EIC IR Optics

J. Scott Berg

FCC-EIC Joint Workshop

October 17, 2022

Electron-Ion Collider

BROOKHAVEN NATIONAL LABORATORY

Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science

IR Requirements

- Optics requirements
  - At IP, zero D_x, D_x', α, specified β
    - Note beams are fairly flat at IP: $\beta_x \approx 10\beta_y$
  - Optics for crab cavities
    - 25 mrad crossing angle
    - High β_x at crab
      - 1300 m for 275 GeV protons
      - 150 m for 18 GeV electrons
    - $n\pi + \pi/2$ horizontal phase advance from IP
    - Betatron match to arcs
    - ESR: phase advance to arcs (chromatic β, dynamic aperture)

IR Requirements

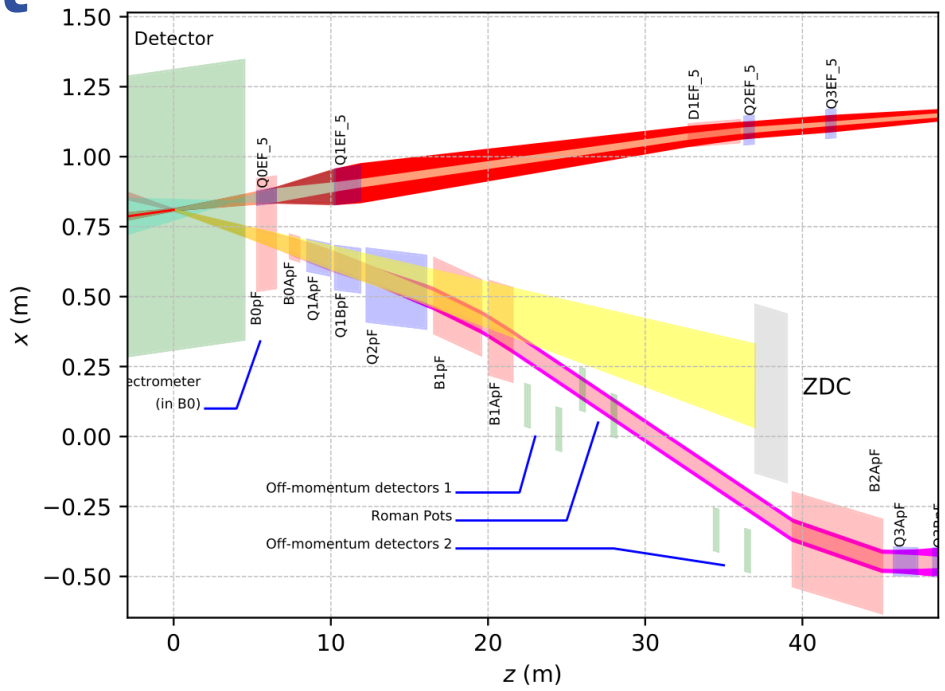
- Detector requirements
  - 4.5 m rear, 5.0 m forward stay-clear
  - First forward hadron magnet is a dipole with an integrated spectrometer
  - Apertures pass particles to far-forward detectors (hadron)
    - 4 mrad neutrals
    - 1.3 GeV/*c* transverse momentum protons (for 275 GeV)
    - Space for far-forward detectors
  - Electron rear, dipole following doublet
    - Bend electrons away from photons (luminosity)
    - Space for low-Q^2 taggers

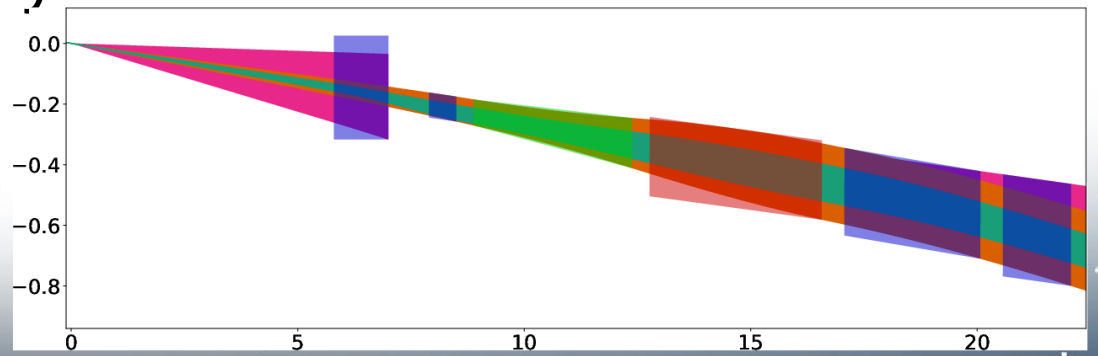
IR Requirements

- Minimize stray field from HSR on ESR (avoid synchrotron radiation and nonlinear fields in ESR)
  - Difficulty: cannot shield spectrometer dipole from far field of ESR final focus quadrupole inside of it
- Spin manipulation
  - HSR: snake (helical dipole) at a specific geometric angle
  - HSR: rotators (helical dipole), one on each side of the IP
  - ESR: solenoid spin rotators for 6–18 GeV
- HSR: use existing RHIC magnets as much as possible

