Optimized Beam Optics for Muon Acceleration

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- Lower initial emittance promised by Ring Coolers (vs Cooling Channel)
  - Simplified front-end linear Pre-accelerator
- Optimized linear optics for 4-pass RLA scheme (200MHz SRF)
  - Special optics for multi-pass linacs – equalized input/output Twiss functions
  - Compact Spr/Rec – 'smooth' transition of optics between linacs and Arcs
- Transverse emittance preservation scheme
  - Chromatic corrections with sextupole families – particle tracking

Initial beam emittance after cooling at 250 MeV/c

rms values		Cooling Channel*	Ring Cooler♣
normalized emittance: ε_x, ε_y	mm·rad	2.4	2.0
longitudinal emittance: ε_l ($\varepsilon_l = \sigma_{\Delta p}\, \sigma_z / m_\mu c$)	mm	27	3
momentum spread: $\sigma_{\Delta p/p}$		0.08	0.025
bunch length: σ_z	mm	163	50

*Study II

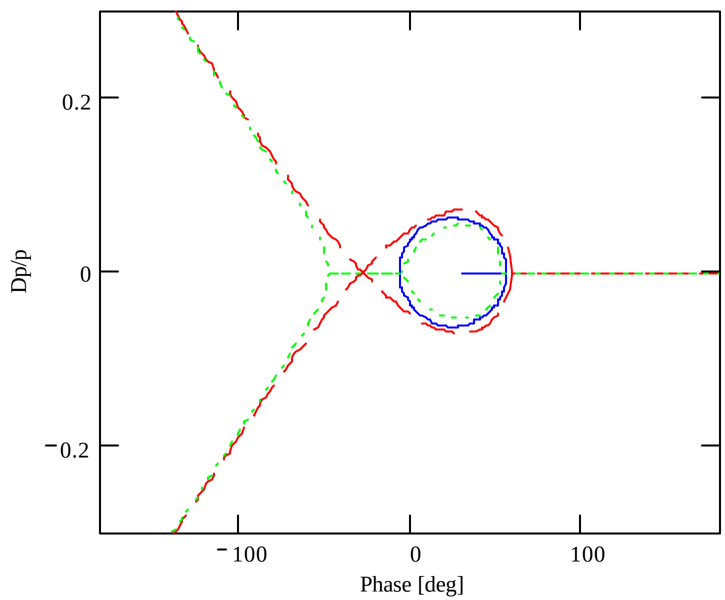
♣Palmer/Kirk/Balbekov

Pre-accelarator acceptance at 250 MeV/c

$A = (2.5)^2\ \varepsilon$		Cooling Channel	Ring Cooler
normalized transv. acceptance	mm·rad	15	12.5
longitudinal emittance: A_l $(A_l = \Delta p\ L/m_\mu c)$ momentum spread: $\Delta p/p$ bunch length: L	mm mm	170 ± 0.20 408	19 ± 0.0625 125

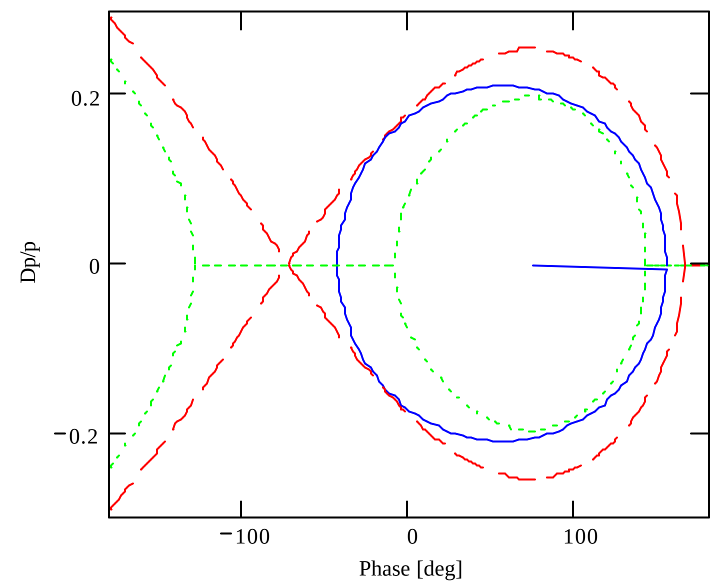
❖Linear Pre-accelerator – Longitudinal dynamics

$\Delta p/p = \pm 0.065$ or $\Delta\phi = \pm 31$



'Ring Cooler' scenario

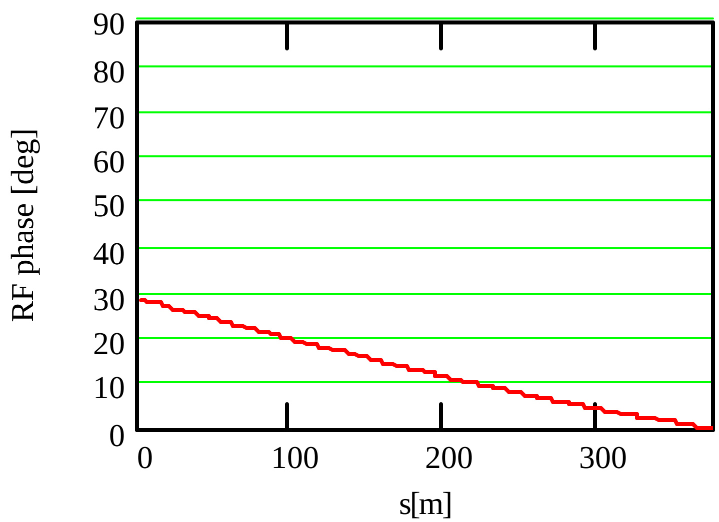
$\Delta p/p = \pm 0.21$ or $\Delta\phi = \pm 89$



