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ESS neutrino Super Beam plus

2nd annual meeting

LEnuSTORM ring progress update

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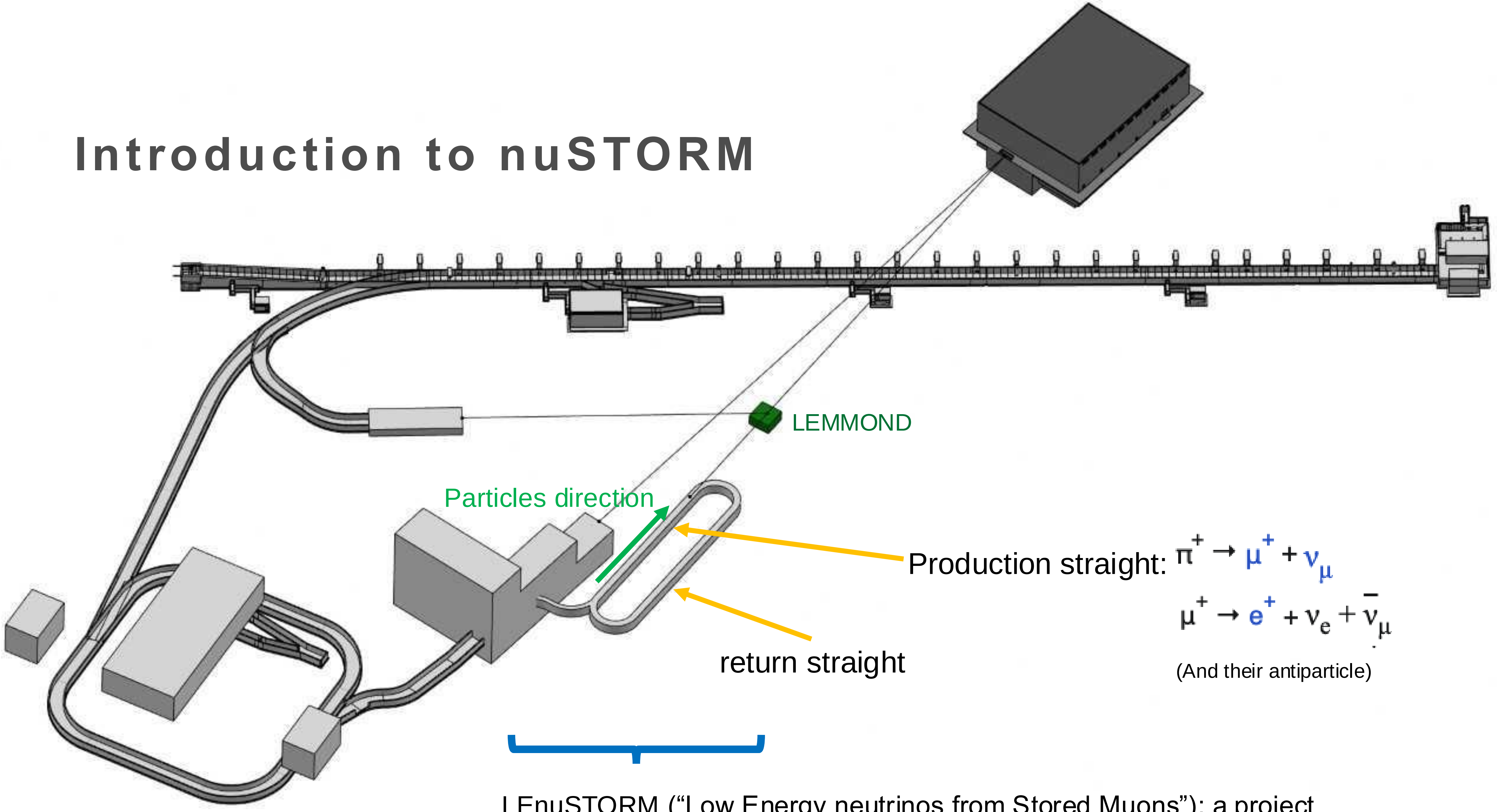
Review milestones and deliverables

1. ~~MS 4.1. (9/2024) Evaluation of the LEnuSTORM requirements and parameter range.~~
2. D 4.1. (1/2025) Review of the LEnuSTORM operation scheme.
3. MS 4.2. (9/2025) Preliminary racetrack ring lattice design.
4. MS 4.3. (12/2025) First estimate of the neutrino flux from LEnuSTORM.

Introduction to nuSTORM



LEnuSTORM (“Low Energy neutrinos from Stored Muons”): a project that uses a muon storage ring to generate low-energy neutrino beams.
- capture, transfer and inject pions, and store muons

Introduction to nuSTORM

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

- Known flux and equal fluxes of electron- and muon-neutrinos.
  - Their energy spectrum can be calculated precisely.
    - To make precise cross-section measurements possible.

- **Our job is to maximise the number of useful neutrinos. → ring design**

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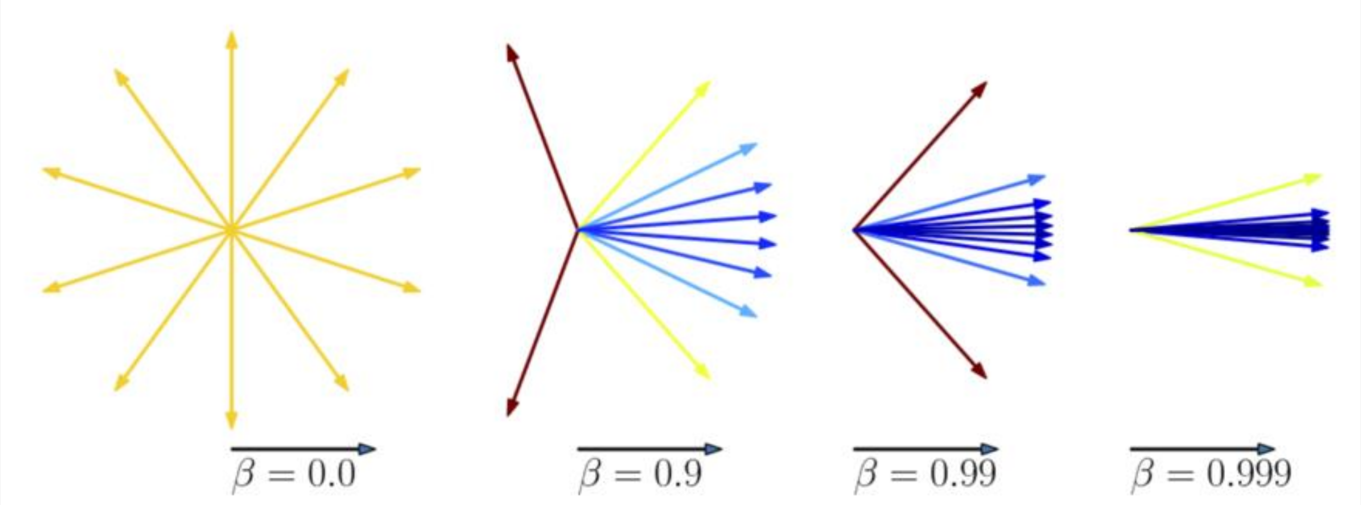
LEnuSTORM ring design challenges

- Relativistic beaming



We have a low energy pion source.

→less Relativistic beaming

→ A wider decayed muon beam.

→increases design difficulty to hold large amounts of the muons.

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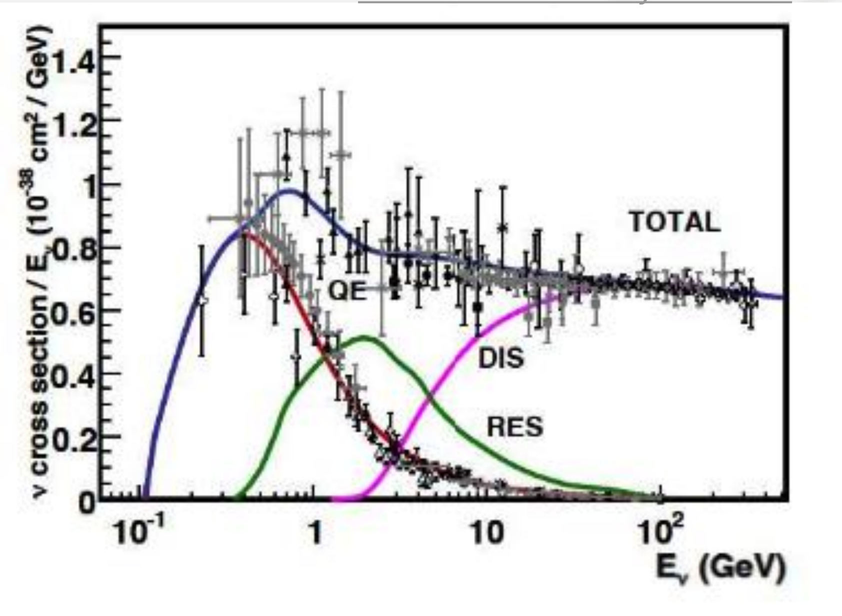
LEnuSTORM ring design Opportunities

[1]J. A. Formaggio and G. P. Zeller, "From eV to EeV: Neutrino cross sections across energy scales," *Rev. Mod. Phys.*, vol. 84, no. 3, pp. 1307–1341, Sep. 2012, doi: 10.1103/RevModPhys.84.1307.



