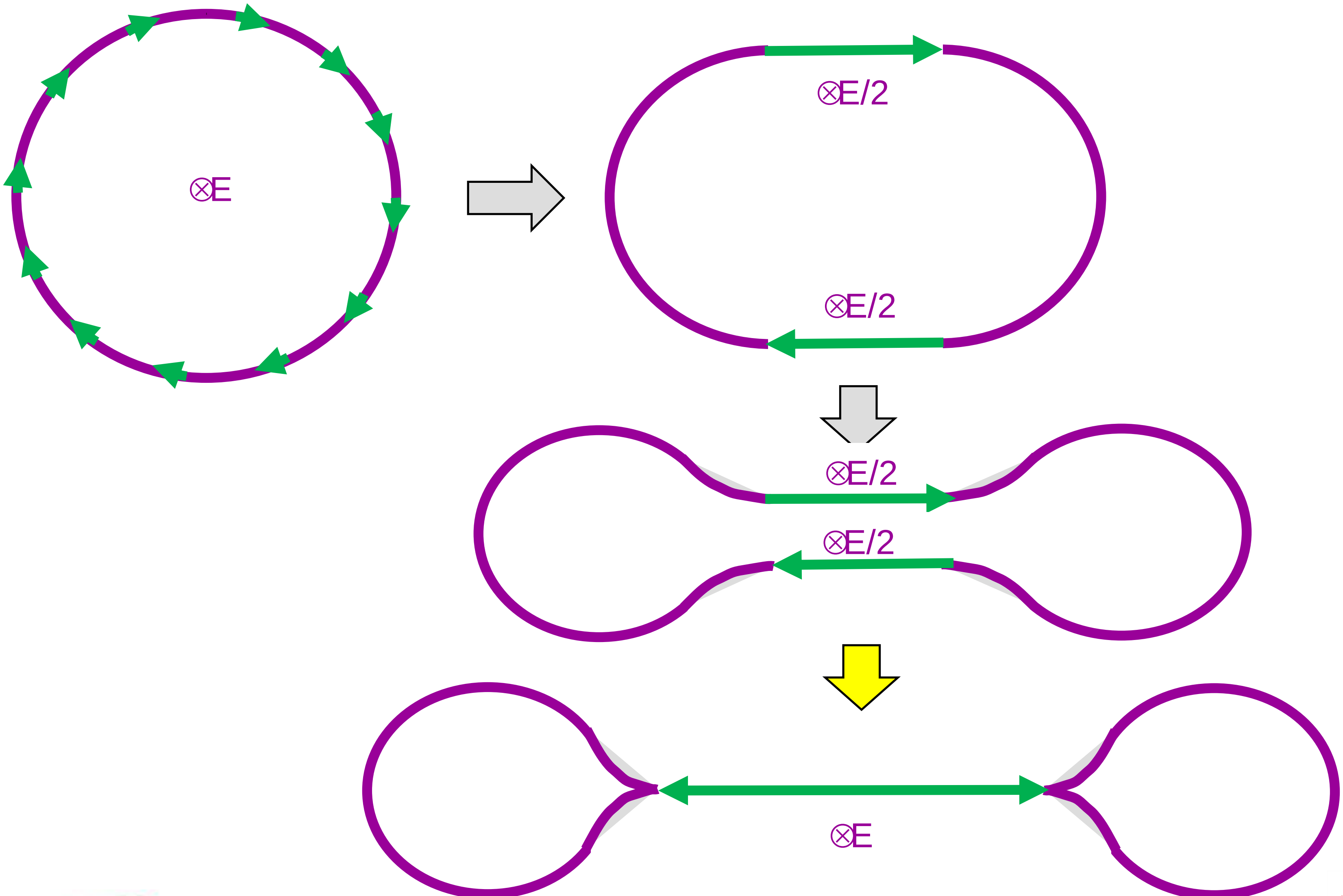
Muon Acceleration for Neutrino Factory and Beyond

Alex Bogacz

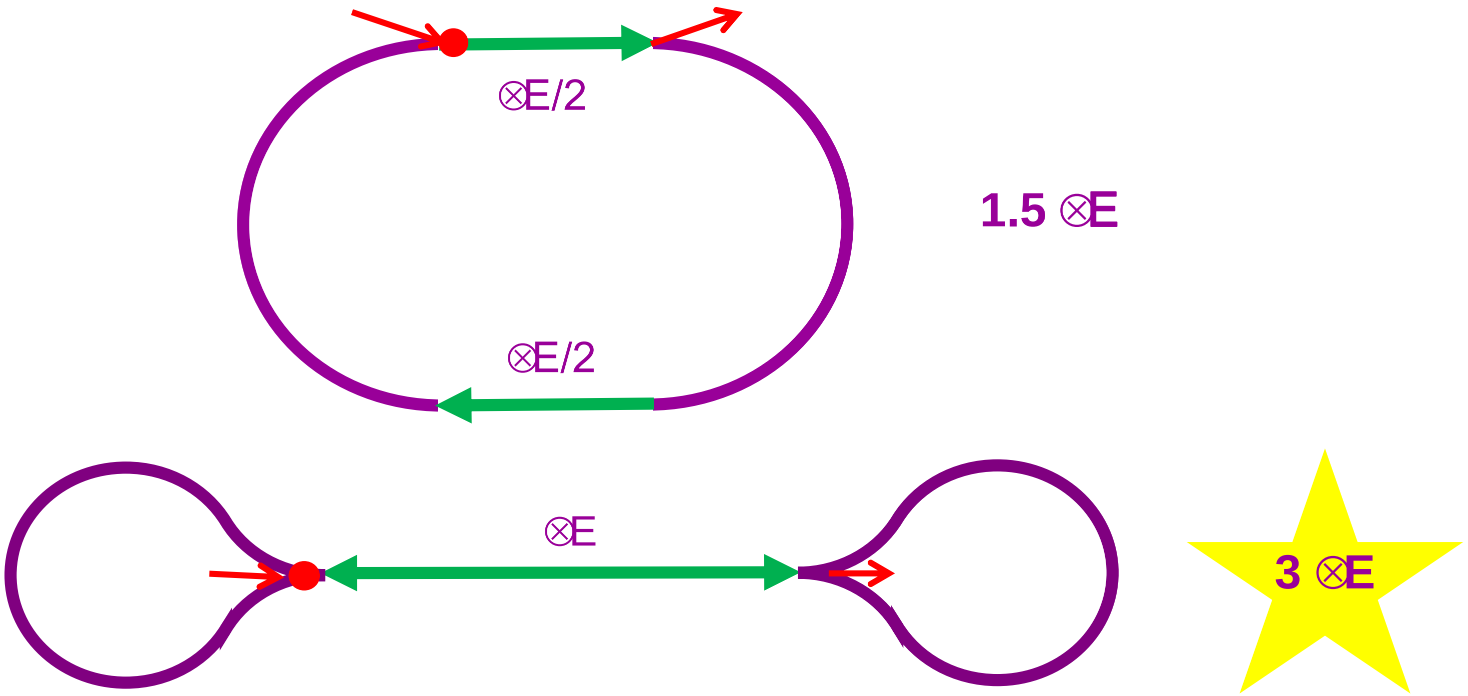
Overview

- Accelerator Topologies: ‘Racetrack vs Dogbone’
- Muon Acceleration for 5 GeV Neutrino Factory
  - Linac + ‘Dogbone’ RLA: Beam Dynamics Issues
    - Full bucket acceleration, Longitudinal compression
    - Longitudinal RF frequency shift: Matching chicane to accommodate $\mu^{\pm}$
    - Transverse Optics: Bi-sected linacs + ‘Droplet’ Arcs
- Extending accelerator complex to 63 GeV Higgs Factory
  - Dogbone RLA with FFAG-like Arcs
    - Proof-of-Concept Optics
    - Demonstration Experiment: JEMMRLA

Accelerator Topologies

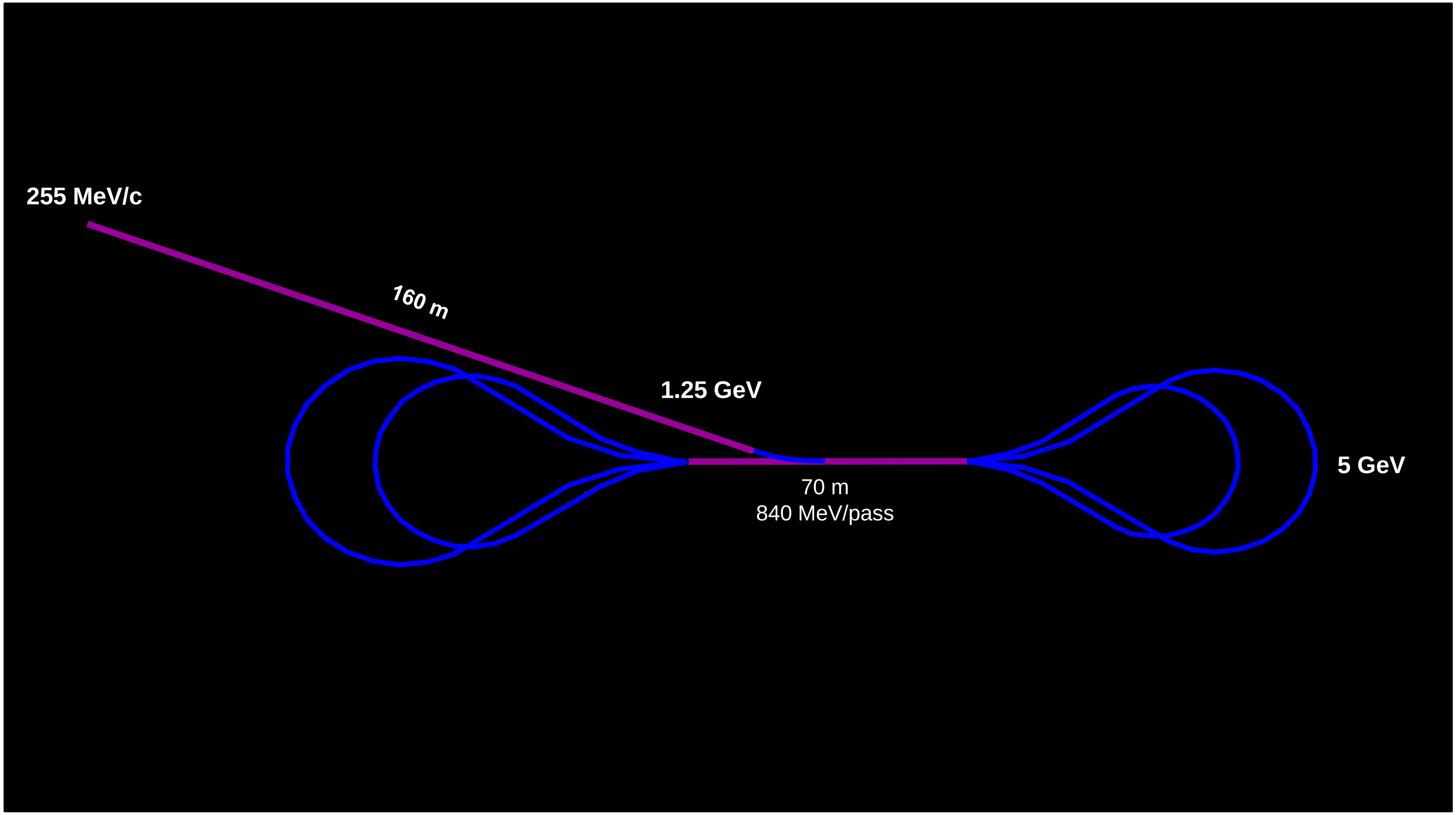


‘Racetrack’ vs ‘Dogbone’ RLA



- Twice the acceleration efficiency
- Better separation of passes
- Simultaneous acceleration of both charge species
- Linac traversed in both direction ⇨ bi-sected linac optics

Linac and RLA to 5 GeV

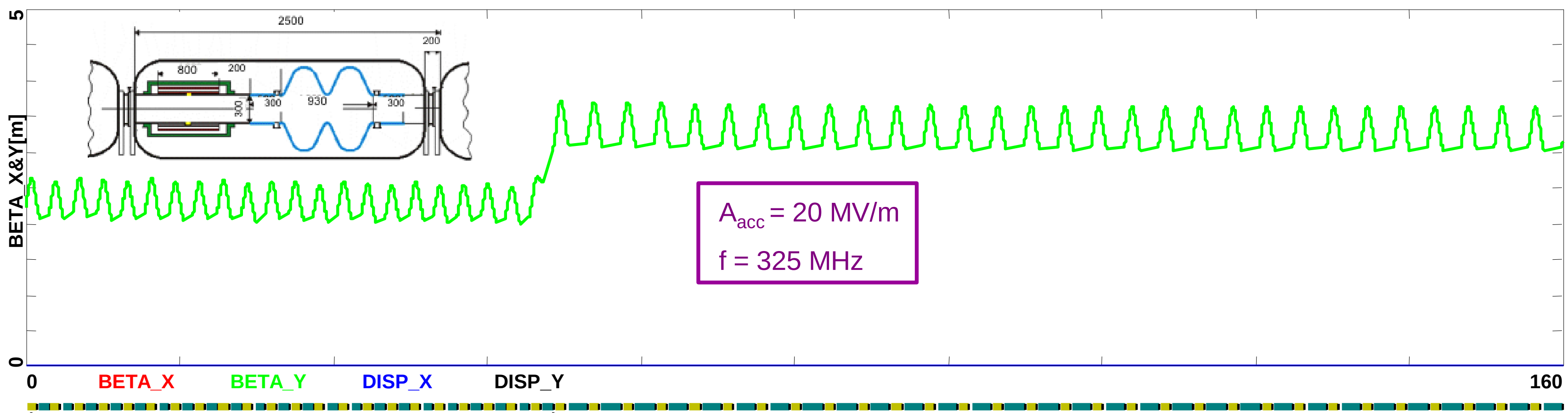


Initial 325 MHz Linac – Transverse Acceptance

p = 255 MeV/c

beta functions

1250 MeV

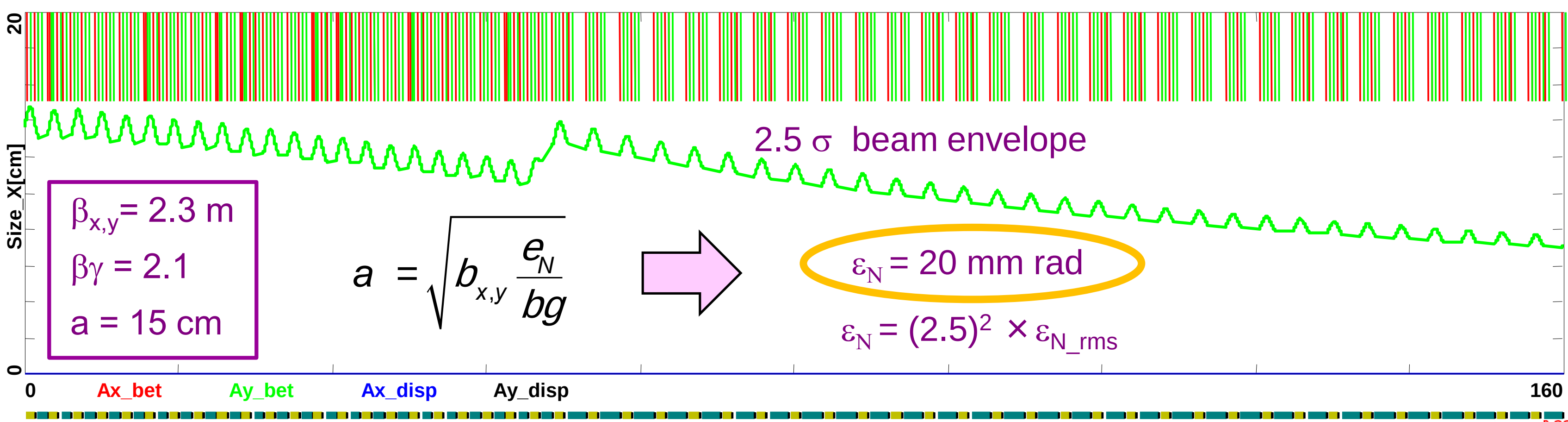


A_{acc} = 20 MV/m

f = 325 MHz

22 short cryos
(2.5 meter, 2-cell cavity)

