Update on RLA studies

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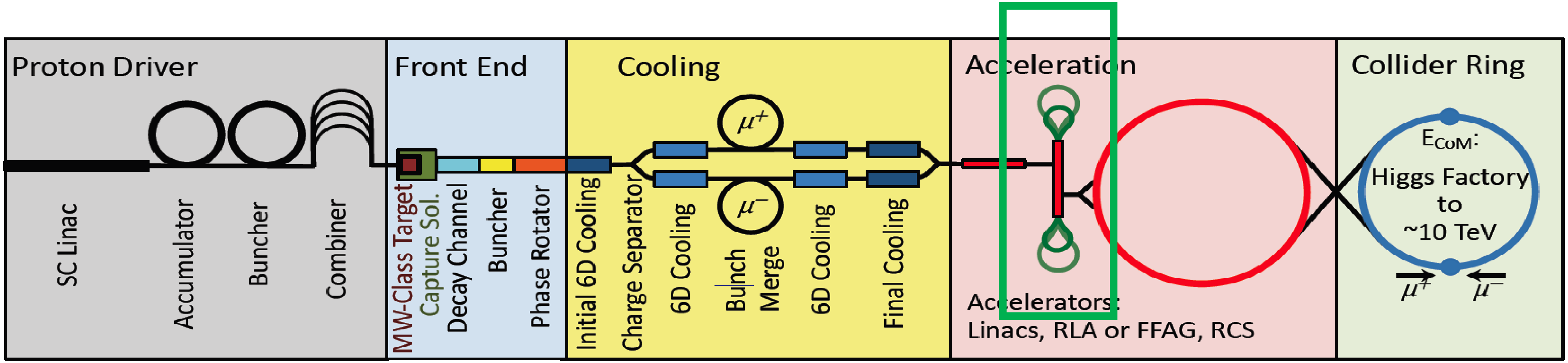
Collider Concept

Acceleration
from 5 GeV to 63 GeV



Short, intense proton bunch

Protons produce pions which decay into muons, muons are captured

Ionisation cooling of muon in matter

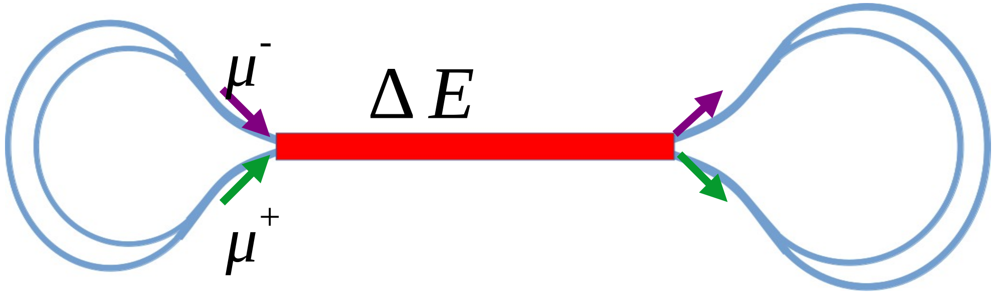
Acceleration to collision energy

Collision

Fully driven by muon lifetime

Accelerator Typologies
‘Racetrack’ vs ‘Dogbone’ RLA

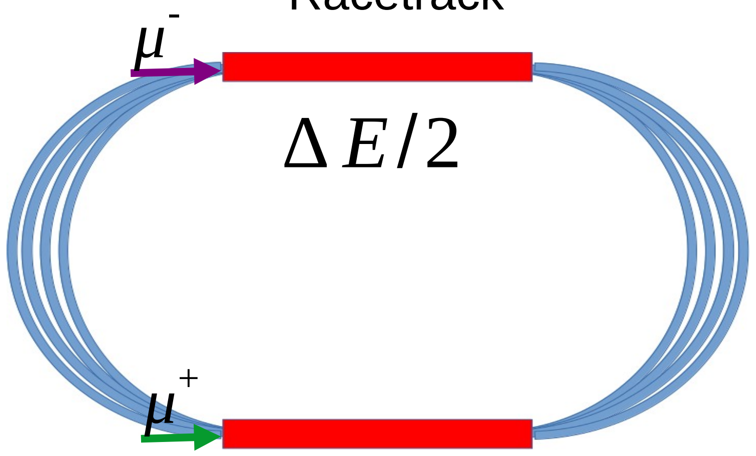
Dogbone



- High efficiency-less number of passes
- Better separation of spreaders

- Beam loading due to following bunches
- Requires symmetric optics due to charge symmetry
- Long arcs

Racetrack

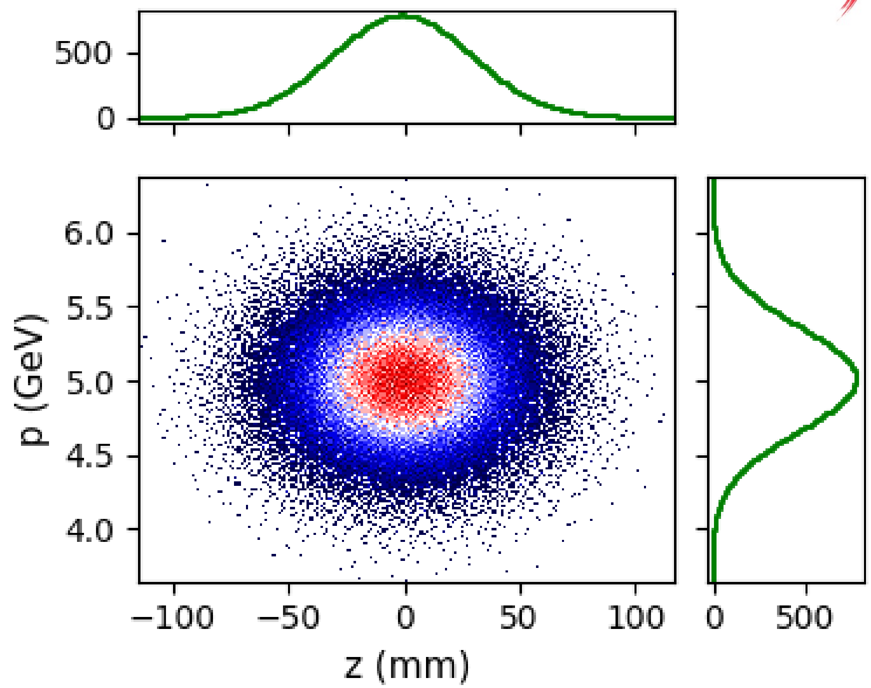


- Any lattice due to symmetric acceleration
- Compact short arcs that fits same tunnel
- Identical beam loading
-
- Low efficiency- more number of passes
- Complex spreader
- ...

S.A. Bogacz, Muon Acceleration Concepts for NuMAX: “Dual-use” Linac and “Dogbone” RLA, JINST, 13, P02002 (2018)

Initial beam parameters

Parameter	Unit	Value
Initial beam energy	GeV	5
Final beam energy	GeV	64
Bunch charge	nC	~400
Transverse emittance	µm.rad	20
Longitudinal emittance	eVs	0.0225
RMS bunch length	mm	30



- Very large energy spread and long bunch length
  - Low frequency acceleration, chromatic aberrations and dispersive effects
- Both longitudinal and transverse emittance needs to be preserved
  - One needs to control higher order terms of lattice
- ...

$$\varepsilon_f \cong \sqrt{\det\left(\mathbf{M}\Sigma_0\mathbf{M}^T + \sigma_\delta^2\mathbf{D}\mathbf{D}^T + 3\sigma_\delta^4\mathbf{T}\mathbf{T}^T\right)}$$

Accelerating module

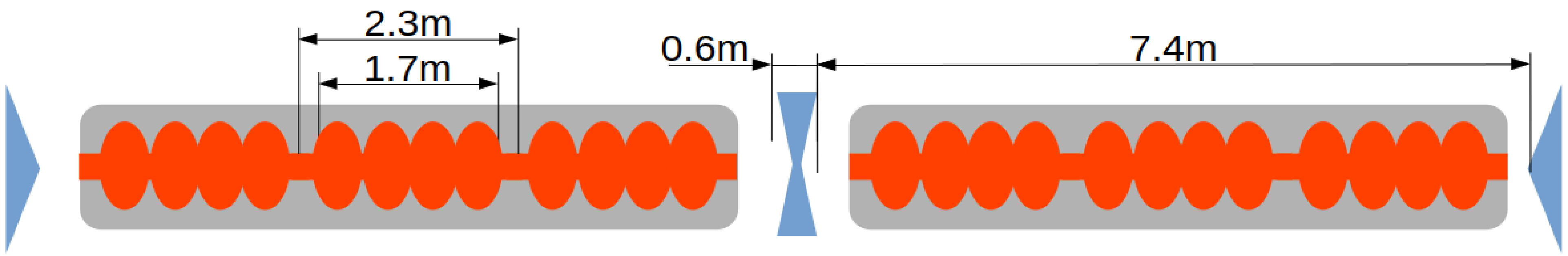


Table 1 – A few LEP cavity parameters

	Cu cavities	s.c. cavities
Frequency	352.209 MHz	352.209 MHz
Number of cells	5	4
Cavity active length	2.13 m	1.70 m
Iris hole diameter	100 mm	241 mm
Shunt impedance/ quality factor	650 Ohm/m[(a)] 1000 Ohm/m[(b)]	276 Ohm/m
Q_o	4×10^4	3×10^9 (Nb, 4.2 K) 2.6×10^6 (loaded)
Design acceleration field	1.5 MV/m	5 MV/m
Total loss factor/ unit length	$403 \frac{V}{pC \bullet m}$	$46 \frac{V}{pC \bullet m}$

