νSTORM Beamline Design

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Outline

- Introduction to *νSTORM* (ν from STORed Muons)
- Design of *νSTORM* Transport Line
- Low Energy Muons from *νSTORM*
- *νSTORM* Muon Decay Ring Design
- Summary

Introduction-Motivation

- For the past decade, a lot of effort has been spent on ν oscillation physics

$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$	$\mu^- \to e^- \nu_\mu \bar{\nu}_e$	
$\bar{\nu}_\mu \to \bar{\nu}_\mu$	$\nu_\mu \to \nu_\mu$	disappearance
$\bar{\nu}_\mu \to \bar{\nu}_e$	$\nu_\mu \to \nu_e$	appearance ("platinum" channel?)
$\bar{\nu}_\mu \to \bar{\nu}_\tau$	$\nu_\mu \to \nu_\tau$	appearance (atmospheric oscillation)
$\nu_e \to \nu_e$	$\bar{\nu}_e \to \bar{\nu}_e$	disappearance
$\nu_e \to \nu_\mu$	$\bar{\nu}_e \to \bar{\nu}_\mu$	appearance: "golden" channel
$\nu_e \to \nu_\tau$	$\bar{\nu}_e \to \bar{\nu}_\tau$	appearance: "silver" channel

Introduction-Motivation

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8 channels accessible by νSTORM

$\mu^+ \to e^+\nu_e\bar{\nu}_\mu$		
$\bar{\nu}_\mu \to \bar{\nu}_\mu$	$\nu_\mu \to \nu_\mu$	disappearance
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Introduction-Motivation(Cont'd)

- 3.8 GeV/c muon decay ring (±10%) + near detector + far detector to study eV-scale ν oscillations and search for sterile ν.
  - $\mu^{+} \rightarrow e^{+} + \nu_{e} + \overline{\nu}_{\mu}, \mu^{-} \rightarrow e^{-} + \nu_{\mu} + \overline{\nu}_{e}$
    - ↳ Well understood neutrino flux + flavor
  - Provides short baseline neutrino oscillation study, cross section measurement, and works as a technology test bed (muon accelerator study, neutrino detector study, etc);
  - No new technology; Simple implementation; More affordable

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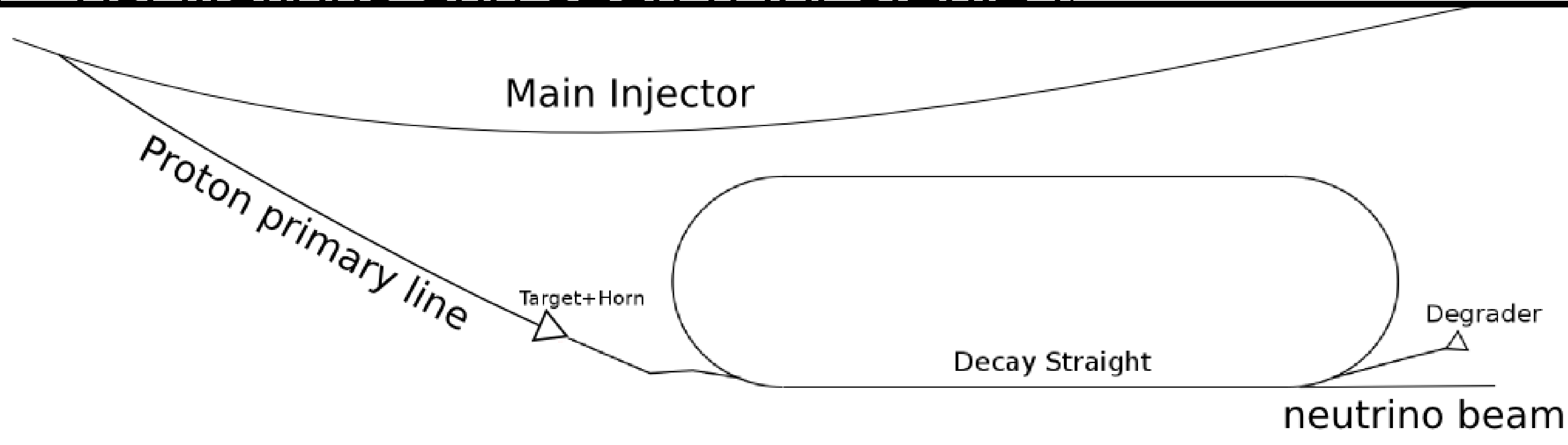
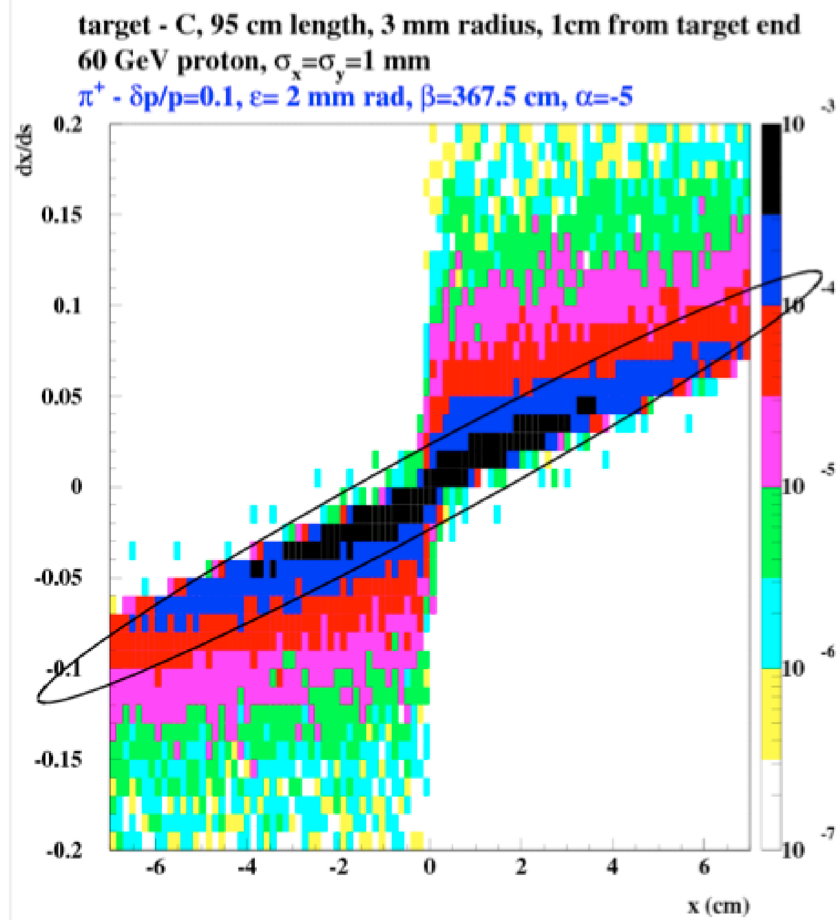


  - No new technology; Simple implementation; More affordable

Introduction-Facility

- 100 KW target station
  - 60-120 GeV protons from Main injector;
  - Magnetic horn to collect π;
  - Target material: graphite;
- A total run exposure of 10^{21} protons over a period of 4-5 years
- Stochastic injection scheme
  - No full-aperture fast kicker or separate pion decay channel needed;
  - Initially proposed by David Neuffer(Fermilab, U.S.)



$\mathcal{E}=2$ mm: yield = 0.064
r< 20 cm: yield = 0.126

Introduction-Facility

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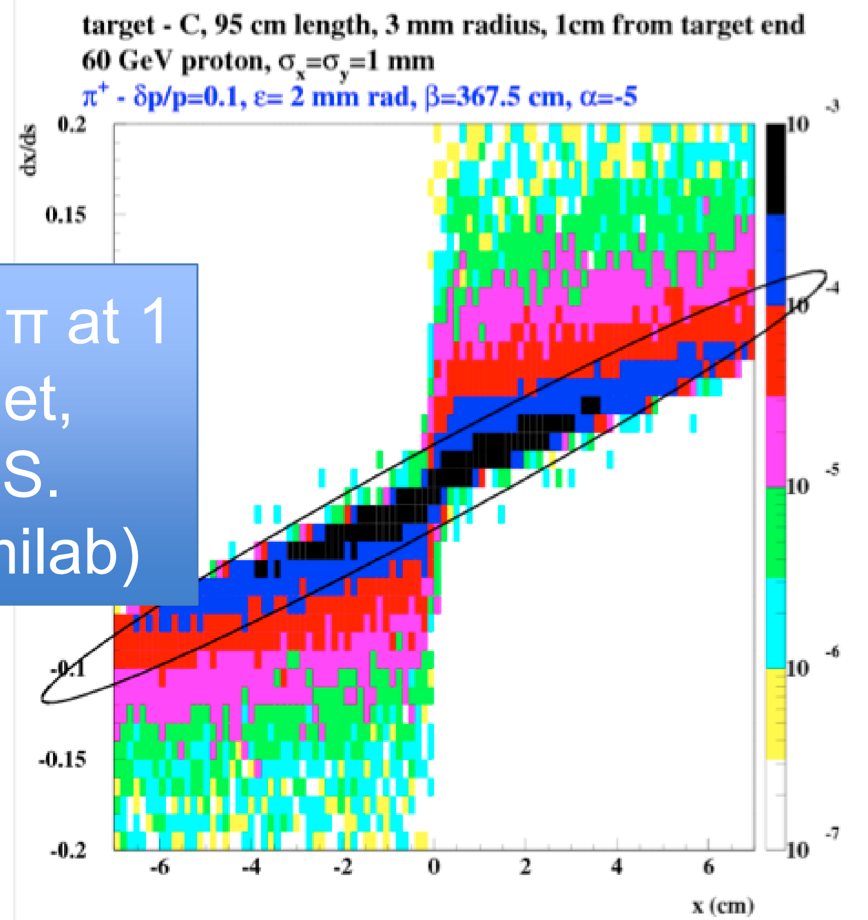
Phase space of π at 1 cm after target, Courtesy of S. Striganov(Fermilab)



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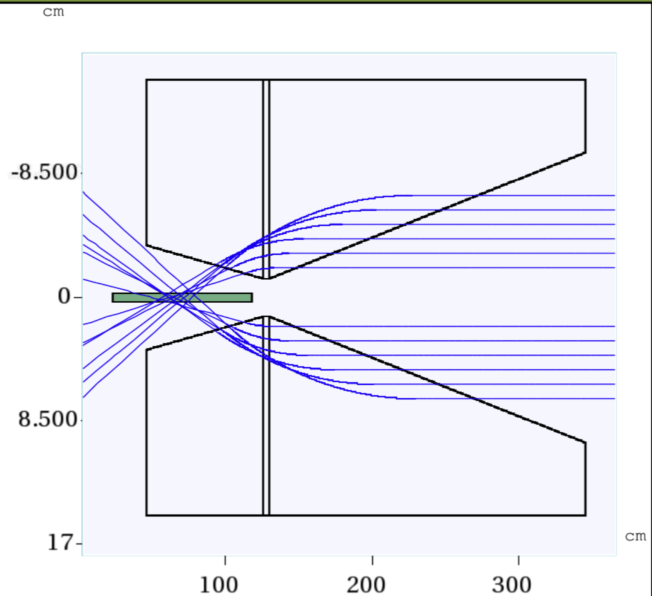
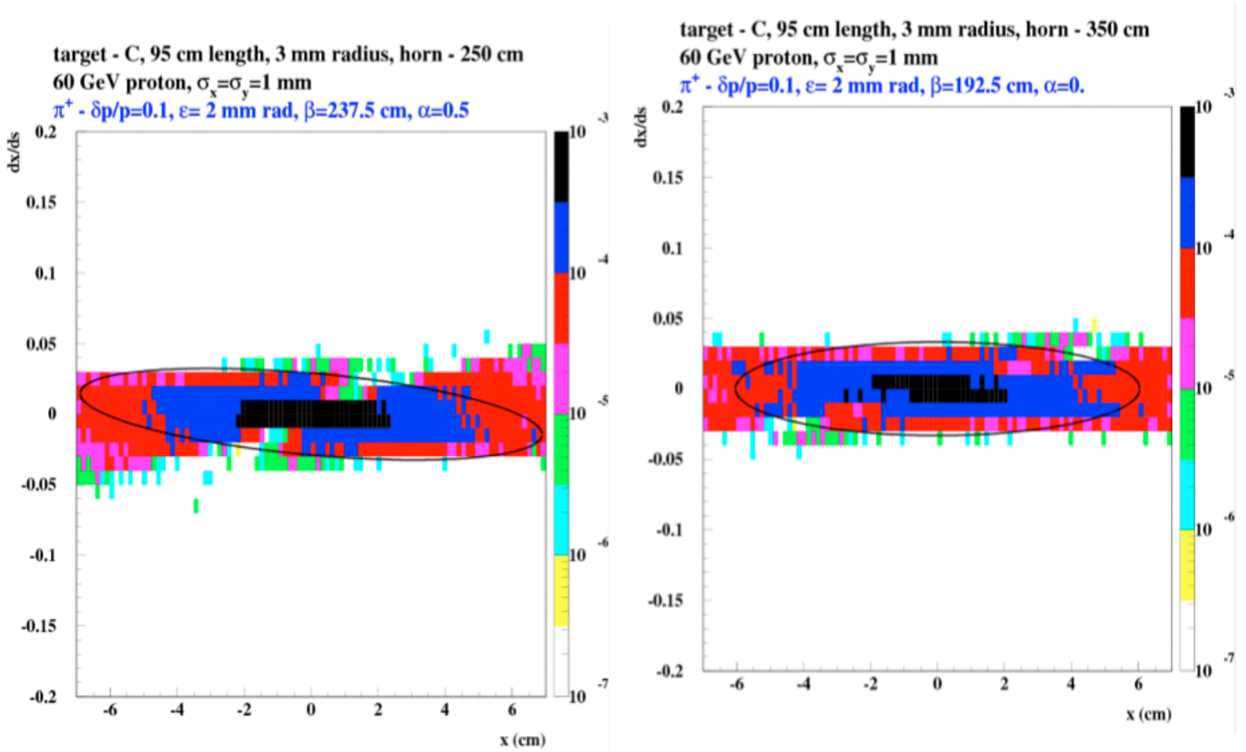
Introduction-π Capture



Use a NuMI-like magnetic horn, after which 0.1 pions per POT are collected in 20cm region, 0.056 pions per POT in 2000 μm acceptance

Phase distribution after horn - graphite target



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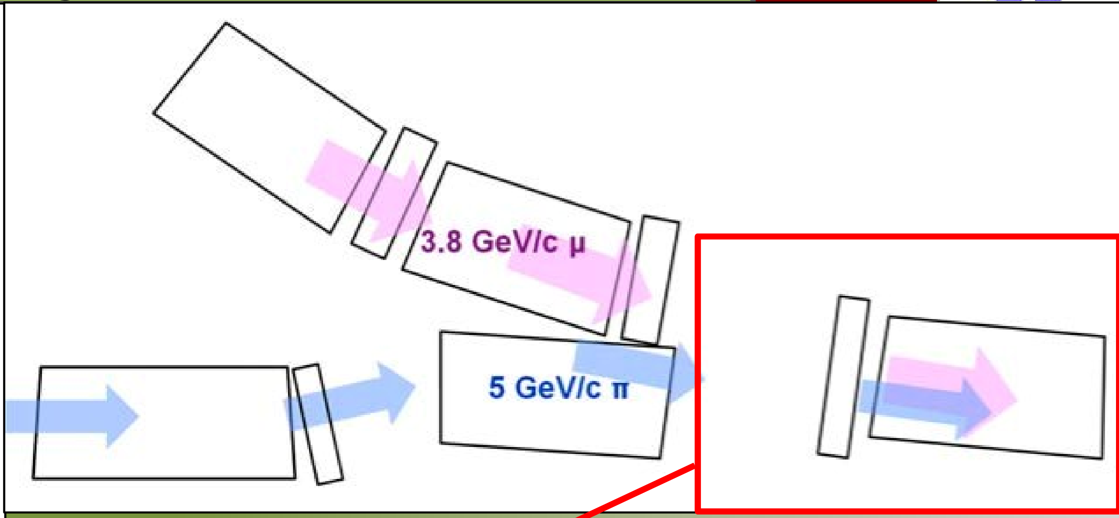
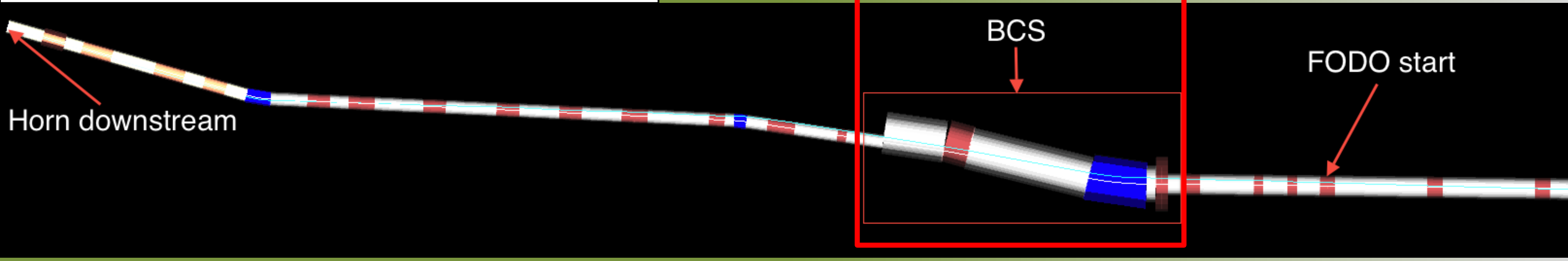
Transport Line Design Strategy

- Design the optics to
  - Achieve a beam size as small as possible by constraining β functions and dispersion;
  - Match Twiss parameters from the horn into the ring;
  - Use the smallest number of magnet families as possible.
- Optics + Simulation design tools
  - MADX(CERN), OptiM(V. Lebedev, Fermilab), apGA(myself)
  - G4Beamline(T. Roberts, Muons Inc.)

Transport Design - Stochastic Injection

- Right: Concept drawing; Bottom: Layout screenshot (White blocks-drift tubes, red-quads, blue-dipoles)
- Circled section is beam combination section for two beams





Transport Design – Details(Cont'd)

Initial Consideration

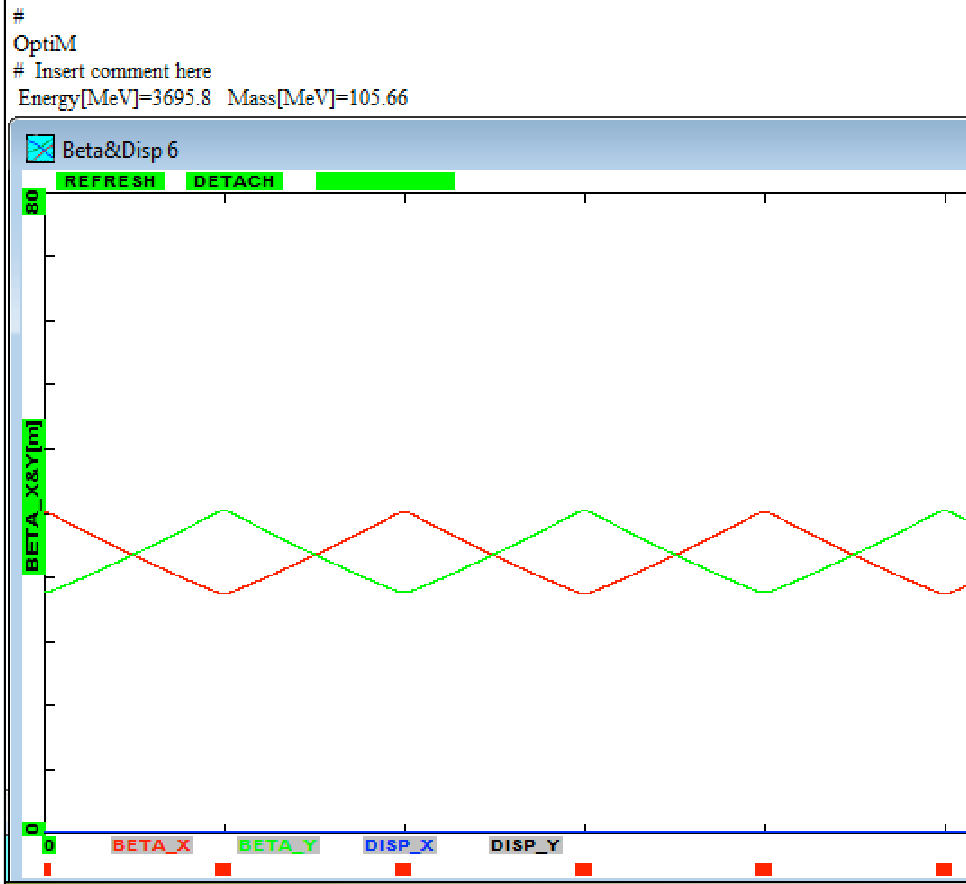
FODO cells for decay ring

Match Twiss of ring lattice to transport lattice, at the injection point

Check the pion flux delivered from horn to injection point

Transport Design – Details(Cont'd)

- Questions:
  - π decay in the straight:
    - 5 GeV/c π and 3.8 GeV/c μ have very different optics;
  - Is there enough space for magnets along the ring and transport?
- Answers:
  - Upper: Periodic $\beta_{x,y}$ for 3.8 GeV/c μ in the FODO cell.
  - Lower: Same FODO cells(lengths, gradients), 5 GeV/c π.



