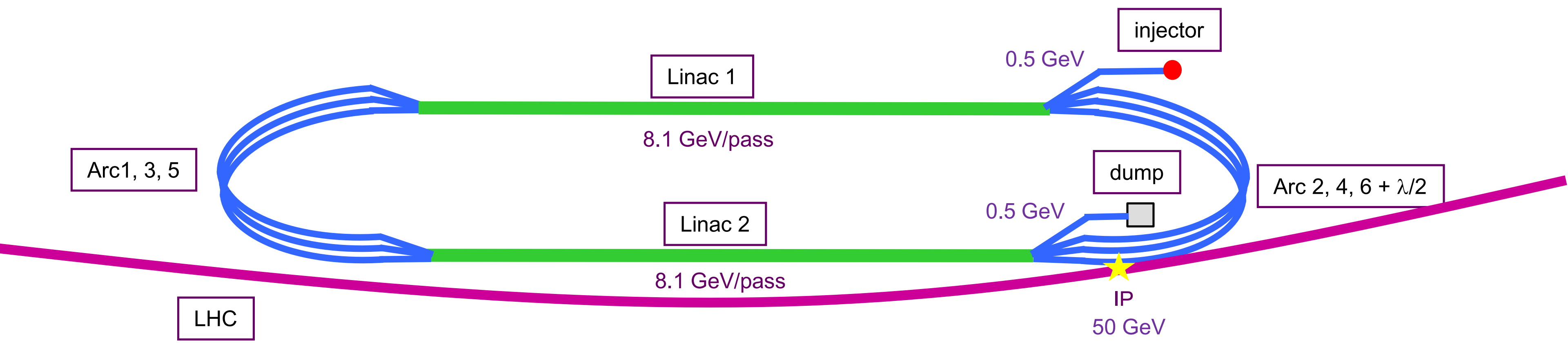
# ERL Lattices for the LHeC/FCC-he and PERLE

Alex Bogacz

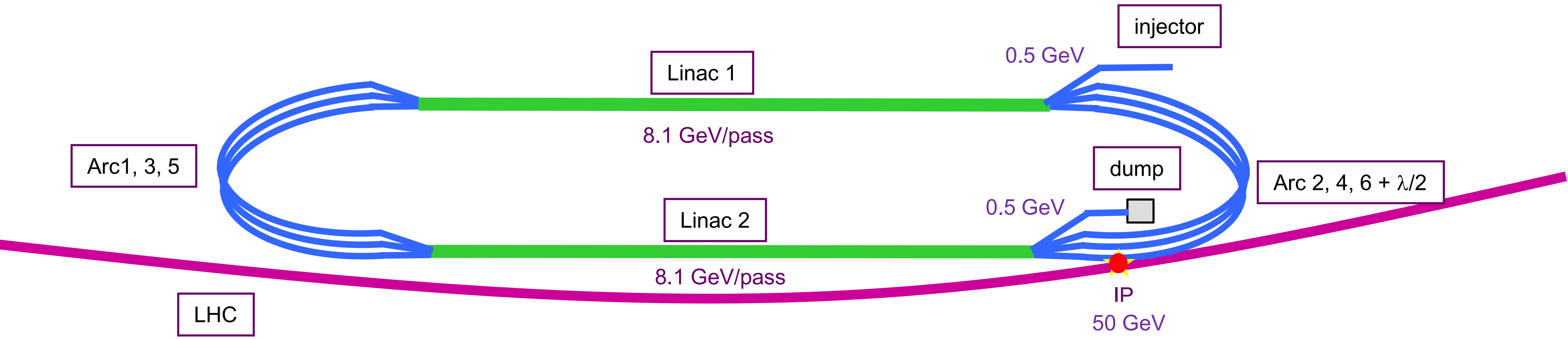
# Overview

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

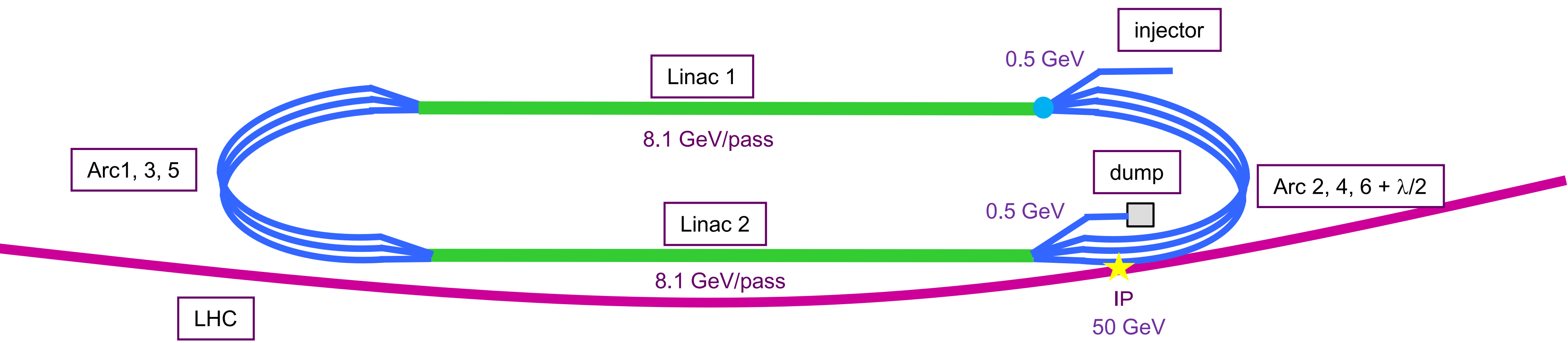
# LHeC Recirculator with Energy Recovery



# 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:

$$\Delta E = \frac{2}{3} r_0 mc^2 \gamma^4 I_2 \qquad I_2 = \int_0^L \frac{1}{\rho^2} ds = \frac{\theta}{\rho},$$

- Natural energy spread due to quantum excitations:

$$\Delta\sigma_E^2 = \frac{55\alpha}{48\sqrt{3}} \left(\hbar c\right)^2 \gamma^7 I_3 \qquad I_3 = \int_0^L \frac{1}{\left|\rho\right|^3} ds = \frac{\theta}{\rho^2},$$

- Emittance dilution due to quantum excitations:

$$\Delta\varepsilon = \frac{55 r_0}{24\sqrt{3}} \frac{\hbar c}{mc^2} \gamma^5 I_5 \qquad I_5 = \int_0^L \frac{H}{\left|\rho\right|^3} ds = \frac{\theta\langle H\rangle}{\rho^2},$$

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

- Momentum Compaction – synchronous acceleration in the linacs:

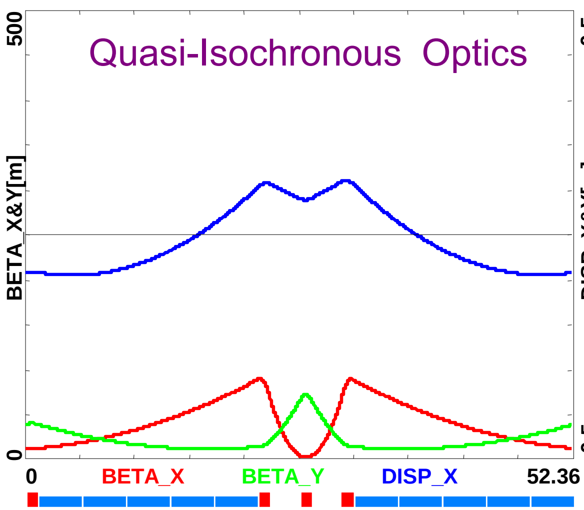
$$M_{56} = \frac{1}{C} I_1 \qquad I_1 = \int_0^L \frac{D}{\rho} ds = \theta\langle D\rangle$$

# Arc Optics – Emittance preserving FMC cells

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

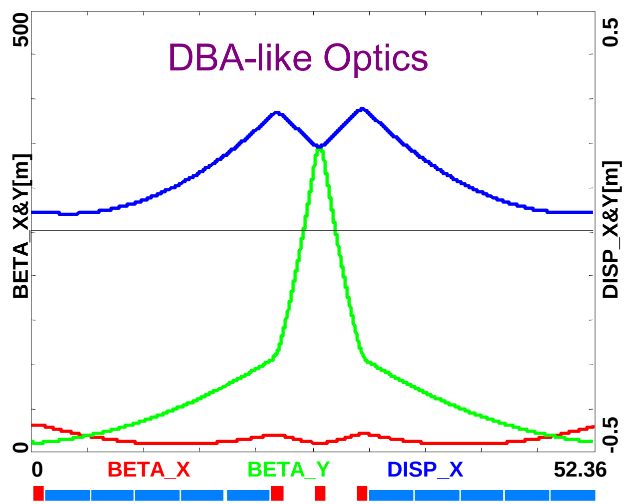
$$H_x = \gamma_x D_x^2 + 2\alpha_x D_x D'_x + \beta_x D'^2_x$$