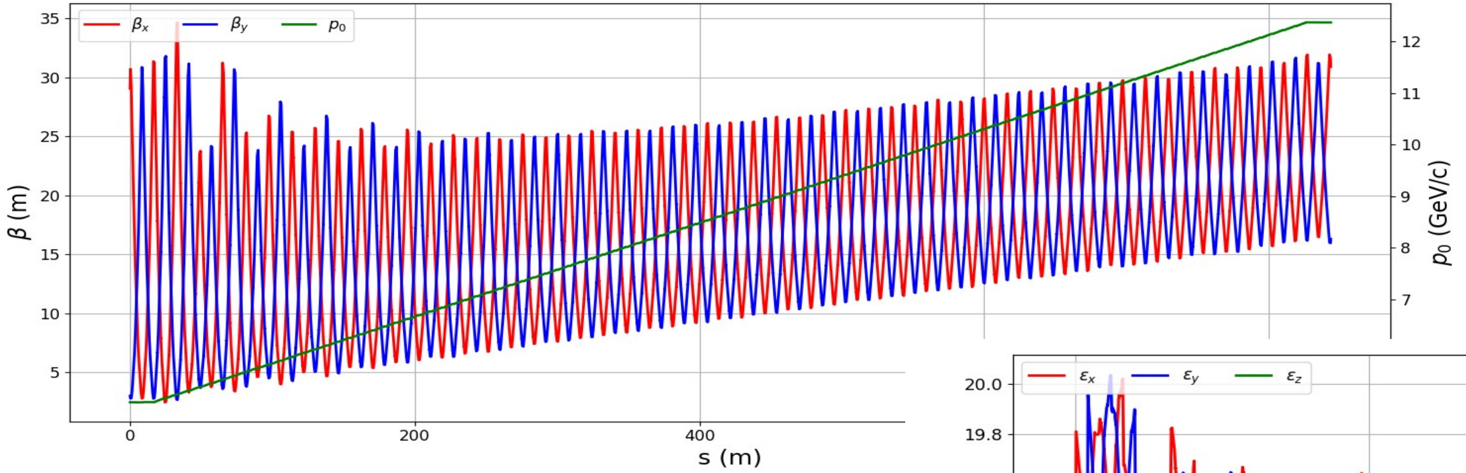
- FODO type lattice with fixed gradient SC quadrupole is proposed
  - Two quads are spaced by one SRF module (housing 3 SRF cavities) , short FODO due to weak quadrupoles at high energy
- The expected gradient for the LEP cavity is 15 MV/m
- We use LEP dimensions for wakefield calculation.
  - For short range wake Karl Bane’s approximation is used

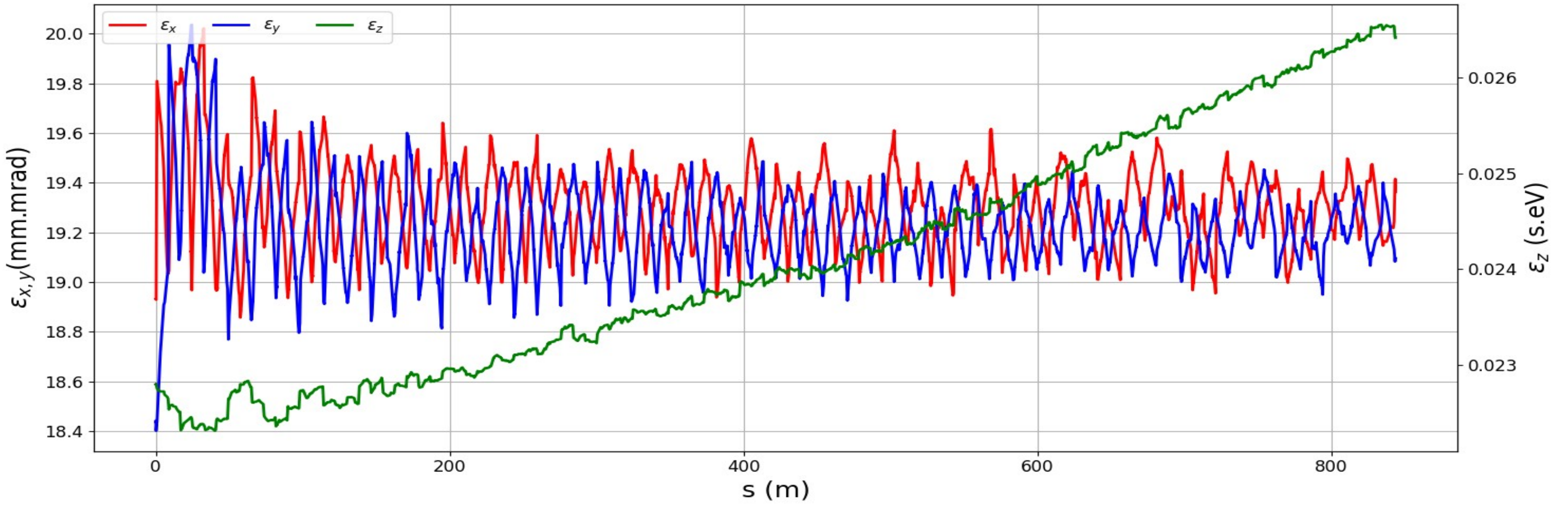
Beam Dynamics in Linac

- Fixed optics due to opposite/multiple acceleration on linac..
- Large initial energy spread causes emittance growth due to chromatic effects by quadrupoles, we use weak quadrupoles
  - Drawback: very weak lattice at high energy

$$x = R_{11}x_0 + R_{12}x'_0 + T_{116}x_0\delta + T_{126}x'_0\delta \ldots$$

$$x' = R_{21}x_0 + R_{22}x'_0 + T_{216}x_0\delta + T_{226}x'_0\delta \ldots$$





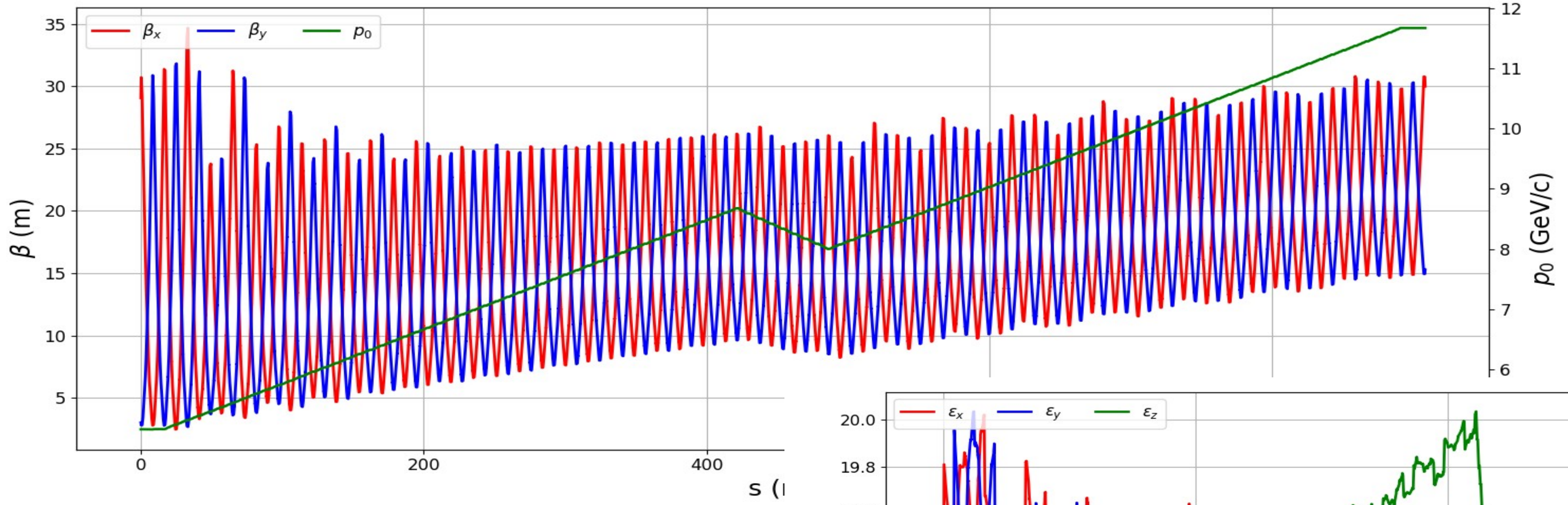
To get 13 GeV/pass one needs 300 Cavity → 100 Module

