Optics optimization in the EIC interaction region

Derong Xu on behalf of EIC lattice design

Brookhaven National Laboratory

Optics Tuning and Corrections for Future Colliders Workshop
CERN, Jun. 26 — 28, 2023

Electron-Ion Collider

Outline

1. EIC overview
2. Geometry Requirements
3. Beam optics matching
4. Crabbing correction
5. Summary
6. Discussion

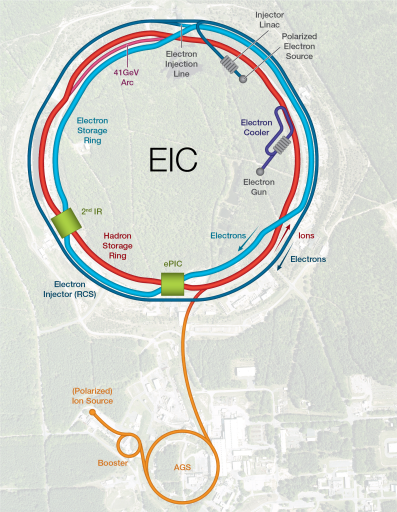
EIC overview

Design goals

- High luminosity: $10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (e-p)
- Center-of-mass energies: $29 - 140\ \mathrm{GeV}$
- Polarized proton and electron beams
- Large range of hadron species
- Possibility of 2nd IR

Major accelerator facilities

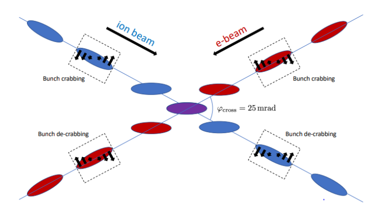
- Hadron Storage Ring (HSR): retain RHIC arcs from blue or yellow ring, but modify the insertions (IR)
- Electron Storage Ring (ESR): newly built, store polarized electron beams for colliding
- Rapid Cycling Synchrotron (RCS): newly built, serve as electron ramping, injection, and polarization



We will focus on HSR-ESR interaction region at 6 o'clock (IR6).

EIC overview

- Large crossing angle 25 mrad
- Local crab crossing: upstream and downstream crab cavities to restore effective head-on collision to compensate geometric luminosity loss
- Large beam-beam parameters, $\mathrm{e} \sim 0.1, \mathrm{p} \sim 0.015$, combination never experimentally demonstrated
- Flat beam $\sigma_y/\sigma_x = 0.09$ to achieve highest e-p luminosity $10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$. **1:10 emittance ratio has been demonstrated in RHIC recently**



Parameter	unit	proton	electron
Circumference	m	3833.8451	
Particle energy	GeV	275	10
Bunch intensity	10^{11}	0.6881	1.7203
# of bunches	-	1160	
Crossing angle	mrad	25	
β^* at IP [H/V]	cm	80/7.2	45/5.6
Beam sizes at IP [H/V]	µm	95/8.5	
Bunch length	cm	6.0	0.7
Energy spread	10^{-4}	6.6	5.5
Transverse tunes [H/V]	-	0.228/0.210	0.08/0.14
Longitudinal tune	-	−0.010	−0.069
Beam-beam parameter [H/V]	-	0.012/0.012	0.070/0.100
Luminosity	$\mathrm{cm}^{-2}\mathrm{s}^{-1}$	10^{34}	

The IR optics should be able to provide: (1) acceptable crabbing, (2) sufficient decoupling at IP, (3) flat beam optics $\beta_y^*/\beta_x^* < 0.1$