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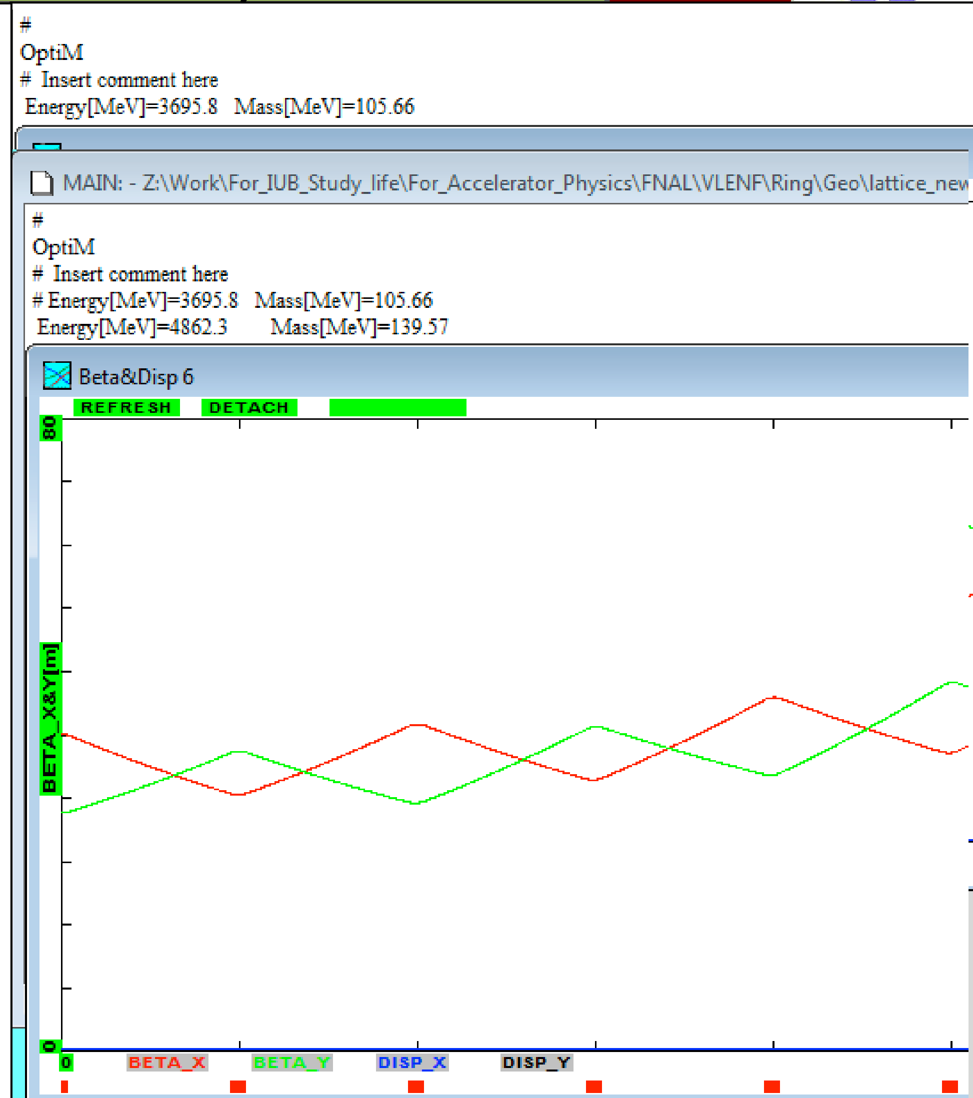
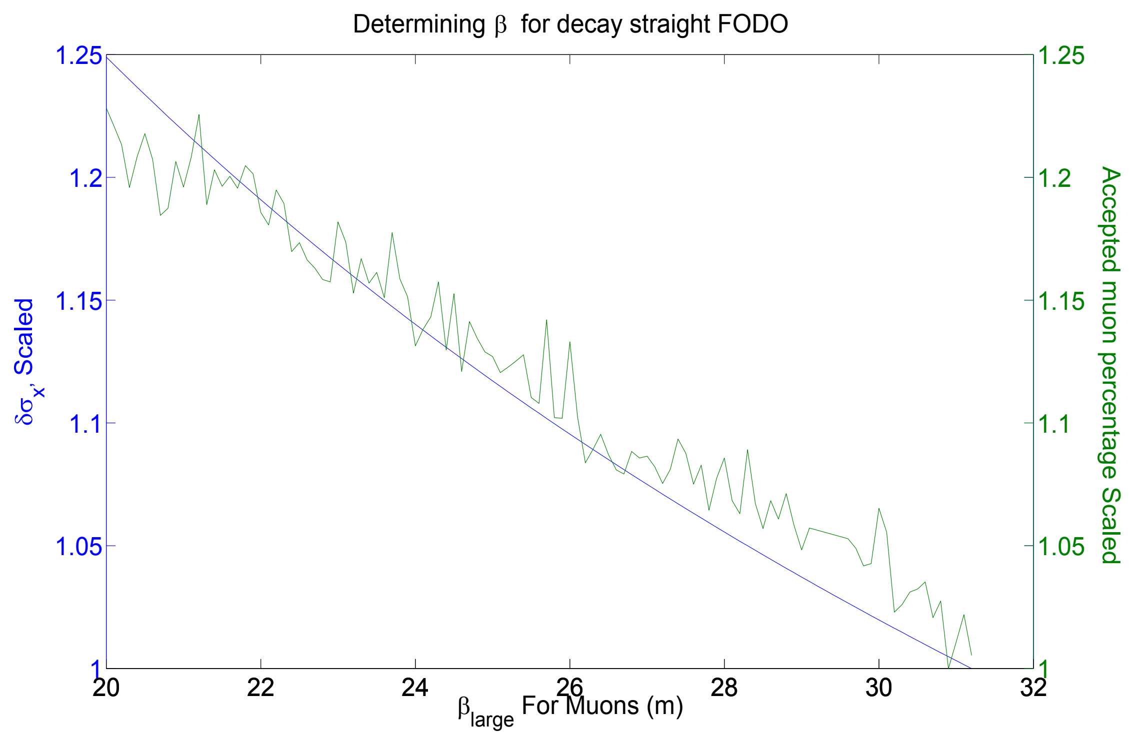


Transport Design – Details(Cont'd)

- Need 1:
  - As many π as possible survive in the decay straight before decay;
- Action 1:
  - Design the FODO cell with 2 sets of periodic Twiss (μ and π).
  - Use π parameters in transport optics matching.



Determine betas for FODO cell:

- Larger β:
  - ➢ Smaller transverse angle acceptance, μ angles from π decay w.r.t parent π determined by energy;
  - ➢ Larger beam size
- Smaller β -> Larger divergence:
  - ➢ ν's not well oriented;
  - ➢ Lower divergence measurement accuracy;

Transport Design – Details(Cont'd)

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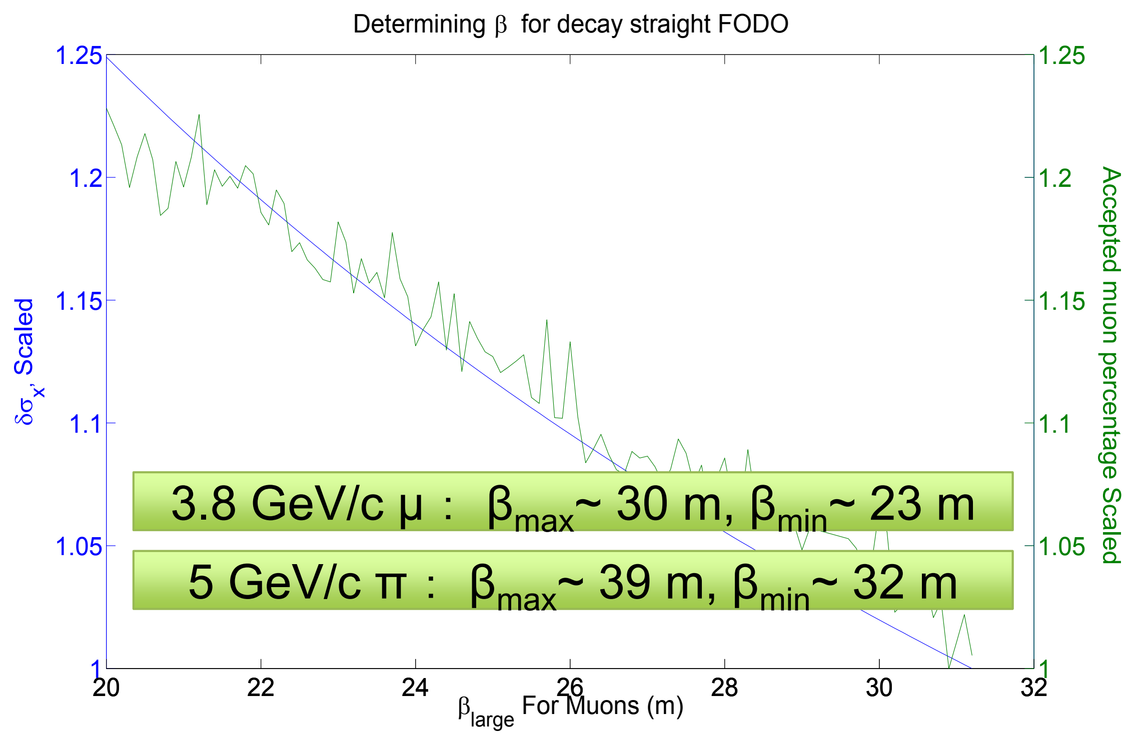

3.8 GeV/c μ : β_{max}~ 30 m, β_{min}~ 23 m

5 GeV/c π : β_{max}~ 39 m, β_{min}~ 32 m

Determine betas for FODO cell:

- Larger β:
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- Smaller β -> Larger divergence:
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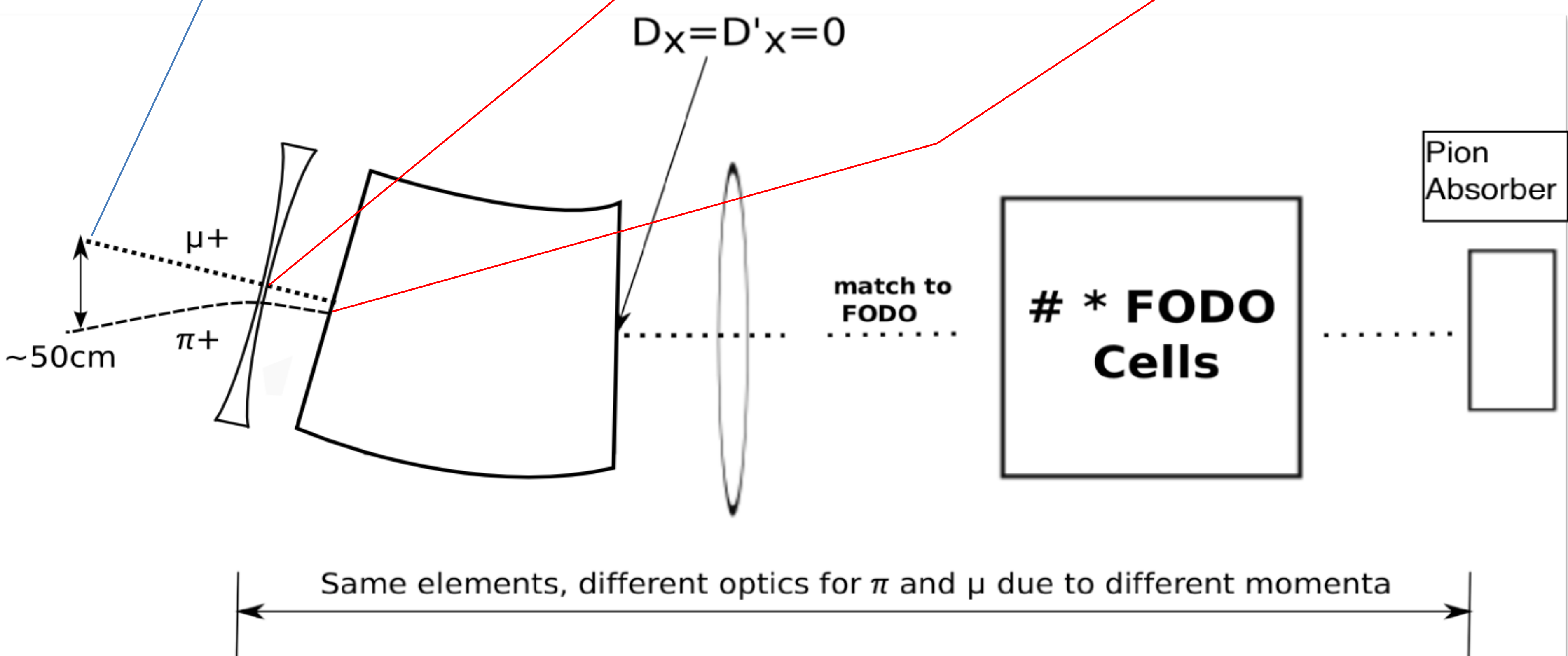
Transport Design – Details(Cont'd)

Need 2:
- Ensure enough separation of the two beams

A pure defocusing quadrupole for μ becomes a combined-function dipole with edge effects for π;

A pure sector dipole for μ has one edge effect on π;

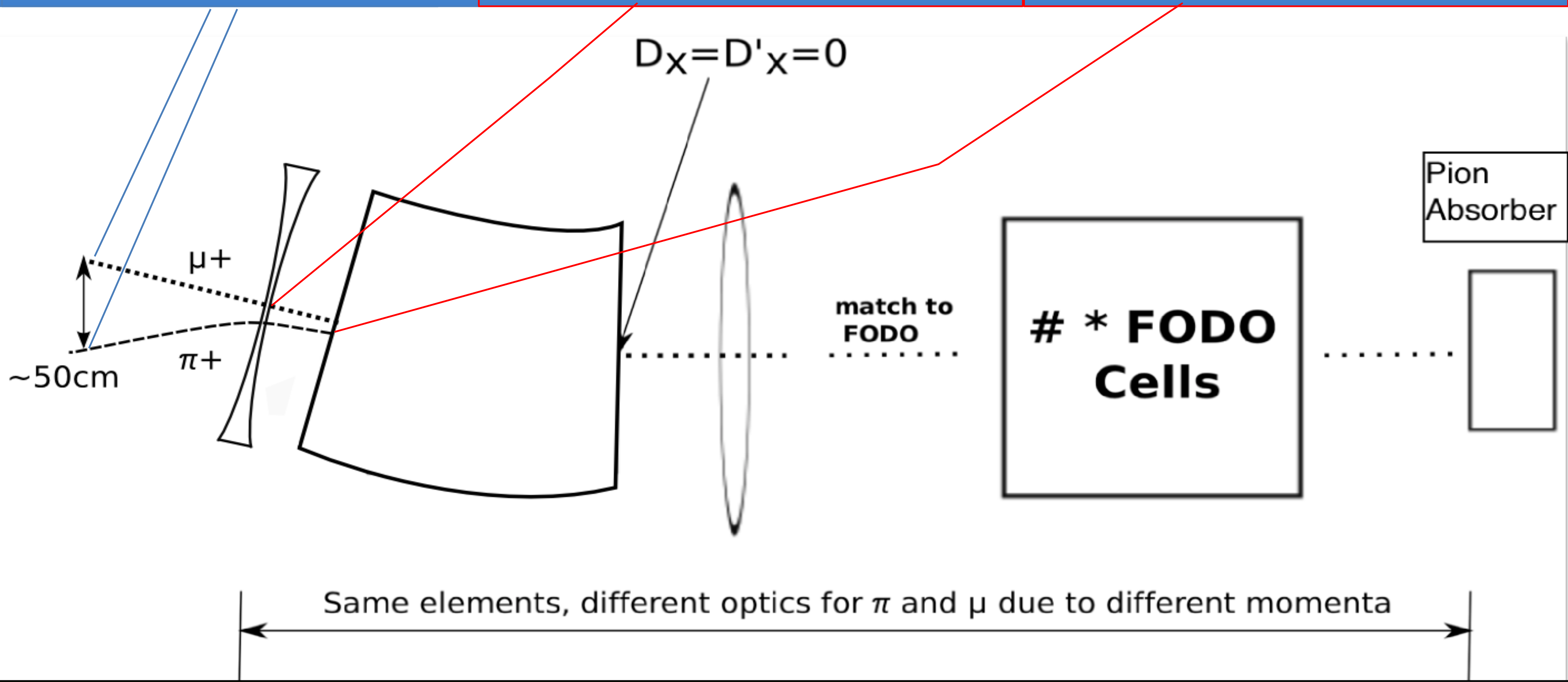


Transport Design – Details(Cont'd)

Action 2:
- Create large dispersion at the injection point to separate π and μ

A pure defocusing quadrupole for μ becomes a combined-function dipole with edge effects for π;

A pure sector dipole for μ has one edge effect on π;



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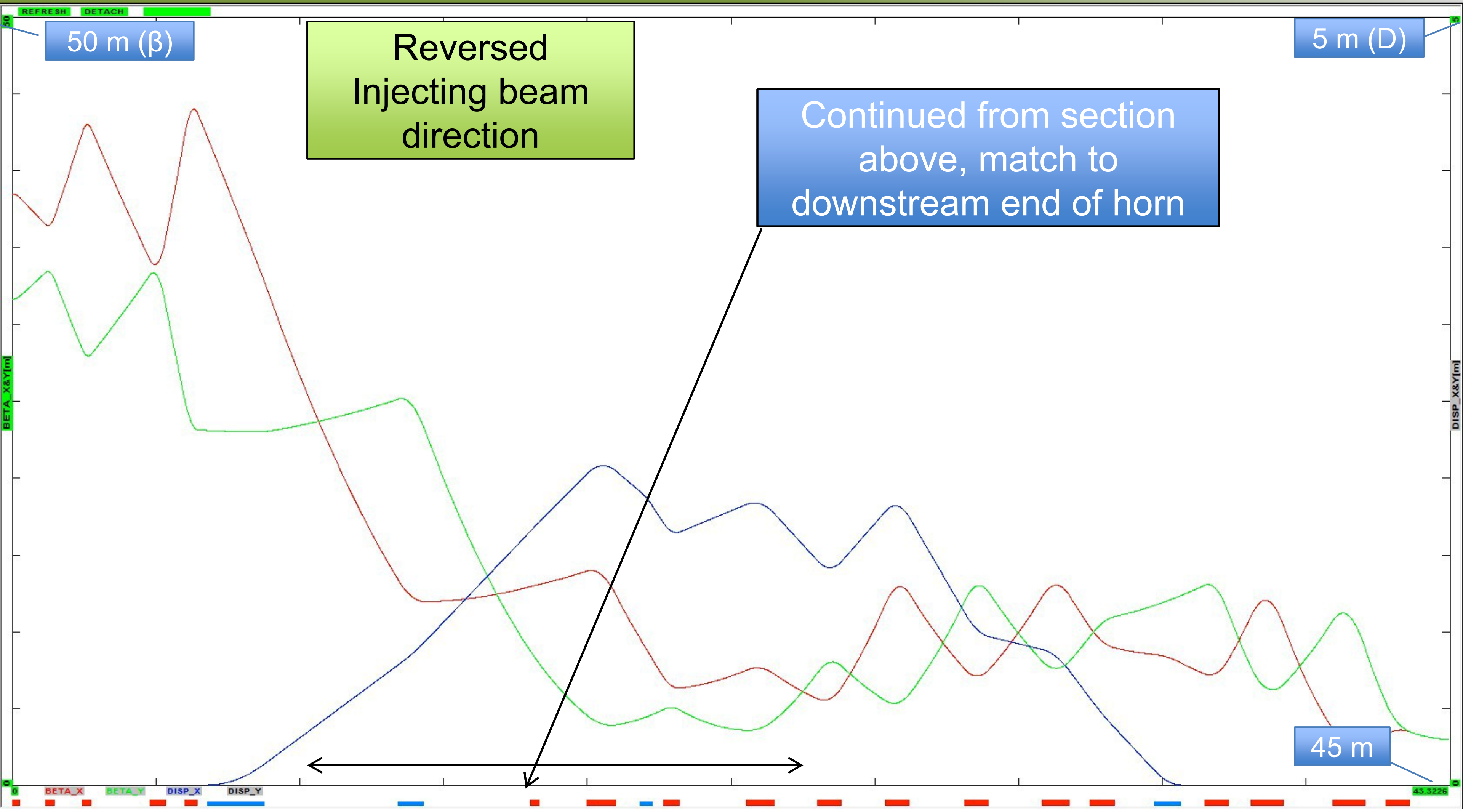

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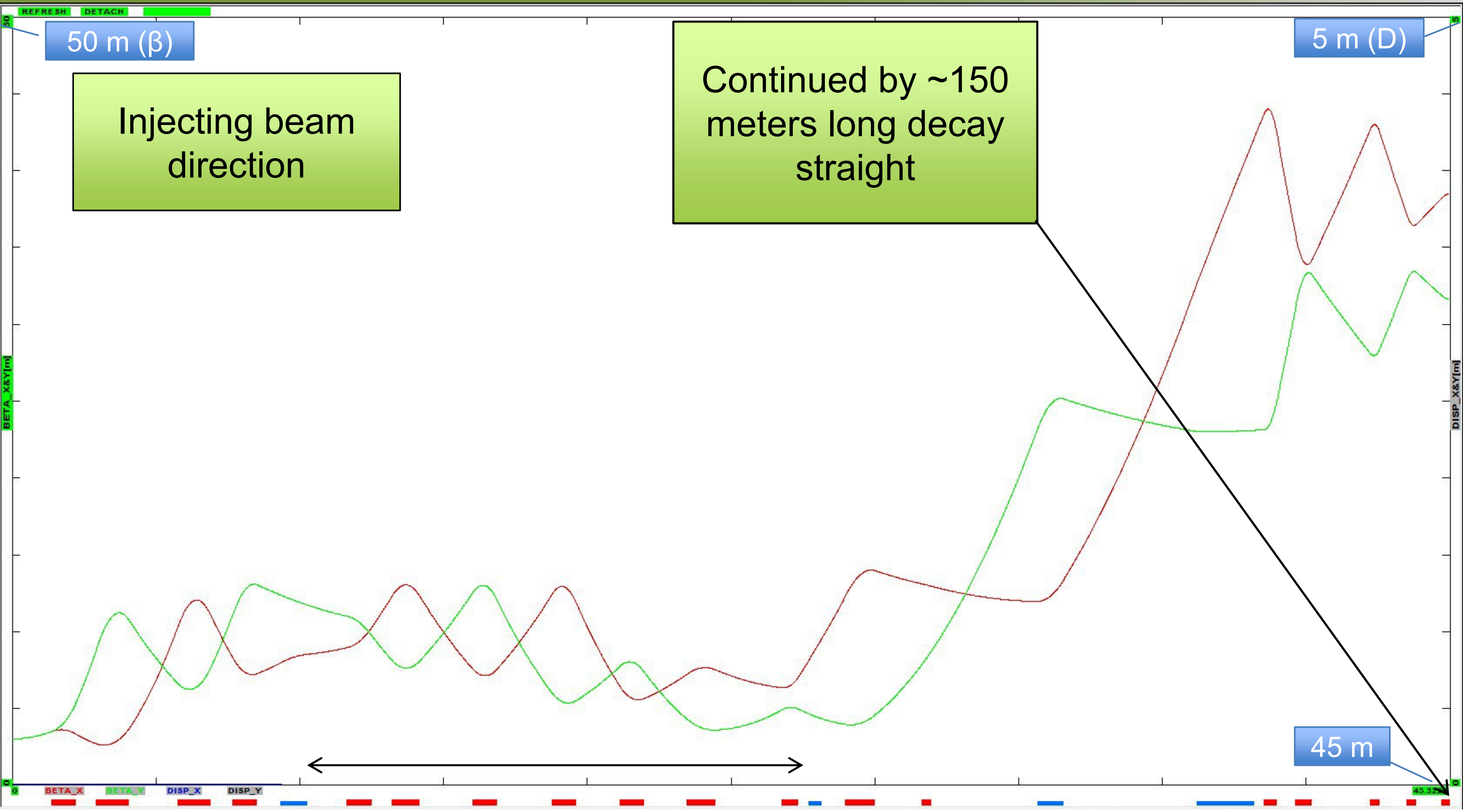

