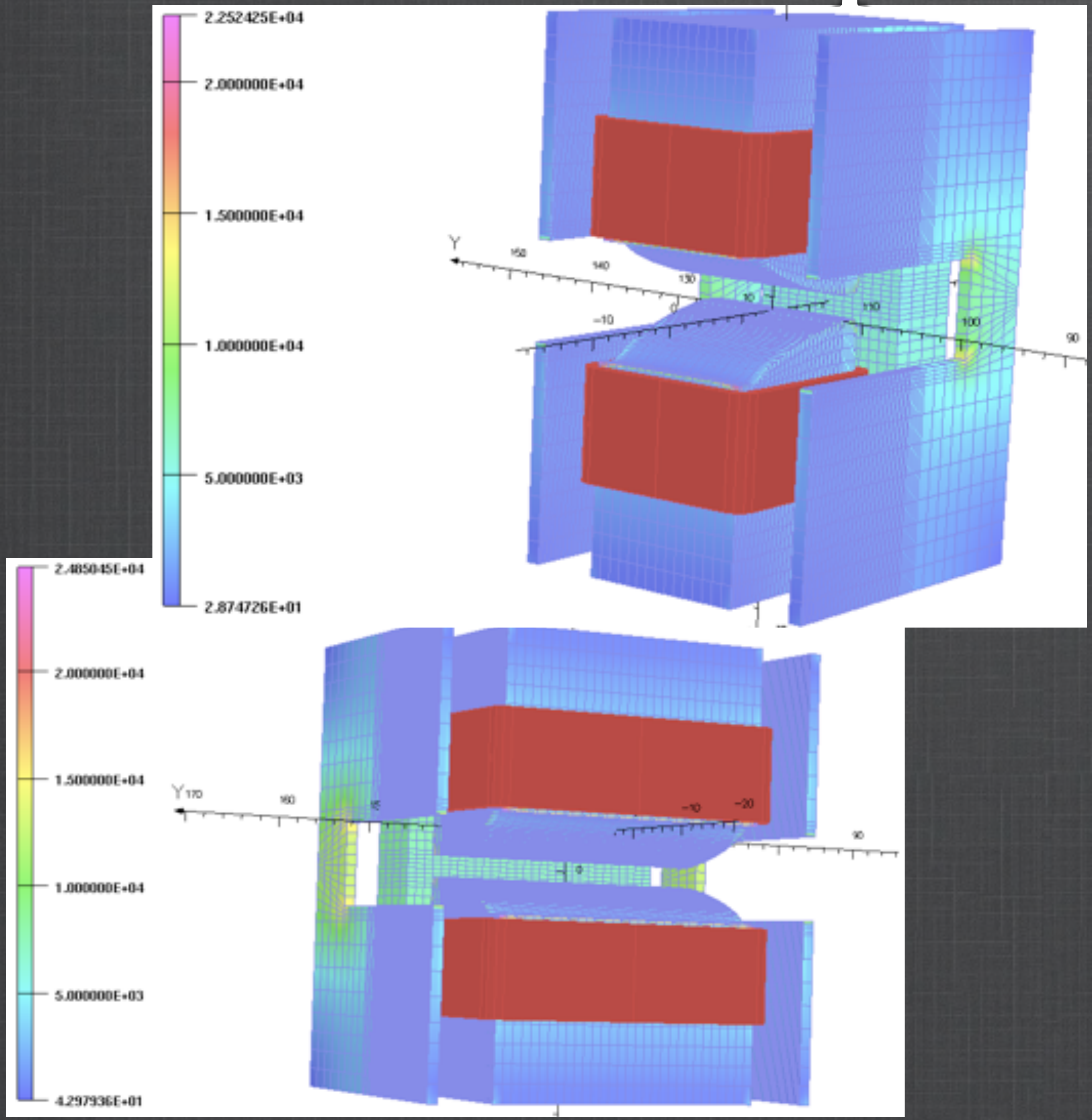


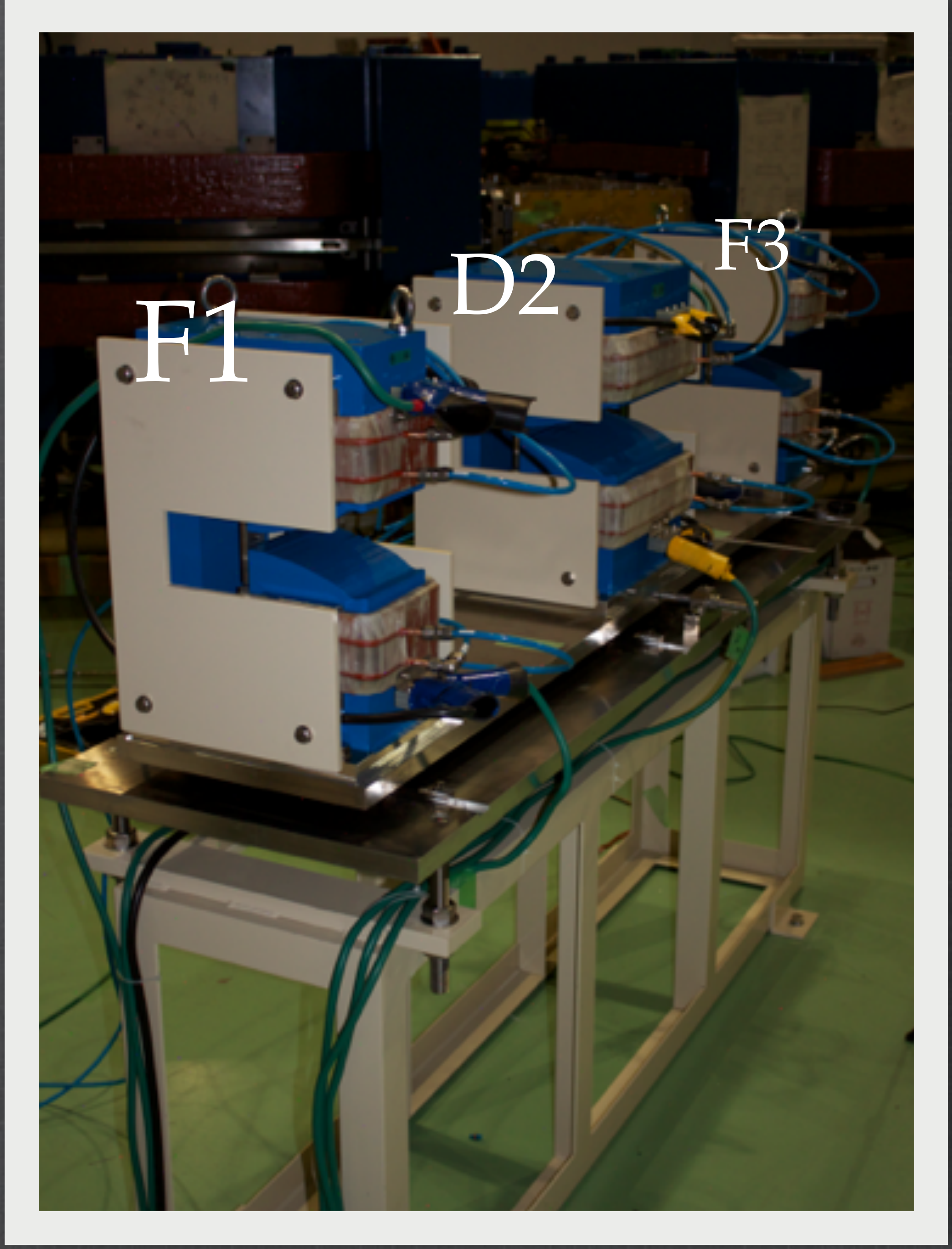
Rectangular case



Tilted straight case

Straight scaling FFAG experiment

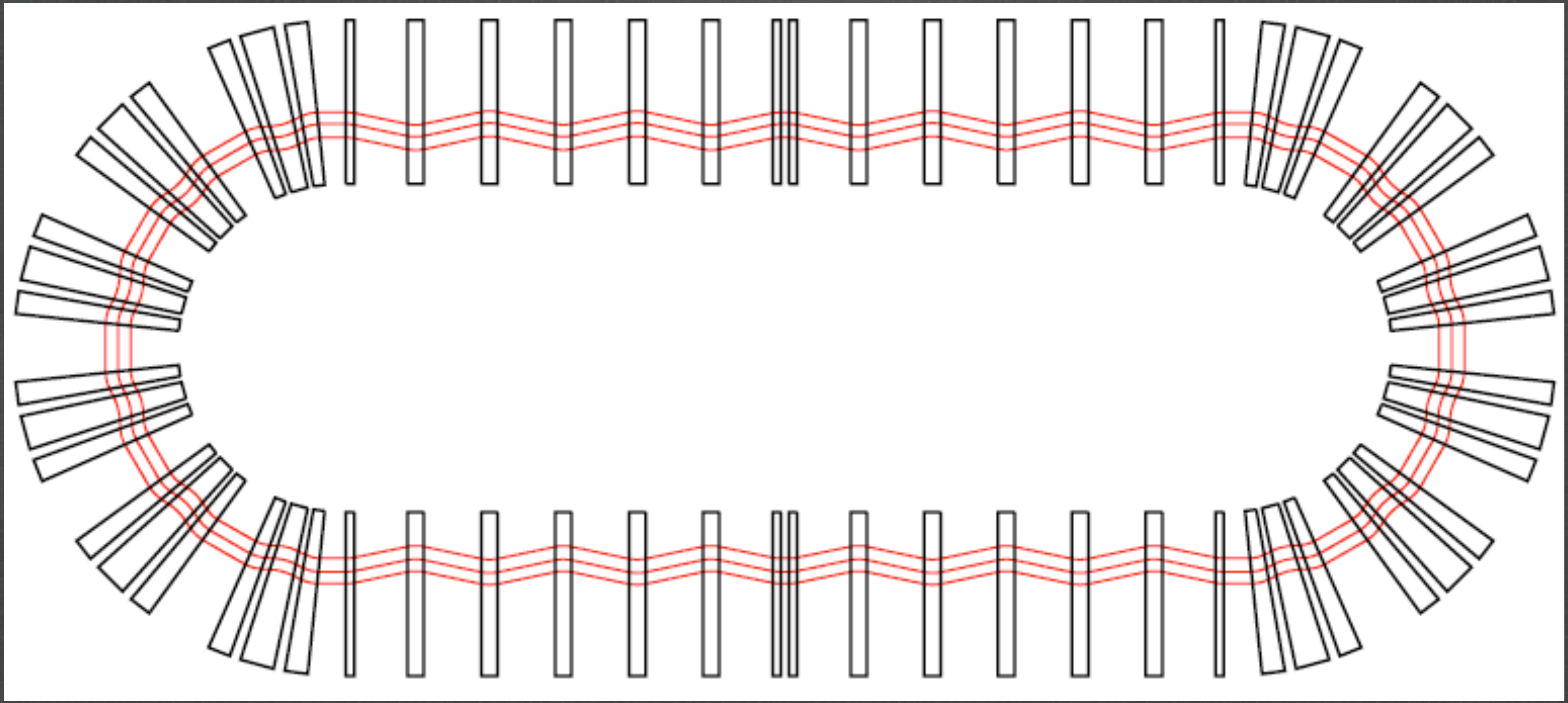




JB. Lagrange *et al.*, Straight scaling FFAG beam line, NIM A, vol. 691, pp. 55-63, ISSN 0168-9002 (2012).

