nuSTORM at FNAL - performance of target, horn, injection and FODO ring

Ao Liu

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Outline

- Motivation and introduction (I'll not preach to the choir)
- Target and Horn
- Injection
- Ring
- Conclusions

Motivation

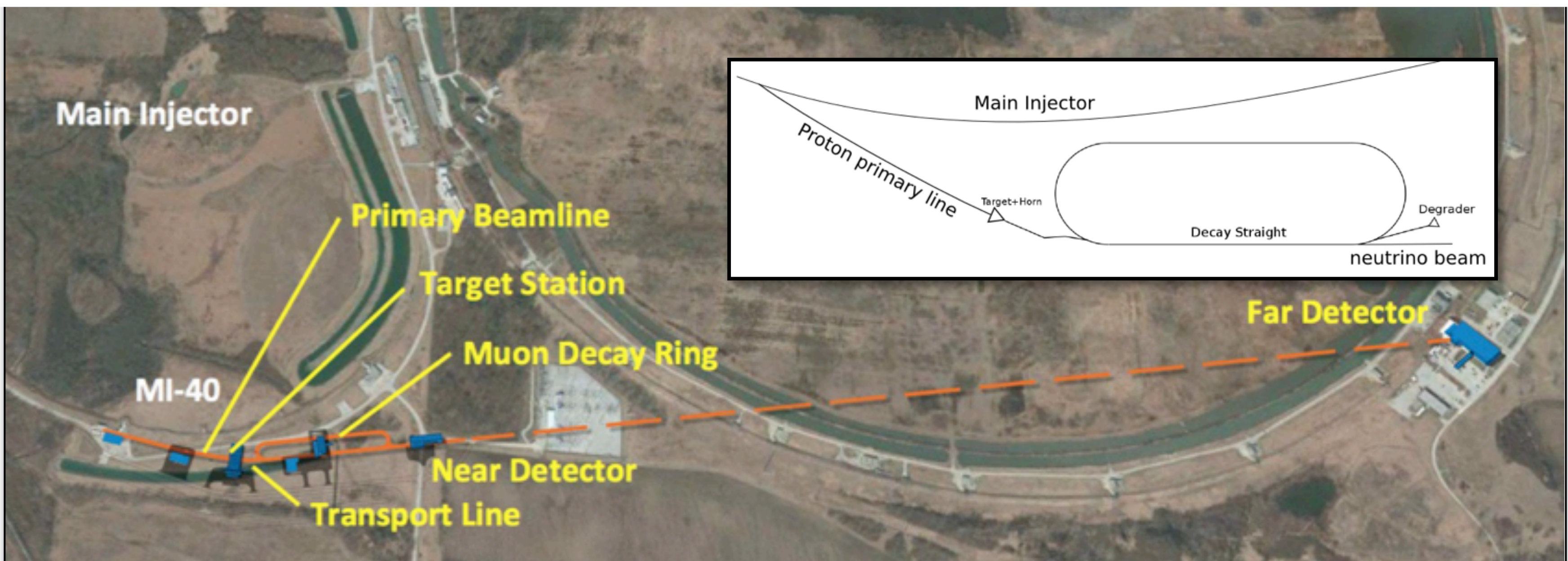
nuSTORM is amazing

Motivation

- Electron neutrino cross section in a wide range of momentum
- Definitive statement about the existence of a light-sterile neutrino
- Accelerator test bed for a muon collider, a neutrino factory, and other muon accelerator facilities

Introduction of nuSTORM at FNAL

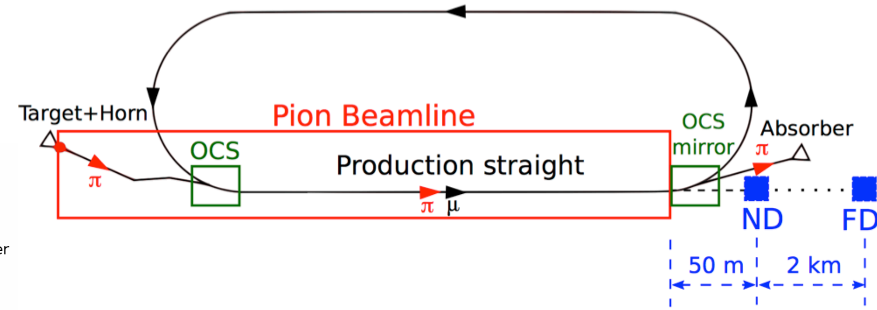
- nuSTORM (neutrinos from STORed Muons)
  - A technically ready-to-be-built simplest representation of a neutrino factory
  - The injection is done by stochastic injection → no fast kickers needed
  - Requires no RF acceleration nor cooling