50 CM/linac (150 cavity per linac)

Longitudinal emittance growth with low frequency cavity

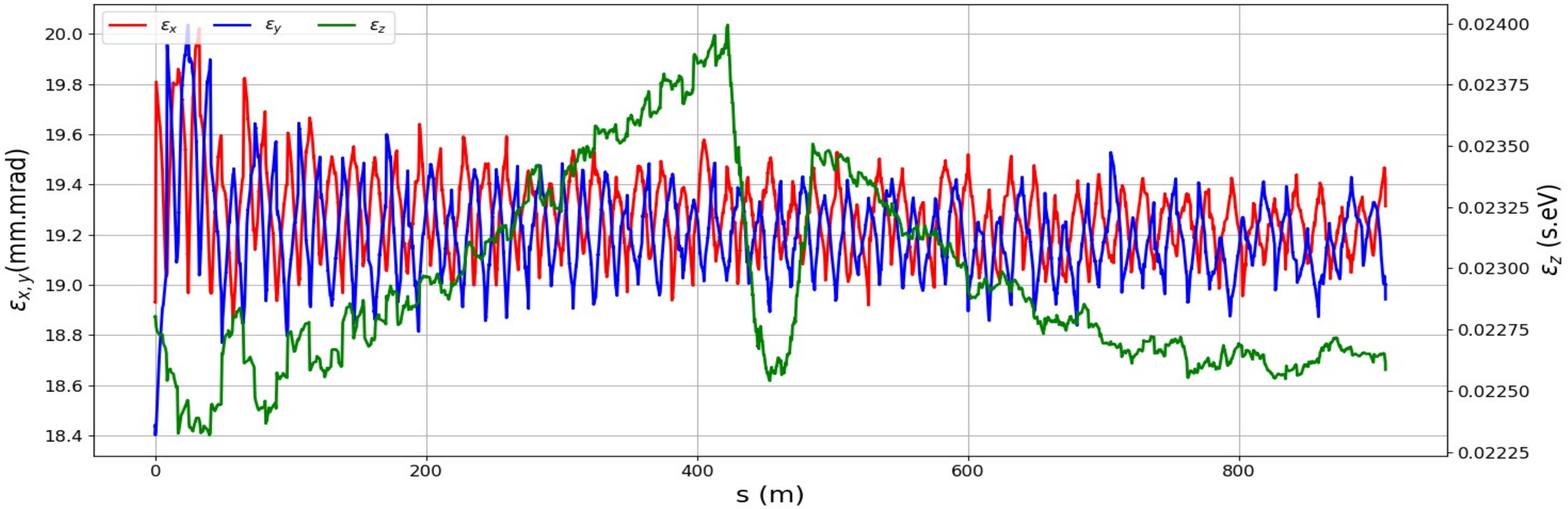
Beam Dynamics in Linac-2

- To minimize uncorrelated energy spread we propose to use harmonic cavity (1050 MHz) at the middle of linac (40 Cavity)



8 CM (40 linearizer cavity per linac)

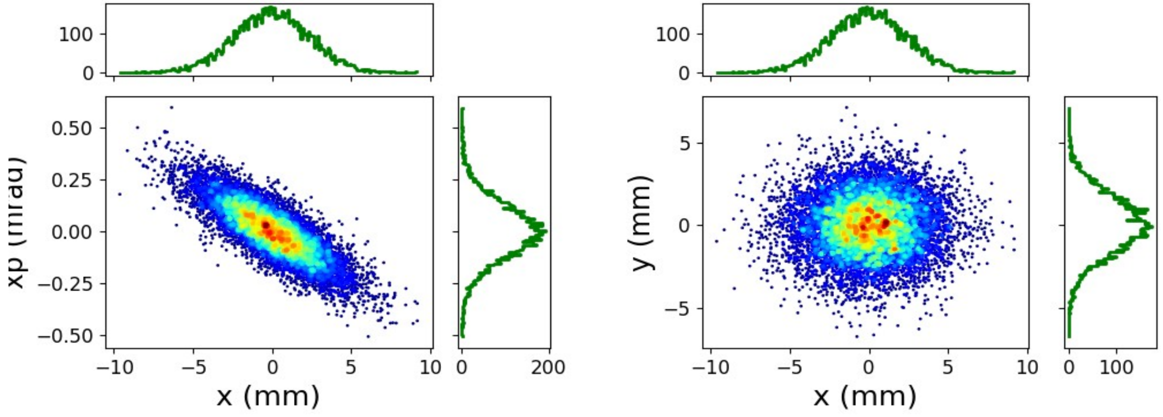
Energy gain : 6.6-7 GeV/linac

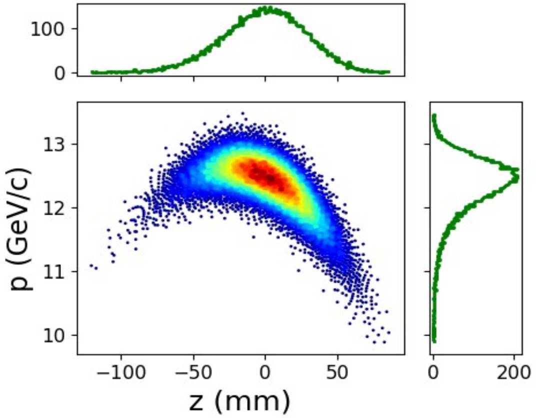


International MUON Collider Collaboration

Beam Dynamics in Linac-3

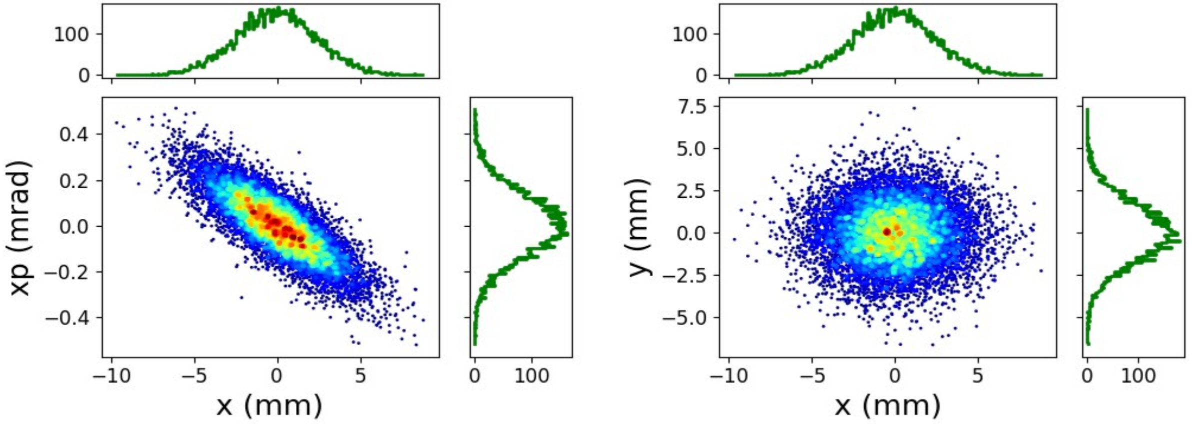
Without linearizer

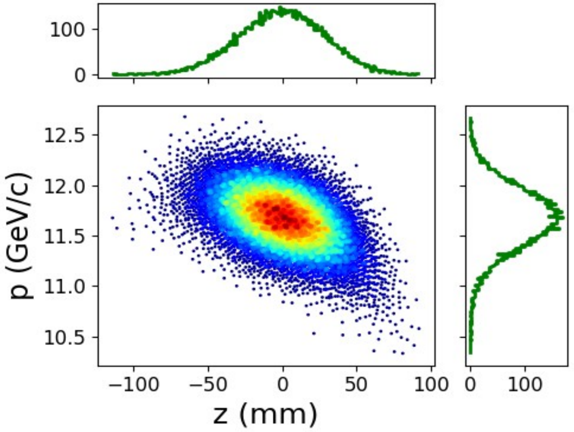




Parameter	Value
E_0 (GeV)	12.26
p_0 (GeV/c)	12.37
Q_b (nC)	3.93e+02
ε_x (mm.mrad)	1.94e+01
ε_y (mm.mrad)	1.91e+01
ε_z (m.MeV/c)	7.92e+00
ε_t (eVs)	0.026
σ_x (mm)	2.26e+00
σ_y (mm)	1.63e+00
σ_z (mm)	2.60e+01
σ_p (MeV/c)	3.76e+02
$\Delta p/p_0$ (%)	3.04e+00

