FFAG Muon decay ring for νSTORM

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Outline

- Overview
- FFAG decay ring
- FFAG Magnets
- Summary & future plans

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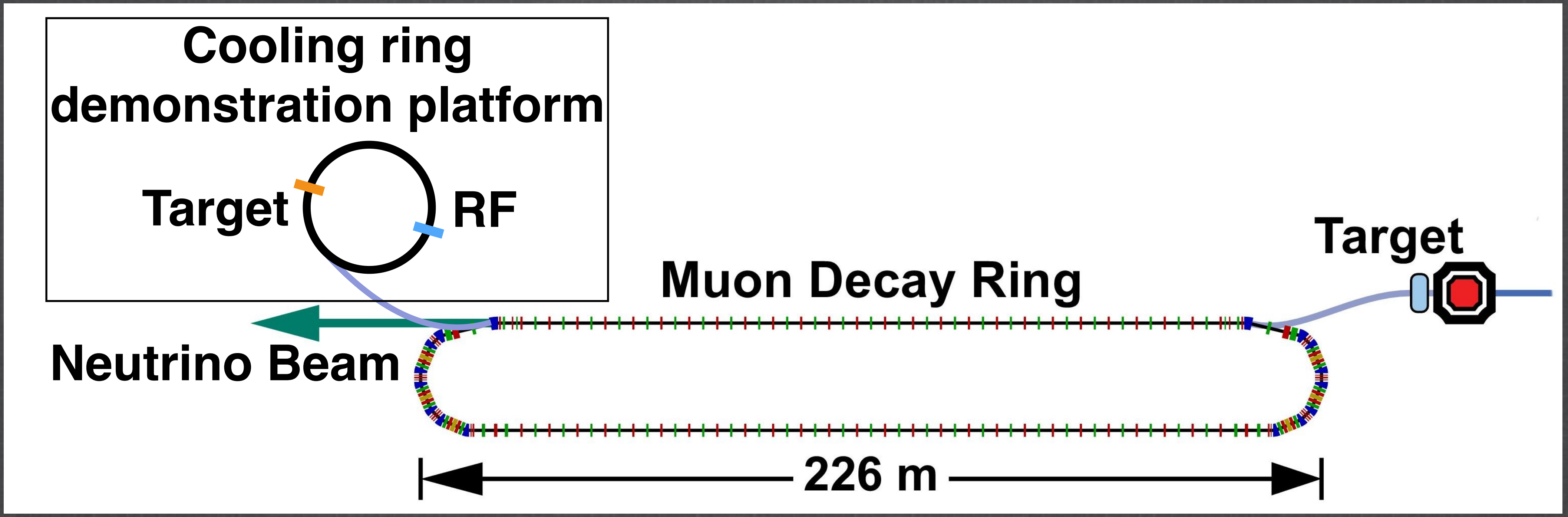
nuSTORM Overview



1. Facility to provide a muon beam for precision neutrino interaction physics
2. Study of sterile neutrinos
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

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

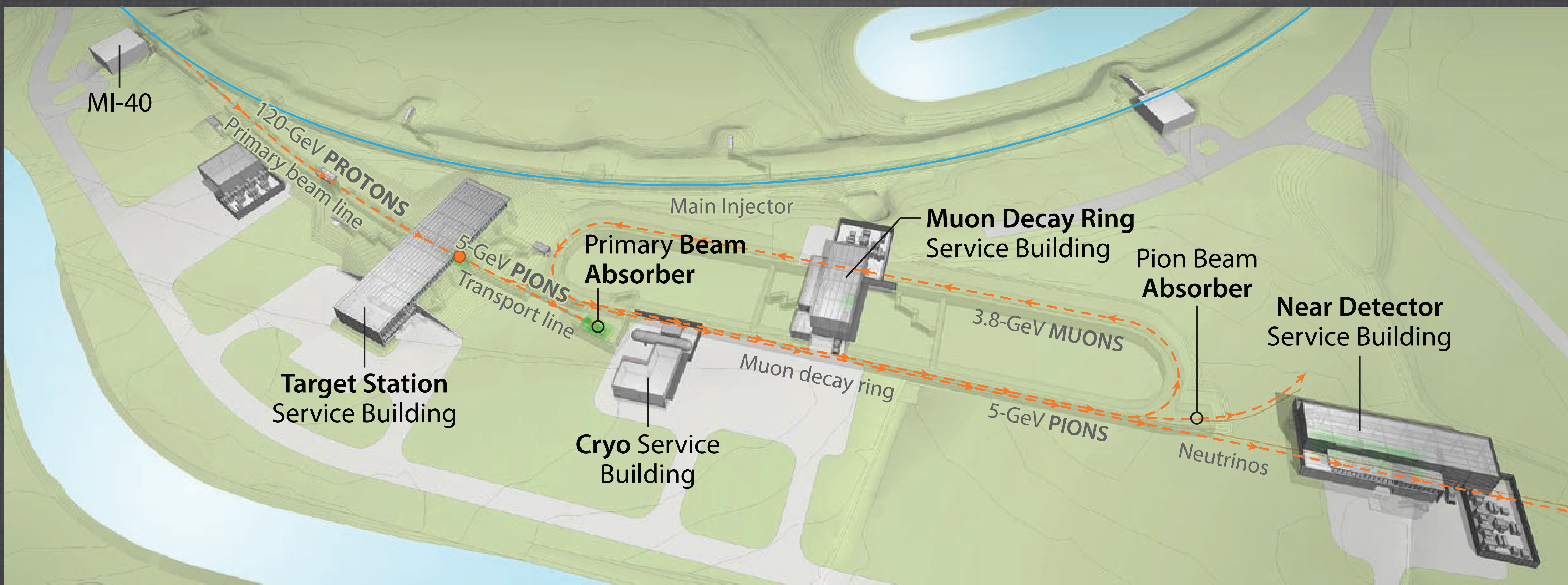
Facility

- 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: 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.

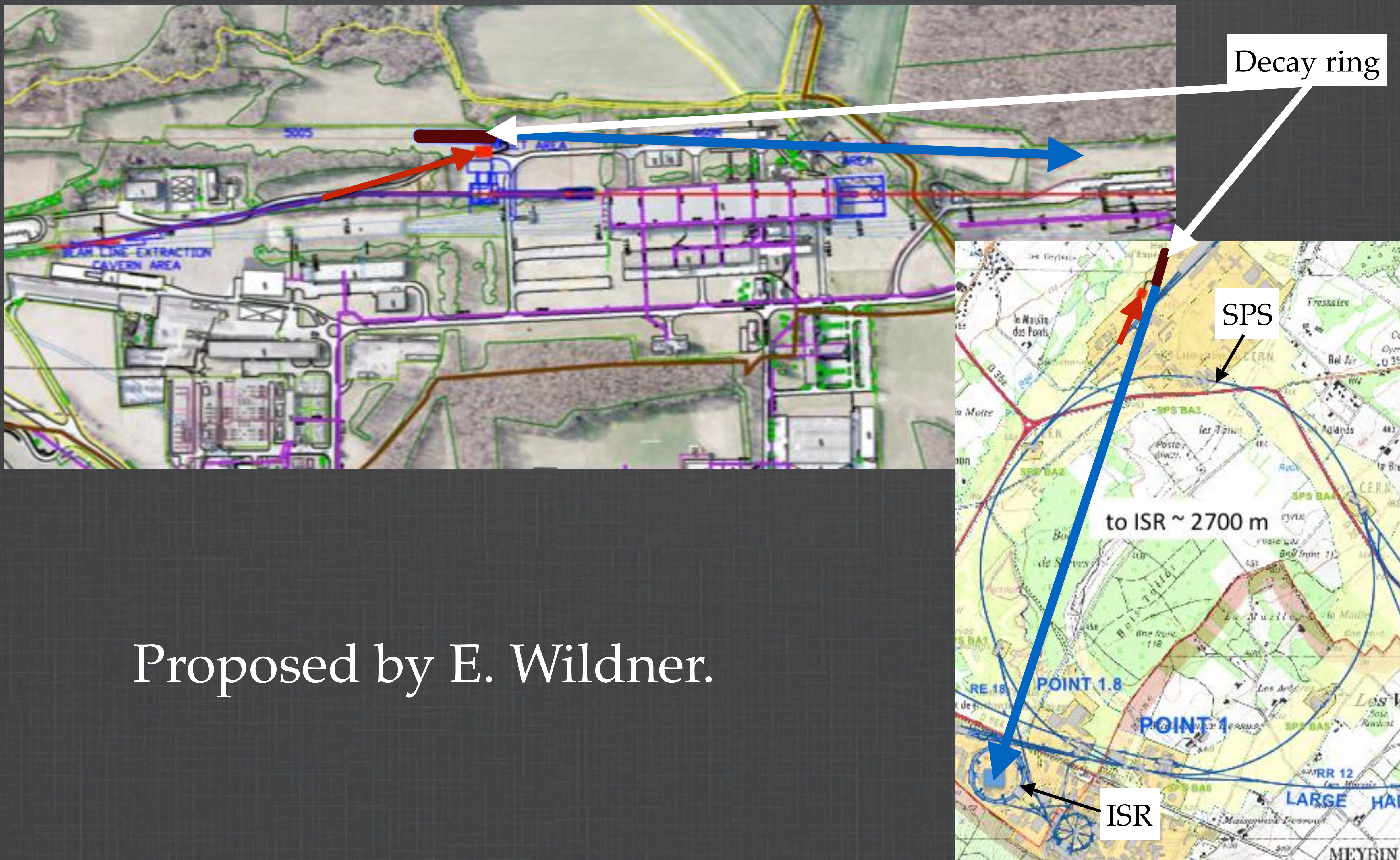
Implementation at FNAL

Implementation at FNAL (2)

Near site view

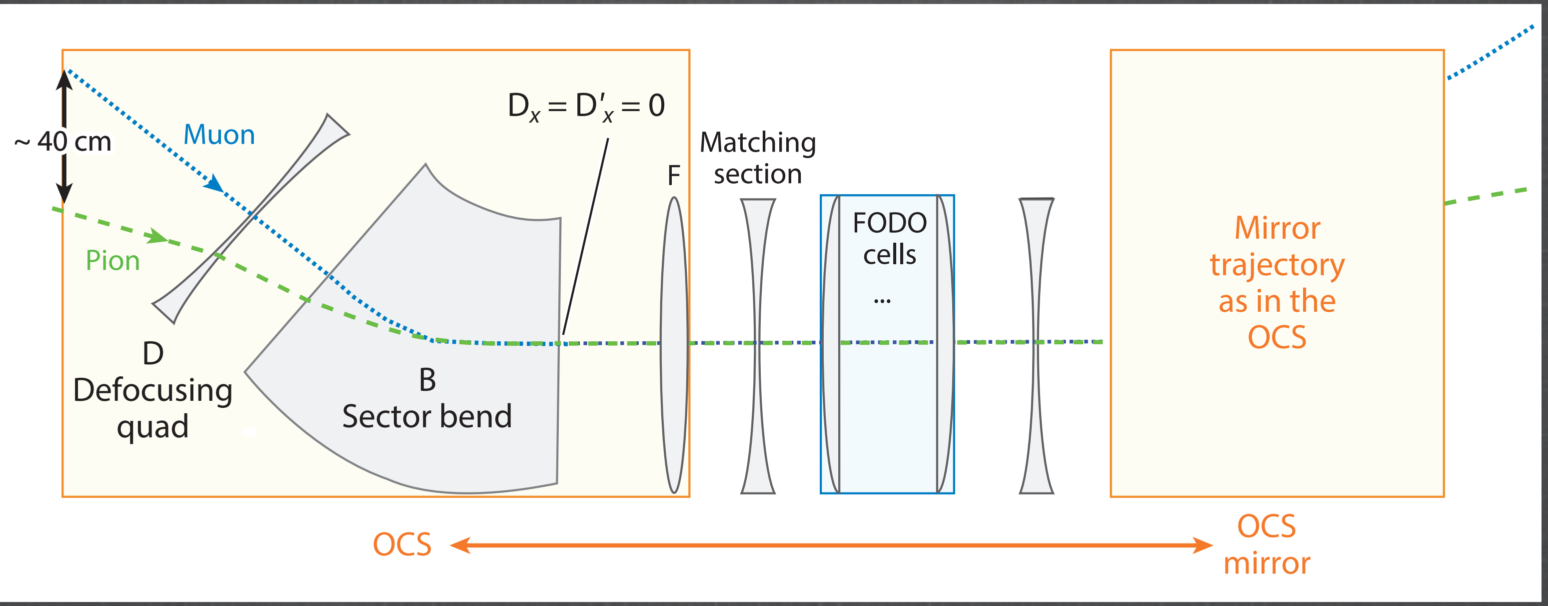


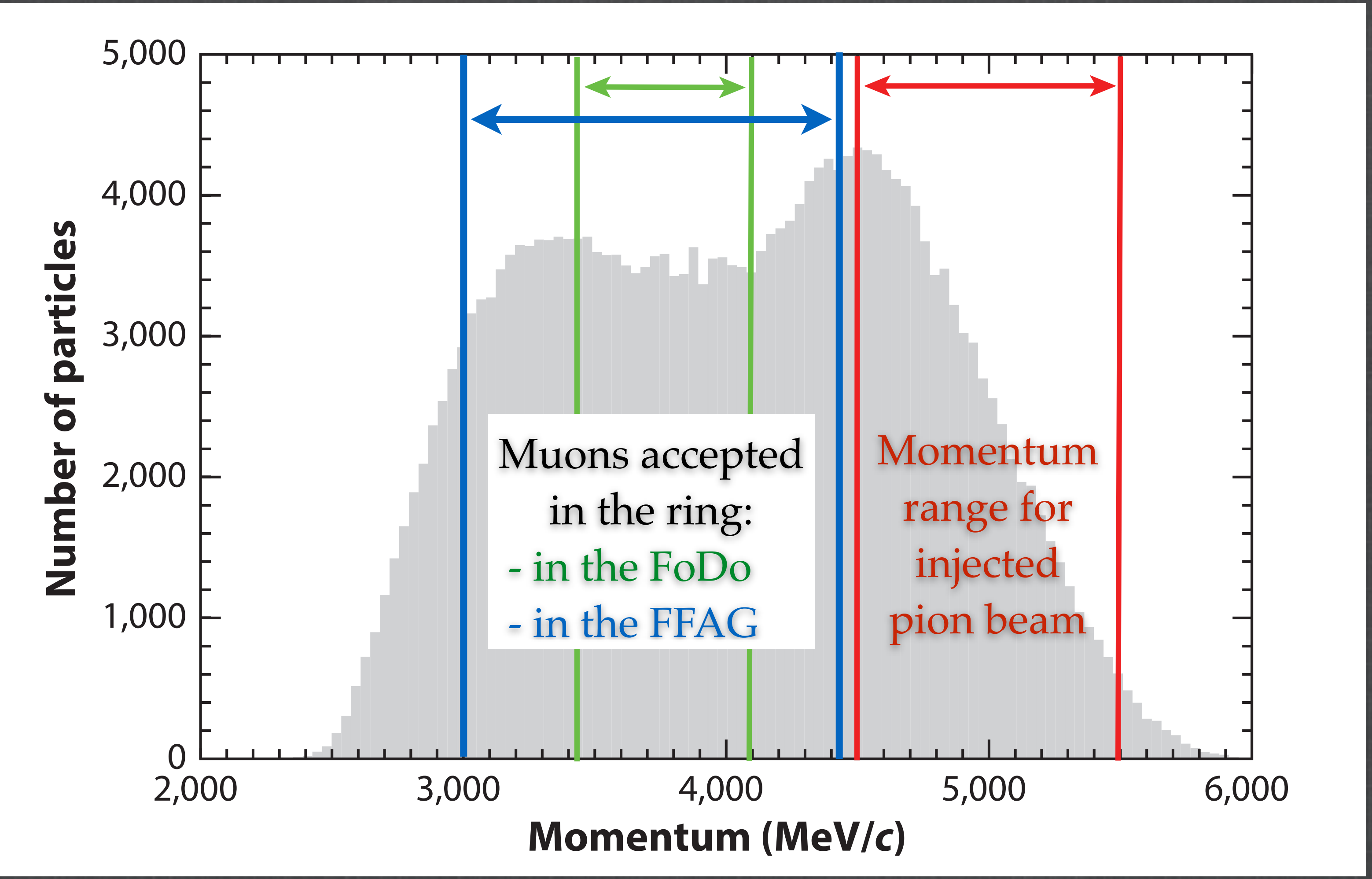
Implementation at CERN



Proposed by E. Wildner.