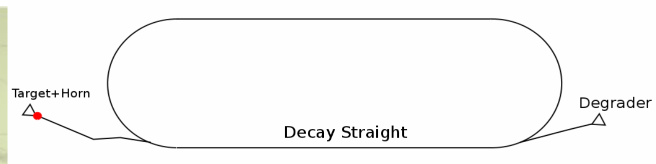


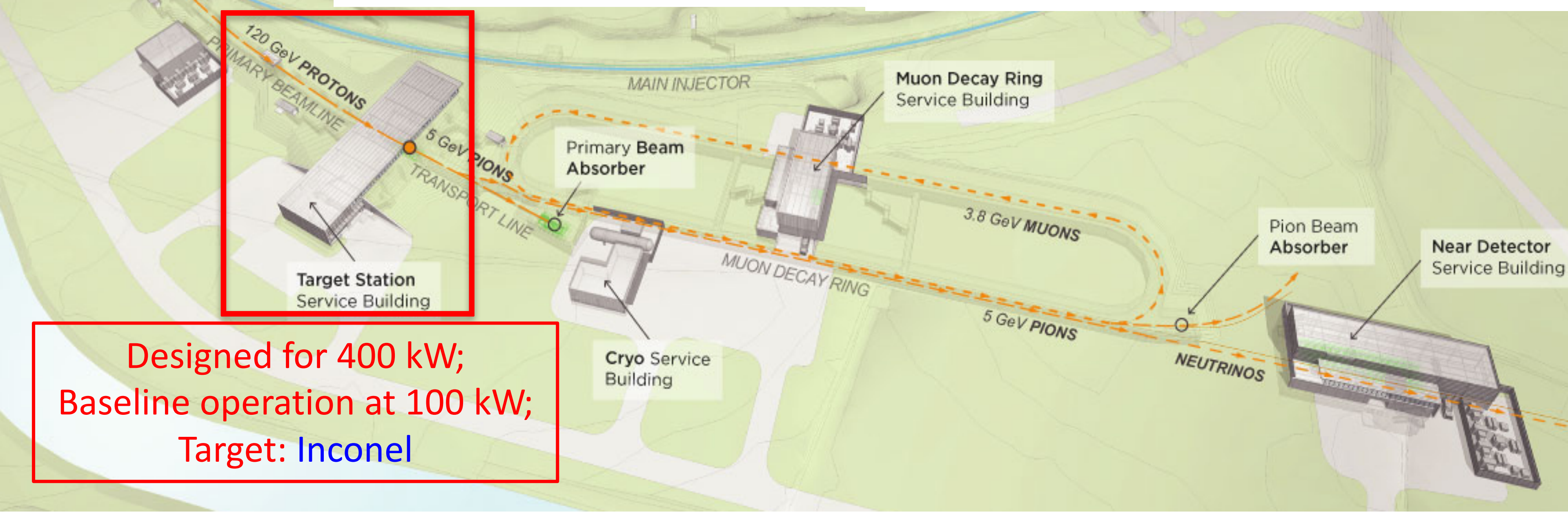
Introduction of nuSTORM at FNAL

- Well understood neutrino beams from a 3.8 ± 10% GeV/c muon storage ring

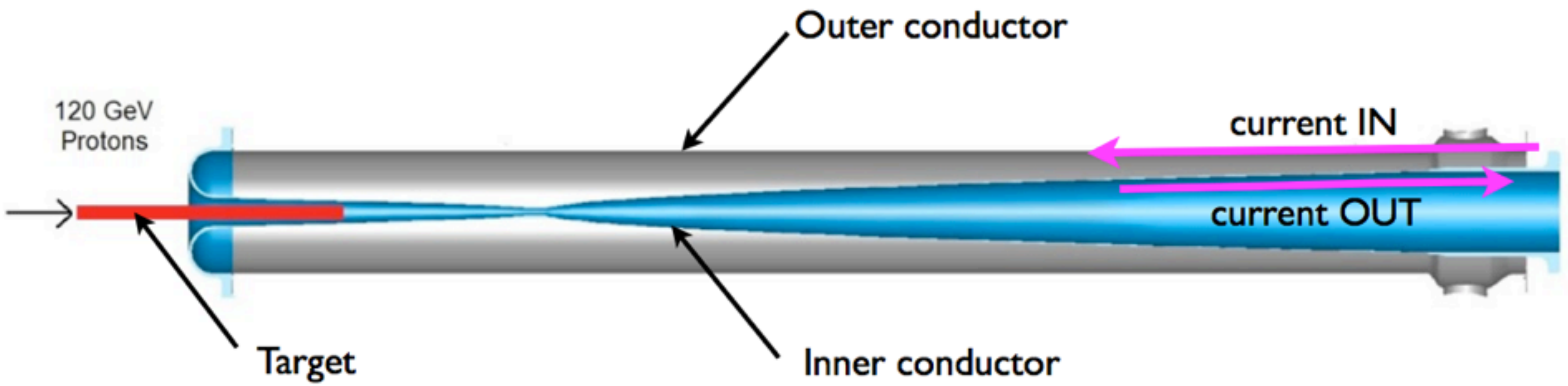
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \qquad \mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$$







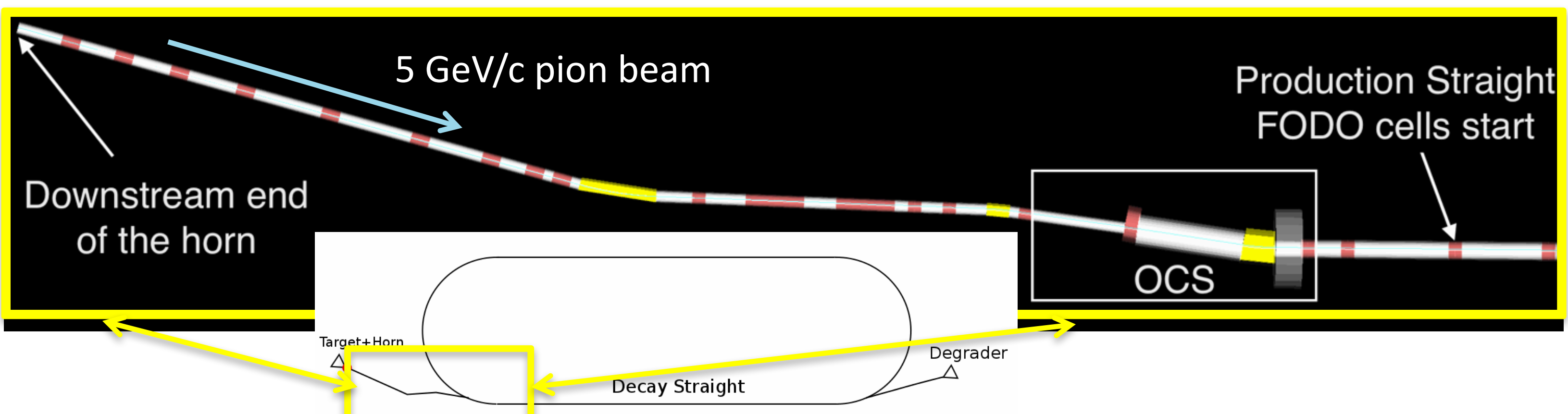
Target and Horn



- Inconel target outperforms other materials
  - Choice of target length presented in later slides
- Horn provides powerful focusing for a target inside the horn
  - Optimization of horn presented in later slides

Design sequence

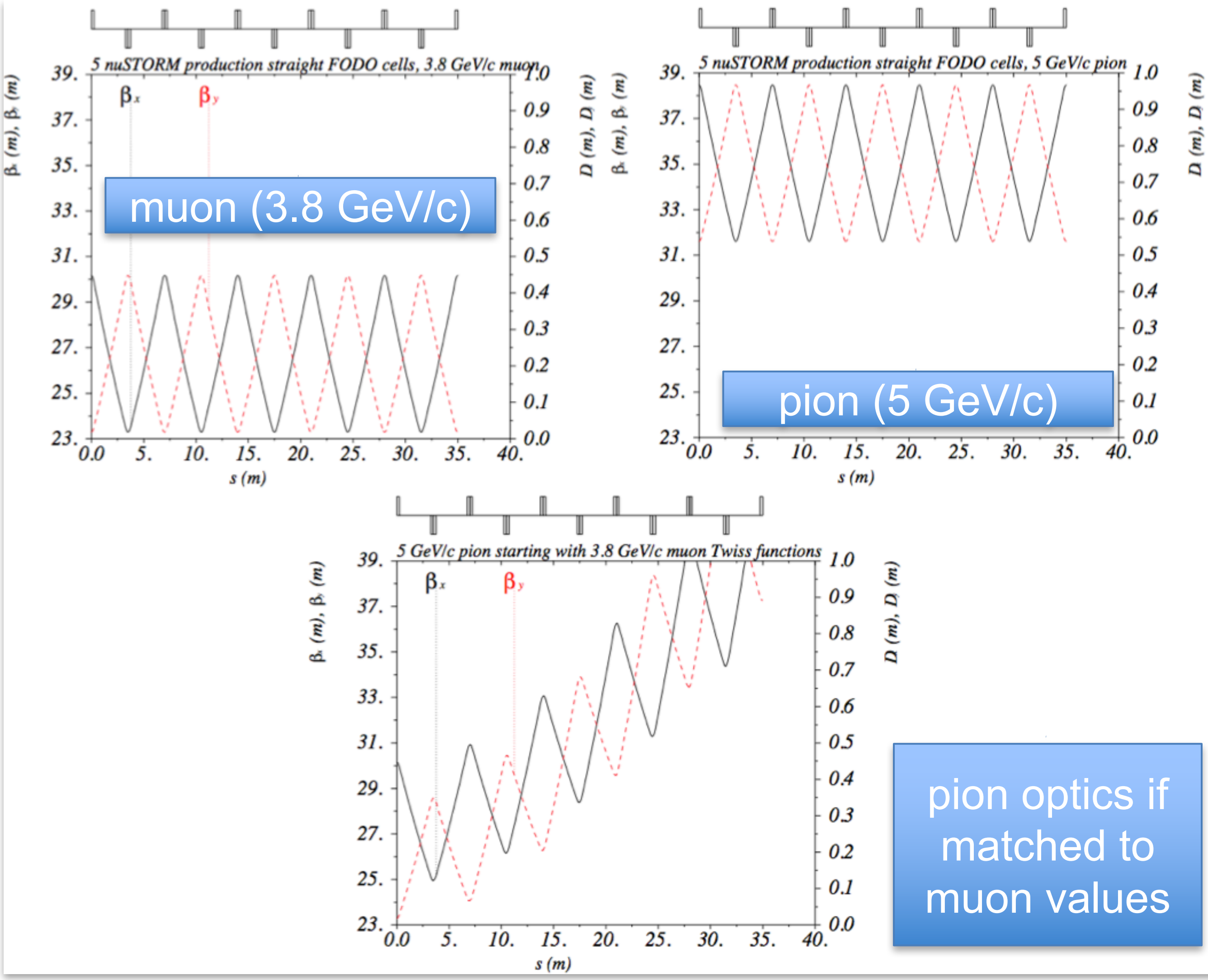
- Design of the nuSTORM facility is unique in many senses
  - Optics of the decay straight section of the FODO ring is determined first, then the injection, horn and target are optimized based on the injection performance
- Multiple design tools used in this design procedure
  - MAD-X as the linear optics and PTC tracking tool
  - G4beamline to track secondaries and generate neutrino flux
  - MARS15 to simulate the target bombarded by the proton beam
- Starts from pion-beamline (pion transport line, the orbit combination section (OCS), the production straight)



