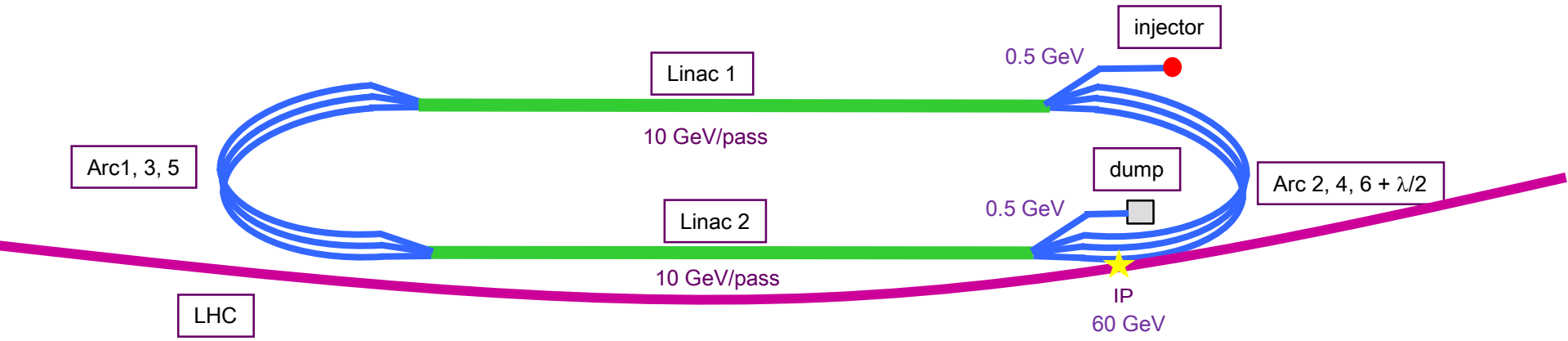
Options for the LHeC ERL – Performance Optimization

Alex Bogacz

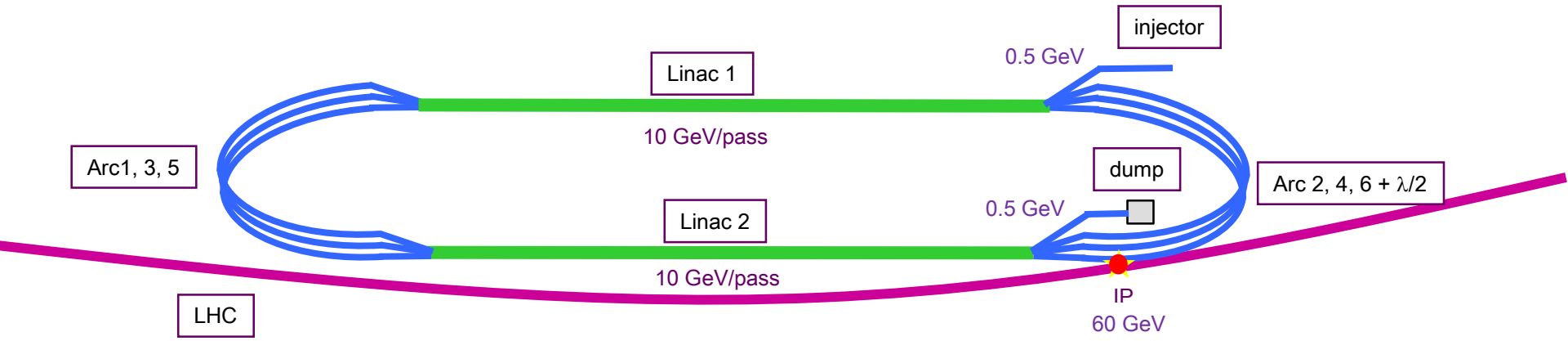
Overview

- 60 GeV Baseline ERL Design
  - Synchrotron radiation effects on beam dynamics
  - Choice of Arc Optics – Emittance preserving lattices
  - Balanced emittance dilution & quasi-isochronicity
  - ERL performance – End-to-end simulation
- 50 GeV ERL Options – Optimizations
  - Emittance dilution due to quantum excitations
  - Circumference considerations
  - Lattice modularity and scalability
  - Staged approach
- Summary

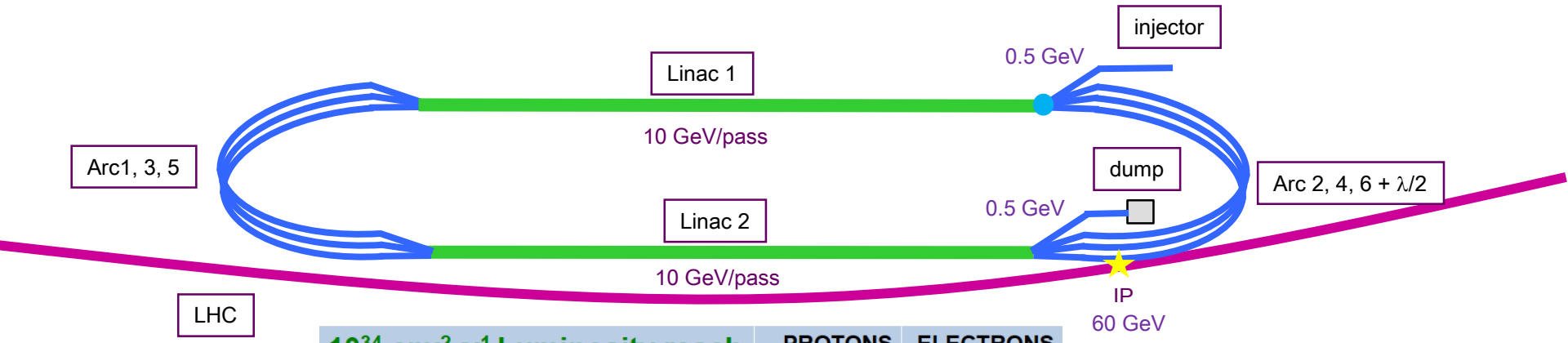
LHeC Recirculator with Energy Recovery



LHeC Recirculator with Energy Recovery



LHeC Recirculator with Energy Recovery



10^{34} cm^{-2} s^{-1} Luminosity reach	PROTONS	ELECTRONS
Beam Energy [GeV]	7000	60
Luminosity [10^{33}cm^{-2}s^{-1}]	16	16
Normalized emittance $\gamma\varepsilon_{x,y}$ [μm]	2.5	20
Beta Function $\beta^*_{x,y}$ [m]	0.05	0.10
rms Beam size $\sigma^*_{x,y}$ [μm]	4	4
rms Beam divergence $\sigma'_{x,y}$ [μrad]	80	40
Average Beam Current [mA]	1112	25 delivered 150 in linacs
Bunch Spacing [ns]	25	25
Bunch Population	2.2*10^{11}	4*10^{9}
Bunch charge [nC]	35	0.64