- 1st Low Energy muon storage ring design
- 1st neutrinos cross section measurement in the MeV range
  - to reduce the systematic error in the ESSnuSB long baseline experiment

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LEnuSTORM requirements and parameter range (MS.4.1.)

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Neutrino energy (detected in LEMMOND)

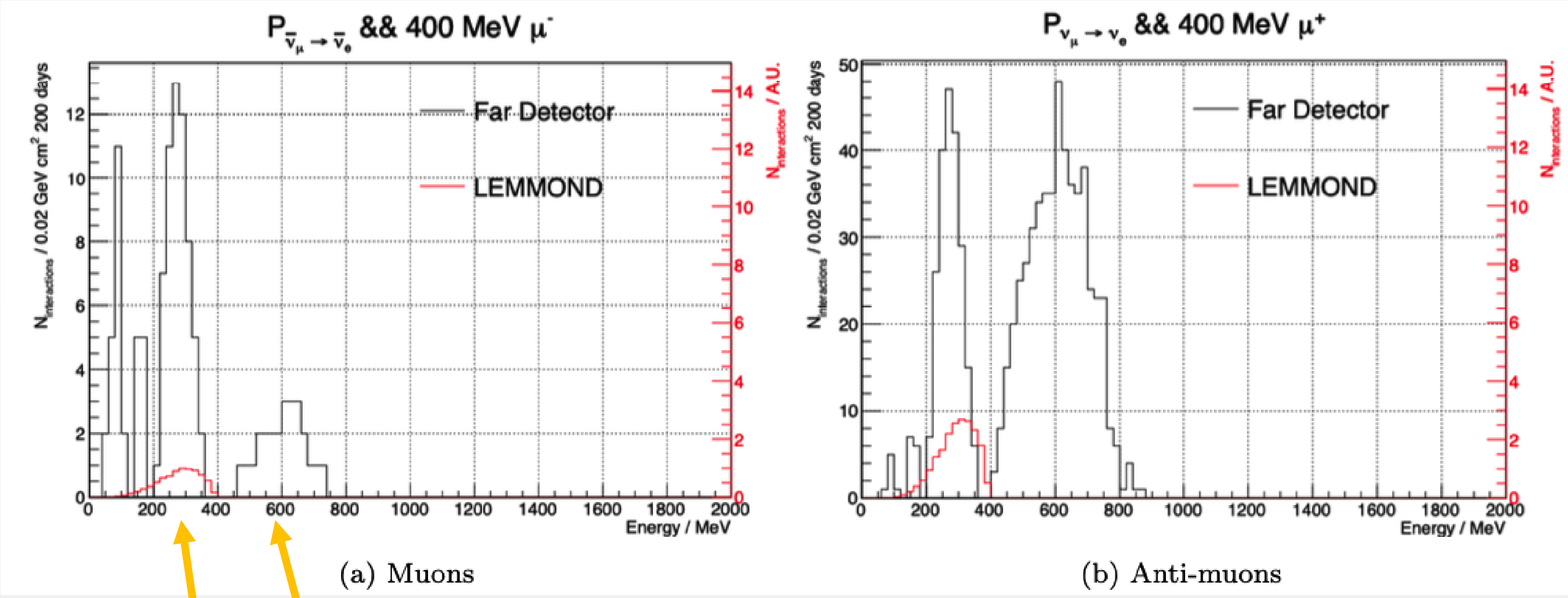
What energy range should we choose?

- Because we want to measure precisely the neutrino interaction cross-sections in the energy range of interest to ESSnuSB, **the energy range should overlap with that in the far detector of ESSnuSB.**
- It is 200 – 400 MeV according to WP5+ people/ ESSnuSB CDR

Muon energy

400 MeV/c!

- Simulation detailed please ask WP5 Leon.



(a) Muons (b) Anti-muons

2nd oscillation max

1st oscillation max

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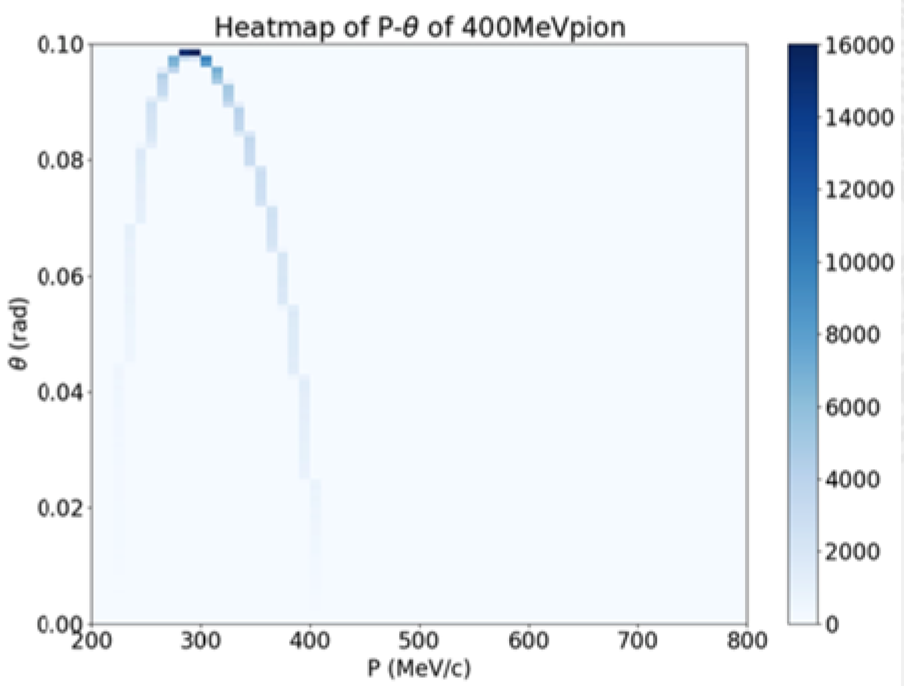
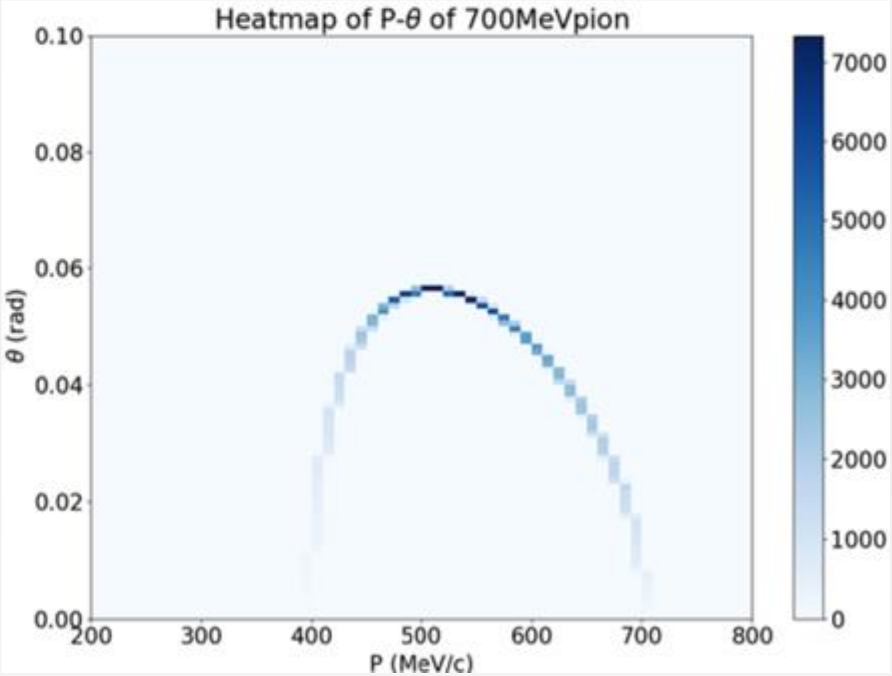
Pion momentum

What pion momentum produces 400 MeV/c muon?

