LHeC Recirculator with Energy Recovery – Beam Optics Choices

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in collaboration with

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LHeC Challenge

Add an *electron* beam to the LHC

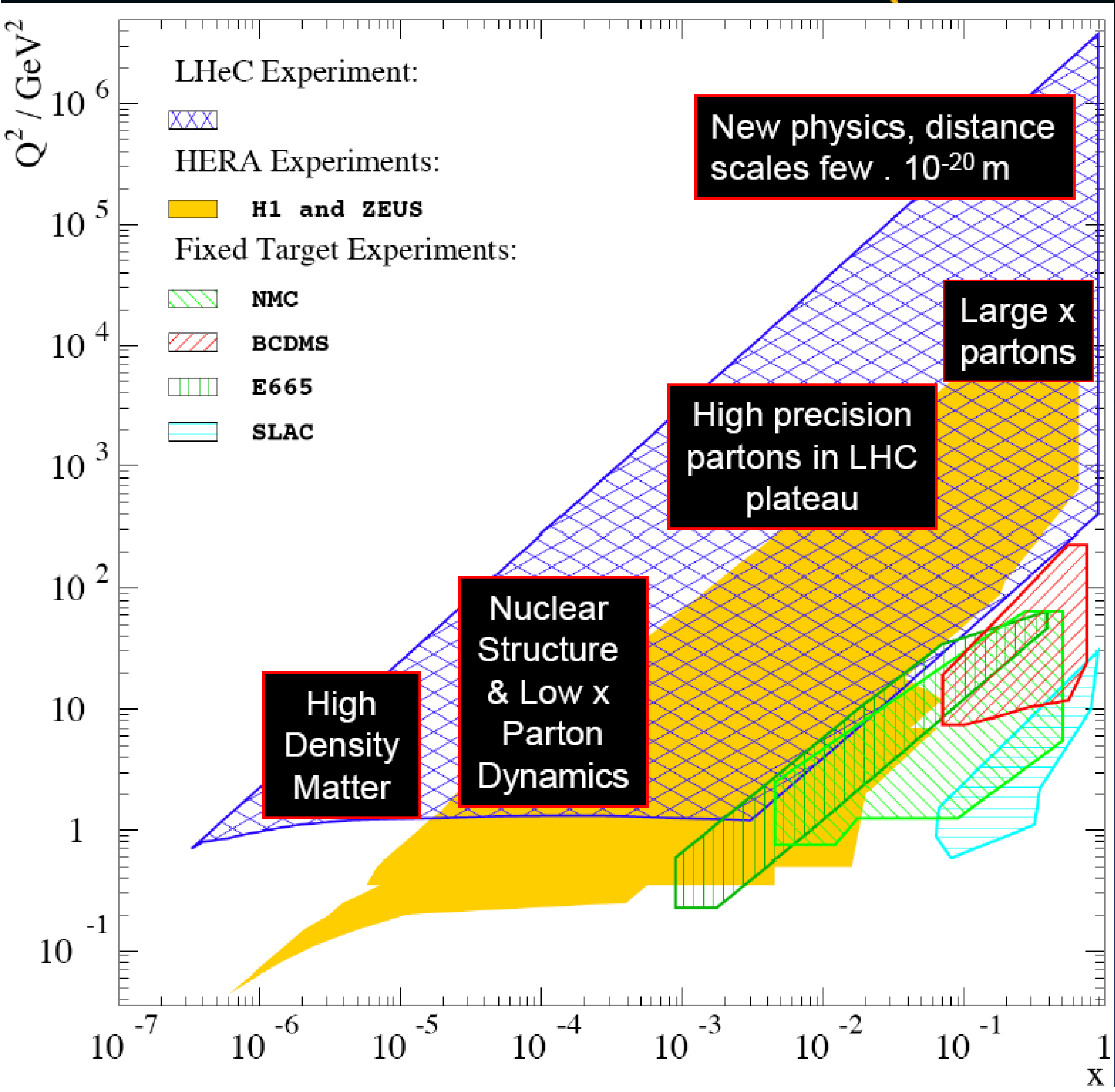
- Next generation $e^{\pm}p$ collider
- $e^{\pm}$ polarized beam
- *eA* collider

Rich physics program: *eq* physics at TeV energies

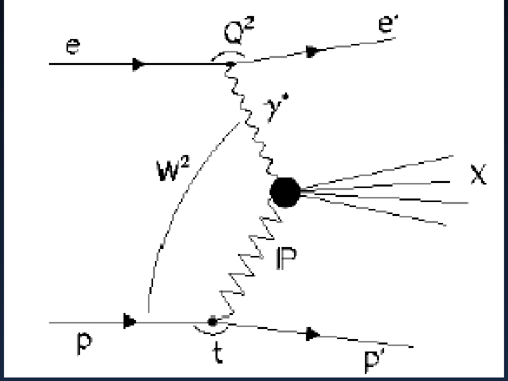
- precision QCD & electroweak physics
- boosting precision and range of LHC physics results
- beyond the Standard Model
- high density matter: low *x* and *eA*

Tevatron/LEP/HERA (Fermiscale) → LHC/LC/LHeC (Terascale)
100 fold increase in luminosity, in Q^2 and $1/x$ w.r.t. HERA

Kinematics & Motivation (60 GeV x 7 TeV *ep*)



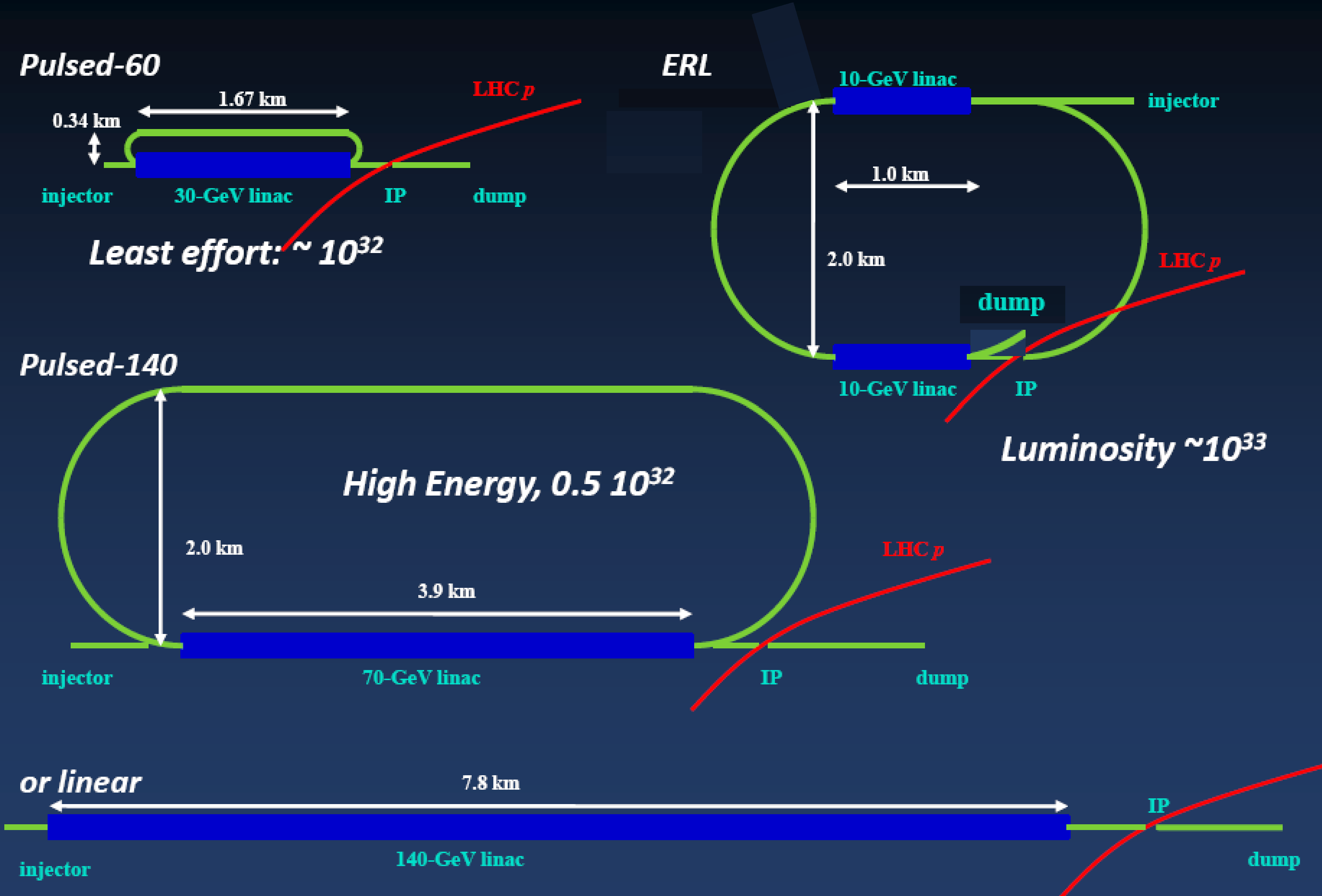
$\sqrt{s} >> 1$ TeV



- High mass (M_{eq}, Q^2) frontier
- EW & Higgs
- Q^2 lever-arm at smallest up to x near to 1 → PDFs
- Low x frontier [x below 10^{-6} at $Q^2 \sim 1$ GeV^2]

→ novel QCD ...

Linac-Ring Configurations



Design Parameters

electron beam	RR	LR ERL	LR
e- energy at IP[GeV]	60	60	140
luminosity [10^{32} $cm^{-2}s^{-1}$]	17	10	0.44
polarization [%]	5 - 40	90	90
bunch population [10^{9}]	26	2.0	1.6
e- bunch length [mm]	10	0.3	0.3
bunch interval [ns]	25	50	50
transv. emit. $\gamma\varepsilon_{x,y}$ [mm]	0.58, 0.29	0.05	0.1
rms IP beam size $\sigma_{x,y}$ [μm]	30, 16	7	7
e- IP beta funct. $\beta^*_{x,y}$ [m]	0.18, 0.10	0.12	0.14
full crossing angle [mrad]	0.93	0	0
geometric reduction H_{hg}	0.77	0.91	0.94
repetition rate [Hz]	N/A	N/A	10
beam pulse length [ms]	N/A	N/A	5
ER efficiency	N/A	94%	N/A
average current [mA]	131	6.6	5.4
tot. wall plug power[MW]	100	100	100

proton beam	RR	LR
bunch pop. [10^{11}]	1.7	1.7
tr.emit.$\gamma\varepsilon_{x,y}$ [μm]	3.75	3.75
spot size $\sigma_{x,y}$ [μm]	30, 16	7
$\beta^*_{x,y}$ [m]	1.8,0.5	0.1$
bunch spacing [ns]	25	25

$ smaller LR *p*-β* value than for nominal LHC (0.55 m):

- reduced *l** (23 → 10 m)
- only one *p* beam squeezed
- IR quads as for HL-LHC

In progress last update 8.7.2010

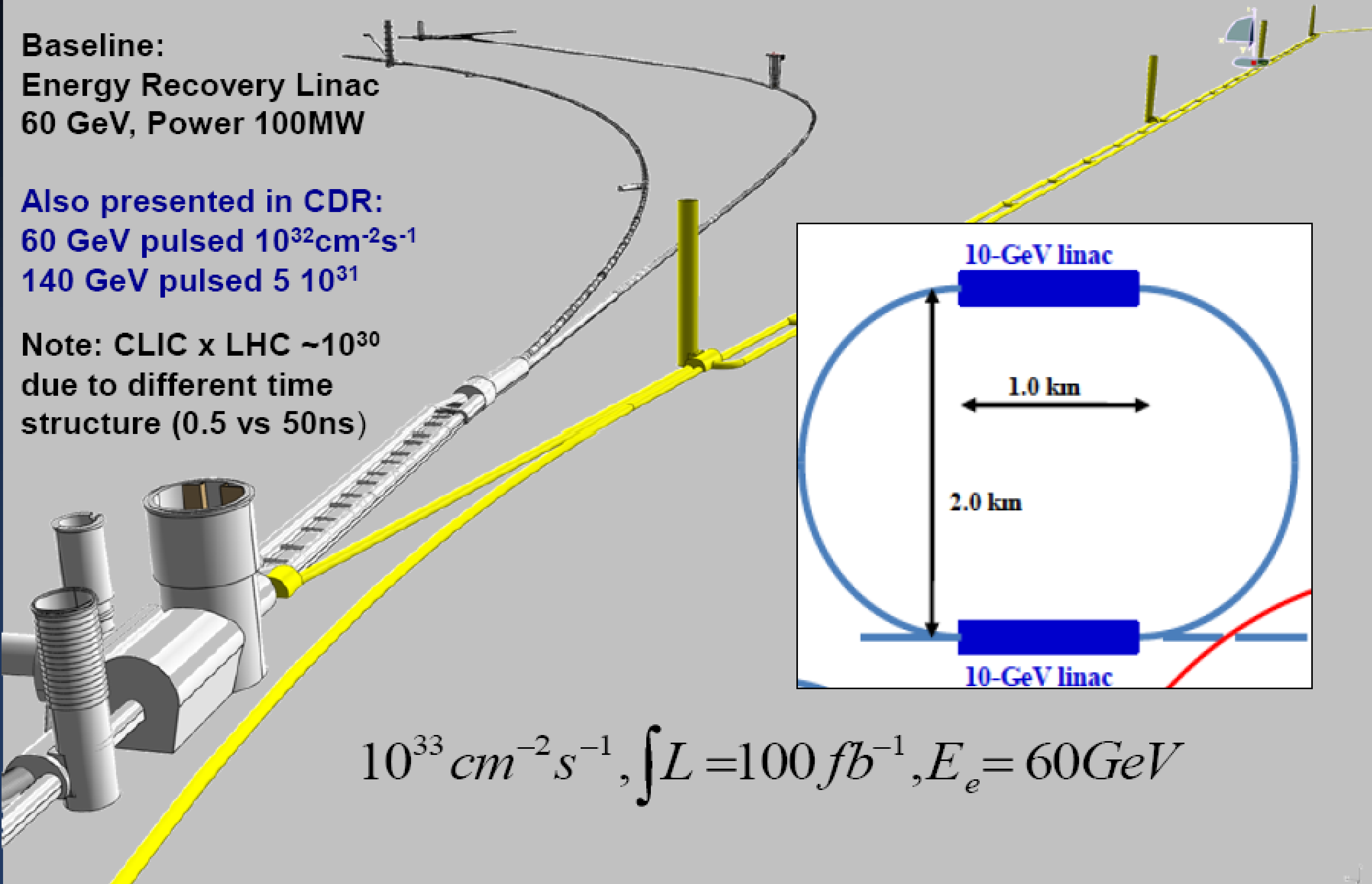
RR = Ring – Ring
LR = Linac –Ring
ERL= Energy Recovery Linac

Linac-Ring Configuration

Baseline:
Energy Recovery Linac
60 GeV, Power 100MW

Also presented in CDR:
60 GeV pulsed $10^{32} cm^{-2}s^{-1}$
140 GeV pulsed 5 10^{31}

Note: CLIC x LHC ~10^{30}
due to different time
structure (0.5 vs 50ns)



$$10^{33} cm^{-2} s^{-1}, \int L = 100 fb^{-1}, E_e = 60 GeV$$

Energy Recovery Recirculating Linacs - Motivation

- Future high energy (multi-tens of GeV), high current (tens of milli-Amperes) beams would require gigaWatt-class RF systems in conventional linacs – a prohibitively expensive proposition. However, invoking energy recovery alleviates extreme RF power demands; required RF power becomes nearly independent of beam current, which improves linac efficiency and increases cost effectiveness.