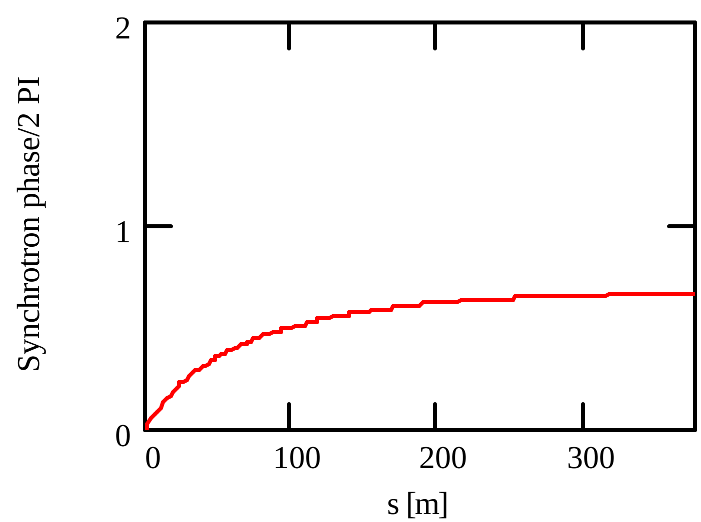
'Study II' scenario

❖ Introduction of 'modest' synchrotron motion in the initial part of the linac

- allows to perform adiabatic bunching/compression of the beam
- prevents head-to-tail 'sag' in acceleration
- 'small' reduction of effective accelerating gradient (2.5 GV instead of 2.2 GV)



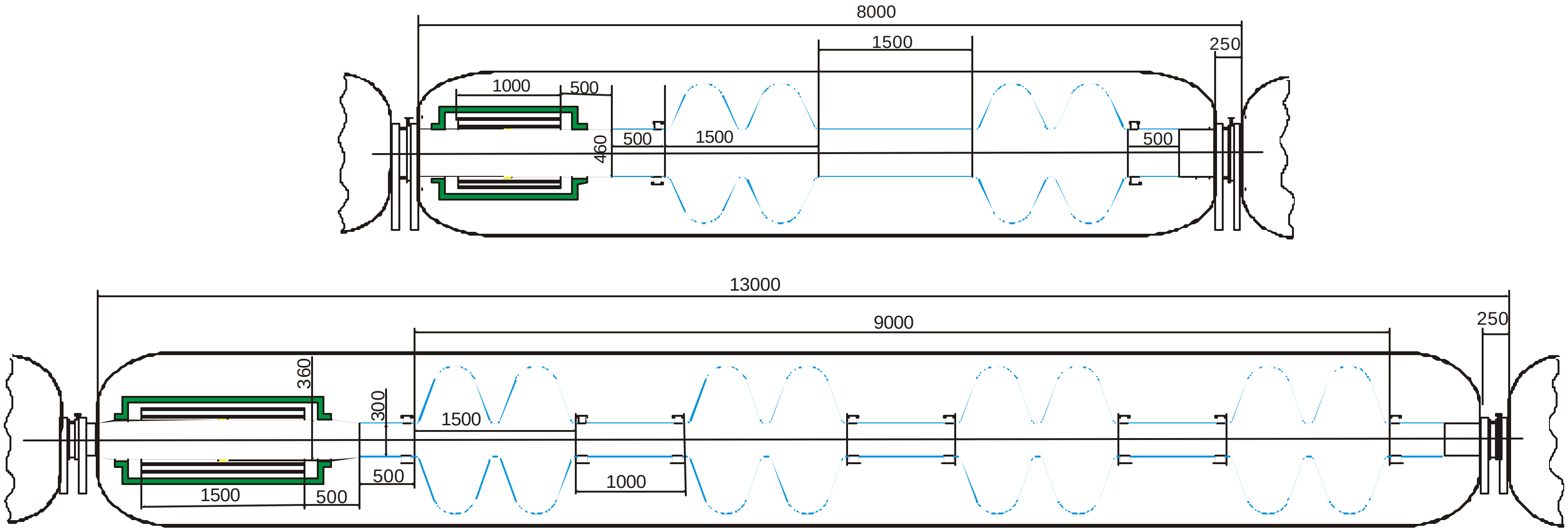
Cavity phase along the linac



Synchrotron phase along the linac

❖Short Pre-accelerator - only two flavors of cryo-modules (medium and long)

- Solenoidal focusing (SC) allows one to accommodate very large beam emittance



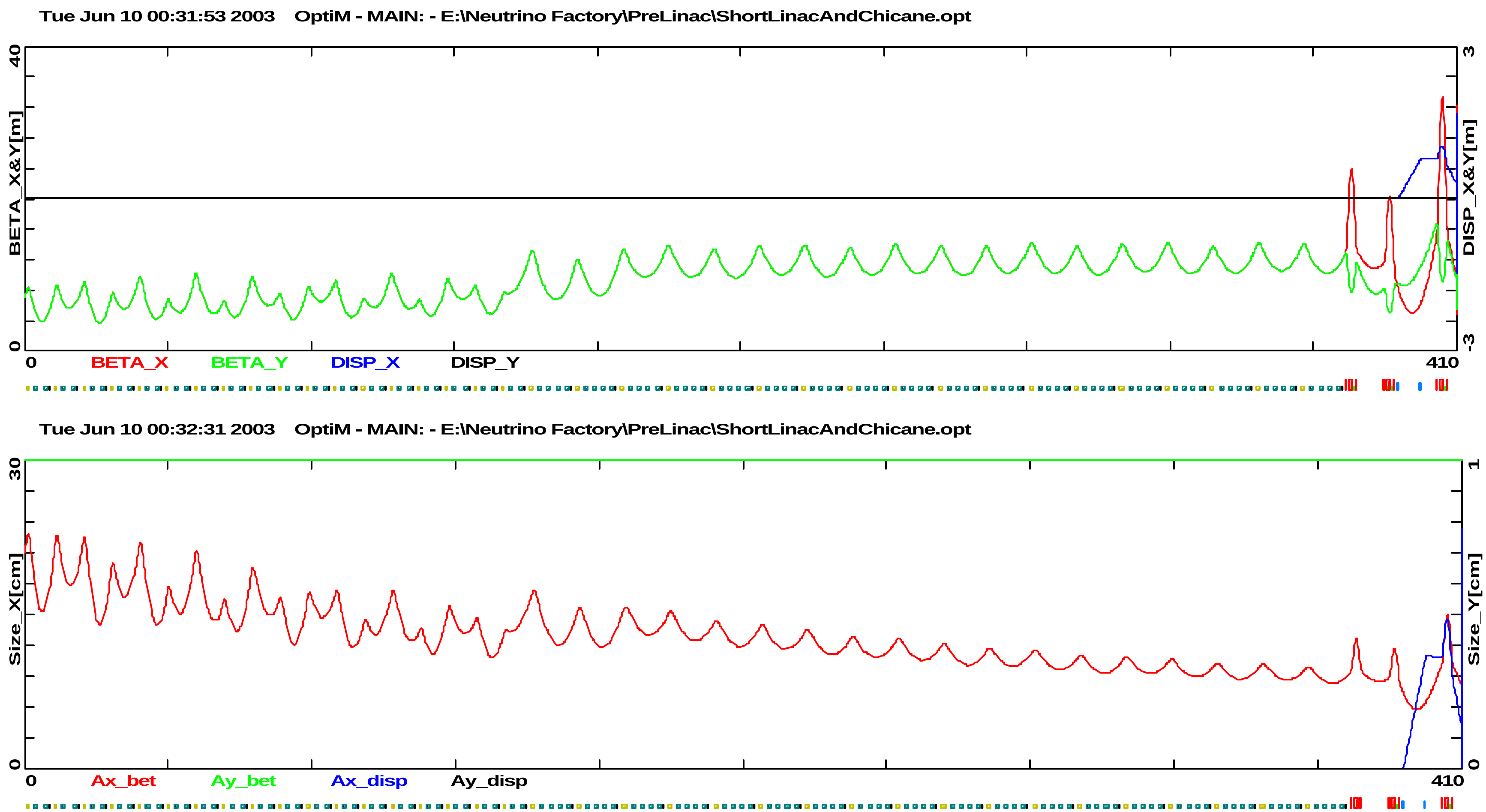
Blue – SC walls of cavities. Red – solenoid coils. Green – magnetic shielding.

