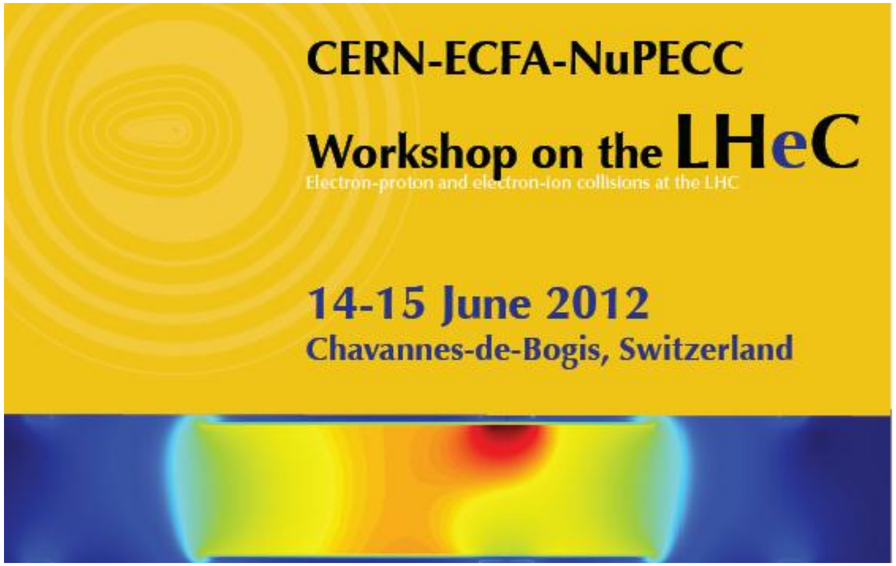
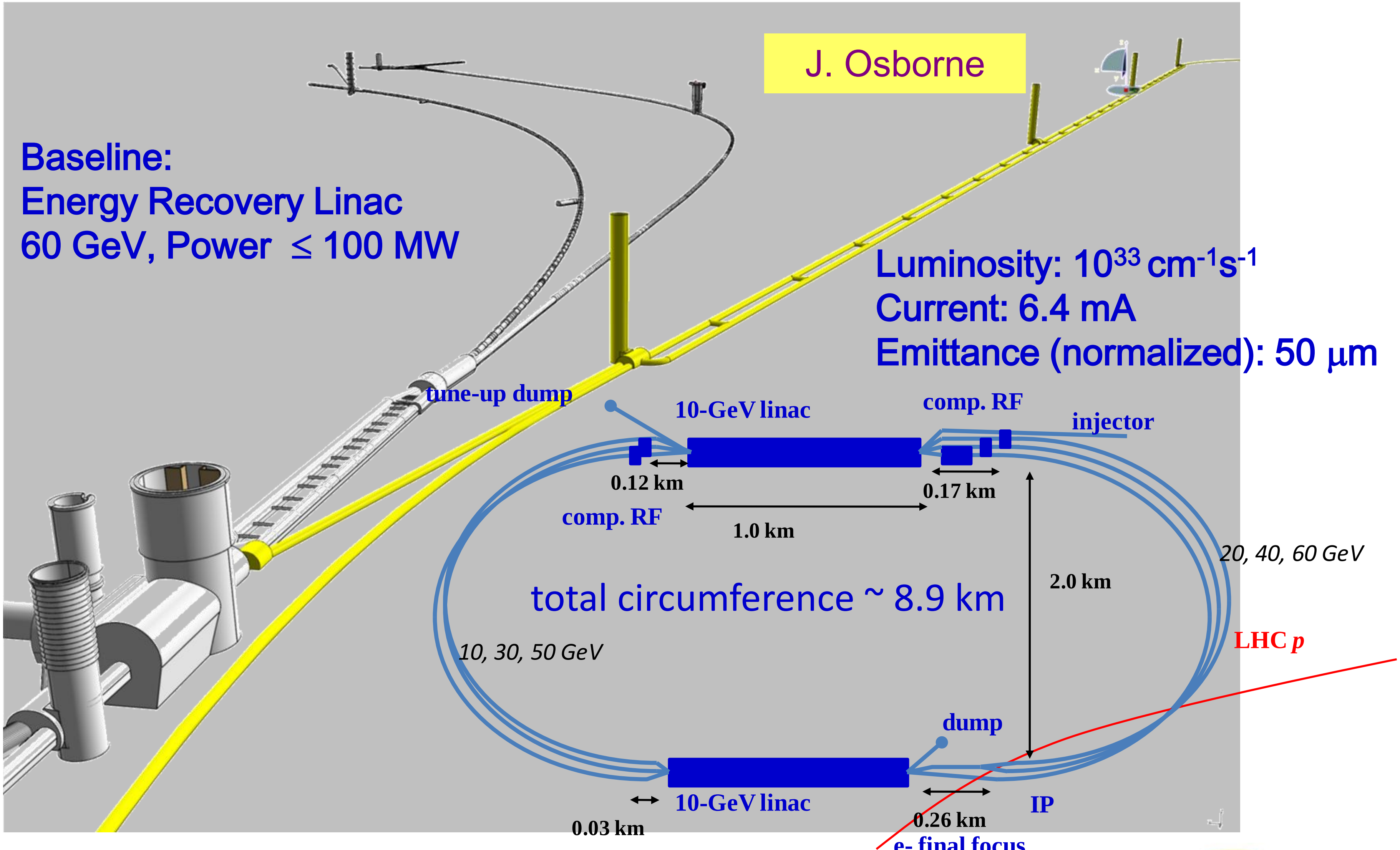
LHeC Recirculator with Energy Recovery – Lattice Design