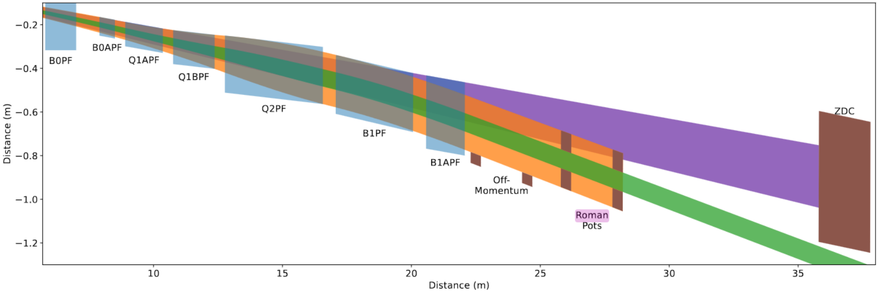
Geometry requirements

Forward side detectors: in the direction of hadron travel

- Center detector at IP: 5 m rear, 5.5 m forward stay clear
- Spectrometer: integrated with first forward hadron magnet
  - Capture large angle charged particles up to 20 mrad
  - Same field for all collision energies
  - The orbit of stored beam is corrected by following dipoles
- Zero-Degree Calorimeter (ZDC)
  - Detect neutral particles within a 4 mrad cone
  - Dipoles steer charged particles away from the ZDC
- Off-Momentum Detectors (OMD)
  - Measure charged particles from nuclear breakup events
  - Outside the beam pipe
  - Particles with smaller rigidity experience more bending, causing them to be deflected outside of the beam pipe
- Roman pots: detect scattered particles beyond 10σ

Geometry requirements

Forward side detectors: in the direction of hadron travel



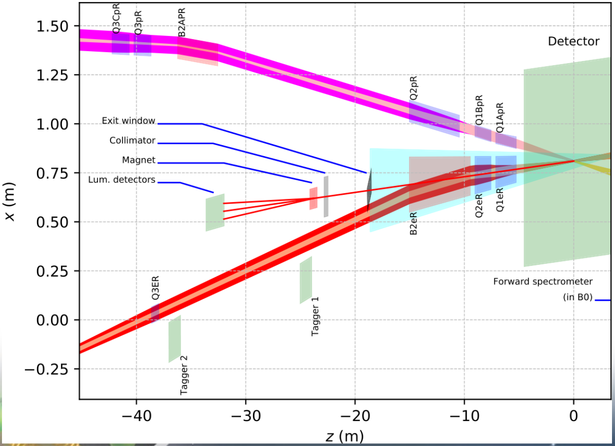
Green: 10 σ proton beam of 275 GeV; orange: protons with the transverse momentum at the IP below 1.3 GeV/c; violet: 4 mrad neutral cone [1]

[1] J. S. Berg et al., IPAC23, MOPL158

Geometry requirements

Rear side detectors: in the direction of electron travel

- Center detector at IP: 5 m rear, 5.5 m forward stay clear
- Luminosity monitor: detect Bethe-Heitler photons
- Taggers for low-Q^2 electrons



Geometry requirements

Spin manipulation: in HSR, snake and rotators are within IR; in ESR, solenoid rotators are located between the IR and the arcs

- HSR: snake (helical dipoles) at a specific geometric angle
- HSR: rotators (helical dipoles), one on each side of the IP
- ESR: solenoid spin rotators, on each side of the IP

Other engineering requirements

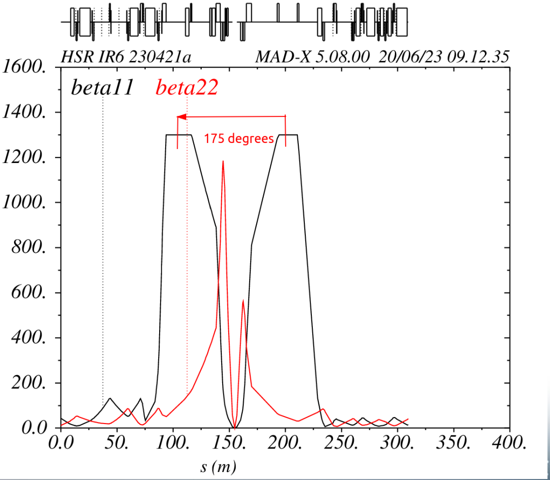
- HSR: use existing RHIC magnets as much as possible
- Minimize stray field from HSR on ESR (avoid nonlinear fields in ESR)
- IP shifted by 81 cm toward the center of RHIC to leave space for RCS

The dipoles are arranged to: (1) provide required crossing angle, (2) separate collision products from stored beam, (3) reserve space for detectors, spin rotators, snake, and crab cavities, (4) avoid geometry conflict

