MEIC

DESIGN STUDEIS FOR MEIC: Medium Energy Electron -Ion Collider at Jlab

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MEIC

Outline

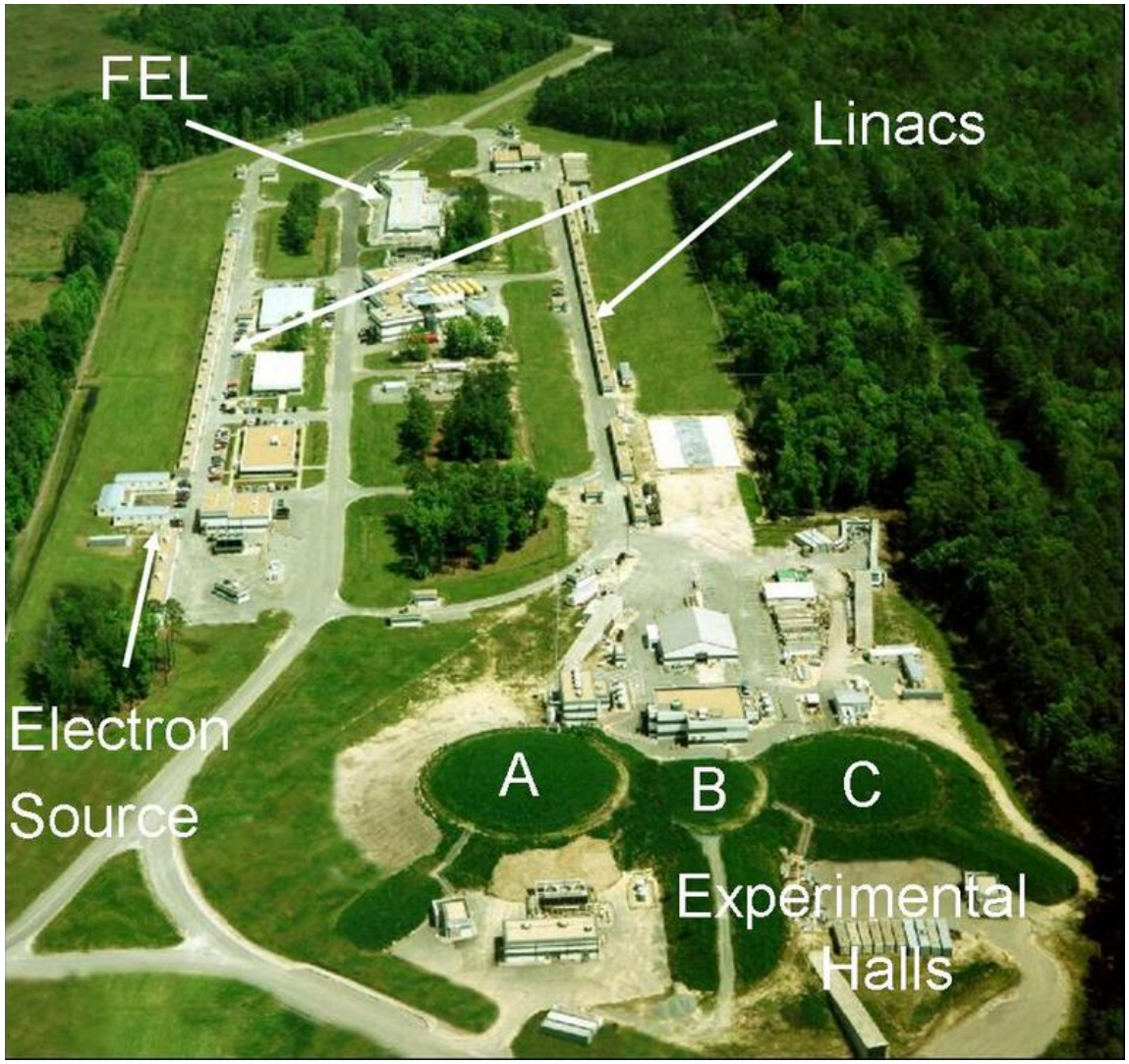
- Introduction to the MEIC
- Machine Design
- Electron Ring
- Chromaticity Correction
- Universal spin rotator
- Summary

MEIC

ELIC: JLAB's Future Nuclear Science Program

- JLab has been developing a design of an electron-ion collider (ELIC) based on the CEBAF recirculating SRF linac for nearly a decade.
- Requirements of the future nuclear science program drives ELIC design efforts to focus on achieving
  - ultra high luminosity per detector (up to 10^{35} at high energy) in multiple detectors
  - very high polarization (>80%) for both electrons & light ions
- **M**edium-energy **E**lectron **I**on **C**ollider (MEIC) project.
  - A stage to be a good compromise between science, technology and project cost
    - Energy range is up to 60 GeV ions and 11 GeV electrons
  - A well-defined upgrade capability to higher energies is maintained
  - High luminosity & high polarization continue to be the design drivers

Jefferson Lab Now



Luminosity

General luminosity formula for any e-p collider

$$L = \frac{N_e N_p N_B f_{rev}}{2\pi\sqrt{{\sigma_{xp}}^2 + {\sigma_{xe}}^2}\sqrt{{\sigma_{yp}}^2 + {\sigma_{ye}}^2}}$$

N_p (N_e) Number of protons (electrons) per bunch
N_B Number of bunches
f_{rev} revolution frequency
σ_p (σ_e) rms beam sizes

ELIC considerations

- Luminosity is dominated by proton beam parameters
  - Minimum achievable ε (space-charge & IBS fundamental limits –cooling solution ?)
  - Minimum achievable β^*
    - limited by FF quad aperture at β_{max} (LHC magnet aperture 70 mm)
    - ability to correct chromaticity specially with 7 m focal length)
    - Hour glass effect - Bunch length ($\beta^* \sim \sigma_s$)

Electron FF parameters are then matched to achieve values of proton beam ($\sigma^*_{p,x} = \sigma^*_{e,x}$ & $\sigma^*_{p,y} = \sigma^*_{e,y}$)

Optimum conditions

1. Beam cross sections of proton & leptons have to match to limit the nonlinearity of the beam-beam interaction

   $\sigma^*_{p,x} = \sigma^*_{e,x}$ $\sigma^*_{p,y} = \sigma^*_{e,y}$

2. The total beam current of lepton beam is limited by the available rf power

   $N_e = I_e/(e \,.\, N_B \,.\, f_{rev})$

3. N_p limited by space charge effects in the injector chain.
4. The beam size at IP limited by β^{max} of protons at IR FF quads

$$L = \frac{I_e N_p \gamma_p}{4\pi e \sqrt{\beta^*_{xp}\beta^*_{yp}}\sqrt{\epsilon_{xN}\epsilon_{yN}}}$$

Luminosity beam-beam tune-shift relationship

- **Linear beam-beam tune shift**

$$\xi_x^i = \frac{N_{\bar{i}} r_i}{2\pi\gamma_i} \frac{1}{\varepsilon_x^i \left(1+\sigma_y/\sigma_x\right)} \qquad \xi_y^i = \frac{N_{\bar{i}} r_i}{2\pi\gamma_i} \frac{1}{\varepsilon_y^i \left(1+\sigma_y/\sigma_x\right)\left(\sigma_x/\sigma_y\right)}$$

- Express Luminosity in terms of the (larger!) vertical tune shift (*i* either 1 or 2)

$$\mathbf{L} = \frac{f\, N_i \xi_y^i \gamma_i}{2 r_i \beta^*}\left(1+\sigma_y/\sigma_x\right) = \frac{I_i}{e}\frac{\xi_y^i \gamma_i}{2 r_i \beta^*}\left(1+\sigma_y/\sigma_x\right)$$

- Necessary, **but not sufficient**, for self-consistent design

- Expressed in this way, and given a "known" limit to the beam-beam tune shift, the only variables to manipulate to increase luminosity are the stored current, the aspect ratio, and the β^* (beta function value at the interaction point)

- Applies to ERL-ring colliders, stored beam (ions) only

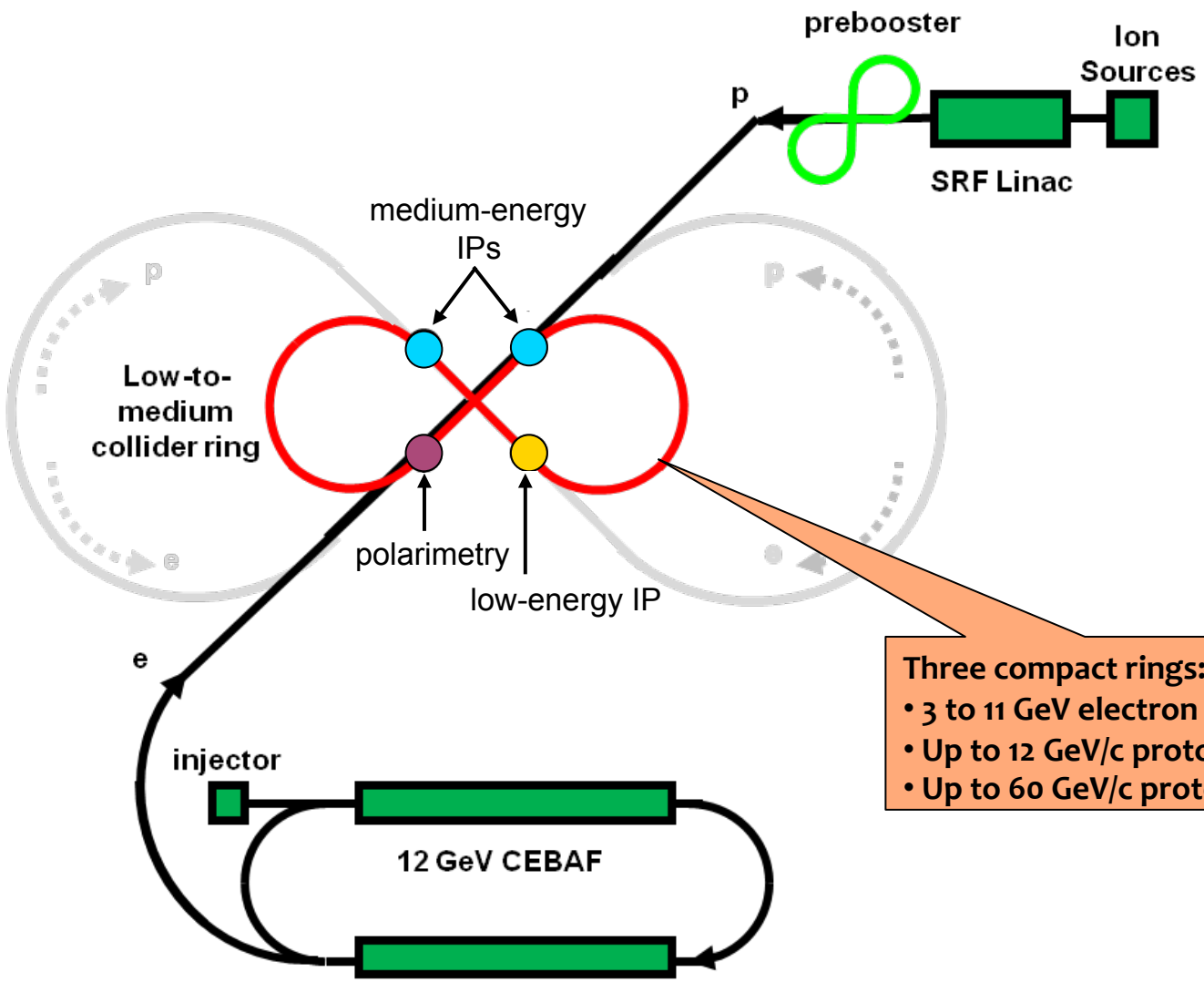
Evolution of the ELIC Design

- Energy Recovery Linac – Storage Ring (ERL-R)
- ERL with Circulator Ring – Storage Ring (CR-R)
- Back to Ring-Ring (R-R) – by taking advantage of CEBAF as full energy polarized injector
- Challenge: high current polarized electron source
  - ERL-Ring: 2.5 A
  - Circulator ring: 20 mA
  - State-of-art: 0.1 mA

- 12 GeV CEBAF Upgrade polarized source/injector already meets beam requirement of ring-ring design