Stochastic injection

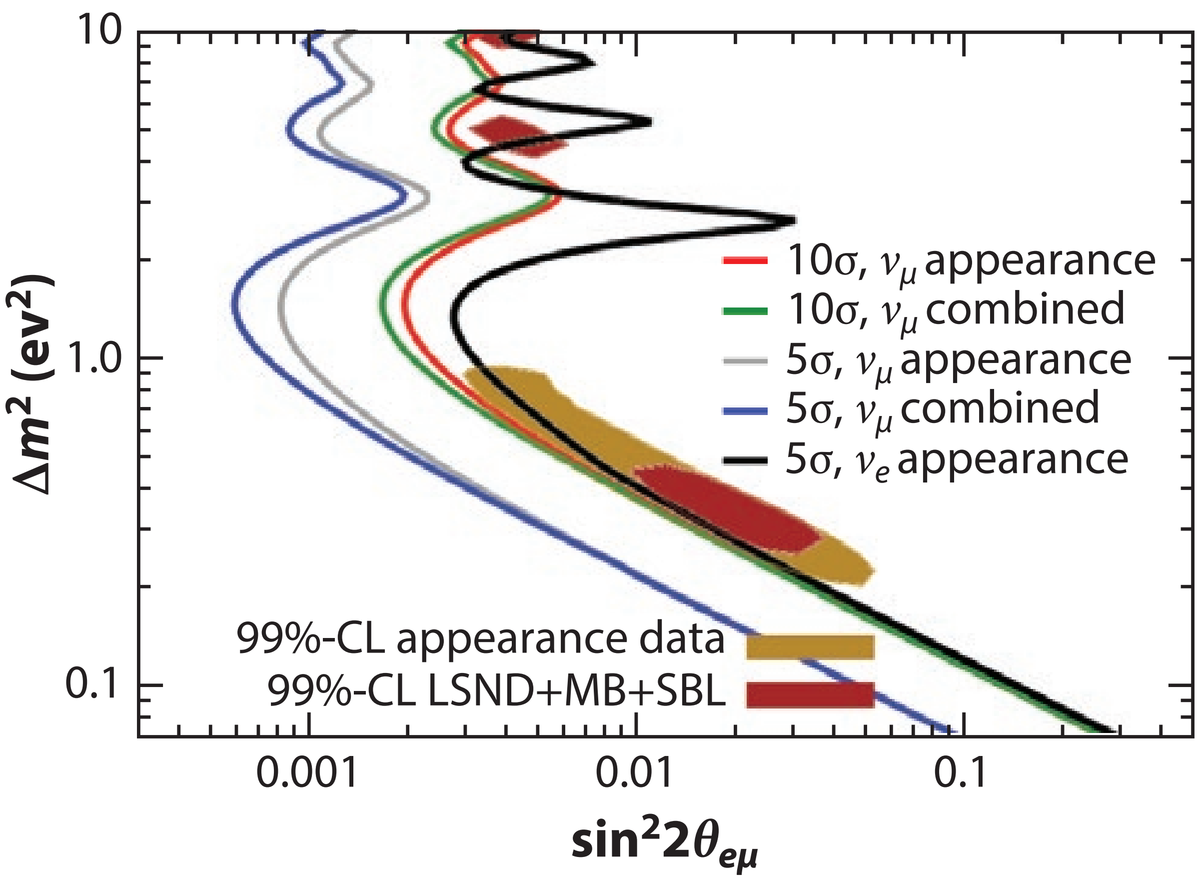




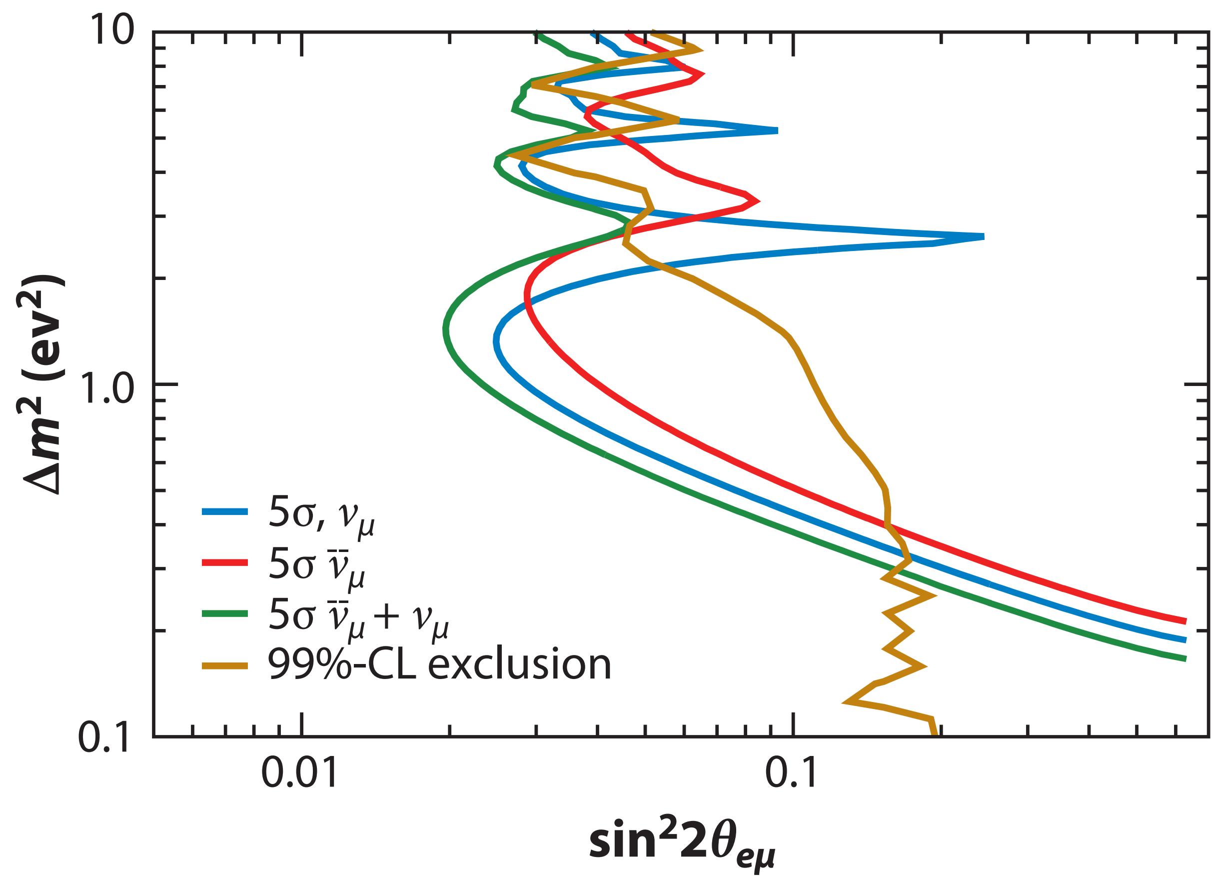
Sterile neutrinos studies

- Assume sample of 3.1×10^{18} useful μ^+ decays
- 1.3 kTon iron-scintillator calorimeter detector.
- Assume a 0.5% rate and 0.5% cross-sectional systematic.
- In absence of interaction studies 0.5%→5%

$\nu_e \rightarrow \nu_\mu$ Appearance Search



$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ Disappearance Search



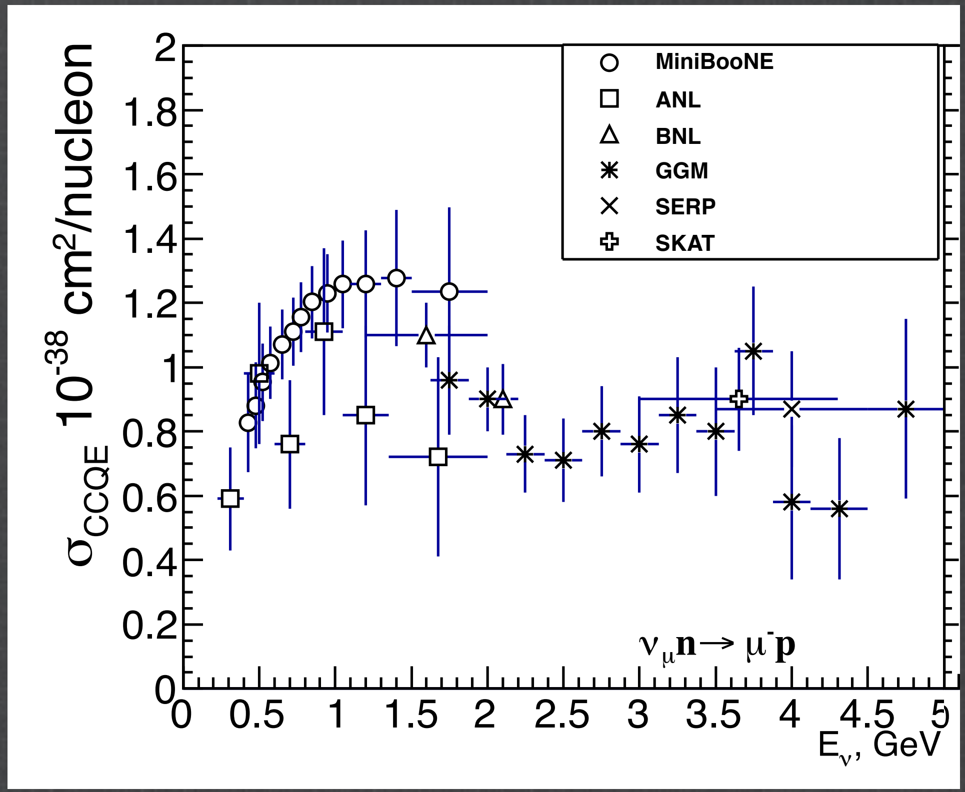
Interaction studies

- Interaction rates must be understood by type. (Dictate significance of systematics in oscillations)
- Many interaction types only accessible with nuSTORM.
- Very little data in ν_e interactions.
  - Gargamelle data from 70s,
  - New results coming T2K and Minerva

Interaction channels

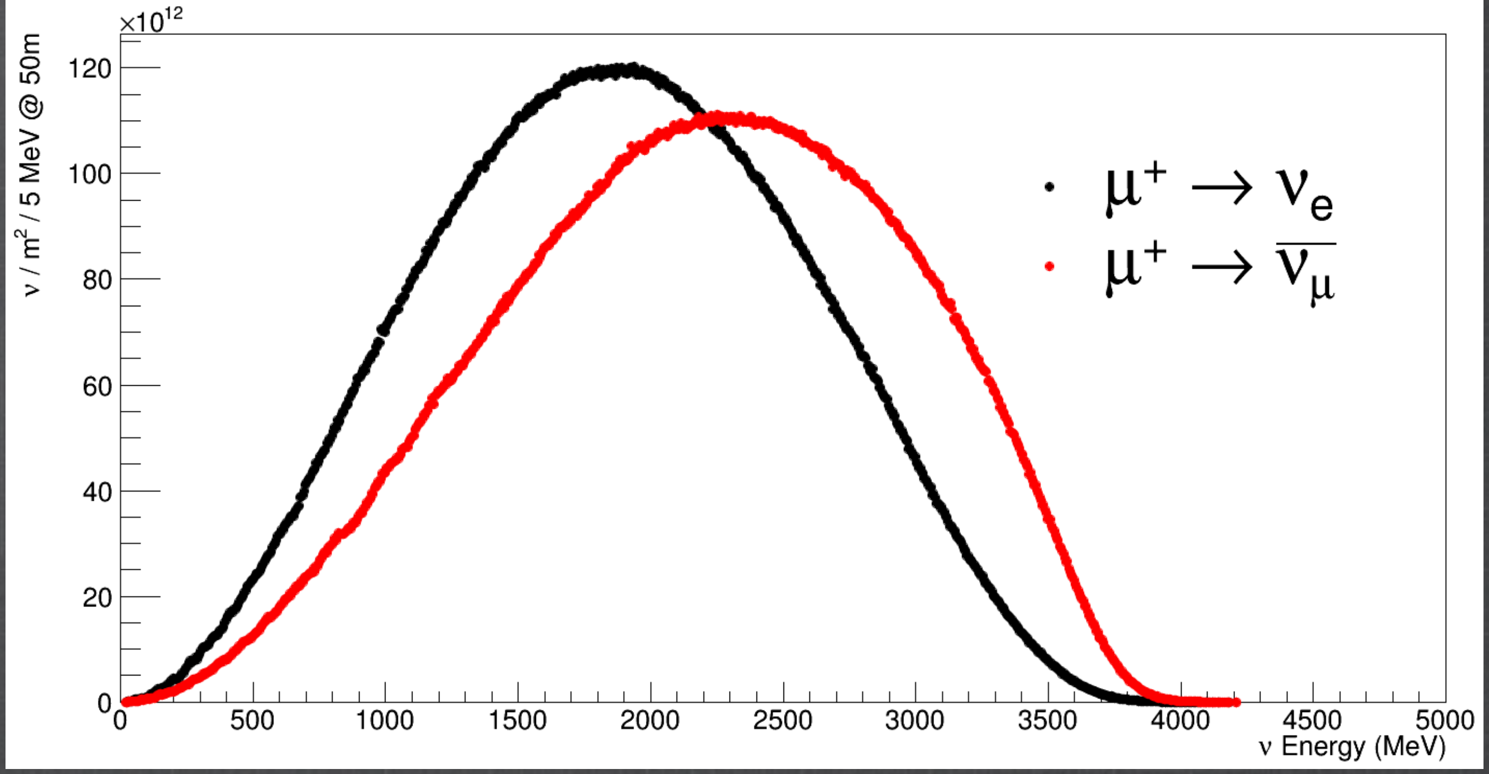
data exist

ID	Stored μ^+	Stored μ^-
1	$\bar{\nu}_\mu p \to \mu^+ n$	$\nu_\mu n \to \mu^- p$
2	$\nu_e n \to e^- p$	$\bar{\nu}_e p \to e^+ n$
3	$\bar{\nu}_\mu n \to \mu^+ \pi^- n$	$\nu_\mu n \to \mu^- \pi^+ n$
4	$\bar{\nu}_\mu p \to \mu^+ \pi^0 p$	$\nu_\mu n \to \mu^- \pi^0 p$
5	$\bar{\nu}_\mu p \to \mu^+ \pi^- p$	$\nu_\mu p \to \mu^- \pi^+ p$
6	$\nu_e n \to e^- \pi^+ n$	$\bar{\nu}_e n \to e^+ \pi^- n$
7	$\nu_e p \to e^- \pi^0 p$	$\bar{\nu}_e p \to e^+ \pi^0 n$
8	$\nu_e p \to e^- \pi^+ p$	$\bar{\nu}_e p \to e^+ \pi^- p$
9	$\bar{\nu}_\mu, \nu_e \to X$	$\nu_\mu, \bar{\nu}_e \to X$