HSR IR Forward Layout

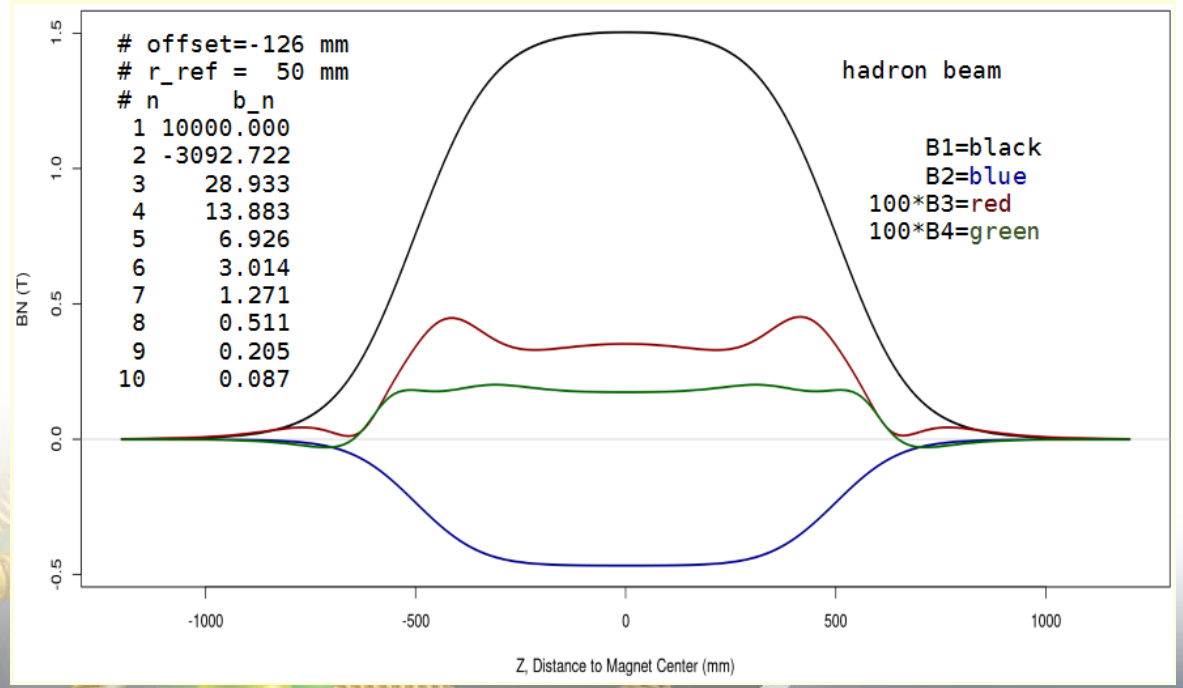
- Magnets aligned to transmit particles required for far-forward detectors
- Spectrometer dipole field same for all energies
  - Following dipoles restore orbit
- Shared ESR/HSR yokes
  - ESR quadrupole inside HSR dipole
- Downstream aperture dominated by
  - $p_T < 1.3$ GeV/c
  - 4 mrad neutrals
- Orient HSR magnets to maximize distance to ESR





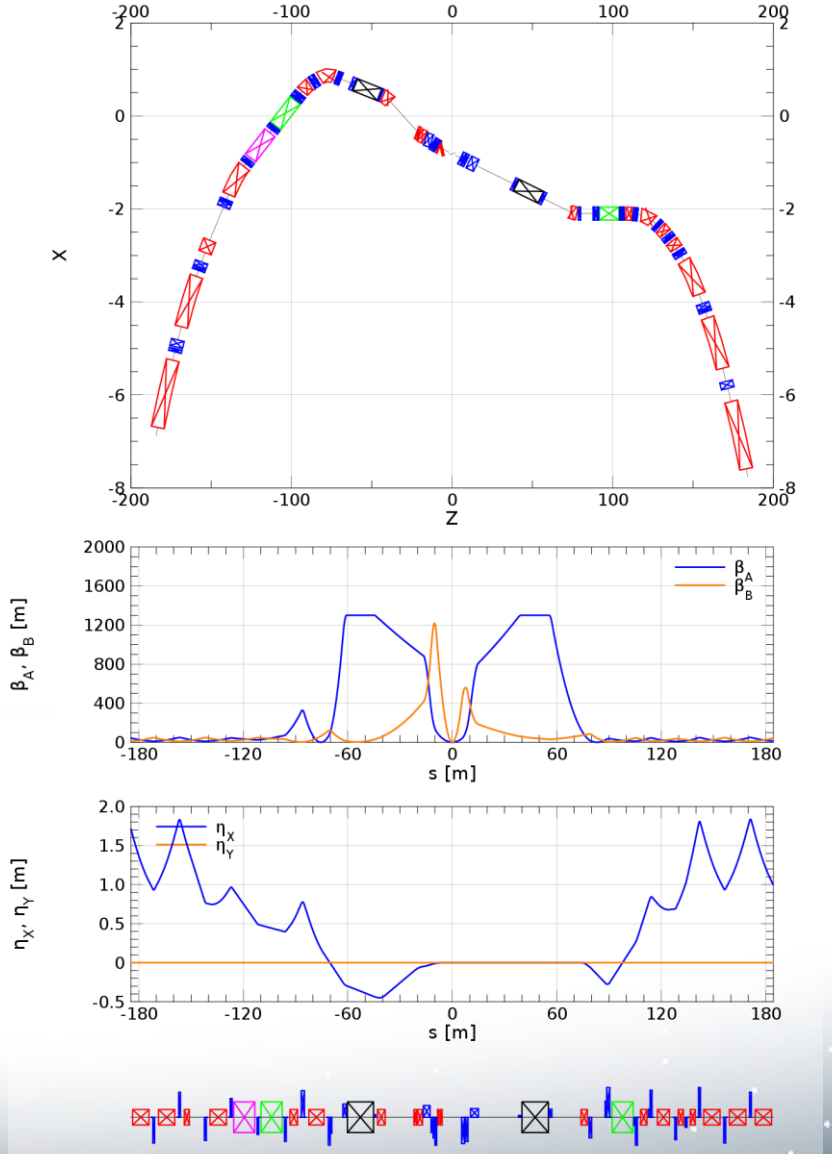
Spectrometer Dipole

- ESR quad inside spectrometer dipole
- Gradient on dipole to zero field at ESR
- ESR quad gives stray field on HSR



