International MUON Collider Collaboration

Beam Dynamics for RLA2 for the Muon Collider

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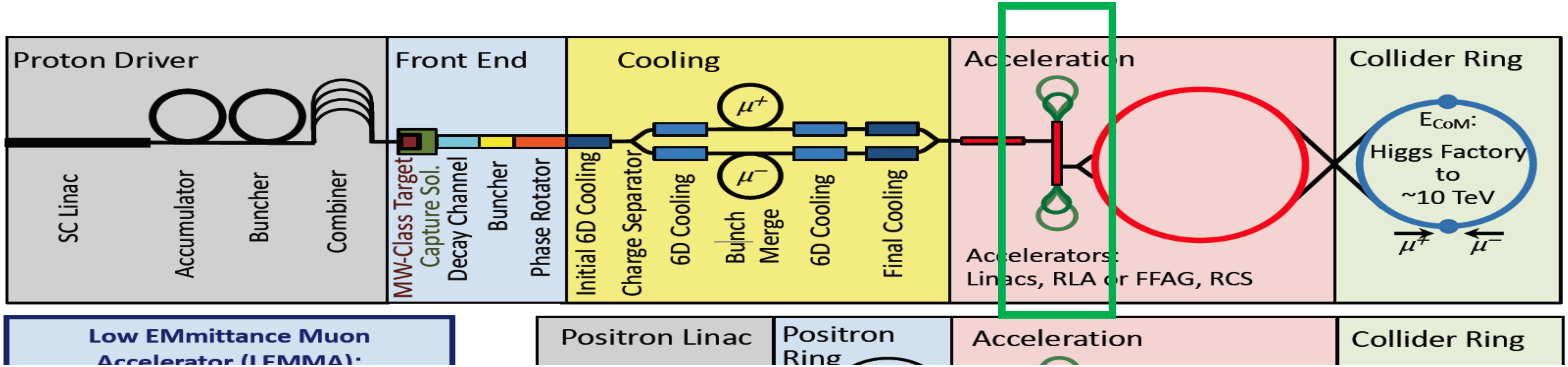
Collider Concept

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

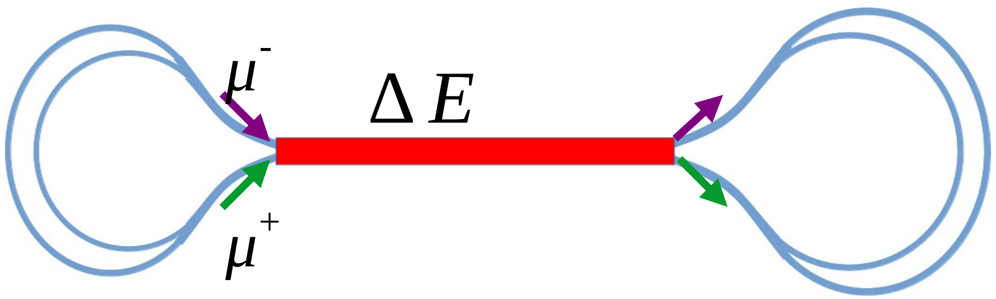
Acceleration to collision energy

Collision

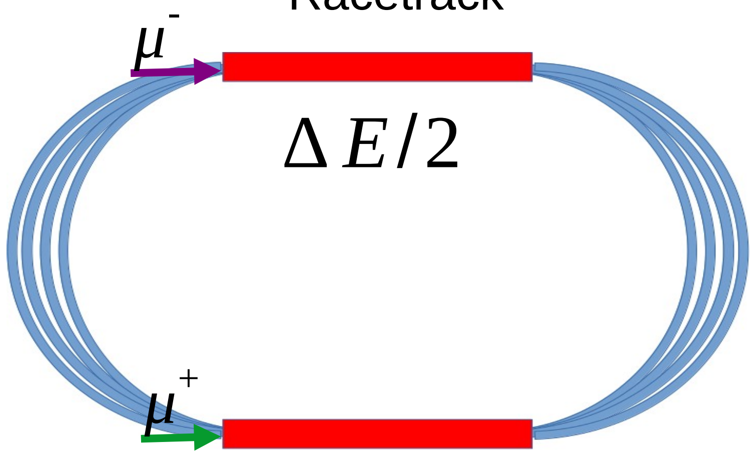
Fully driven by muon lifetime

Accelerator Typologies
‘Racetrack’ vs ‘Dogbone’ RLA

Dogbone



Racetrack



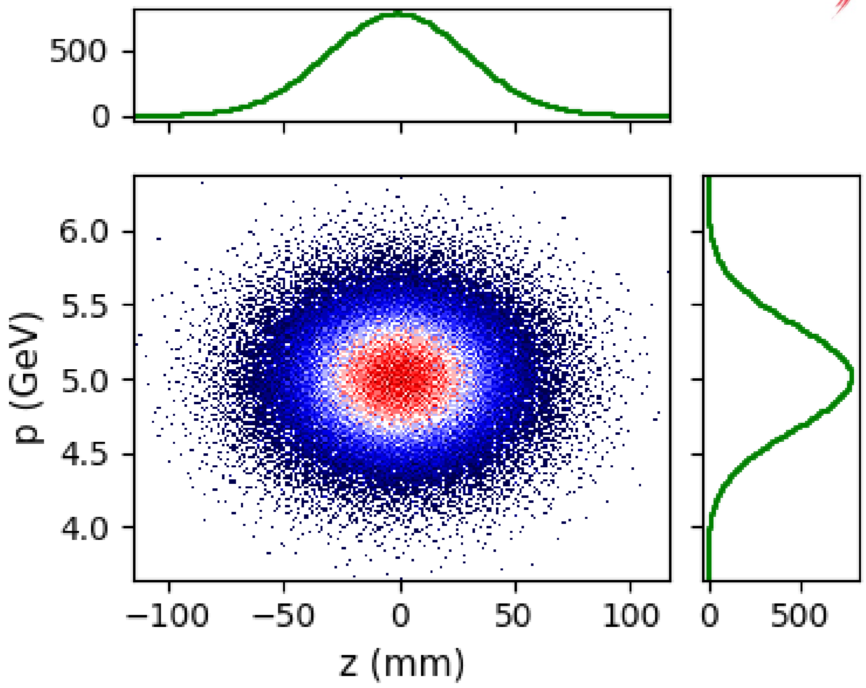
- High efficiency-less number of passes
- Better separation of spreaders

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

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

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



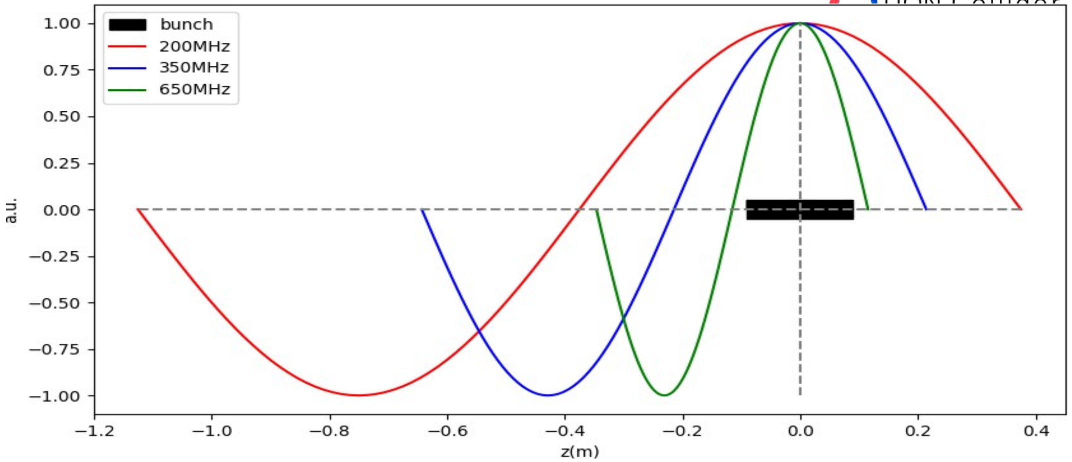
- Very large energy spread and long bunch length
  - Low frequency acceleration, chromatic aberrations and dispersive effects
- Both longitudinal and transverse emittance needs to be preserved
  - One needs to control higher order terms of lattice

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

- Rapid acceleration
- ...

Choice of RF frequency

- We have RMS ~ 30 mm bunch → 200 mm full length
- Typically the total bunch length should be < 10% of λ_{RF}
- To preserve longitudinal emittance lower frequency is preferable
  - …
- Reasonable frequency would be 350 MHz which is SC RF cavities of LEP

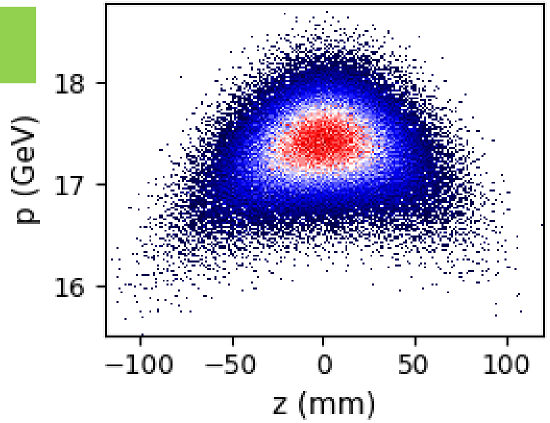


Parameter	Value
p_0 (GeV)	17.32
ε_z (mm.keV)	11.33
σ_z (mm)	30.12
σ_p (MeV)	378.04
$\Delta p/p_0$ (%)	2.18

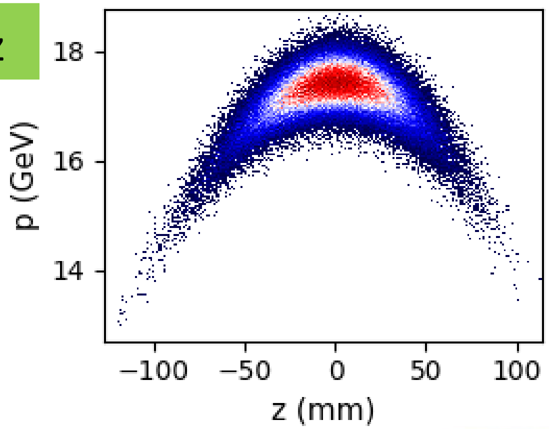
Parameter	Value
p_0 (GeV)	17.16
ε_z (mm.keV)	16.26
σ_z (mm)	30.12
σ_p (MeV)	543.24
$\Delta p/p_0$ (%)	3.17

Parameter	Value
p_0 (GeV)	16.70
ε_z (mm.keV)	39.34
σ_z (mm)	30.01
σ_p (MeV)	1342.07
$\Delta p/p_0$ (%)	8.04

