Beam Dynamics Issues of Muon Acceleration

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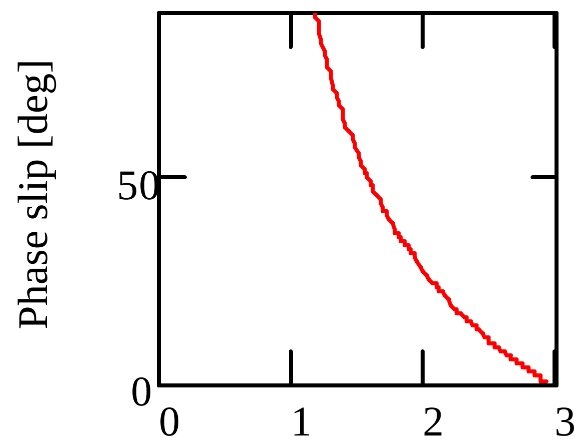
- Choice of acceleration scheme and technology – Recirculating Linear Accelerator (RLA) based on 200MHz superconducting RF
- Machine layout & parameters (Study II – 20GeV scenario)
- Beam transport in large acceptance RLA – challenges & design choices
- 'Odd Arcs' – proof-of-principle lattices
- Chromatic corrections with sextupoles– particle tracking

Choice of acceleration scheme

- Muon survival excludes use of conventional circular accelerators – it demands a high-gradient (~16 MV/m average gradient) linac or RLA, FFAG?

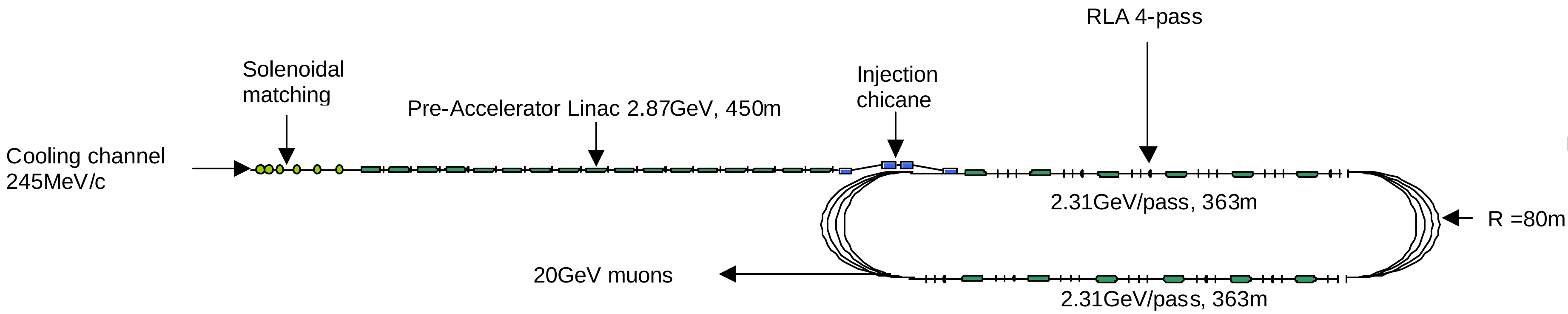
- Recirculator (RLA)
  - less expensive than linac
  - can not be used right after cooling at 210 MeV/c:
    - initial beam is not sufficiently relativistic – phase slip for higher passes
    - energy ratio (final/initial) should not be too large (<10)
  - high injection energy (2480 MeV)
  - number of passes should be limited to about 4 (for large $\Delta p/p$ and emittance)



Choice of acceleration technology

- Large transverse and longitudinal acceptances drive the design to low RF frequency (e.g. 201.25 MHz already used at the ionization cooling channel)
  - Normal-conducting RF – not feasible at high gradients
    - unachievably high peak power of the RF sources.
  - Super-conducting RF – much more attractive solution.
    - RF power delivered to the cavities over an extended time – RF source peak power reduced.
    - Cavity design not limited by a requirement of low shunt impedance – significantly larger apertures.

20GeV Muon Accelerator Complex – Study II



245MeV/c - 20GeV Muon acceleration

- Conceptual design for the entire accelerator complex:
  - SC cavities and solenoids – cryo-module layout and shielding
  - Layout and lattice design for: solenoidal matching section, linear pre-accelerator, injection chicane, linacs, spreaders/recombiners and all 7 arcs
- Requirement of high periodicity and 'smooth' transition between different kinds of optics, Linac-Spreader-Arc-Recombiner-Linac
  - Principle of uniform focusing periodicity (90^0) – cancellation of chromatic effects
- Solenoidal matching section after the cooling channel (beta~25cm to ~5m)
- Off-crest bunch compression in Linear Pre-accelerator
- Chromatic correction of the longitudinal non-linearities – Emittance budget

Machine parameters

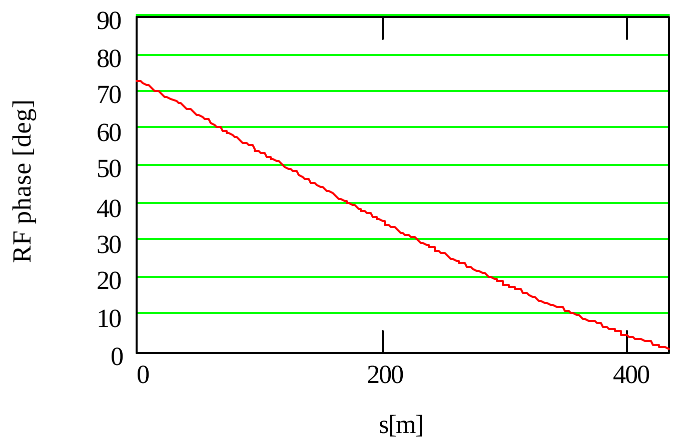
Injection momentum/Kinetic energy	MeV	245/161
Final energy	GeV	20
Initial normalized acceptance rms normalized emittance	mm·rad mm·rad	15 2.4
Initial longitudinal acceptance, $\Delta p L_b/m_\mu$ momentum spread, $\Delta p/p$ bunch length, L_b rms energy spread rms bunch length	mm mm mm	170 ±0.21 ±407 0.084 163
Number of bunches per pulse		67
Number of particles per per pulse		$3 \cdot 10^{12}$
Bunch/accelerating frequency	MHz	201.25/201.25
Average repetition rate	Hz	15
Time structure of muon beam		6 pulses at 50 Hz with 2.5 Hz repetition rate
Average beam power	kW	150

Beam transport choices

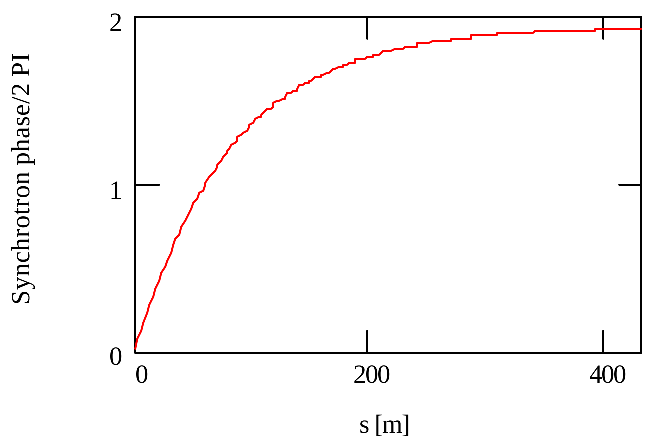
- Solenoidal focusing (SC) in the Linear Pre-accelerator
  - saves space
  - allows one to accommodate very large beam emittance
- SC quads (triplets) and dipoles in RLA (lower power consumption)
- Single dipole (horizontal) separation of multi-pass beams in RLA
  - No need to maintain achromatic Spreaders/Recombiners
  - Compact Spreaders/Recombiners – minimized emittance dilution

Linear Pre-accelarator – Longitudinal dynamics

- Introduction of synchrotron motion in the initial part of the linac (initial: $\Delta p/p=\pm 21\%$ or $\Delta f=\pm 89$)
  - allows to perform adiabatic bunching/compression of the beam
    - prevents head-to-tail 'sag' in acceleration (final: $\Delta p/p=\pm 7.5\%$ or $\Delta f=\pm 23$)
  - reduces effective accelerating qradient (total voltage of 2.8 GV instead 2.2 GV)