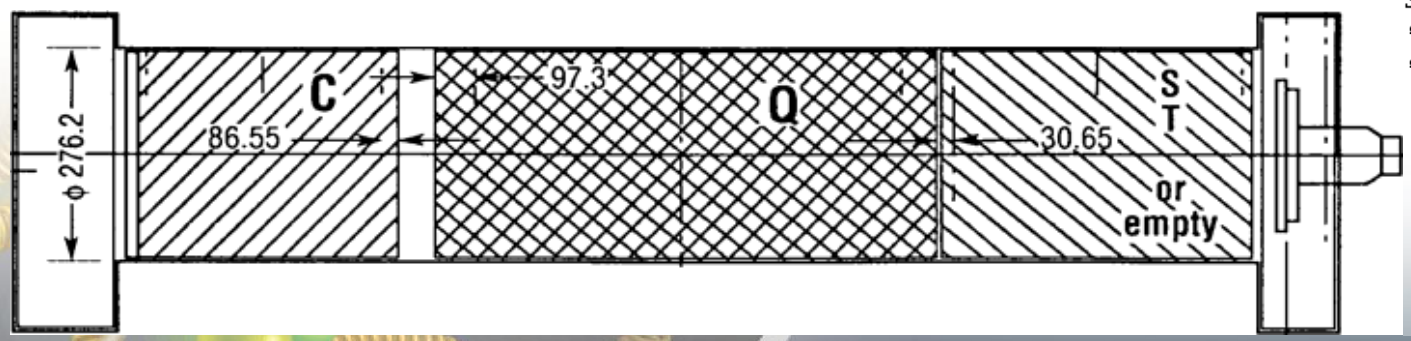
HSR Optics

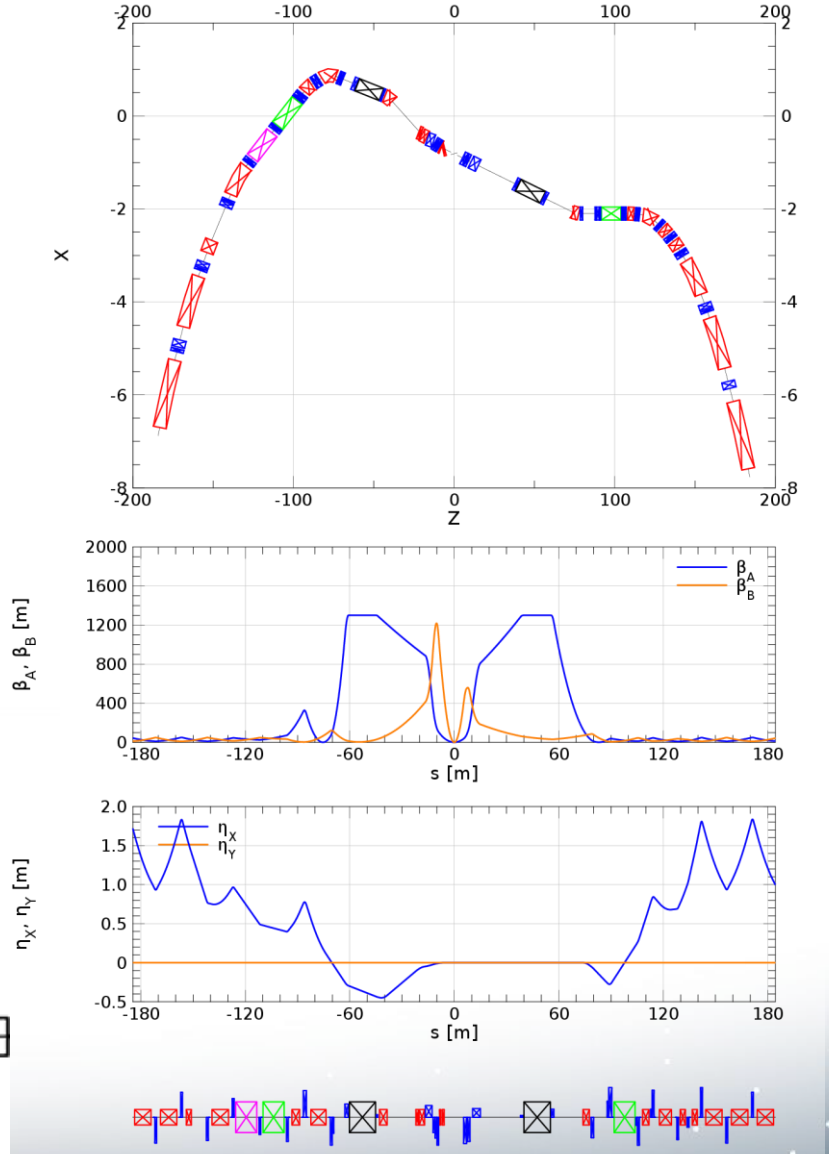
- Doublet focusing near IR, vertical focus first
- Dipoles near IR on forward side create dispersion amplitude
- β_x remains high to crab
  - Horizontal phase to crab naturally close to $\pi/2$
- Outside crabs, reduce β_x as gently as possible (chromaticity)
- Match RHIC arcs



HSR Optics

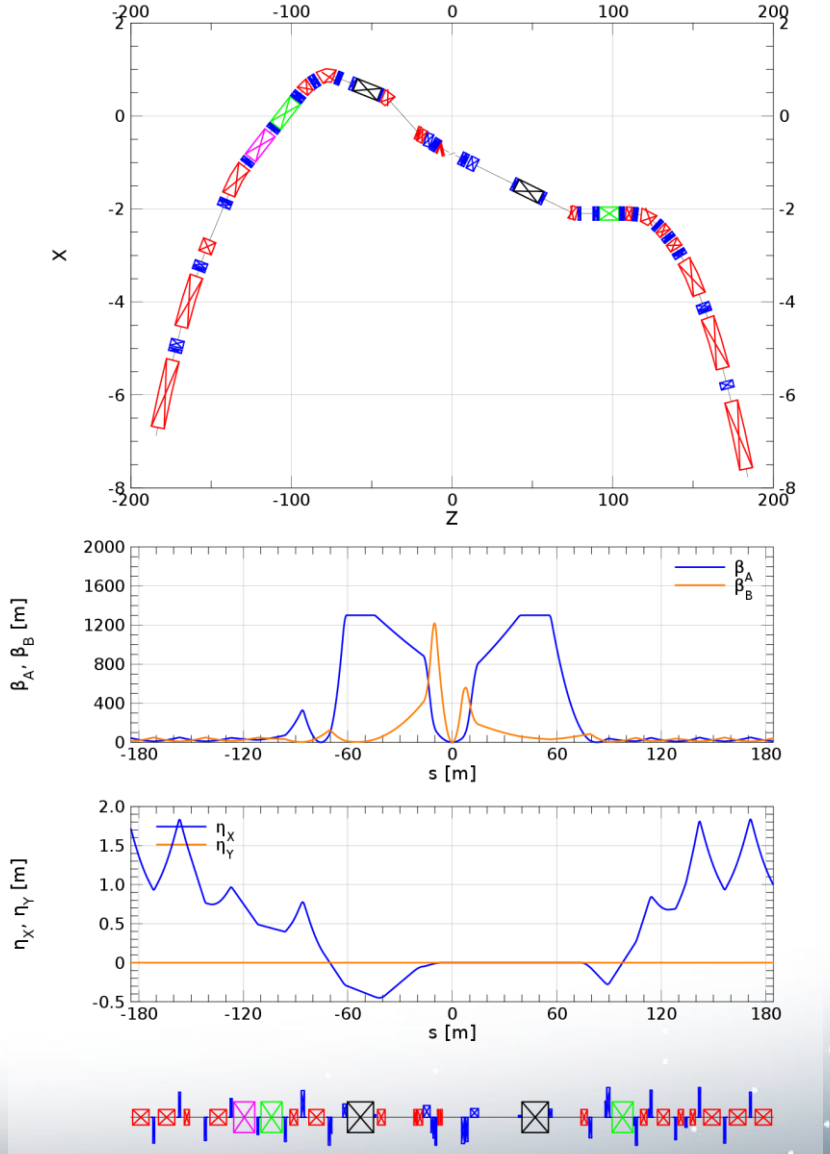
- Match using mostly RHIC magnets
- IP 81 cm inside RHIC IP, tilted
- Snake angle specified
- Two rotators, IP side of snake, ideally parallel
- IP to crab space: detectors
- Space very constrained