(2011)

Racetrack FFAG



νSTORM Racetrack FFAG

Constraints:

- in the straight part, the scallop must be as small as possible to keep reasonable the size of the detector.
- 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 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).

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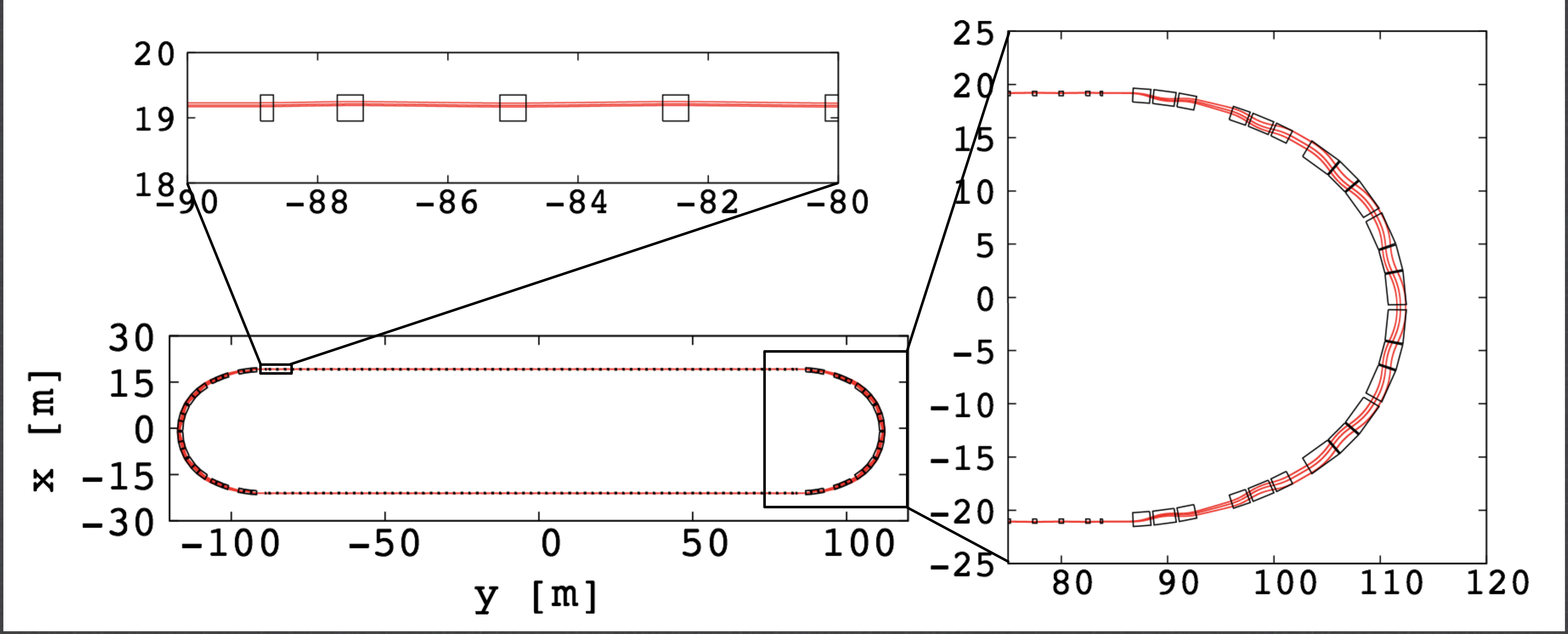
Doublet solution

muon 3.8 GeV/c ± 16% - Circumference: 500 m

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



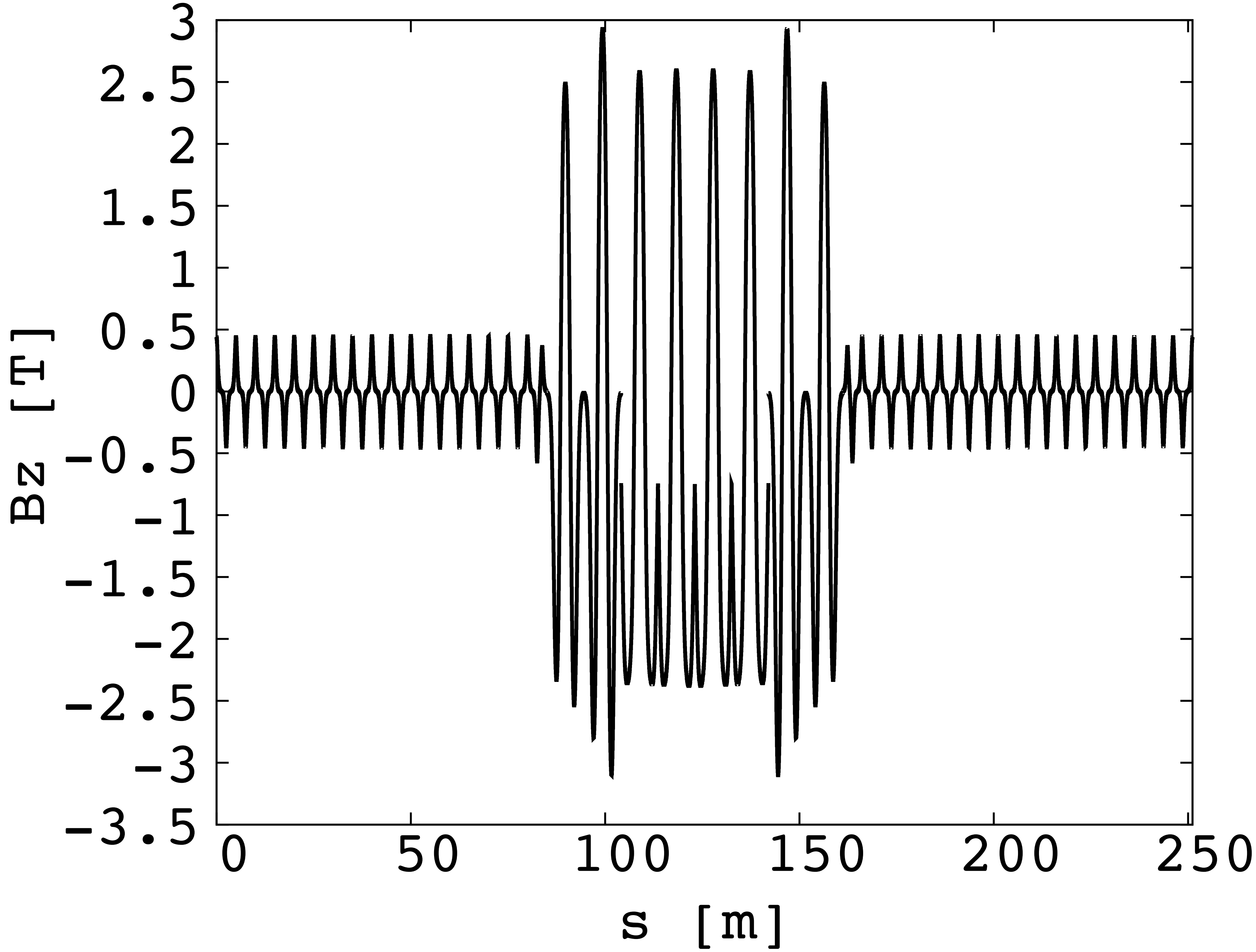
Doublet solution

Cell parameters

	Circular Section	Matching Section	Straight Section
Type	FDF	FDF	Doublet
Cell radius/length [m]	17.6	36.2	5
Opening angle [deg]	30	15	
k-value/m-value	6.043	25.929	5.5 m^{-1}
Packing factor	0.92	0.58	0.16
Maximum magnetic field [T]	2.5	3.3	1.5
horizontal excursion [m]	1.3	1.1	0.4
Full gap height [m]	0.45	0.45	0.45
Average dispersion /cell [m]	2.5	1.3	0.18
Number of cells /ring	4×2	4×2	35×2