Arc 1 , Arc2



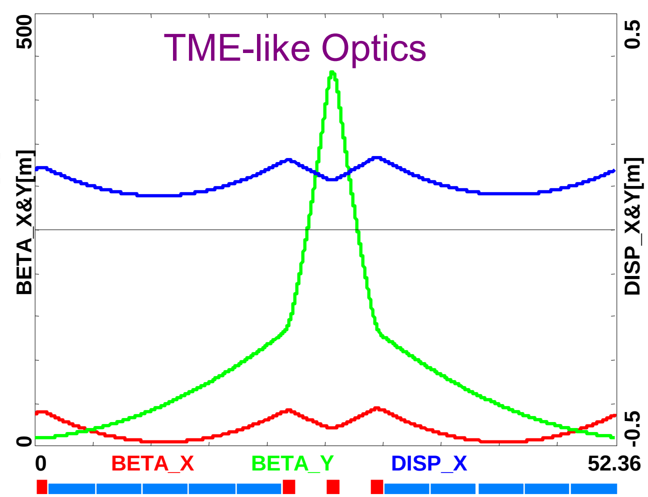

$$\langle H \rangle = 8.8 \times 10^{-3}\ m$$

Arc 3, Arc 4




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

Arc 5, Arc 6



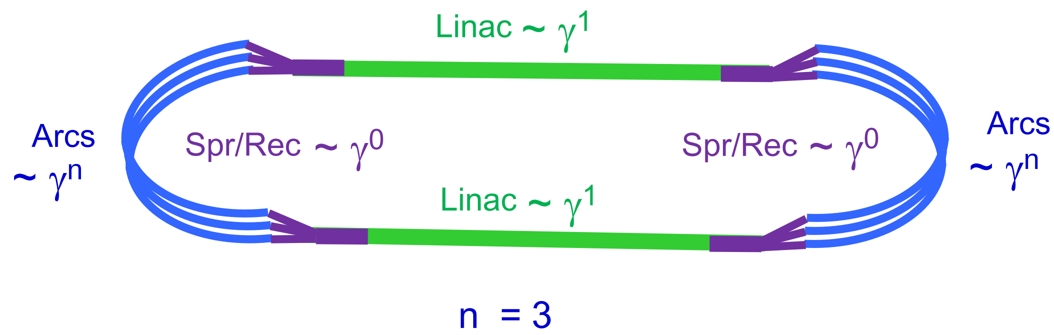

$$\langle H \rangle = 1.2 \times 10^{-3}\ m$$

# Energy Scaling – Preserving Emittance Dilution

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

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

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



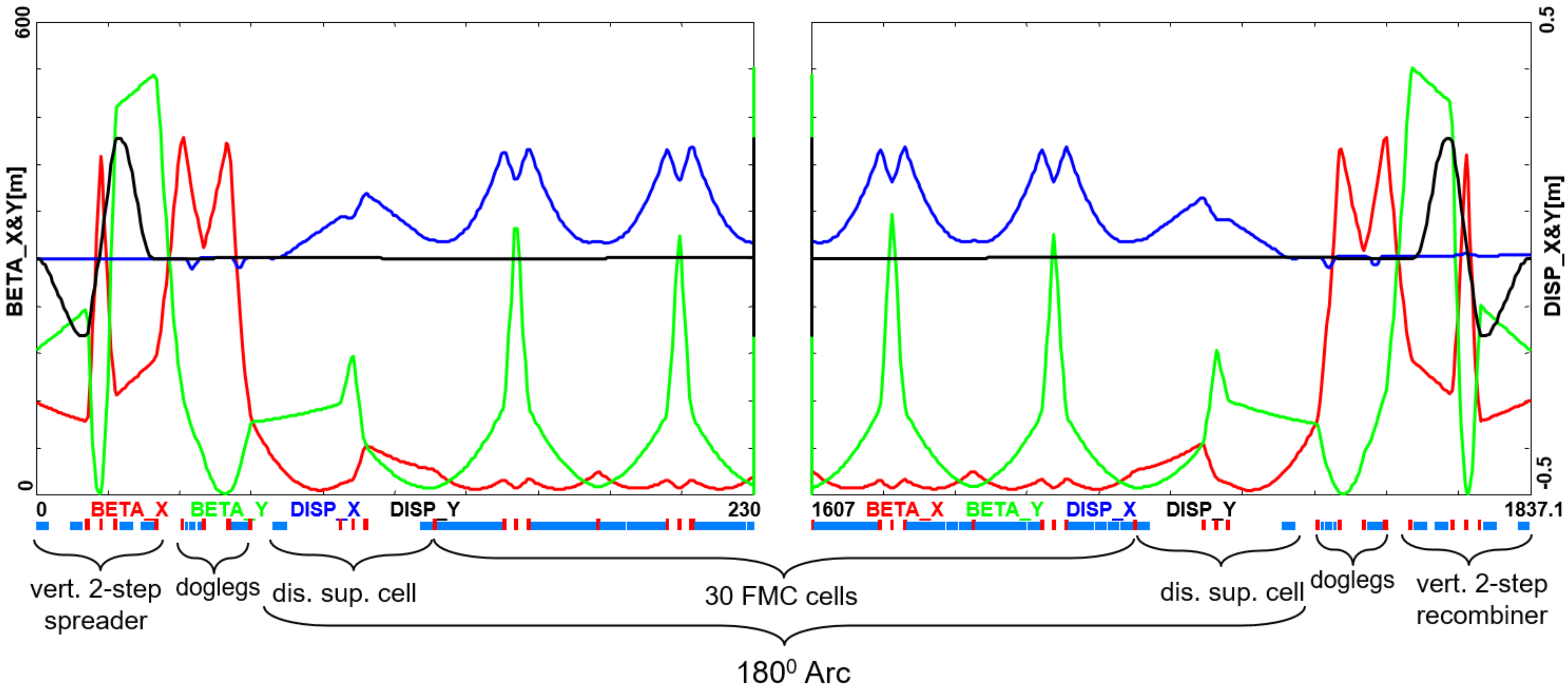

| ⅕ | |
|---|---|
| E [GeV] | 49.1 |
| Linac | 824 |
| Arc Radius [m] | 549 |
| Spr/Rec Matching [m] | 76 |
| Circumference [m] | 5400 |

| ⅓ | |
|---|---|
| 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)