With linearizer





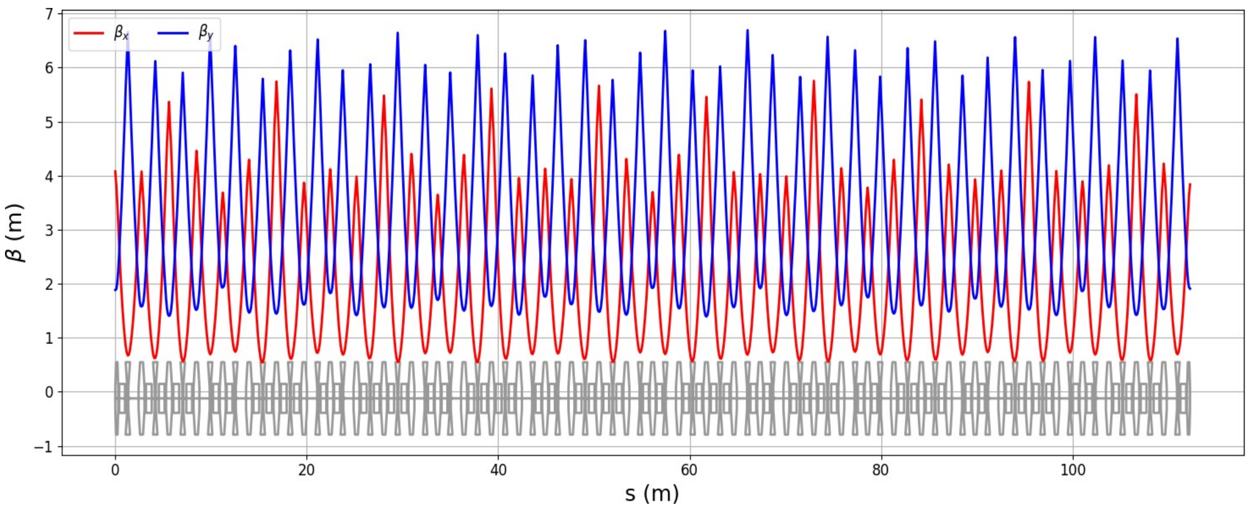
Parameter	Value
E_0 (GeV)	11.57
p_0 (GeV/c)	11.67
Q_b (nC)	3.92e+02
ε_x (mm.mrad)	1.93e+01
ε_y (mm.mrad)	1.89e+01
ε_z (m.MeV/c)	6.77e+00
ε_t (eVs)	0.023
σ_x (mm)	2.29e+00
σ_y (mm)	1.62e+00
σ_z (mm)	2.73e+01
σ_p (MeV/c)	2.78e+02
$\Delta p/p_0$ (%)	2.38e+00

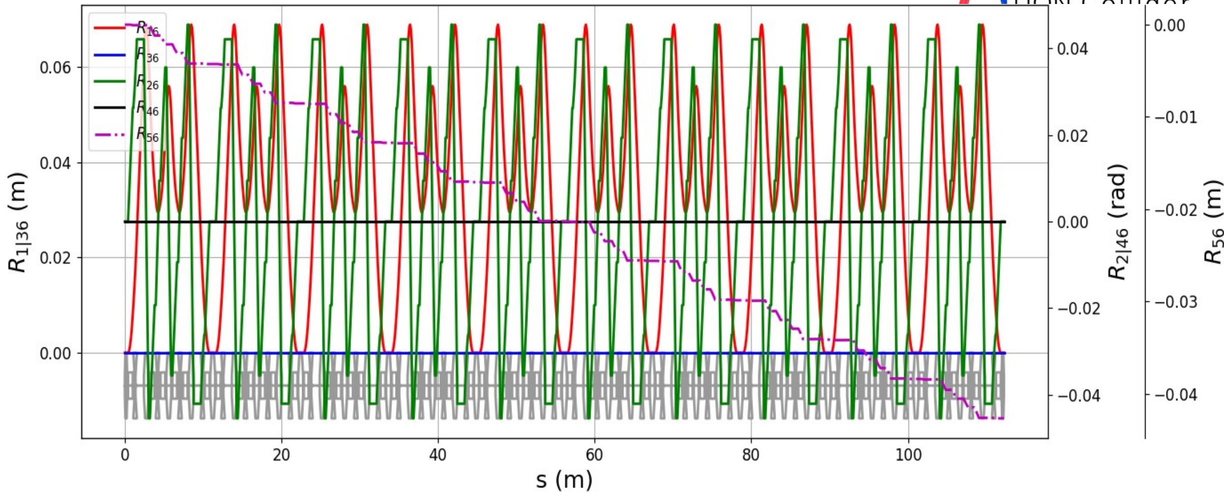
Arc Considerations

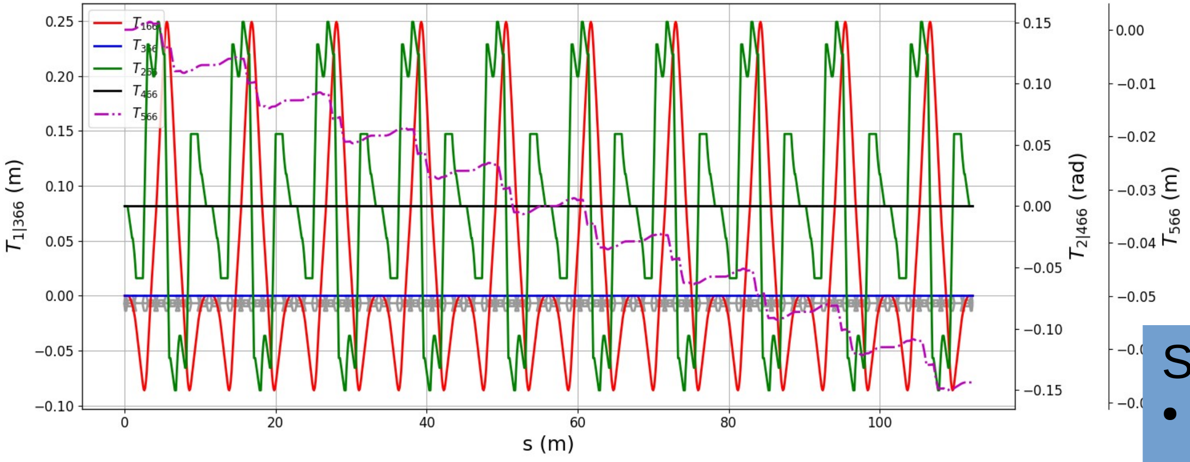
- As compact as possible !
  - SC magnets (max 8.5 T)
- Higher order terms needs to be controlled due to high energy spread
  - Second order achromat lattice
- High energy spread for first passes
  - Small momentum compaction factor and chromaticity
- Fitting same tunnel if possible
- …
- Usually sextupoles are needed to correct second-order dispersion in the bending plane but one can create second order achromat by adjusting the space between magnets..
  - In order to not to use any sextupole we propose to use same principle

Y. Sun, PRSTAB, 14, 060703 (2011)

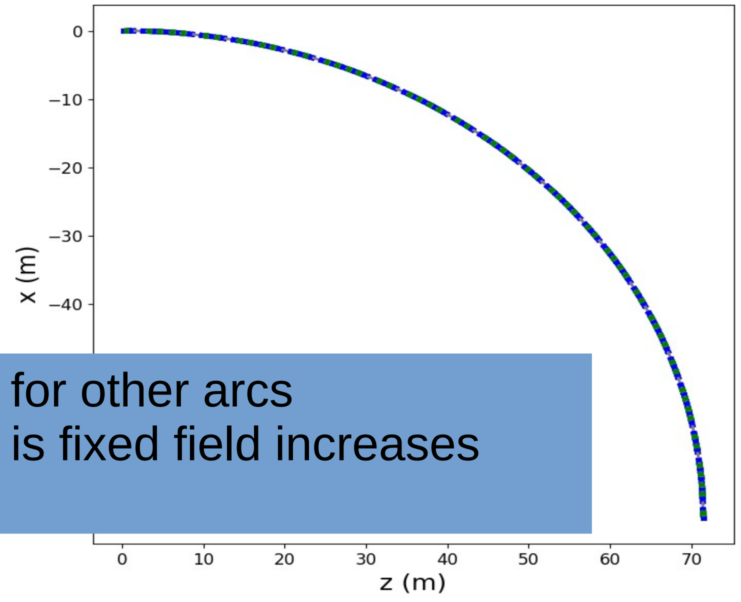
ARC Lattice (2nd order achromat FODO)







Large energy acceptance (> 2%)
Compact (~120 m)



