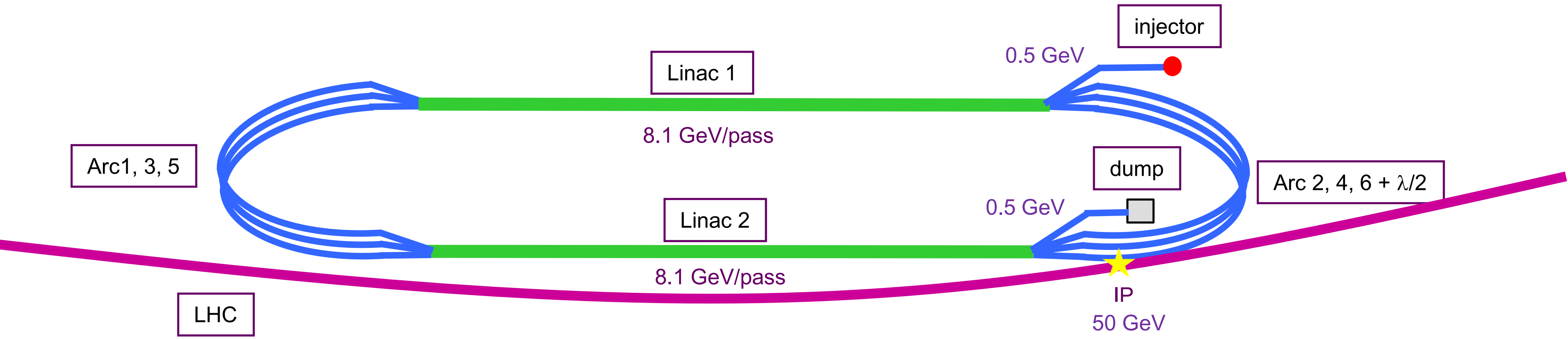
ERL Lattices for the LHeC/FCC-he and PERLE

Alex Bogacz

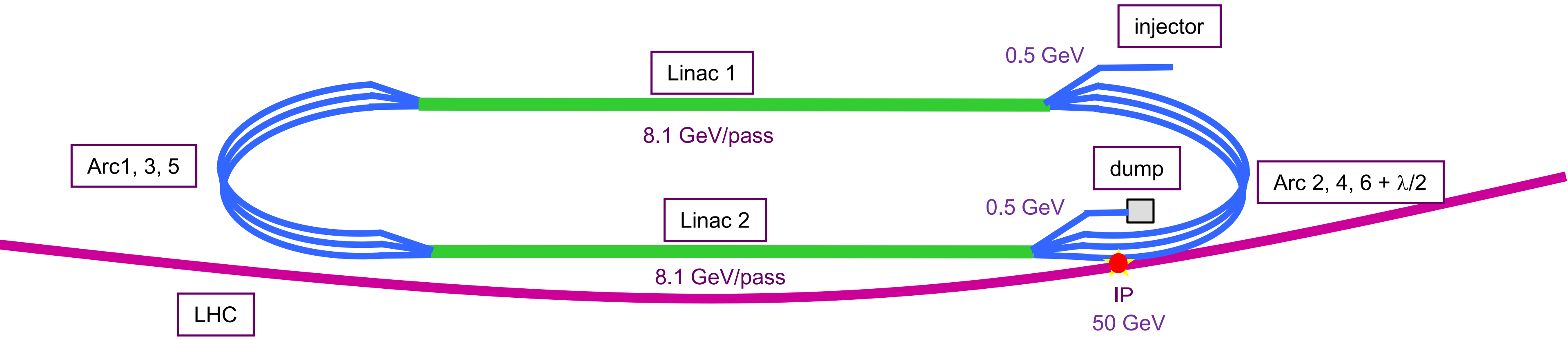
Overview

- New Baseline – 50 GeV ERL
  - Synchrotron radiation effects on beam dynamics
  - Energy scaling considerations
  - Arc optics – Emittance preserving lattices & quasi-isochronicity
  - Multi-pass linac optics
- Higher Energy ERL Options for FCC-he
  - 60 and 100 GeV ERLs
- PERLE Design
  - Lattice modularity, FMC Arc Optics

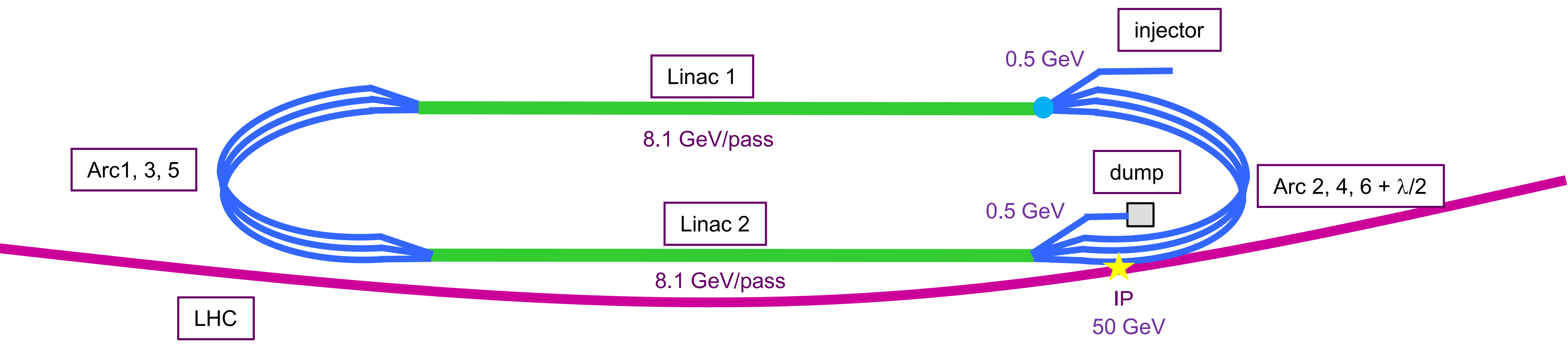
LHeC Recirculator with Energy Recovery



LHeC Recirculator with Energy Recovery



LHeC Recirculator with Energy Recovery



peak luminosity approaching 10^{34} cm^{-2}s^{-1}	unit	parameters
Maximum electron energy	GeV	49.19
Bunch charge	pC	499
Bunch spacing	ns	24.95
Electron current	mA	20
Transverse normalized emittance	µm	20
Total energy gain per linac	GeV	8.114
Frequency	MHz	801.58
Acceleration gradient	MV/m	19.73
Return arc radius (length)	m	536.4 (1685.1)
Total ERL length	km	5.332

Synchrotron Radiation Effects – Beam Dynamics

- Synchrotron radiated energy:

$$DE = \frac{2}{3} r_0 mc^2 g^4 I_2 \qquad I_2 = \grave{o}_0^L \frac{1}{r^2} ds = \frac{q}{r},$$

- Natural energy spread due to quantum excitations:

$$Ds_E^2 = \frac{55a}{48\sqrt{3}} (\hbar c)^2 g^7 I_3 \qquad I_3 = \grave{o}_0^L \frac{1}{|r|^3} ds = \frac{q}{r^2},$$

- Emittance dilution due to quantum excitations:

$$De = \frac{55 r_0}{24\sqrt{3}} \frac{\hbar c}{mc^2} g^5 I_5 \qquad I_5 = \grave{o}_0^L \frac{H}{|r|^3} ds = \frac{q\langle H\rangle}{r^2},$$

$$H = gD^2 + 2aDD' + bD'^2$$

- Momentum Compaction – synchronous acceleration in the linacs:

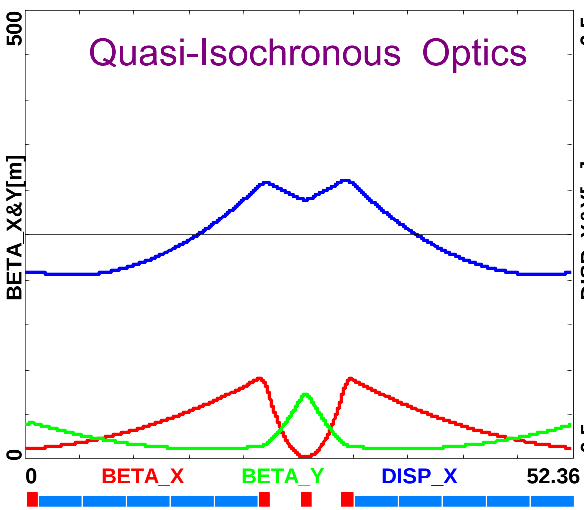
$$M_{56} = \frac{1}{C} I_1 \qquad I_1 = \grave{o}_0^L \frac{D}{r} ds = q\langle D\rangle$$

Arc Optics – Emittance preserving FMC cells

$$\Delta\epsilon_x = \frac{55 r_0}{24\sqrt{3}} \frac{\hbar c}{mc^2} \gamma^5 \langle H_x \rangle \frac{\pi}{\rho^2}$$

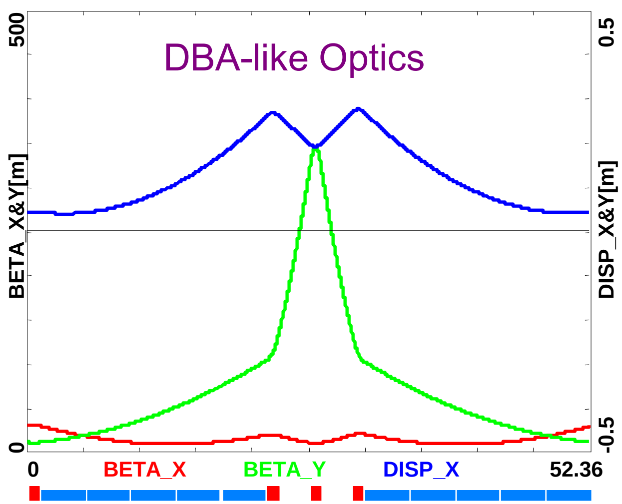
$$H_x = \gamma_x D_x^2 + 2\alpha_x D_x D_x' + \beta_x D_x'^2$$

Arc 1 , Arc2



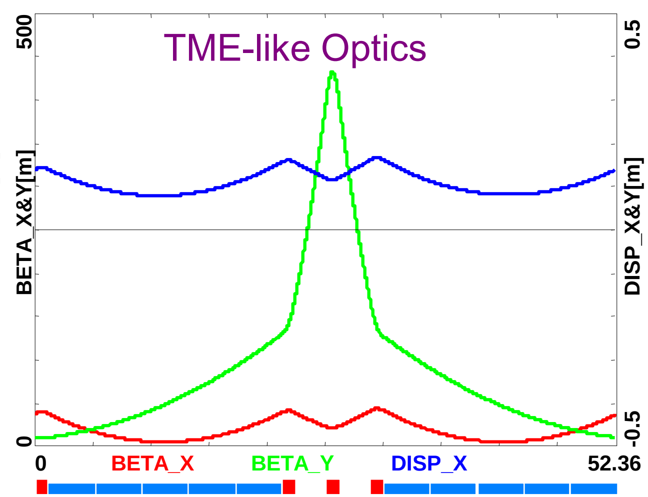
$$\langle H \rangle = 8.8 \times 10^{-3}\ m$$