HSR Optics

- Two large-aperture high-field dipoles
  - One is near crab (aperture)
- Large-aperture iron quad on IP side of crab
- Re-cryostated RHIC IR quads (arc side of crab)

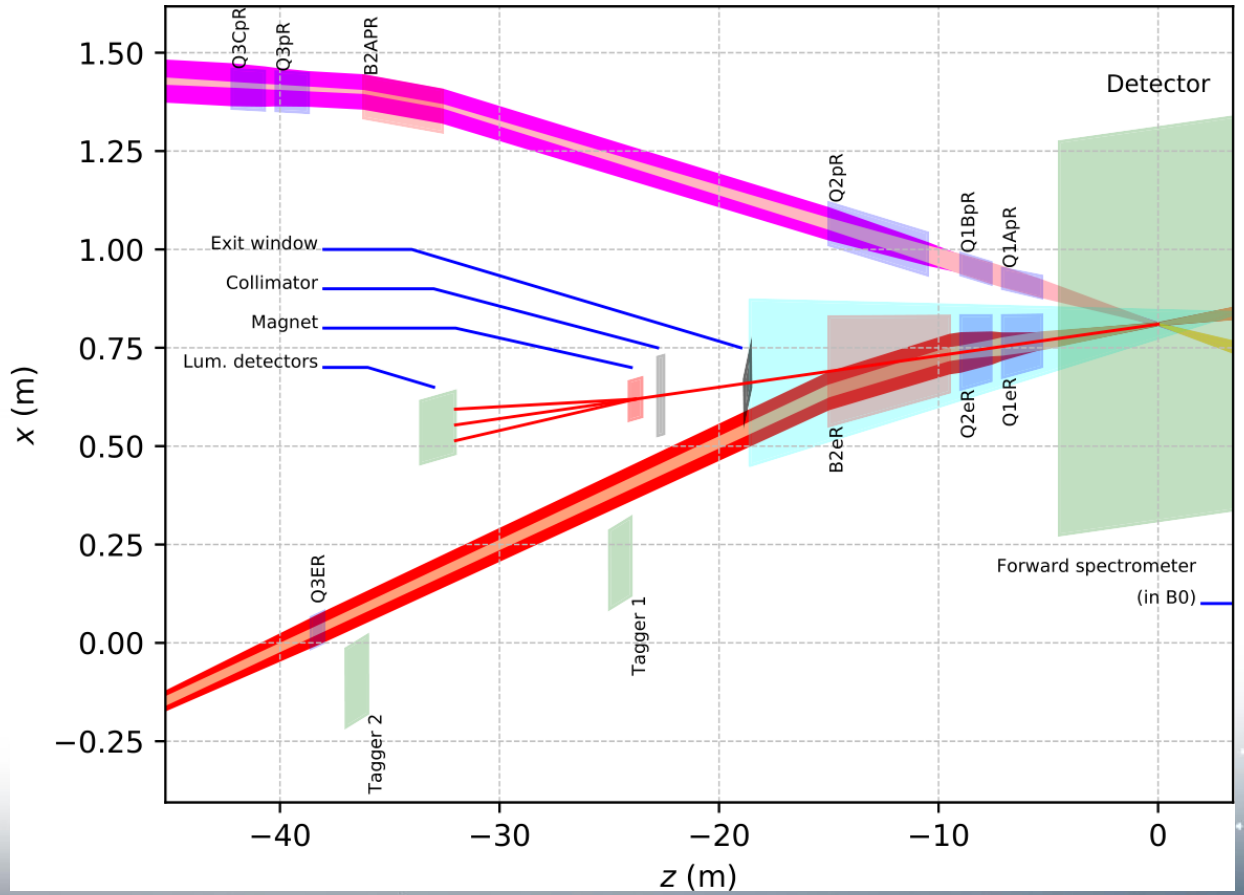


Crabbing Closure

- Phase advance between crabs 5° short of 180°. Leaves residual crabbing around the ring.
- Difficult/expensive to close in IR6
  - Almost no space available
  - Match heavily constrained
  - Could consider significant re-design of near IR
  - Could close with combination of IR6/IR8
  - Some ideas for using dispersion at accelerating at RF cavities to close, but lattice functions don’t look favorable
- Ongoing studies will determine whether closure is necessary