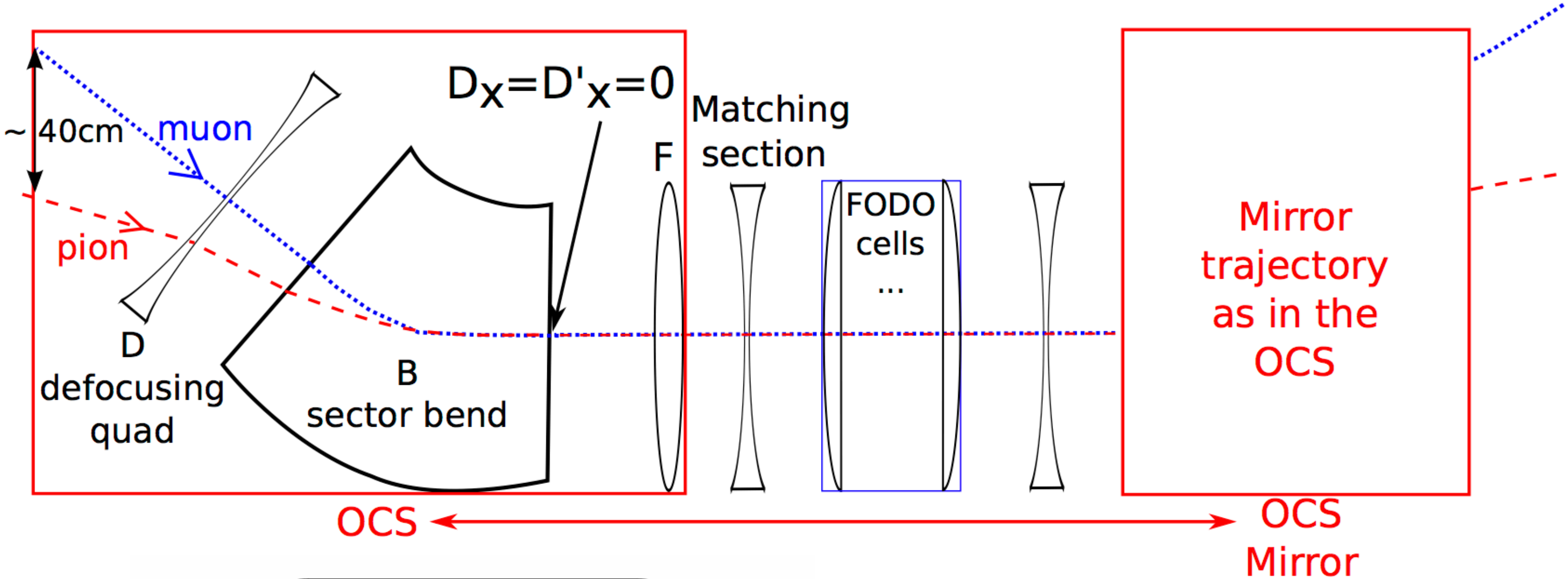
~ 150 m FODO cells

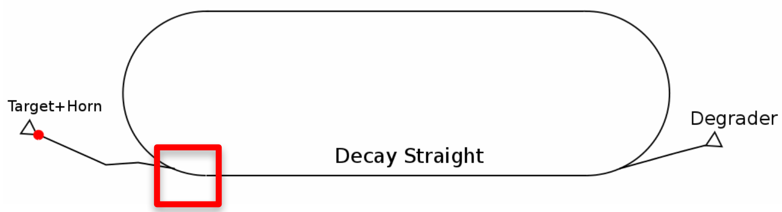
Pion beamline – decay straight FODO cell

- In order to realize stochastic injection, FODO cells have to accept two beams at different momenta
- Not a traditional design like in g-2 where pion and muon beams are at same P

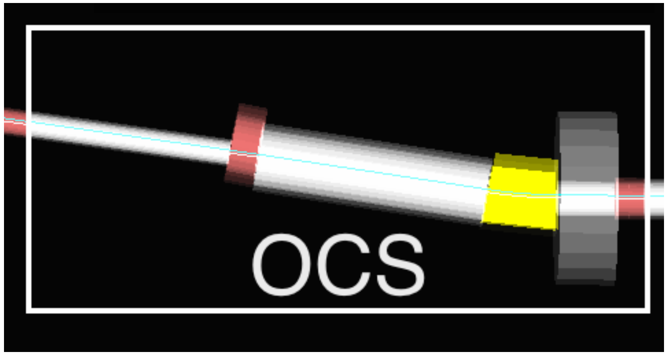


Pion beamline – Orbit Combination Section (OCS)

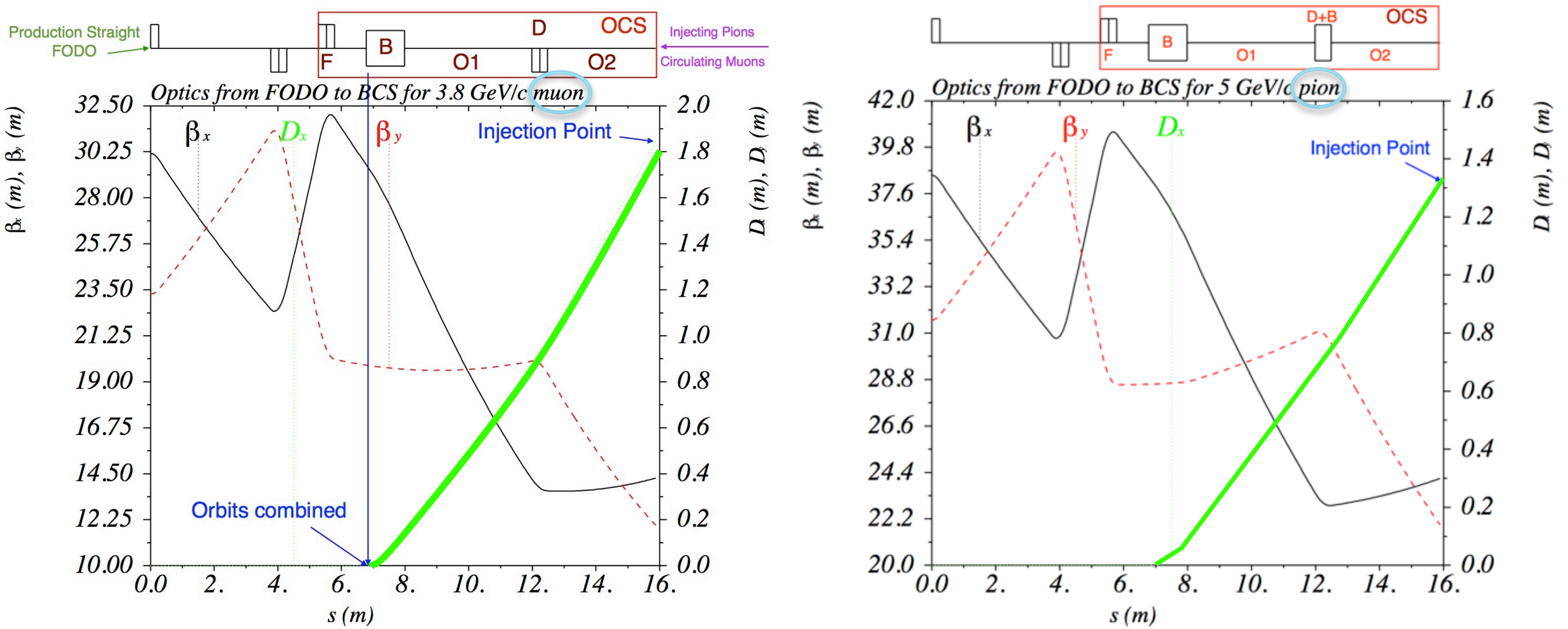




- OCS brings the reference orbits of pions and muons together after injection
- Requires large aperture magnets (D and B)