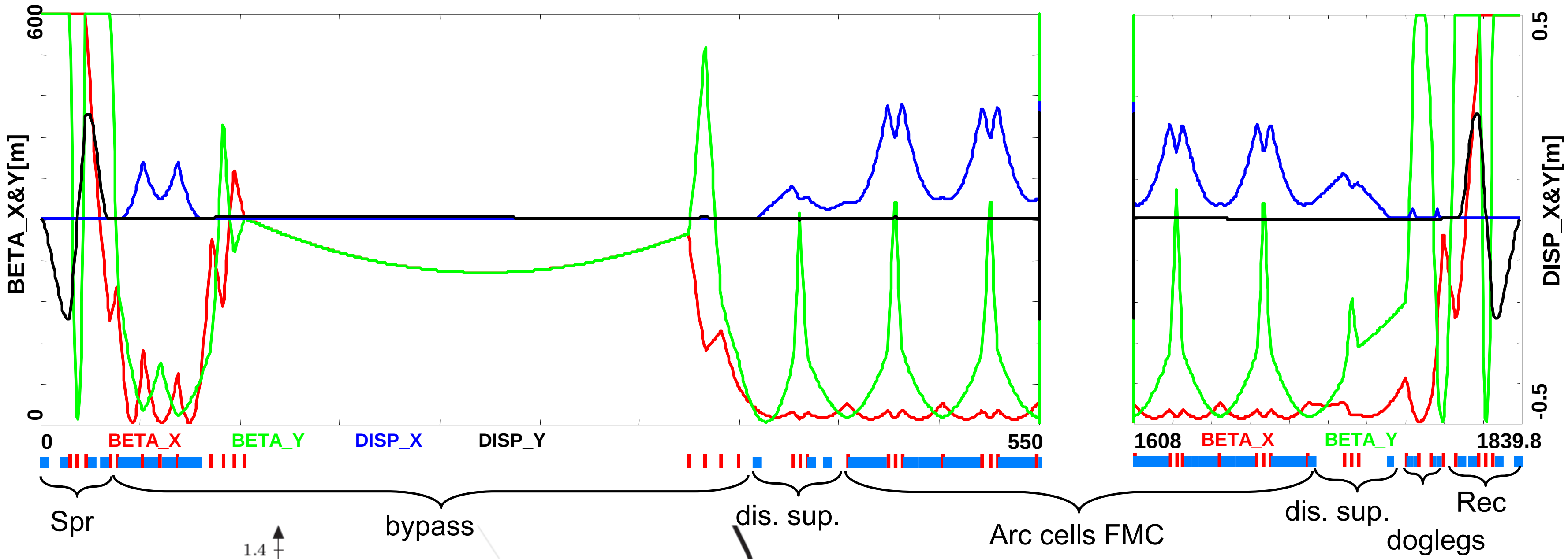


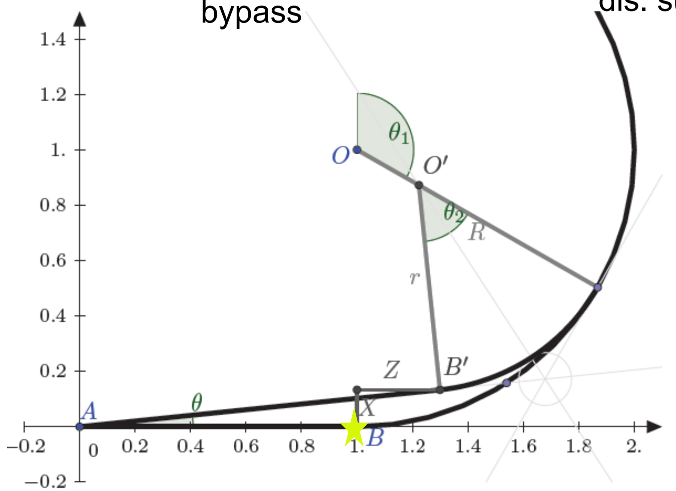

**Arc dipoles:**

$Lb=400 cm

$B=1.12 kGauss

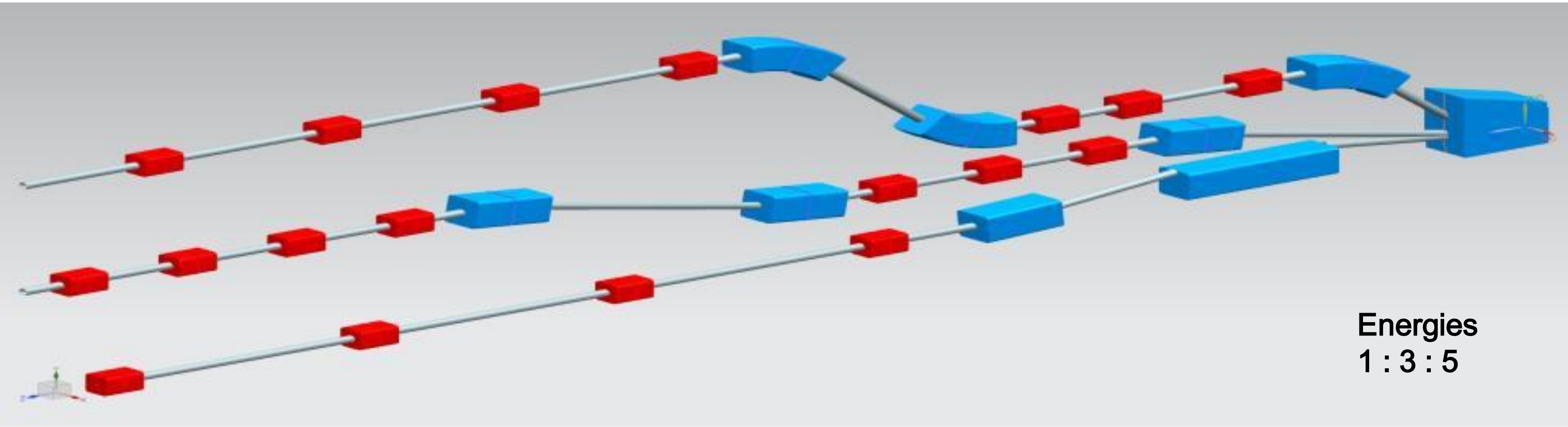
# Arc 4 (with bypass) Optics (33.0 GeV)

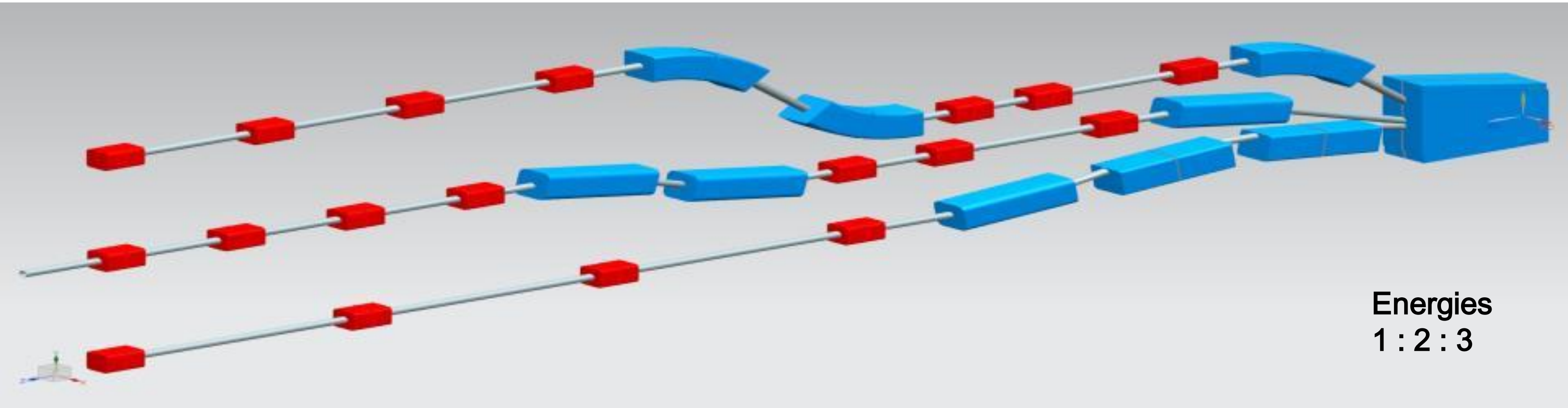



$$X = R + (R - r)\cos(\theta_1) + r\cos(\theta_1 + \theta_2)$$
$$Z = (R - r)\sin(\theta_1) + r\sin(\theta_1 + \theta_2)$$

# Vertical Switchyard Architecture



# Energy Loss and Emittance Dilution in Arcs

| Beamline | Beam energy [GeV] | $\Delta E$ [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 |

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

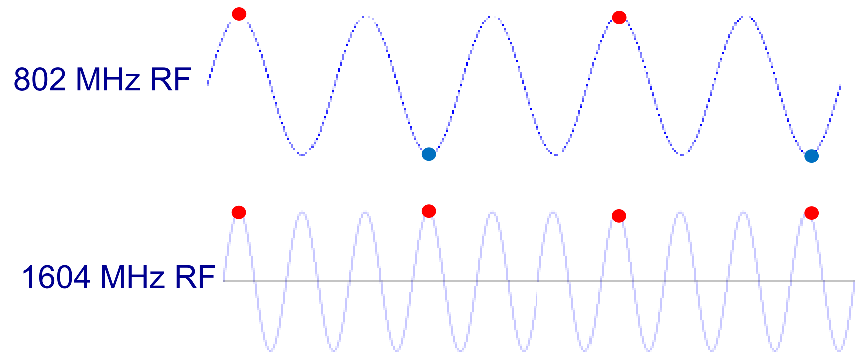
| | |
|---|---|
| Total Energy Loss [GeV] | 1.6 |
| Normailzed Emittance Dilution before IP [mm mrad] | 7.4 |
| Net Normailzed Emittance Dilution [mm mrad] | 28.4 |
| Net Natural Momentum Spread | 0.001 |

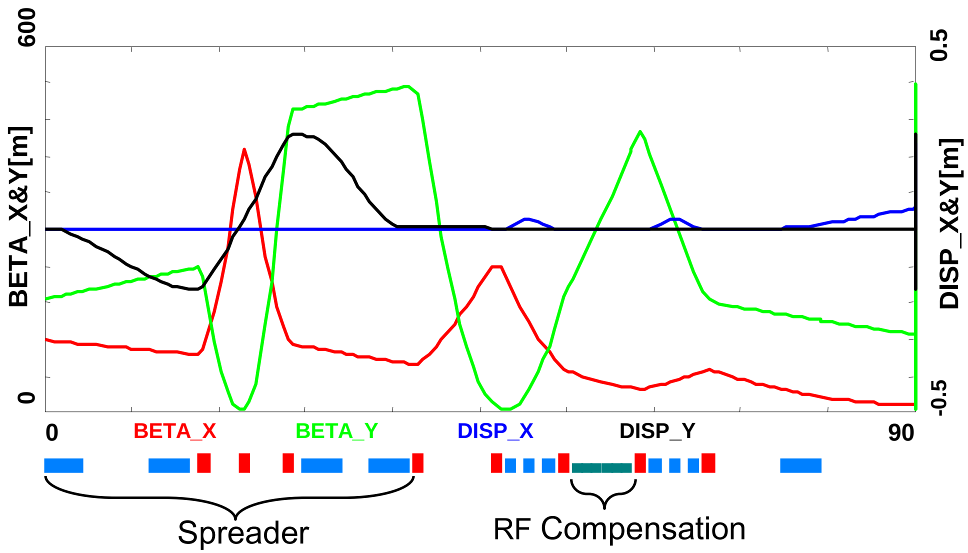
| | |
|---|---|
| R [m] | 536.4 |
| r [m] | 398.8 |