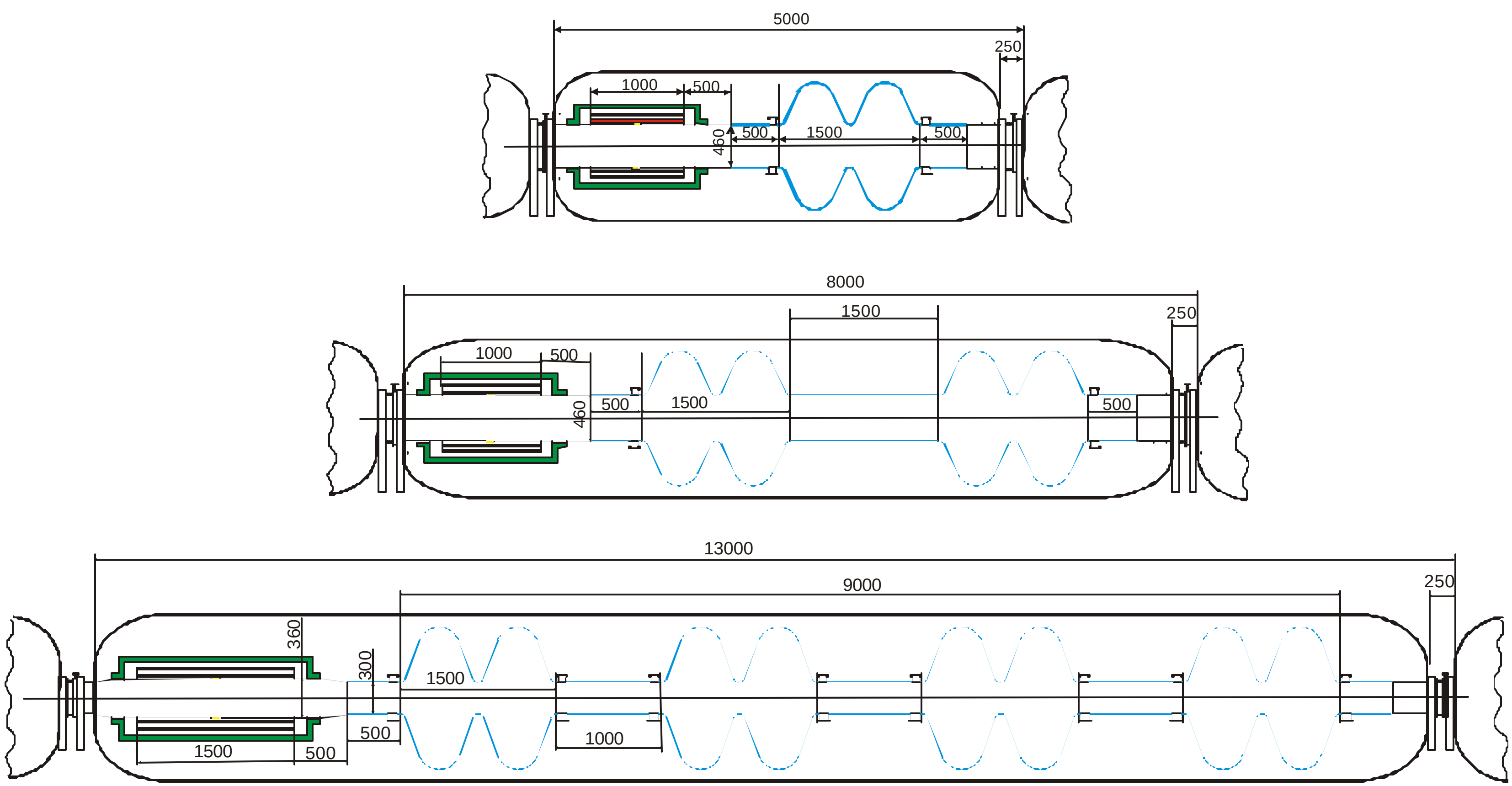


Accelerating phase along linac



Synchrotron phase along the linac

❖Three flavors of lattice cells and cryo-modules – short, medium and long



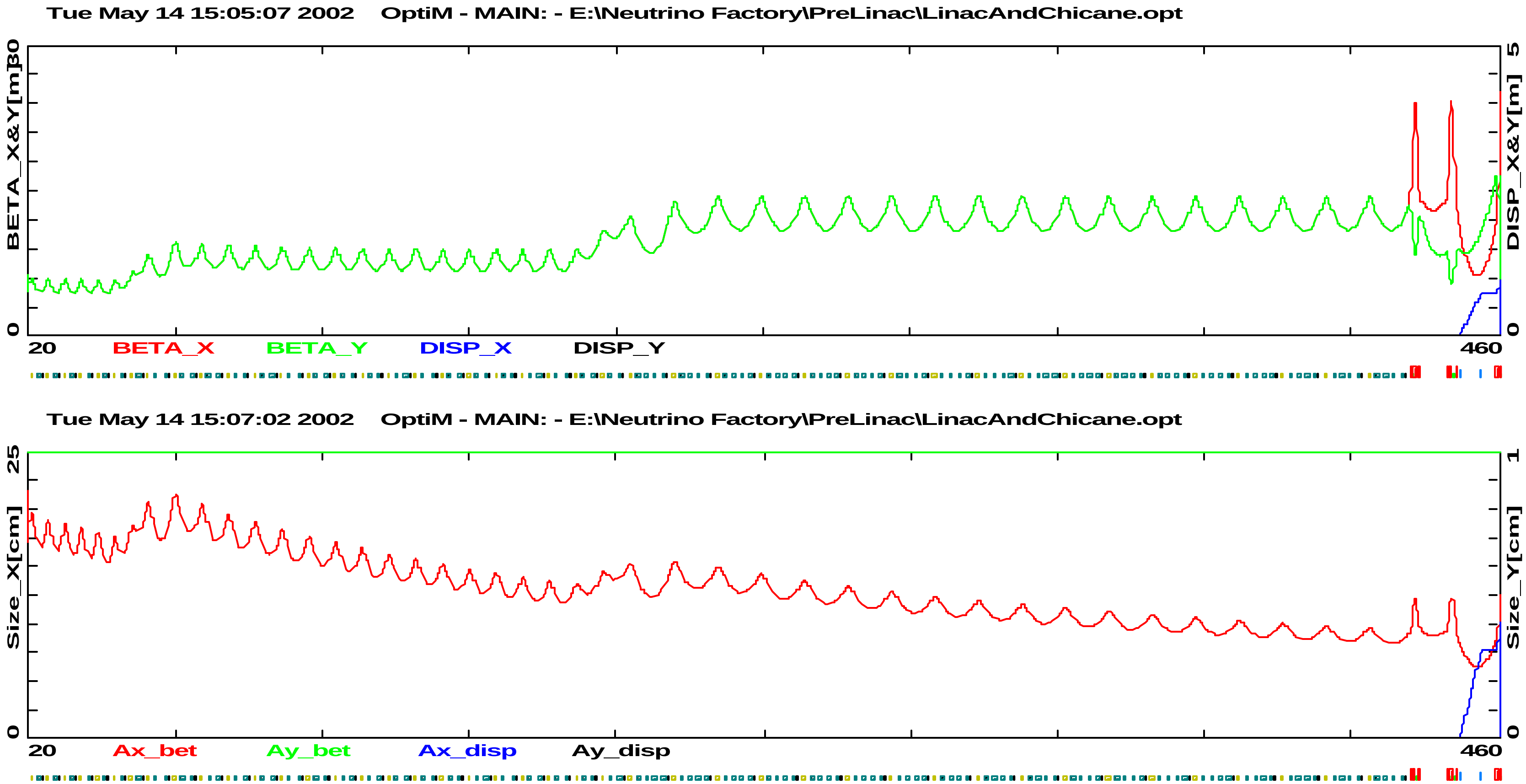
Blue – SC walls of cavities. Red – solenoid coils. Green – magnetic shielding.

