EIC Beam Dynamics Challenges

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Electron-Ion Collider

BROOKHAVEN NATIONAL LABORATORY · Jefferson Lab · U.S. DEPARTMENT OF ENERGY · Office of Science

Outline

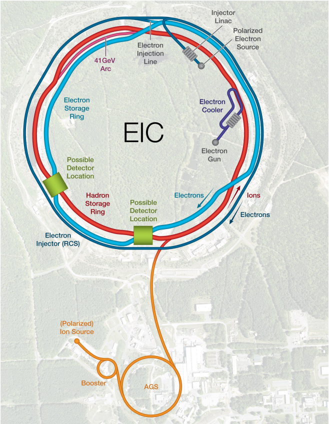
Introduction — Electron Ion Collider

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

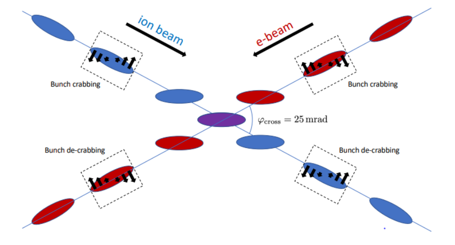
- High luminosity: $10^{33} - 10^{34}\ \mathrm{cm^{-2}s^{-1}}$
- center-of-mass energies: $20 - 140\ \mathrm{GeV}$
- Polarized proton and electron beams: 70%
- Large range of hadron species: Proton - Uranium
- Possibility of 2nd IR



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

Luminosity — Overview

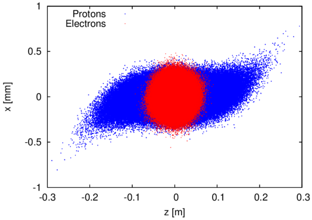
- Large crossing angle 25 mrad, fast separation to avoid parasitic collision
- Local crab crossing: upstream and downstream crab cavities to restore effective head-on collision to compensate geometric luminosity loss
- Large beam-beam parameters, $\mathrm{e} \sim 0.1, \mathrm{p} \sim 0.015$, combination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

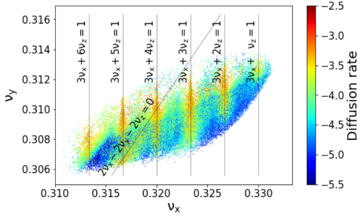


Parameter	unit	proton	electron
Circumference	m	3833.8451	
Particle energy	GeV	275	10
Bunch intensity	10^{11}	0.668	1.72
# of Bunches	-	1160	
Crossing angle	mrad	25	
β^* at IP	cm	80/7.2	45/5.6
Beam sizes at IP	µm	95/8.5	
Bunch length	cm	6	2
Energy spread	10^{-4}	6.6	5.5
Transverse tunes	-	0.228/0.210	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}	

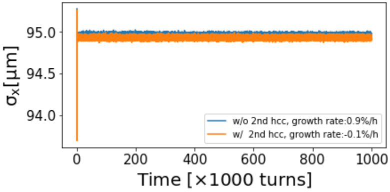
Luminosity — Synchro-betatron resonances (SBR)

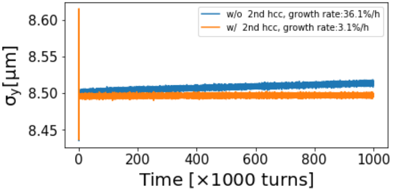
- Crabbed offset, due to sinusoidal kick from the crab cavities, drives higher-order SBR in the proton beam $\Delta x = -\theta_c \left[\sin(k_c z)/k_c - z\right]$
- $\nu_x = 0.228, \nu_y = 0.210$ to mitigate SBR