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

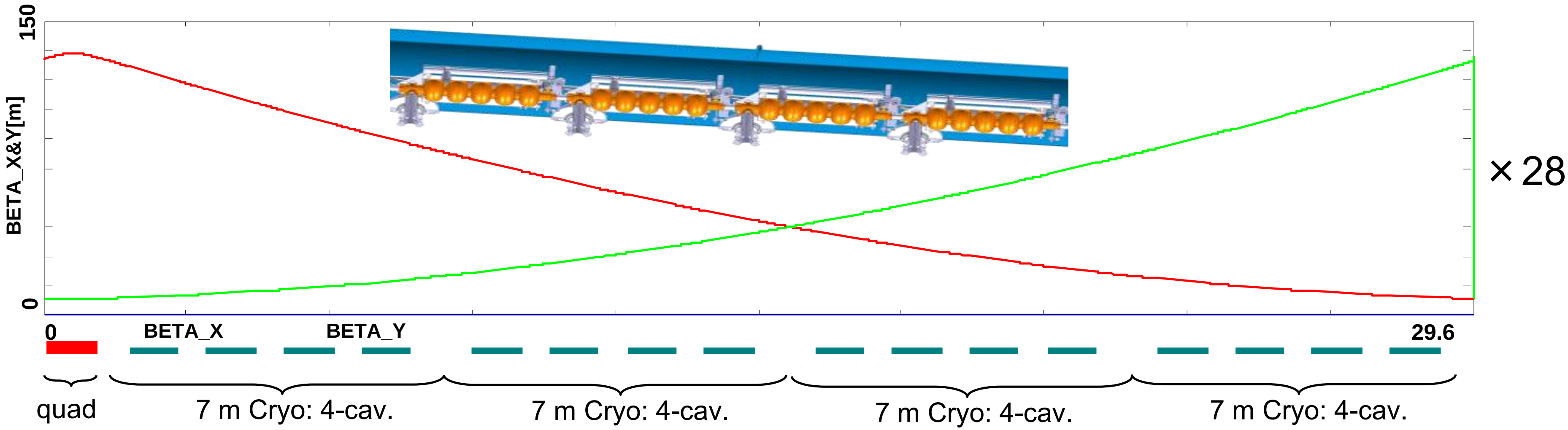
# 2-nd Harmonics RF Compensation of SR Losses

| Arc number | $\Delta E$ [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 |



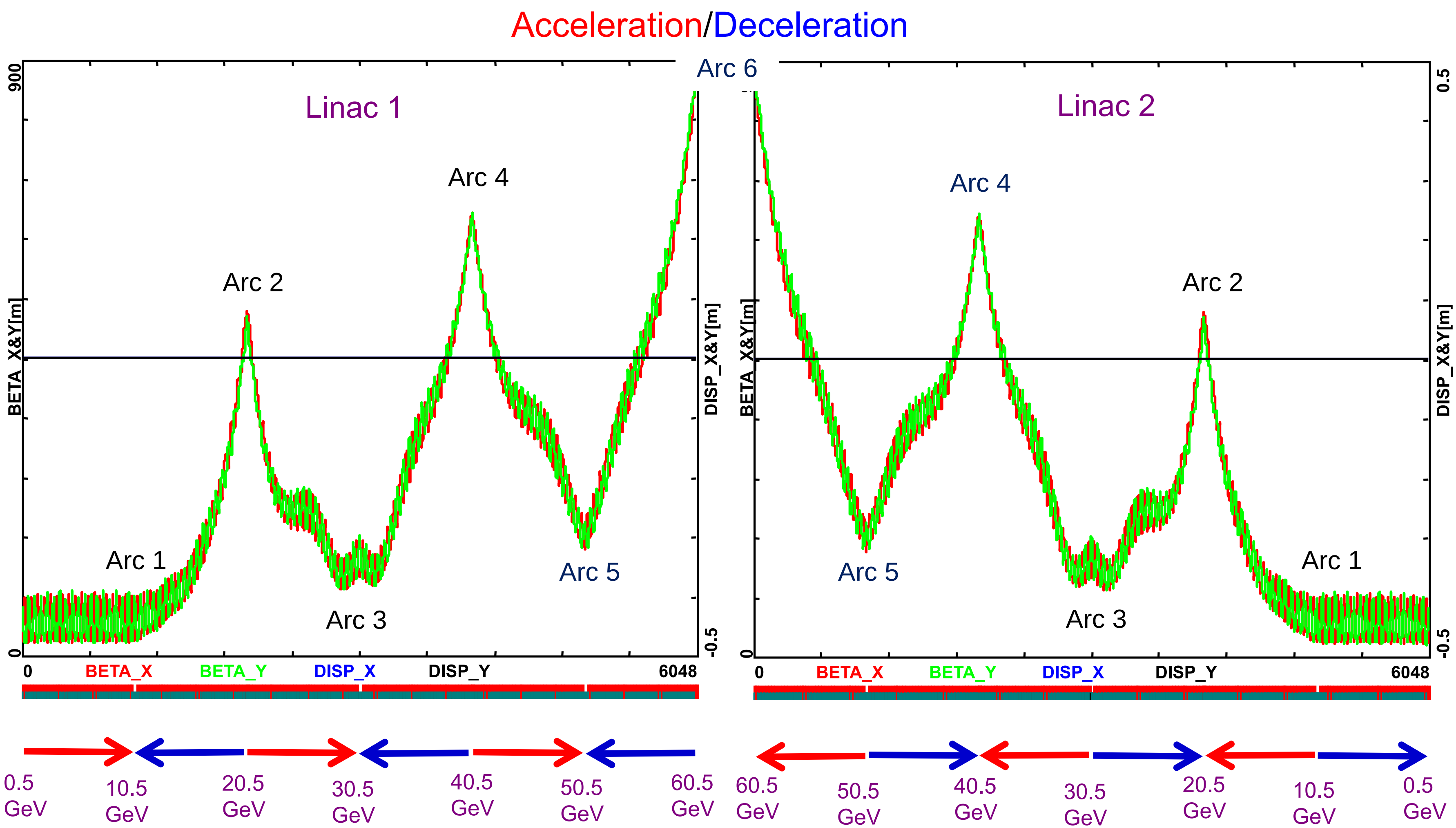



# Cryo Unit Layout/Optics – Half-Cell $130^0$ FODO

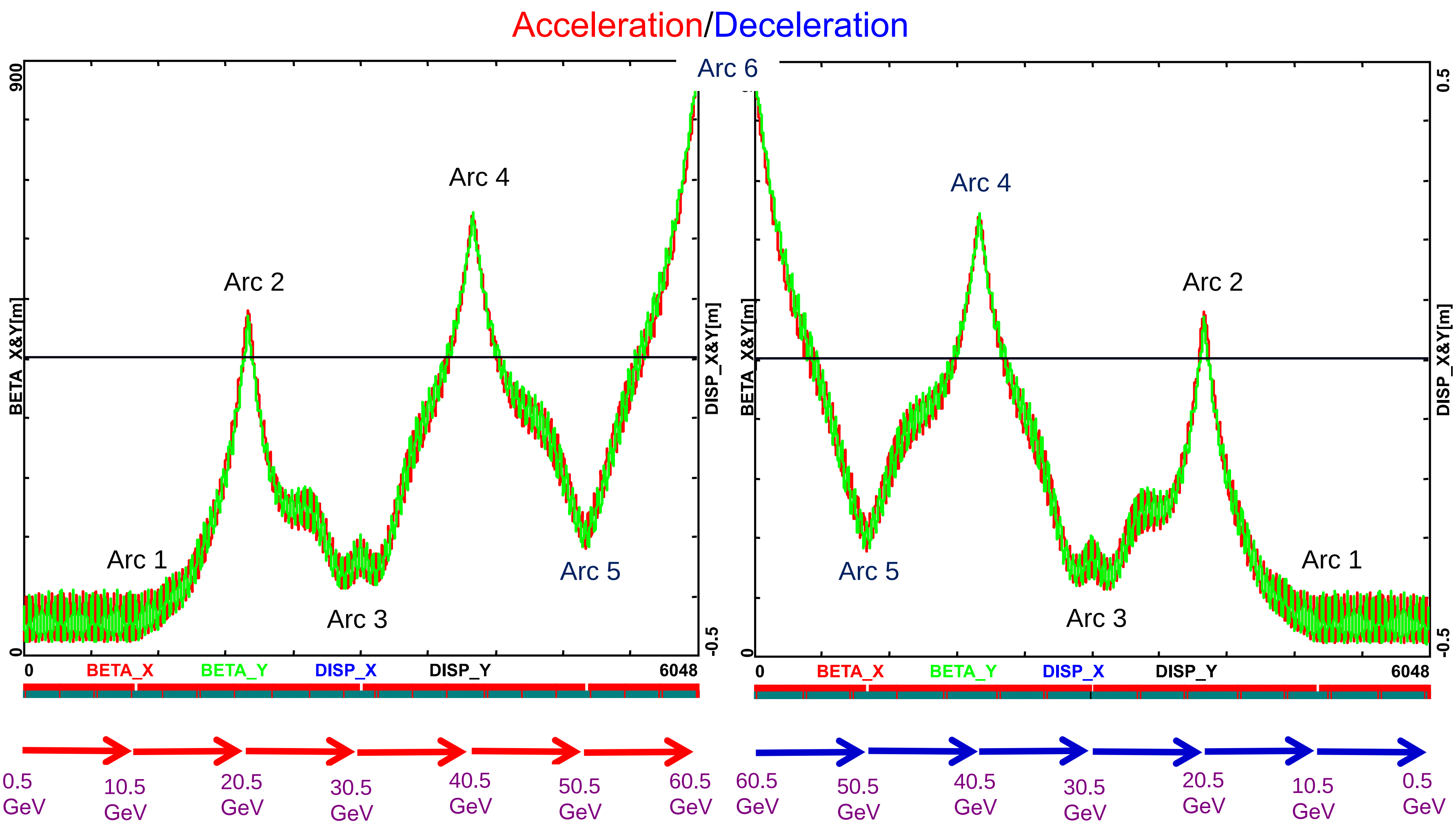



| Description | unit | parameters |
|---|---|---|
| Total energy gain per linac | GeV | 8.114 |
| Frequency | MHz | 801.58 |
| Acceleration gradient | MV/m | 19.73 |
| Cavity iris diameter | mm | 130 |
| Number of cells per cavity | | 5 |
| Cavity length (active/real estate) | m | 0.918/1.5 |
| Cavities 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