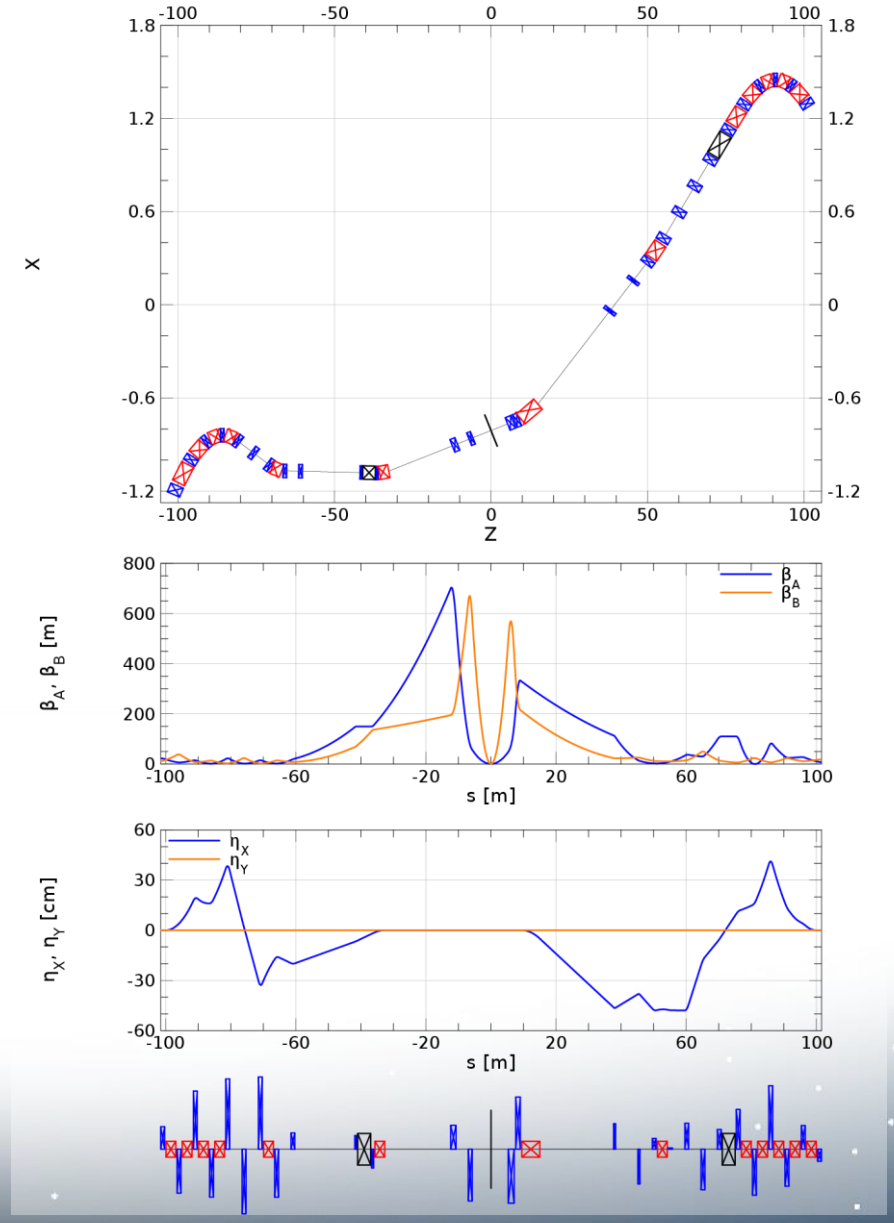
ESR Rear IR layout

- Dipole to separate beam from photons
- Photons used for luminosity monitoring
- Taggers for low-Q^2 electrons
- ESR magnets share yoke with HSR magnets



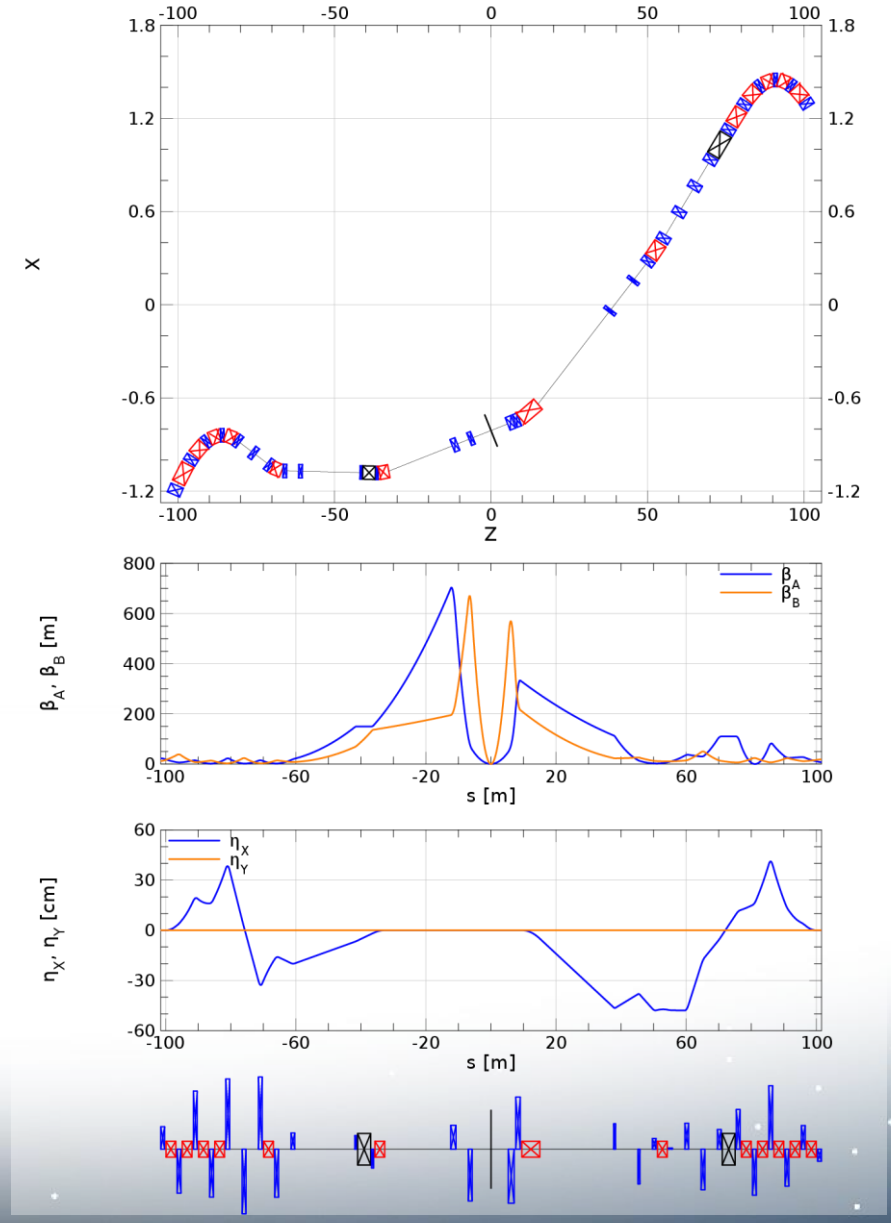
ESR Optics

- Doublet focusing near IR, vertical focus first
- Dipole in IR rear creates dispersion amplitude
- Horizontal phase of 2π between crabs
  - Phase to forward crab just above $\pi/2$
  - If $\pi/2$, β_x too high (transverse collective)
  - Rear crab far away to get $\approx 3\pi/2$
  - Polarimeter on forward side
- β_x forward stays above crab β_x
- Just outside crabs, reduce β_x gently (chromaticity)