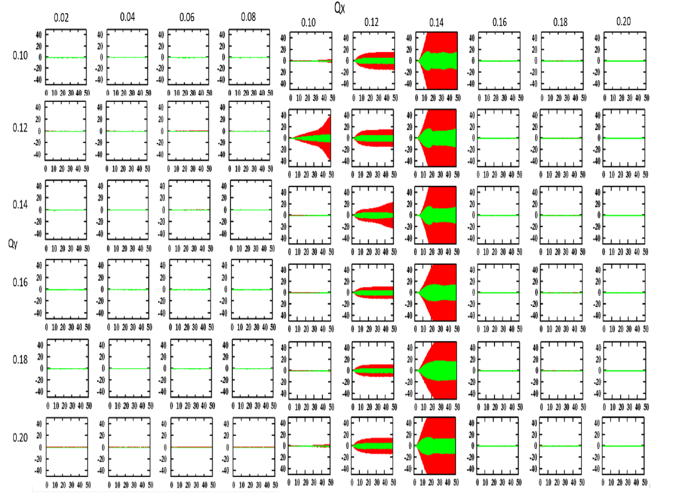
- 2nd order harmonic crab cavity is used to flatten the crabbed offset





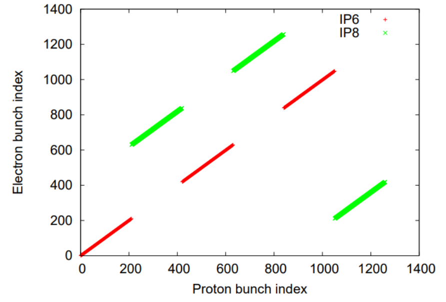
Luminosity — Coherent beam-beam effects

Electron tune scan to avoid coherent instability, red: proton H centroid, green: electron H centroid. Electron working point: $(0.08, 0.06)$



Luminosity — Collision with two IPs

- A 2nd IR is reserved at IP8 for future upgrade. However, with same beam-beam parameters, sum luminosity $\propto 1/N_{\mathrm{IP}}$
- Time sharing, one IR taking data while the other one is idle
- Or **luminosity sharing**, change bunch filling pattern, so that half bunches collide at IP6, and the other bunches collide at IP8

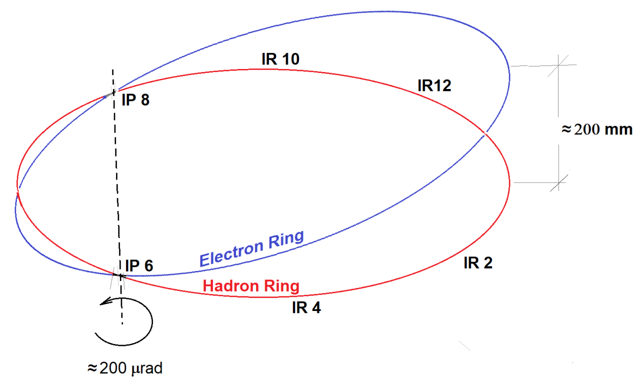


- The other half electron bunches are shifted by 3 RF buckets
- IP8 should be moved away from IP6 for synchronization
- Each bunch only collides **once per turn**

Luminosity — Tilted ESR

HSR lies in horizontal plane, while ESR is tilted by $\sim 200\ \mu\mathrm{rad}$

- Resolve interferences between rings, transfer lines, cooler ERL in IR2
- Avoid vertical bends around ring crossing points to preserve polarization
- Effect on dynamics: $-4\ \mathrm{mrad}$ rotation around s axis before collision, and $4\ \mathrm{mrad}$ rotation after collision — vertical crabbing needed



Polarization — Overview

The EIC physics program requires highly polarized hadron and electron beams with alternating spin orientation for the electron bunches

Polarized hadron beam:

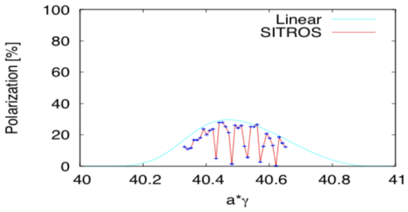
- Improvements of AGS: 70% achieved at extraction
- Four additional Siberian snakes will be installed in HSR:
  - increase polarization transmission for protons on the ramp to 275 GeV to $\sim 100\%$
  - sufficiently suppress spin resonance width for the polarized ^{3}He
- spin rotators based on helical dipoles to transform spin directions

Polarized electron beam:

- 85% longitudinal polarization in the source
- RCS serves as acceleration and injection at full energy, high periodicity to be free of intrinsic spin resonances
- Frequent "**swap-out**" injection to keep time-averaged polarization