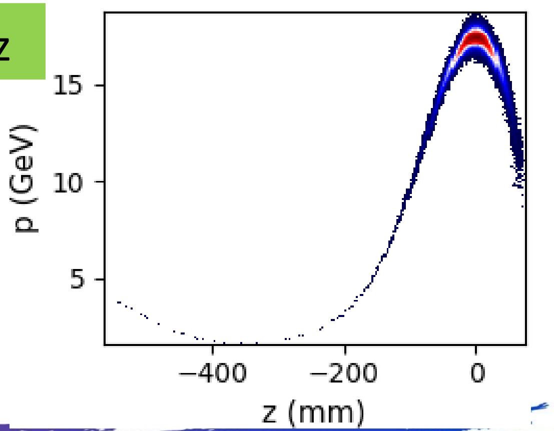
200MHz



350MHz



650MHz



Accelerating module

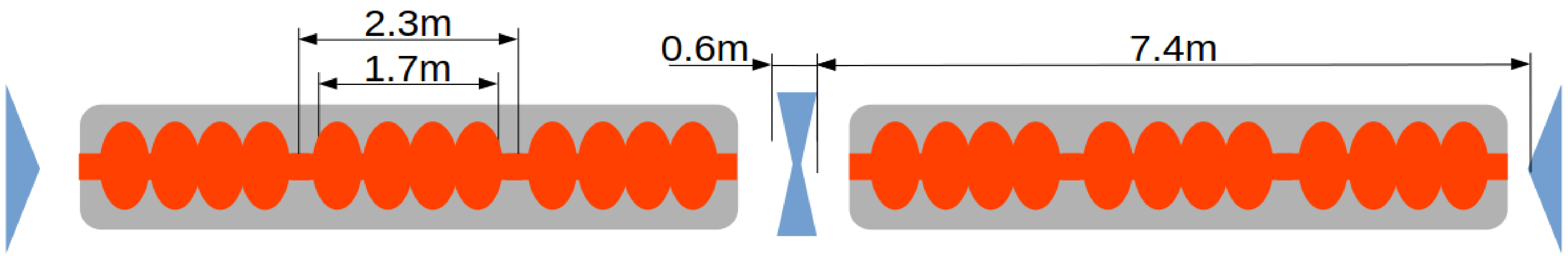


Table 1 – A few LEP cavity parameters

	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	$403 \frac{V}{pC \bullet m}$	$46 \frac{V}{pC \bullet m}$

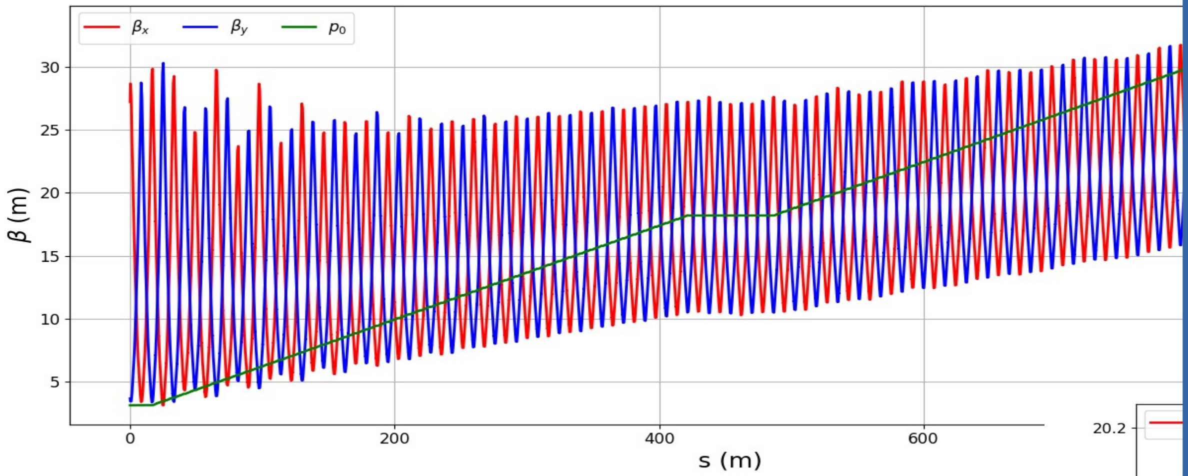
- FODO type lattice with fixed gradient SC quadrupole is proposed
  - Two quads are spaced by one SRF module (housing 3 SRF cavities) , short FODO due to weak quadrupoles at high energy
- The expected gradient for the LEP cavity is 15 MV/m (Alexej Grudiev)
- We used same dimensions for wakefield calculation.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

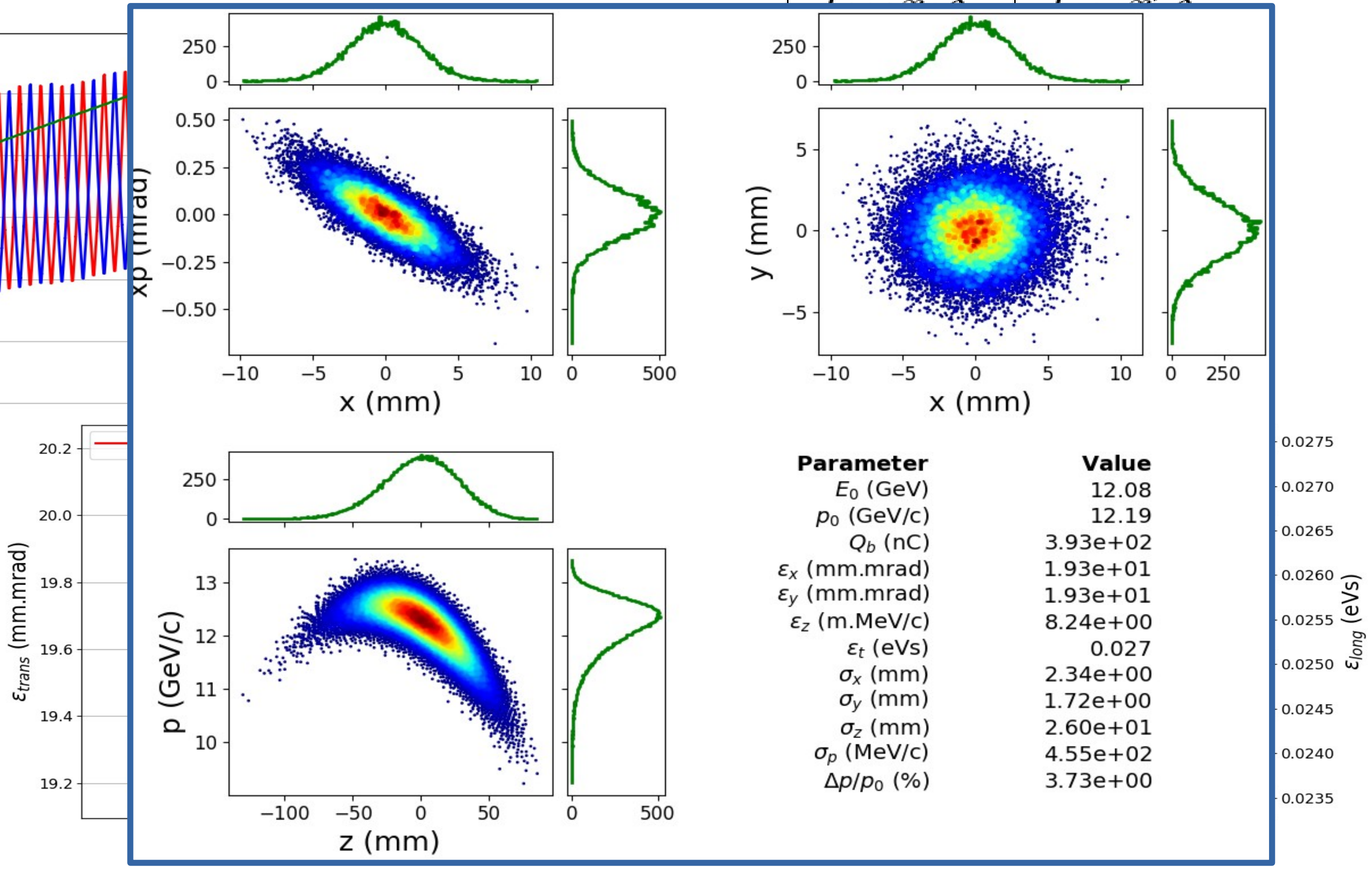
Beam Dynamics in Linac

- Fixed optics due to opposite acceleration on other 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