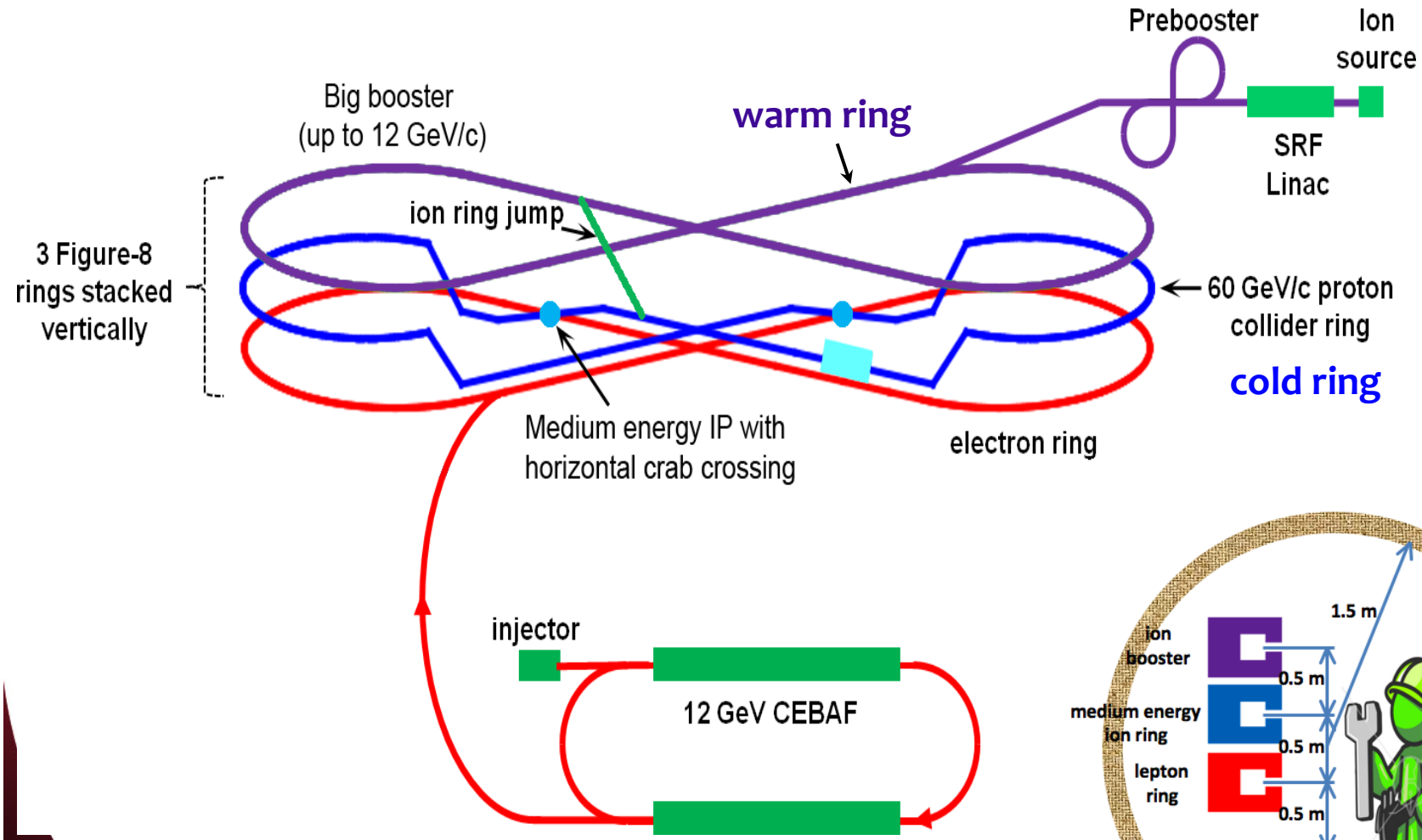
- CEBAF-based R-R design preserves high luminosity and high polarization (+polarized positrons…)

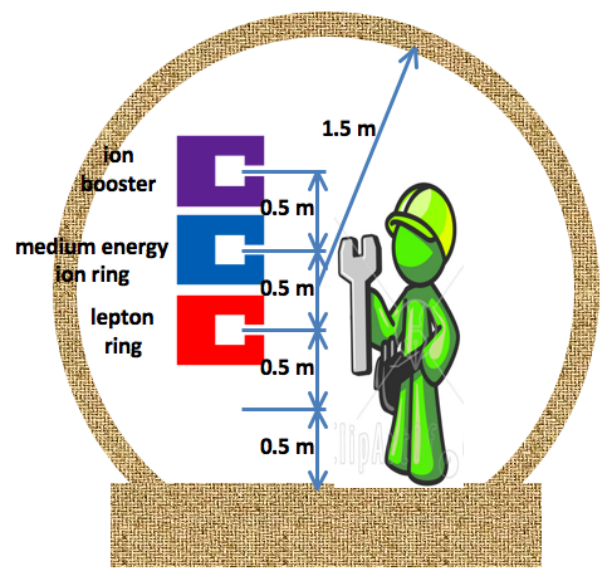
Medium Energy EIC



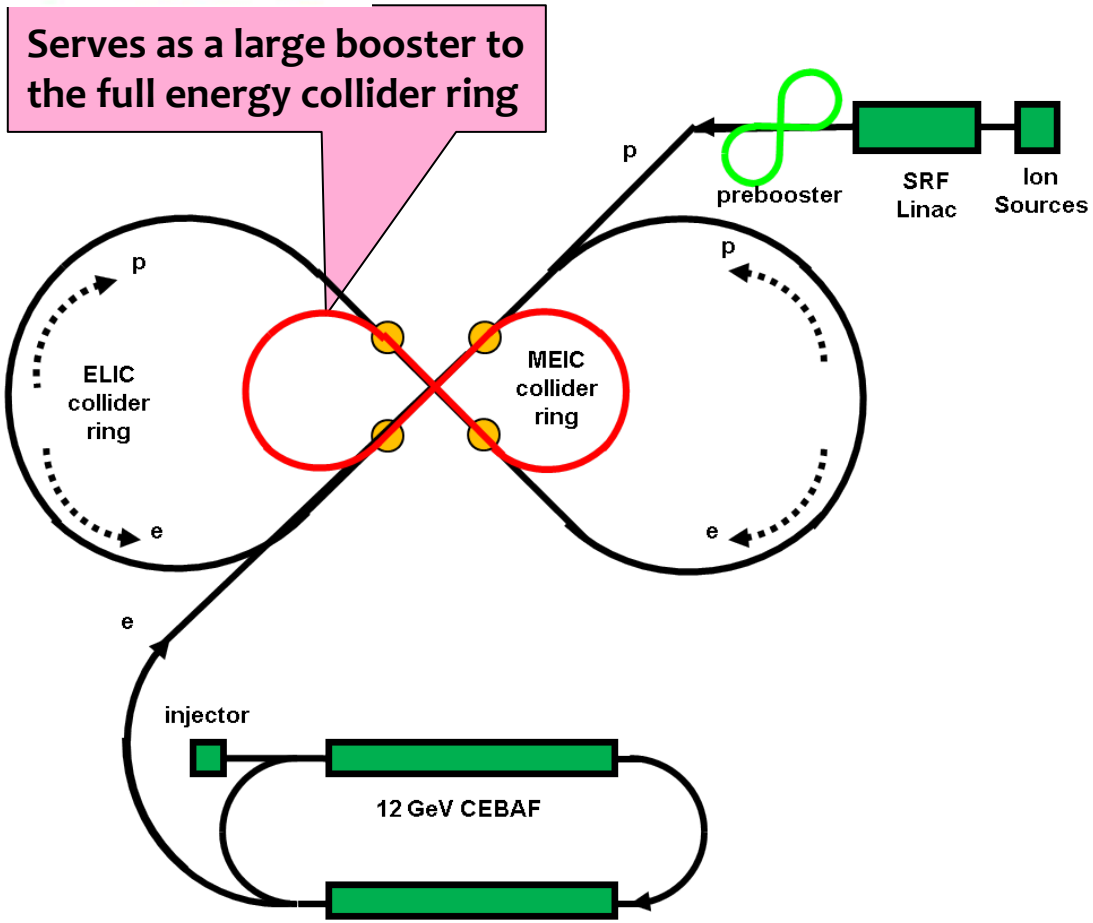
Three compact rings:
- 3 to 11 GeV electron
- Up to 12 GeV/c proton (warm)
- Up to 60 GeV/c proton (cold)

Detailed Layout

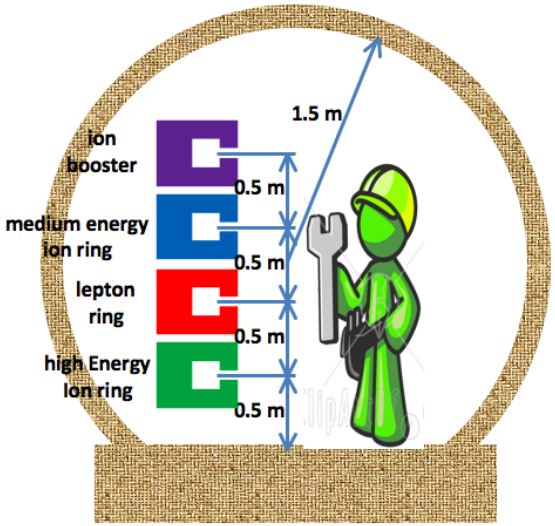




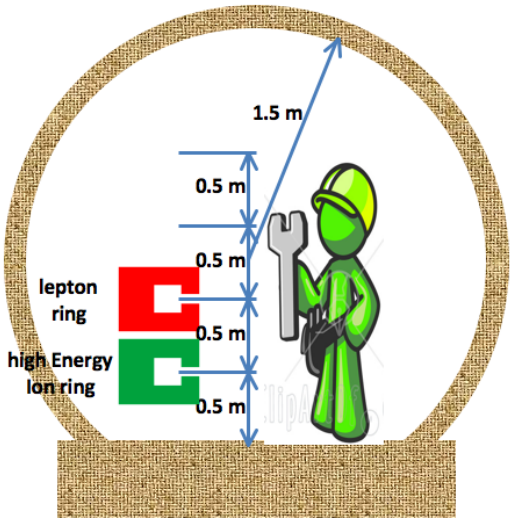
ELIC: High Energy & Staging



Straight section



Arc



Stage	Max. Energy (GeV/c)		Ring Size (m)	Ring Type		IP #
	p	e		p	e	
Medium	96	11	1000	Cold	Warm	3
High	250	20	2500	Cold	Warm	4

Ring-Ring Design Features

- Ultra high luminosity
- Polarized electrons and polarized light ions
- Up to three IPs (detectors) for high science productivity
- "*Figure-8*" ion and lepton storage rings
  - Ensures spin preservation and ease of spin manipulation
  - Avoids energy-dependent spin sensitivity for all species
- Present CEBAF injector meets MEIC requirements
  - 12 GeV CEBAF can serve as a full energy injector
    - Simultaneous operation of collider & CEBAF fixed target program possible
- Experiments with polarized positron beam would be possible

Figure-8 Ion Rings

- Figure-8 optimum for polarized ion beams
  - Simple solution to preserve full ion polarization by avoiding spin resonances during acceleration
  - Energy independence of spin tune
  - *g-2* is small for deuterons; a figure-8 ring is the only practical way to arrange for longitudinal spin polarization at interaction point
  - Transverse polarization for deuteron looks feasible
  - Long straights can be useful
    - Allows multiple interactions in the same straight – can help with chromatic correction
  - Only disadvantage is relatively small cost increase

MEIC Adopts Proven Luminosity Approaches

High luminosity at B factories comes from

- Very small β* (~6 mm) to reach very small spot sizes at collision points
- Very short bunch length (σ_z~ β*) to avoid hour-glass effect
- Very small bunch charge which makes very short bunch possible
- High bunch repetition rate restores high average current and luminosity
- Synchrotron radiation damping

➔ **KEK-B and PEPII already over $2x10^{34}$ /cm^2/s**

		KEK B	MEIC
Repetition Rate	MHz	509	1500
Particles per Bunch	10^{10}	3.3/1.4	0.42/1.25
Beam current	A	1.2/1.8	1/3
Bunch length	cm	0.6	1/0.75
Horizontal & Vertical β*	cm	56/0.56	10/2
Luminosity per IP, 10^{33}	$cm^{-2}s^{-1}$	20	5.6 ~ 11

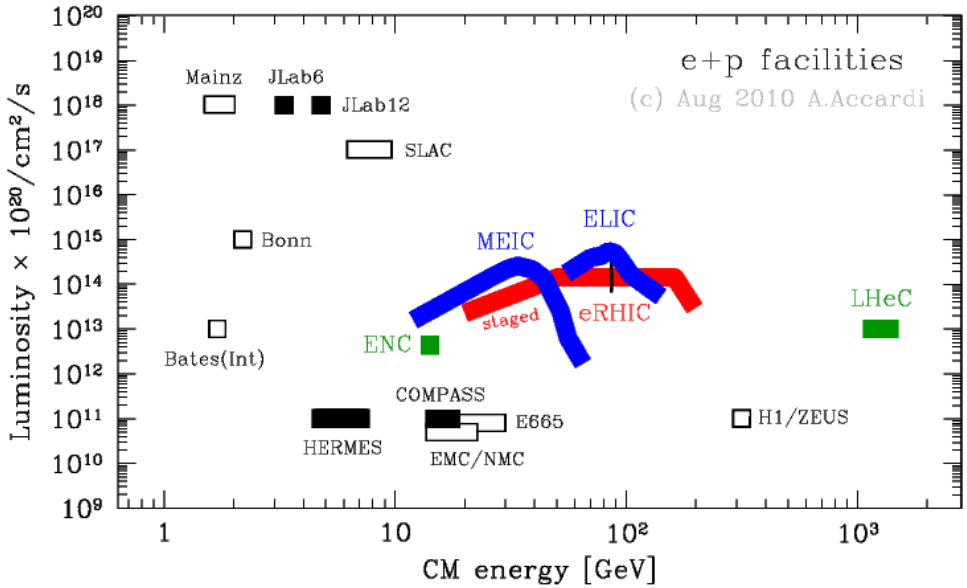
JLab believes these ideas should be replicated in the next electron-ion collider

