# Lattice Design Choices for LHeC ERL

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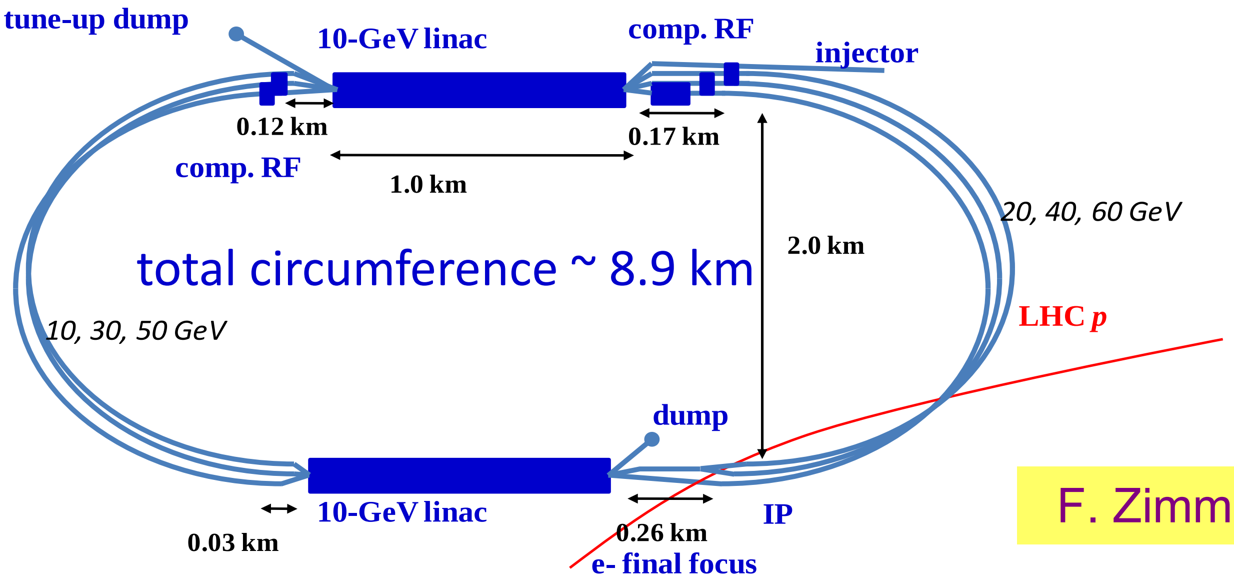
**Workshop on the LHeC**
Electron-proton and electron-ion collisions at the LHC

**20-21 January 2014**
**Chavanne-de-Bogis, Switzerland**

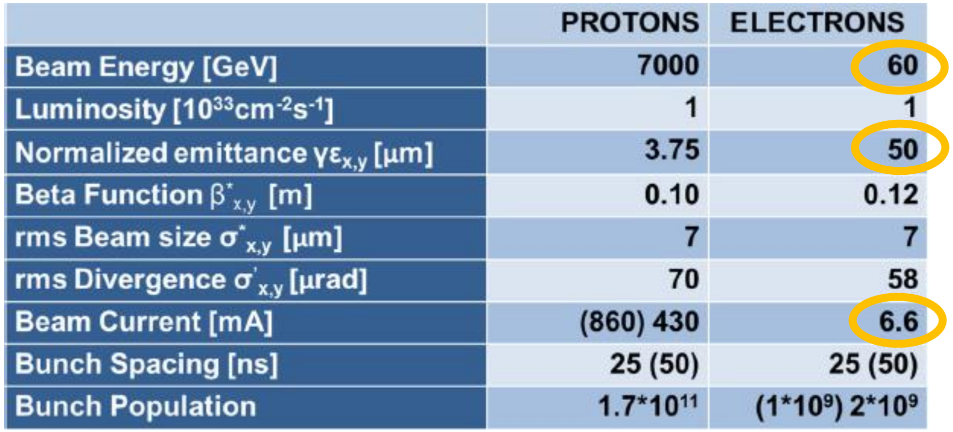
# Linac-Ring Option – LHeC Recirculator



F. Zimmermann

## RECIRCULATOR COMPLEX

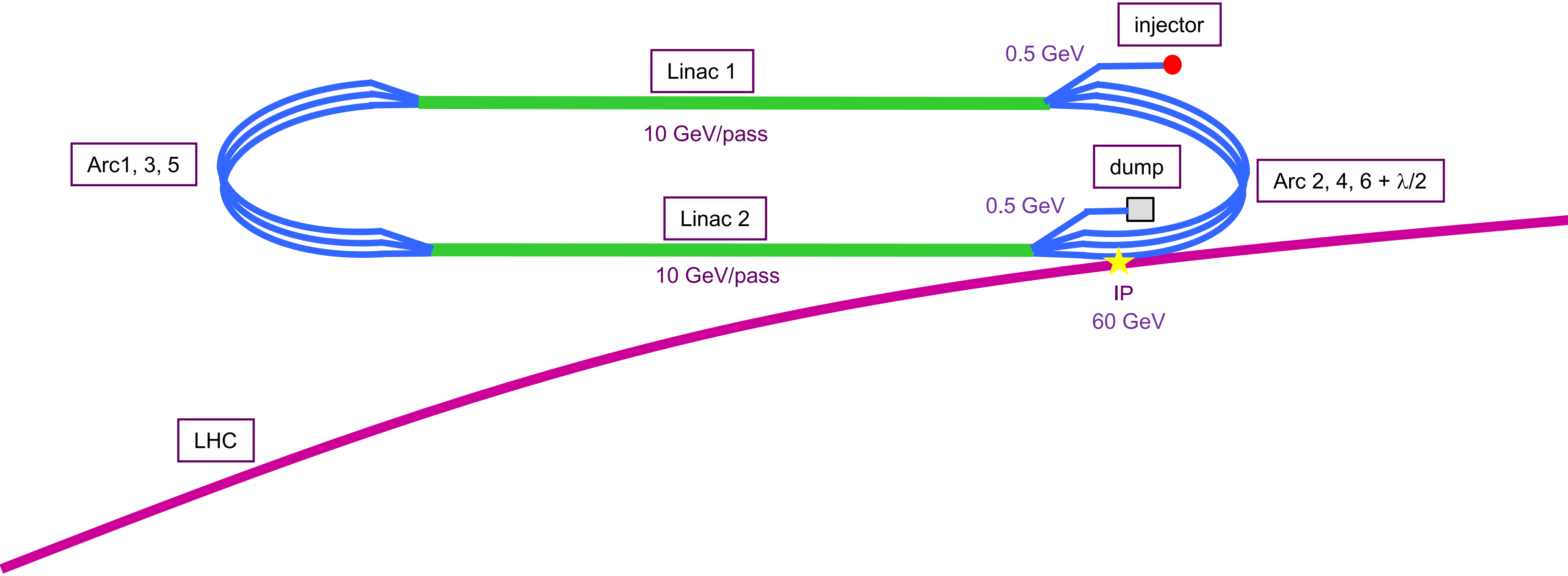
1. 0.5 Gev injector
2. Two SCRF linacs (10 GeV per pass)
3. Six 180° arcs, each arc 1 km radius
4. Re-accelerating stations
5. Switching stations
6. Matching optics
7. Extraction dump at 0.5 GeV



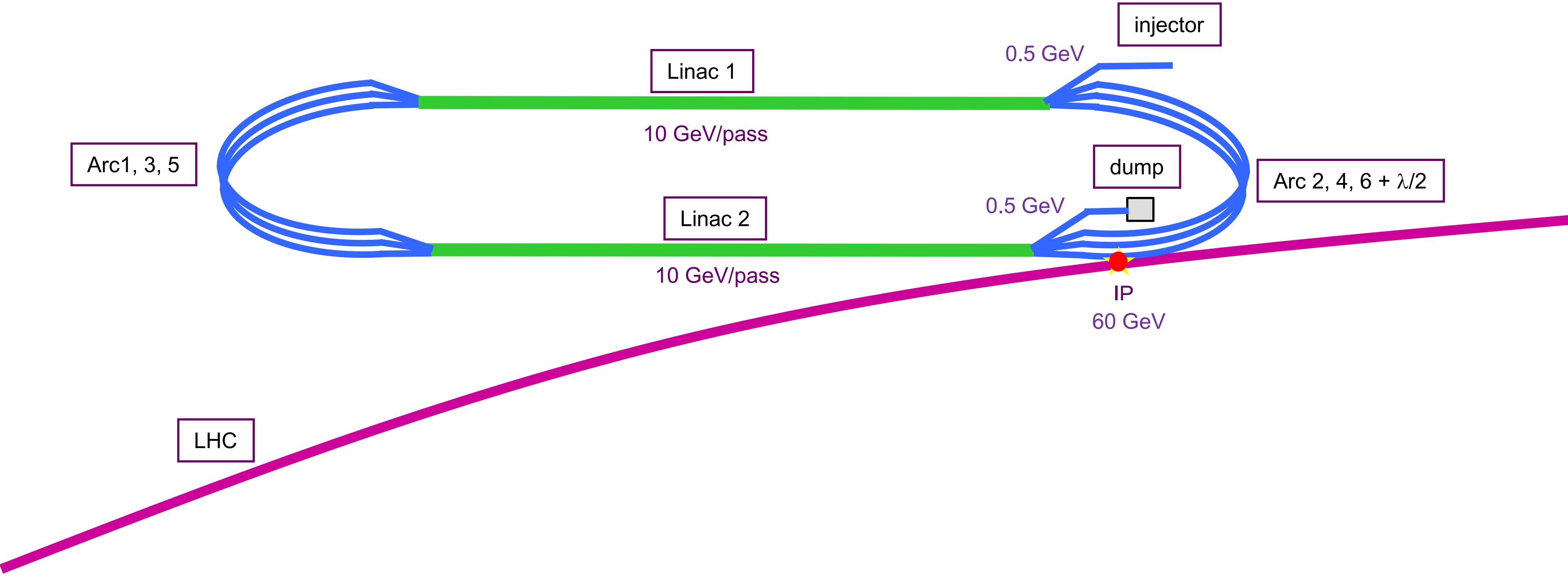
| | PROTONS | ELECTRONS |
|---|---|---|
| Beam Energy [GeV] | 7000 | 60 |
| Luminosity [$10^{33}$cm$^{-2}$s$^{-1}$] | 1 | 1 |
| Normalized emittance $\gamma\varepsilon_{x,y}$ [μm] | 3.75 | 50 |
| Beta Function $\beta^{*}_{x,y}$ [m] | 0.10 | 0.12 |
| rms Beam size $\sigma^{*}_{x,y}$ [μm] | 7 | 7 |
| rms Divergence $\sigma'_{x,y}$ [μrad] | 70 | 58 |
| Beam Current [mA] | (860) 430 | 6.6 |
| Bunch Spacing [ns] | 25 (50) | 25 (50) |
| Bunch Population | 1.7*$10^{11}$ | (1*$10^{9}$) 2*$10^{9}$ |

The baseline 60 GeV ERL option proposed can give an e-p luminosity of $10^{33}$ cm$^{-2}$s$^{-1}$ (extensions to $10^{34}$ cm$^{-2}$s$^{-1}$ and beyond are being considered)