- 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.).

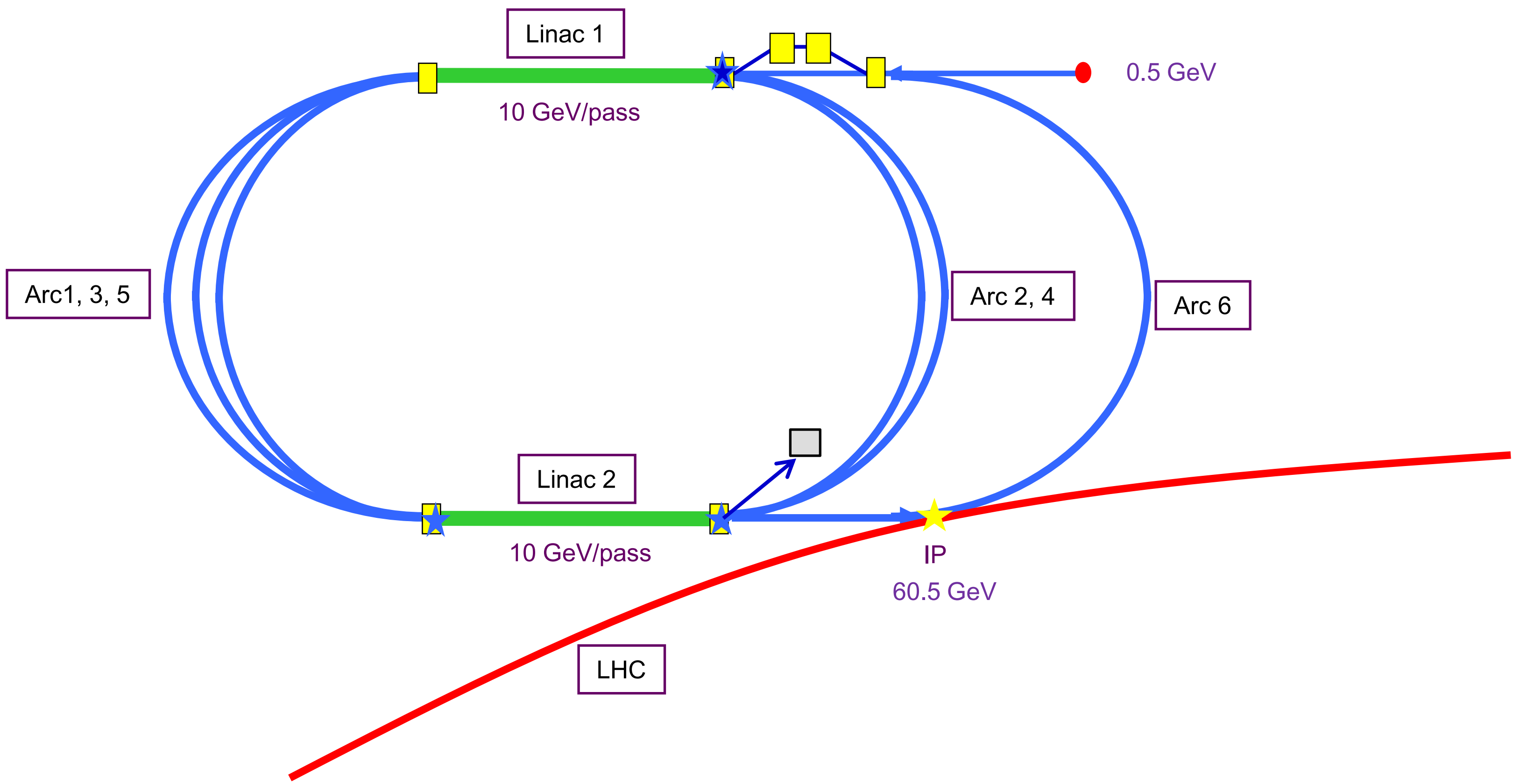
- RLAs that use superconducting RF structures can provide exceptionally fast and economical acceleration to the extent that the focusing range of the RLA quadrupoles allows each particle to pass several times through each high-gradient cavity.

- GeV scale energy recovery demonstration with high ratio of accelerated-to-recovered energies (50:1) was carried out on the CEBAF RLA (2003)

Overview - Design Choices

- Examples of ER RLA's
  - CEBAF ER Exp & Jlab's FEL
- Multi-pass linac Optics in ER mode
  - Choice of linac Optics - 130^0 FODO vs 'No quad' focusing
  - Choice of quad gradient profile in the linacs
  - Single pass wake-field effects
  - Linear lattice: 3-pass 'up' + 3-pass 'down'
- Arc-to-Linac Synchronization - Momentum compaction
  - Quasi-isochronous lattices
  - Choice of Arc Optics -135^0 FODO vs FMC (Flexible Momentum Compaction)
- Arc Optics Choice - Emittance preserving lattices
  - Various flavors of FMC lattices in the second stability region (Im. γ_t, DBA, TEM)
- Emittance dilution & momentum spread due to quantum excitations
  - Magnet apertures

LHeC Recirculator with ER

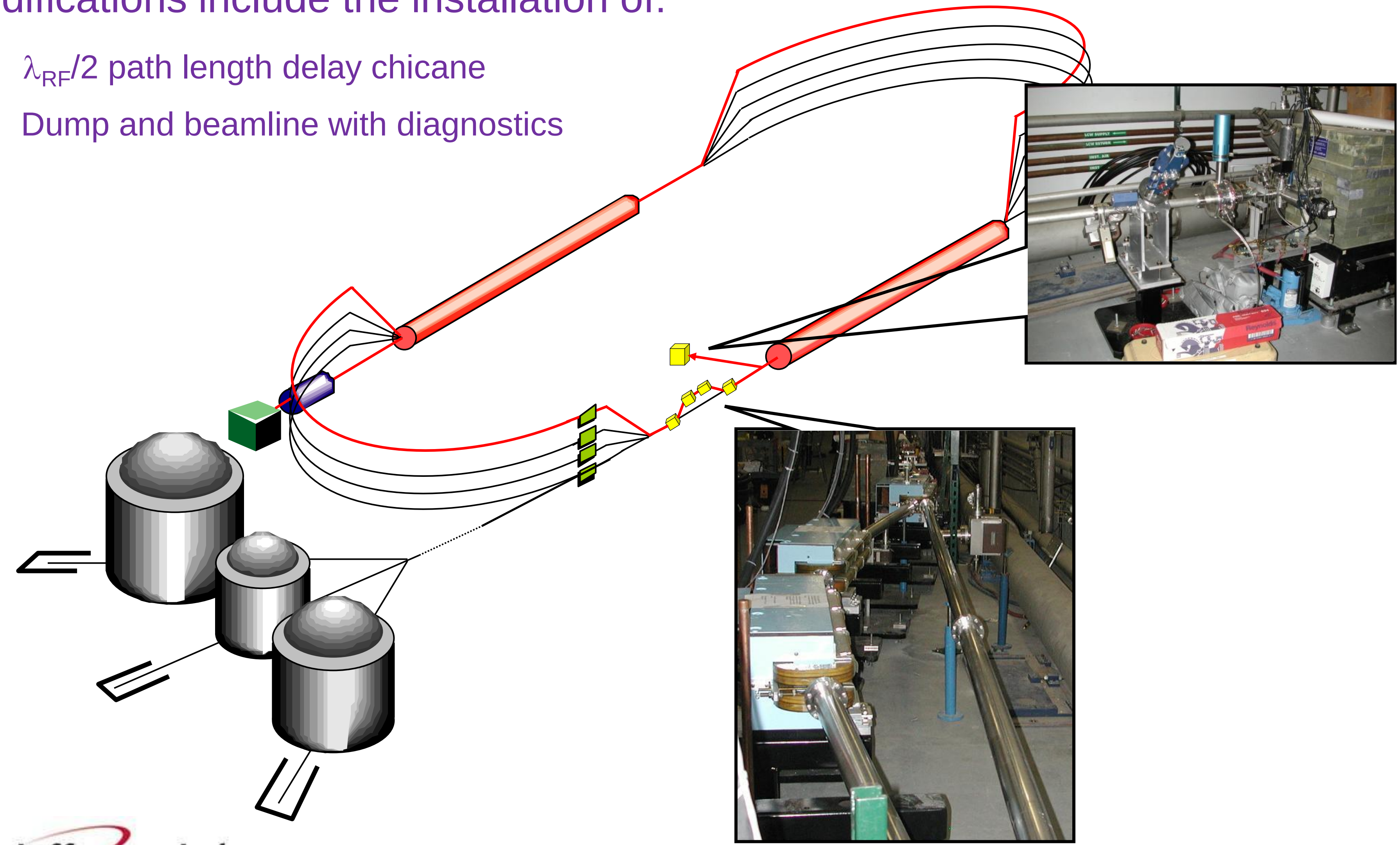


CEBAF - ER Experiment (2003)

Modifications include the installation of:

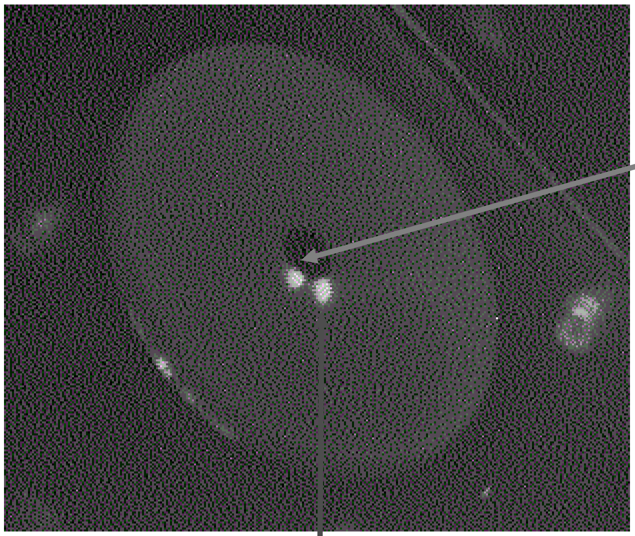
$\lambda_{RF}/2$ path length delay chicane