30 medium cryos
(3.5 meter 4-cell cavity)



2.5 σ beam envelope

$\beta_{x,y}$ = 2.3 m

$\beta\gamma$ = 2.1

a = 15 cm

$$a = \sqrt{\beta_{x,y}\frac{\varepsilon_N}{\beta\gamma}}$$

ε_N = 20 mm rad

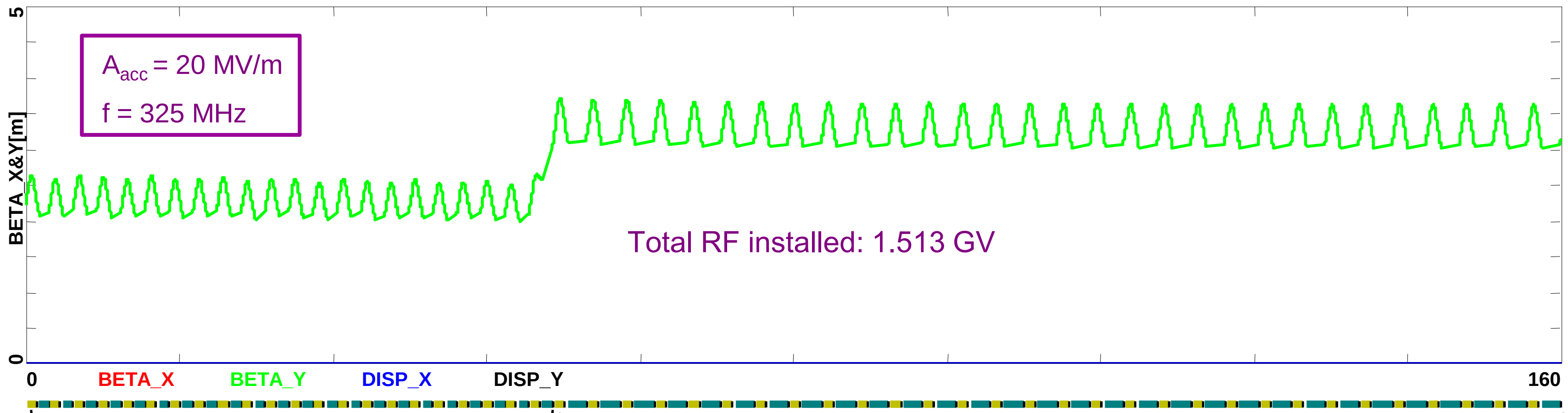
$\varepsilon_N = (2.5)^2 \times \varepsilon_{N\_rms}$

Initial Linac – Longitudinal Matching

p = 255 MeV/c

beta functions

1250 MeV



22 short cryos
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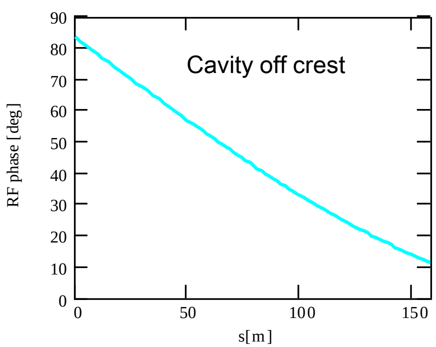
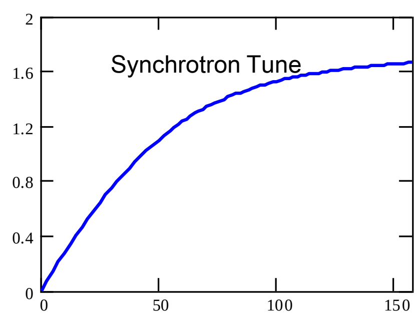
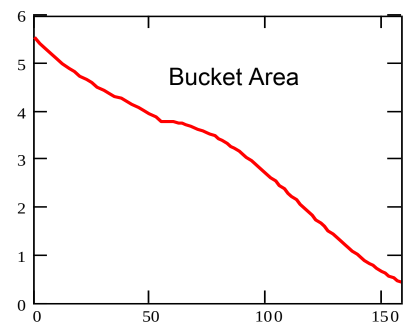
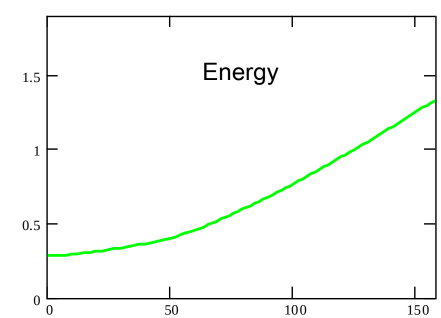