- Cryo-module design driven by limiting power of the fundamental couplers (~1 MW) – 1 coupler per cell required

Pre-accelerator – cryo-module parameters

	Medium cryo-module	Long cryo-module
Number of periods	18	18
Total length of one period	8 m	13 m
Number of cavities per period	2	4
Number of cells per cavity	2	2
Number of couplers per cavity	2	2
Cavity accelerating gradient	15 MV/m	17 MV/m
Real-estate gradient	5.59 MV/m	7.79 MV/m
Aperture in cavities (2*a*)	460 mm	300 mm
Aperture in solenoids (2*a*)	460 mm	360 mm
Solenoid length	1 m	1.5 m
Solenoid maximum field	2.1 T	4.2 T

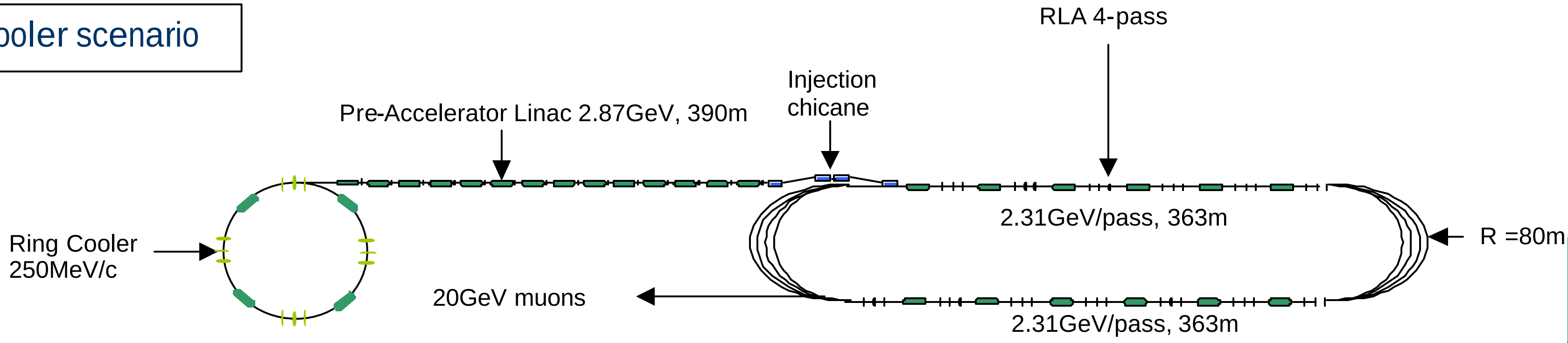
❖Linear Pre-accelerator – Lattice layout, Beam envelope



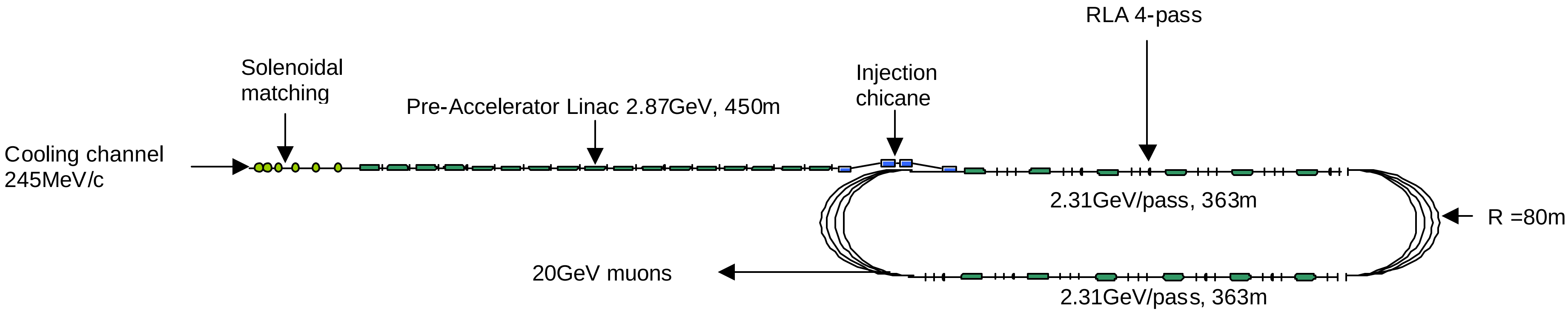
Beta-functions & beam envelopes (2.5s) (from 250MeV/c to 2392MeV)

❖RLA based muon accelerator complex (245MeV/c – 20GeV)

