Muon Acceleration: NuMAX and Beyond

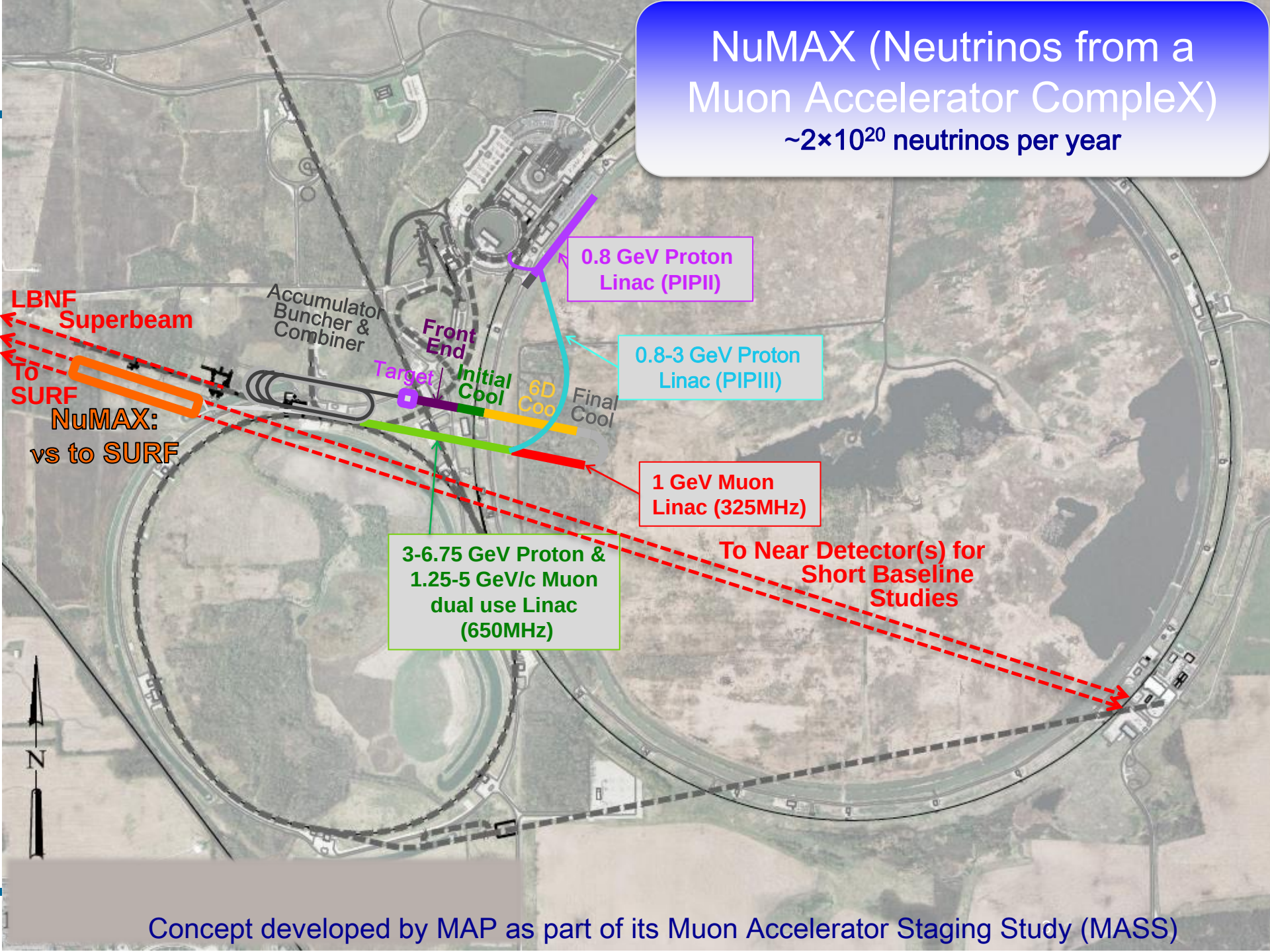
Alex Bogacz

NuFact 2014
Glasgow, Scotland

August 25-30, 2014

Overview

- Develop cost effective concepts for acceleration of muon beams for a post-LBNF Neutrino Factory and beyond…
  - Exploration of dual-use (H^- and muon) linac concepts and other efficient acceleration options for muons alone.
  - Reducing the cost while maintaining performance through proper balance between the cooling systems (4D/6D) and the acceptance of the acceleration complex (transverse/longitudinal).
  - Exploring efficient acceleration beyond 5 GeV via RLAs (Higgs Factory).
- The main thrust is to explore the means to make the muon complex at Fermilab affordable in the future.
- Significant groundwork was already laid by the IDS-NF efforts and by MAP.

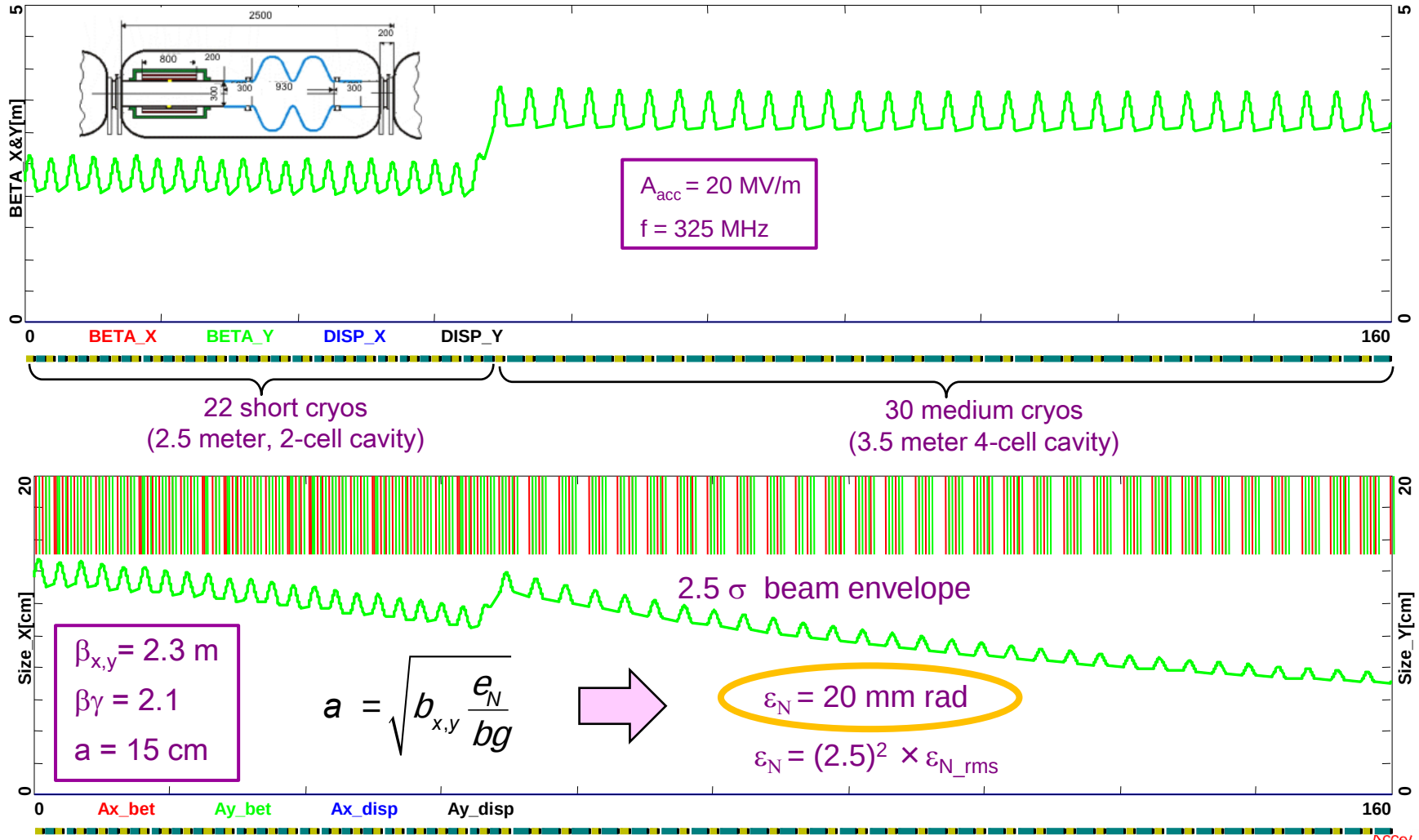

NuMAX (Neutrinos from a Muon Accelerator CompleX)
~2×10^20 neutrinos per year
0.8 GeV Proton Linac (PIPII)
0.8-3 GeV Proton Linac (PIPIII)
1 GeV Muon Linac (325MHz)
3-6.75 GeV Proton & 1.25-5 GeV/c Muon dual use Linac (650MHz)
LBNF Superbeam
To SURF
NuMAX: νs to SURF
Accumulator Buncher & Combiner
Front End
Target
Initial Cool
6D Coo
Final Cool
To Near Detector(s) for Short Baseline Studies
N
Concept developed by MAP as part of its Muon Accelerator Staging Study (MASS)