- 400 – 700 MeV/c
- But only 400 and 700 MeV/c pions produce 400 MeV/c muons at a sharp angle below 0.04 rad

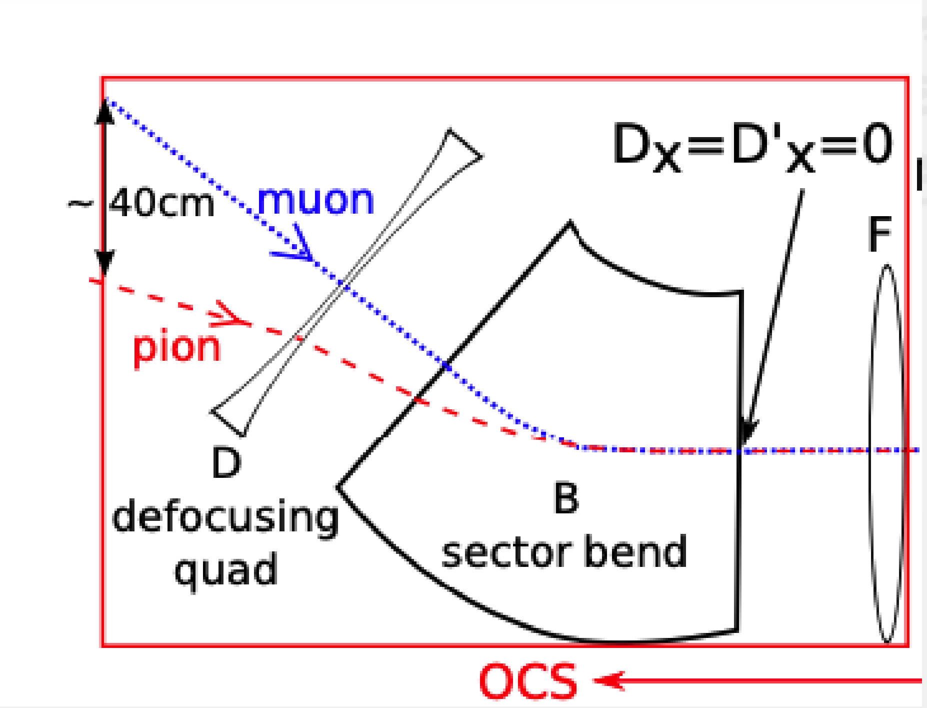




Pion momentum

400 or 700? 700!

1. 700 MeV/c pions have smaller emission angles than the 400 MeV/c pions from our source.
2. A benefit of an efficient pion injection using the stochastic injection method.
3. the higher momentum implies a longer lifetime, the requirement on the maximum length of the pion transfer is somewhat relaxed = the pions to decay in the straight section.



A. Liu, "Design and simulation of the nuSTORM facility," Apr. 2015, Accessed: Sep. 11, 2023. [Online]. Available: https://scholarworks.iu.edu/dspace/handle/2022/19806

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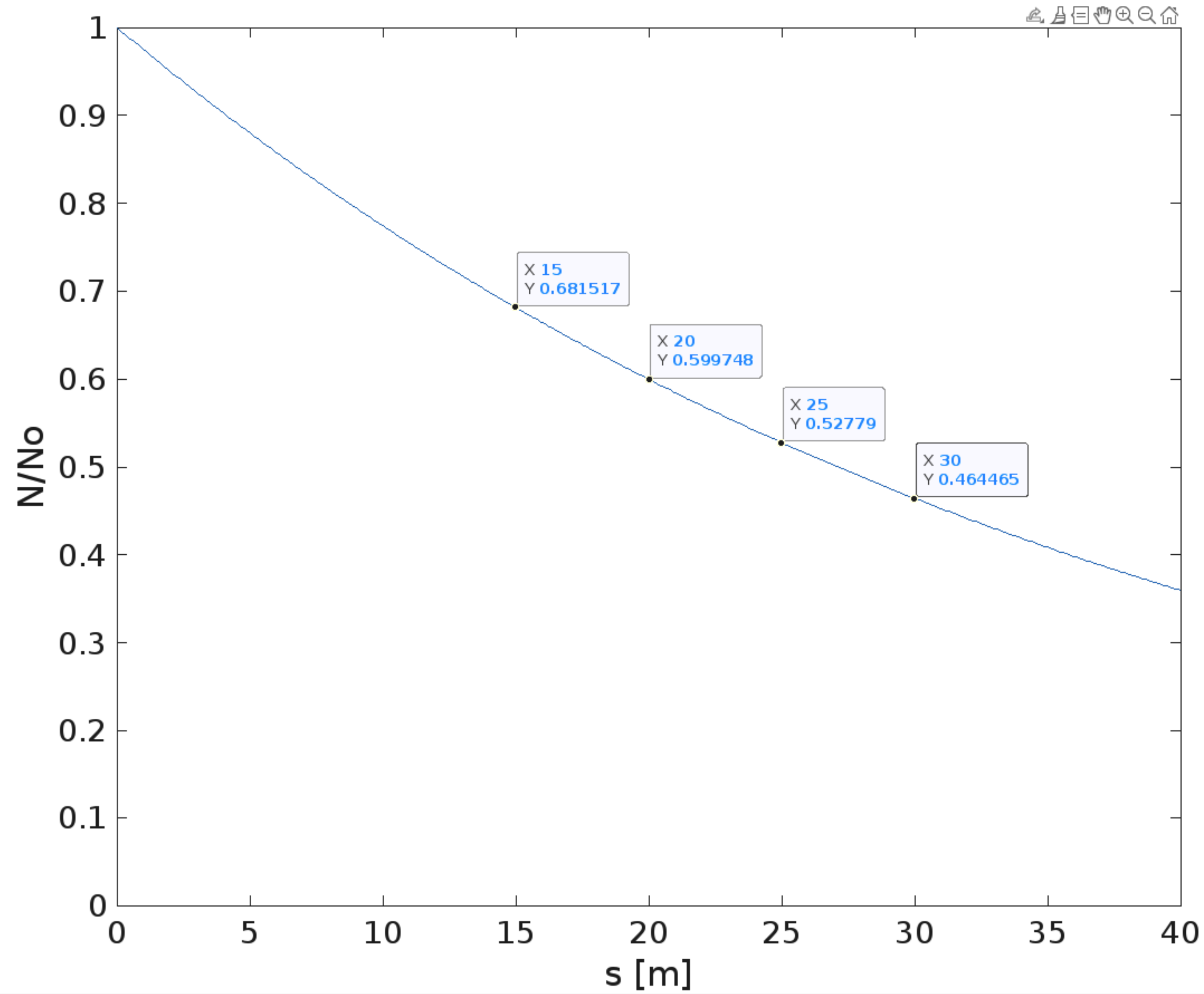
Beamline dimensions

- Pion transfer line
  - The decay length of a 700 MeV/c pion is 39 m.
  - We are aiming to design a transfer line that is less than 20 m long, in order to have a more than 60% chance that the transferred pion decays after the transfer line.

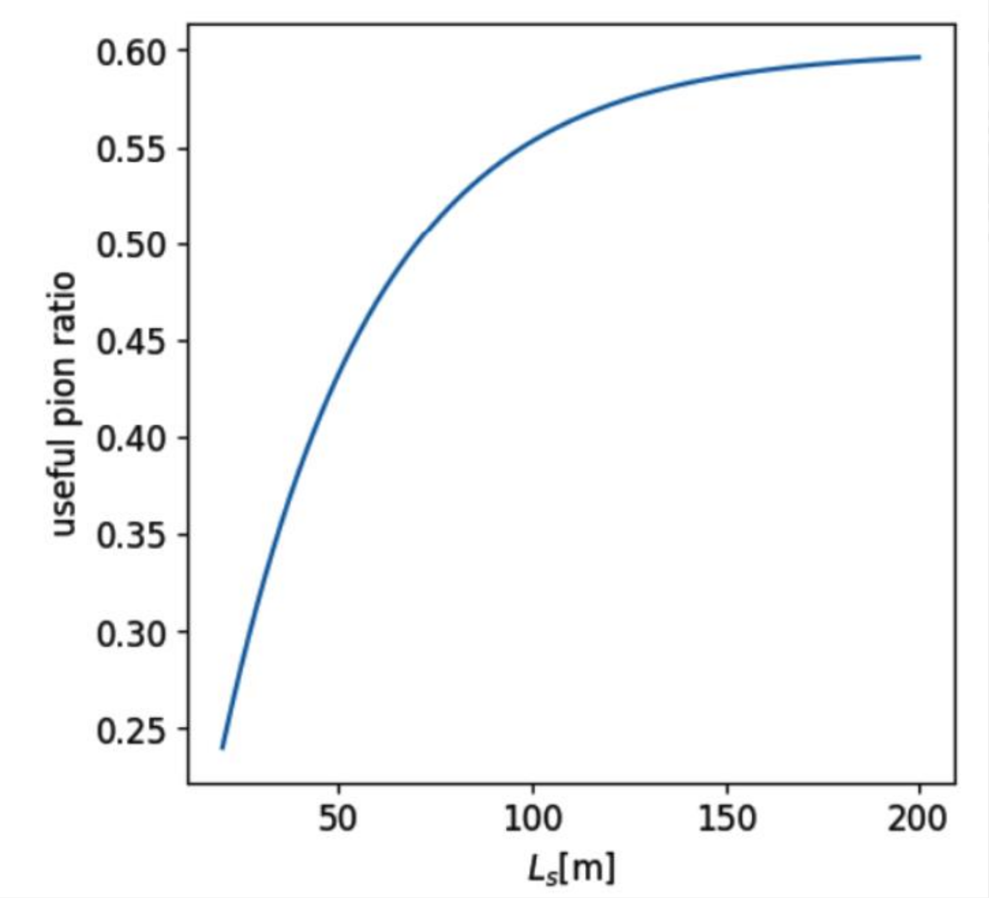


Beamline dimensions

- Straight section
  - The ratio of pions that decay inside the straight section compared to the initial number of pions at the begining of the transfer line:

$$R_\pi = e^{-\frac{L_t}{\tau_\pi}}(1 - e^{-\frac{L_s}{\tau_\pi}})$$

  - To balance performance and cost, Ls = 75 m as a more probable length.