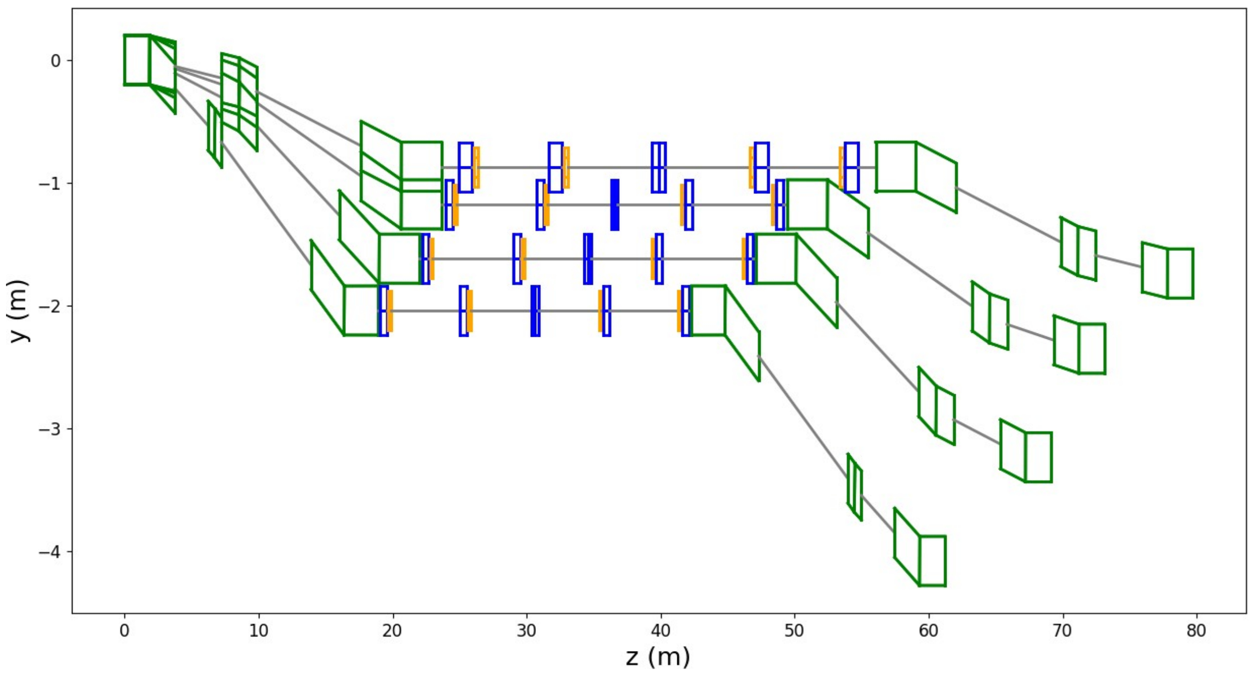
Same lattice is used for other arcs

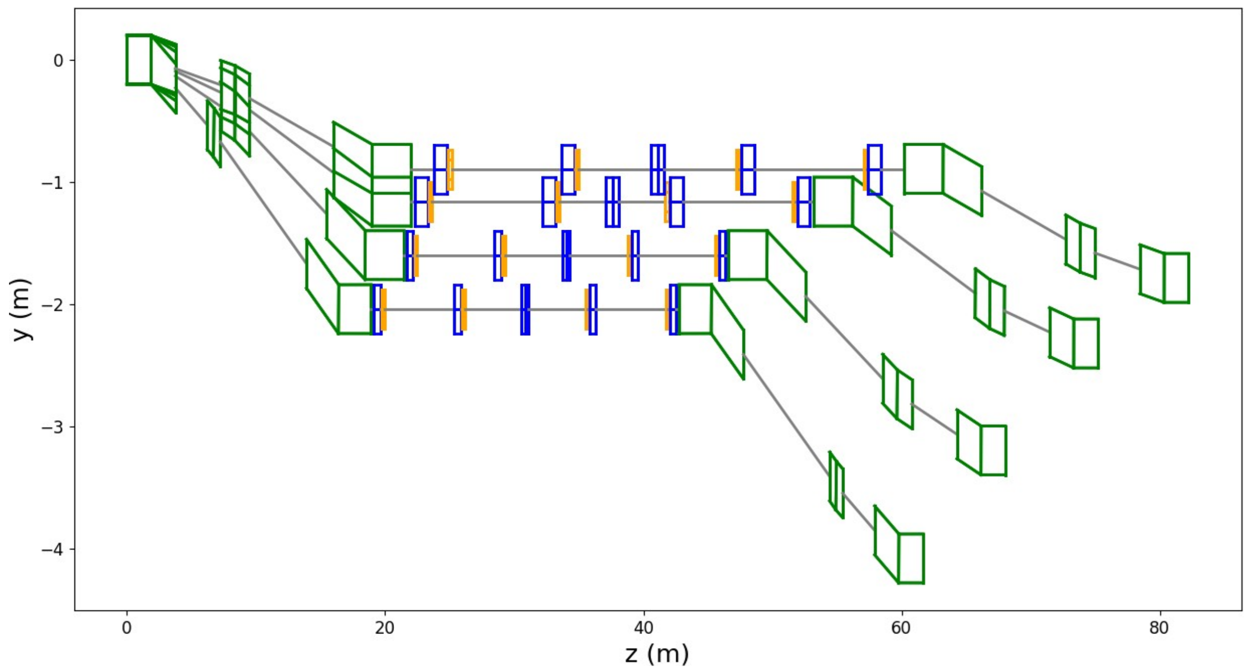
- The bending angle is fixed field increases with energy

Injection / Extraction

- The matching to the linac/arcs are performed by spreaders..
  - Fixed optics
- Smooth bending due to large energy spread
  - Normal conducting magnets (max 2T)
- Large aperture at low energy , small aperture at high energy, long matching section

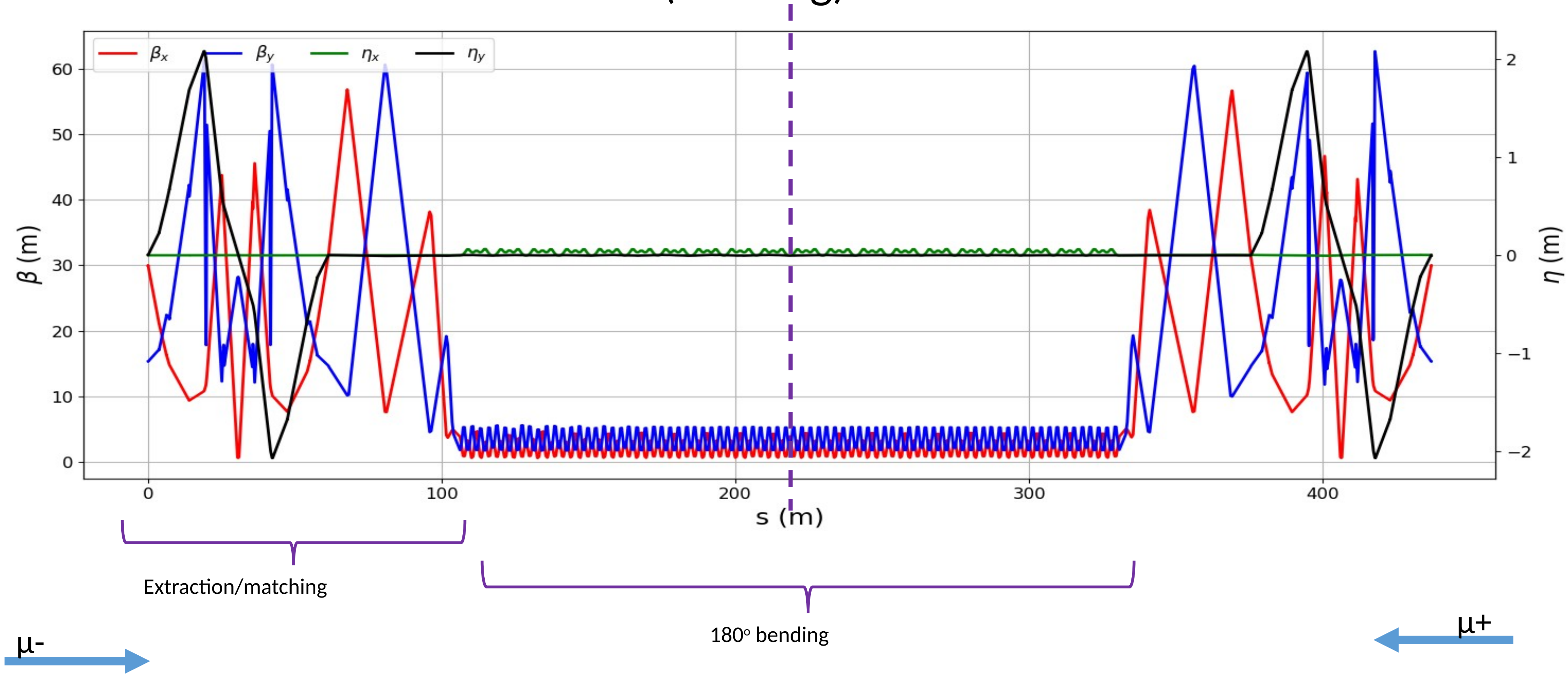
Bending: green
Quadrupole: blue
Sextupole: orange