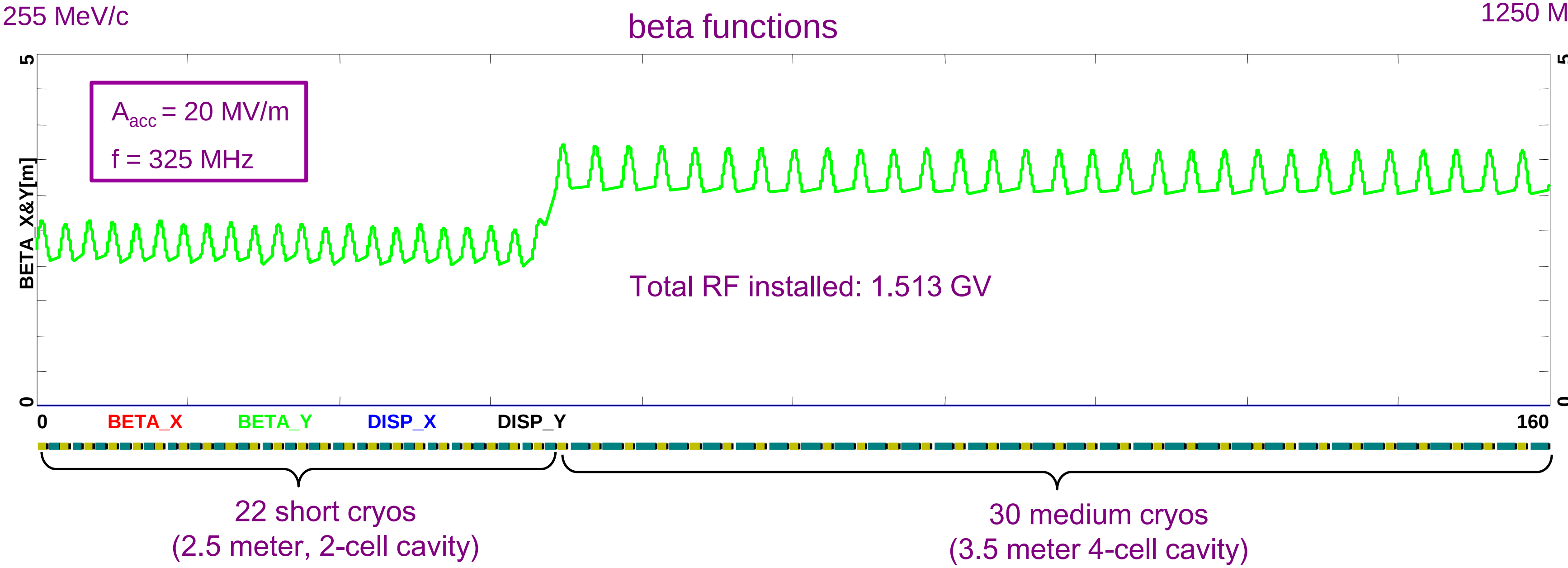


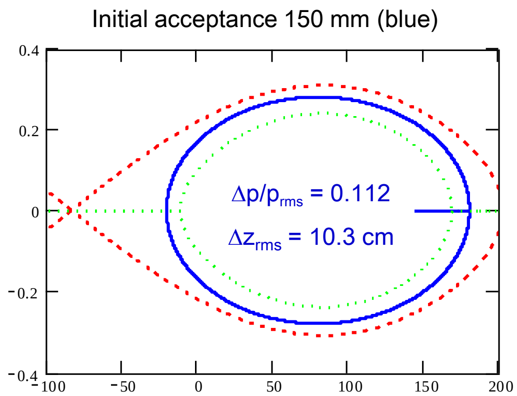


Initial Linac – Longitudinal Acceptance

p = 255 MeV/c

1250 MeV

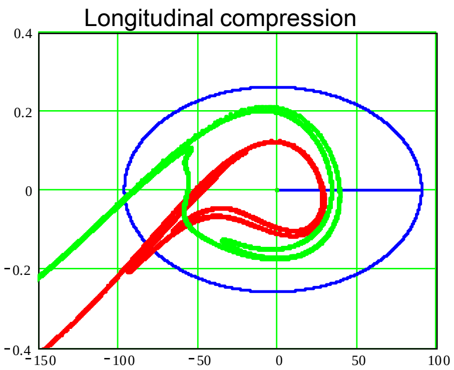




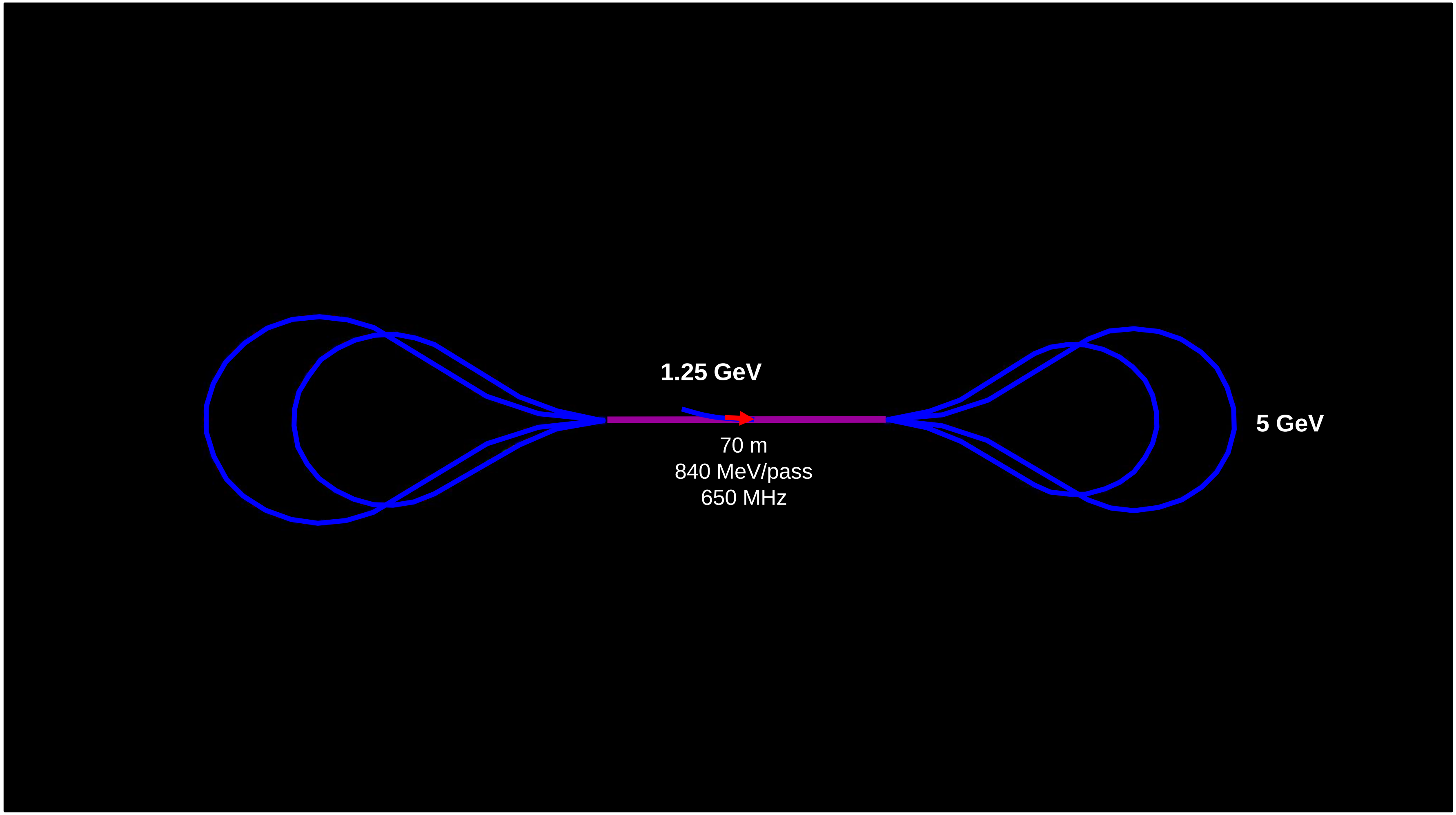
Longitudinal acceptance

ε_{Long} = 150 mm

$\varepsilon_{Long} = (2.5)^2 \times \varepsilon_{Long\_rms}$

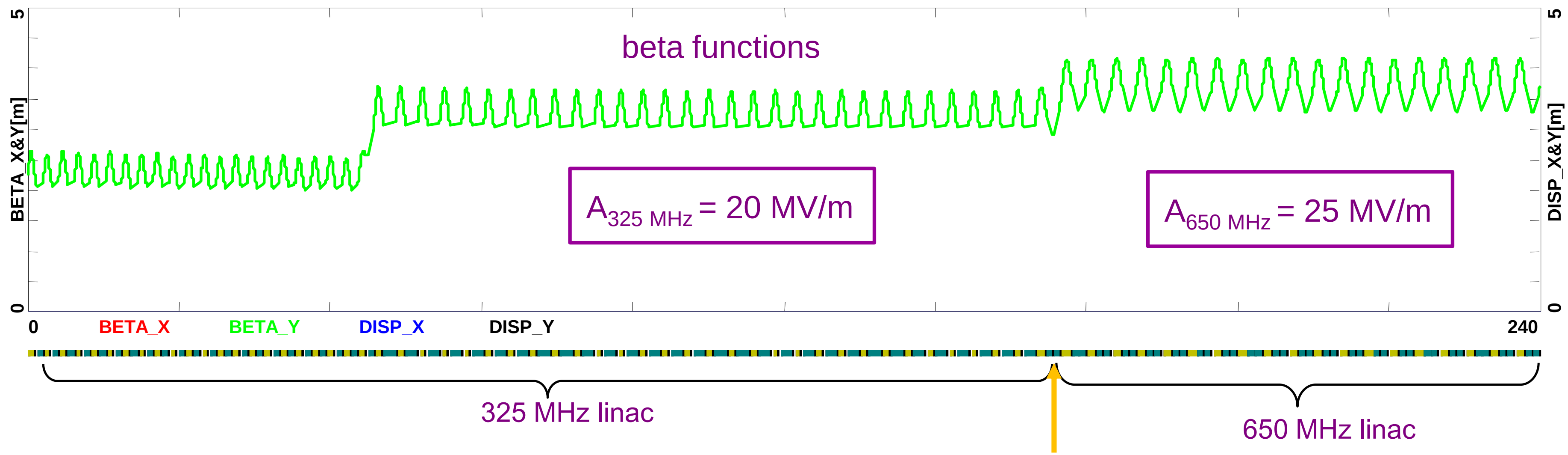


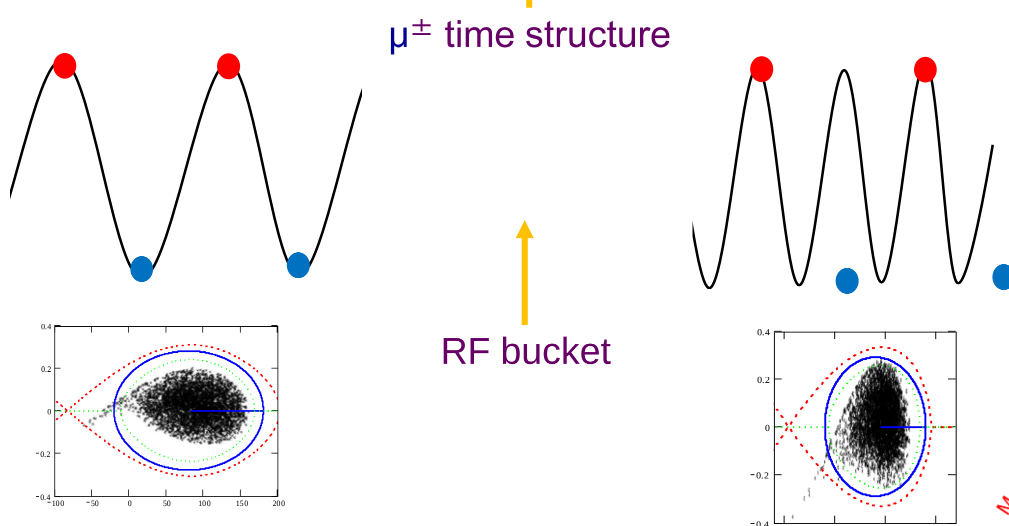
RLA to 5 GeV



325 MHz – 650 MHz Transition

p = 255 MeV/c 1.25 GeV

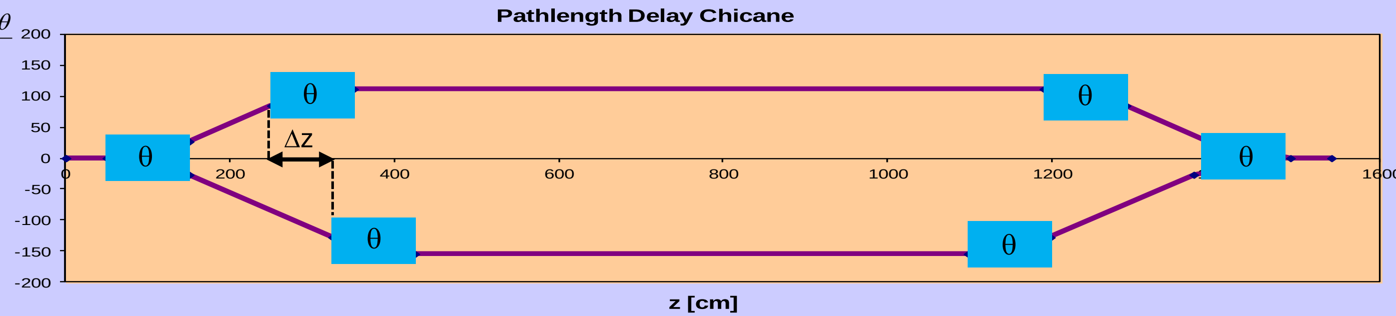




Delay/Compression Chicane

$$\Delta S = 2 \times \Delta z \frac{1-\cos\theta}{\cos\theta}$$

$$\Delta S = \frac{\lambda}{2}$$



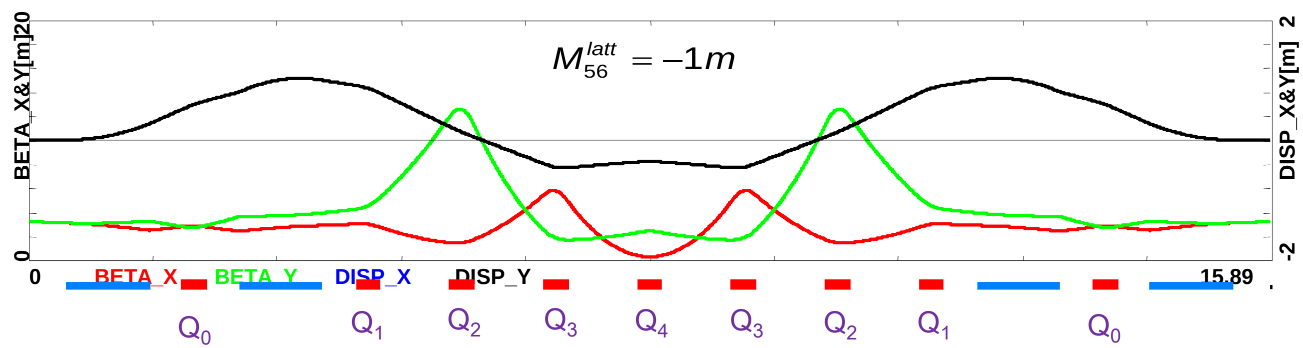
$\lambda = 46.12$ cm

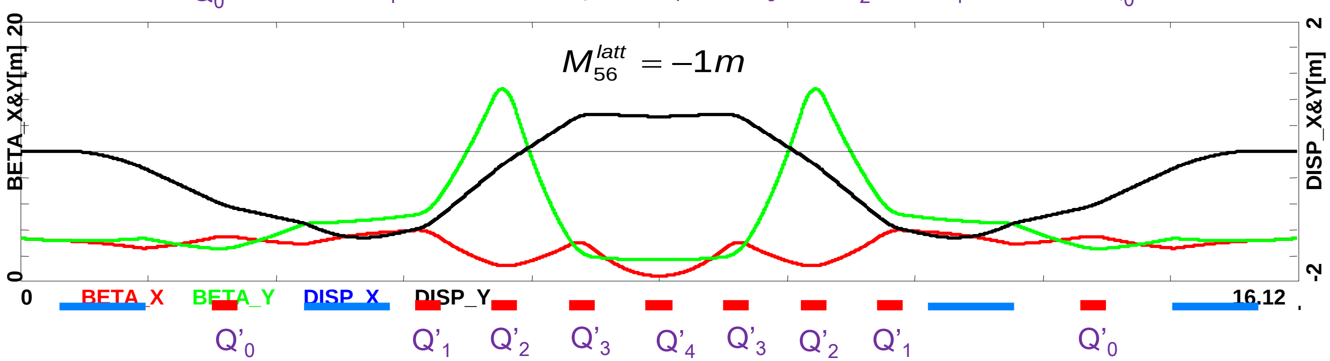
$\theta = 30^0$

$\Delta z = 74.53$ cm

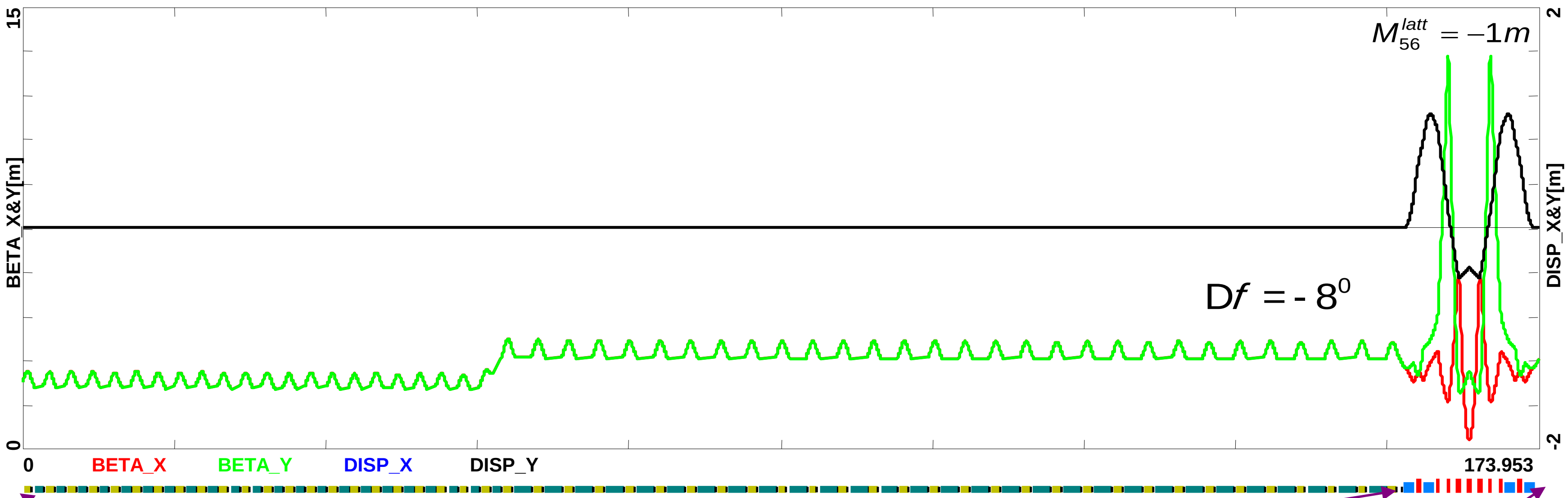
5 free parameters needed to match: 2 betas + 2 alphas + disp.