❖Parameters of the long, intermediate and short periods of Linear Pre-accelerator

	Short cryo-module	Intermediate-length cryo-module	Long cryo-module
Number of periods	11	16	19
Total length of one period	5 m	8 m	13 m
Number of cavities per period	1	2	4
Number of cells per cavity	2	2	2
Number of couplers per cavity	2	2	2
Cavity accelerating gradient	15 MV/m	15 MV/m	17 MV/m
Real-estate gradient	4.47 MV/m	5.59 MV/m	7.79 MV/m
Aperture in cavities (2*a*)	460 mm	460 mm	300 mm
Aperture in solenoids (2*a*)	460 mm	460 mm	360 mm
Solenoid length	1 m	1 m	1.5 m
Solenoid maximum field	2.1 T	2.1 T	4.2 T

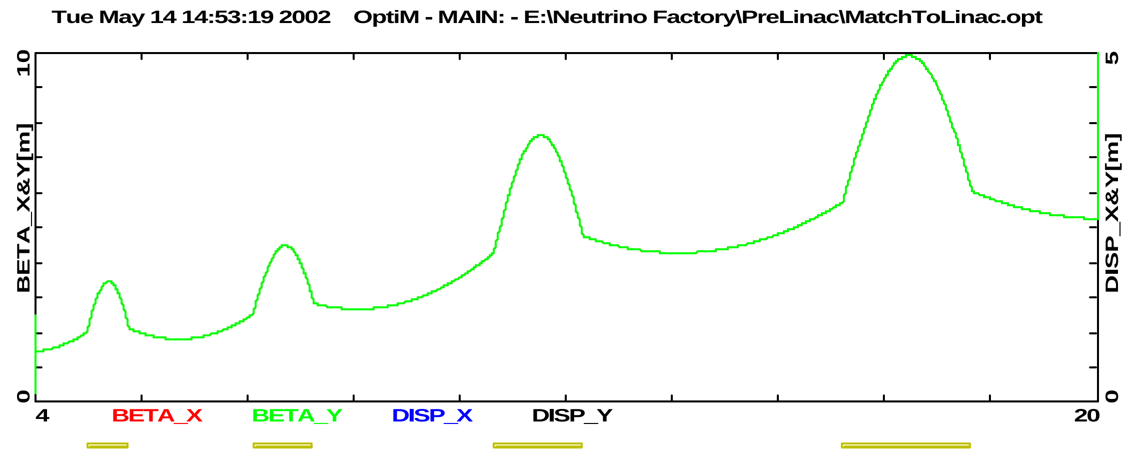
- The layout of cryo-modules is driven by limiting power of the fundamental coupler at acceptable level (below 1 MW – requires 1 coupler per cell) and by maintaining sufficient decoupling of the cavities.

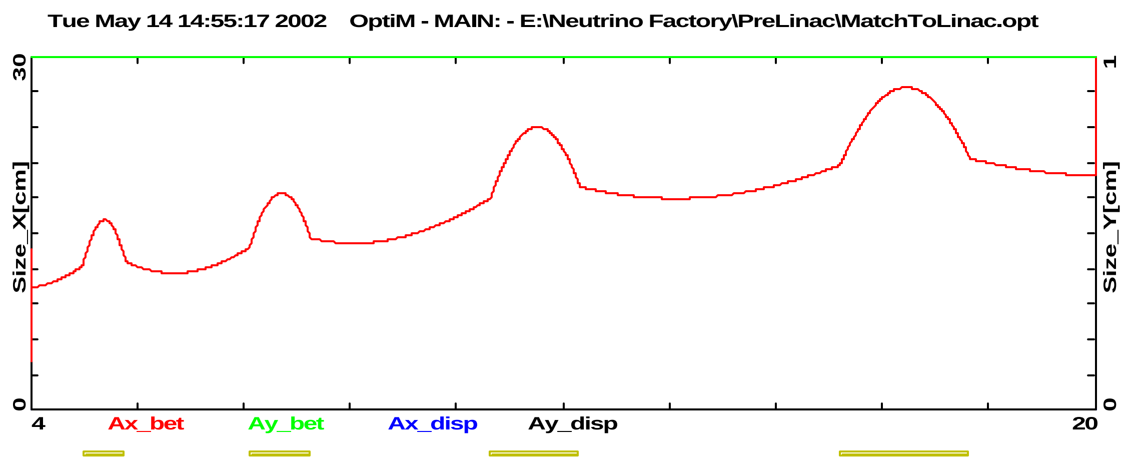
Linear Pre-accelerator – Lattice layout, Beam envelope



Beta-functions & beam envelopes (2.5σ) (161MeV to 2392MeV)

Solenoidal matching section – Lattice layout, Beam envelope





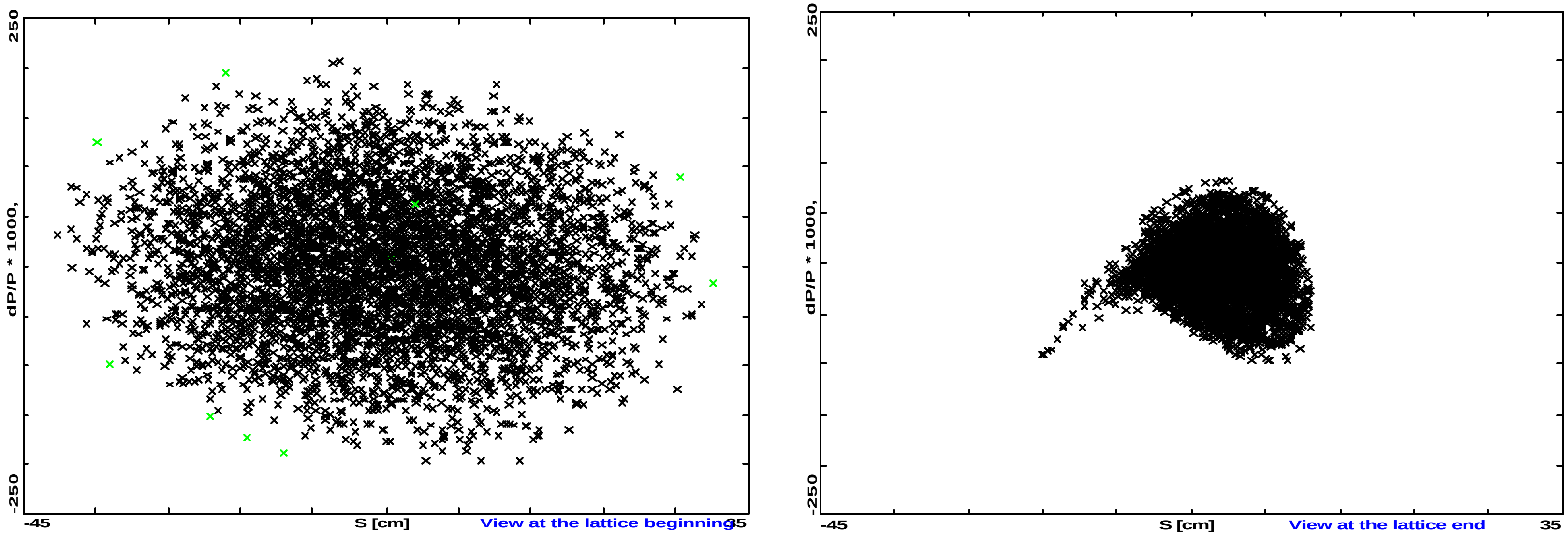
L/A[cm]	B[kG]
64.0973	35.8649
92.9411	24.7344
134.765	17.0582
195.409	11.7643

Beta-functions & beam envelopes (2.5σ) at 161MeV

❖ Main parameters of Linear Pre-accelerator

Injection momentum / Kinetic energy	245/ 161 MeV
Final momentum / Kinetic energy	2583 / 2480 MeV
Total linac length	433 m
Acceptance: initial / final (no emittance dilution)	7.5 / 0.62 mm·rad
Momentum spread: initial / final	$\pm$0.21 / $\pm$0.075
Total bunch length: initial / final	814 / 190 mm; 197 / 46 deg
Total installed accelerating voltage	2.87 GeV

- Longitudinal phase space at the beginning and at the end of Linear Pre-accelerator