Synchrotron Radiation Effects

- Synchrotron radiated energy:

$$\Delta E = \frac{2}{3} r_0 mc^2 \gamma^4 I_2$$

$$I_3 = \int_0^L \frac{1}{r^2} ds = \frac{q}{r},$$

- Natural energy spread due to quantum excitations:

$$\Delta\sigma_E^2 = \frac{55\alpha}{48\sqrt{3}} (\hbar c)^2 \gamma^7 I_3$$

$$I_3 = \int_0^L \frac{1}{|r|^3} ds = \frac{q}{r^2},$$

- Emittance dilution due to quantum excitations:

$$\Delta\varepsilon = \frac{55 r_0}{24\sqrt{3}} \frac{\hbar c}{mc^2} \gamma^5 I_5$$

$$I_5 = \int_0^L \frac{H}{|r|^3} ds = \frac{q\langle H \rangle}{r^2},$$

$$H = \gamma D^2 + 2\alpha DD' + \beta D'^2$$

Arc Optics – Beam Dynamics Issues

- Emittance dilution due to quantum excitations:

$$D\varepsilon = \frac{55 r_0}{24\sqrt{3}} \frac{\hbar c}{mc^2} \gamma^5 I_5$$

$$I_5 = \int_0^L \frac{H}{|r|^3} ds = \frac{q\langle H \rangle}{r^2},$$

$$H = \gamma D^2 + 2\alpha DD' + \beta D'^2$$

- Momentum Compaction – synchronous acceleration in the linacs:

$$M_{56} = \frac{1}{C} I_1$$

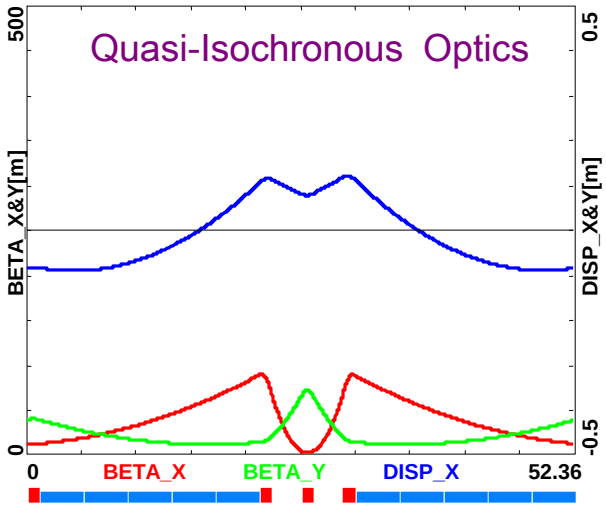
$$I_1 = \int_0^L \frac{D}{r} ds = q\langle D \rangle$$

Arc Optics – Emittance preserving FMC cells

$$De_x^N = \frac{55 r_0}{24\sqrt{3}} \frac{\hbar c}{mc^2} g^6 \langle H_x \rangle \frac{p}{r^2}$$

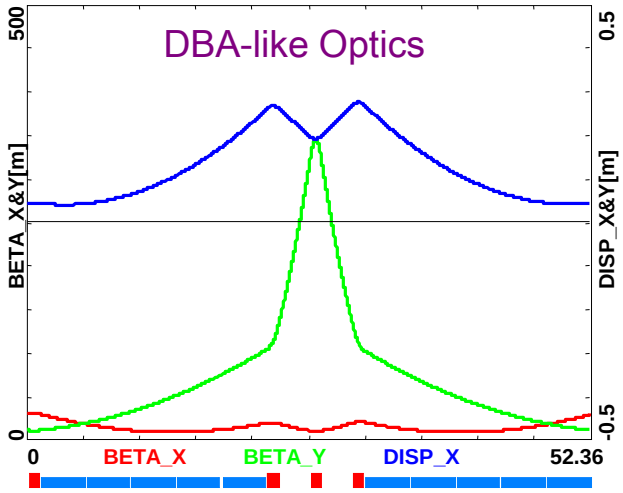
$$H_x = g_x D_x^2 + 2a_x D_x D_x' + b_x D_x'^2$$

Arc 1 , Arc2



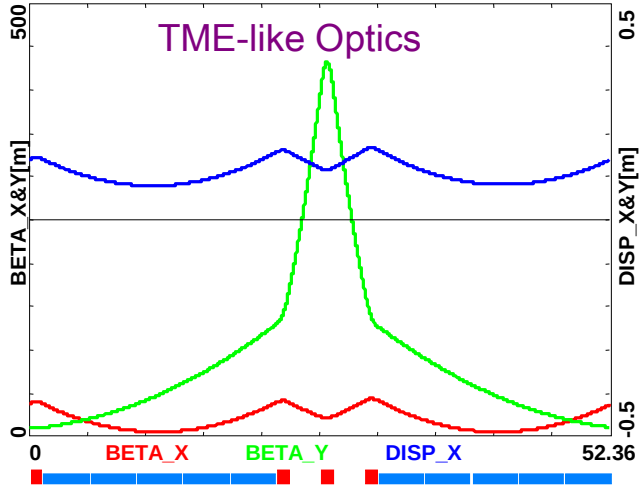
$\langle H \rangle = 8.8 \times 10^{-3}\ m$

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 Loss and Emittance Dilution in Arcs

	E [GeV]	DE [MeV]	$De_N^{arc}[m\ rad]$	$De_N[m\ rad]$	$D^{arc}s_{DE/E}$	$Ds_{DE/E}$
Arc 1	10.5	1	2.7E-09	2.7E-09	3.9E-06	3.9E-06
Arc 2	20.5	11	1.5E-07	1.5E-07	2.1E-05	2.4E-05
Arc 3	30.5	51	4.1E-07	5.6E-07	5.6E-05	8.0E-05
Arc 4	40.5	160	2.2E-06	2.8E-06	1.1E-04	1.9E-04
Arc 5	50.5	387	4.6E-06	7.4E-06	2.0E-04	3.9E-04
Arc 6	60.5	797	1.4E-05	2.1E-05	3.1E-04	7.0E-04
Arc 5	50.5	387	4.6E-06	2.5E-05	2.0E-04	8.9E-04
Arc 4	40.5	160	2.2E-06	2.8E-05	1.1E-04	1.0E-03
Arc 3	30.5	51	4.1E-07	2.81E-05	5.6E-05	1.06E-03
Arc 2	20.5	11	1.5E-07	2.82E-05	2.1E-05	1.08E-03
Arc 1	10.5	1	2.7E-09	2.825E-05	3.9E-06	1.09E-03
Dump	0.5			2.825E-05		1.09E-03