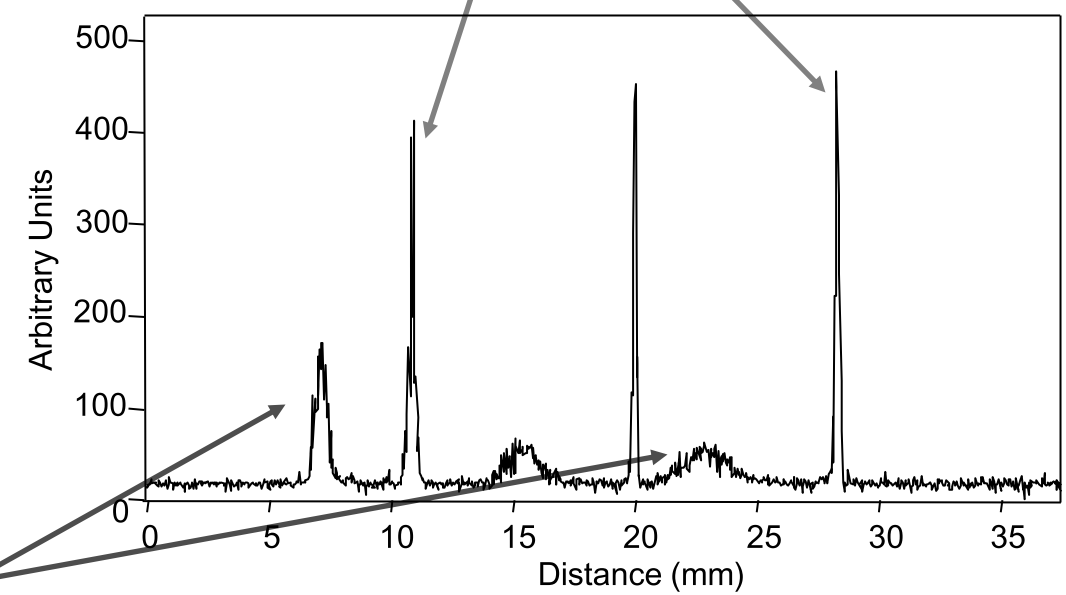
Dump and beamline with diagnostics



Transverse beam profiles

Beam viewer near the exit of the South Linac

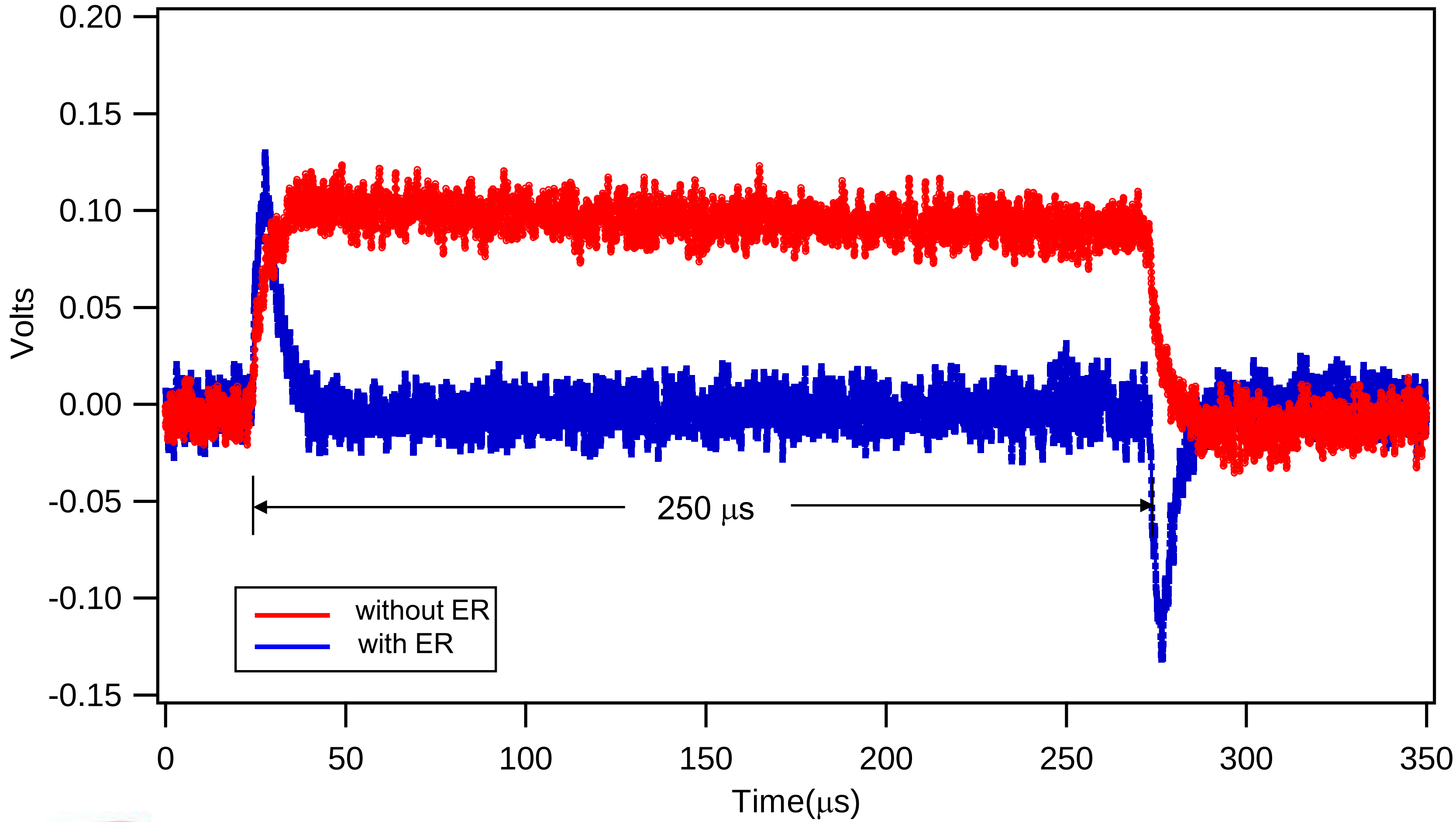




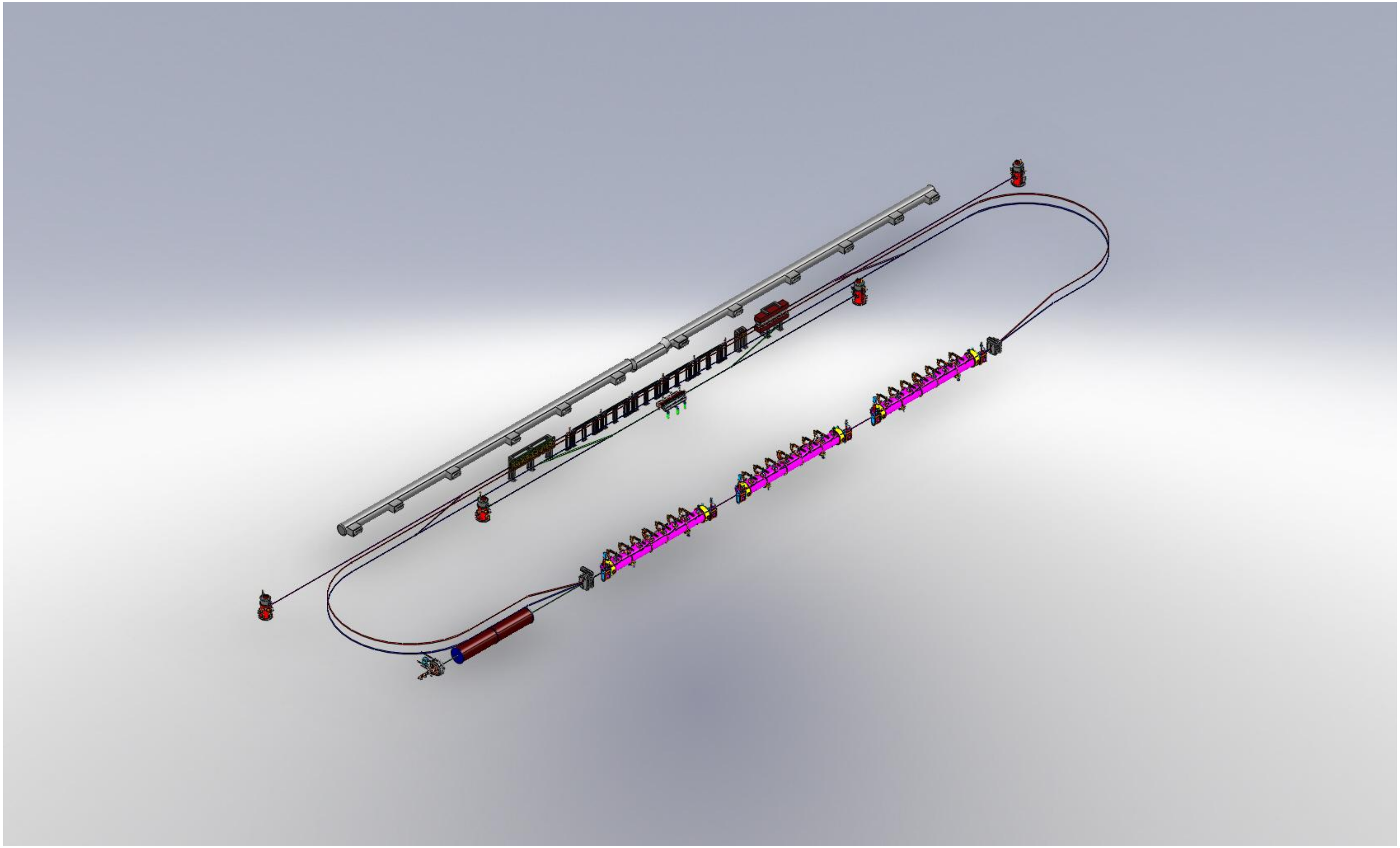
3-wire scanner x 2 beams = 6 peaks

RF Response to Energy Recovery

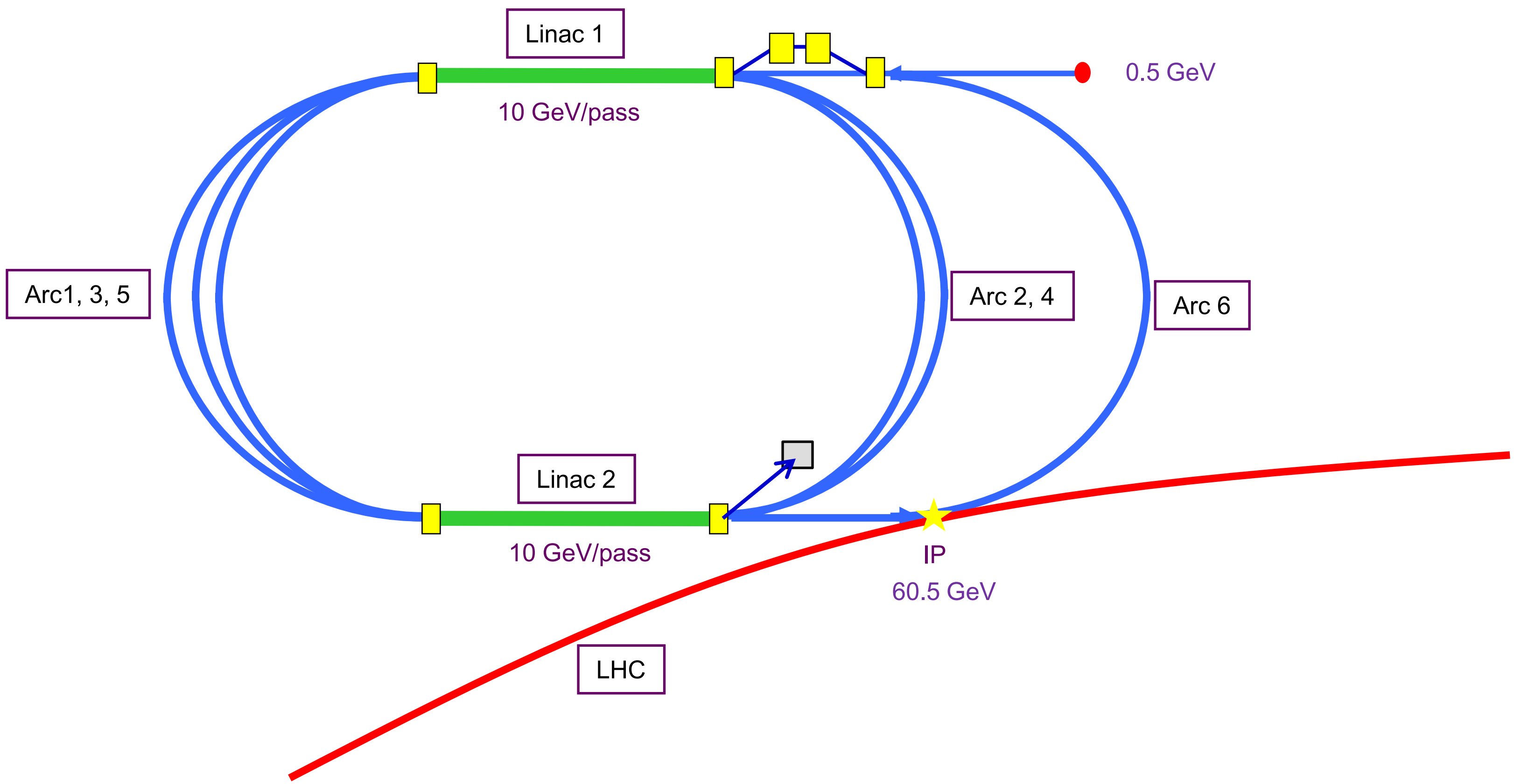
- Gradient modulator drive signals with and without energy recovery in response to 250 μsec beam pulse entering an RF cavity