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

$$x' = R_{21}x_0 + R_{22}x'_0$$



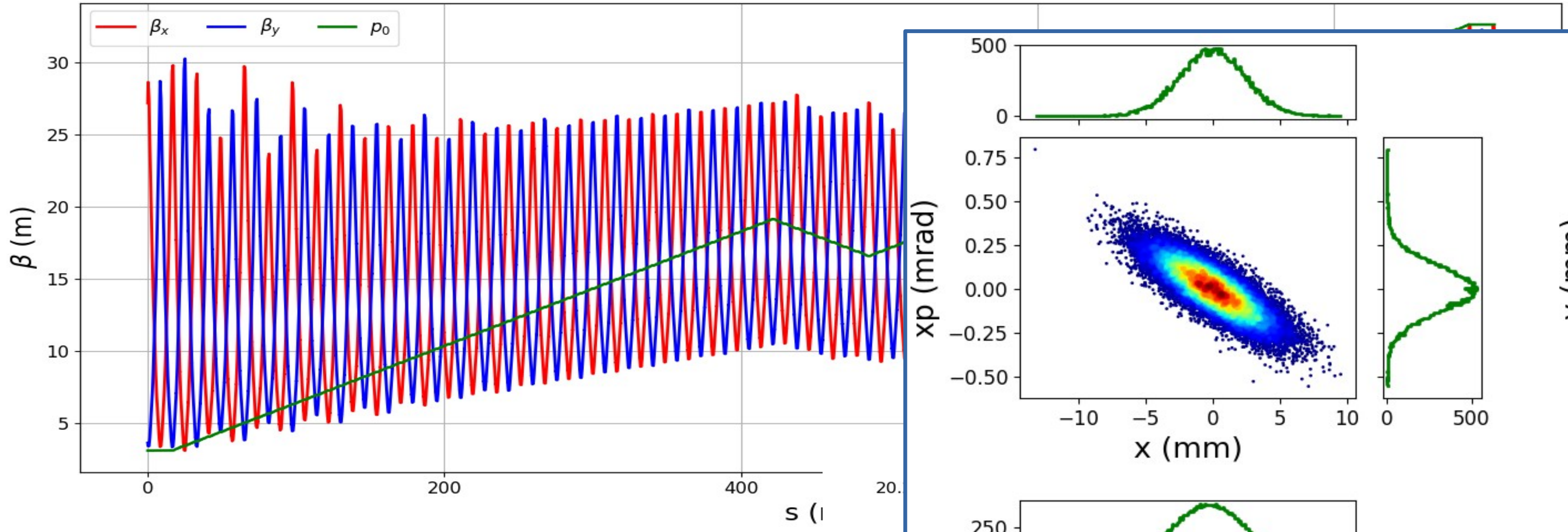


100 CM (300 cavity per linac)

Longitudinal emittance growth with low frequency cavity

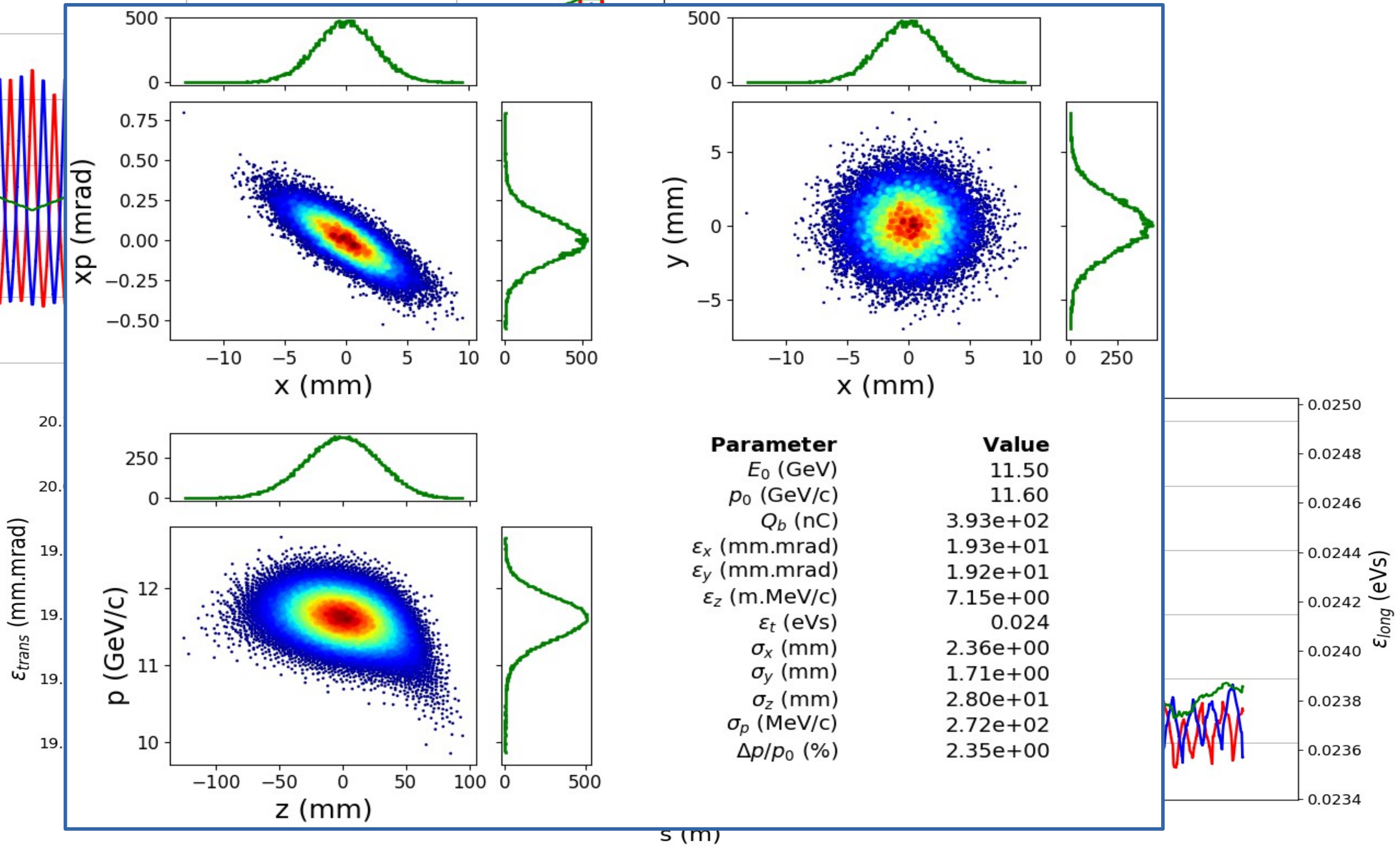
Beam Dynamics in Linac-2

- To minimize uncorrelated energy spread we propose to use harmonic cavity (1050 MHz) at the middle of linac (56 Cavity)



8 CM (40 linearizer cavity per linac)

6.6-7 GeV/linac



Parameter	Value
E_0 (GeV)	11.50
p_0 (GeV/c)	11.60
Q_b (nC)	3.93e+02
ϵ_x (mm.mrad)	1.93e+01
ϵ_y (mm.mrad)	1.92e+01
ϵ_z (m.MeV/c)	7.15e+00
ϵ_t (eVs)	0.024
σ_x (mm)	2.36e+00
σ_y (mm)	1.71e+00
σ_z (mm)	2.80e+01
σ_p (MeV/c)	2.72e+02
$\Delta p/p_0$ (%)	2.35e+00

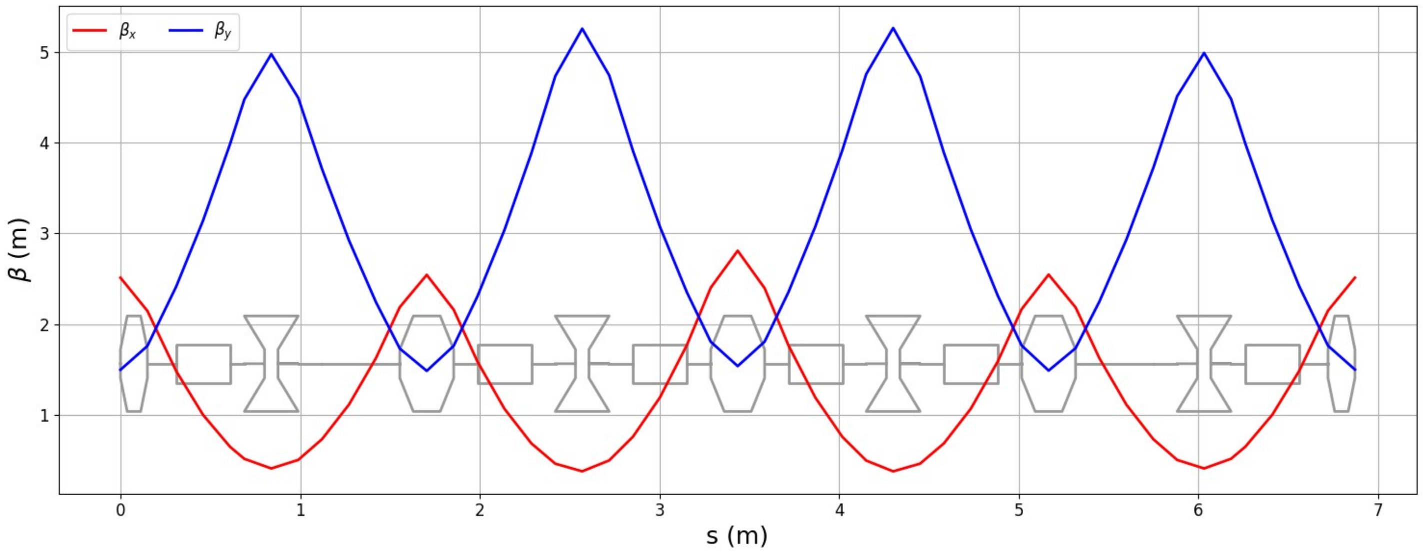
Arc Considerations

- As compact as possible !
  - SC magnets (max 10 T)
- Higher order terms needs to controlled due to high energy spread
  - Second order achromat
- High energy spread for first passes
  - Small momentum compaction factor and chromaticity
- Fitting same tunnel if possible
- . ..

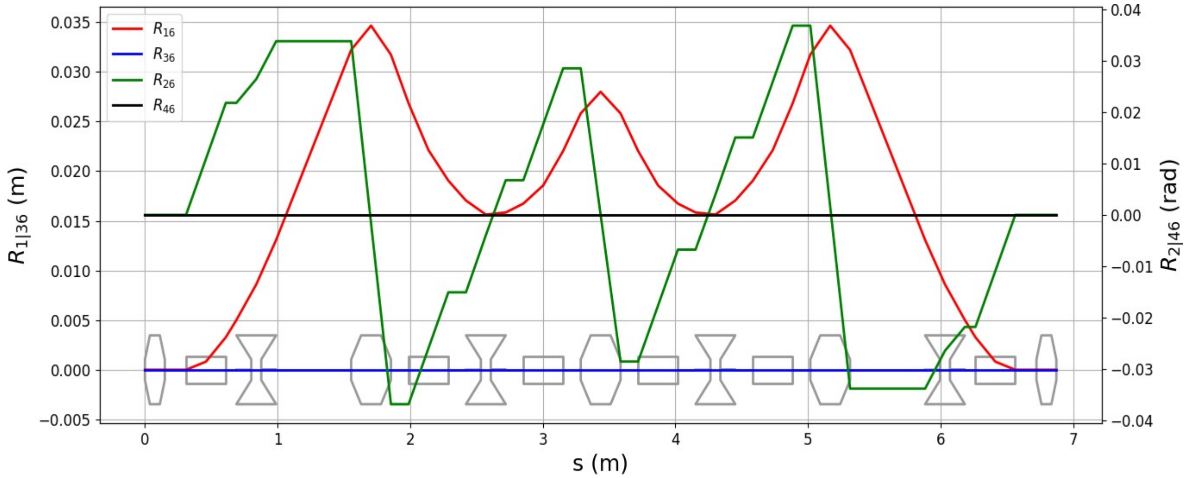
- Usually sextupoles are needed to correct second-order dispersion in the bending plane but one can create second order achromat by adjusting the space between magnets..
  - In order to not to use any sextupole magnets we propose to use same principle

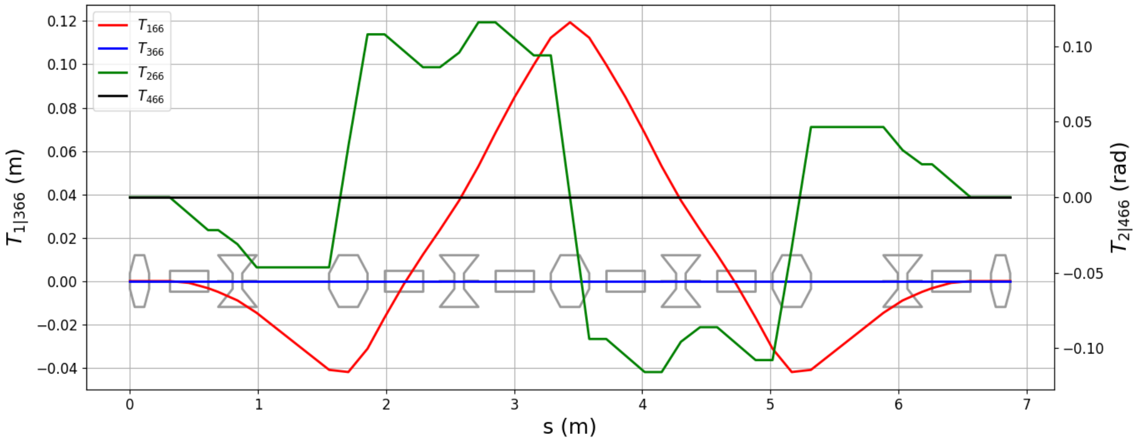
Y. Sun, PRSTAB, 14, 060703 (2011)

ARC 1-2 (12 identical cell for 90° bending)