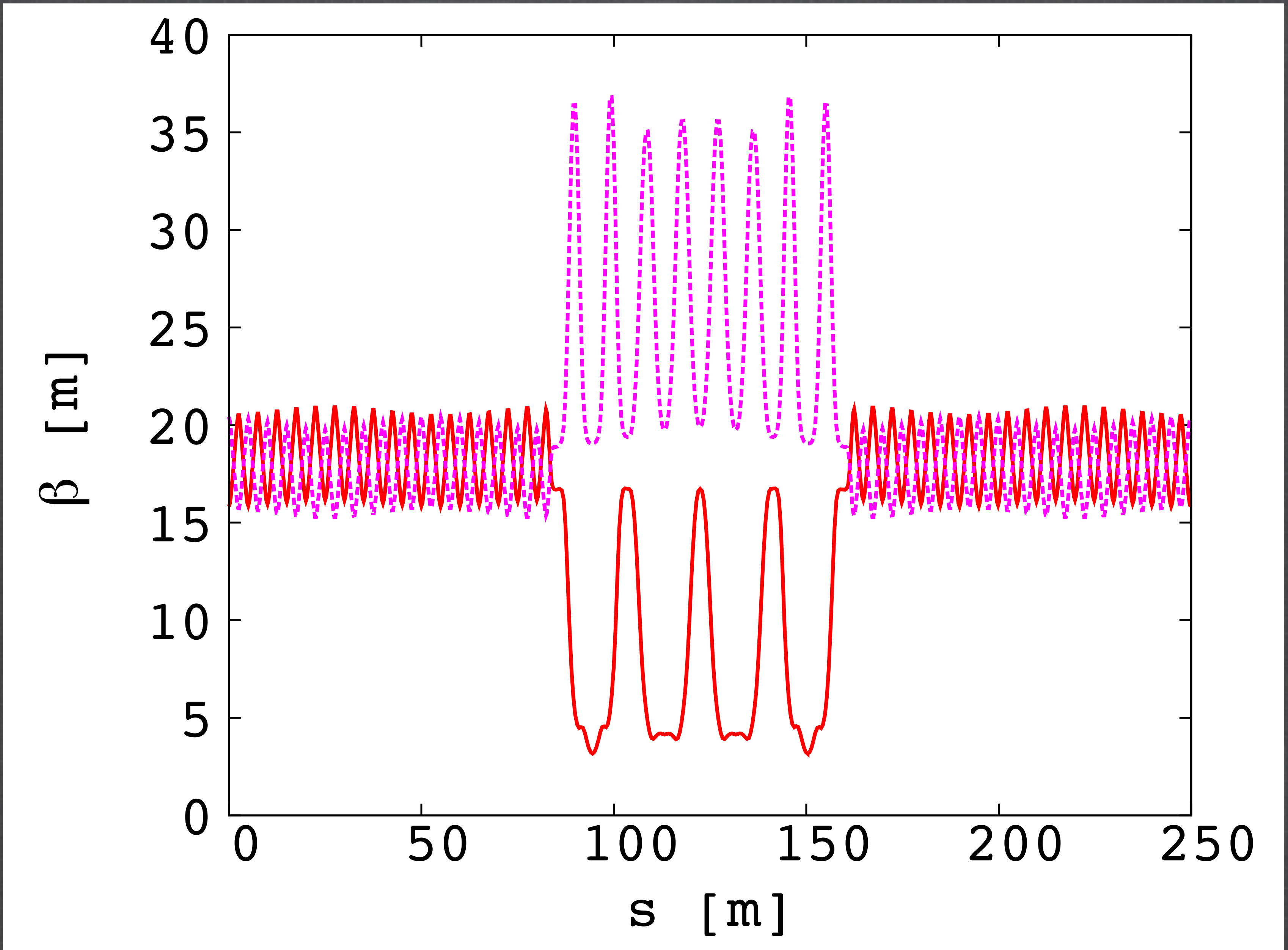
Doublet solution

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



Doublet solution

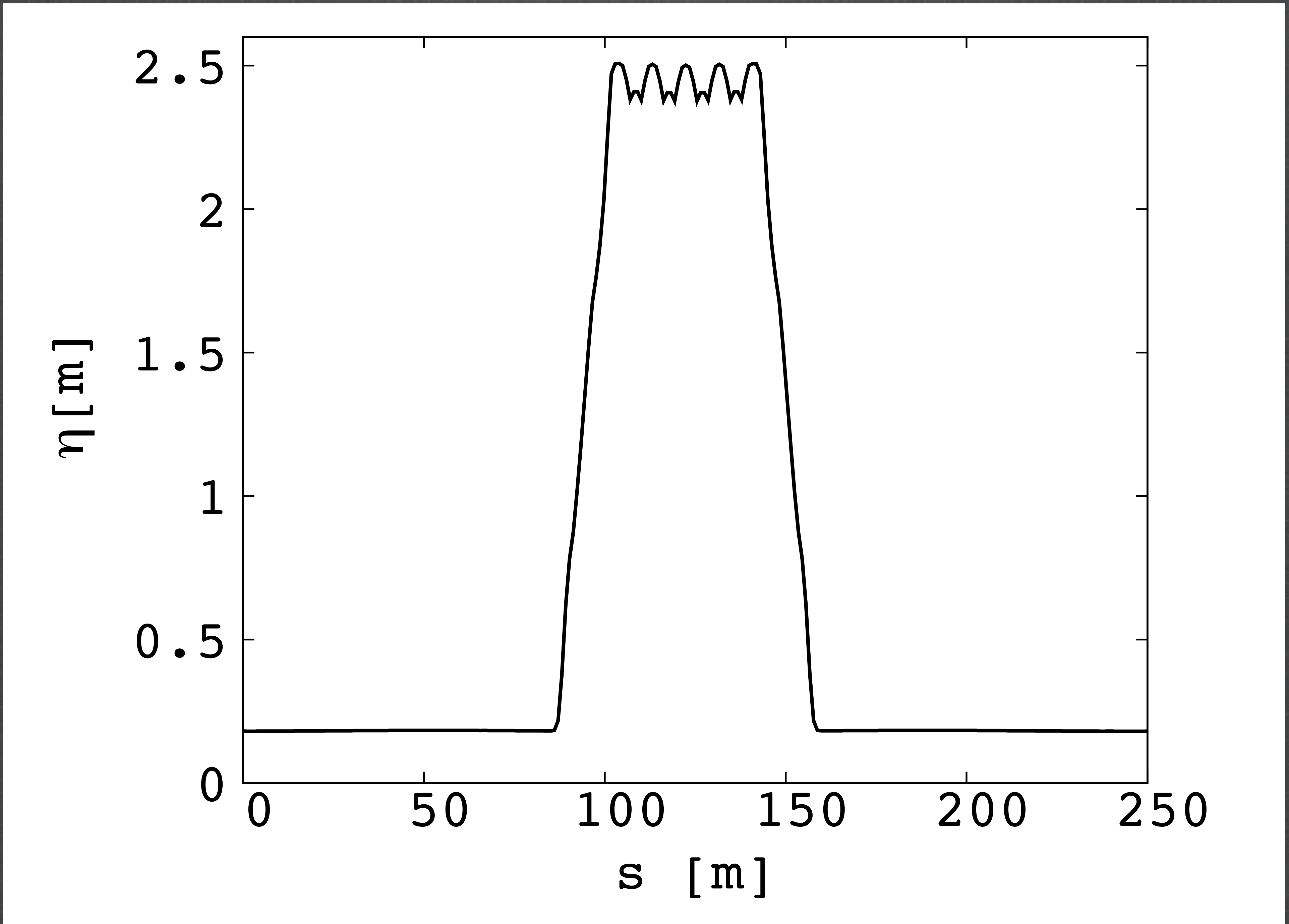
Beta-functions at matching momentum



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

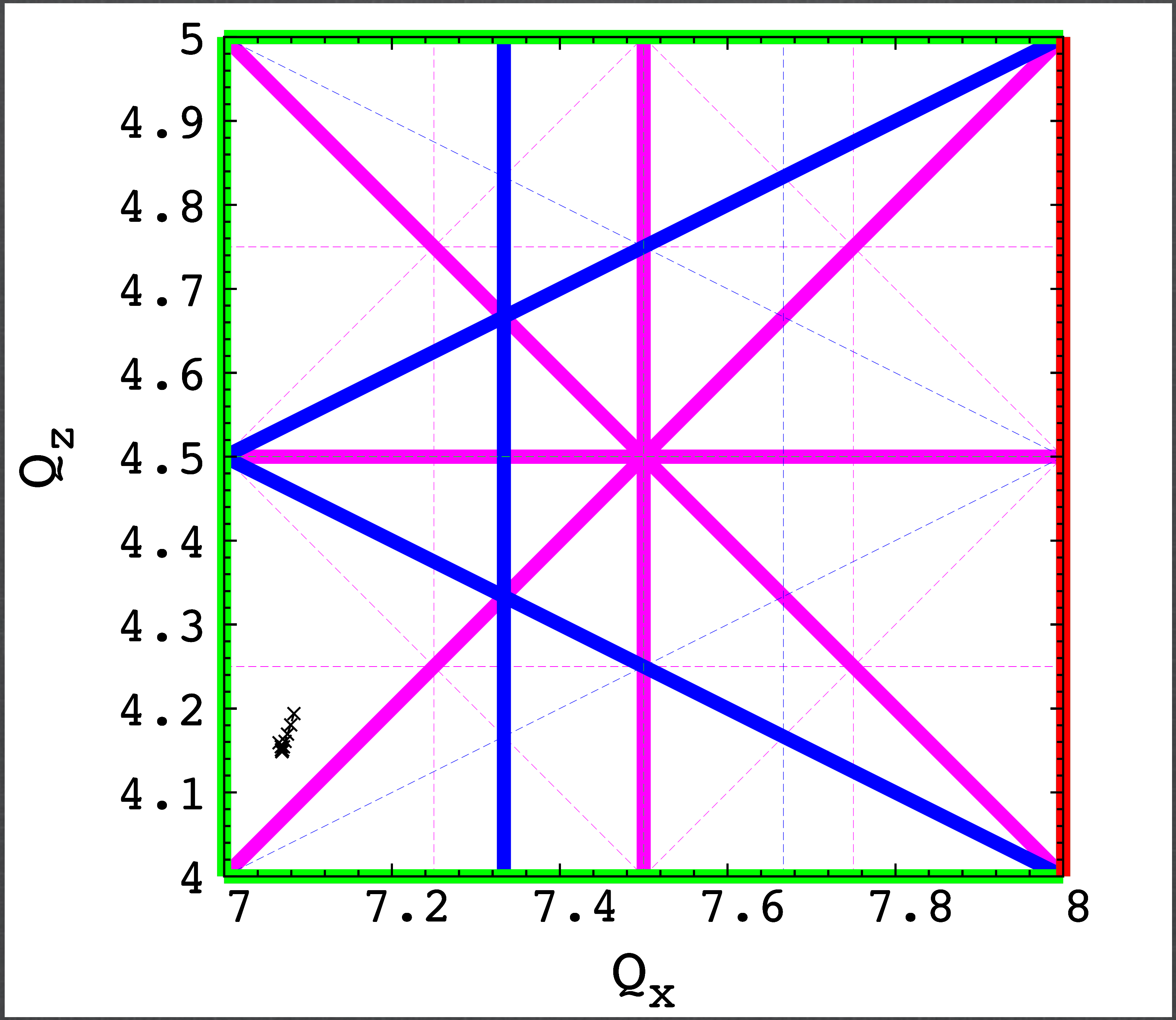
Doublet solution

Dispersion function at matching momentum



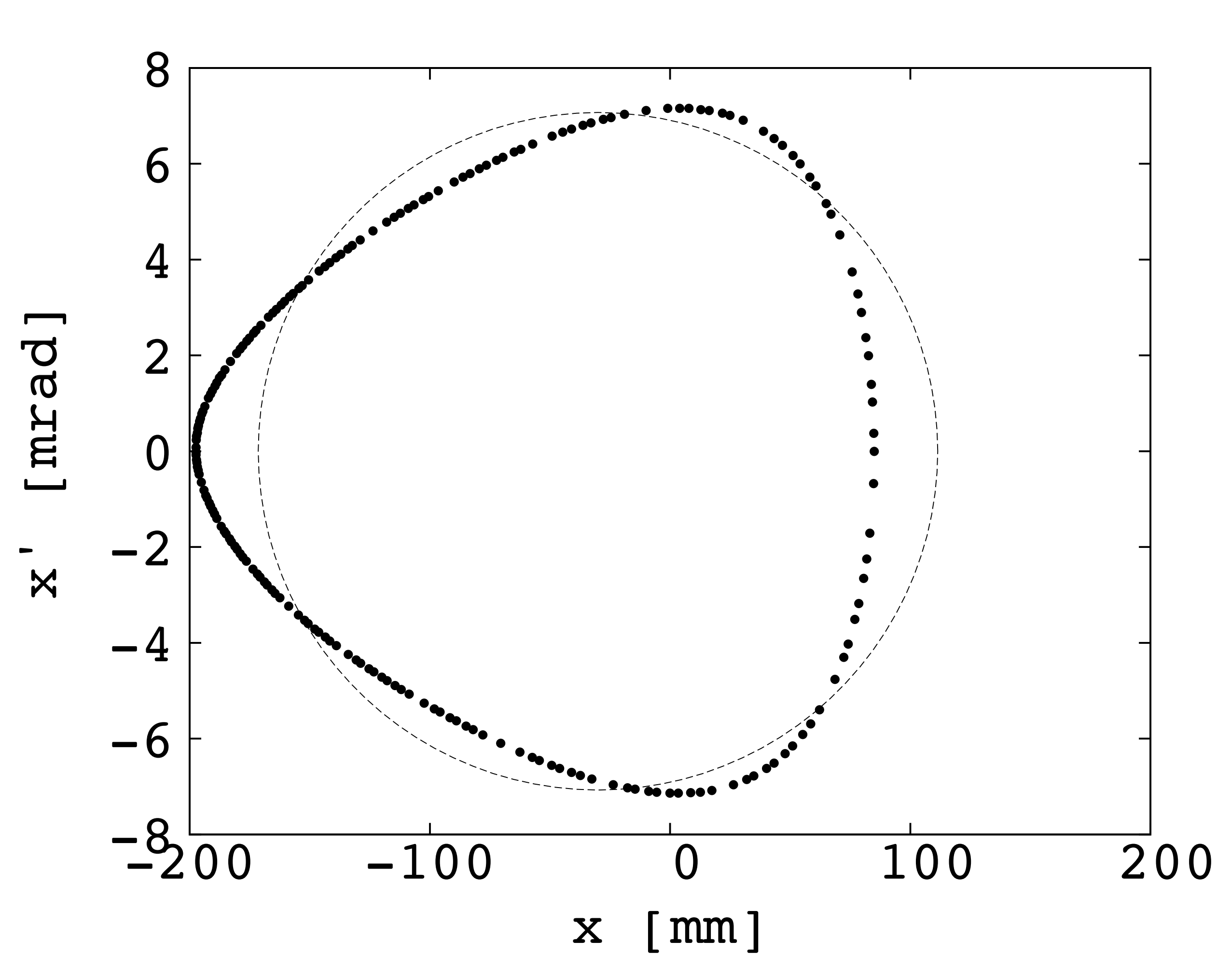
Doublet solution