JLAMP – RLA FEL with ER

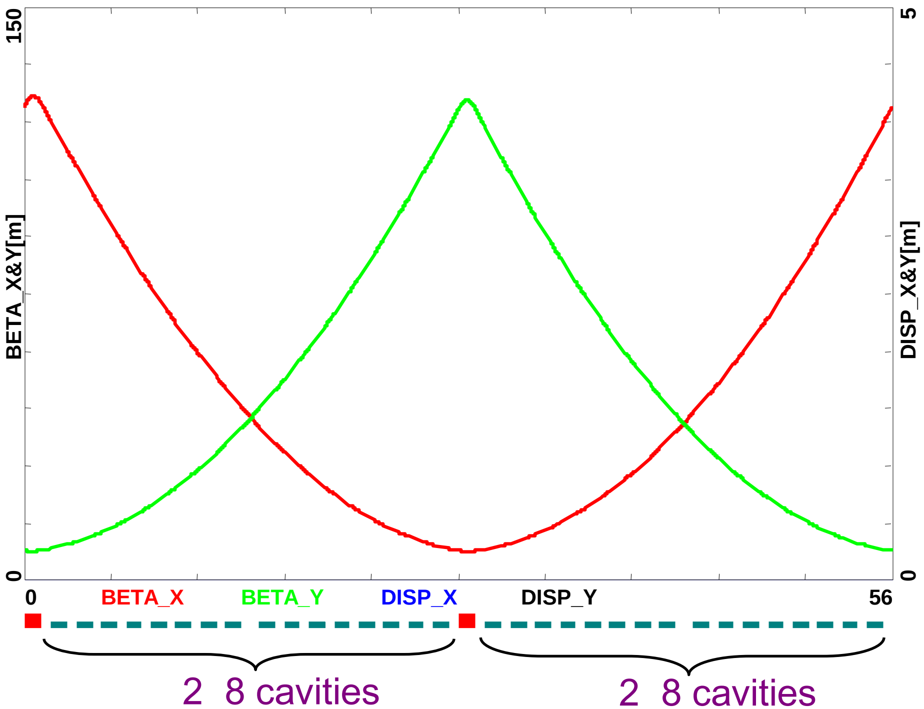


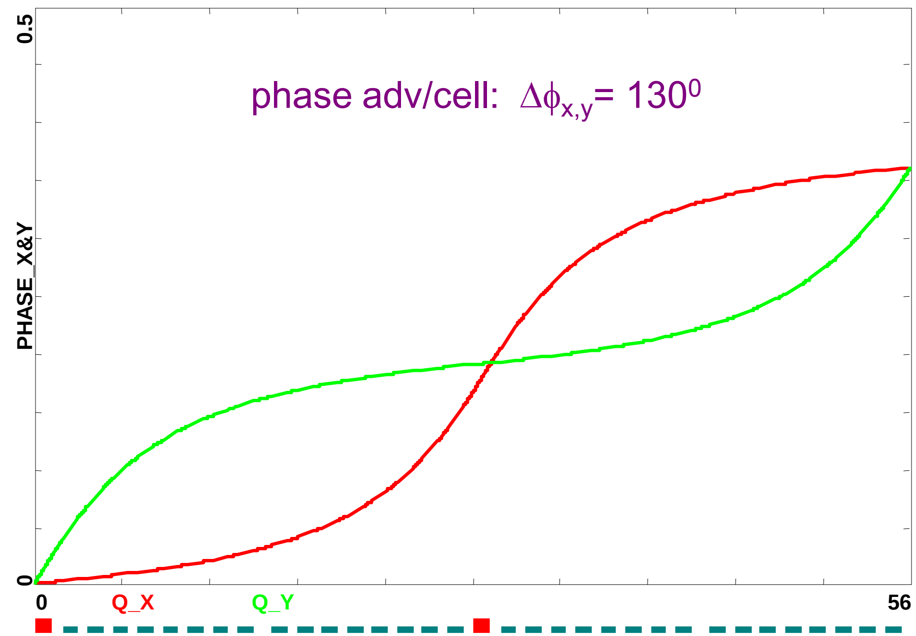
Linacs – LHeC Recirculator with ER



Linac Optics – 130^0 FODO Cell

E = 0.5 GeV





linac quadrupoles

Lq=100 cm

GF= 0.103 Tesla/m

GD= -0.161 Tesla/m

700 MHz RF:

Lc =100 cm

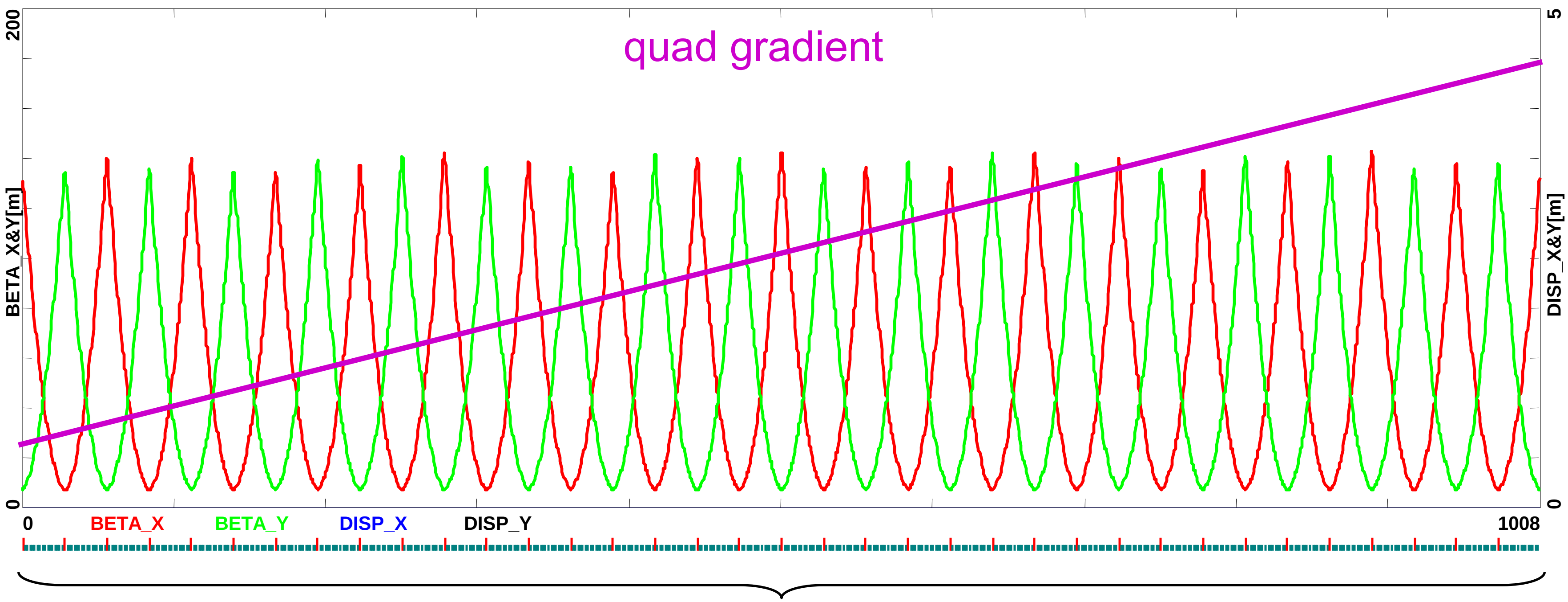
5-cell cavity

Grad = 17.361 MeV/m

ΔE= 555.56 MV

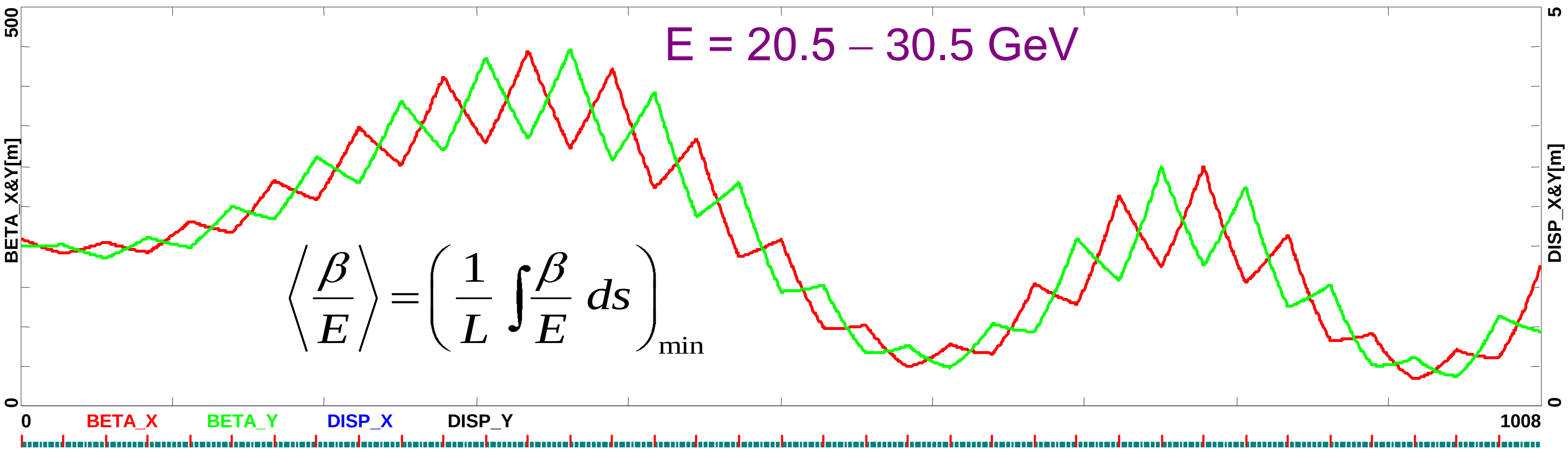
Linac 1 – Focusing profile

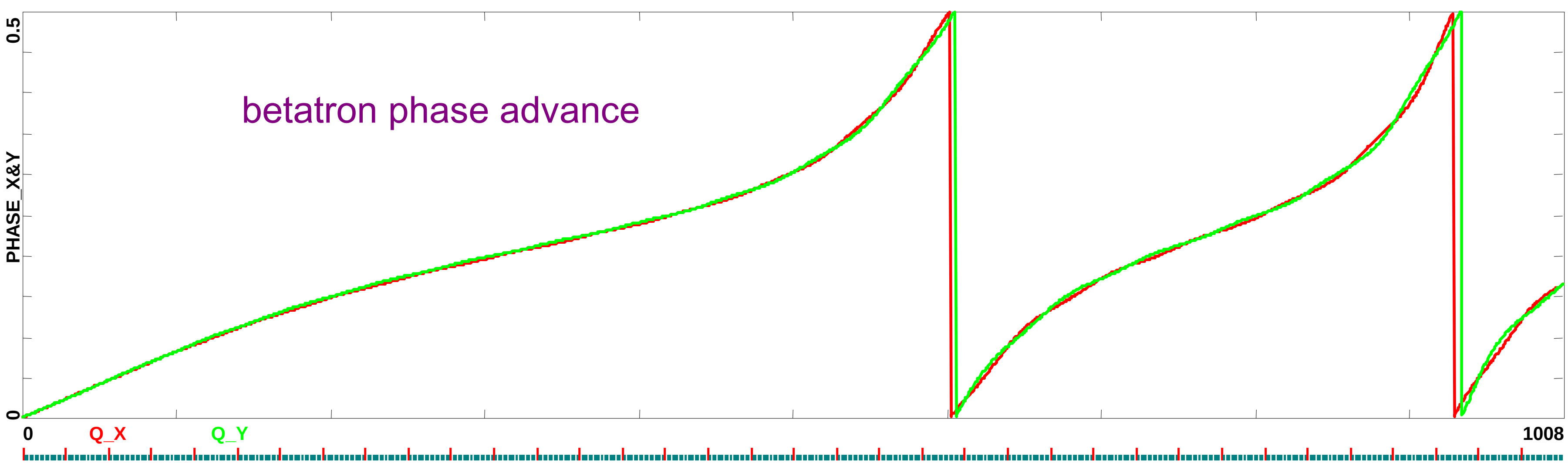
E = 0.5 – 10.5 GeV



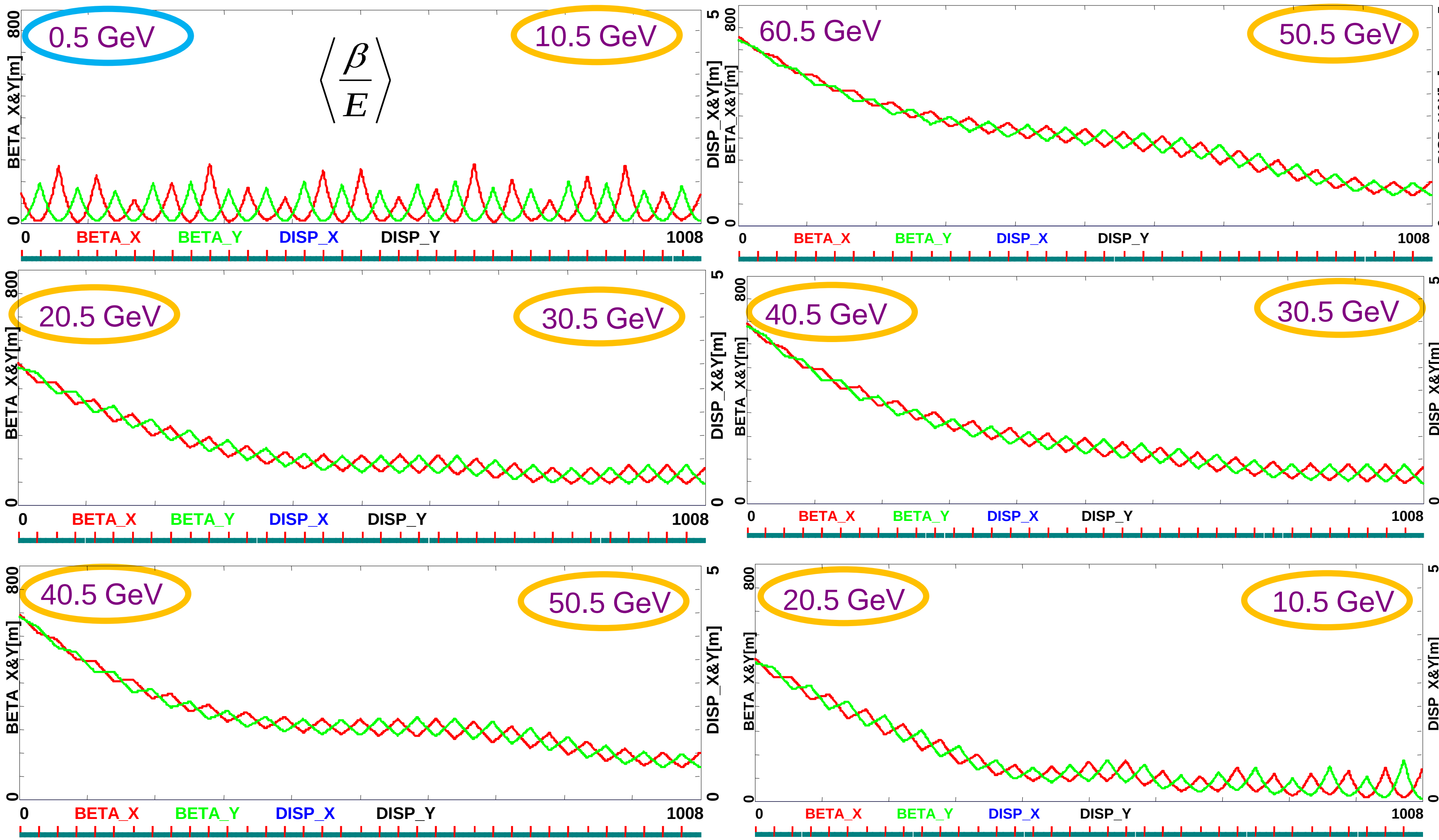
18 FODO cells (18   2   16 = 576 RF cavities)