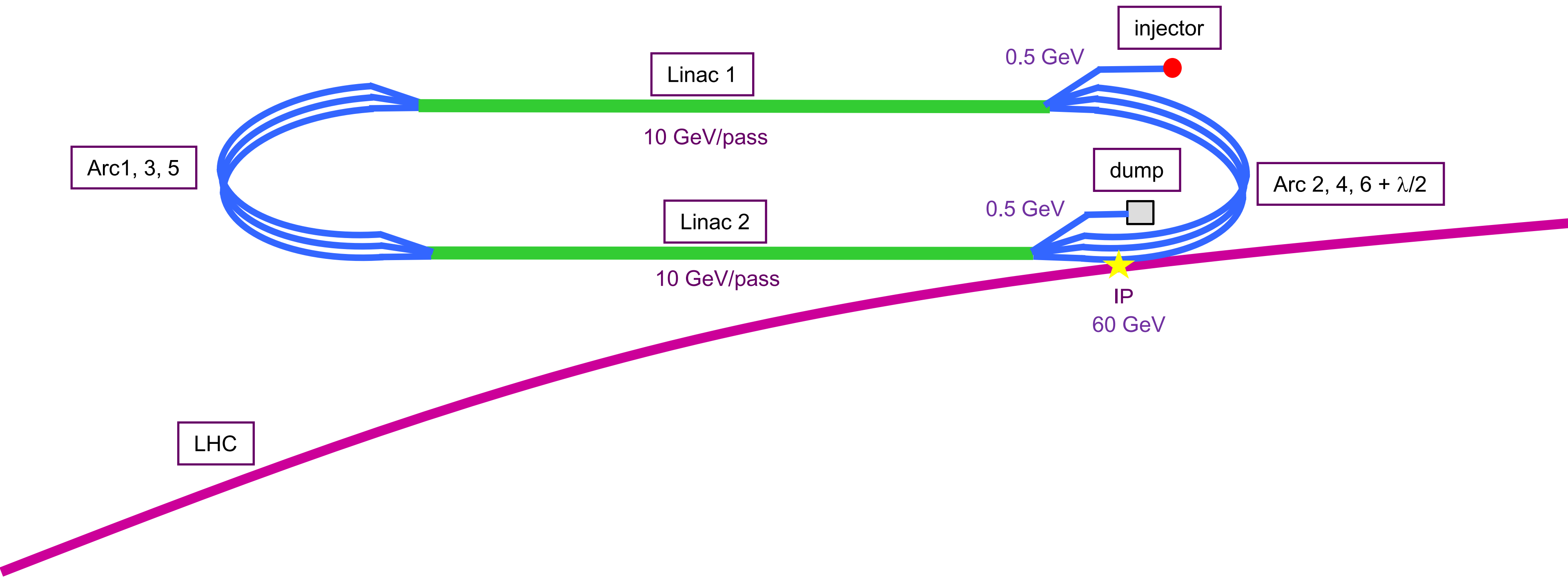
Alex Bogacz



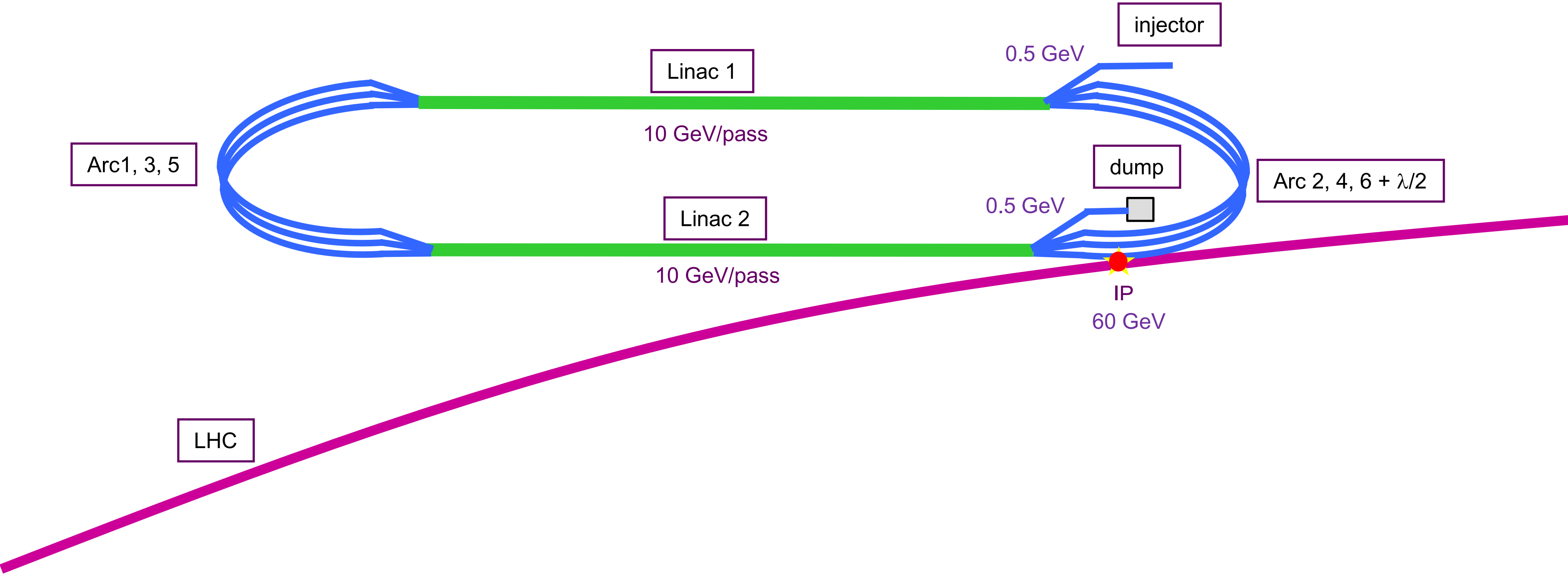
Linac-Ring Option



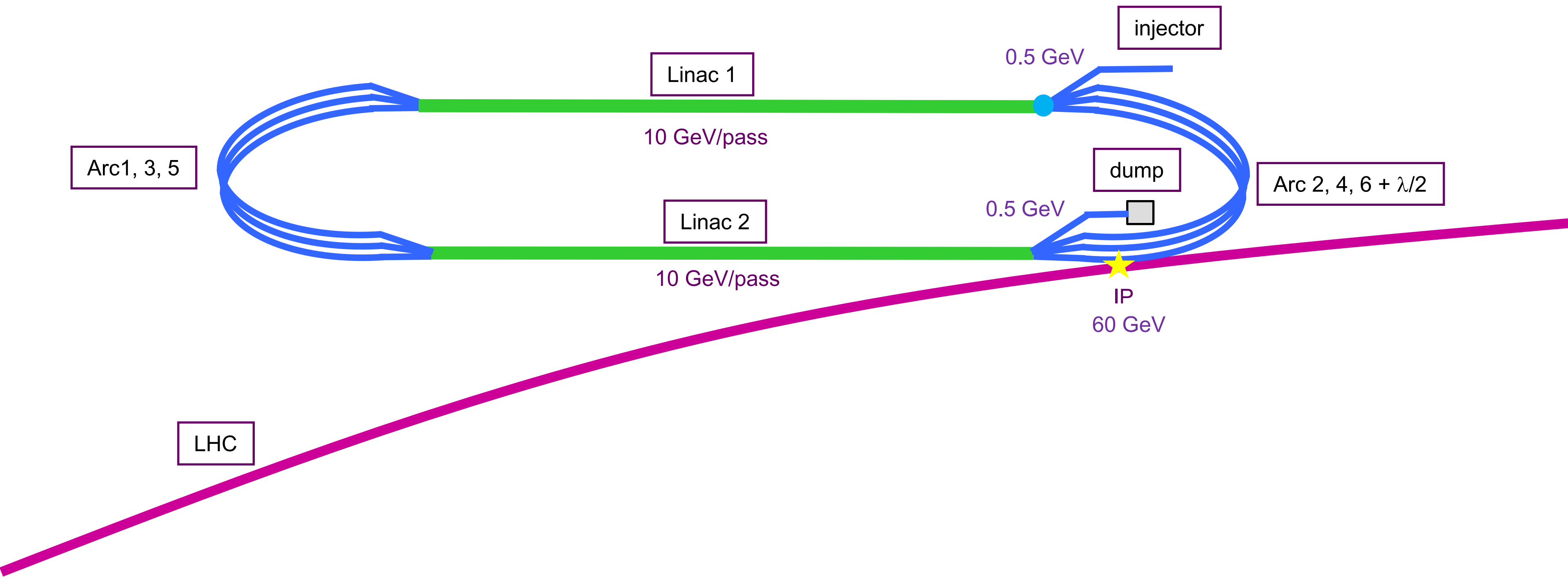
LHeC Recirculator with ER



LHeC Recirculator with ER



LHeC Recirculator with ER



Why Energy Recovering Linacs (ERL)?

- 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** – η_{ERL}) ⇨ Required RF power becomes nearly independent of beam current.

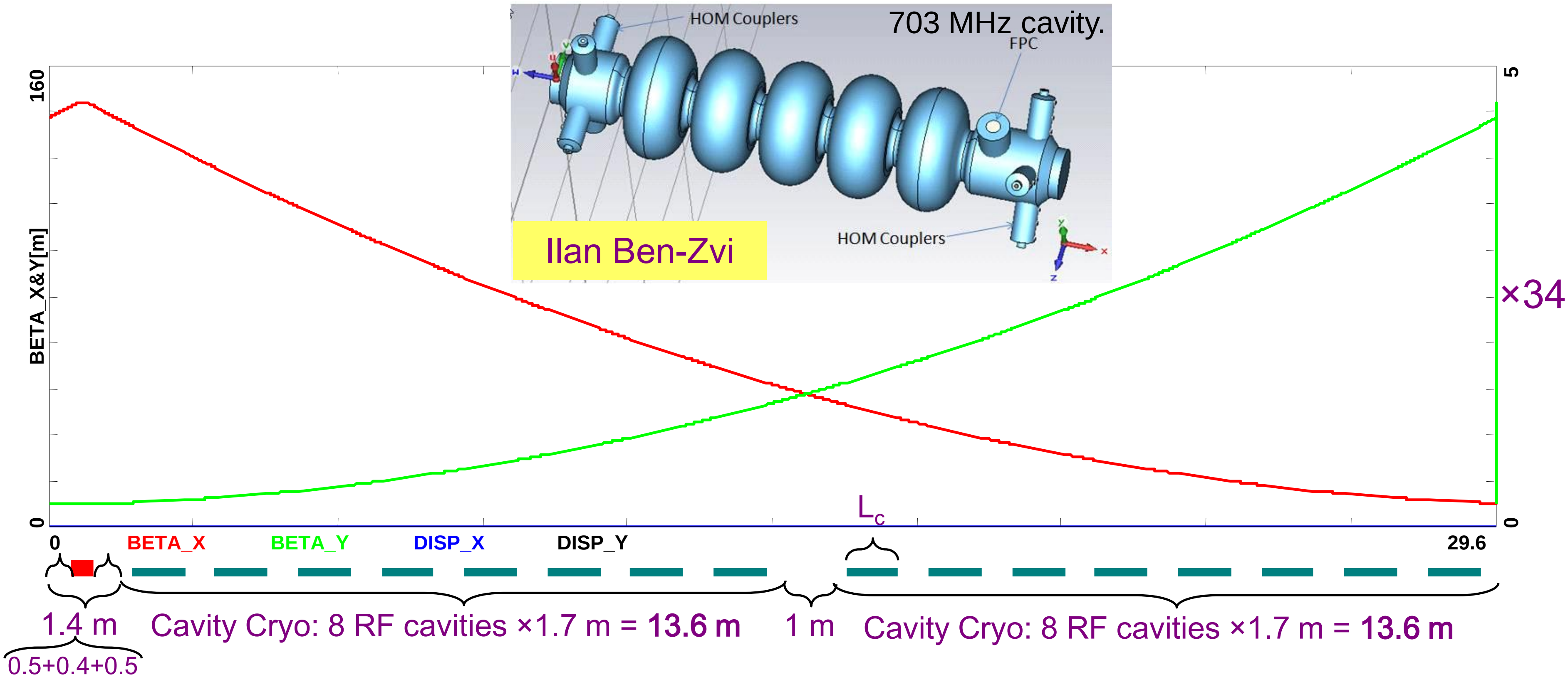
- **Energy Recovering Linacs** promise efficiencies of storage rings, while maintaining beam quality of linacs: superior emittance and energy spread and short bunches (sub-pico sec.).

- GeV scale Energy Recovery demonstration with high ER ratio (η_{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)