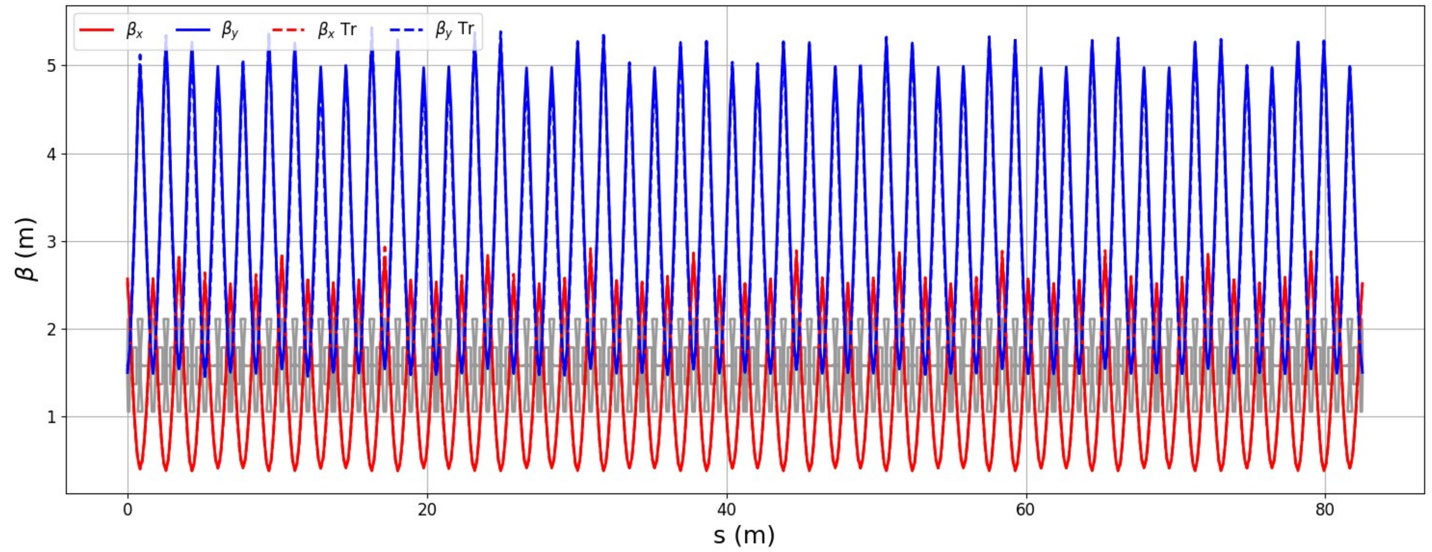


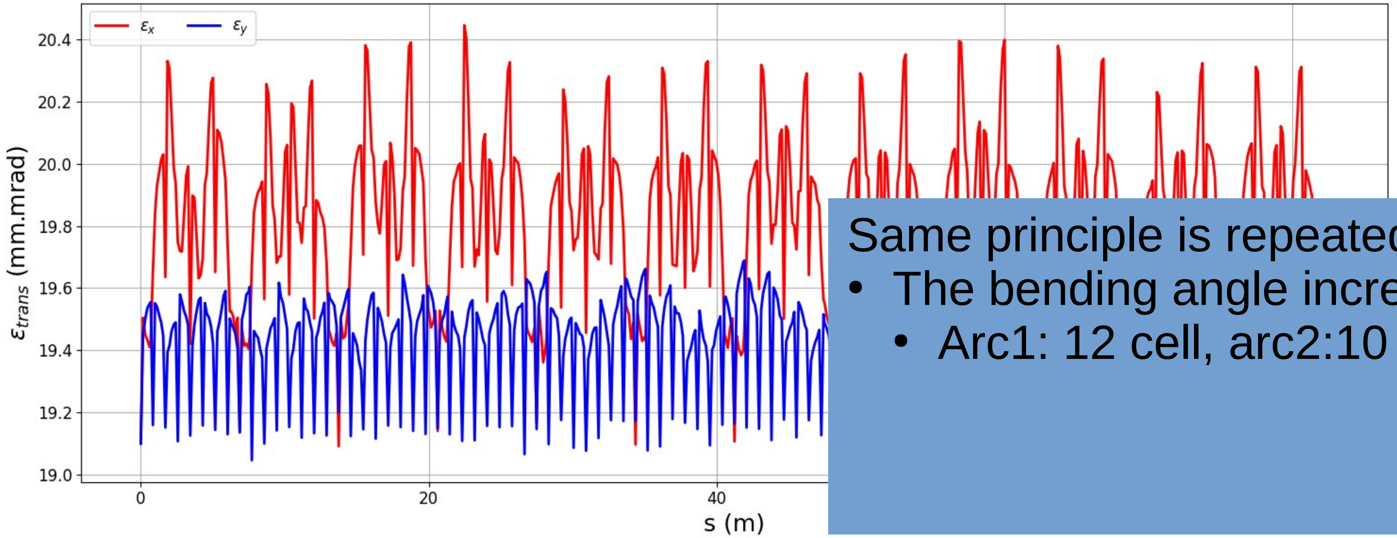
Parameter	Value
p_0 (MeV)	1.2e+04
L (m)	6.87
$< \beta_x >$ (max, min) (m)	1.30 (2.81, 0.37)
$< \beta_y >$ (max, min) (m)	3.12 (5.27, 1.48)
$< \eta_x >$ (max, min) (m)	0.017 (0.035, 9.6e-10)
$\Delta\nu_x$	1.3
$\Delta\nu_y$	0.41
$\Delta\mu_x$ (deg)	450.04
$\Delta\mu_y$ (deg)	147.66
θ_x (deg)	7.50
ξ_x	-1.4
ξ_y	-1
ξ_x	-1.4
ξ_y	-1
α_{px}	0.051
H_x	-3.5e-05

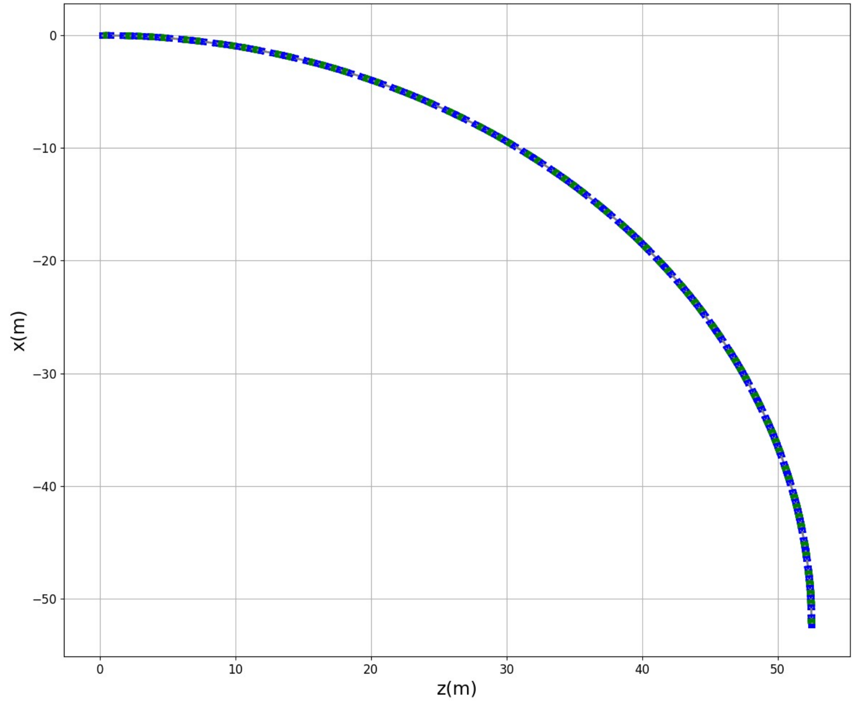




ARC 1-2







Same principle is repeated for other arcs

- The bending angle increased with energy
  - Arc1: 12 cell, arc2:10 cell, arc3:8 cell arc4:6 cell

Last ARC (6 identical cell for 90^o bending)

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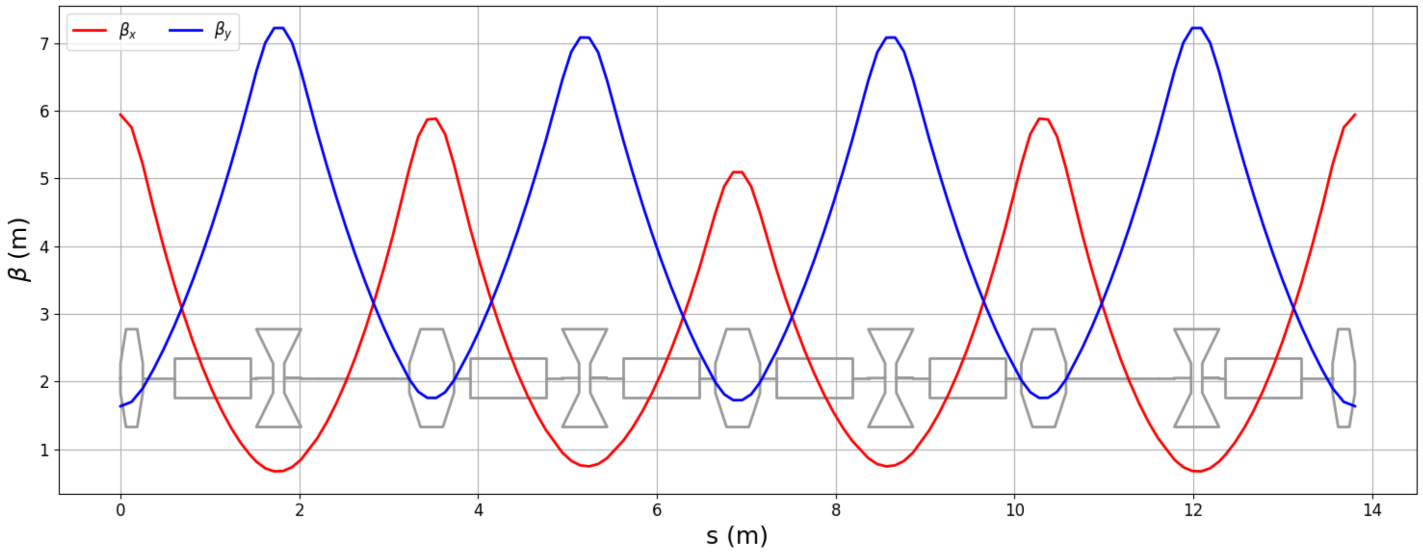
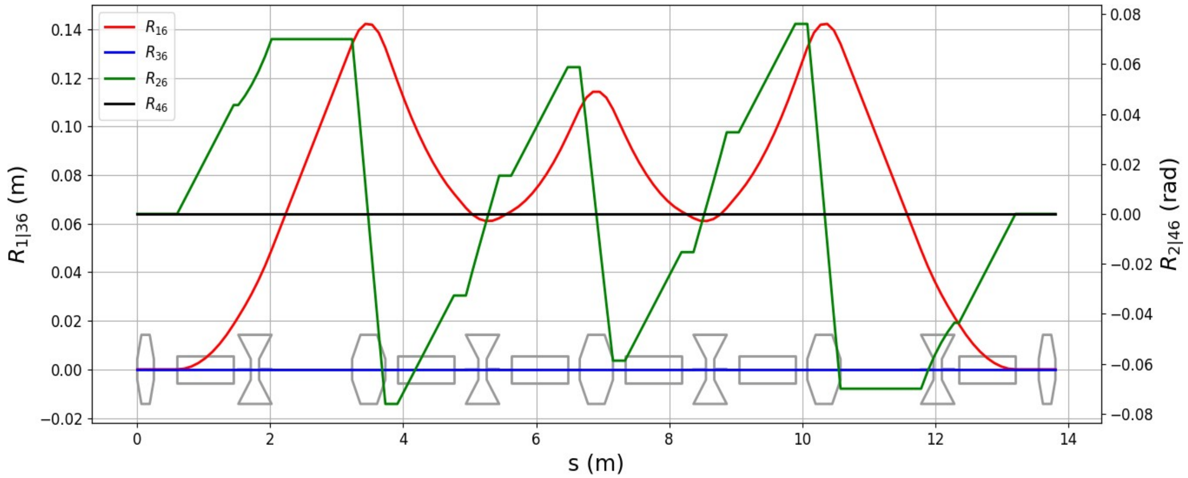
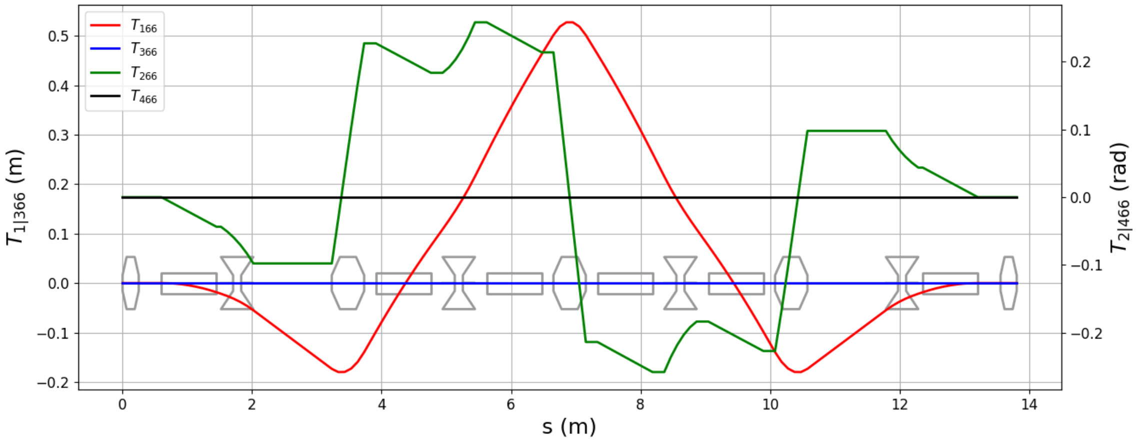