Arc 3, Arc 4



$$\langle H \rangle = 2.2 \times 10^{-3}\ m$$

Arc 5, Arc 6



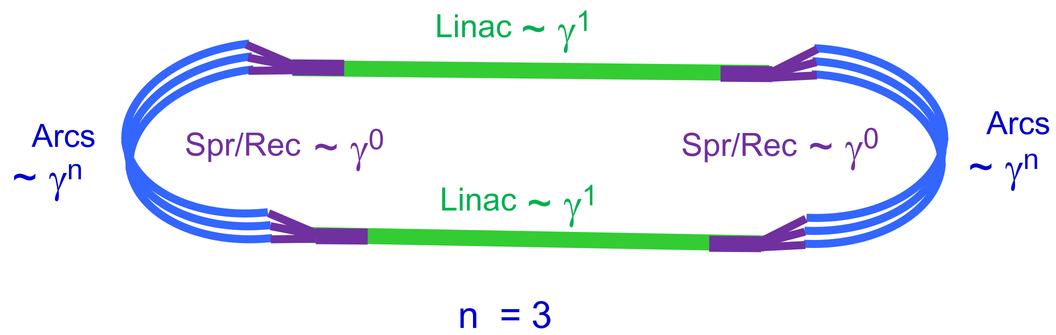
$$\langle H \rangle = 1.2 \times 10^{-3}\ m$$

Energy Scaling – Preserving Emittance Dilution

$$\Delta E = \frac{2\pi}{3} r_0\, mc^2 \frac{\gamma^4}{\rho}, \quad \text{Arc} \sim \gamma^4$$

$$\Delta \epsilon_N = \frac{2\pi}{3} C_q r_0 < H > \frac{\gamma^6}{\rho^2}, \quad \text{Arc} \sim \gamma^3$$

$$\frac{\Delta \epsilon_E^2}{E^2} = \frac{2\pi}{3} C_q r_0 \frac{\gamma^5}{\rho^2}, \quad \text{Arc} \sim \gamma^{5/2}$$



1/5

E [GeV]	49.1
Linac	824
Arc Radius [m]	549
Spr/Rec Matching [m]	76
Circumference [m]	5400

1/3

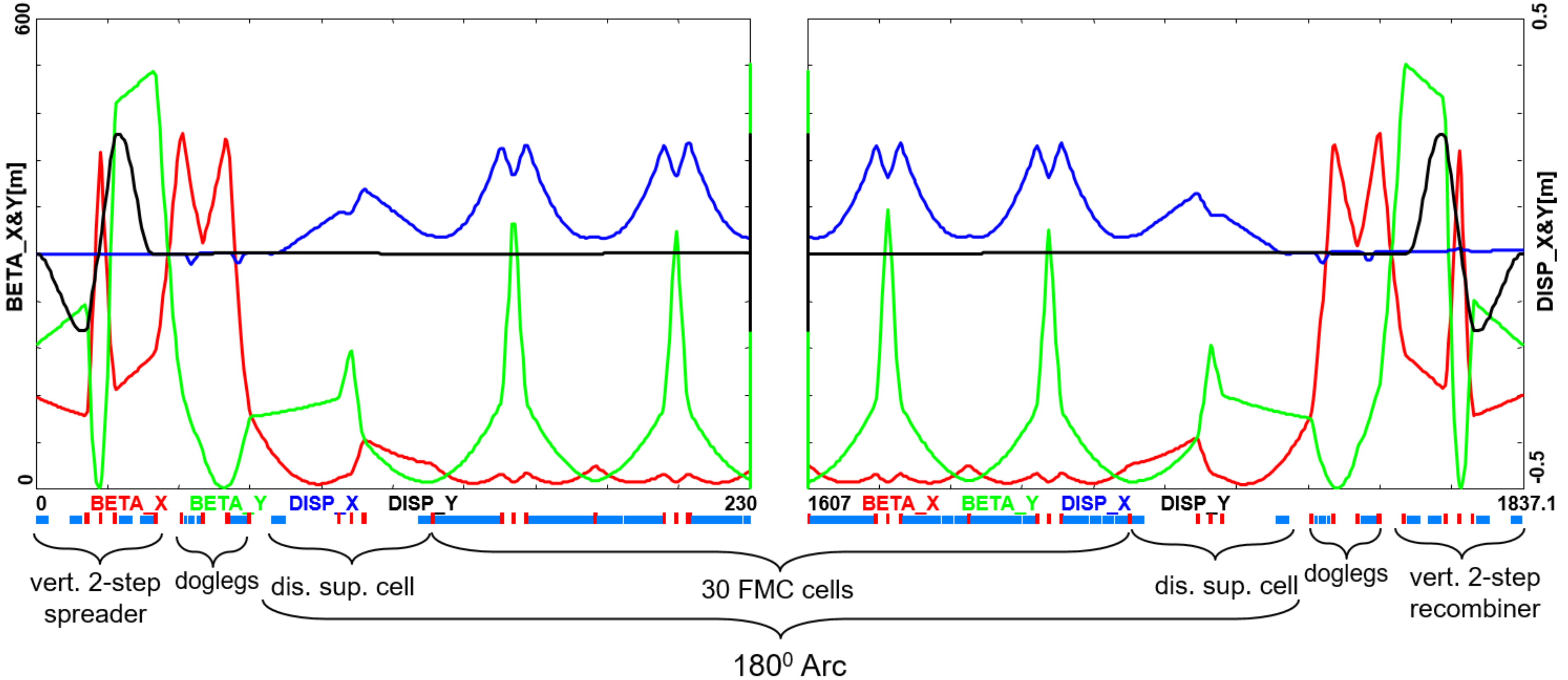
E [GeV]	61.1
Linac	1025
Arc Radius [m]	1058
Spr/Rec Matching [m]	76
Circumference [m]	9000

1/12

E [GeV]	31.3
Linac	525
Arc Radius [m]	142
Spr/Rec Matching [m]	76
Circumference [m]	2248

Normailzed Emittance Dilution before IP [mm mrad]	7.4

Arc 3 Optics (24.9 GeV)

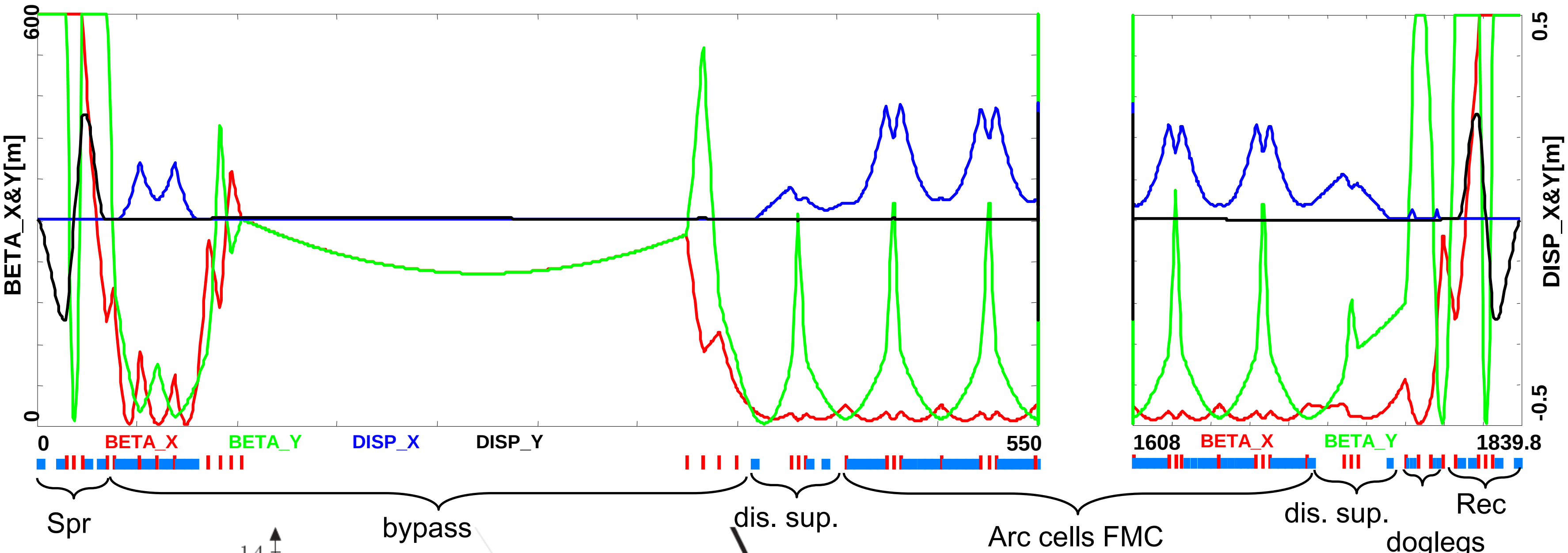


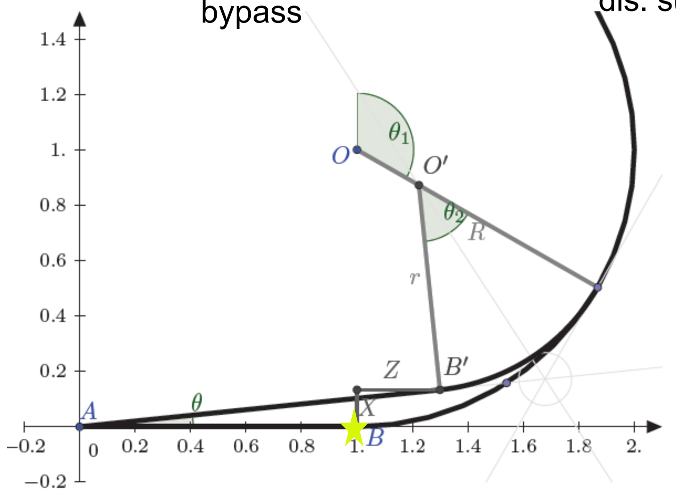
Arc dipoles:

$Lb=400 cm

$B=1.12 kGauss

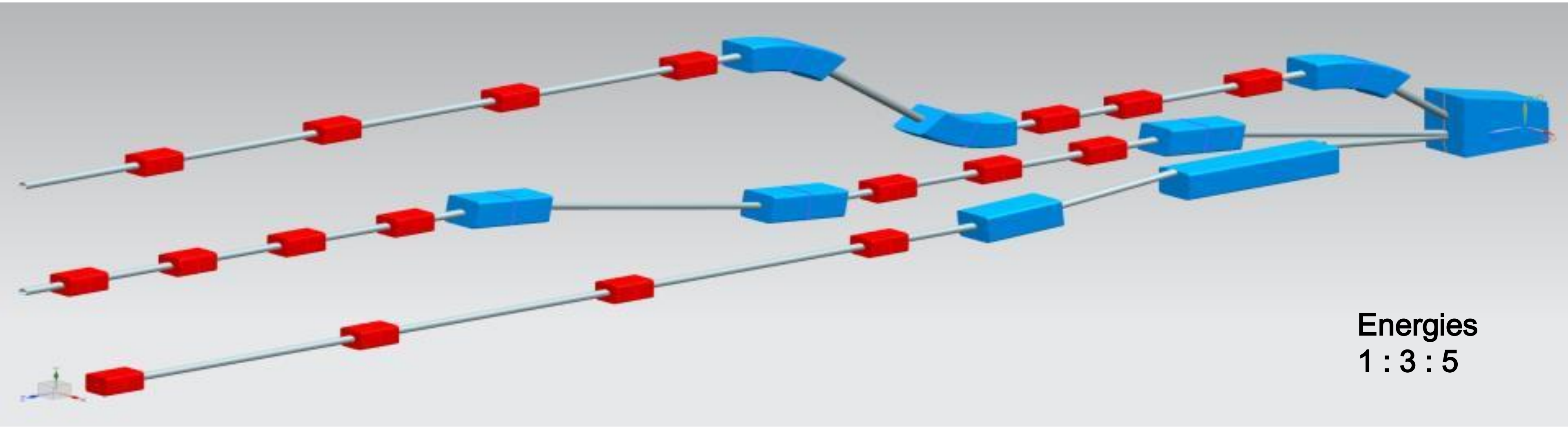
Arc 4 (with bypass) Optics (33.0 GeV)

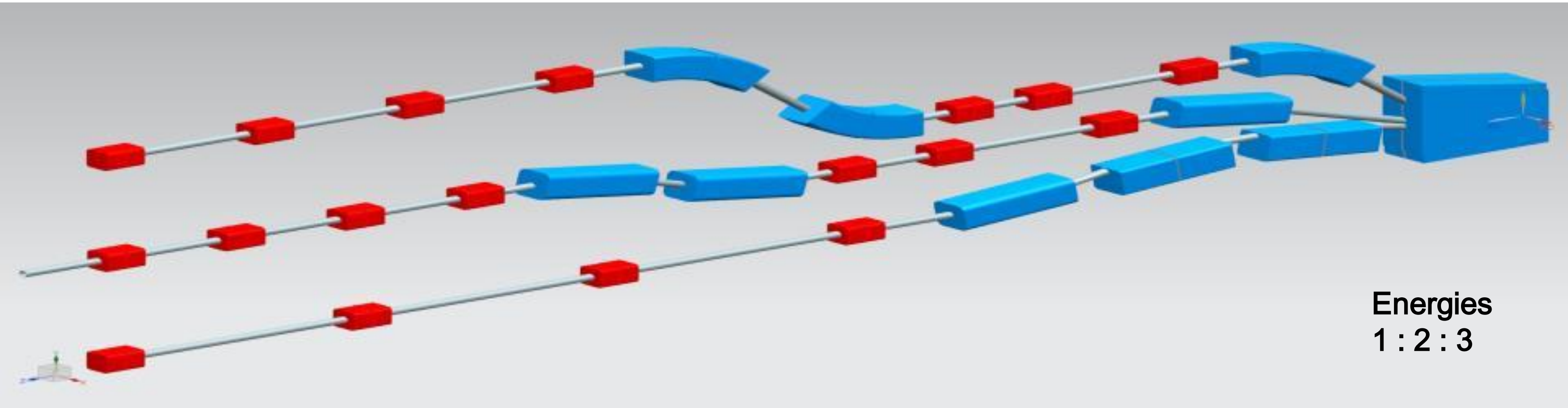




$$X = R + (R - r)\cos(\theta_1) + r\cos(\theta_1 + \theta_2)$$
$$Z = (R - r)\sin(\theta_1) + r\sin(\theta_1 + \theta_2)$$

Vertical Switchyard Architecture





Energy Loss and Emittance Dilution in Arcs

Beamline	Beam energy [GeV]	ΔE [MeV]	$\Delta\epsilon_N$ [mm mrad]	$\Delta\sigma_{\frac{\Delta E}{E}}$ [%]
Arc 1	8.62	1	0.0029	0.00044
Arc 2	16.73	9	0.16	0.0028
Arc 3	24.85	42	0.57	0.0090
Arc 4	32.96	131	2.8	0.022
Arc 5	41.08	316	7.4	0.043
Arc 6	49.19	649	21.0	0.078
Arc 5	41.08	316	25.6	0.10
Arc 4	32.96	131	27.9	0.11
Arc 3	24.85	42	28.3	0.12
Arc 2	16.73	9	28.4	0.12
Arc 1	8.62	1	28.4	0.12
Dump	0.5		28.4	0.12

$$\Delta\sigma_{\frac{\Delta E}{E}} = \sqrt{\frac{\Delta\epsilon^2_E}{E^2}}$$

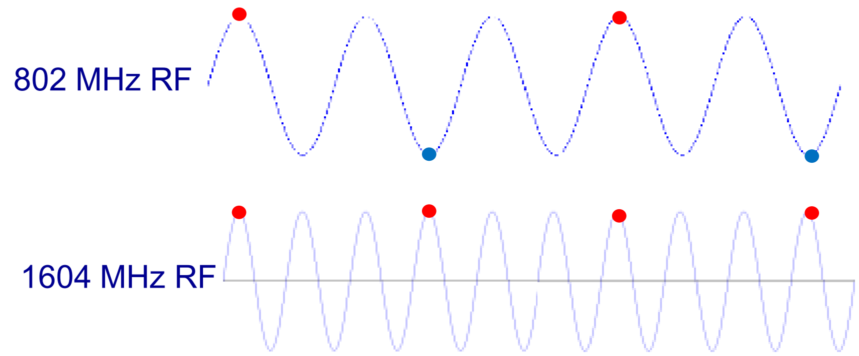
Total Energy Loss [GeV]	1.6
Normailzed Emittance Dilution before IP [mm mrad]	7.4
Net Normailzed Emittance Dilution [mm mrad]	28.4
Net Natural Momentum Spread	0.001

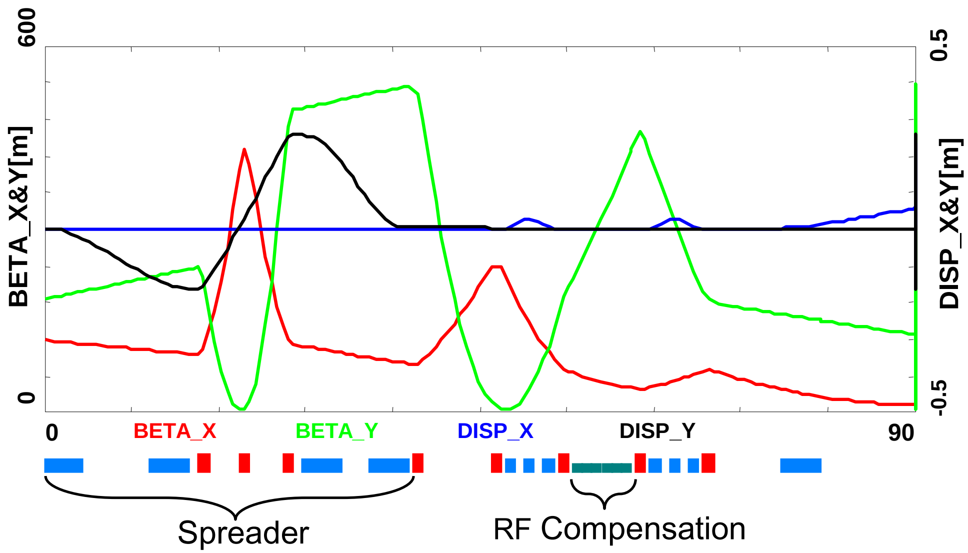
R [m]	536.4
r [m]	398.8

Challenge: decelerating beam (and synchrotron radiation-driven energy spread) adiabatically **anti-**damp.

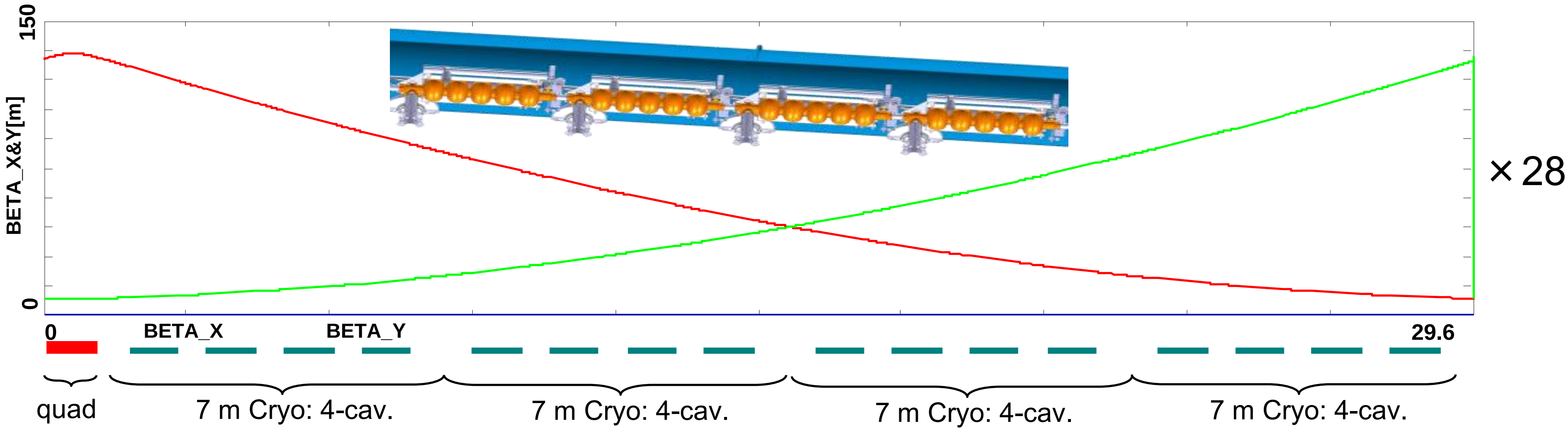
2-nd Harmonics RF Compensation of SR Losses