Linac 3 (Linac 1, pass 2) – Optics

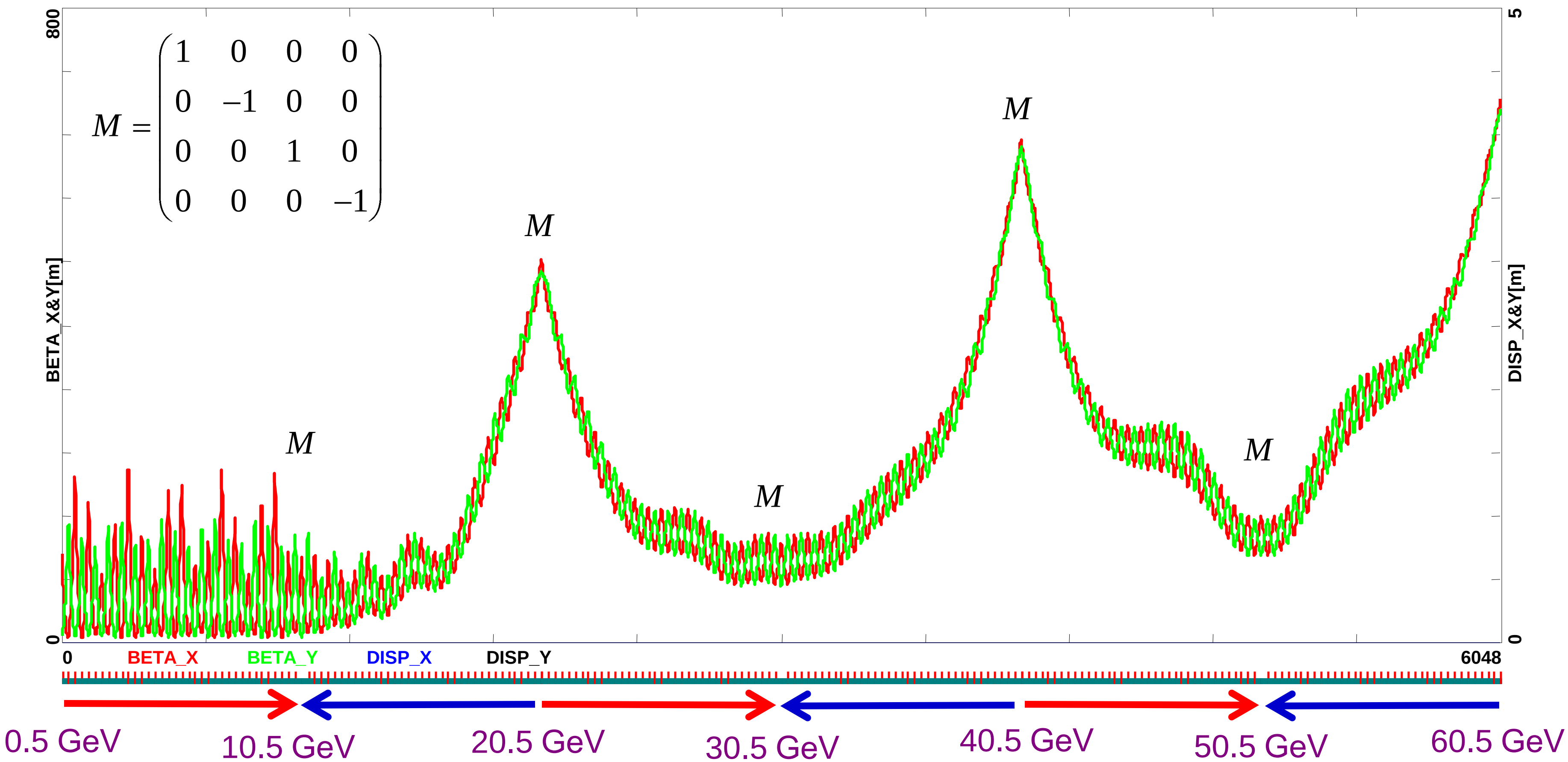




Linac 1 – multi-pass + ER Optics

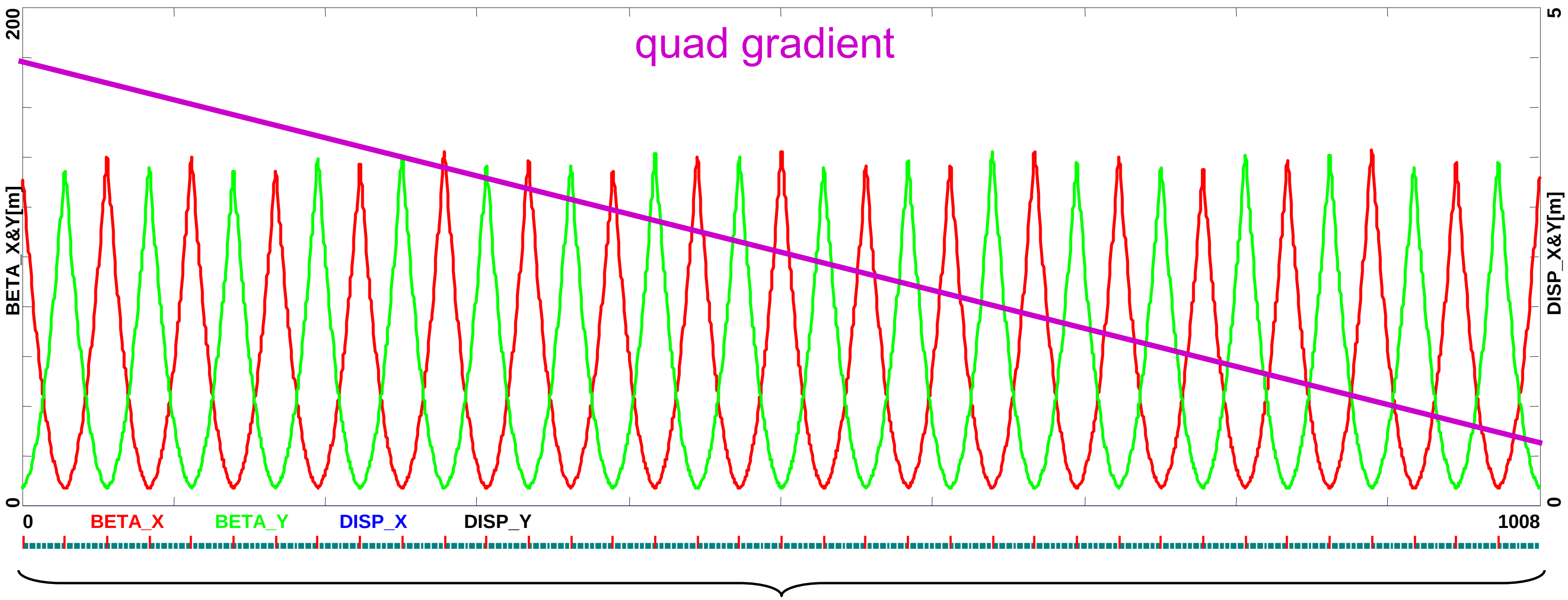


Linac 1 – Multi-pass ER Optics



Linac 2 – Focusing profile

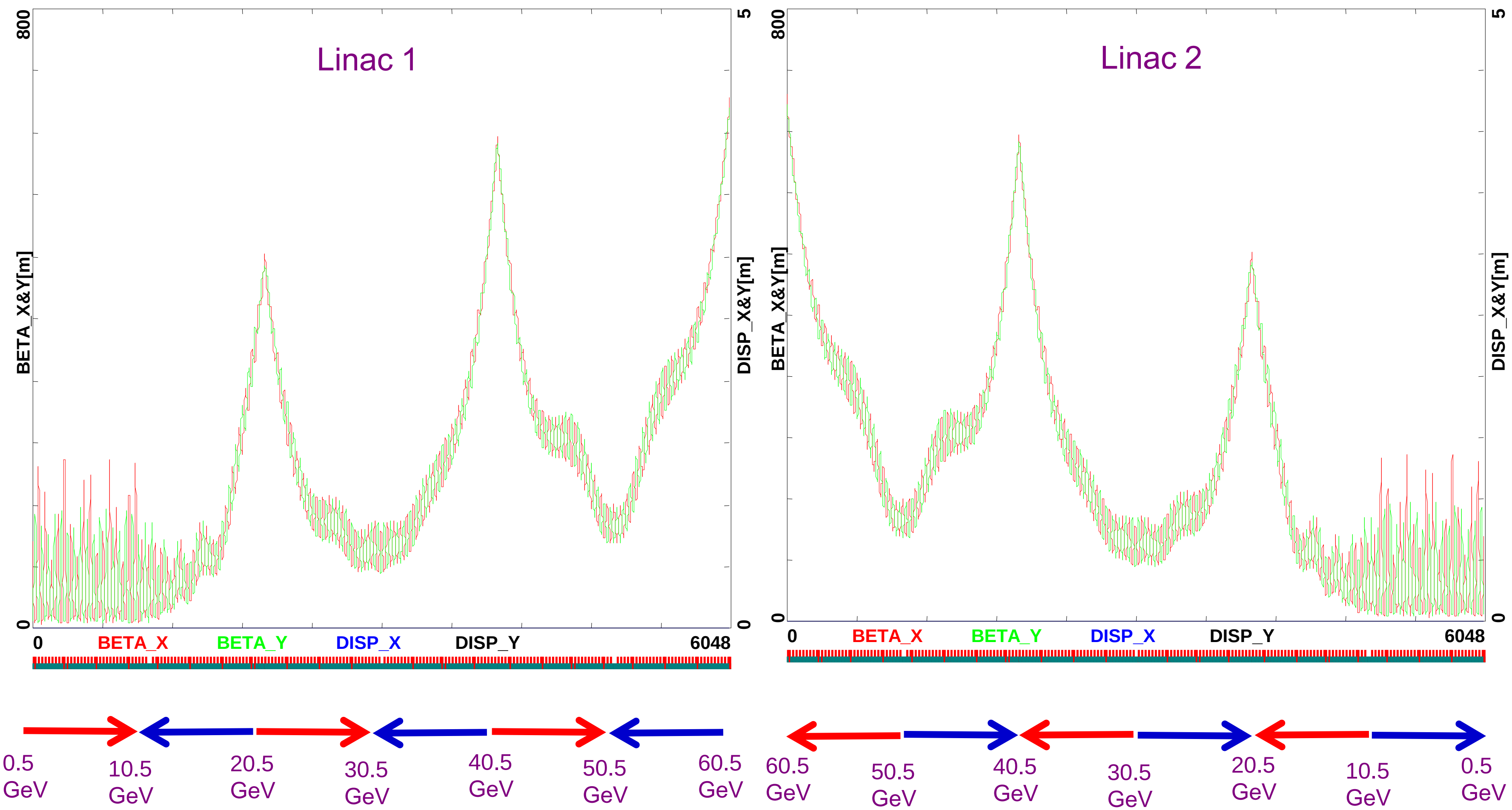
E = 10.5 – 0.5 GeV (ER)



18 FODO cells (18 2 16 = 576 RF cavities)

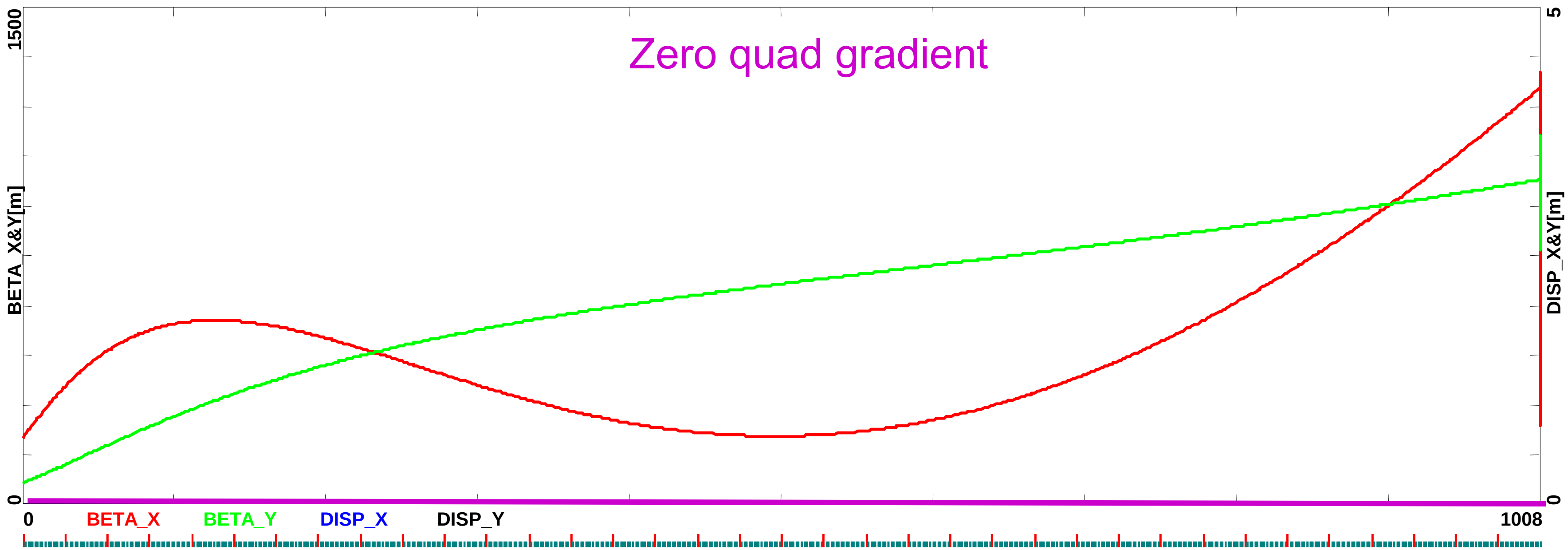
Linac 2 multi-pass optics with ER – mirror symmetric to Linac 1

Linac 1 and 2 – Multi-pass ER Optics



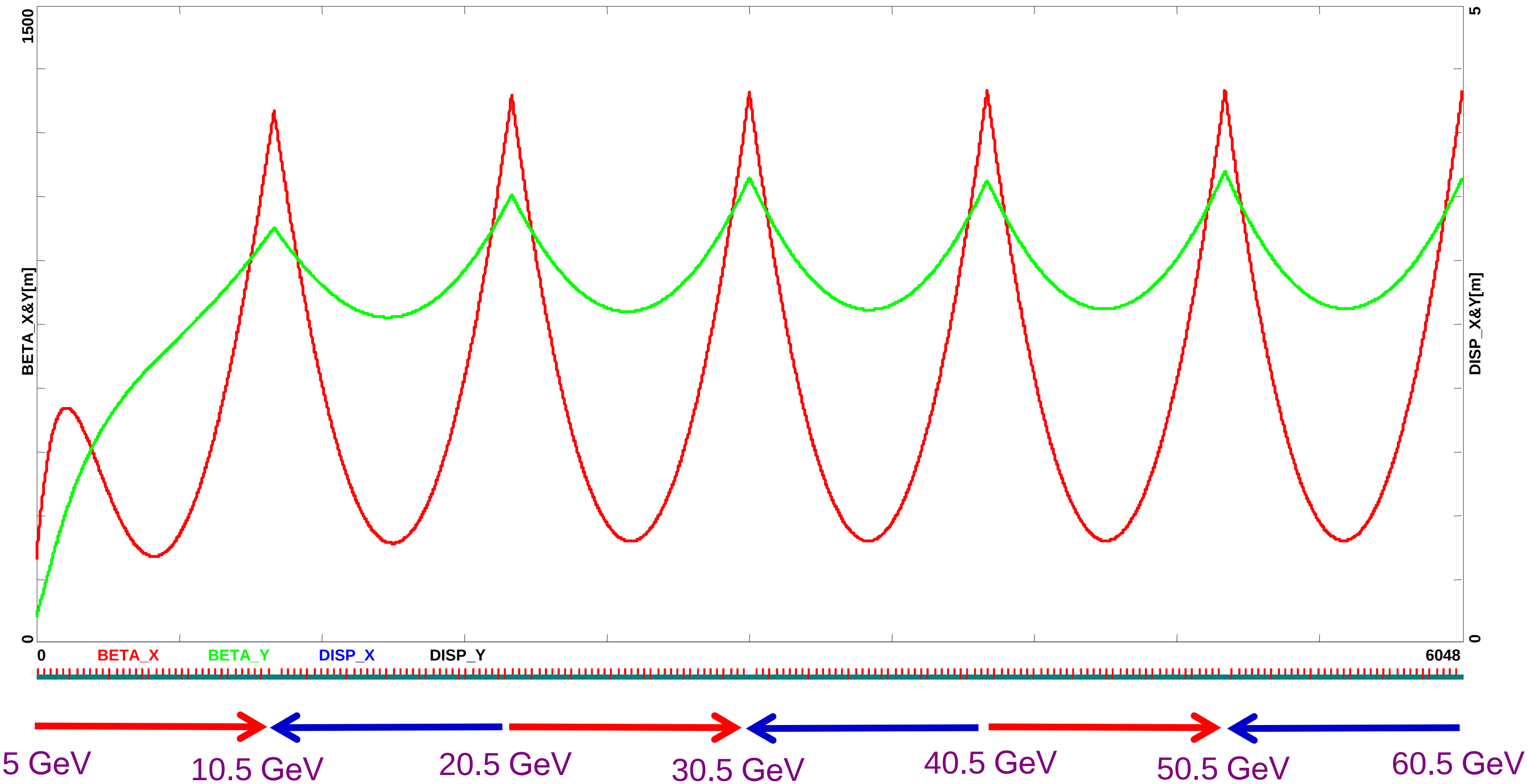
Linac 1 – ‘NO quad’ focusing profile

E = 0.5 – 10.5 GeV



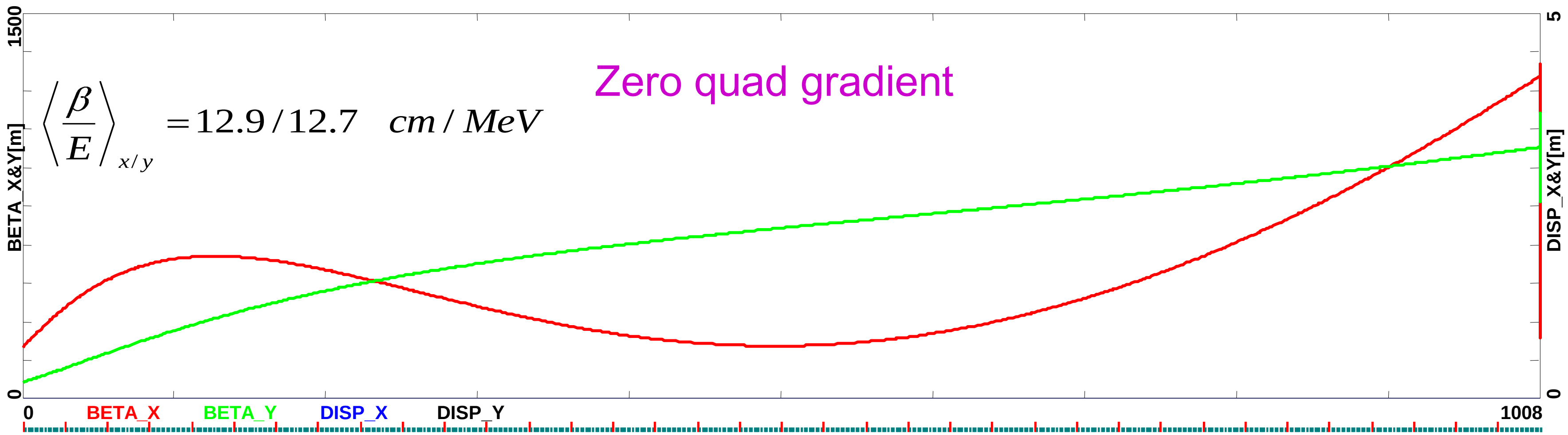
18 FODO cells (18 2 16 = 576 RF cavities)