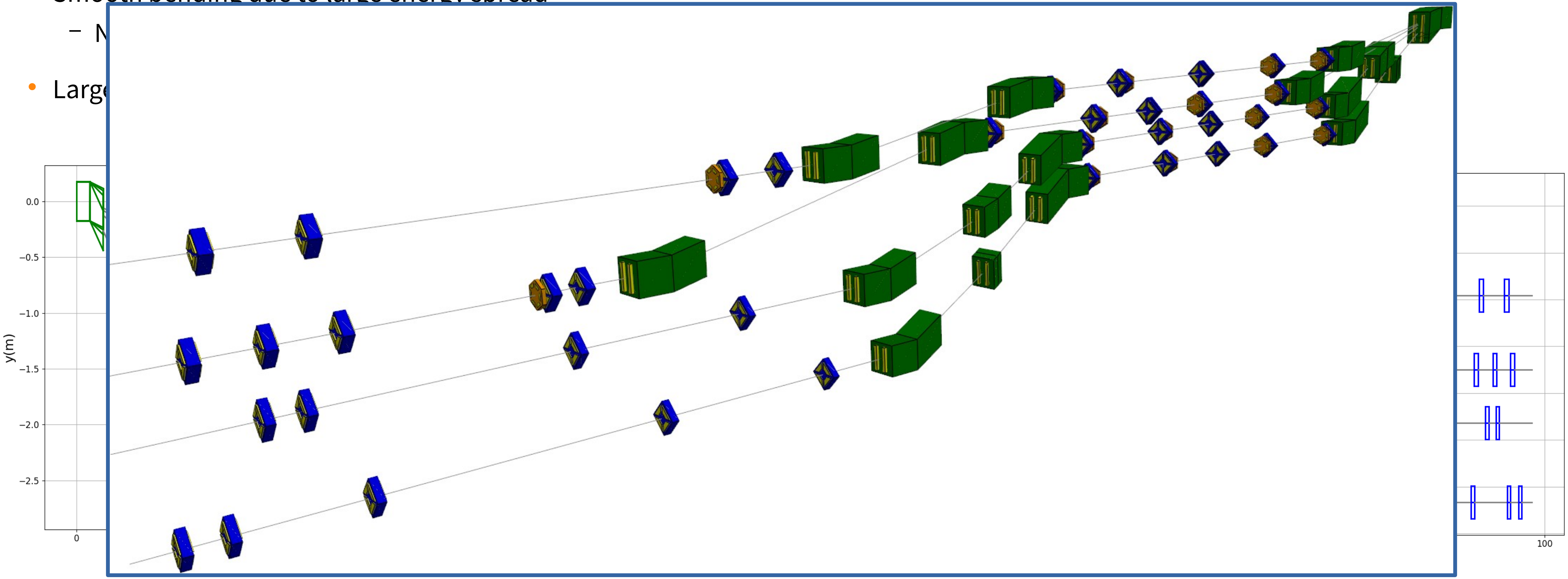
Parameter	Value
p_0 (MeV)	5.2e+04
L (m)	13.81
$<\beta_x>$ (max, min) (m)	2.69 (5.94, 0.68)
$<\beta_y>$ (max, min) (m)	4.10 (7.22, 1.64)
$<\eta_x>$ (max, min) (m)	0.067 (0.14, 1.4e-09)
$\Delta\nu_x$	1.3
$\Delta\nu_y$	0.67
$\Delta\mu_x$ (deg)	460.44
$\Delta\mu_y$ (deg)	239.81
θ_x (deg)	15.00
ξ_x	-1.6
ξ_y	-1.1
ξ_x	-1.6
ξ_y	-1.1
α_{px}	0.42
H_x	-0.0033





Injection / Extraction

- The matching to the linac/arcs are performed by spreaders..
  - Fixed optics
- Smooth bending due to large energy spread
  - N
- Larg



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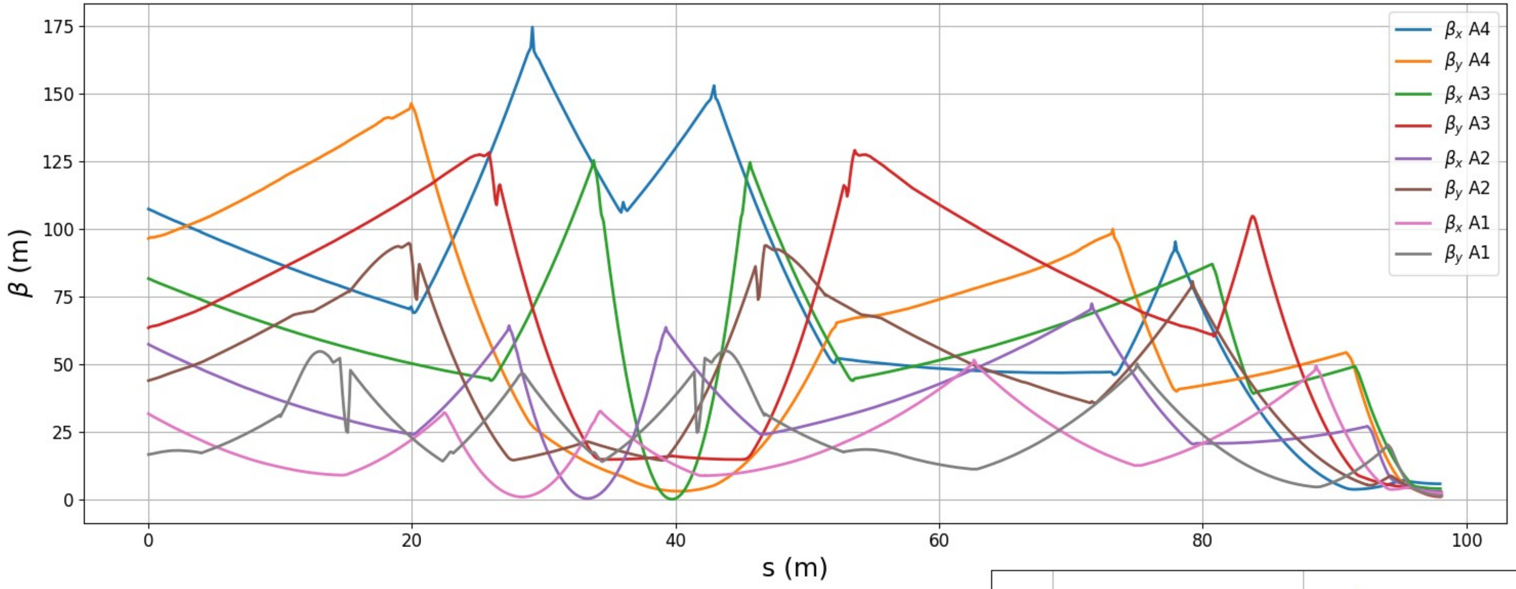
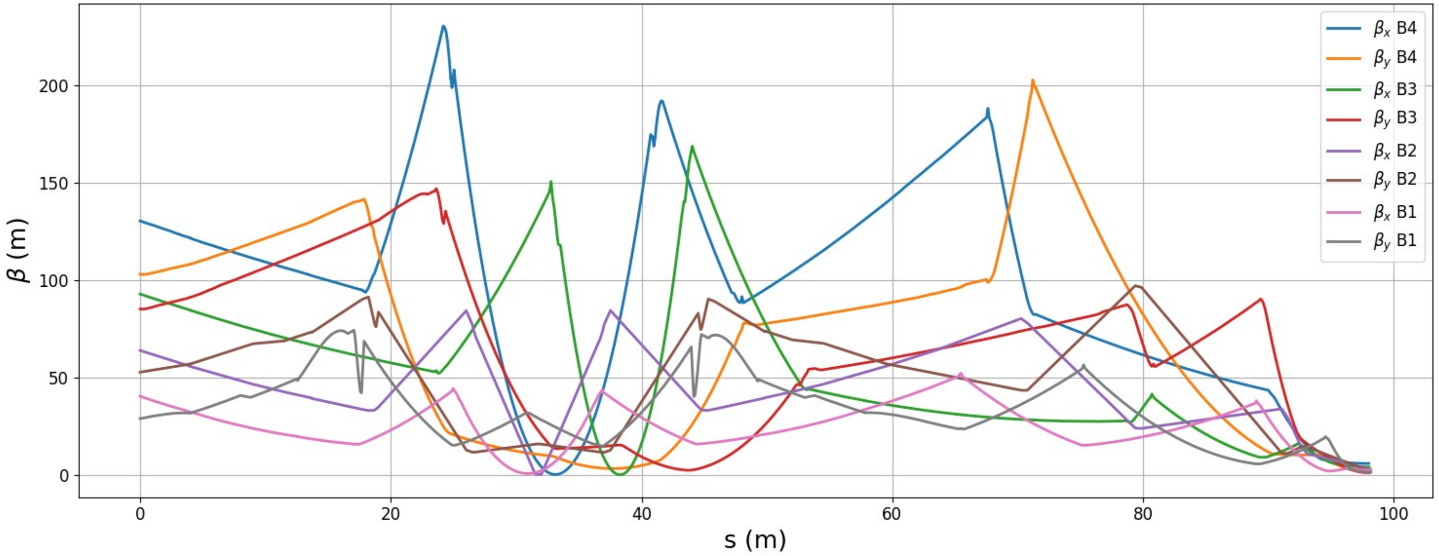
Injection / Extraction matching to linac/arc