Arc number	ΔE [MeV]	P [MW]	Cryomodules
1	1	0.03	0
2	9	0.4	0
3	42	2.1	1
4	131	6.6	1
5	316	15.8	2
6	649	32.5	5





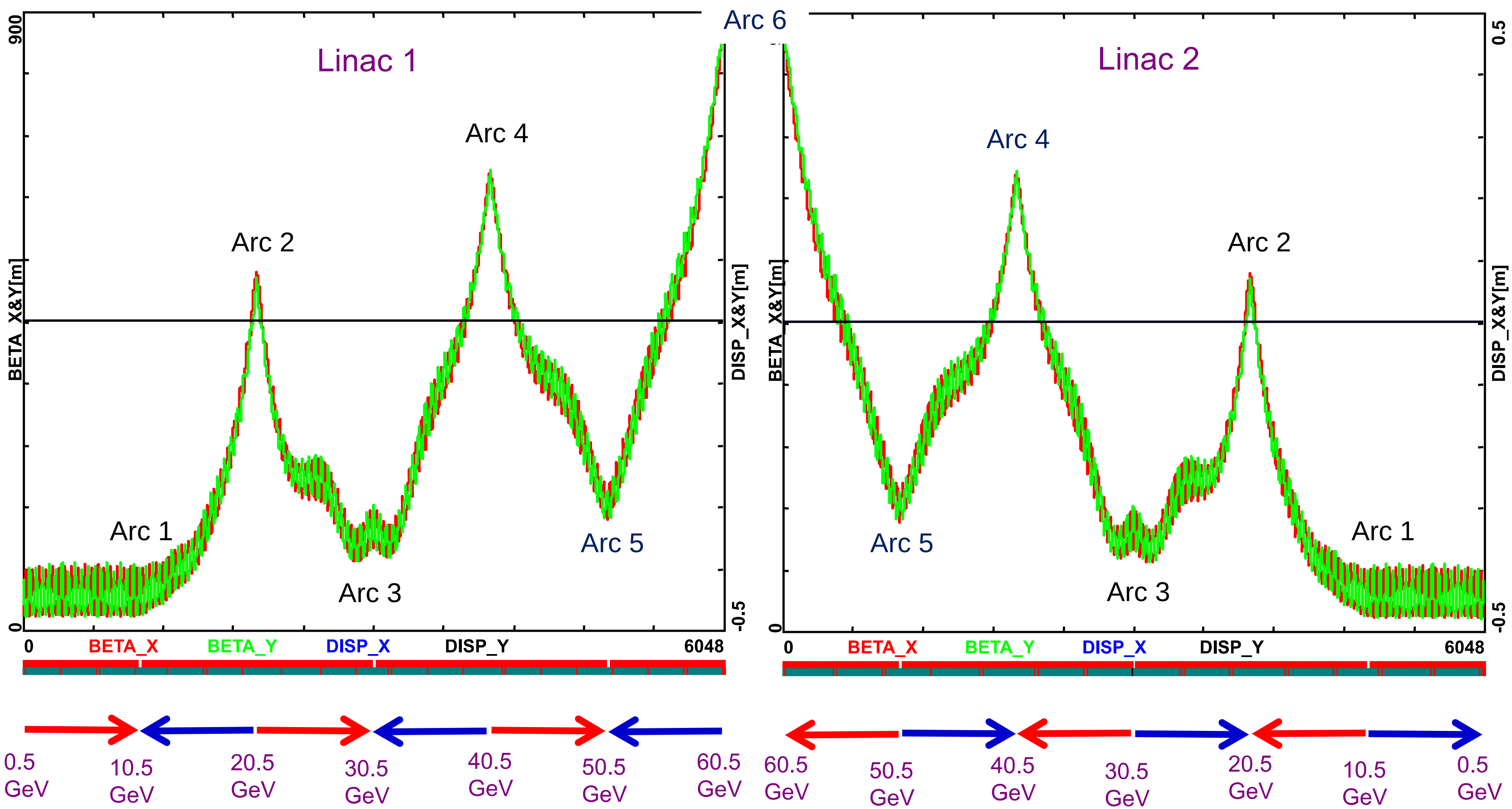
Cryo Unit Layout/Optics – Half-Cell 130^0 FODO



Description	unit	parameters
Total energy gain per linac	GeV	8.114
Frequency	MHz	801.58
Acceleration gradient	MV/m	19.73
Cavity iris diameter	mm	130
Number of cells per cavity		5
Cavity length (active/real estate)	m	0.918/1.5
Cavities per cryomodule		4
Cryomodule length	m	7
Length of 4-CM unit	m	29.6
Acceleration per cryomodule (4-CM unit)	MeV	289.8
Total number of cryomodules (4-CM units) per linac		112 (28)

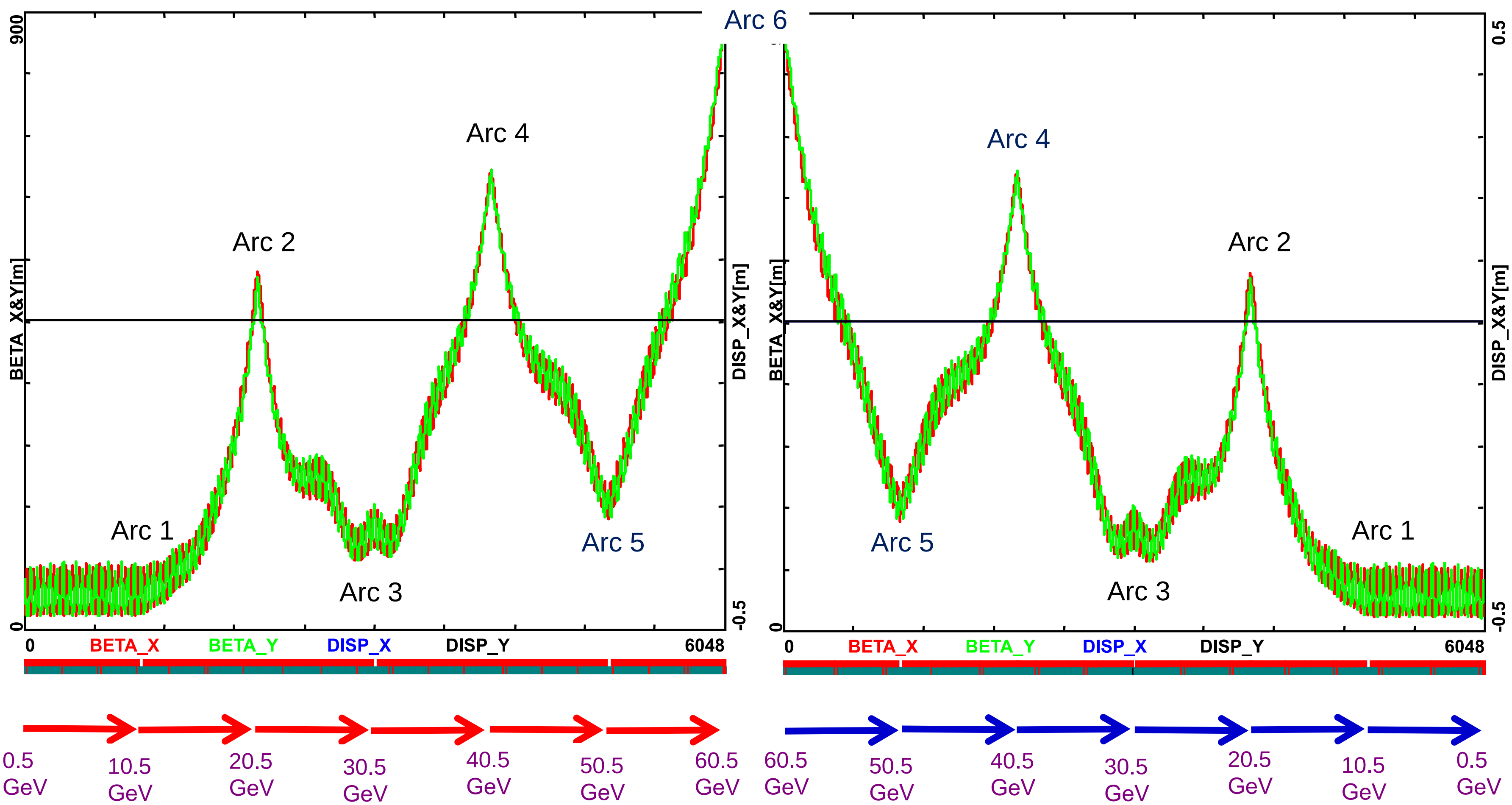
Linac 1 and 2 – Multi-pass ER Optics

Acceleration/Deceleration



Linac 1 and 2 – Multi-pass ER Optics

Acceleration/Deceleration



End-to-End ERL Tracking (PLACET 2)

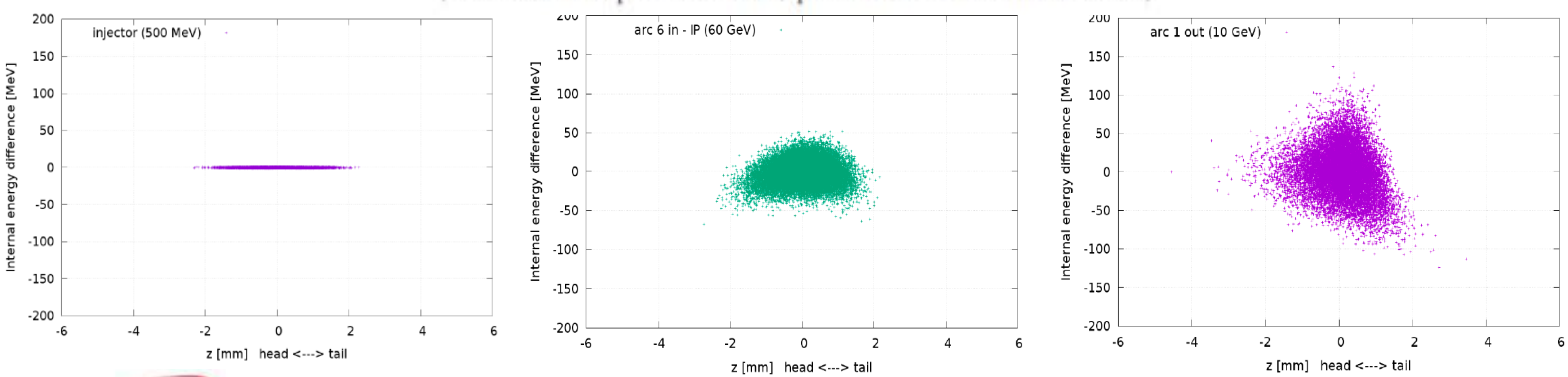
PHYSICAL REVIEW SPECIAL TOPICS—ACCELERATORS AND BEAMS **18**, 121004 (2015)