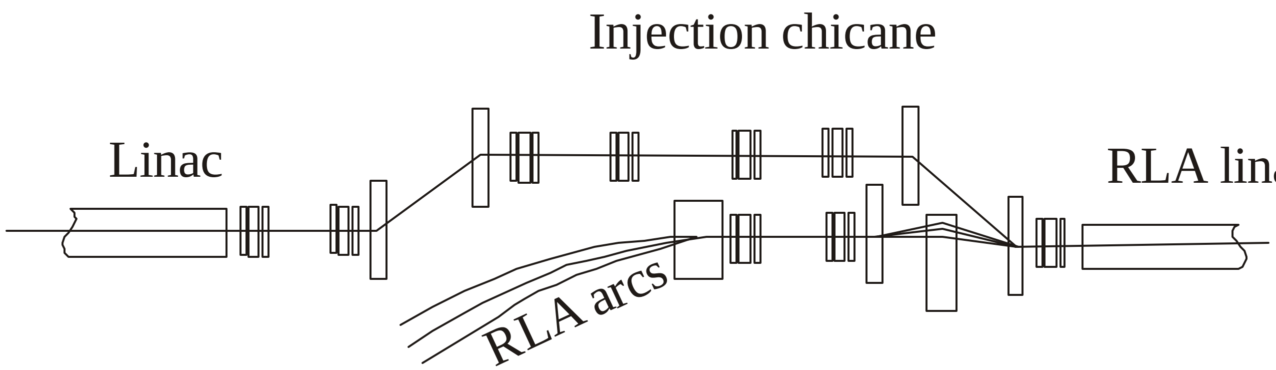


Lost particles (0.2%) are marked green

Main parameters for the RLA

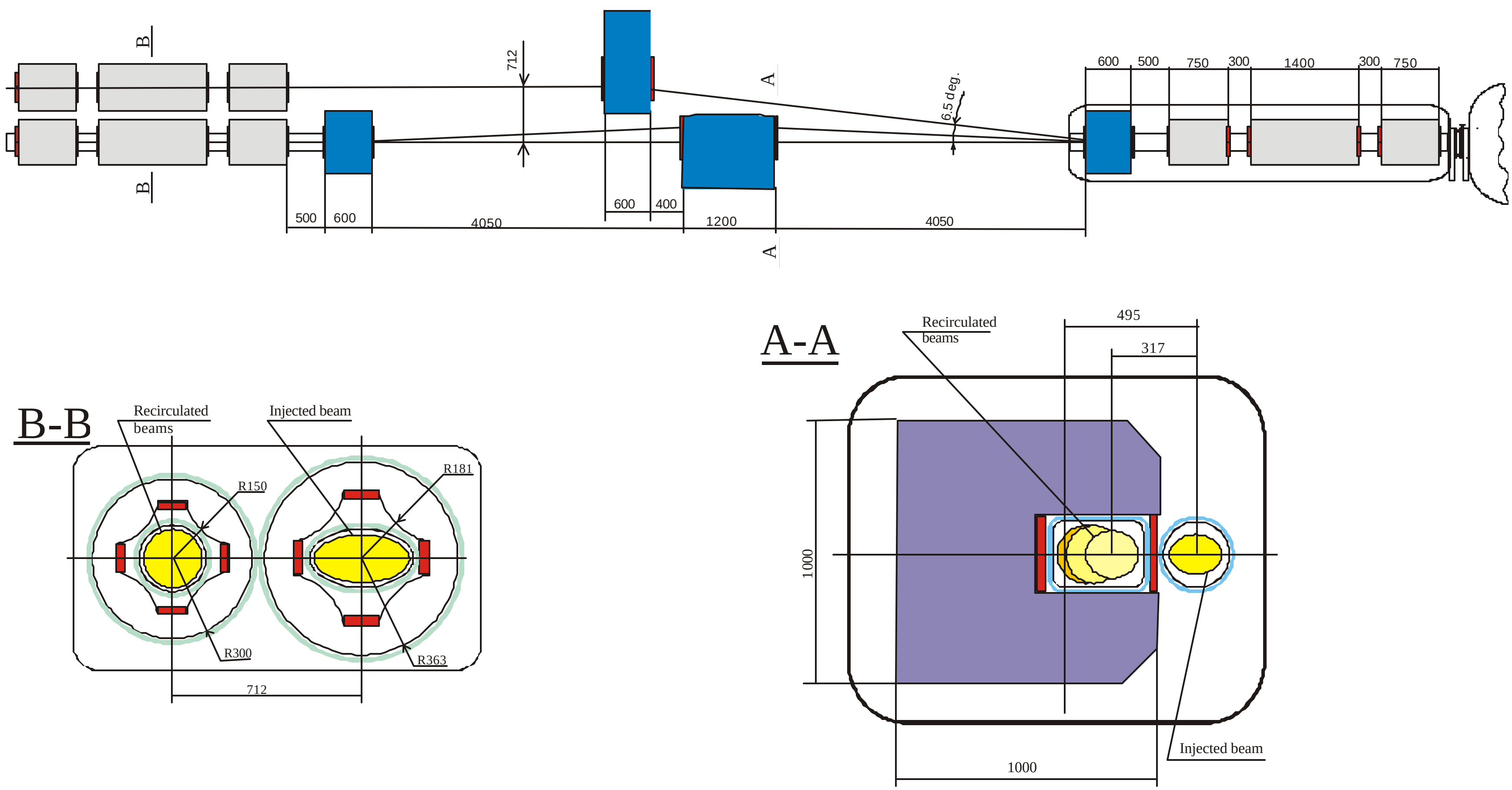
Initial energy	2.3918 GeV
Final energy	20 GeV
Number of passes	4
Total initial energy acceptance	±9.2%
Total final energy acceptance	±1.9%
Initial transverse acceptance	635 mm·mrad
Final transverse acceptance, e_x / e_y	157/108 mm·mrad
Total voltage per linac	2.3347 GV
Circumference	≈1300 m

Injection to RLA

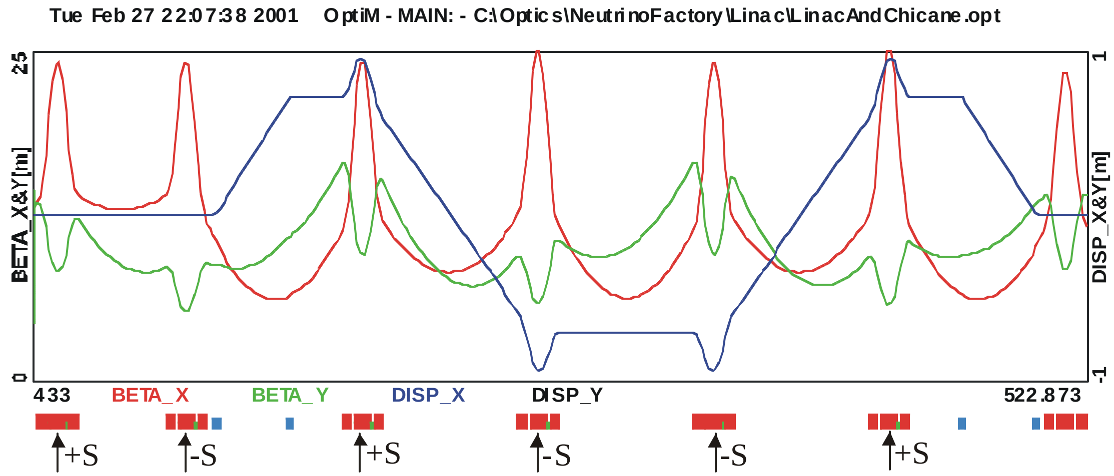


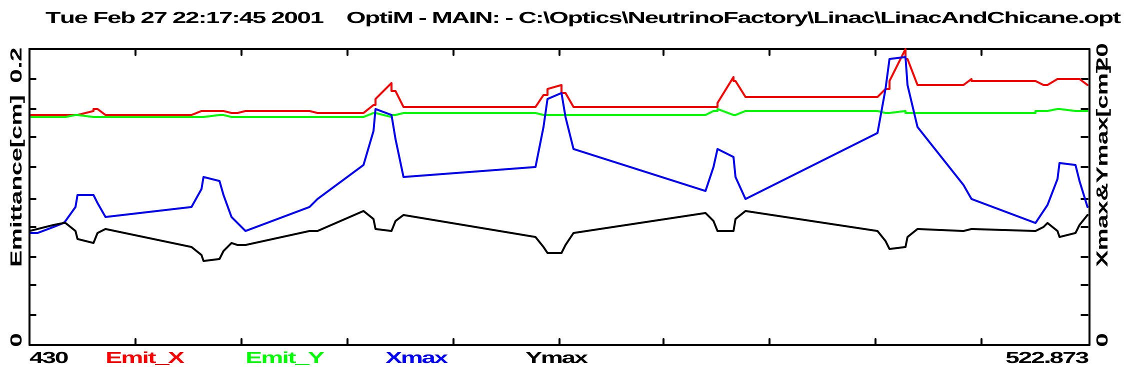
- Four-dipole chicane – sufficiently long to bypass incoming higher energy arcs.
- Triplet focusing replaces solenoidal focusing (linac pre-accelerator) – long straight sections necessary for beam separation at injection.
- Triplet focusing matches the solenoidal focusing period and the period of the downstream RLA linac (betatron phase advance per cell is chosen to be 90 deg – preferable for chromatic effects compensation)