Beam optics matching

HSR optics at 275 GeV: hadron beam goes from right to left

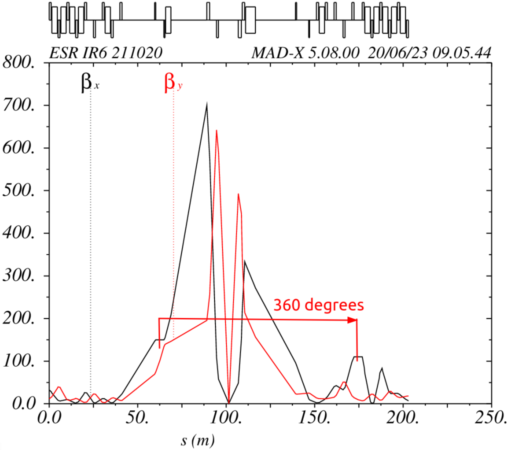
- The Twiss functions are matched to the arcs at both ends
- The IP is well decoupled and matched
- β_x remains high to crabs. Phase advance between crabs is 175° which leaves residual crabbing around the ring



Beam optics matching

ESR optics at 18 GeV: electron beam goes from left to right

- The Twiss functions are matched to Spin Rotators (solenoid module)
- The IP is well decoupled and matched
- β_x falls within the range of 110 $\sim$ 150 m at crabs. Phase advance between crabs is exactly 360°. The phase advance from upstream crab cavity to IP is 91.3°

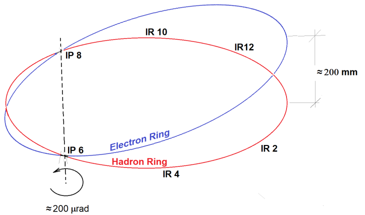


Note: the electron working point is $(0.08, 0.14, -0.069)$, determined by beam-beam and polarization study

Crabbing correction

Systematic distortion to the crabbing

- The crabbing closure in HSR
- The center detector solenoid introduces the vertical crabbing
- The tilted ESR introduces the vertical crabbing [2]

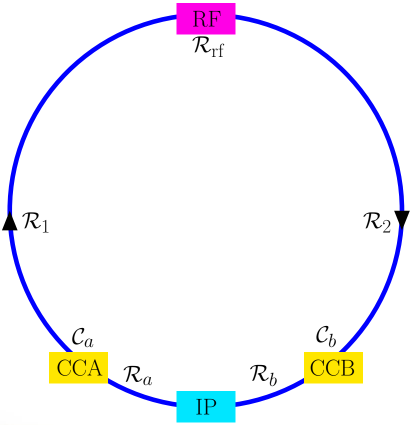


- The interplay between momentum and crabbing dispersion: the momentum dispersion cannot be suppressed at RF cavity and crab cavities

[2] D. Xu et al., IPAC22, WEPOPT049

Crabbing correction

A simple accelerator model with RF cavity and crab cavities [3]



When the crab cavities are turned off

$$\mathcal{R}_t = \mathcal{R}_b \mathcal{R}_2 \mathcal{R}_{\rm rf} \mathcal{R}_1 \mathcal{R}_a \tag{1}$$

When the crab cavities are turned on, the one-turn transfer matrix before collision is

$$\mathcal{R}_{t,b} = \mathcal{R}_b \mathcal{C}_b \mathcal{R}_b^{-1} \mathcal{R}_t \mathcal{R}_a^{-1} \mathcal{C}_a \mathcal{R}_a \tag{2}$$

To provide an effective head-on collision

$$\boldsymbol{\zeta}_b^* = (-\theta_c, 0, 0, 0)^{\rm T}, \ \boldsymbol{\eta}_b^* = \mathbf{0}_{4\times 1} \tag{3}$$

The one-turn transfer matrix after collision is

$$\mathcal{R}_{t,a} = \mathcal{R}_a^{-1} \mathcal{C}_a \mathcal{R}_a \mathcal{R}_b \mathcal{C}_b \mathcal{R}^{-1} \mathcal{R}_t \tag{4}$$

Closing the crab and momentum dispersion

$$\boldsymbol{\zeta}_a^* = \mathbf{0}_{4\times 1}, \ \boldsymbol{\eta}_a^* = \mathbf{0}_{4\times 1} \tag{5}$$