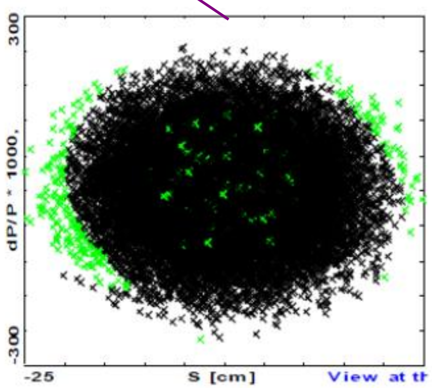
$$M_{56}^{latt} = \int \frac{D}{r} ds$$

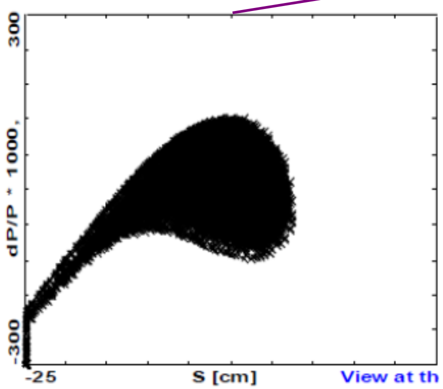


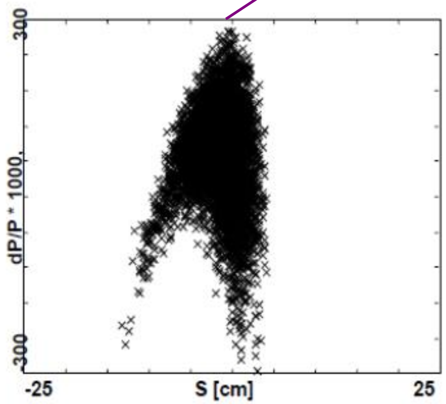


Longitudinal Compression with M_{56}

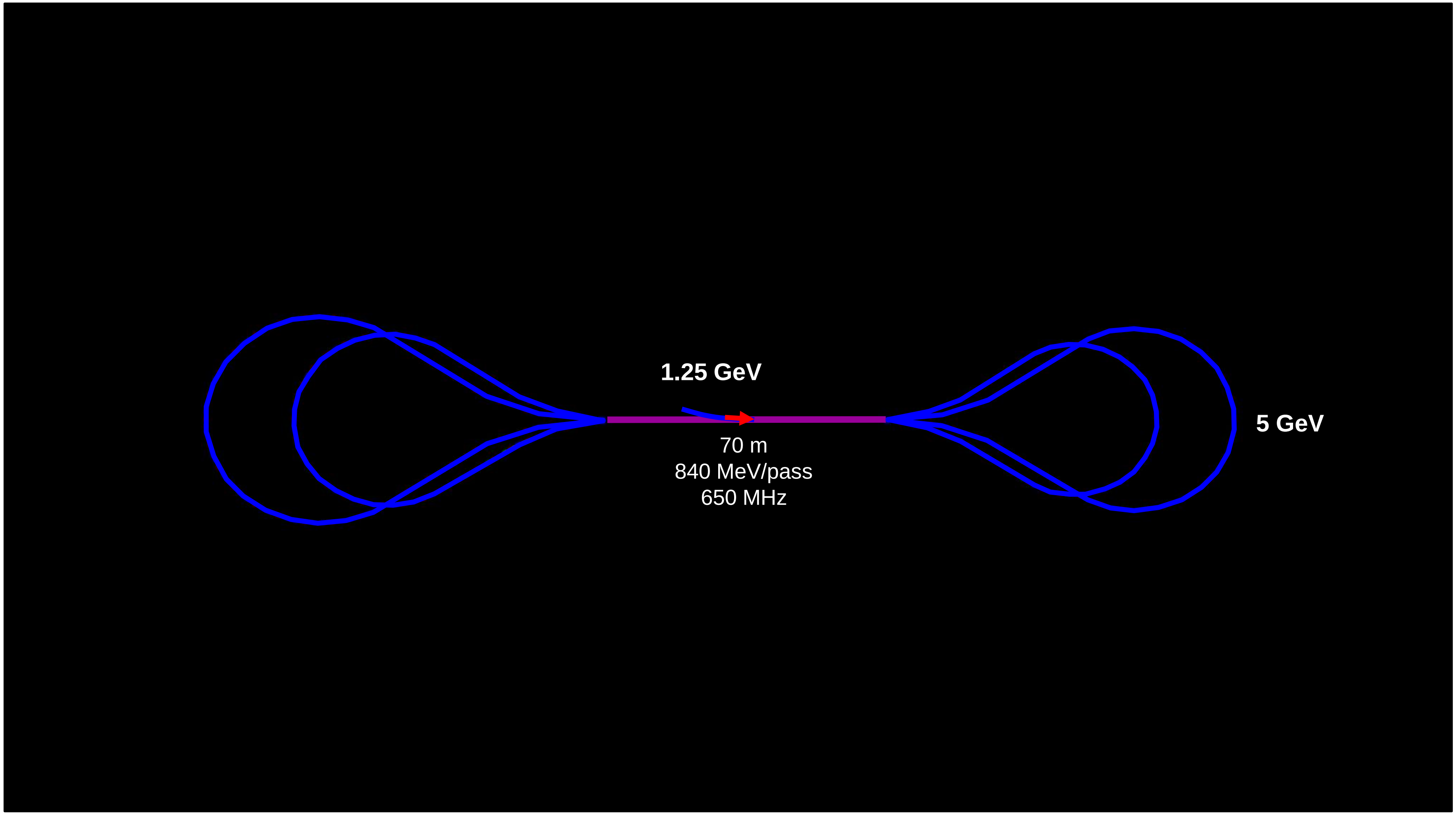






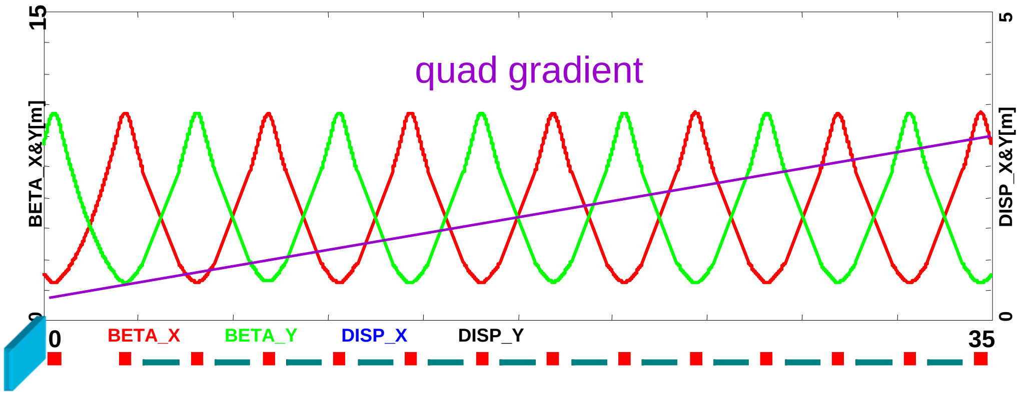


RLA to 5 GeV



Bi-sected Linac Optics

'half pass', 1250-1625 MeV

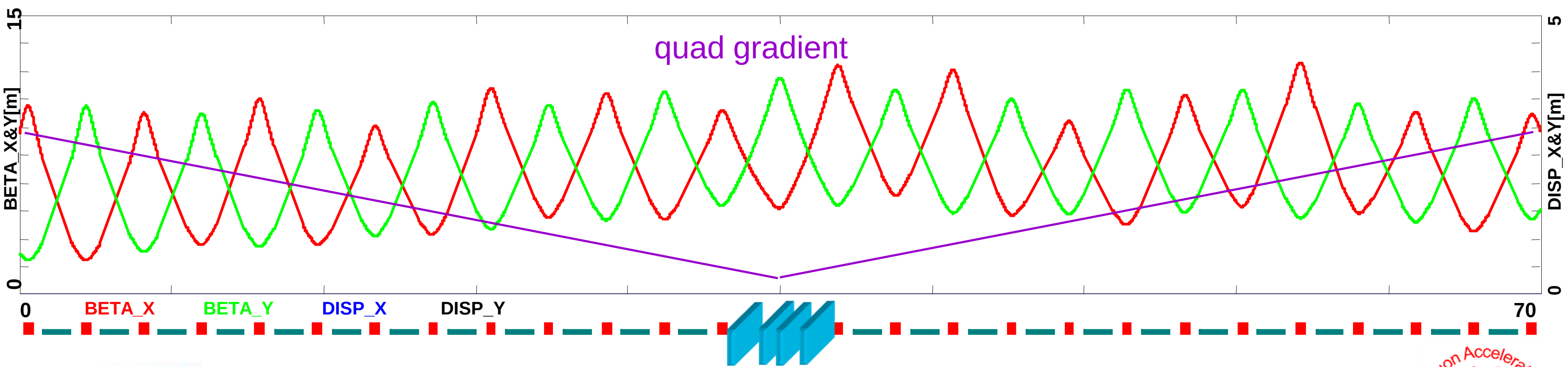


initial phase adv/cell 90 deg. scaling quads with energy

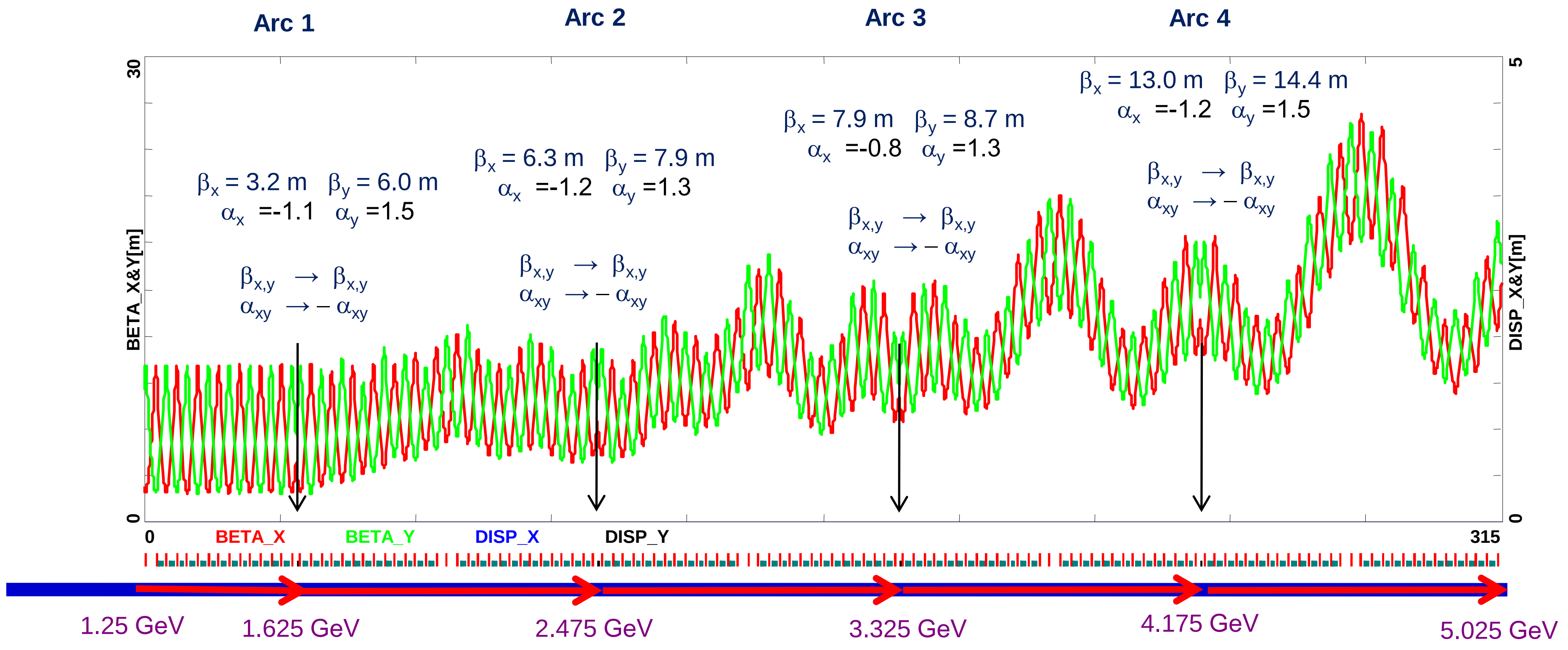
4 meter 90 deg. FODO cells
25 MV/m, 650 MHz, 2 × 4-cell cavity