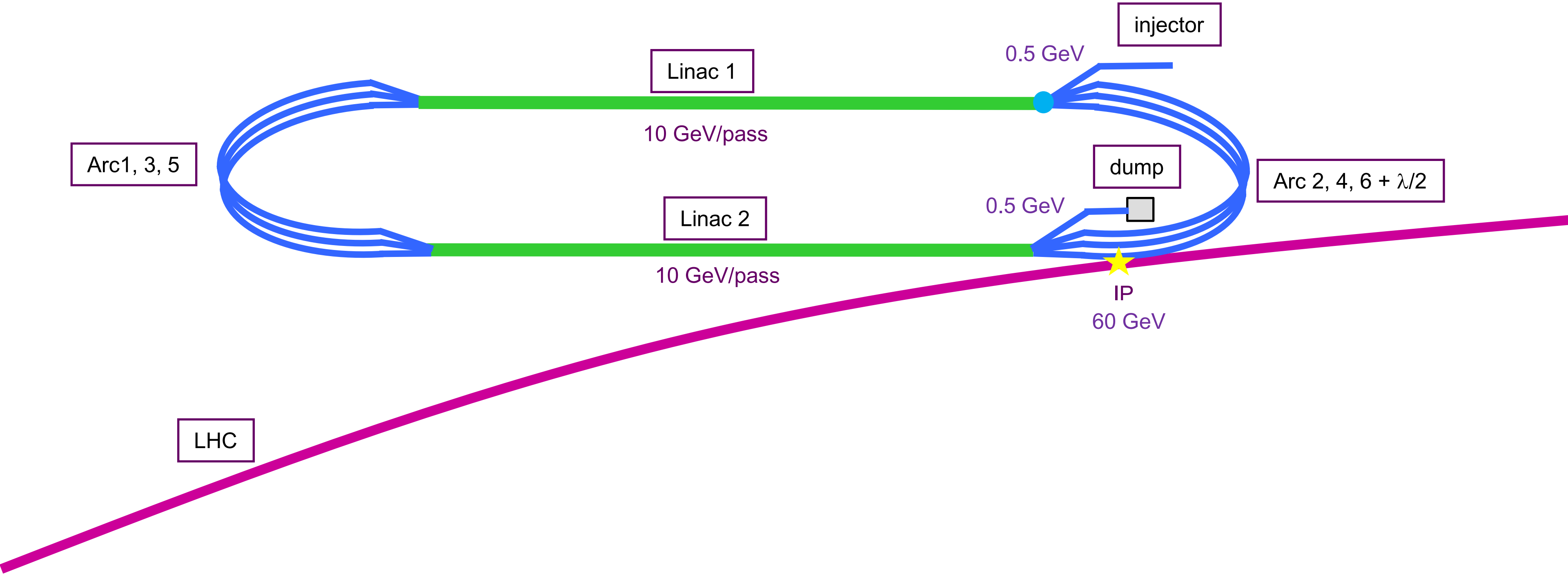
# LHeC Recirculator with ER



# LHeC Recirculator with ER



# LHeC Recirculator with ER



# Why Energy Recovering RLA?

- High energy (**60 GeV**), high current (**6.4 mA**) beams: (**384 MW** beam power) would require sub GW (**0.8 GW**)-class RF systems in conventional linacs .

- Invoking Energy Recovery alleviates extreme **RF power demand** (power reduced by factor (**$1 - \eta_{ERL}$**) ⇨ Required **RF power** becomes nearly independent of **beam current**.

- Energy Recovering Linacs promise **efficiencies of storage rings**, while maintaining **beam quality of linacs**: superior emittance and energy spread and short bunches (sub-pico sec.).

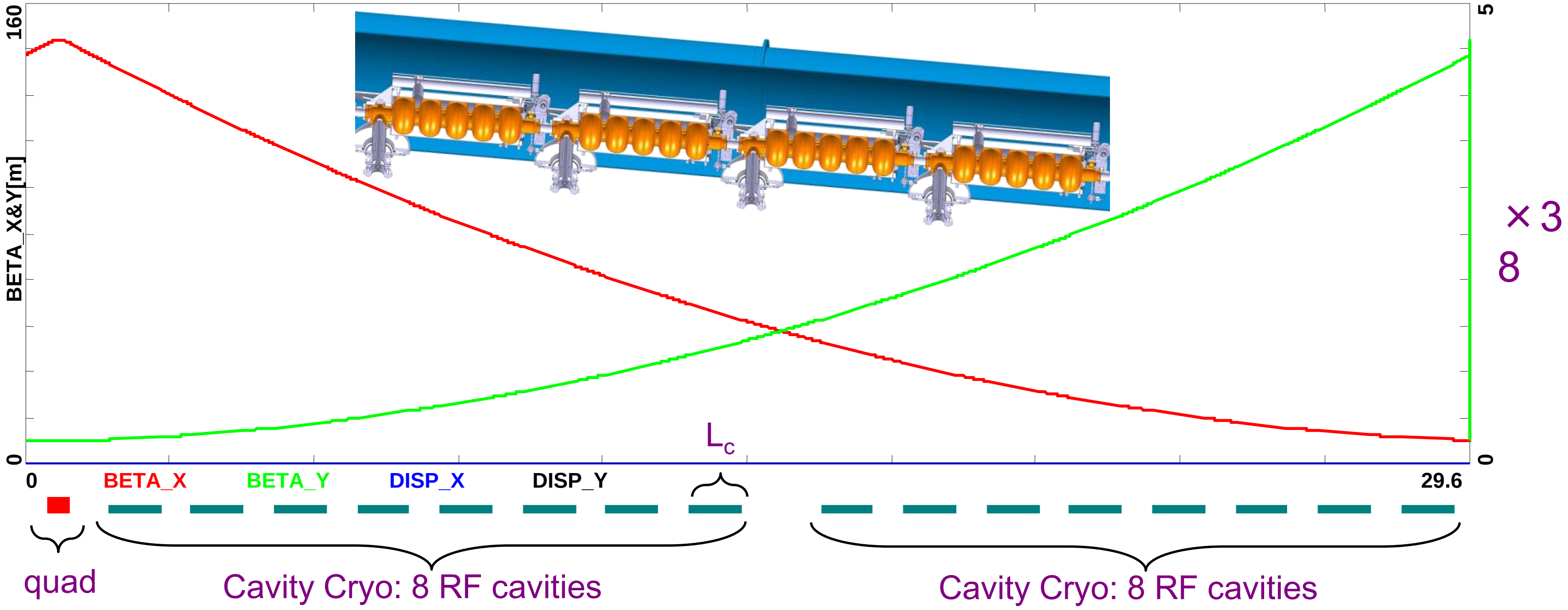
- GeV scale Energy Recovery demonstration with high ER ratio ($\eta_{ERL} = 0.98$) was carried out in a large scale SRF Recirculating Linac (**CEBAF ER Exp. in 2003**)

- **No adverse effects** of ER on beam quality or RF performance: gradients, Q, cryo-load observed – mature and reliable technology (next generation light sources)

# Beam Dynamics Challenges/Mitigations

| | |
|---|---|
| Incoherent and coherent synchrotron radiation related effects on the electron beam | |
| energy losses | Size/Layout |
| longitudinal emittance increase | Size/Layout |
| transverse emittance increase | Lattice |
| Beam Breakup Instability (BBU) | |
| single beam | Lattice |
| multi-pass | Lattice |
| Depolarization effects | Lattice |

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



quad

Cavity Cryo: 8 RF cavities

Cavity Cryo: 8 RF cavities

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

$\lambda$ = 37.38 cm

$L_c$ = $5\lambda/2 = $ 93.45 cm

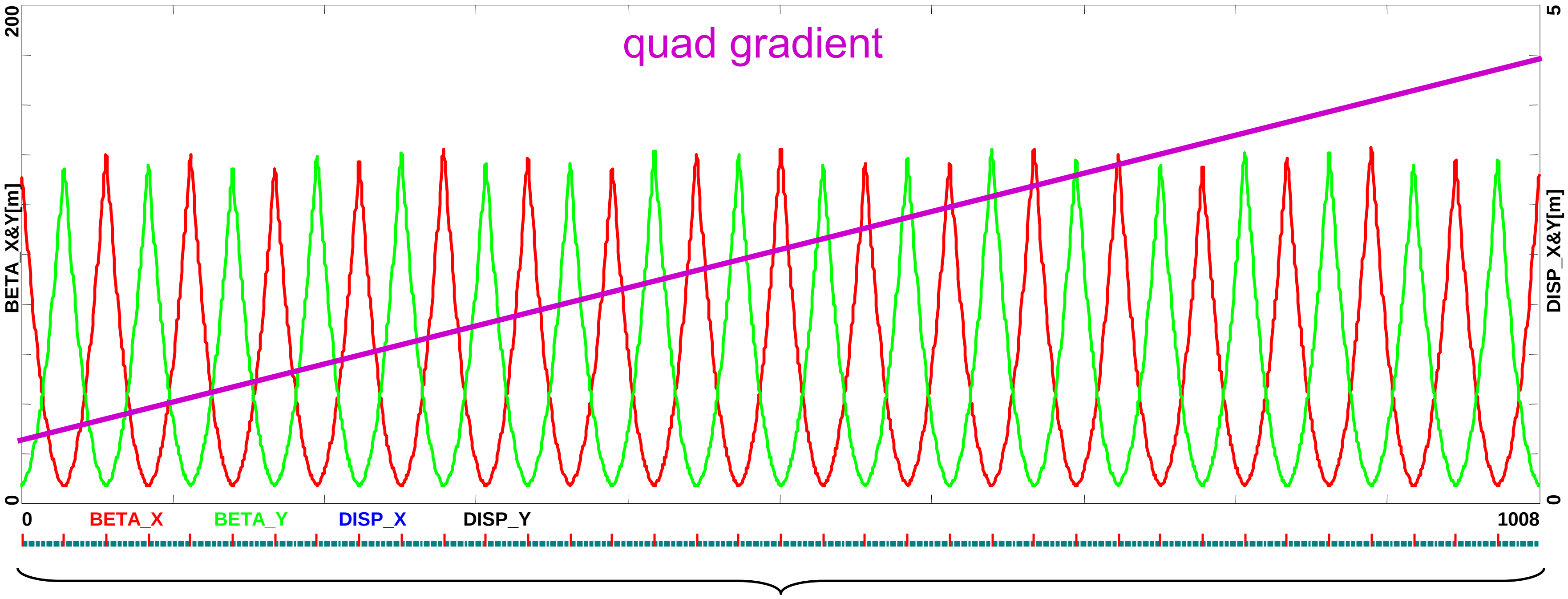
Grad = 18 MeV/m (16.8 MeV per cavity)