Pion decay ratio in the straight section as a function of Ls with Lt = 20 m.

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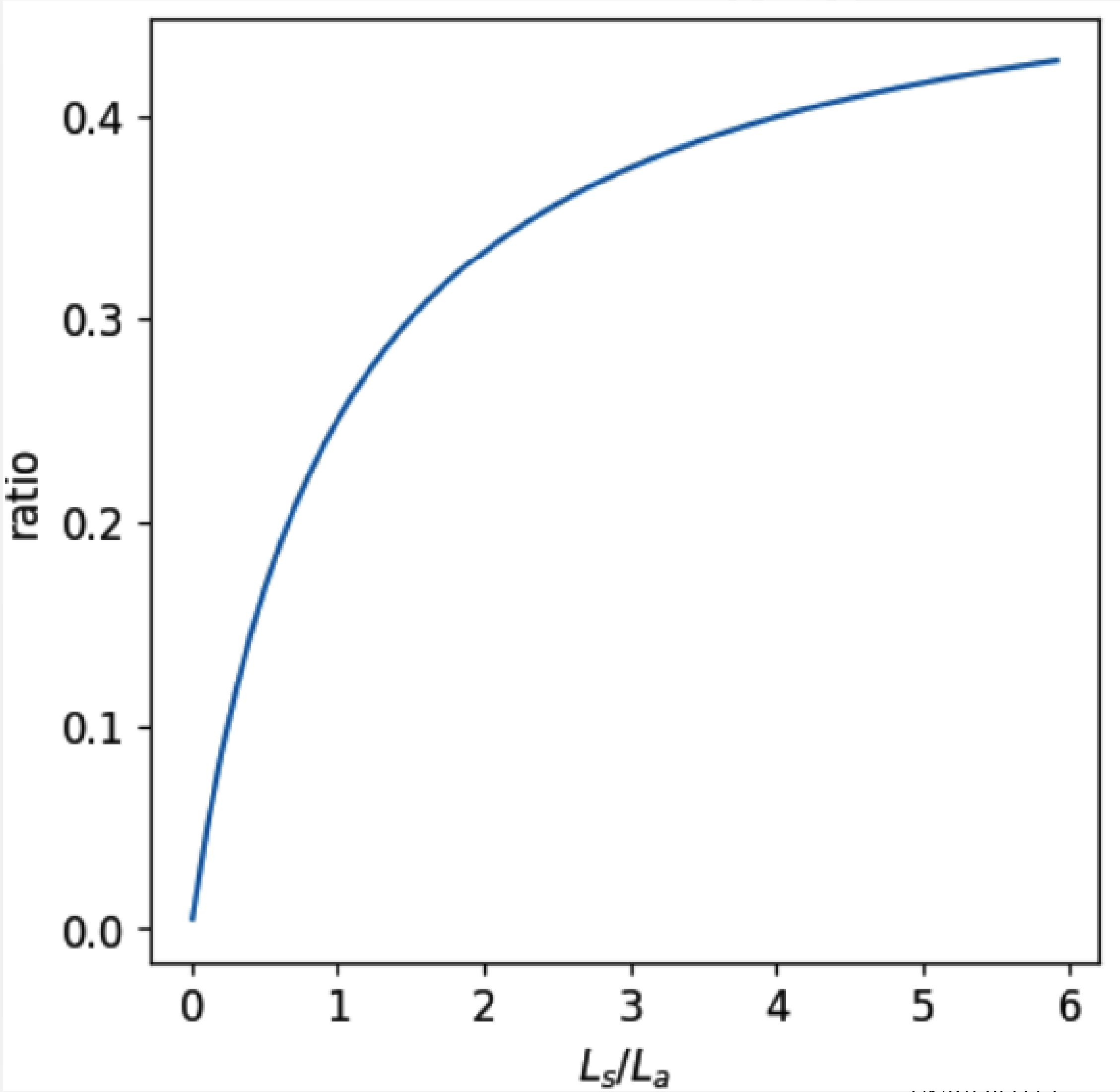
Beamline dimensions

- Arc section
  - the number of neutrinos that can reach the detector is proportional to the ratio of the length of the straight section to the ring circumference.
  - In a two-arcs-racetrack ring design, this ratio is given by

$$R_\nu = \frac{L_s}{2L_s + 2L_a} = \frac{1}{2(1 + L_a/L_s)}$$

  - the ratio flattens out at around Ls/La > 3.
  - We believe that Ls/La ≤ 3 is a cost-efficient value that does not compromise the performance.



Beamline dimensions

- Aperture radius
  - Previous studies: 0.3 m
  - 0.1 m: too many particles lost for a wide, highly divergence beam
  - 0.3 m: dispersion too high in a long dipole (need to be proved)
    - The length of the bending dipole has to be increased to at least 1.2 m to reduce the fringe field effect. The long length will increase the dispersion of the arc, which leads to large beam size and potentially high beam losses.
    - High cost
  - 0.2 m: it seems quite a balanced choice so far.

Muon beam divergence

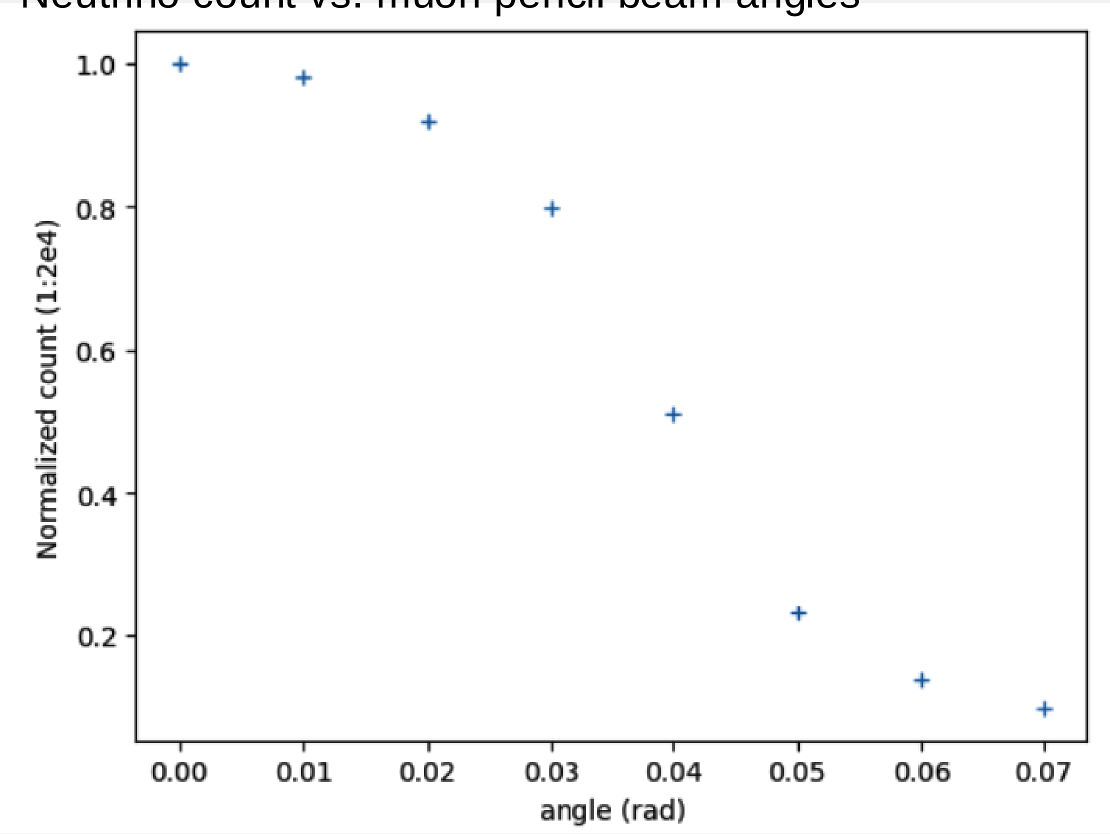
- A real muon beam has a wide divergence.
  - We cannot get all muons.
  - It has to have a cut-off angle.

- A simulation to decide a cut-off angle for the beamline design
  - For each one, a pencil 400 MeV/c muon beam at one angle.
  - Several runs have been done for different angles.
  - Muons travel 50 m space
  - Record the neutrino count at the detector.

Muon beam divergence

- The result

Neutrino count vs. muon pencil beam angles



- Select a cut-off angle, say 50% at 0.04.