1-pass, 1625-2475 MeV

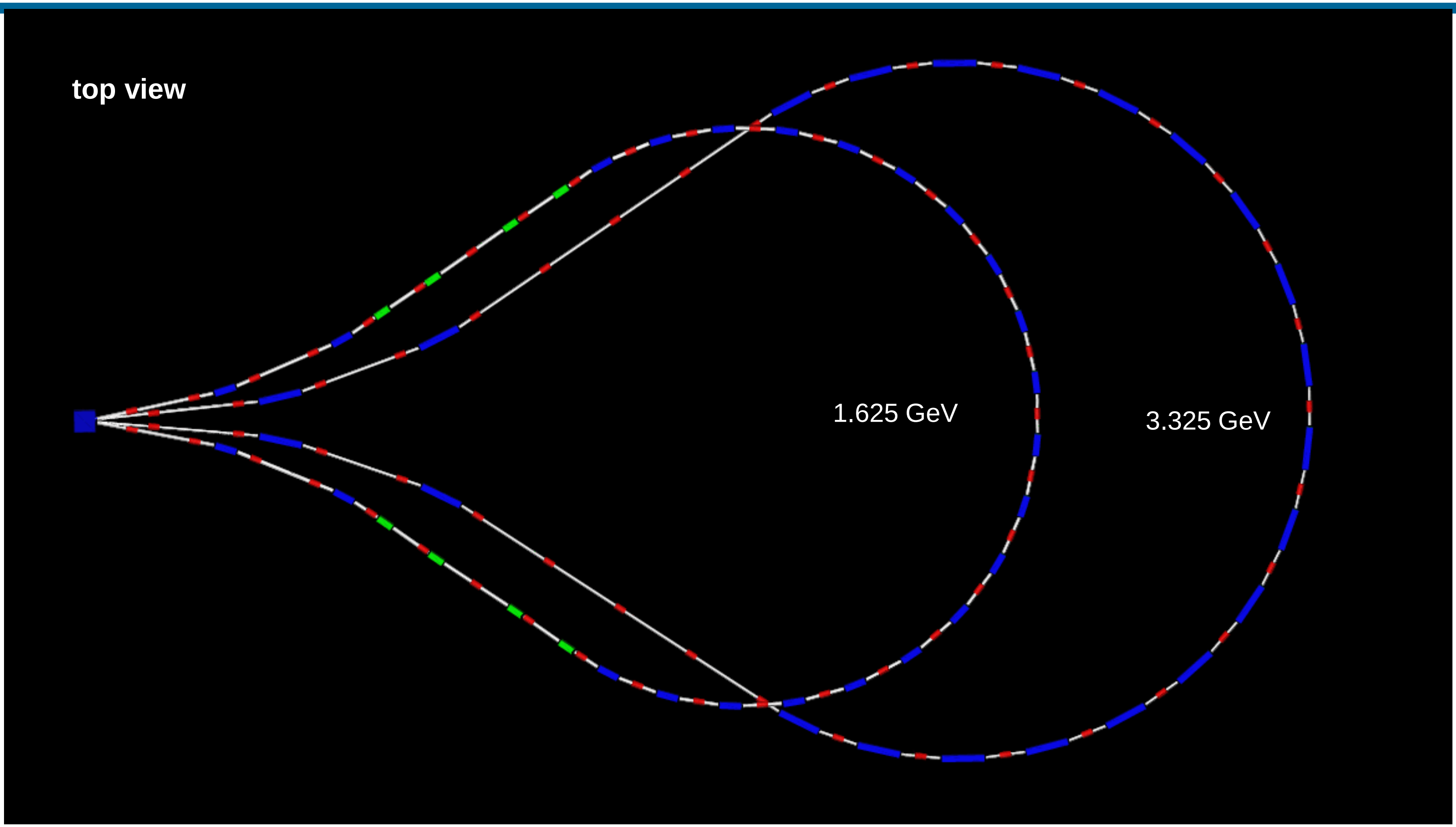
mirror symmetric quads in the linac

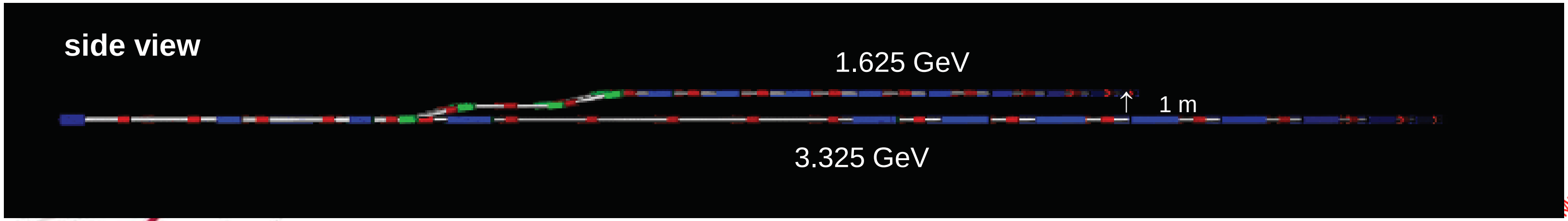


Multi-pass Linac Optics

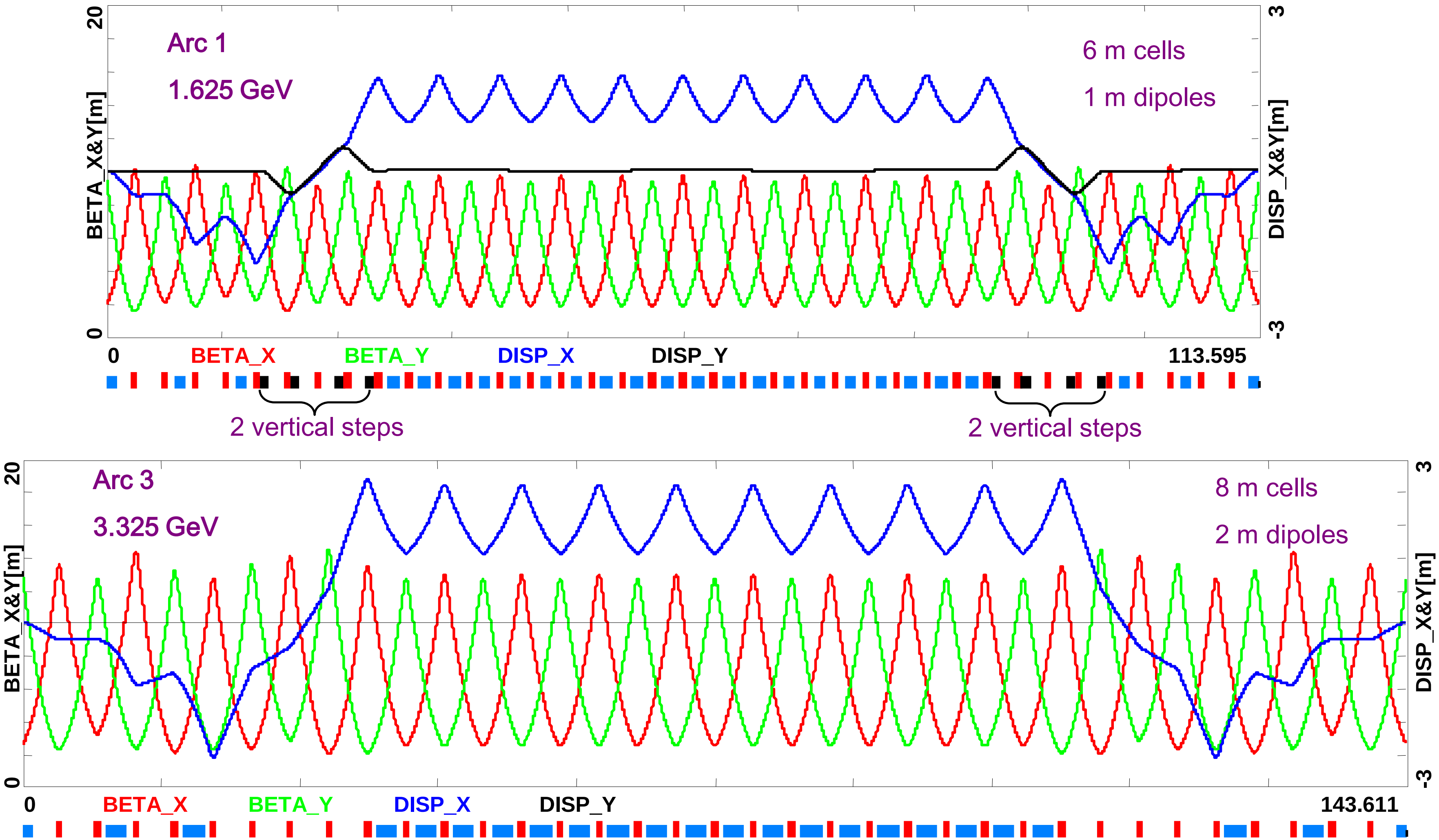


Arc 1 and Arc 3

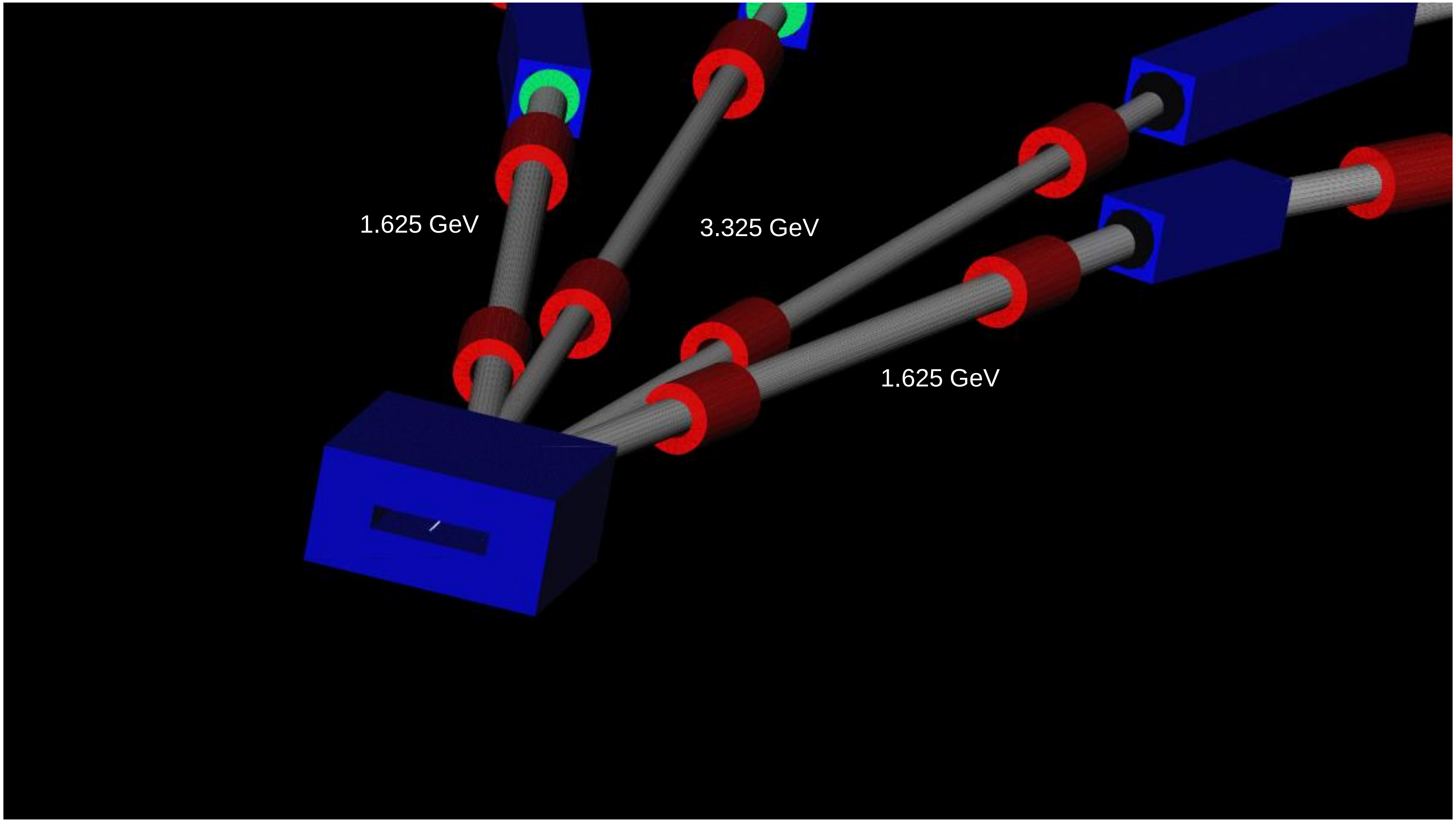




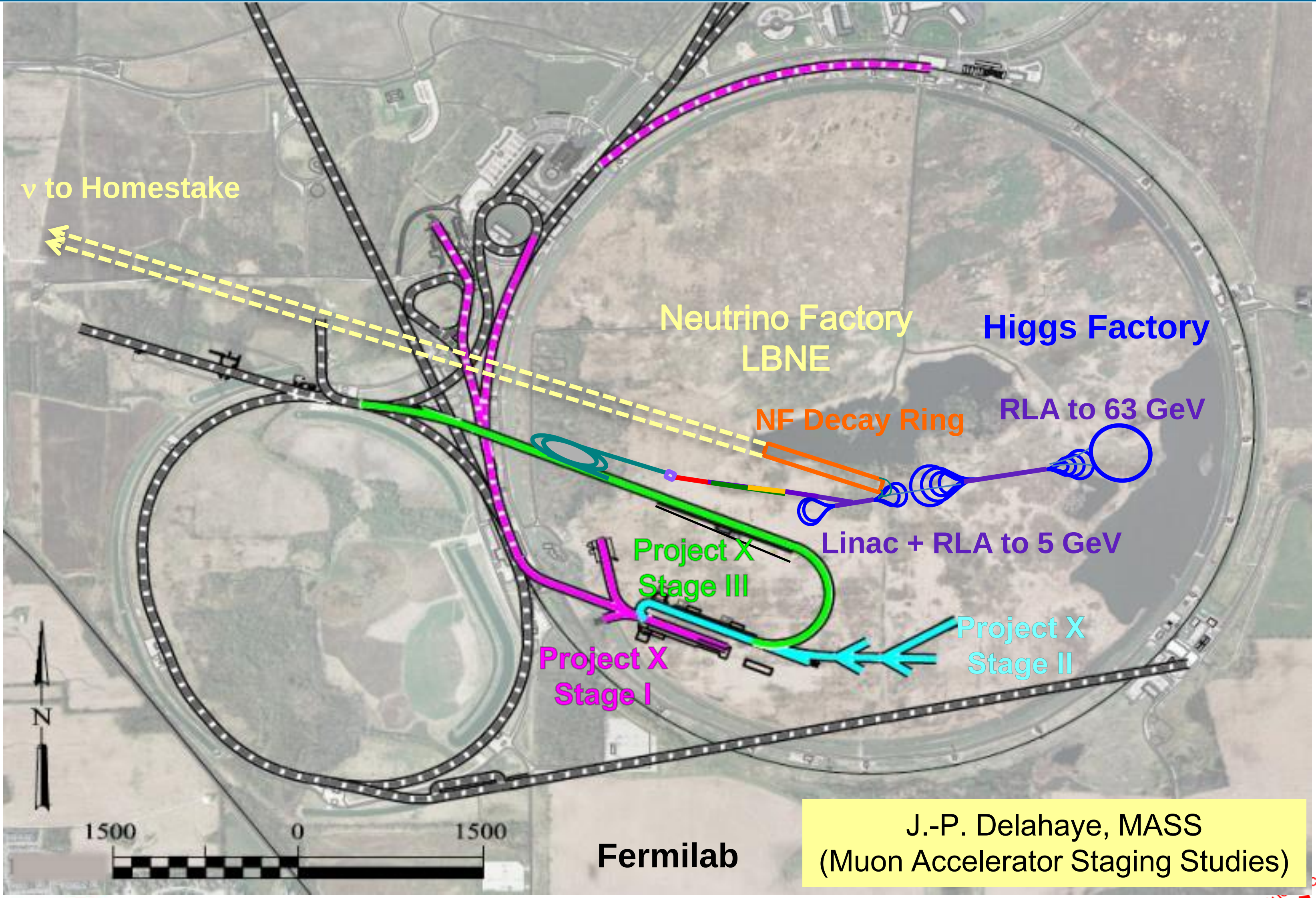
Arc 1 and 3 – Optics



Switchyard – Arc 1 and 3

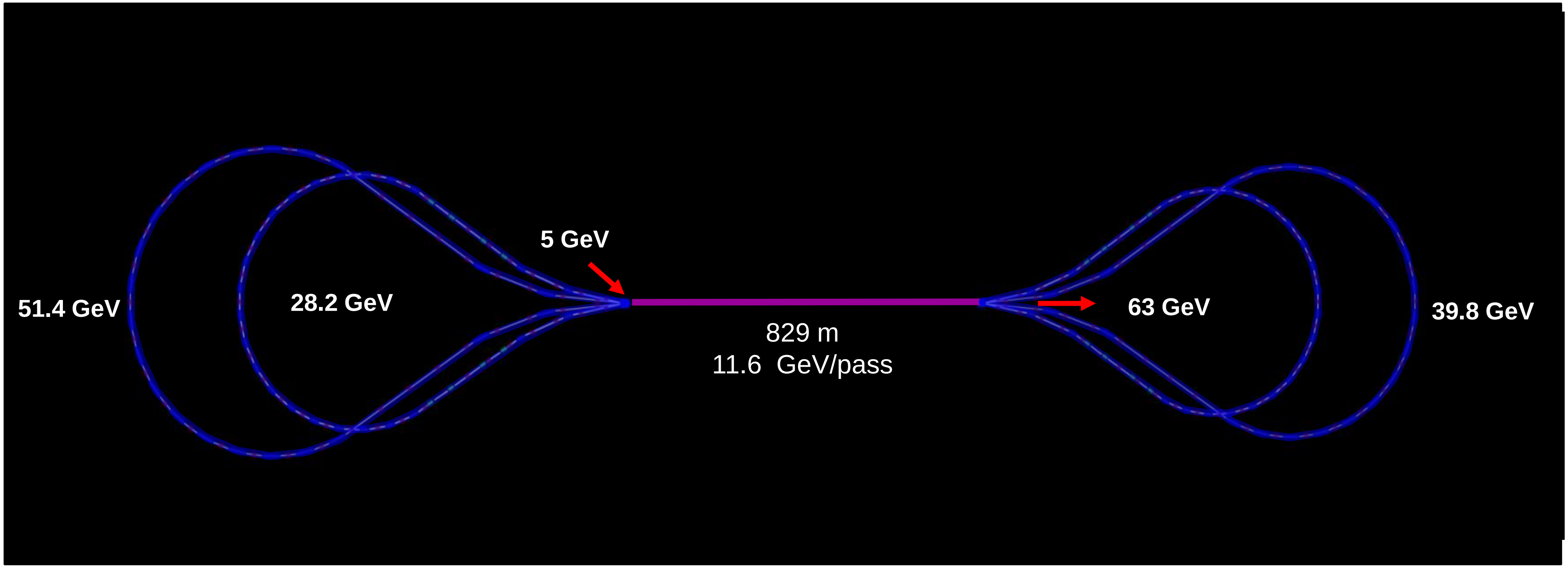


Future Muon Facilities – Muon Acceleration

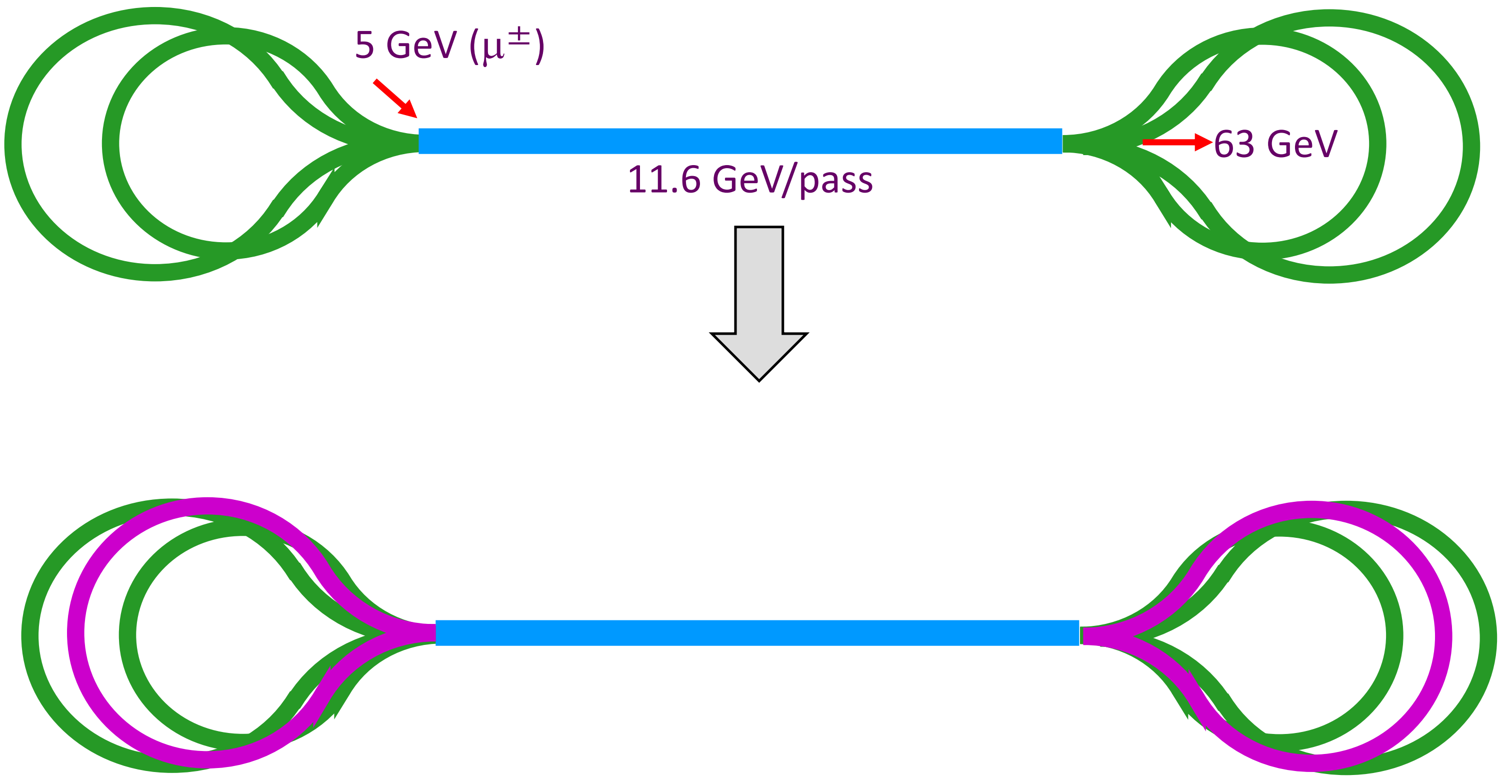


J.-P. Delahaye, MASS
(Muon Accelerator Staging Studies)