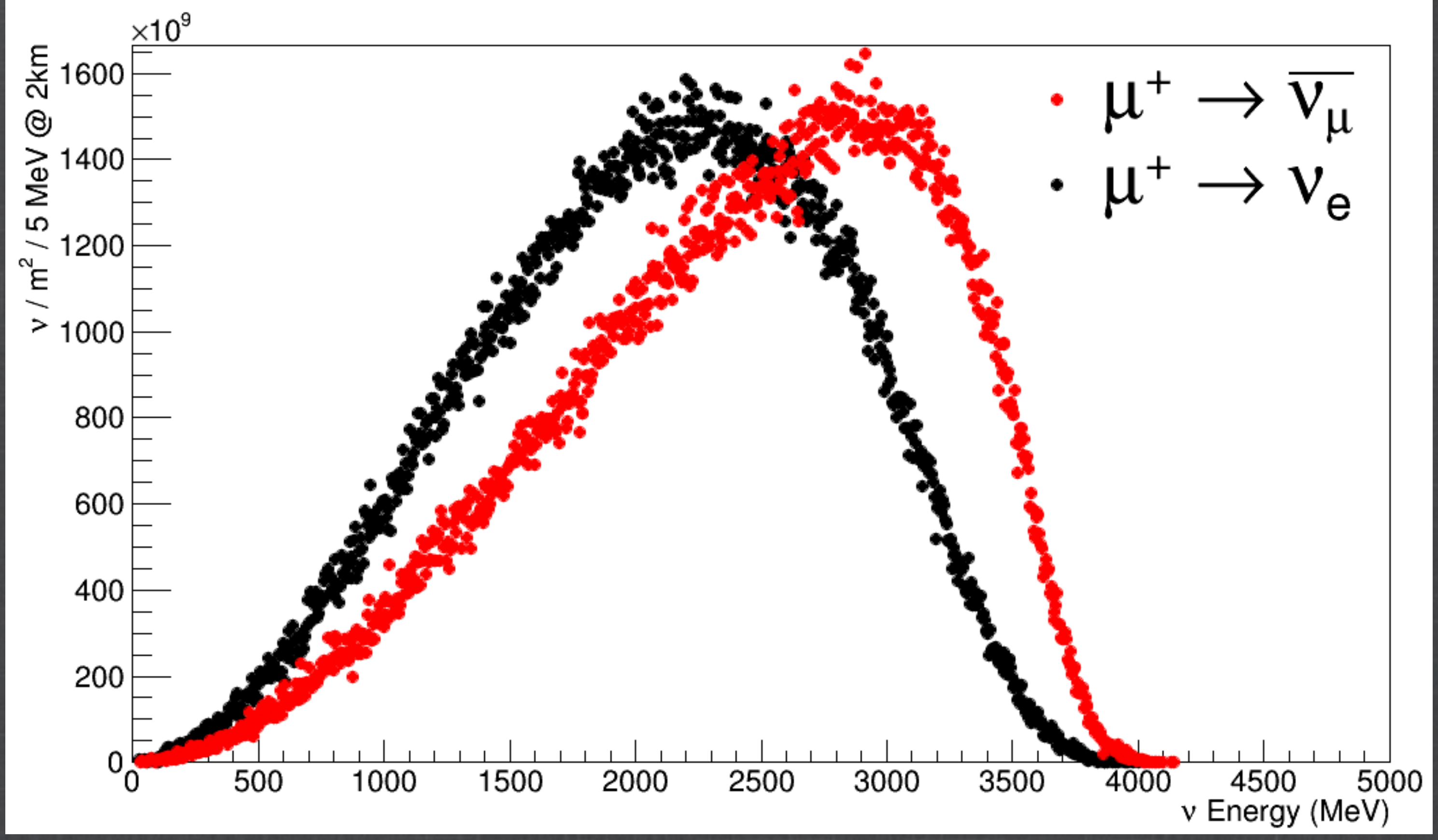


Flux from muon decays (FoDo)

Near detector:
50 m from the end of the decay straight with a 3 m radius.



Far detector:
2 km from the end of the decay straight with a 3 m radius.
Full muon simulation and decays.



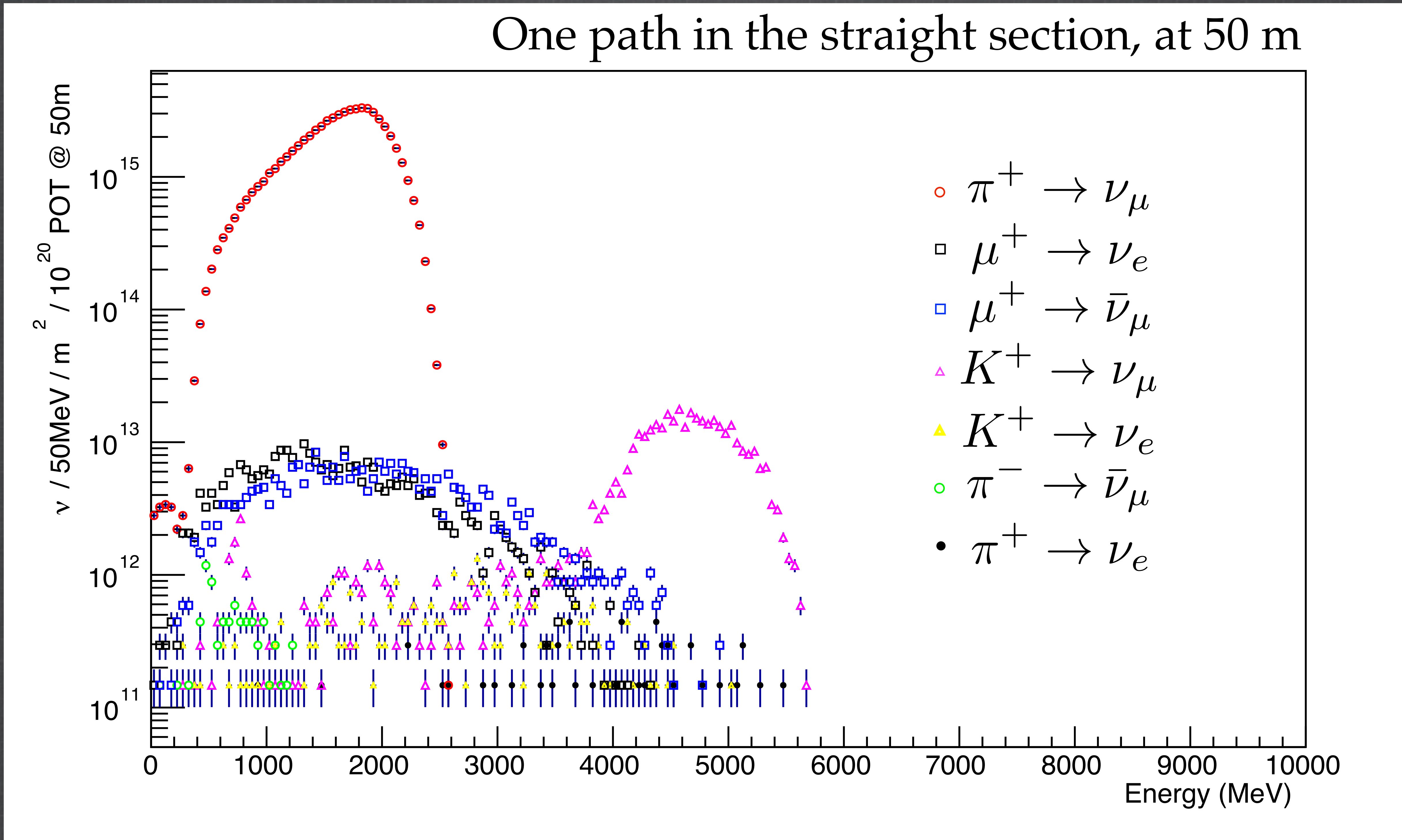
Hybrid facility

Stochastic injection gives access to a pion beam decaying in the straight section as well as muon beam decay.

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

$$\mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu}_\mu \qquad \pi^+ \longrightarrow \mu^+ + \nu_\mu$$

Near detector flux from pion/kaon decay (FoDo)



Cross-section measurement

Flux uncertainties a significant contribution to cross-sections

Experiment	Flux Error
MiniBooNE	6.7—10.5%
T2K	10.9%
Minerva	12%
nuSTORM	$<$1%

Event Rate per 10^{21} POT, 100 tonnes at 50 m

μ^+		μ^-	
Channel	N_{evts}	Channel	N_{evts}
$\bar{\nu}_\mu$ NC	1,174,710	$\bar{\nu}_e$ NC	1,002,240
ν_e NC	1,817,810	ν_μ NC	2,074,930
$\bar{\nu}_\mu$ CC	3,030,510	$\bar{\nu}_e$ CC	2,519,840
ν_e CC	5,188,050	ν_μ CC	6,060,580
π^+		π^-	
ν_μ NC	14,384,192	$\bar{\nu}_\mu$ NC	6,986,343
ν_μ CC	41,053,300	$\bar{\nu}_\mu$ CC	19,939,704

nuSTORM measurements limited by detector systematics.

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FFAG accelerator

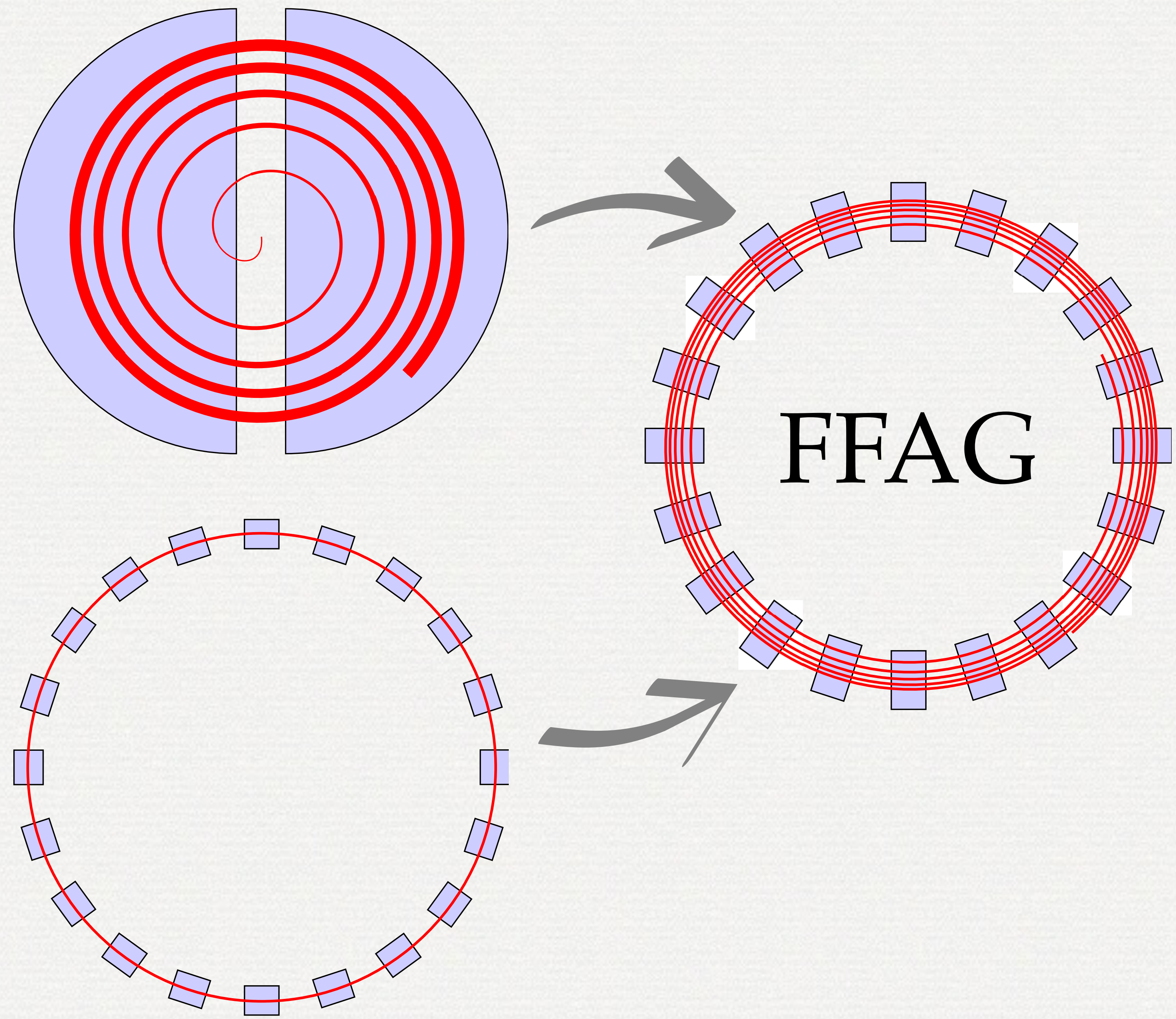
FIXED FIELD ALTERNATING GRADIENT

It combines

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

AND

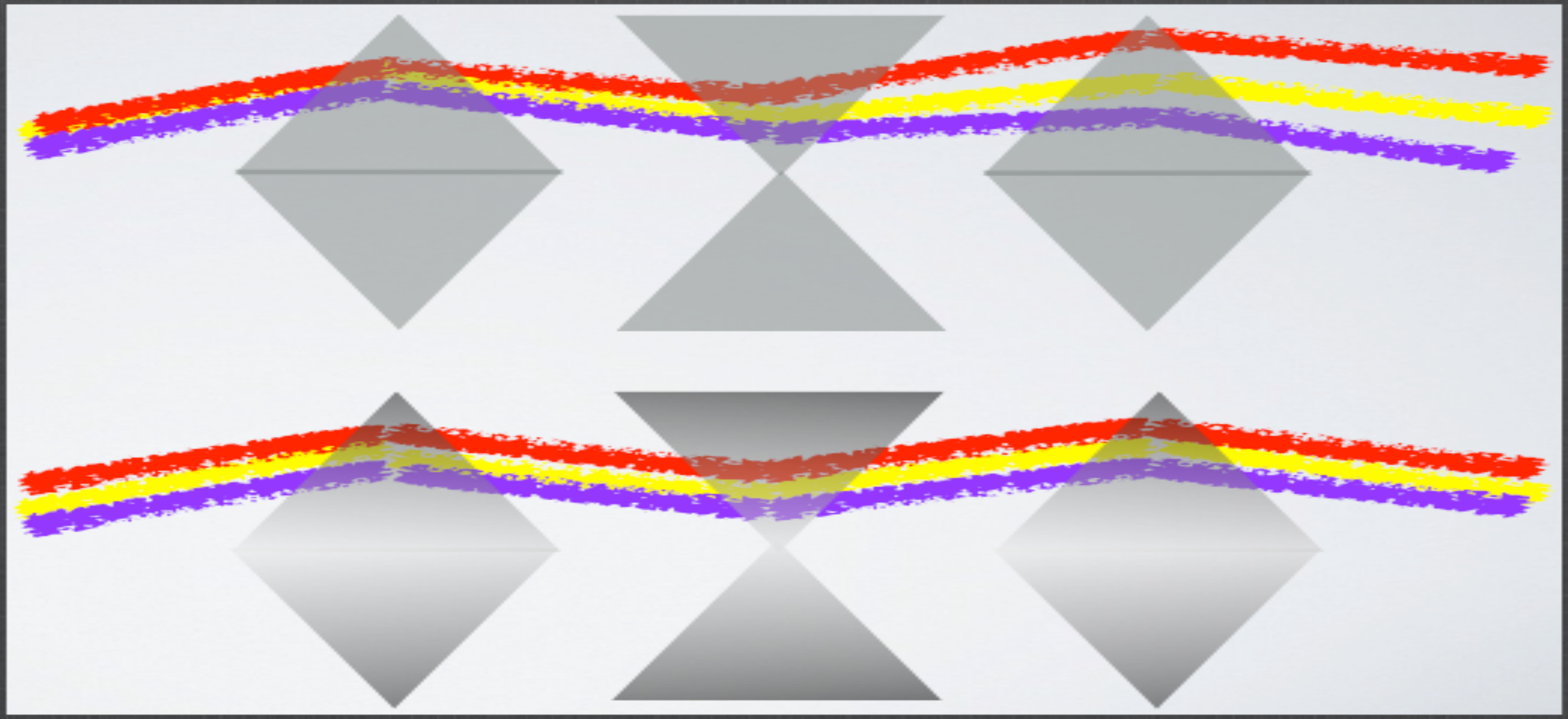
- **a strong focusing.** like synchrotrons:



Zero-chromatic FFAG

Advantages:

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

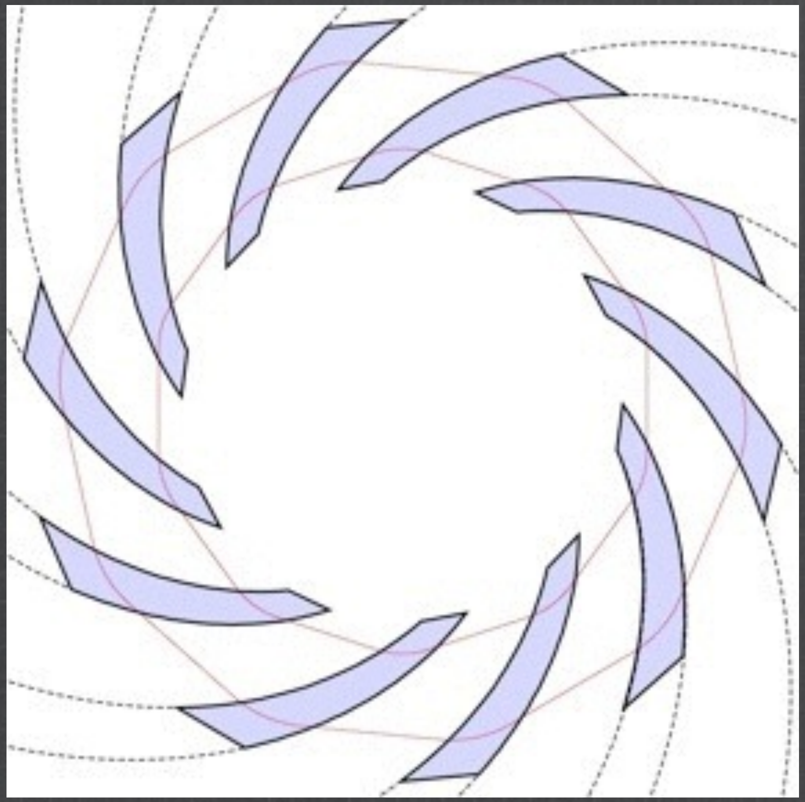


→ Quasi-zero beam loss!

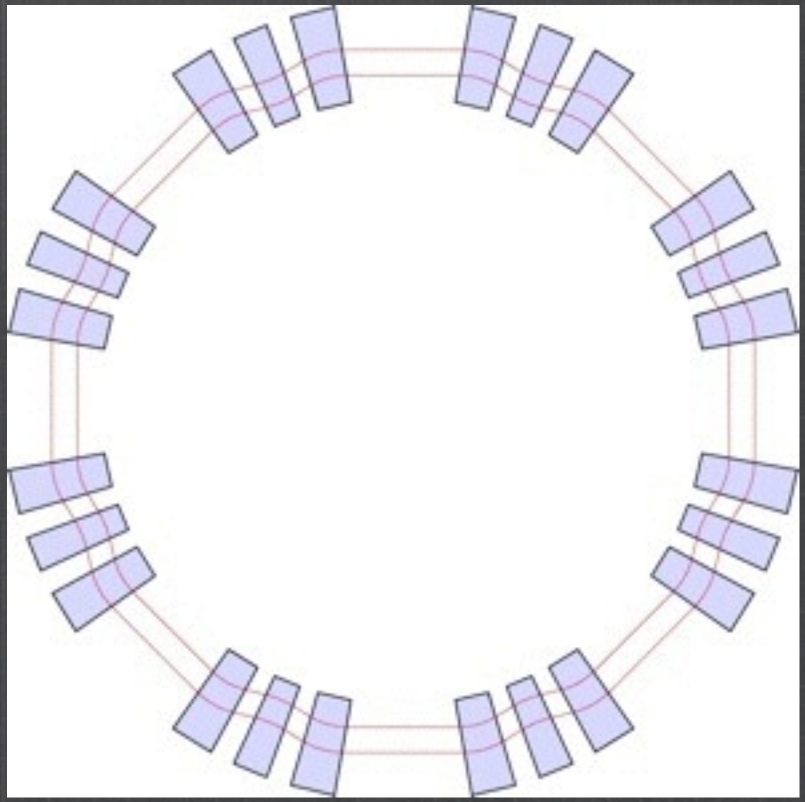
Circular case

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

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



Spiral sector: $\zeta = const.$

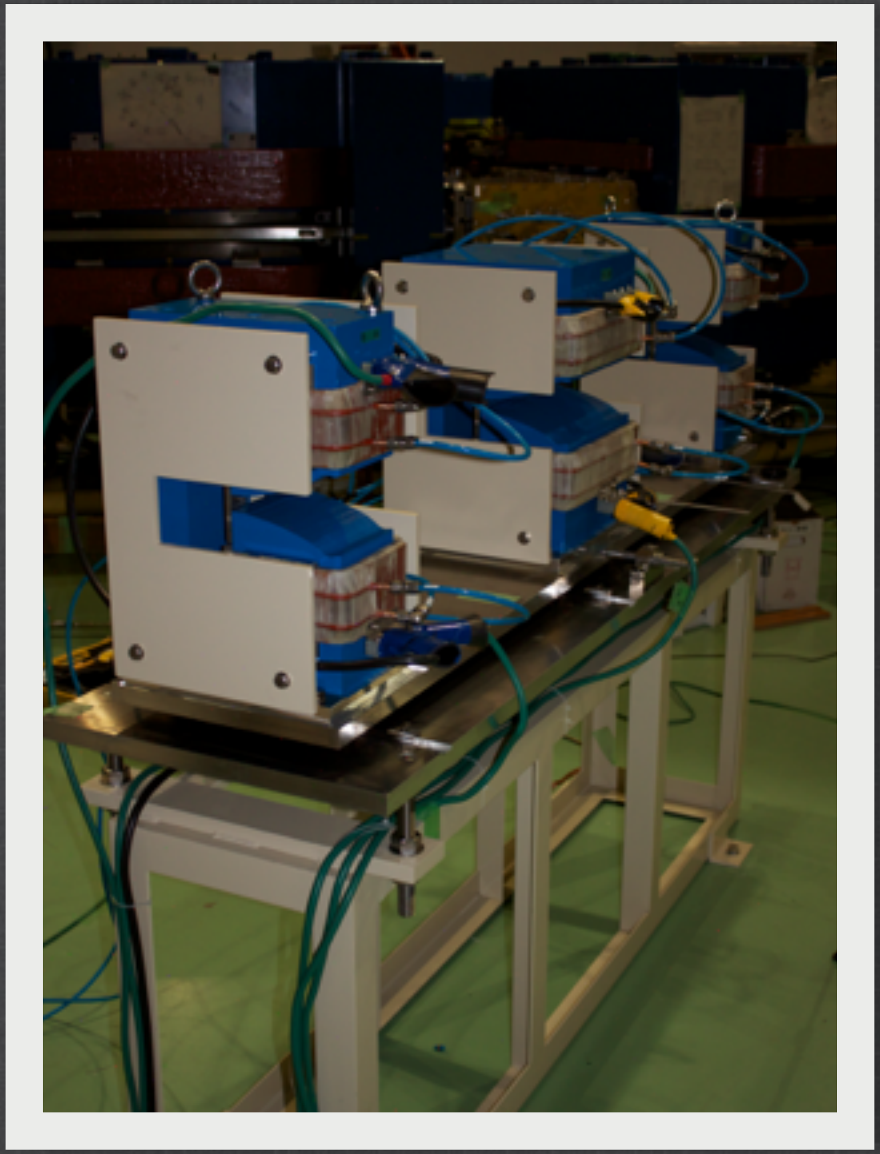


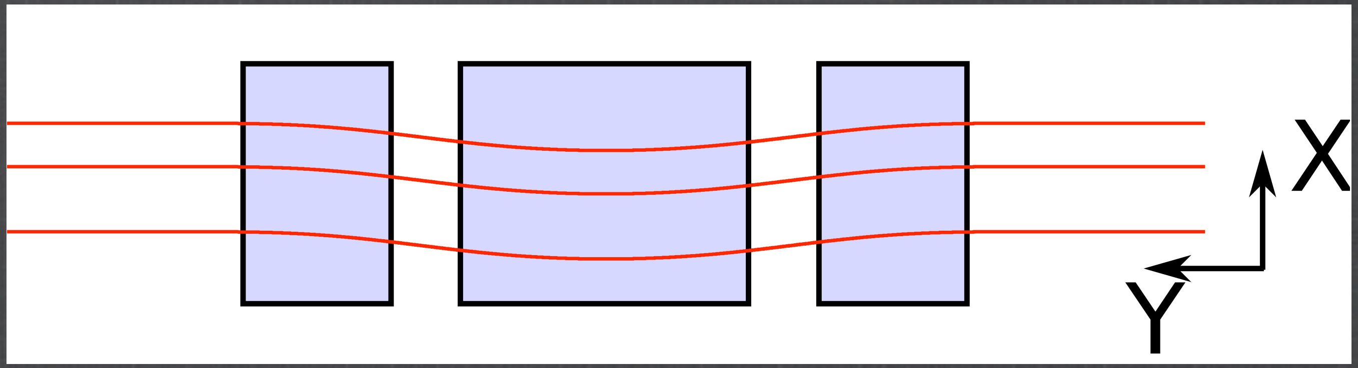
Radial sector: $\zeta = 0$

Straight case

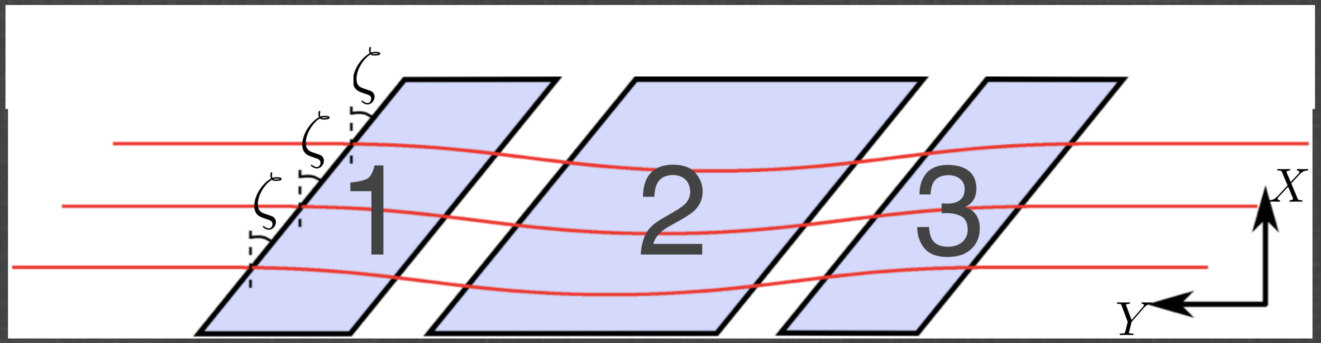
Constant normalised field gradient: $m = \frac{1}{\bar{B}}\frac{d\bar{B}}{X}$

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



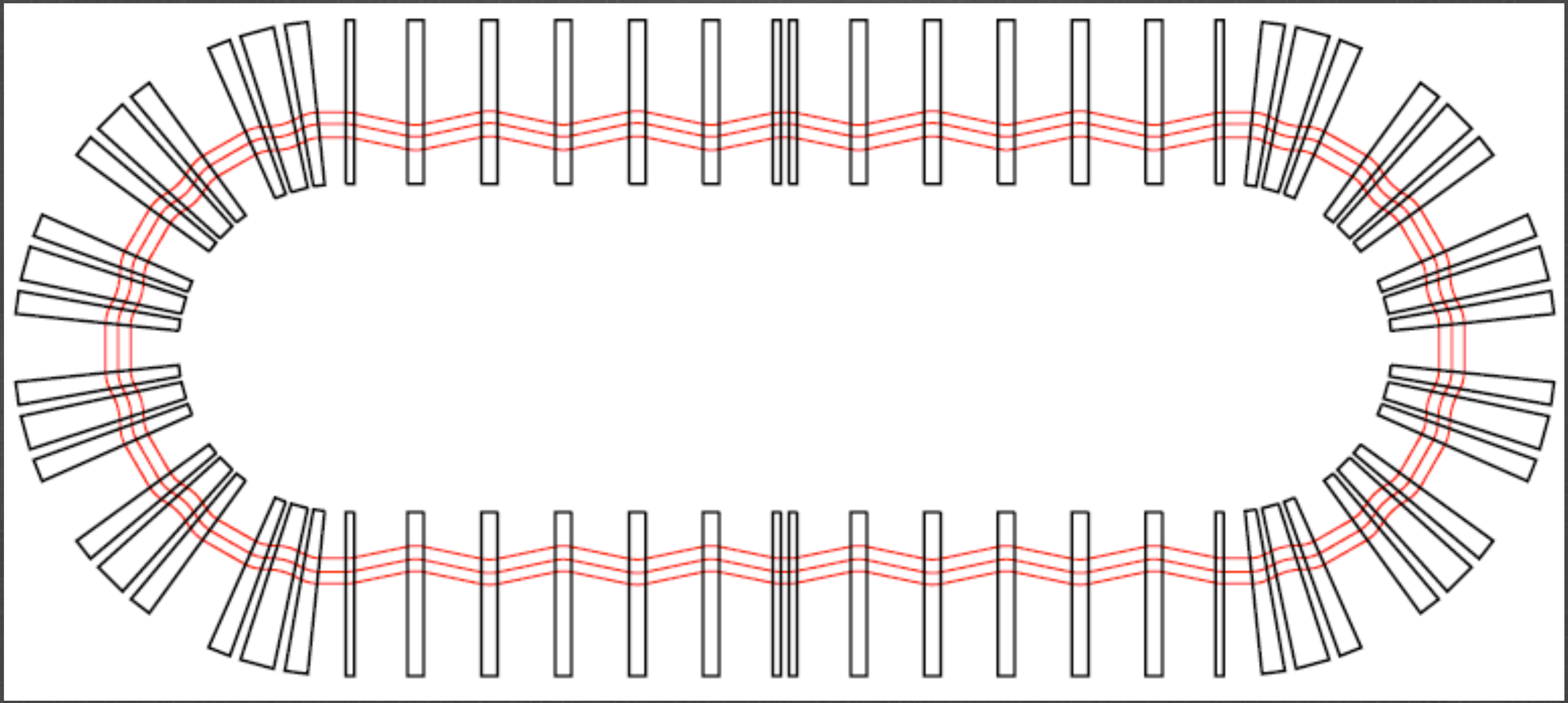


Rectangular case: $\zeta = 0$



Tilted straight case: $\zeta = const.$

Racetrack FFAG



νSTORM Racetrack FFAG

Constraints:

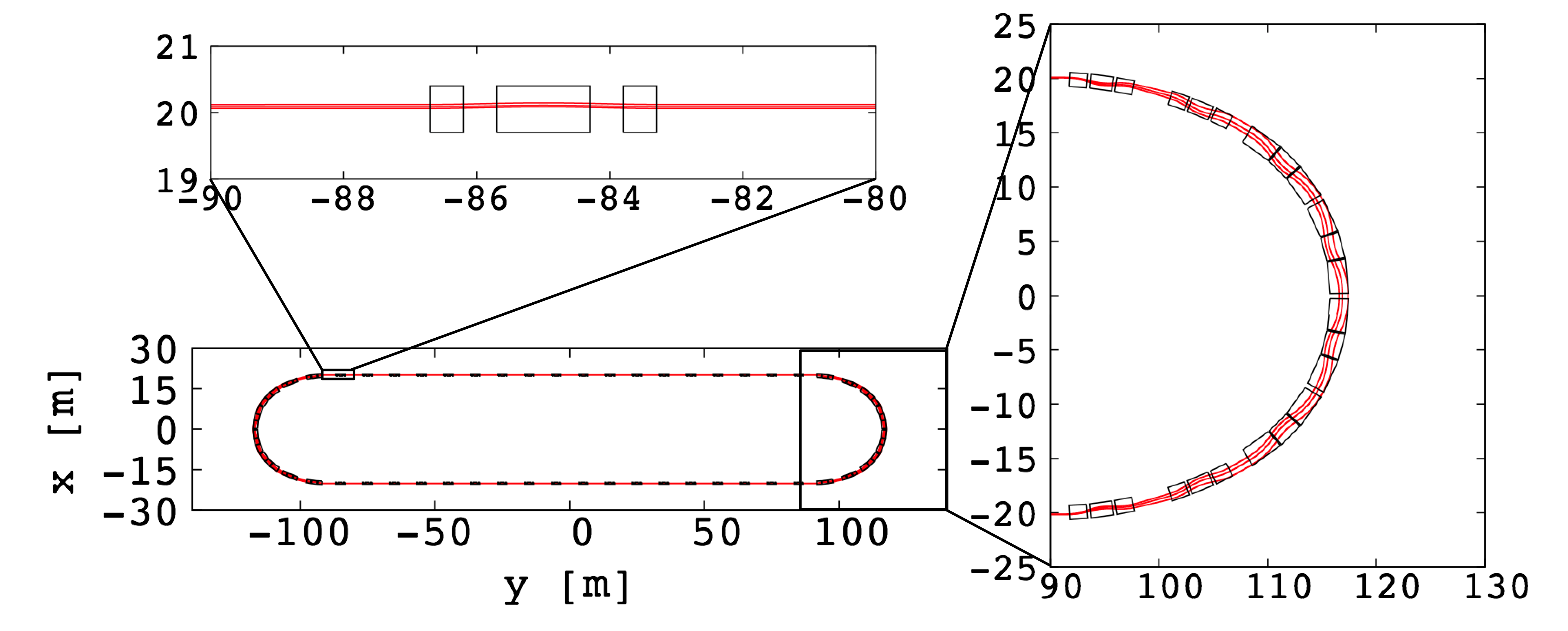
- in the straight part, the **scallop effect** must be as small as possible to collect the maximum number of neutrinos at the far detector.

- **Stochastic injection**: in the dispersion matching section, a drift length of 2.6 m is necessary to install a septum.

- to keep the ring as small as possible, **SC magnets in the arcs** are considered. **Normal conducting magnets in the straight part** are used.

- **large transverse acceptance** is needed in both planes: 1 π mm.rad (2?).

Triplet solution



J.-B. Lagrange et al., "Progress on the Design of the Racetrack FFAG Decay Ring for nuSTORM", WEPWA043, IPAC15, Richmond, USA (2015)

Changes in the design

- Increase momentum acceptance
-> from 3.8 GeV/c ±16% to 3.7 GeV/c ±19% (accept lower momentum)

- Beam emittance increases 1 π.mm.rad to 2 π.mm.rad
-> increase the DA (reduce the gradient in the straight section).

- Triplet cell has few parameters for adjustments and 2 kinds of magnet design
-> Quadruplet cell, all magnets identical.

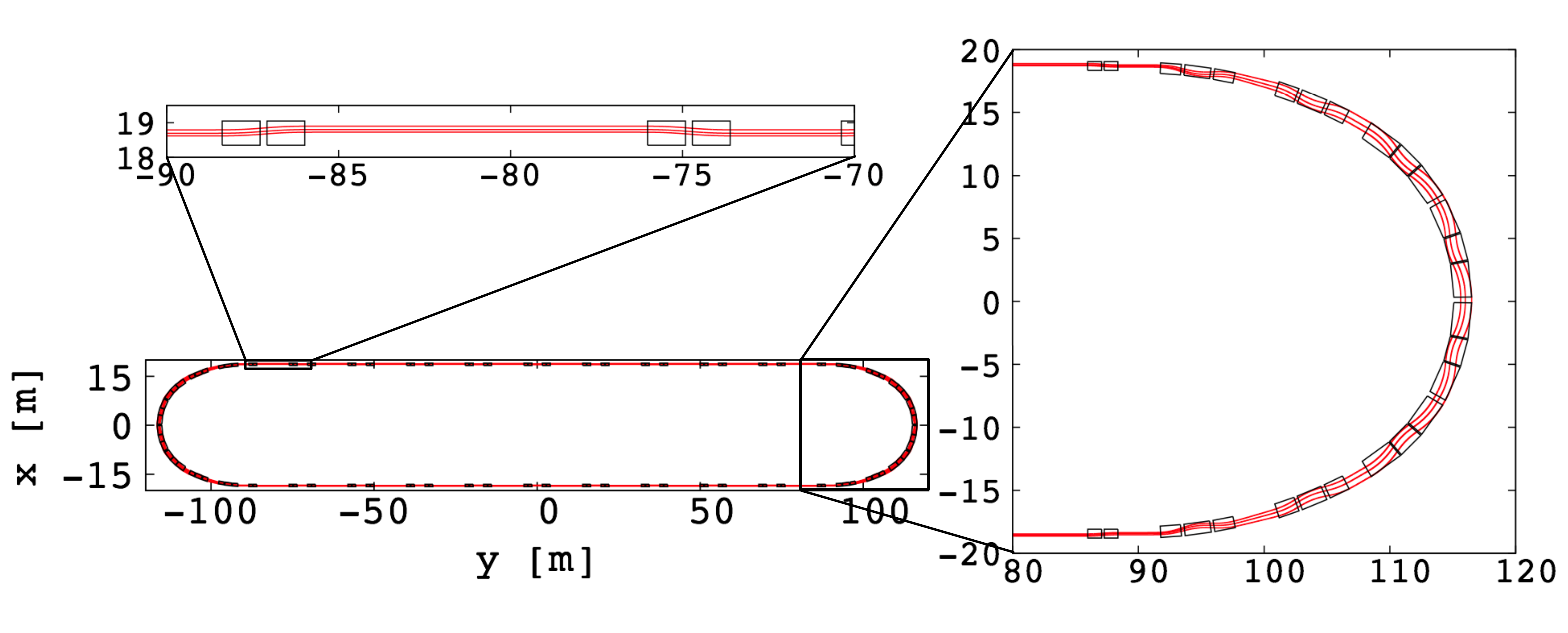
- Long cell is better: few magnets, not dominated by fringe fields.

Changes in the design (2)

→ Consequences of low gradient in the straight section:

- PROS:
  - increase the DA.
  - reduce the maximum dispersion in the arc.
- CONS:
  - reduce the efficiency of muon capture.

Quadruplet solution



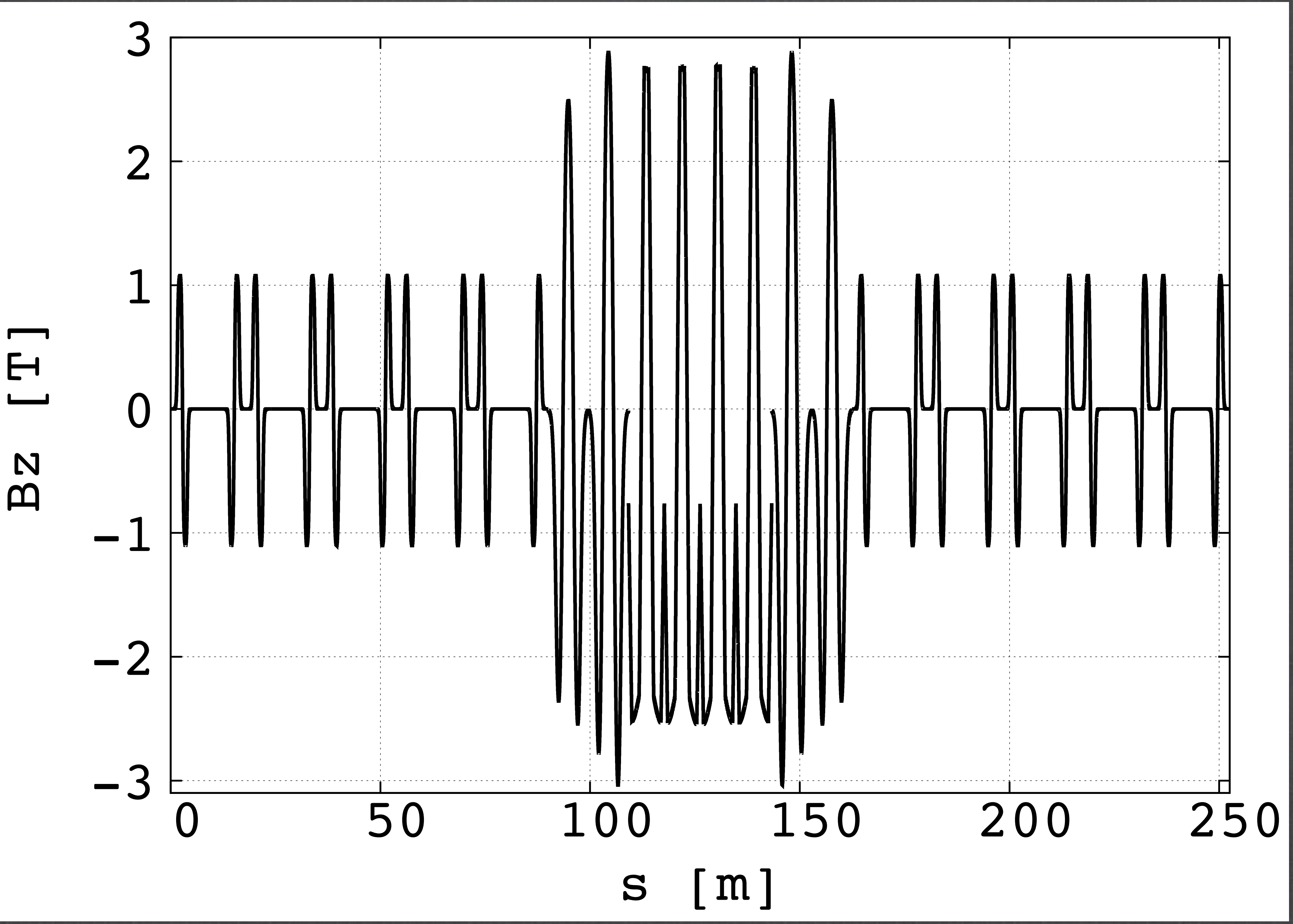
Quadruplet solution

Cell parameters

	Circular Section	Matching Section	Straight Section
Type	FDF	FDF	DFFD
Cell radius/length [m]	15.8	36.1	18
Opening angle [deg]	30	15	
k-value/m-value	6.123	26.	2.2 m^{-1}
Packing factor	0.92	0.58	0.24
Maximum magnetic field [T]	2.5	3.3	1.7
horizontal excursion [m]	1.4	0.9/1.3	0.7
Full gap height [m]	0.5	0.5	0.5
Average dispersion /cell [m]	2.23	1.34	0.45
Number of cells /ring	4×2	4×2	10×2