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

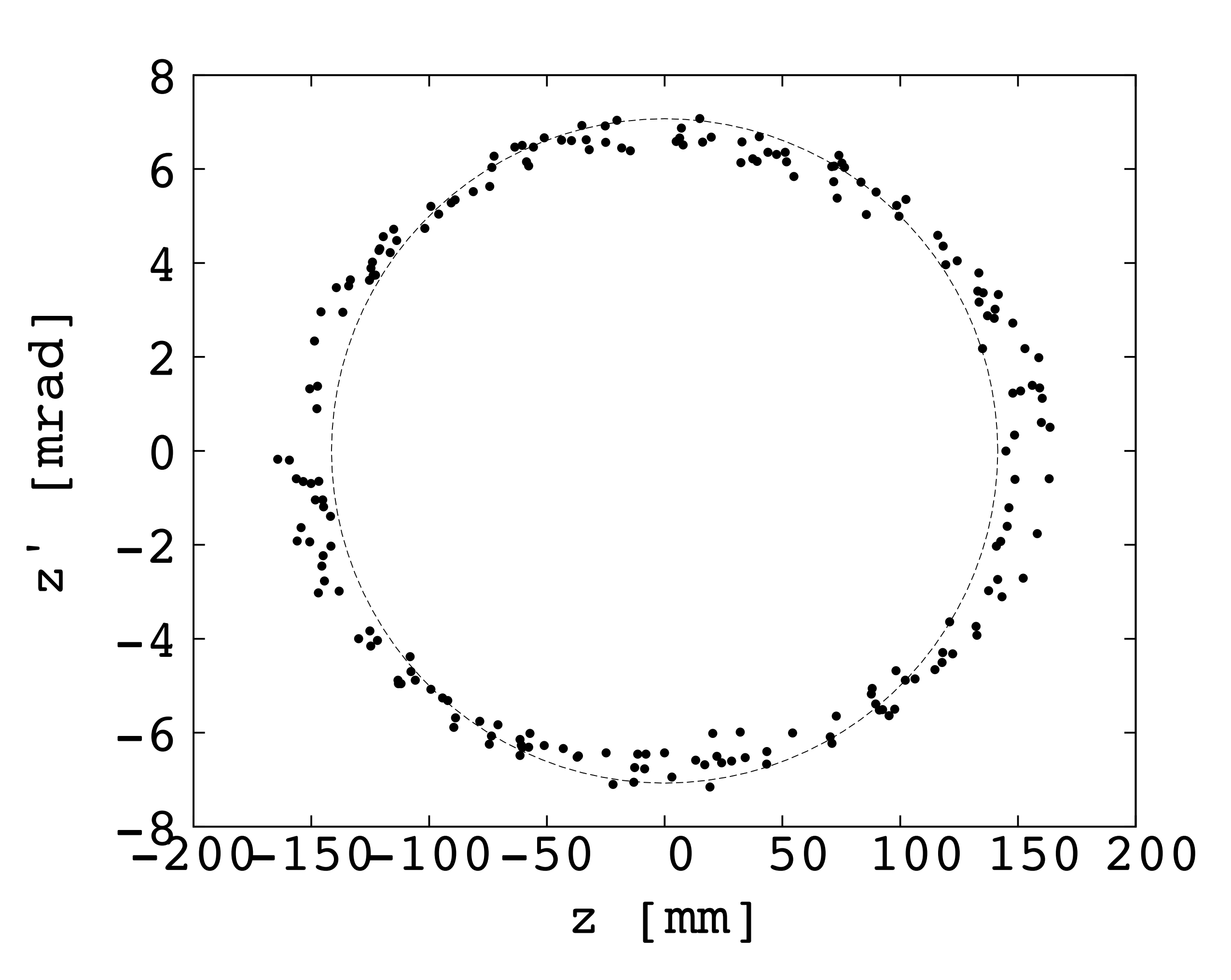


Doublet solution

Transverse acceptance



Maximum horizontal stable amplitude over 100 turns



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Motivations

1300 km decay scenario incompatible with scallop of the closed orbit.

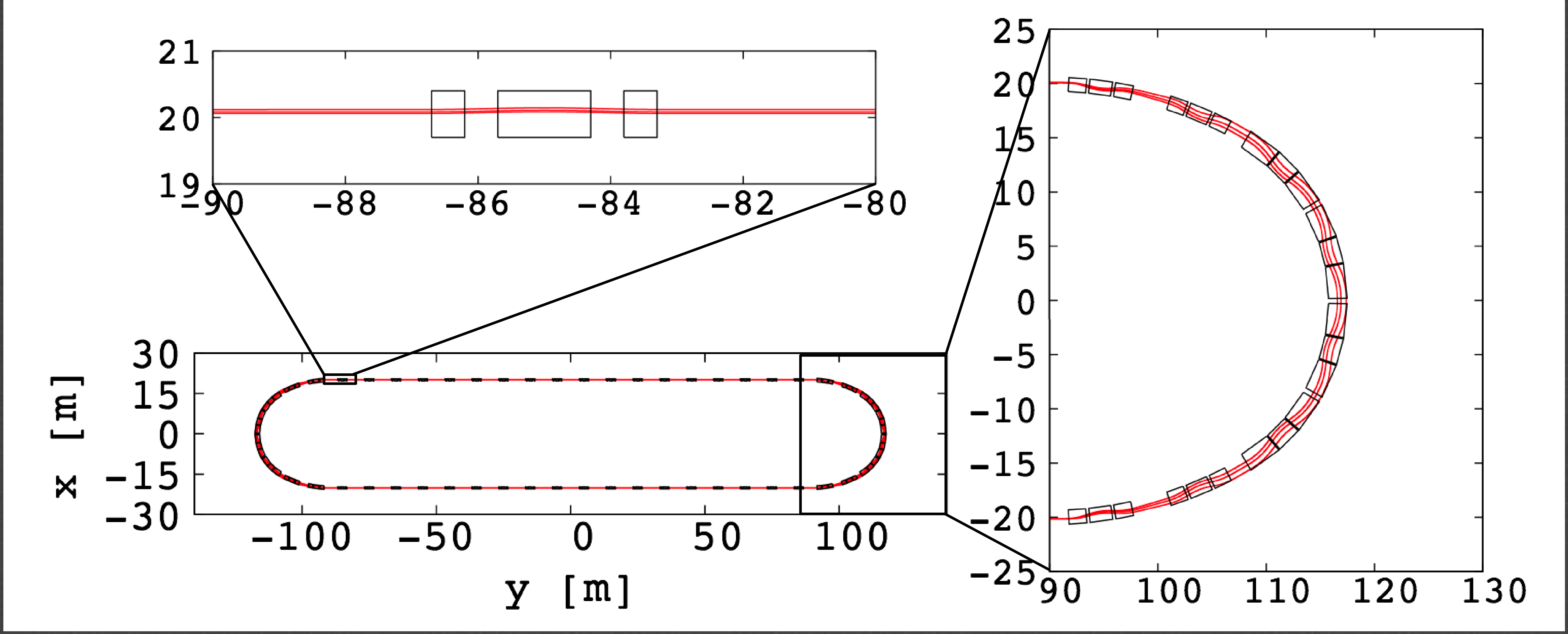
Doublet in the straight section cannot be used.

→ Triplet in the straight section.