ESR Optics

- Match very constrained, mainly by dispersion, especially rear
  - Zero dispersion at spin rotators
  - Horizontal phase advance constraint to crab
  - Geometric match forces (mostly) dipole layout
- Beta functions need to be raised for rear crab
  - Significant horizontal chromaticity generated near rear crab



ESR Spin Rotation

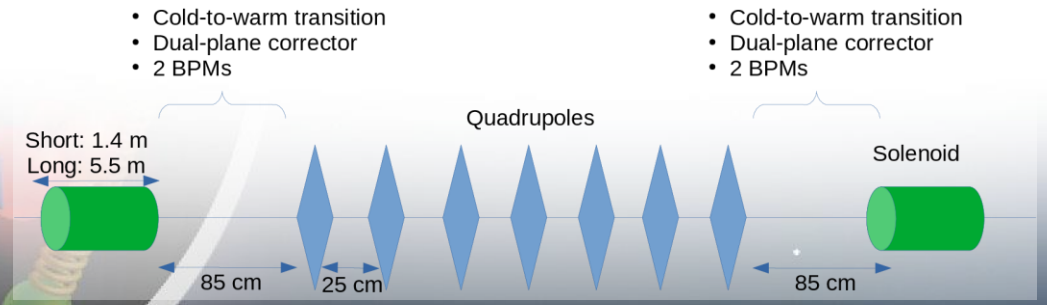
- Use solenoid modules to rotate spin from vertical to midplane
- Geometric angle from solenoids to IP set so spin is longitudinal at IP
  - One “long” solenoid module for 18 GeV
  - One “short” solenoid module for 6 GeV
  - Both used for 10 GeV
- 5 GeV won’t be perfectly longitudinal at the IP
  - Short solenoid module would need an even larger angle from the IP; geometry issues
  - Very close to having a full solution for this

ESR Spin Rotation

- Solenoid module consists of two solenoids, separated by 5–7 quadrupole
  - Transfer maps in two planes are negative of each other to decouple
  - In each plane, to remove dependence of spin on horizontal amplitude, map is of the form

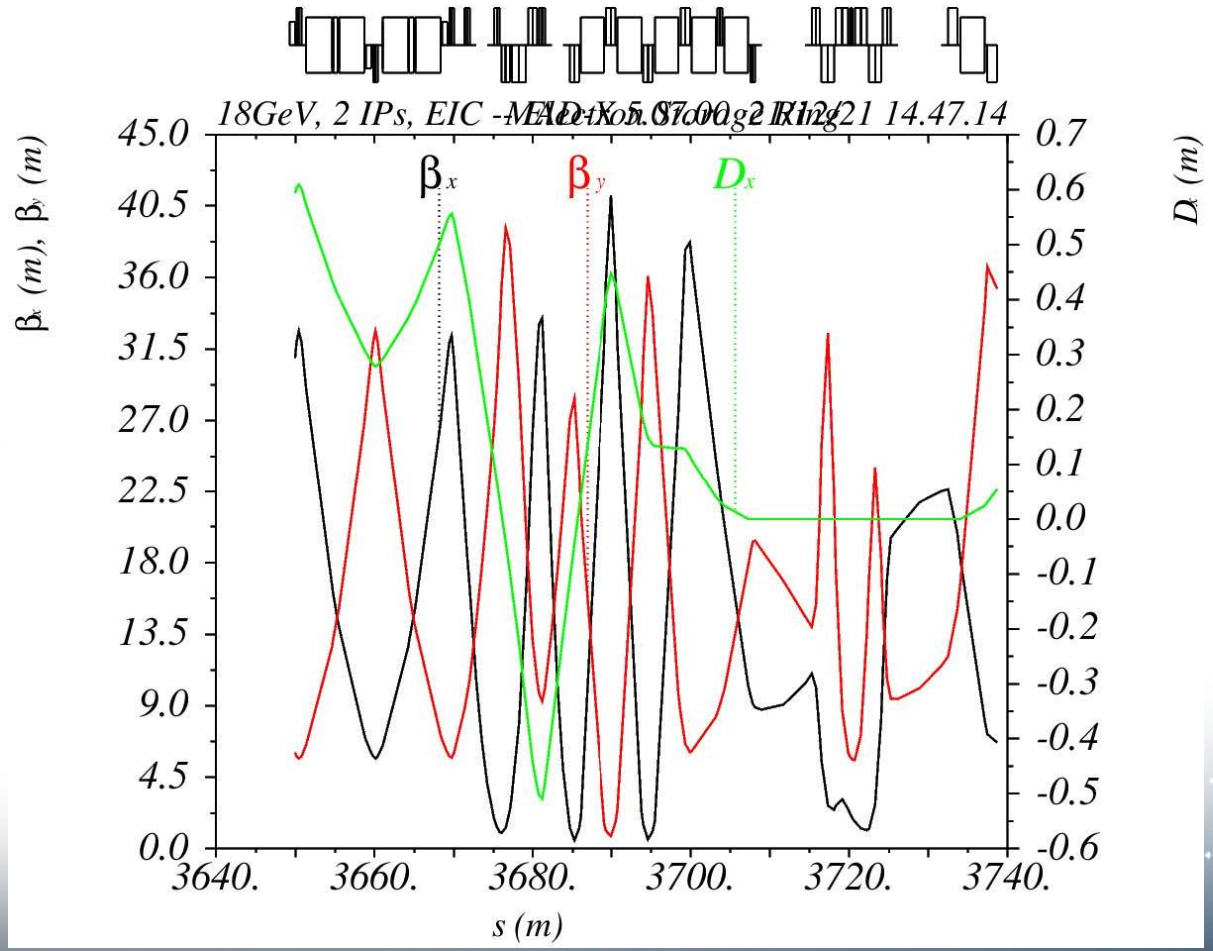
$$\begin{bmatrix} 0 & -2/|K_s| \\ |K_s|/2 & m_{22} \end{bmatrix}$$