❖The last period of injection chicane – separation point



❖Injection chicane – chromaticity correction scheme





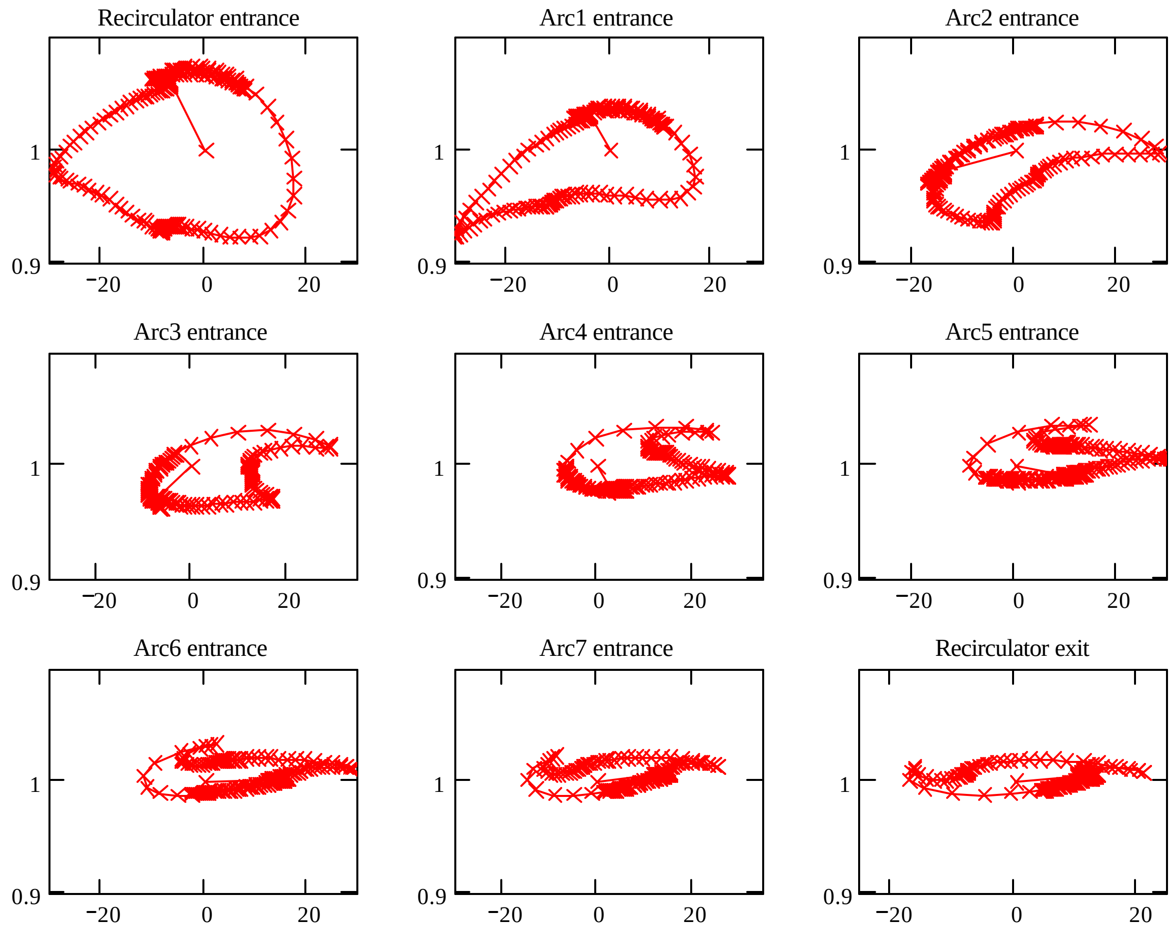
Optimum ratio of sextupole and quadrupole components: S/G = 0.00355 cm^{-1}, (corresponds to 7% correction of quadrupole gradient at radius of 20 cm)

❖Acceleration parameters for RLA, M_{56} = 1.4 m

	Kinetic energy [GeV]	Gang phase [deg]	Total energy spread, $2\Delta p/p$ [%]	Horizontal acceptance, [mm mrad]	Vertical acceptance, [mm mrad]
Entrance	2.480	-5	15.0	669	638
Arc 1	4.756	-23	11.3	384	350
Arc 2	6.884	-23	8.9	292	253
Arc 3	9.017	-23	6.7	244	202
Arc 4	11.150	-23	5.8	216	171
Arc 5	13.284	-20	5.0	198	150
Arc 6	15.462	-16	4.4	187	134
Arc 7	17.690	-5	3.4	178	122
Exit	20.000		3.2	157	108

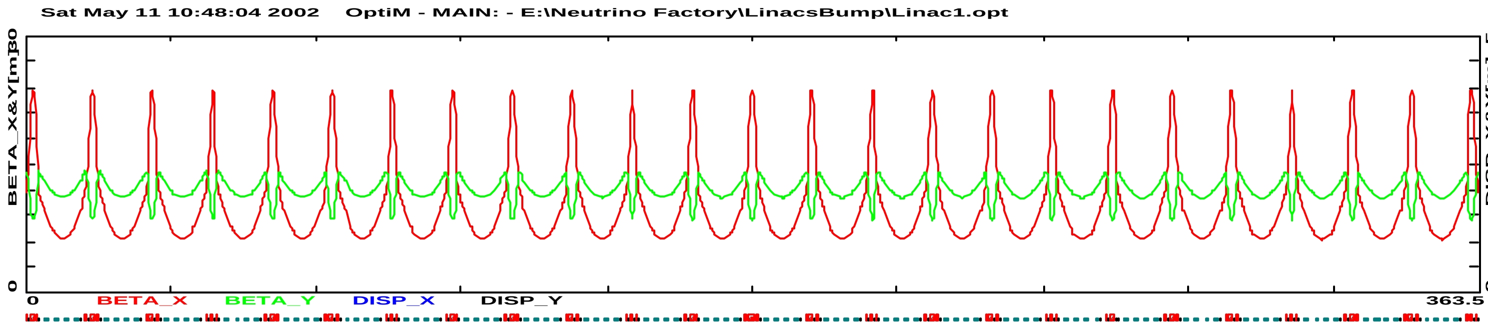
Total voltage per linac = 2.3347 GV at 200 MHz
horizontal/vertical emittance dilution 9%/4% per arc

❖Longitudinal dynamics in the RLA

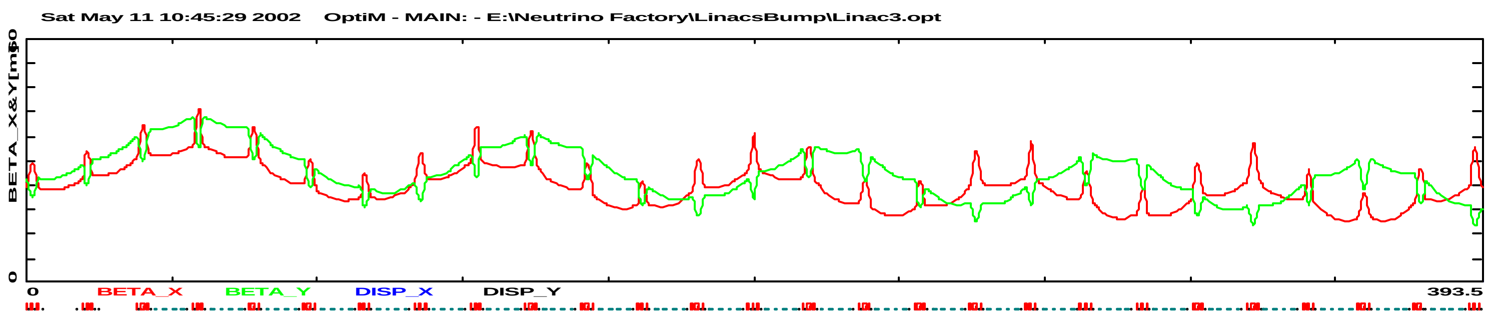


Longitudinal phase space in the recirculator

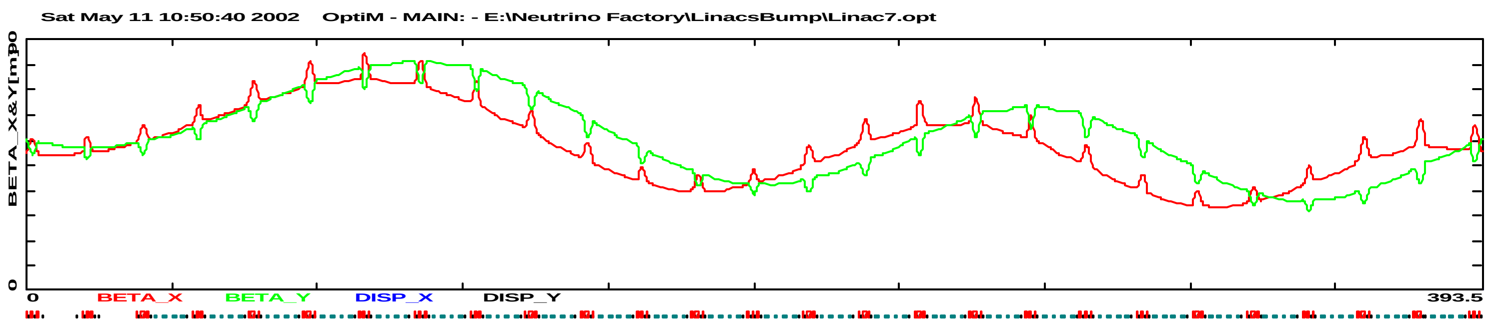
❖Layout of lattice period of the first recirculator linac - multi pass beams