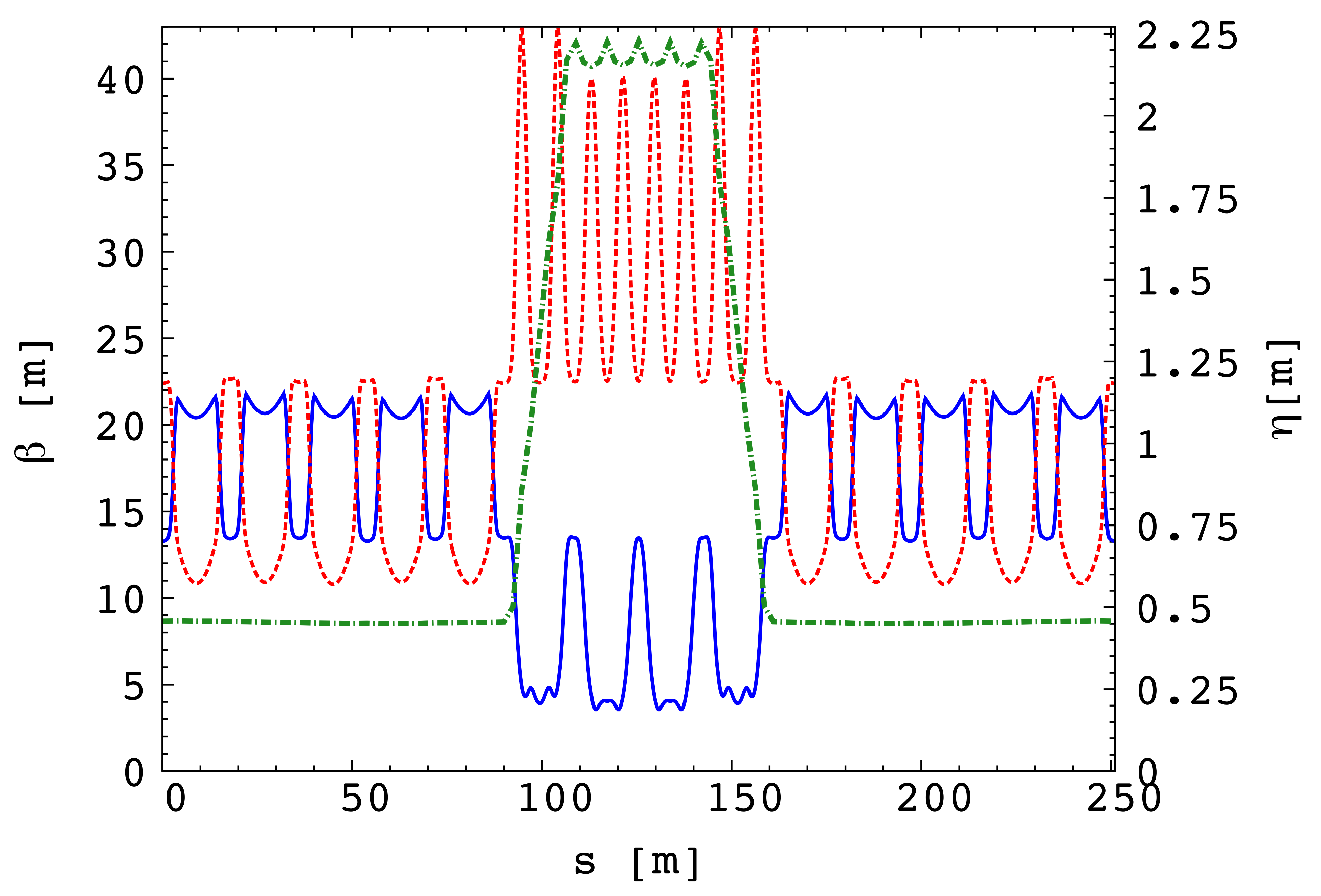
Quadruplet solution

Magnetic field for P_{max} (+19%)



Quadruplet solution

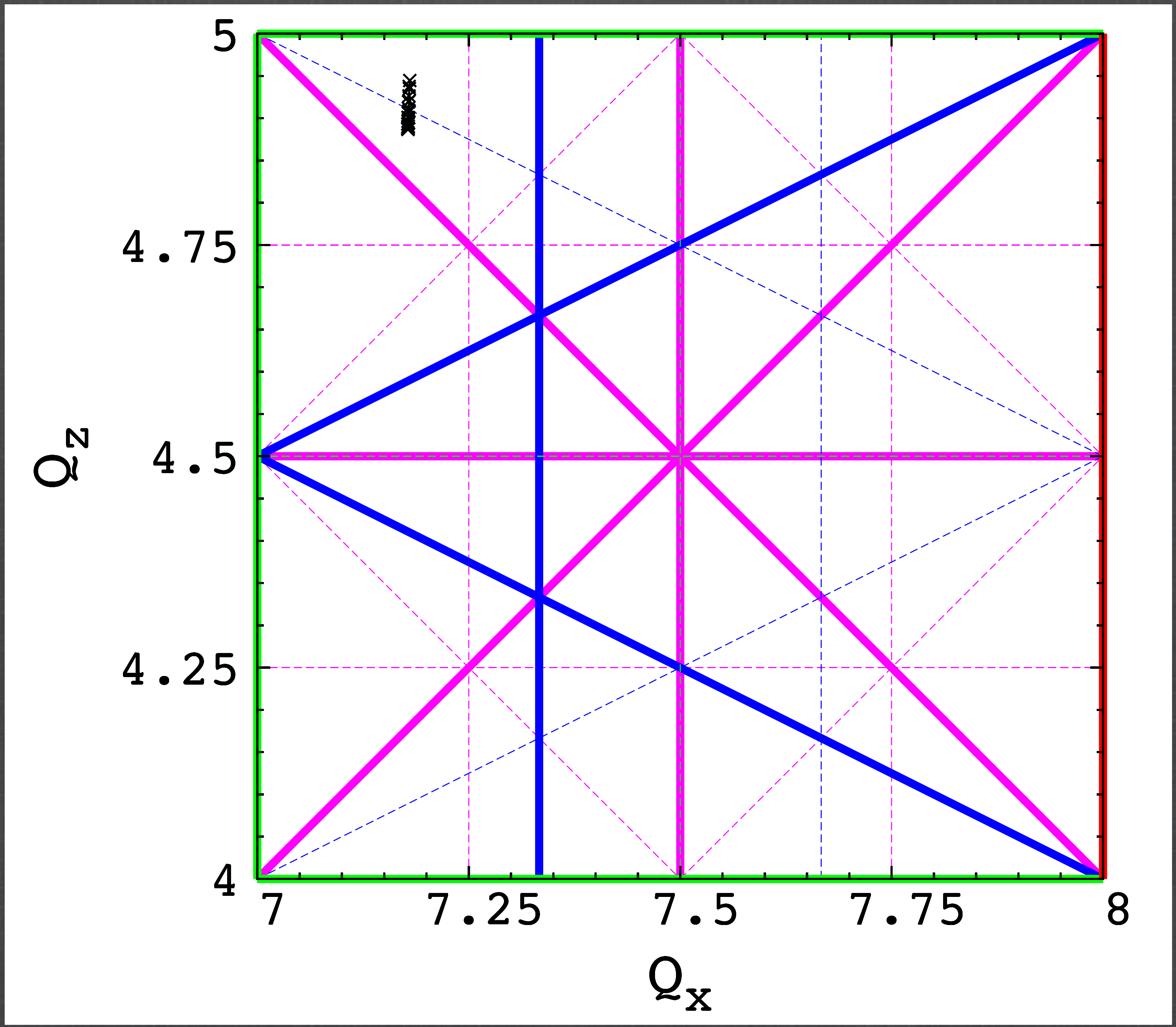
Beta-functions and dispersion at matching momentum



Horizontal (plain blue), vertical (dotted red) beta-functions and dispersion (mixed green) for half of the ring.

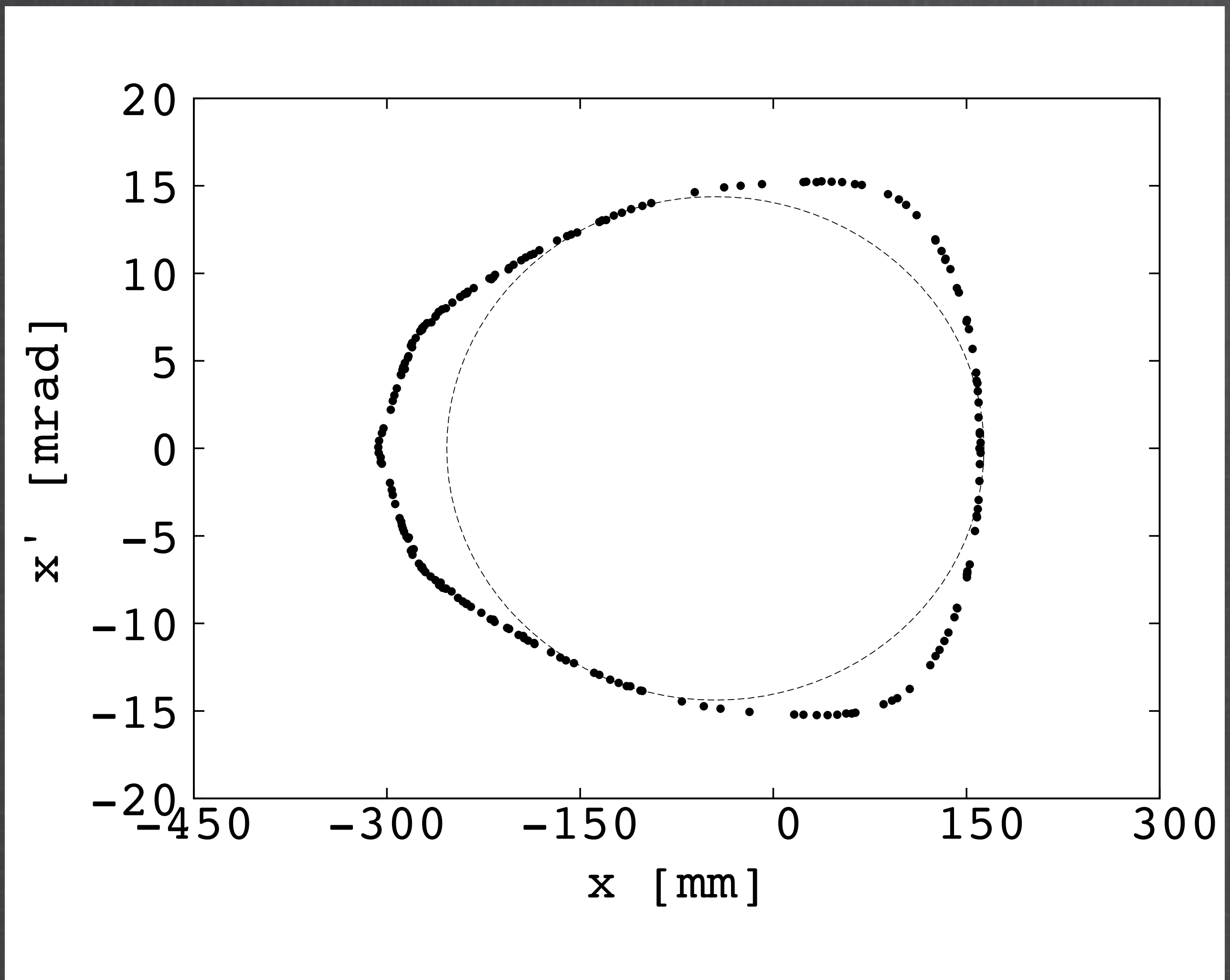
Quadruplet solution

Tune diagram $\frac{\Delta P}{P} = \pm 19\%$



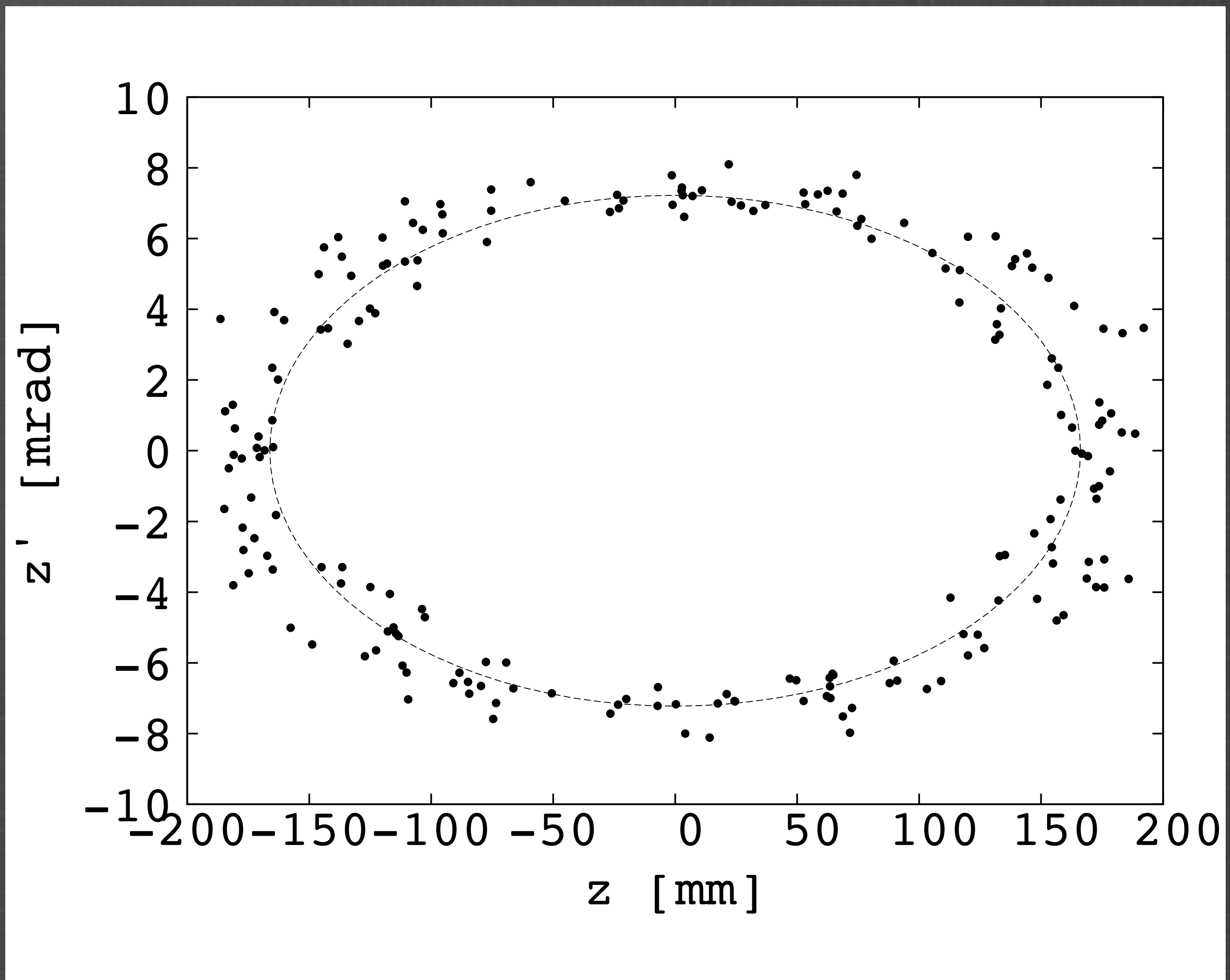
Quadruplet solution

Transverse acceptance



Maximum horizontal stable amplitude over 100 turns

(Dotted ellipse represents 3 π.mm.rad)