$\Delta$E= 269.14 MV per Cryo Unit

D. Schulte

# 10 GeV Linac – Focusing profile

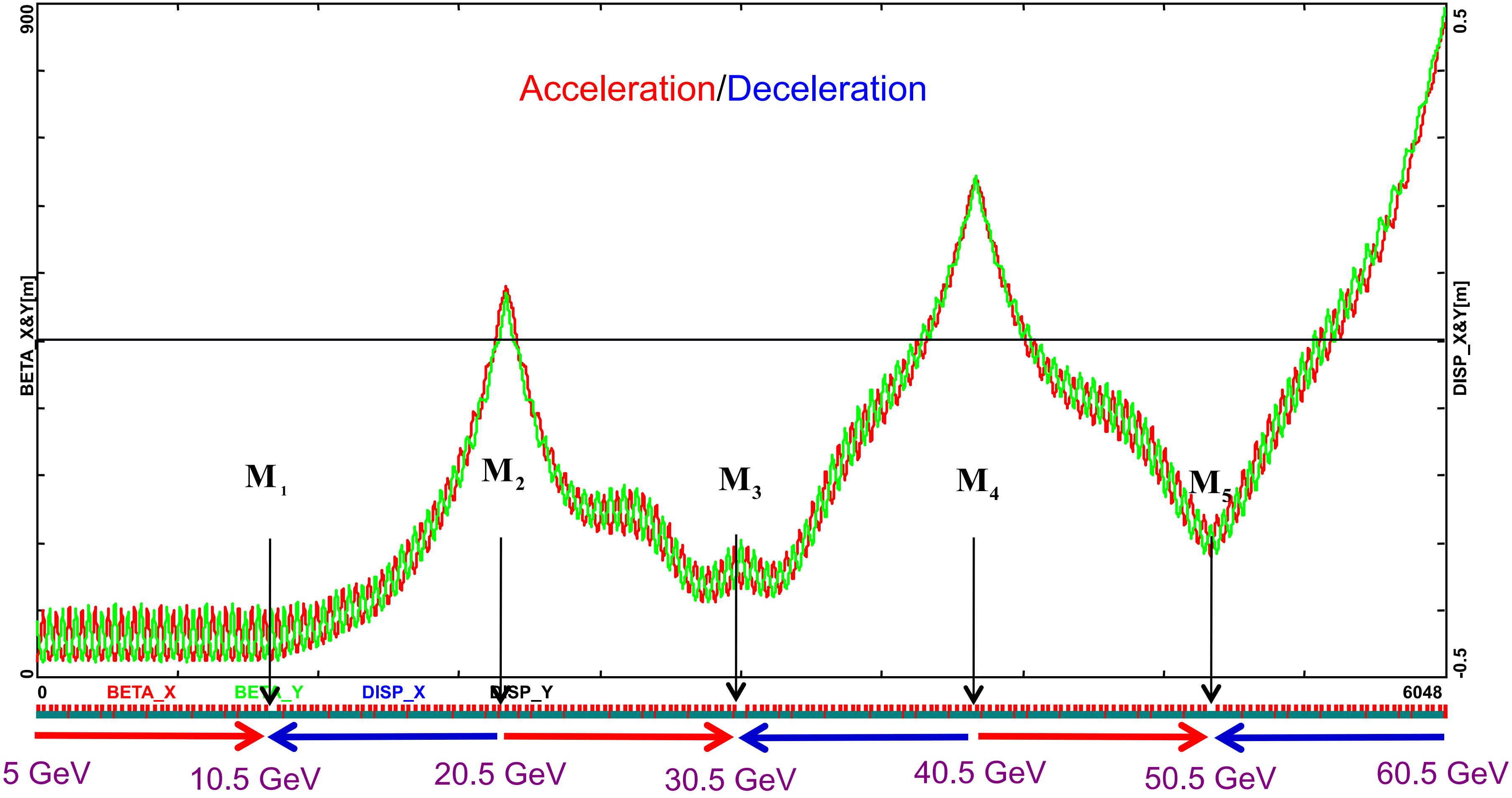
E = 0.5 – 10.5 GeV



19 FODO cells (19 × 2 × 16 = 608 RF cavities)

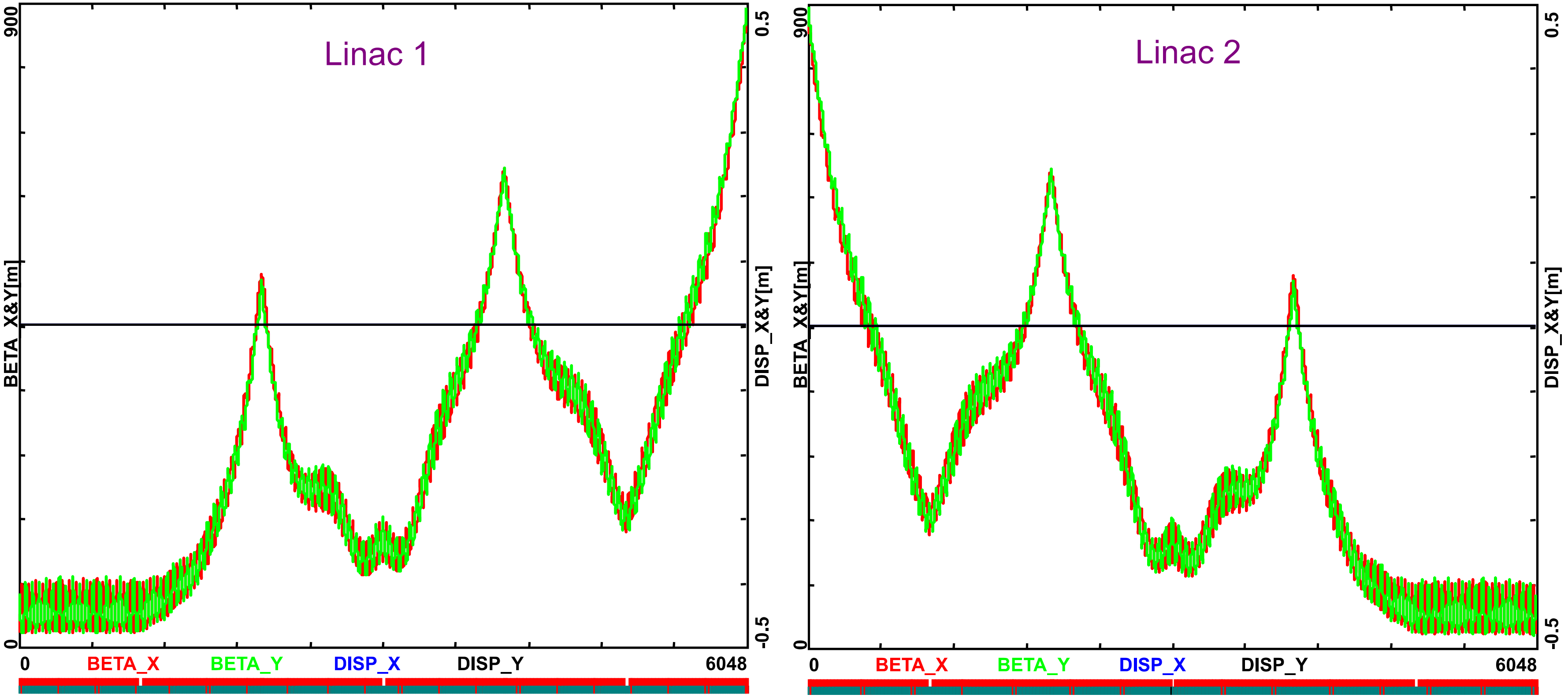
$$\left\langle \frac{\beta}{E} \right\rangle = \left( \frac{1}{L} \int \frac{\beta}{E}\, ds \right)_{\min}$$

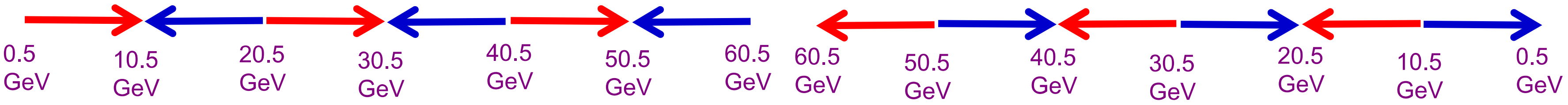
# Linac 1 – Multi-pass ER Optics



# Linac 1 and 2 – Multi-pass ER Optics

Acceleration/Deceleration





0.5 GeV
10.5 GeV
20.5 GeV
30.5 GeV
40.5 GeV
50.5 GeV
60.5 GeV

60.5 GeV
50.5 GeV
40.5 GeV
30.5 GeV
20.5 GeV
10.5 GeV
0.5 GeV

# Arc Optics – Beam Dynamics Issues

- Natural momentum spread due to quantum excitations:

$$\boxed{\frac{\Delta\sigma_E^2}{E^2} = \frac{55\alpha}{24\sqrt{3}}\left(\frac{\hbar c}{mc^2}\right)^2 \gamma^5 I_3}$$

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

- Emittance dilution due to quantum excitations:

$$\boxed{\Delta\epsilon^N = \frac{55\, r_0}{48\sqrt{3}}\,\frac{\hbar c}{mc^2}\,\gamma^6 I_5}$$

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

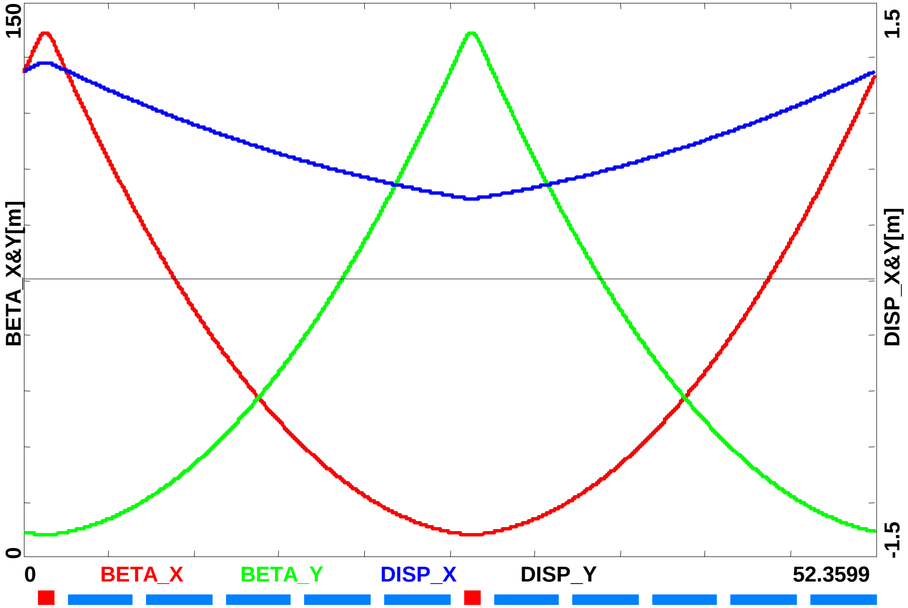
$$H = \gamma D^2 + 2\alpha DD' + \beta D'^2$$

- Momentum Compaction – synchronous acceleration in the linacs:

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

$$I_1 = \int_0^L \frac{D}{\rho}\,ds$$

# $135^0$ FODO Cell



$$\Delta\varepsilon^N = \frac{55\, r_0}{48\sqrt{3}} \frac{\hbar c}{mc^2} \gamma^6 \langle H \rangle \frac{\theta}{\rho^2}$$