Pass 1



Pass 2



Pass 4

Beam transport issues in RLA

- Maintaining short matching regions in Spreaders/Recombiners, compact arcs

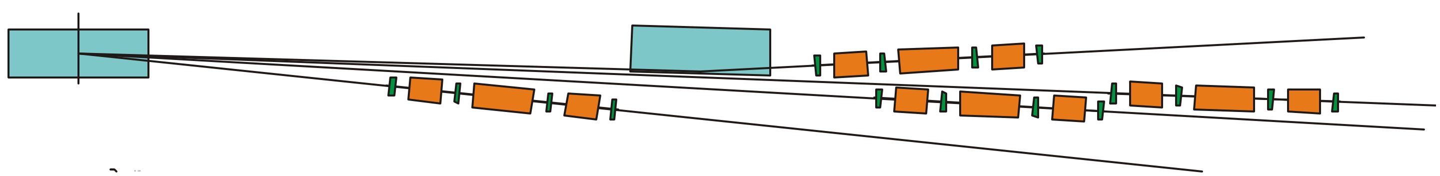
- Maintaining manageable beam sizes
  - need for short cells or periods
  - vertical size small (due to uniform focusing and small betas)
  - limits on dispersion and beta functions (beam envelopes)

- Longitudinal Acceptance
  - need for momentum compaction management, M_{56} = 1.4 m
  - accounting for nonlinear effects (Spreaders/Recombiners)

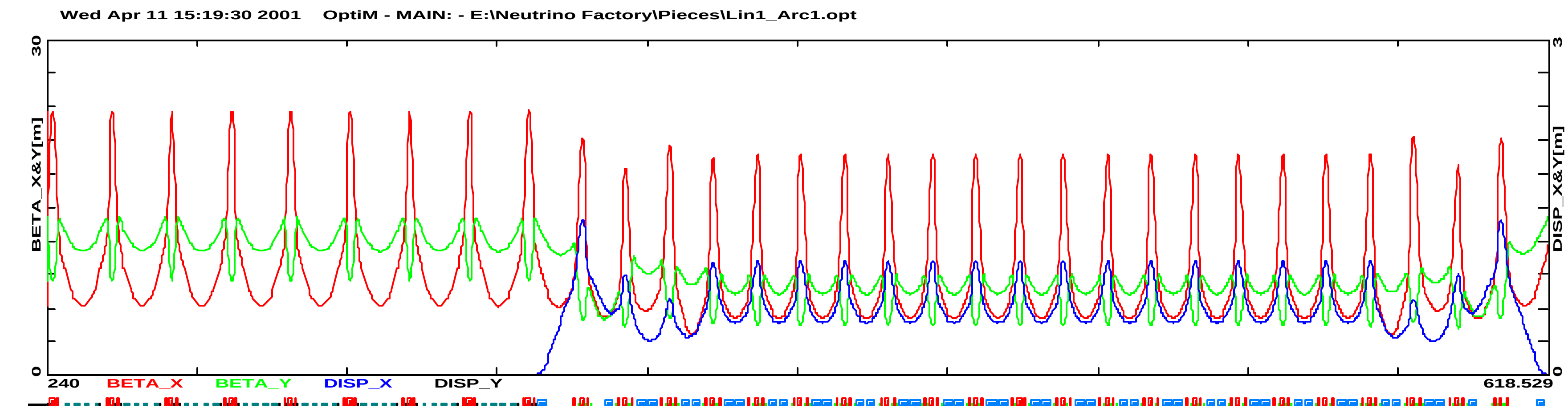
Design choices – Arc optics

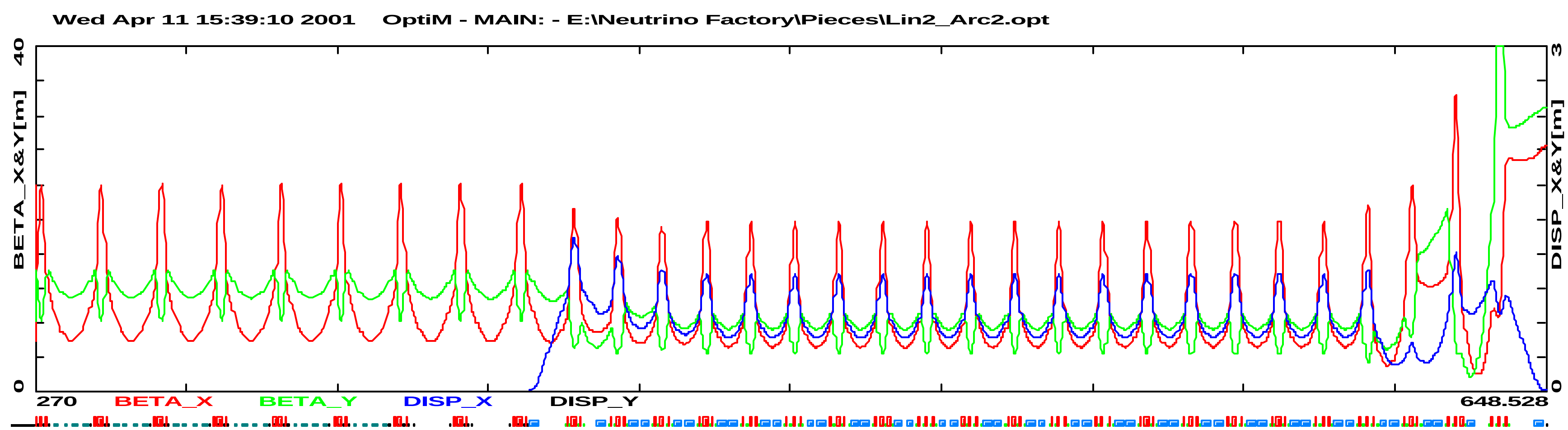
❖Spreader-Recombiner configuration

- single dipole, horizontal separation without dispersion suppression (vertical separation not feasible)
- compact structures for Spreaders/Recombiners
- need for sextupole corrections in S/R



Beam separation scheme for 'Odd Arc' Spreaders

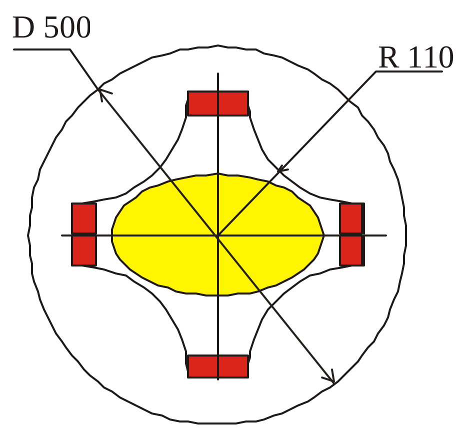




Arc1 & 2 Optics - beta-functions and the horizontal dispersion matched to both adjacent linacs