Total Energy Loss [GeV]	2.0
Normailzed Emittance Dilution before IP [mm mrad]	7.4
Net Normailzed Emittance Dilution [mm mrad]	28.2
Net Natural Momentum Spread	0.001

R [m]	1000.0
r [m]	743.6

End-to-End ERL Tracking (Placet 2)

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

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

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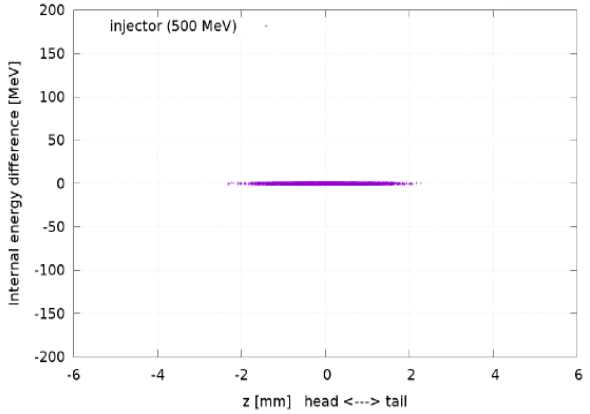
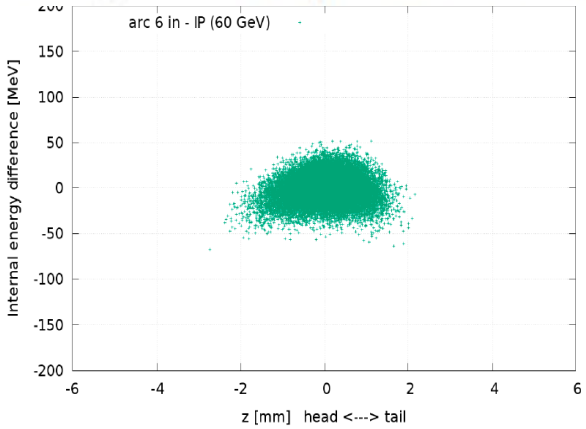
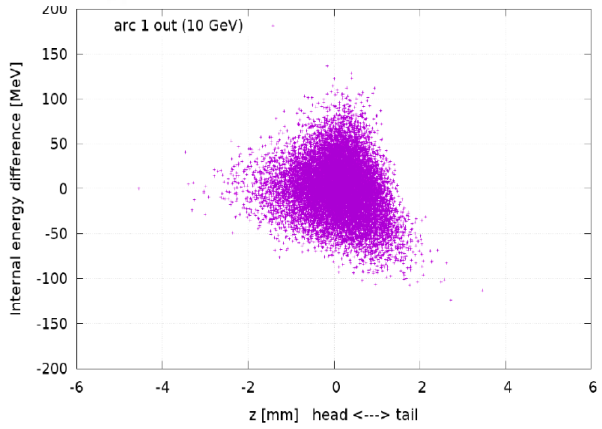
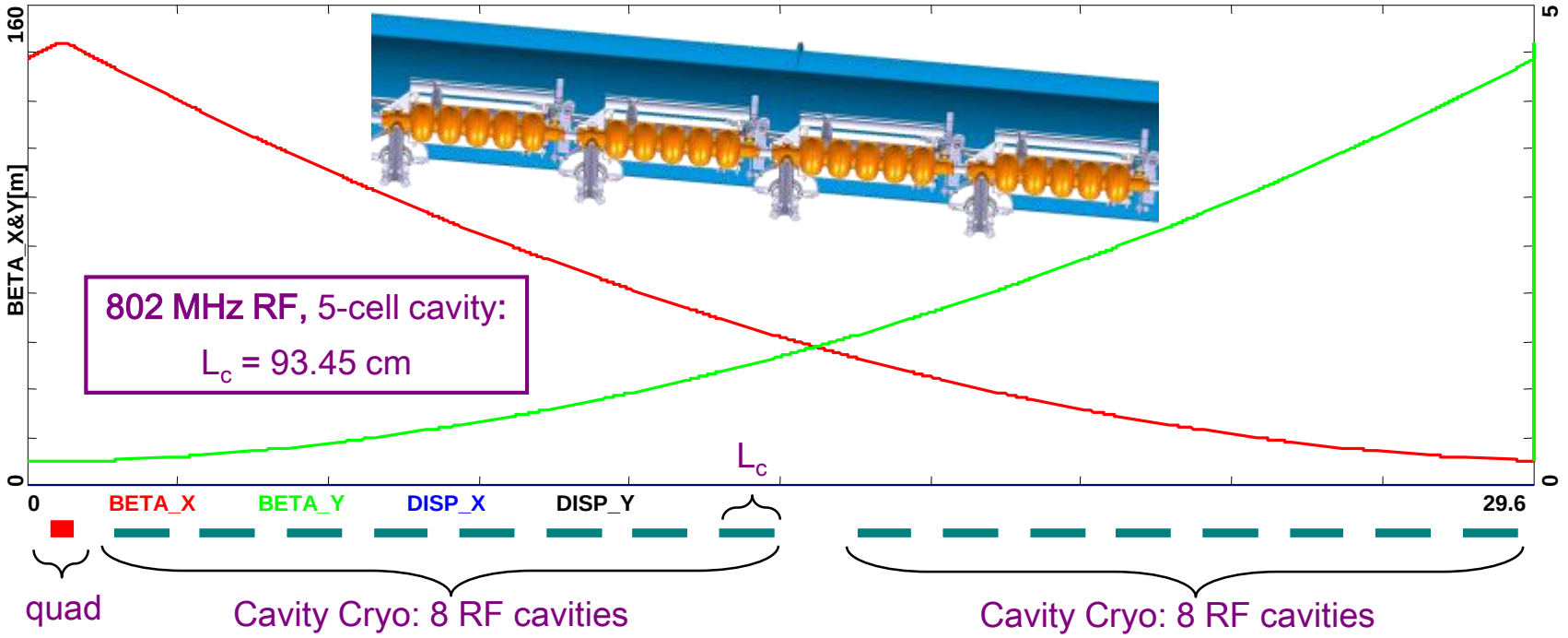