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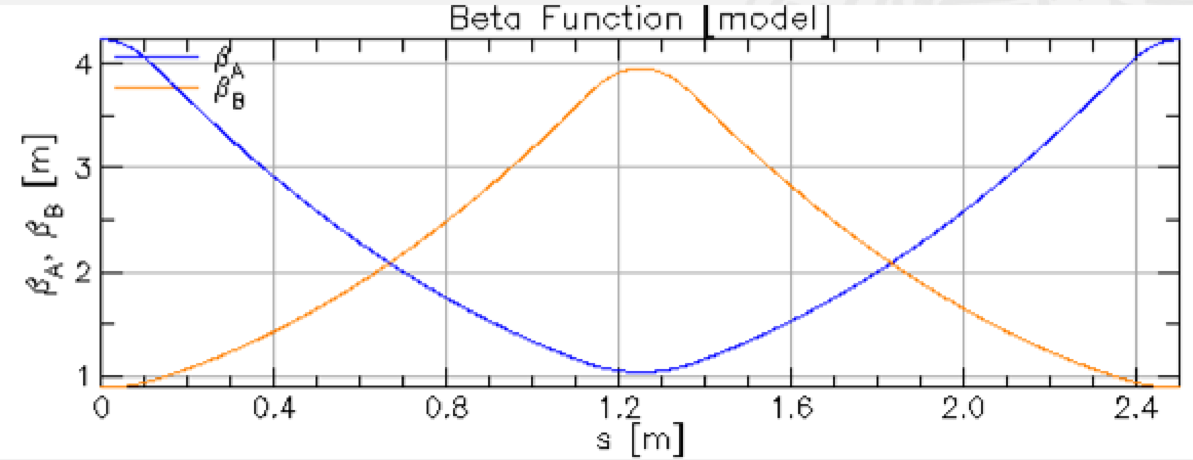
Twiss parameter: the beta function



- In order to capture as many muons as possible:

1. Assume an aperture.
2. Design a beamline with as low beta values as possible.

Because of $\sigma_x^2(s) = \epsilon\beta(s)$,the smaller the beta, the higher emittance and thus number of muons.

That gives β_{max} and β_{min}.

3. At horizontal focusing quadrupole: $\sigma_{x,\max}^2 = \epsilon\beta_{max}$. Subsitute aperture radius into maximum beam spread, $\sigma_{x,max}$, find the emittance value, ϵ.

4. At horizontal defocusing quadrupole: $\sigma_{x\prime,\max}^2 = \frac{\epsilon}{\beta_{min}}$. Sub ϵ from the previous step to find out the minimum divergence, see if it is larger than 0.04 rad, the cut-off muon divergence.

Example:

1. $\frac{\emptyset}{2}$ =0.2 m. 2. β_{max} = 4.5 m, β_{min} = 1m

3. $\epsilon = \frac{0.2^2}{4.5} = 8.9$ mmrad (Acceptance)

4. $\sigma_{x\prime,\max} = \sqrt{\frac{8.9 \times 10^{-3}}{1}} = 0.09$rad. > 0.04 rad. This beamline is okay!

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Summarise the numbers

- Neutrino energy range: 200-400 MeV
- Muon
  - reference energy: 400 MeV/c
  - cut-off divergence for beamline design: 0.04 rad.
- Pion reference energy: 700 MeV/c

- Length of pion transfer line: < 20 m
  - Length of straight: 75 m
- Length of arc: <Ls/3 ~ 25 m
- Aperture radius: 0.2 m

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A new ring design

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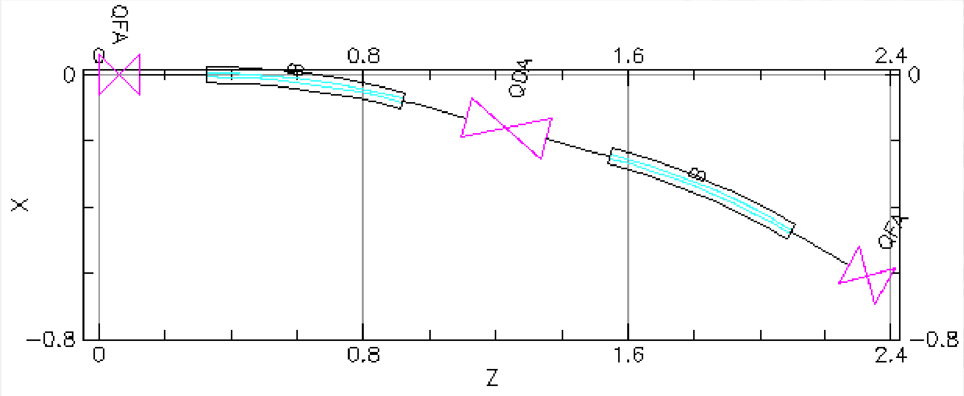
A new ring design
(capture-as-many-muons-as-possible design)

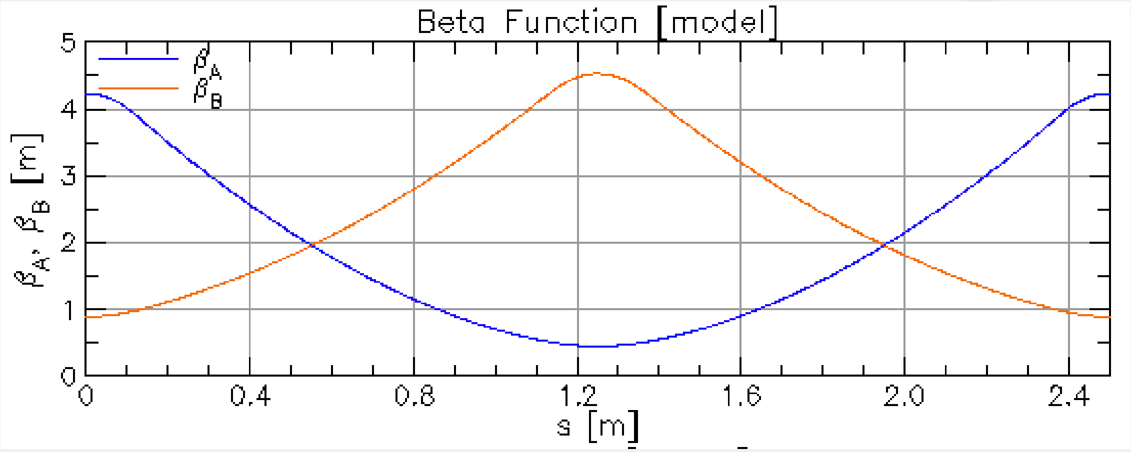
- Arc fodo cell
  - Total length: 2.5 m

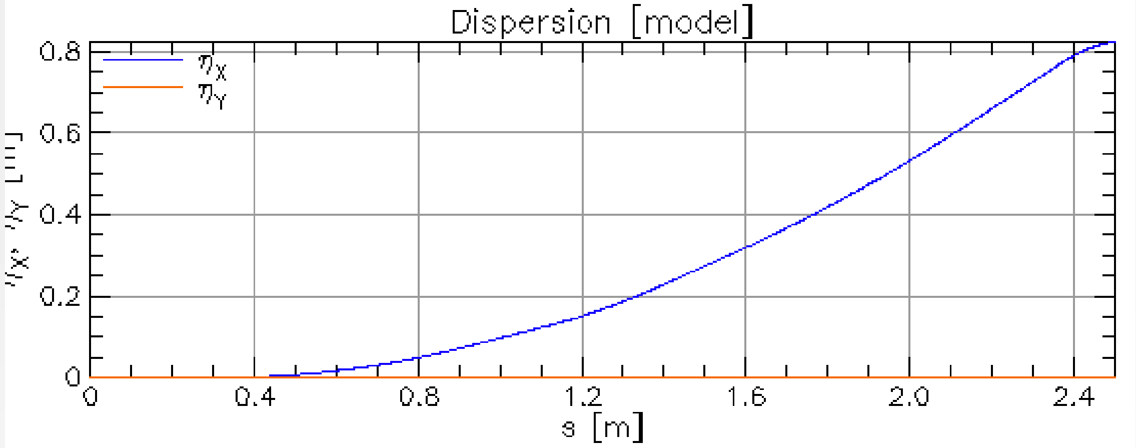
    Q: 0.25 m;

    B: 0.6 m;