Design Parameters for a Full Acceptance Detector

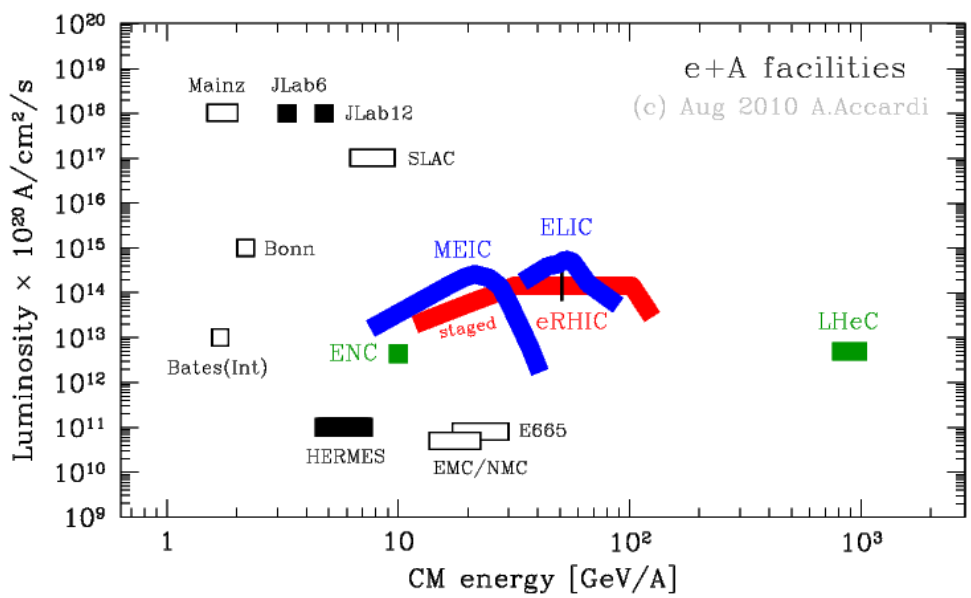
		Proton	Electron
Beam energy	GeV	60	5
Collision frequency	GHz	1.5	1.5
Particles per bunch	10^{10}	0.416	1.25
Beam Current	A	1	3
Polarization	%	> 70	~ 80
Energy spread	10^{-4}	~ 3	7.1
RMS bunch length	mm	10	7.5
Horizontal emittance, normalized	μm rad	0.35	54
Vertical emittance, normalized	μm rad	0.07	11
Horizontal β*	cm	10	10
Vertical β*	cm	2	2
Vertical beam-beam tune shift		0.007	0.03
Laslett tune shift		0.07	Very small
Distance from IP to 1st FF quad	m	7	3.5
Luminosity per IP, 10^{33}	$cm^{-2}s^{-1}$	5.6	

Luminosity Vs. CM Energy

e + p facilities

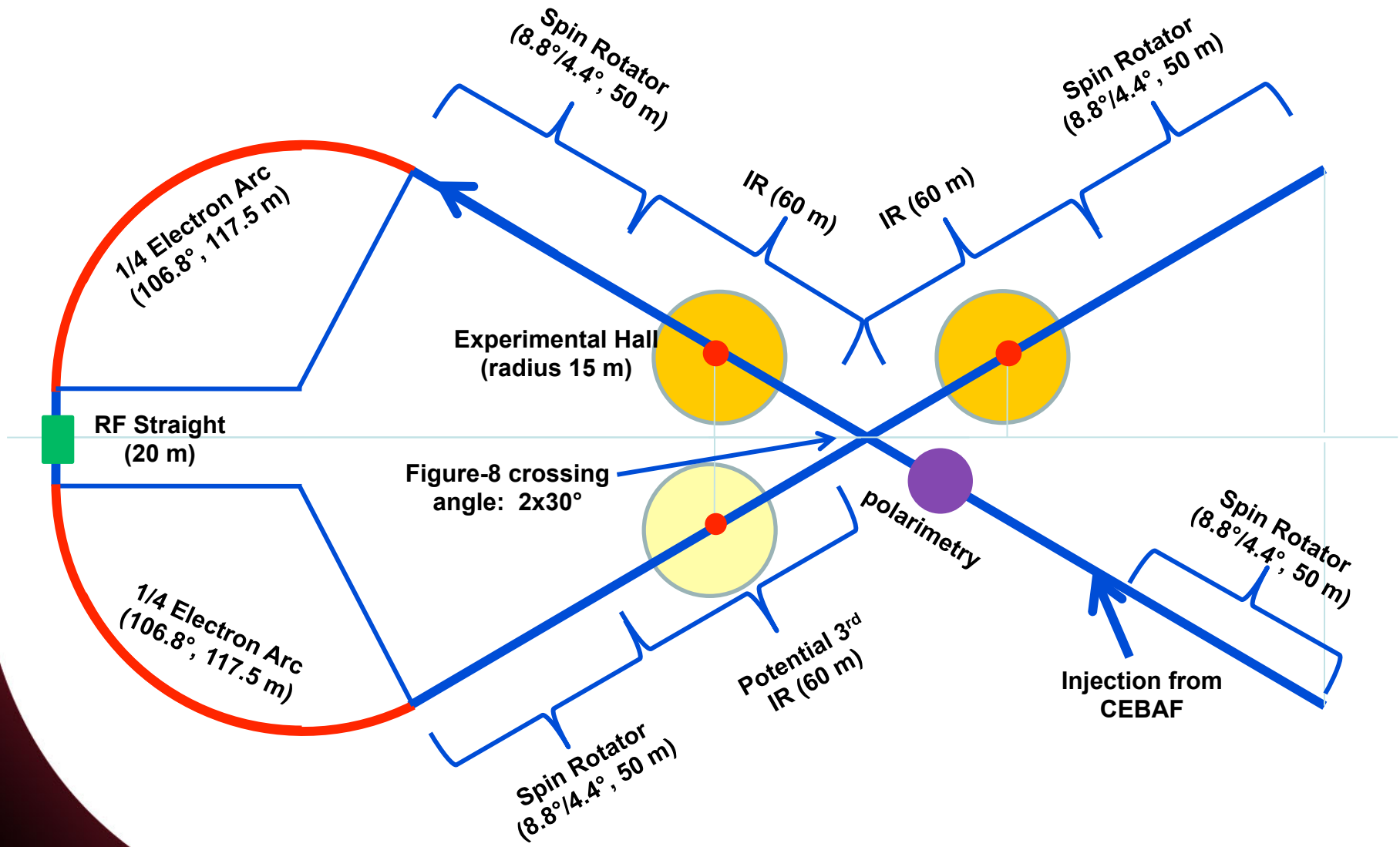


e + A facilities



https://eic.jlab.org/wiki/index.php/Machine_designs

MEIC Electron Figure-8 Collider Ring



Electron Collider Ring

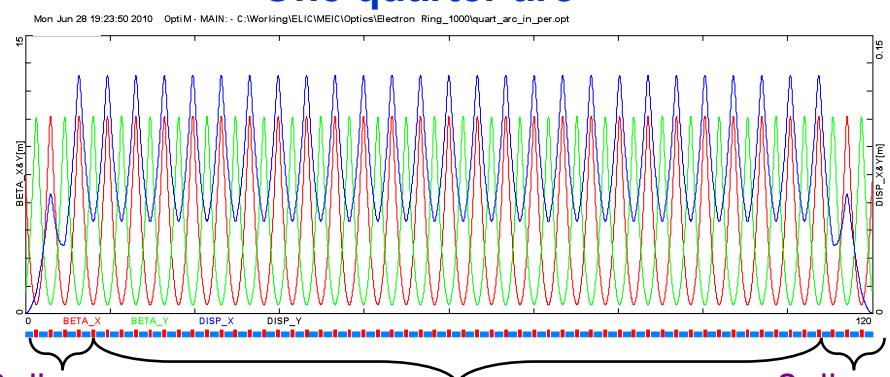
Electron ring is designed in a modular way

- two long (140 m) straights (for two IPs)
- two short (20 m) straights (for RF module), dispersion free
- four identical (106.8º) quarter arcs, made of 135º phase advance FODO cell with dispersion suppressing
- four 50 m long electron spin rotator blocks

135º FODO Cell for arc

	Length	Field
Dipole	1.1 m	1.25 T (2.14 deg)
Quad	0.4 m	9 kG/cm
Cell	4 m	

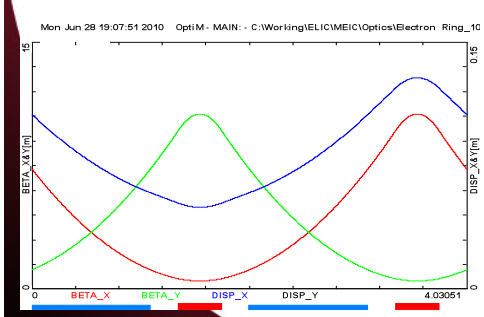
One quarter arc

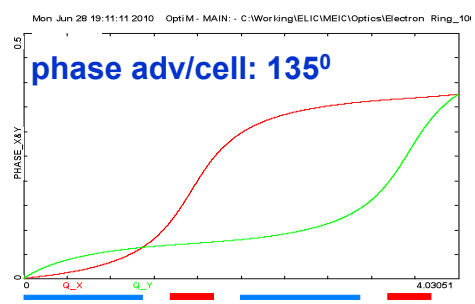


2 dis. sup. cells

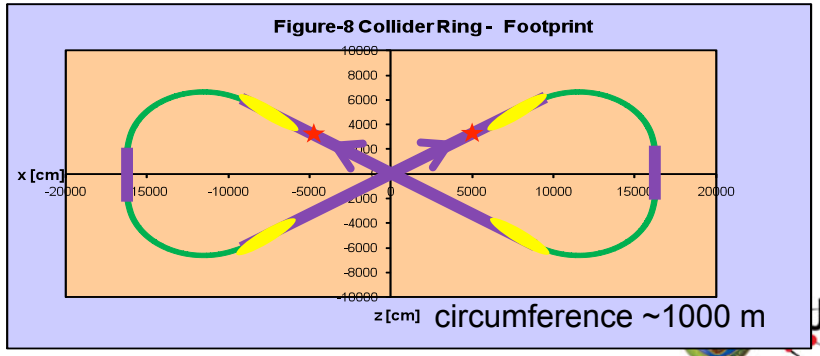
26 FODO cells

2 dis. sup. cells



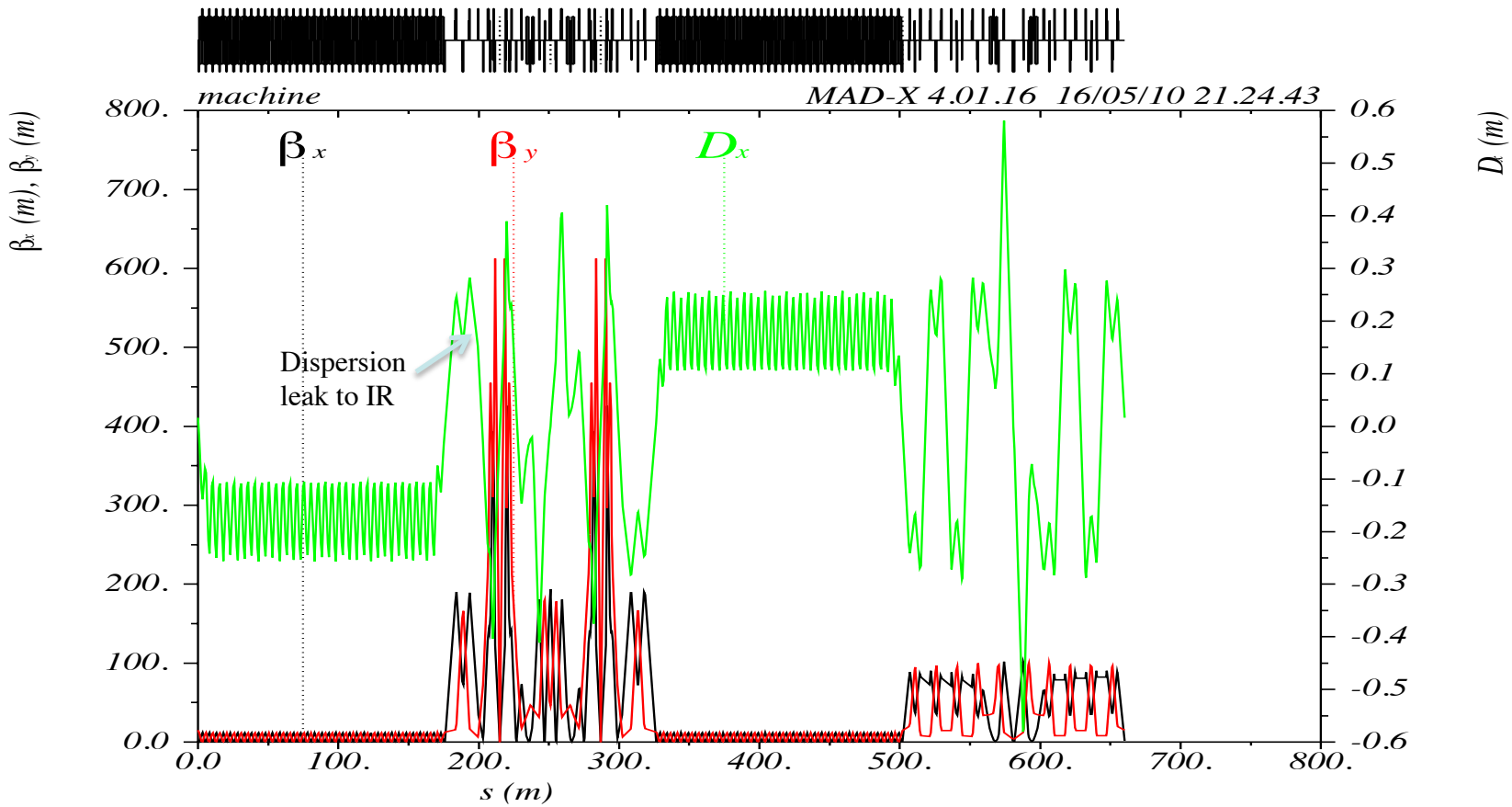


phase adv/cell: 135⁰



circumference ~1000 m

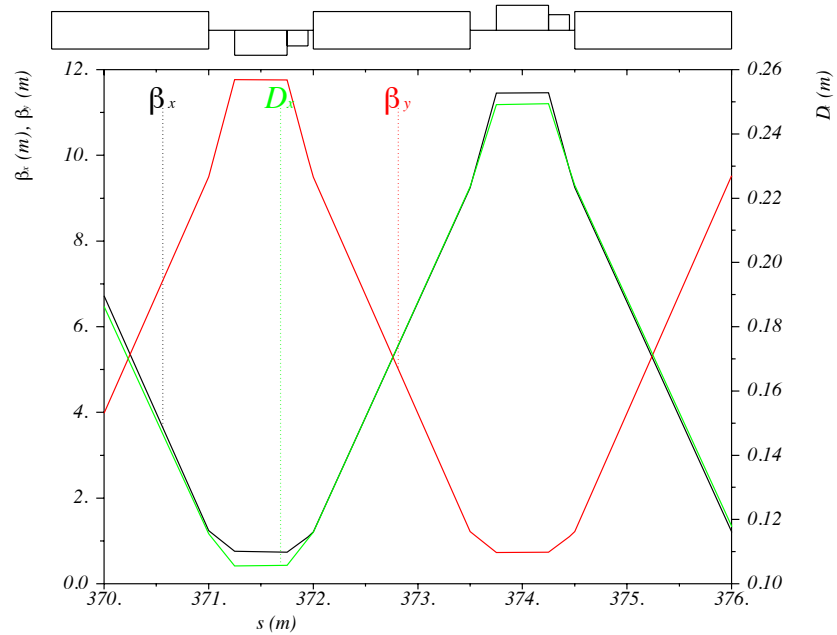
MEIC ring



A. Bogacz

Arc Cells

- 135 phase advance per cell for minimum equilibrium emittance
- Dispersion is well tailored to add chromatic correction sextupoles