Initial 325 MHz Linac – Transverse Acceptance

p = 255 MeV/c

beta functions

1250 MeV

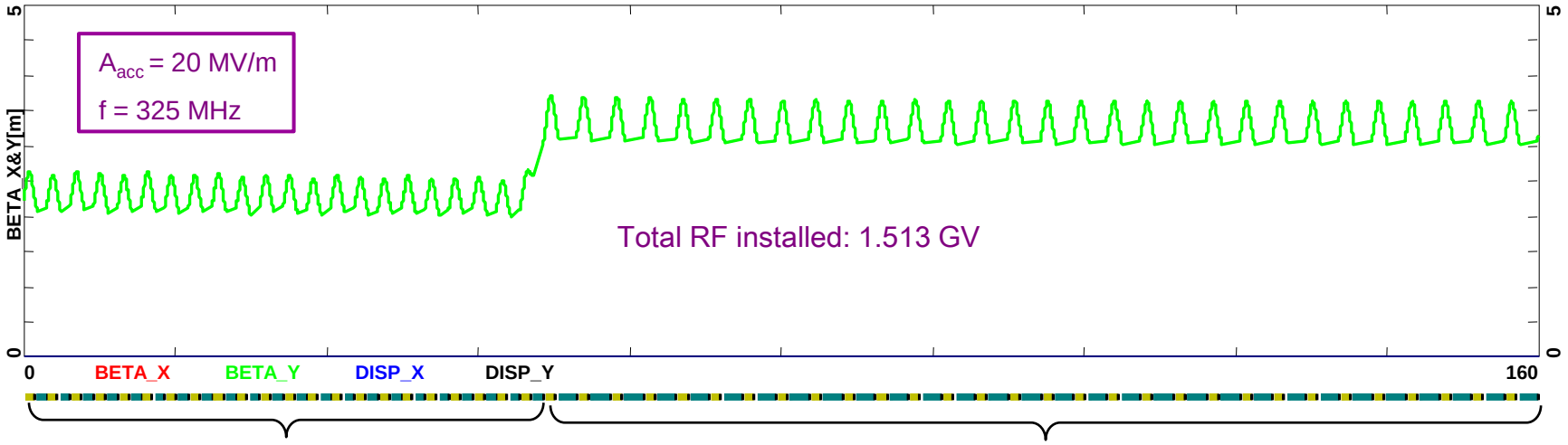


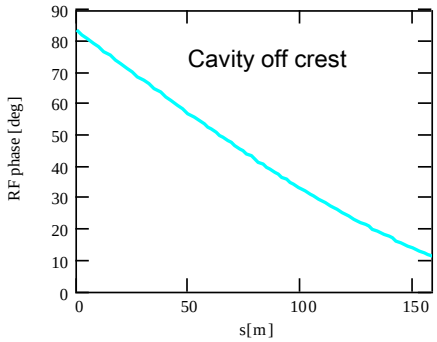
Initial Linac – Longitudinal Profile

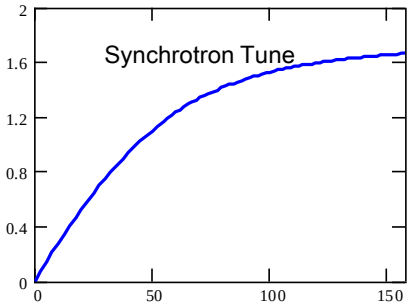
p = 255 MeV/c

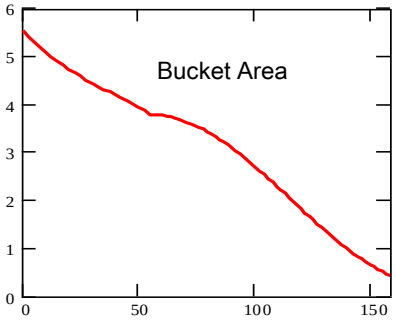
beta functions

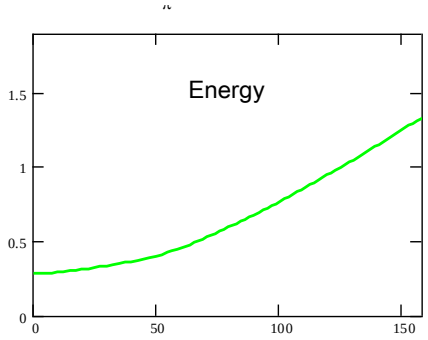
1250 MeV









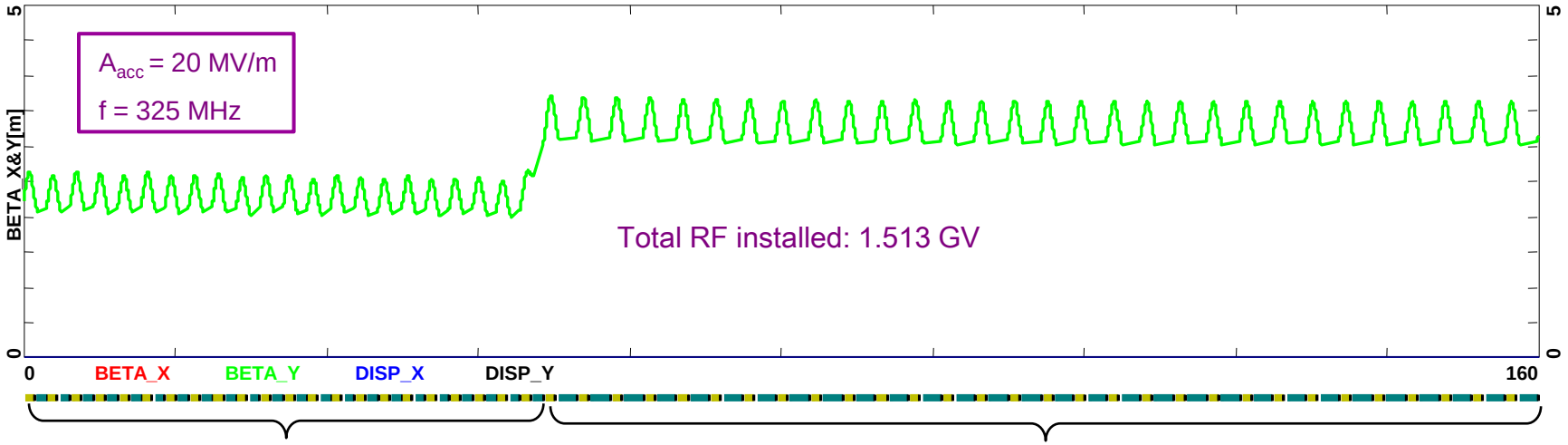


Initial Linac – Longitudinal Acceptance

p = 255 MeV/c

beta functions

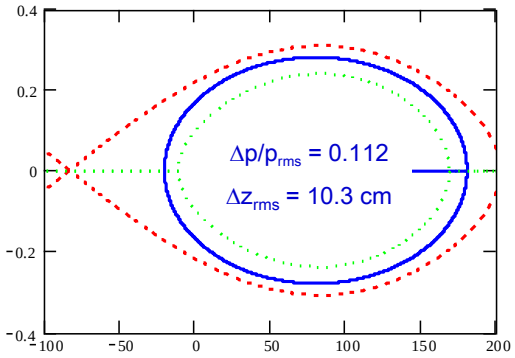
1250 MeV



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

30 medium cryos
(3.5 meter 4-cell cavity)

Initial acceptance 150 mm (blue)