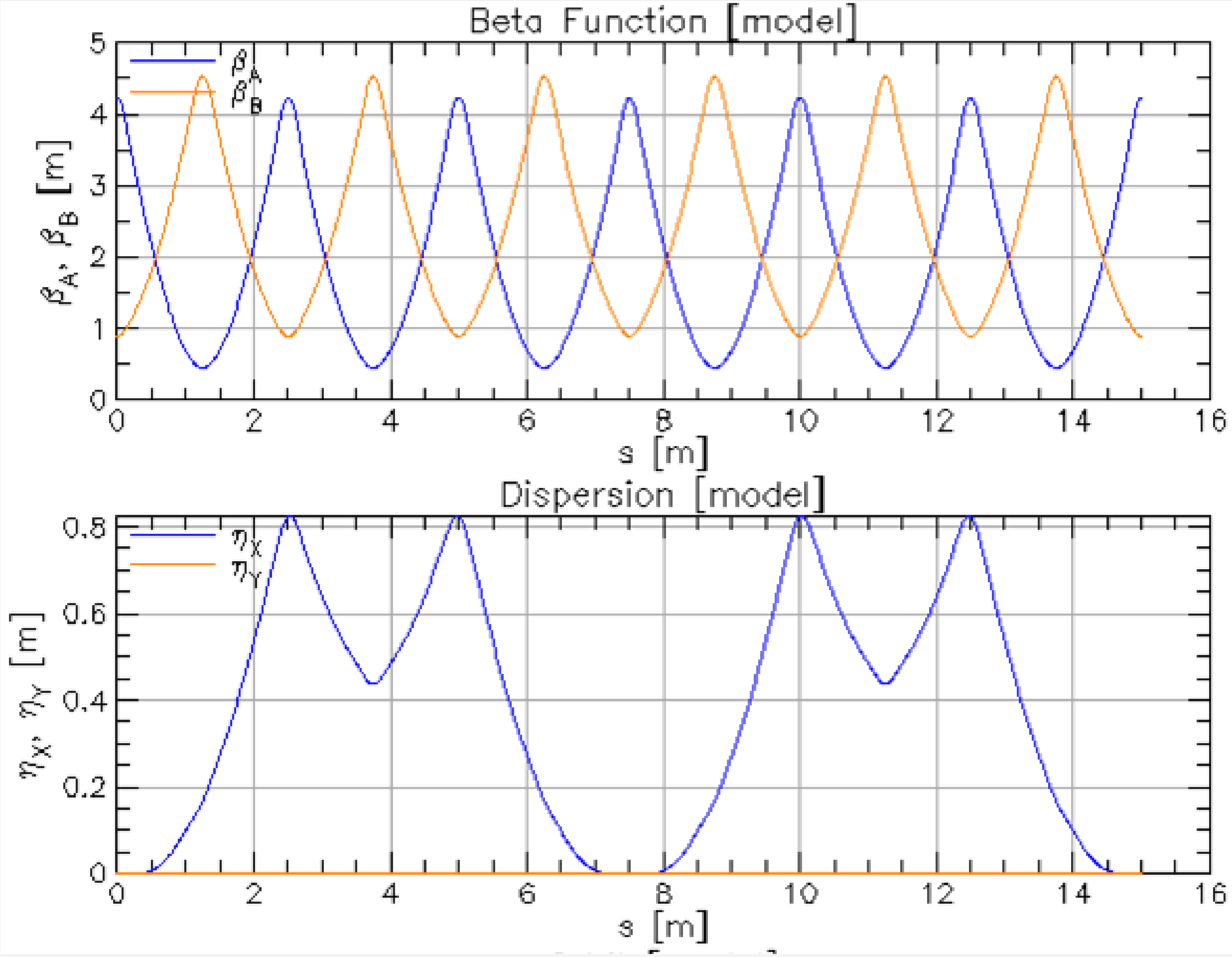
    D: 0.2 m
  - Magnetic strength (1.5 T)
    - $K1_{f,\ arc} = 5.45\ m^{-2}$
    - $K1_{d,arc} = -4.56\ m^{-2}$
  - phase advances: 120/77 degree
  - Beta: 0.5 – 4.5 m
  - Max dispersion: 0.8 m

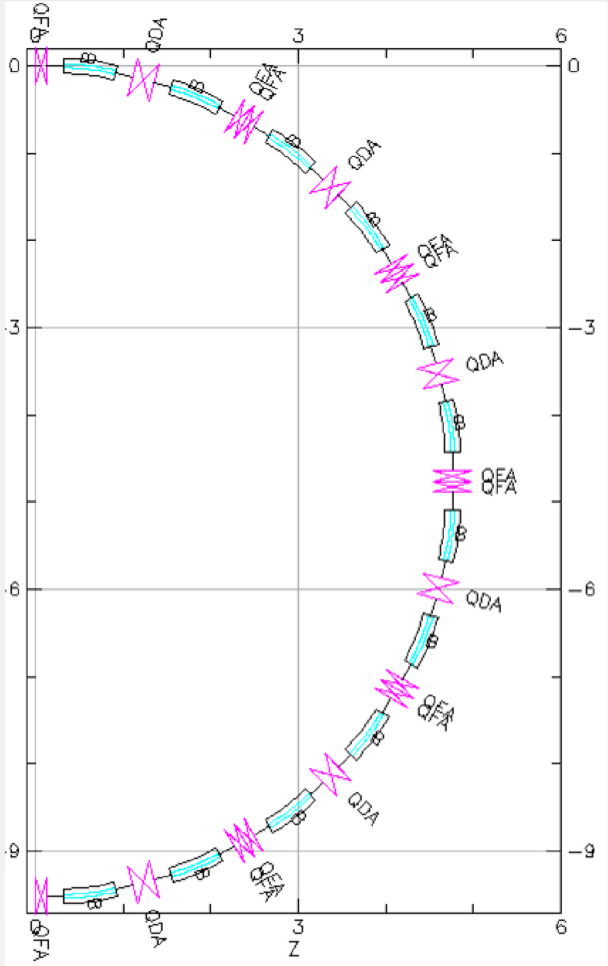






- Full arc
    - 15 m





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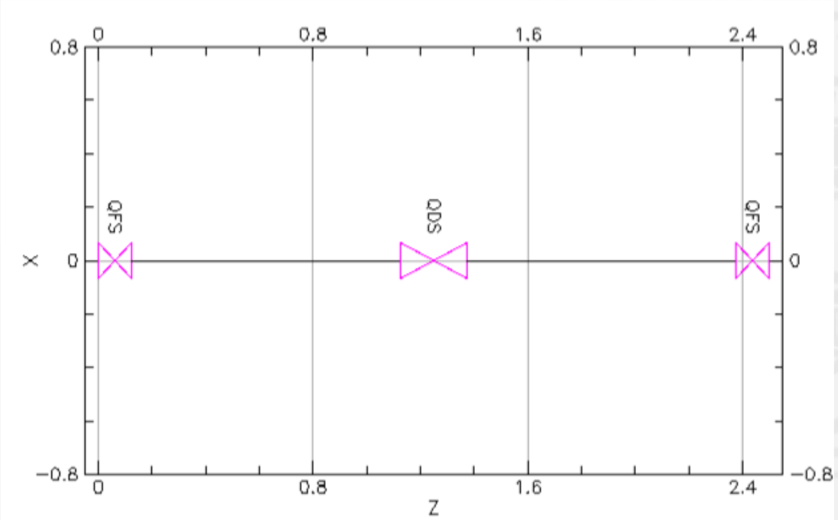
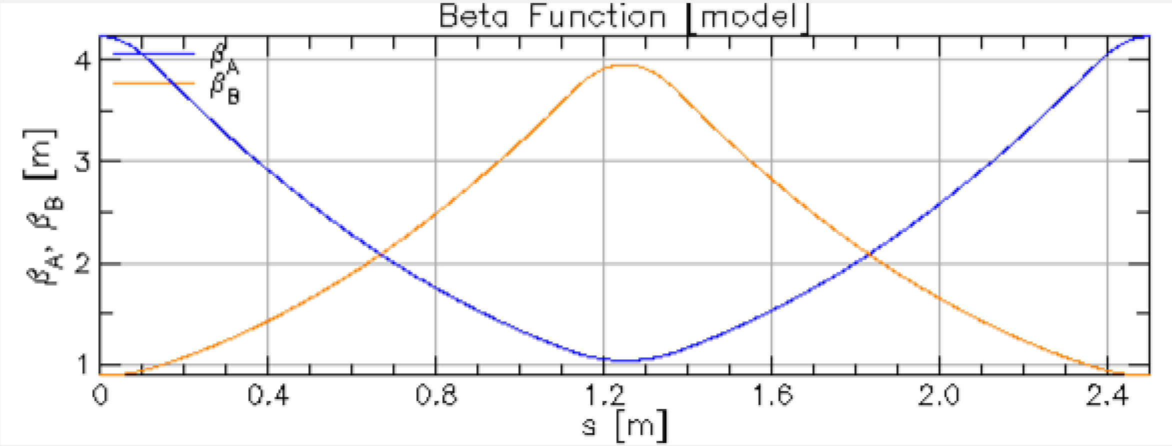
- Straight fodo cell
  - Same length as arc
  - Match to the same beginning/end beta and alpha as the arc cell
  - Phase advances: 70/80
  - Magnetic strength
    - $K1_{f,\,s} = 4.20\ m^{-2}$
    - $K1_{f,\,s} = -4.48\ m^{-2}$