Arc dipoles:	**Arc quadrupoles**
Lb=1.10 m	Lq=0.40 m
B=1.25 T	G= 0.99 T
ang=2.14 deg.	
rho = 29.4 meter	

135^0 FODO offers emittance preserving optics

– 〈H〉 minimum for FODO lattices

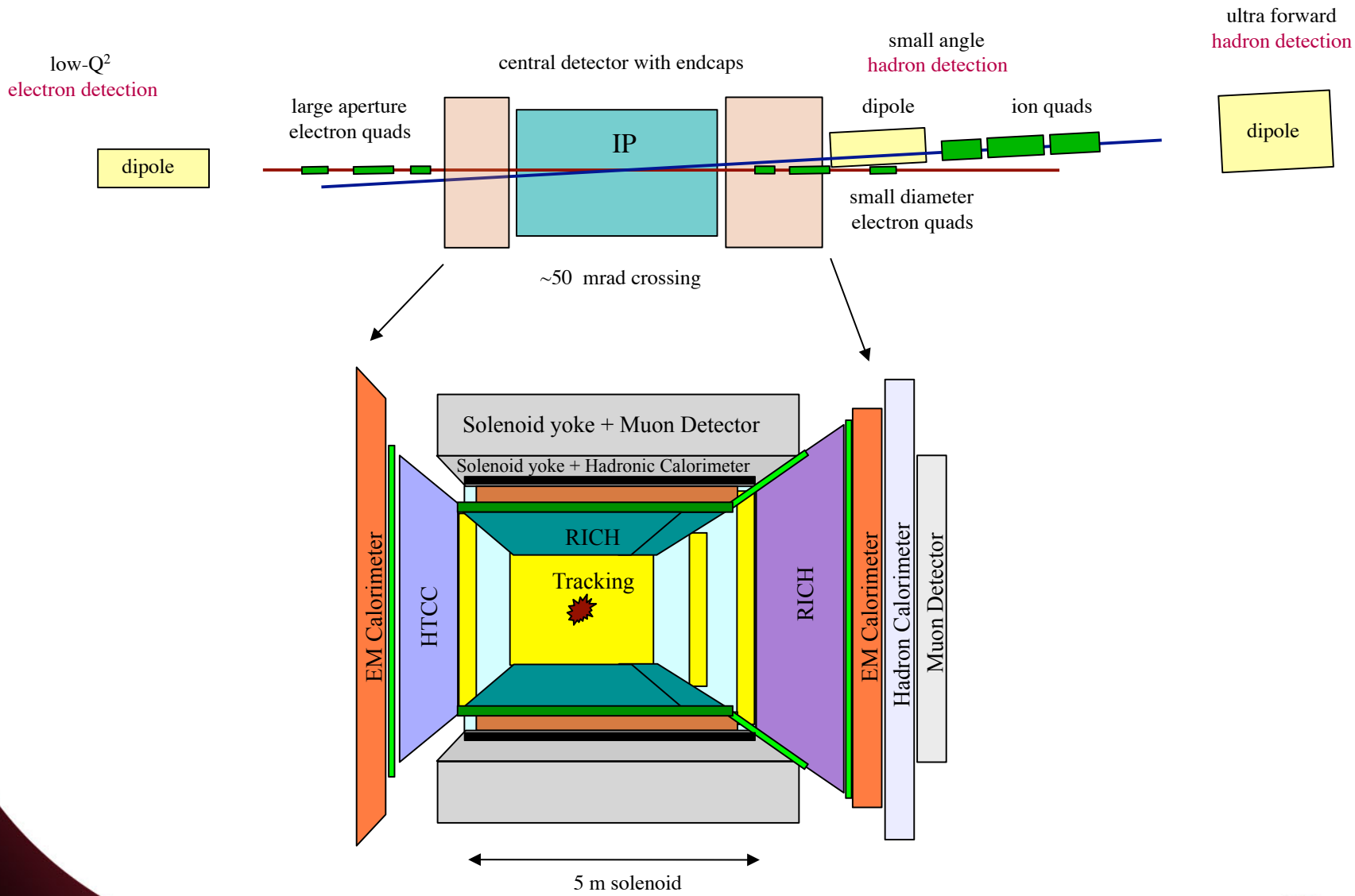
Synchrotron radiation power per meter less than 20 kW/m

Interaction Region

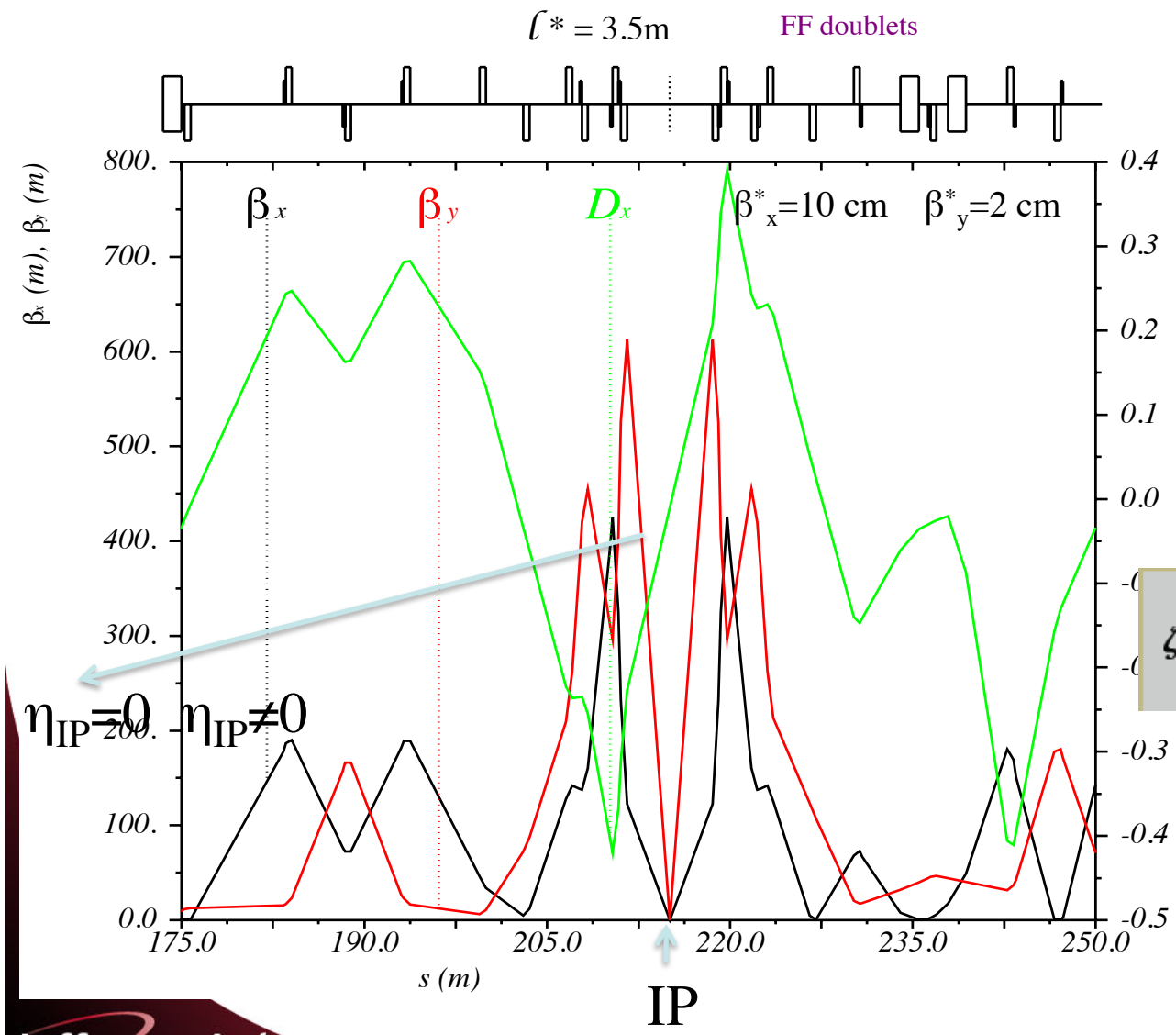
$$\beta_x^* = 10\,cm$$
$$\beta_y^* = 2\,cm$$

- 'Relaxed' IR Design:
- Beam Stay Clear and FF quad apertures
- Chromaticity Compensating Optics
  - Uncompensated dispersion in the straights
  - Anti-symmetric dispersion pattern across the IR
  - Dedicated Symmetric Inserts around the IR
- Forward detection/tagging, low Q^2 tagging

Detector and IR layout



Interaction Region



$$\beta^{ff} \approx \frac{\ell^{*2}}{\beta^*} = \frac{3.5^2}{2\times10^{-2}} \approx 6.5\times10^2\, m$$

$$\zeta_{IR} \sim \frac{f^2}{\beta^*}\frac{1}{f} = \frac{f}{\beta^*}$$

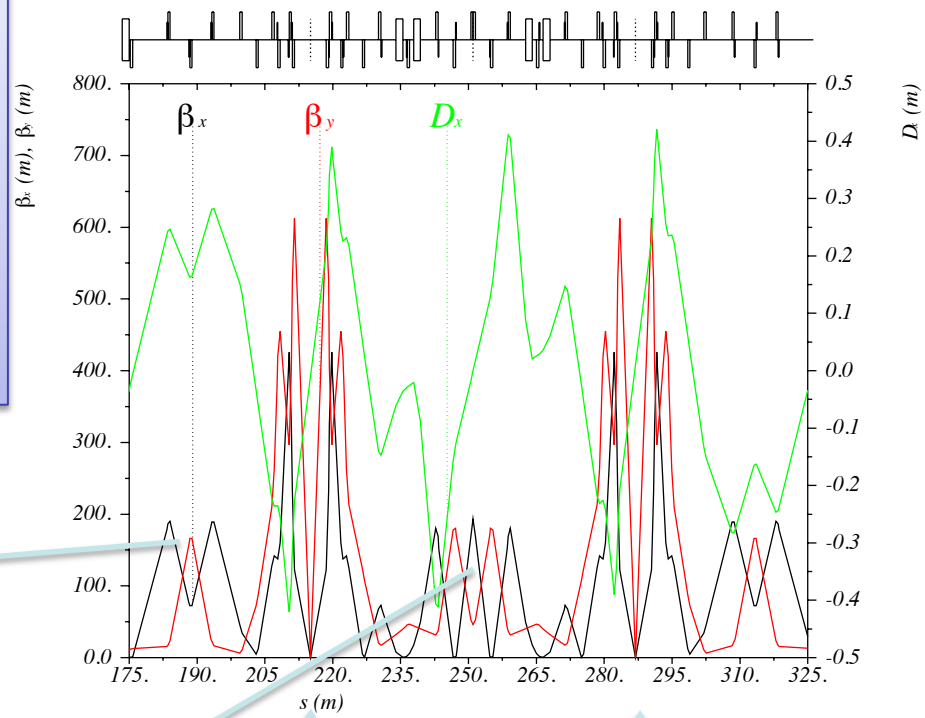
$$\zeta_1 := \frac{1}{4\pi}\int_0^l \underbrace{\beta_x}_{\beta^{\max}}(-\underbrace{g_0}_{g_0^{FF}} + \eta_0 g_1)\, ds;$$

Natural Chromaticity:

$\zeta_x = -47$ $\zeta_y = -66$

Two Interaction Region

Two Symmetric IP's at the same straight with antisymmetric dispersion Phase between IP1-IP2 adjusted to cancel second order chromaticity.