Triplet solution

muon 3.8 GeV/c ± 16% - Circumference: 510 m

Straight: **180 m,** maximum scallop angle**: 24 mrad**



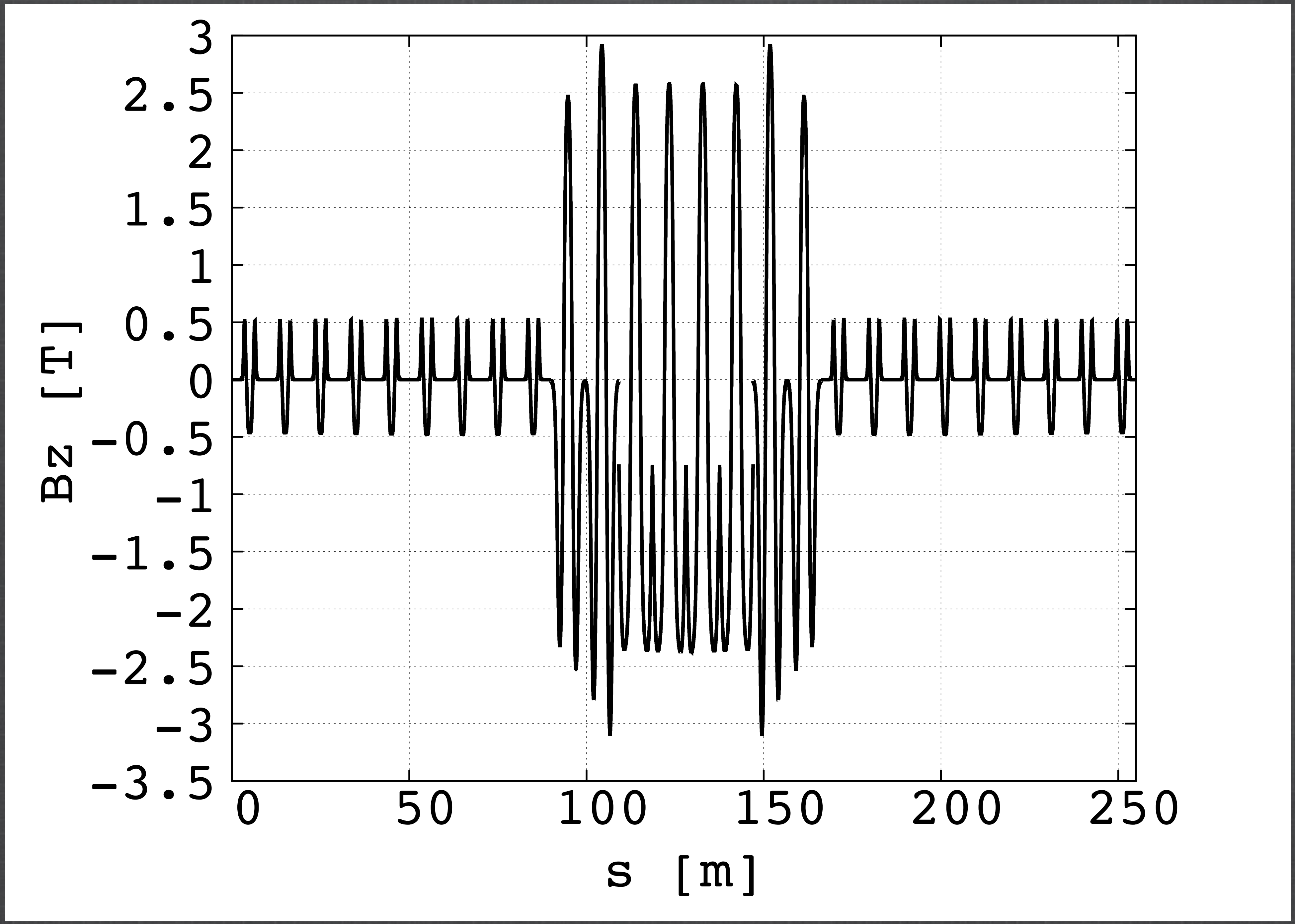
Triplet solution

Cell parameters

	Circular Section	Matching Section	Straight Section
Type	FDF	FDF	DFD
Cell radius/length [m]	17.6	36.2	10
Opening angle [deg]	30	15	
k-value/m-value	6.057	26.	5.5 m^{-1}
Packing factor	0.92	0.58	0.24
Maximum magnetic field [T]	2.5	3.3	1.5
horizontal excursion [m]	1.3	1.1	0.6
Full gap height [m]	0.45	0.45	0.45
Average dispersion /cell [m]	2.5	1.3	0.18
Number of cells /ring	4×2	4×2	36×2