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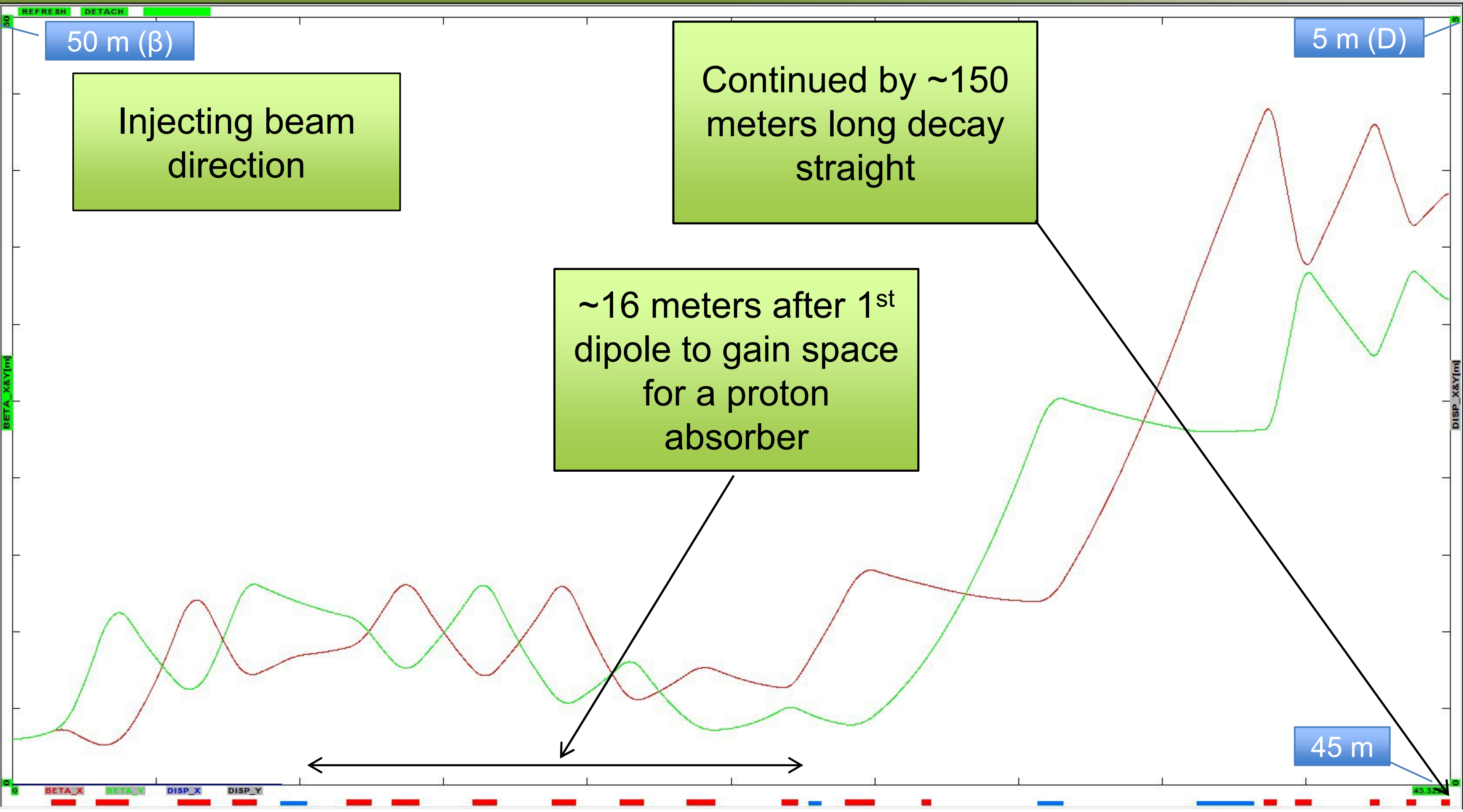
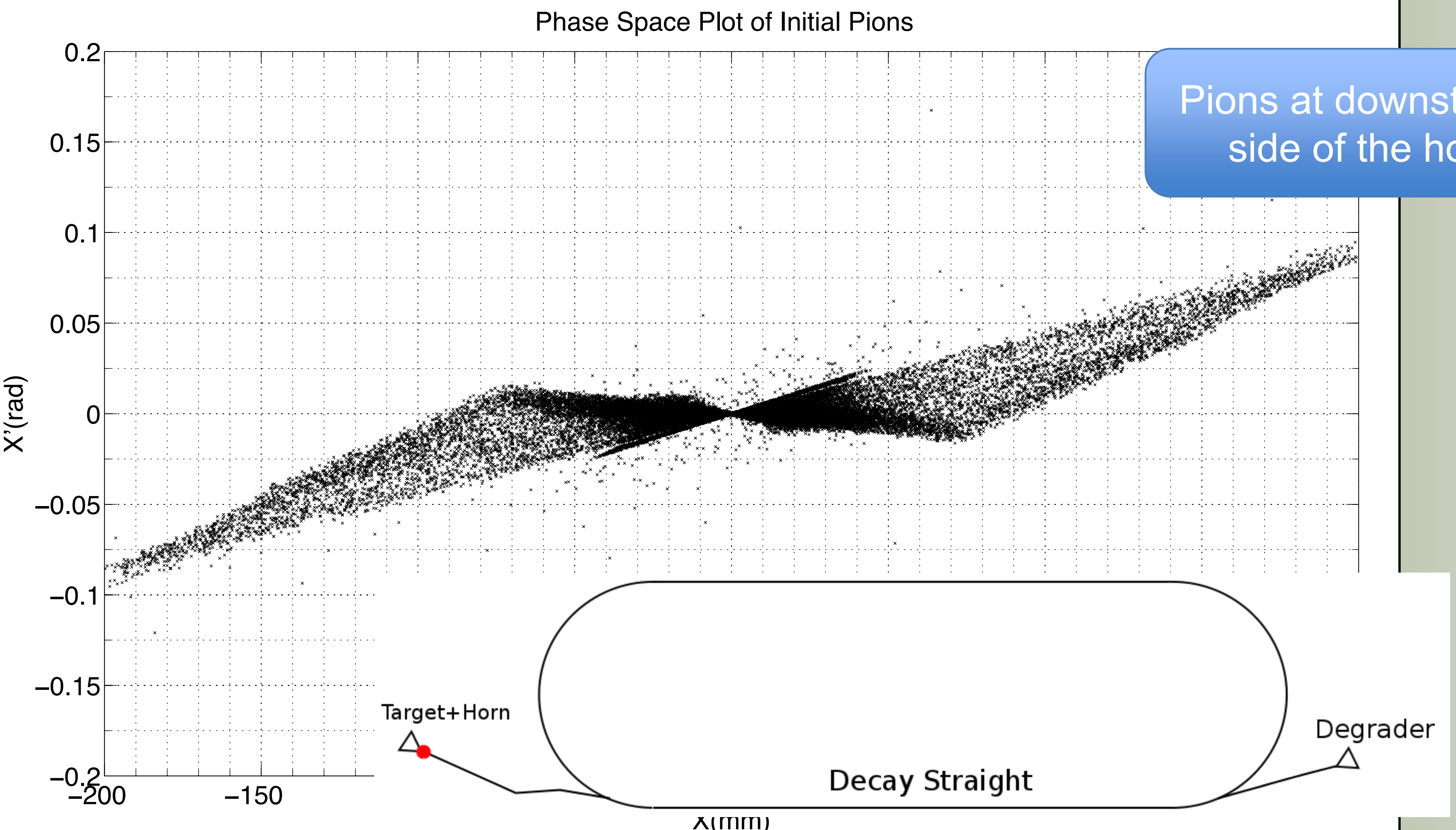


Transport Design – Simulation(Cont'd)

Pions at downstream side of the horn

Transport Design – Simulation(Cont'd)



Pions at downstream side of the horn

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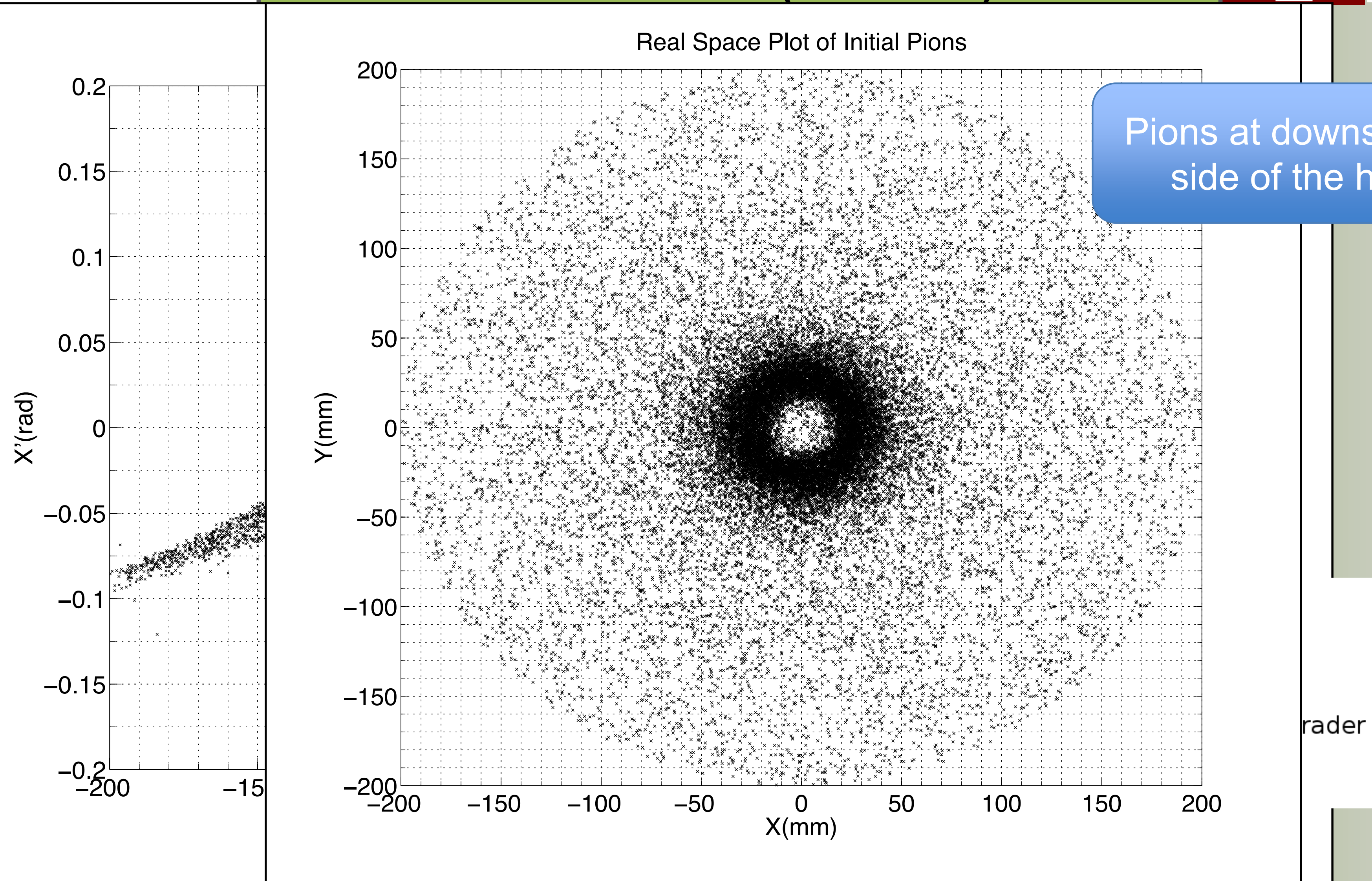

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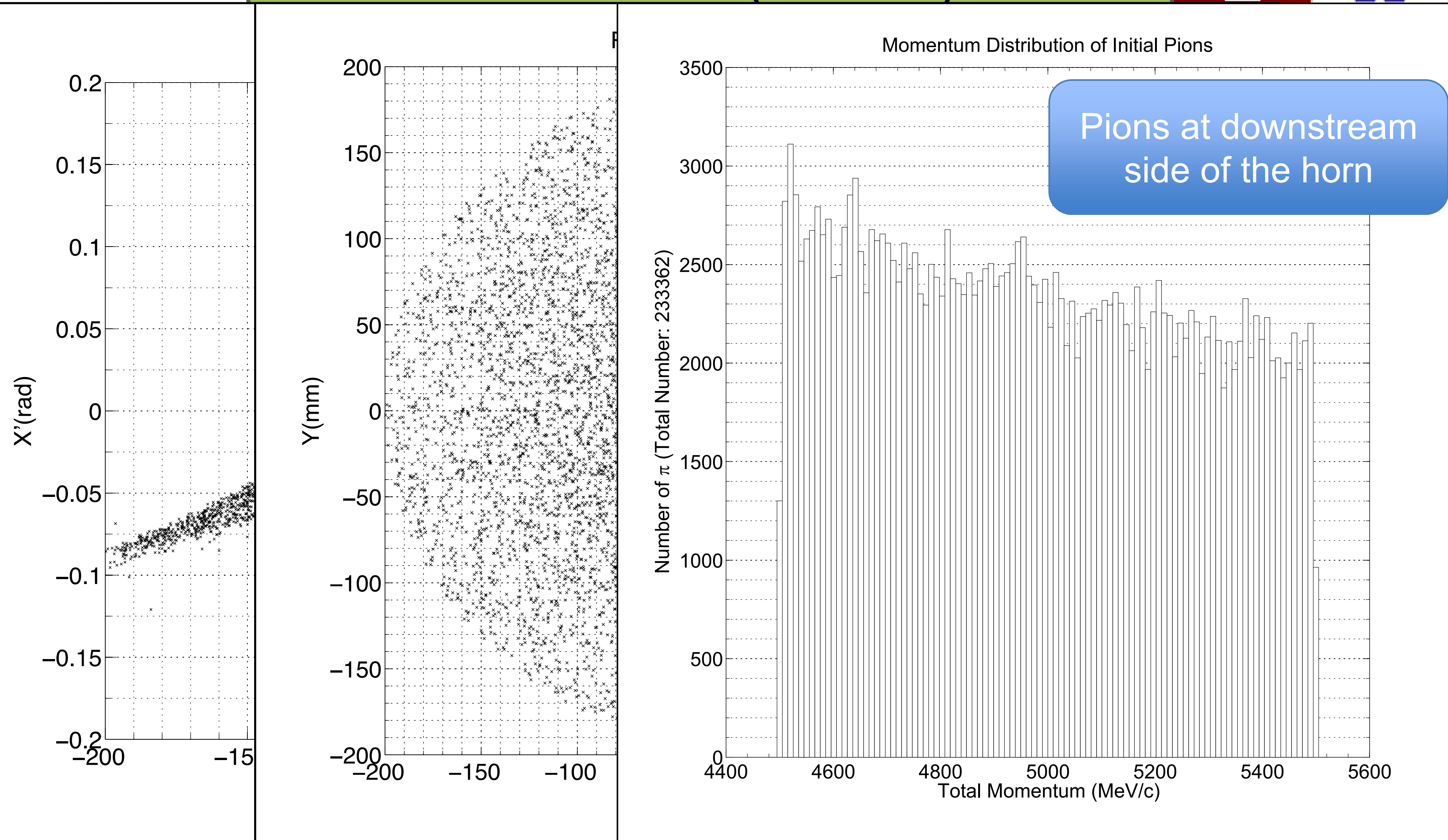

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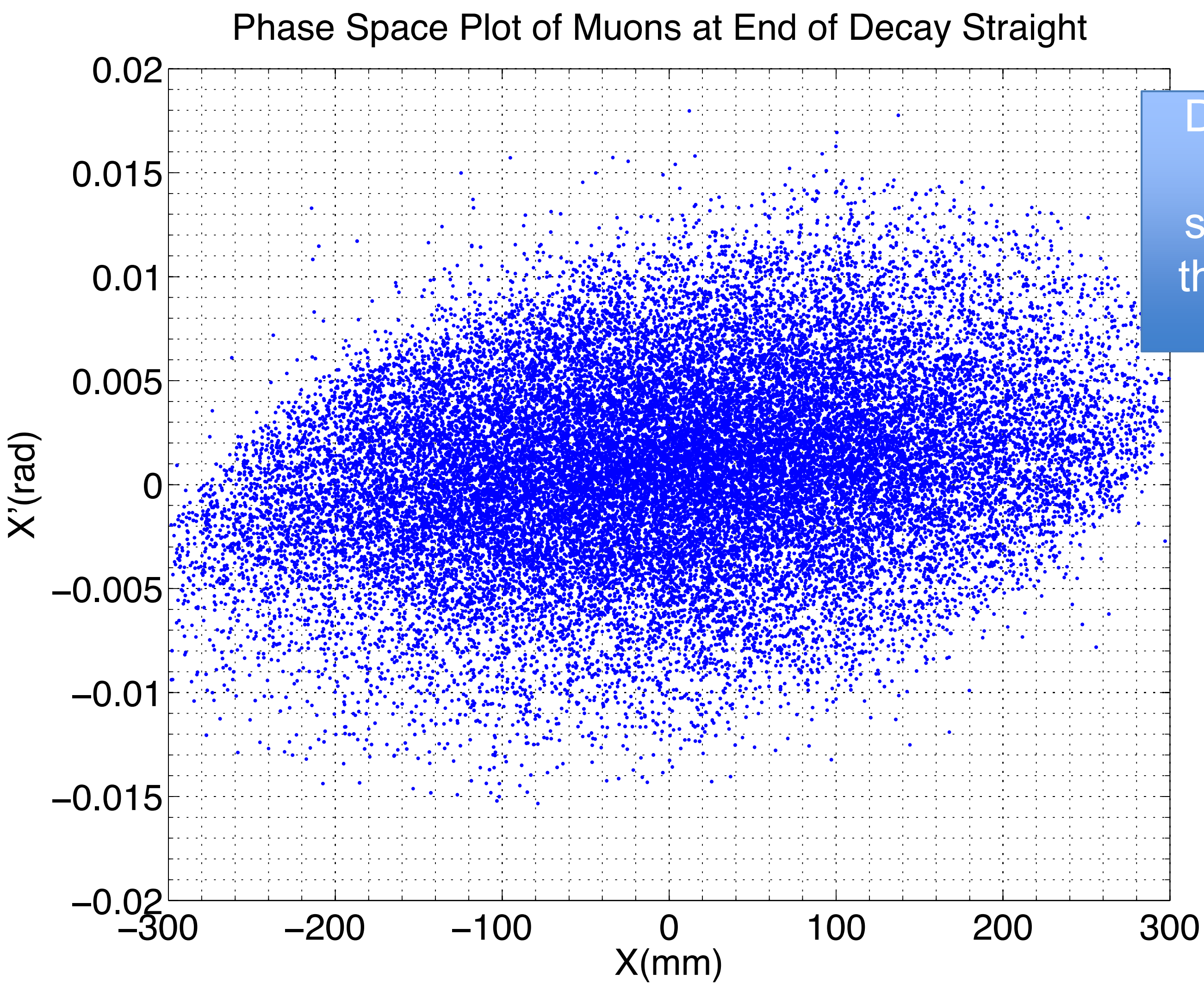
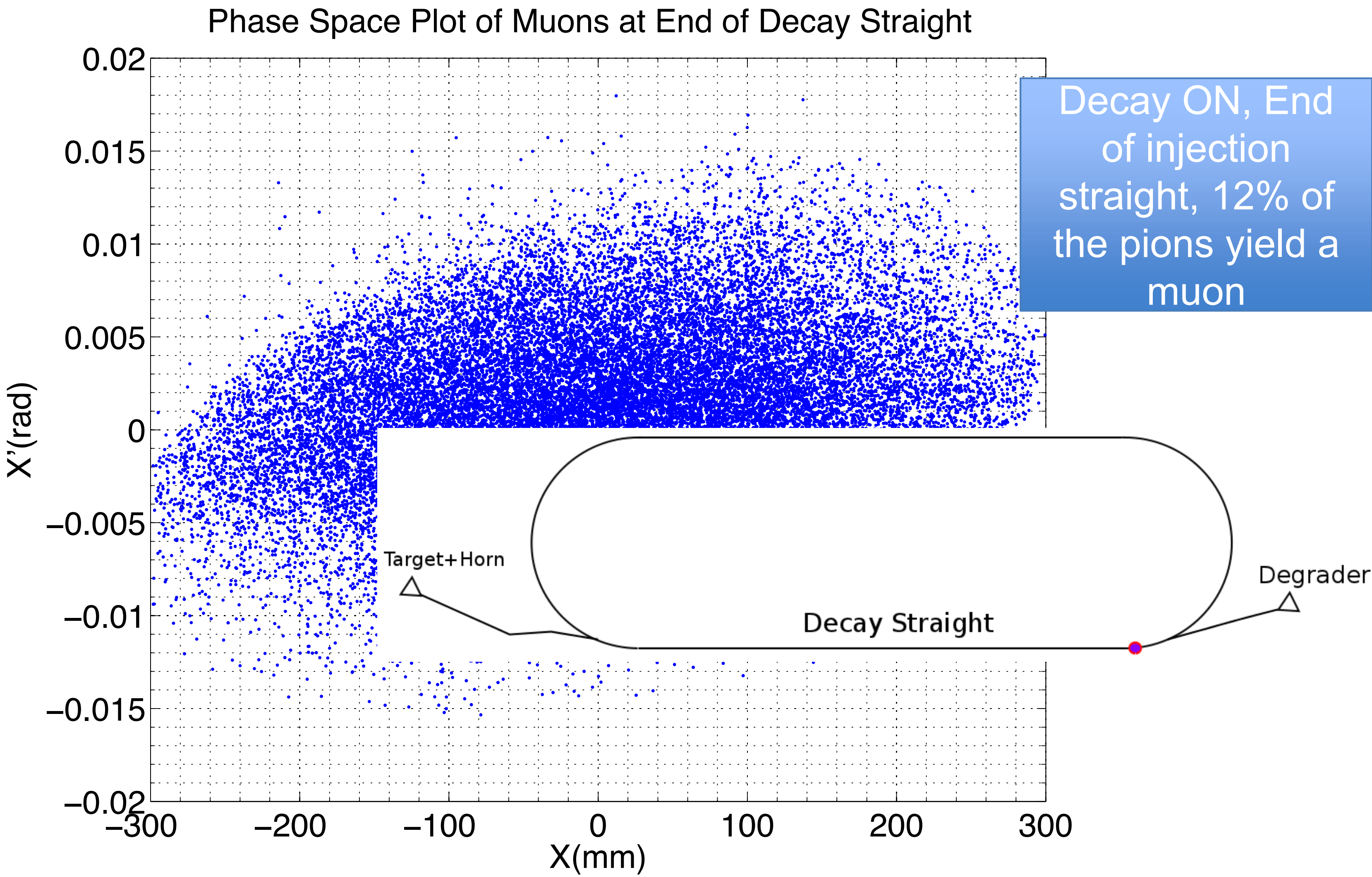


Decay ON, End of injection straight, 12% of the pions yield a muon

Transport Design – Simulation(Cont'd)