# Linac 1 and 2 – Multi-pass ER Optics



# End-to-End ERL Tracking (PLACET 2)

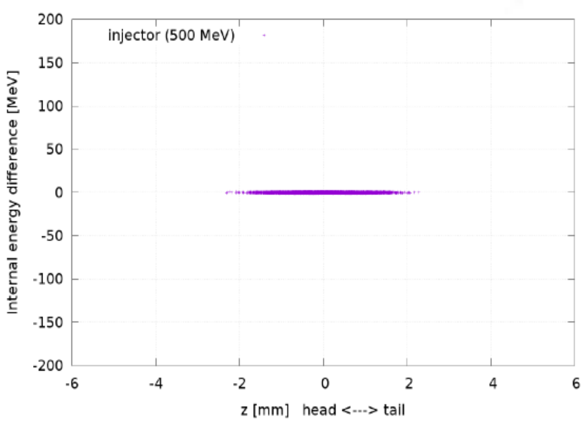
PHYSICAL REVIEW SPECIAL TOPICS—ACCELERATORS AND BEAMS **18,** 121004 (2015)

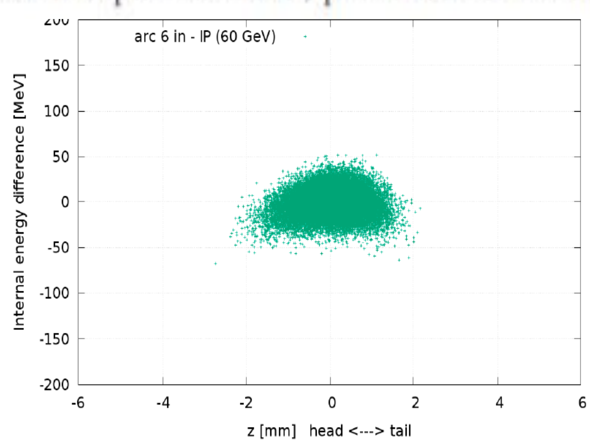
*

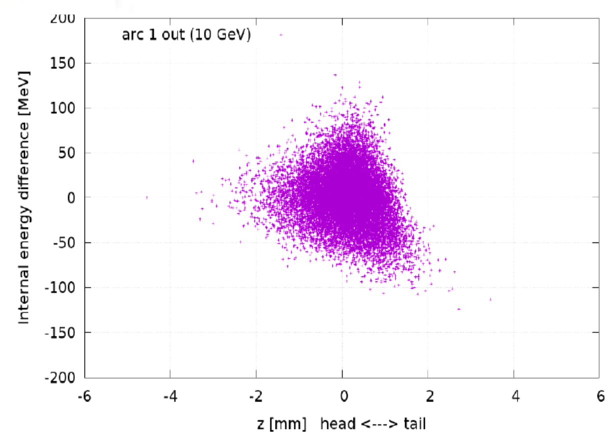
## Beam-dynamics driven design of the LHeC energy-recovery linac

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 | $\mu$m | $2.2 \to 1.1$ | 10 |
| IP betafunction | mm | 150 | $42 \to 52$ |
| Nominal RMS beam size | $\mu$m | $2.5 \to 1.8$ | $1.9 \to 2.1$ |
| Waist shift | mm | 0 | $65 \to 70$ |
| Bunch population | $10^{10}$ | $10 \to 5$ | 0.31 |
| Bunch spacing | ns | 25 | 25 |
| Luminosity | $10^{33}\text{cm}^{-2}\text{s}^{-1}$ | $18.3 \to 14.3$ | |
| Int. luminosity per 10 years | $[\text{ab}^{-1}]$ | 1.2 | |

# FCC-he ERLs

| Parameter | Unit | Protons | Electrons |
|---|---|---|---|
| Beam energy | GeV | 50000 | 60 |
| Normalised emittance | $\mu$m | $2.2 \rightarrow 1.1$ | 10 |
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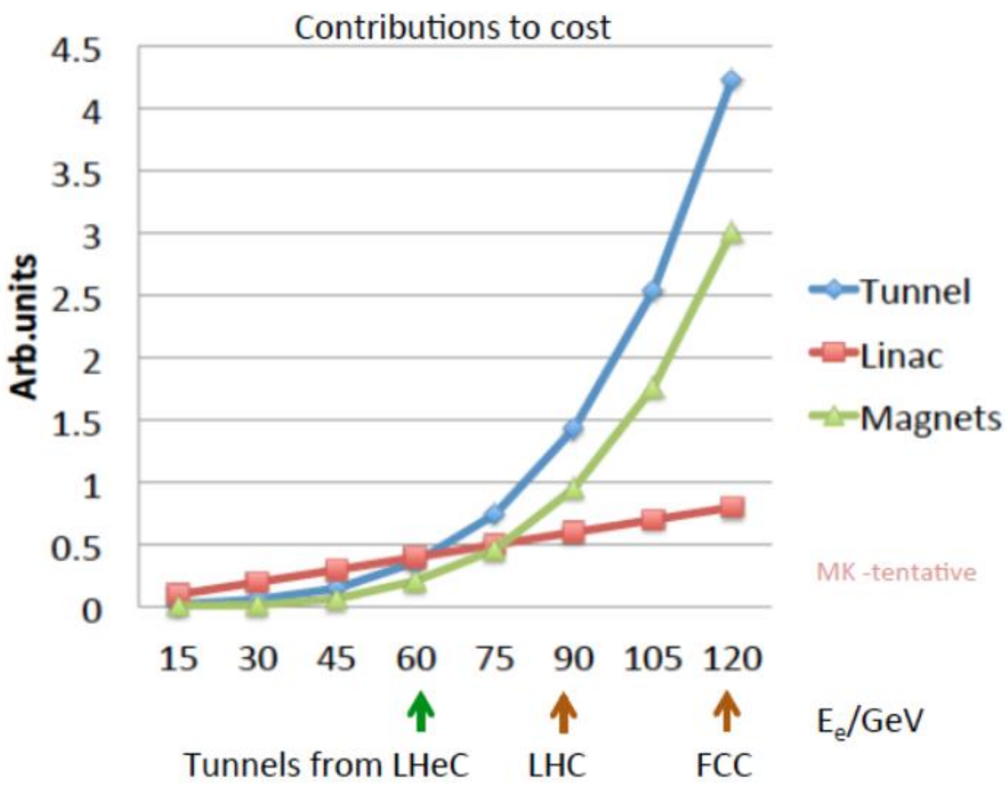
| Waist shift | mm | 0 | $65 \rightarrow 70$ |
| Bunch population | $10^{10}$ | $10 \rightarrow 5$ | 0.31 |
| Bunch spacing | ns | 25 | 25 |
| Luminosity | $10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ | $18.3 \rightarrow 14.3$ | |
| Int. luminosity per 10 years | $[\mathrm{ab}^{-1}]$ | 1.2 | |

| 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 ~ $\gamma^4$

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

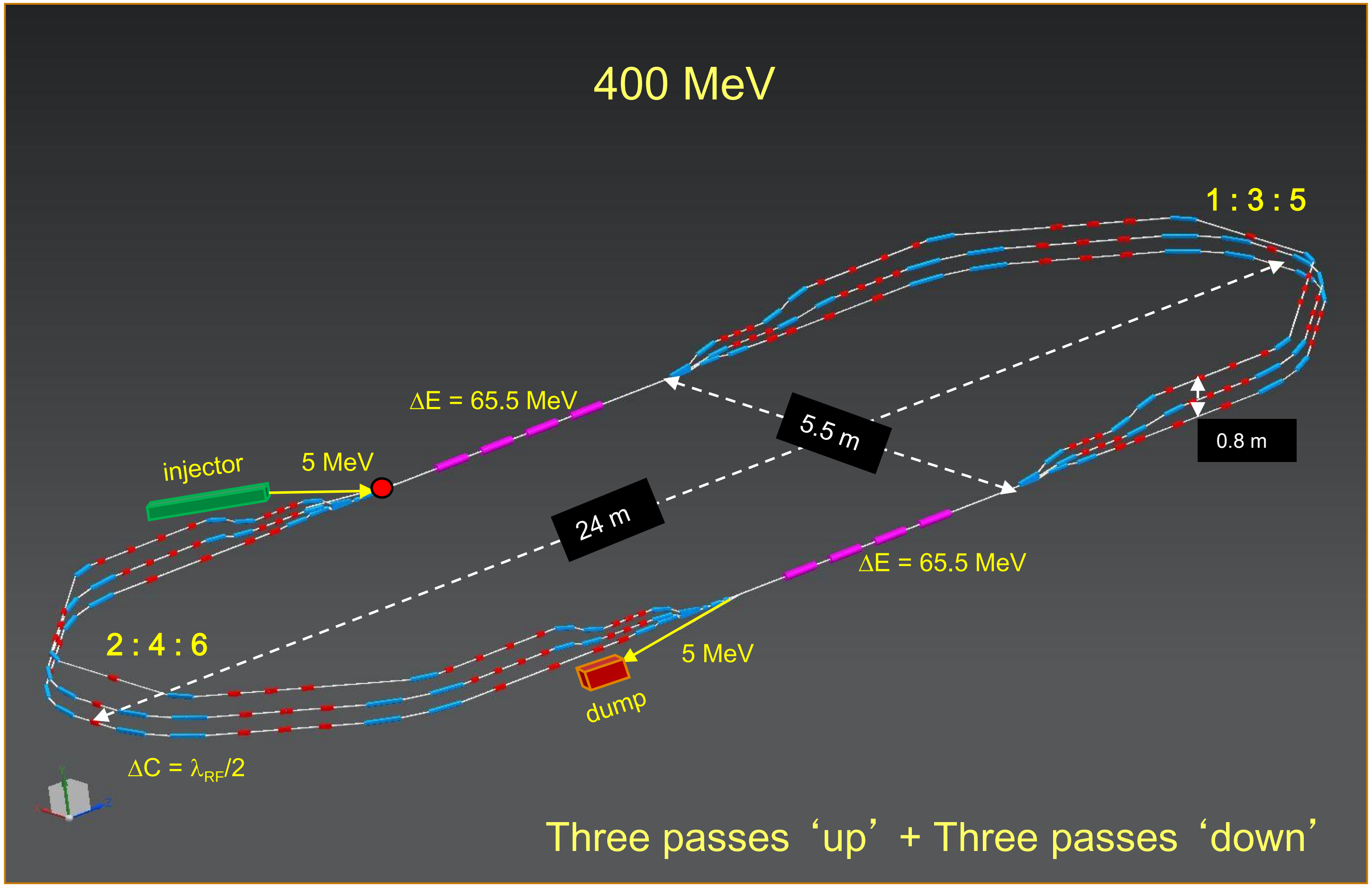
$$\frac{\Delta\epsilon_E^2}{E^2} = \frac{2\pi}{3} C_q r_0 \, \frac{\gamma^5}{\rho^2},$$