Ring Cooler scenario



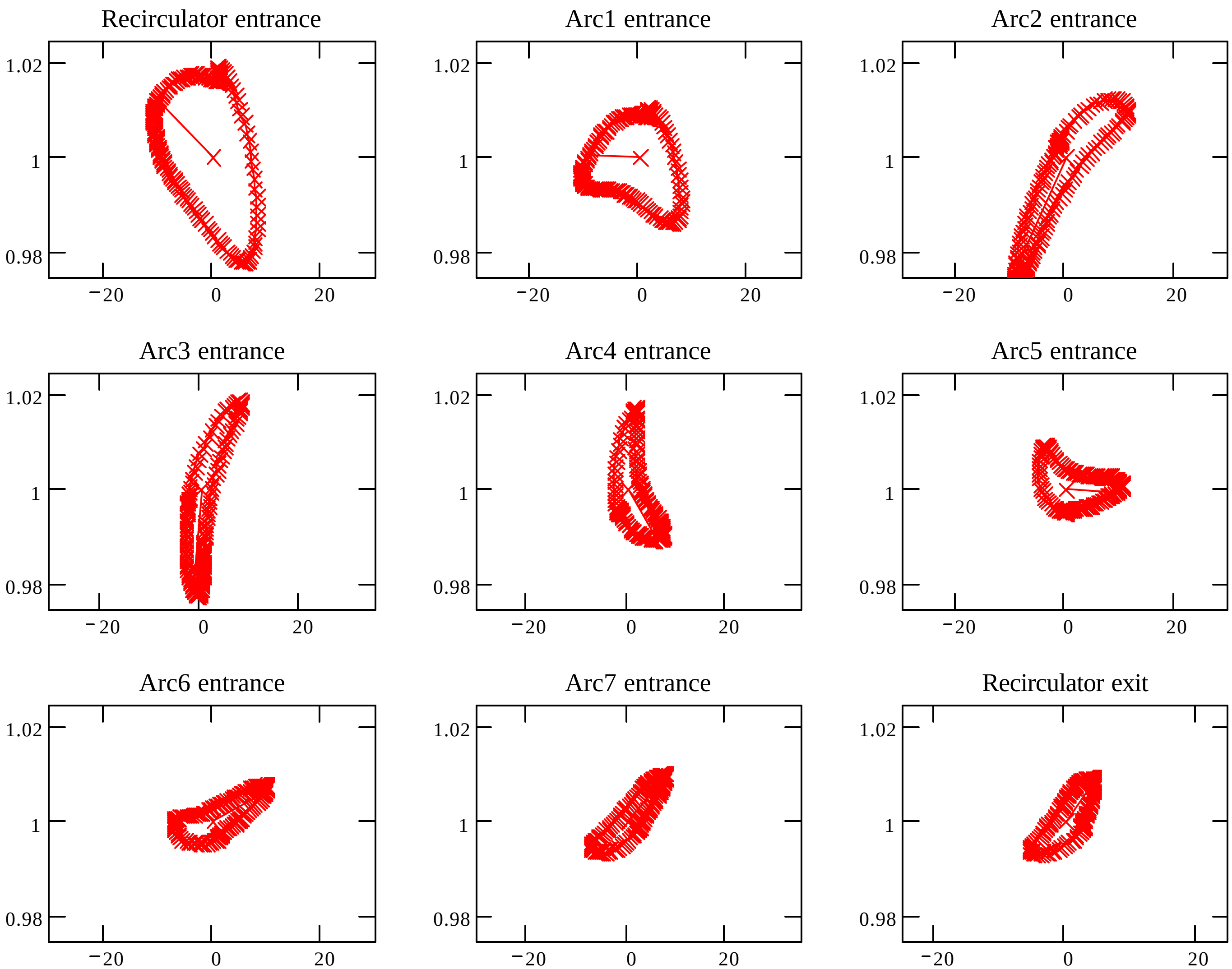
Study II scenario



Main parameters for the RLA

Initial energy	2.39 GeV
Final energy	20 GeV
Number of passes	4
Total initial energy acceptance	±0.02
Total final energy acceptance	±0.008
Initial transverse acceptance	600 mm·mrad
Final transverse acceptance, $\varepsilon_x / \varepsilon_y$	150/100 mm·mrad
Total voltage per linac	2.3347 GV
Circumference	≈1300 m

❖Longitudinal dynamics in the RLA, $M_{56} = 0.9$ m



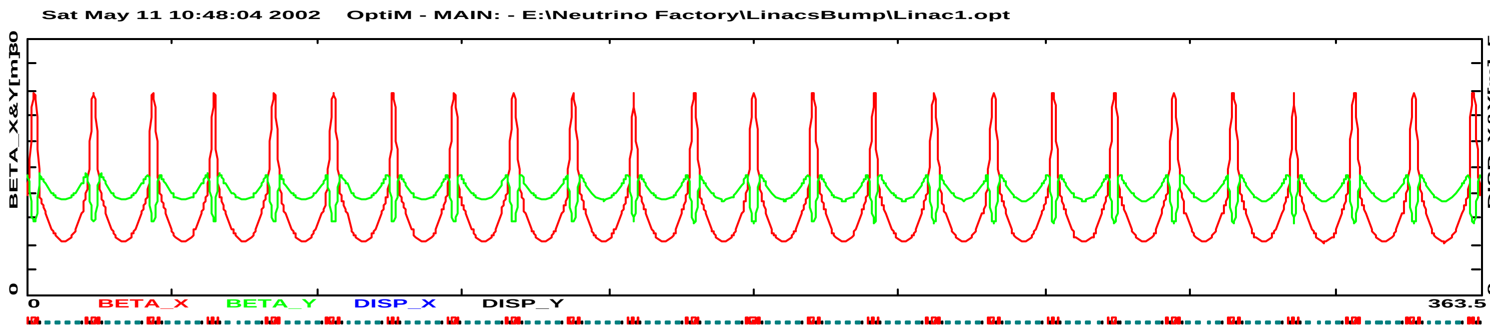
$$\Delta p_{tot} = \begin{pmatrix} 0.0207 \\ 0.0121 \\ 0.0199 \\ 0.0205 \\ 0.0139 \\ 0.007 \\ 0.0062 \\ 0.0083 \\ 0.0081 \end{pmatrix}$$