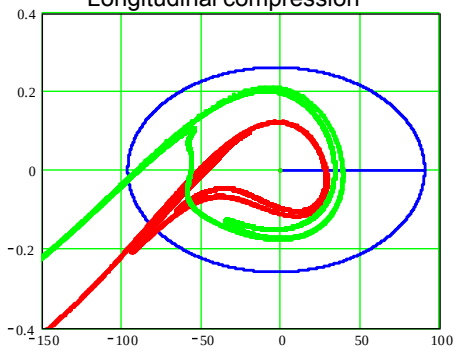


Longitudinal acceptance

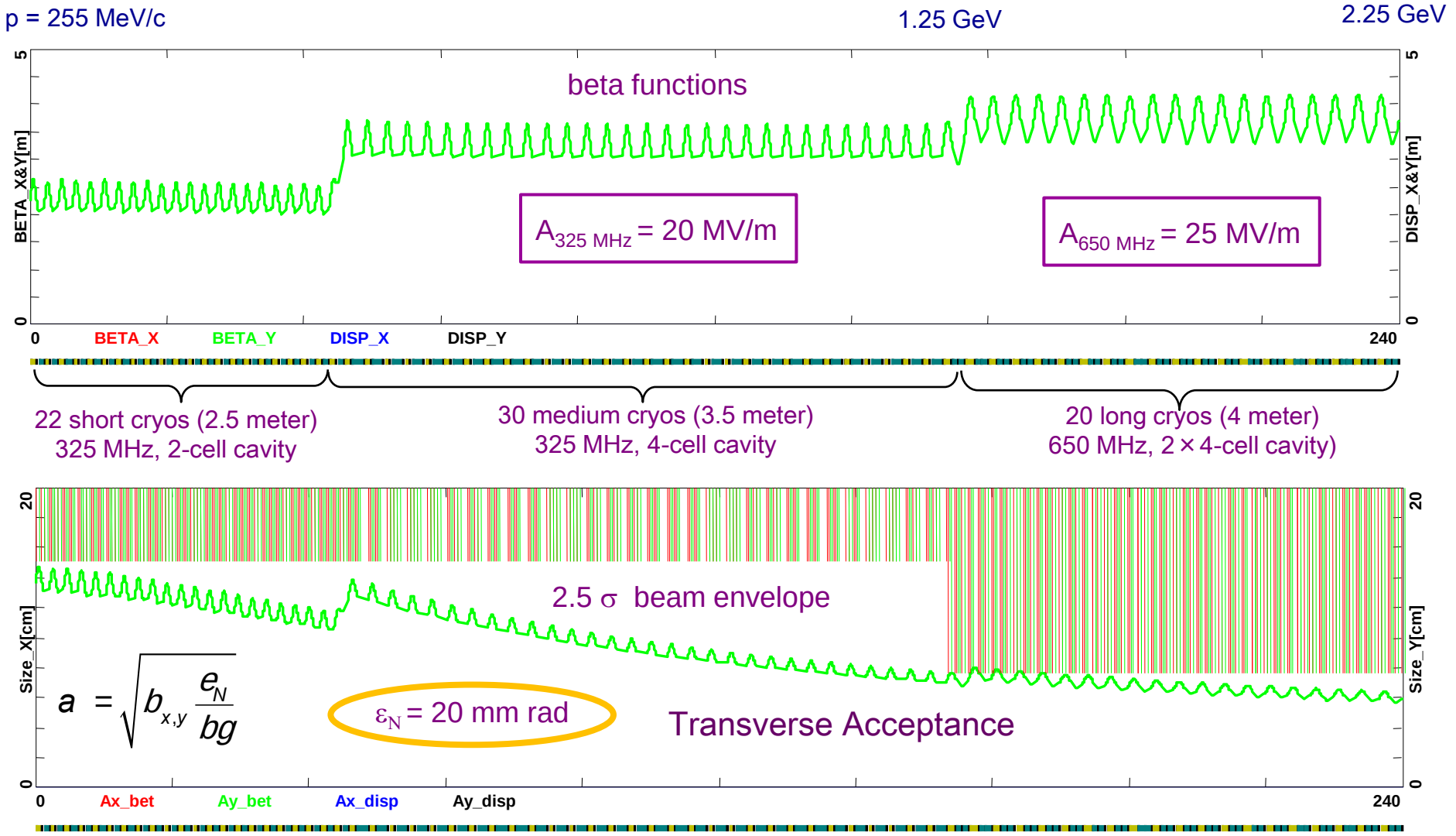
ε_{Long}= 150 mm

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

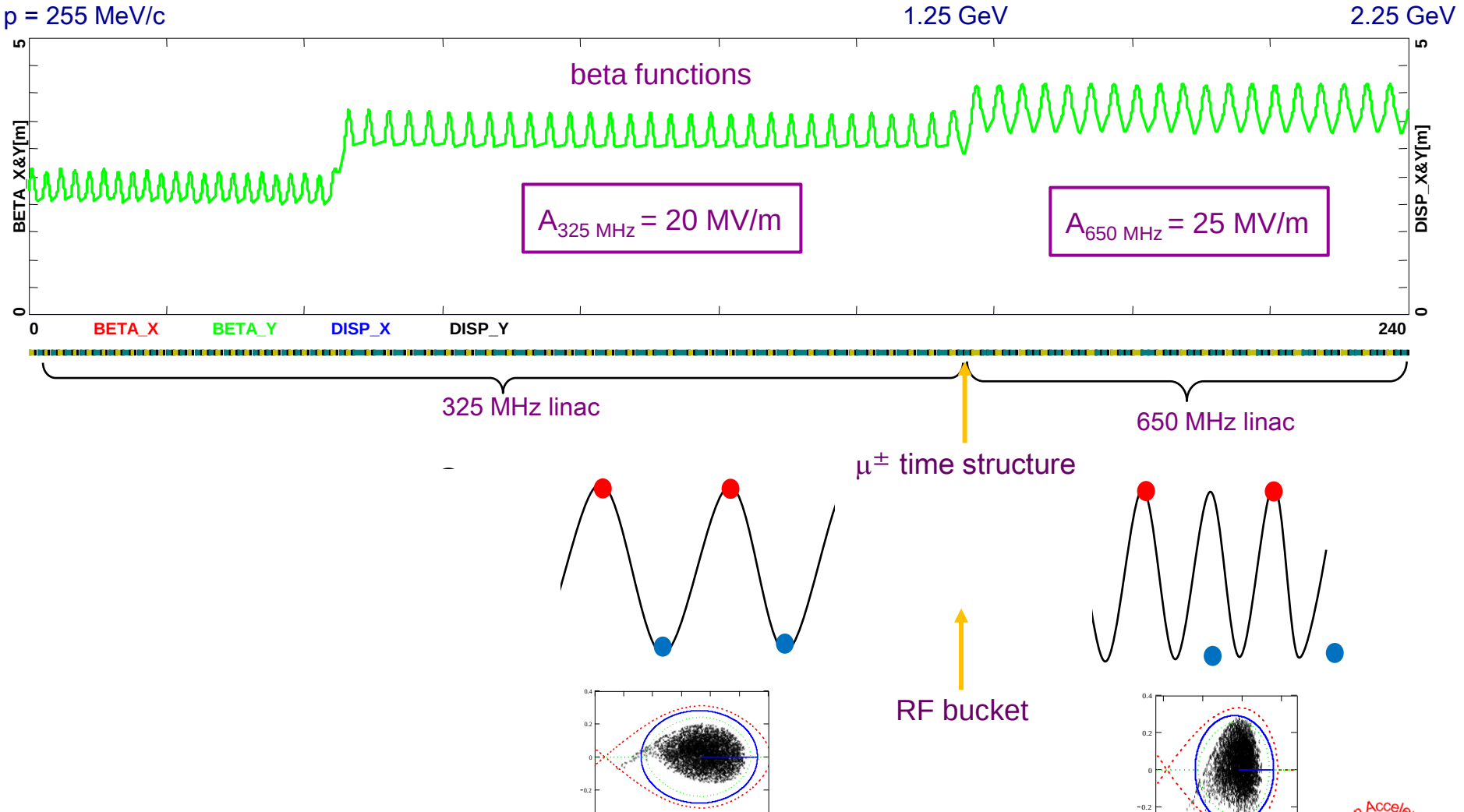
Longitudinal compression



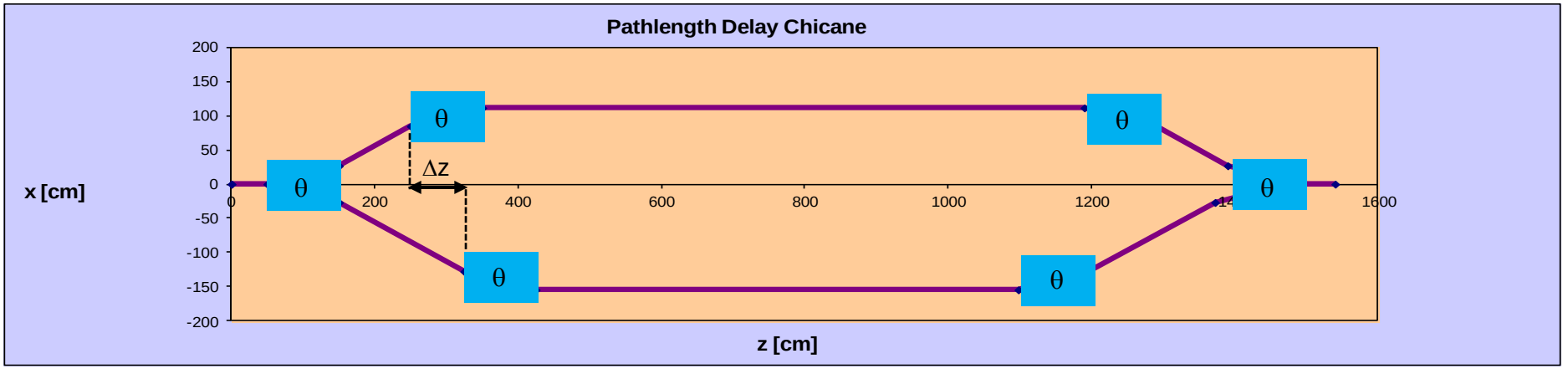
325 MHz – 650 MHz Linac



325 MHz – 650 MHz Transition



Path-length Delay Chicane



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

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

$$\Delta z = \frac{\lambda}{4} \times \frac{\cos\theta}{1-\cos\theta}$$

$$\lambda = 46.122 \text{ cm}$$

$$\theta = 30^0$$

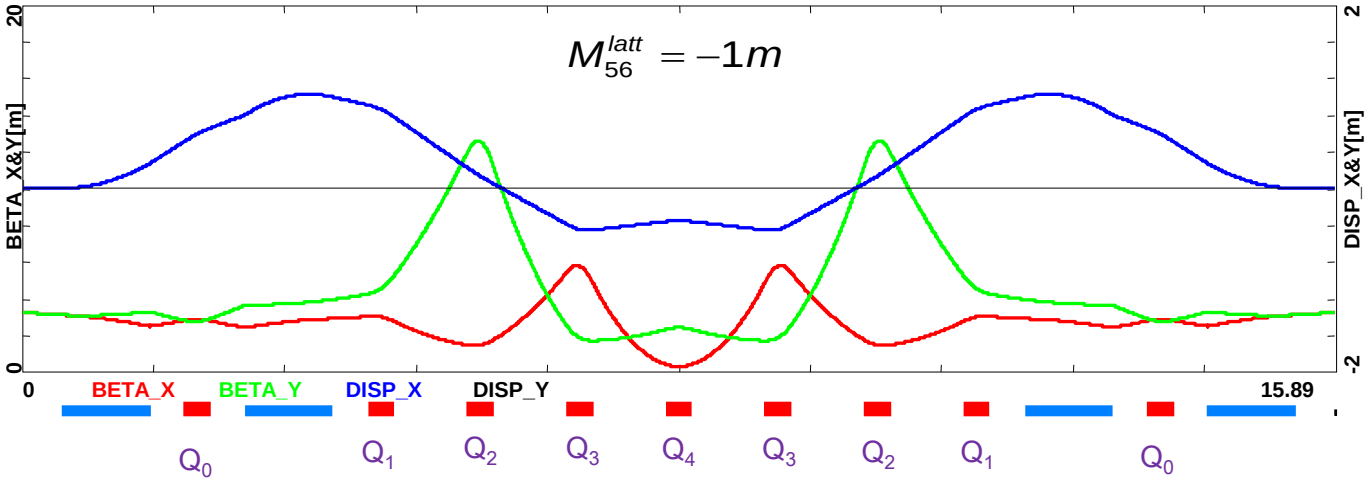
$$\Delta z = 74.534 \text{ cm}$$

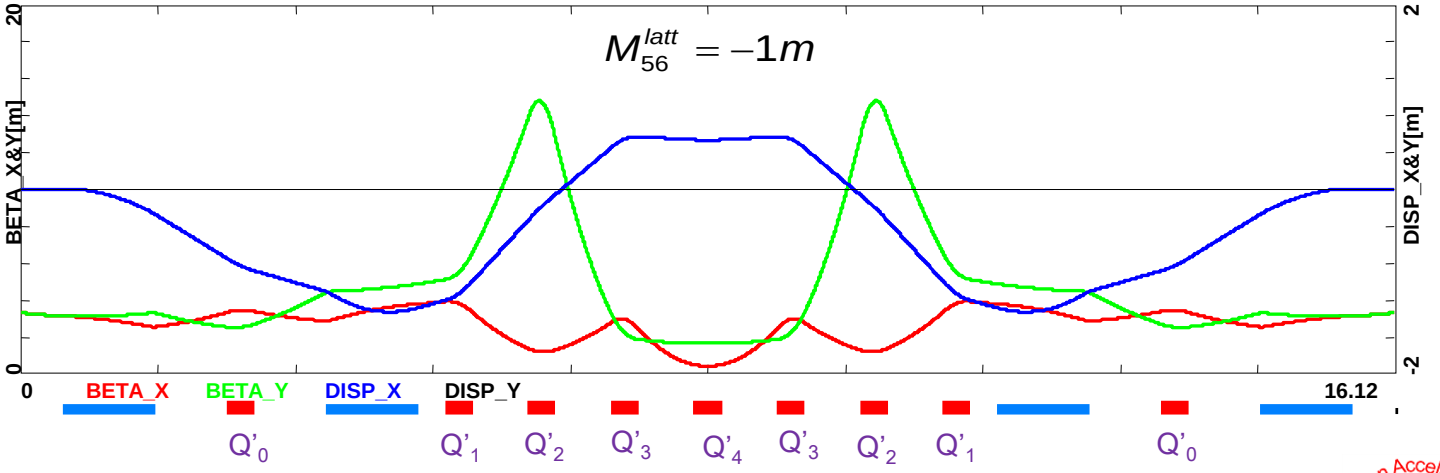
$$\frac{\cos\theta}{1-\cos\theta} = \frac{1}{2}\left(c\tan^2\frac{\theta}{2} - 1\right)$$

Delay/Compression Chicane – Optics

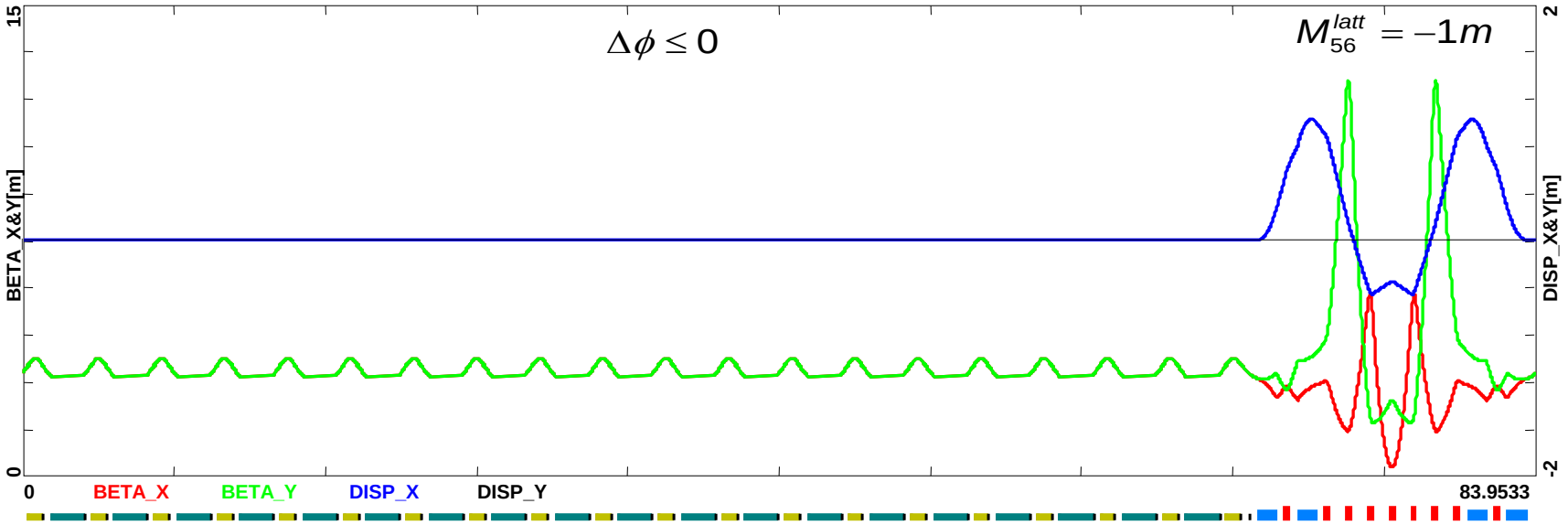
5 free parameters needed to match: 2 betas + 2 alphas + disp.