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

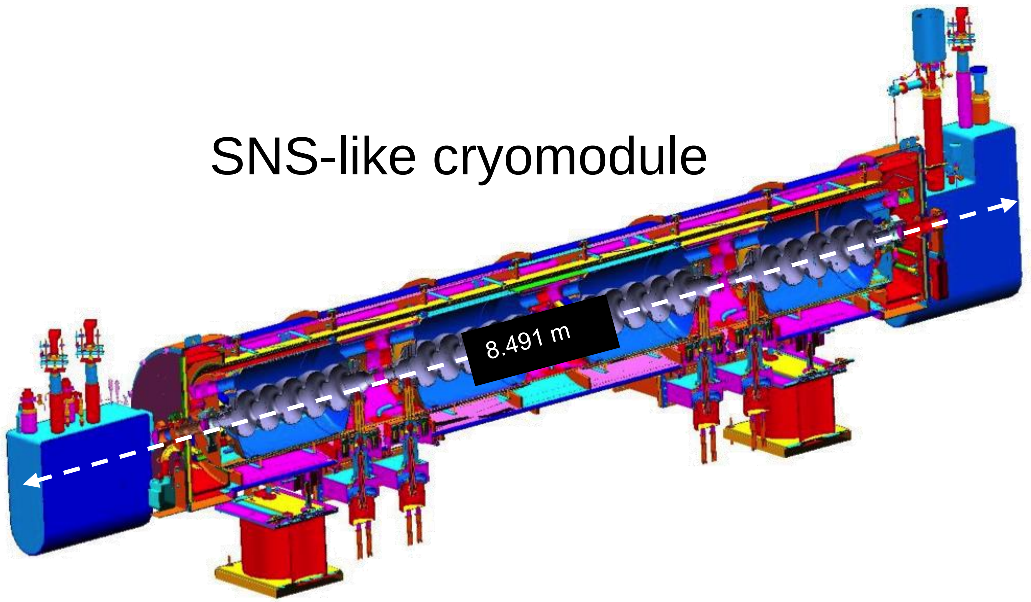
PERLE



# 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 | |

# Linac, Cryo-module - Layout



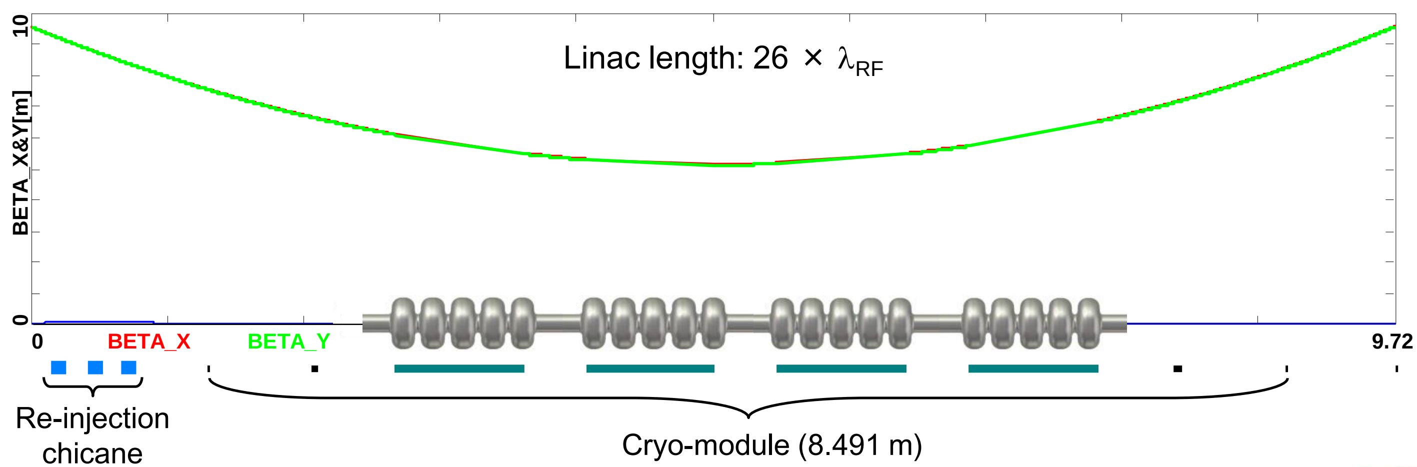

**801.58 MHz RF,** 5-cell cavity:

$\lambda$ = 37.40 cm

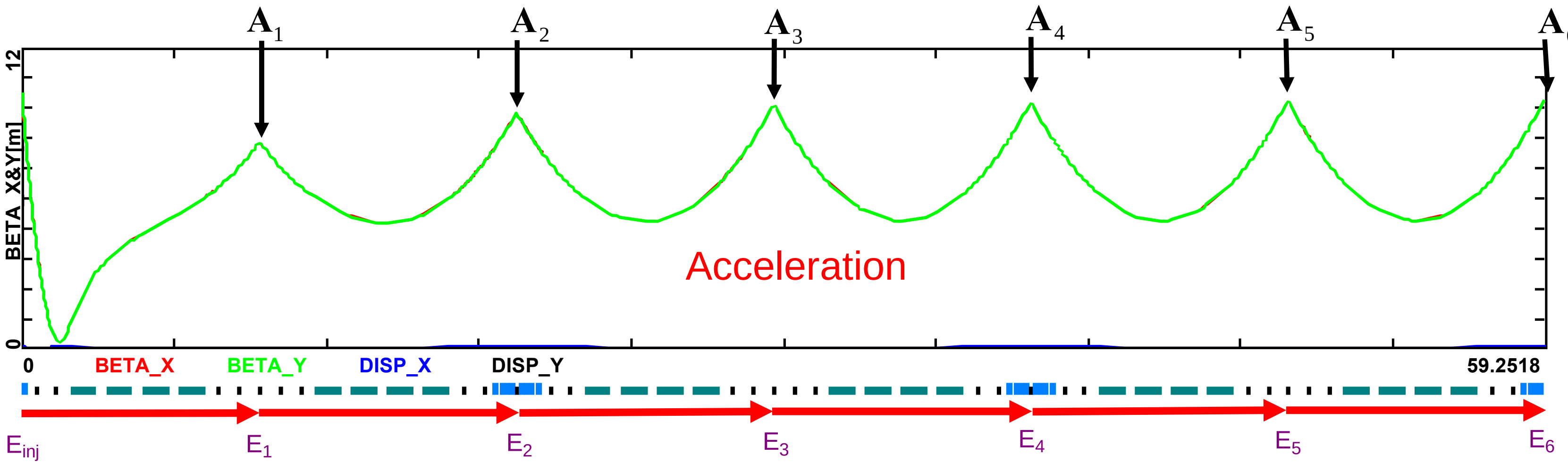
$L_c = 5\lambda/2 = 93.50$ cm

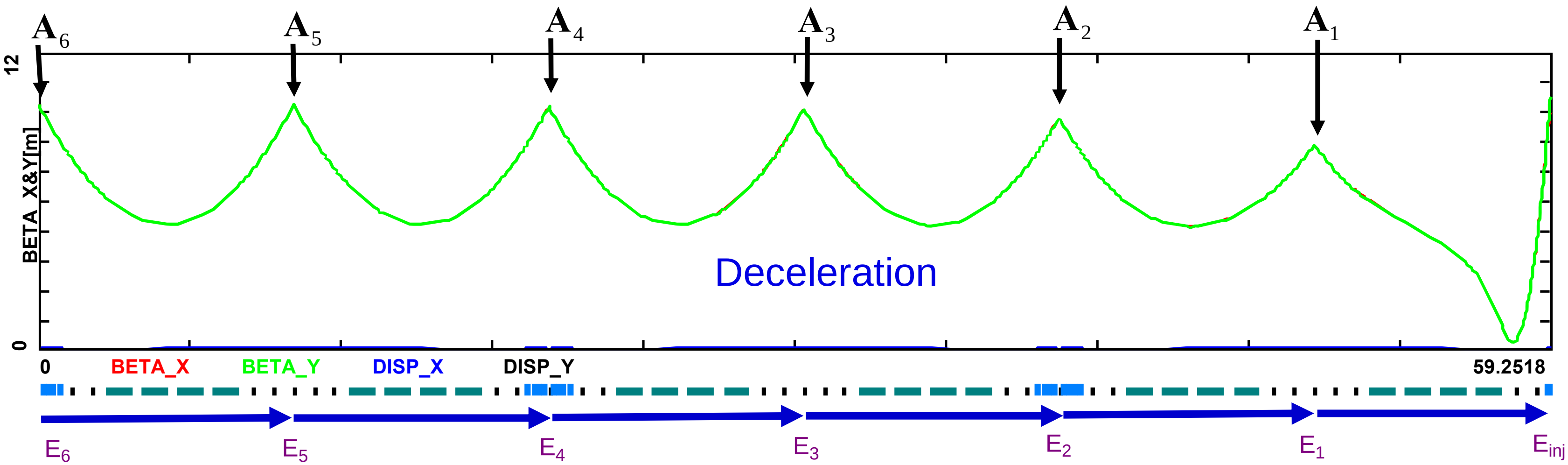
Grad = 17.5 MeV/m (16.4 MeV per cavity)