Beam transport choices

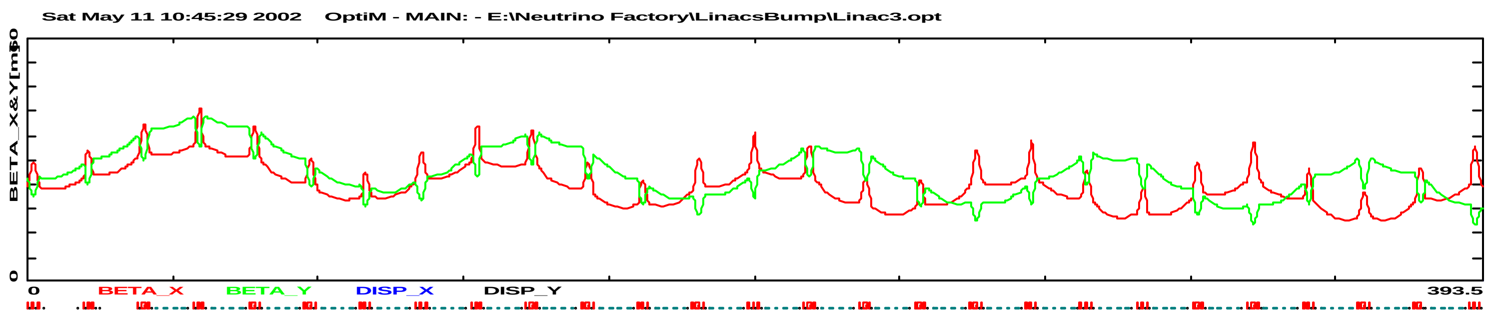
- Principle of uniform focusing periodicity (90°) – cancellation of chromatic effects
- Single dipole (horizontal) separation of multi-pass beams in RLA
  - No need to maintain achromatic Spreaders/Recombiners
  - Compact Spreaders/Recombiners – minimized emittance dilution
- SC dipoles and quads (triplets) in RLA (2 Tesla dipoles/1 Tesla quads)
- Requirement of high periodicity and 'smooth' transition between different kinds of optics, linac-spreader-arc-recombiner-linac