*at* 50.5 *GeV* ⇨

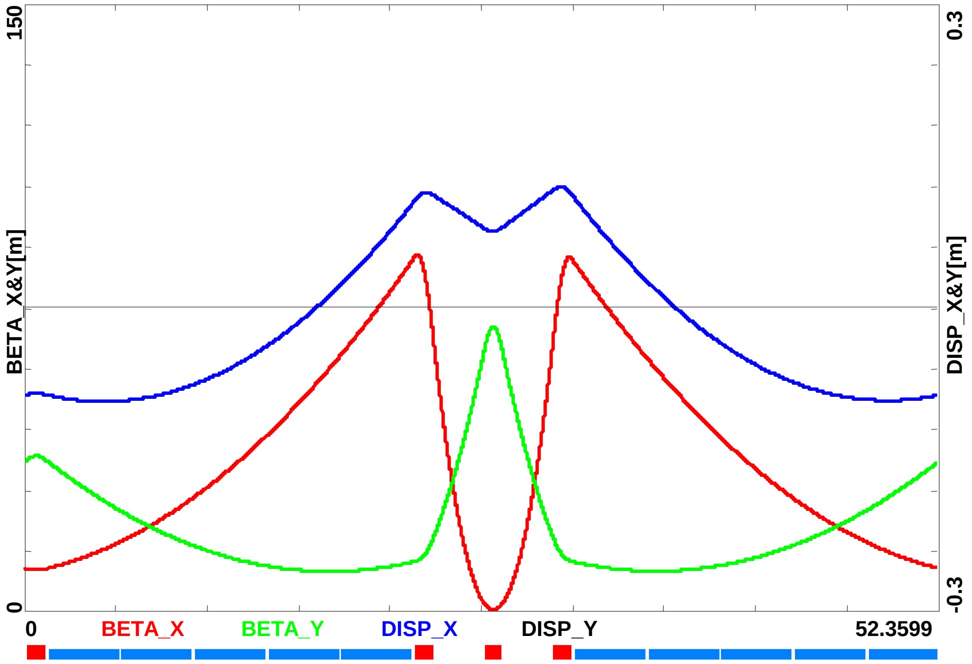
$$\langle H \rangle = 2.2 \times 10^{-2} m$$

$$\Delta\varepsilon^N = 82\ micron\ rad$$

# Flexible Momentum Compaction (FMC) Cell

Emittance dispersion

〈H〉avereged over bends



Momentum compaction

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

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

factor of 2.5 smaller than $135^0$ FODO

$$M_{56} = -\int \frac{D}{\rho} ds = -\theta_{bend} \langle D \rangle$$

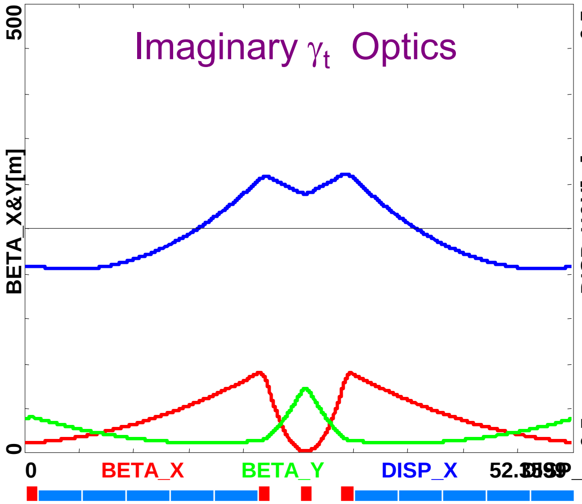
$$M_{56} = 1.16 \times 10^{-3}\ \mathrm{m}$$

factor of 27 smaller than $135^0$ FODO

# Arc Optics – Emittance preserving FMC cell

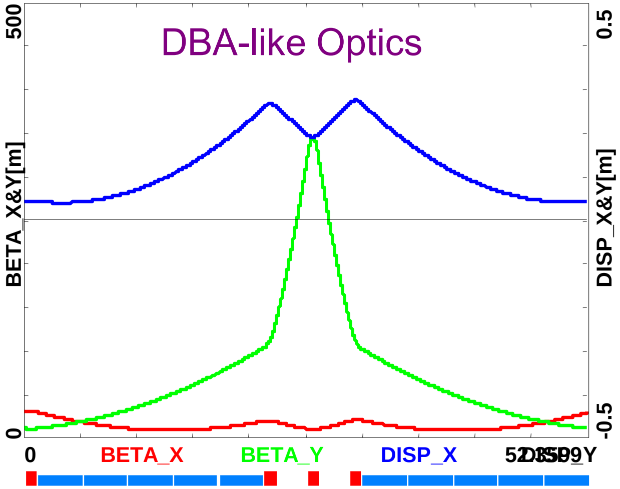
$$\Delta\varepsilon^N = \frac{55\, r_0}{48\sqrt{3}} \frac{\hbar c}{mc^2} \gamma^6 \langle H \rangle \frac{\theta}{\rho^2} \qquad H = gD^2 + 2aDD' + bD'^2$$

Arc 1 , Arc2



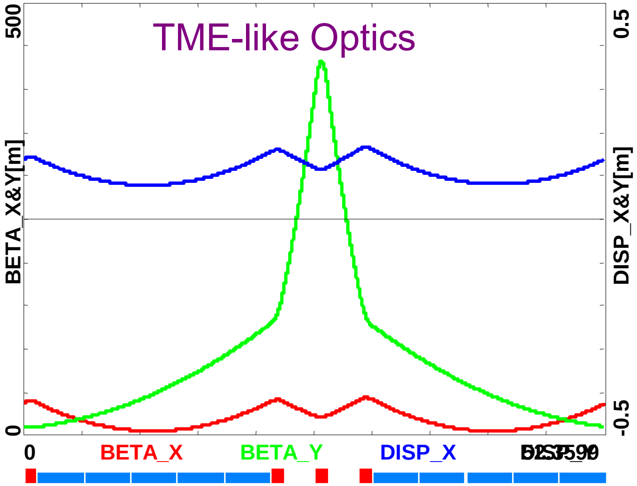
$$\langle H \rangle = 8.8 \times 10^{-3}\ m$$

Arc 3, Arc 4



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

Arc5, Arc 6



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

factor of 18 smaller than FODO

total emittance increase in Arc 5: $\Delta\varepsilon_x^N = 4.268\ \mu m$ rad

# Energy Loss and Emittance Dilution in Arcs

| ARC | E [GeV] | ΔE [MeV] | σE/E [%] |
|---|---|---|---|
| 1 | 10.4 | 0.678 | 0.00052 |
| 2 | 20.3 | 9.844 | 0.00278 |
| 3 | 30.3 | 48.86 | 0.00776 |
| 4 | 40.2 | 151.3 | 0.01636 |
| 5 | 50.1 | 362.3 | 0.02946 |
| 6 | 60 | 751.3 | 0.04829 |
| 7 | 50.1 | 362.3 | 0.06366 |
| 8 | 40.2 | 151.3 | 0.08065 |
| 9 | 30.3 | 48.86 | 0.10808 |
| 10 | 20.3 | 9.844 | 0.16205 |
| 11 | 10.4 | 0.678 | 0.31668 |
| dump | 0.500 | 0 | 6.66645 |

Energy loss and Integrated energy spread induced by SR

Total loss per particle about ~1.9 GeV

Compensated by additional linacs
20.3 MW

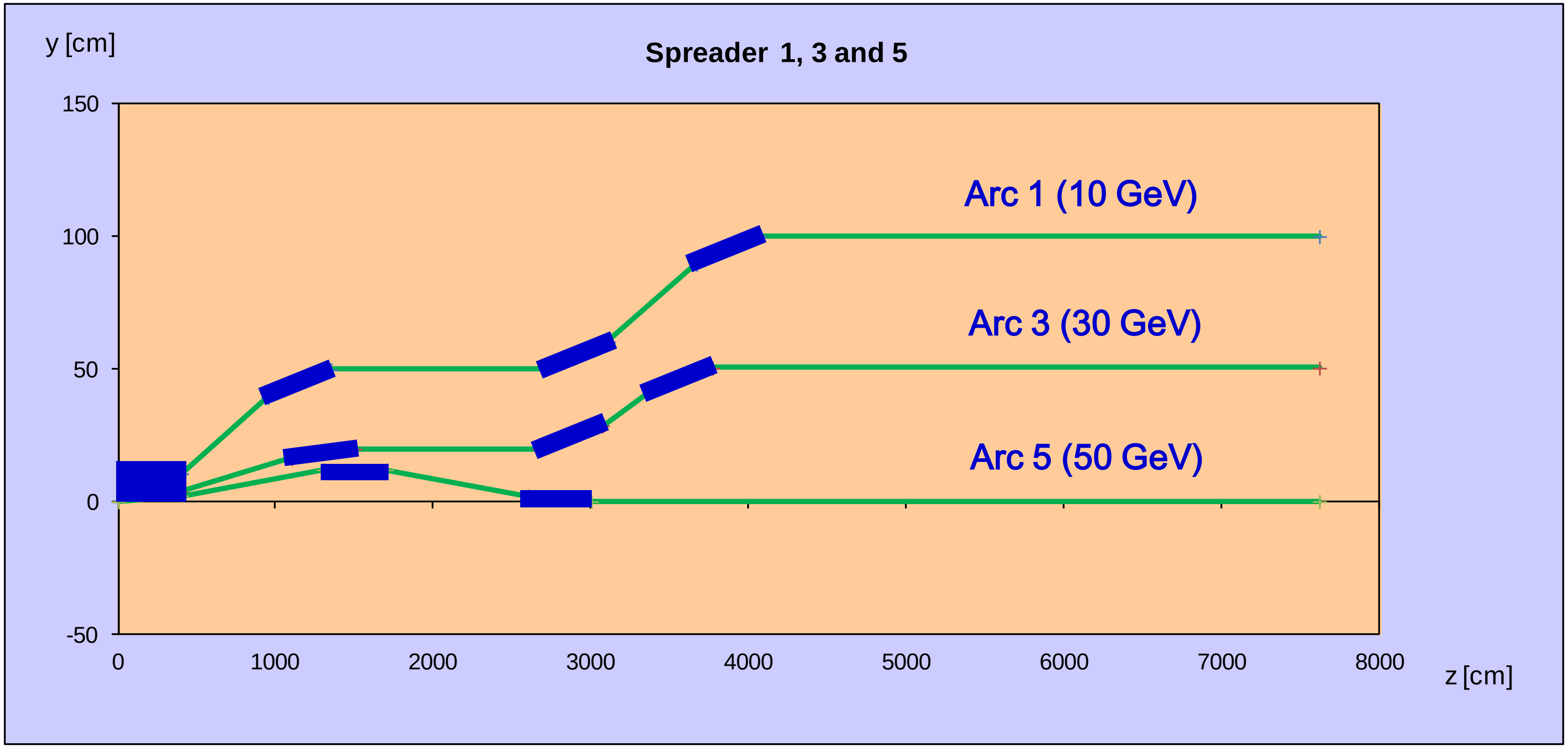
| ARC | E [GeV] | $\Delta\varepsilon_{ARC}$ [μm] | $\Delta\varepsilon_t$ [μm] |
|---|---|---|---|
| 1 | 10.4 | 0.0025 | 0.0025 |
| 2 | 20.3 | 0.140 | 0.143 |
| 3 | 30.3 | 0.380 | 0.522 |
| 4 | 40.2 | 2.082 | 2.604 |
| 5 | 50.1 | 4.268 | 6.872 |
| 6 | 60 | 12.618 | 19.490 |
| 5 | 50.1 | 4.268 | 23.758 |
| 4 | 40.2 | 2.082 | 25.840 |
| 3 | 30.3 | 0.380 | 26.220 |
| 2 | 20.3 | 0.140 | 26.360 |
| 1 | 10.4 | 0.0025 | 26.362 |

Integrated Emittance growth including all previous arcs

Before the IP a total growth of ~ 7 μm is accumulated
The final value is ~ 26 μm

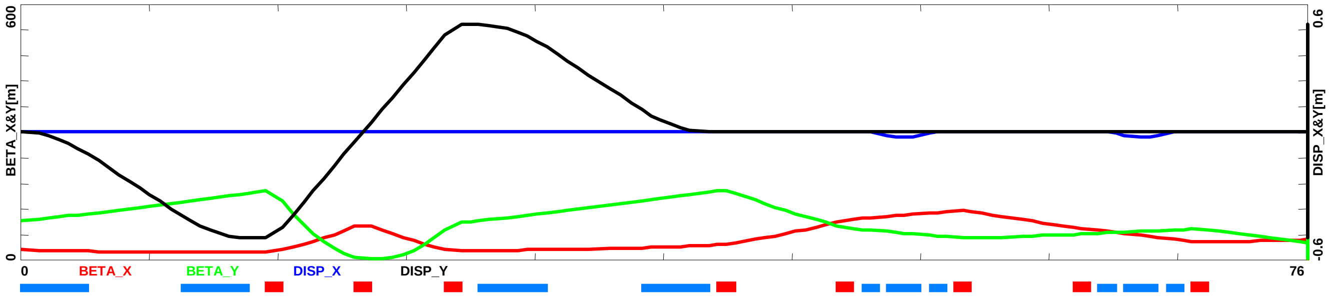
A. Valloni

# Vertical Separation of Arcs



# Vertical Spreaders – Optics

Spr. 1

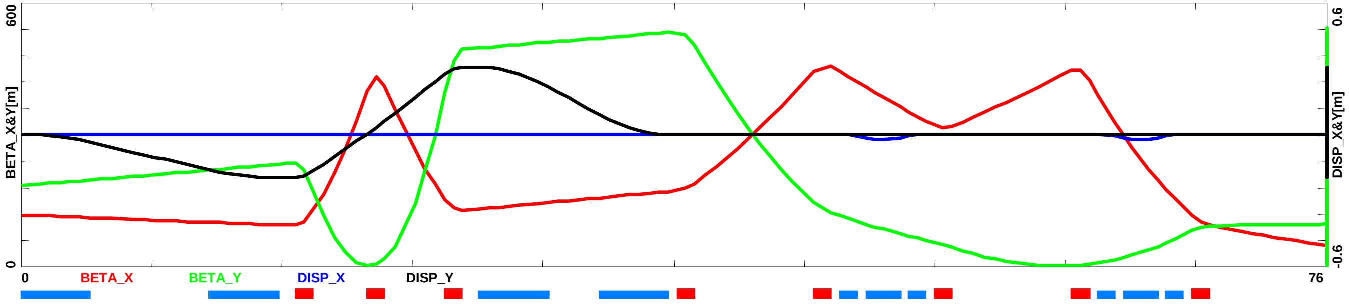


vertical step I

vertical step II

path-length adjustment
‘doglegs’