$\Delta E$= 65.5 MeV per Cryo-module

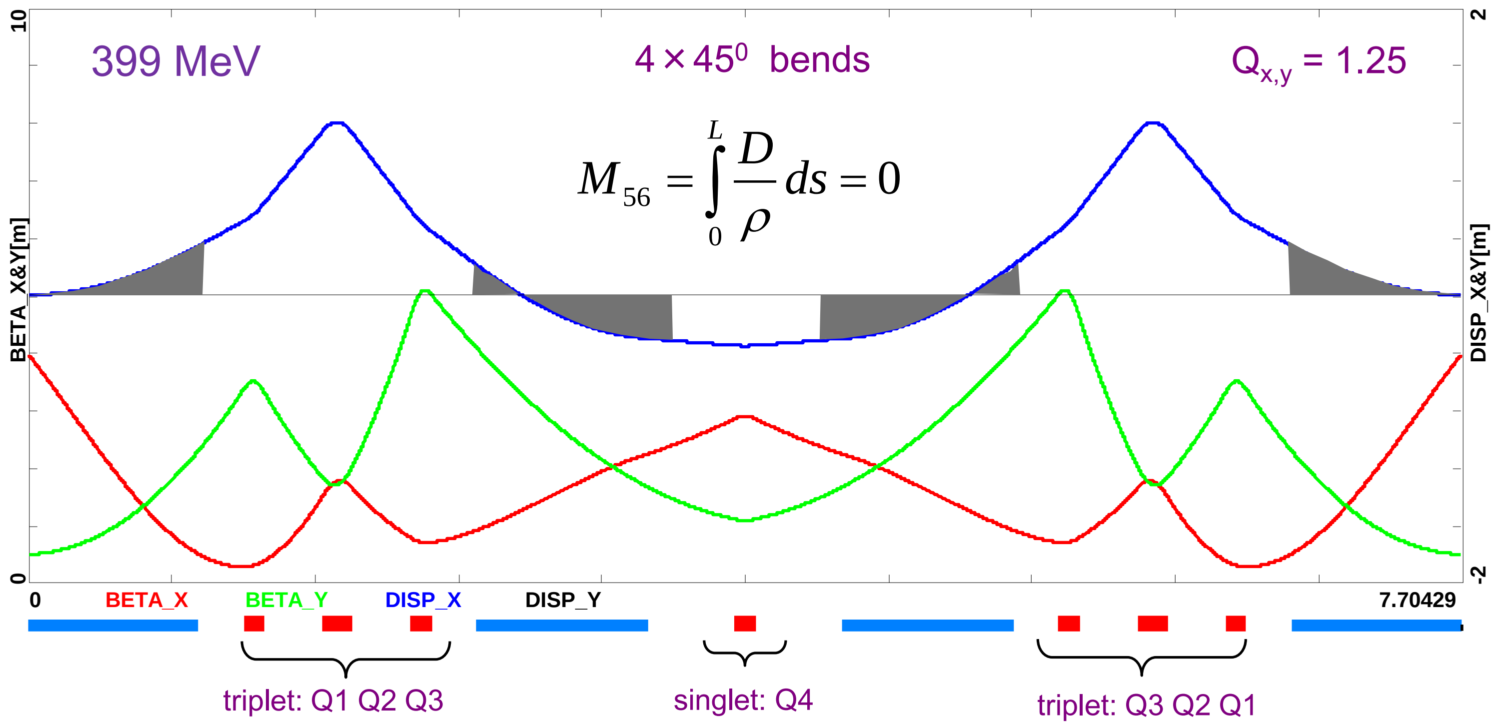


# Multi-pass ER Optics



# Arc 6 (5,4) Optics – FMC Lattice



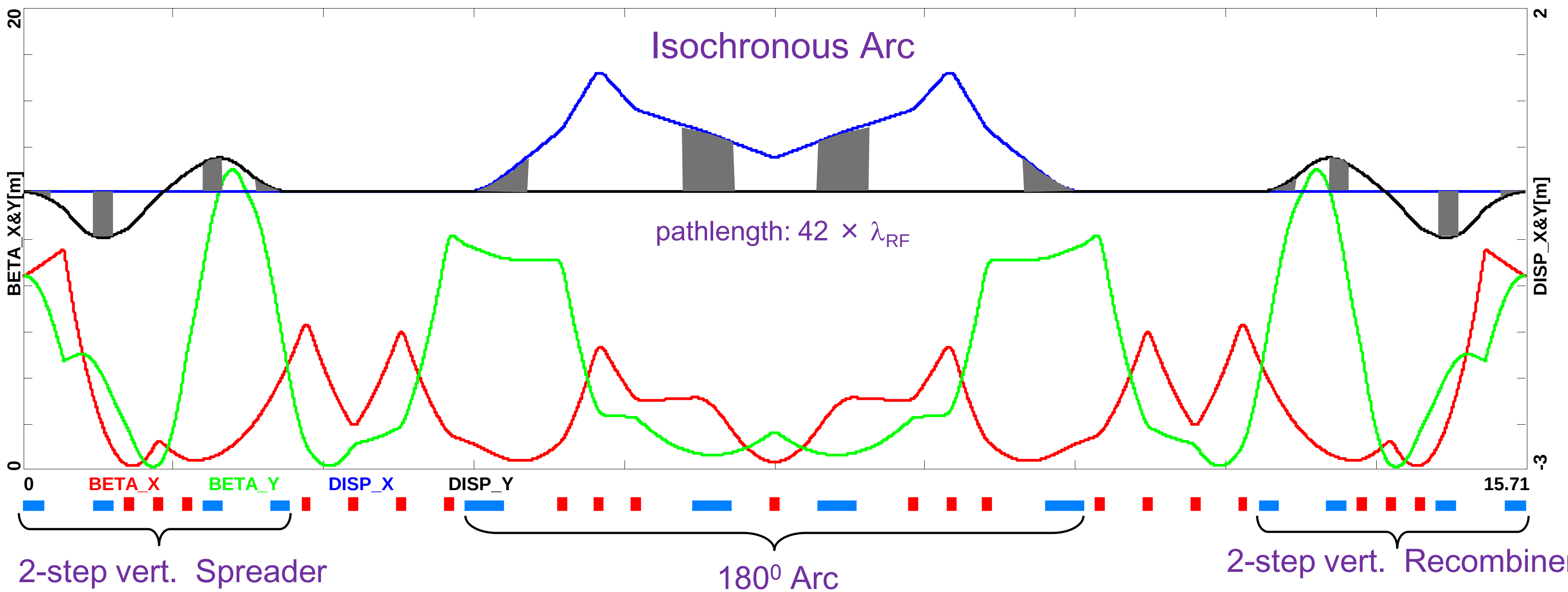

**Dipoles:** (91.2 cm long)

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 options – ⅕ of the LHC circumference
  - All lattice building blocks are available from 60 GeV design
  - Same performance in terms of synchrotron radiation effects
- FCC High Energy Options (60 and 100 GeV)
  - Same performance in terms of synchrotron radiation effects
- 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