The beam optics is matched with crab cavities off. However, the linear beam optics is affected by the crab cavity. There are not enough knobs to perfectly match $\boldsymbol{\zeta}_b^*, \boldsymbol{\zeta}_a^*, \boldsymbol{\eta}_b^*$ and $\boldsymbol{\eta}_a^*$ in both ESR and HSR

[3] D. Xu et al., Phys. Rev. Accel. Beams 25, 071002

Crabbing correction in ESR

Problems

- The phase advance between crab cavities cannot be matched to 180°
- The tilted ESR and detector solenoid generate vertical crabbing

Solutions [4]

- Moving rear side crab to $\sim 270^\circ$ so that the phase advance between upstream and downstream crab cavities is exactly 360°
- Introducing vertical crabbing by using skew windings on quadrupoles between IP and crab cavities

The dispersion in ESR is matched to

$$\zeta_b^* = (-\theta_c, X, 0, 0)^{\mathrm{T}}, \quad \boldsymbol{\eta}_b^* \approx \mathbf{0}_{4\times 1}, \quad \zeta_a^* = (0,0,0,0)^{\mathrm{T}}, \quad \boldsymbol{\eta}_a^* \approx \mathbf{0}_{4\times 1}$$

Out of crab cavities, skew quadrupole windings are employed to finish betatron decoupling [5]

[4] D. Xu et al., IPAC22, WEPOPT050

[5] B. R. Gamage et al., IPAC21, TUPAB041

Crabbing correction in ESR

Detailed compensation scheme for ESR [6]

- Constraints per Derong's scheme (36 in total, 16 related to coupling):

  At the crab cavities: $\beta_x = 150$ m, $\alpha_x = 0$

  Transverse decoupling at IP: $M_{13}^{in\to IP} = 0$, $M_{14}^{in\to IP} = 0$, $M_{23}^{in\to IP} = 0$, $M_{24}^{in\to IP} = 0$

  Dispersion suppression at IP: $D_x = D_y = 0$ m, $D'_x = D'_y = 0$

  Optics fixed at IP: $\beta_x^{IP} = const$, $\beta_y^{IP} = const$, $\alpha_x^{IP} = \alpha_y^{IP} = 0$

  Optics at the entrance and exit of the IR fixed: $\beta_{x,y}^{in}$, $\alpha_{x,y}^{in}$, D_x^{in}, $D_x'^{\,in}$, $\beta_{x,y}^{out}$, $\alpha_{x,y}^{out}$, D_x^{out}, $D_x'^{\,out}$ all fixed, $D_y^{in,out} = 0$ m, $D_y'^{\,in,out} = 0$

  Betatron phase advance across the IR is fixed: $\mu_{x,y}^{in\to out} = const$

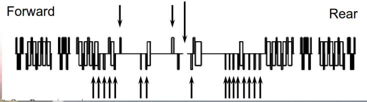
  IR transversely decoupled: $M_{13}^{in\to out} = 0$, $M_{14}^{in\to out} = 0$, $M_{23}^{in\to out} = 0$, $M_{24}^{in\to out} = 0$

  Crabbing correction: $|M_{22}^{crab\to IP}| < 0.4$, $M_{32}^{crab\to IP} = 0$, $M_{42}^{crab\to IP} = 0$, $M_{12}^{crab\to crab} = 0$, $M_{32}^{crab\to crab} = 0$, $M_{42}^{crab\to crab} = 0$

- Variables (45 in total):

  13 normal + 9 skew quad strengths in the forward direction

  16 normal + 9 skew quad strengths in the rear direction



[6] V. S. Morozov, May 26, 2023, presented at EIC IR weekly design meeting

Crabbing correction in HSR

Crabbing closure in HSR

- The crab dispersion cannot be closed by the upstream and downstream crab cavities themselves — the phase advance between them is 175°
- Possible solution 1: install additional crab cavity out of IR6
- Possible solution 2: excite momentum dispersion at RF cavity to close the crab dispersion [7]
- Possible solution 3: live with the crabbing leakage, but match the following condition for beam-beam performance

$$\boldsymbol{\zeta}_b^* = (-\theta_c, 0, 0, 0)^{\mathrm{T}}, \ \boldsymbol{\eta}_b^* = \mathbf{0}_{4\times 1}$$

