Luminosity tuning for future Electron-Ion Collider

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Electron-Ion Collider

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Outline

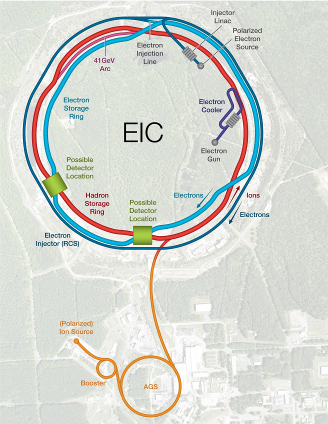
Introduction — Electron Ion Collider (EIC)

Science goals

- How does the mass of the nucleon arise?
- How does the spin of the nucleon arise?
- What are the emergent properties of dense systems of gluons?

Design goals

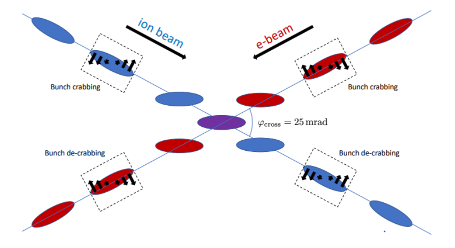
- High luminosity: $10^{33} - 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- center-of-mass energies: $20 - 140\ \mathrm{GeV}$
- Polarized proton and electron beams: 70%
- Large range of hadron species: Proton - Uranium
- Possibility of 2nd IR



HSR — Hadron Storage Ring
ESR — Electron Storage Ring
RCS — Rapid Cycling Synchrotron

Introduction — EIC beam-beam features

- 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 $10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$



Parameter	unit	proton	electron
Circumference	m	3833.8451	
Particle energy	GeV	275	10
Bunch intensity	10^{11}	0.668	1.72
# of Bunches	-	1160	
Crossing angle	mrad	25	
β^* at IP	cm	80/7.2	45/5.6
Beam sizes at IP	μm	95/8.5	
Bunch length	cm	6	2
Energy spread	10^{-4}	6.6	5.5
Transverse tunes	-	0.228/0.210	0.08/0.06
Longitudinal tune	-	0.01	0.069
BB parameter	-	0.012/0.012	0.07/0.10
Luminosity	$\mathrm{cm}^{-2}\mathrm{s}^{-1}$	10^{34}	

Crab dispersion tuning — Crab cavity

Crab cavities introduce $z-$dependent transverse kick

$$\zeta = \left(\frac{\partial x}{\partial z}, \frac{\partial x'}{\partial z}, \frac{\partial y}{\partial z}, \frac{\partial y'}{\partial z}\right)^{\mathrm{T}}$$

Sinusoidal kick from a thin crab cavity

$$\Delta p_x = -\frac{\theta_c}{k_c \Lambda}\sin(k_c z), \qquad \Delta p_z = -\frac{x\theta_c}{\Lambda}\cos(k_c z)$$

To the first order, $\zeta = (0, -\theta_c/\Lambda, 0, 0)^{\mathrm{T}}$

- Ideally, two thin crab cavities apart with $n\pi$ phase advance form a **closed crab dispersion bump**
- At the momentum dispersion free section, the crab dispersion is propagated by $\zeta_2 = M\zeta_1$

Crab dispersion tuning — Crab dispersion

When both momentum and crab dispersion are present, the transverse and longitudinal motion can be decoupled via two successive transformation [1]

$$\begin{bmatrix} x \\ p_x \\ y \\ p_y \\ z \\ \delta \end{bmatrix} = \begin{bmatrix} \mathbf{1}_{4\times4} & \mathbf{0}_{4\times1} & \boldsymbol{\eta} \\ -(J\boldsymbol{\eta})^{\mathrm{T}} & 1 & 0 \\ \mathbf{0}_{1\times4} & 0 & 1 \end{bmatrix} \begin{bmatrix} \mathbf{1}_{4\times4} & \boldsymbol{\zeta} & \mathbf{0}_{4\times1} \\ \mathbf{0}_{1\times4} & 1 & 0 \\ (J\boldsymbol{\zeta})^{\mathrm{T}} & 0 & 1 \end{bmatrix} \begin{bmatrix} \bar{x} \\ \bar{p}_x \\ \bar{y} \\ \bar{p}_y \\ \bar{z} \\ \bar{\delta} \end{bmatrix}$$

- There are other methods to diagonalize the linear transfer matrix
- $\boldsymbol{\eta}$ — momentum dispersion, $\boldsymbol{\zeta}$ — crab dispersion
- The transverse coordinate

$$\mathbf{X} = \ldots + \boldsymbol{\zeta}\bar{z} + \boldsymbol{\eta}\bar{\delta}$$