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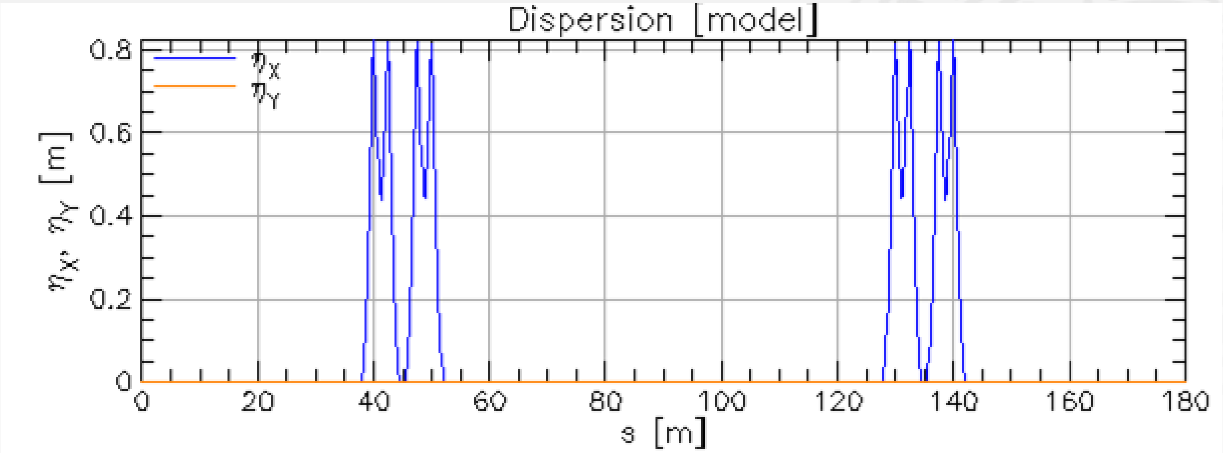
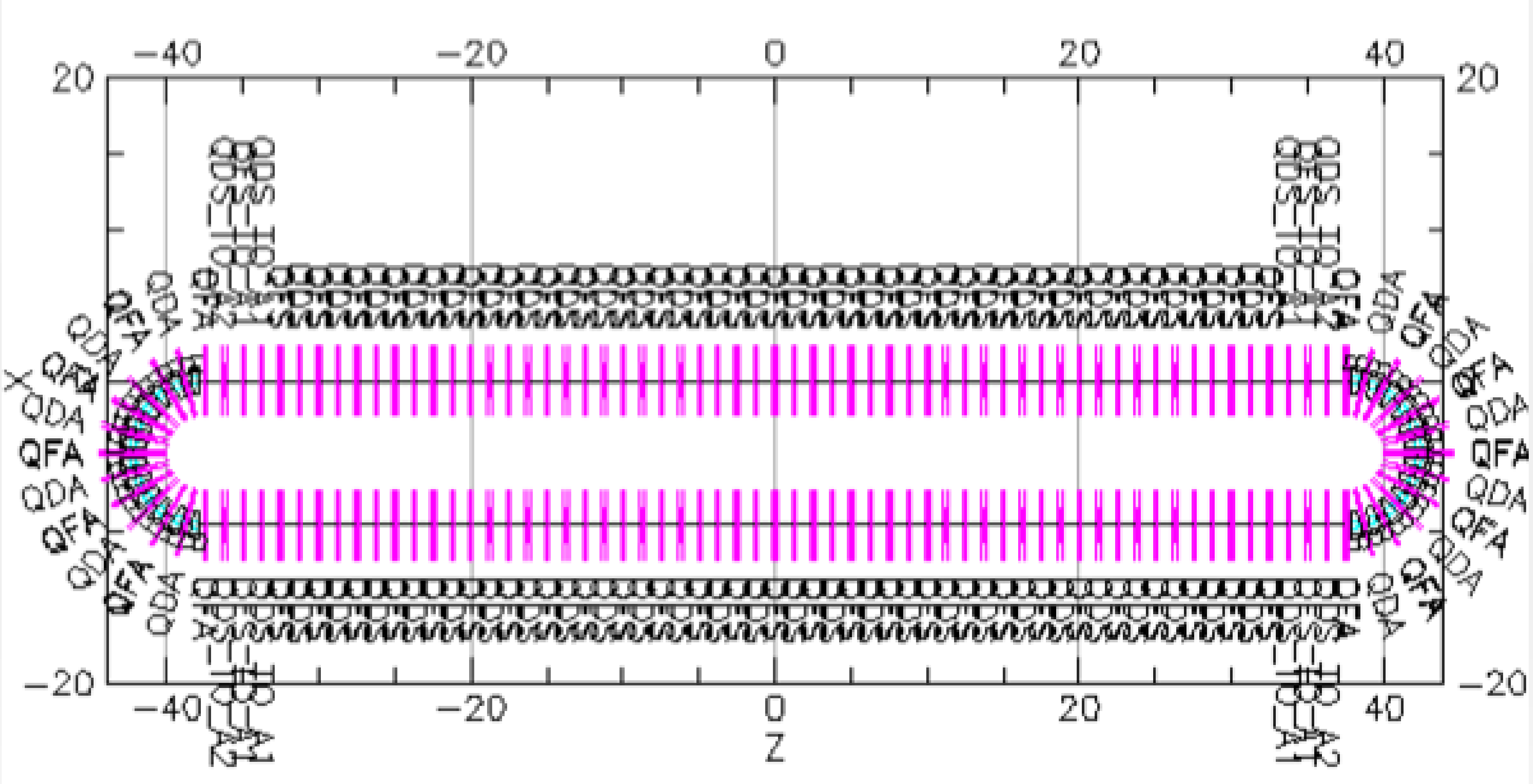
- Full ring

    - 15 m/arc
    - 75m/straight
    - 180 m in total





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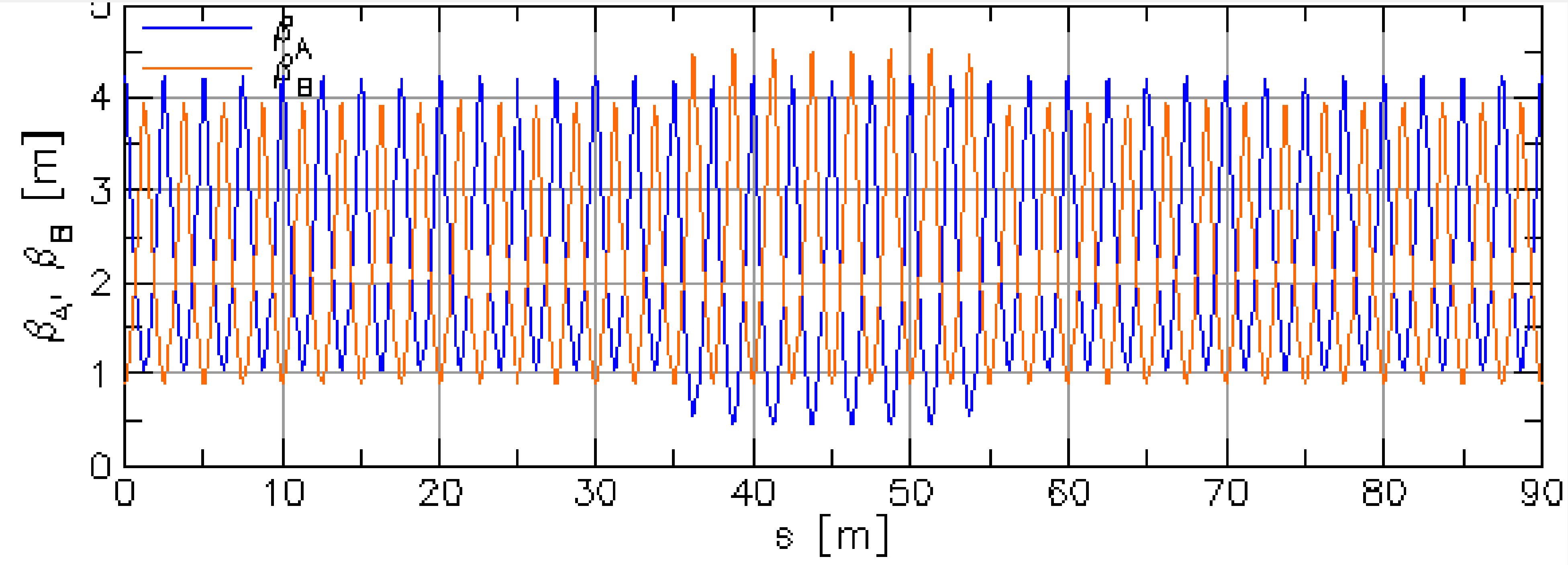
Full ring

- Tune: 16.58/16.36
- Chromaticity: -19.94/-19.50



Half of the ring

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Full ring

Tracking (w/o chromaticity correction, 50 turns, paraxial approximation)

Aperture	ϵ [mmrad]	δ	Survival rate after 50 turns, %
0.3	2	0.1	51
0.3	3	0.1	40
0.2	3	0.1	20
0.1	3	0.1	0

(Fermi lab condition!)