Polarization — Depolarization in ESR

- Spin matching of spin rotator optics minimized beam depolarization, especially at 18 GeV
- Spin simulation studies with magnet errors showed that with one interaction region the average polarization of at least 70% is achievable. Studies with two IRs are underway
- Vertical emittance can be achieved using vertical bumps in ESR arcs, with depolarization at an acceptable level



Orbit corrected to rms: $\sim$ 0.15 mm, coupling corrected to below 0.005. SITROS includes nonlinear sextupole fields and quantum excitation

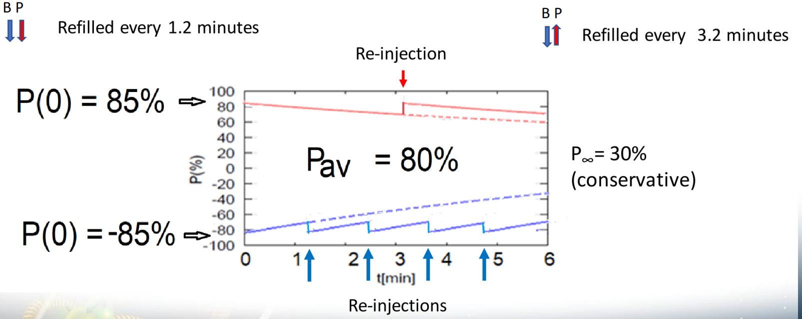
Assumed quadrupole RMS misalignments

horizontal offset	δx^Q	200 μm
vertical offset	δy^Q	200 μm
roll angle	$\delta \psi^Q$	200 μrad

At 18 GeV with 2.5 min refill time: 16% asymptotic polarization corresponds to 70% average polarization

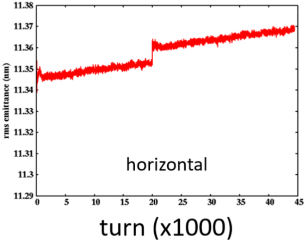
Polarization — Electron bunch replacement

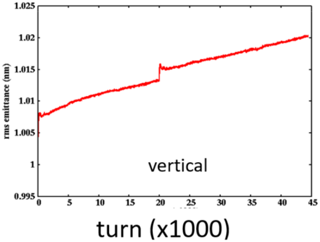
- Physics program requires bunches with spin "**up**" and spin "**down**" (in the arcs) to be stored **simultaneously**
- Initial polarization $\sim$ 85% decays towards $P_\infty <\sim 50\%$: Sokolov-Ternov self-polarization and spin diffusion
- Frequent injection is necessary to keep time-averaged polarization
- At 18 GeV, every bunch is replaced (on average) after 2.2 min with RCS cycling rate of 2Hz



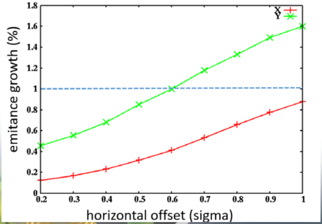
Polarization — Electron bunch replacement

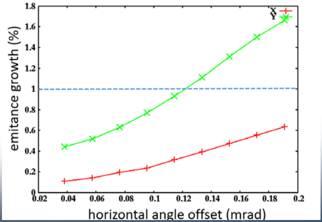
0.1% emittance growth when injection on orbit





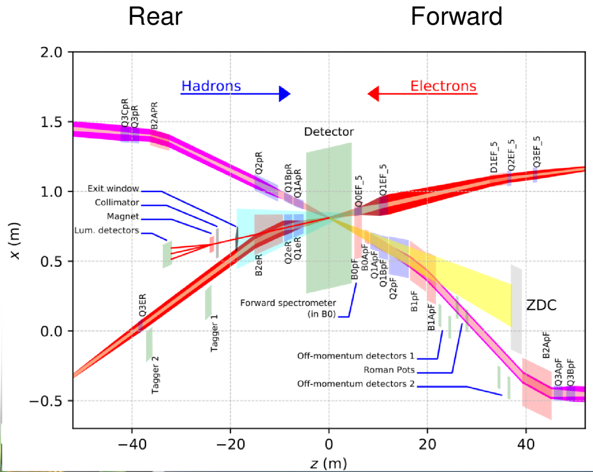
1% emittance growth corresponding to $60\mu m$ or $0.12 mrad$ injection errors





Linear Beam Optics — IR design

- Strong focusing at IP, HSR:80/7.2 cm, ESR:45/5.6 cm
- Crab cavities: high β_x, specific Ψ_x, and enough installation space
- Accommodation to detector: 4.5 m rear, 5.0 m forward stay-clear...