Spr. 3

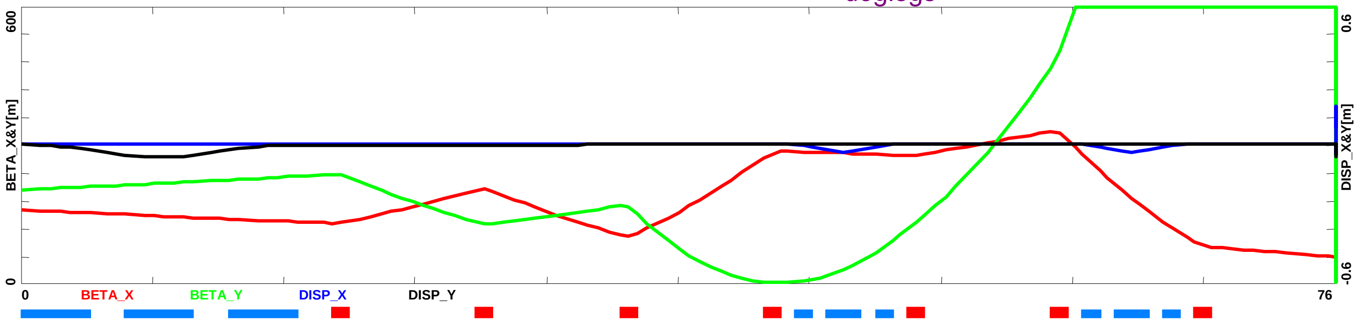


vertical step I

vertical step II

path-length adjustment
‘doglegs’

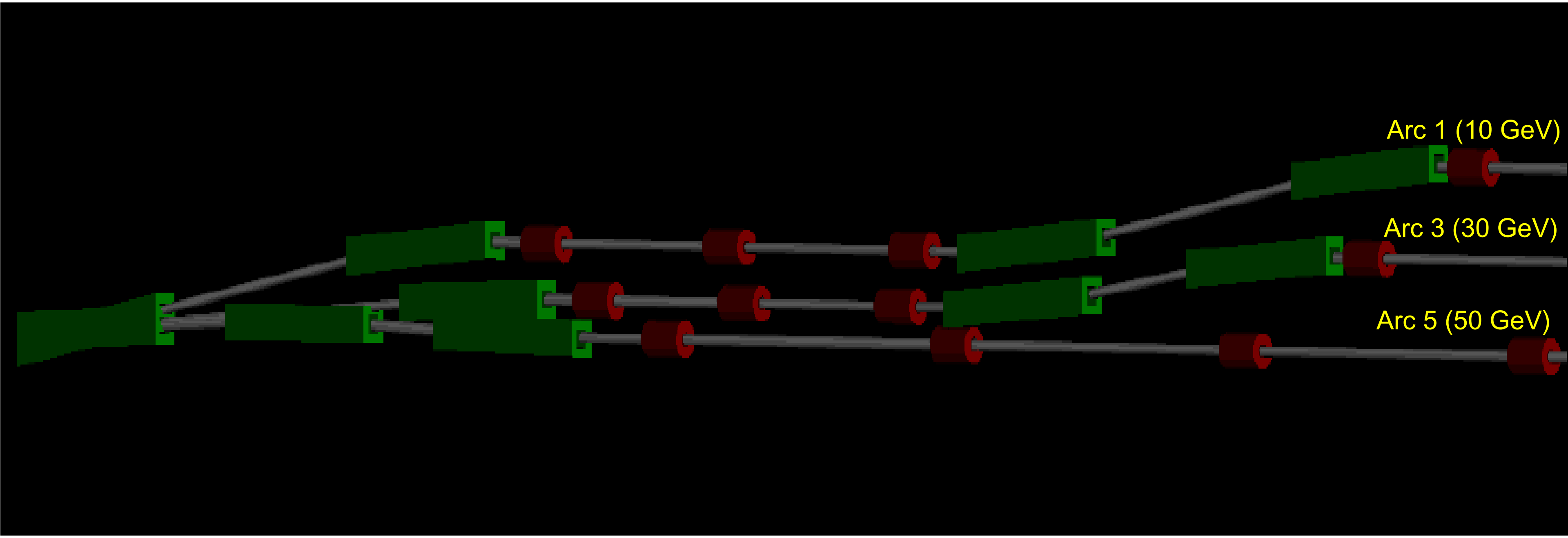
Spr. 5



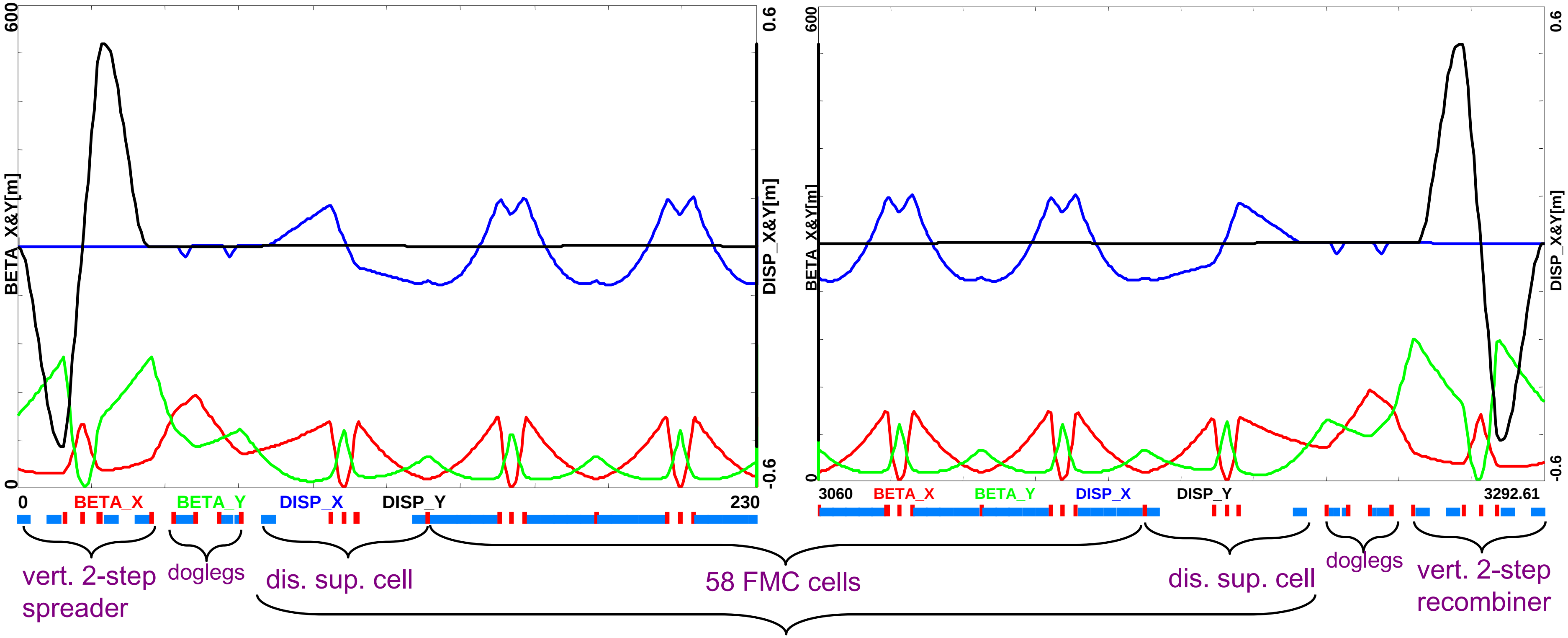
vertical chicane

path-length adjustment
‘doglegs’