[1] D. Xu et al., Combined effects of crab dispersion and momentum dispersion in colliders with local crab crossing scheme

Crab dispersion tuning — Requirement

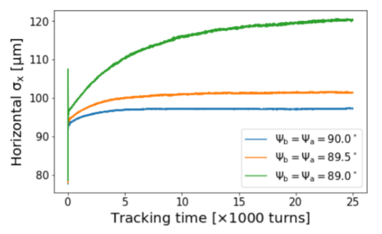
Before collision — requirement from the crossing angle

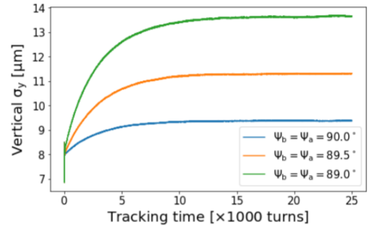
$$\zeta^* = (12.5\ \mathrm{mrad}, 0, 0, 0)$$

Out of crab cavity bump — linear synchro-betatron resonances if the crab dispersion leaks out of IR, possible reduction of DA

$$\zeta = (0, 0, 0, 0)$$

An example: non-ideal phase advance between crab cavities





Non-closed crab dispersion bump reduces the luminosity

Crab dispersion tuning — Distortions and knobs

Distortions

- Detector solenoid — vertical crabbing
- Tilted ESR — vertical crabbing
- Magnet errors between crab cavities — crab dispersion leakage
- The non-zero momentum dispersion at crab cavities or RF cavities — additional crab dispersion sources

Knobs

- Upstream and downstream crab cavity voltages
- Quadrupole strength, including skew components to correct vertical crabbing, between crab cavities

The transfer matrix from upstream crab cavitiy to IP (M), and to downstream crab cavity (N), have to be matched [1]

$$M = \begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & 0 & m_{23} & m_{24} \\ m_{31} & 0 & m_{33} & m_{34} \\ m_{41} & 0 & m_{43} & m_{44} \end{bmatrix} \quad N = \begin{bmatrix} n_{11} & 0 & n_{13} & n_{14} \\ n_{21} & n_{22} & n_{23} & n_{24} \\ n_{31} & 0 & n_{33} & n_{34} \\ n_{41} & 0 & n_{43} & n_{44} \end{bmatrix}$$

[1] D. Xu et al., Detector solenoid compensation in the EIC Electron Storage Ring

Crab dispersion tuning — What is observable

How to measure the crab dispersion when tuning the knobs

- New hardware: head-tail monitor in hadron machine (test in SPS [1]), and synchrotron light monitor in electron machine [2]
- The crab dispersion closure is important in both ESR and HSR. Is turn-by-turn data available to recognize the crab dispersion?

$$\mathbf{X} = ... + \boldsymbol{\zeta}\overline{z} + \boldsymbol{\eta}\overline{\delta}$$

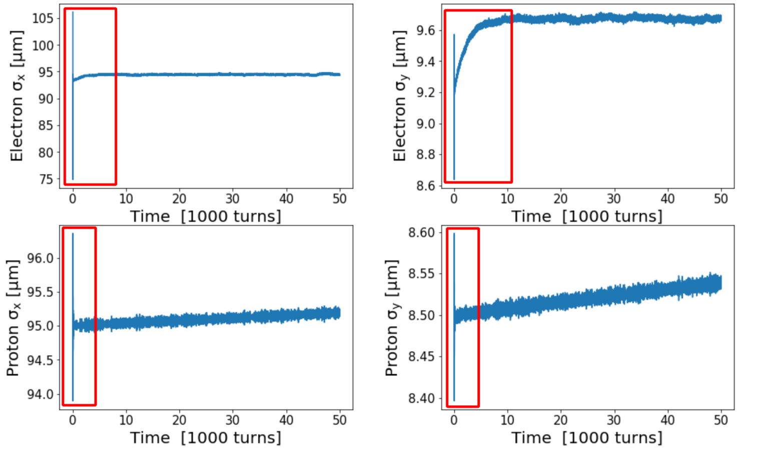
  Assuming the beam is stored with an momentum offset, a BPM at momentum dispersion free section may be reactive to non-zero crab dispersion

- The Bayesian approach [3]may be helpful to fit the crab dispersion

[1] R. Calaga et al., First demonstration of the use of crab cavities on hadron beams
[2] H. Ikeda et al., Crabbing angle measurement by streak camera at KEKB
[3] Y. Li et al., Bayesian approach for linear optics correction

Peak luminosity prediction — Simulation

Beam size evolution by strong-strong simulation



Fast change in the first few thousand turns

Peak luminosity prediction — Possible reasons

Possible reasons in a simple model

- Dynamic β
- Resonances
- Coherent motion
- Synchrotron radiation

Potential cross talk between beam-beam and other effects in real machines

- Impedance
- Magnet non-linearity
- Space charge
- ...