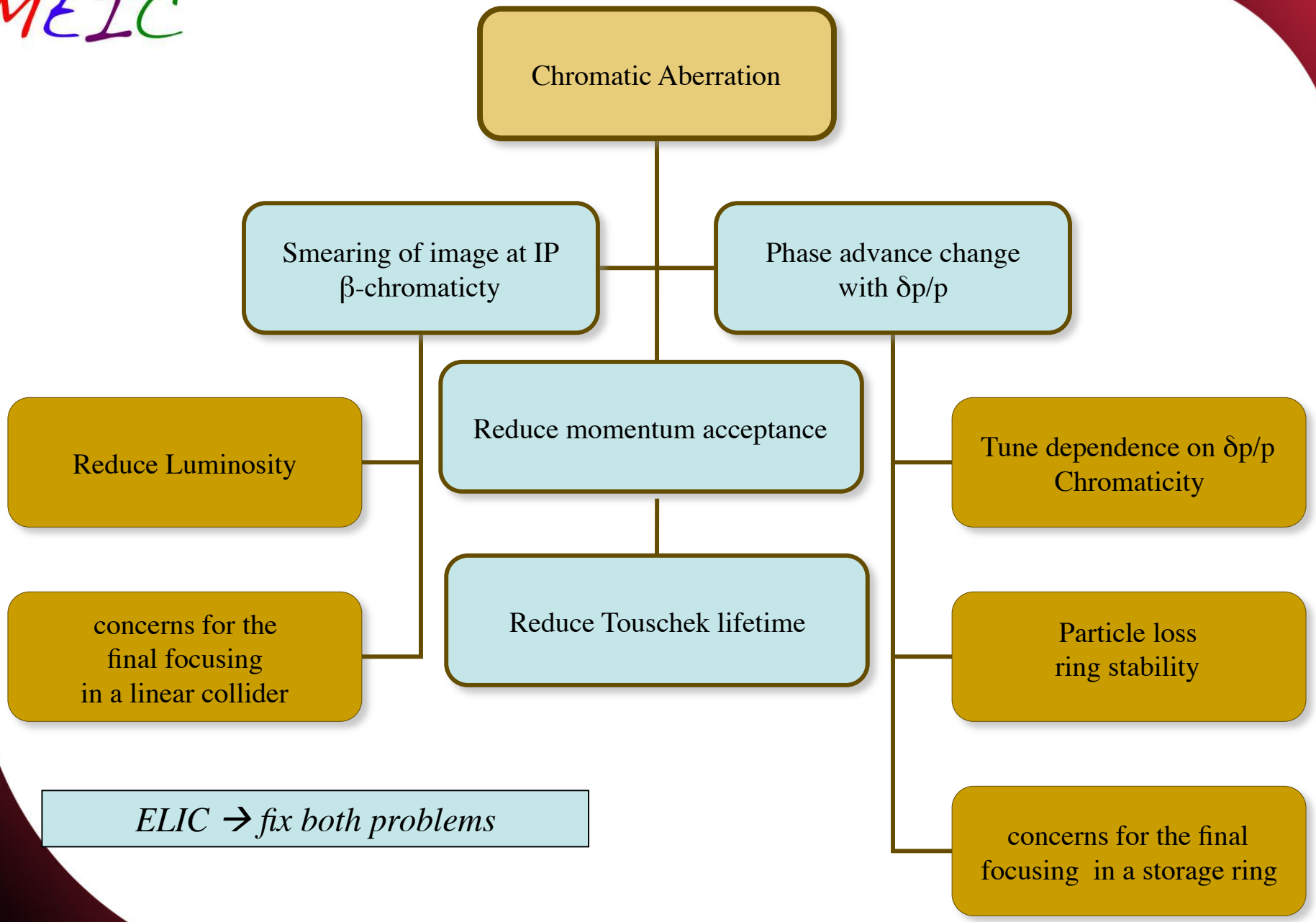
Matching to Arc

Matching to second IR

IP

IP

MEIC



ELIC → fix both problems

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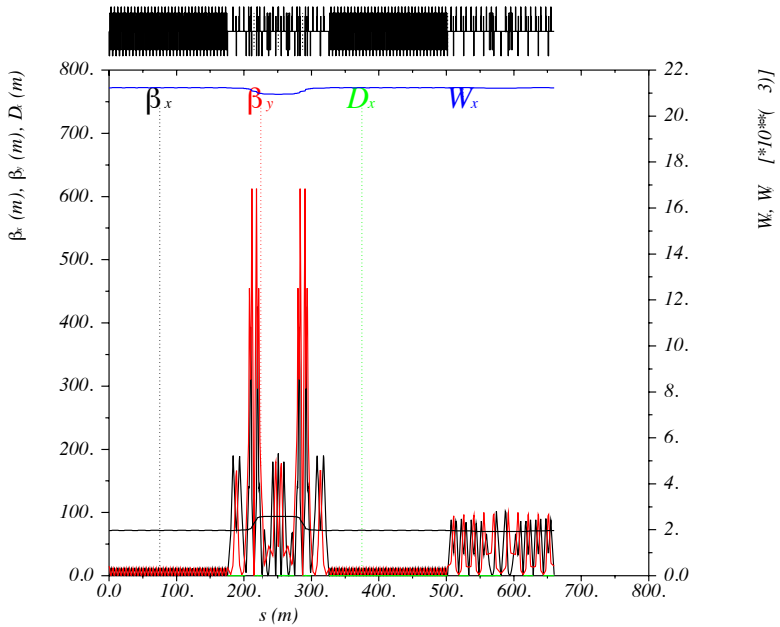
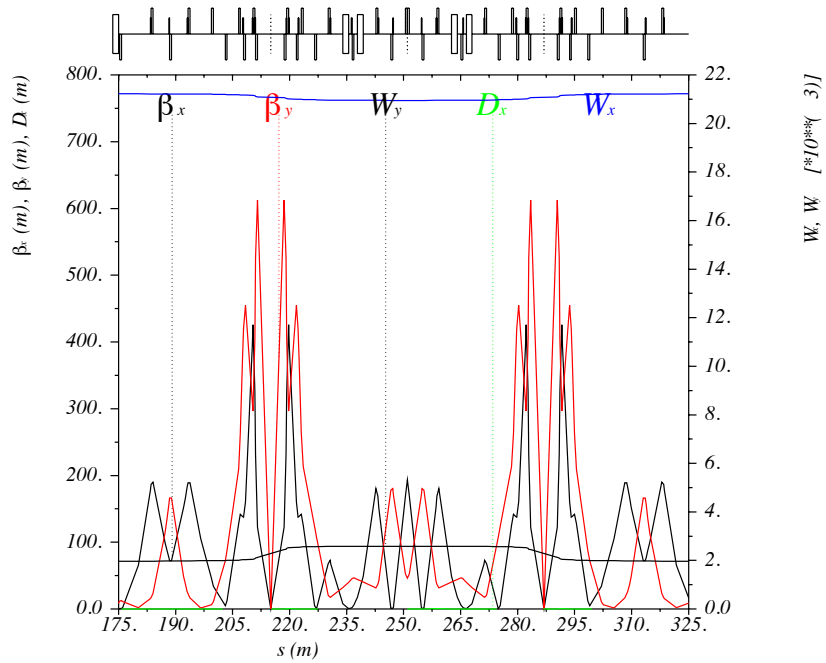
Montague Chromatic function

Sextupoles off





Chromaticity

Analytical Approach

The Hamiltonian of a particle moving in a circular accelerator

$$\mathrm{H(x,y,p}_x, p_y) = -(1+\mathrm{x}\,K_x)\sqrt{(1+\delta)^2 - {p_x}^2 - {p_y}^2} + \tfrac{1}{2}\,(1+xK_x)^{\,2} + \sum_{n=0}^{\infty} \tfrac{g_n}{(n+2)!} \sum_{m=0}^{(n/2)+1} (-1)^m \times \mathrm{Binomial}[n+2, m] x^{n+2-2m} y^{2m}$$

Expansion of the tune with momentum deviation δ_p

$$\zeta = \sum \delta^n \zeta_n$$

First Order Chromaticity

$$\zeta_{1x} = \frac{1}{4\pi} \int_0^s \left(-\beta_x \left(K^2 + g_0 - g_1\eta_0\right) - 2\alpha_x K \eta_0' + \gamma_x K \eta_0\right) ds$$

Radius of curvature

Quadrupole field

Sextupole field

Dispersion

α & β twiss parameters

$$\zeta_{1y} = \frac{1}{4\pi} \int_0^s \left(\beta_y \left(g_0 - g_1\eta_0\right) + \gamma_y K \eta_0\right) ds$$

$$\gamma = \left(K^2 + g_0\right)\beta + \frac{1}{2}\beta''$$

Chromaticity

Analytical Approach

- Second Order Chromaticity:

$$\zeta_{2x}=\frac{1}{4\pi}\left(\int_0^l \beta[s]G_2[s]ds-\frac{1}{16}\mu_0 a_1^2[0]-\sum_{n=1}^{\infty}\frac{\mu_0^3}{8\left(\mu_0^2-\pi^2 n^2\right)}\left(a_1^2[n]+b_1^2[n]\right)\right)$$

Where

$$a_{x,1}[\mathrm{n}]=\frac{2}{\mu_x}\int_0^l\left(\left(G_{1,x}-\frac{1}{2\beta_x}\left(\frac{2\pi n}{\mu_x}\right)^2 K_x\eta_0\right)\mathrm{Cos}\left[\frac{2\pi n}{\mu_x}\phi_x\right]+\frac{2\pi n}{\mu_x}\left(\frac{\alpha_x}{\beta_x}K_x\eta_0-K_x\eta_0'\right)\mathrm{Sin}\left[\frac{2\pi n}{\mu_x}\phi_x\right]\right)ds$$

$$b_{x,1}[\mathrm{n}]:=\frac{2}{\mu_x}\int_0^l\left(\left(G_{1,x}-\frac{1}{2\beta_x}\left(\frac{2\pi n}{\mu_x}\right)^2 K_x\eta_0\right)\mathrm{Sin}\left[\frac{2\pi n}{\mu_x}\phi_x\right]-\frac{2\pi n}{\mu_x}\left(\frac{\alpha_x}{\beta_x}K_x\eta_0-K_x\eta_0'\right)\mathrm{Cos}\left[\frac{2\pi n}{\mu_x}\phi_x\right]\right)ds$$

Φ betatron phase

$$G_{1,x}=-\beta_x\left(K_x^2+g_0-g_1\eta_0\right)-2\alpha_x K_x\eta_0'+\gamma_x K_x\eta_0$$

Manipulating Chromaticity

Analytical Approach

– Assuming straight section (MEIC IR case)

$$\zeta_1 = \frac{1}{4\pi} \int_0^l \beta_x \left(-g_0 + \eta_0 g_1\right) ds$$

$\zeta_1 \sim 0$ for Sextupole field $g_1 \sim g_0/\eta_0$

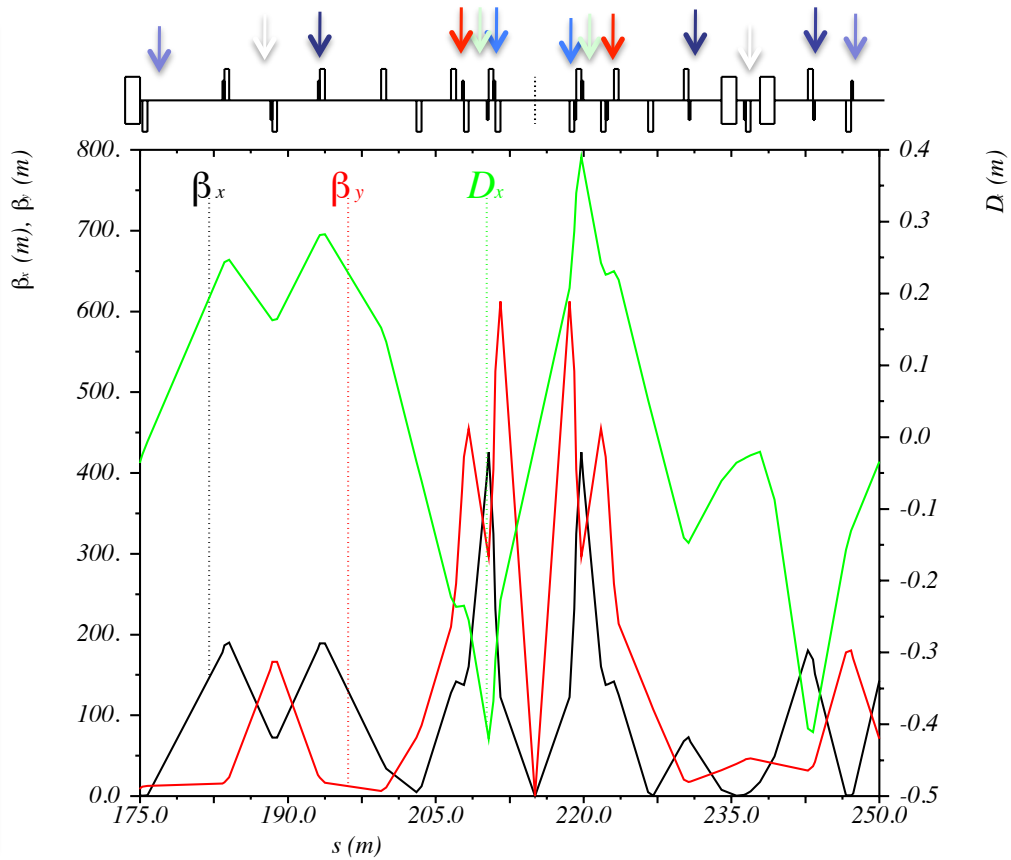
$$\zeta_2 = \frac{1}{4\pi} \int_0^l \left(\beta_x \frac{g_0 \eta_1}{\eta_0} + \frac{3}{2}\beta_x g_0 \eta_0^2 + \frac{3}{4}\eta_0^2 \beta_x'' + \frac{\beta_x}{2} g_2 \eta_0^2\right) ds$$

$\zeta_2 \sim 0$ for octupole field

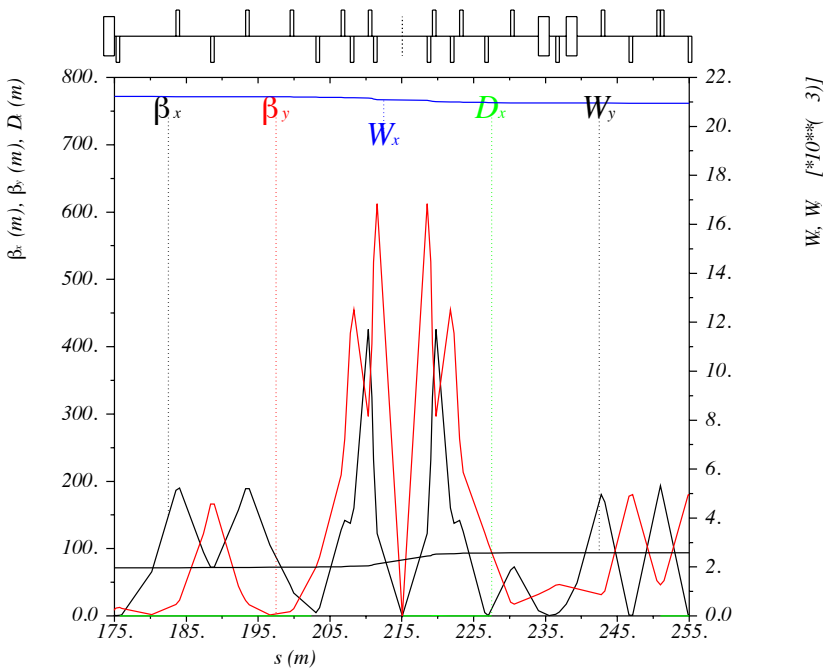
$$g_2 = \frac{-2}{\beta_x \eta_0^2}\left(\beta_x g_0 \left(\frac{\eta_1}{\eta_0} + \frac{3}{2}\eta_0^2\right) + \frac{3}{4}\eta_0^2 \beta_x''\right)$$