❖Optimized linac optics for multi pass beams – smooth transition Arc-linac

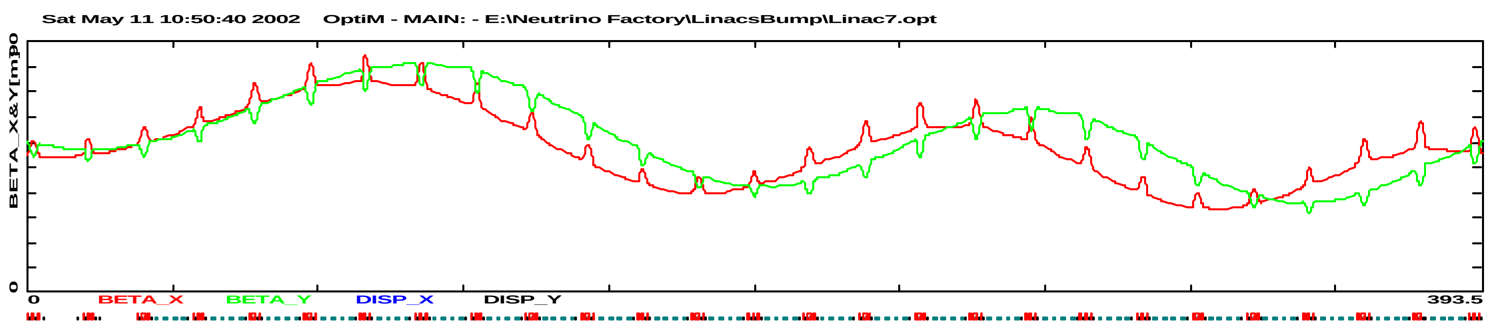
Pass 1



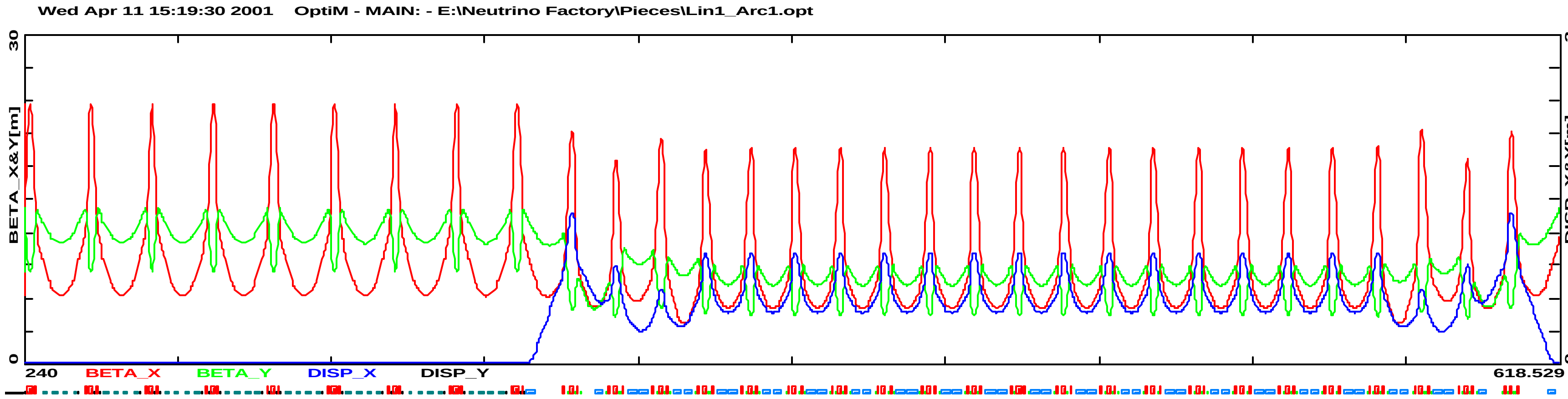
Pass 2

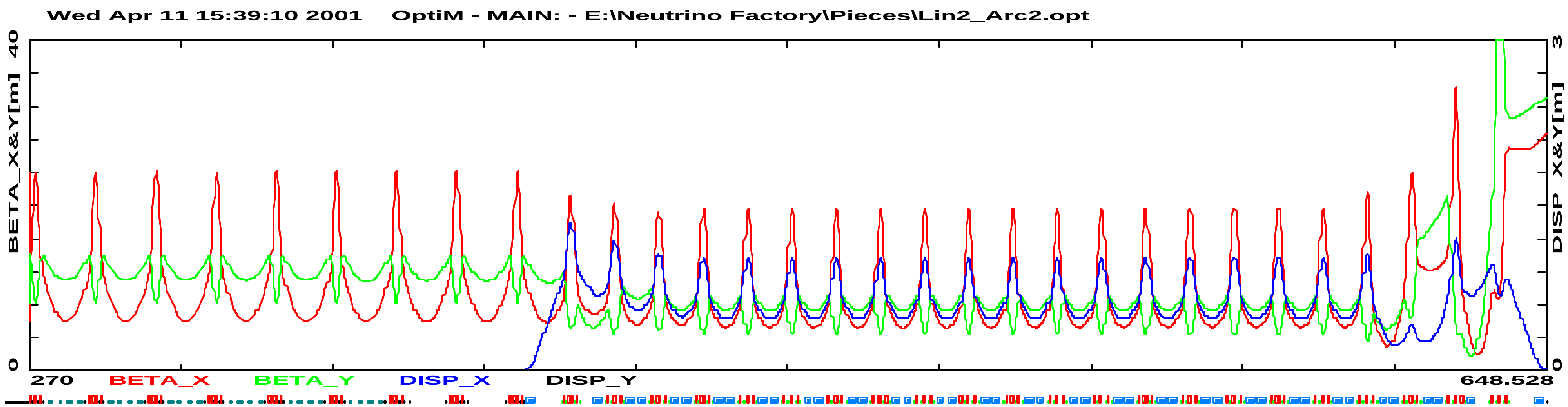


Pass 4

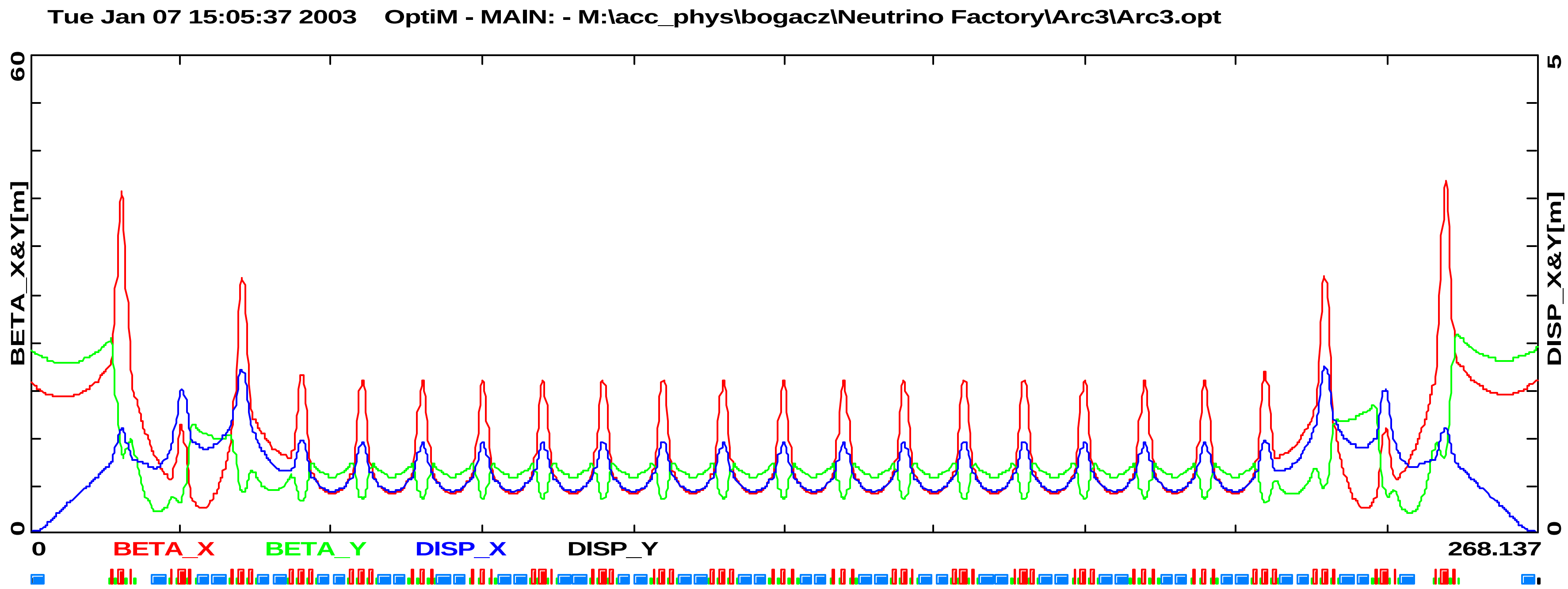


❖Arc 1 and 2 optics – smooth transition in Spreaders/Recombiners