$$M_{56} = \int \left(\frac{1}{\gamma^2} - \frac{D}{\rho} \right) ds$$

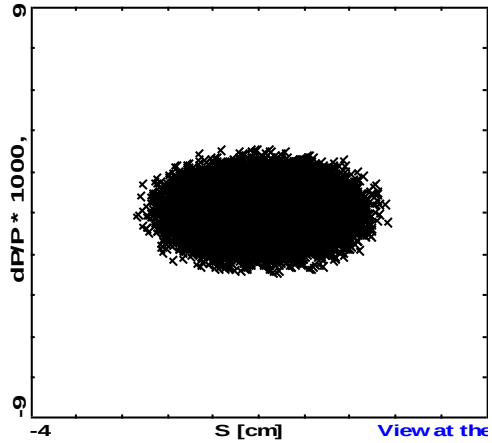


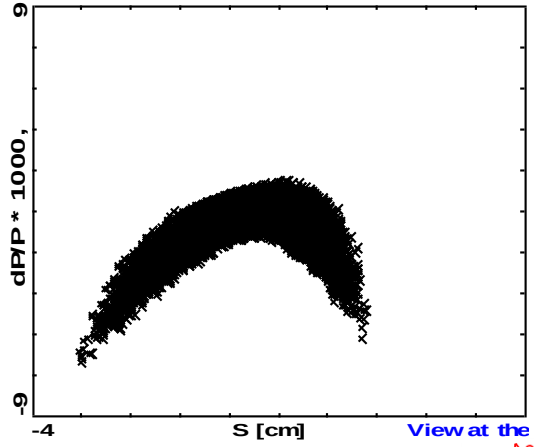


Longitudinal Compression with M_{56}

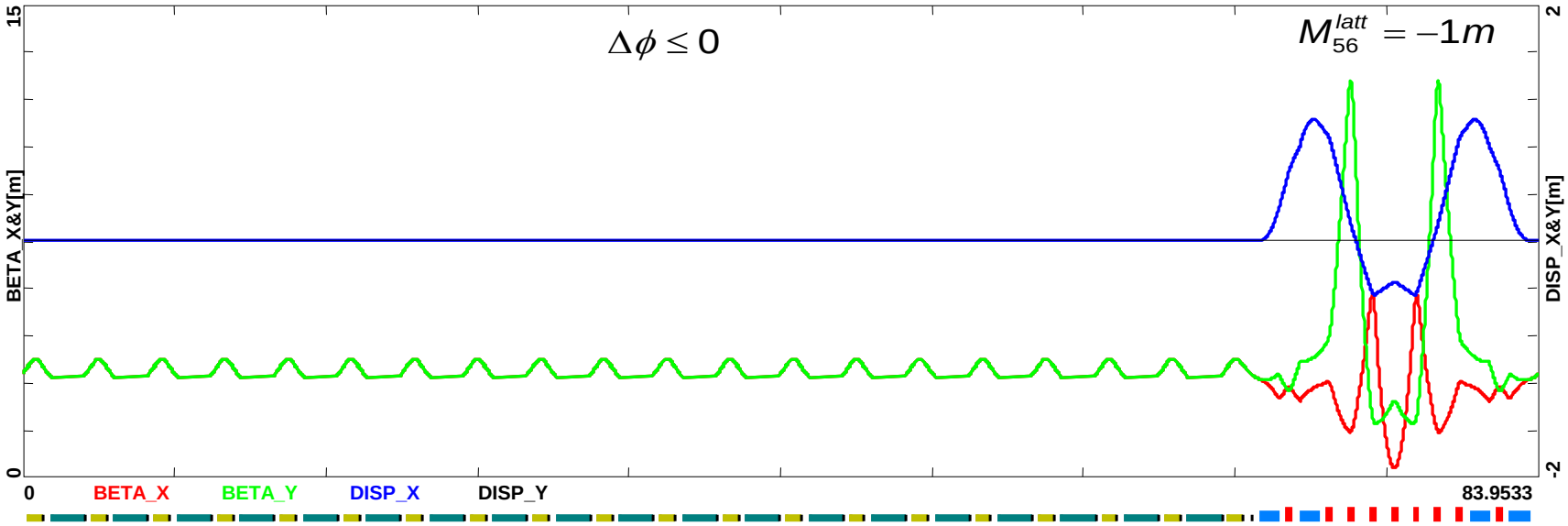


$\Delta\phi = 0$

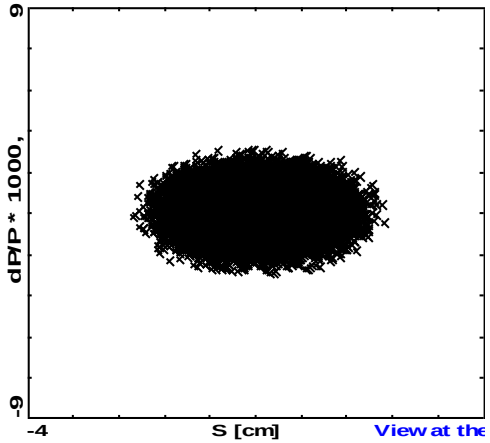


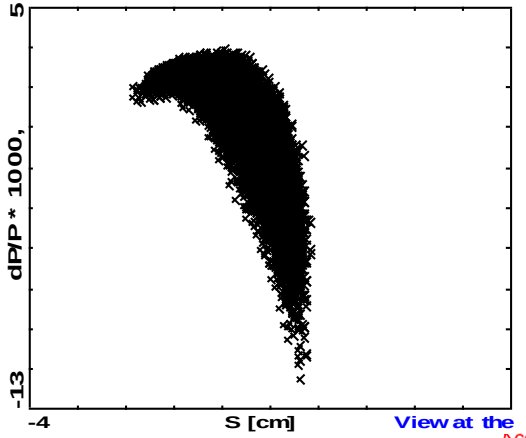


Longitudinal Compression with M_{56}

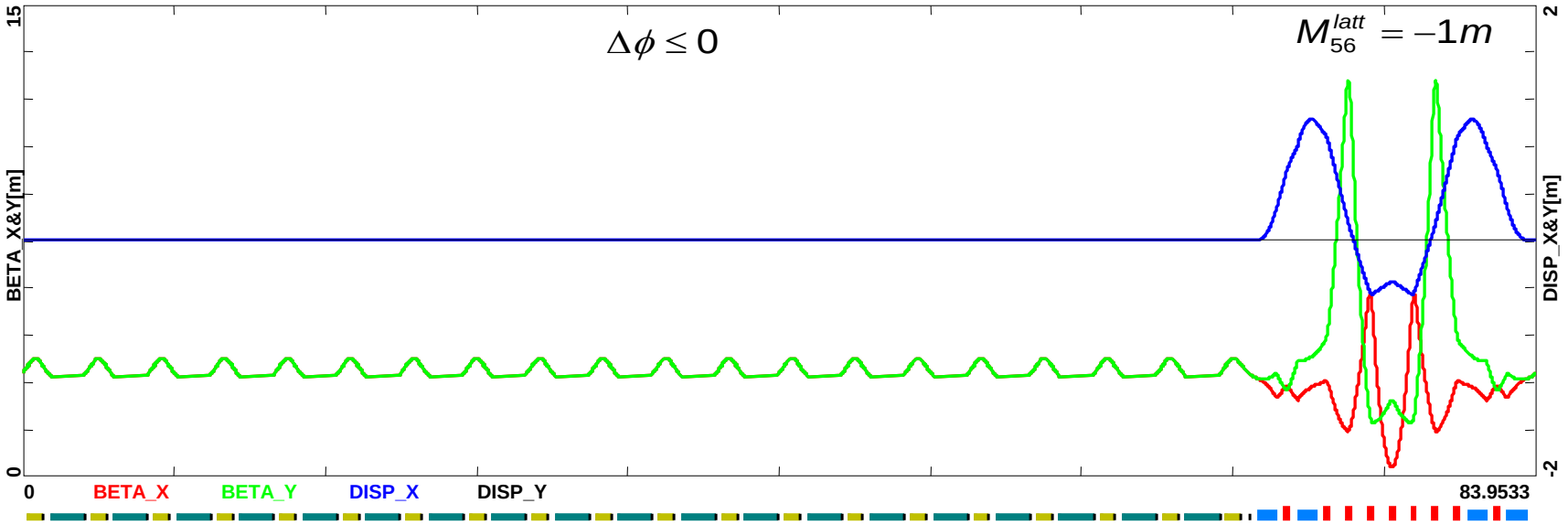


$\Delta\phi = -5^0$

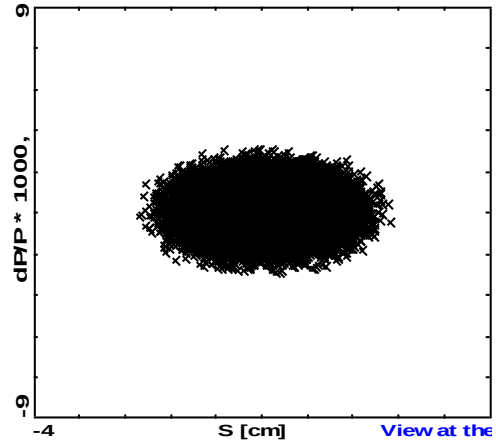


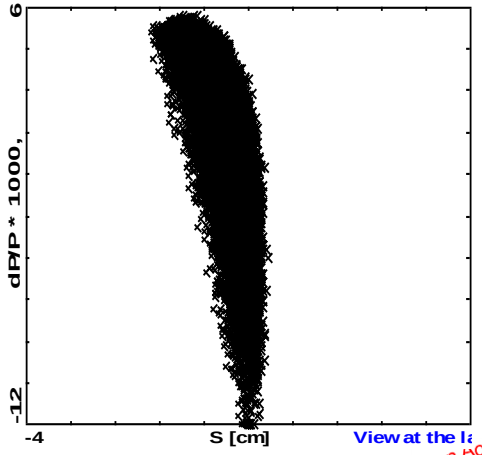


Longitudinal Compression with M_{56}

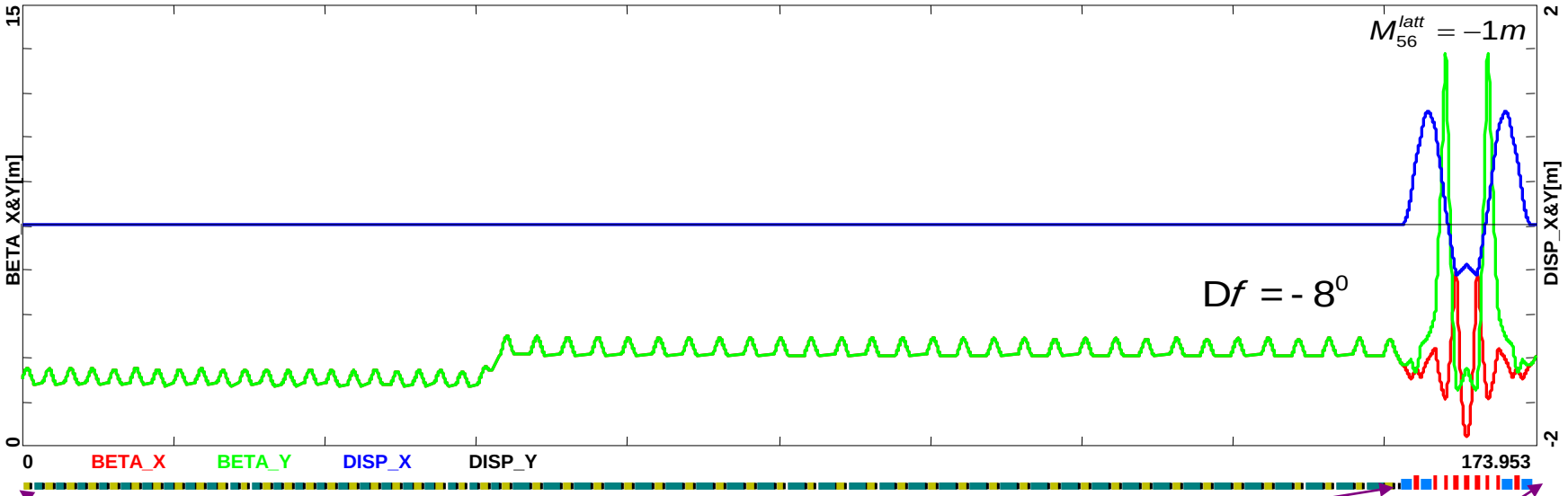


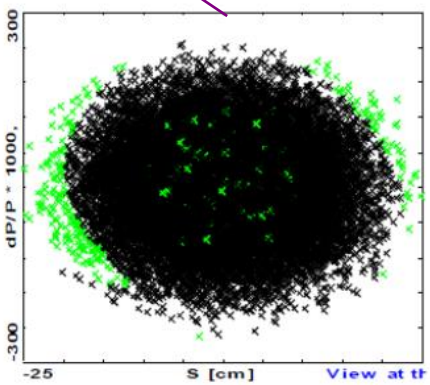
$\Delta\phi = -8^0$

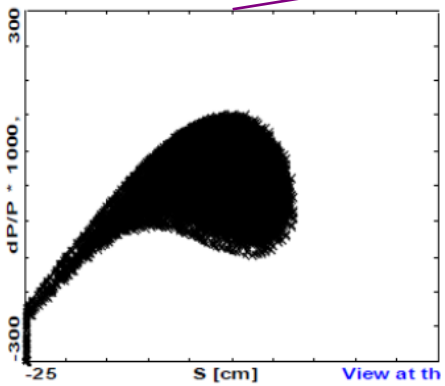


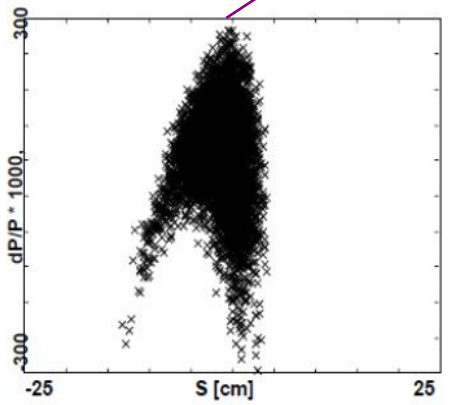


Longitudinal Compression with M_{56}

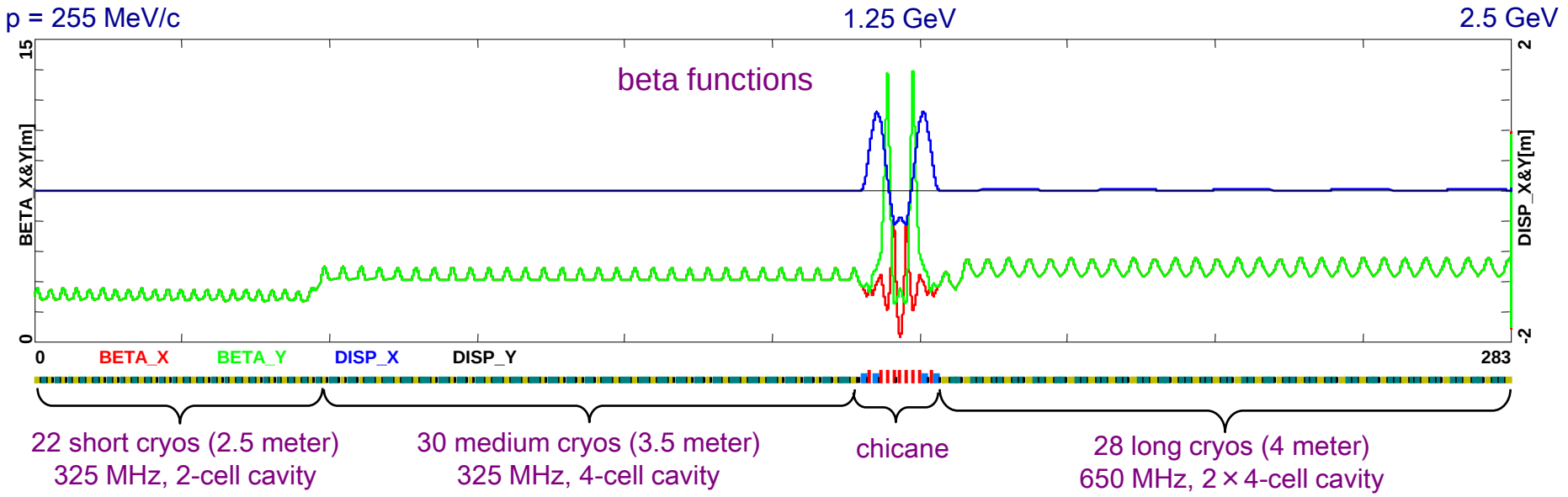