Correction of vertical crabbing due to transverse coupling in HSR

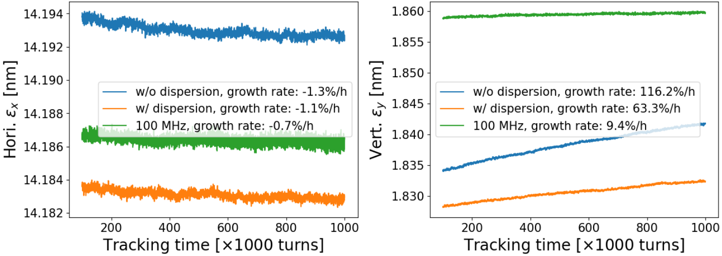
- Possible solution 1: install skew winding on quadrupoles between crab cavities and IP — less nonlinear crabbing tail [8] in vertical
- Possible solution 2: rotate CC cryomodules — independent knobs

[7] D. Xu et al., IPAC23, MOPA040

[8] D. Xu et al., Phys. Rev. Accel. Beams 24, 041002

Crabbing correction in HSR

Weak-strong simulation for global crabbing scheme, including tilted ESR and detector solenoid. The vertical CC is used to correct vertical crabbing. left: horizontal emittance evolution, right: vertical emittance evolution



Blue: after correction, $\boldsymbol{\zeta}_b^* = (-\theta_c, 0, 0, 0)^{\mathrm{T}}$, $\boldsymbol{\eta}_b^* \approx \mathbf{0}_{4\times1}$
Orange: after correction, $\boldsymbol{\zeta}_b^* = (-\theta_c, 0, 0, 0)^{\mathrm{T}}$, $\boldsymbol{\eta}_b^* = \mathbf{0}_{4\times1}$
Green: same as orange, but the frequency of vertical crab cavity is halved

The momentum dispersion should be corrected after the crab cavities turned on. The nonlinear crabbing tail leads to vertical emittance growth.

Summary

Have IR lattice designs that

- Meet physics requirements
- Match the required optics for crab crossing collison
- Are matched into the rest of the ring

The crabbing control presents a considerable challenge

- A solution has been found for the ESR to close and correct the crabbing within IR. The solution has undergone multiple iterations in tandem with the evolution of the ESR lattice.
- The study for the HSR is in progress. The global crabbing scheme has been tested by weak-strong simulation. The crabbing control in the HSR may be integrated with the global decoupling system

The EIC IR is very tight on space. Knobs outside of IR handle nonlinear optimization in ESR [9] and HSR [10]

[9] Y. Cai et al., Phys. Rev. Accel. Beams 25, 071001

[10] Y. Luo et al., IPAC22, WEPOPT037

Discussion — crabbing tuning in real machine

Knobs to control crabbing

- Upstream and downstream crab cavity voltages
- Quadrupoles in IR, including skew windings

Observable

- BPM, luminosity...
- Possible hardware to measure crabbing: head-tail monitor in hadron machine [11], and synchrotron light monitor in electron machine [12]

Objectives

- Crabbing closure in ESR due to the working point $(0.08, 0.14, -0.069)$
- Required crabbing and momentum dispersion before collision in HSR

Problem: the hardware cannot provide enough observable

- Restore linear 6D model at IP from turn-by-turn data?

For further discussion, please contact: dxu@bnl.gov

[11] R. Calaga et al., Phys. Rev. Accel. Beams 24, 062001, First demonstration of the use of crab cavities on hadron beams

[12] H. Ikeda et al, PAC07, Crabbing angle measurement by streak camera at KEKB

Acknowledgement

- J.S. Berg, M. Blaskiewicz, A. Drees, X. Gu, C. Liu, H. Lovelace III, Y. Luo, D. Marx, C. Montag, S. Peggs, V. Ranjbar, N. Tsoupas, P. Vadim, M. Valette, F. Willeke (BNL)
- E. Gianfelice-Wendt (FNAL)
- Y. Hao (MSU)
- V. Morozov (ORNL)
- B. R. Gamage, T. Satogata (TJNAF)

Thank you for your attention.