# Vertical Separation of Arcs



# Arc 1 Optics (10 GeV)



vert. 2-step spreader

doglegs

dis. sup. cell

58 FMC cells

dis. sup. cell

doglegs

vert. 2-step recombiner

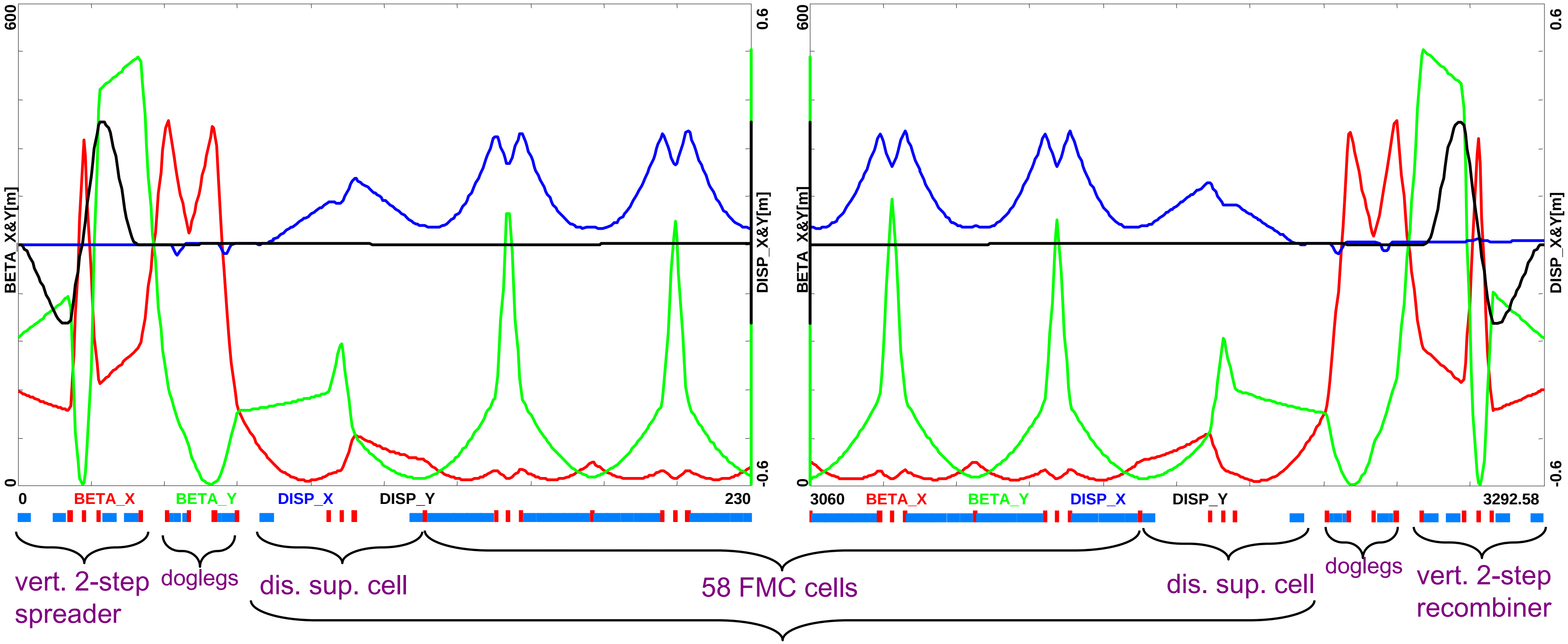
180 deg. Arc

**Arc dipoles:**

$Lb=400 cm

$B=0.47 kGauss

# Arc 3 Optics (30 GeV)



vert. 2-step spreader

doglegs

dis. sup. cell

58 FMC cells

dis. sup. cell

doglegs

vert. 2-step recombiner

180 deg. Arc

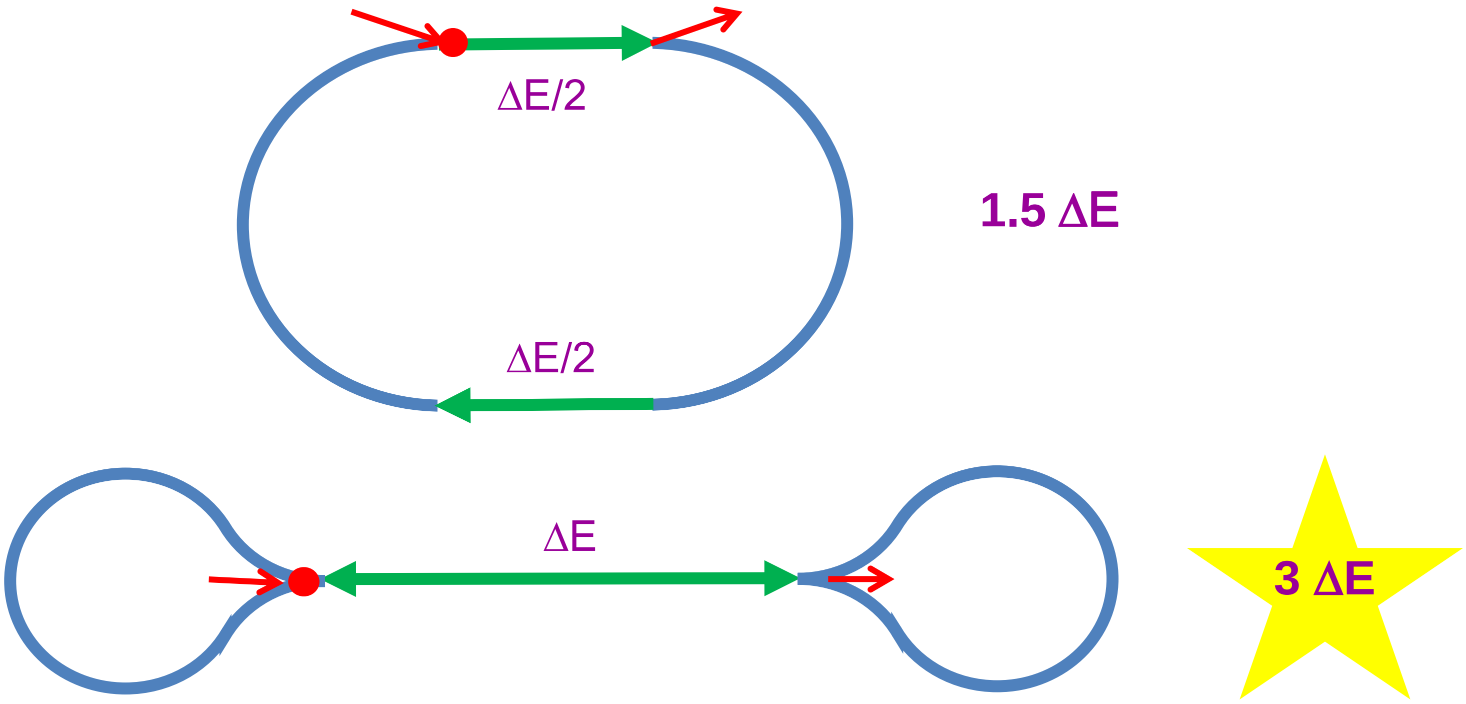
**Arc dipoles:**

$Lb=400 cm

$B=1.37 kGauss

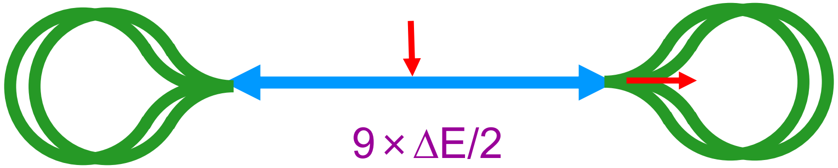
# ‘Racetrack’ vs ‘Dogbone’ RLA

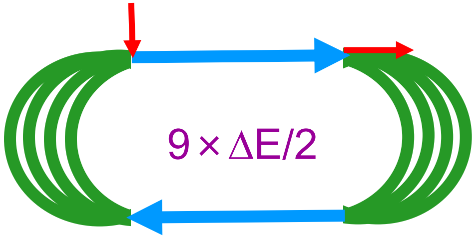
Twice the acceleration efficiency for the ‘Dogbone’ topology