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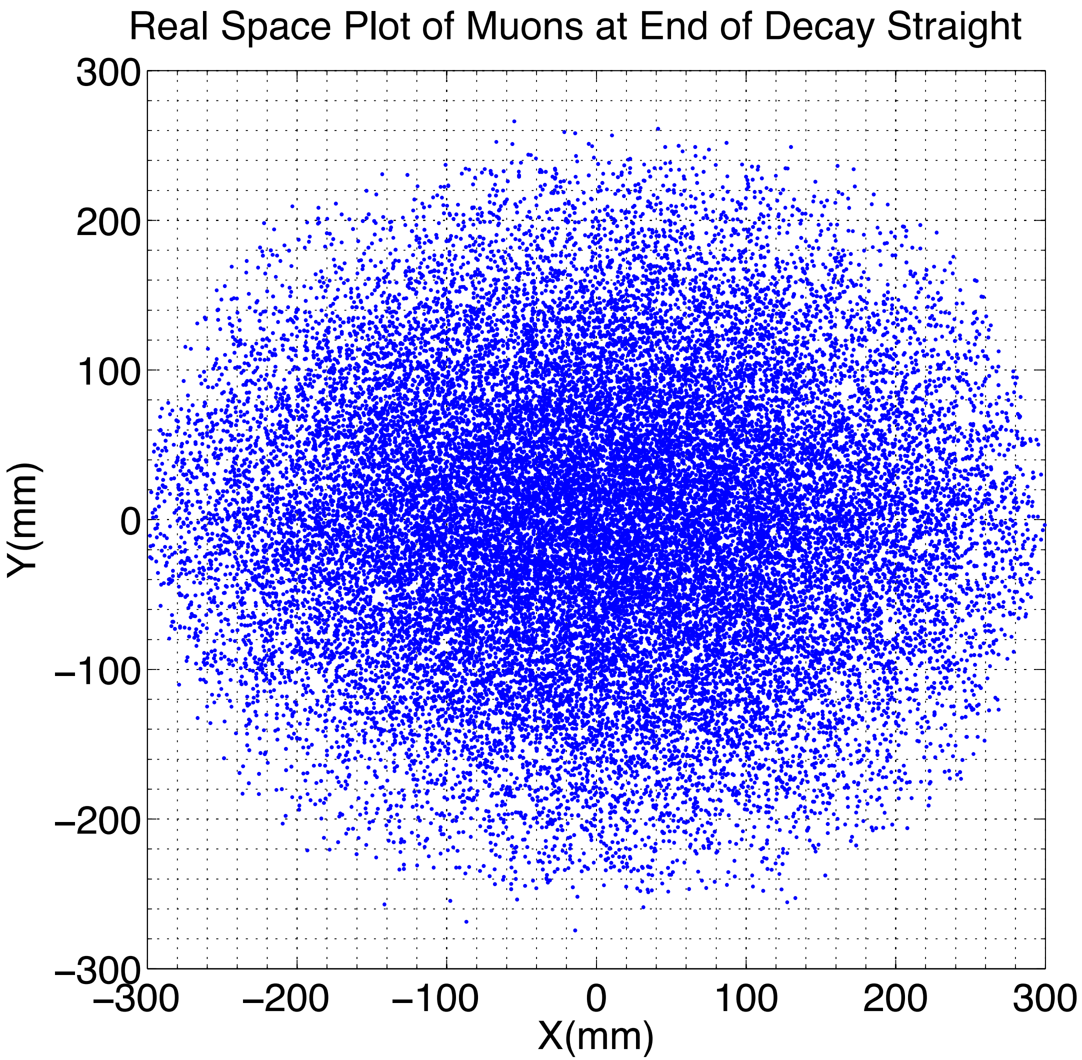

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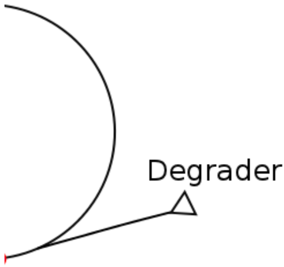
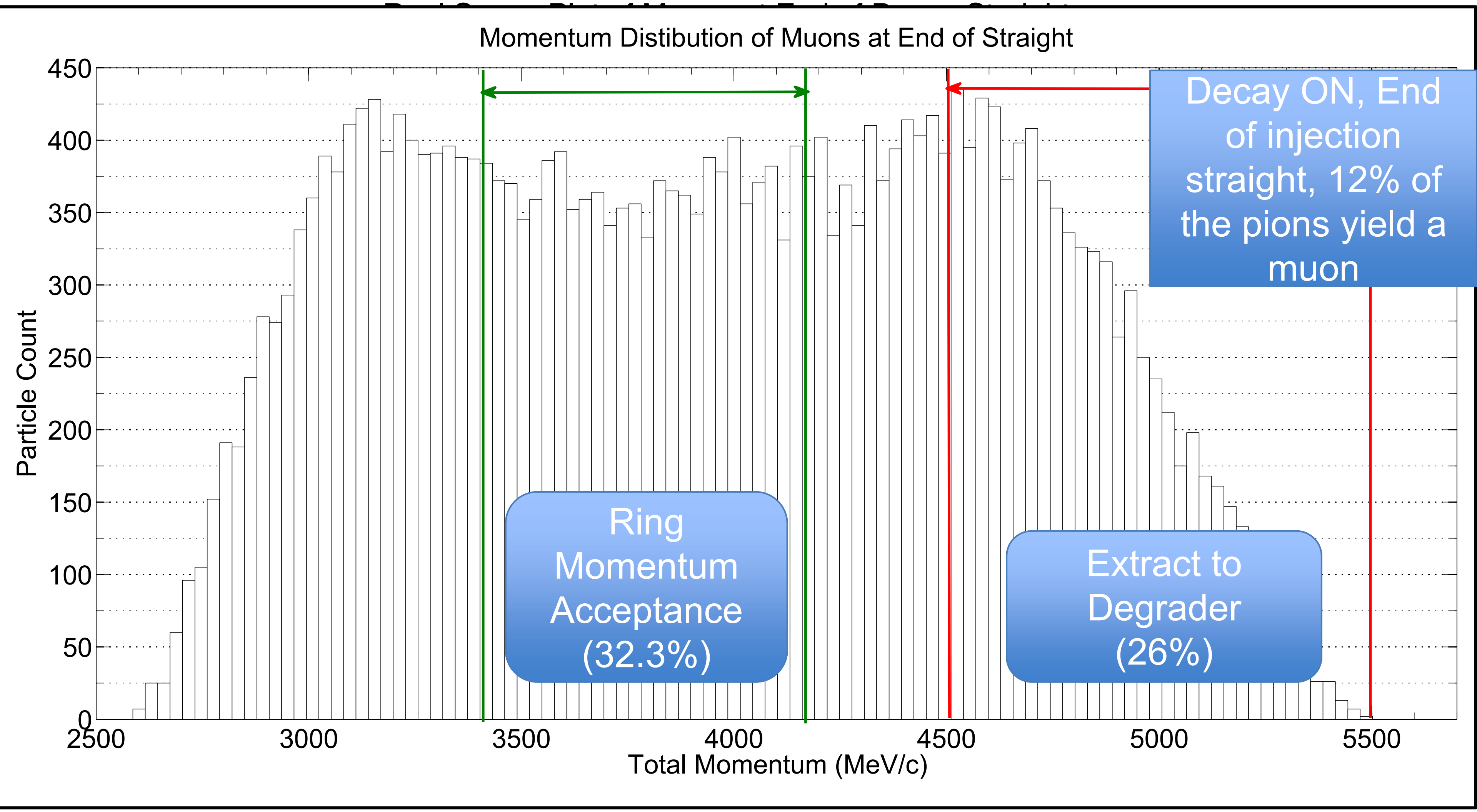
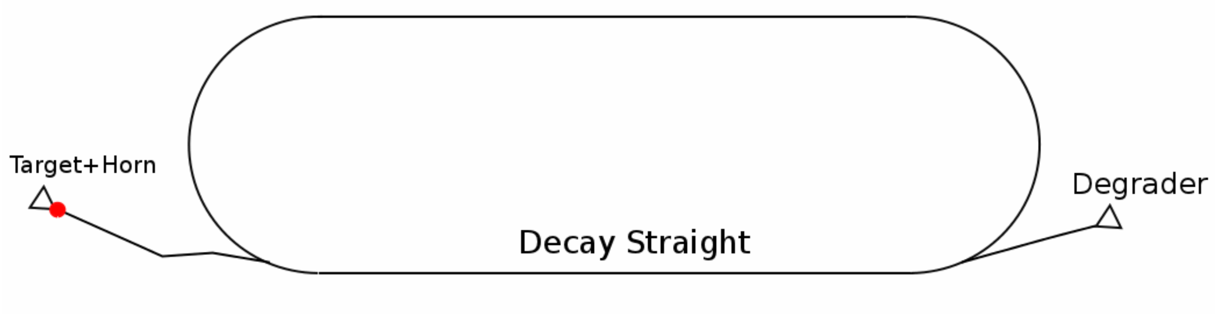


Transport Design – Simulation(Cont'd)



Transport Design - Summary

- Able to achieve 0.04 muon per pion at downstream side of the horn, within 3.8±10% GeV/c band.
  - Roughly 2 times the number νSTORM proposed in LOI paper;
  - Injection scheme can also be used to extract, both π and μ



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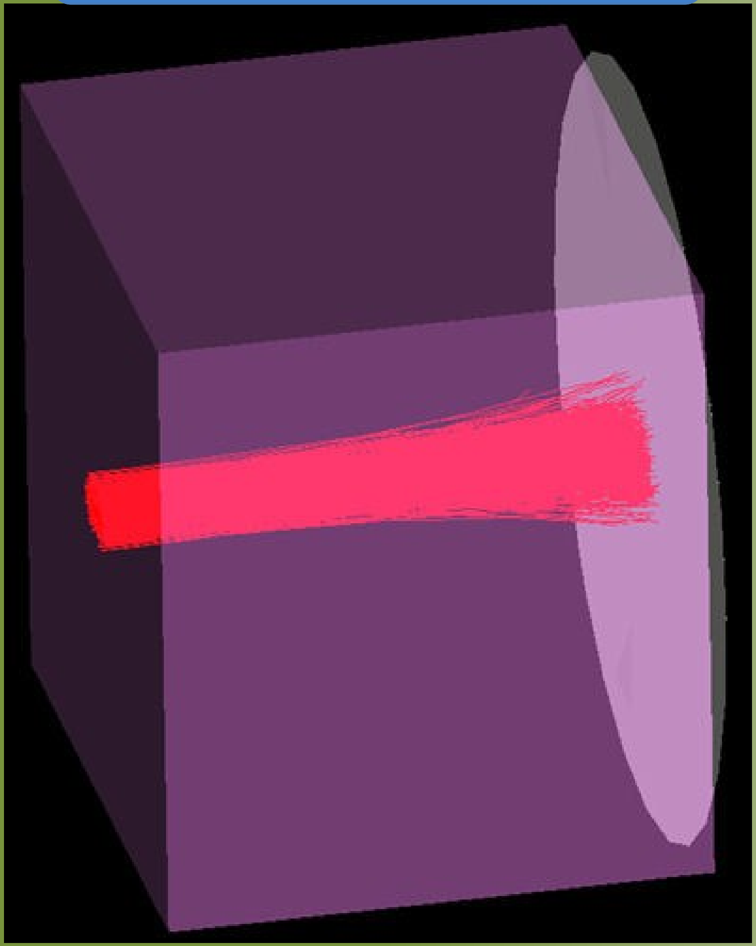
Low Energy Muons

Assume μ within 5 ± 0.5 GeV/c bin can be extracted



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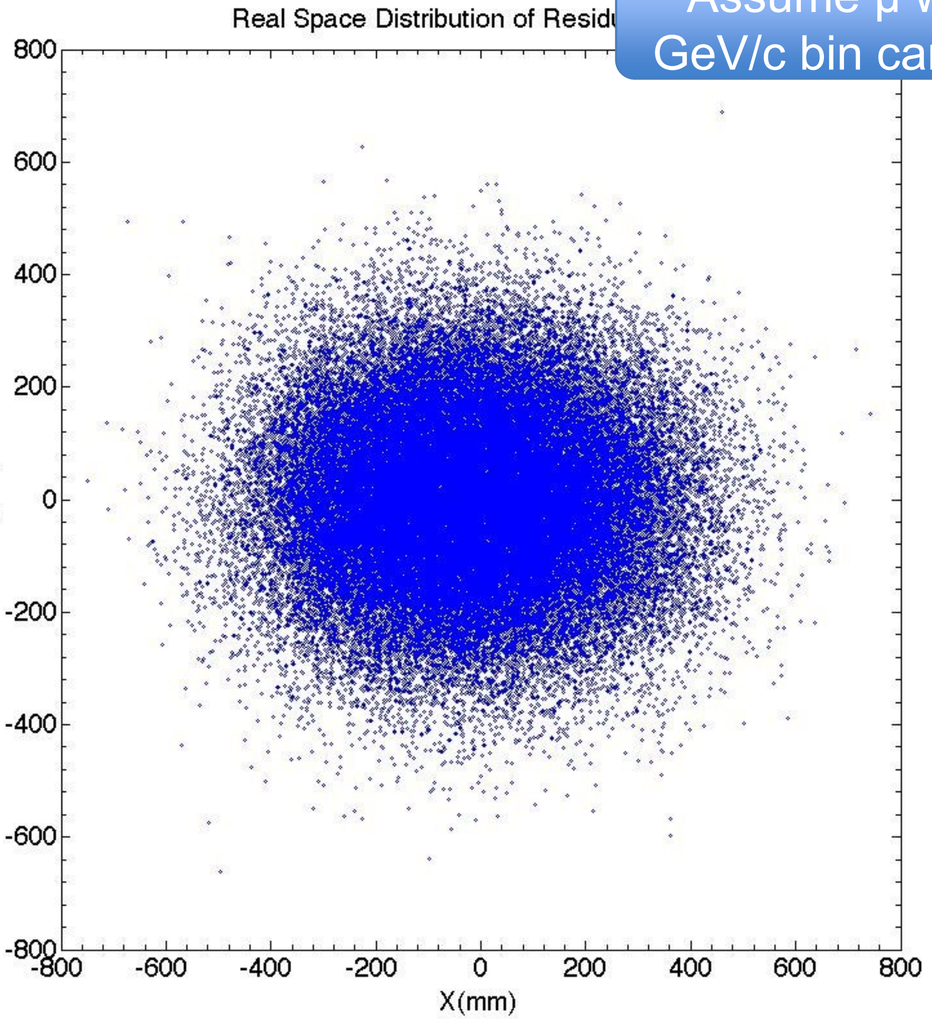

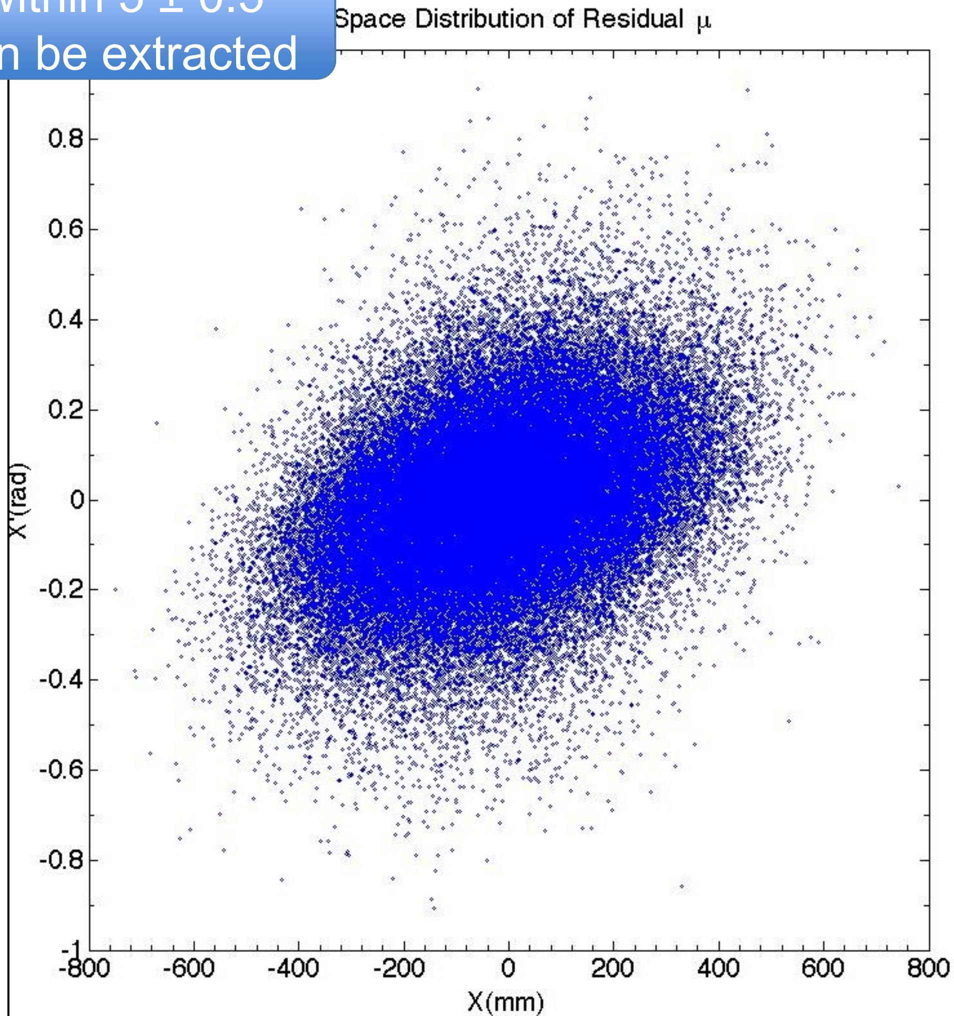

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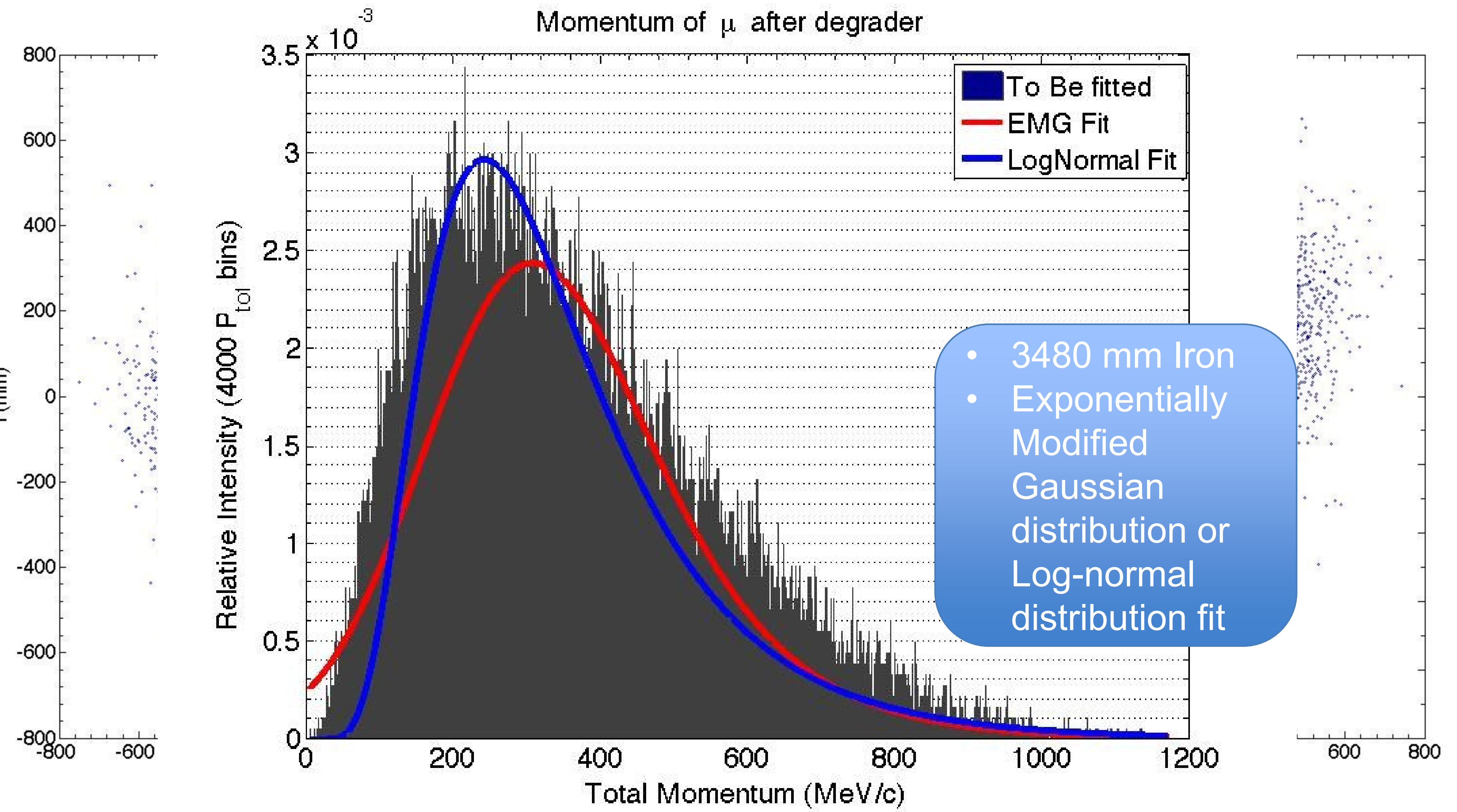

- 3480 mm Iron
- Exponentially Modified Gaussian distribution or Log-normal distribution fit