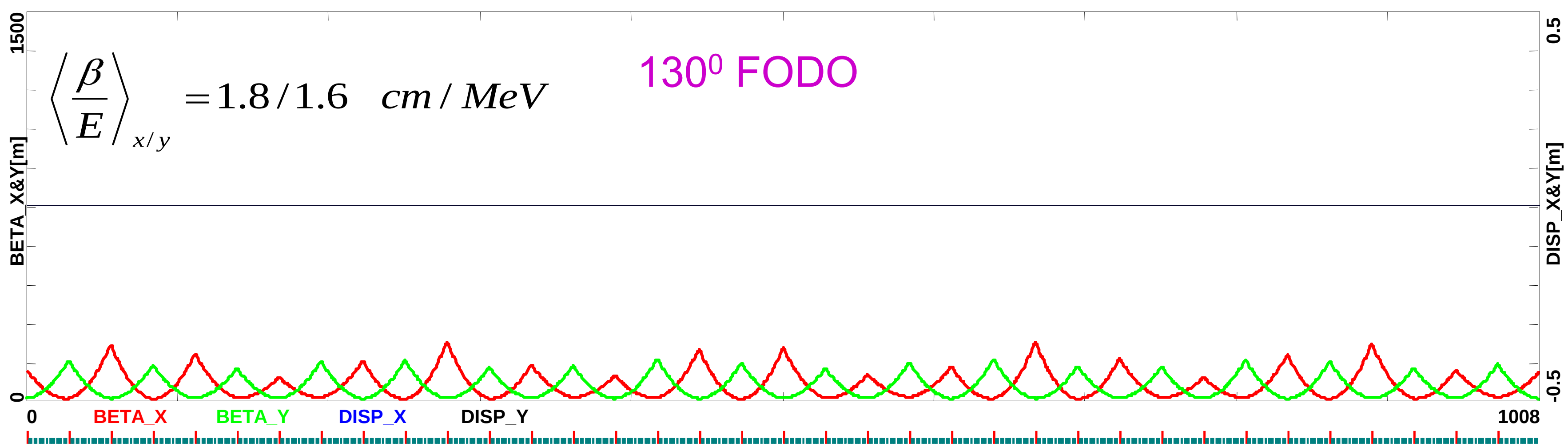
Linac 1 'NO quad' – Multi-pass ER Optics



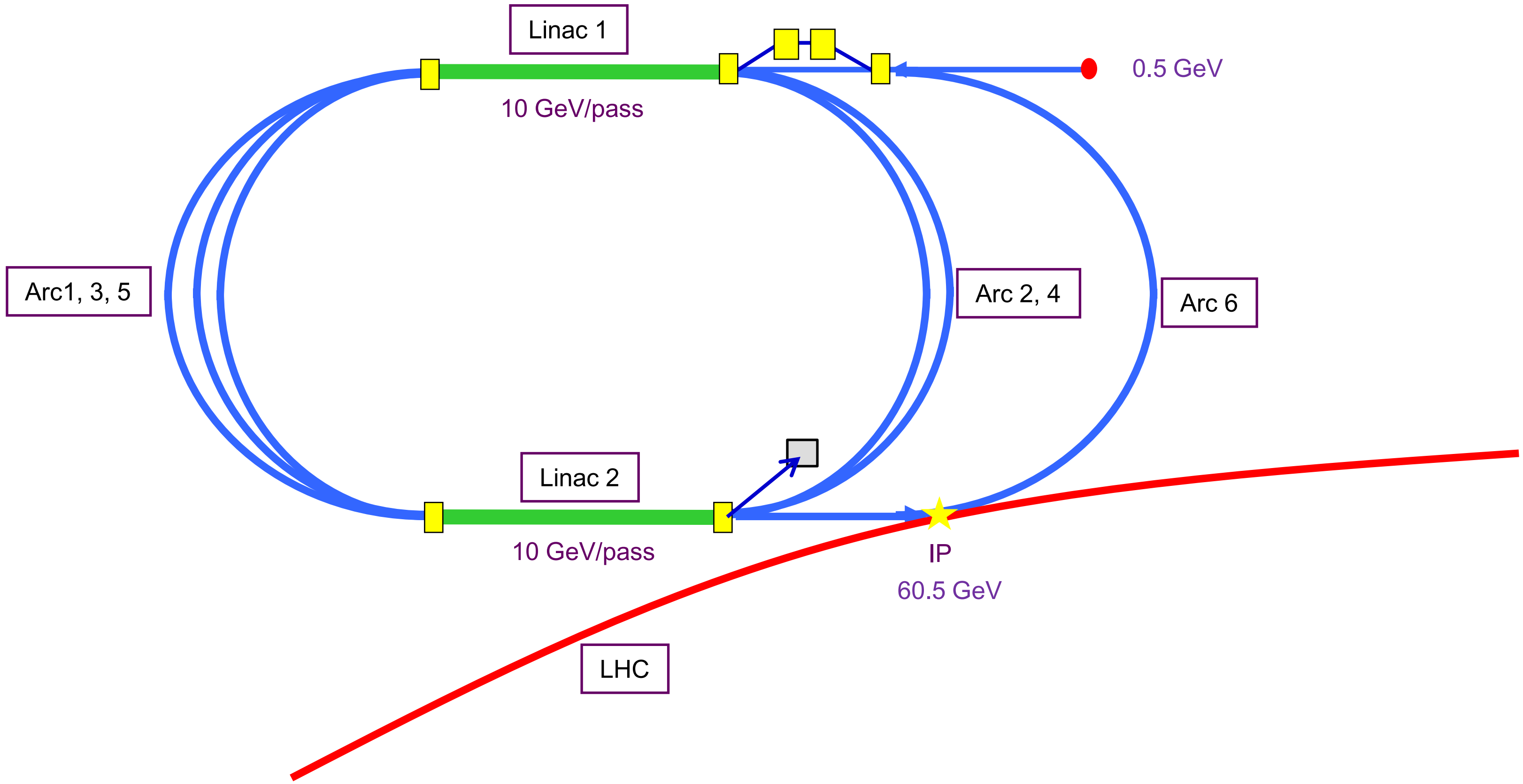
‘NO quad’ vs 130^0 FODO

E = 0.5 – 10.5 GeV



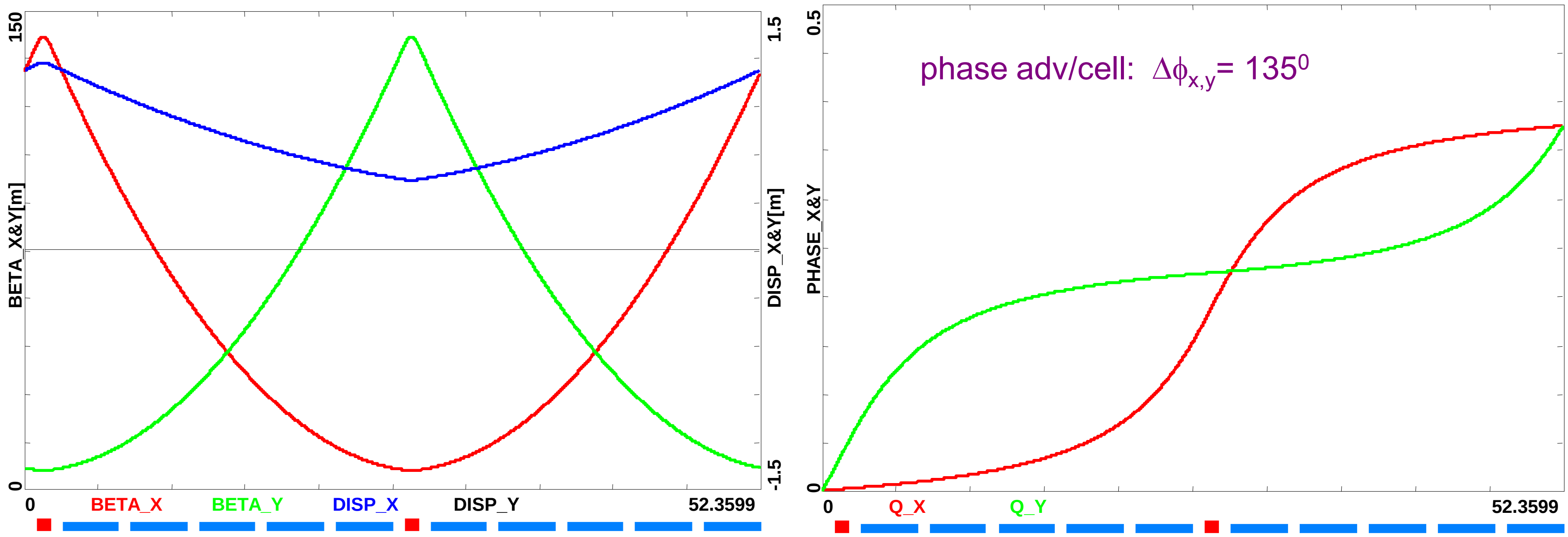


Arcs – LHeC Recirculator with ER



Arc Optics - 135^0 FODO Cell

50.5 GeV



Arc dipoles:

$Lb=400 cm

$B=2.2 kGauss

$ang=0.3 deg.

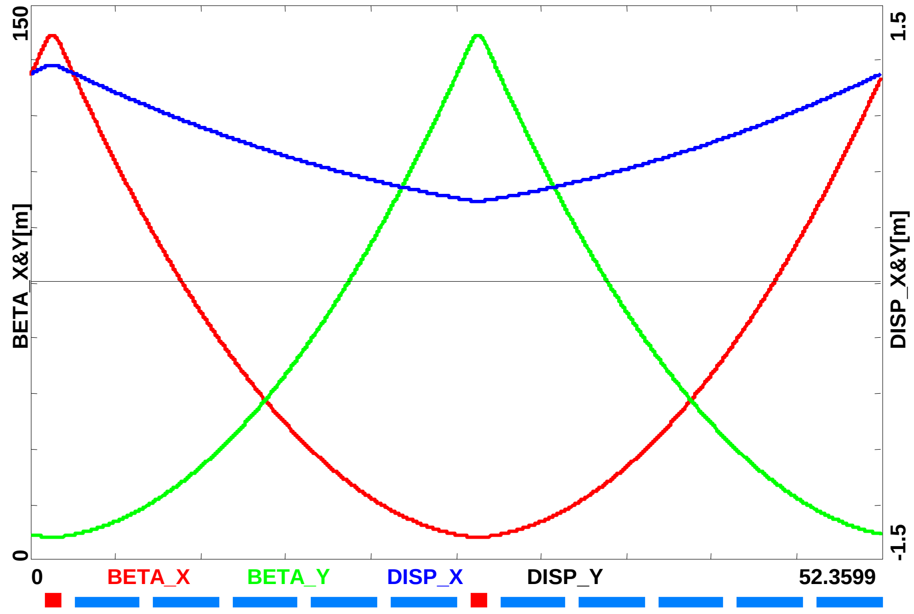
$rho = 764 meter

Arc quadrupoles

$Lq=100 cm

$G= 1.2 kG/cm

135^0 FODO Cell



Emittance dispersion

⟨H⟩ averaged over bends

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

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

Momentum compaction

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

$$M_{56} = 3.19 \times 10^{-2} \text{ m}$$

Quasi-isochronous condition – Arc into Linac

Momentum compaction

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

$$\Delta C = -M_{56} \frac{\Delta p}{p}$$

$$\Delta \phi_{RF} = \frac{360 \times \Delta C}{\lambda_{RF}} = -\frac{360}{\lambda_{RF}} N_{cell} M_{56}^{cell} \frac{\Delta p}{p}$$

$$\frac{\Delta p}{p} = 3 \times 10^{-4}$$

$$\lambda_{RF} = 0.428 \text{ m}$$

$$N_{cell} = 60$$

⇩

$$M_{56}^{FODO} = 3.19 \times 10^{-2} m$$

$$\Delta \phi_{RF} = 0.5 \deg$$

Emittance growth due to quantum excitations

$$\Delta\varepsilon^N = \frac{2}{3} C_q\, r_0\, \gamma^6 I_5$$

$$C_q = \frac{55}{32\sqrt{3}} \frac{\hbar c}{mc^2} = 3.8319 \times 10^{-13}\ \mathrm{m},$$

$$r_0 = 2.818 \times 10^{-15}\ \mathrm{m},$$

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

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

$$total\ bend\ of\ the\ arc:\quad \theta \in \ 0, 2\pi$$

$$\Delta\varepsilon^N = \frac{2}{3} C_q\, r_0\, \gamma^6 \langle H \rangle \frac{\theta}{\rho^2}$$

$$for\ 180^0\ arc:\quad \theta = \pi$$

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

$$at\ 50.5\, GeV \Rightarrow$$

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

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

Momentum spread due to quantum excitations

$$\frac{\Delta\sigma_E^2}{E^2} = \frac{55\alpha}{48\sqrt{3}}\left(\frac{\hbar c}{mc^2}\right)^2 \gamma^5 \int_0^L \frac{1}{\rho^3}\,ds$$

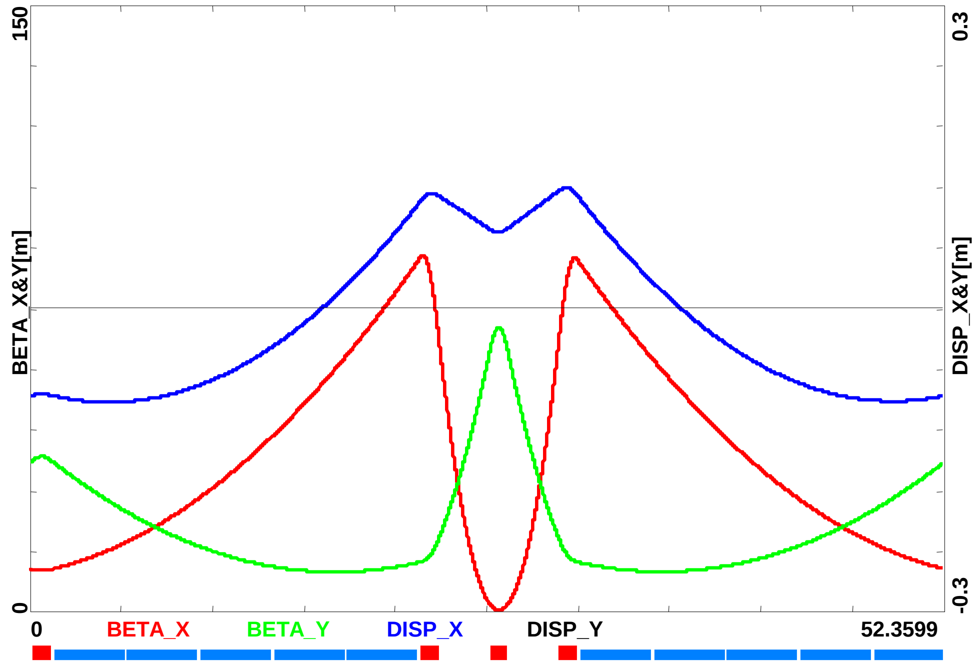
$$\int_0^L \frac{1}{|\rho|^3}\,ds = \frac{\theta}{\rho^2},$$

$$total\ bend\ of\ the\ arc: \quad \theta \in \ 0, 2\pi$$

$$\frac{\Delta\sigma_E^2}{E^2} = \frac{55\alpha}{48\sqrt{3}}\left(\frac{\hbar c}{mc^2}\right)^2 \gamma^5 \frac{\theta}{\rho^2}$$

$$for\ 180^0\ arc: \quad \theta = \pi$$

Quasi-isochronous FMC Cell



Emittance dispersion

⟨H⟩ avereged over bends

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

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

factor of 2.5 smaller than FODO

Momentum compaction

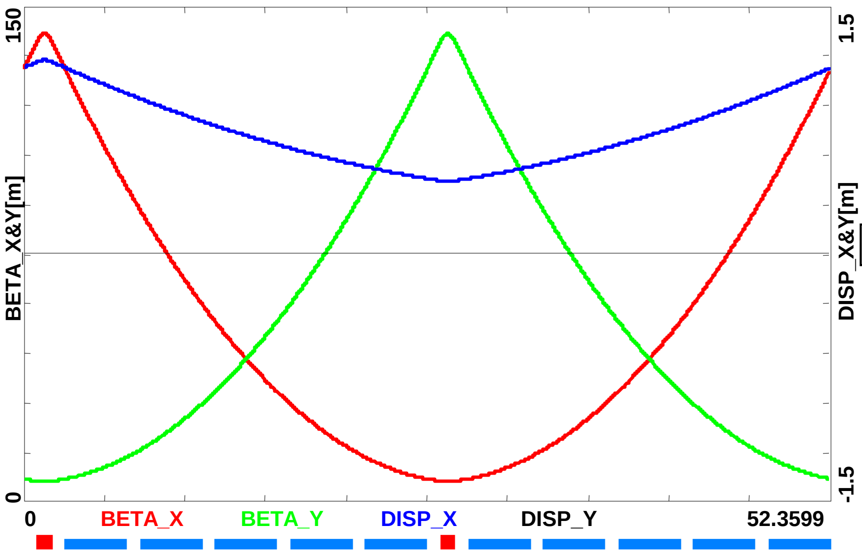
$$M_{56} = -\int \frac{D}{\rho}\, ds = -\theta_{bend} \langle D \rangle$$