Multi-pass ERL Optics

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



721.4 MHz RF, 5-cell cavity:

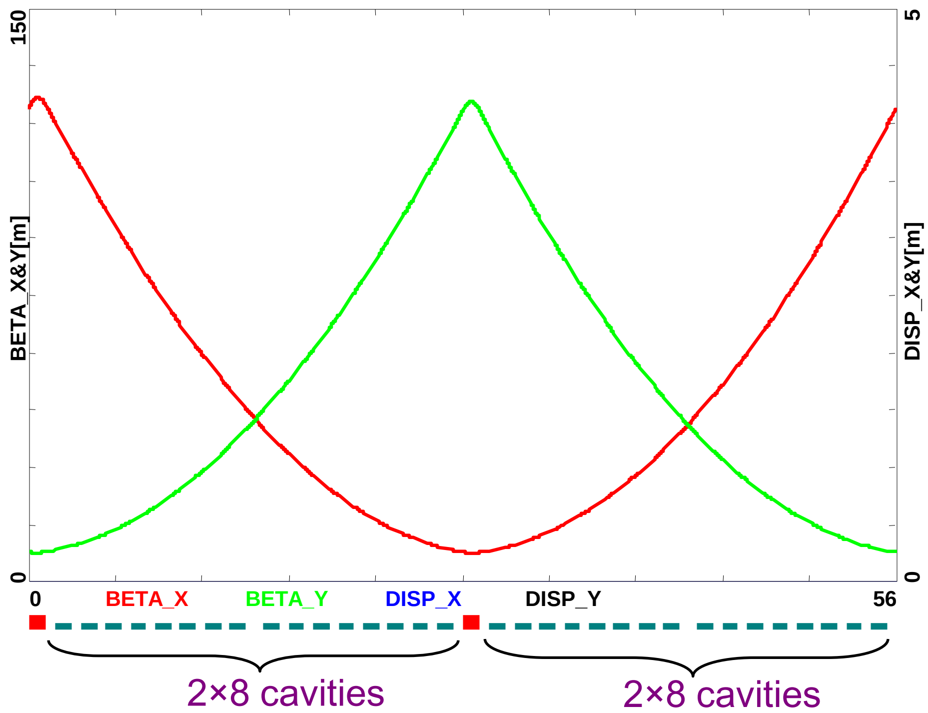
λ = 41.557 cm

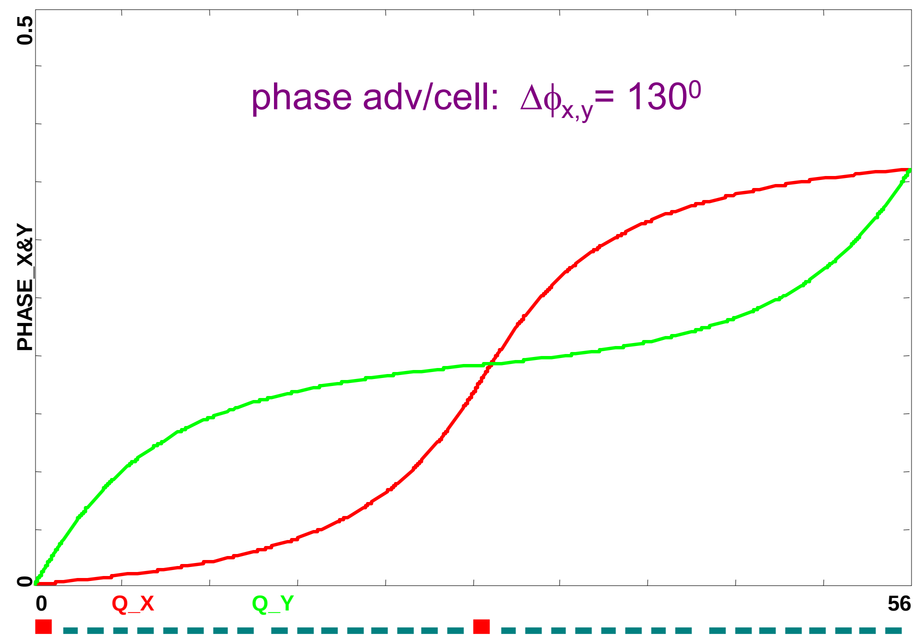
$L_c = 5\lambda/2 = 103.89$ cm

Grad = 18 MeV/m (18.7 MeV per cavity)

ΔE= 299.21 MV per Cryo Unit

Linac Optics – 130^0 FODO Cell





linac quadrupoles:

End of the linac: E =10.5 GeV

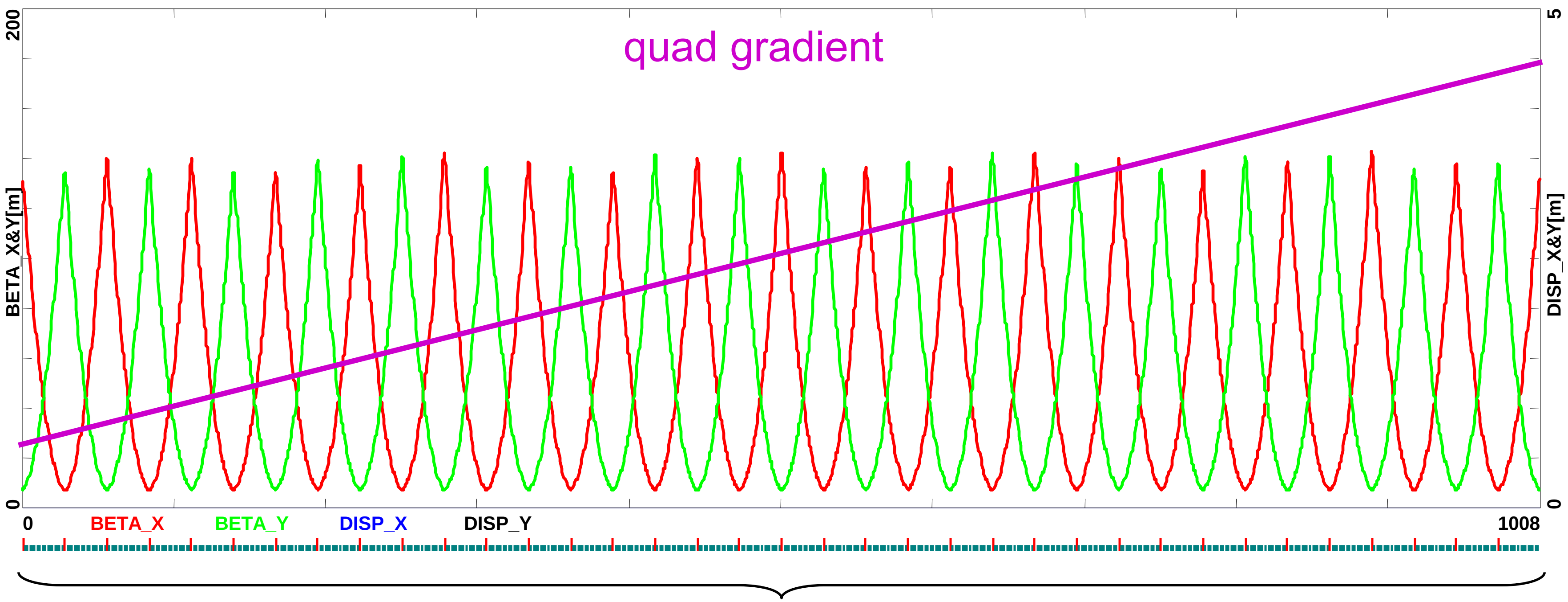
L_q = 40 cm

G_F = 5.17 Tesla/m

G_D = -5.32 Tesla/m

Linac 1 – Focusing profile

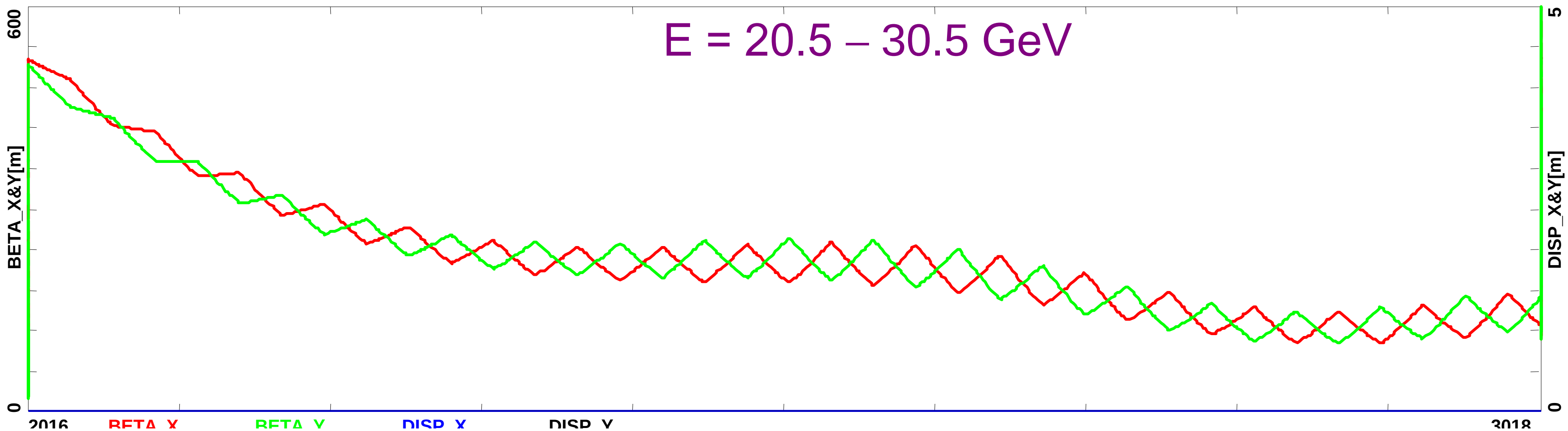
E = 0.5 – 10.5 GeV

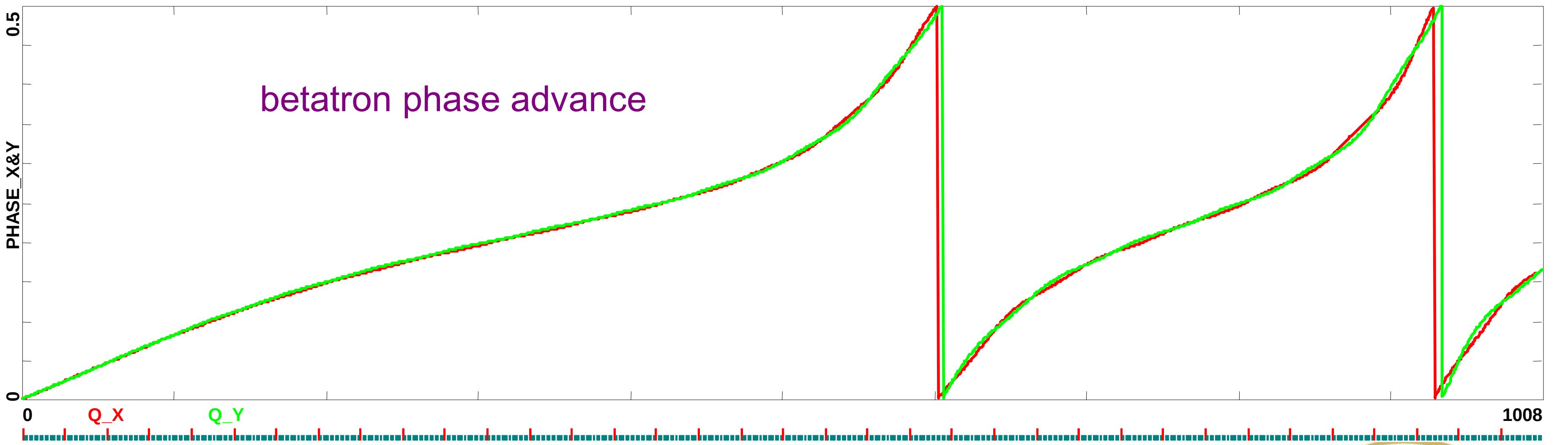


17 FODO cells (17 × 2 × 16 = 544 RF cavities)

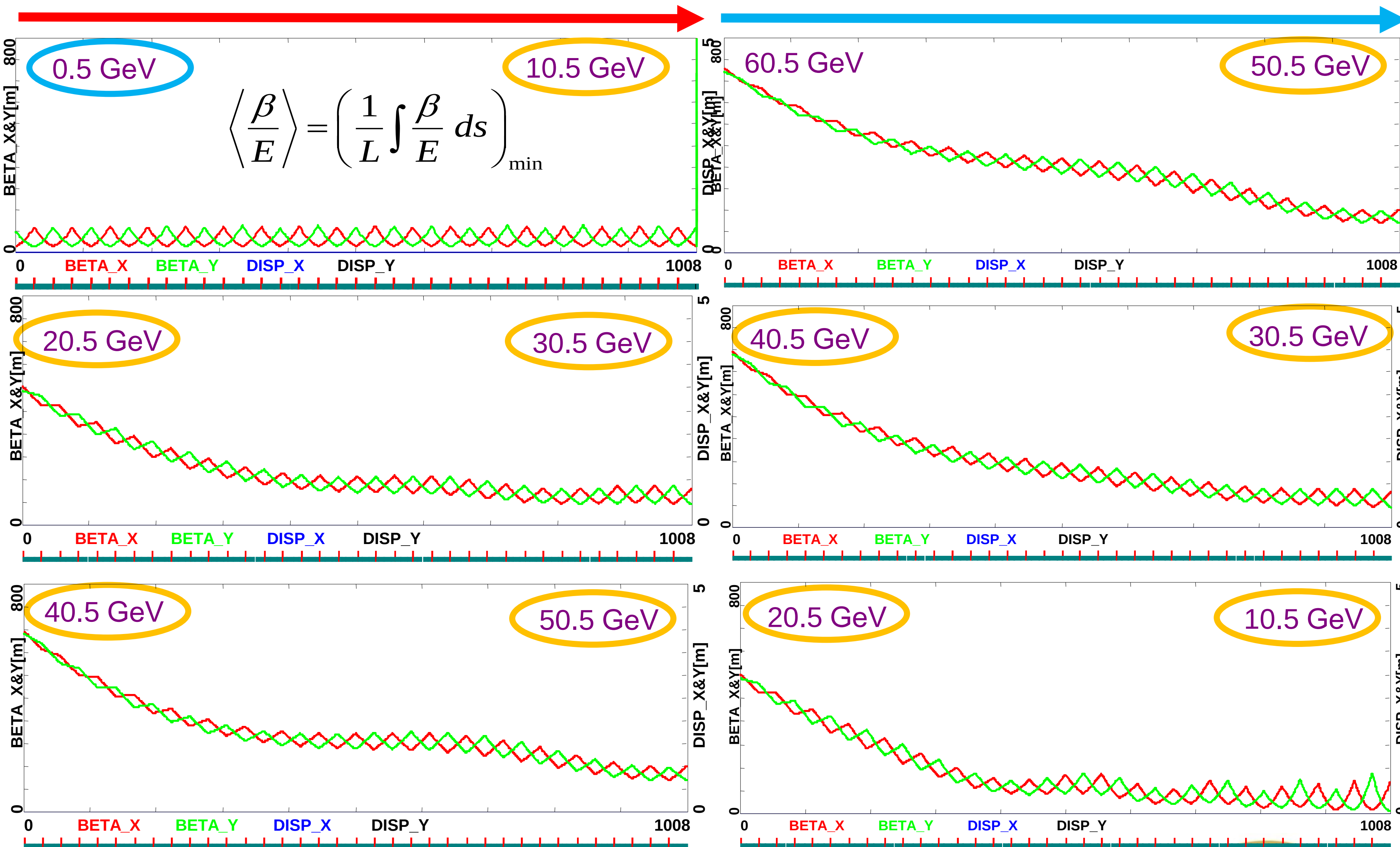
$$\left\langle \frac{\beta}{E} \right\rangle = \left(\frac{1}{L} \int \frac{\beta}{E}\, ds \right)_{\min}$$

Linac 3 (Linac 1, pass 2) – Optics



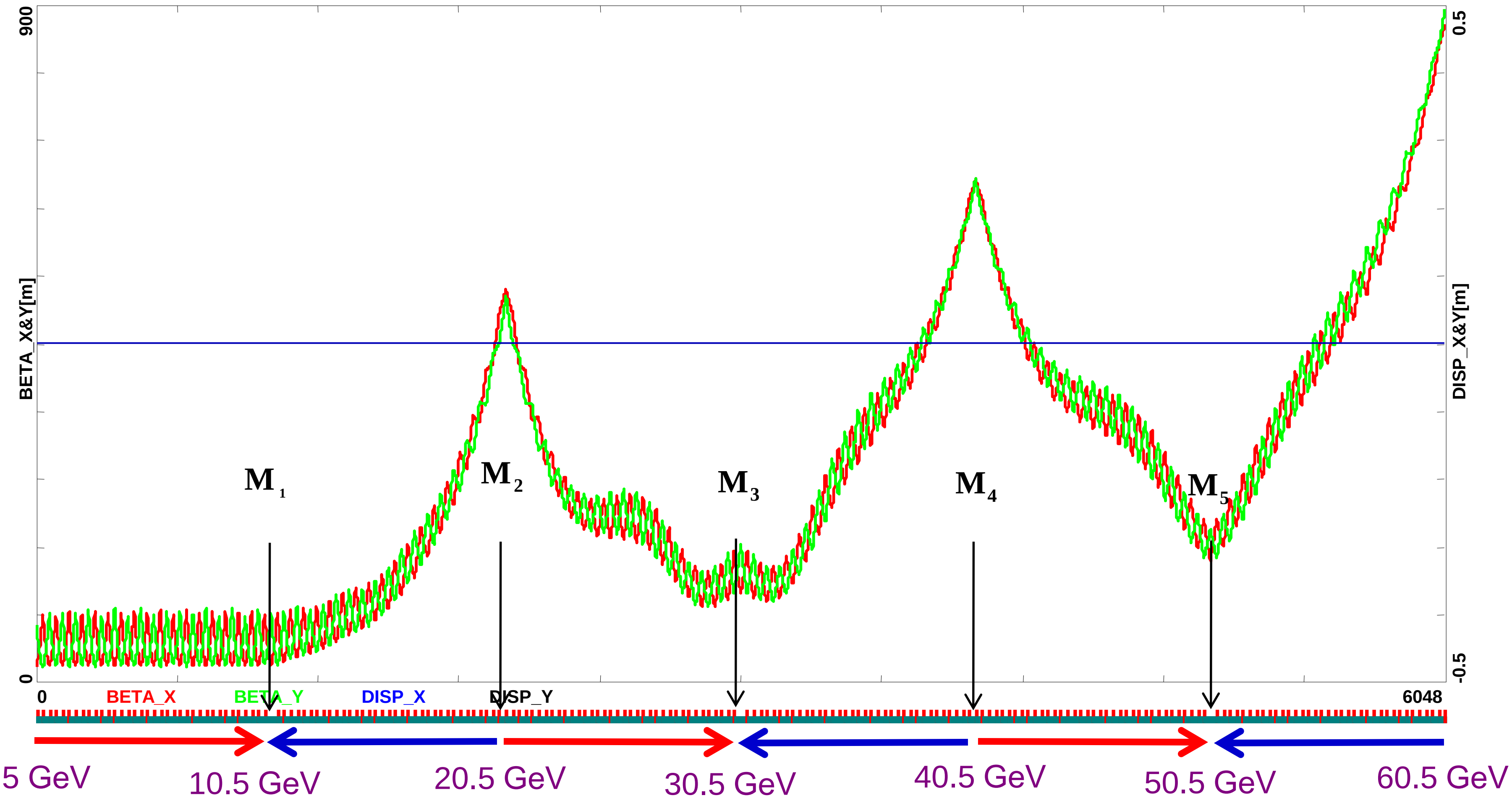


Linac 1 – multi-pass + ER Optics



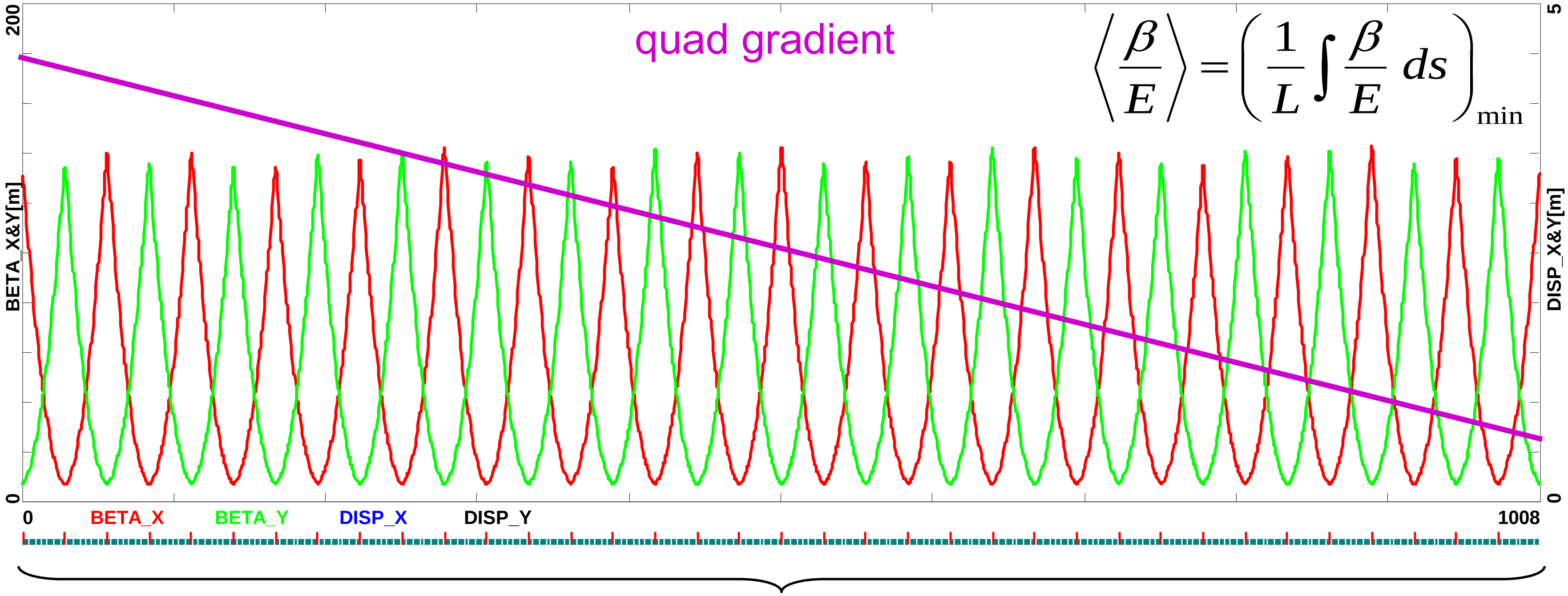
$$\left\langle \frac{\beta}{E} \right\rangle = \left(\frac{1}{L} \int \frac{\beta}{E}\, ds \right)_{\min}$$