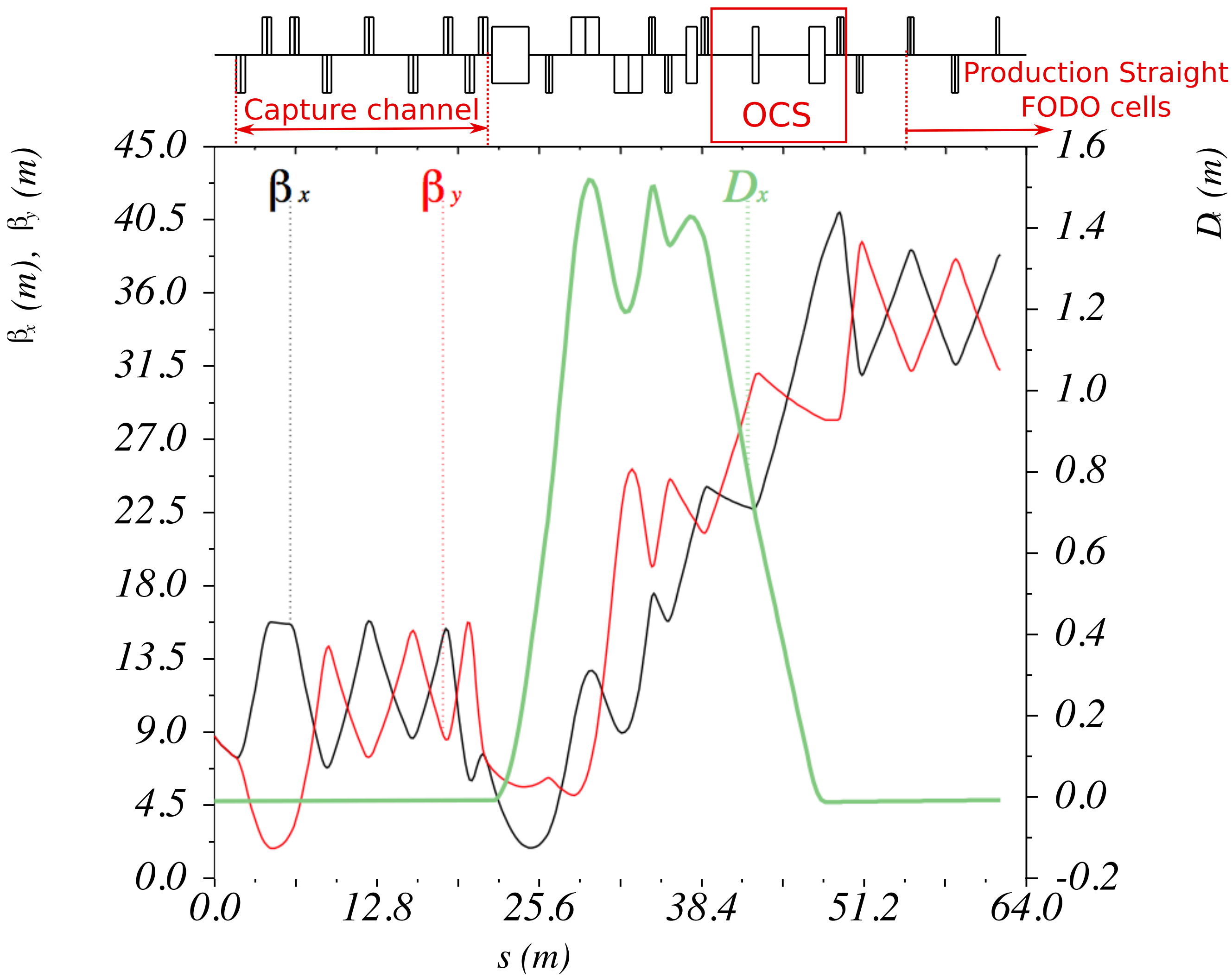


Optics of pions and muons to OCS



- Twiss at the injection point needed to continue optic design in the pion transport line
- Dispersion is the key parameter to allow enough separation at the injection point
  - Trade-off: beam size grows with dispersion so beta functions have to be small. Dispersion to follow has to be reduced quickly.

Pion beamline optics



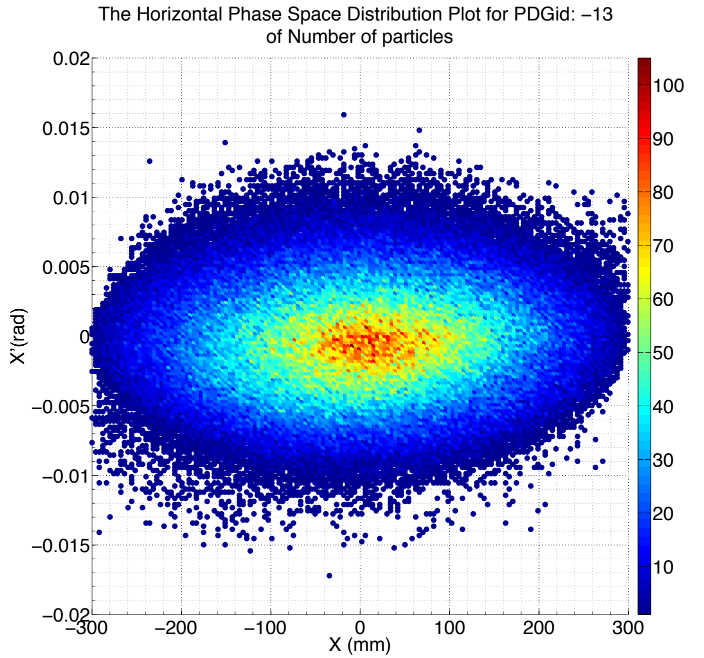
From the OCS, Twiss are matched to the pion optics at the downstream face of the baseline collection horn

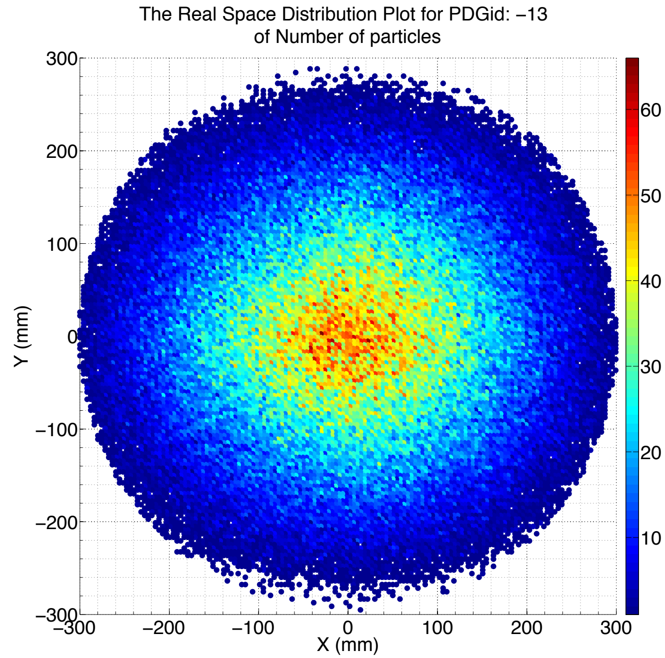
In this figure, pions move from left to right