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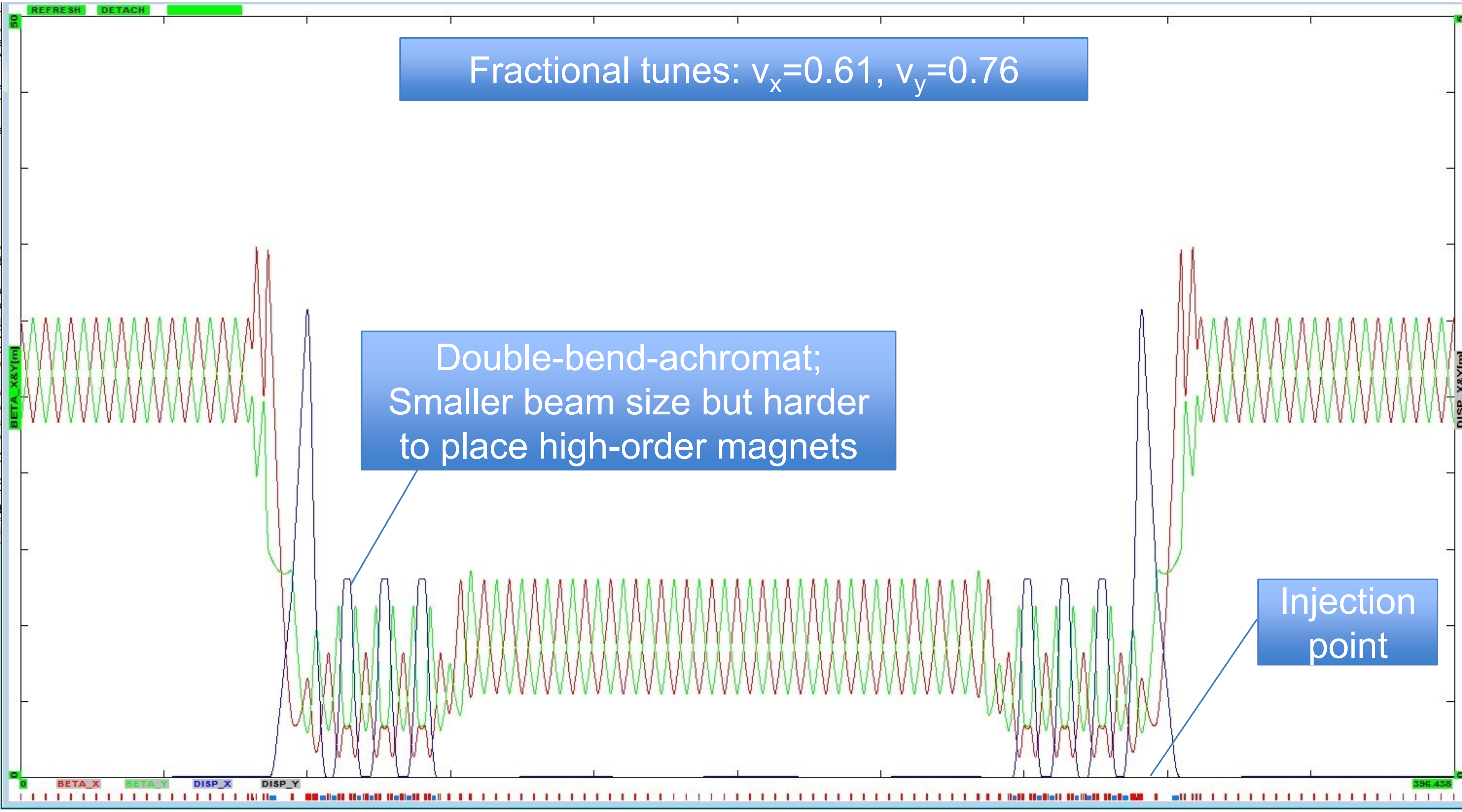
Muon Decay Ring -- Goals

- The injection scenario has been shown to work well. Next step – to design a ring which can accept the μ from π decay.
  - Large dispersion at injection; Require compact arcs;
  - First FODO ring to pursue such a large momentum acceptance (±10%) and phase space acceptance (2 mm).
    - Higher order chromatic effects include high-order dispersion and tune shift, which increases requirements for the arcs (more higher-order magnets) to correct them.
  - Relatively small number of turns required for μ decay(e.g. 450 meters circumference – 85% decay in 100 turns)
- Racetrack FFAG is also under study;
  - Y. Mori, J.B. Lagrange (Kyoto U); J. Pasternak (Imperial College)

Muon Decay Ring – A Start



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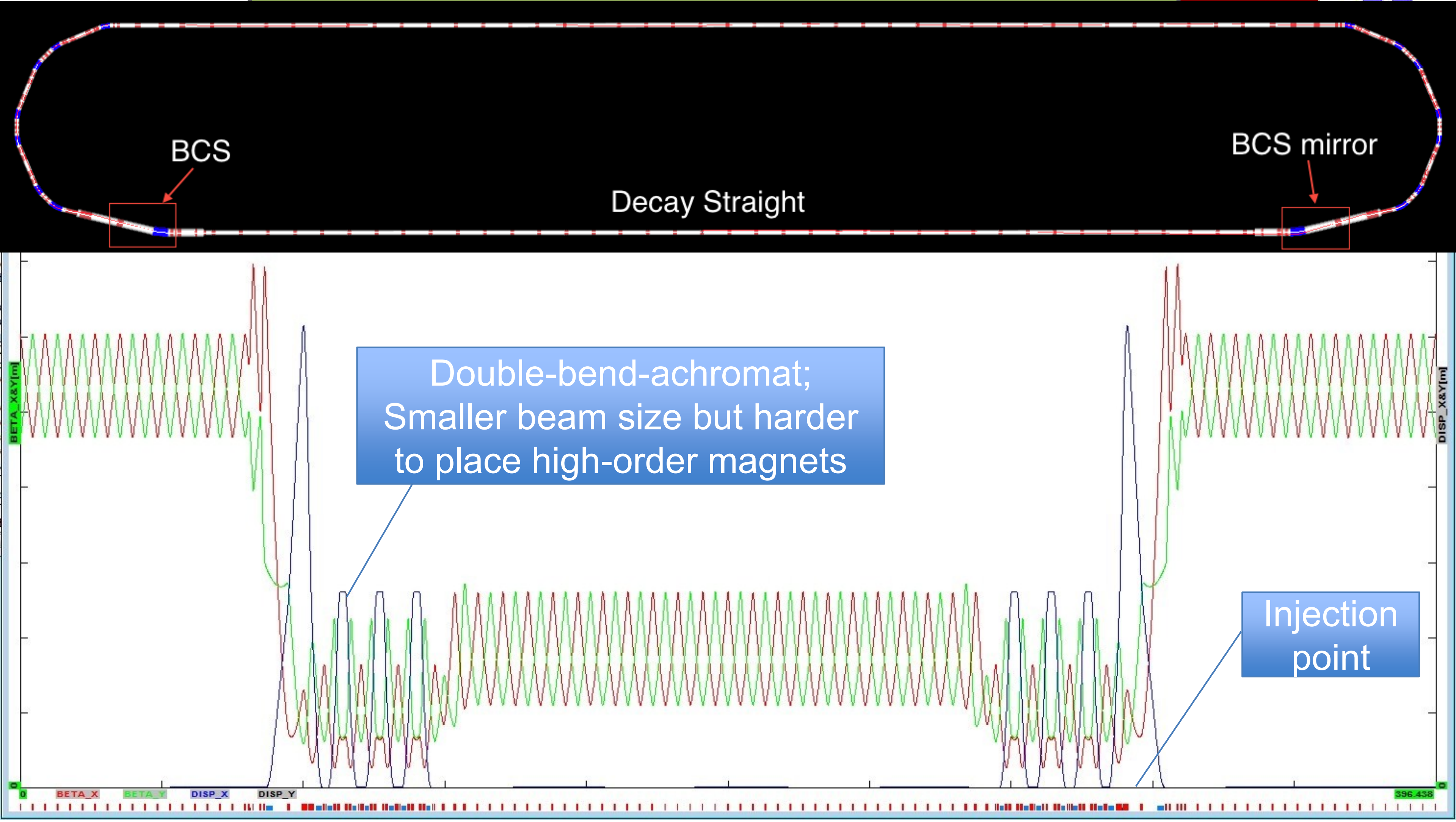

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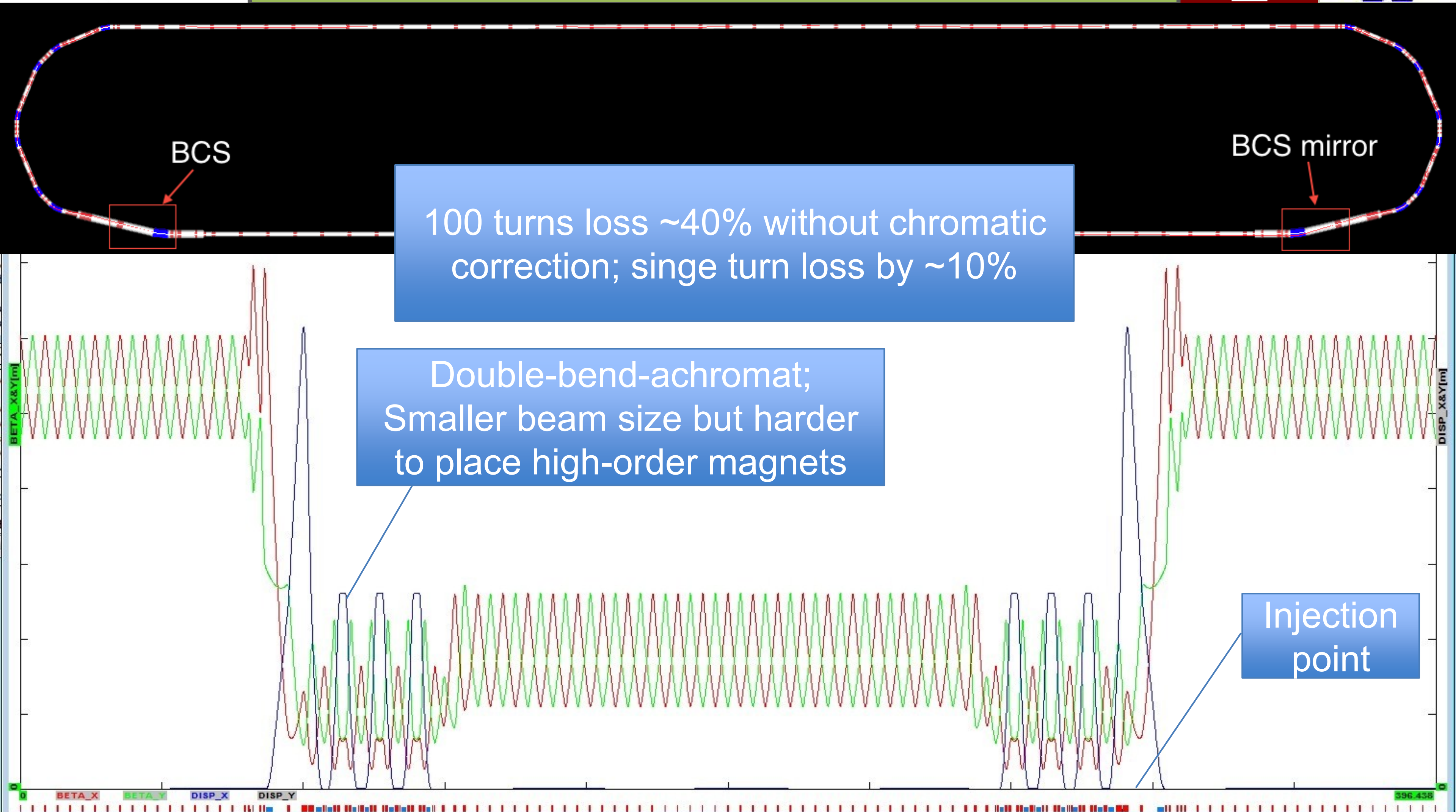

Ring Design Future

- Study effects of tune chromaticity and beta beat;
- Consider longer arc lengths with more space for magnets;
- Non-achromat FODO cells to be considered;
- Apply G4beamline for simulations of neutrino flux at near + far detector.

Fermilab Site Plan

Conclusions

- Injection scenario was proved to work by simulations from G4beamline; careful designs of decay straight, the BCS, and the transport line have been done.
- We expect the ring performance to be dramatically improved with further work.
- vSTORM is in progress – Proposal will be on Fermilab Physics Advisory Committee table soon.

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- Backup

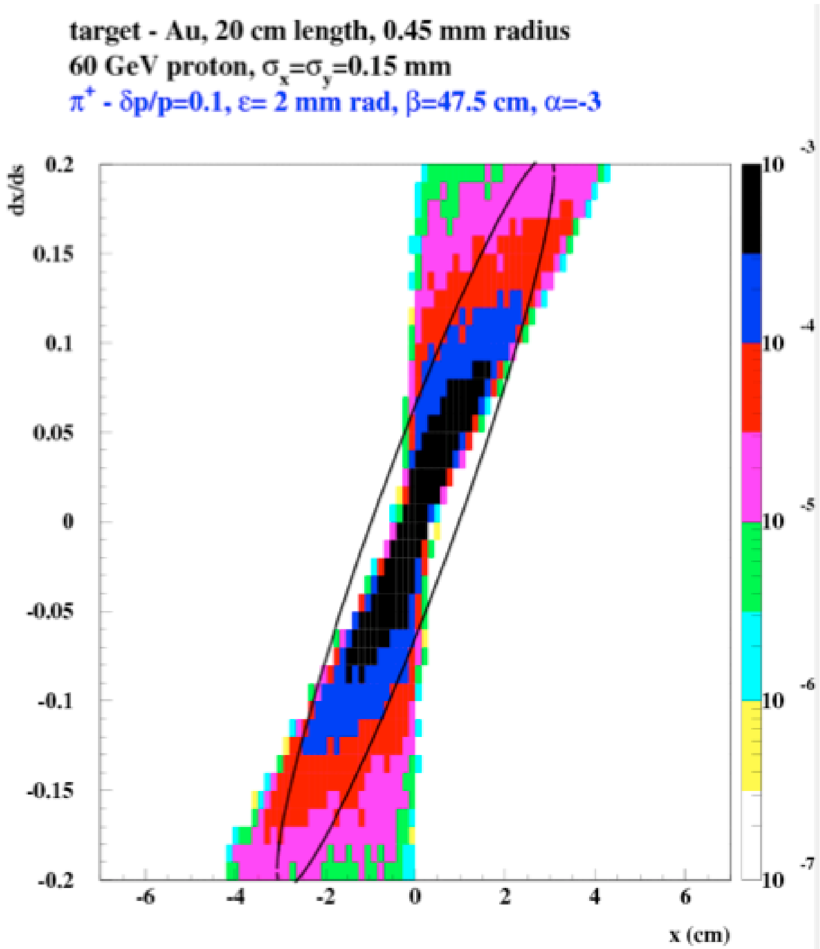
Introduction - Target

Table I. π^+ yield/POT with 60 GeV/c protons, into 2 mm radian acceptance.

material	momentum (GeV/c)	±15%	±10%	±5%	target length (cm)	density (g/cm^3)
Carbon	3	0.085	0.056	0.028	27.3	3.52
Carbon	5	0.099	0.067	0.033	32.2	3.52
Inconel	3	0.131	0.087	0.044	19.2	8.43
Inconel	5	0.136	0.091	0.045	27.0	8.43
Tantalum	3	0.164	0.109	0.054	15.3	16.6
Tantalum	5	0.161	0.107	0.053	21.3	16.6
Gold	3	0.177	0.118	0.059	18.0	19.32
Gold	5	0.171	0.112	0.056	21.0	19.32

- Able to achieve ~ 0.11 π per POT in ± 10% bin;
- Medium/Heavy targets preferred;
- Courtesy of S. Striganov (Fermilab)

Introduction – π Production (Old)



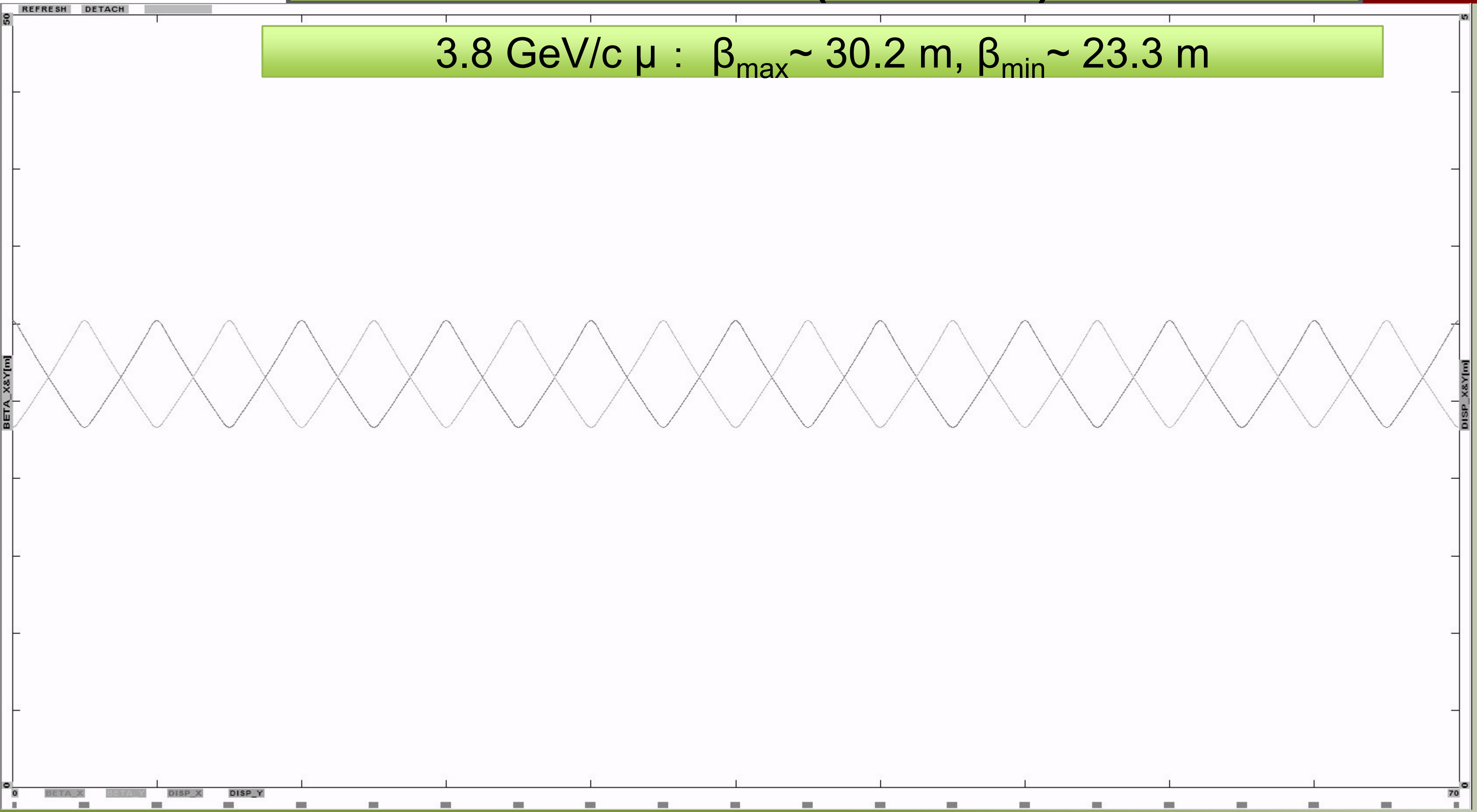
$\mathcal{E}$=2 mm: yield = 0.094

r< 20 cm: yield = 0.118

- Pion phase space distribution at 1 cm after target
- Vertical: x' (rad)
- Horizontal: x (cm)

Transport Design – Details(Cont'd)

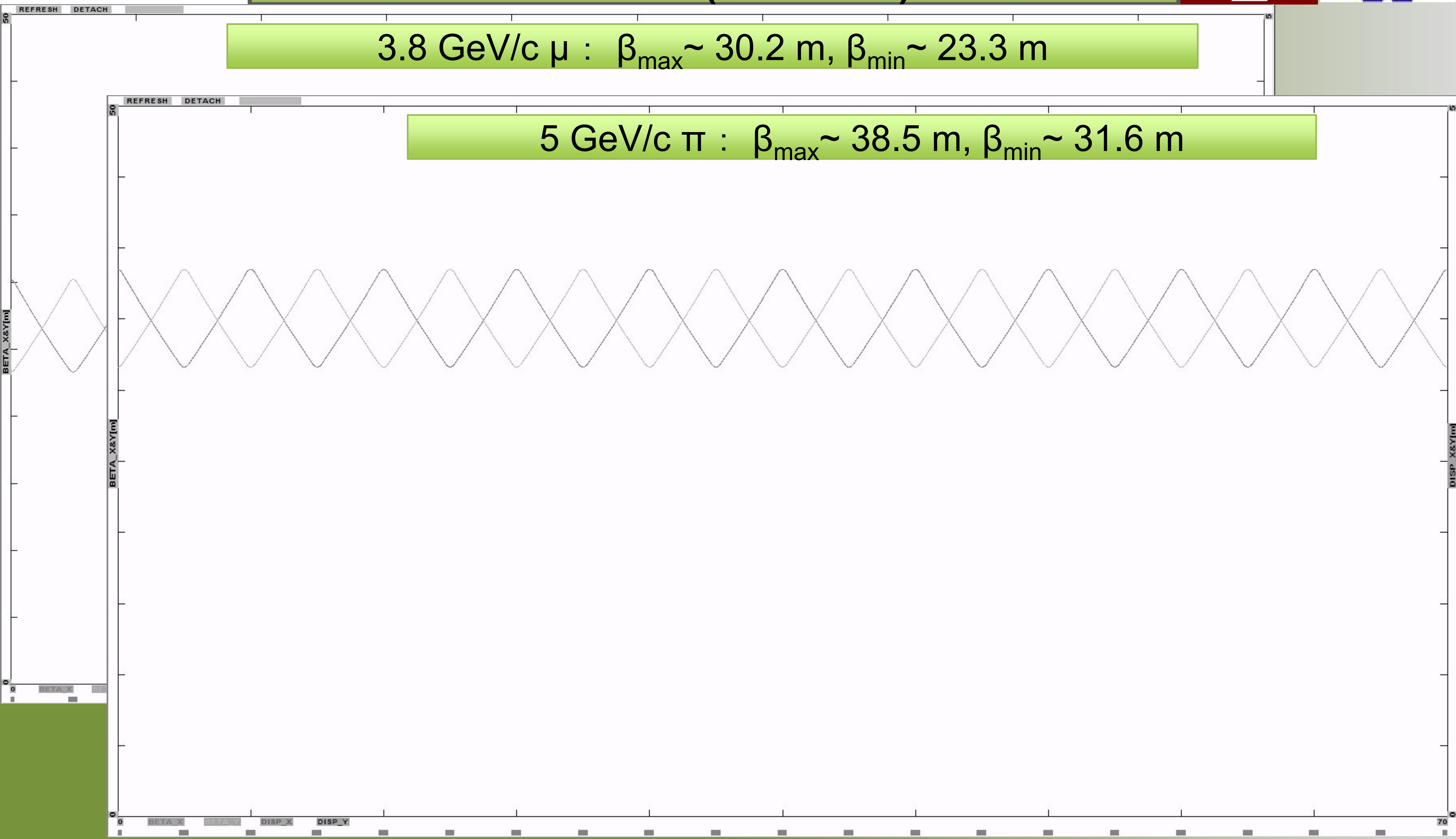
3.8 GeV/c μ : β_{max}~ 30.2 m, β_{min}~ 23.3 m



Transport Design – Details(Cont'd)