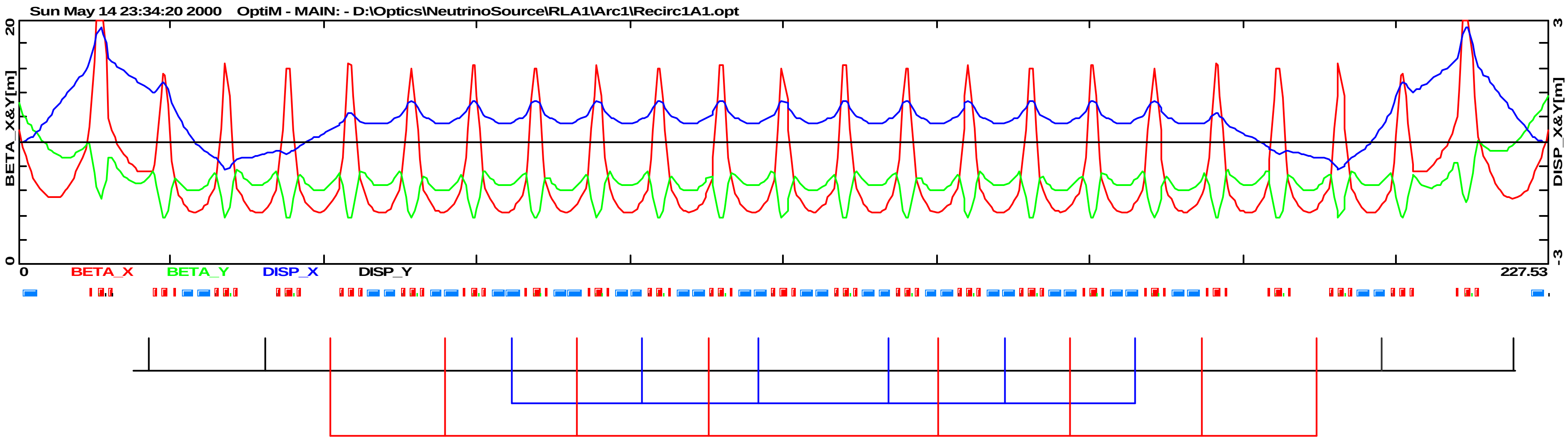
Arc Proper - Optics architecture

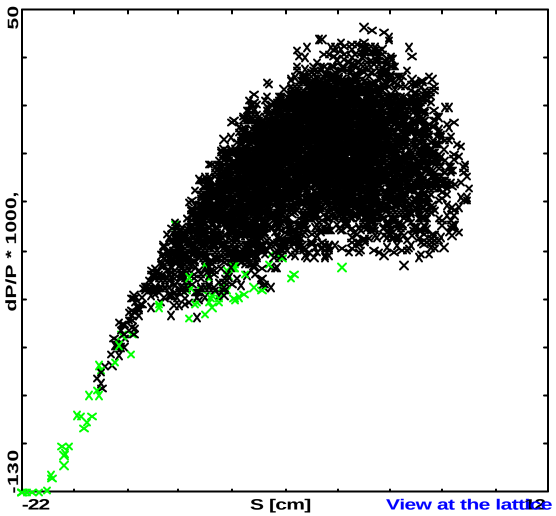
- rotationally phased 90^0 (horizontal and vertical) high periodicity triplet cells
- need for sextupole corrections in Arcs
- 2 Tesla dipoles for the highest energy arc
- 1 Tesla quadrupole field at the aperture

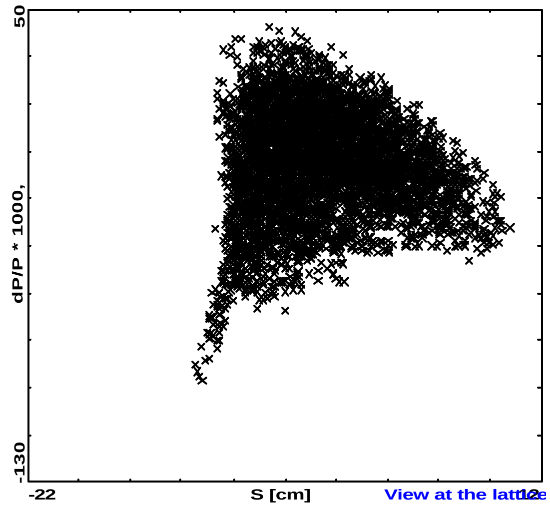


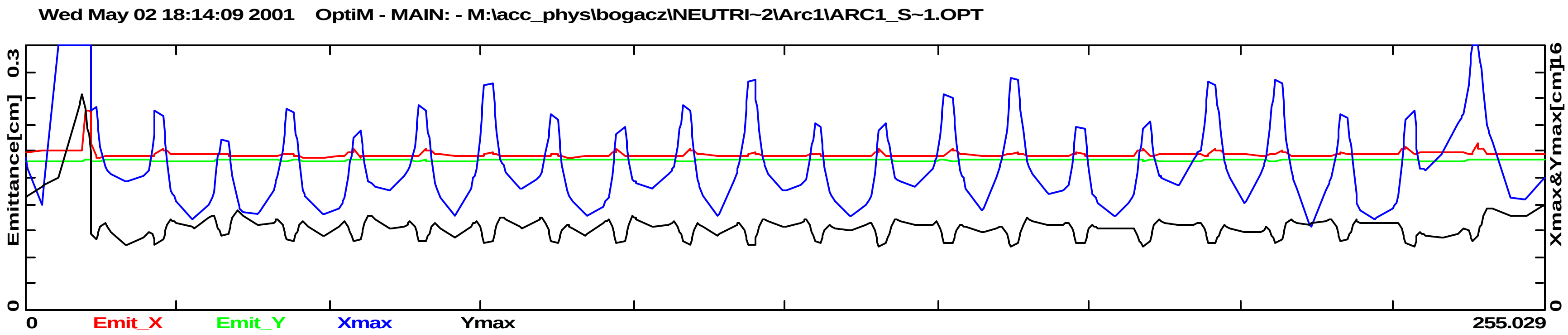
Typical large aperture Spr/Rec quadrupole

❖Arc 1 optics - Scheme of sextupole correction (3 families of sextupoles)

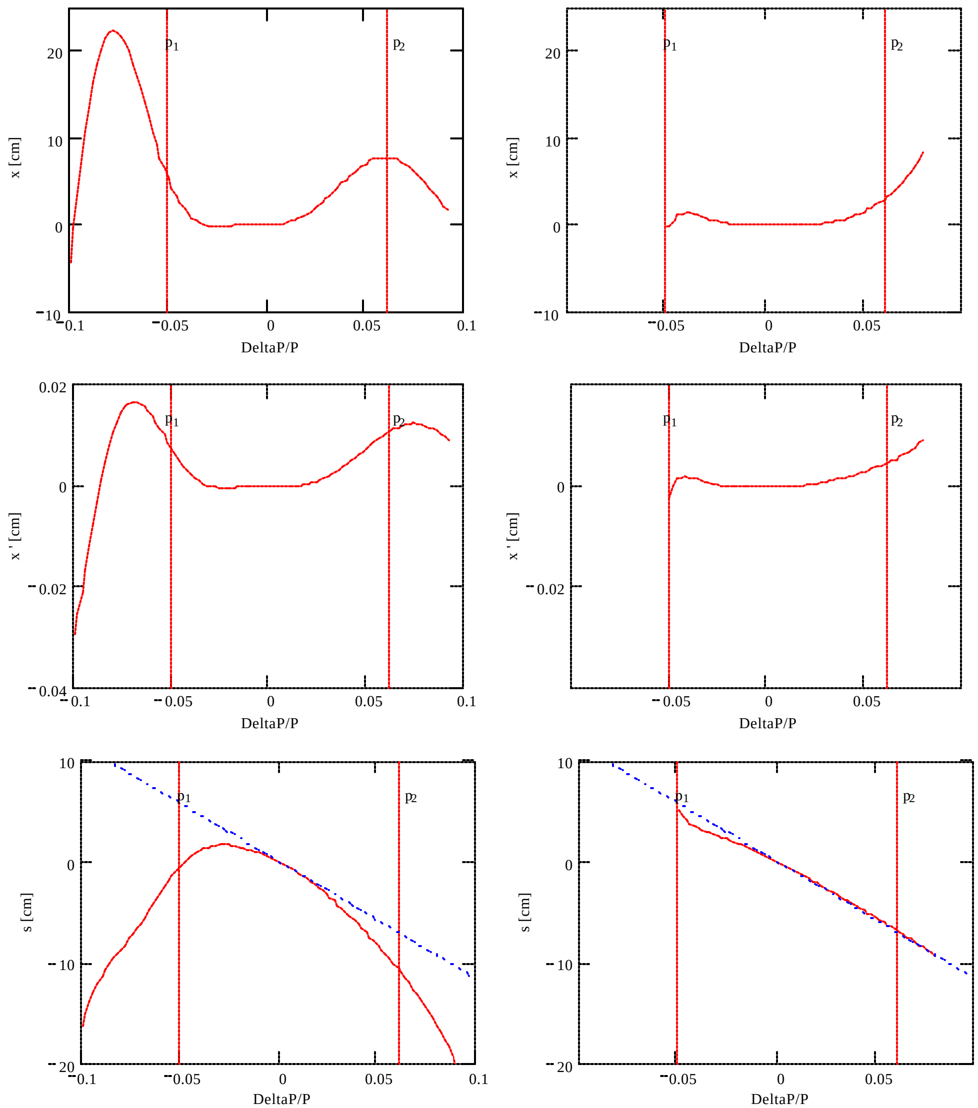








Arc 1, multi-particle tracking with sextupole corr. (integrated sext. 280 kG/cm per triplet) < 1% of particles lost on 12 cm aperture, no horizontal emittance dilution