Linac 1 – Multi-pass ER Optics



Linac 2 – Focusing profile

E = 10.5 – 0.5 GeV (ER)

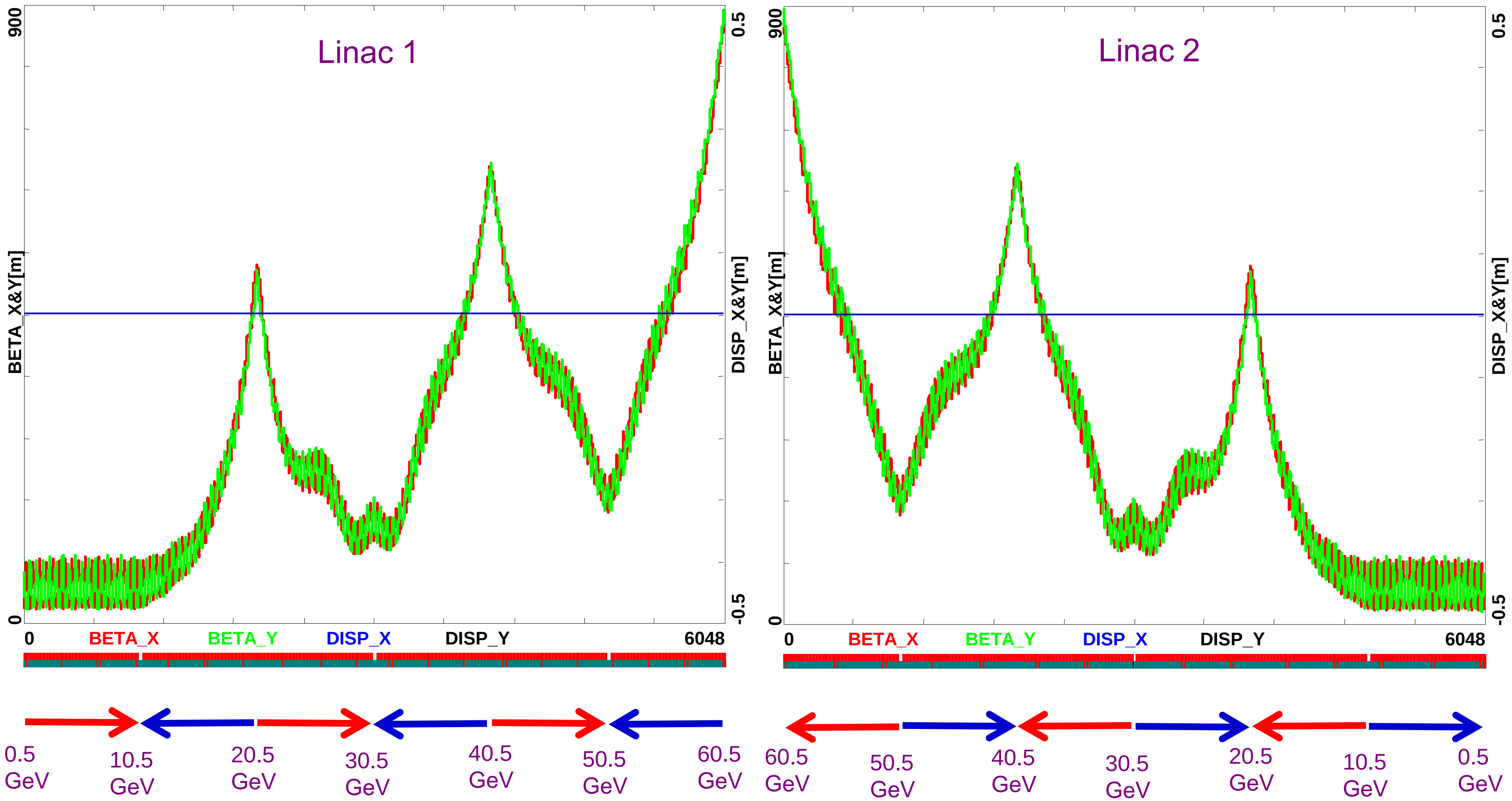


$$\left\langle \frac{\beta}{E} \right\rangle = \left(\frac{1}{L} \int \frac{\beta}{E} \, ds \right)_{\min}$$

17 FODO cells (17 × 2 × 16 = 544 RF cavities)

Linac 2 multi-pass optics with ER – mirror symmetric to Linac 1

Linac 1 and 2 – Multi-pass ER Optics



Arc Optics

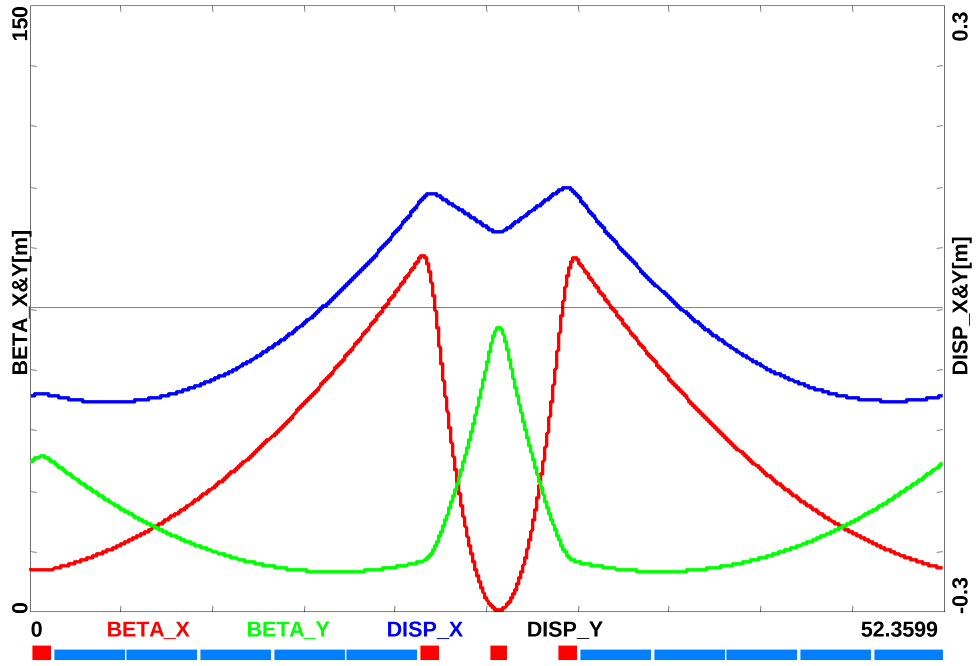
- Minimized emittance dilution due to quantum excitations:

$$I_5 = \int_0^L \frac{H}{|\rho|^3} ds, \quad H = \gamma D^2 + 2\alpha D D' + \beta D'^2$$

- Quasi-isochronous optics – synchronous acceleration in the linacs:

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

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 135⁰ FODO

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

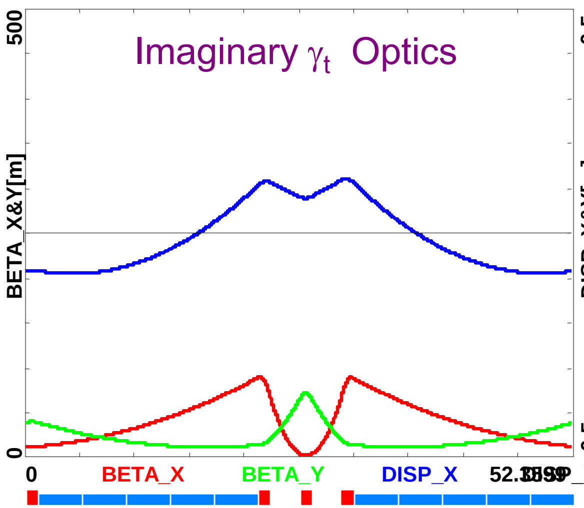
$$M_{56} = 1.16 \times 10^{-3}\ \mathrm{m}$$

factor of 27 smaller than 135⁰ FODO

Arc Optics – Emittance preserving FMC cell

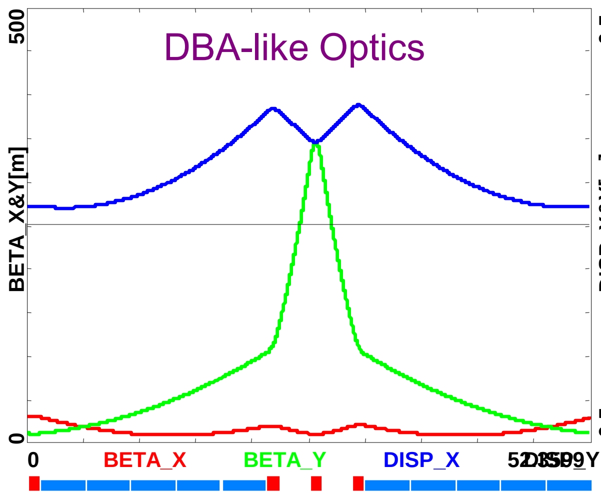
$$\Delta\varepsilon^N = \frac{4}{3} C_q \, r_0 \, \gamma^6 \langle H \rangle \frac{\pi}{\rho^2}, \qquad H = \gamma D^2 + 2\alpha D D' + \beta D'^2$$