3.8 GeV/c μ : β_{max}~ 30.2 m, β_{min}~ 23.3 m

5 GeV/c π : β_{max}~ 38.5 m, β_{min}~ 31.6 m



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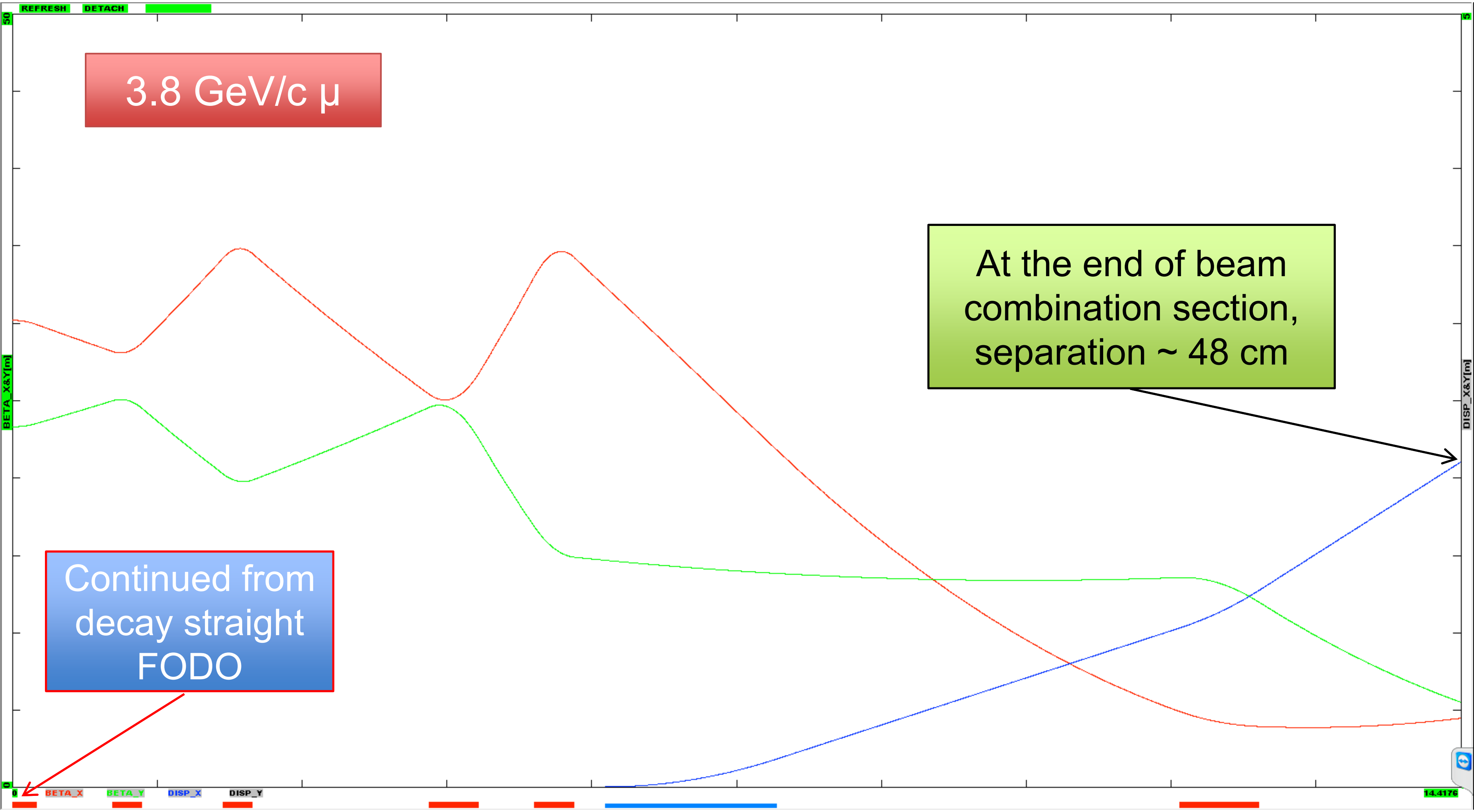
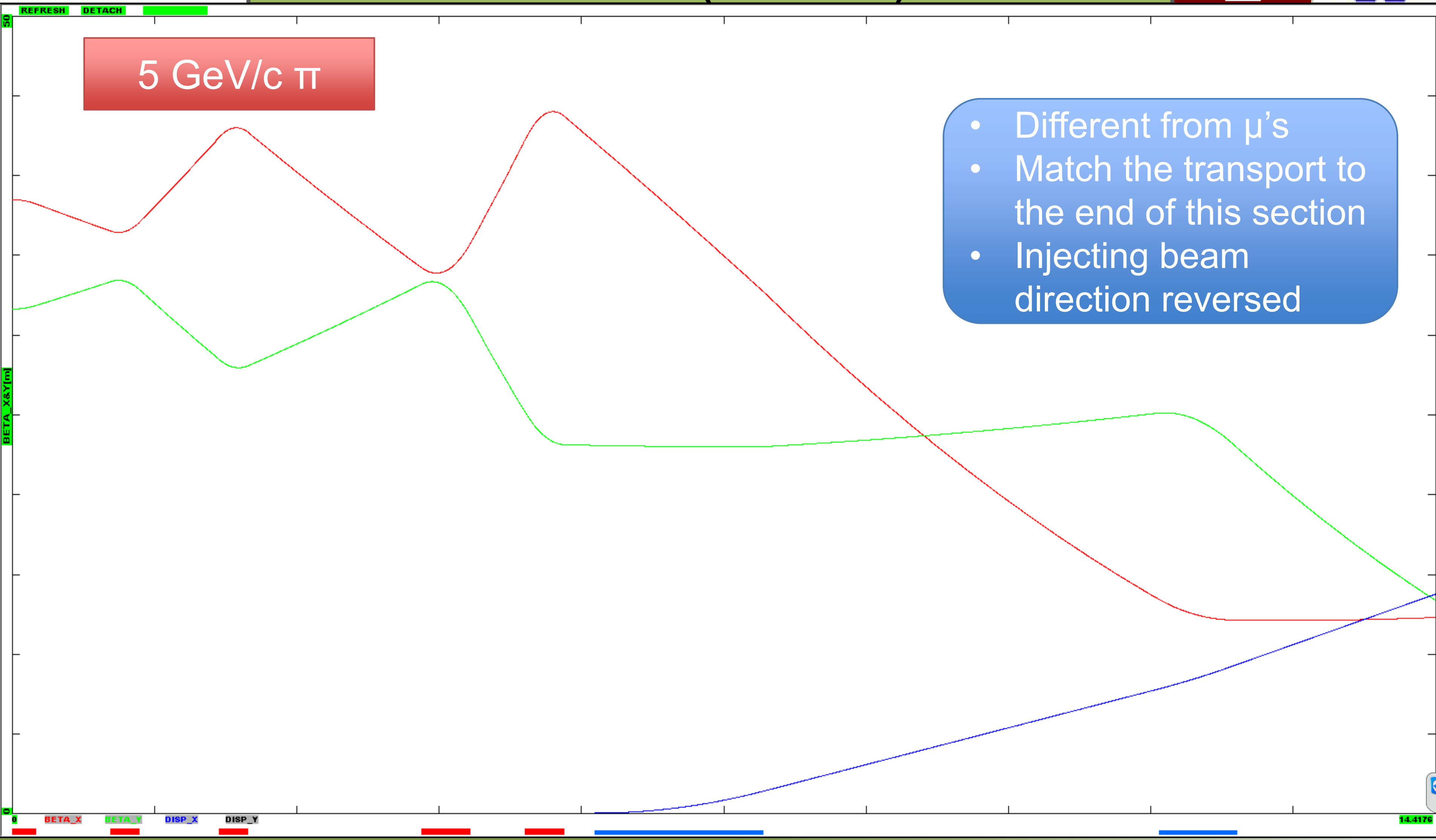


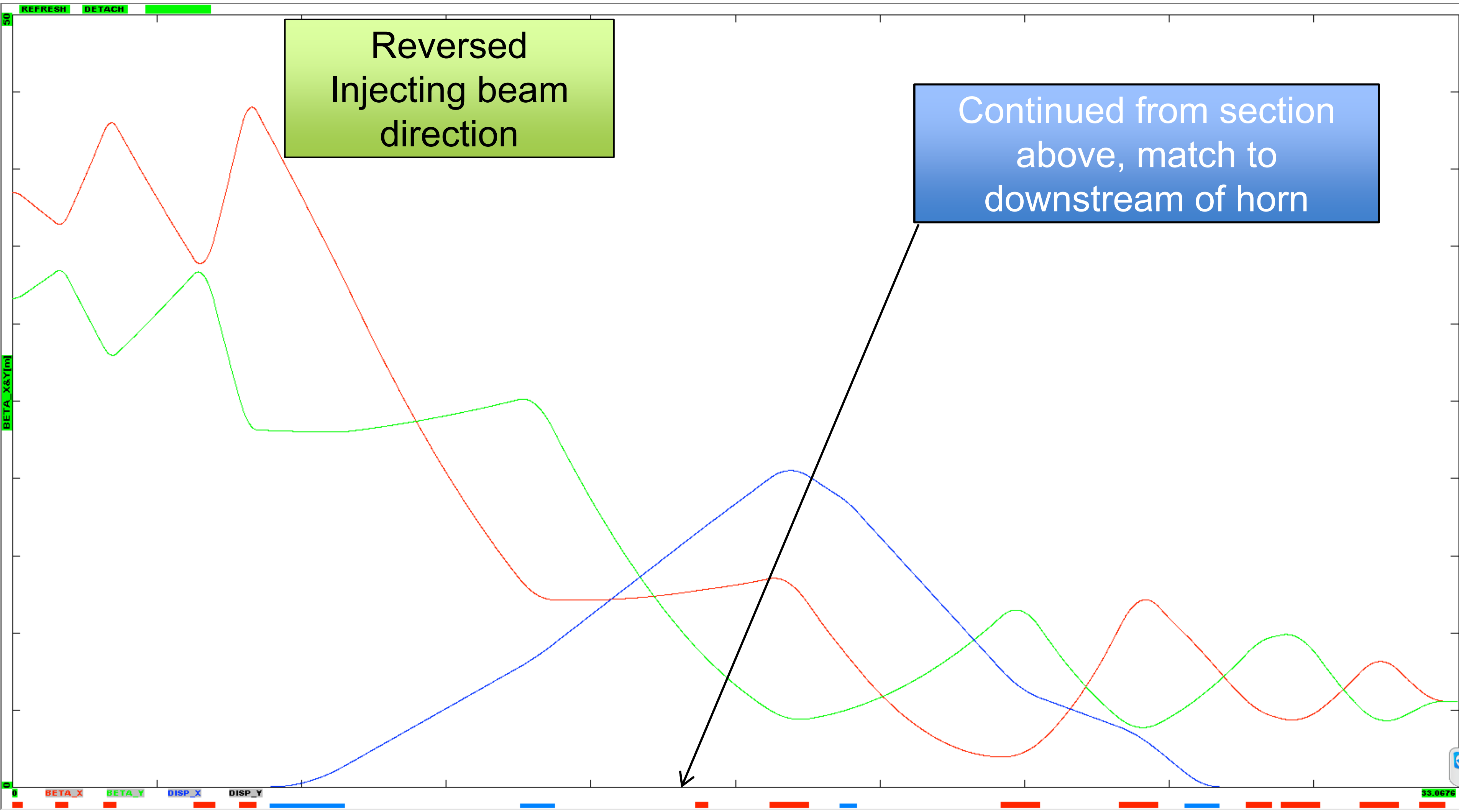
Transport Design – Details(Cont'd)

5 GeV/c π



- Different from μ's
- Match the transport to the end of this section
- Injecting beam direction reversed

Transport Design – Details(Cont'd)(Old)



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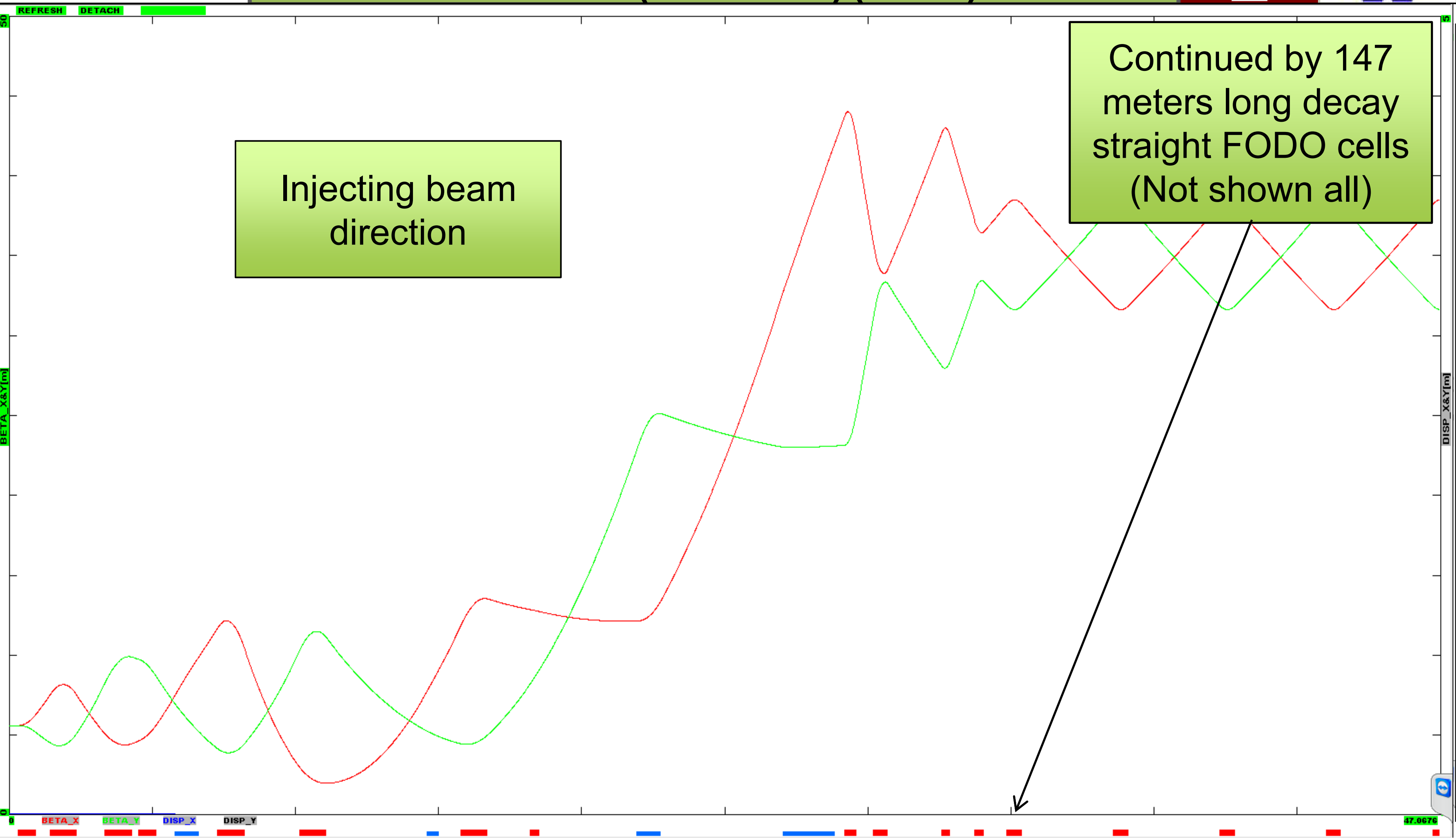
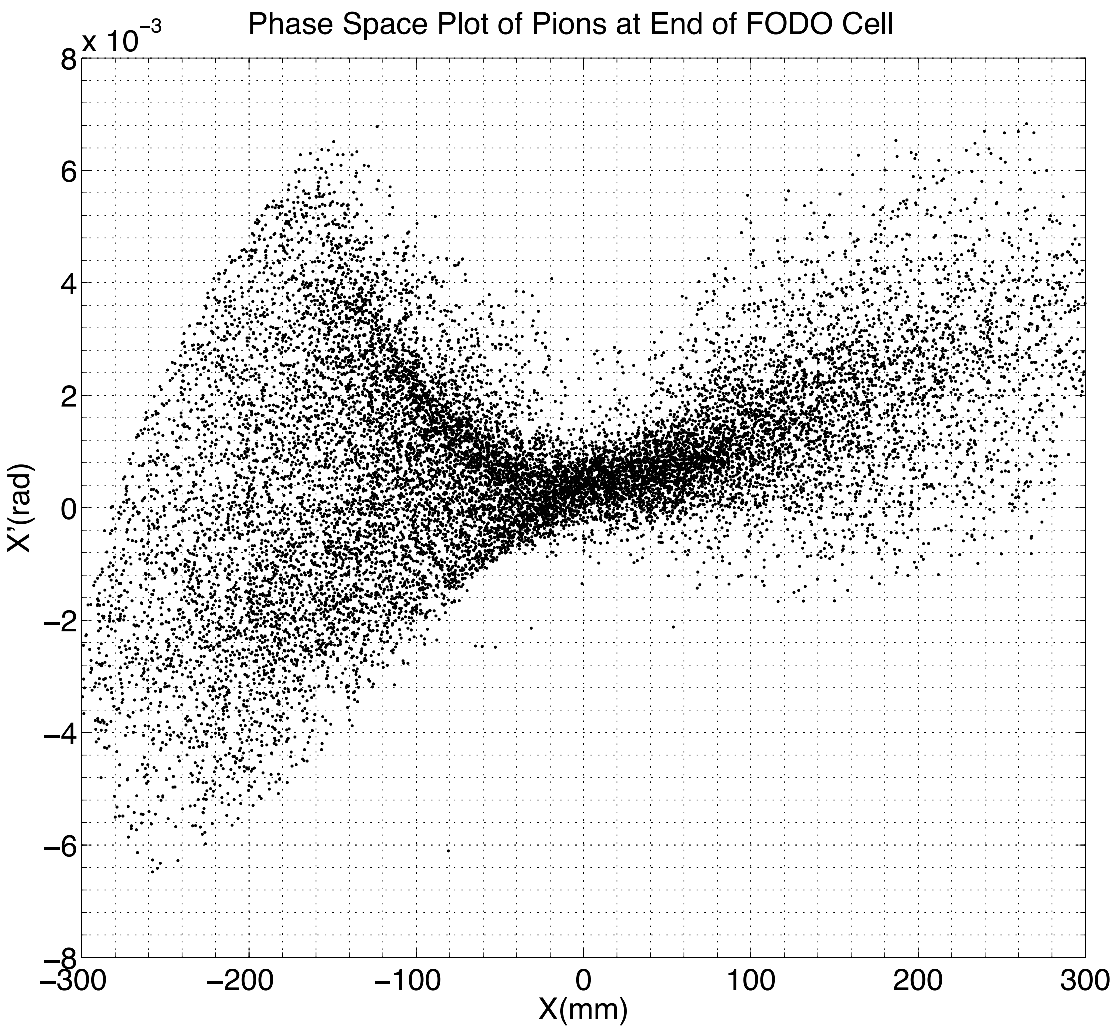
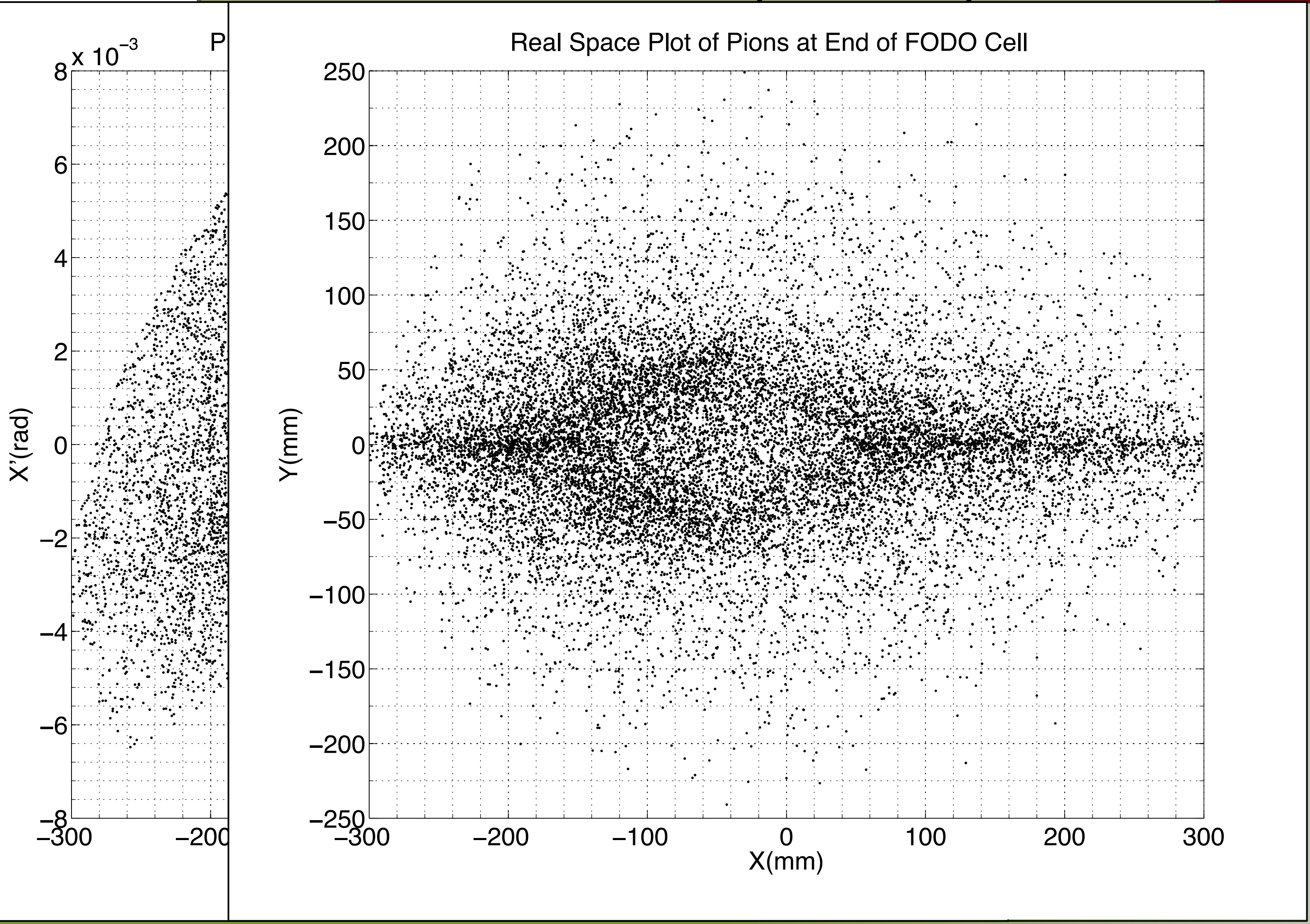


Transport Design – Simulation(Cont'd)