  - Optimize to keep pole tip OK for warm quads, overall length (geometry)



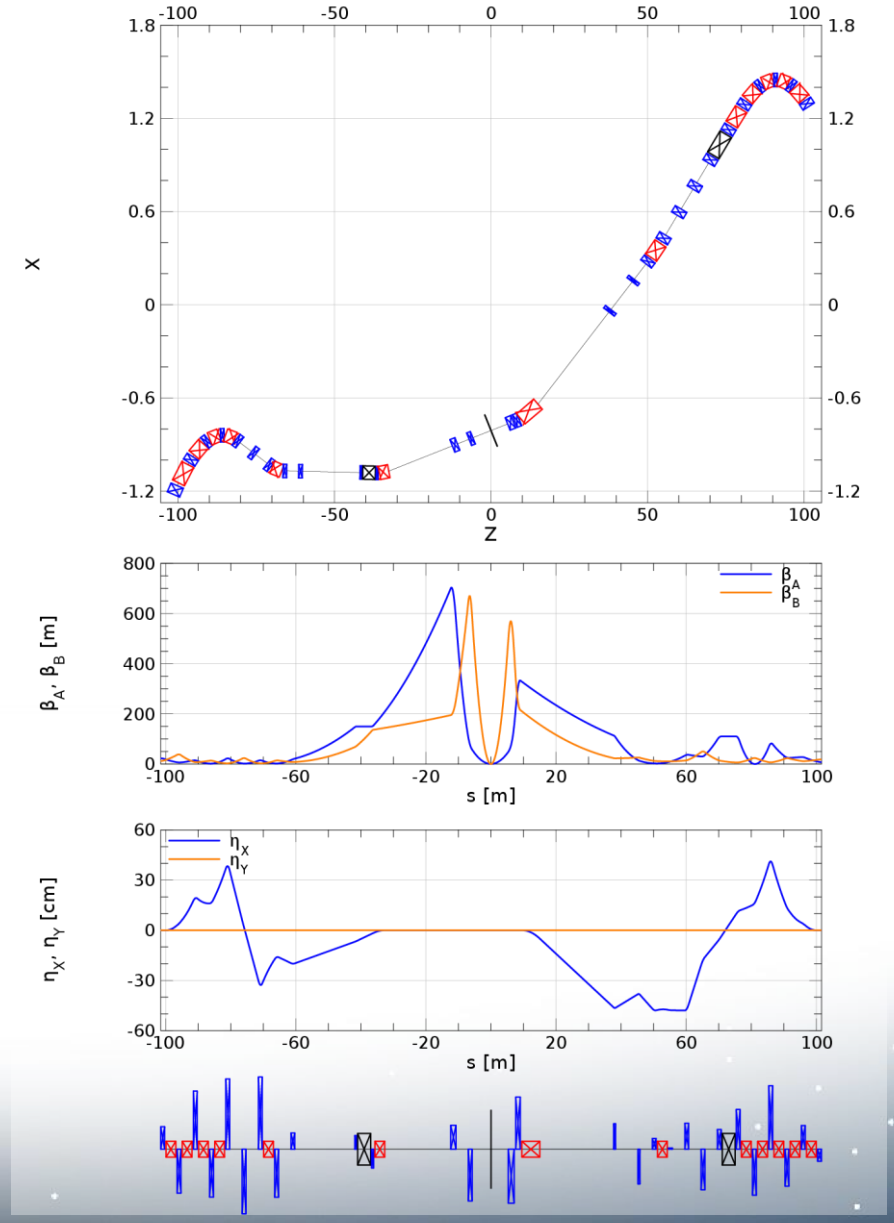
ESR Spin Rotation

- Ideally, zero dispersion in solenoids
  - For 10 and 18 GeV, zero dispersion in long solenoids
  - Small dispersion in short solenoids for 6 and 10 GeV (can't make it zero)
  - Match using end of arc and quadrupoles between rotator modules