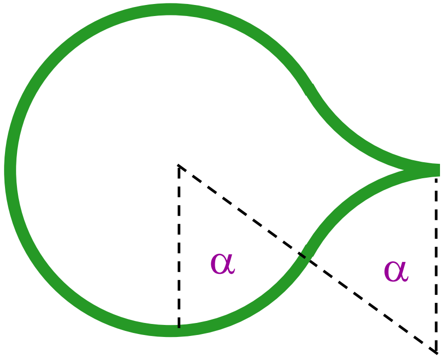


Challenge: traversing linac in **both directions** while accelerating

# ‘Dogbone’ vs ‘Racetrack’ – Arc-length



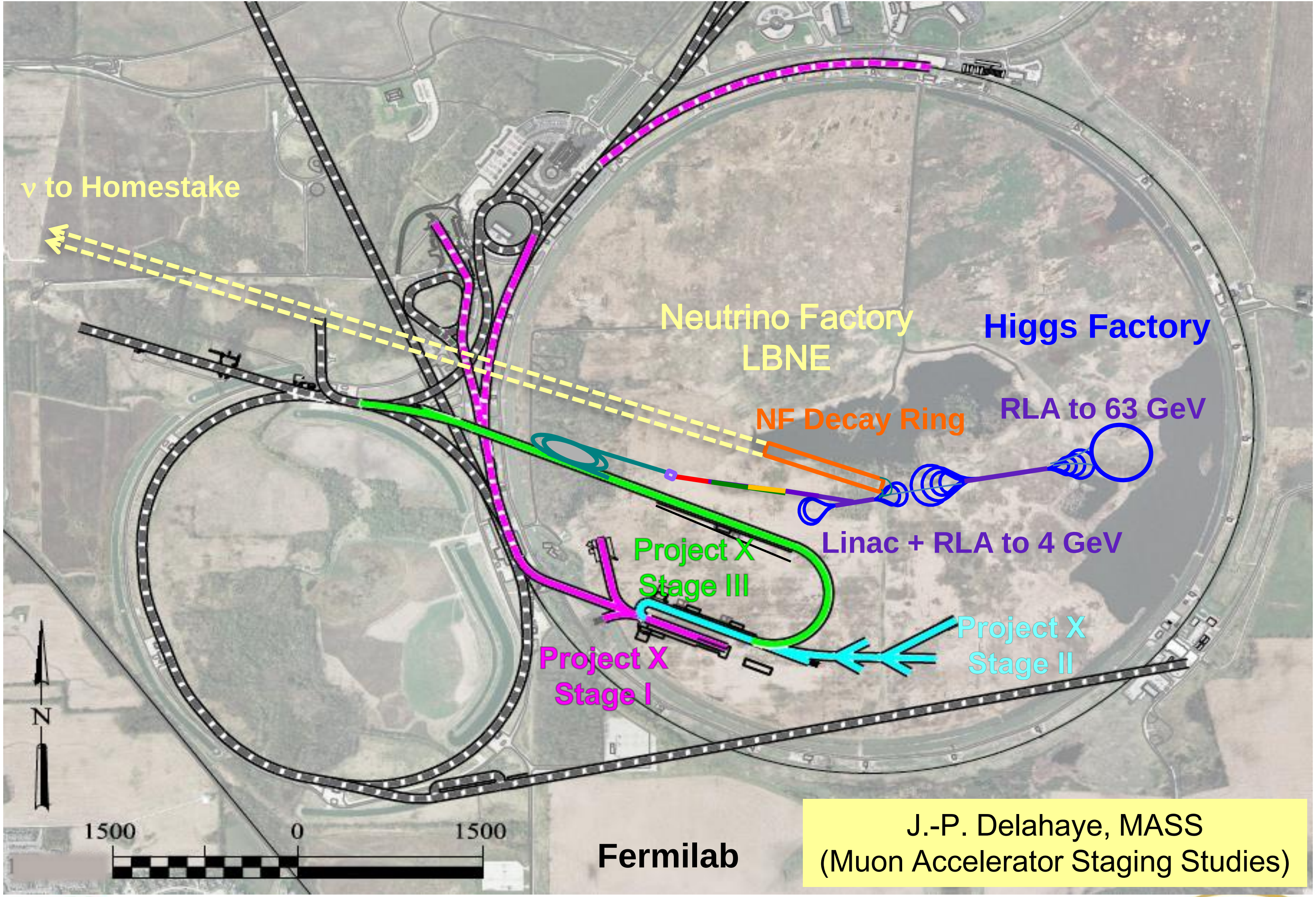


n ×  $= n(\pi + 4\alpha)R$

2n ×  $= 2n\pi R$

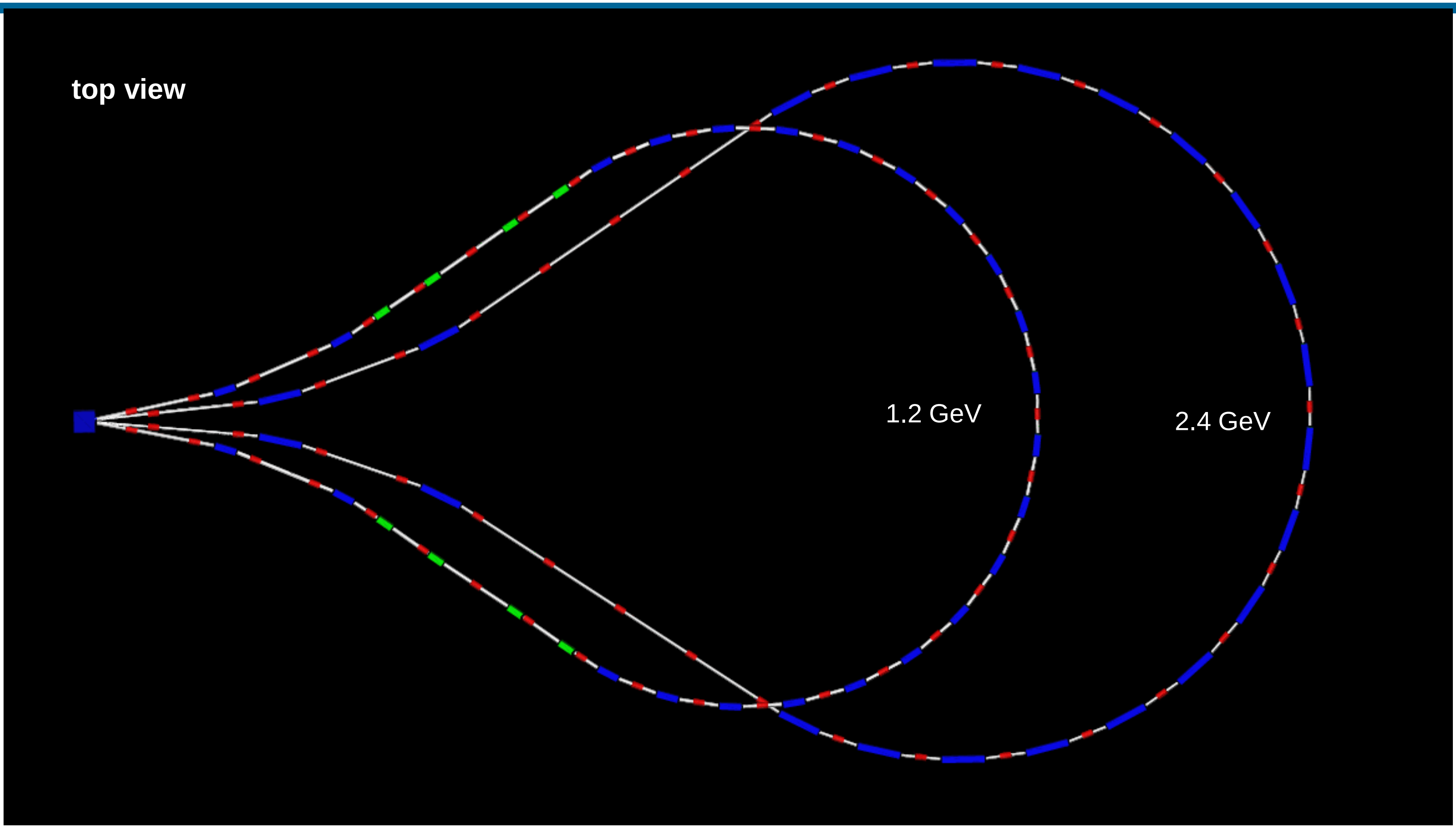
Net arc-length break even: if $\alpha = \pi/4$

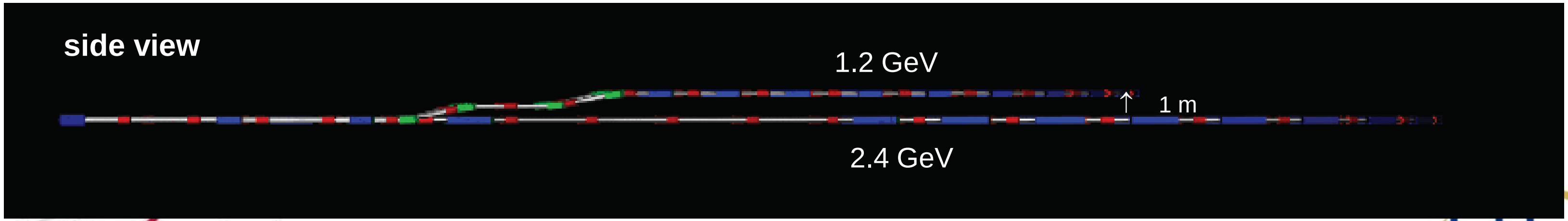
# Future Muon Facilities – Muon Acceleration



J.-P. Delahaye, MASS
(Muon Accelerator Staging Studies)

# Droplet Arcs – Layout

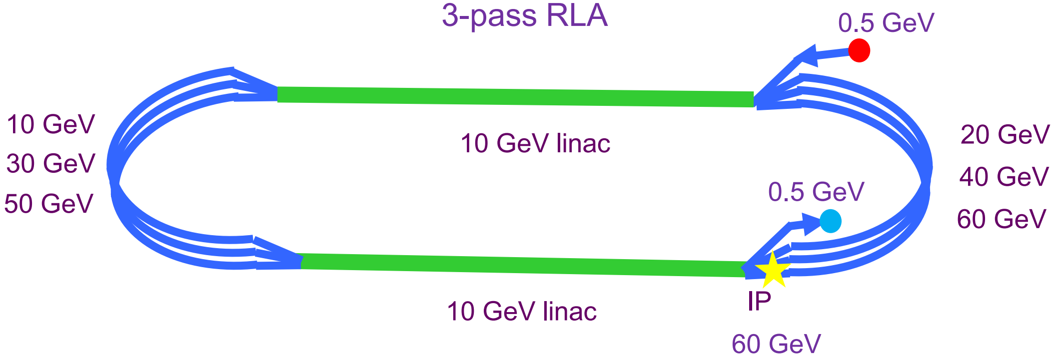




# ‘Racetrack’ vs ‘Dogbone’ ERL for LHeC

## Baseline

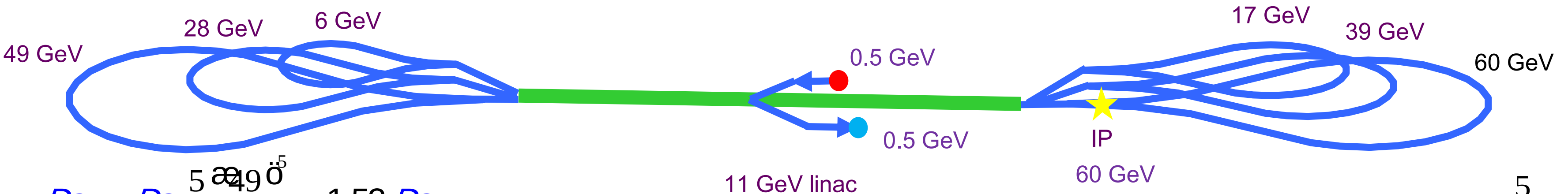
3-pass RLA



$$\Delta\epsilon_0 \approx \langle H\rangle \frac{\gamma^5}{\rho^2}$$

## Option I

5.5-pass RLA

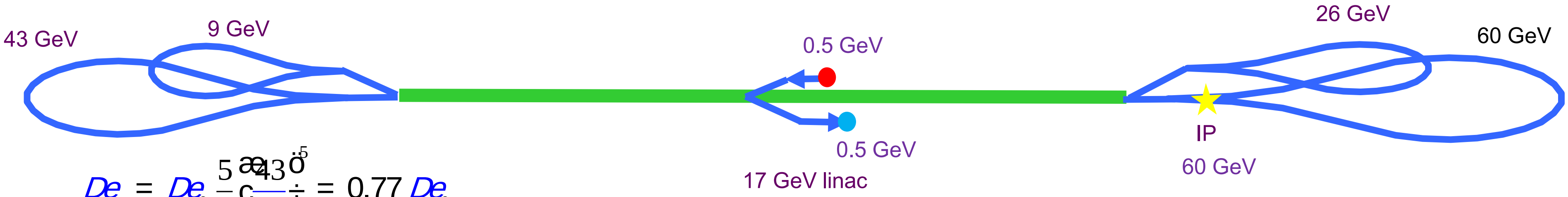


$$\Delta\epsilon = \Delta\epsilon_0 \frac{5}{3}\left(\frac{49}{50}\right)^5 = 1.52\,\Delta\epsilon_0$$

$$\alpha = \pi/6 \qquad \frac{5}{3} = \frac{300}{180}$$

## Option II

3.5-pass RLA

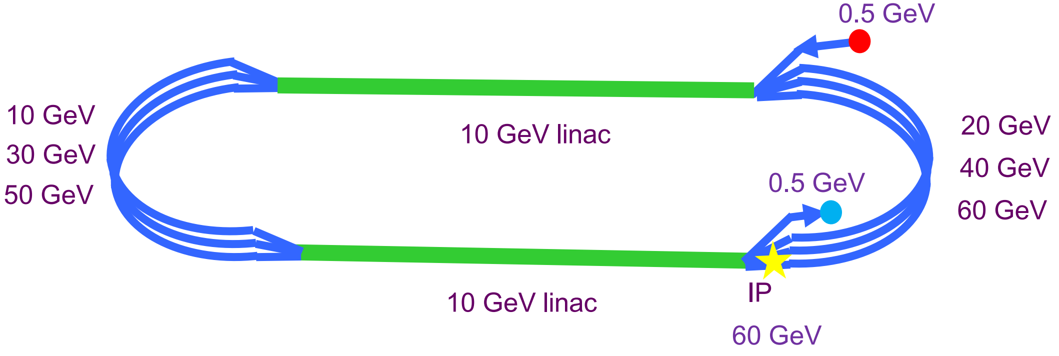


$$\Delta\epsilon = \Delta\epsilon_0 \frac{5}{3}\left(\frac{43}{50}\right)^5 = 0.77\,\Delta\epsilon_0$$