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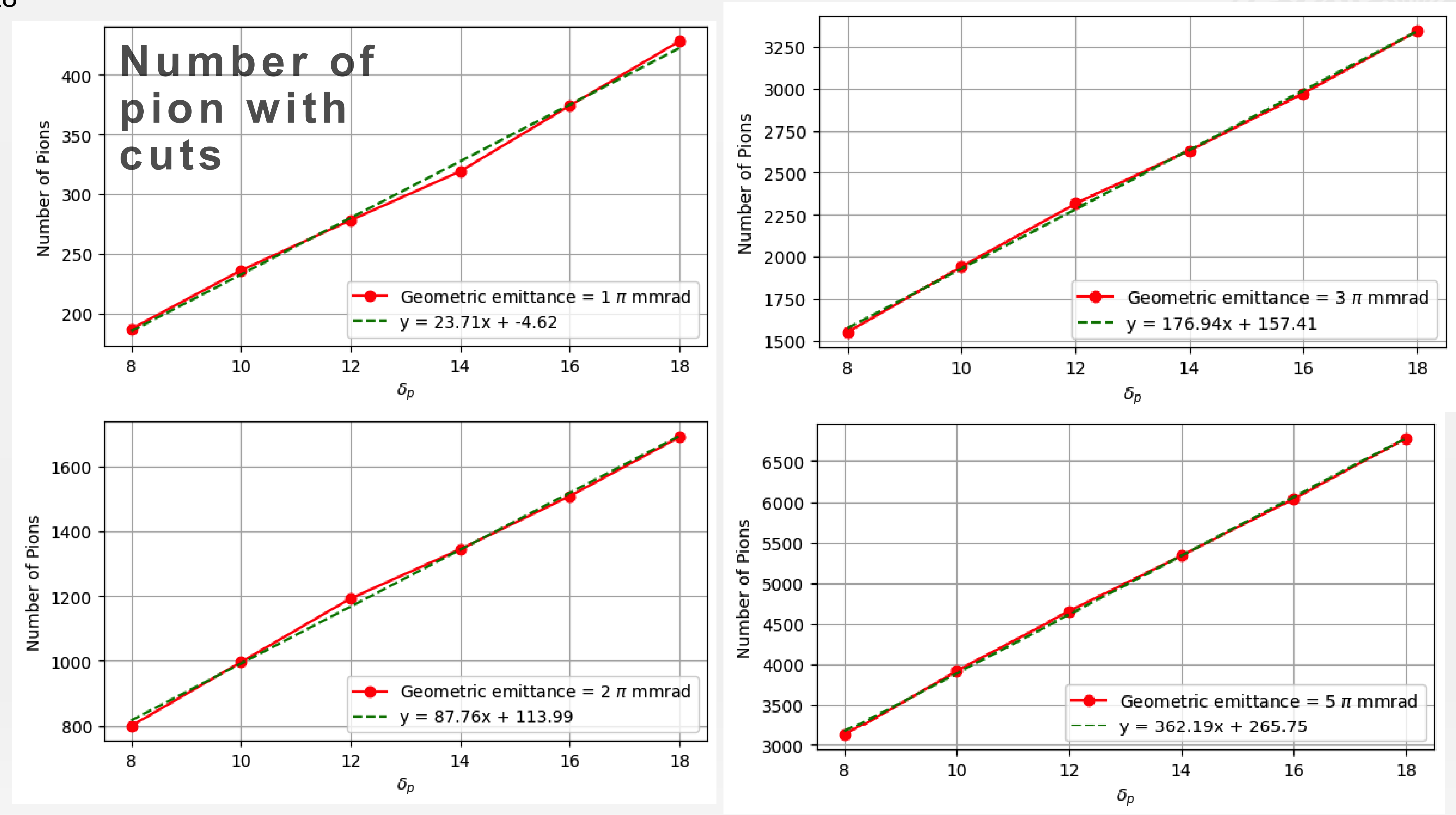
Number of pion with cuts

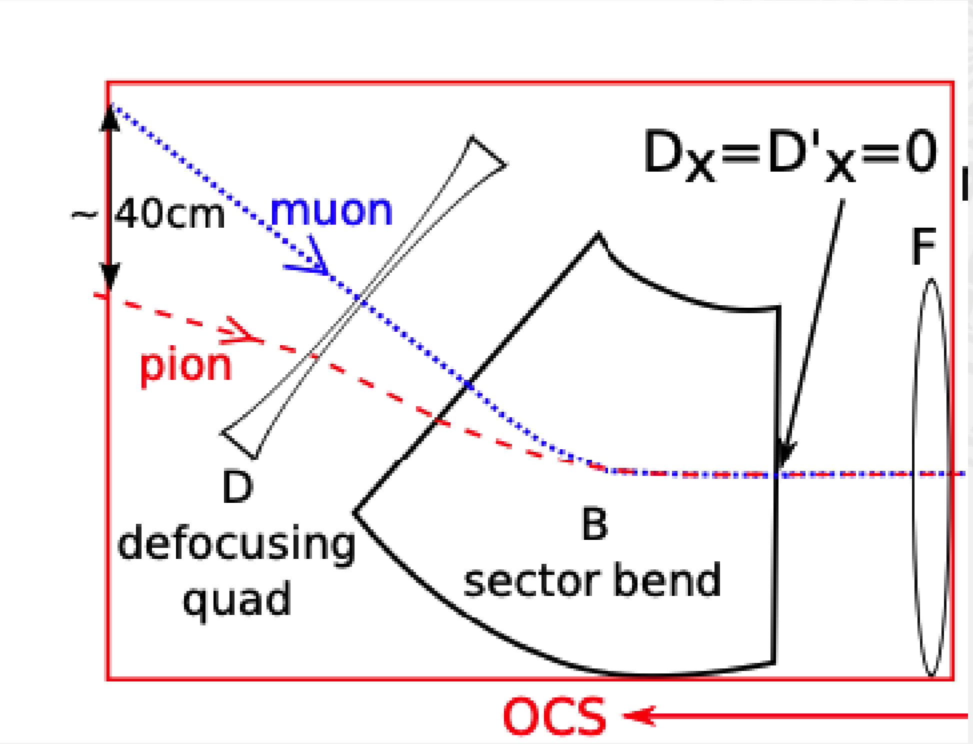


Injection

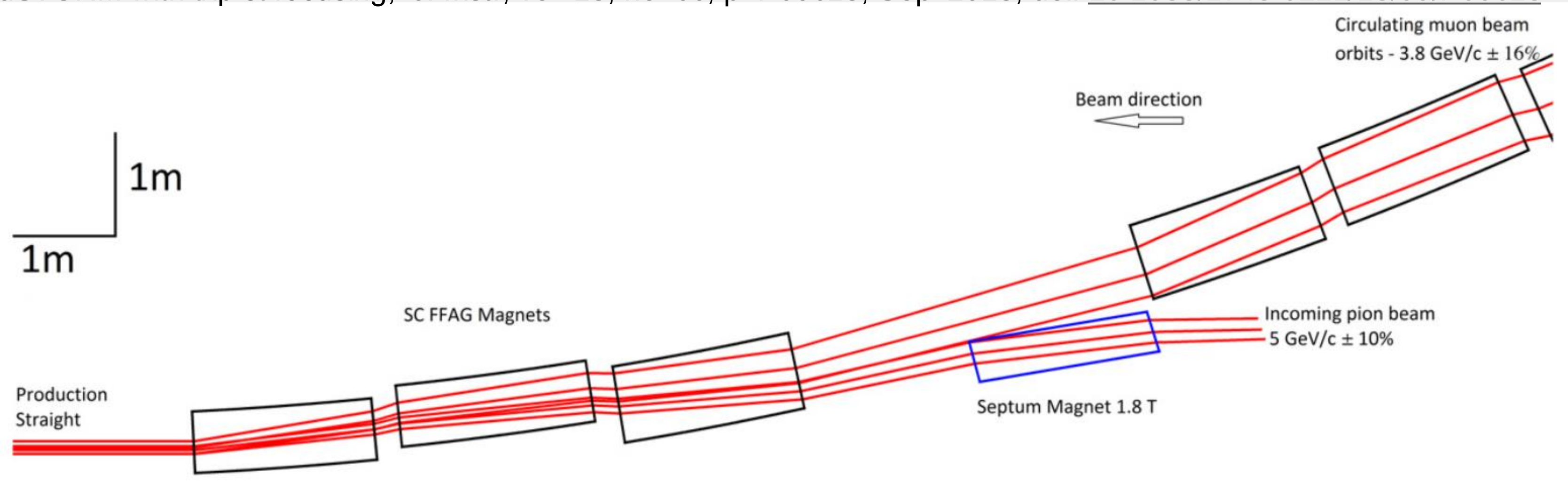
If stochastic injection:

- 15m arc
  - 0.09 -0.276 rad (16º)
  - 20 cm drift
- 20m arc
  - 0.11 - 0.234 rad (13º)
  - 45 cm drift

Or use septum magnet



J.-B. Lagrange, R. B. Appleby, J. M. Garland, J. Pasternak, and S. Tygier, “Racetrack FFAG muon decay ring for nuSTORM with triplet focusing,” *J. Inst.*, vol. 13, no. 09, p. P09013, Sep. 2018, doi: 10.1088/1748-0221/13/09/P09013.



Preliminary flux estimation

Table 1: The ratio (right column) of the particle (pion/muon/neutrino) left because of the item on the left column estimation of a number of neutrinos coming out from the production straight (last row).

Reason of the loss		**ratio left**
Horn focusing		0.167 (POT)
Transfer line momentum and emittance cuts (assumed perfect horn)		1
Injection		0.5
Muons from pion decay:	momentum acceptance cut	1
	emittance	0.1
	decay probability	0.5
Muons survival in the ring:	one straight-to-ring circumference ratio	0.4
	chromaticity	0.5
Muon to neutrino: decay emission angle cut		0.035
Total		2.34e-5 (POT)

- But it seems a real horn will turn out the ratio 1e-2. (instead of 1 in the table)

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Preliminary flux estimation

Table 2: Estimation of a number of neutrinos coming out from the production straight.

	Number
number of proton per subpulse	2.2e14
number of proton in a second	2.2e14 * 14
number of neutrino per type in a subpulse reaching the LEMMOND	2.2e14 * 2.34e-5 = 5.14e9
number of neutrino per type in a second reaching the LEMMOND	2.2e14 * 14 * 2.4e-5 = 7.20e10

Outlook

- Chromaticity correction
  - Sextupole only?
  - FFA?
- Particle tracking
  - With and without decay
- Injection
- D4.1
- …