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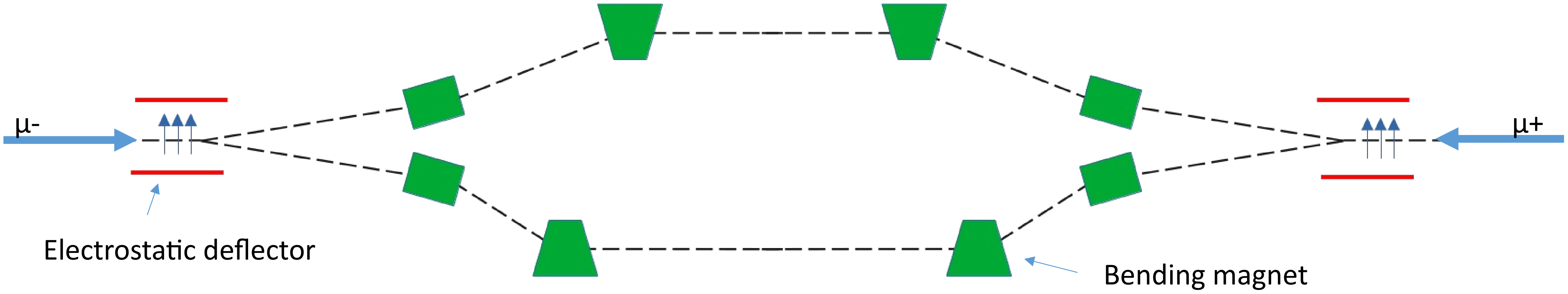
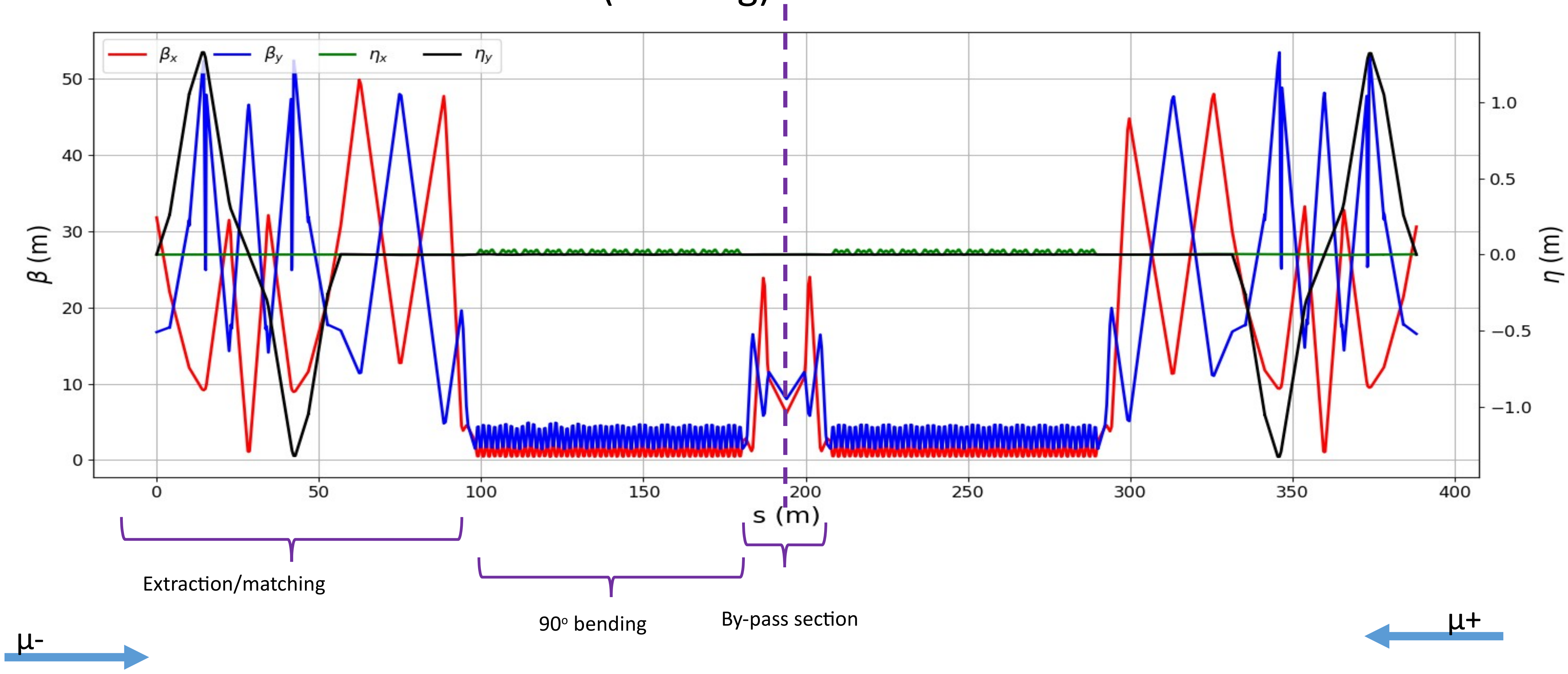
By-pass section

- The phase of beam respect to RF is defined by the arc length.
  - 1 degree RF phase (@350 MHz) is 2.4 mm (0.85 mm for 1 GHz)
- If the beam is injected off-energy to the arc it is impossible to adjust path length within ± several mm
- It is also useful to avoid meeting the opposite propagating bunches



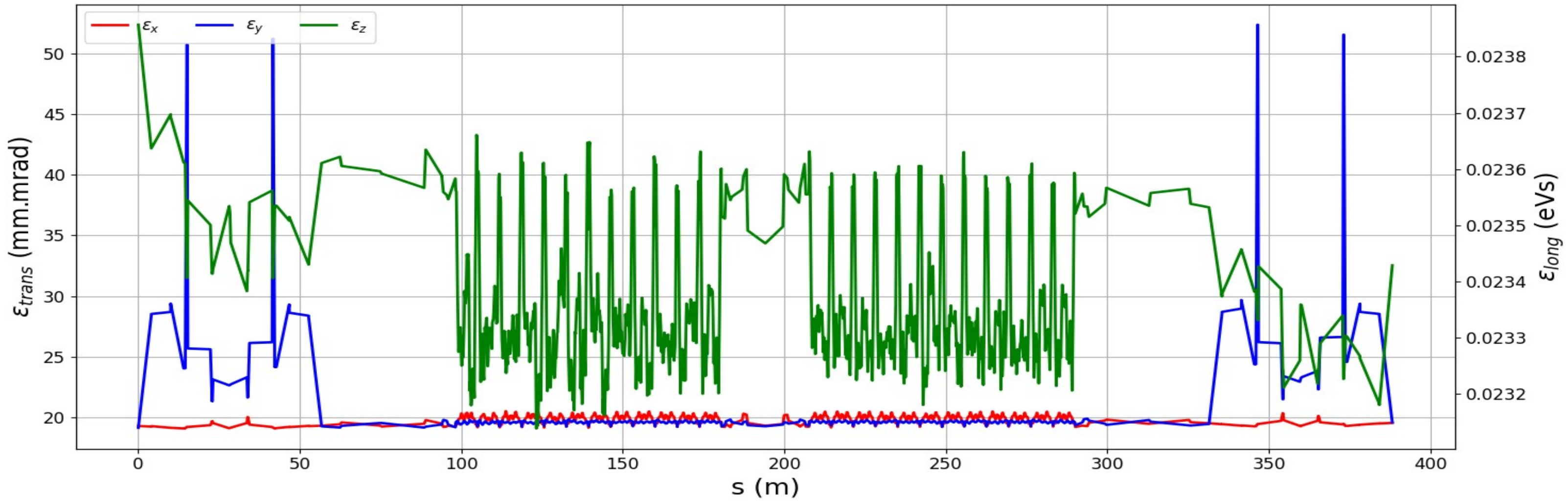
Beam dynamics in arcs

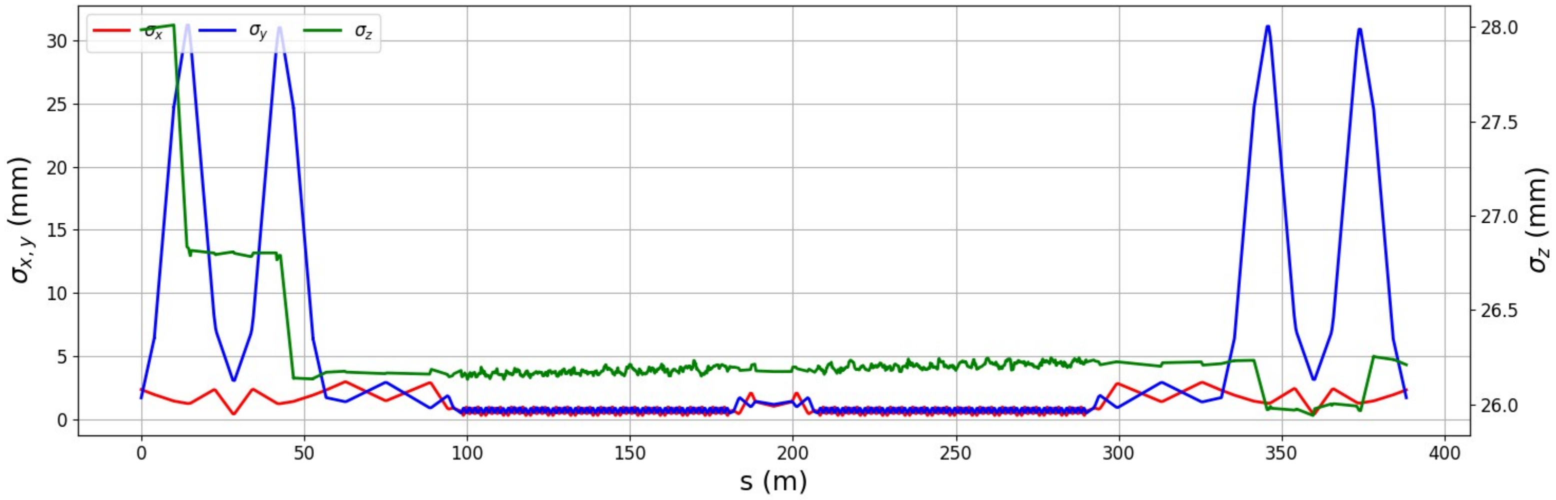
- Start to end simulation in first arc (tracking)