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

factor of 27 smaller than FODO

Arc Optics – 135^0 FODO vs FMC Cell

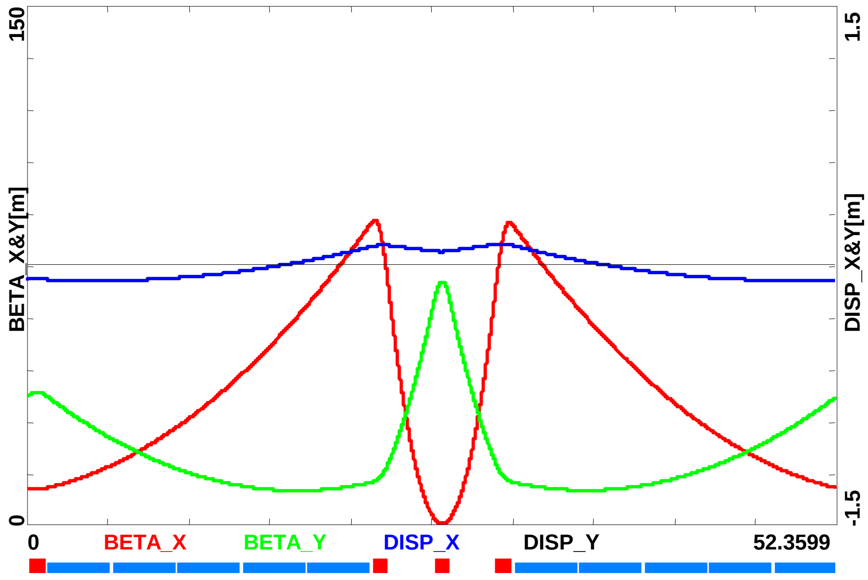
135^0 FODO



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

$$M_{56} = 3.19 \times 10^{-2}\ \mathrm{m}$$

FMC Cell



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

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

Quasi-isochronous condition – Arc into Linac

Momentum compaction

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

$$\Delta C = -M_{56} \frac{\Delta p}{p}$$

$$\Delta\phi_{RF} = \frac{360 \times \Delta C}{\lambda_{RF}} = -\frac{360}{\lambda_{RF}} N_{cell} M_{56}^{cell} \frac{\Delta p}{p}$$

$$\frac{\Delta p}{p} = 3\times 10^{-4}$$

$$\lambda_{RF} = 0.428 \text{ m}$$

$$N_{cell} = 60$$

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

$$\Delta\phi_{RF} = 0.018 \deg$$

factor of 27 smaller than FODO

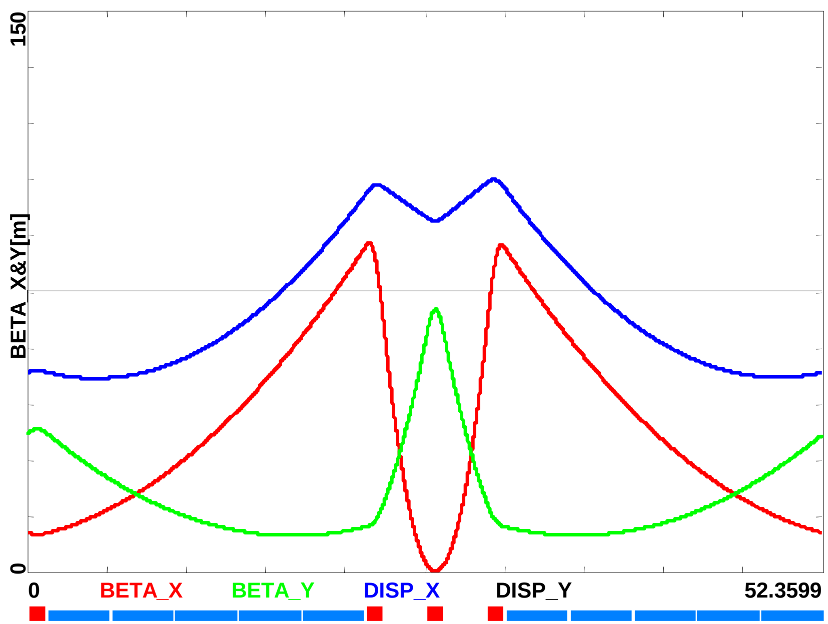
$$M_{56}^{FODO} = 3.19\times 10^{-2} m$$

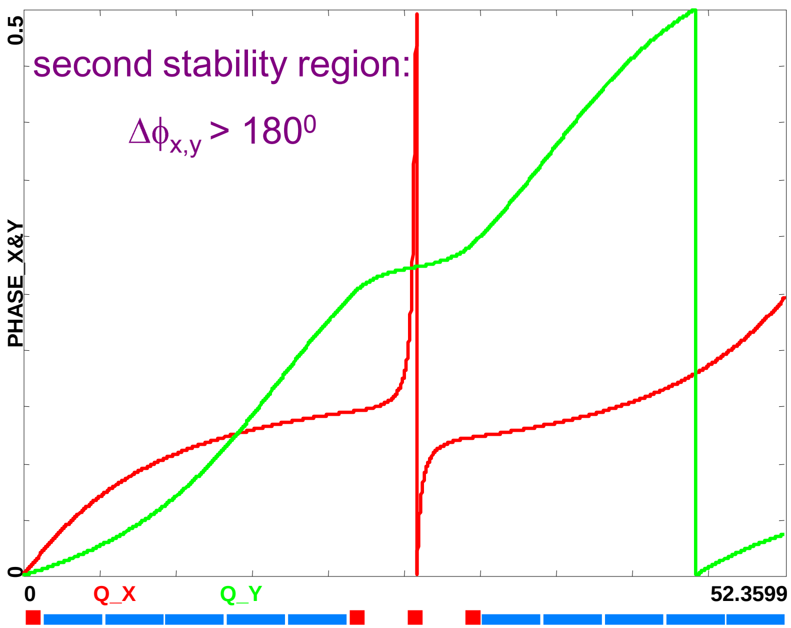
$$\Delta\phi_{RF} = 0.5 \deg$$

FMC 'Imaginary γ_t' Cell

50.5 GeV

60×





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

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

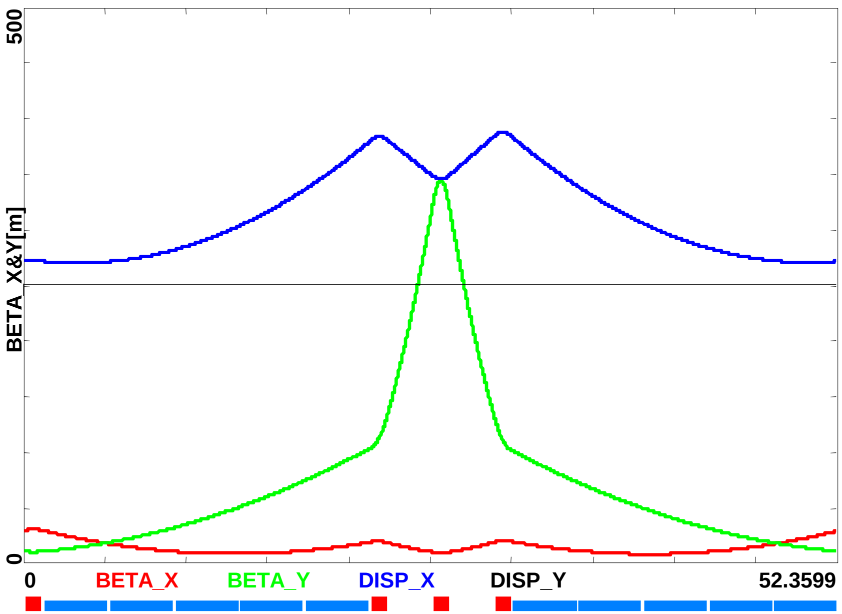
Arc dipoles:
$Lb=400 cm
$B=2.2 kGauss
$ang=0.3 deg.
$rho = 764 meter

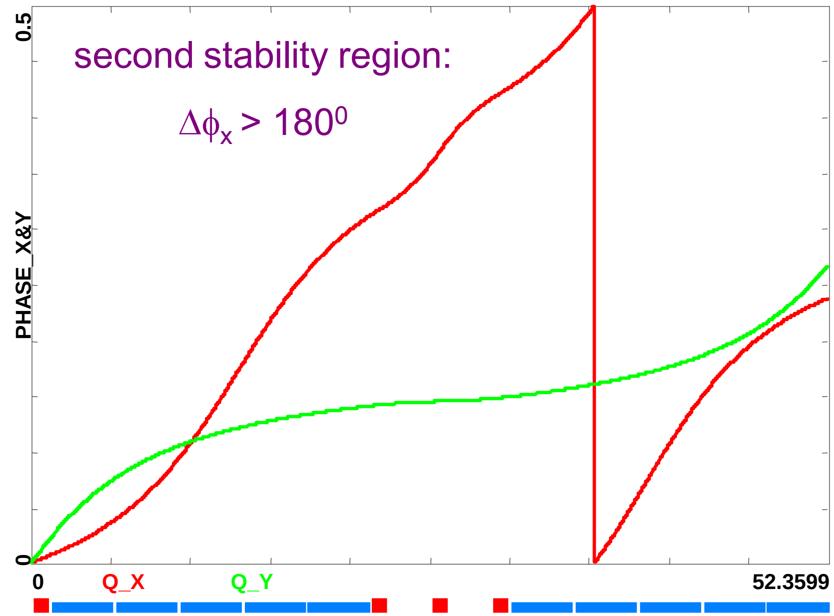
Arc quadrupoles
$G0= -1.53 kG/cm
$G1= 5.06 kG/cm
$G2= -5.32 kG/cm
$G3= 5.07 kG/cm

FMC ‘Double Bend Achromat’ Cell

50.5 GeV

60×





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

$$M_{56} = 5.6 \times 10^{-3}\ m$$

Arc dipoles:

$Lb=400 cm

$B=2.2 kGauss

$ang=0.3 deg.

$rho = 764 meter

Arc quadrupoles

$G0= 2.05 kG/cm

$G1= 2.90 kG/cm

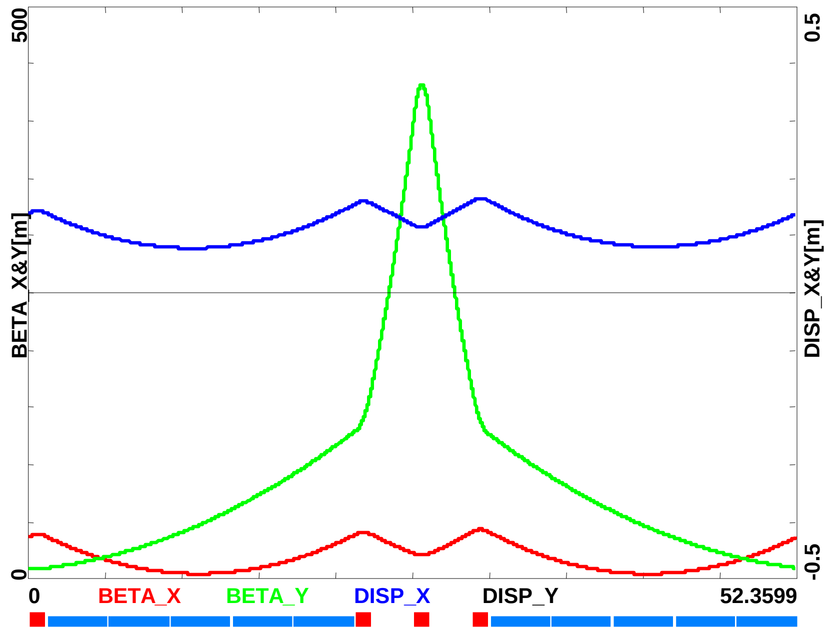
$G2= -4.07 kG/cm

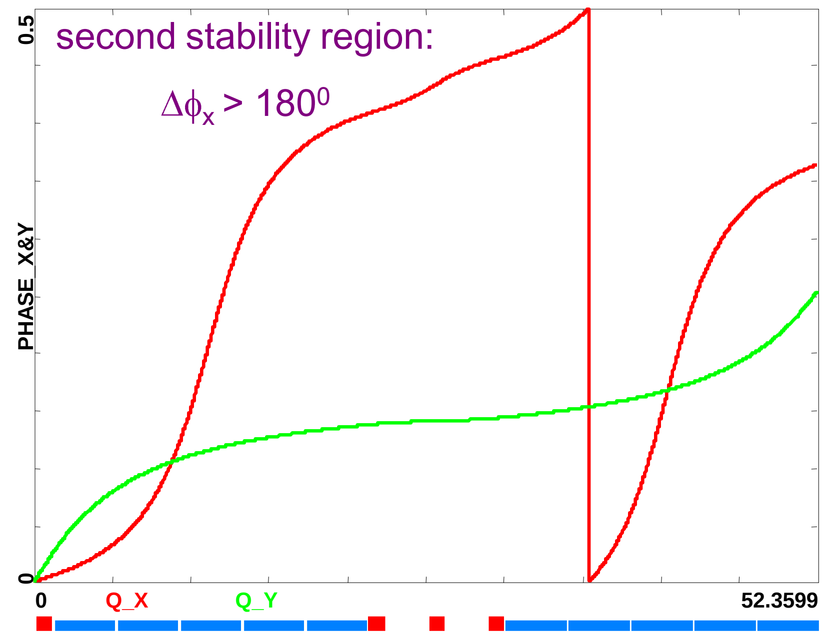
$G3= 2.97 kG/cm

FMC ‘Theoretical Emittance Minimum’ Cell

50.5 GeV

60×





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

$$M_{56} = 5.7 \times 10^{-3}\ m$$

Arc dipoles:

$Lb=400 cm

$B=2.2 kGauss

$ang=0.3 deg.