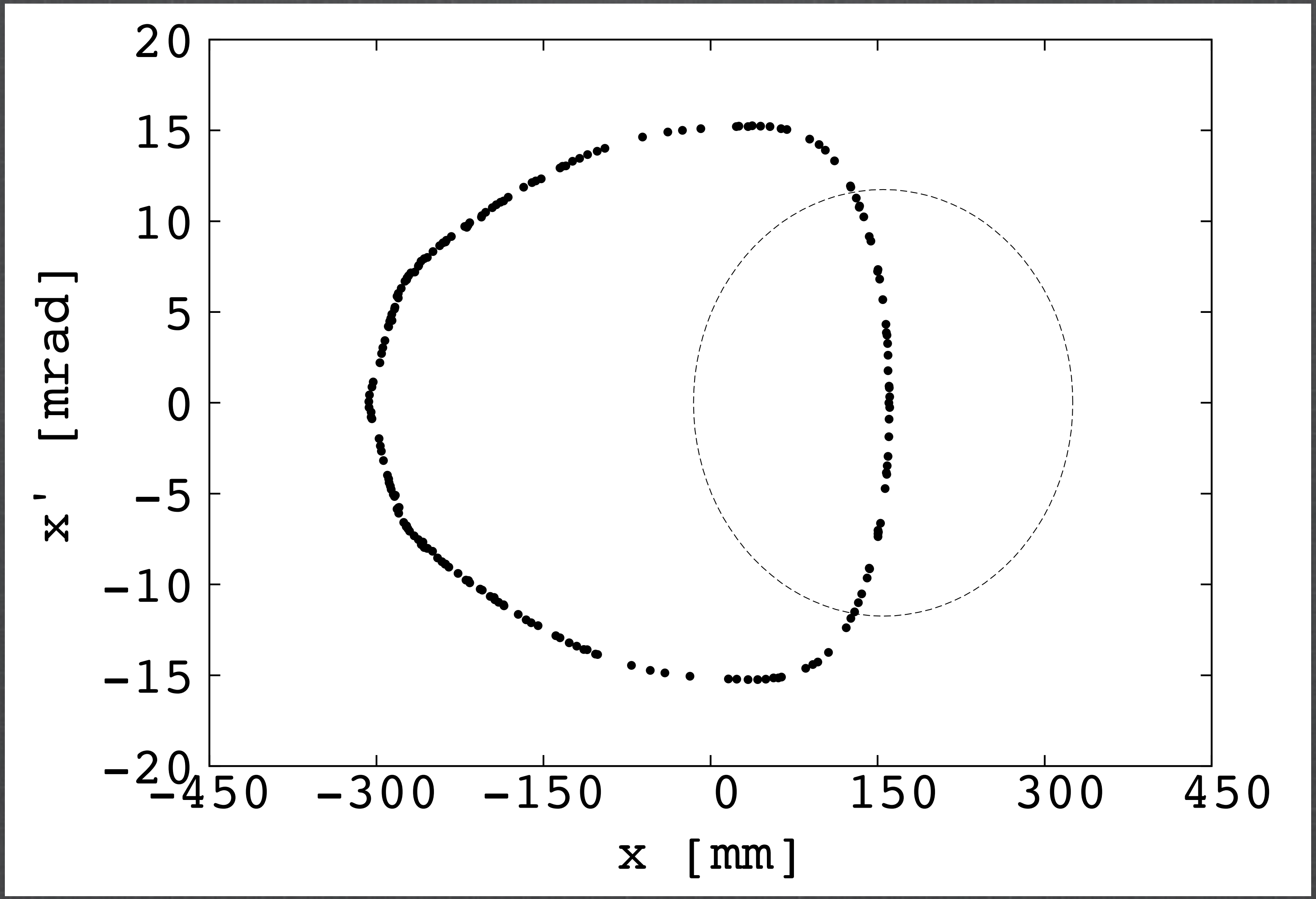


Maximum vertical stable amplitude over 100 turns

(Dotted ellipse represents 1.2 π.mm.rad)

Quadruplet solution

Muon capture efficiency



Maximum vertical stable amplitude over 100 turns

(Dotted ellipse represents 2 π.mm.rad 5 GeV/c pion beam position)

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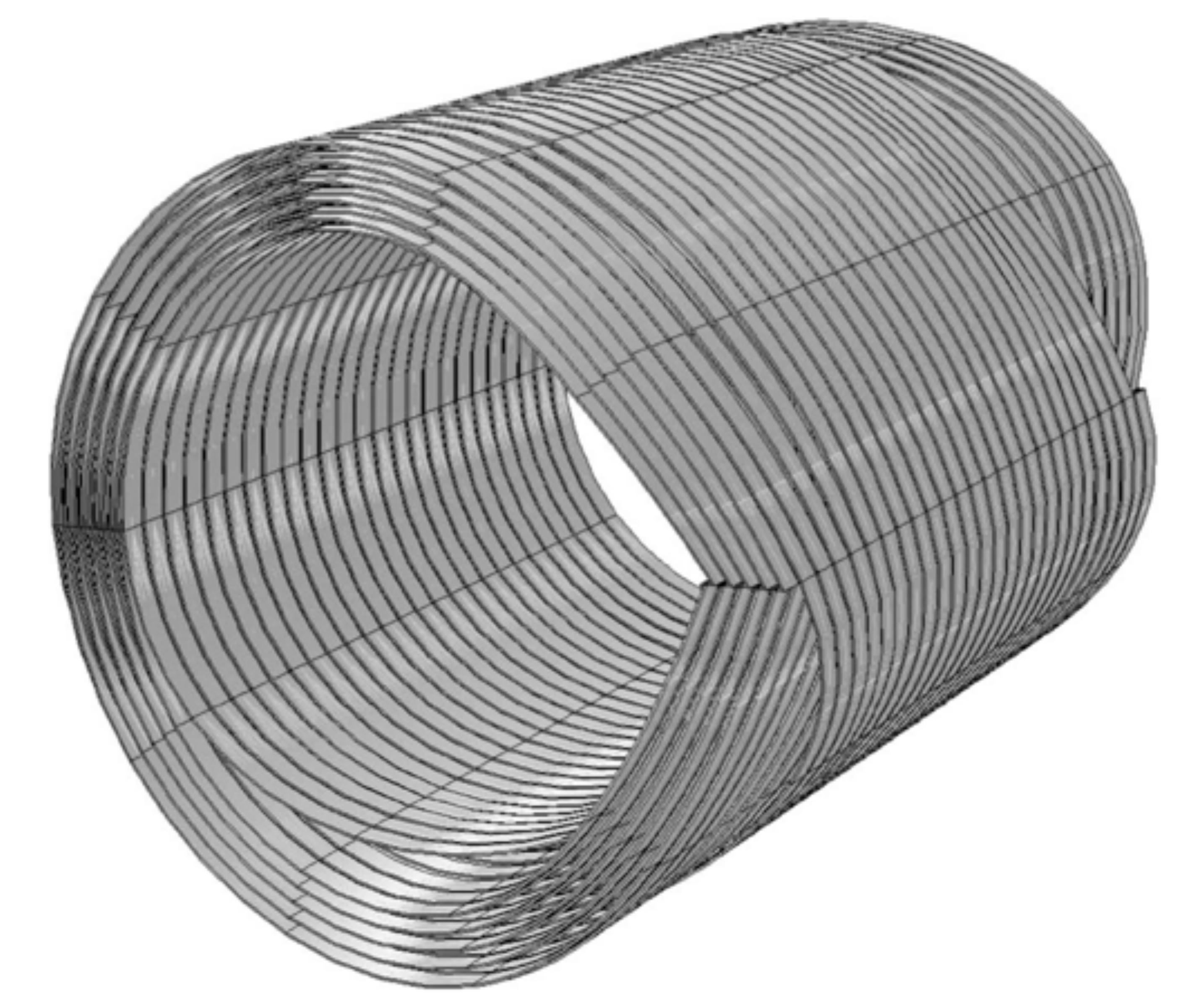
Superconducting arc magnets

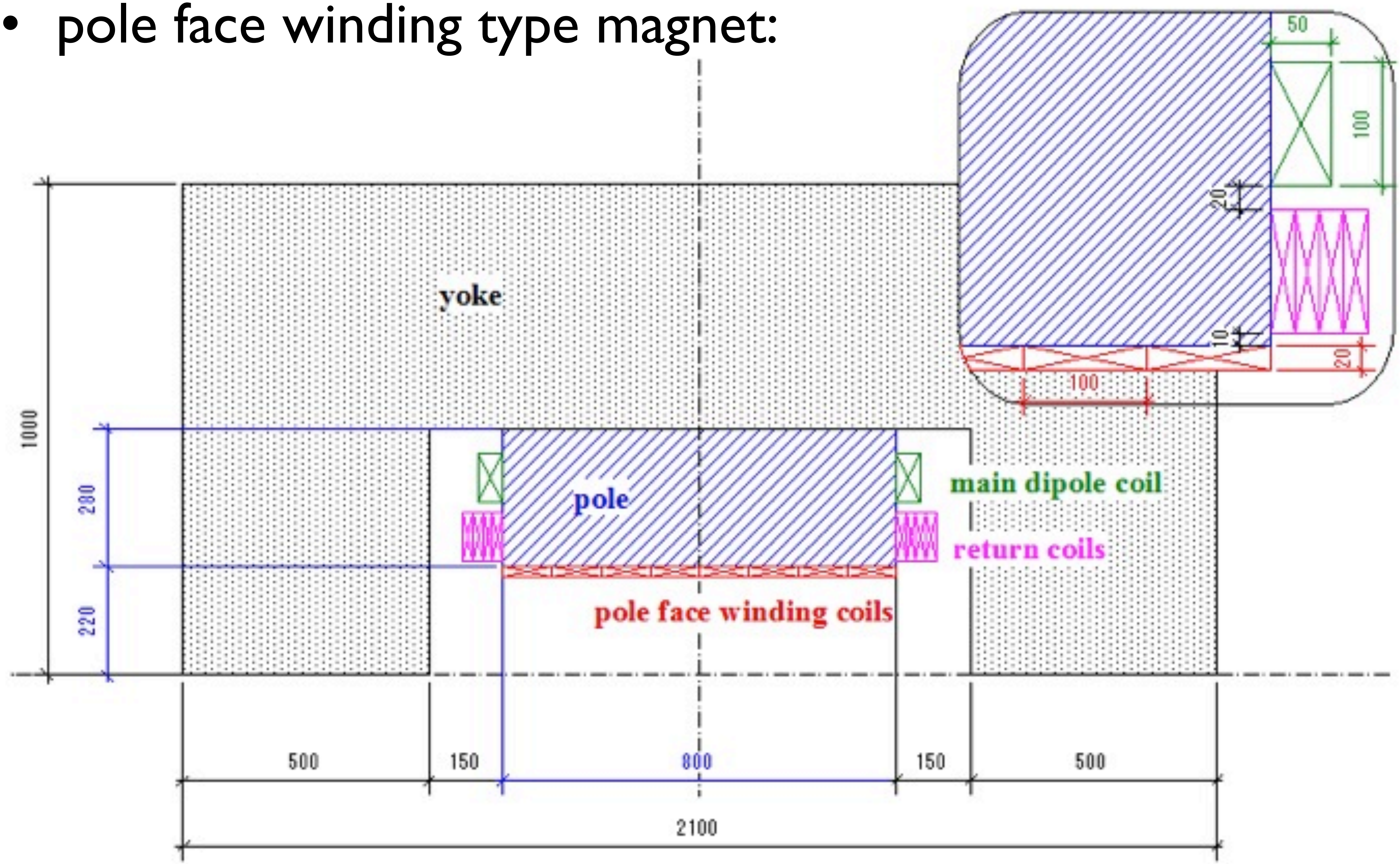


PAMELA "F" magnet

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

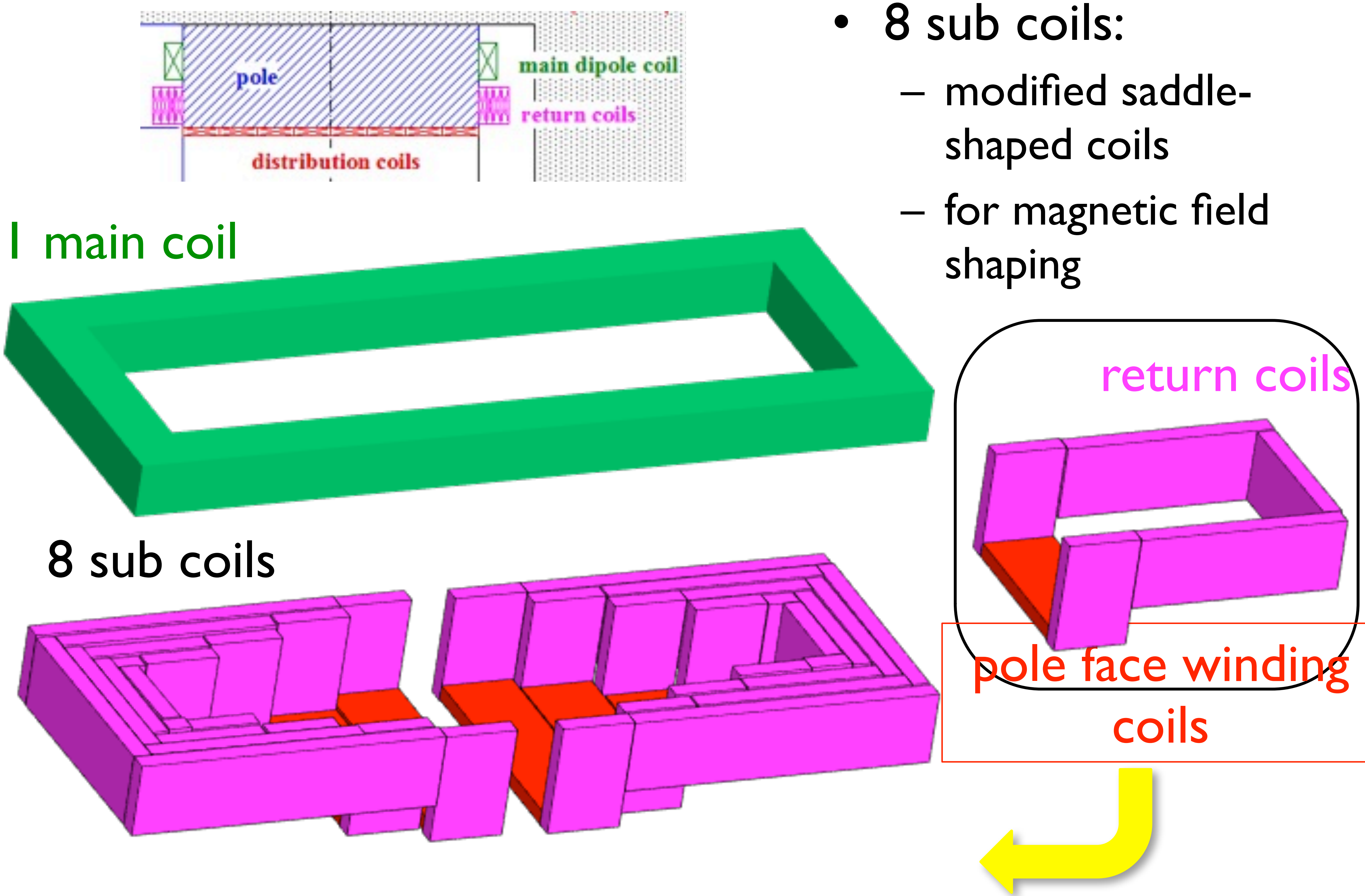
Straight FFAG magnets

- pole face winding type magnet:



Straight FFAG magnets

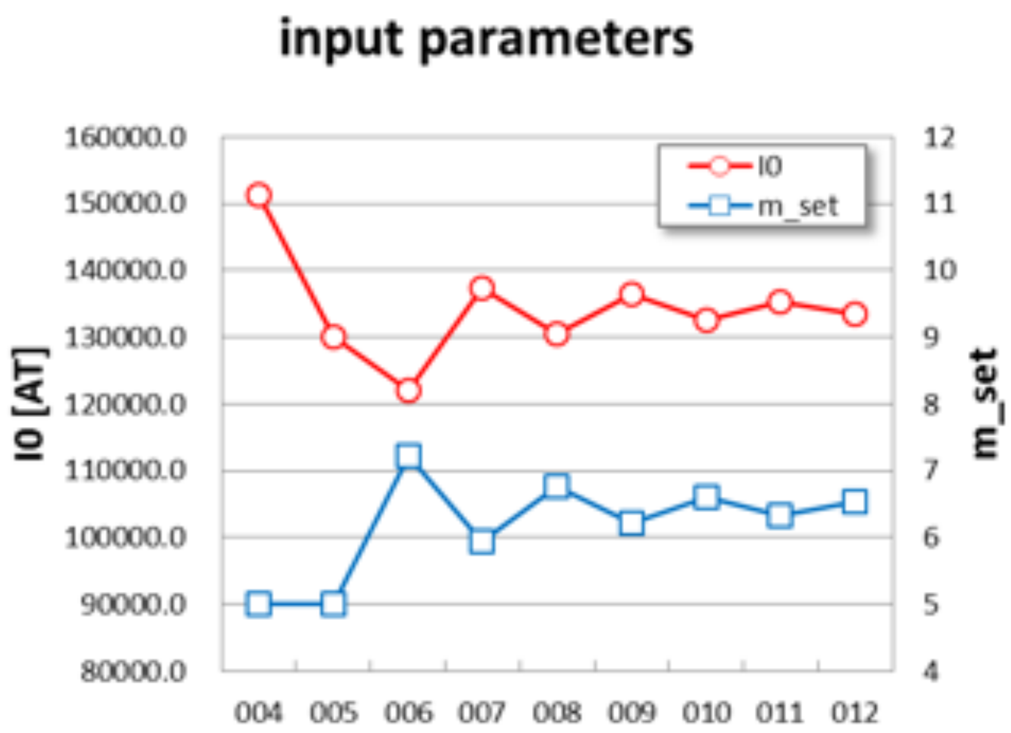
Coils configuration

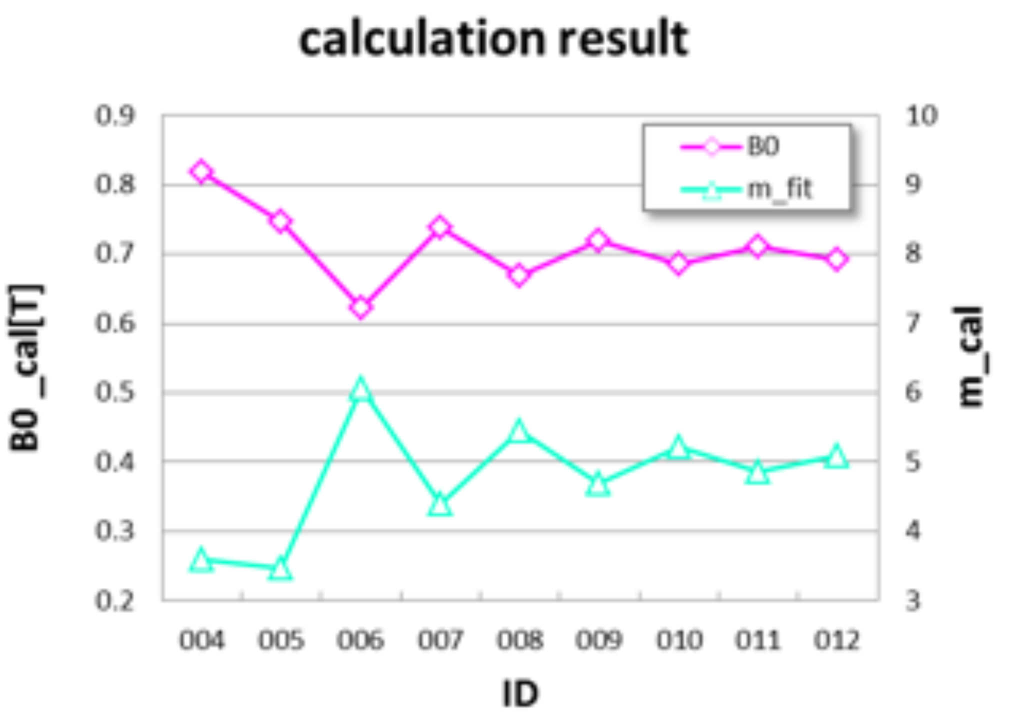


- 8 sub coils:
  - modified saddle-shaped coils
  - for magnetic field shaping

Straight FFAG magnets

Result (1)





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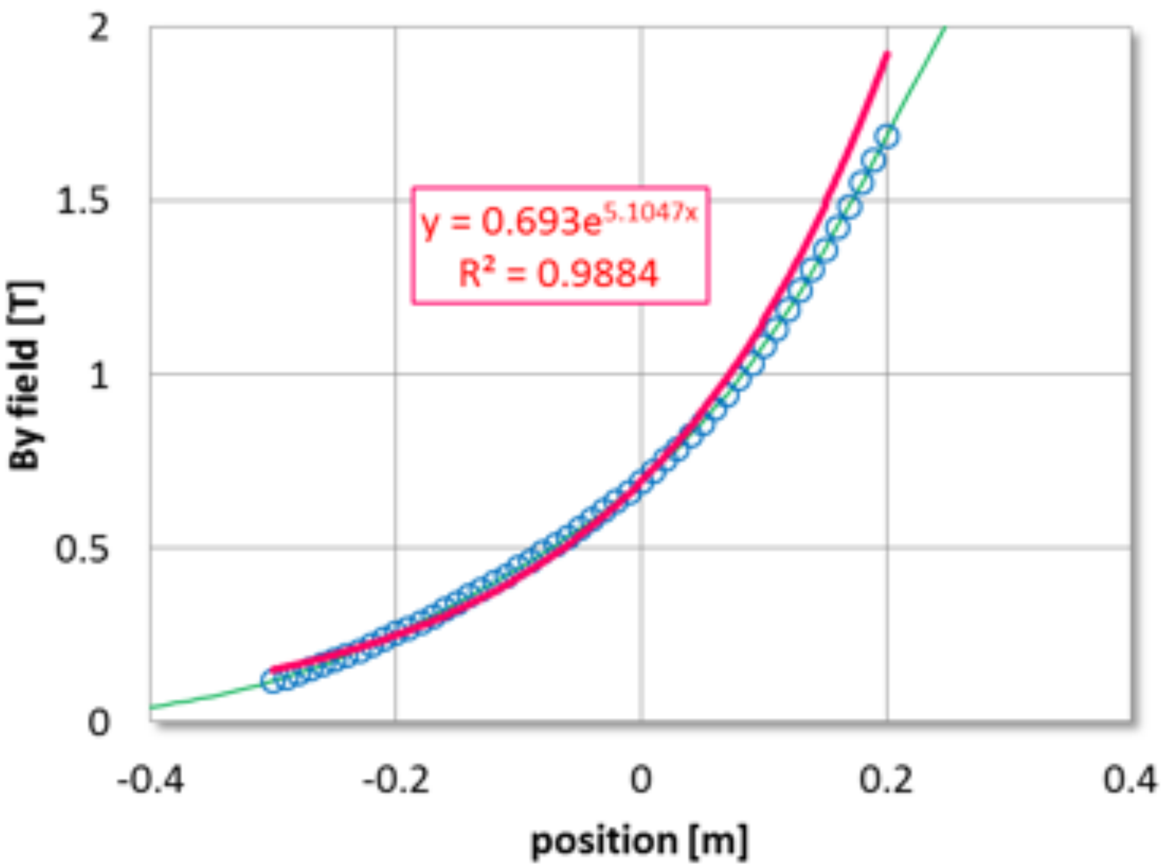

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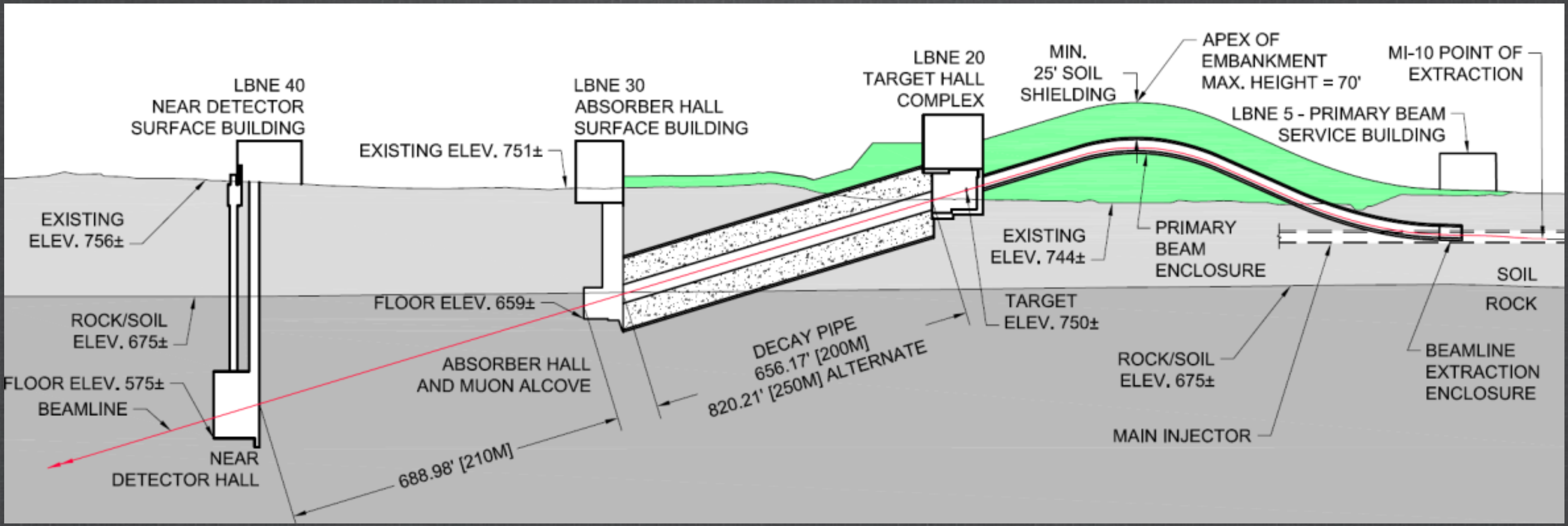
Summary

- nuSTORM produces a new type of conventional neutrino beam from pion decay and muon decay
- Facility with strong physics interest (Sterile neutrino search, Cross-section measurements, long-baseline oscillation search), and accelerator and detector R&D test bed.
- New zero-chromatic FFAG decay ring designed with large DA, large momentum acceptance.
- FFAG magnets are feasible.

Future plans

- Multi-particle tracking to confirm the DA.
- Optimisation of the tune point.
- Realistic magnetic field in tracking for FFAG and FoDo (Enge Fringe field fall-offs, no discontinuity).
- Study of tolerance to errors (field error and misalignment) in FFAG and FoDo lattices.
- Investigation of a zero-dispersion (chromatic!) straight capture section with FFAG arcs to increase muon capture efficiency and reduce chromaticity of FoDo.

Moving forward



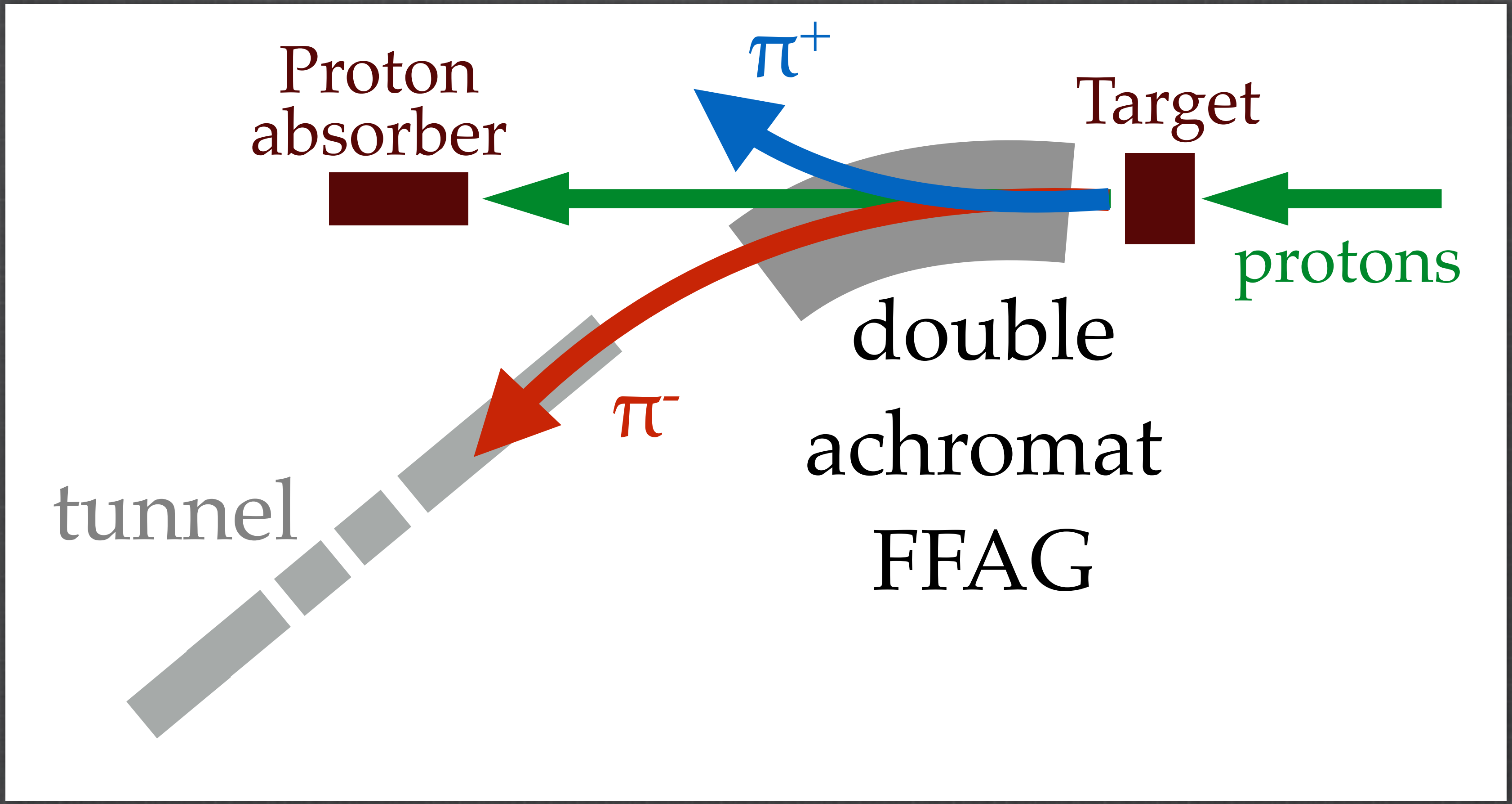
(LBNF Letter of Intent, Jan 2015)

Decay pipe:

- 6 (4?) m diameter filled with Helium,
- 7 m of concrete around the pipe to shield it

→ 20 m diameter tunnel!!!!

Moving forward (2)



Pion beam line

- clean, well known flux
- smaller tunnel (conventional pion beam line does not require much shielding)

→ **nuPIL? (<u>Neutrinos from PIon beam Line</u>)**

Let's stay in Wonderland and see how deep the rabbit-hole goes!

Thank you for your attention