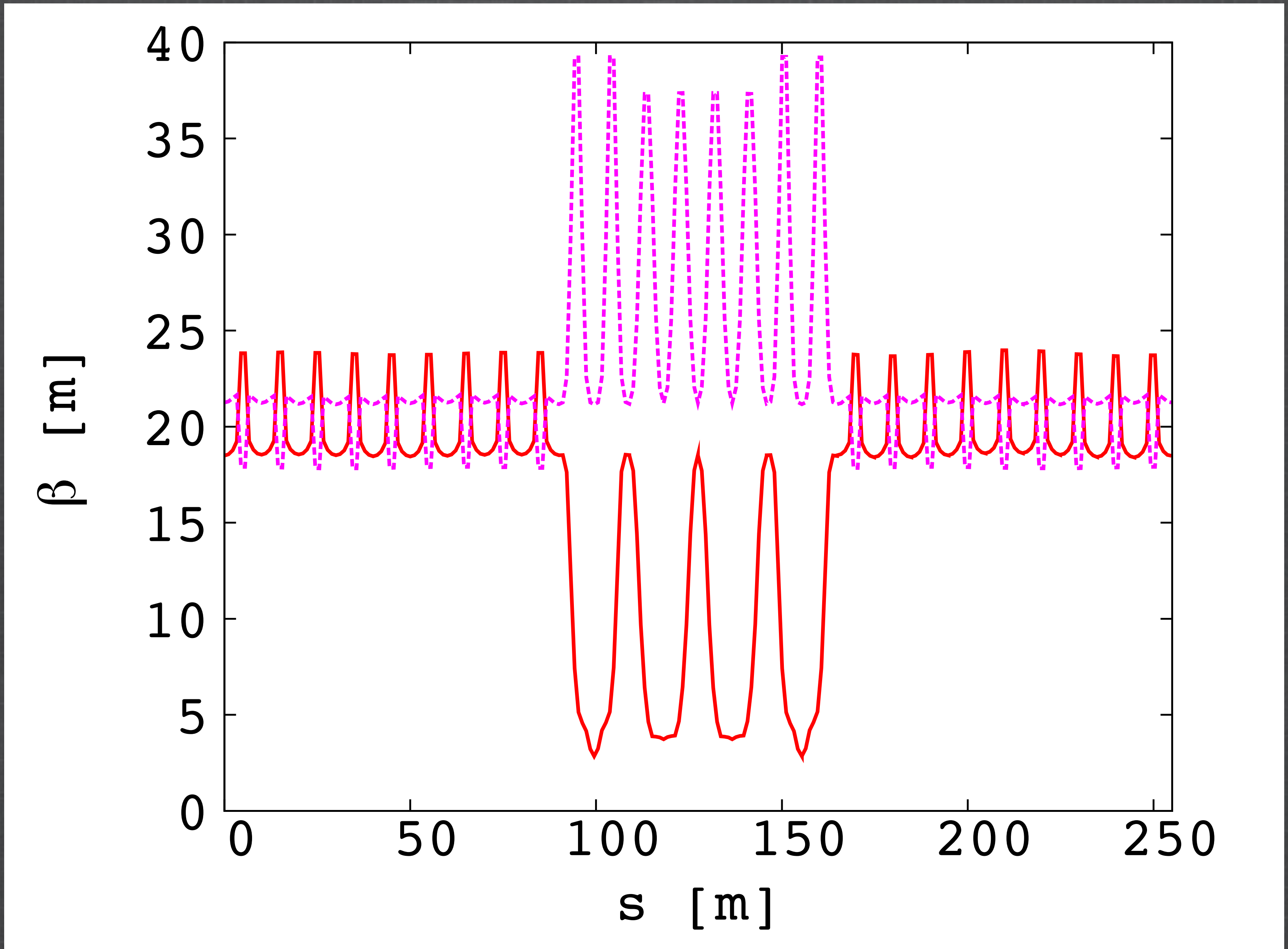
Triplet solution

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



Triplet solution

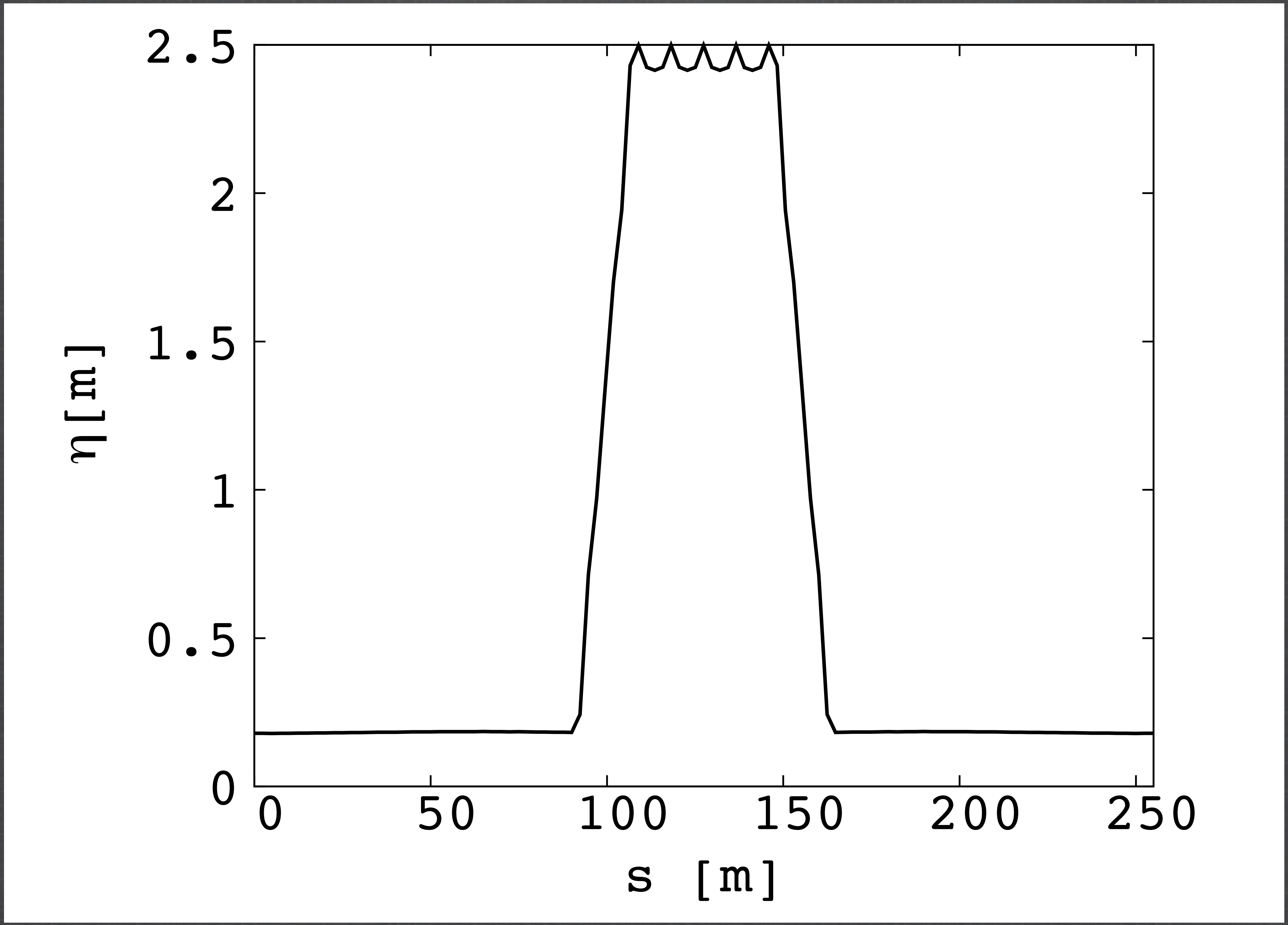
Beta-functions at matching momentum



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

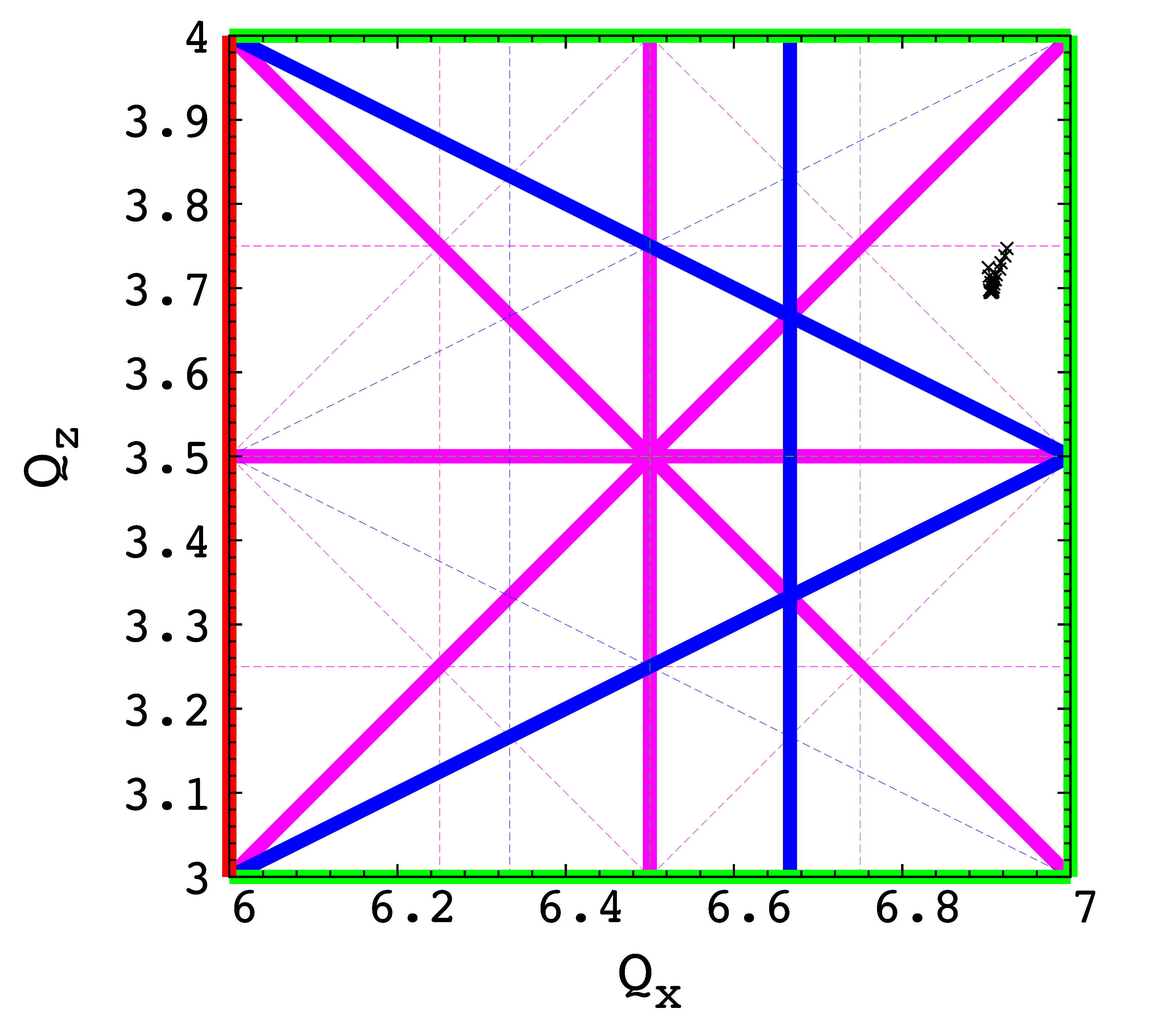
Triplet solution

Dispersion function at matching momentum



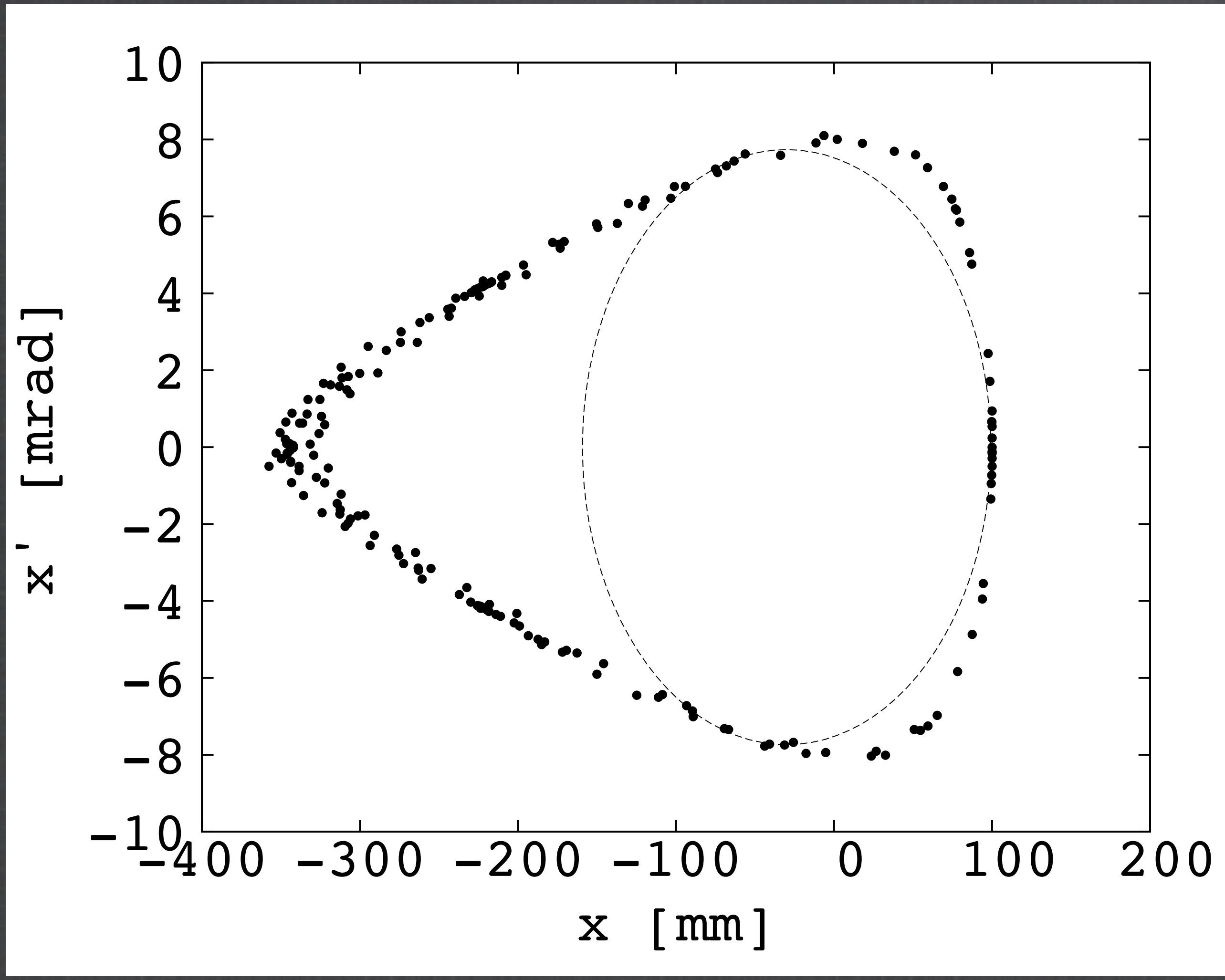
Triplet solution

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

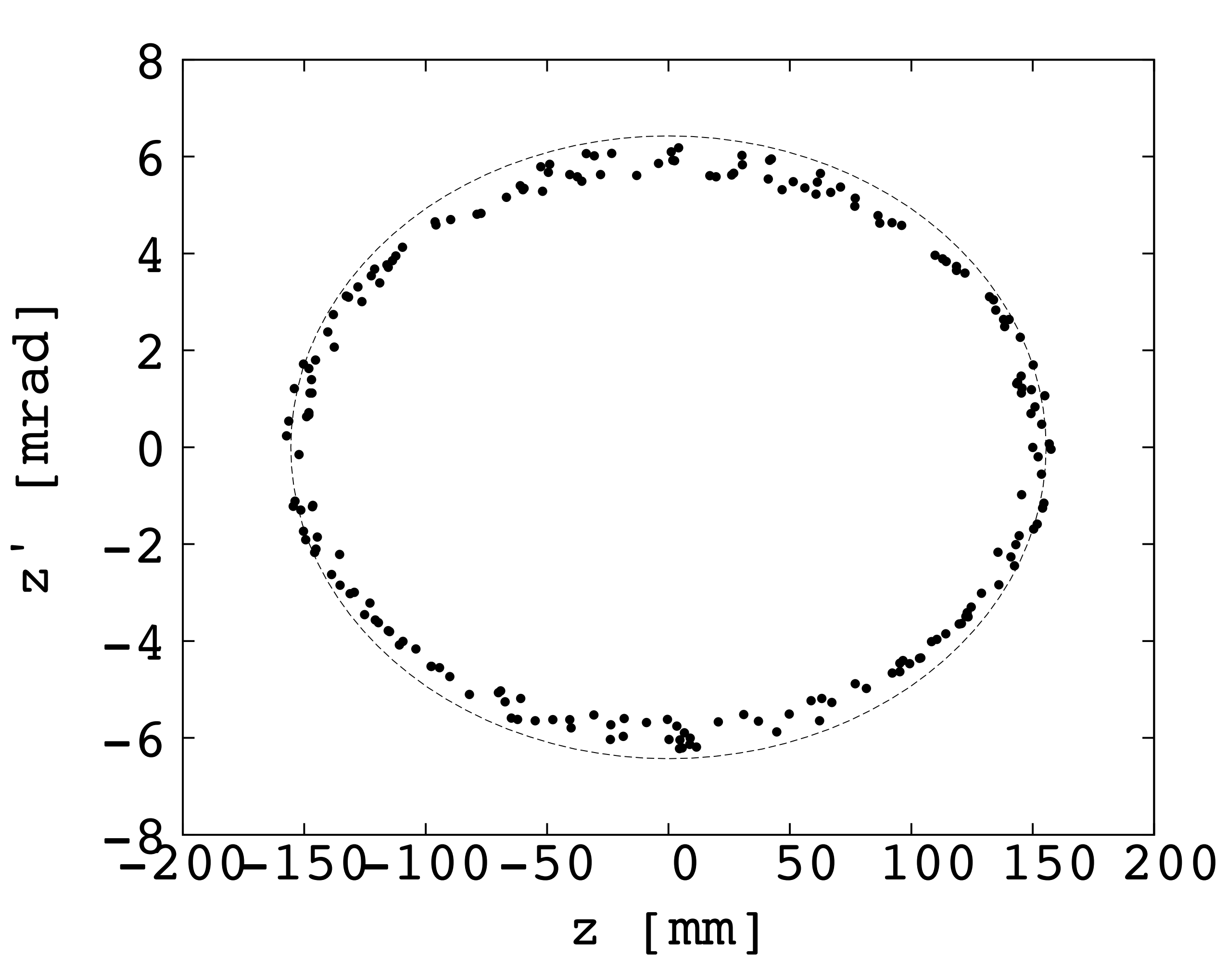


Triplet solution

Transverse acceptance



Maximum horizontal stable amplitude over 100 turns