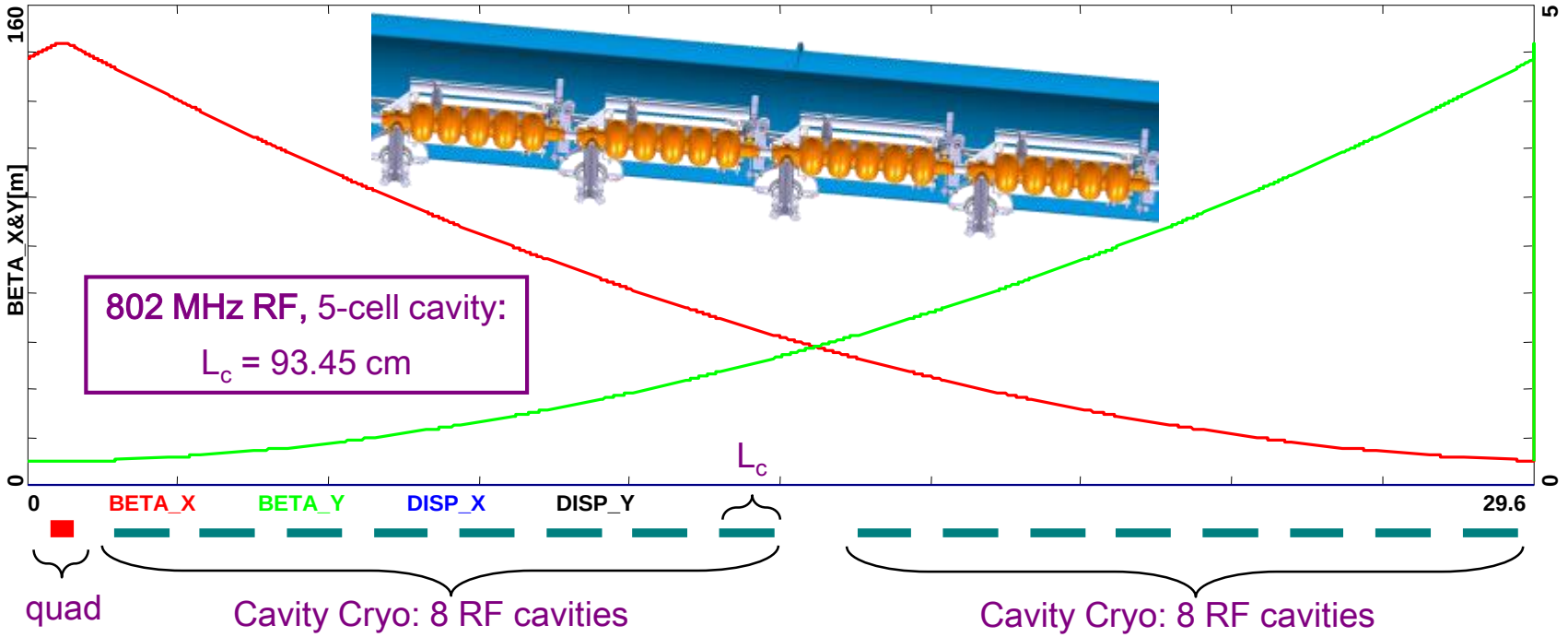


Cryo Unit Layout/Optics – Half-Cell 130^0 FODO



Linac energy [GeV]	10
Cavity gradient [MV/m]	20.0
Cryo-unit length [m]	29.6
Energy gain / cryo-unit [MeV]	299.0
Number of cryo-units	34
Linac length [m]	1006.4

Linac for 50 GeV 3-pass ERL



Linac energy [GeV]	8.33
Cavity gradient [MV/m]	20
Cryo-unit length [m]	29.6
Energy gain/cryo-unit [MeV]	299.04
Number of cryo-units	28
Linac length [m]	828.8

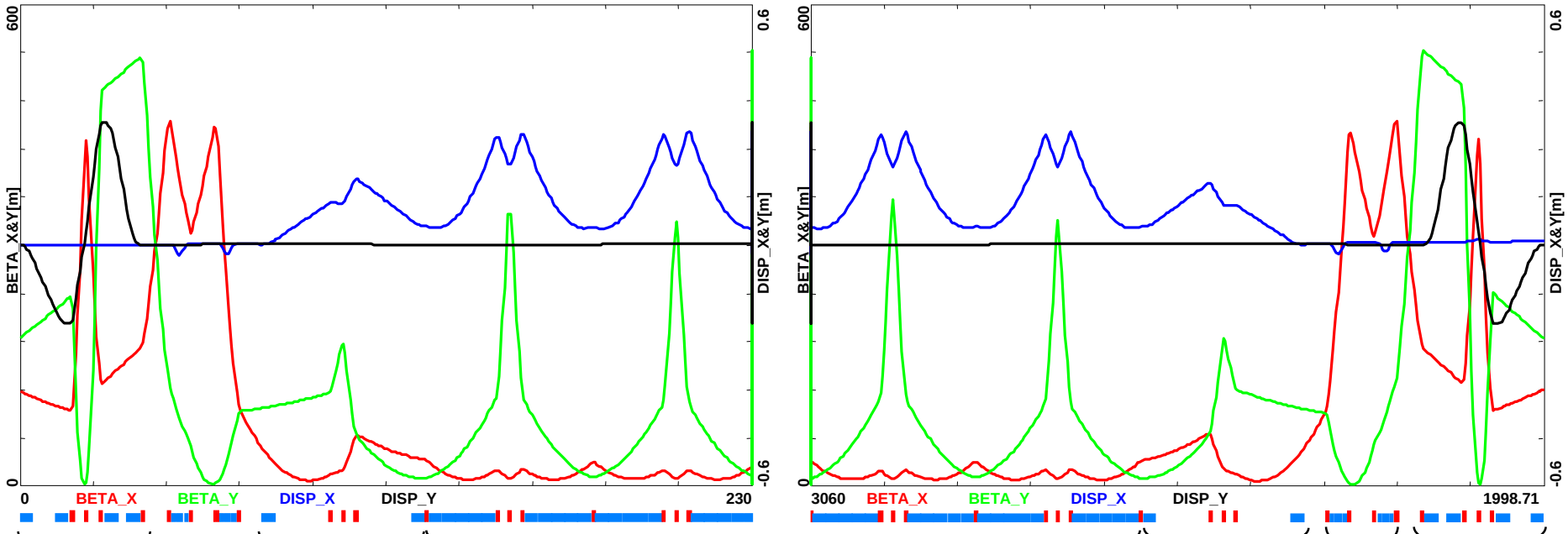
50 GeV ERL Optimized for Synchrotron Radiation