*

Beam-dynamics driven design of the LHeC energy-recovery linac

Dario Pellegrini, Andrea Latina, and Daniel Schulte
CERN, Geneva CH-1211, Switzerland

S. Alex Bogacz
Jefferson Lab, Newport News, Virginia 23606, USA
(Received 3 September 2015; published 23 December 2015)



FCC-he ERLs

EDMS 17979910 | FCC-ACC-RPT-0012 V1.0, 6 April, 2017

Future Circular Collider Study
FCC-he Baseline Parameters

Oliver Brüning[1], John Jowett[1], Max Klein[2],
Dario Pellegrini[1], Daniel Schulte[1], Frank Zimmermann[1]
[1] CERN, [2] University of Liverpool

Parameter	Unit	Protons	Electrons
Beam energy	GeV	50000	60
Normalised emittance	μm	$2.2 \rightarrow 1.1$	10
IP betafunction	mm	150	$42 \rightarrow 52$
Nominal RMS beam size	μm	$2.5 \rightarrow 1.8$	$1.9 \rightarrow 2.1$
Waist shift	mm	0	$65 \rightarrow 70$
Bunch population	10^{10}	$10 \rightarrow 5$	0.31
Bunch spacing	ns	25	25
Luminosity	10^{33}cm^{-2}s^{-1}	$18.3 \rightarrow 14.3$	
Int. luminosity per 10 years	[ab^{-1}]	1.2	

FCC-he ERLs

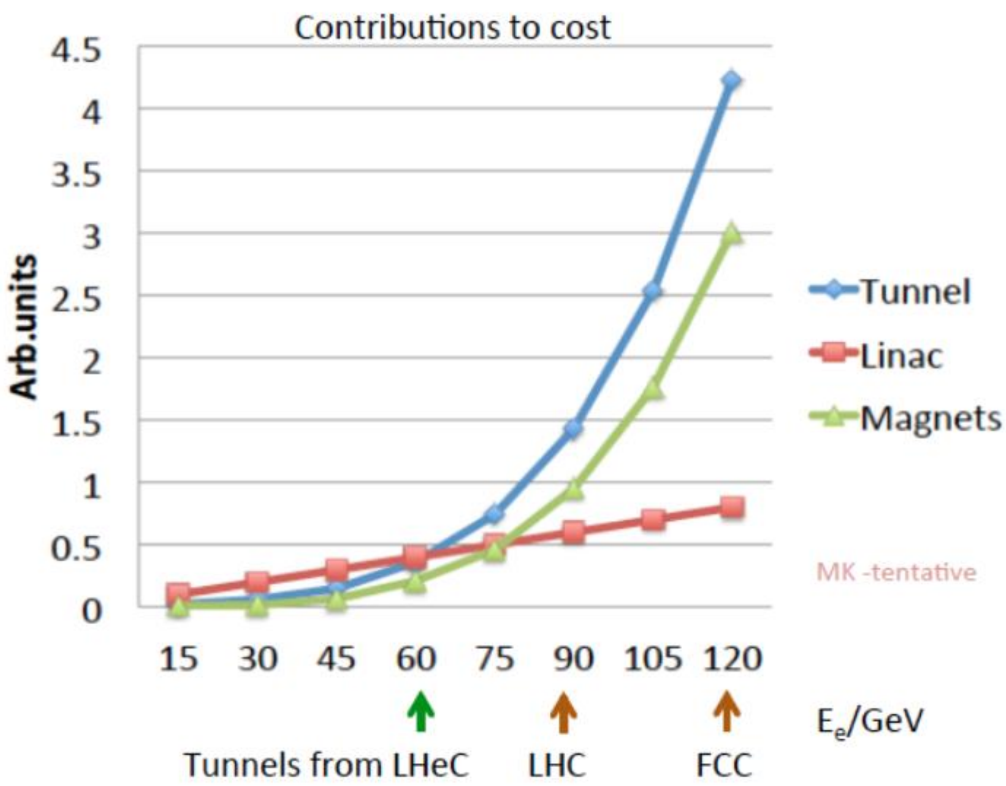
Parameter	Unit	Protons	Electrons
Beam energy	GeV	50000	60
Normalised emittance	μm	$2.2 \rightarrow 1.1$	10
IP betafunction	mm	150	$42 \rightarrow 52$
Nominal RMS beam size	μm	$2.5 \rightarrow 1.8$	$1.9 \rightarrow 2.1$
Waist shift	mm	0	$65 \rightarrow 70$
Bunch population	10^{10}	$10 \rightarrow 5$	0.31
Bunch spacing	ns	25	25
Luminosity	$10^{33}\text{cm}^{-2}\text{s}^{-1}$	$18.3 \rightarrow 14.3$	
Int. luminosity per 10 years	$[\text{ab}^{-1}]$	1.2	

⅓	
E [GeV]	61.1
Linac	1025
Arc Radius [m]	1058
Spr/Rec Matching [m]	76
Circumference [m]	9000

$$\Delta E = \frac{2\pi}{3} r_0 \, mc^2 \frac{\gamma^4}{\rho}$$

FCC - 100 GeV	
E [GeV]	100.0
Linac	1677
Arc Radius [m]	7716
Spr/Rec Matching [m]	76
Circumference [m]	52139

Energy dependence of the main component cost



$$\Delta E = \frac{2\pi}{3} r_0 \, mc^2 \, \frac{\gamma^4}{\rho}$$

Arc ~ γ^4

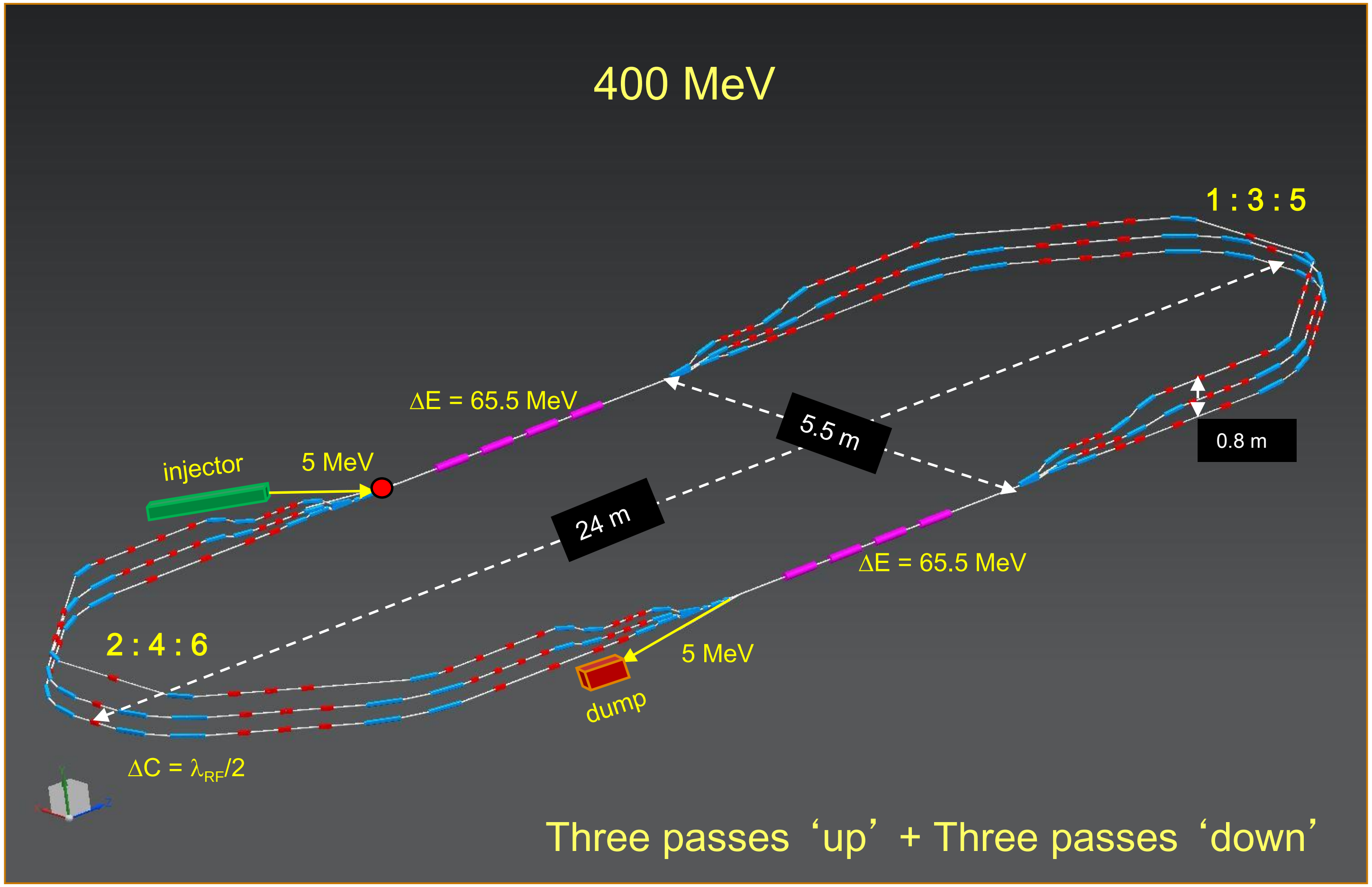
$$\Delta \epsilon = \frac{2\pi}{3} C_q r_0 < H > \frac{\gamma^5}{\rho^2}$$

$$\frac{\Delta \epsilon_E^2}{E^2} = \frac{2\pi}{3} C_q r_0 \, \frac{\gamma^5}{\rho^2},$$

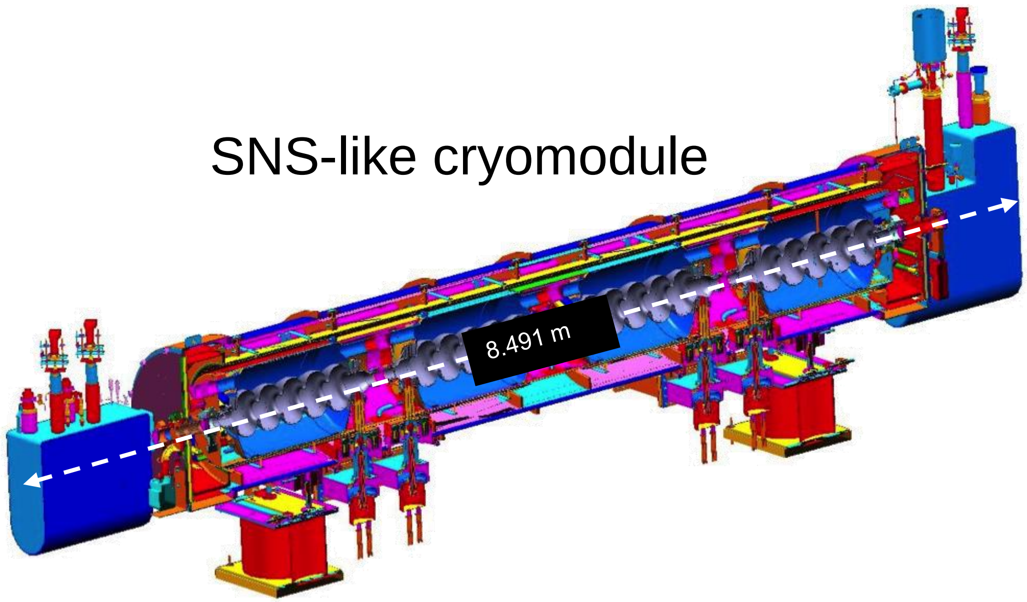
Arc ~ $\gamma^{5/2}$

The LHeC ERL at 60 GeV (about 9 km), for which linac and tunnel cost would be approximately equal and the magnet cost would be slightly smaller. If one used a tunnel of the LHC size (triple the original ERL circumference), the tunnel cost would dominate, while the linac and magnet costs would stay comparable up to about 90 GeV.