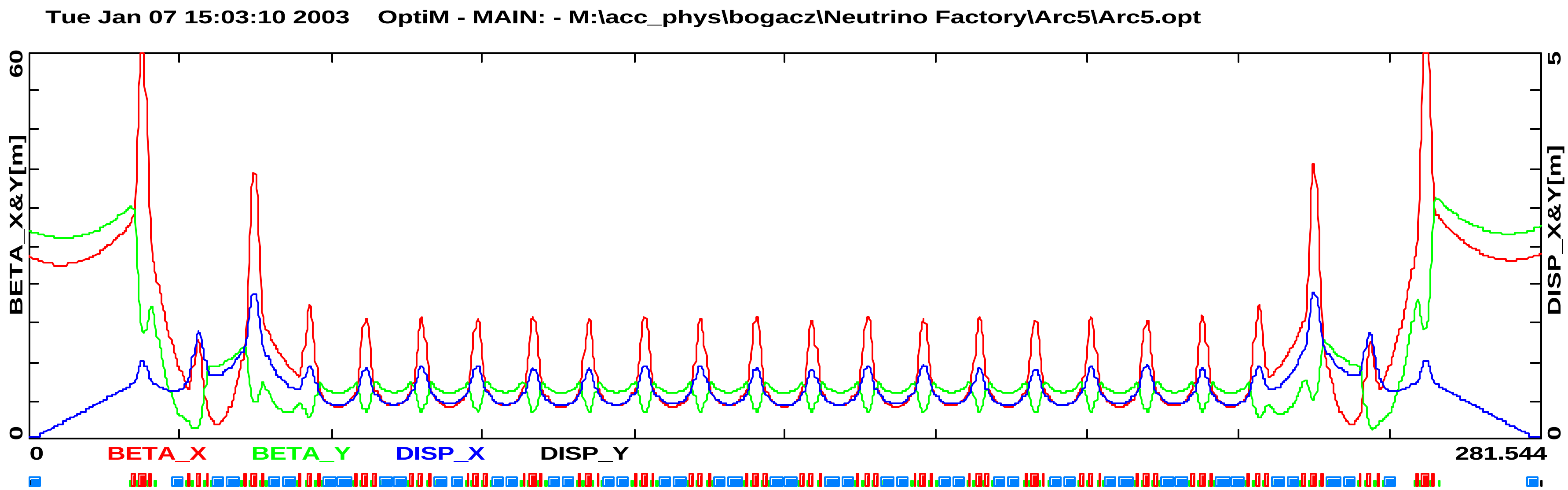




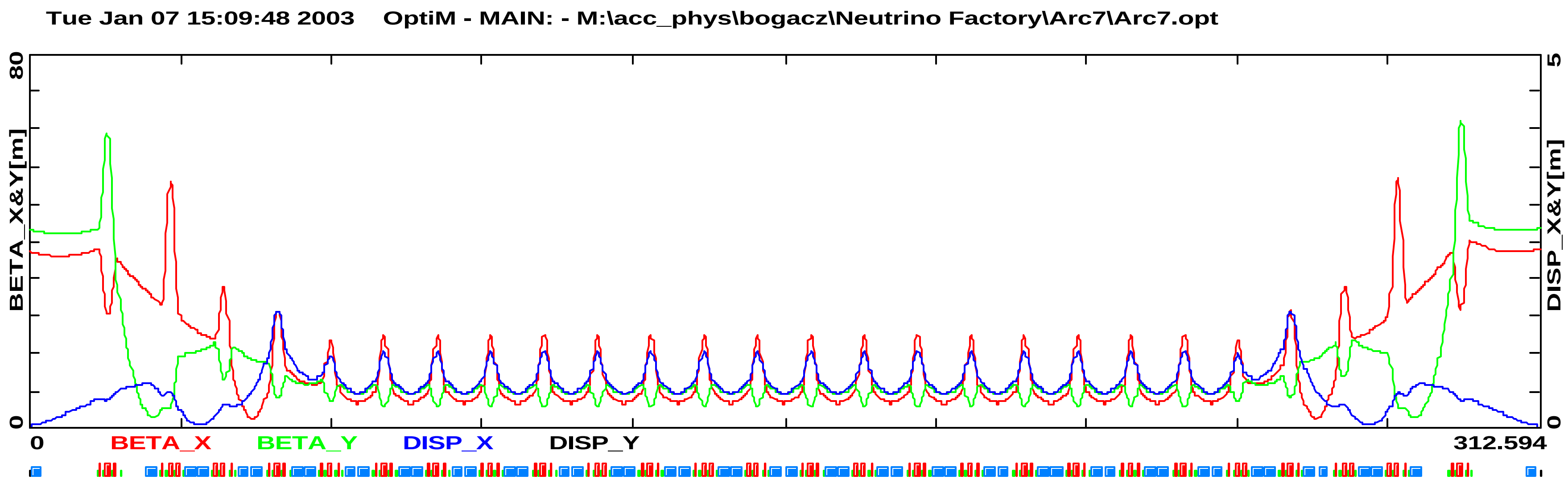
❖Arc 3 Optics - beta-functions and the horizontal dispersion matched to both adjacent linacs.



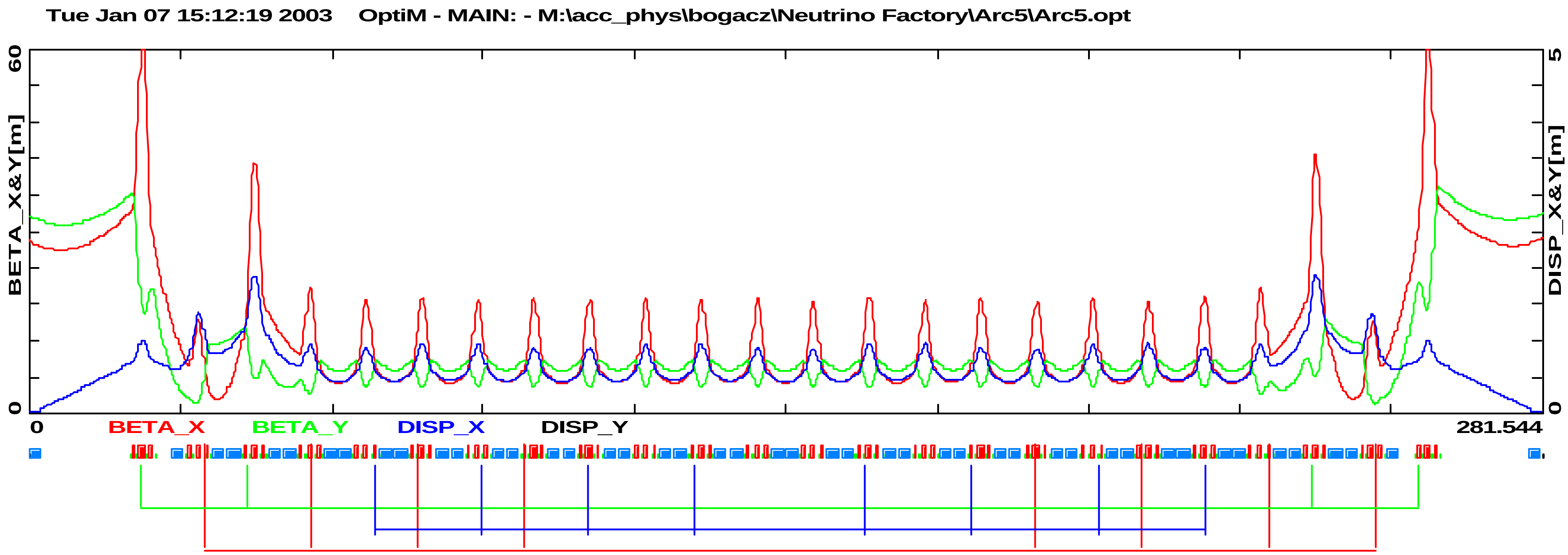
❖ Arc 5 Optics - beta-functions and the horizontal dispersion matched to both adjacent linacs, larger difference of Twiss functions.