Local Chromatic Correction

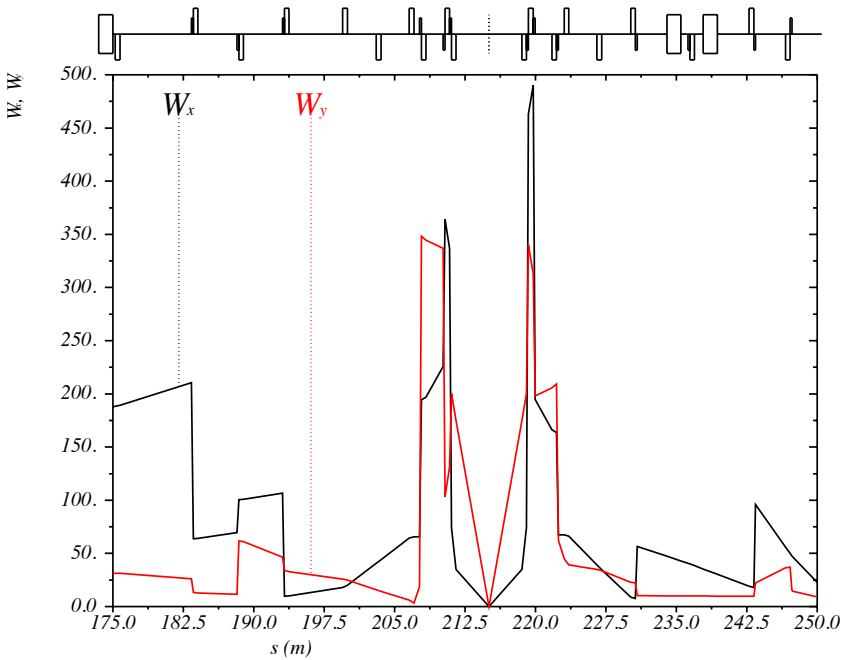
- Six Sextupole pairs placed semi-symmetrically around IP
  - the closest pair to IP was applied to eliminate the Wx,y at IP
  - five pairs confine chromatic functions within the IR
- β correction sextupoles around IP reduced W's from 10^3 to 10^{-4} range and be confined to acceptable values at end of IR
- Second order chromaticity arising from IRs final focus quadrupoles and correcting sextupoles was mitigated by fixing the phase advance between the two symmetric IR to be π.(1/2 + n) (where n is an integer number)



Local Chromatic Correction

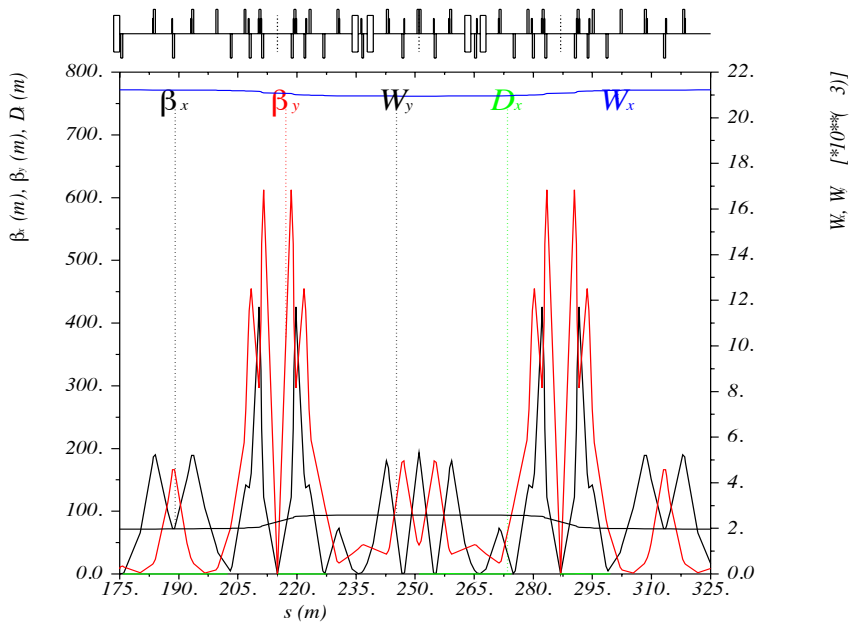


Sextupoles off



Sextupoles on

Local Chromatic Correction



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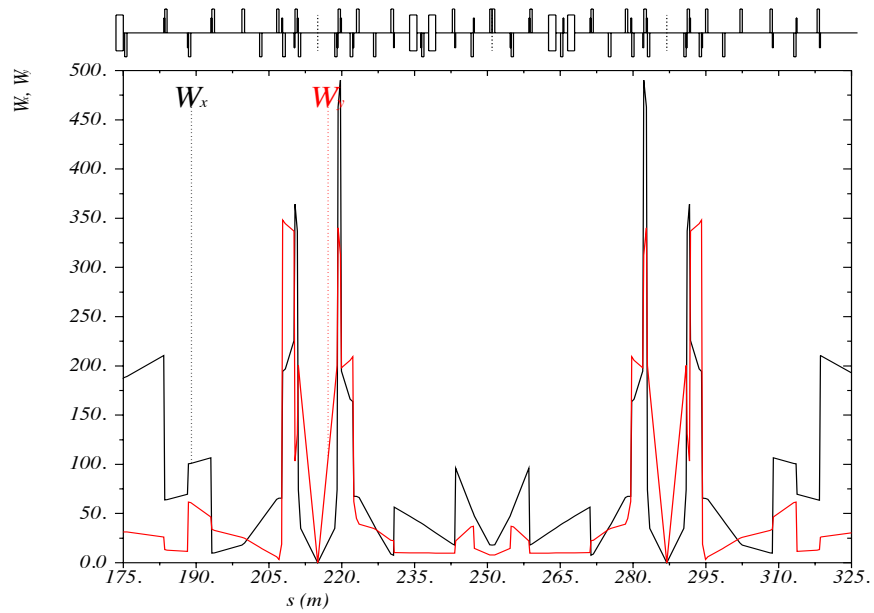
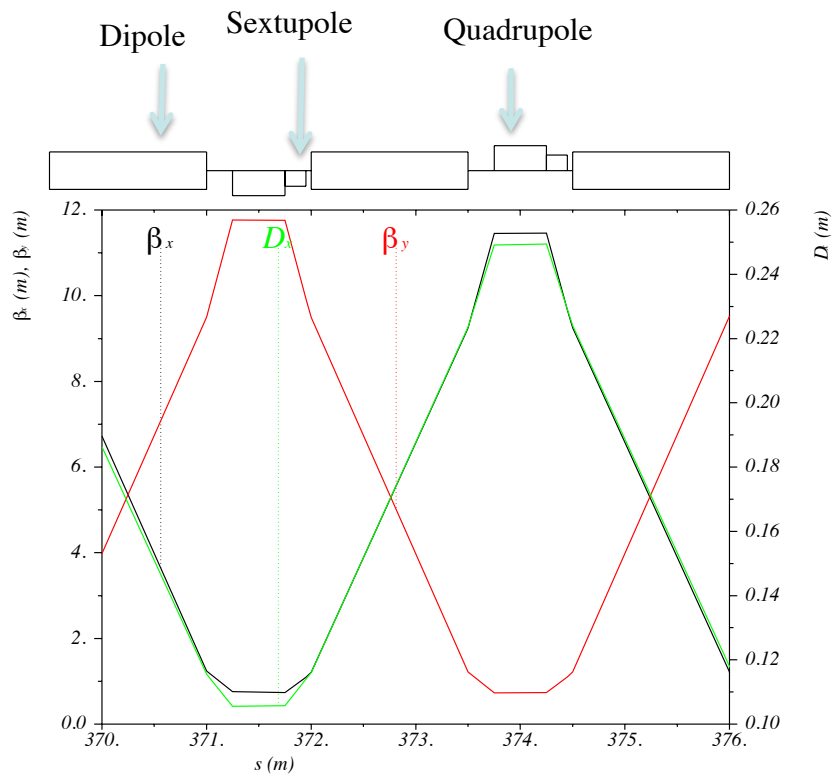


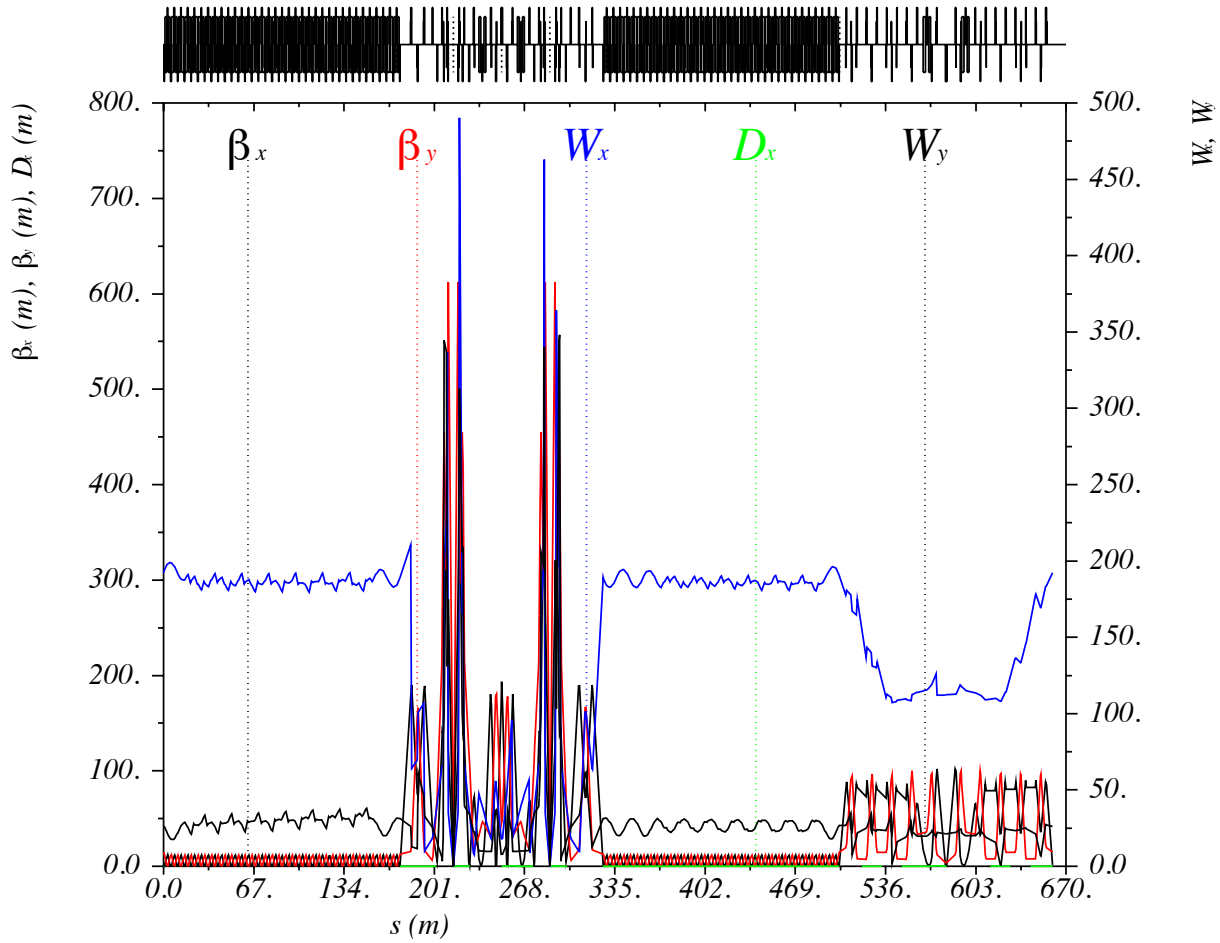
Sextupoles on

Global Chromatic Correction

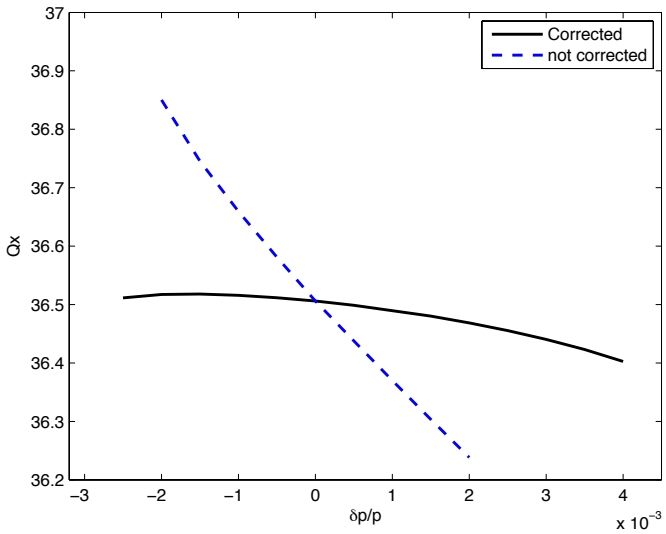
- families of sextupoles in the arcs & IP free straight
- Arc:
  - Four interleaved sextupoles families
  - Every family member at (3π) -I transformation from each other to cancel second order aberrations from those sextupoles.
- IP free straight with special symmetric insertion blocks, the sextupoles were placed in a non interleaved families with -I transformation apart as well.