At the downstream face of the horn (left) the dispersion should be 0

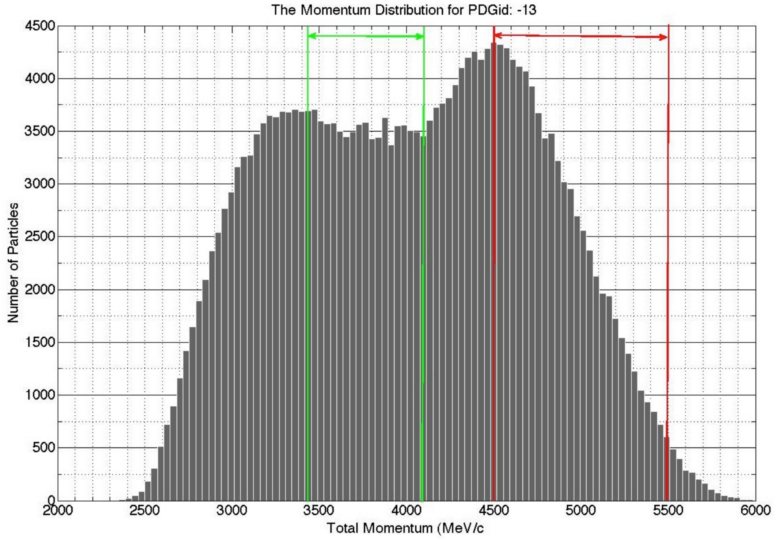
The 2nd dipole was added to ensure target station is not too close to the decay ring

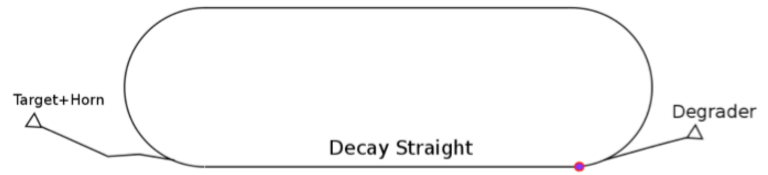
Muons at the end of decay straight after injection





Summary:
0.014 muons within the desired 2000 µm phase space acceptance and the 3.8±10% GeV/c momentum acceptance





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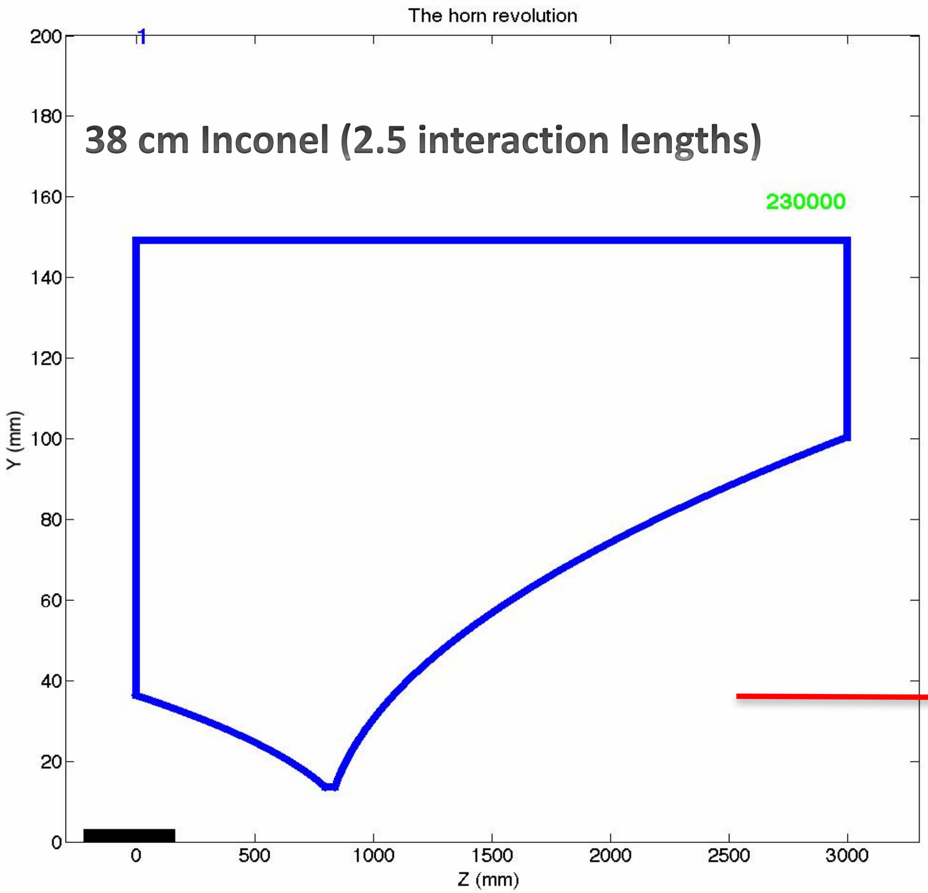
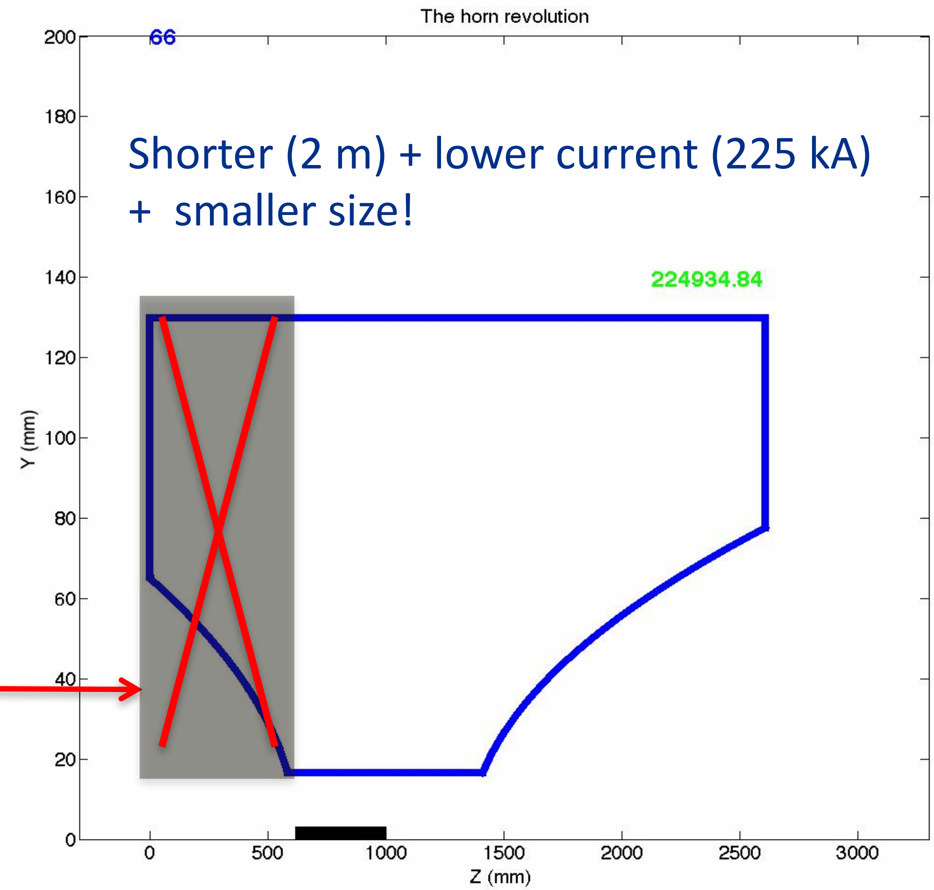
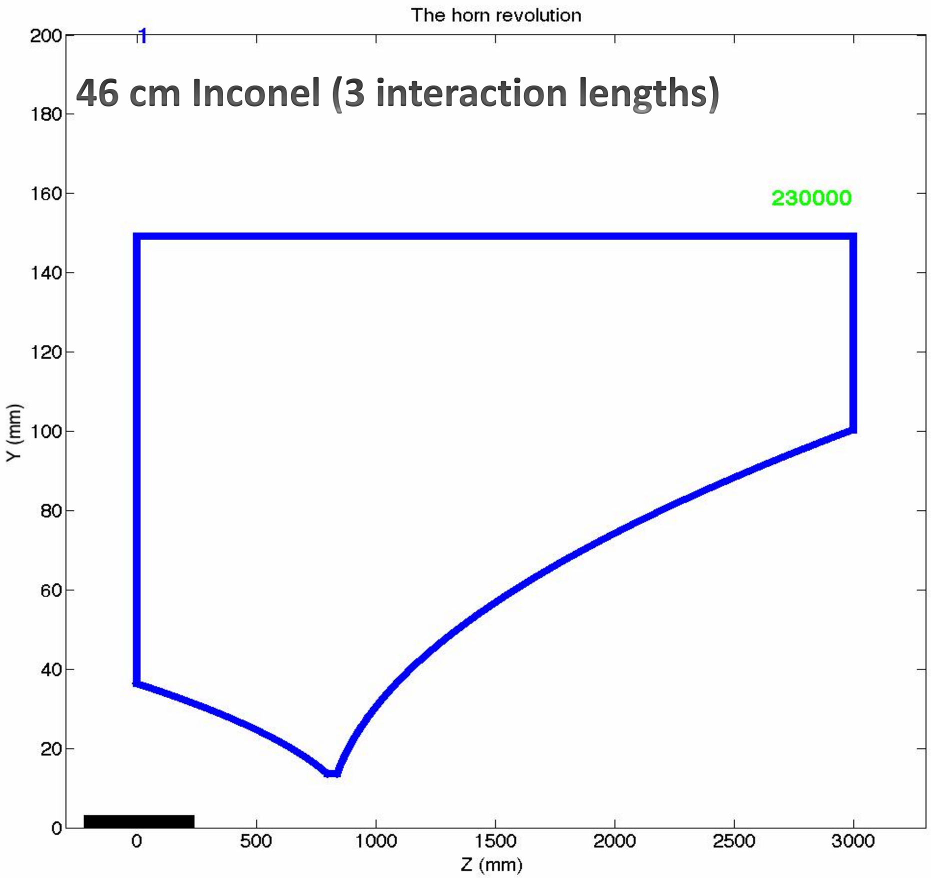
Horn Optimization using the Genetic Algorithm