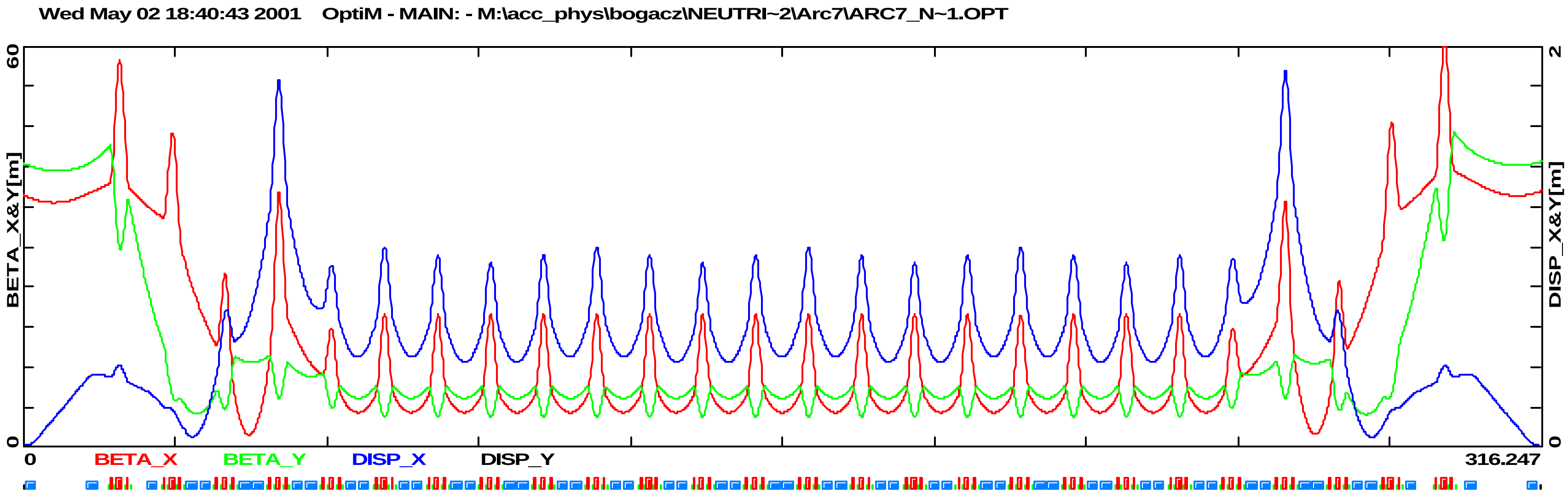
Chromaticity correction

Non-linearity for

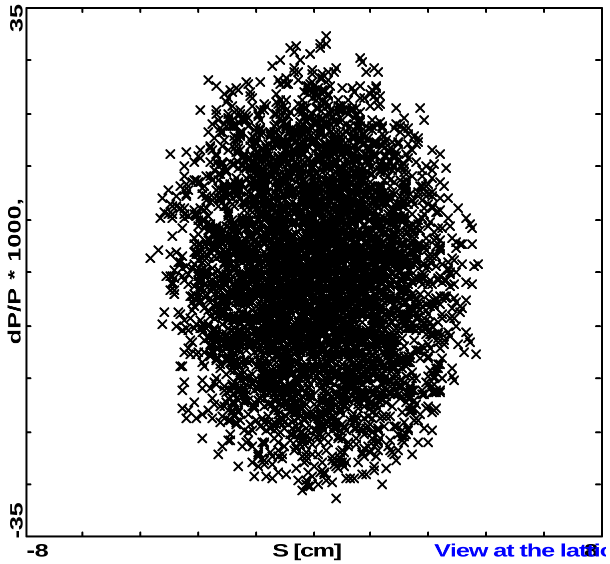
- Dispersion
- Dispersion-prime
- M_{56}

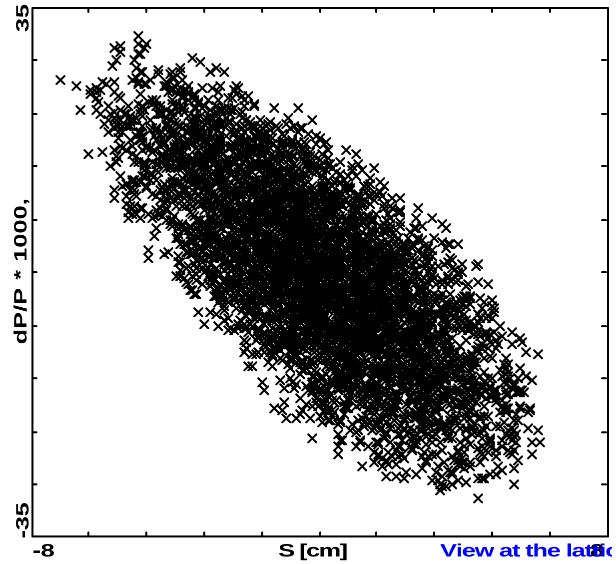
For the cases of

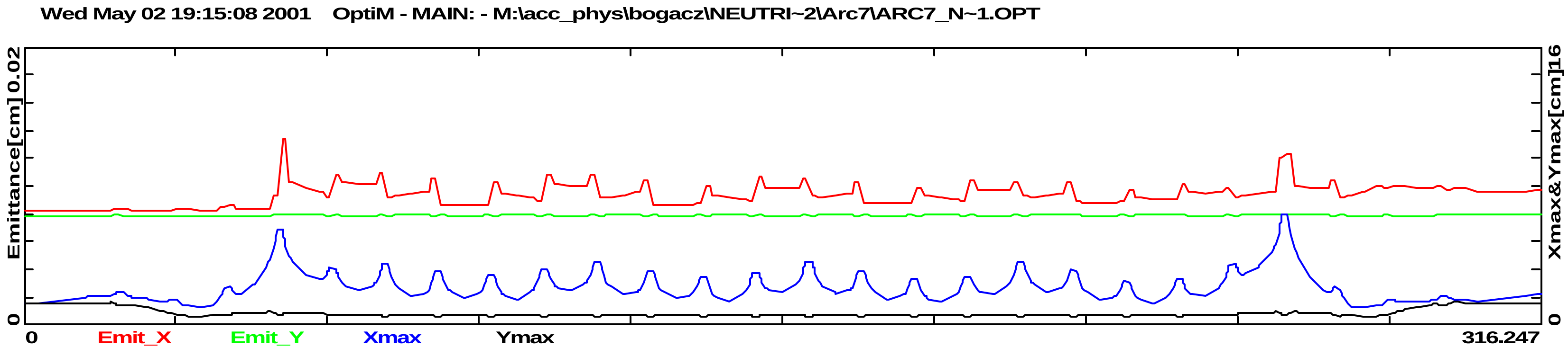
- no sextupole corrections
- 3 sextupole families



Arc 7 Optics - beta-functions and the horizontal dispersion matched to both adjacent linacs, much larger difference (compared to Arc 1) between the values of beta functions in the adjacent linacs and Arc 7; A quest to maintain 'smooth' transition of beta functions across Spreaders/Recombiners.







Arc 7 - multi-particle tracking without any sext. correction, no particles lost on 12 cm aperture

Summary

- Already done…
  - Acceleration design choices driven by beam transport issues (choice of RF technology, RF frequency, cryo-modules, separation, matching schemes)
  - Overall accelerator complex architecture (245MeV/c Matching section, 2.8 GeV Linear Pre-accelerator, Injection chicane, 2.8-to-20 GeV 4-pass RLA)
  - 'Odd Arcs' proof-of-principle lattice design including spreaders/recombiners
  - Emittance dilution control in higher arcs via families of sextupoles
- Still to come…
  - 'Even Arcs' optics – lattice design and technical specs for magnets
  - Chromatic corrections in higher arcs to effectively restore longitudinal space linearity
  - Multi-particle tracking studies throughout the entire accelerator
  - Field errors and tolerances
  - Further optimization of different style cryo-modules