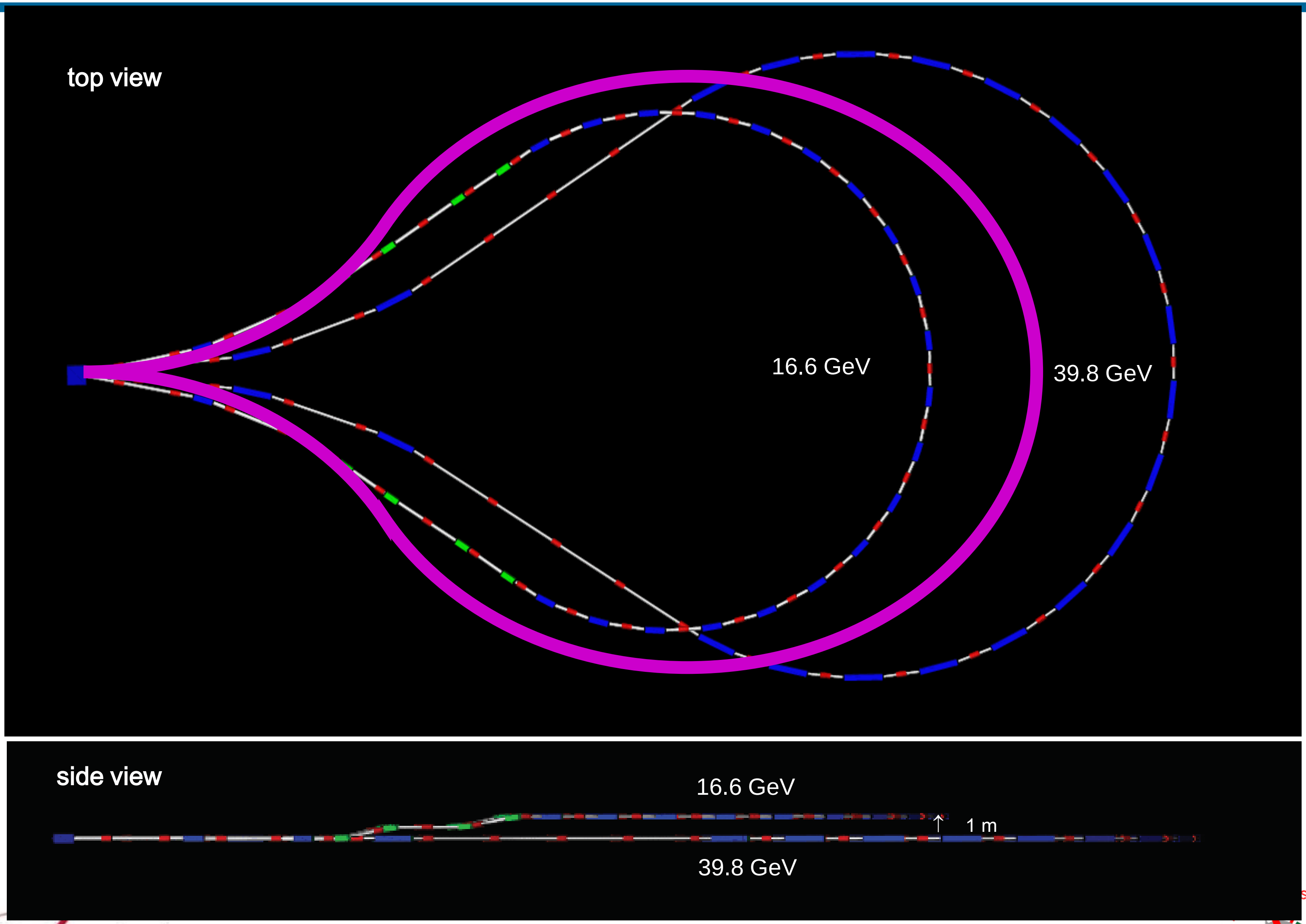
Higgs Factory: 5-pass RLA 5–63 GeV



Multi-pass Arc Muon RLA



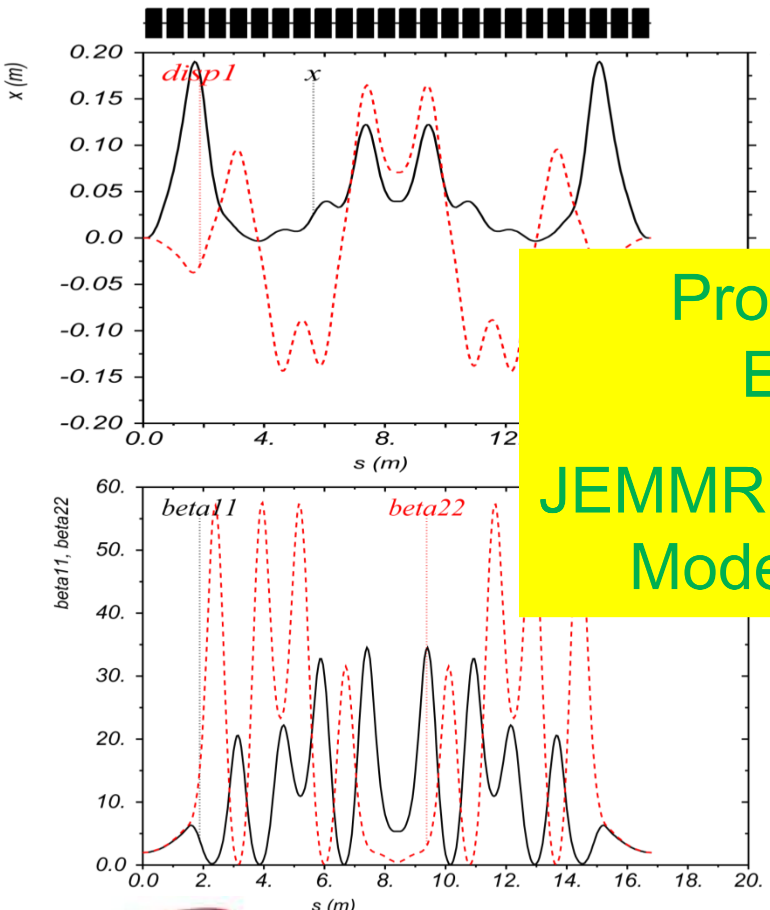
Single- vs Multi- pass Droplet Arcs



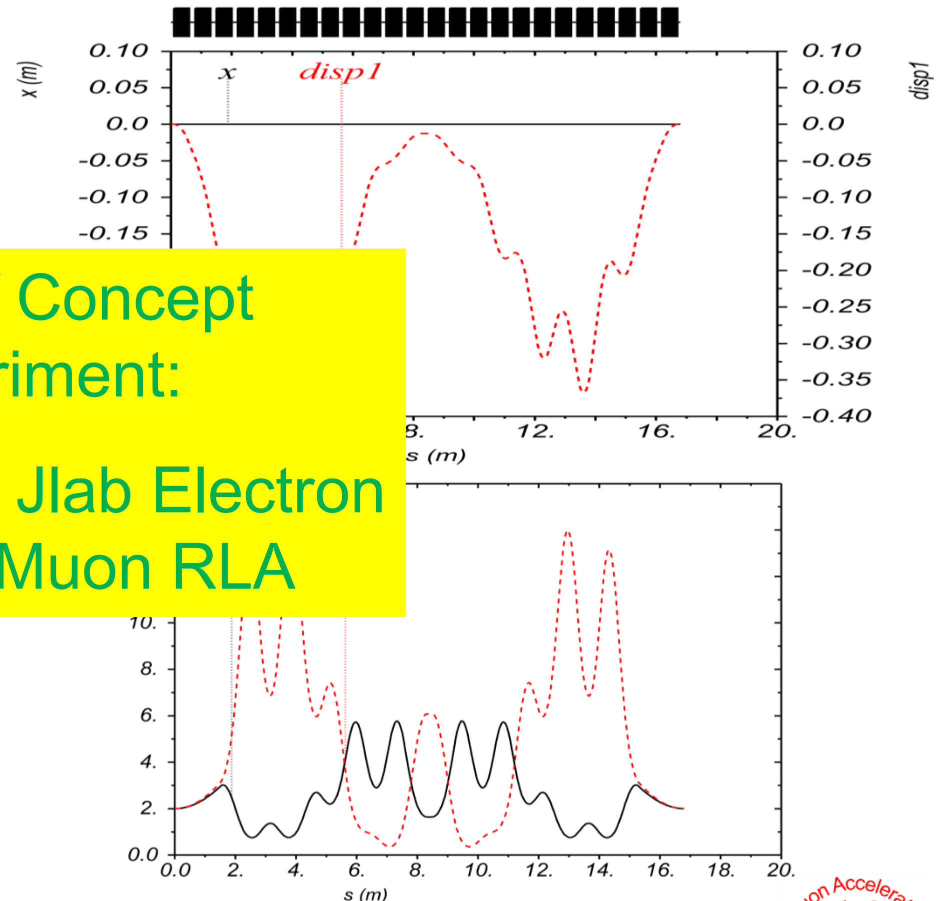
Super-Cell Optics for $P_2/P_1 = 2$

- Each arc is composed of symmetric super cells consisting of linear combined-function magnets (each bend: 2.5^0)

P



2xP



Proof-of Concept Experiment:

JEMMRLA – Jlab Electron Model of Muon RLA

Summary

- 5 GeV Neutrino Factory based on multi-pass 'Dogbone' RLA
  - Linac (255 MeV – 1.25 GeV) Longitudinal Dynamics
  - Delay/Compression Chicane – Transition from 325 to 650 MHz SRF
  - RLA Optics (1.25 – 5 GeV) – 4 droplet Arcs and multi-pass linac
- Optimized RLA scheme for Higgs Factory
  - RLA with multi-pass arcs
  - Proof-of-Concept experiments: JEMMRLA and CBETA

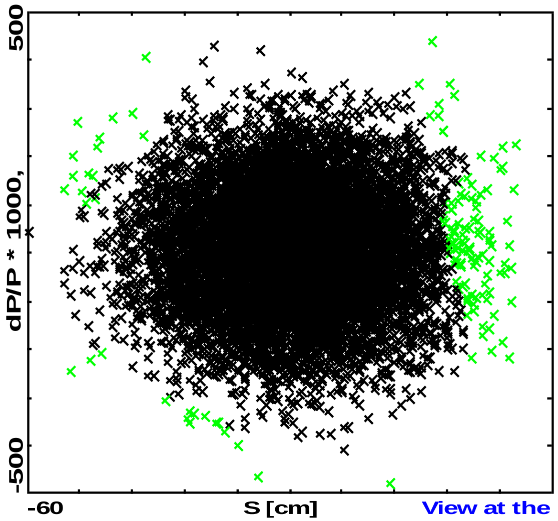
Thank you for your Attention!

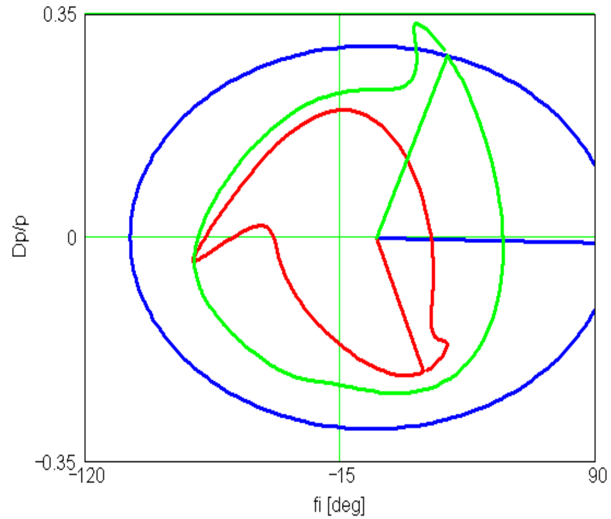
Questions?

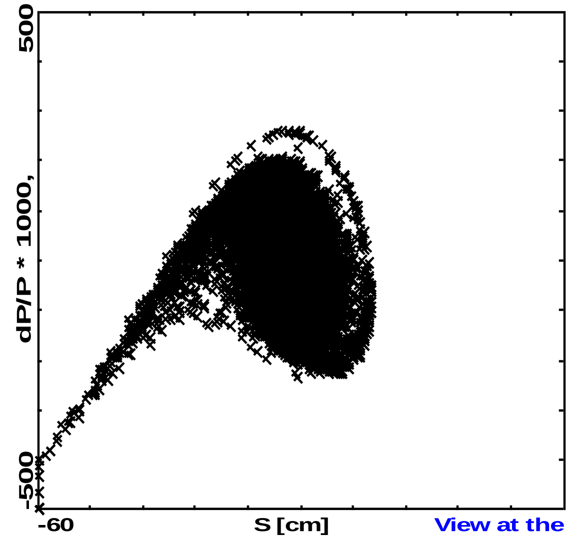
Backup Slides

0.4-1.5 GeV Linac – Transmission

Transmission: 1.4% loss

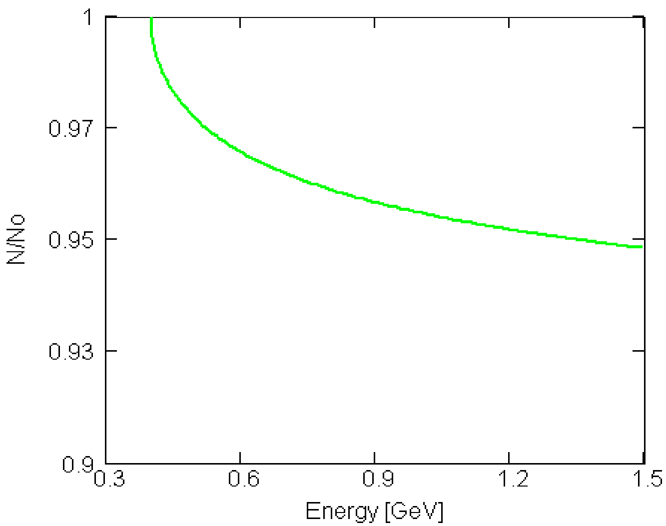






$$\frac{N}{N_0} = e^{-\frac{\tau}{\tau_\mu}}$$

Muon decay: 5% loss



Total loss: 6.4%

Beam Loading

J.S. Berg
J.-P. Delahaye

stored energy in a cavity: $\frac{V^2}{\omega(R/Q)}$

fractional reduction in the cavity voltage : $\frac{\Delta V}{V} = \frac{enN\omega(R/Q)\cos\phi}{V}$