# ‘Racetrack’ vs ‘Dogbone’ ERL for LHeC

## Baseline

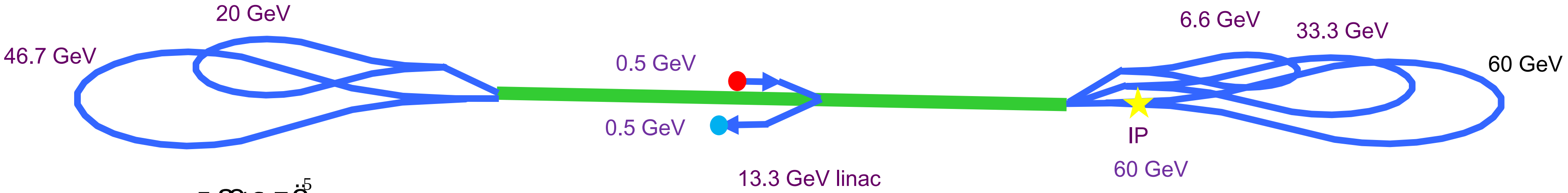
3-pass RLA



$$\Delta\epsilon_0 \approx \langle H\rangle \frac{\gamma^5}{\rho^2}$$

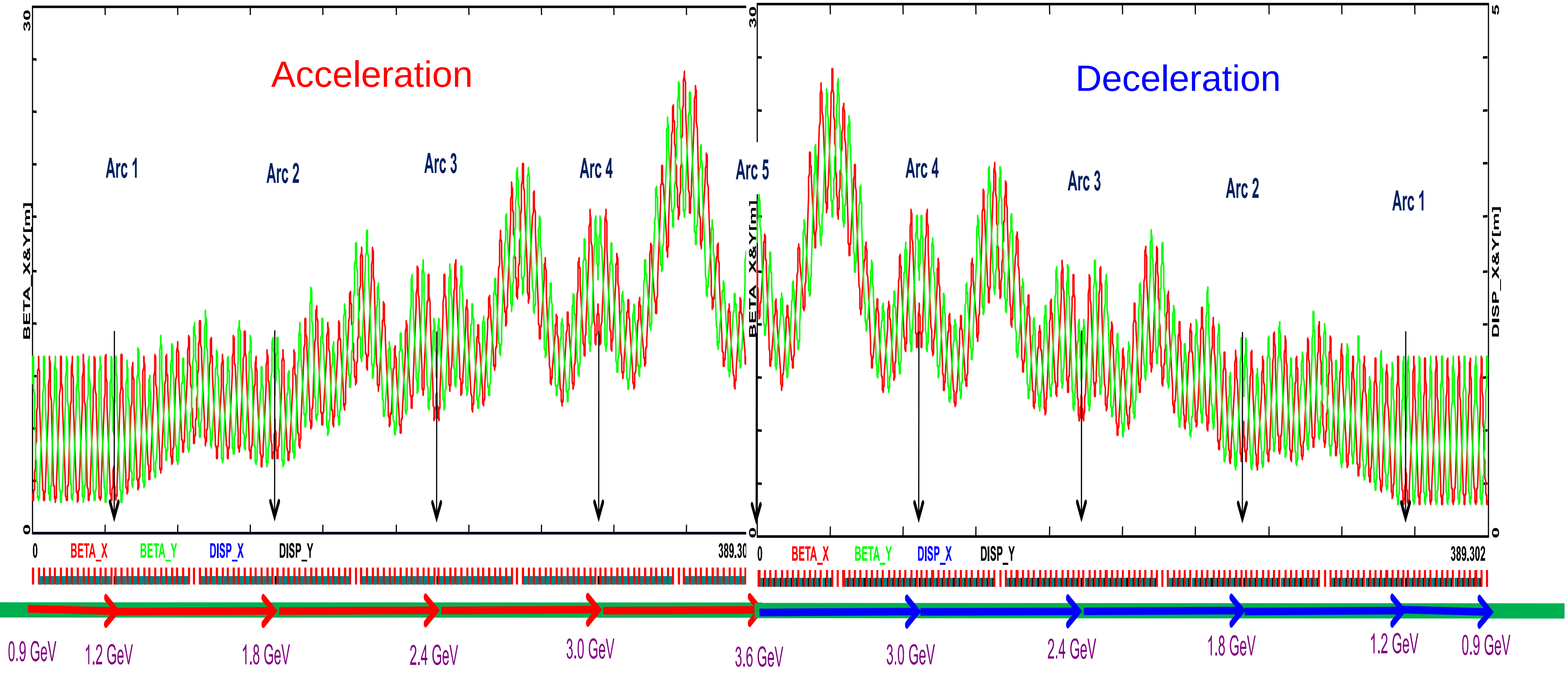
## Option III

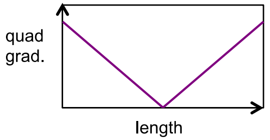
4.5-pass RLA



$$\Delta\epsilon = \Delta\epsilon_0 \frac{5}{3}\left(\frac{46.7}{50}\right)^5 = 1.18\,\Delta\epsilon_0$$

# ‘Dogbone’ RLA – Multi-pass Linac Optics





# **Pros** and **Cons** of a ‘Dogbone’ RLA

- High **acceleration efficiency** (≤2) – traversing the linac in both directions while accelerating
- Better **orbit separation at** linac’s end ~ energy difference between consecutive passes (2DE) vs (DE) in case of the ‘Racetrack’
- Suppression of **depolarization** effects Beam trajectory can be made to follow a Figure-8 path (by reversing field directions in opposing droplet arcs)

- Beams of different energies moving in the opposite direction through the linac – orbit separation needed to avoid **parasitic collisions**.
- As linac length and number of passes are increased, the **BBU threshold** can be a problem.
- Travelling ‘**clearing gaps**’ to alleviate ion trapping – No solution found

# Summary

- High luminosity Linac-Ring option – ERL
  - RF power nearly independent of beam current.
- Multi-pass linac Optics in ER mode
  - Choice of linac RF and Optics – 800 MHz SRF and $130^0$ FODO
  - Linear lattice: 3-pass 'up' + 3-pass 'down'
- Arc Optics Choice – Emittance preserving lattices
  - Quasi-isochronous lattices
  - Flexible Momentum Compaction Optics
  - Balanced emittance dilution & momentum compaction
- Complete Arc Architecture
  - Vertical switchyard
  - Matching sections & path-length correcting 'doglegs'
- 'Dogbone' ERL Option

# Special Thanks to:

Frank Zimmermann

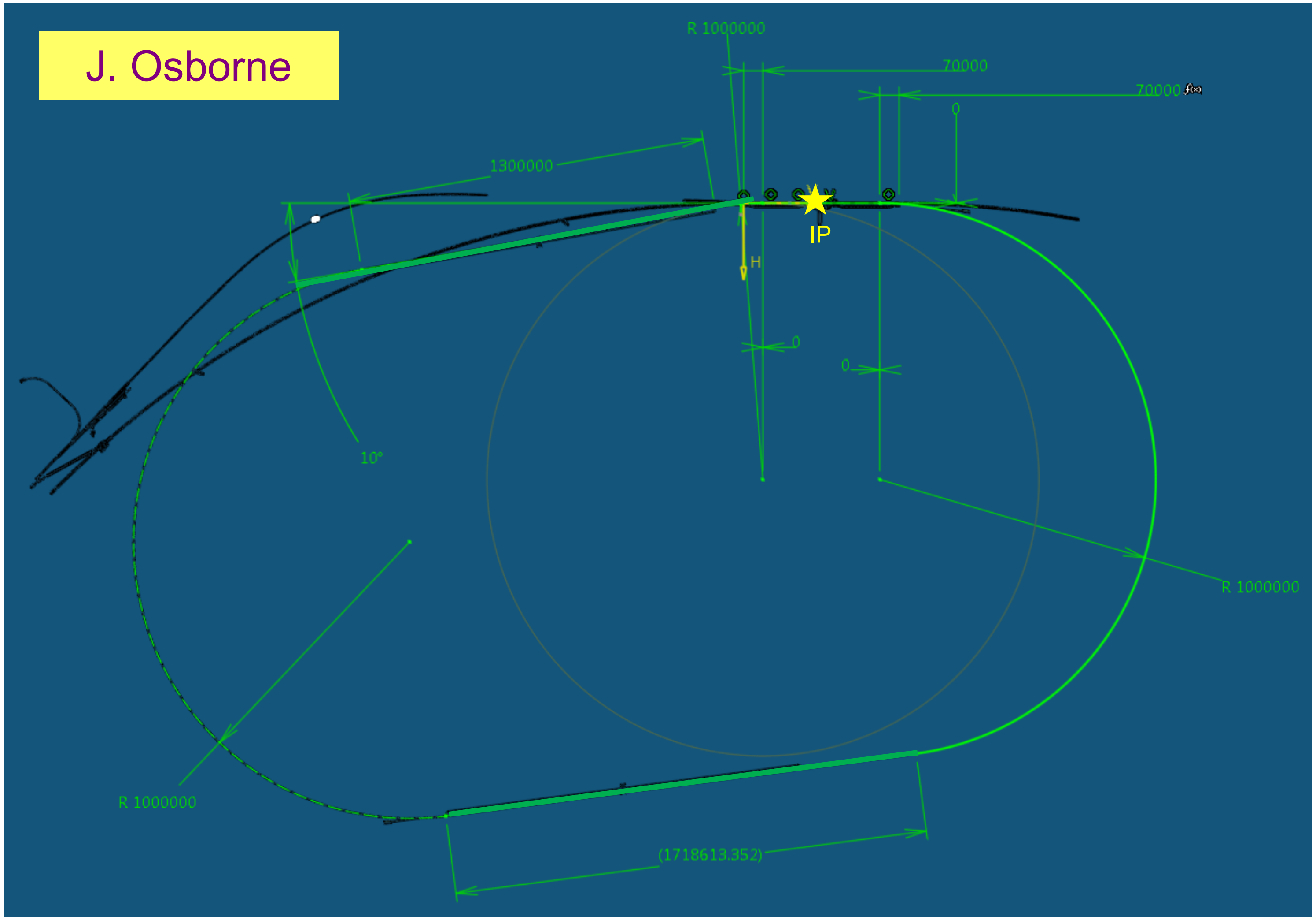
Daniel Schulte

and

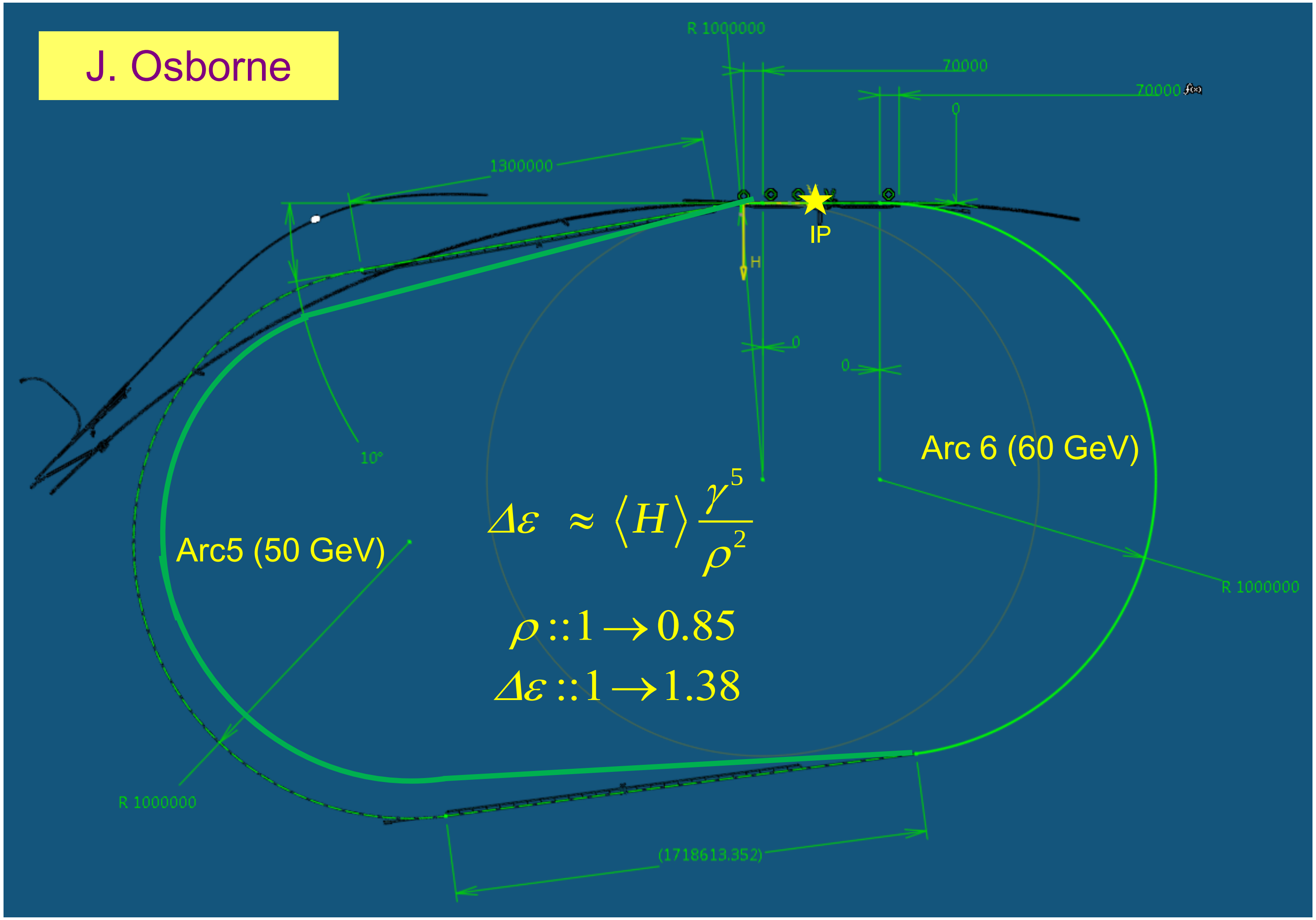
Erk Jensen

# Backup Slides

# Linac–Ring:  Dimensions/Layout


J. Osborne

# Linac–Ring:  Dimensions/Layout


**J. Osborne**

$$\Delta\varepsilon \approx \left\langle H \right\rangle \frac{\gamma^5}{\rho^2}$$

$$\rho :: 1 \rightarrow 0.85$$

$$\Delta\varepsilon :: 1 \rightarrow 1.38$$