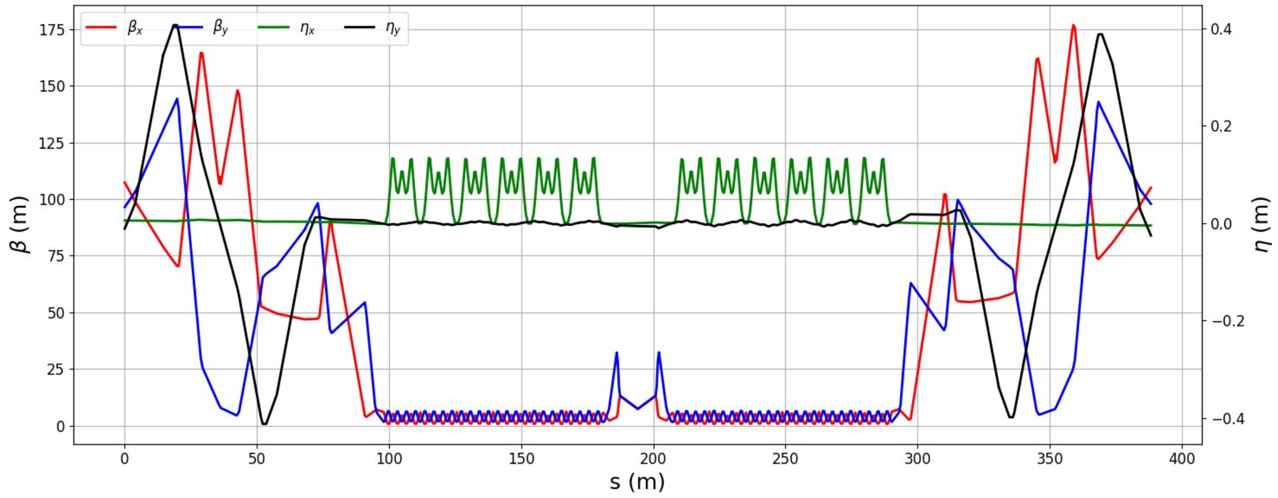
Beam dynamics in arcs

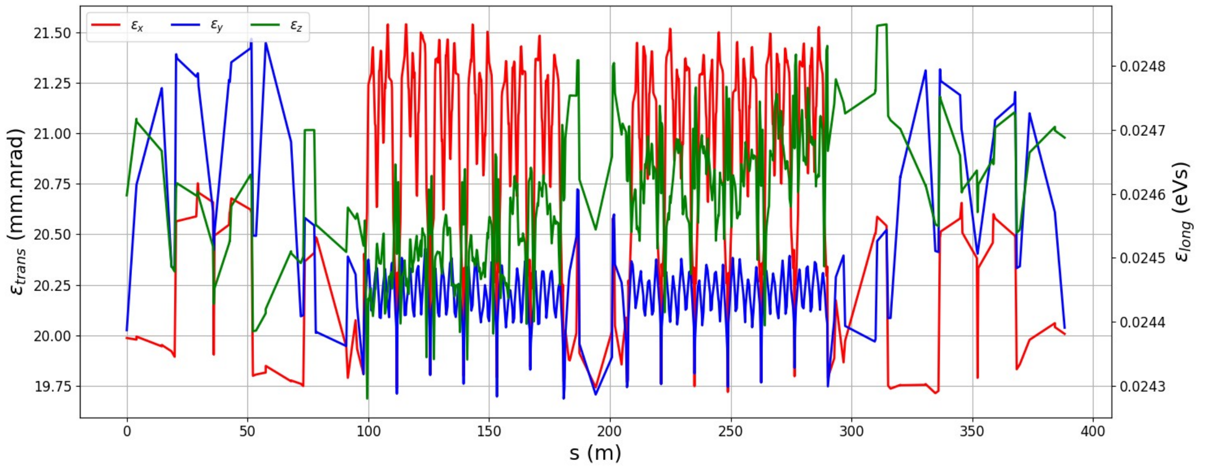
- Start to end simulation in first arc (tracking)