Linear Beam Optics — Crab dispersion control

Crab cavities introduce $z-$dependent transverse kick

$$\zeta = \left(\frac{\partial x}{\partial z}, \frac{\partial x'}{\partial z}, \frac{\partial y}{\partial z}, \frac{\partial y'}{\partial z}\right)^{\mathrm{T}}, \ \zeta_2 = M\zeta_1$$

Crab dispersion closure

- Ideally, two thin crab cavities apart with $n\pi$ phase advance form a **closed crab dispersion bump**
- In both rings, the crab cavities **can not** be matched to exactly $\pi/2$
- In ESR, the bump has to be closed because $\nu_x \approx \nu_z$. This is accomplished by moving rear side crab to $\sim 3\pi/2$ (2π between both crabs)
- In HSR, the crab dispersion bump is **not** closed (5° away from π). Crab cavity voltages can be adjusted to provide $\zeta^* = (12.5\ \mathrm{mrad}, 0, 0, 0)$
- Exploring the necessity of and options for locally closing crab dispersion
- Reasonable momentum dispersion constraints at crab cavities to reduce their combined effects

Linear Beam Optics — Crab dispersion control

Vertical crabbing

- Sources: tilted ESR, detector solenoid
- Vertical crab cavities can provide knobs to control vertical crab dispersion. However, (1) hard to match, (2) conflict with impedance budget
- Skew quadrupoles are feasible and efficient to control vertical crabbing
- In ESR, the required skew component strength is $1.2\ \mathrm{T/m}$. In HSR, it may combine with the global decoupling system.

Dynamical control — crab cavity RF noise

- The crab dispersion changes dynamically due to RF phase and amplitude noise. The transverse emittance growth $\propto \theta_c^2$
- Compared with HL-LHC, EIC sensitivity to RF noise is 4000 times higher; the emittance growth tolerance is 3 orders of magnitude higher
- The RF noise threshold for the HSR will be very **hard** to achieve. A dedicated feedback system is **needed**

Linear Beam Optics — ESR spin rotation

The aim of the spin rotators is: (1) to rotate the spin from the vertical direction in the arcs to the longitudinal direction at the IPs; (2) to minimize beam depolarization.

ESR spin rotator composes of solenoids and dipoles

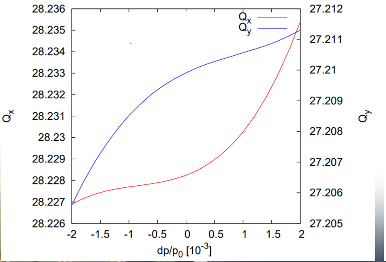
- In dipoles, spin rotated around vertical axis by $\psi = a\gamma\theta$. In solenoids, spin rotated around longitudinal axis by $\varphi = (1 + a)KL$
- One “long” solenoid module for 18 GeV, $\varphi_1 = 0, \psi_2 = \varphi_2 = \pi/2$
- One "short" solenoid module for 6 GeV, $\varphi_1 = \psi_1 + \psi_2 = \pi/2$
- Both solenoid modules used for 10 GeV
- Matching for 5 GeV electrons is ongoing

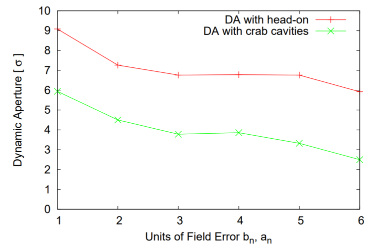
Dynamic Aperture — HSR overview

- HSR will reuse arcs of both Yellow and Blue RHIC rings
- Sufficient DA after the linear chromaticity is corrected. More sextupole families are available for further DA optimization
- IR magnetic field errors dominate hadron ring DA reduction

$$\Delta B_y + \mathrm{i}\Delta B_x = B(R_{\mathrm{ref}})\left[10^{-4}\sum_{n=0}^{N_{\max}}(b_n+\mathrm{i}a_n)\frac{(x+\mathrm{i}y)^n}{R_{\mathrm{ref}}^n}\right]$$