PERLE@Orsay - Layout



Linac, Cryo-module - Layout



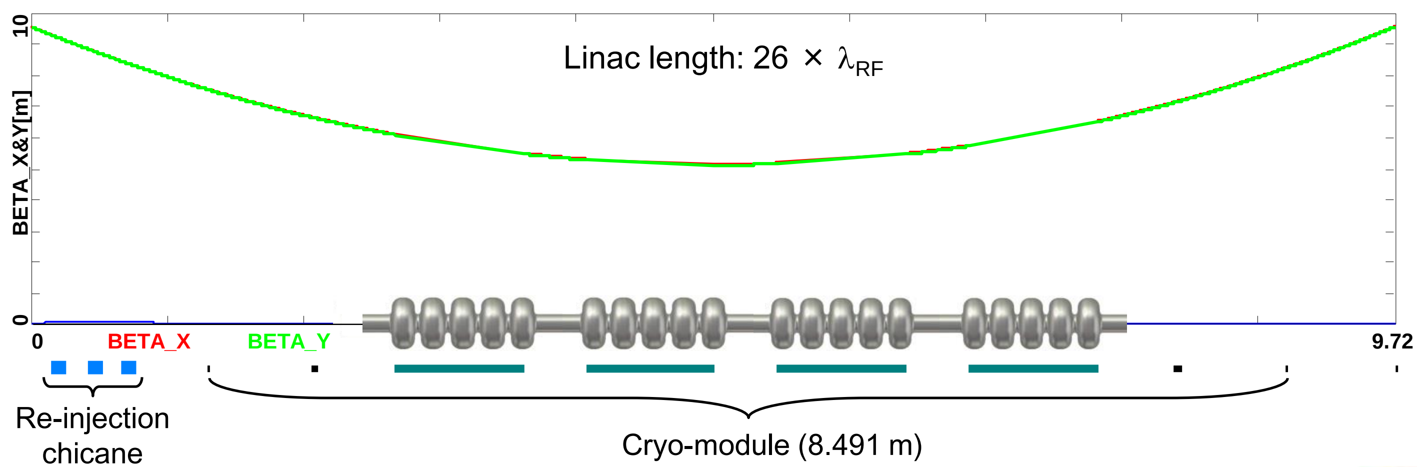
801.58 MHz RF, 5-cell cavity:

λ = 37.40 cm

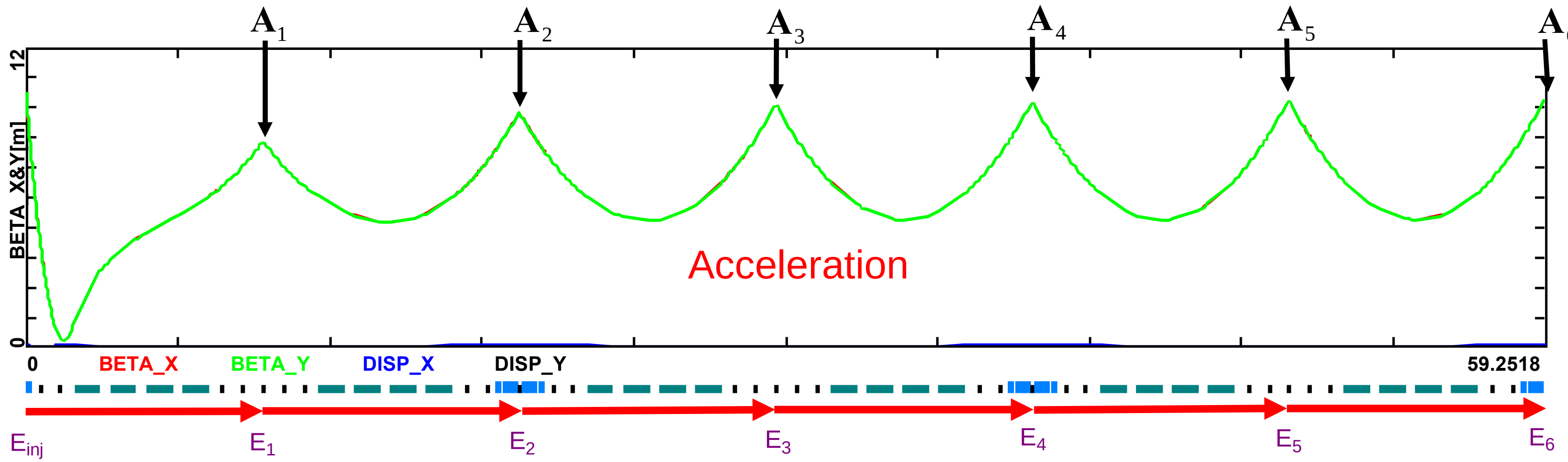
$L_c = 5\lambda/2 = 93.50$ cm

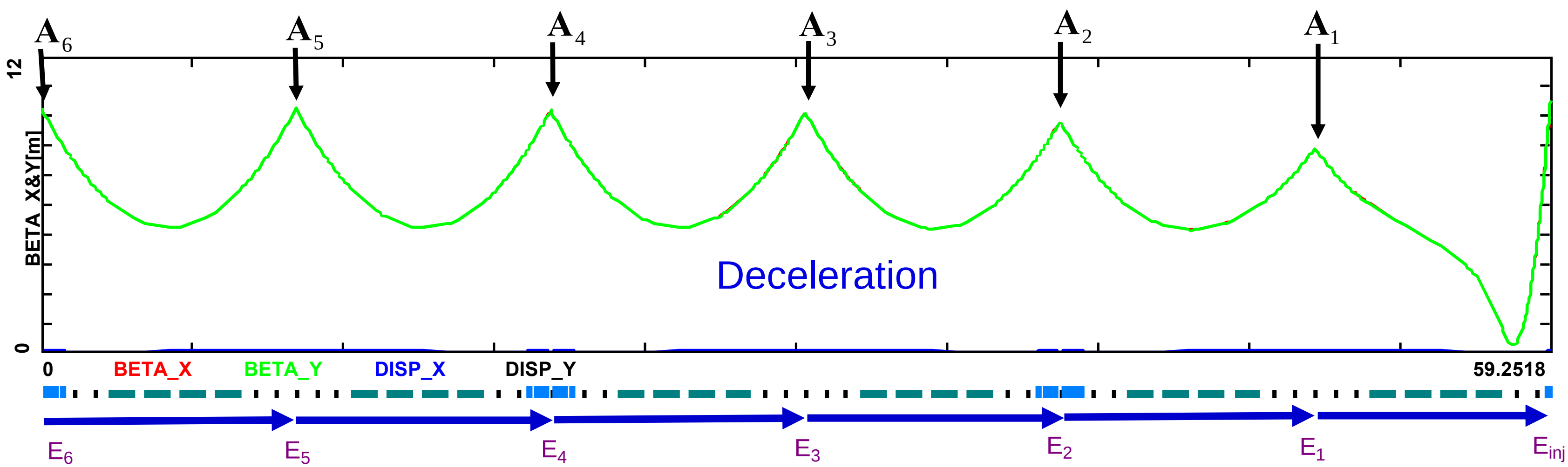
Grad = 17.5 MeV/m (16.4 MeV per cavity)