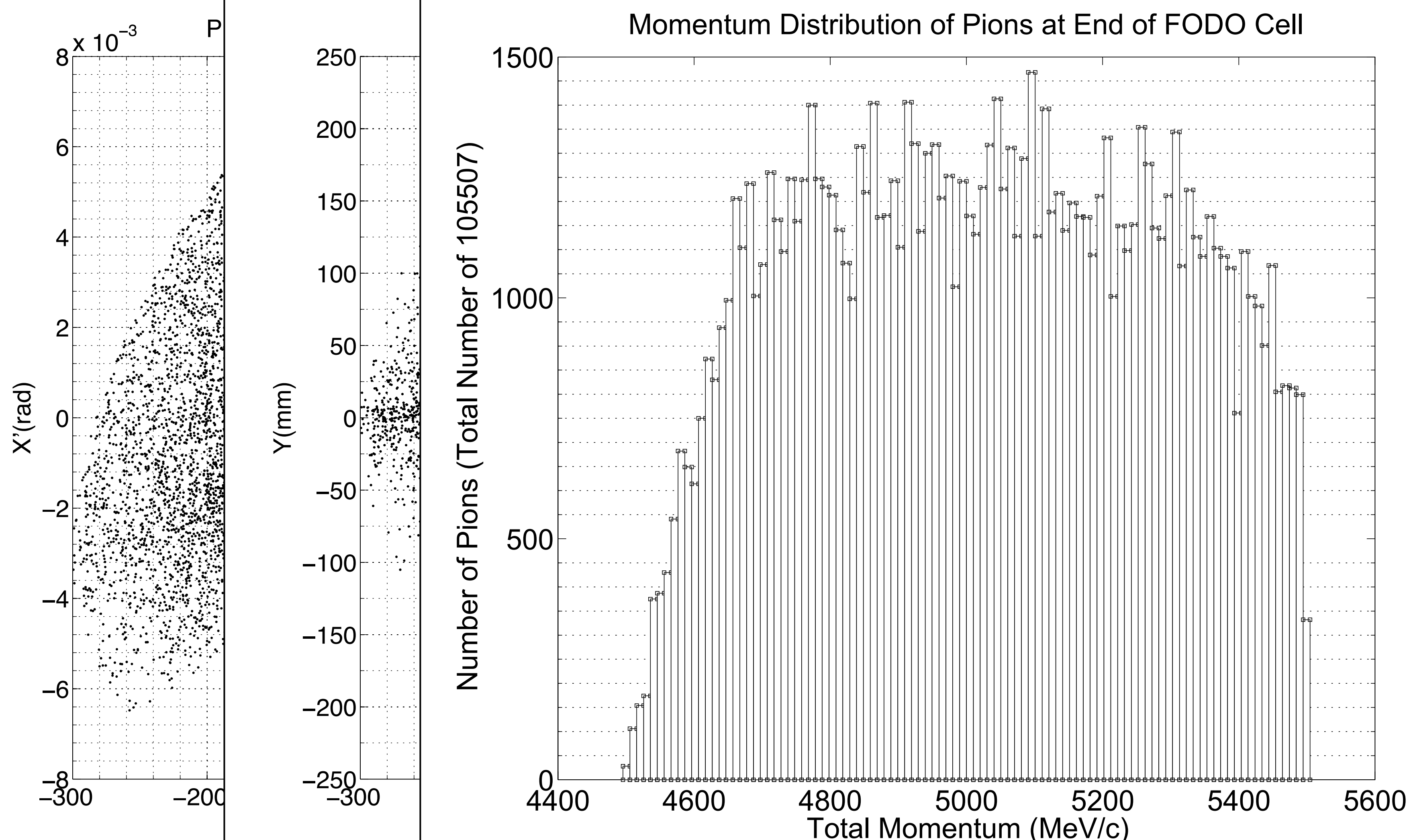


Gold Target Deacay OFF, End of injection straight, 54%

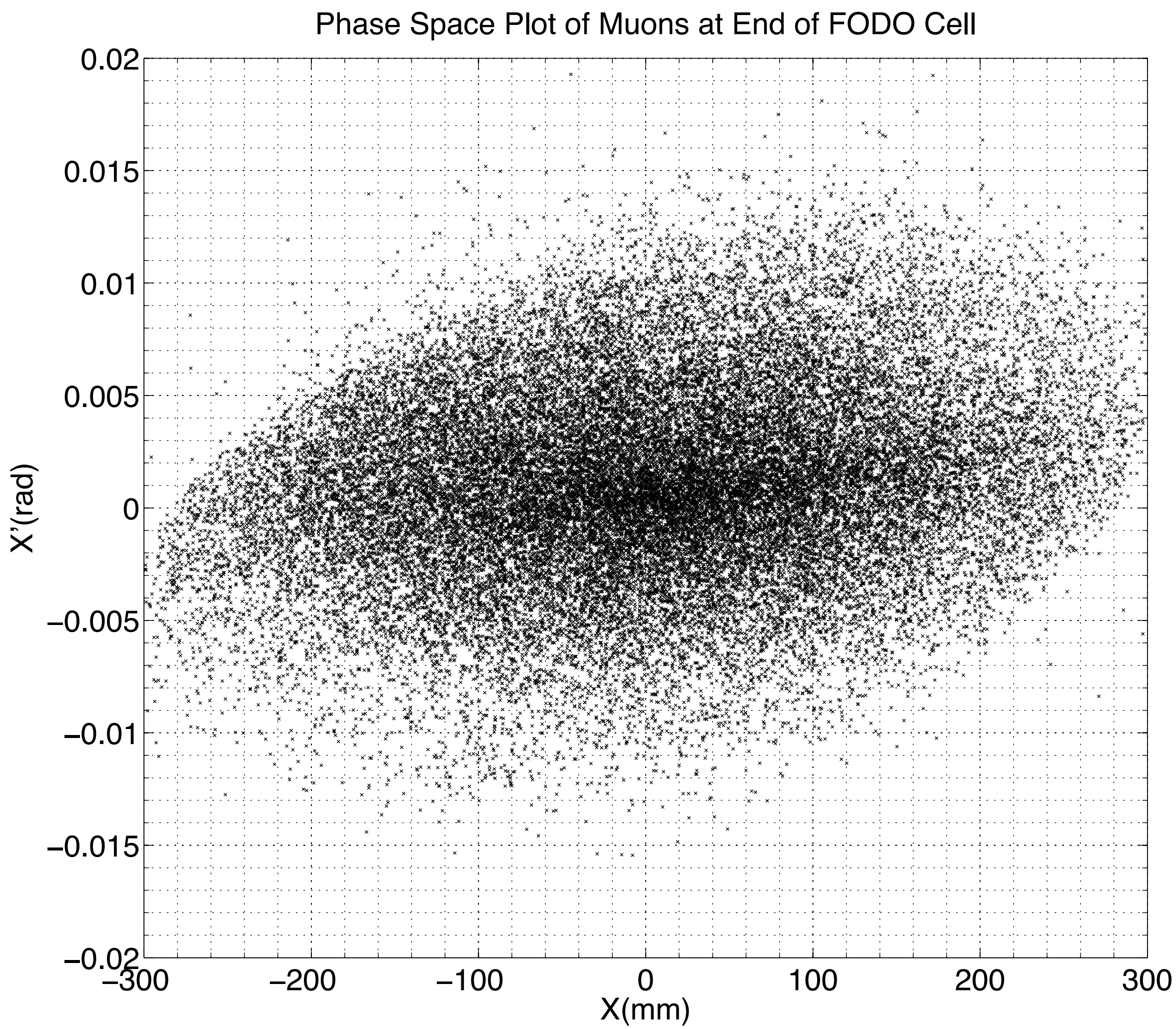
Transport Design – Simulation(Cont'd)



Transport Design – Simulation(Cont'd)

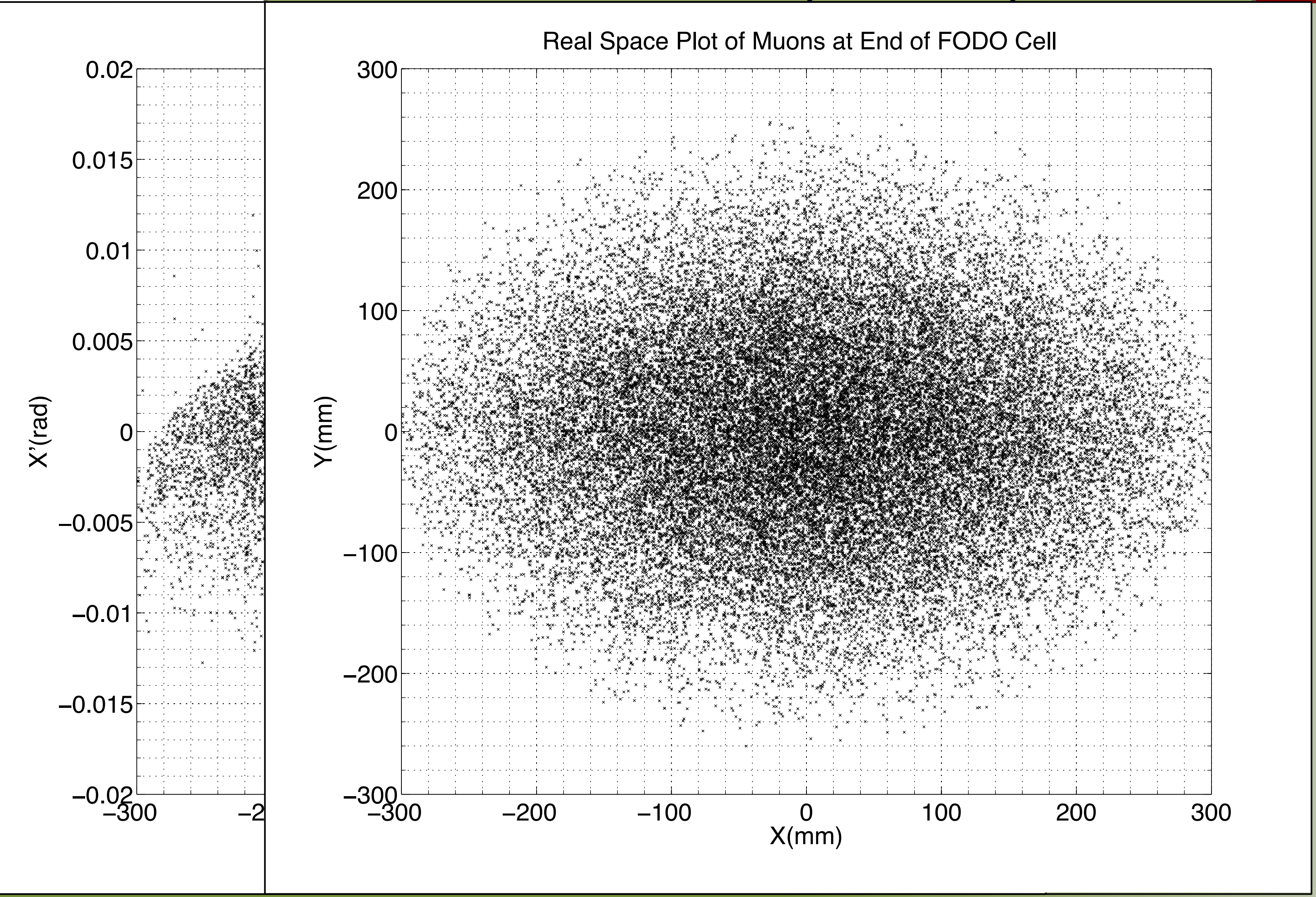


Transport Design – Simulation(Cont'd)

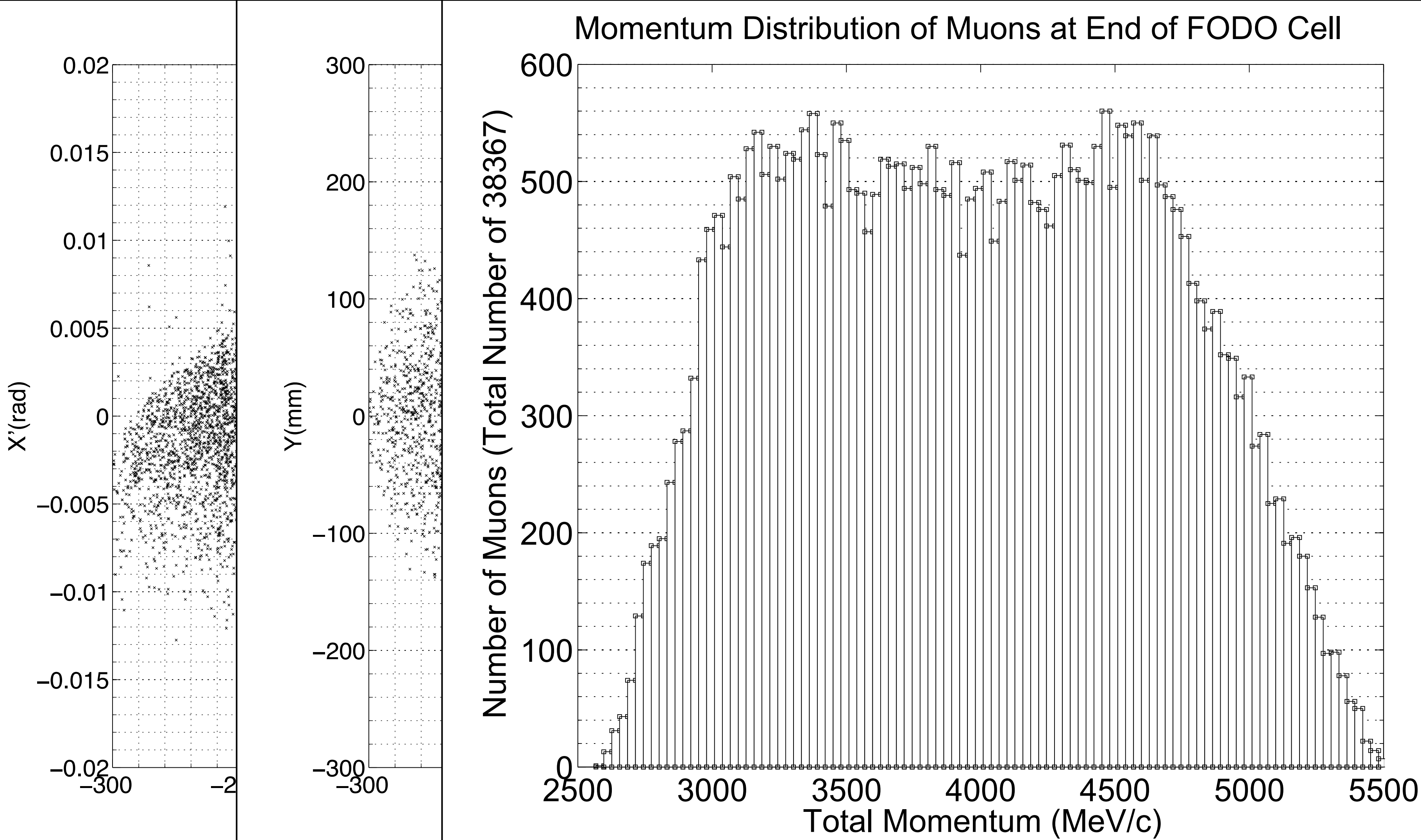


Gold Target Deacay ON, End of injection straight muons, 19%

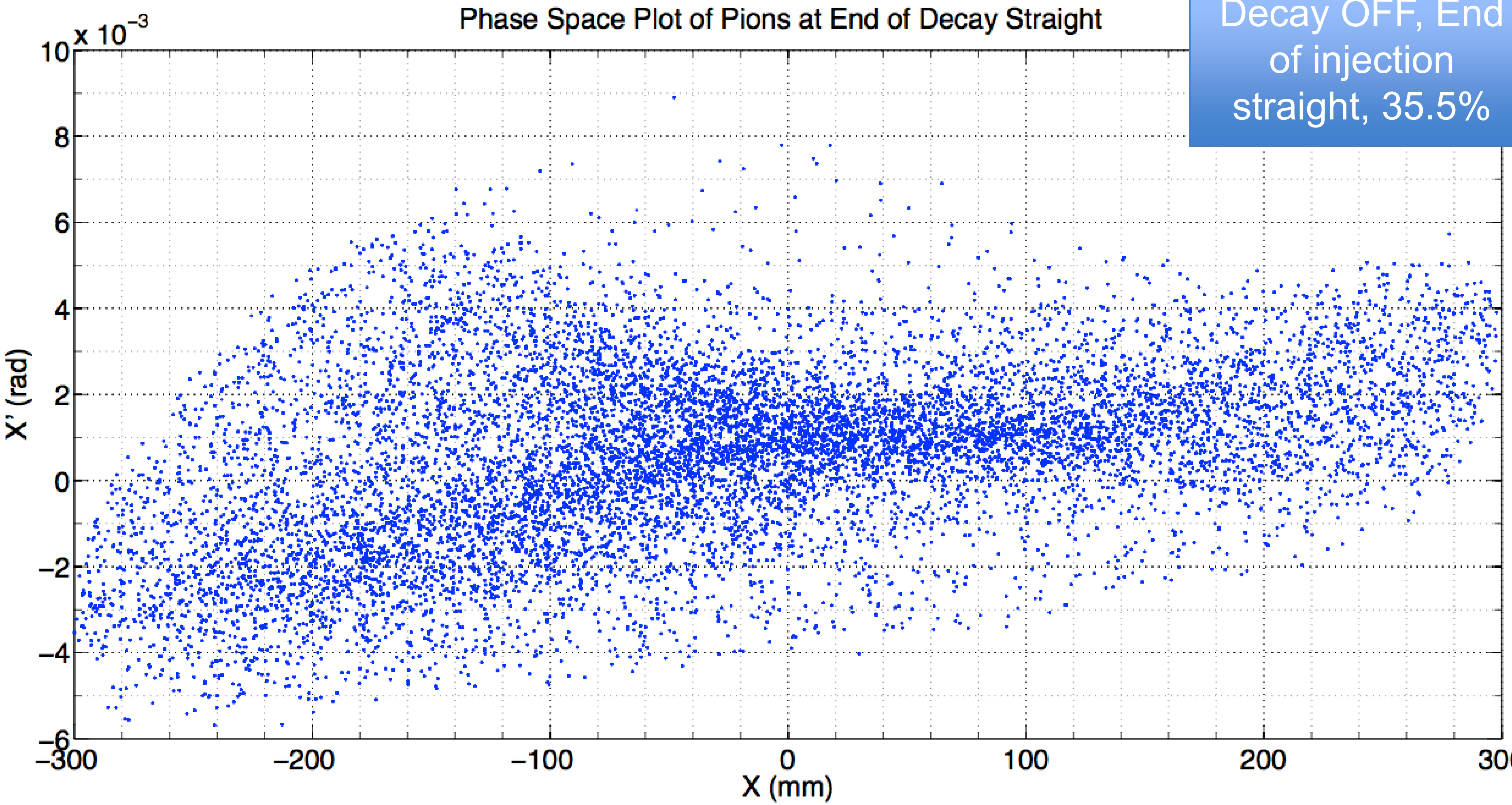
Transport Design – Simulation(Cont'd)



Transport Design – Simulation(Cont'd)



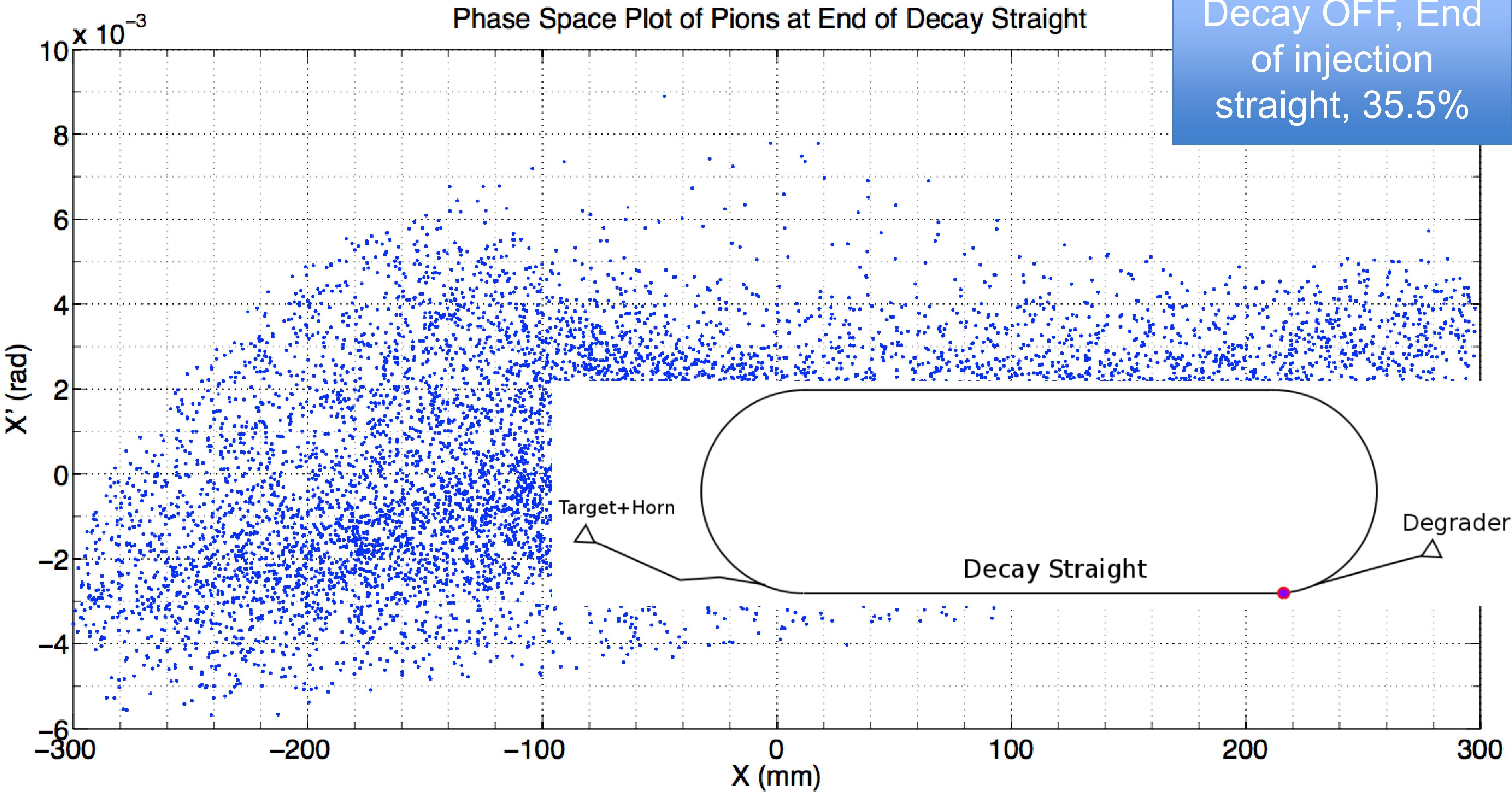
Transport Design – Simulation(Cont'd)