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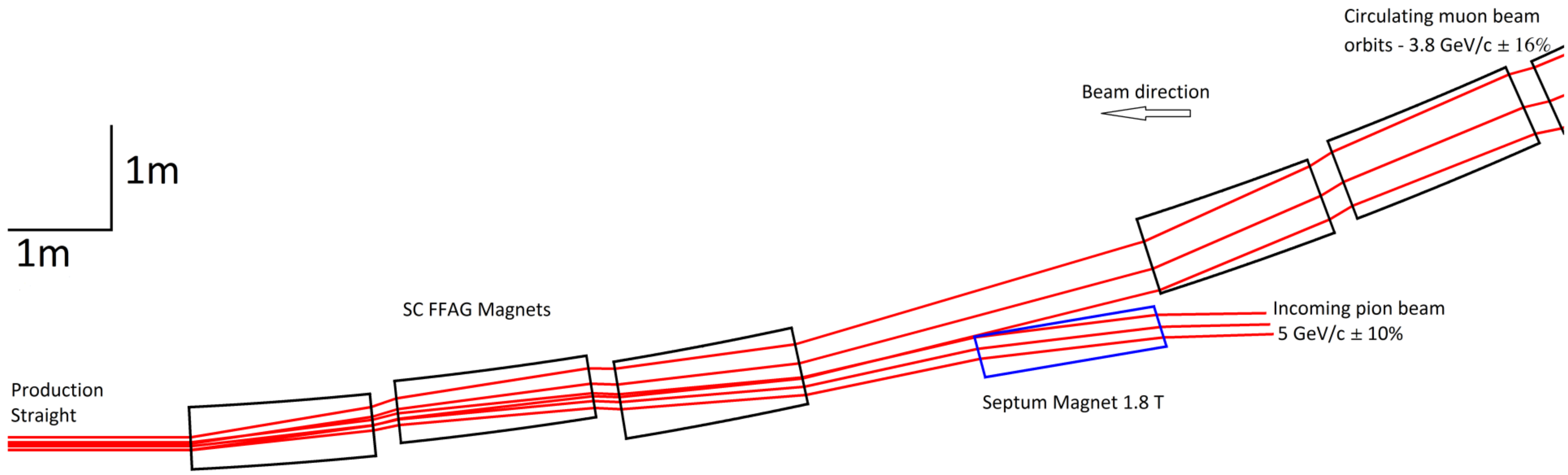
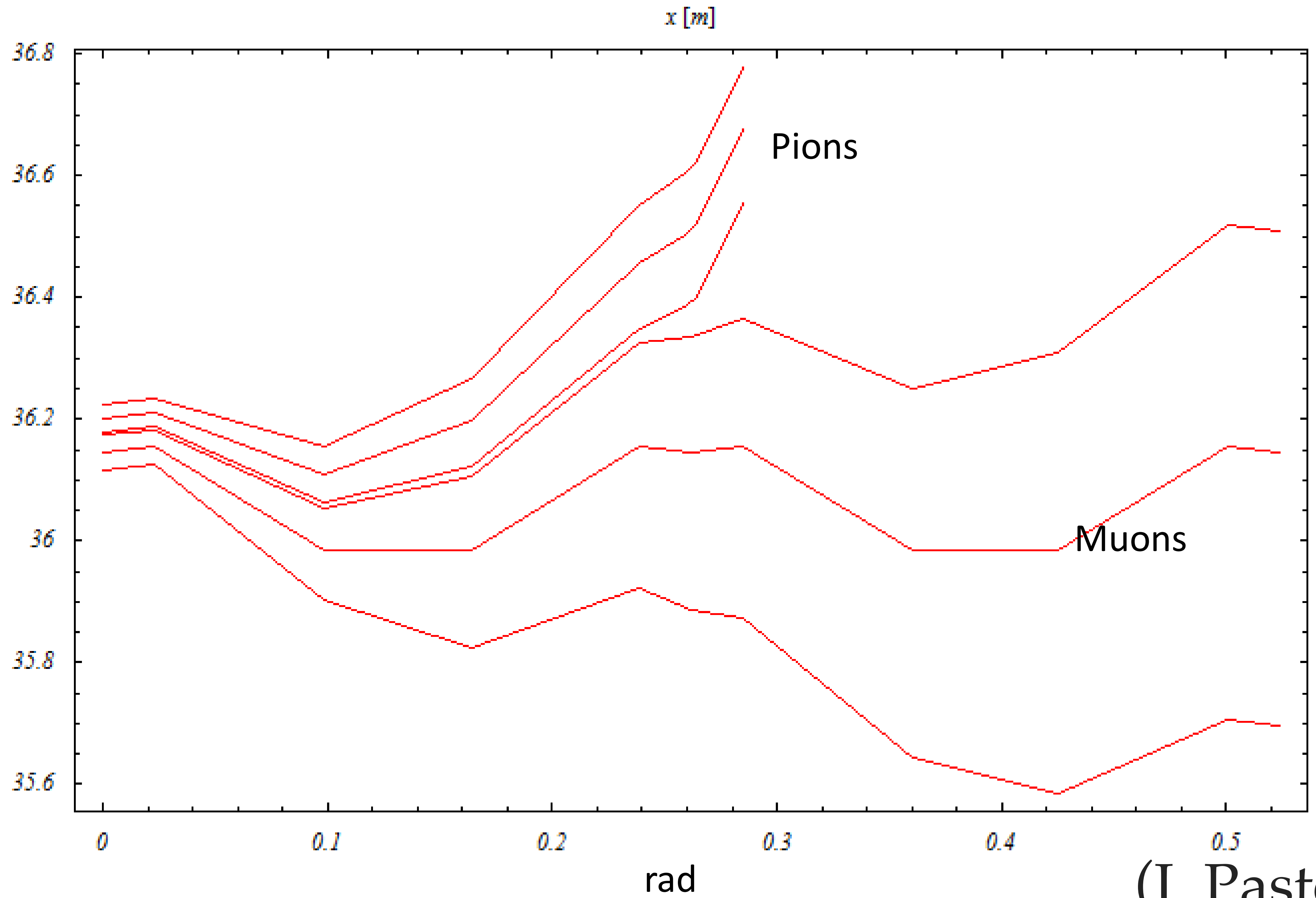
Injection



(J. Pasternak)

Injection



(J. Pasternak)

Injection

- Septum field 1.4 T (room temperature)
- Septum thickness/length ~2cm/~72cm
- It requires SC dipole/septum of 4 T and 6 cm thickness to be placed upstream (72 cm in length)
- It gives 20 cm beam clearance at the upstream FFAG magnet.
- Alternatively we could use ~2cm/164 cm SC septum with 1.8T (results are pretty the same)

(J. Pasternak)

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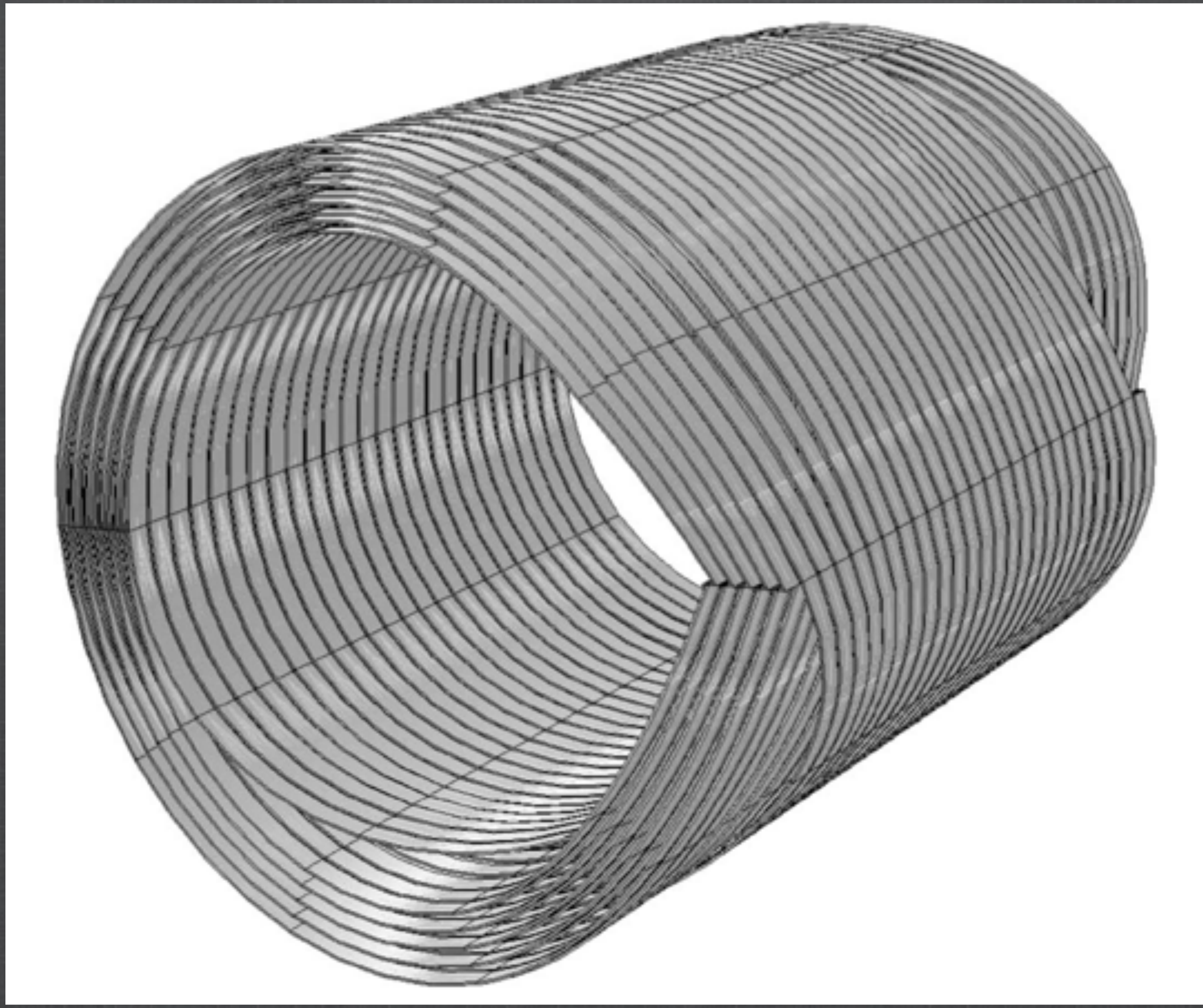
Superconducting magnets