RF gradient G defined as: $V = n_C G\pi c/\omega$

$$\frac{\Delta V}{V} = \frac{enN\omega^2[(R/Q)/n_C]\cos\phi}{\pi G c}$$

fractional voltage reduction:

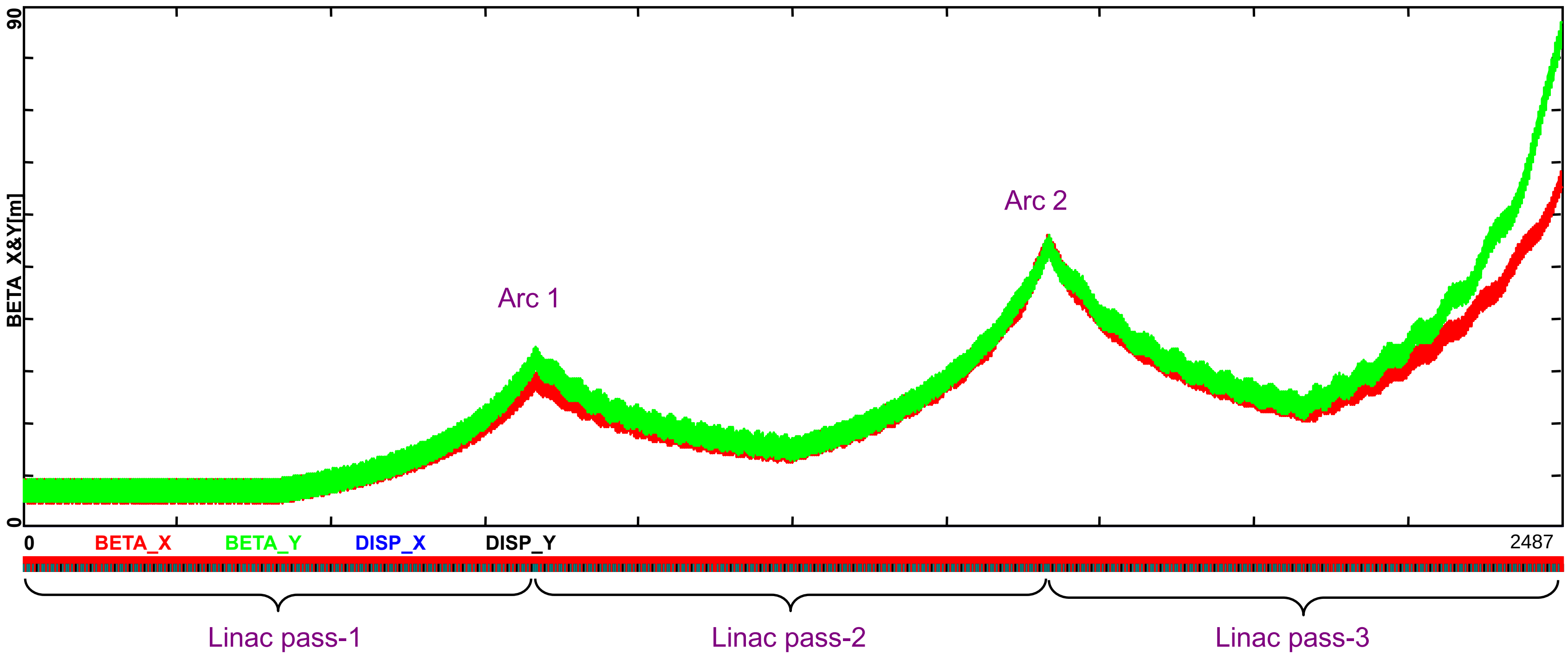
$(R/Q)/n_C = 114\,\Omega$

$\phi = 0$

Particles	2×10^{12}	4×10^{12}	2×10^{12}	4×10^{12}
Frequency	325 MHz	325 MHz	650 MHz	650 MHz
Passes	Relative reduction (%)			
3	2	5	8	16
5	4	8	13	26
7	6	11	18	36
9	7	15	23	47

Multi-pass Linac – Bisected Optics

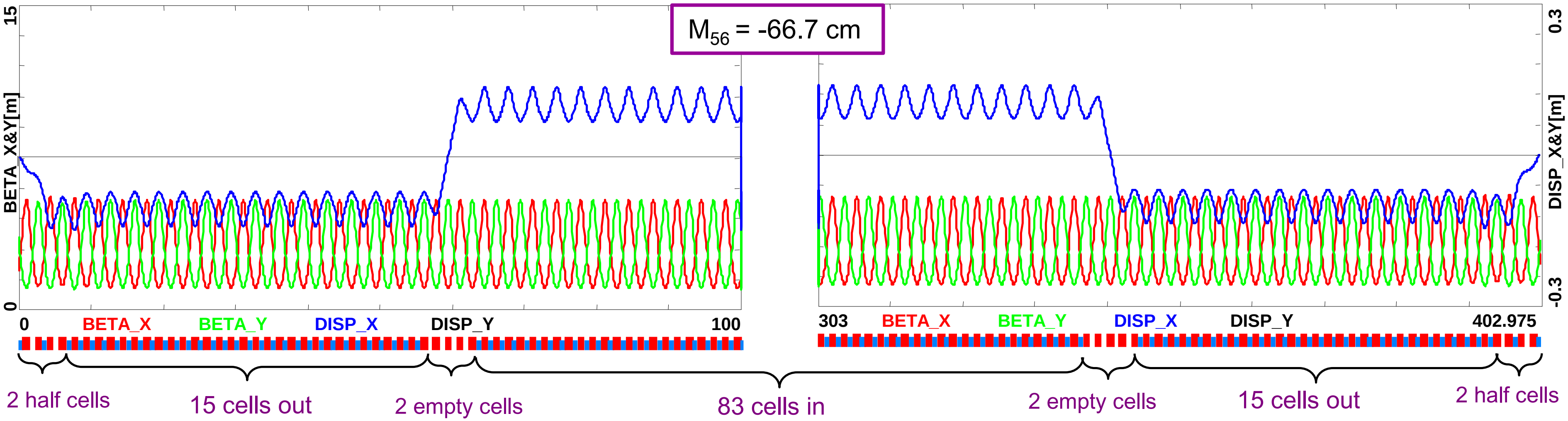
E = 5–63 GeV



RF	f[MHz]	cells/cavity	Grad [MV/m]	phase [deg]
	650	5	25	22

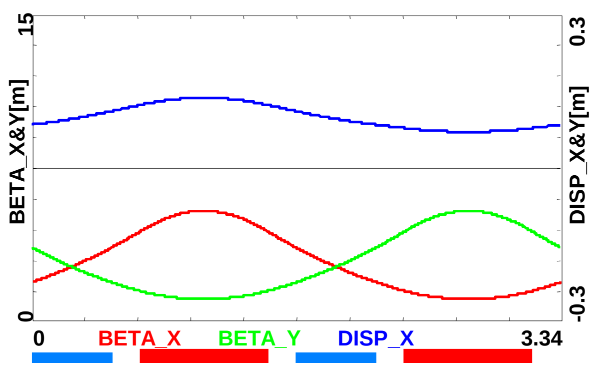
Arc Optics – Longitudinal Distortion

E = 24 GeV



$$n_i = 5n_o + 8$$

90⁰ FODO



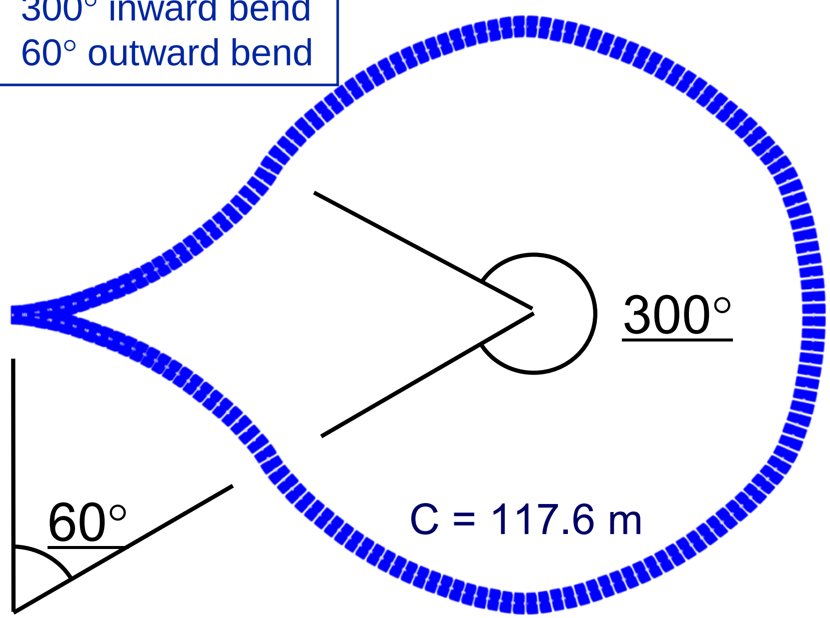
Quads	L[cm]	G[kG/cm]
qF	80	10.2924
qD	80	-10.2788

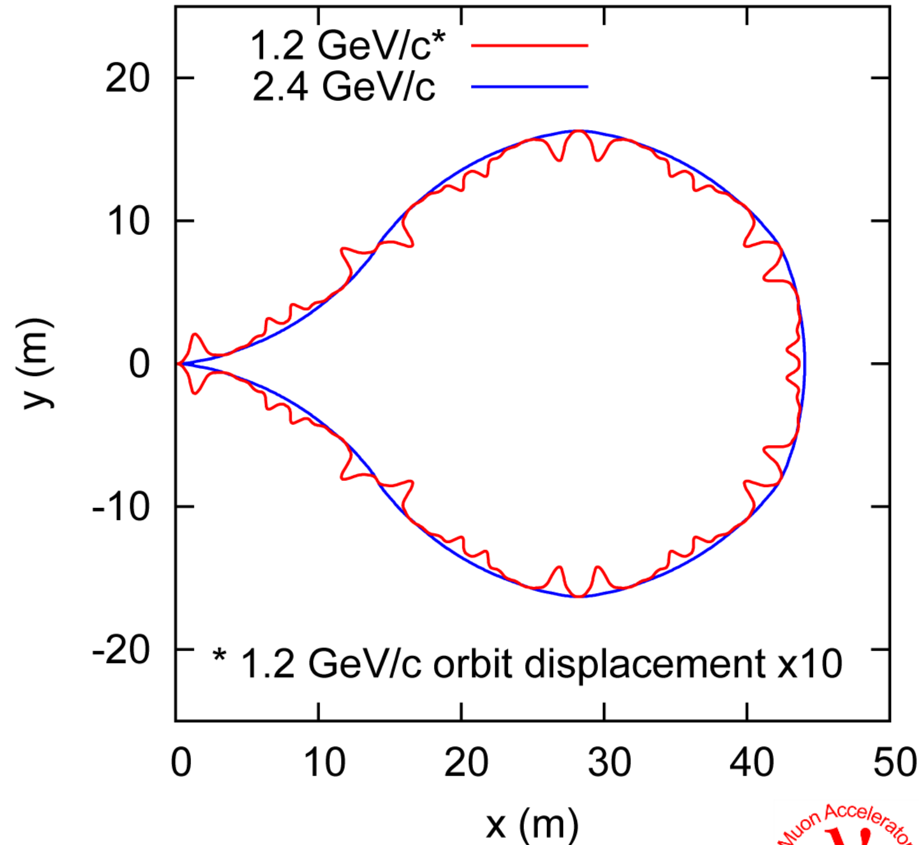
Dipoles	L[cm]	B[kG]	bend angle [deg]
	50.00	49.3116	1.7647

Two-pass Arc Layout

- Simple closing of arc geometry when using similar super cells
- 1.2 / 2.4 GeV/c arc design used as an illustration can be scaled/optimized for higher energies preserving the factor of 2 momentum ratio of the two passes

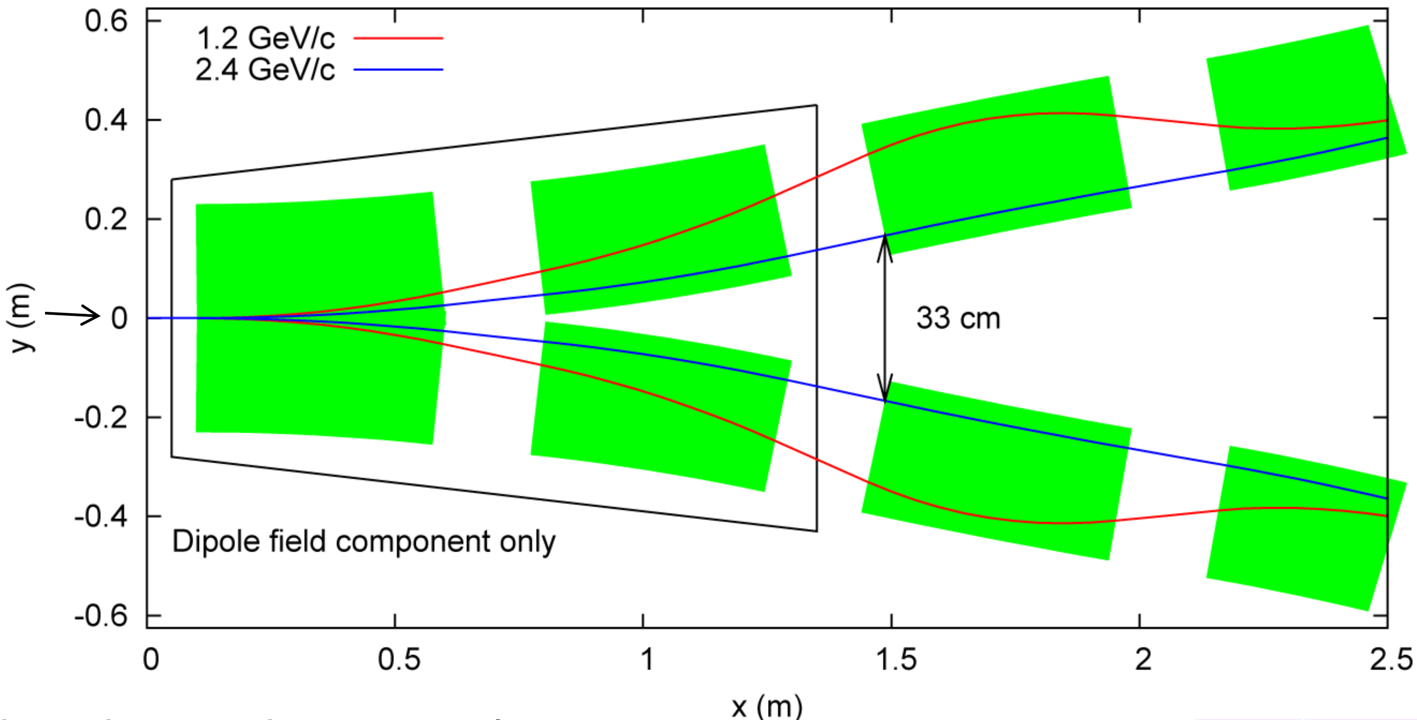
Droplet arc:
- 60° outward bend
- 300° inward bend
- 60° outward bend