There is no analytical formula available to predict the equilibrium yet. Currently, in simulation, a trial-and-error tuning is needed to get the optimal parameter set.

Peak luminosity prediction — Surrogate model

A Gaussian process surrogate model may be useful to determine the peak luminosity or equilibrium sizes

Possible inputs	Parameter count
Twiss functions at IP (3 planes)	12
Emittance in 3 planes	6
Beam current	2
Crab cavity setup	2
Working points?	6

- Assuming constant beam distribution which is modeled by 6-D sizes
- Each input in above table is actually controlled by a complex physical system which consists of numerous knobs
- Different working point means different resonance model. Can we take the working point as an effective input?

It is time consuming to get a data point in both simulation and operation.

Luminosity lifetime prediction — Modeling

In Electron Storage Ring (ESR)

- Radiation damping time — 50 ms, which beam-beam relies on heavily
- Emittance growth time due to IBS — $\sim$ minutes
- Touschek lifetime — a few hours
- Polarization lifetime — $\sim$ minutes, which requires swap-out injection frequently

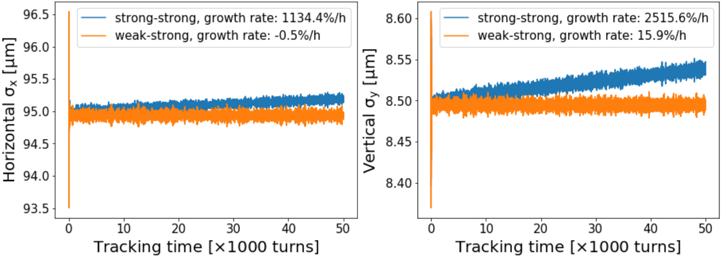
In Hadron Storage Ring (HSR)

- Setup time — typically one hour
- Hadron beam storage time — $\geq$ 8 hours
- IBS growth time for the high luminosity parameters — 3.4 hours in longitudinal plane and 2.0 hours in horizontal plane
- Required cooling time — $\leq$ 2 hours

Strong Hadron Cooling is still under study. It is desirable that beam-beam doesn't cause significant emittance growth during whole storage time

Luminosity lifetime prediction — Noise vs growth

Proton beam size evolution by weak-strong and strong-strong simulation



- The significant growth in strong-strong simulation is mainly caused by numerical noise which is the nature of particle-in-cell (PIC) method
- The numerical noise can only be reduced by using more macro-particles, more slices, and larger grids — simulation time is too long

Can we replace the PIC solver by a neural network? Possible input: (1) $\sim 10^6$ particle coordinates, (2) moments, $< x >, < x^2 >, < x^3 > \ldots$

Online optimization

The peak luminosity and luminosity lifetime depends on many sub-systems

- The optimization of beam-beam parameters: high peak luminosity vs less emittance growth rate
- Dynamic aperture: 10 σ for ESR design, and 5 σ for HSR design, re-optimization is needed in the real machine by available sextupoles [1]
- Orbit ripple: amplitude should be suppressed at the betatron frequency and its harmonic
- Strong hadron cooling: electron quality, hadron/electron optics at overlap section

The luminosity lifetime tuning is complex task. The target is **changing with time**, and **full of noise**. The variable space is **high-dimensional**. The online optimization may be needed.

[1] D. Marx et al., this workshop, Optimization of Dynamic Aperture for EIC

Summary

EIC is still in the design process. Our motivation is to find possible methods to tune or operate future machine. Otherwise, we will have to modify our design

- Crab dispersion tuning — problem: how to measure crab dispersion, possible method: new hardware + turn by turn data analysis
- Peak luminosity prediction — problem: unable to predict the equilibrium state with beam-beam, possible method: Gaussian process surrogate model
- Luminosity lifetime prediction — problem: large numeric noise causing artificial growth, the optimization goal is noisy and dynamic, possible method: replacing PIC solver by a neural network
- Online optimization — problem: too many knobs, the optimization goal is noisy and dynamic, possible method: online optimization

Thank you for your attention.