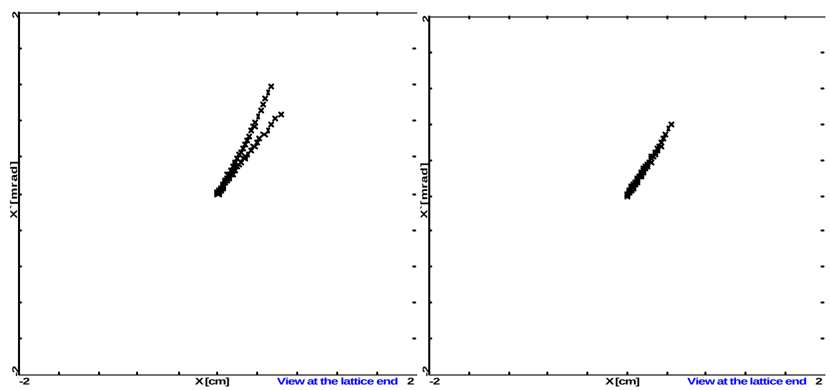
❖Arc 7 Optics - beta-functions and the horizontal dispersion matched to both adjacent linacs, much larger Twiss functions difference (compared to Arc 1, 3 and 5)



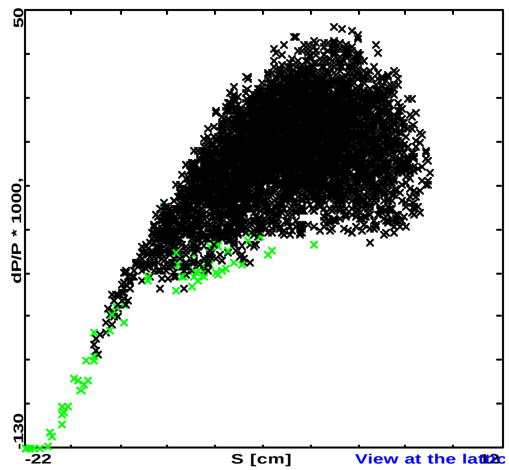
❖Chromatic Corrections Scheme in the Arcs – Arc 5 example

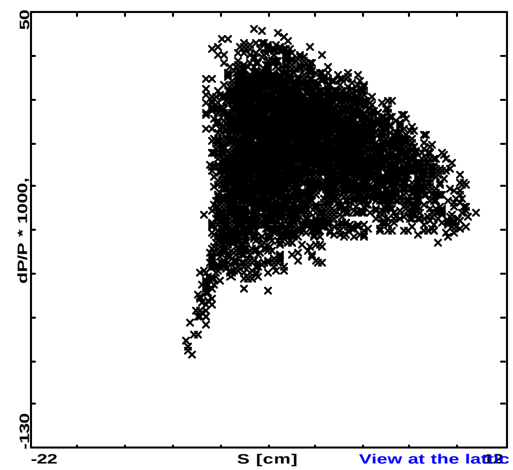


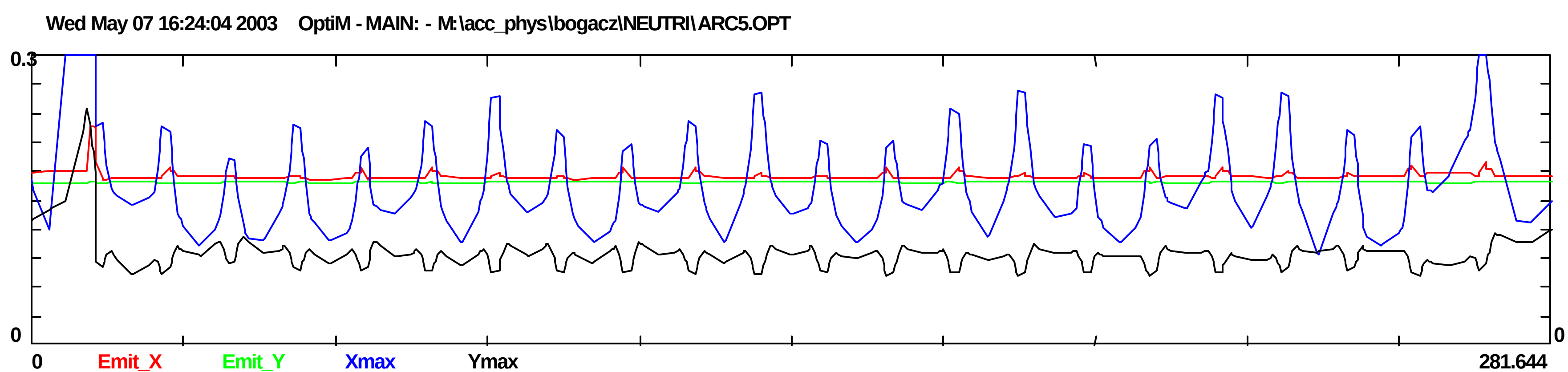
- Three families of sextupoles (**R**, **B** and **G**); each family configured as follows:
  - 4 focusing quads have build-in sextupole component, SdL=0.15 kG/cm
    - it corresponds to S=1 G/cm^2 or ≈5% correction for G at r = 20 cm
  - Quads are shifted by π/2 in betatron phase and their effects are canceled in linear approximation
    - 4 quads are better than 2 shifted by π (case of complete cancellation for small energy spread)
  - The sextupole gradient is chosen to minimize the total emittance growth
  - Particle displacement for uncompensated and compensated chromaticity



- Arc 5 emittance preservation via chromatic corrections – particle tracking shows no emittance dilution with 0.8% particles loss (‘clipping’ of large amplitude tails)







Summary

- Lower initial emittance of a Ring Cooler
  - Shorter linear Pre-accelerator, momentum compression down to $\Delta p/p=\pm 0.02$
  - Further longitudinal compression in the RLA, small M_{56}=0.9m ($\Delta p/p=\pm 0.008$)
- Lattice improvements to RLA scheme – better optimized linear optics
  - Special optics for multi-pass linacs – equalized input/output Twiss functions
  - 'Smooth' transition of optics between linacs and Arcs – compact Spr/Rec
- Emittance preservation scheme – nonlinear corrections in the Arcs
  - Chromatic corrections in the Arcs to effectively restore longitudinal space linearity (via three families of sextupoles)
  - Multi-particle tracking studies (Arc-by-Arc) show no emittance dilution for all Arcs, with small level (~ 1%) of particle loss.