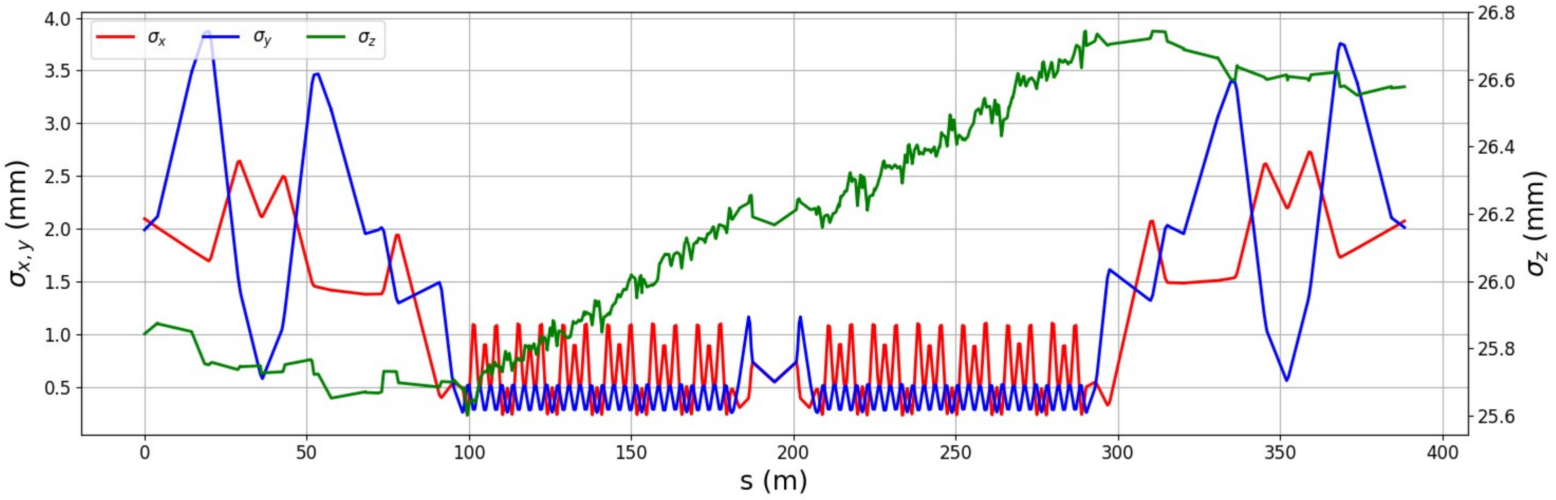




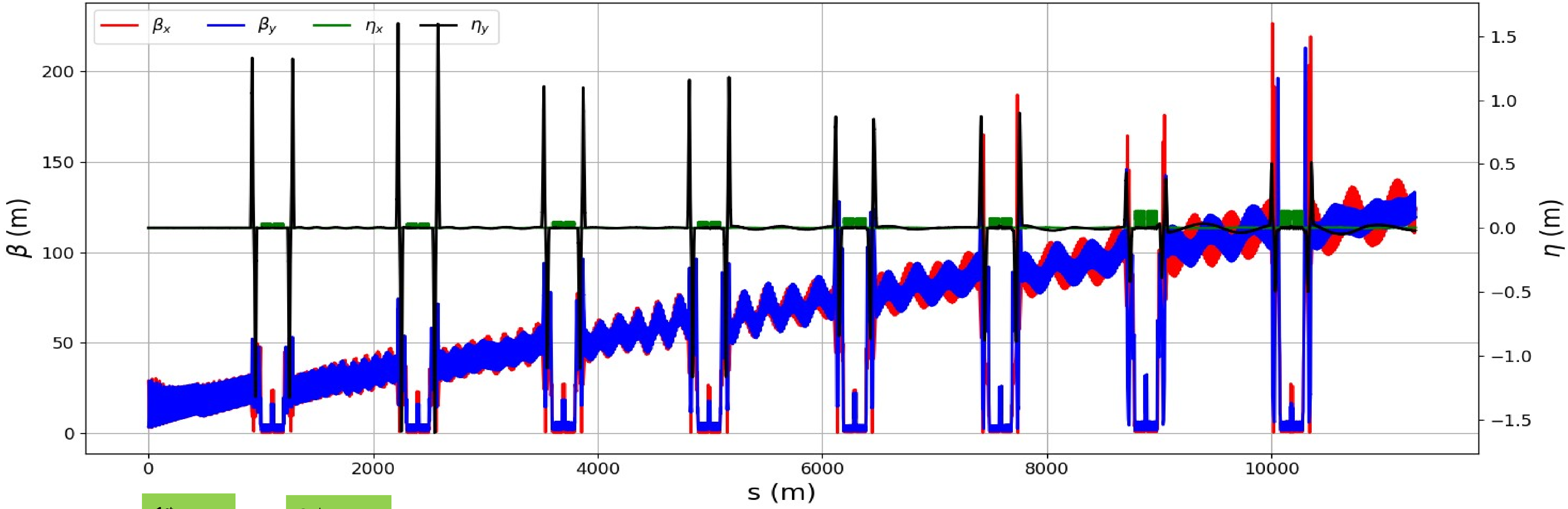
Beam dynamics in last arc







Start to end of all machine



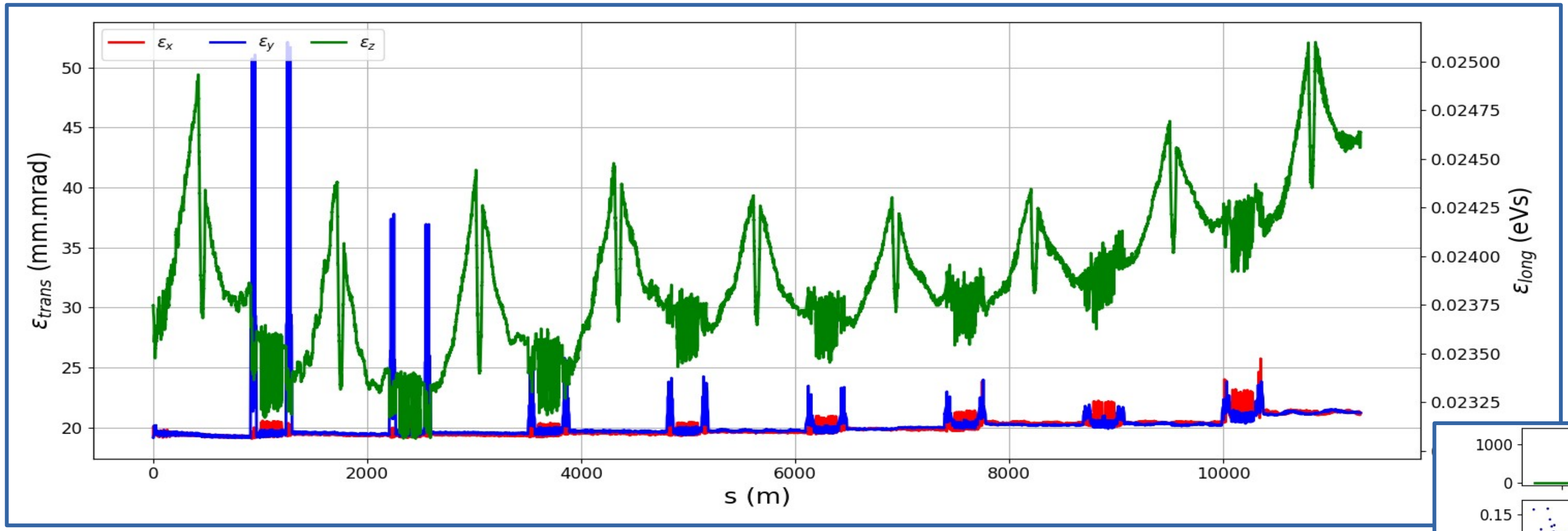
1st pass

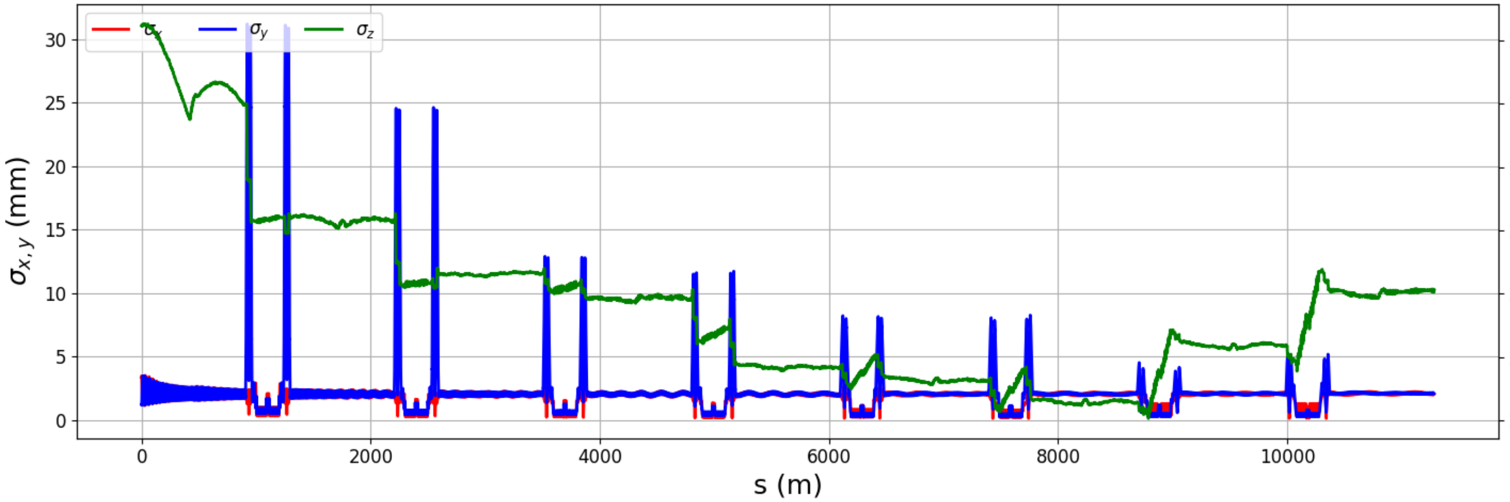
2nd pass

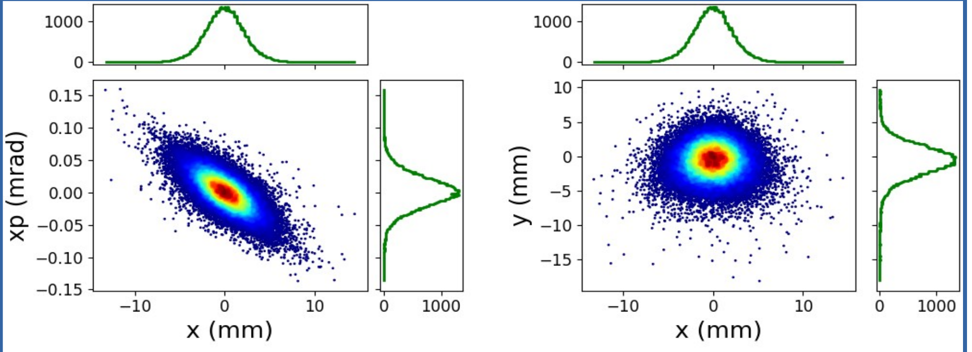
1st arc

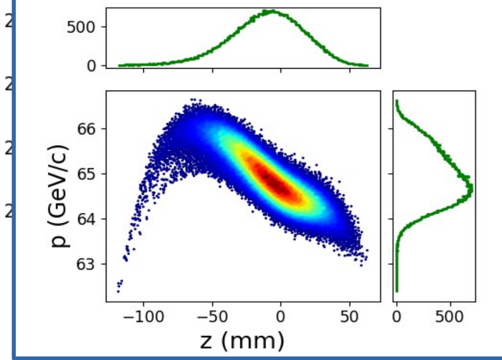
....

Start to end simulation of entire machine



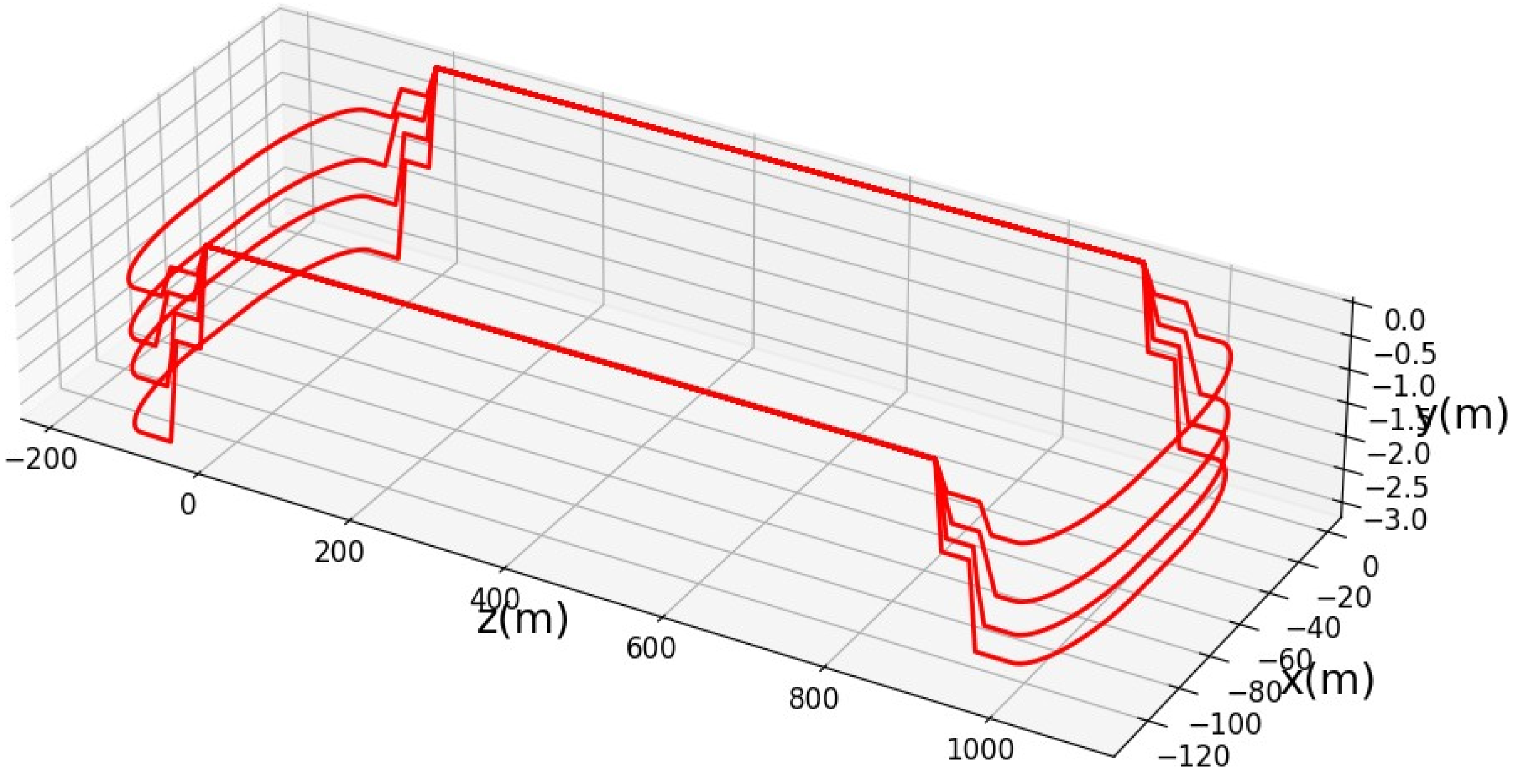




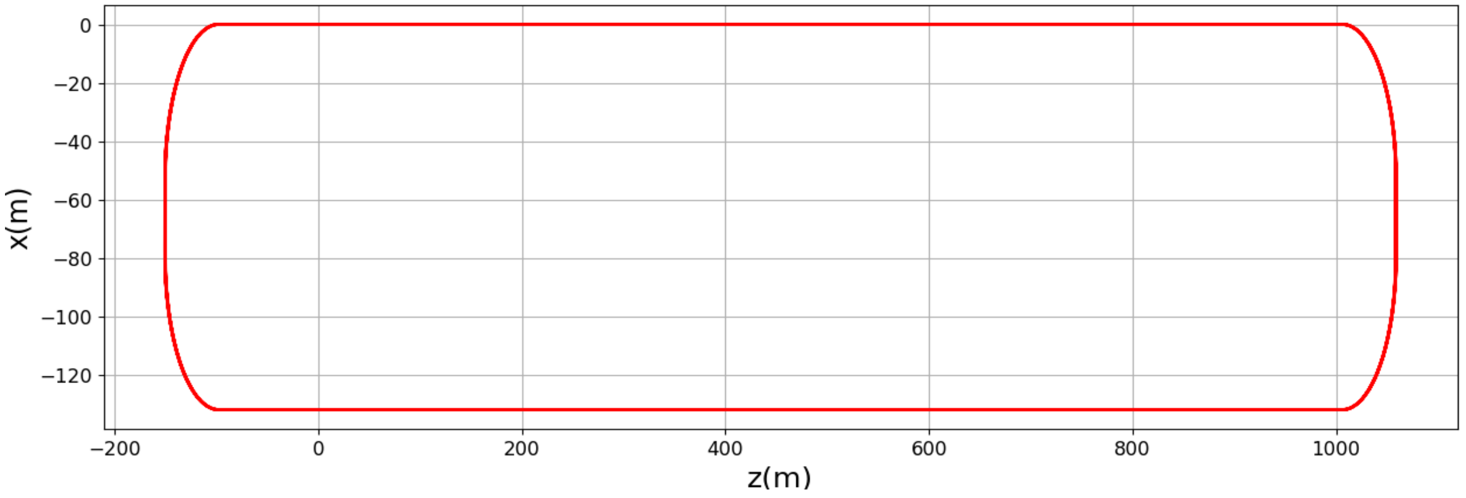


Parameter	Value
E_0 (GeV)	64.81
p_0 (GeV/c)	64.92
Q_b (nC)	3.69e+02
ϵ_x (mm.mrad)	2.13e+01
ϵ_y (mm.mrad)	2.12e+01
ϵ_z (m.MeV/c)	7.39e+00
ϵ_t (eVs)	0.025
σ_x (mm)	2.07e+00
σ_y (mm)	2.04e+00
σ_z (mm)	2.51e+01
σ_p (MeV/c)	5.88e+02
$\Delta p/p_0$ (%)	9.05e-01

Footprint



−200
0
200
400
600
800
1000
z(m)
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
y(m)
0
−20
−40
−60
−80
−100
−120
x(m)



0
−20
−40
−60
−80
−100
−120
x(m)
−200
0
200
400
600
800
1000
z(m)

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
- One can improve longitudinal emittance and transverse emittance meets the target value
  - I need to improve last arc
- 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

Thanks for your attention