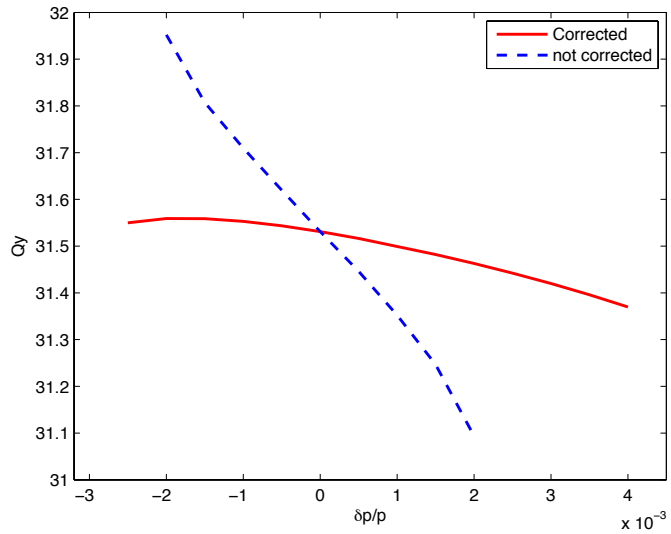


Global Chromatic Correction



Tune Variation with *δp/p*

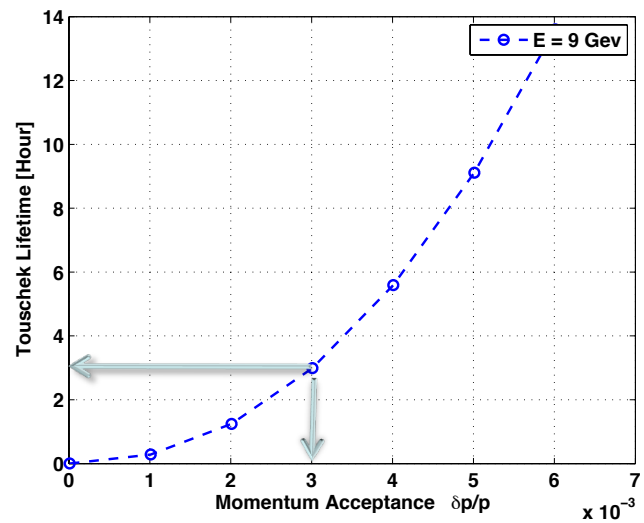




Touschek Lifetime

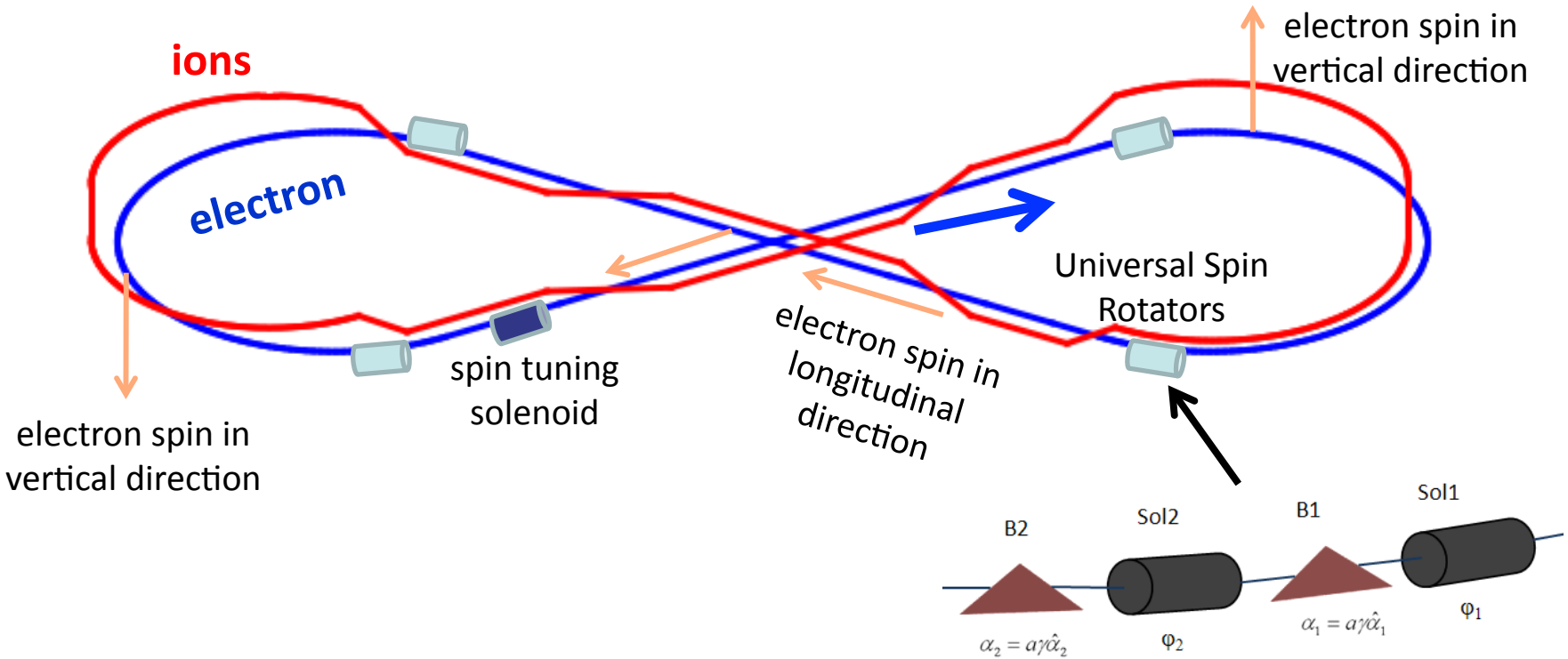
$$\frac{1}{\tau_{\text{Touschek}}} \approx \frac{N r_0^2 c}{8\pi\gamma^3\sigma_s L}\sum_{i=1}^{N}\frac{D(\xi)\Delta s_i}{\sigma_x(s_i)\sigma_y(s_i)\sigma_{x'}(s_i)\delta_{acc}^2(s_i)}$$

- Accurate estimate of the Touschek effect is obtained by estimating the integral equation as a sum over all N elements in the lattice.
- The beam parameters(α , β & η)are all assumed constant at end of each of the N lattice elements
- Momentum acceptance for the lattice:
  - Constant across the whole lattice



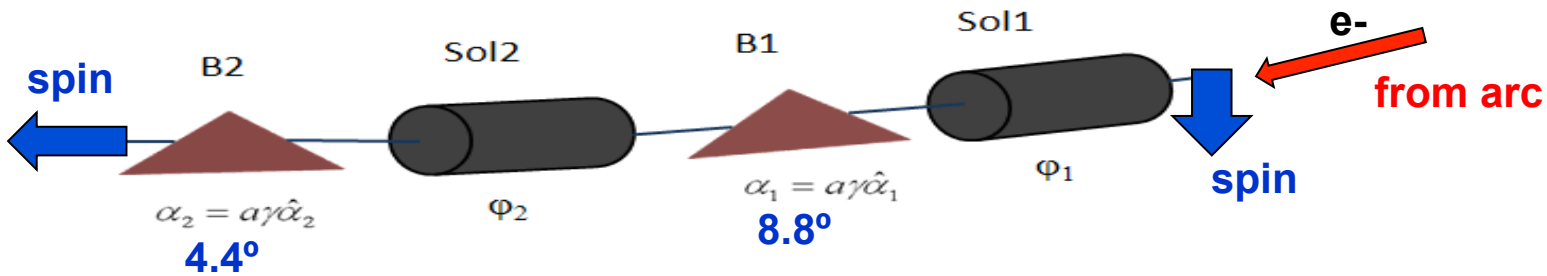
0.003 momentum acceptance for the lifetime to reach 3 hours

Electron Polarization in Figure-8 Ring



- Polarized electron beam is injected at full energy from 12 GeV CEBAF
- Electron spin is in vertical direction in the figure-8 ring, taking advantage of self-polarization effect
- Spin rotators will rotate spin to longitudinal direction for collision at IP, than back to vertical direction in the other half of the ring

Universal Spin Rotator



- The last two arc dipole sections interleave with two solenoids
- The rotator works by adjusting spin rotation angles in solenoids depending on the beam energy.
- X-Y betatron coupling introduced by solenoids must be compensated

E	Solenoid 1		Solenoid 2		Spin rotation	
	spin rot.	BDL	spin rot.	BDL	arc bend 1	src bend 2
GeV	rad	T m	rad	T m	rad	rad
3	π/2	15.7	0	0	π/3	π/6
4.5	π/4	11.8	π/2	23.6	π/2	π/4
6	0.63	12.3	π-1.23	38.2	2π/3	π/3
9	π/6	15.7	2π/3	62.8	π	π/2
12	0.62	24.6	π-1.23	76.4	4π/3	2π/3

Optics Coupling Compensation

- X-Y beam coupling introduced by solenoids is compensated locally
- Each solenoid is divided into two equal parts and a set of quadrupoles is inserted between them to cancel coupling

➢Emma rotator

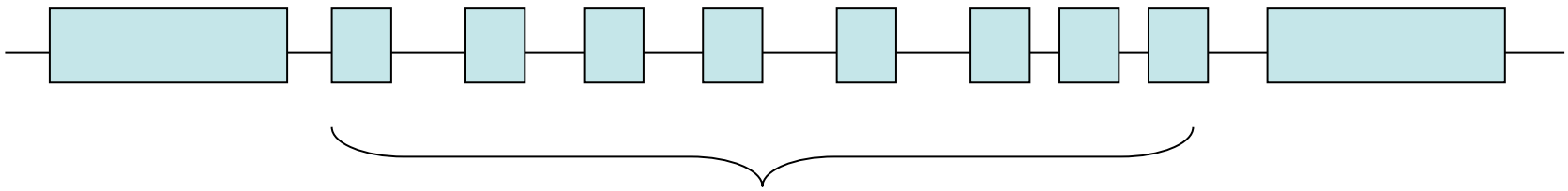
➢More general solution (*Litvinenko*)

$$M_{sol} = \begin{pmatrix} \cos^2\Phi & \frac{\sin 2\Phi}{S} & \frac{\sin 2\Phi}{2} & \frac{2\sin^2\Phi}{S} \\ \frac{-S\sin 2\Phi}{4} & \cos^2\Phi & \frac{-S\sin^2\Phi}{2} & \frac{\sin 2\Phi}{2} \\ \frac{-\sin 2\Phi}{2} & \frac{-2\sin^2\Phi}{S} & \cos^2\Phi & \frac{\sin 2\Phi}{S} \\ \frac{S\sin^2\Phi}{2} & \frac{-\sin 2\Phi}{2} & \frac{-S\sin 2\Phi}{4} & \cos^2\Phi \end{pmatrix}$$

Φ=B L/2
B solenoid field strength
L length respectively

Challenges:
1. Work at all energies
2. Independent of solenoid strength
3. Space economy (we need at least four of USR)
4. Modular to be easily matched and implemented at different places along the ring

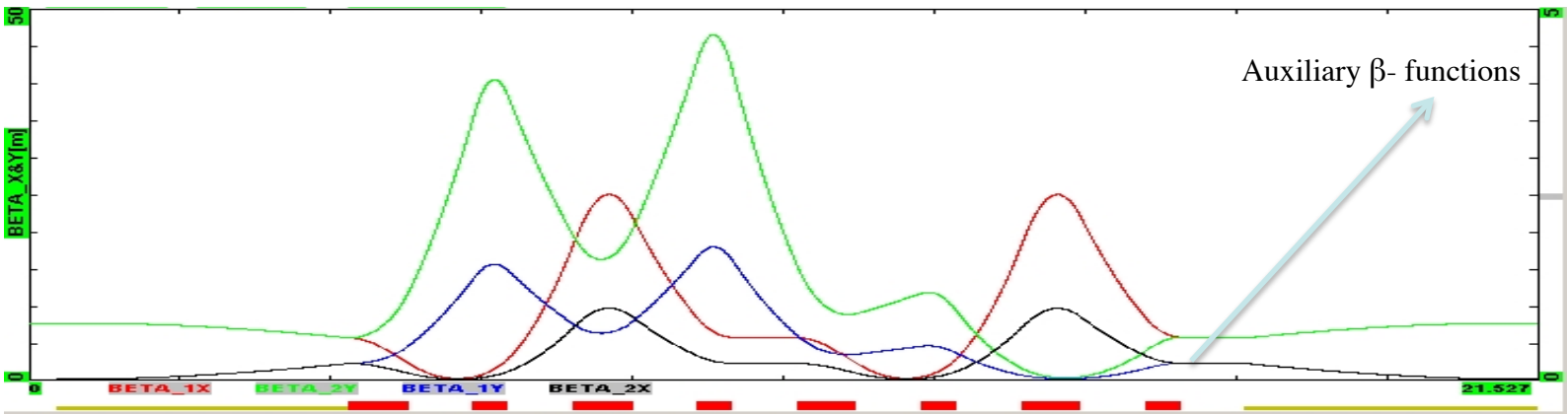
Emma Rotator



$$M_{COMP} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

$$M_{sol}.M_{COMP}.M_{sol} = \begin{pmatrix} A & 0 \\ 0 & B \end{pmatrix}$$

Emma Rotator



21.5 m

Disadvantages:

1. Very long
2. Requires 8 quads with different strengths
3. Require 8 quads for matching (un-modular)

From element 1(oA) to Element 19(csol)
Matrix. Energy increase[MeV]=0 From 9000 to 9000