‘Droplet’ Arc – Spreader/Recombiner

- First few magnets of the super cell have dipole field component only, serving as Spreader/Recombiner

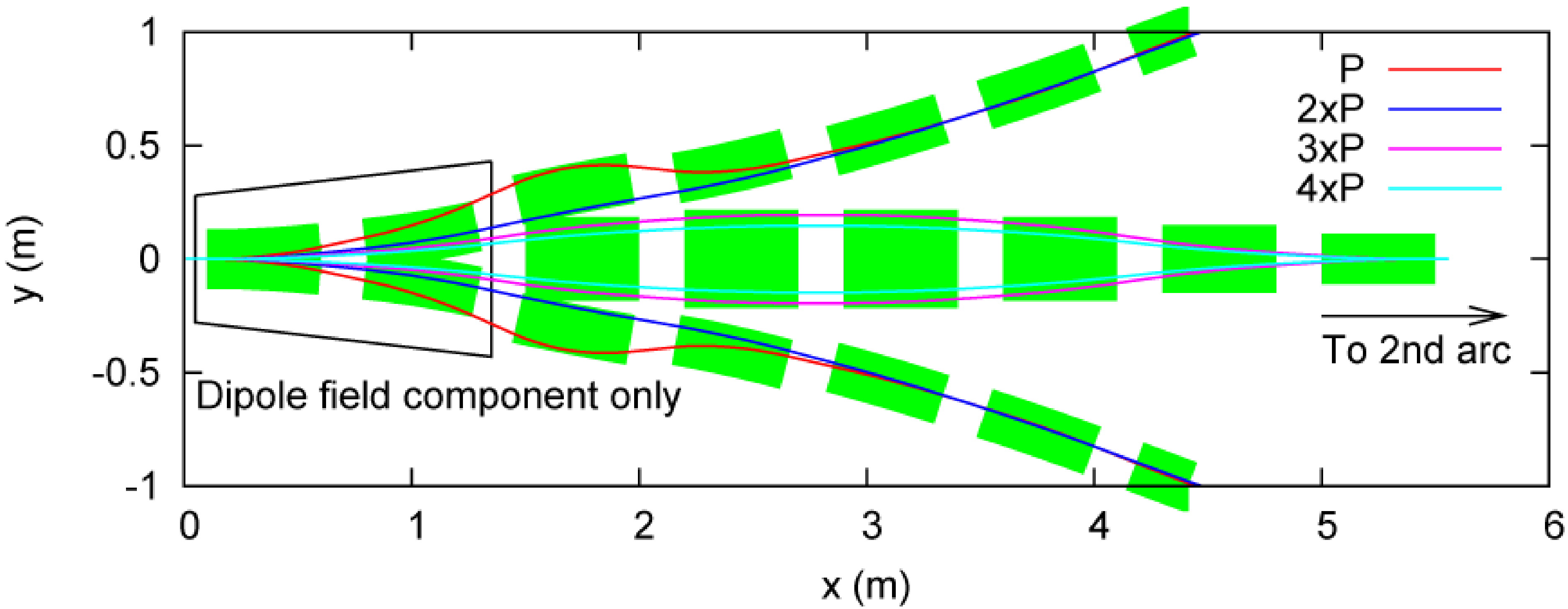


* Trajectories are shown to scale

B	1 .7 Tesla
G	28 Tesla/m

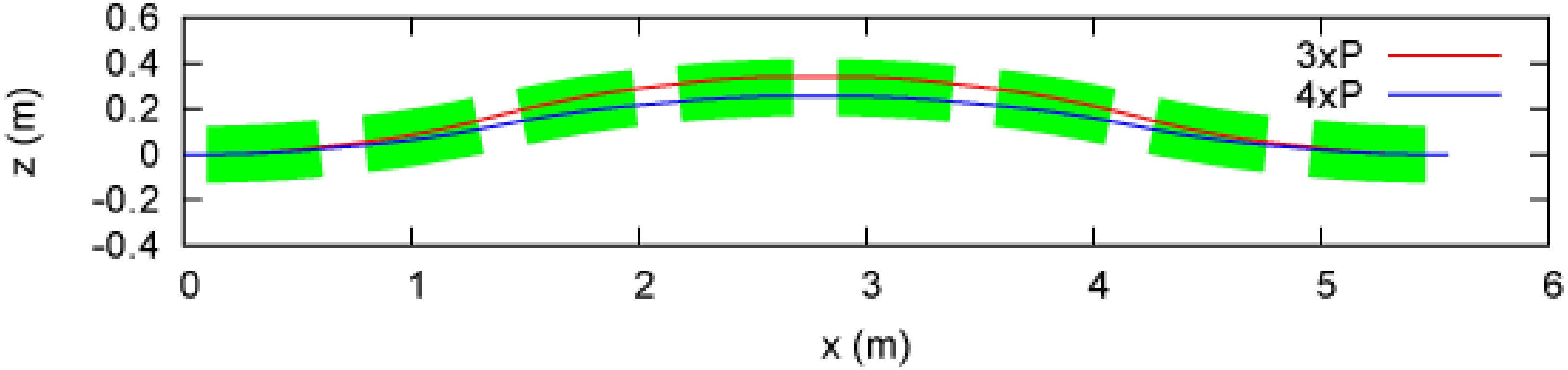
A pair of 2-pass Arcs – Switchyard

- Lower momentum arc is the most challenging because of the highest momentum ratio; have a solution but still plenty of room for optimization

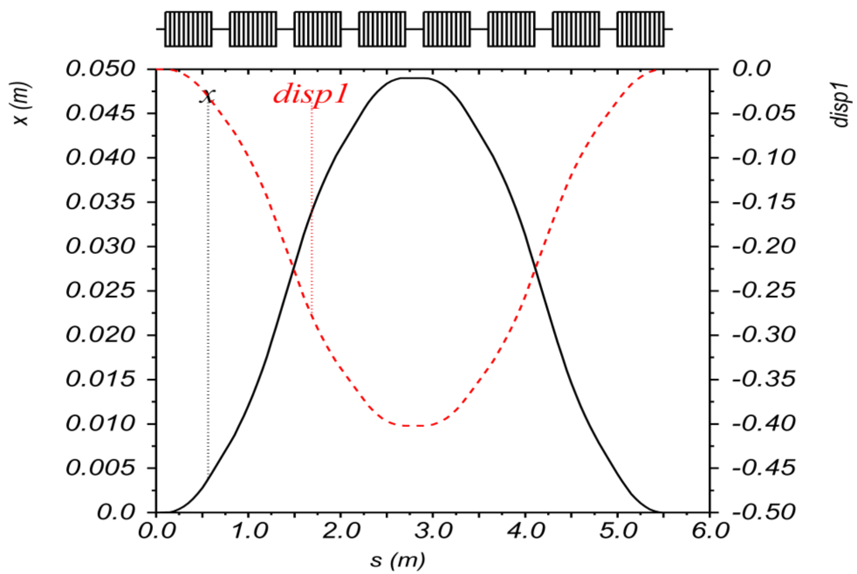


* Trajectories are shown to scale

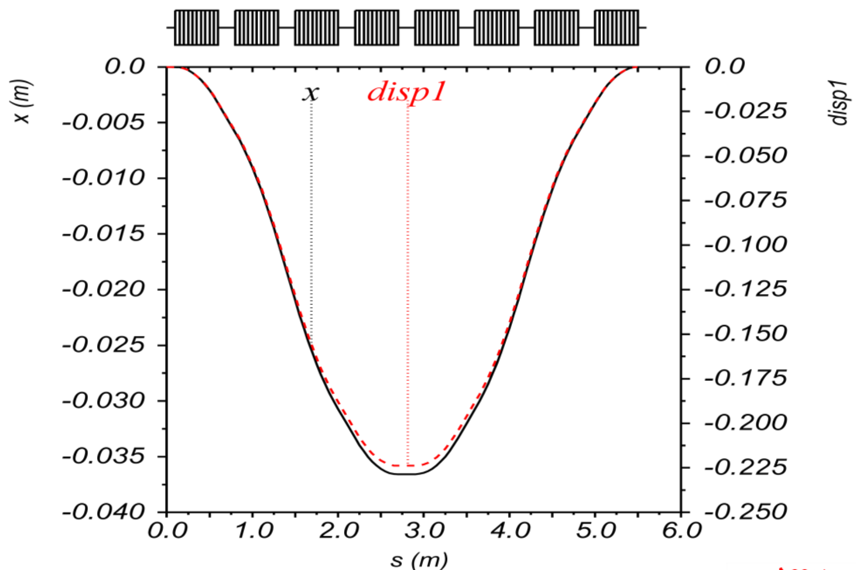
Vertical Bypass Concept



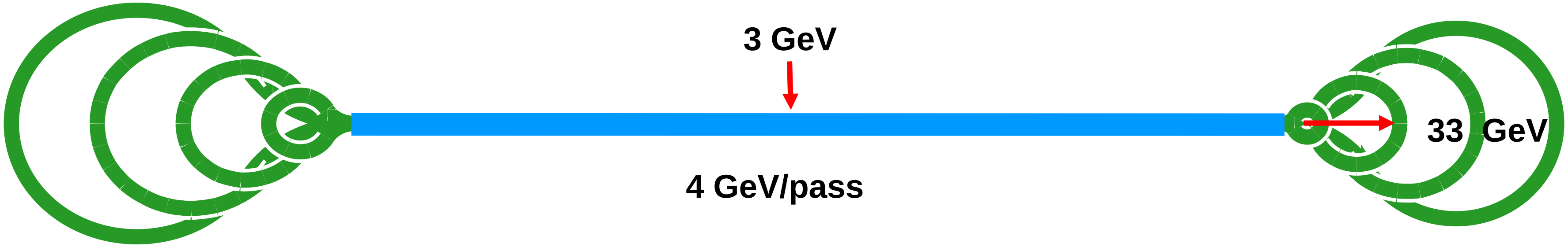
- 3xP



- 4xP



'Pulsed' quad Dogbone RLA

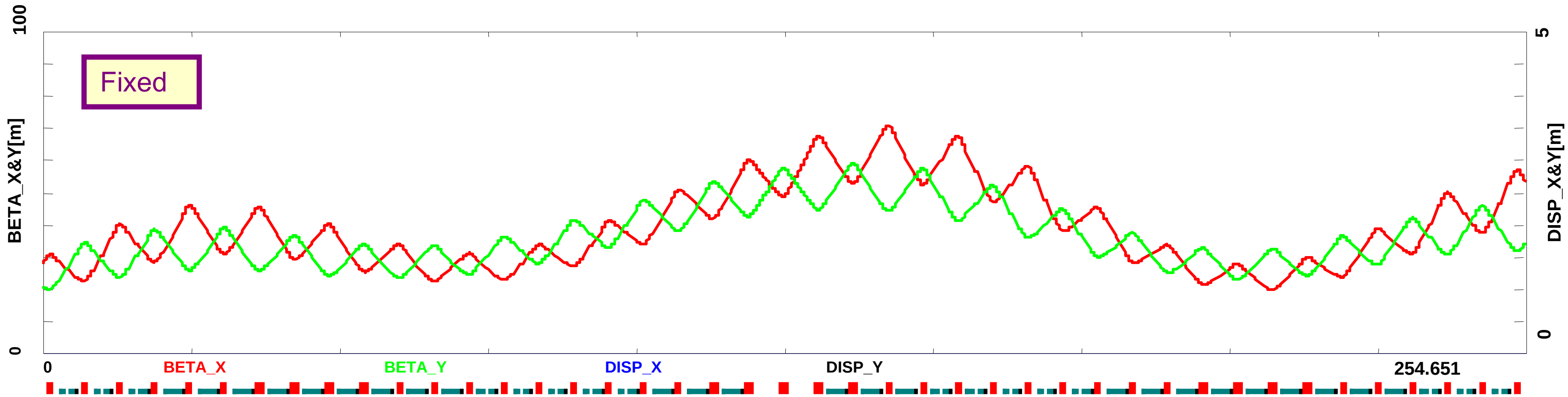


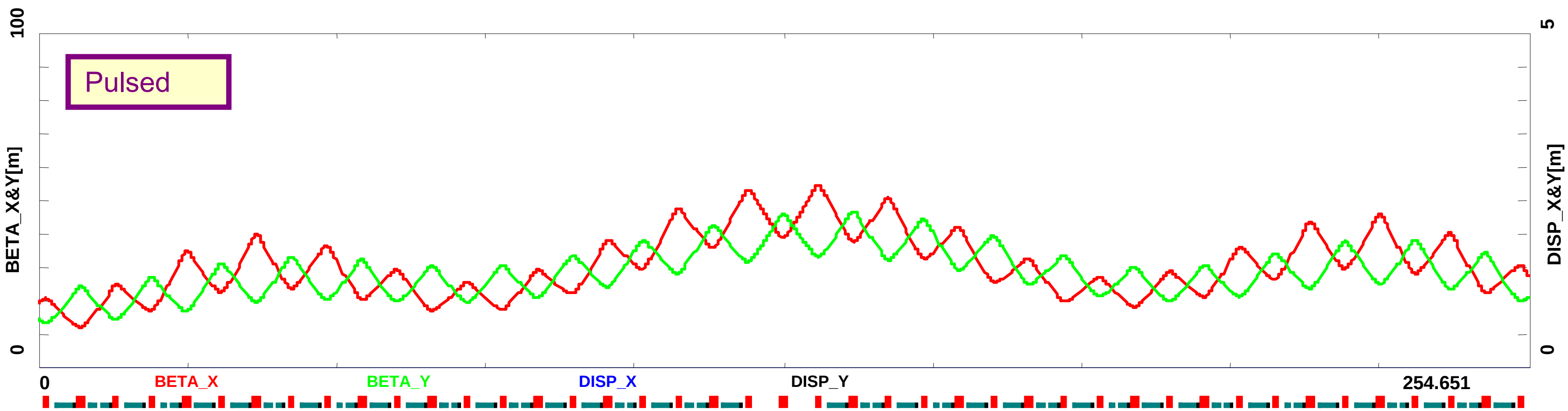
- Quad pulse would assume 500 Hz cycle ramp with the top pole field of 1 Tesla.
- Equivalent to: maximum quad gradient of G_{max} =2 kGauss/cm (5 cm bore radius) ramped over τ = 10^{-3} sec from the initial gradient of G_0 =0.1 kGauss/cm (required by 90^0 phase advance/cell FODO structure at 3 GeV) G_8 =13 G_0 = 1.3 kGauss/cm
- These parameters are based on similar applications for ramping corrector magnets such as the new ones for the Fermilab Booster Synchrotron that have 1 kHz capability

$$T \approx 8 \times \frac{500+250}{3\times10^{-8}} \sec = 2\times10^{-5} \sec$$

$$\frac{T}{\tau} \approx 2\times10^{-2}$$

‘Fixed’ vs ‘Pulsed’ linac Optics (8-pass)





'Fixed' vs 'Pulsed' linac Optics (12-pass)