	E [GeV]	DE [MeV]	$De_N^{arc}[m\ rad]$	$De_N[m\ rad]$	$Ds^{arc}_{DE/E}$	$Ds_{DE/E}$
Arc 1	8.7	1	2.7E-09	2.7E-09	4.2E-06	4.2E-06
Arc 2	17.1	9	1.5E-07	1.5E-07	2.3E-05	2.7E-05
Arc 3	25.4	43	4.1E-07	5.6E-07	6.1E-05	8.8E-05
Arc 4	33.7	133	2.2E-06	2.8E-06	1.2E-04	2.1E-04
Arc 5	42.1	322	4.6E-06	7.4E-06	2.2E-04	4.3E-04
Arc 6	50.4	664	1.4E-05	2.1E-05	3.4E-04	7.6E-04
Arc 5	42.1	322	4.6E-06	2.5E-05	2.2E-04	9.8E-04
Arc 4	33.7	133	2.2E-06	2.8E-05	1.2E-04	1.1E-03
Arc 3	25.4	43	4.1E-07	2.81E-05	6.1E-05	1.16E-03
Arc 2	17.1	9	1.5E-07	2.82E-05	2.3E-05	1.19E-03
Arc 1	8.7	1	2.7E-09	2.825E-05	4.2E-06	1.19E-03
Dump	0.4			2.825E-05		1.19E-03

Total Energy Loss [GeV]	1.7
Normailzed Emittance Dilution before IP [mm mrad]	7.4
Net Normailzed Emittance Dilution [mm mrad]	28.2
Net Natural Momentum Spread	0.001

R [m]	578
r [m]	429.8

Arc 3 Optics (25.4 GeV)



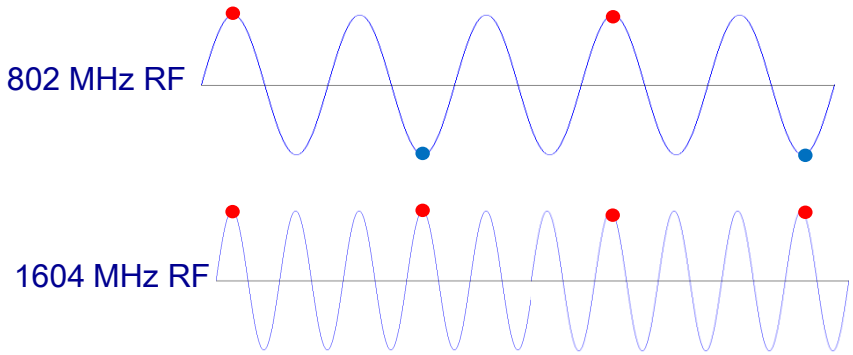
Arc dipoles:

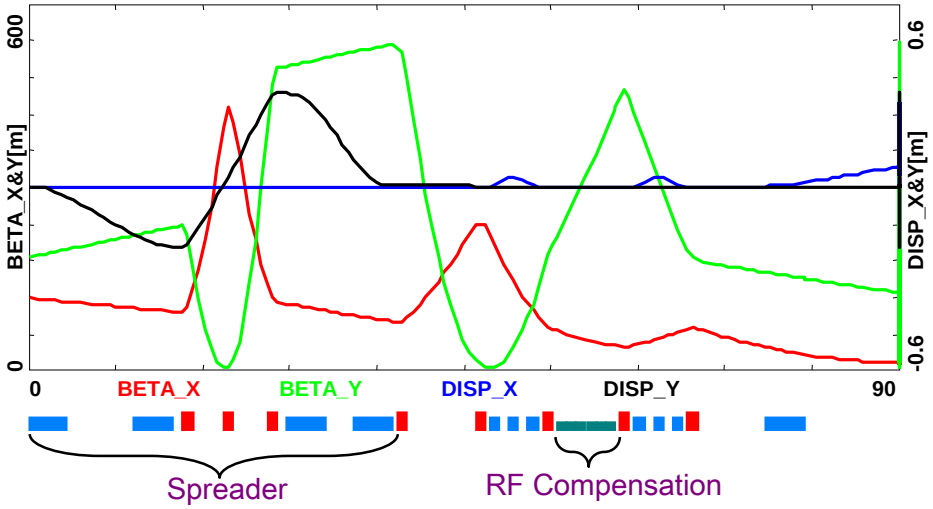
$Lb = 400 cm

$B =1.97 kGauss

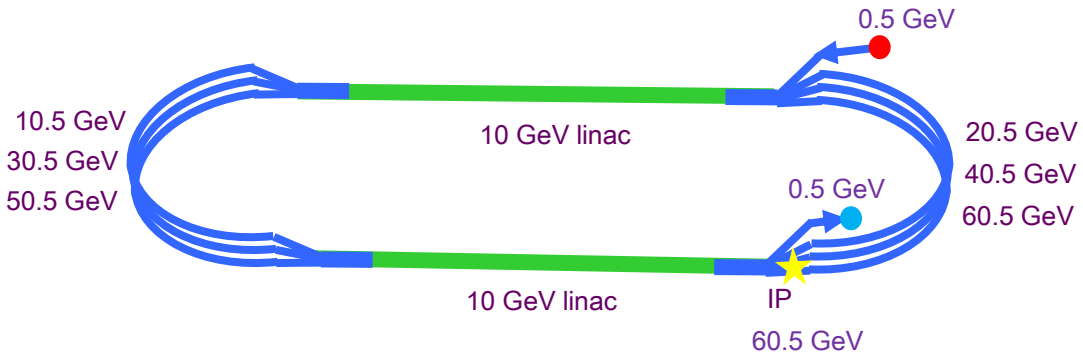
2-nd Harmonics RF Compensation of SR Losses

	E [GeV]	DE [MeV]	comp. cryos
Arc 1	8.7	1	0
Arc 2	17.1	9	0
Arc 3	25.4	43	1
Arc 4	33.7	133	1
Arc 5	42.1	322	3
Arc 6	50.4	664	5
Arc 5	42.1	322	3
Arc 4	33.7	133	1
Arc 3	25.4	43	1
Arc 2	17.1	9	0
Arc 1	8.7	1	0
Dump	0.4		