- Tracking with beam-beam: 3σ drop from head-on to crab collision with 1 unit IR field errors (due to crab dispersion and IR field errors)

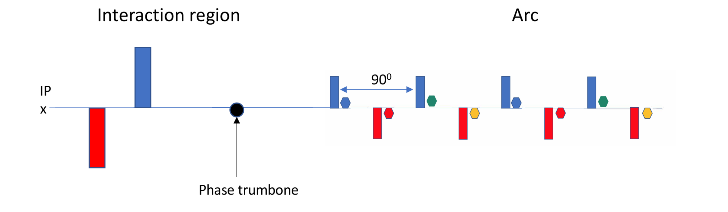




Dynamic Aperture — ESR overview

Dynamic aperture and momentum aperture of lower energies lattice are sufficient. $18\ \mathrm{GeV}$ lattice with a 2nd IR is **most** challenging

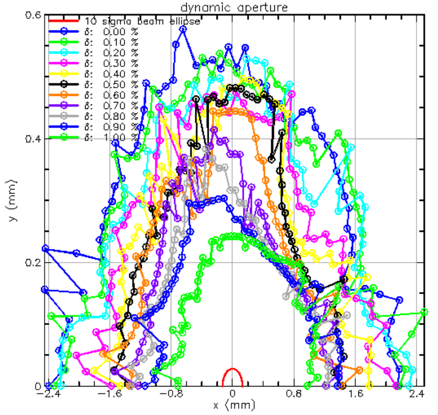
- Optimization goal: 10σ in all three planes
- Fractional tunes close to integer: selected by spin and beam-beam dynamics
- Setting the phase advance between IRs to $(2n+1)\pi/2$ helps, but not sufficient
- No space for local chromatic compensation
- The off-momentum β-beating and the chromaticity from the final focusing doublet are corrected in the neighboring arc section

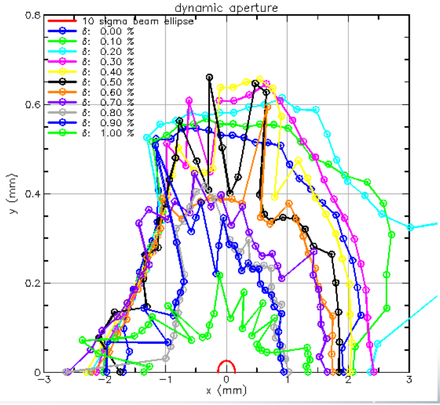


Dynamic Aperture — ESR $18\ \mathrm{GeV}$ tracking results

Bare lattice

With beam-beam, crab cavities, detector solenoid, and crab dispersion correction by skew quadrupoles





10σ with $\sigma_\delta = 0.1\%$ is **achieved** for the 18 GeV lattice with 2 IRs

Collective Effects — Overview

In ESR, average current: $2.5\ \mathrm{A}$ with bunch charge of $28\ \mathrm{nC}$

- No single bunch instabilities, component heating needs water cooling
- With a $591\ \mathrm{MHz}$ RF system $\sigma_z = 7\ \mathrm{mm}$, $I_{\mathrm{peak}} = 480\ \mathrm{A}$
- Large tune spread caused by beam-beam interaction provide Landau damping for transverse coupled-bunch instability and ion instability
- Longitudinal damper is needed

In HSR, average current: $1\ \mathrm{A}$

- RHIC vacuum chamber is not designed for EIC beam
- Vulnerable to electron cloud instability and high resistive losses from beam-induced currents
- The vacuum chamber of the HSR SC magnets and their cold interconnects will be updated with a beam screen to present sufficiently **low** impedance and **low** secondary electron-emission yield (SEY)

Collective Effects — ESR impedance budget

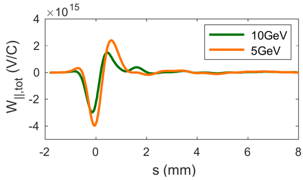
- We have initial designs for main components and wakefield calculations
- Beam is stable at single bunch current of 2.2 mA required for regular operation at 2.5 A within 1160 bunches