X[cm]	Px	Y[cm]	Py	dL[cm]	dP/P
4.448049e-01	6.900133e+02	-2.182095e-06	-5.649690e-04	0.000000e+00	0.000000e+00
-1.193280e-03	3.970758e-01	2.518591e-09	-4.434267e-07	0.000000e+00	0.000000e+00
2.182095e-06	5.649690e-04	-4.448071e-01	6.900133e+02	0.000000e+00	0.000000e+00
2.518591e-09	4.434267e-07	1.193277e-03	-3.970763e-01	0.000000e+00	0.000000e+00
0.000000e+00	0.000000e+00	0.000000e+00	0.000000e+00	1.000000e+00	6.939013e-06
0.000000e+00	0.000000e+00	0.000000e+00	0.000000e+00	0.000000e+00	1.000000e+00

General Case

$$M_{COMP} = \begin{pmatrix} M & 0 \\ 0 & -M \end{pmatrix} \qquad M_{sol}.M_{COMP}.M_{sol} = \begin{pmatrix} A & 0 \\ 0 & B \end{pmatrix}$$

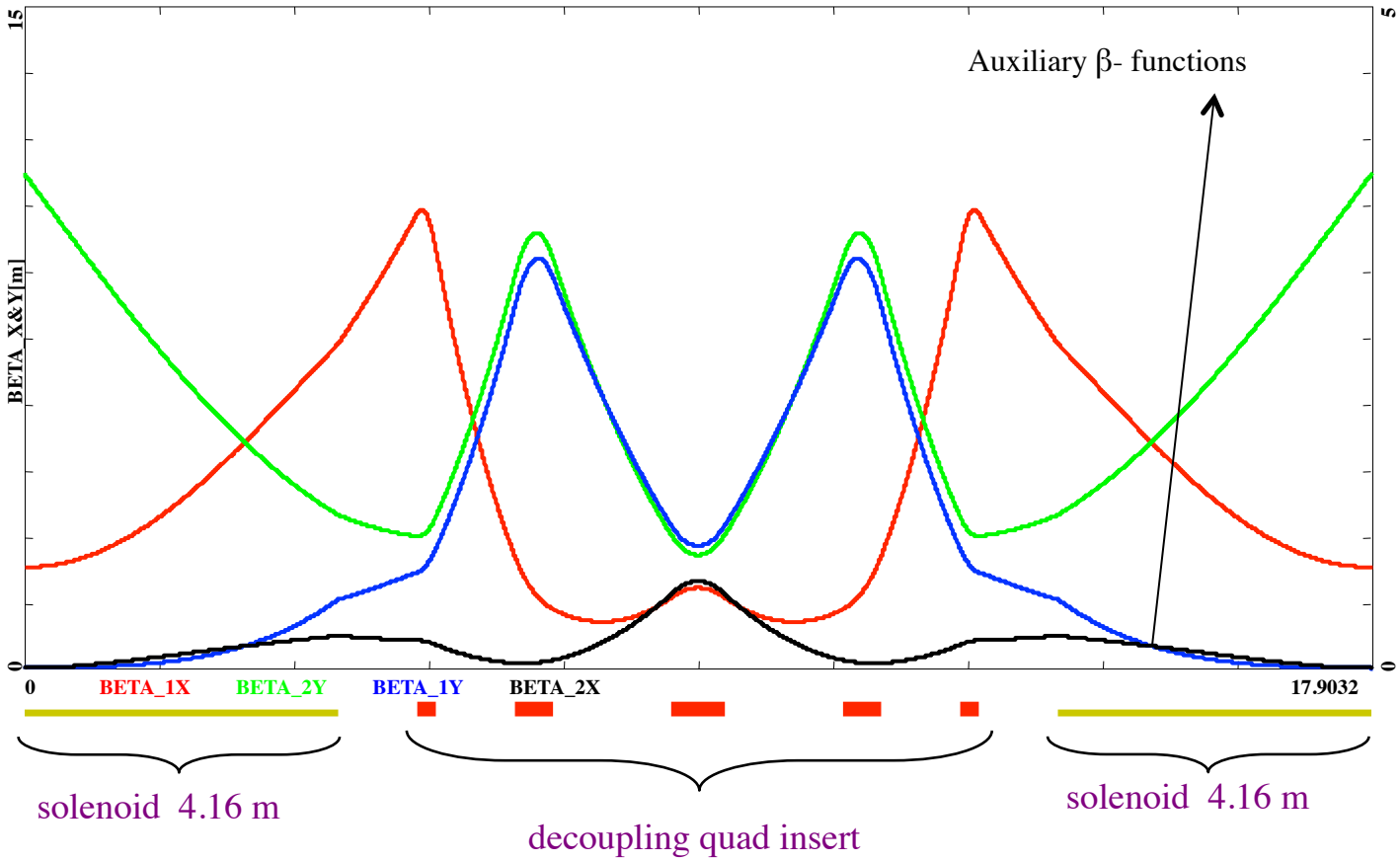
- Three required optimization parameters to fulfill four conditions (M_{COMP}) minus simplicity of the system.

MEIC Spin Rotator

$$M = \begin{pmatrix} a & b & 0 & 0 \\ c & d & 0 & 0 \\ 0 & 0 & -a & -b \\ 0 & 0 & -c & -d \end{pmatrix}$$

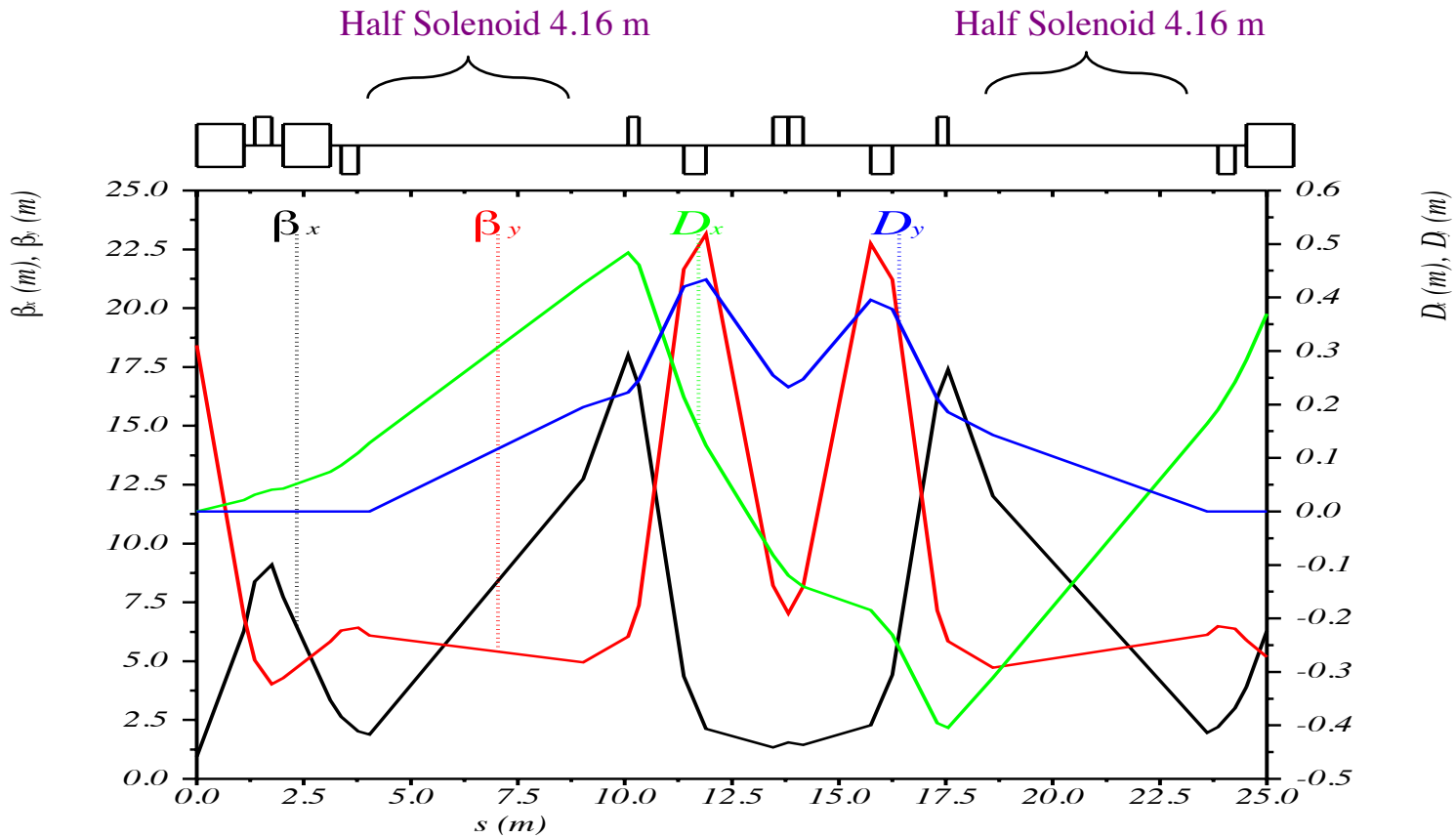
- A set of two symmetric doublets separated by one quadrupole is designed to meet the three conditions
- The compactness incorporated in the optimization process yielding relatively short drifts in between quadrupoles

Locally decoupled solenoid



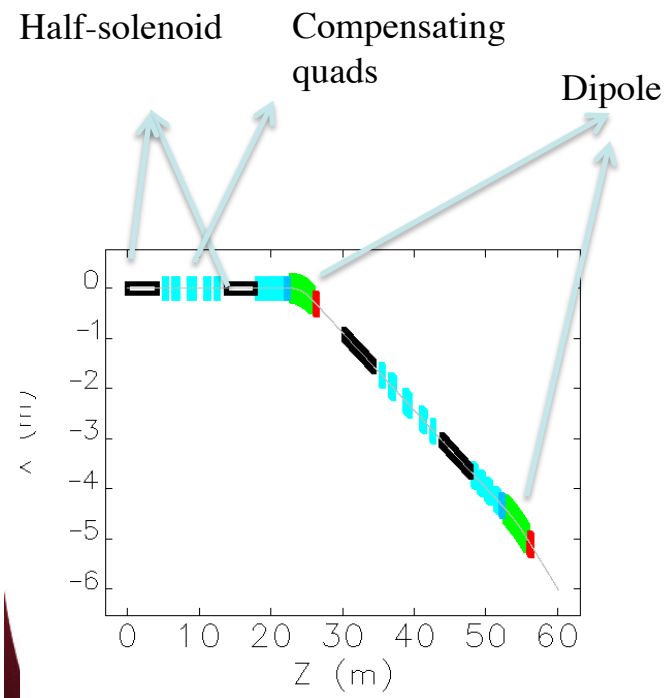
$$M = \begin{pmatrix} C & 0 \\ 0 & -C \end{pmatrix}$$

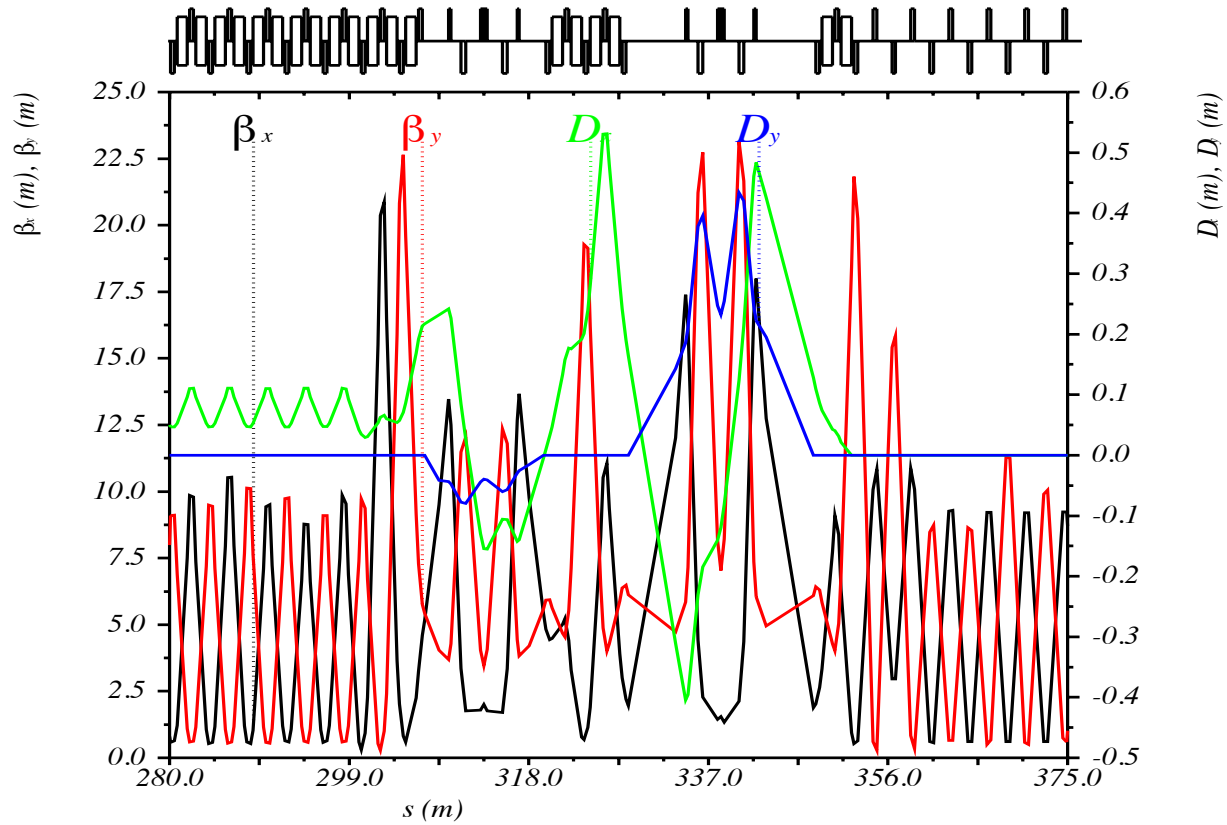
Locally decoupled solenoid



The symmetric insert: requires only four parameters to match the insert to the end of the arc and to the FODO cells of the straight. This will reduces number of matching quadrupoles to only four.

Spin Rotator in Arc





MEIC

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