ΔE= 65.5 MeV per Cryo-module

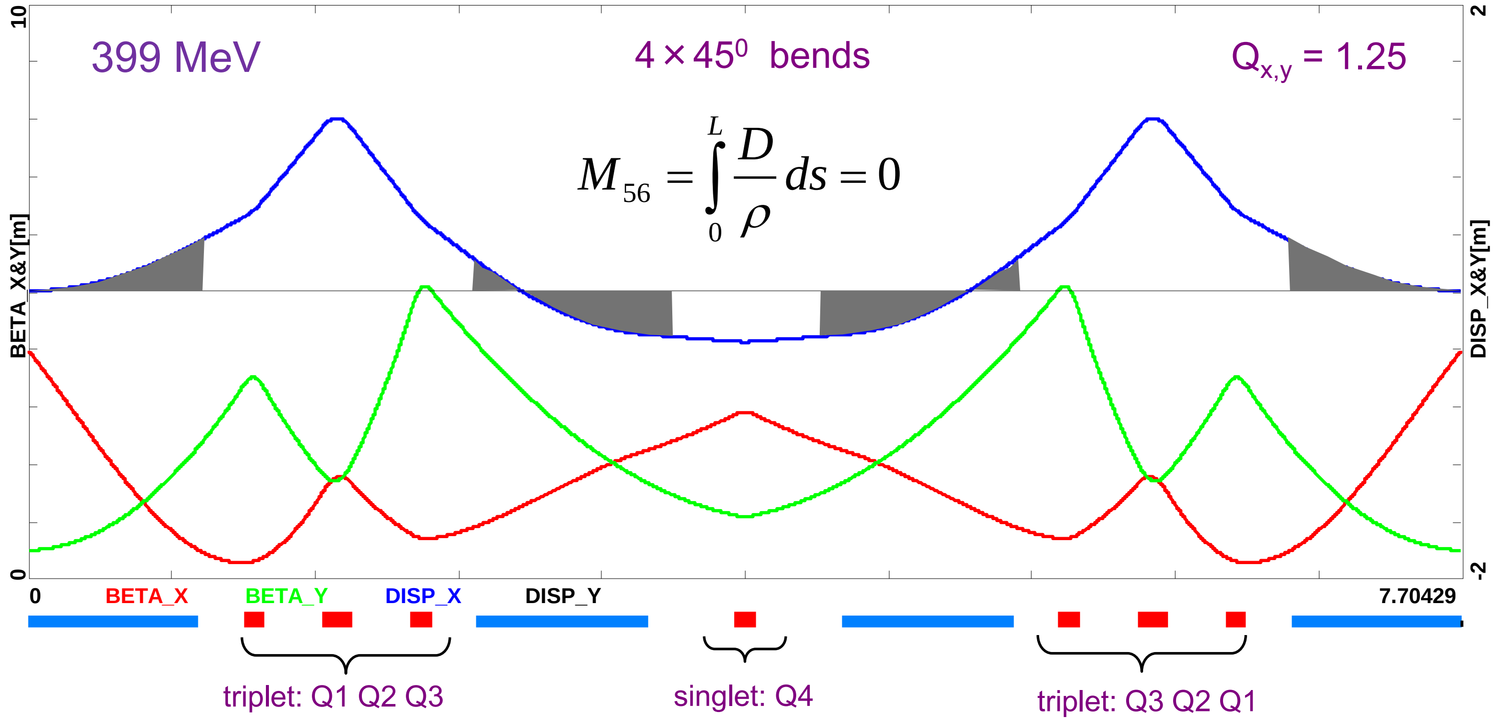


Multi-pass ER Optics





Arc 6 (5,4) Optics – FMC Lattice



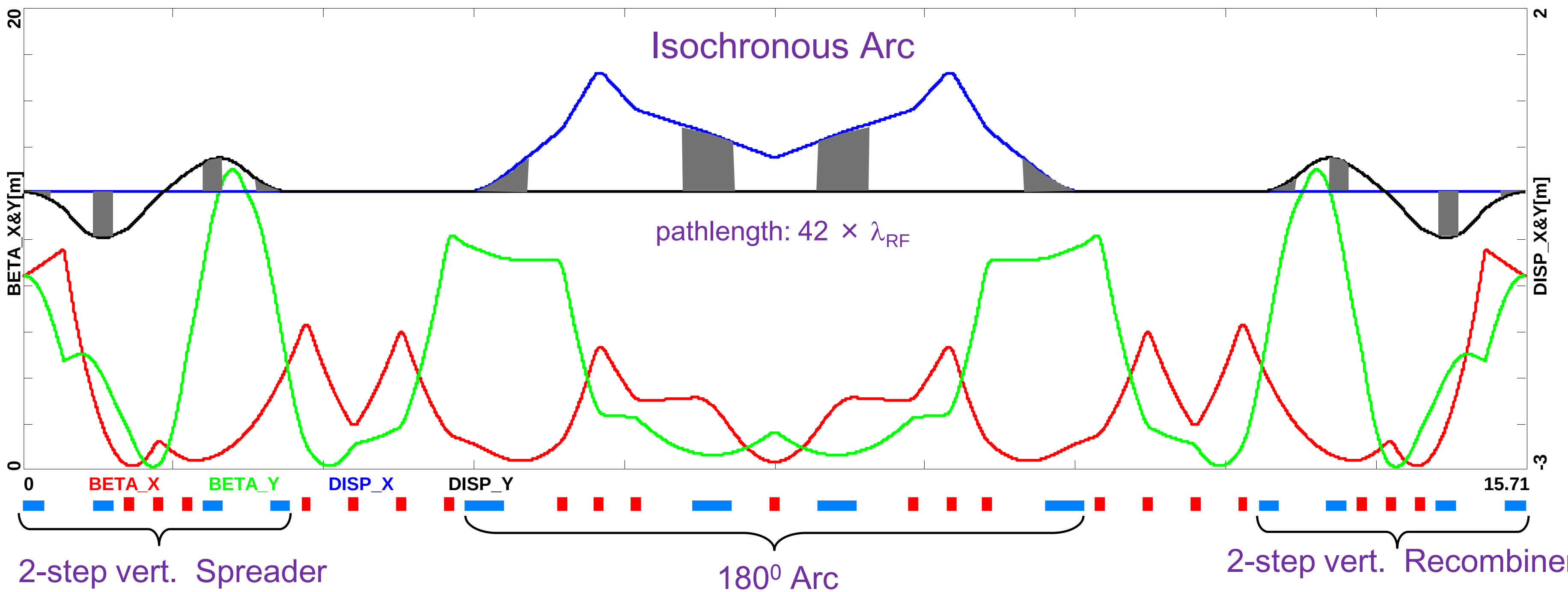
Dipoles: (91.2 cm long)

B = 1.2 Tesla

Quadrupoles:

Q1	L[cm] =10	G[T/m] = - 23.6
Q2	L[cm] =15	G[T/m] = 28.2
Q3	L[cm] =10	G[T/m] = - 22.4
Q4	L[cm] =10	G[T/m] = 8.6

Arc 1 Optics (71 MeV)



Spr. dipoles:

4× 45^0 bends

L = 20 cm

B = 9.5 kGauss

Arc dipoles :

4×45^0 bends

L = 45.6 cm

B = 4.5 kGauss

Rec. dipoles:

4× 45^0 bends

L = 20 cm

B = 9.5 kGauss

quads: L = 10 cm G ≤ 1 kGauss/cm

Summary

- 50 GeV ERL Baseline
  - Lower energy option – ⅕ of the LHC circumference
  - All lattice building blocks are available from 60 GeV design
  - Same performance in terms of SR emittance dilution
- FCC-he ERL Options (60 and 100 GeV)
  - Same performance in terms of SR energy loss
- PERLE@Orsay (400 MeV)
  - 'Test bed' for next generation of high power ERLs
  - 'Lean design', fewer magnet varieties, 1.2 Tesla curved bends
  - Flexible Momentum Compaction Optics

Special Thanks to:

Max Klein

and

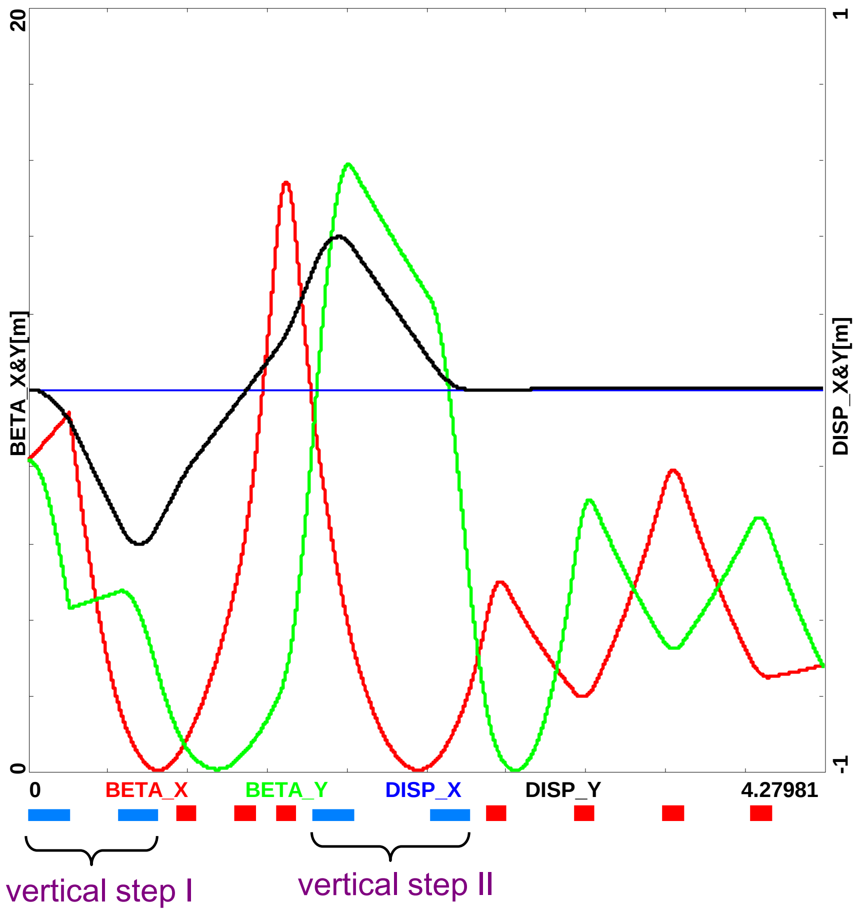
Oliver Brüning

Thank you for your attention!

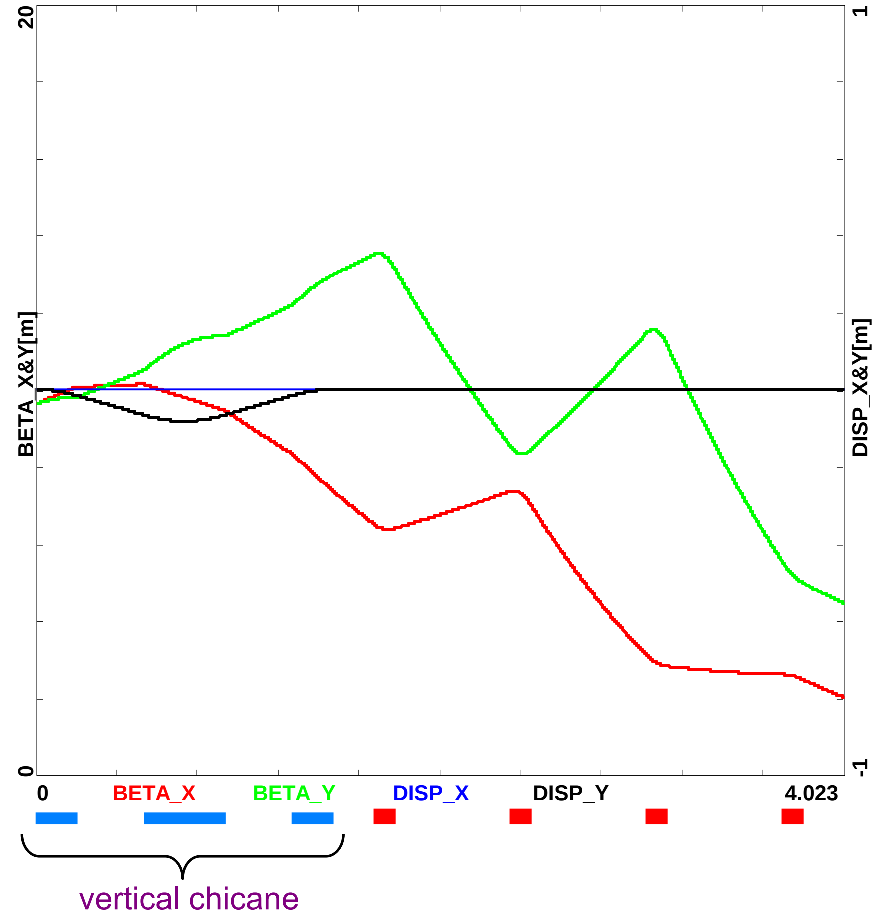
Backup Slides

Vertical Spreaders – Optics

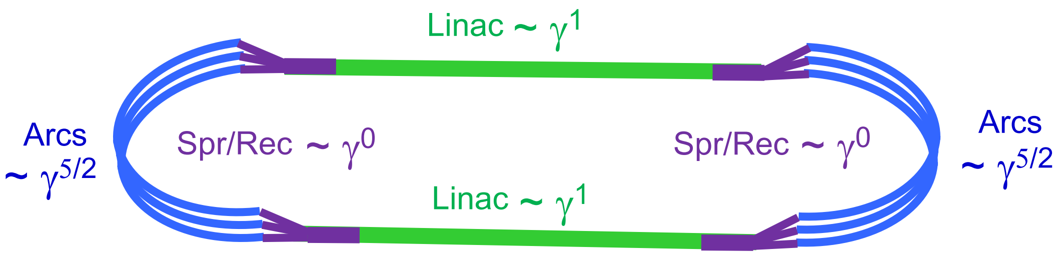
Spr. 1 (71 MeV)