Components	Abbreviation	Number	Status
Bellows	BLW	350	✓ x2 (NEG)
Collimator Ramp[1]	CLM	16	✓
Horizontal In-Vacuum Collimator	HIVC	3	TBD
Vertical In-Vacuum Collimator	VIVC	3	TBD
Crab Cavity	CRBCVT	2	✓
Beam Position Monitor[2]	BPM	494	✓
Gate Valve[2]	GV	30	✓
Stripline Kicker[2]	SK	18	✓
Main RF Cavity[2]	CVT	23	✓
Tapered Transition in RF Section	TPRD	9?	TBD
Multipole Chamber Absorber	MPABS	292	✓
Dipole Chamber Absorber	DPABS	250	✓
Flange Joints	FLNG	1500	TBD
Resistive Wall	RW	-	✓

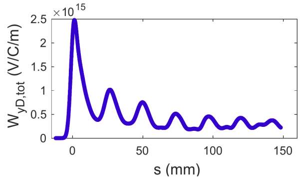
1 - SKEKB design ✓ - Included into the total W(s)

2 - NSLS-II design

The total longitudinal wakefield simulated for a 0.3 mm bunch length at 5 GeV and 10/18 GeV energies.

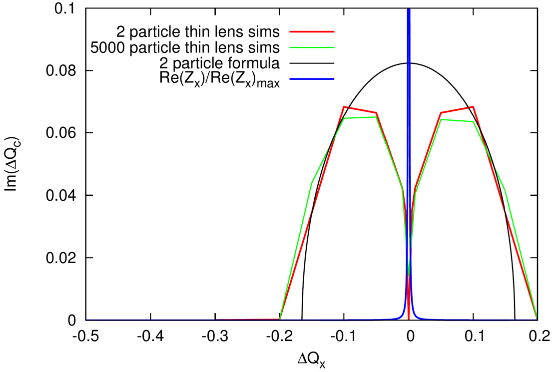


The total vertical dipole wakefield simulated for a 2 mm bunch length.



Collective Effects — Fundamental crabbing mode

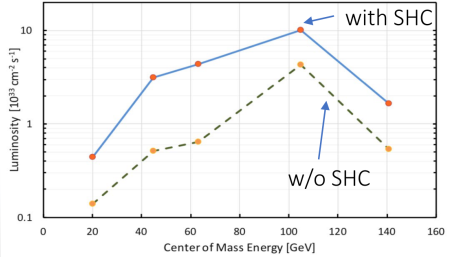
Transverse Crab cavities with big R/Q can lead to transverse coupled bunch instabilities: high $Q \sim 10^6$, and high $\beta_x \sim 1300\ \mathrm{m}$ in 275 GeV HSR



RF feedback is **required** on the crab cavities, $Q_{\mathrm{eff}} = 300$ for 197 MHz and $Q_{\mathrm{eff}} = 600$ for 394 MHz

Strong Hadron Cooling — Overview

- Luminosity benefits strongly (factor $\approx 3 - 10$) from cooling the transverse and longitudinal hadron beam emittance
- IBS longitudinal and transverse growth time is 2-3 hours. The cooling time shall be equal to or less than the growth time from all sources
- Cooling at 275 GeV and 100 GeV based on Coherent electron Cooling (CeC); 41 GeV cooling under study.
- Low energy cooling (Pre-cooling based on LEReC) is used to obtain initial parameters of proton beam: must cool the hadron beam normalized vertical emittance from 2.5 $\mu\mathrm{m}$ to 0.3 $\mu\mathrm{m}$ in 2 hours



Summary — Challenges resolved and in progress

Challenges from design parameters: luminosity $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (factor 100 beyond HERA), both beams of time average polarization $> 70\%$

- Beam-beam parameters, achievable in simulation
- Electron bunch replacement, sufficient injection errors
- Spin rotators design, $6 - 18$ GeV, 5 GeV
- Strong hadron cooling

Challenges from crab cavities

- Higher-order SBR, tune optimization and 2nd-order harmonic
- Crab dispersion control, ESR, HSR closure
- RF feedback to cure RF noise and large transverse impedance
- HSR DA reduction, 1IR with reasonable IR field error

Challenges from 2 IRs

- ESR Chromatic correction, 10σ achieved with 2 IRs
- Luminosity sharing, bunch filling pattern
- HSR DA,ESR depolarization...

Acknowledgement

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Thank you for your attention.