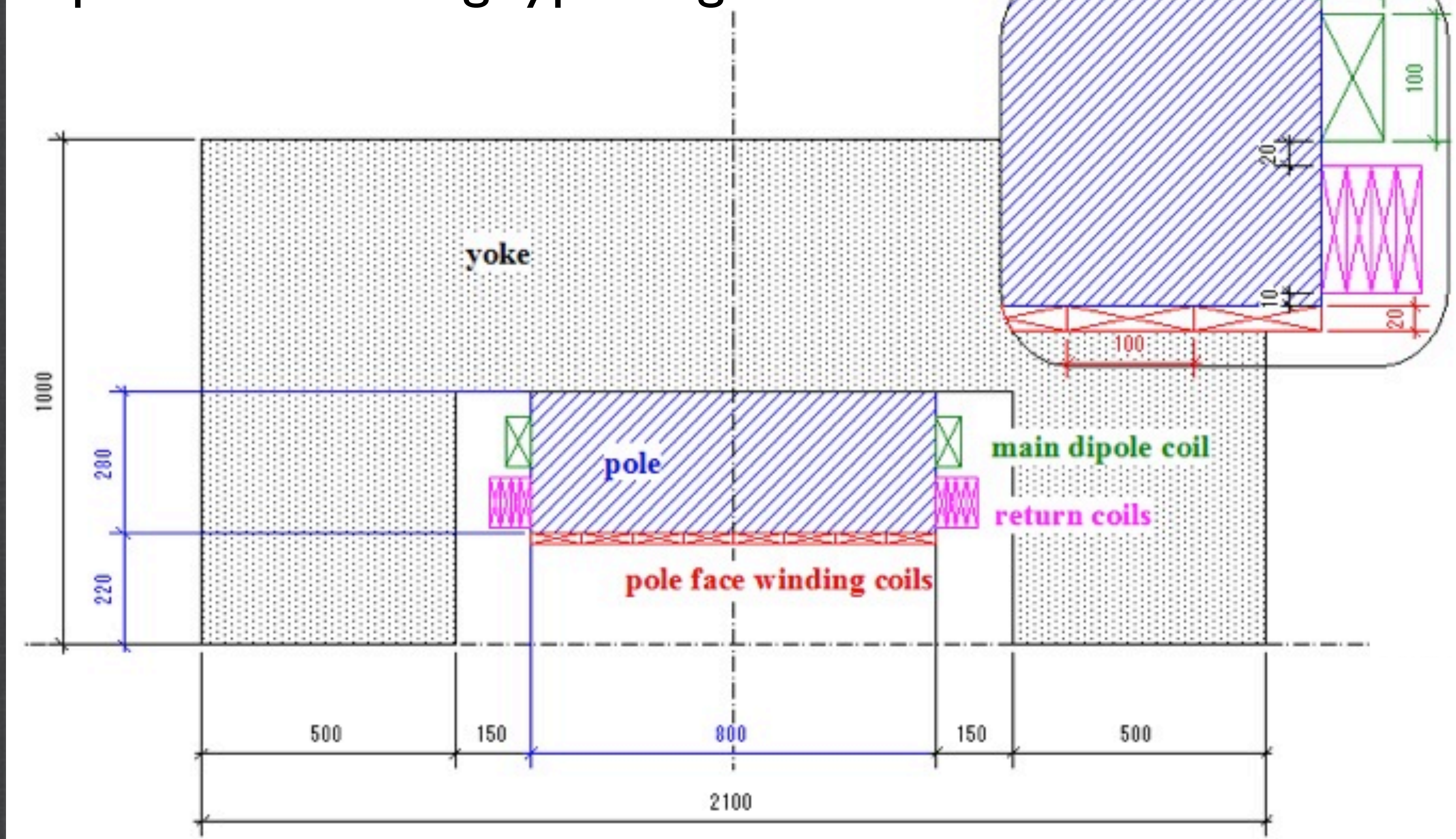


PAMELA “F“ magnet

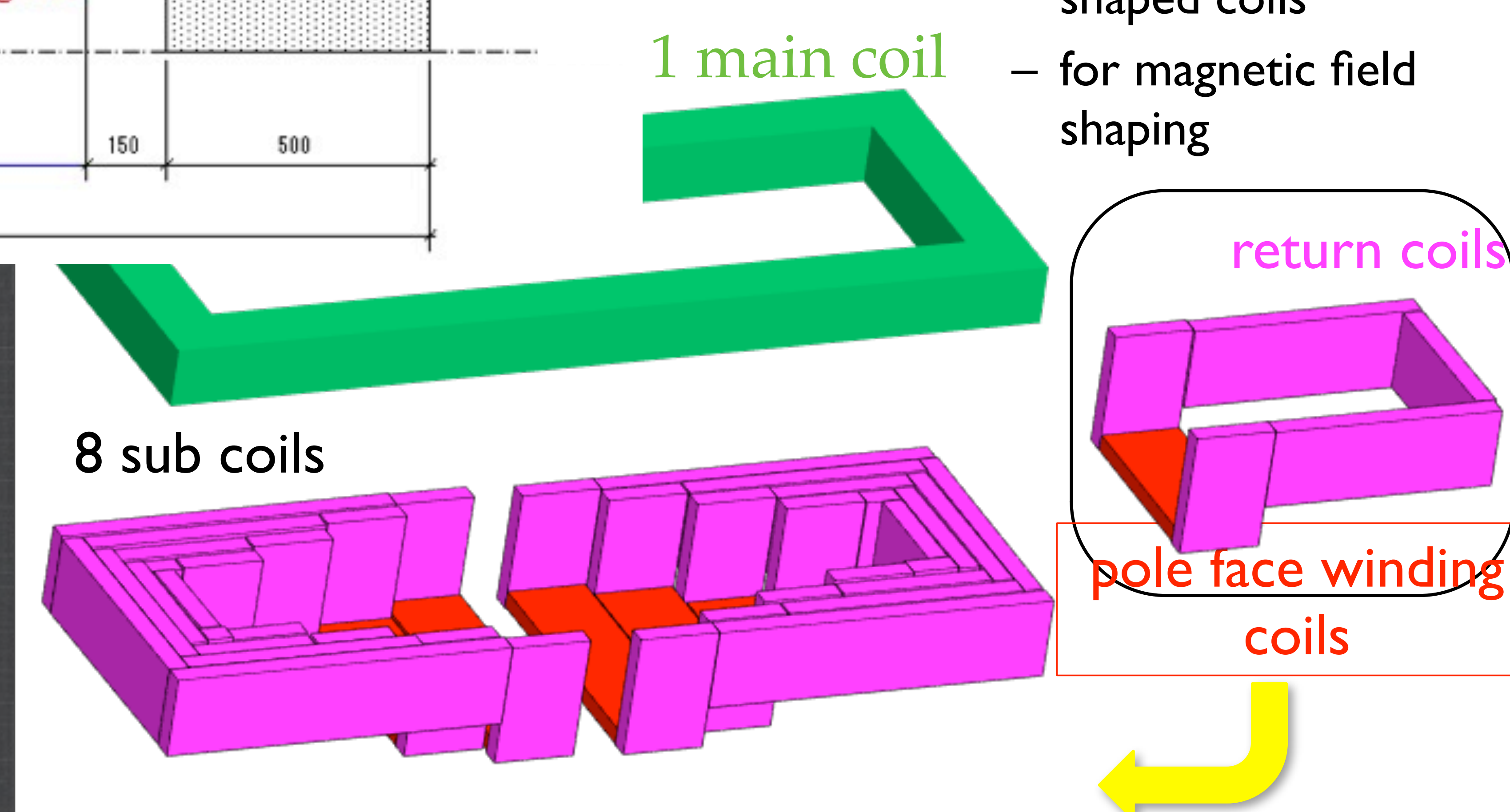
The Advantages and Challenges of Helical Coils for Small Accelerators—A Case Study, H. Witte *et al*. *IEEE, 22 (2), 2012*.

Straight FFAG magnet

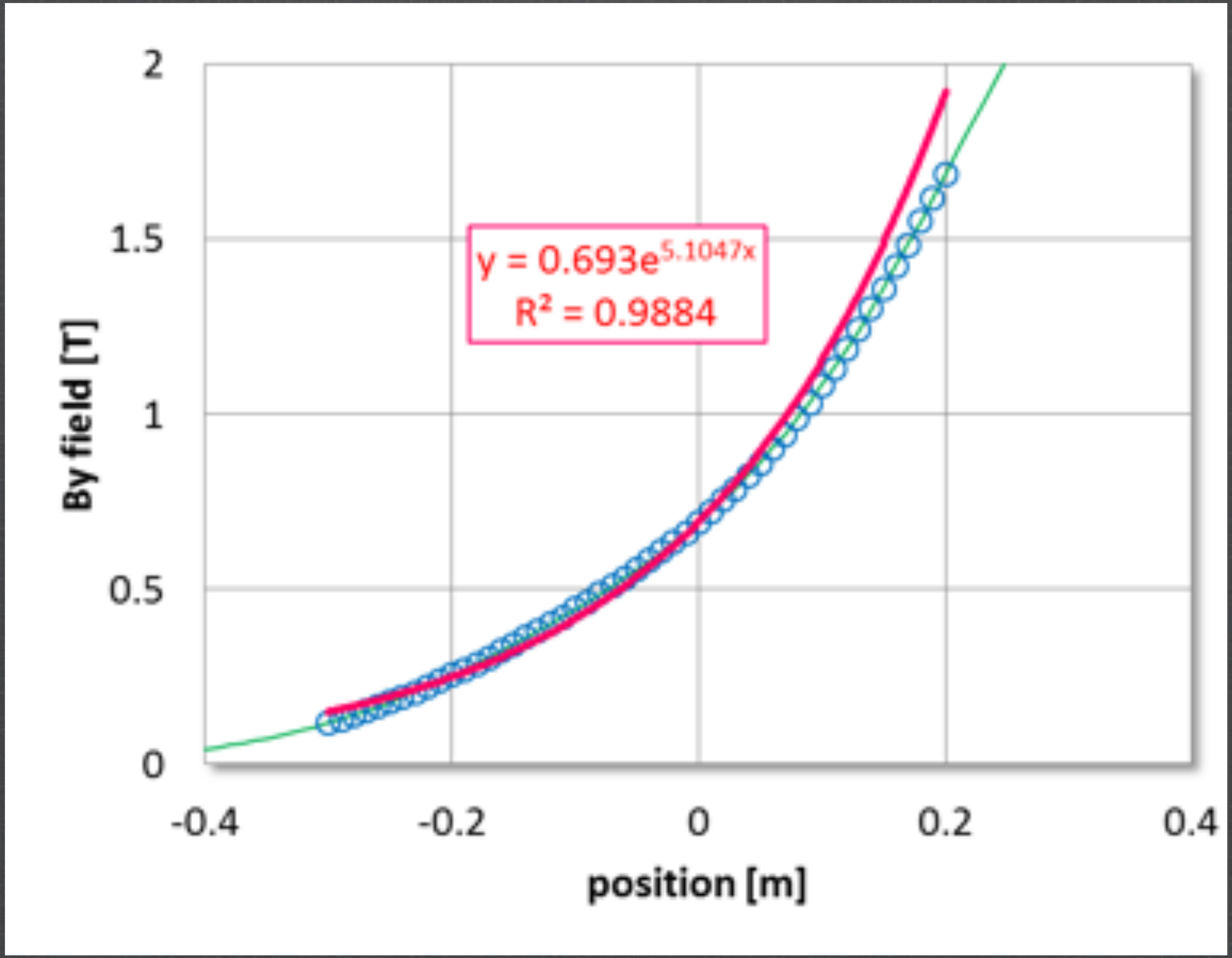
- pole face winding type magnet:



- 8 sub coils:
  - modified saddle-shaped coils
  - for magnetic field shaping



Straight FFAG magnet



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Future improvements

- Small scallop angle in the straight: reduce the portion of the straight cell with scallop in the triplet solution.
- Larger DA: smaller gradient (m-value) in the straight section.
- Smaller magnets in the arcs: reduce the maximum dispersion in the arcs (> 1.3 m necessary for injection).
- Neutrino flux estimation from pion & muon decay for doublet and triplet FFAG lattice, and comparison with FODO lattice.

Thank you for your attention