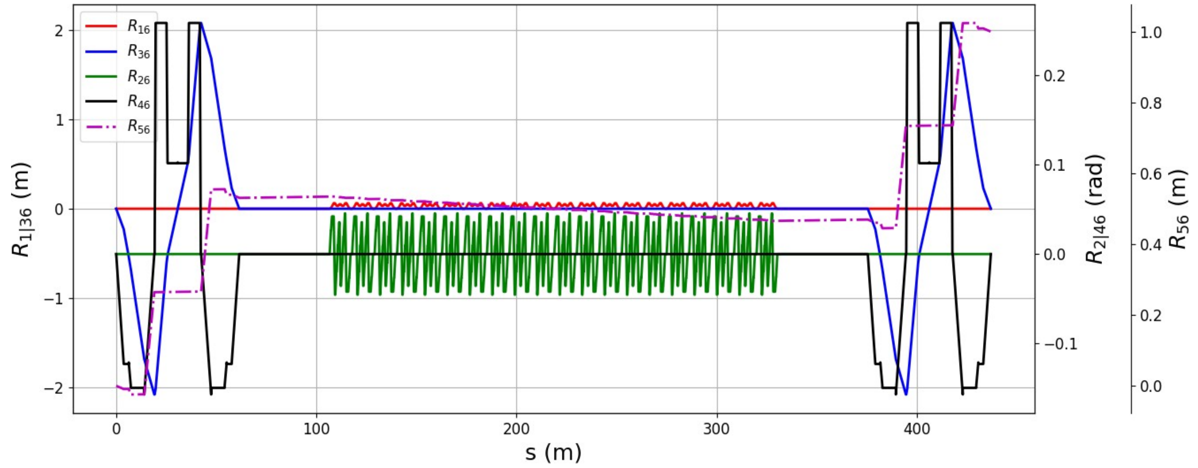
Beam dynamics in arcs

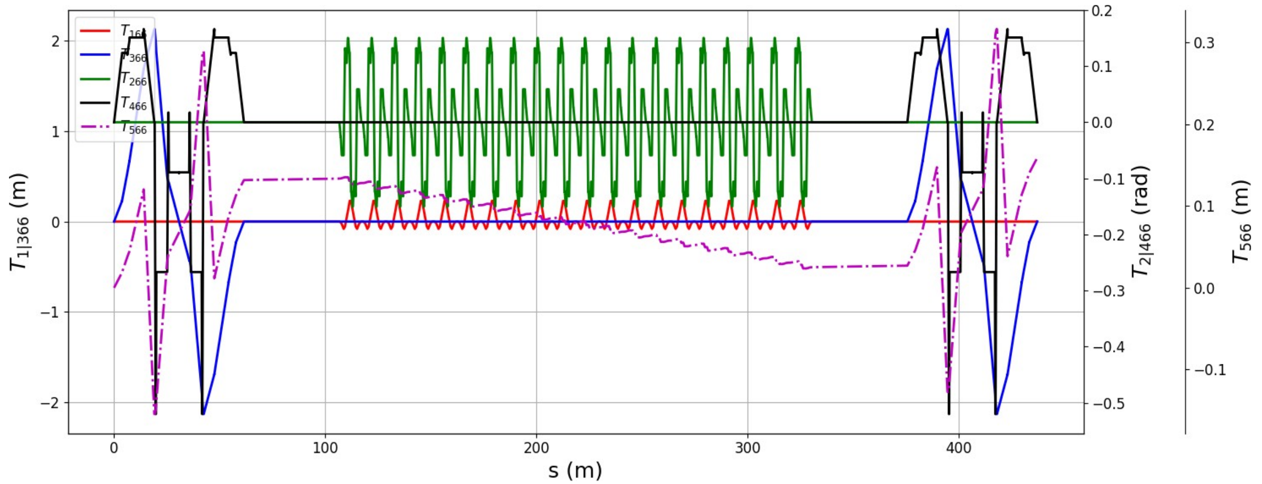
- Start to end simulation in first arc (tracking)

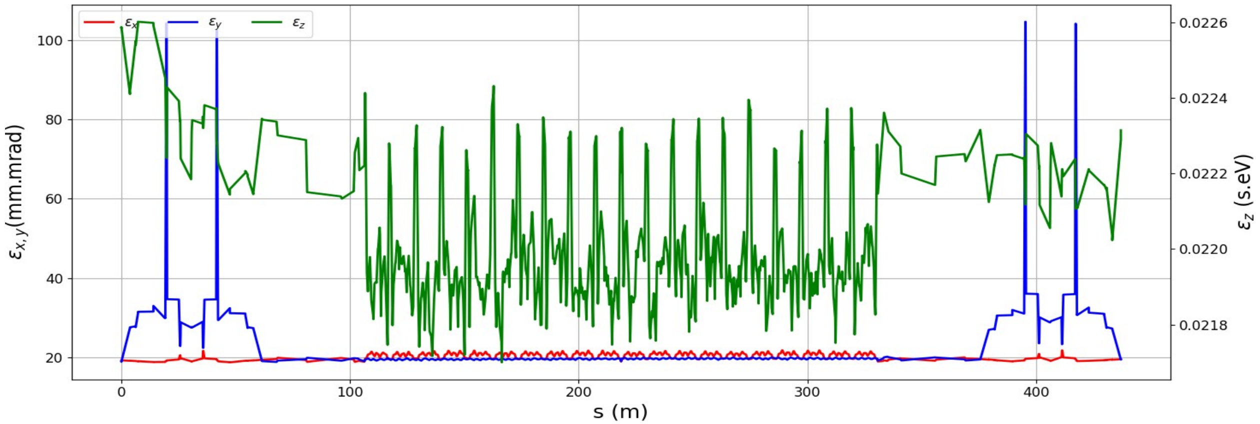


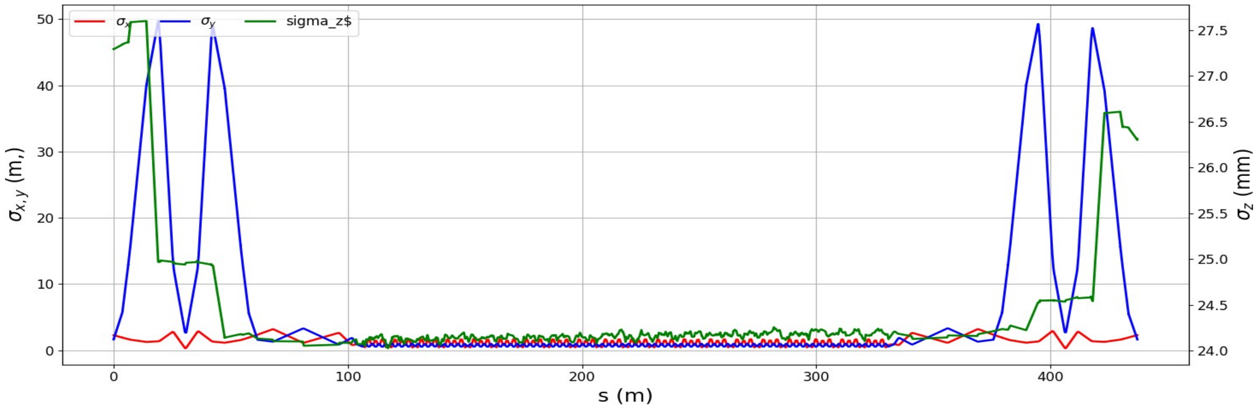
Beam dynamics in arcs

- Start to end simulation in first arc (optics & tracking)