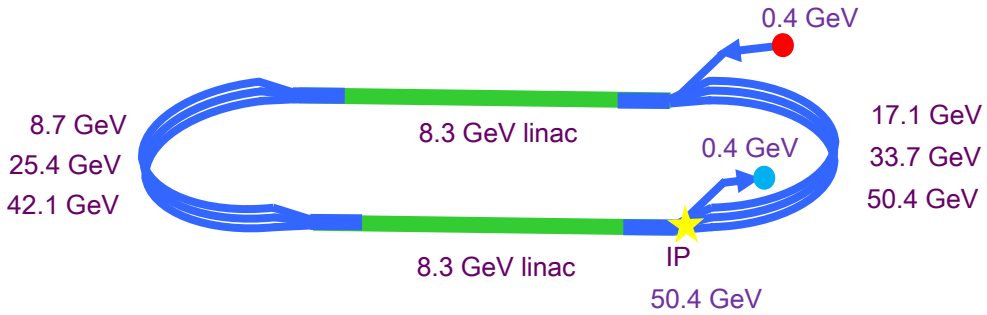




60 vs 50 GeV ERL Options – Layout



R [m]	1000.0
Arc [m]	3141.6
Straight [m]	1298.4
Circumference [m]	8880.0



R [m]	578.0
Arc [m]	1815.8
Straight [m]	1120.8
Circumference [m]	5873.3

27000/3 = 9000

27000/4 = 6750

27000/5 = 5400

50 GeV ERL □ Small Emittance Option

	E [GeV]	DE [MeV]	$De_N^{arc}[m\ rad]$	$De_N[m\ rad]$	$Ds_{DE/E}^{arc}$	$Ds_{DE/E}$
Arc 1	8.7	0	1.8E-09	1.8E-09	3.5E-06	3.5E-06
Arc 2	17.1	7	1.0E-07	1.0E-07	1.8E-05	2.2E-05
Arc 3	25.4	35	2.7E-07	3.8E-07	5.0E-05	7.2E-05
Arc 4	33.7	109	1.5E-06	1.9E-06	1.0E-04	1.7E-04
Arc 5	42.1	264	3.1E-06	4.9E-06	1.8E-04	3.5E-04
Arc 6	50.4	544	9.1E-06	1.4E-05	2.8E-04	6.3E-04
Arc 5	42.1	264	3.1E-06	1.7E-05	1.8E-04	8.0E-04
Arc 4	33.7	109	1.5E-06	1.9E-05	1.0E-04	9.1E-04
Arc 3	25.4	35	2.7E-07	1.89E-05	5.0E-05	9.55E-04
Arc 2	17.1	7	1.0E-07	1.90E-05	1.8E-05	9.74E-04
Arc 1	8.7	0	1.8E-09	1.899E-05	3.5E-06	9.77E-04
Dump	0.4			1.899E-05		9.77E-04