Spr. 5 (333 MeV)



Energy Scaling – Preserving Emittance Dilution



$$\Delta\epsilon_x = \frac{55 r_0}{24\sqrt{3}} \frac{\hbar c}{mc^2} \gamma^5 \langle H_x \rangle \frac{\pi}{\rho^2}$$

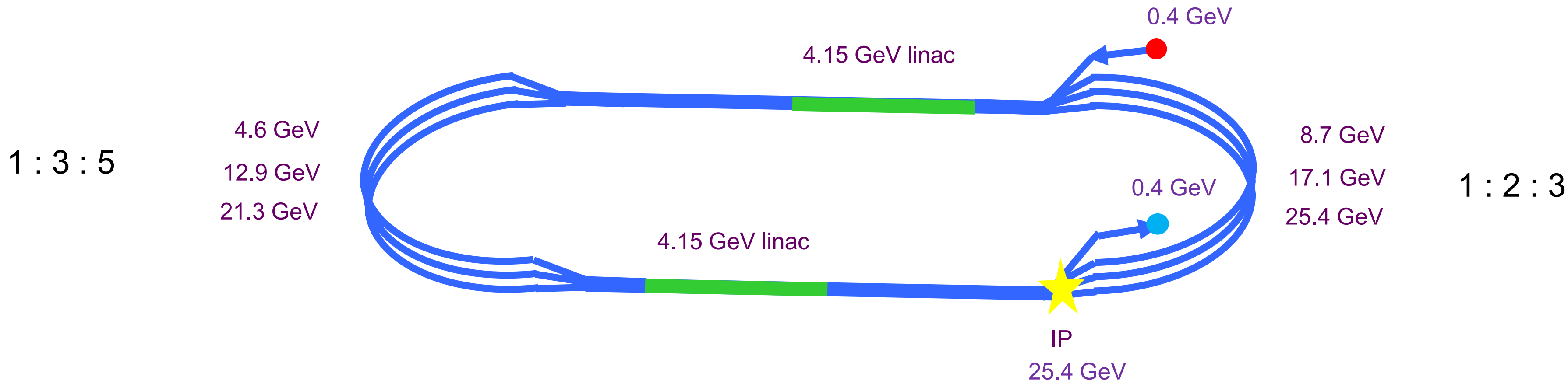
1/5

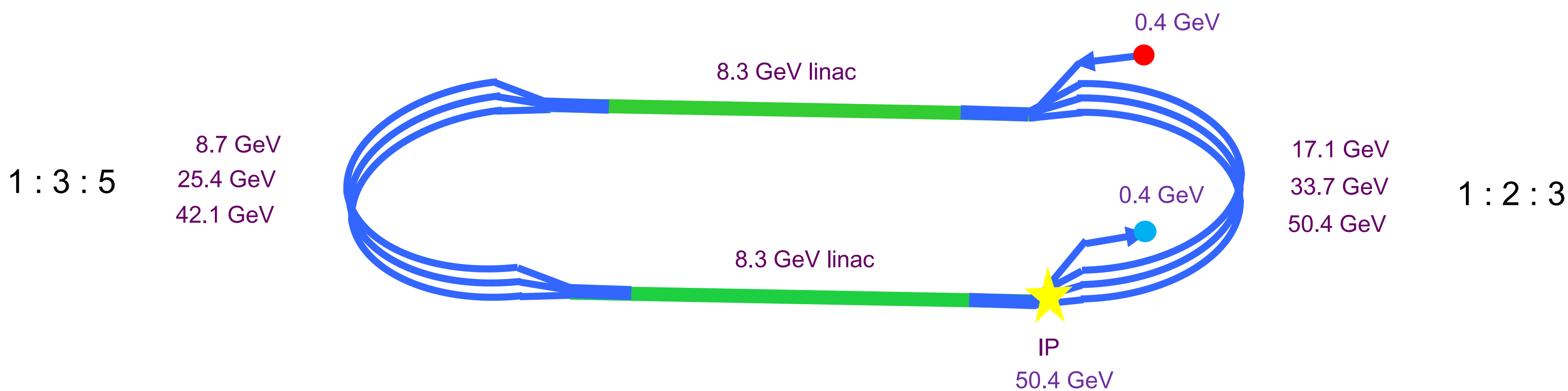
Cavity gradient [MV/m]	19.73
Cryo-unit length [m]	29.60
Energy gain /cryo-unit [MeV]	289.83
Number of cryo-units	28.00
Linac length [m]	828.80
Linac energy [GeV]	8.12
Net energy gain [GeV]	48.69
Injection Energy [GeV]	0.50
Total Energy [GeV]	49.19

Circumference [m]	5331.8
Linac [m]	828.8
Straight [m]	76.0
Arc [m]	1685.1
R [m]	536.4

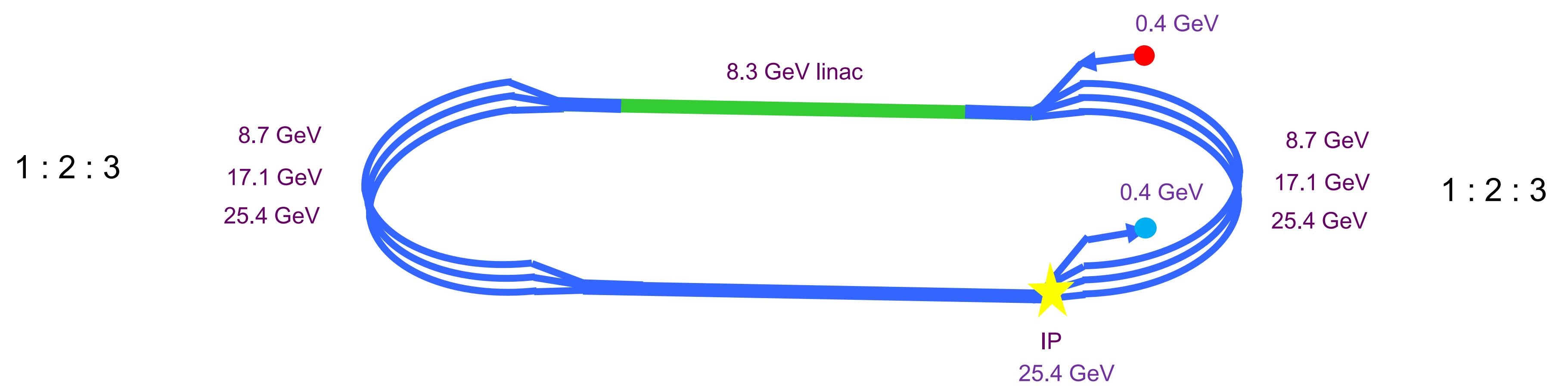
Normailzed Emittance Dilution before IP [mm mrad]	7.4

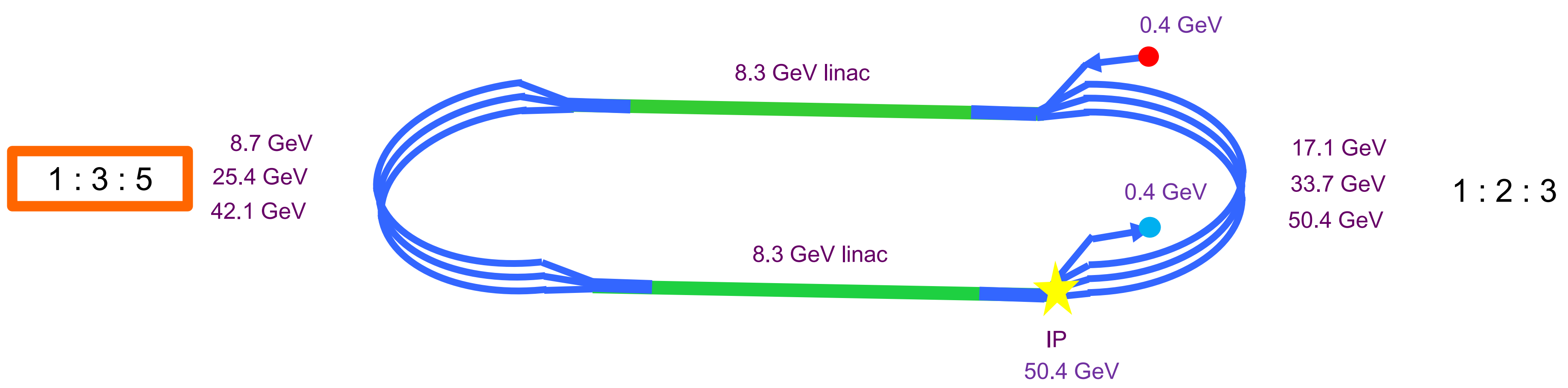
25 to 50 GeV ERL – Staging





25 to 50 GeV ERL – Staging





PERLE@Orsay - Baseline Parameters

TARGET PARAMETER	VALUE	
Injection energy [MeV]	**5**	
Maximum energy [MeV]	**400**	
Normalised emittance $\gamma\varepsilon_{x,y}$ [mm mrad]	6	
Average beam current [mA]	15	(375 pC)
Bunch spacing [ns]	25	(20^{th} sub-harmonic)
Bunch length (rms) [mm]	3	
RF frequency [MHz]	801.58	
Duty factor	CW	