Decay OFF, End of injection straight, 35.5%

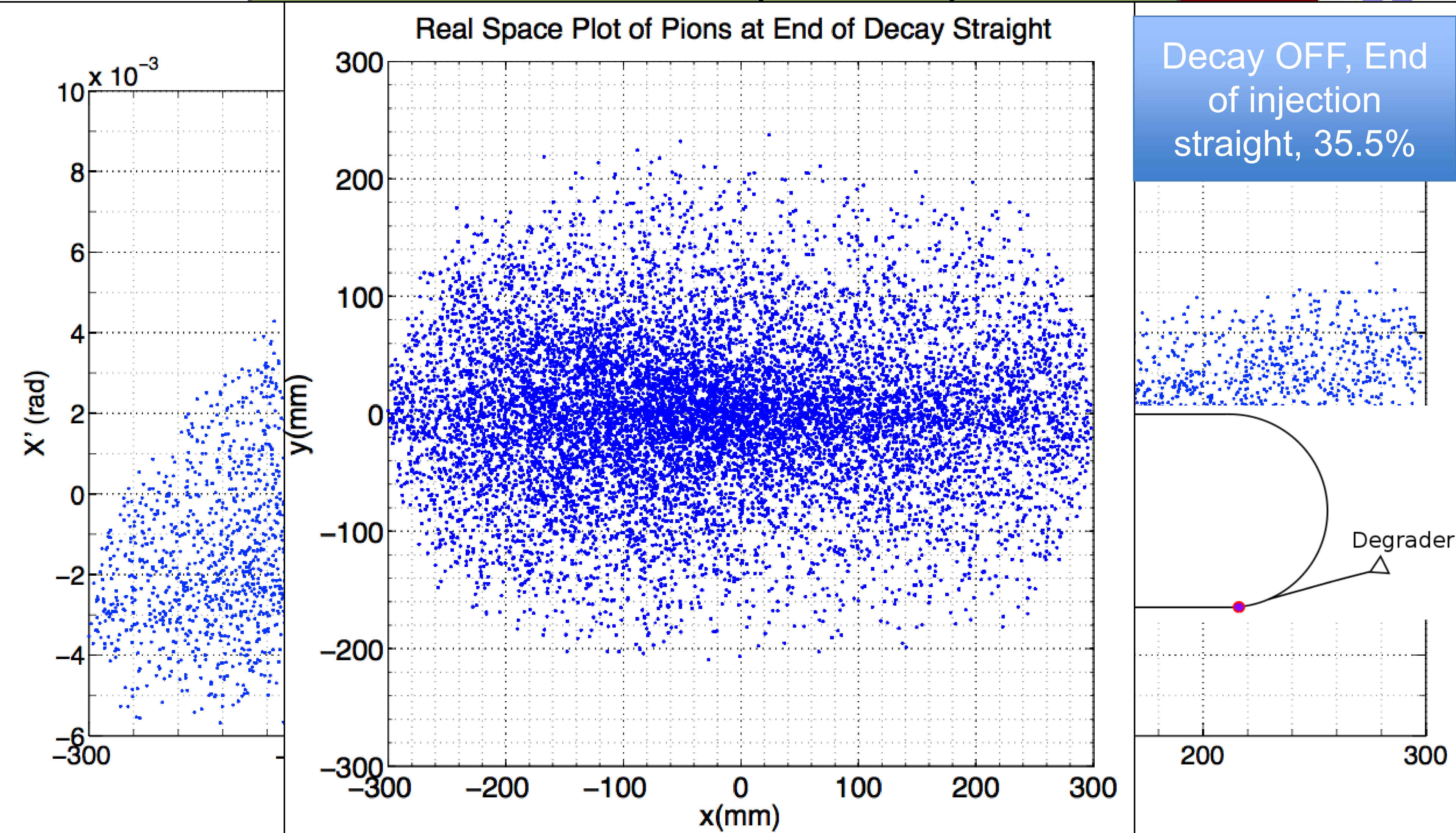
Transport Design – Simulation(Cont'd)

Decay OFF, End of injection straight, 35.5%

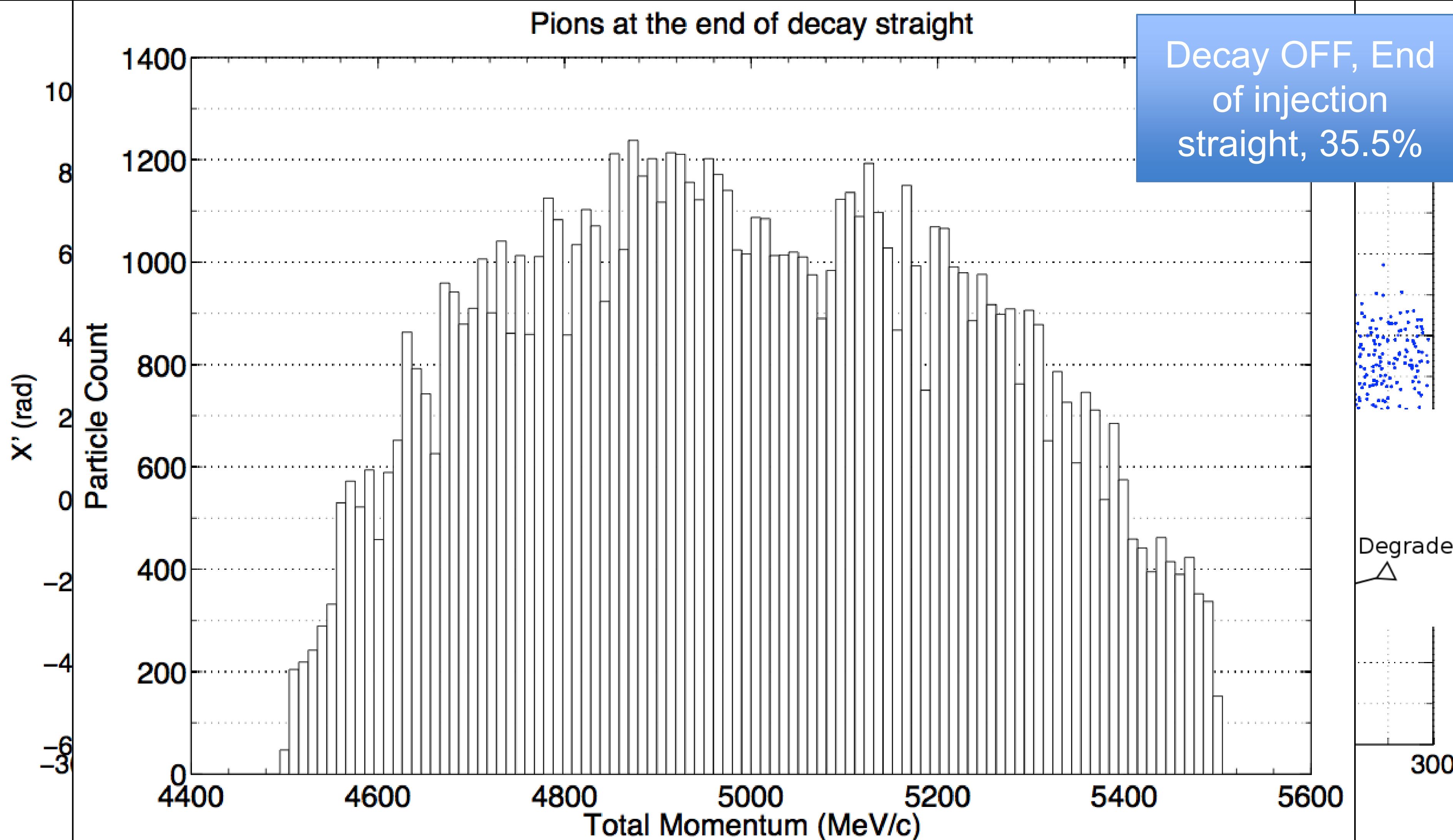


Transport Design – Simulation(Cont'd)

Decay OFF, End of injection straight, 35.5%

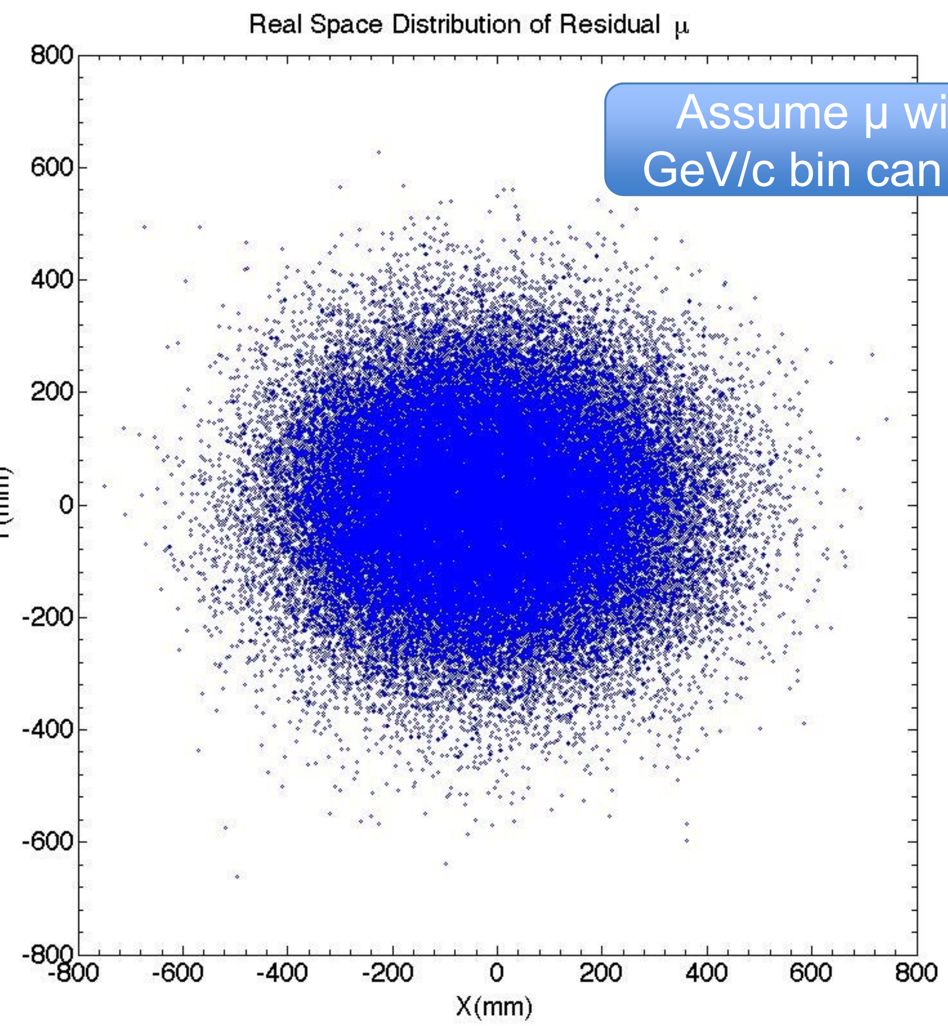


Transport Design – Simulation(Cont'd)

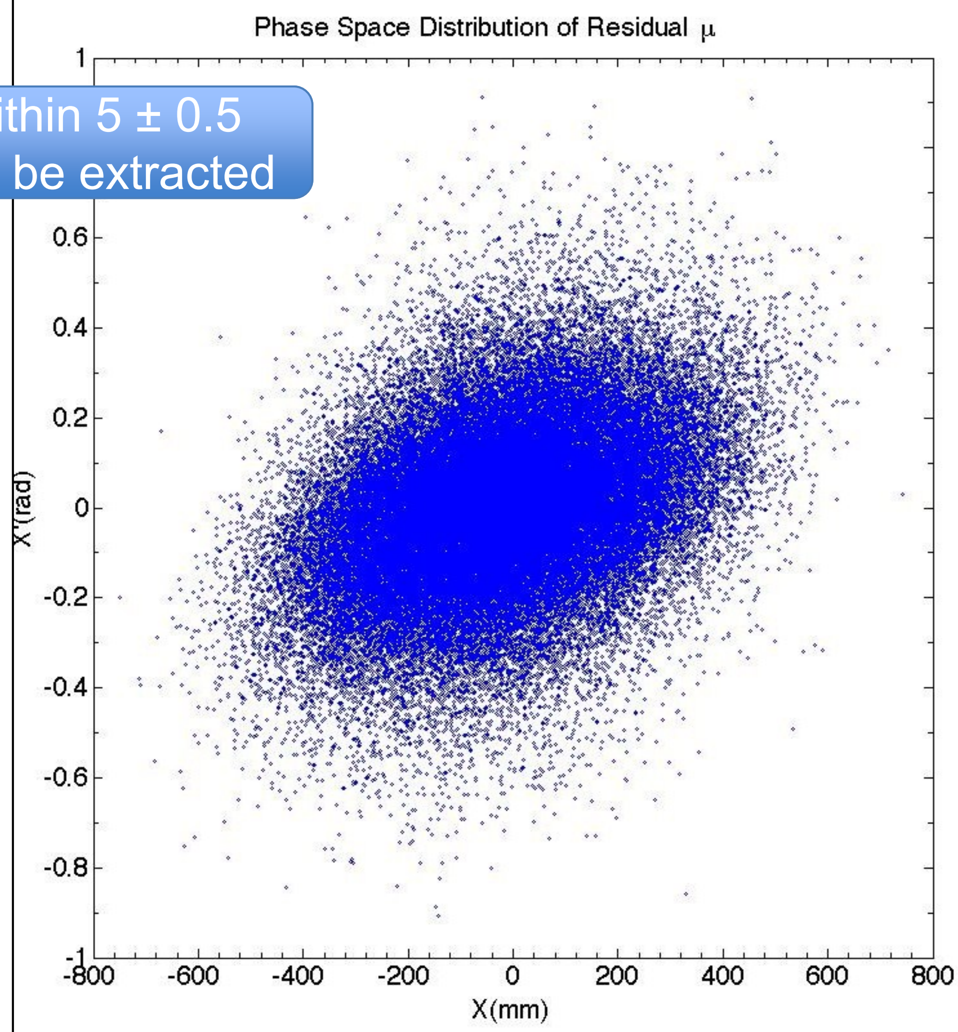


Decay OFF, End of injection straight, 35.5%

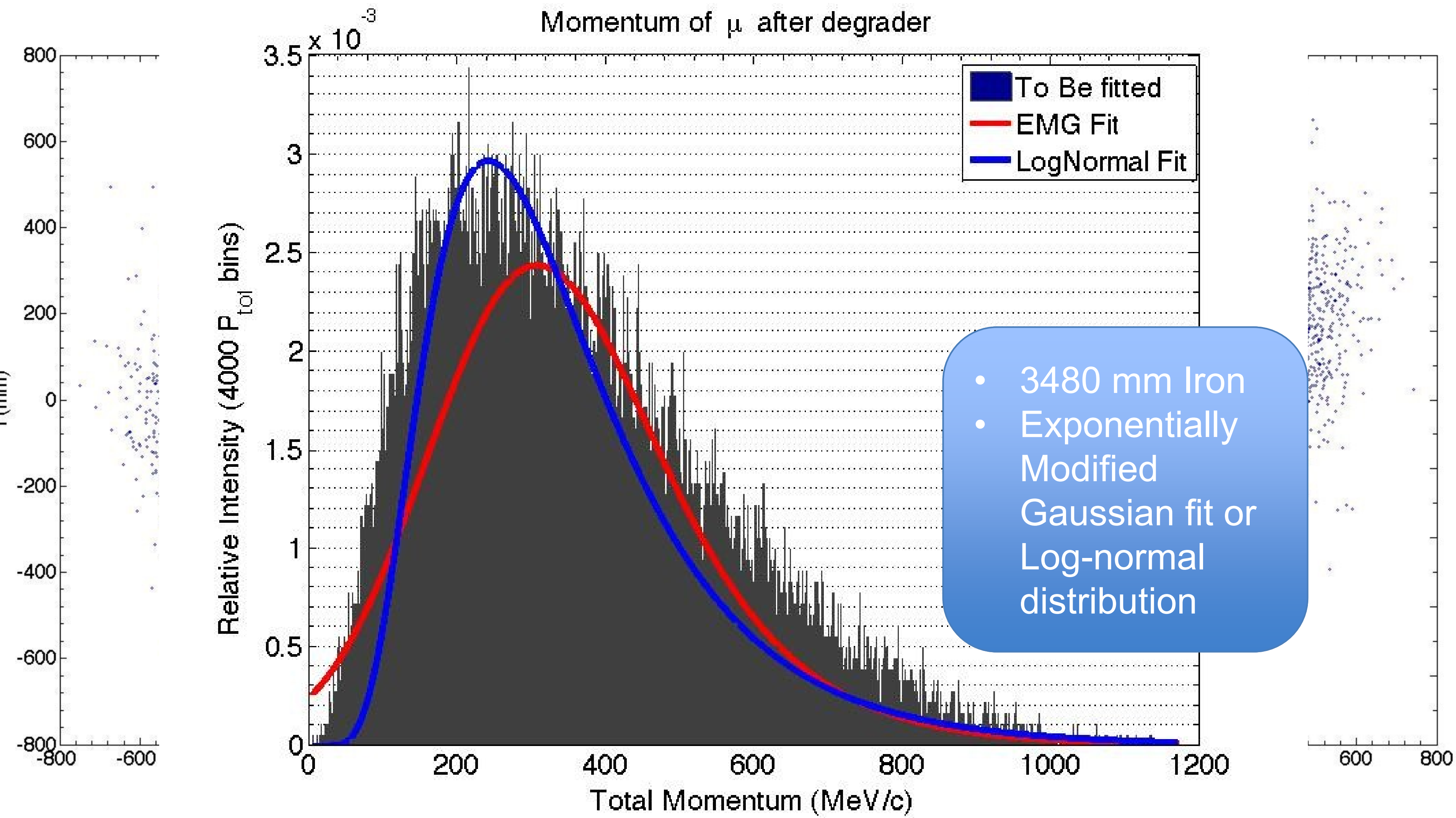
Low Energy Muons



Assume μ within 5 ± 0.5 GeV/c bin can be extracted

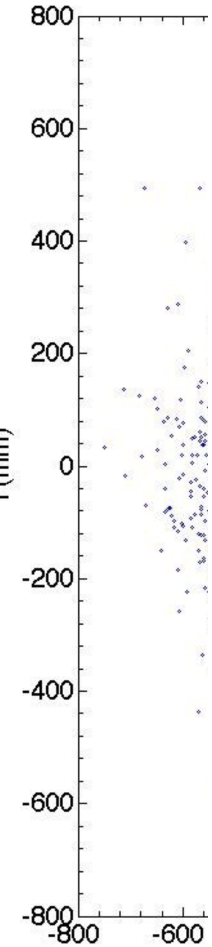


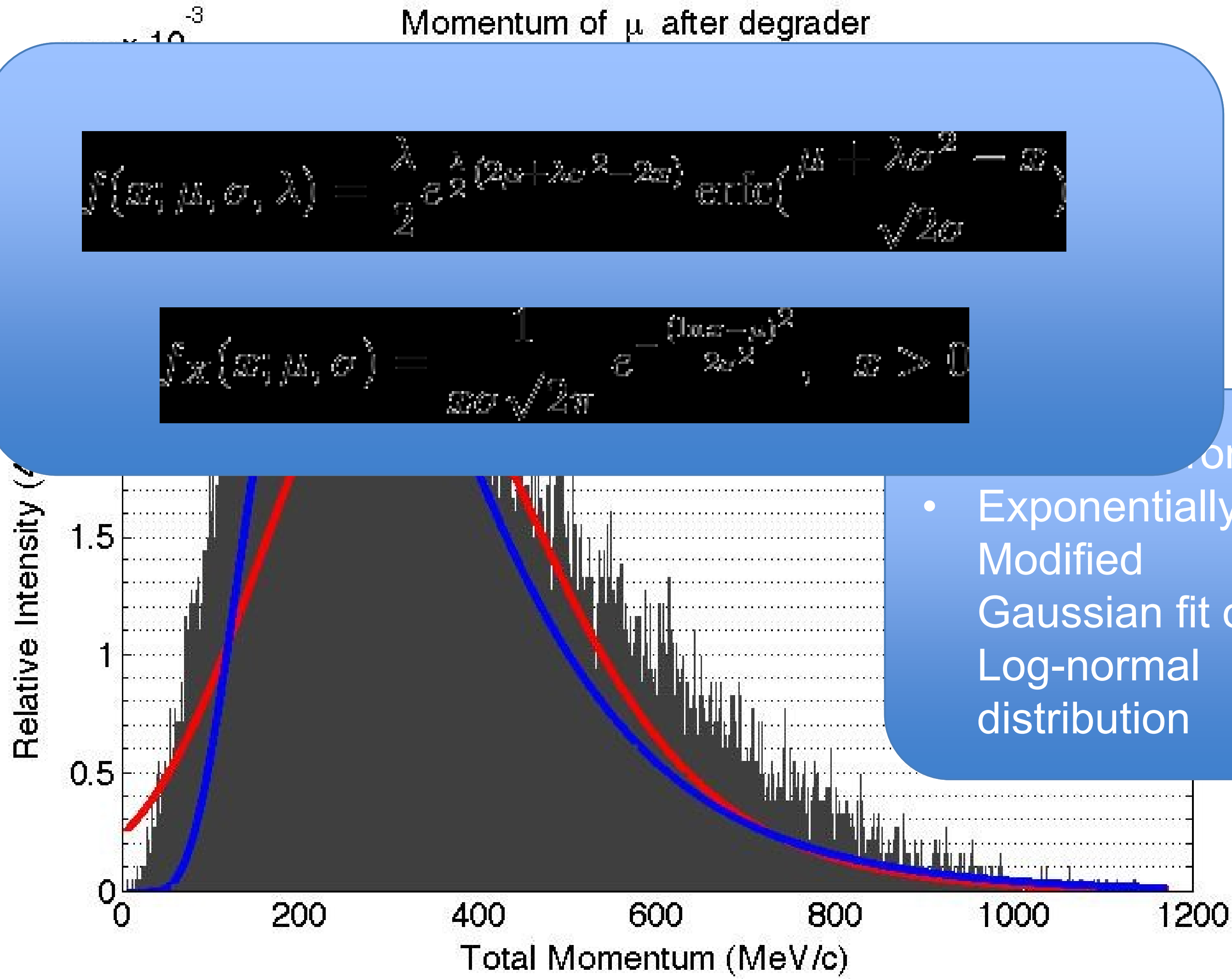
Low Energy Muons



- 3480 mm Iron
- Exponentially Modified Gaussian fit or Log-normal distribution

Low Energy Muons



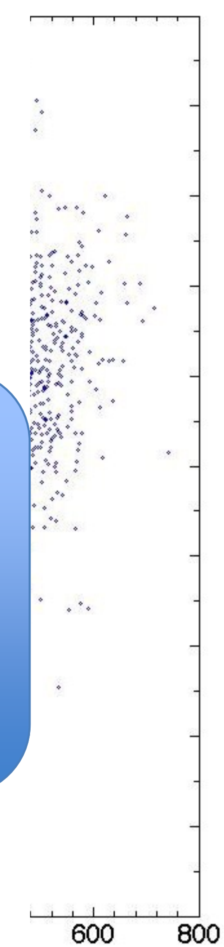


$$f(x;\mu,\sigma,\lambda) = \frac{\lambda}{2} e^{\frac{\lambda}{2}(2\mu+\lambda\sigma^2-2x)} \operatorname{erfc}\left(\frac{\mu+\lambda\sigma^2-x}{\sqrt{2}\sigma}\right)$$

$$f_X(x;\mu,\sigma) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-\frac{(\ln x-\mu)^2}{2\sigma^2}}, \quad x>0$$

...on

- Exponentially Modified Gaussian fit or Log-normal distribution



Higher-order Dispersion Correction