R [m]	705.0
Arc [m]	2214.8
Straight [m]	1120.8
Circumference [m]	6671.2

27000/4 = 6750

R [m]	705
r [m]	524.2

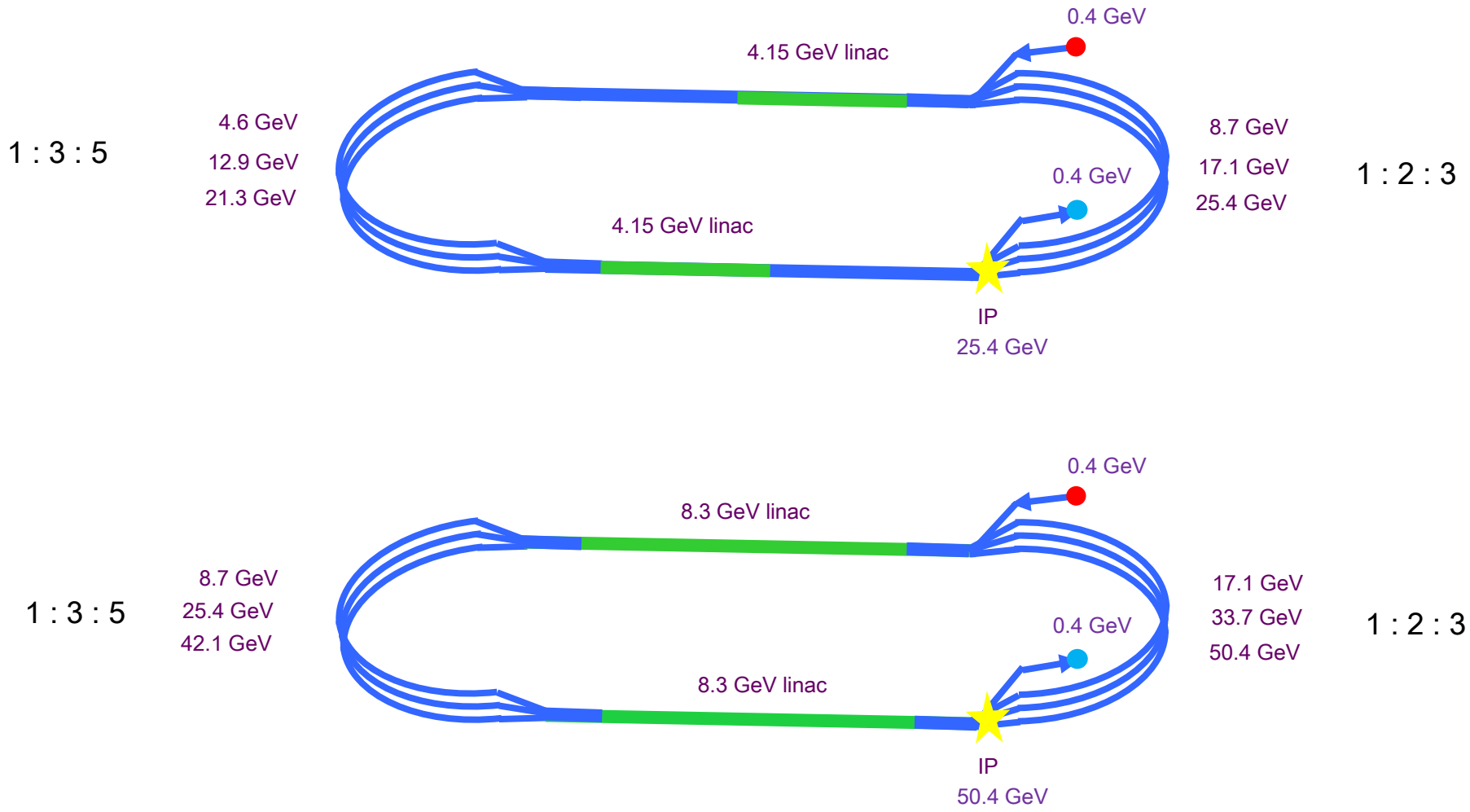
50 GeV ERL □ Small Emittance Option

	E [GeV]	DE [MeV]	$De_N^{arc}[m\ rad]$	$De_N[m\ rad]$	$Ds_{DE/E}^{arc}$	$Ds_{DE/E}$
Arc 1	8.7	0	1.8E-09	1.8E-09	3.5E-06	3.5E-06
Arc 2	17.1	7	1.0E-07	1.0E-07	1.8E-05	2.2E-05
Arc 3	25.4	35	2.7E-07	3.8E-07	5.0E-05	7.2E-05
Arc 4	33.7	109	1.5E-06	1.9E-06	1.0E-04	1.7E-04
Arc 5	42.1	264	3.1E-06	4.9E-06	1.8E-04	3.5E-04
Arc 6	50.4	544	9.1E-06	1.4E-05	2.8E-04	6.3E-04
Arc 5	42.1	264	3.1E-06	1.7E-05	1.8E-04	8.0E-04
Arc 4	33.7	109	1.5E-06	1.9E-05	1.0E-04	9.1E-04
Arc 3	25.4	35	2.7E-07	1.89E-05	5.0E-05	9.55E-04
Arc 2	17.1	7	1.0E-07	1.90E-05	1.8E-05	9.74E-04
Arc 1	8.7	0	1.8E-09	1.899E-05	3.5E-06	9.77E-04
Dump	0.4			1.899E-05		9.77E-04

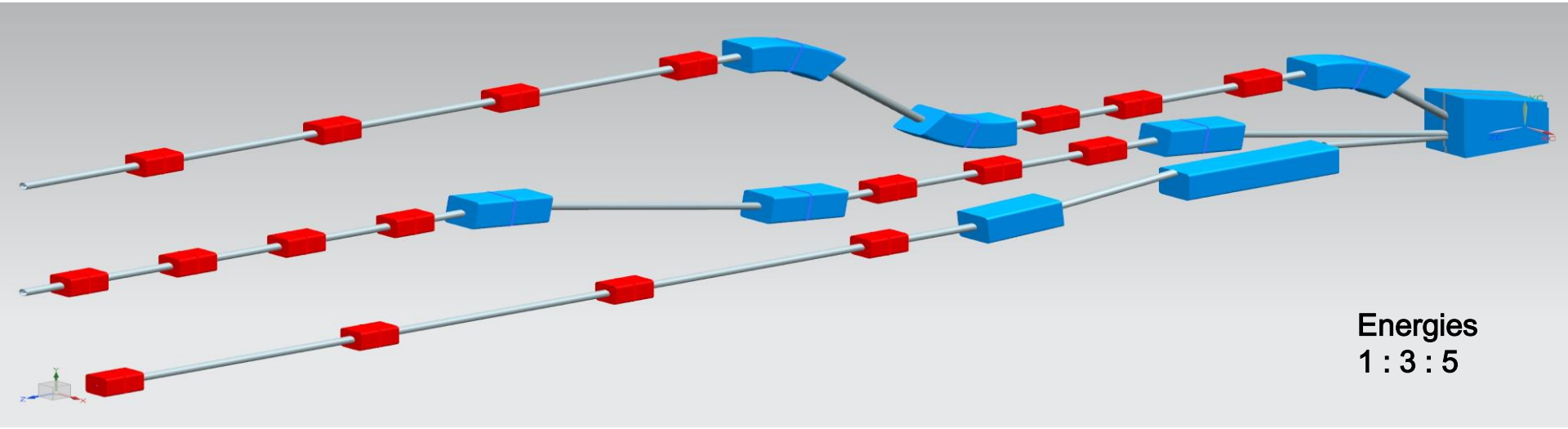
Total Energy Loss [GeV]	1.4
Normailzed Emittance Dilution before IP [mm mrad]	4.9
Net Normailzed Emittance Dilution [mm mrad]	19.0
Net Natural Momentum Spread	0.001