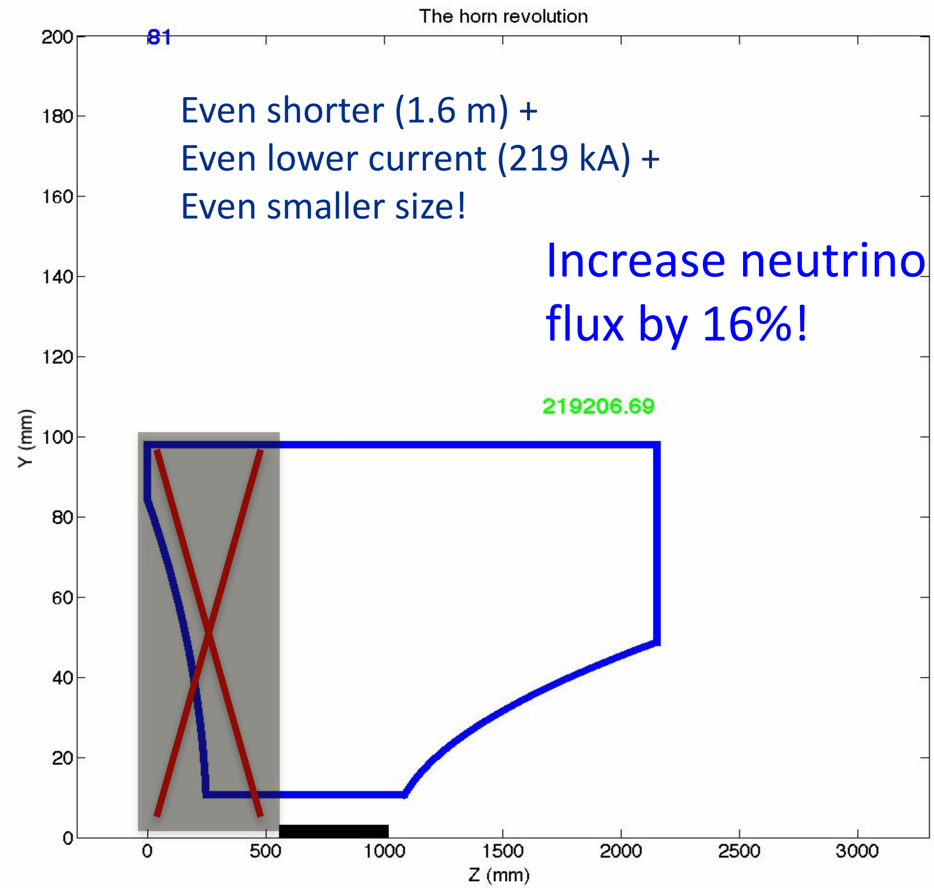




Pion beamline optics redesigned, tracking redone to reflect new optics;
μ+ in both 2000 μm and 3.8±10% GeV/c increased by 8.3%

Pion beamline optics





$N_{\mu,P}$ and $N_{\pi,\varepsilon}$ increased by ~20%; (If just changing the target length: ~5%)

μ+ in both 2000 μm and 3.8±10% GeV/c increased by ~16% (Compared to the pre-optimization 38 cm Inconel + baseline horn)