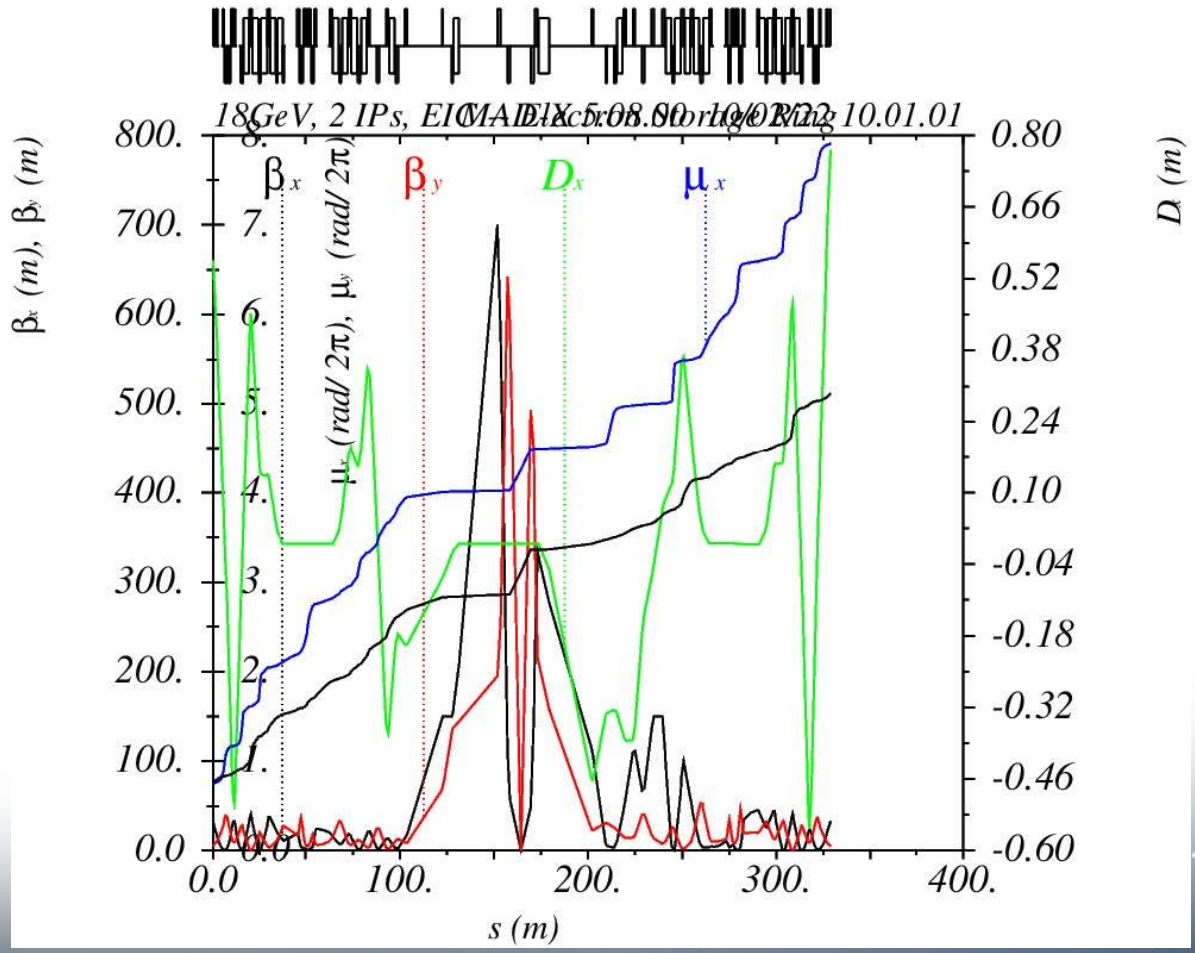
ESR Layout

- Spin rotator geometry is pretty rigid, fixed location and direction at end of long solenoid
- Significant bending required to steer beam to IP
- IP 81 cm inside of RHIC IP, plus horizontal tilt w.r.t. RHIC tunnel axis
- Dipoles sometimes placed to reduce dispersion amplitude rather than optimally for geometry



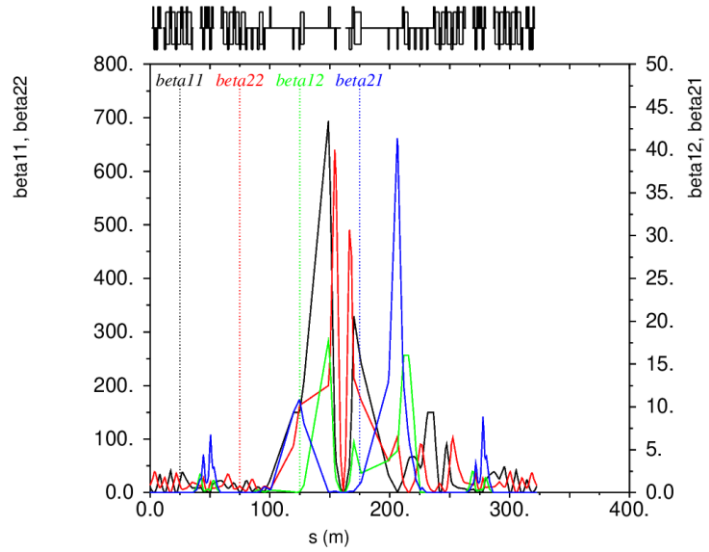
Phase to Arcs

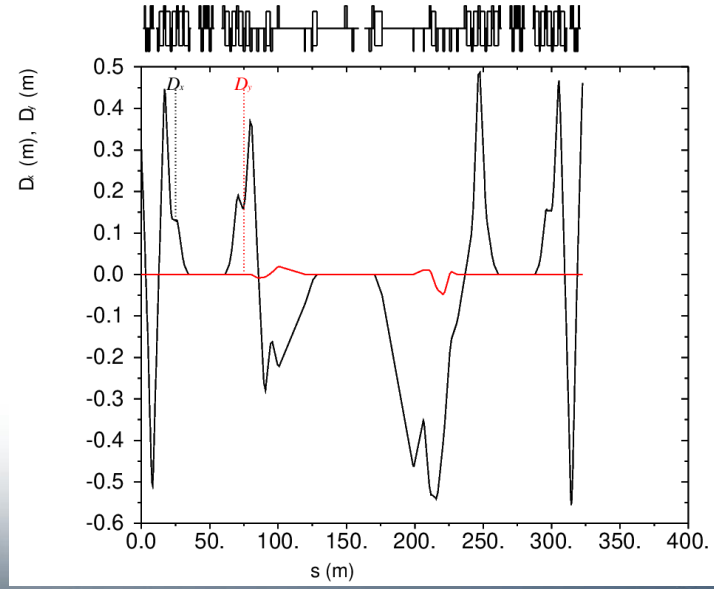
- To reduce chromatic functions in ring and improve DA, adjust phase advance between IP and arc
- Use combination of IR matching section and quads between rotator modules
- Since fit is very constrained, leads to increased beta functions and chromaticity



Solenoid Compensation

- Detector solenoid introduces coupling
- Coupling is corrected with skew quadrupoles
- ESR: one final focus quad has a skew quadrupole winding, then 7–8 other skew quadrupoles
- Need to correct
  - Linear coupling
  - Vertical dispersion
  - Vertical component of crabbing





Plots: V. Morozov

Solenoid Compensation

- HSR more complex
- Two skew quadrupoles (one a winding in a final focus dipole) between IP and crab cavities to remove vertical crabbing component
- Solenoid aligned to ESR, so need 2 skew dipoles to correct orbit before crab cavities (again, one in a final focus dipole)
- Insufficient skew quadrupoles available to correct coupling locally, will correct globally
- Work in progress

Summary

- Have IR lattice designs that
  - Meet physics requirements
  - Are matched into the rest of the ring
  - In HSR, match mostly with RHIC magnets
- Main challenges
  - Very tight on space
  - Constrained geometry and many horizontal constraints make dispersion matches challenging
- Study need for crab bump closure, find a solution if necessary
- Coupling from detector solenoid corrected for ESR, HSR will be done

Acknowledgements

- Other contributors: G. Hoffstaetter, J. Kewisch, C. Liu, D. Marx, V. Morozov, Y. Nosochkov, R. Palmer, B. Parker, V. Ptitsyn, M. Signorelli, S. Tepikian, H. Witte