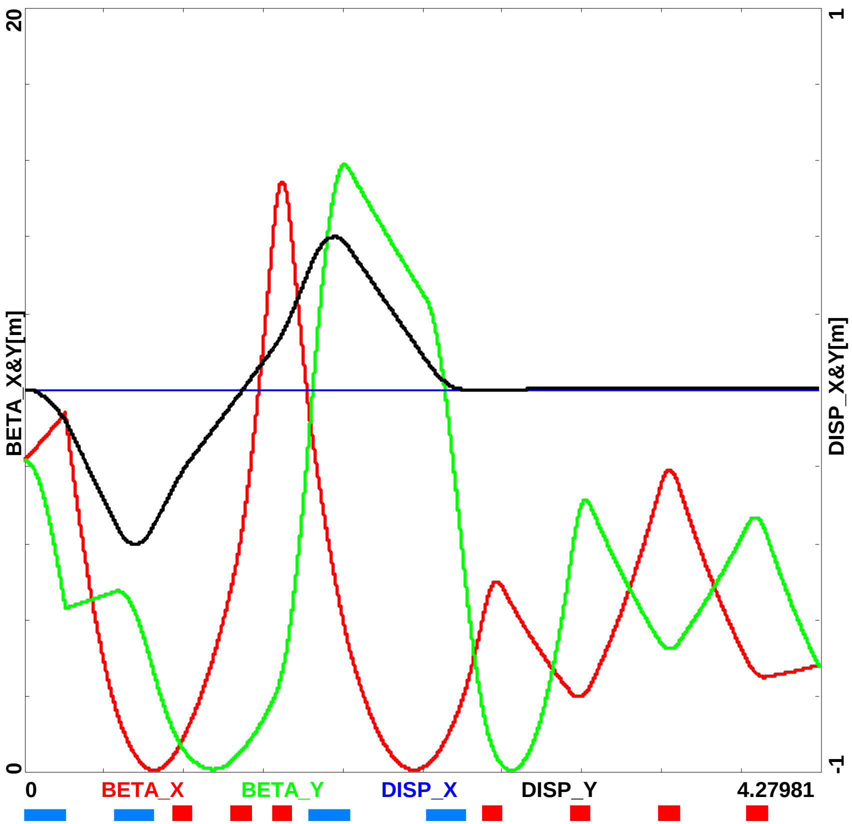
Oliver Brüning

# Thank you for your attention!

# Backup Slides

# Vertical Spreaders – Optics

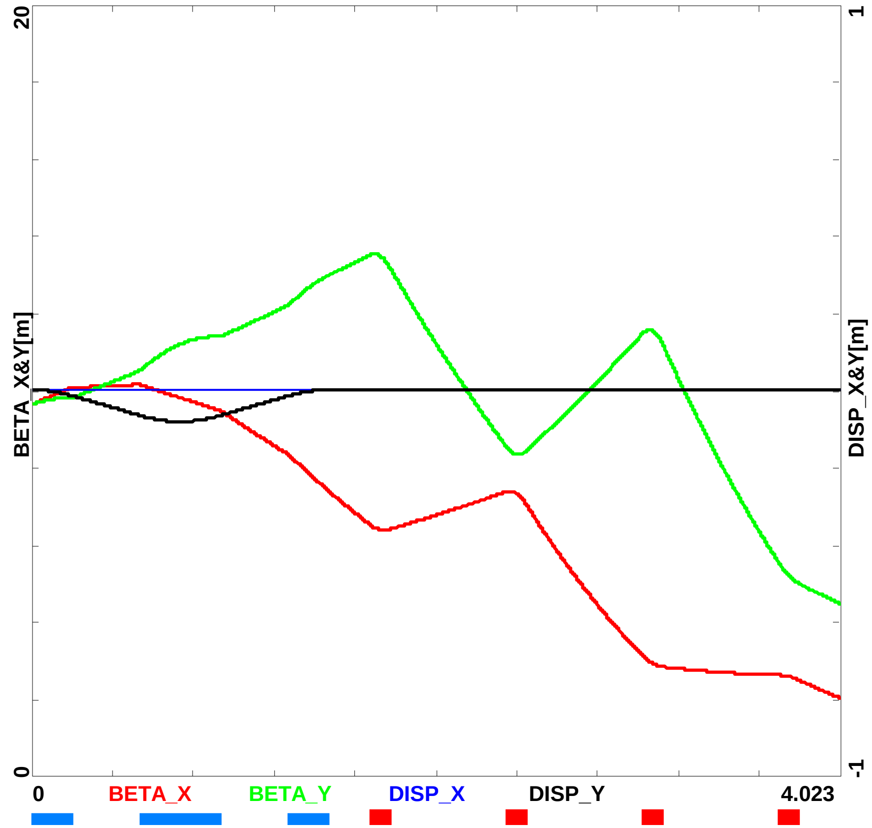
## Spr. 1 (71 MeV)




vertical step I

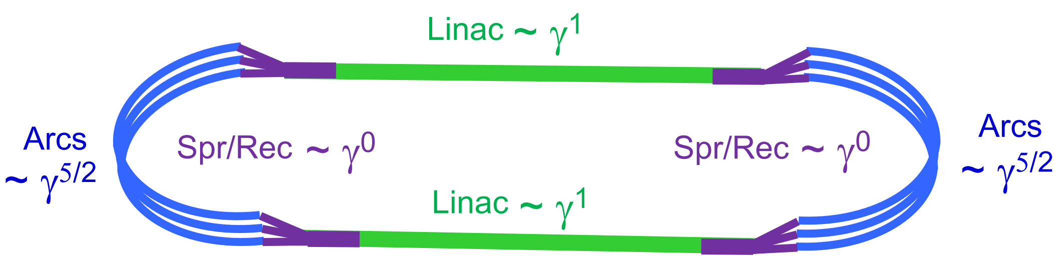
vertical step II

## Spr. 5 (333 MeV)




vertical chicane

# Energy Scaling – Preserving Emittance Dilution




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

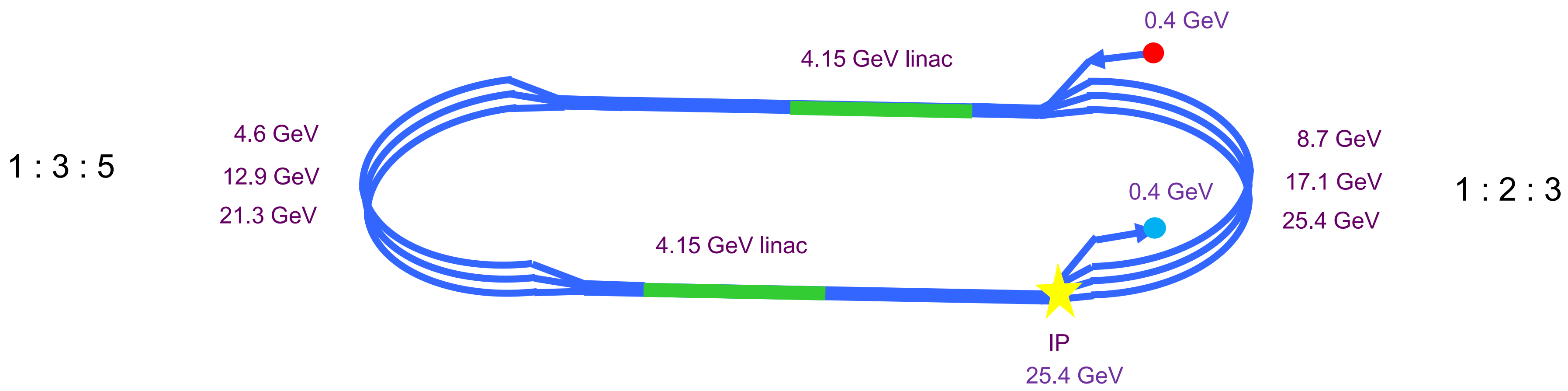
**⅕**

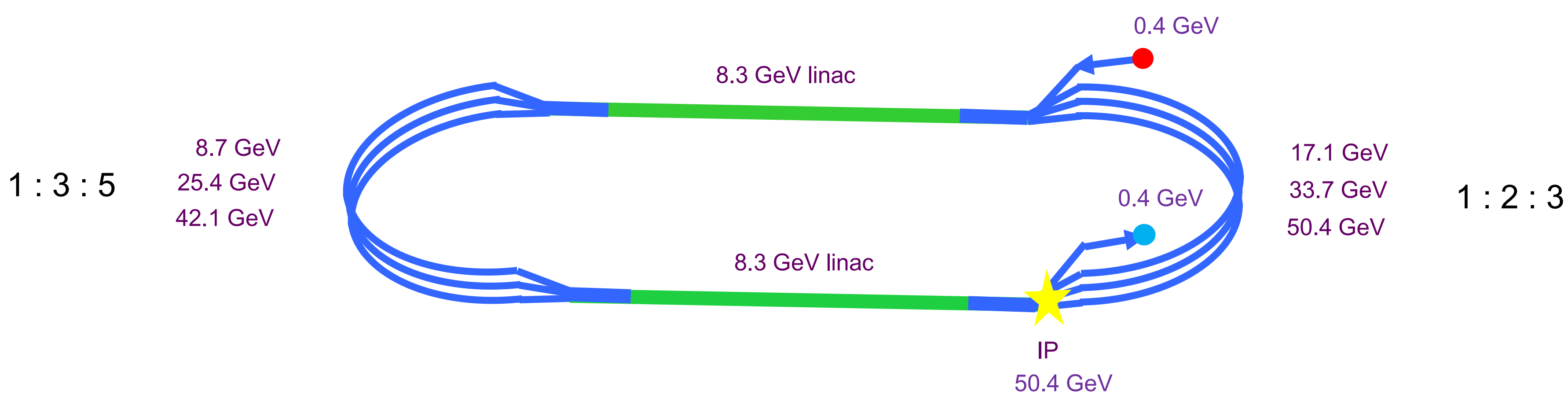
| | |
|---|---|
| Cavity gradient [MV/m] | 19.73 |
| Cryo-unit length [m] | 29.60 |
| Energy gain /cryo-unit [MeV] | 289.83 |
| Number of cryo-units | 28.00 |
| Linac length [m] | 828.80 |
| Linac energy [GeV] | 8.12 |
| Net energy gain [GeV] | 48.69 |
| Injection Energy [GeV] | 0.50 |
| Total Energy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