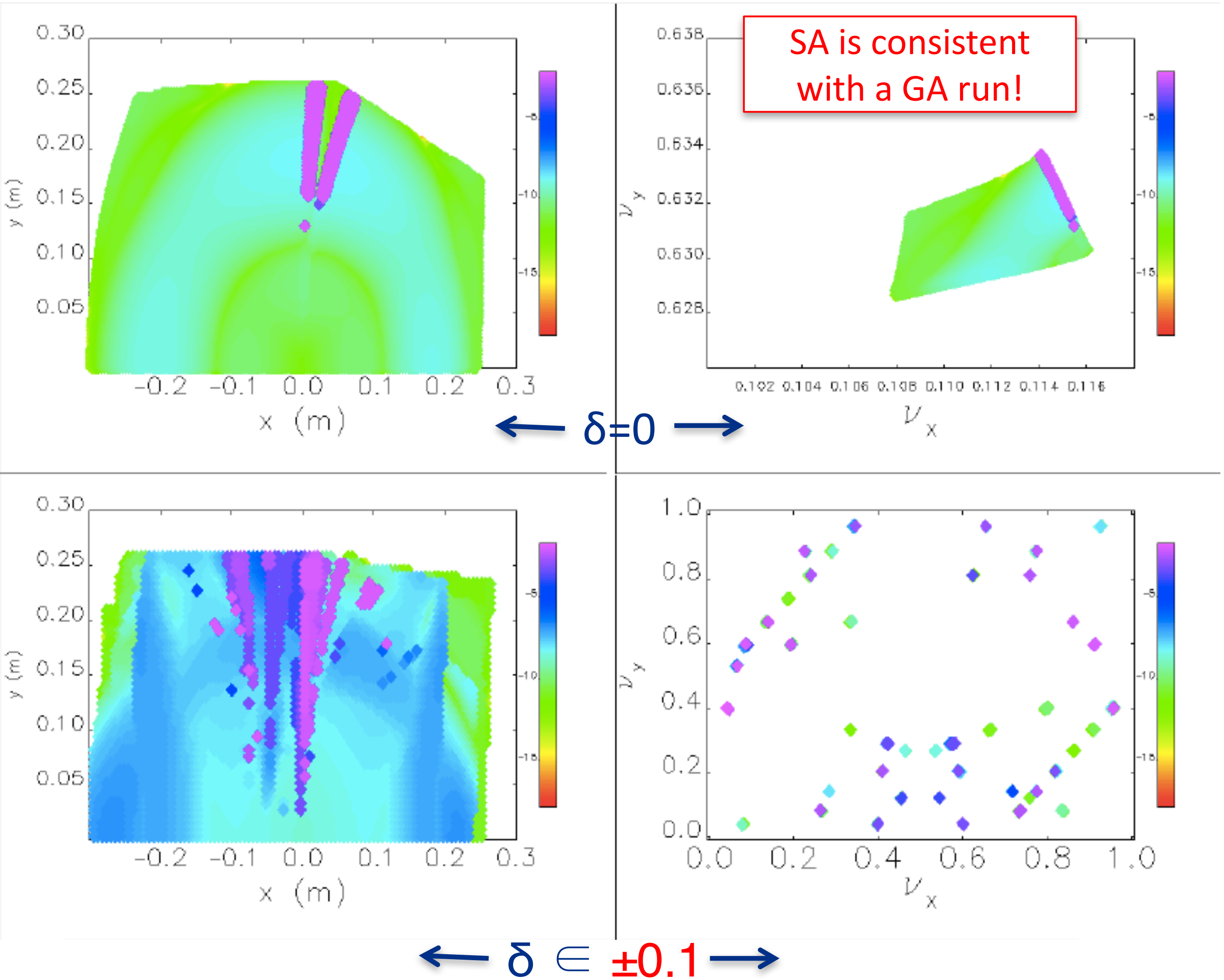
FODO ring design

- nuSTORM decay ring has many challenges
  - Large transverse beam admittance, 2000 μm rad (UNNORMALIZED),
  - Large momentum spread, δ within ± 0.1
  - Length of the arcs limited, few available spaces for sextupoles
- Use combined function dipole in the arcs
  - Smaller natural chromaticity (-4.11, -6.62), 60% transmission for 100 turns
  - Allow dispersion to propagate from OCS into arcs and design periodic dispersion in the arc cells, suppress beta function to limit beam size
  - Large aperture combined function magnets need R&D (superconducting)
- DBA cells designed as a comparison: harder to implement sextupole corrections and lower acceptance

FODO ring and sextupole correction

- Where to put sextupole / sextupolar field
  - Drift space in the arcs (dispersive) but space is limited by the length ratio of arcs v.s. straight;
  - Sextupolar field in combined function dipoles but strength is limited by the pole tip field allowance
  - Above are all the dispersive locations
- How to set strength of sextupoles
  - The sextupoles will correct not only chromaticity but also higher order terms such as geometric abberations, 2^{nd} order dispersion and so forth
  - Beam is large and has large momentum spread: many orders of nonlinearities
  - Use the Simulated Annealing (SA) and MAD-X PTC tracking to directly optimize acceptance

FODO ring and sextupole correction



FMA (performed by ***elegant***)

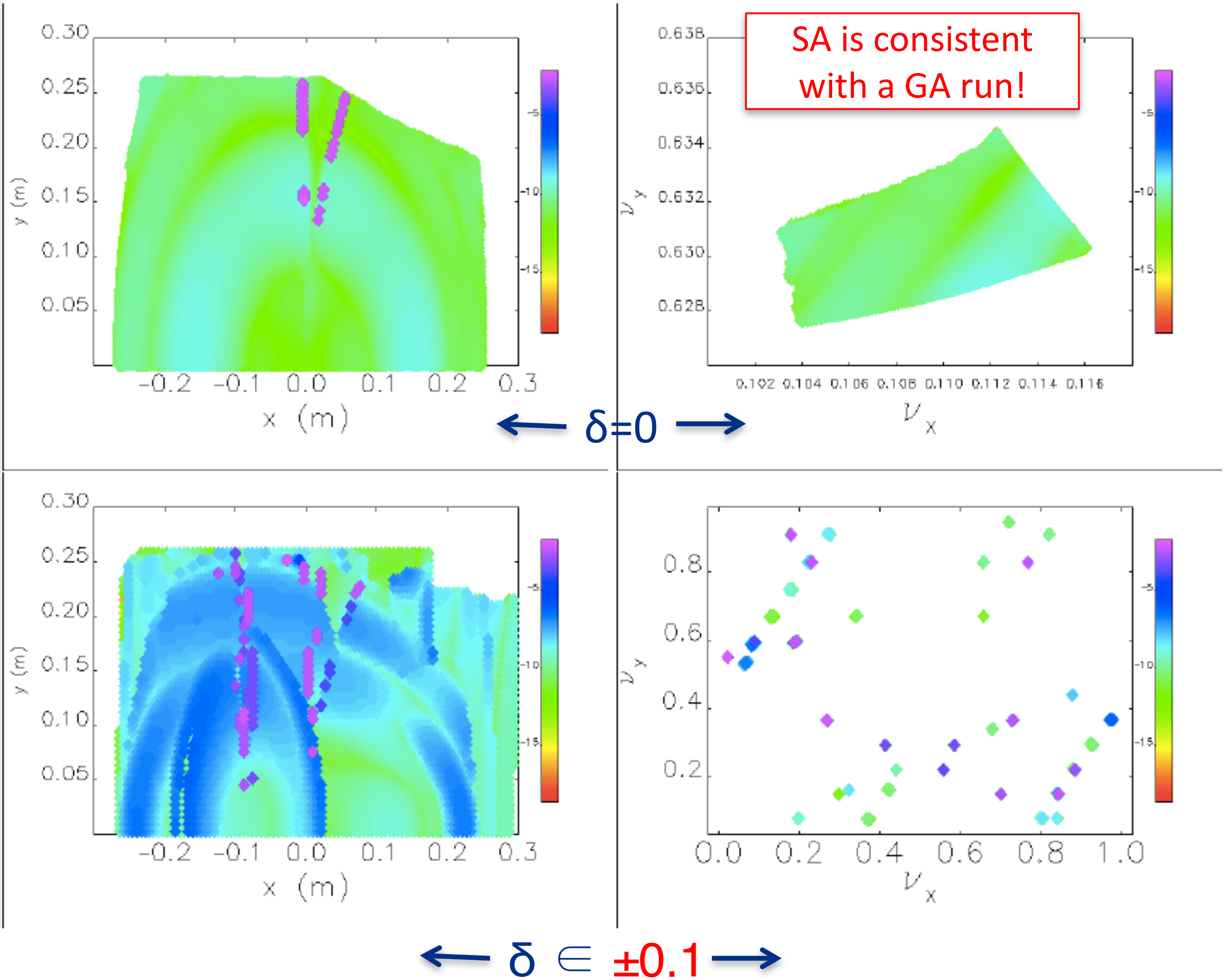
Low tune shifts with amplitude before sextupole correction;