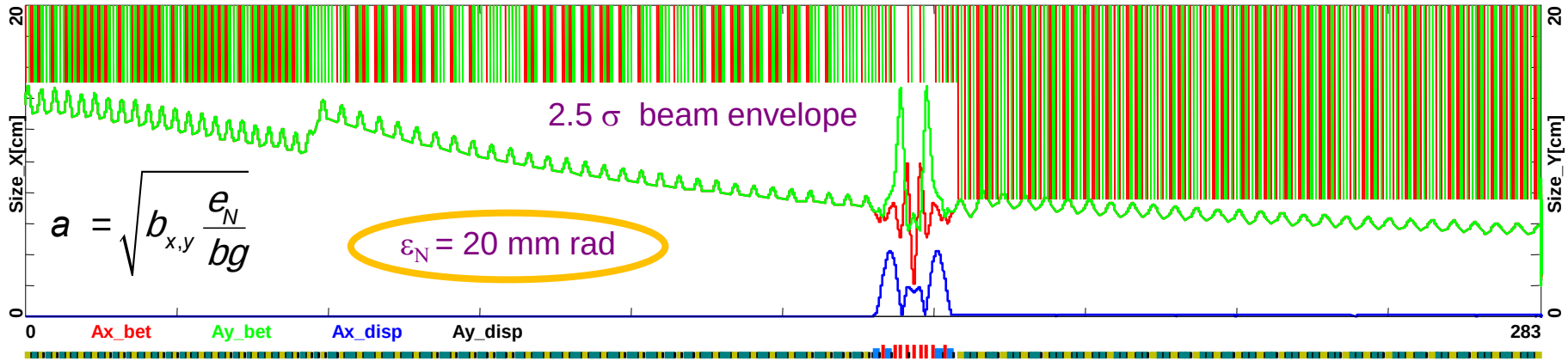




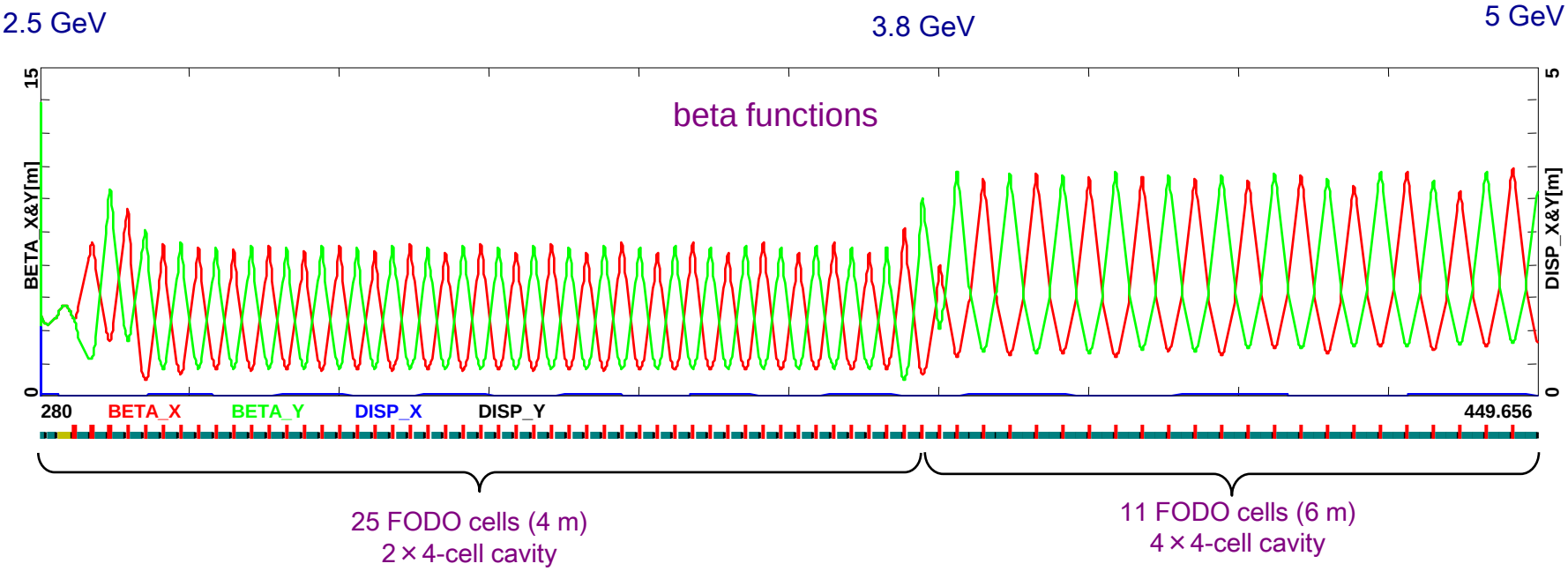


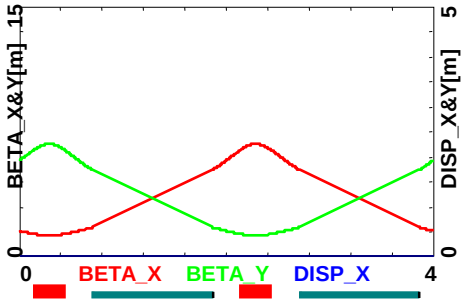
325 MHz – 650 MHz Linac

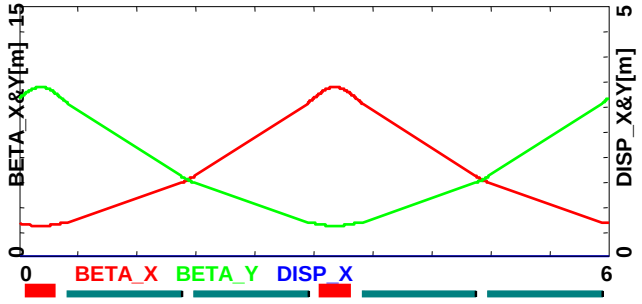




650 MHz FODO Linac

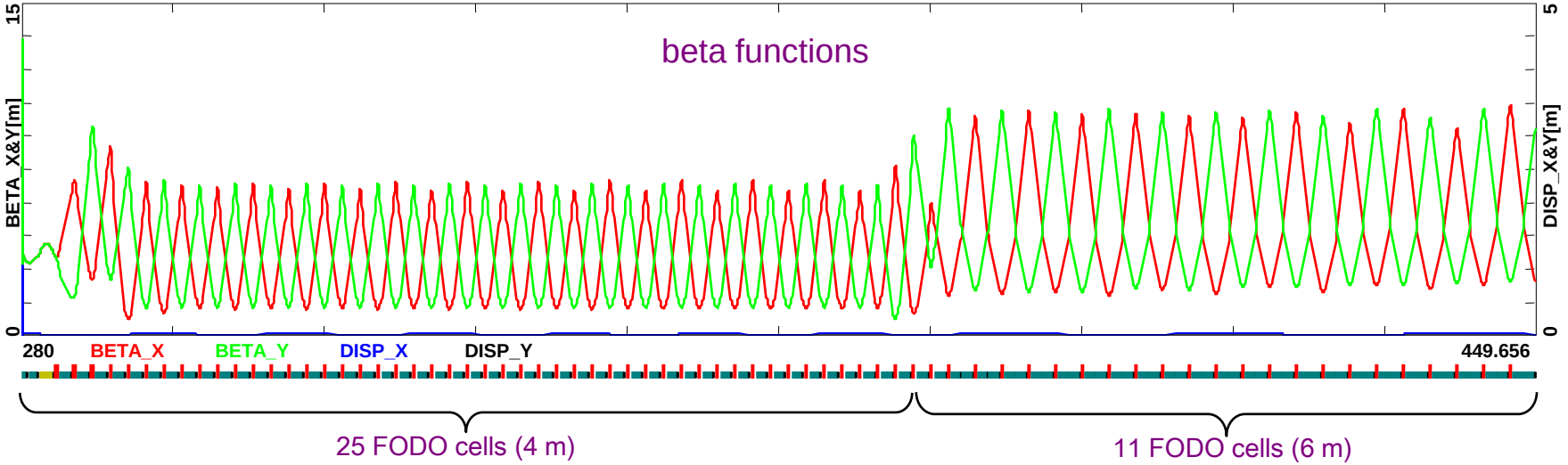




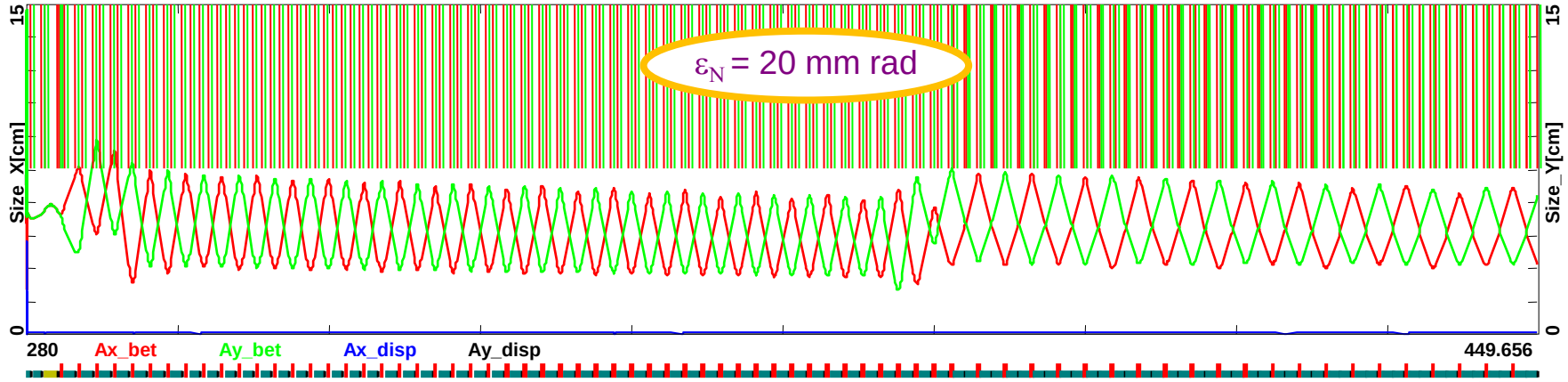


650 MHz FODO Linac

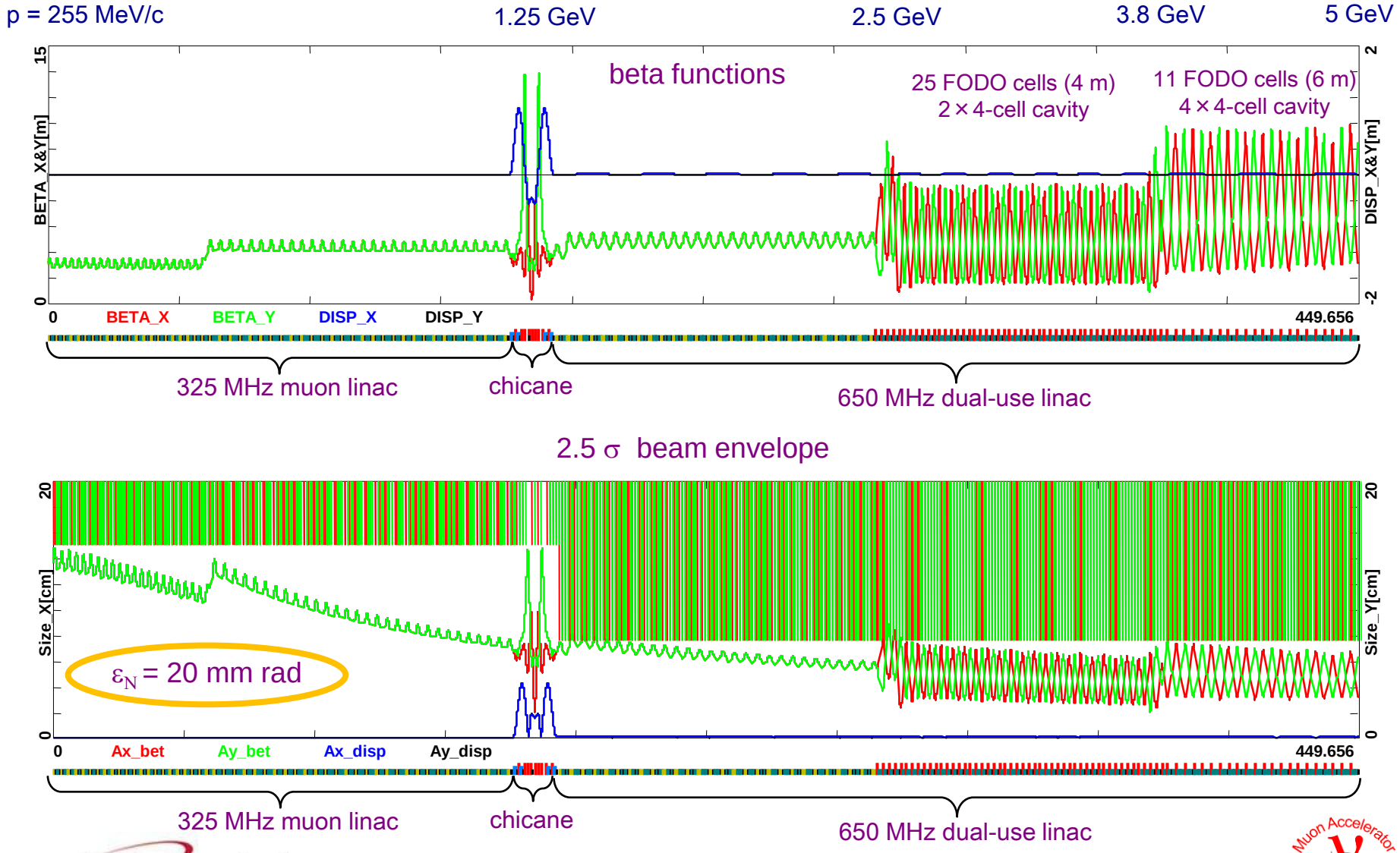
2.5 GeV 3.8 GeV 5 GeV



2.5 σ beam envelope



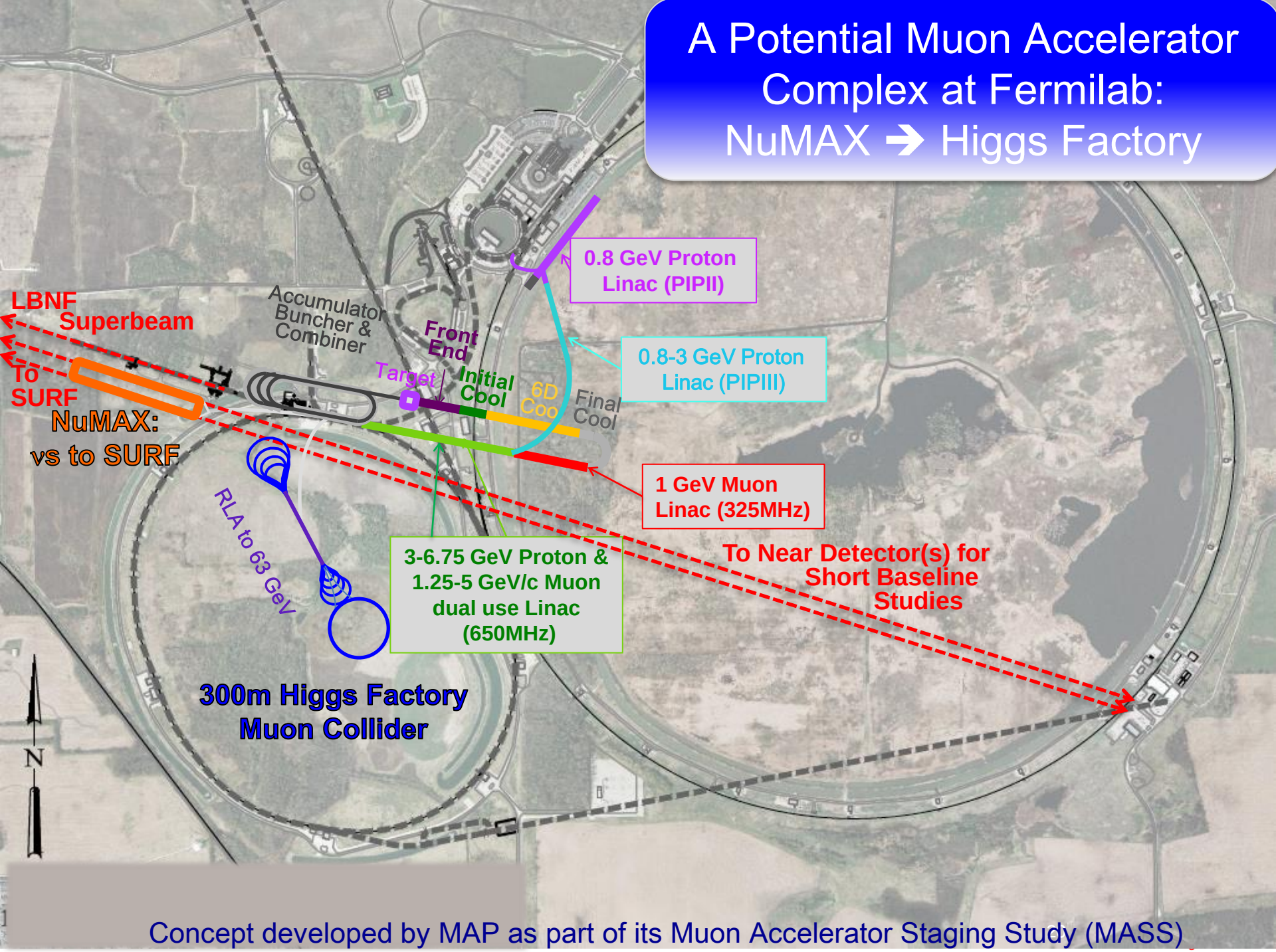
325 MHz – 650 MHz Linac



Compatibility with H^- Acceleration

- So far, the presented linac design was optimized for muon acceleration only.
  - We have developed a diverse modular linac structure composed of various style solenoid focusing FOFO cells and quadrupole based FODO cells.
- Further studies will follow to address compatibility with H^- acceleration. They will focus on:
  - H^- injection into the linac (effect of a chicane bend on ion stripping)
  - H^- betatron matching into the linac
  - H^- dynamics in a strongly focusing solenoid based FOFO channel
  - Different phase requirements for muon and H^- acceleration ⇨ cavity-by-cavity phase adjustment needs to be made to switch between species
- Depending on the results of the above H^- compatibility study, one will optimize the dual-use linac with appropriate combination of the developed lattice modules.

A Potential Muon Accelerator Complex at Fermilab: NuMAX ➔ Higgs Factory



Concept developed by MAP as part of its Muon Accelerator Staging Study (MASS)

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: $V = n_C G\pi c/\omega$

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

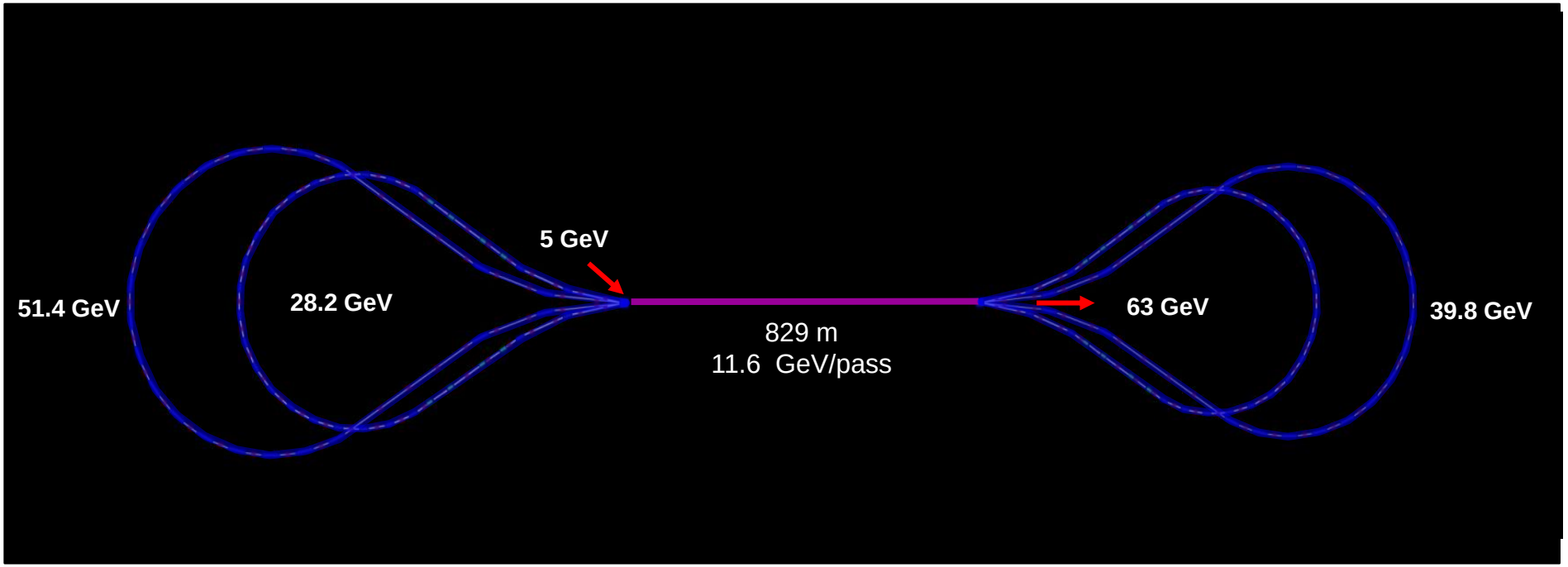
fractional voltage reduction:

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

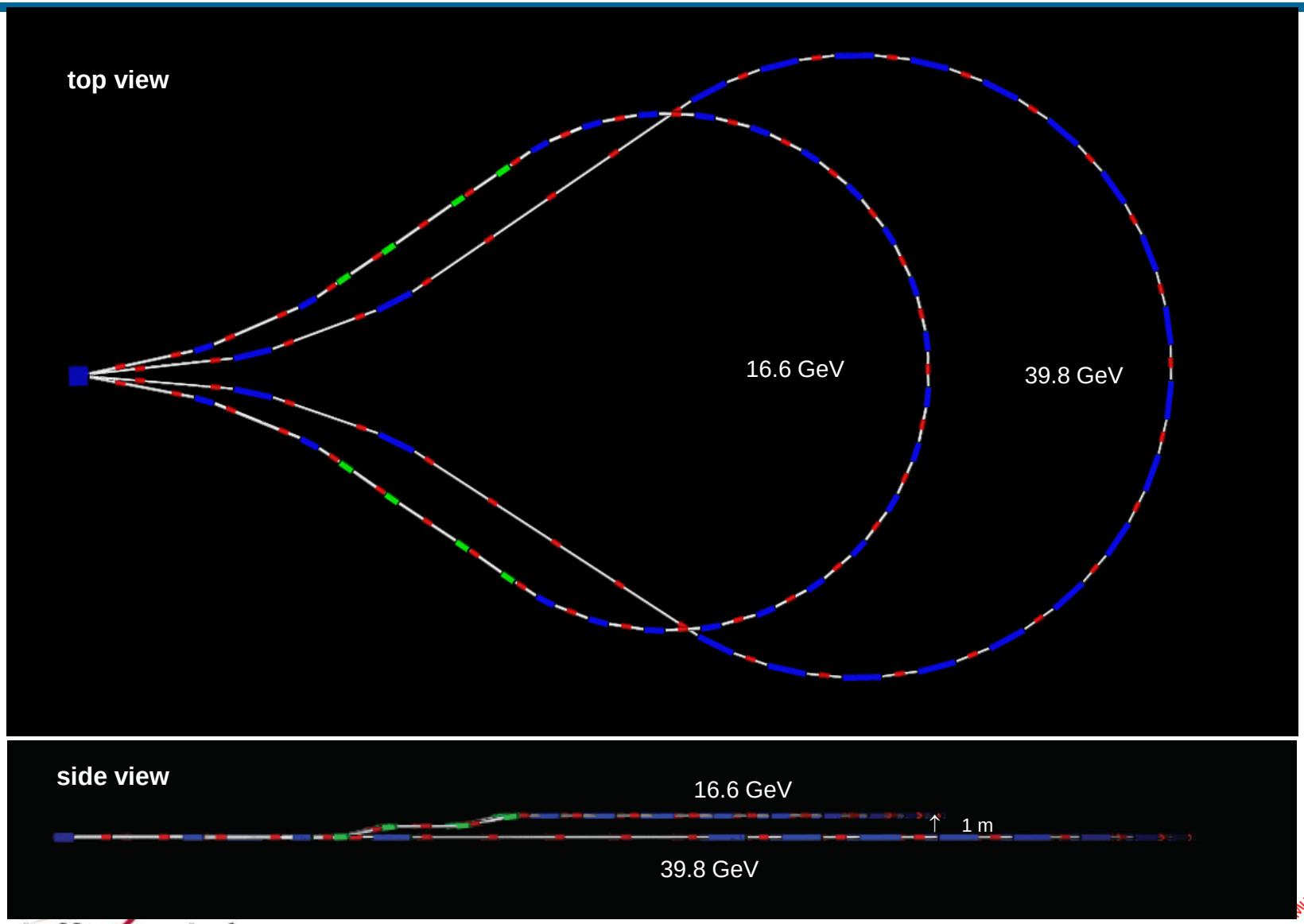
$\phi = 0$

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

5-pass RLA 5–63 GeV

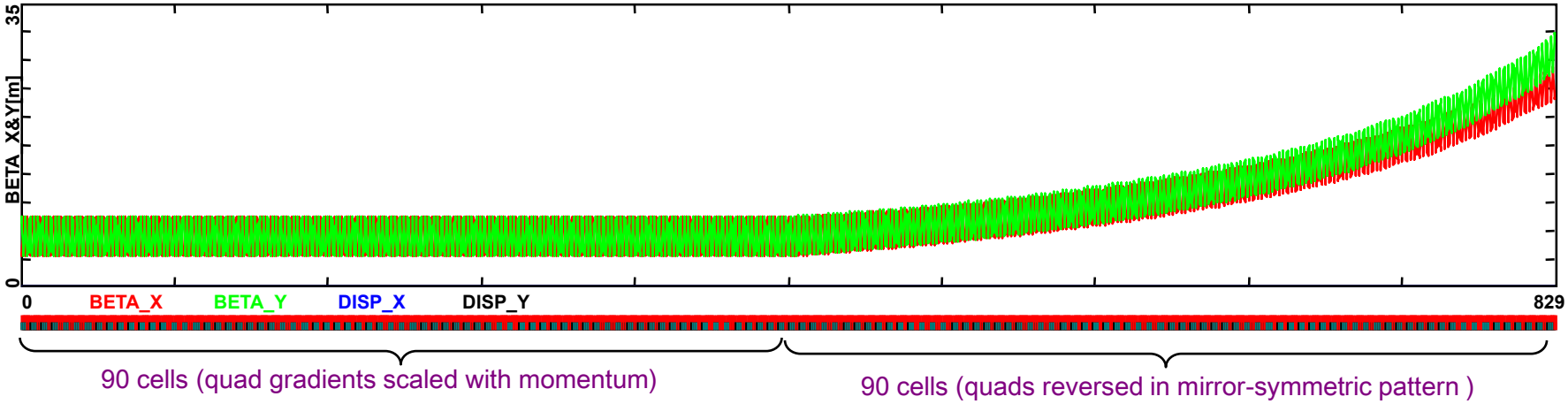


Arc 1 and Arc 3



Linac – Bisected Optics

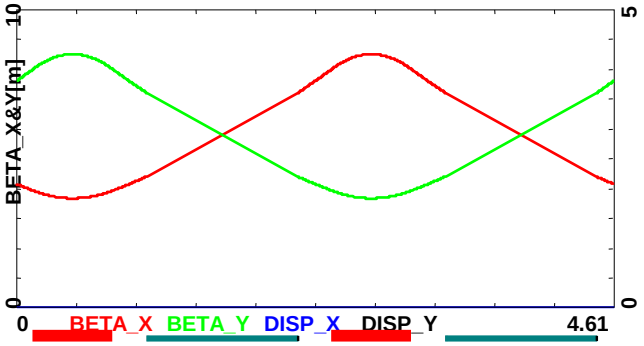
E = 5–16.6 GeV

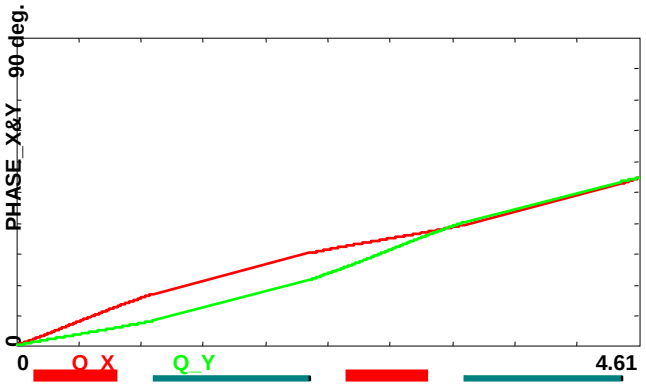


90 cells (quad gradients scaled with momentum)

90 cells (quads reversed in mirror-symmetric pattern)