Arc 1 , Arc2



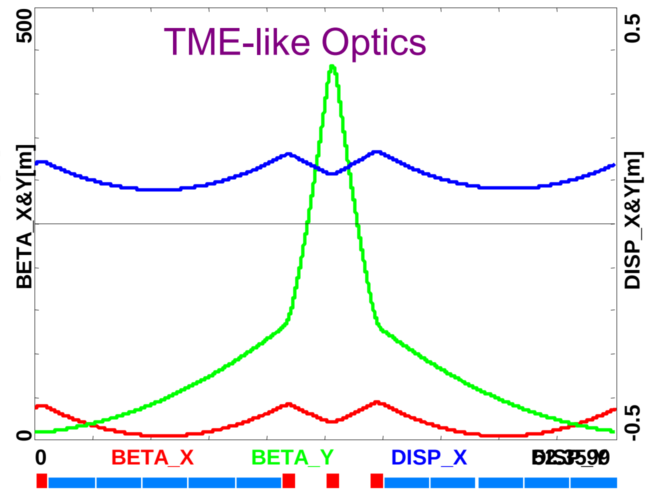
$$\langle H \rangle = 8.8 \times 10^{-3} \; m$$

Arc 3, Arc 4



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

Arc5, Arc 6



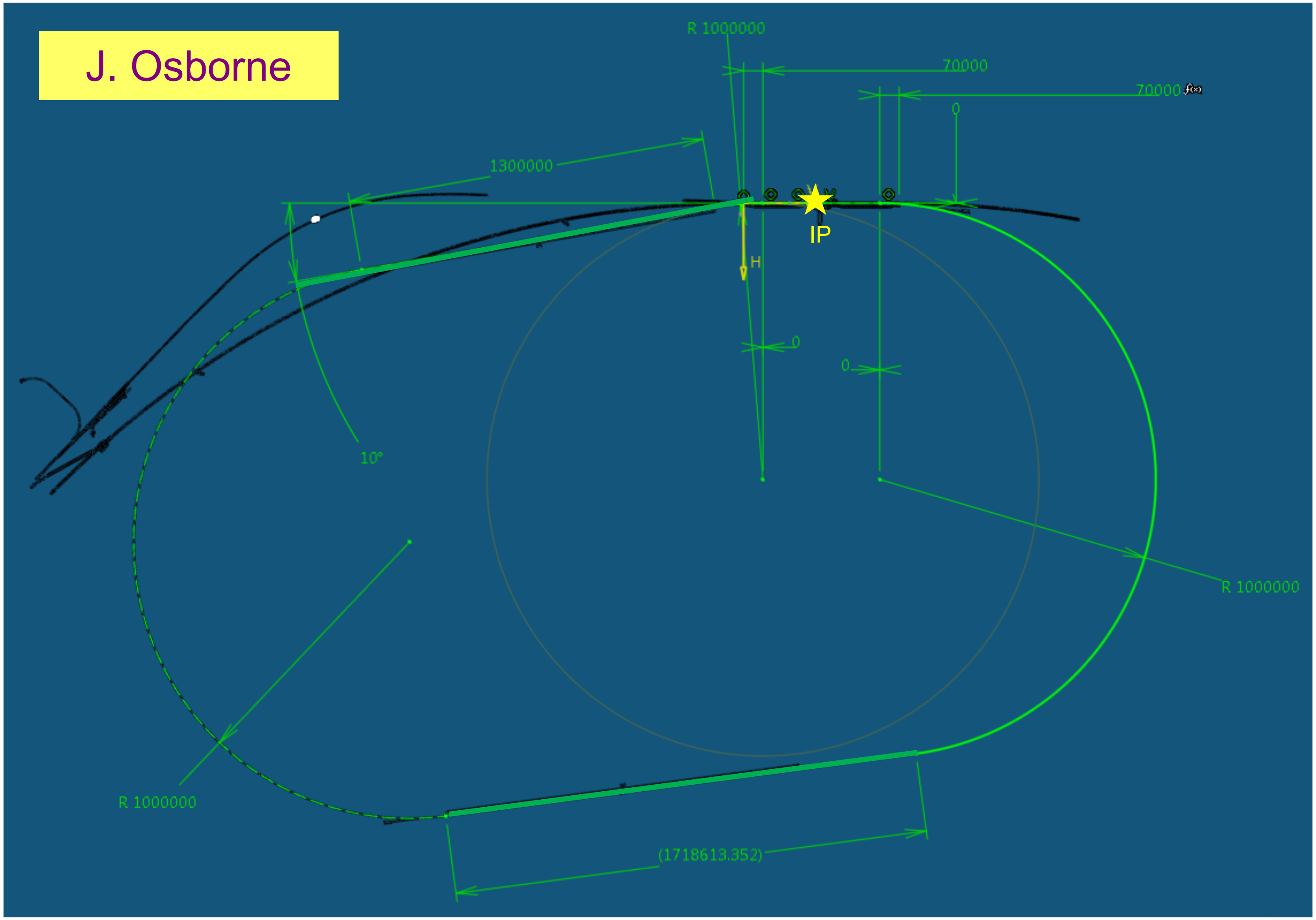
$$\langle H \rangle = 1.2 \times 10^{-3} \; m$$

factor of 18 smaller than FODO

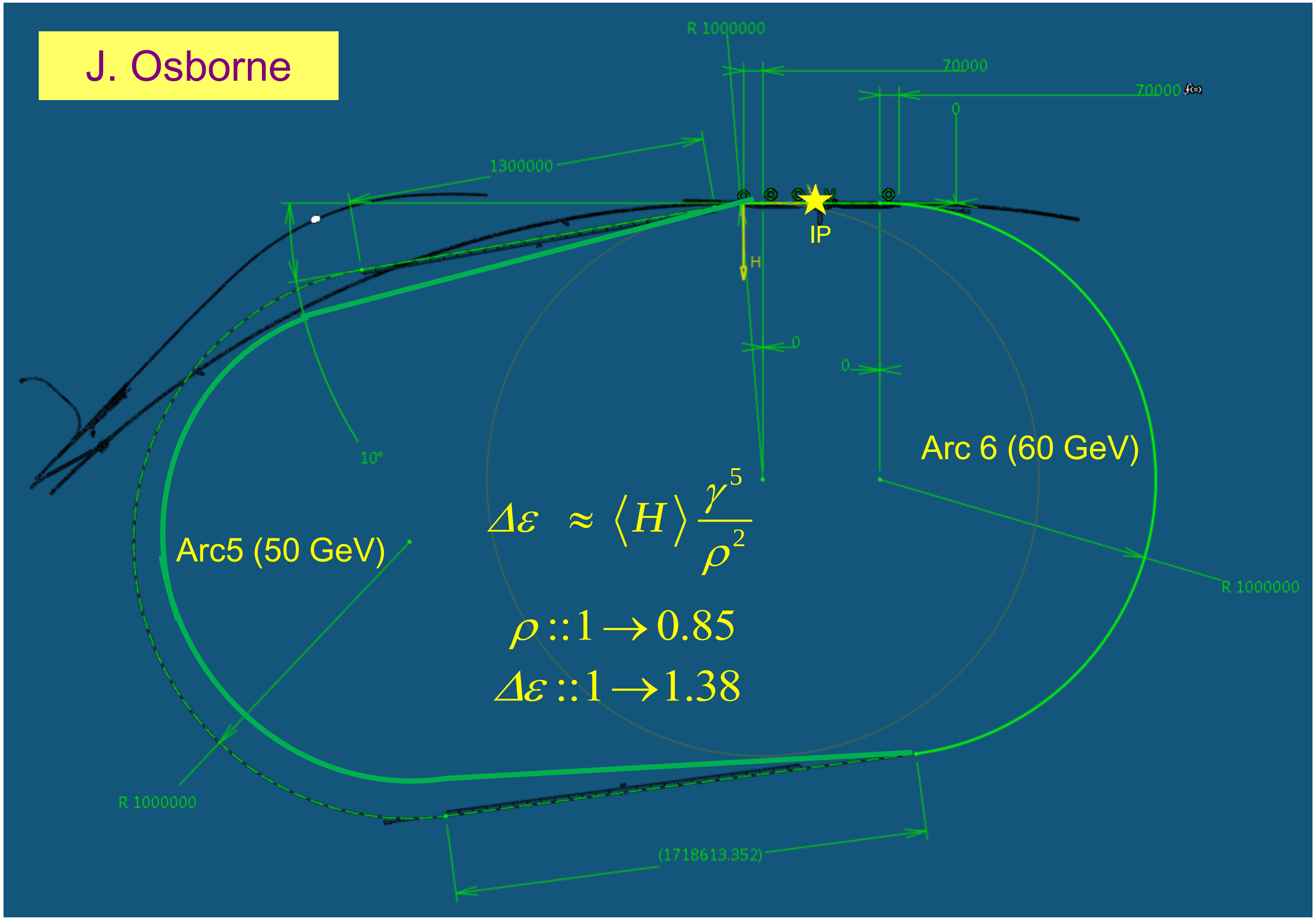
total emittance increase (all 5 arcs): $\Delta\varepsilon_x^N$ = 1.25 × 4.5 μm rad = 5.6 μm rad

emittance growth due to disruption in the collision 15%-180% (without/with rematch the outgoing optics)