With sextupoles, SA corrects mainly:

1. Second order chromaticity $d^2\nu_{x,y}/d\delta^2$: -3.62 to 0.41, -10.7 to -3.79
2. Second order dispersion: D_2: 21.2 to 1.57

Acceptance increases from 58% to 67%

FODO ring and sextupole correction



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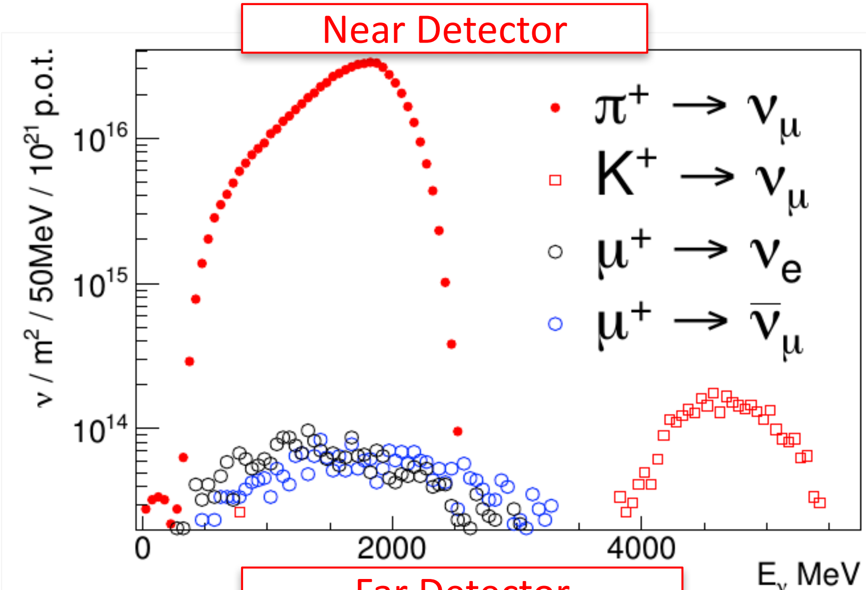
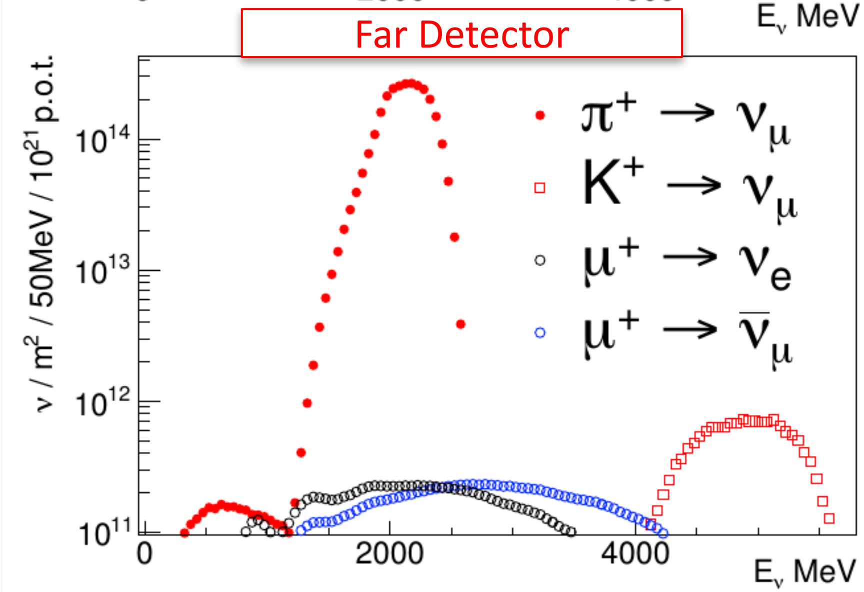
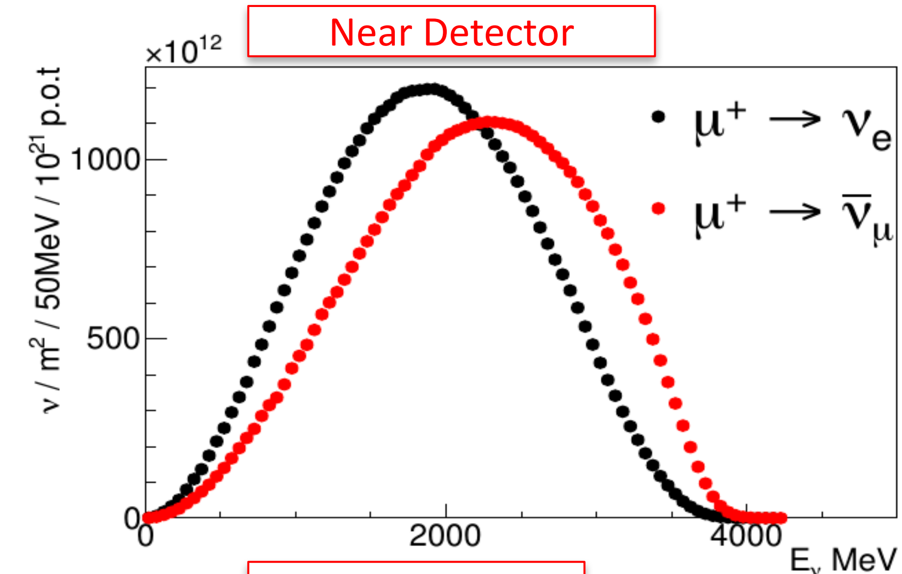
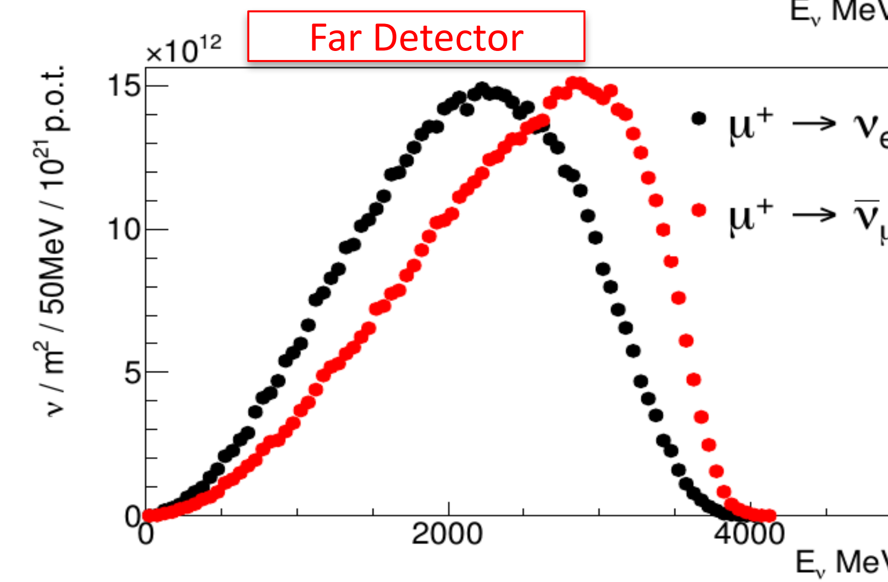
Neutrino flux at nuSTORM









Conclusions

- Designs for the nuSTORM target, horn, pion beamline and FODO ring have been done
- Performance of the design can be used as a benchmark for the future optimizations
- nuSTORM @ FNAL facility design experience can be readily applied to nuSTORM @ CERN
- Looking forward to continuation of interest in and development of nuSTORM