$rho = 764 meter

Arc quadrupoles

$G0= 2.92 kG/cm

$G1= 2.89 kG/cm

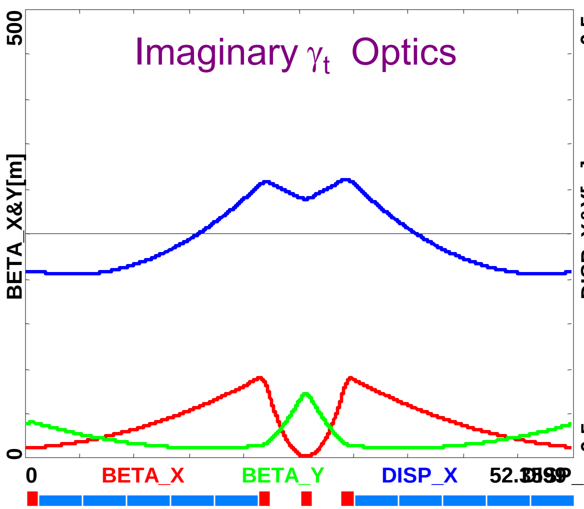
$G2= -4.08 kG/cm

$G3= 2.97 kG/cm

Arc Optics – Cumulative emittance growth

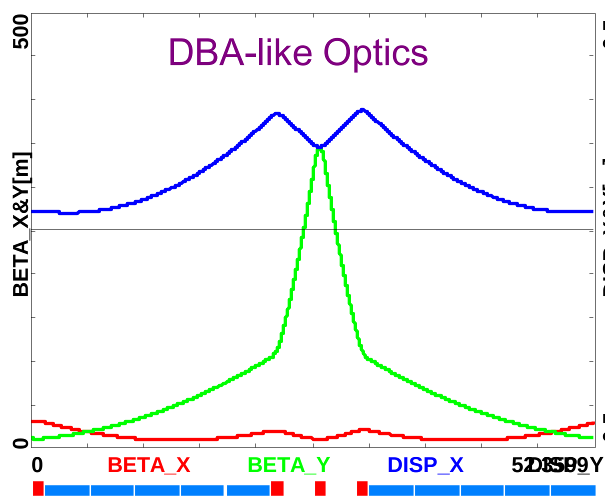
$$\Delta\varepsilon^N = \frac{2}{3} C_q \, r_0 \, \gamma^6 \langle H \rangle \frac{\pi}{\rho^2}, \qquad H = \gamma D^2 + 2\alpha D D' + \beta D'^2$$

Arc 1 , Arc2



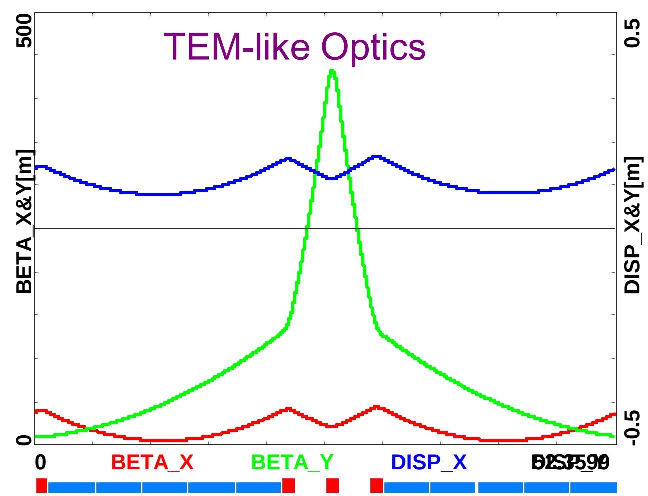
$\langle H \rangle = 8.8 \times 10^{-3}\ m$

Arc 3



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

Arc 4 , Arc5, Arc 6



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

factor of 18 smaller than FODO

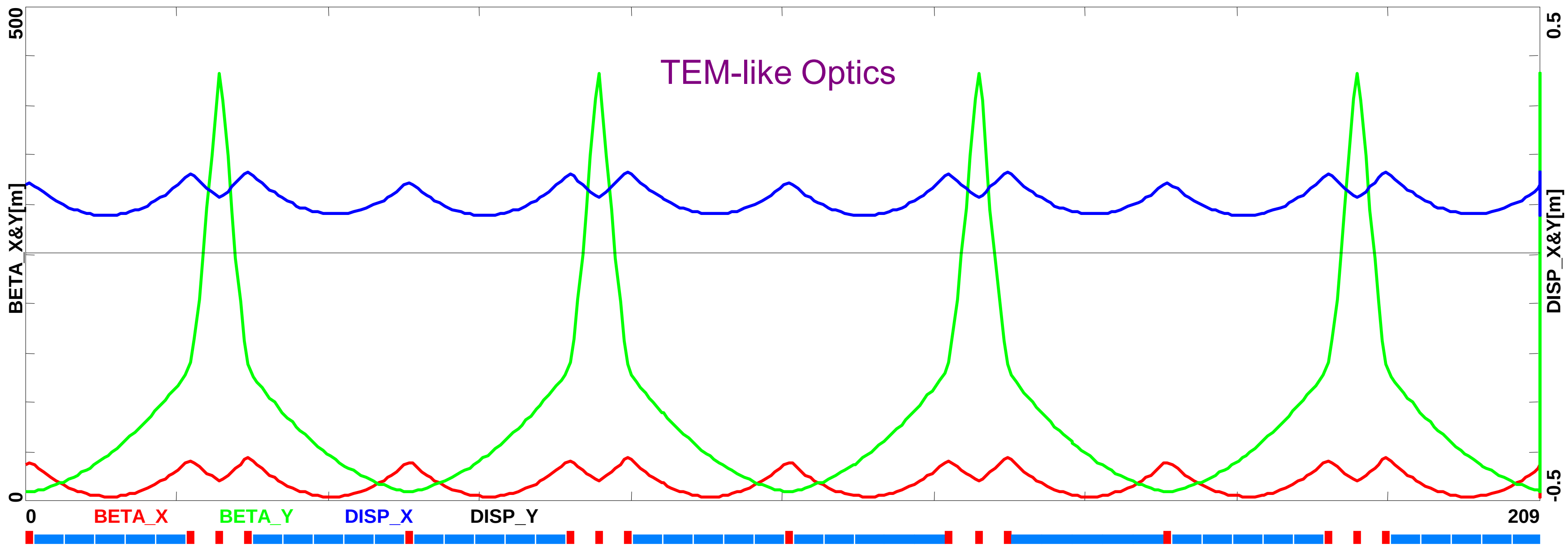
total emittance increase (all 5 arcs): $\Delta\varepsilon_x^N = 1.25 \times 4.5\ \mu\text{m rad} = 5.6\ \mu\text{m rad}$

Highest Arc Optics – Emittance growth

$$\Delta\varepsilon^N = \frac{2}{3} C_q\, r_0\, \gamma^6 \langle H \rangle \frac{\pi}{\rho^2}$$

50.5 GeV, $\gamma = 10^5$

$$\frac{\Delta\sigma_E^2}{E^2} = \frac{55\alpha}{48\sqrt{3}} \left(\frac{\hbar c}{mc^2}\right)^2 \gamma^5 \frac{\theta}{\rho^2}$$



emittance increase (last arc): $\Delta\varepsilon_x^N = 4.5\ \mu\text{m rad}$

RMS fluctuations of $\Delta E/E0 = 2.7 \times 10^{-4}$

total emittance increase (all 6 arcs): $\Delta\varepsilon_x^N = 1.25 \times 4.5\ \mu\text{m rad} = 5.6\ \mu\text{m rad}$

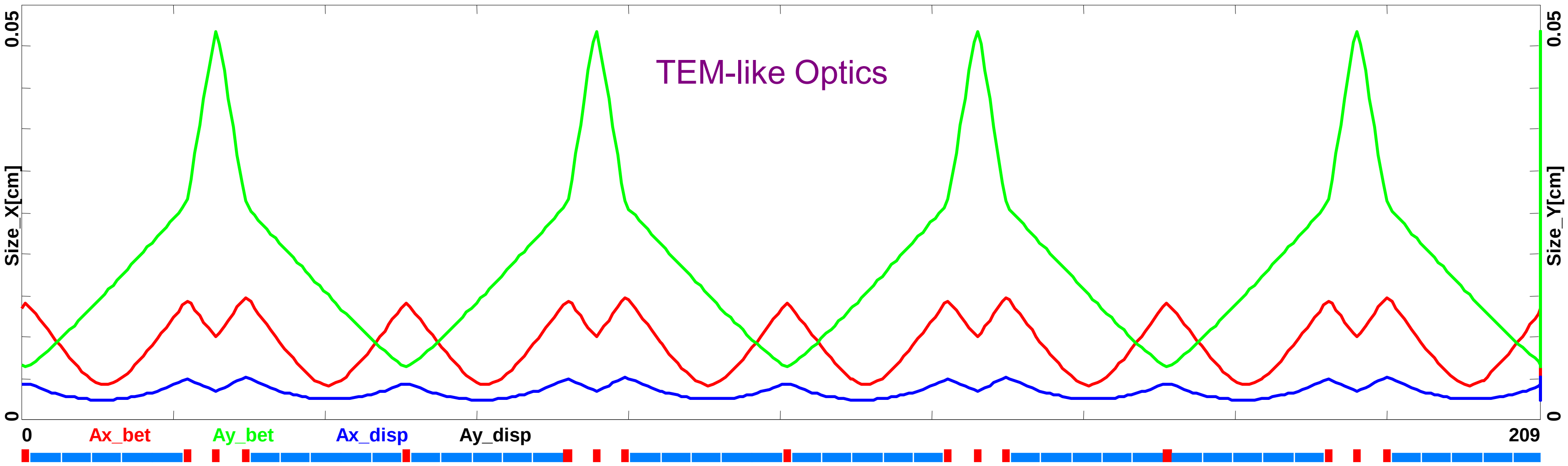
Arc 5 – Beam envelopes, Magnet apertures

Last pass before IR, 50.5 GeV

ε_x^N = 50 μm rad

$\Delta p/p$= 2.7 × 10^{-4}

12 × σ_{RMS} (beam stay clear) ~ 48 mm



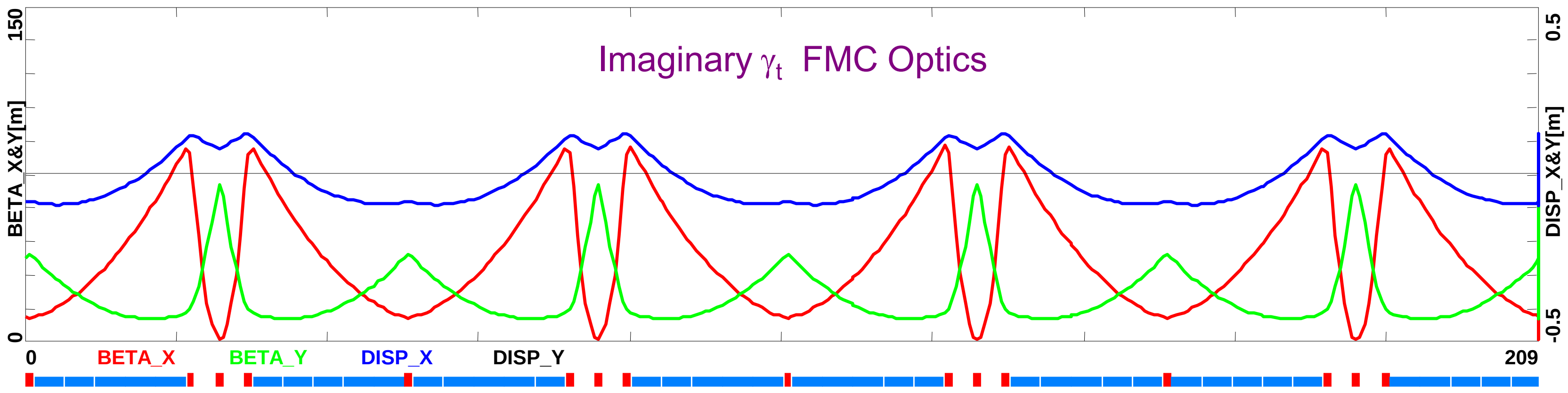
Arc 1 – Beam envelopes, Magnet apertures

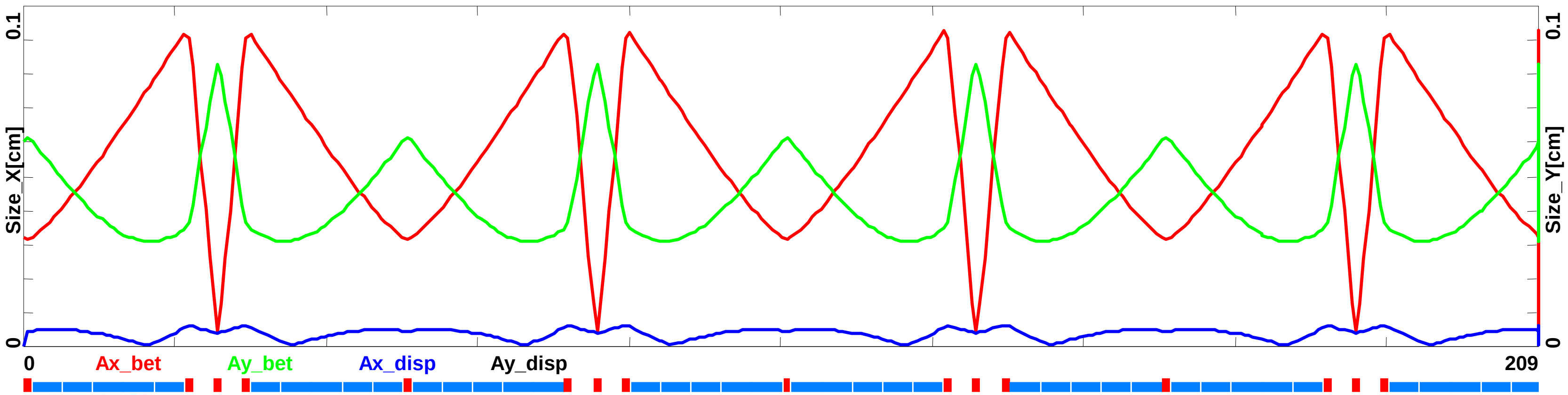
ε_x^N = 200 μm rad

$\Delta p/p$= 5 × 10^{-4}

ER lowest pass, 10.5 GeV

12 × σ_{RMS} (beam stay clear) ~ 96 mm





Conclusions

- Proof-of-existence ER RLAs: Jlab FEL, CEBAF-ER
- Solution for Multi-pass linac Optics in ER mode
  - Choice of linac Optics - 130^0 FODO
  - Linear lattice: 3-pass 'up' + 3-pass 'down'
  - Optimized quad gradient profile in the linacs (single-pass wake-field effects)
- Arc-to-Linac Synchronization - Momentum compaction
  - Quasi-isochronous lattices
  - Choice of Arc Optics - Flexible Momentum Compaction
- Arc Optics Choice - Emittance preserving lattices
  - Arcs based on variations of FMC optics (Im. γ_t, DBA, TEM)
- Acceptable level of emittance dilution & momentum spread
  - Magnet apertures