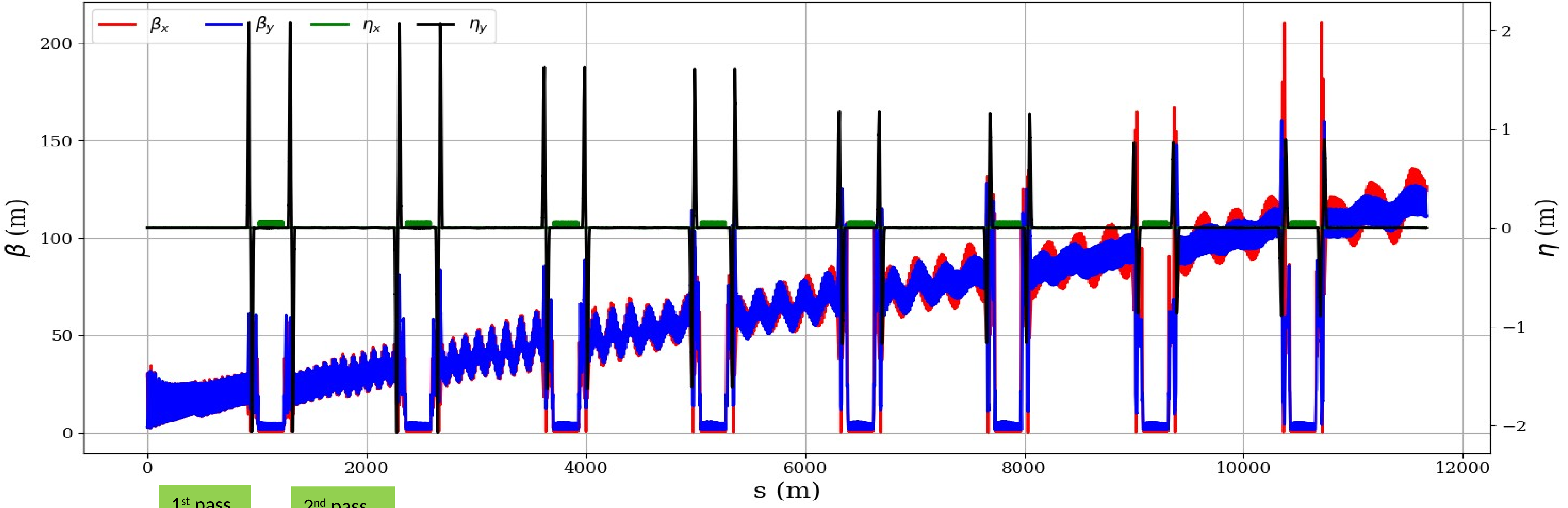








Start to end of all machine



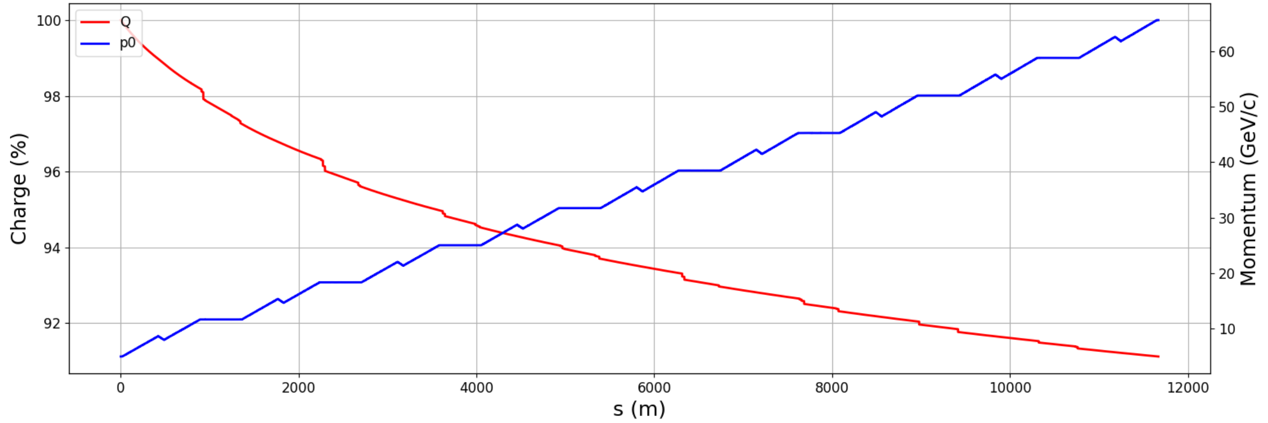
1st pass

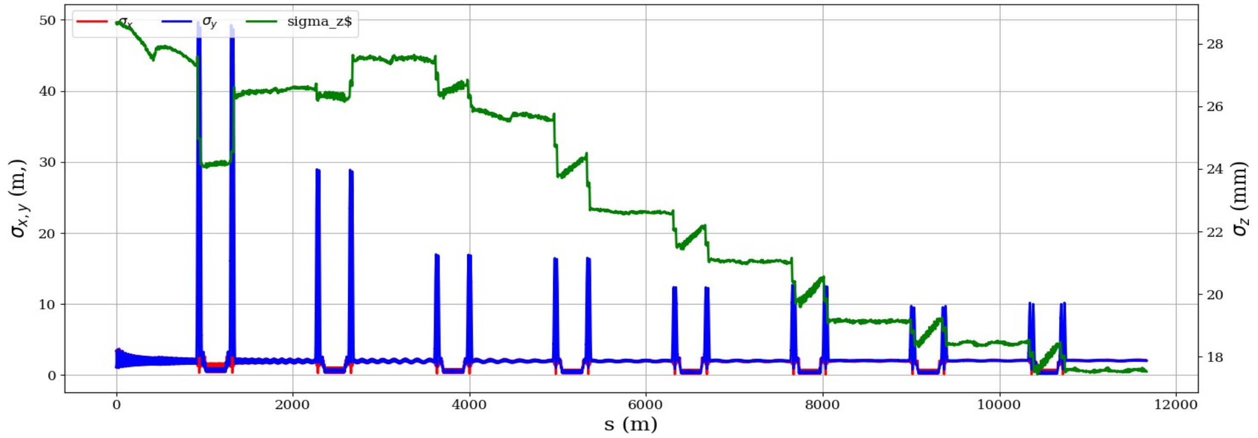
2nd pass

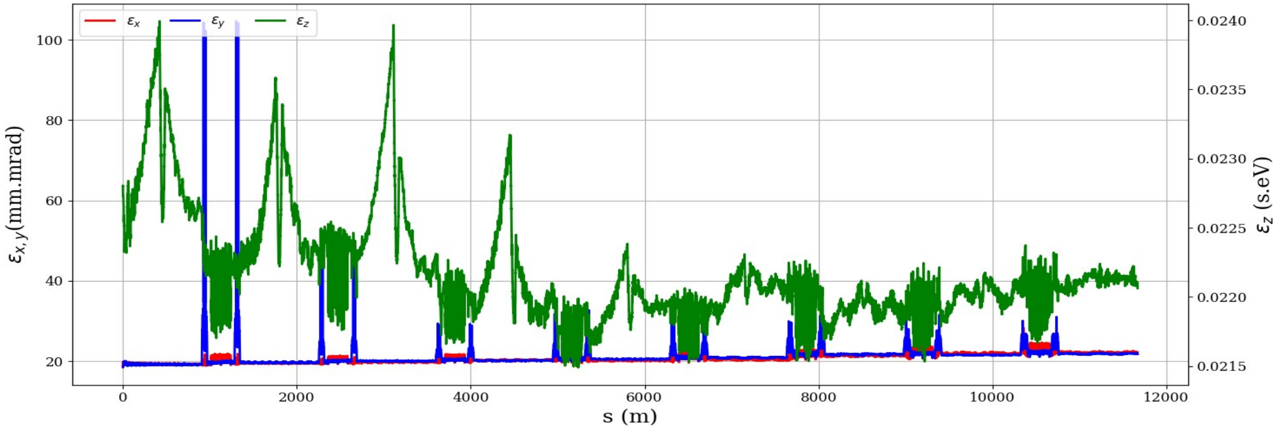
1st arc

……

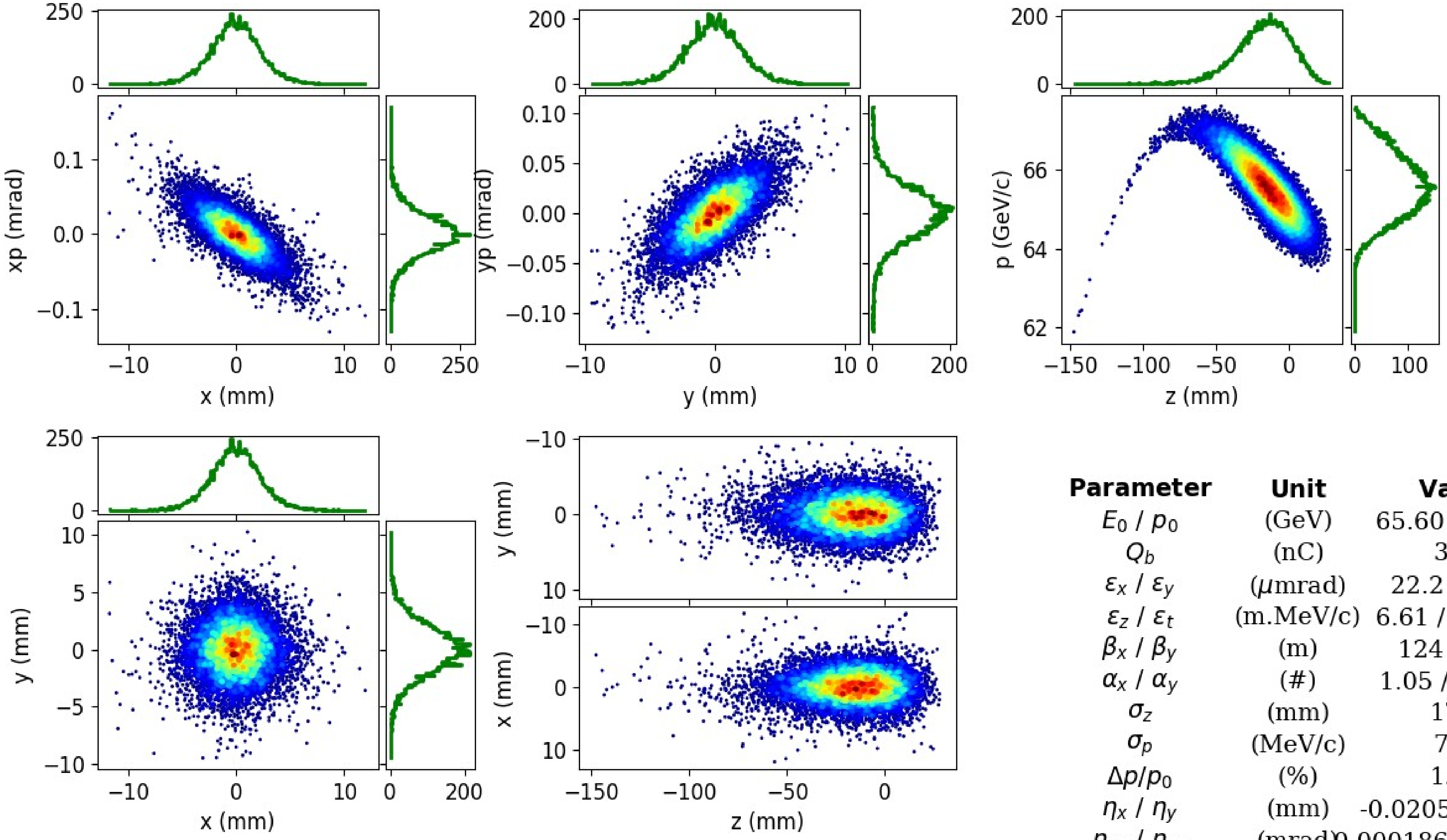
Start to end simulation of entire machine