Linac–Ring: Dimensions/Layout



Linac–Ring: Dimensions/Layout

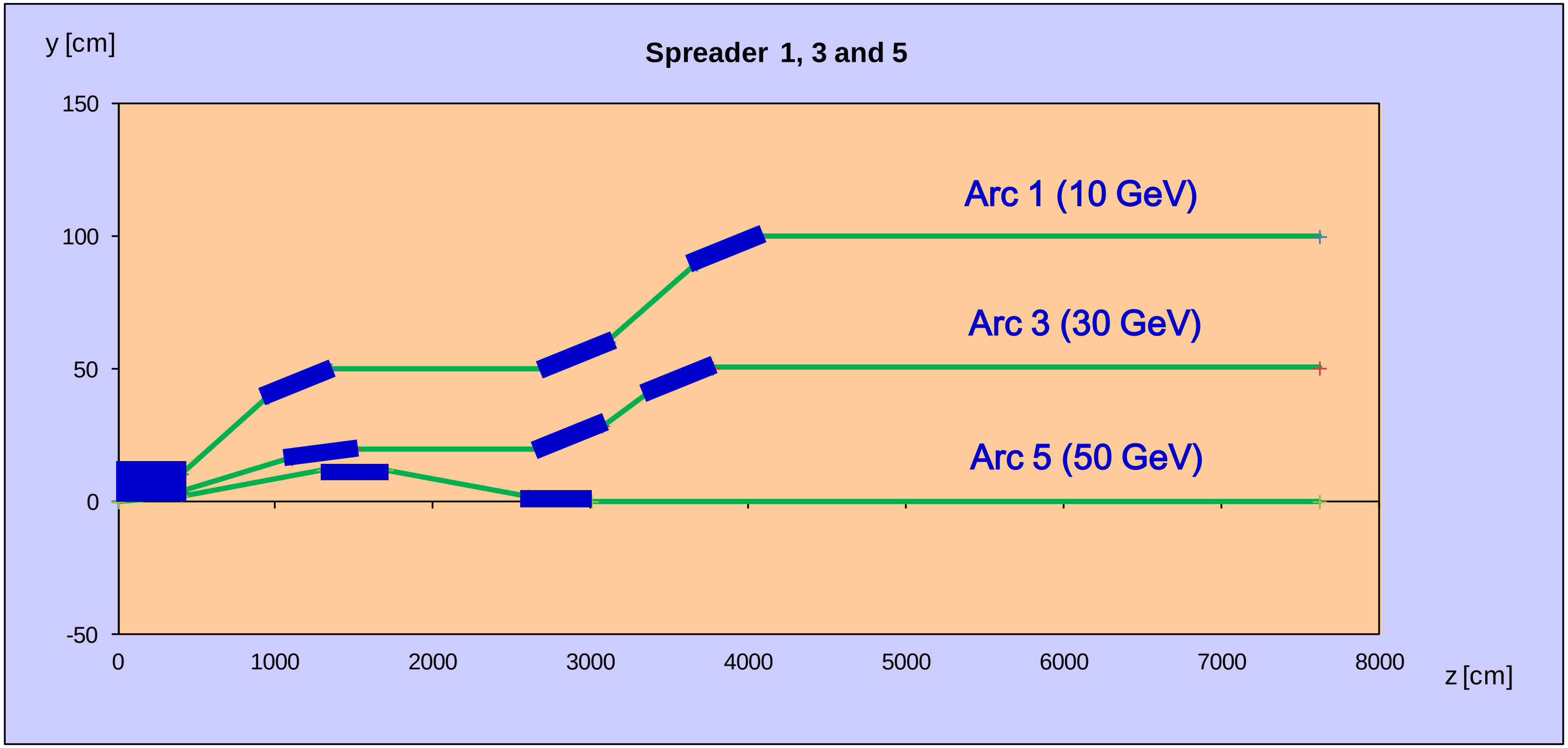


$$\Delta\varepsilon \approx \langle H \rangle \frac{\gamma^5}{\rho^2}$$

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

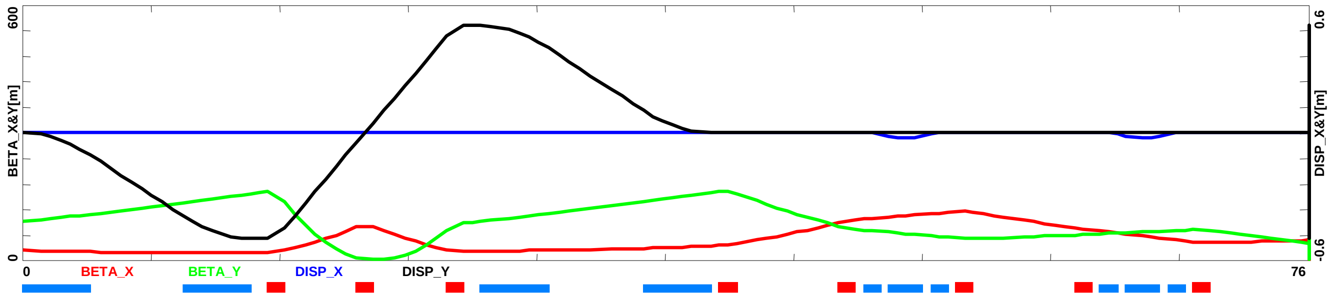
$$\Delta\varepsilon :: 1 \rightarrow 1.38$$

Vertical Separation of Arcs



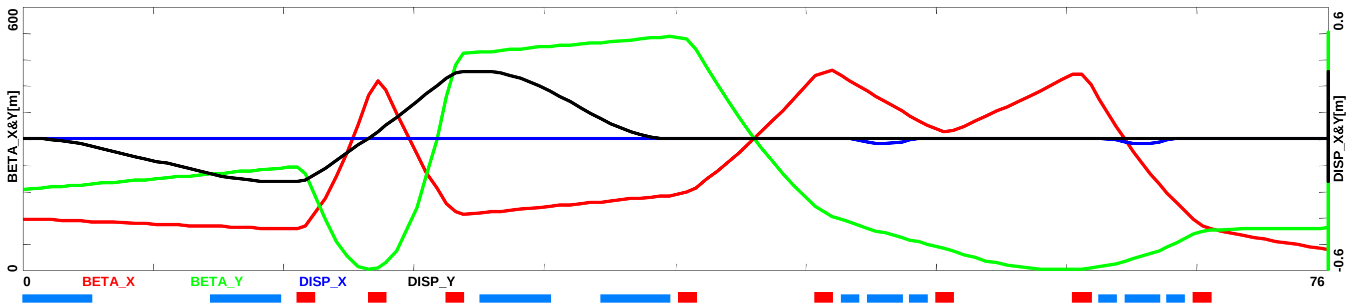
Vertical Spreaders - Optics

Spr. 1



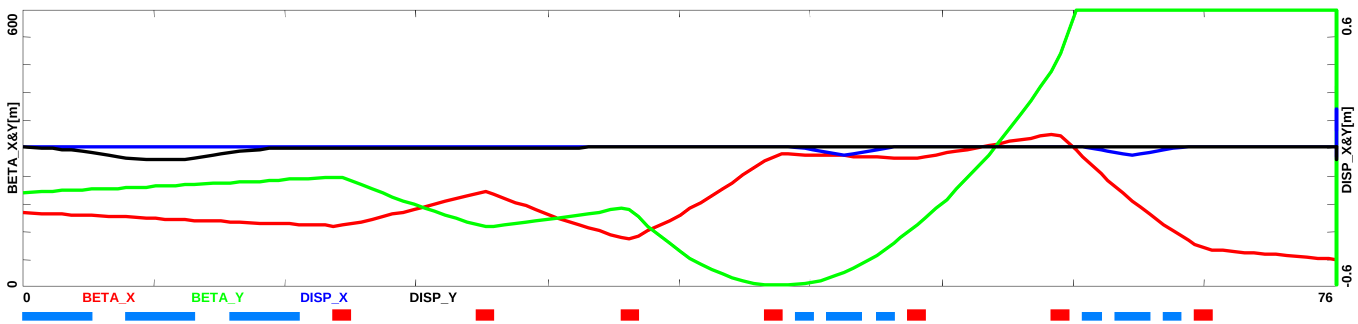
vertical step I
vertical step II
path-length adjustment ‘doglegs’

Spr. 3



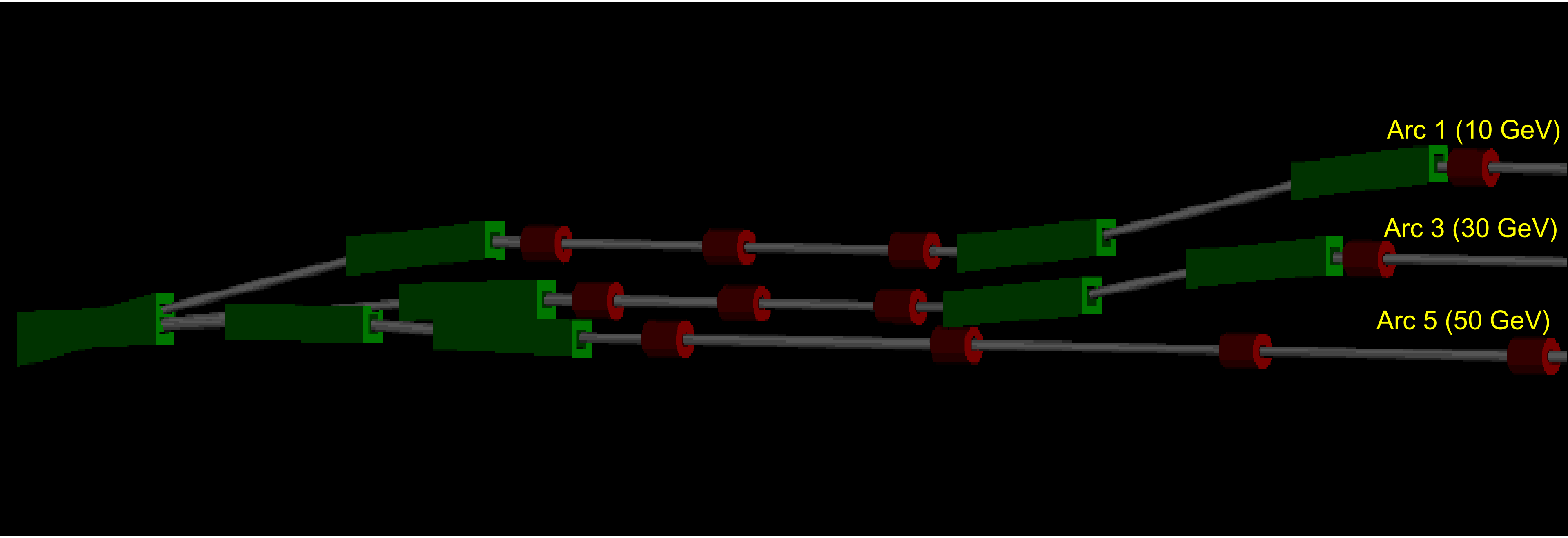
vertical step I
vertical step II
path-length adjustment ‘doglegs’