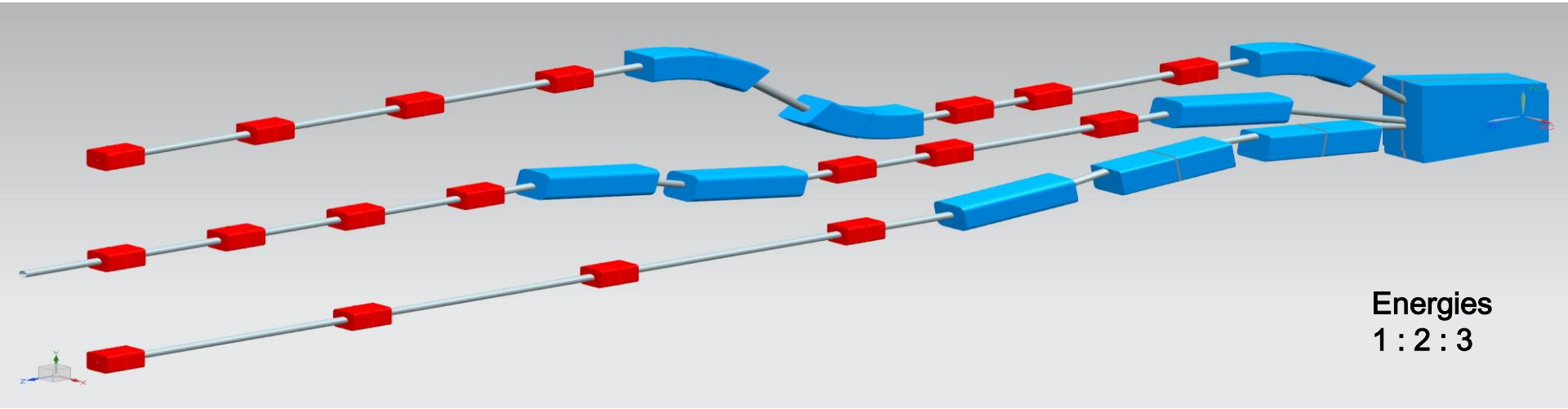
R [m]	705
r [m]	524.2

25 to 50 GeV ERL – Staging



Vertical Switchyard Architecture





25 GeV ERL Synchrotron Radiation Effects

	E [GeV]	DE [MeV]	$De_N^{arc}[m\ rad]$	$De_N[m\ rad]$	$Ds^{arc}_{DE/E}$	$Ds_{DE/E}$
Arc 1	4.4	0	2.8E-11	2.8E-11	6.2E-07	6.2E-07
Arc 2	8.5	0	1.6E-09	1.6E-09	3.3E-06	3.9E-06
Arc 3	12.7	2	4.3E-09	5.9E-09	8.9E-06	1.3E-05
Arc 4	16.9	7	2.4E-08	3.0E-08	1.8E-05	3.1E-05
Arc 5	21.0	17	4.8E-08	7.8E-08	3.1E-05	6.2E-05
Arc 6	25.2	34	1.4E-07	2.2E-07	4.9E-05	1.1E-04
Arc 5	21.0	17	4.8E-08	2.7E-07	3.1E-05	1.4E-04
Arc 4	16.9	7	2.4E-08	2.9E-07	1.8E-05	1.6E-04
Arc 3	12.7	2	4.3E-09	2.98E-07	8.9E-06	1.70E-04
Arc 2	8.5	0	1.6E-09	2.99E-07	3.3E-06	1.73E-04
Arc 1	4.4	0	2.8E-11	2.992E-07	6.2E-07	1.73E-04
Dump	0.2			2.992E-07		1.73E-04

Total Energy Loss [GeV]	0.09
Normailzed Emittance Dilution before IP [mm mrad]	0.08
Net Normailzed Emittance Dilution [mm mrad]	0.30
Net Natural Momentum Spread	0.0002

R [m]	702
r [m]	522.0

Summary

- 60 GeV Baseline ERL Option
  - Well studied design…
  - All lattice building blocks are available
  - High modularity and scalability of lattices
  - ERL performance validated by End-to-end simulation
- 50 GeV ERL Options – Optimizations
  - Same performance in terms of synchrotron radiation effects
  - Viable 6.7 km circumference ERL with enhanced performance
  - Staged approach: ‘adding RF to both linacs’
  - Linear scaling of all magnets

Special Thanks to:

Max Klein

and

Oliver Brüning

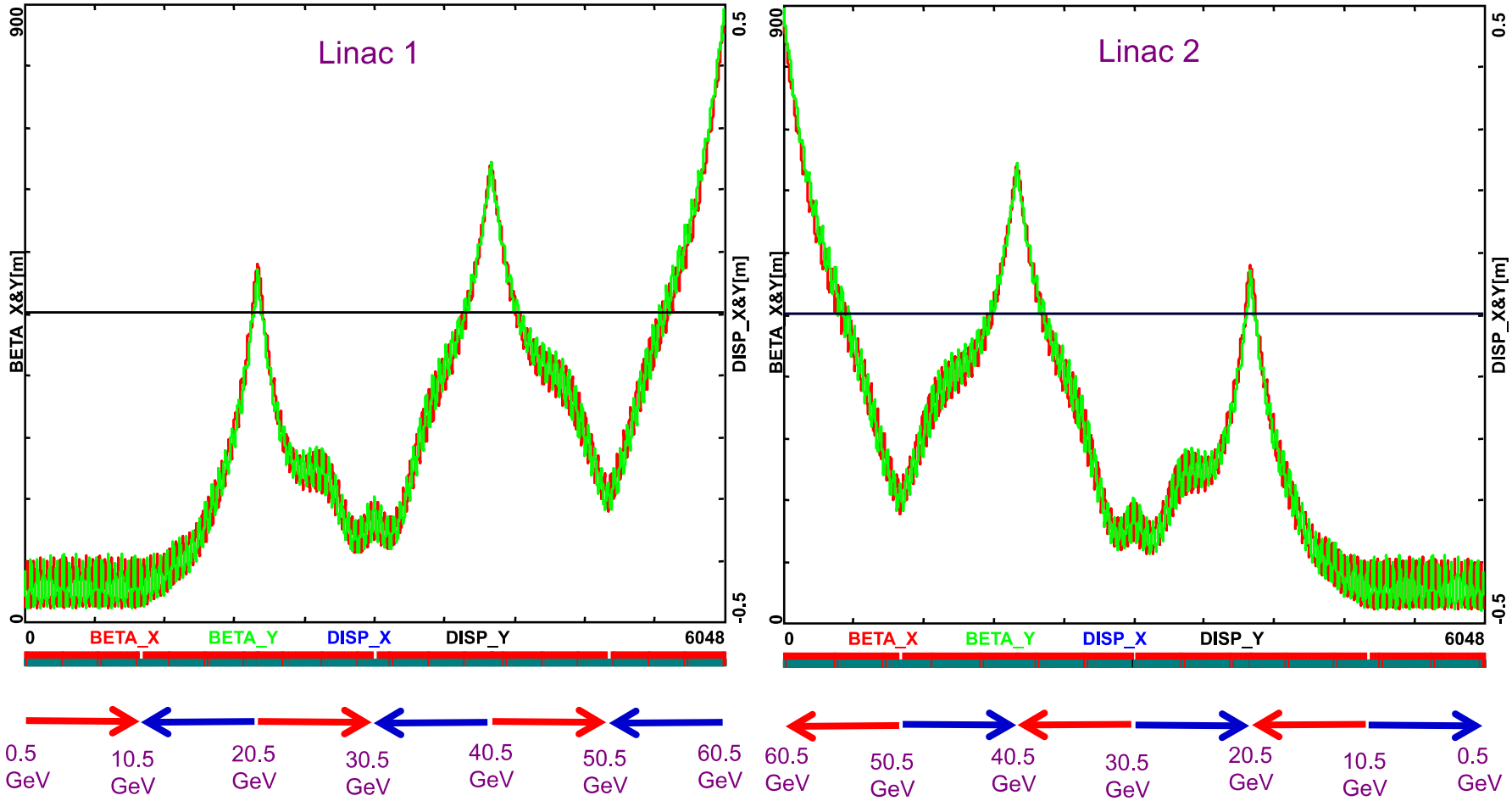
Thank you for your Attention!

Questions?

Backup Slides

Linac 1 and 2 – Multi-pass ER Optics

Acceleration/Deceleration



25 to 50 GeV ERL – Staging