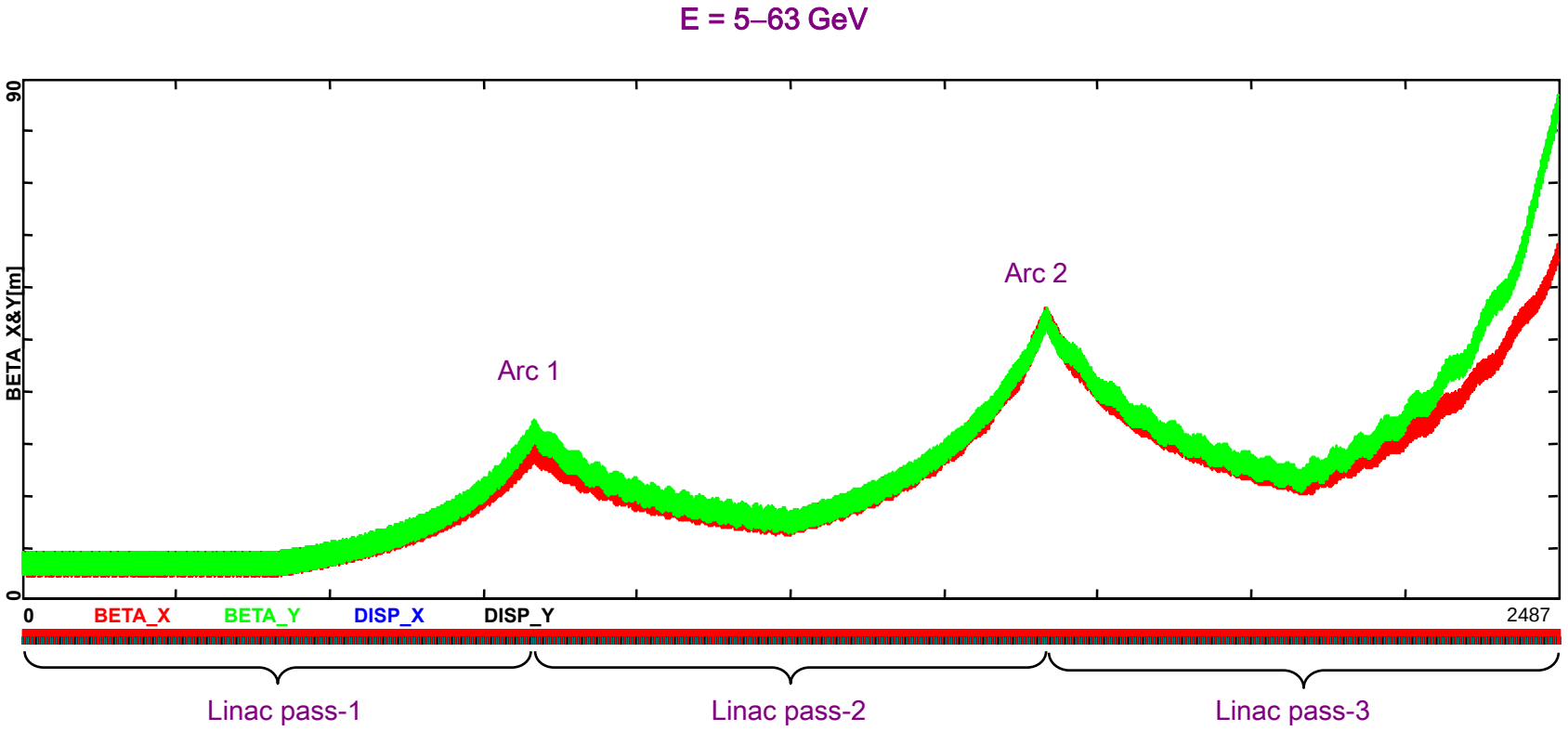
49^0 FODO





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

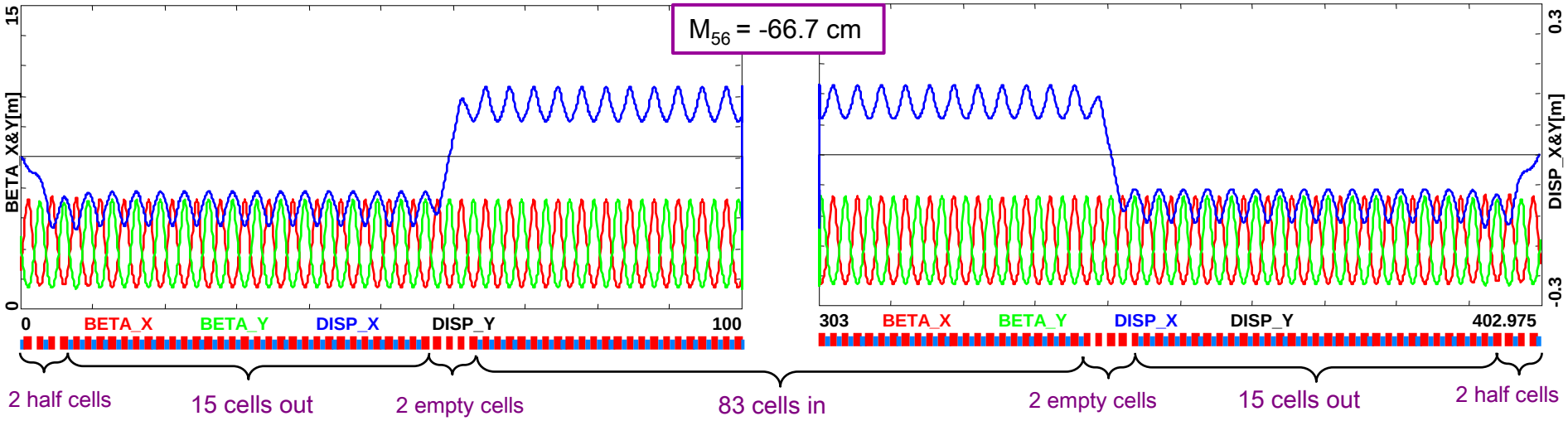
Multi-pass Linac – Bisected Optics



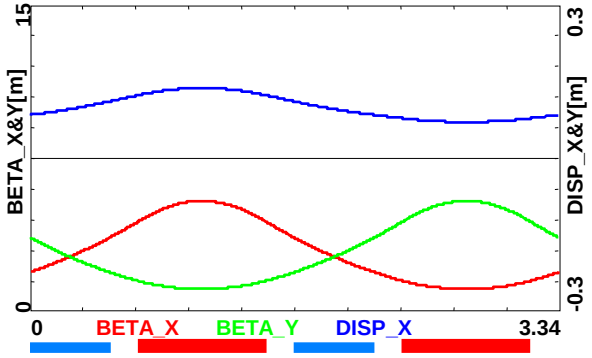
RF	f[MHz]	cells/cavity	Grad [MV/m]	phase [deg]
	650	5	25	22

Arc Optics – Longitudinal Distortion

E = 24 GeV



90^0 FODO

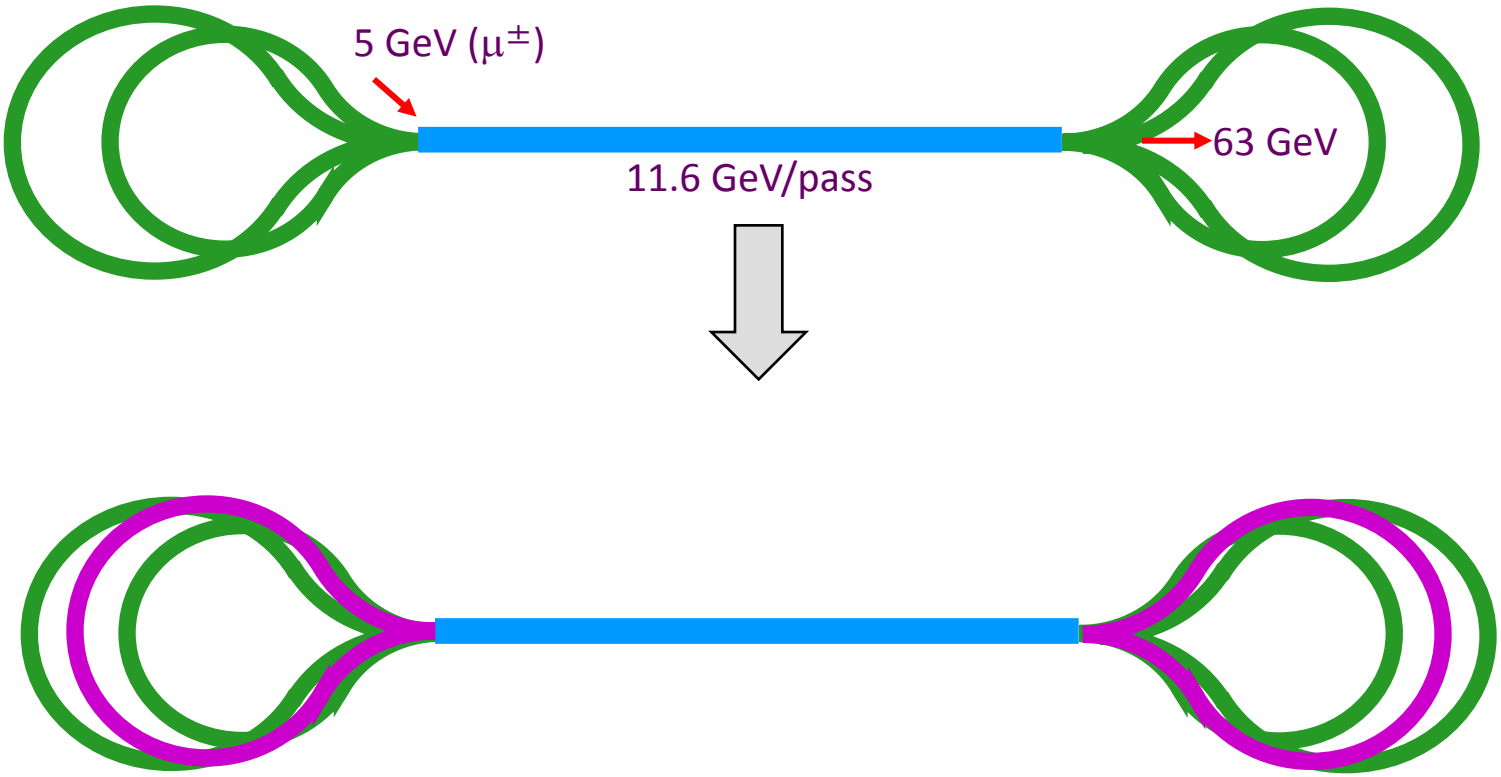


$$n_i = 5n_o + 8$$

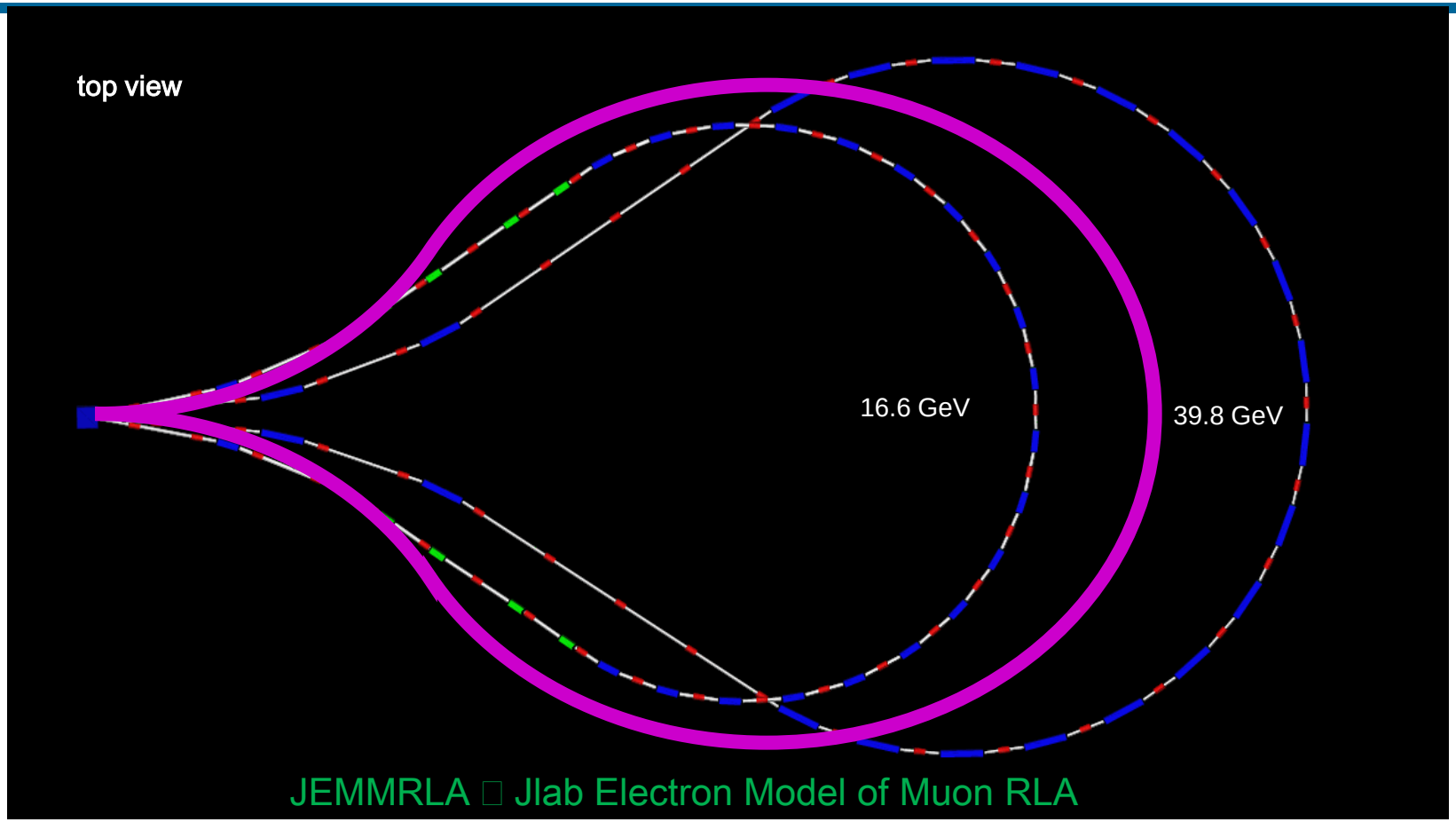
Quads	L[cm]	G[kG/cm]
qF	80	10.2924
qD	80	-10.2788

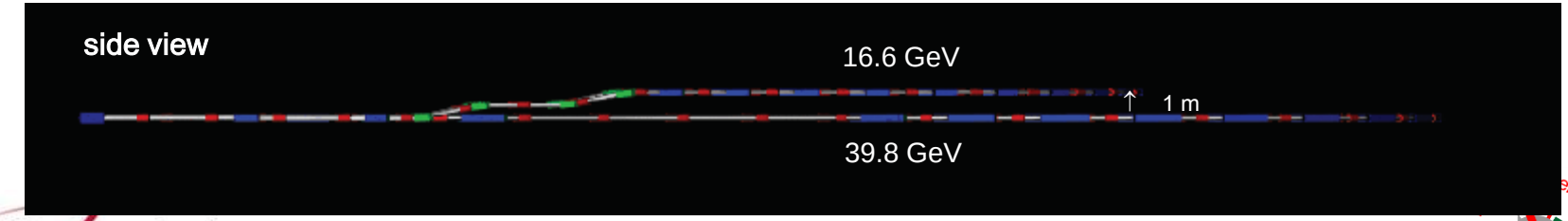
Dipoles	L[cm]	B[kG]	bend angle [deg]
	50.00	49.3116	1.7647

Multi-pass Arc Muon RLA



Single- vs Multi- pass Droplet Arcs





Summary

- The main thrust is to develop concepts for acceleration of muon beams for a cost effective, stageable Neutrino Factory and then Higgs Factory.
- We propose expansion of D&S efforts on muon acceleration for NuMAX and beyond:
  - Utilizing building blocks (schemes and lattices) developed by the IDS-NF and taking advantage of the opportunities identified by MASS for staging.
  - Reducing the cost while maintaining performance exploiting interplay between the cooling systems and the acceptance of the accelerator.
  - Fully explore dual-use linac concept through muon/H^- compatibility study, which will lead to a cost optimized acceleration complex.
  - Optimize RLA scheme for Higgs Factory:
    - Number of passes (beam loading)
    - RLA with multi-pass arcs