Spr. 5

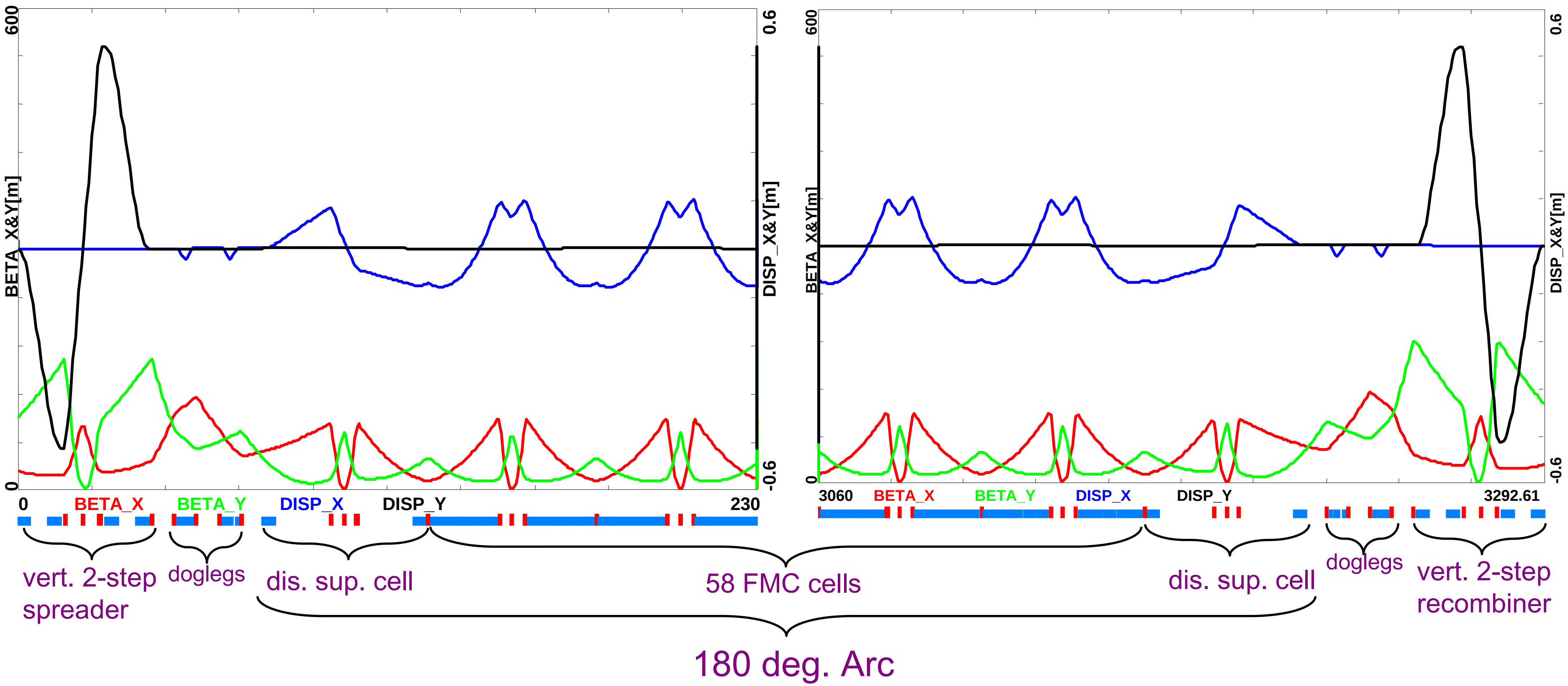


vertical chicane
path-length adjustment ‘doglegs’

Vertical Separation of Arcs



Arc 1 Optics (10 GeV)

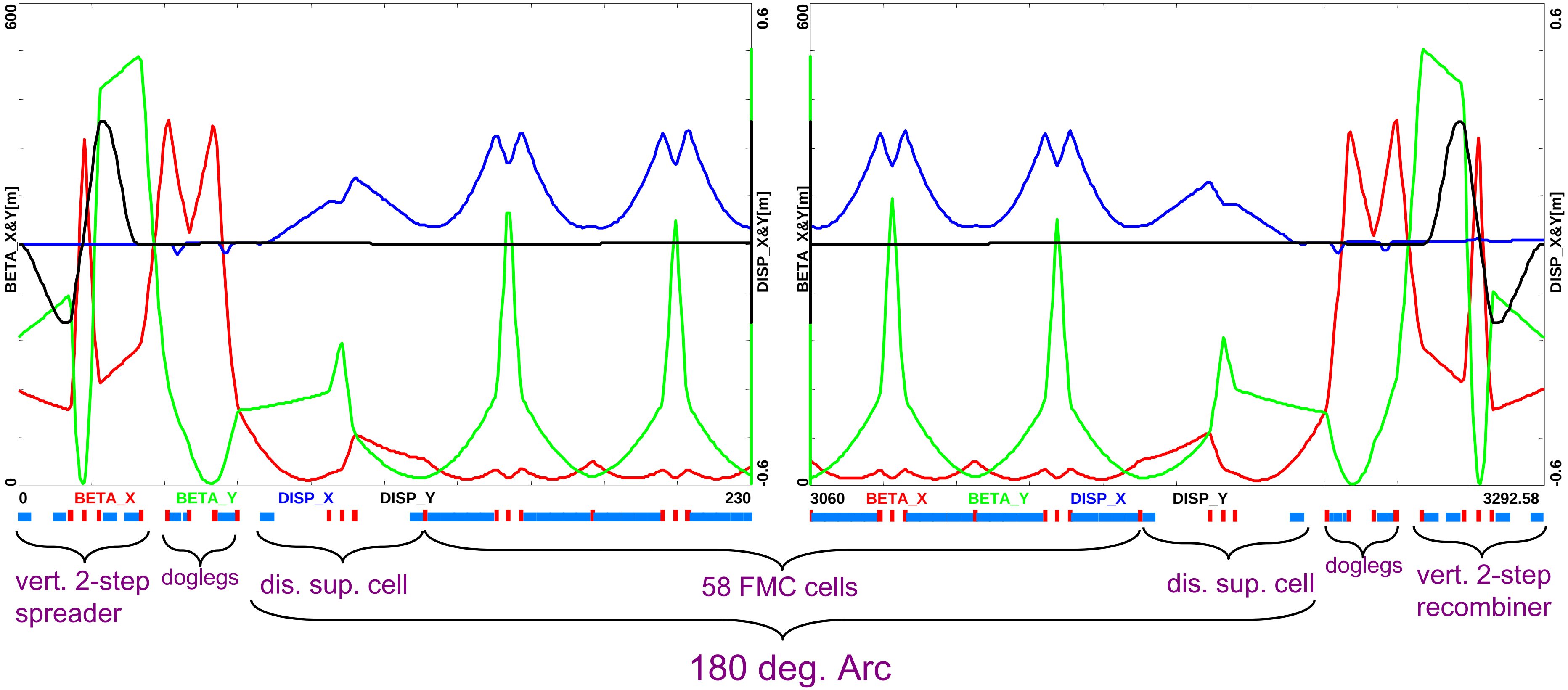


Arc dipoles:

$Lb=400 cm

$B=0.47 kGauss

Arc 3 Optics (30 GeV)

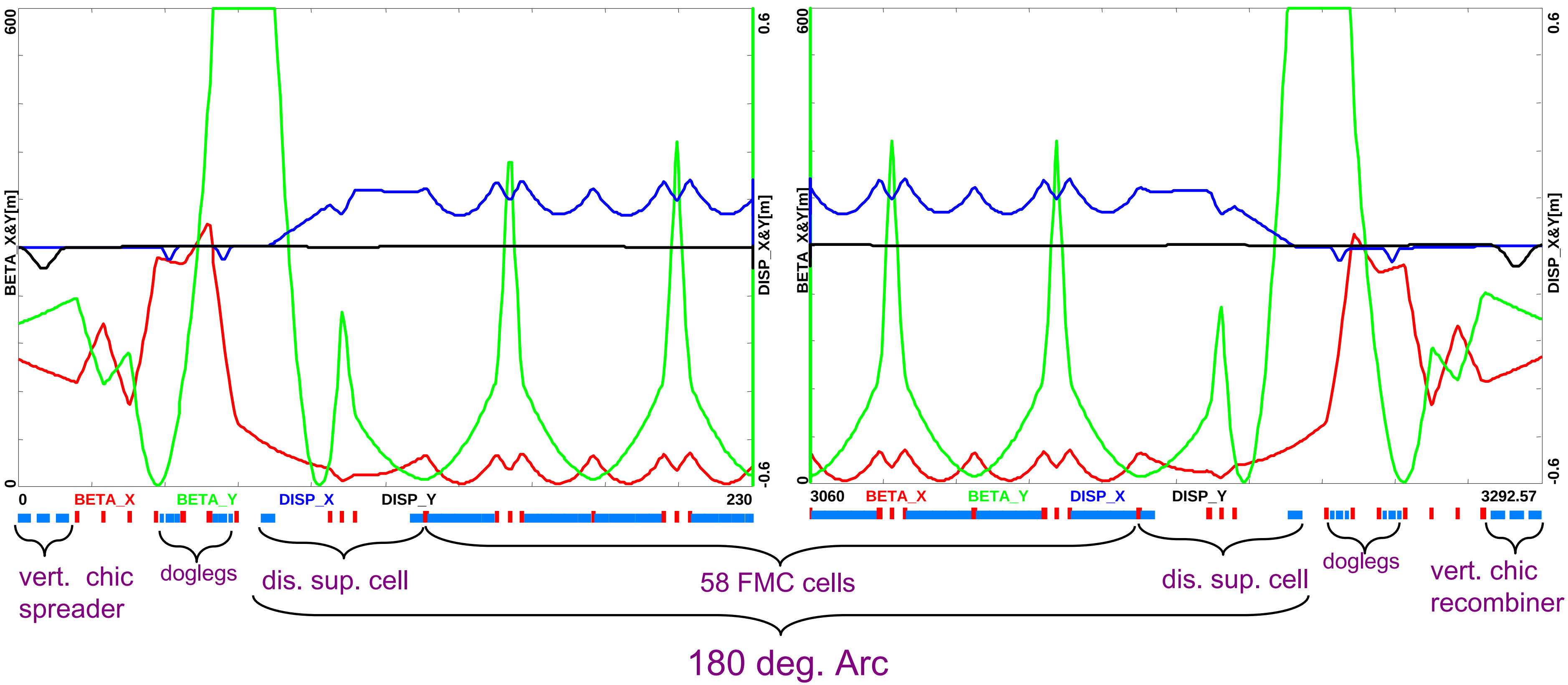


Arc dipoles:

$Lb=400 cm

$B=1.37 kGauss

Arc 5 Optics (50 GeV)



Arc dipoles:

$Lb=400 cm

$B=2.27 kGauss

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 – 720 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’

Special Thanks to:

Frank Zimmermann

Daniel Schulte

and

Max Klein