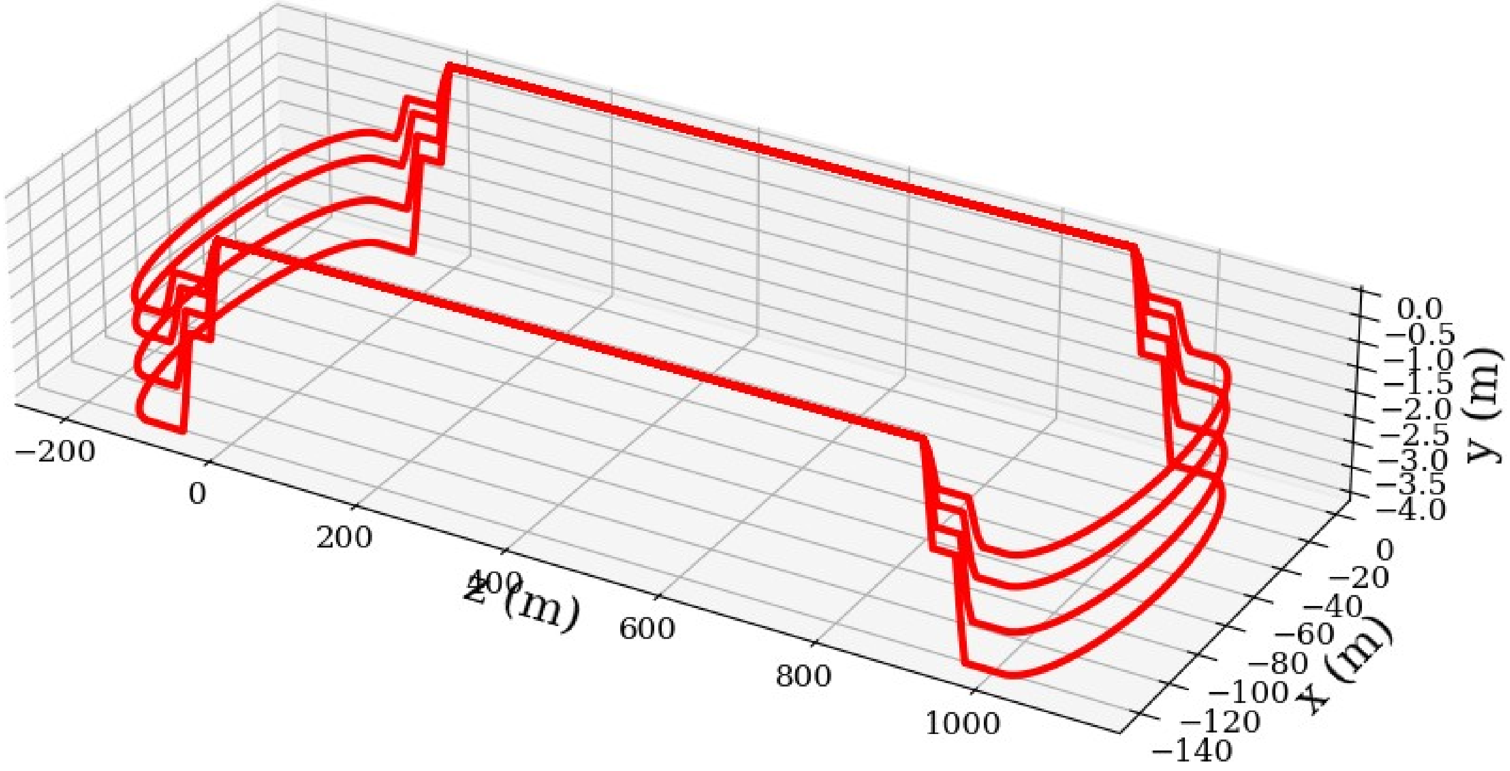


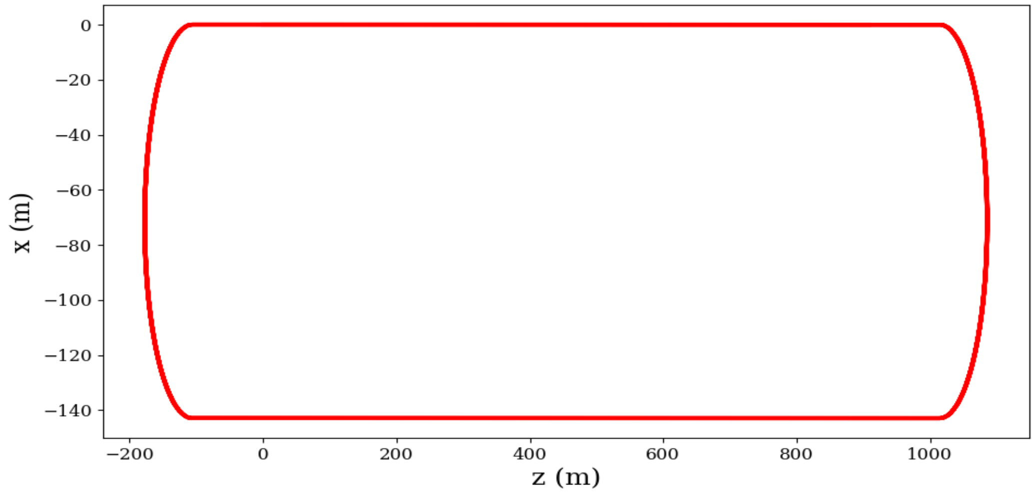
Phase space at the end of machine

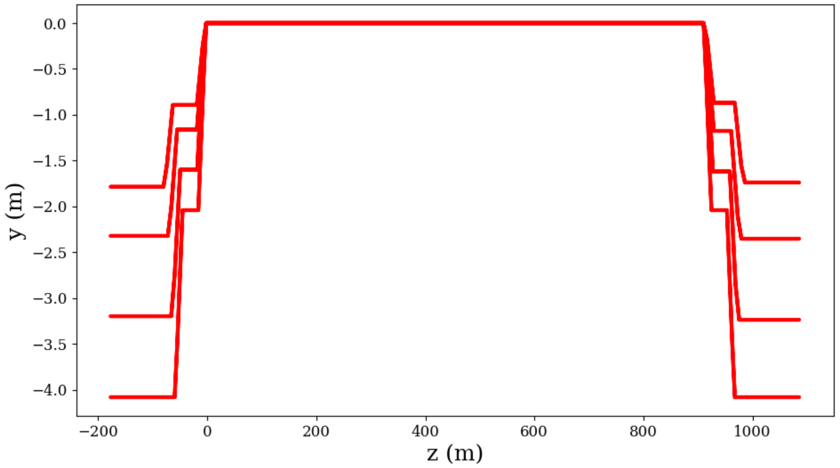


Parameter	Unit	Value
E_0 / p_0	(GeV)	65.60 / 65.49
Q_b	(nC)	364
ε_x / ε_y	(μmrad)	22.2 / 21.7
ε_z / ε_t	(m.MeV/c)	6.61 / 0.0221
β_x / β_y	(m)	124 / 111
α_x / α_y	(#)	1.05 / -0.856
σ_z	(mm)	17.5
σ_p	(MeV/c)	734
$\Delta p/p_0$	(%)	1.12
η_x / η_y	(mm)	-0.0205 / -0.153
η_{xp} / η_{yp}	(mrad)	0.000186 / -0.00202

Footprint







Conclusion

- Racetrack acceleration scheme has been proposed for the RLA
  - For dogbone matching co-propagating bunches was impossible for non symmetric lattice
- FODO type 2nd order achromat lattice without sextupoles is suitable for recirculating beam
- Longitudinal emittance and transverse emittance meets the target value
  - One needs to desing injection/extraction
- The Muon survival meets target value
  - We have 93 %
- The number of structures are increased about 80 but total length of machine is more less the same..
  - Machine fits into one tunnel..
- 3.5 pass instead of 4.5 would make spreader design simpler
  - Better separation and shorter beamline

Thank you for your attention