Beam Dynamics Challenges in the Design of Electron-Ion Collider

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Electron-Ion Collider

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

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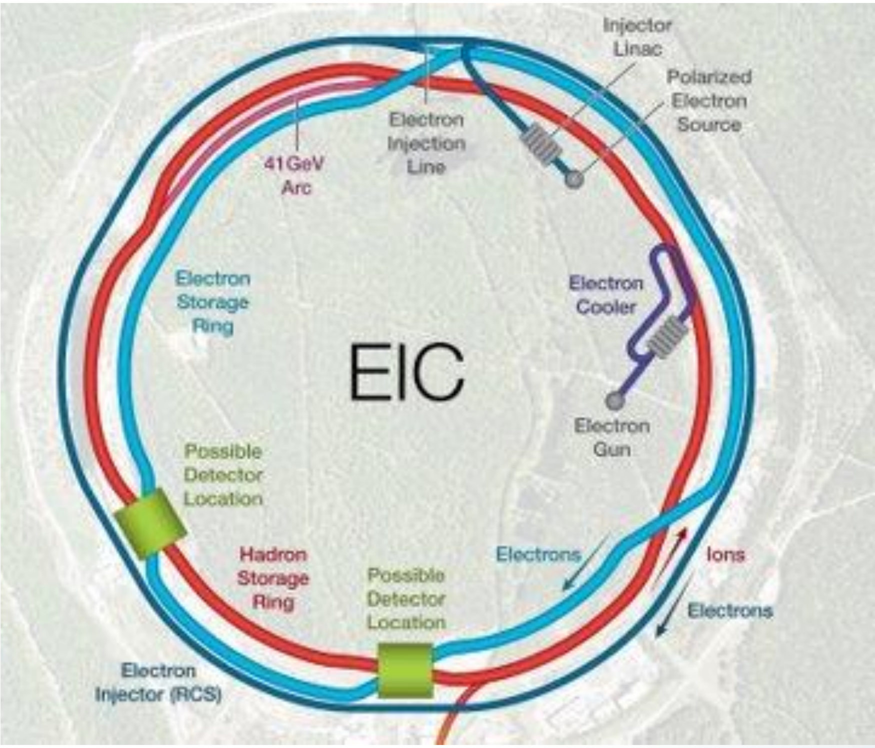
  machine imperfections, crab cavity noises,
  PS current ripples, bunch merging in ESR,
  low field at RCS injection, strong hadron Cooling
- Summary

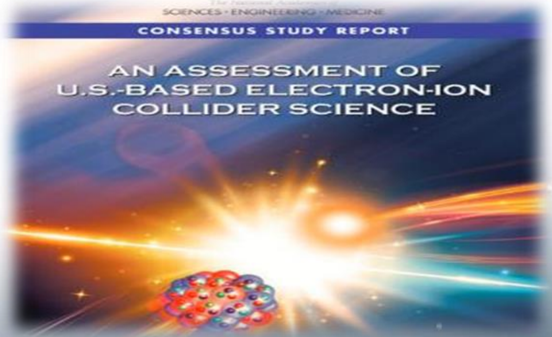


EIC Project Requirements

Project Design Goals:

- High Luminosity: L= $10^{33} – 10^{34} cm^{-2} sec^{-1}$, 10 – 100 fb^{-1}/year
- Highly Polarized Beams: 70%
- Large Center of Mass Energy Range: E_{cm} = 20 – 140 GeV
- Large Ion Species Range: protons – Uranium
- Large Detector Acceptance and Good Background Conditions
- Accommodate a Second Interaction Region (IR)

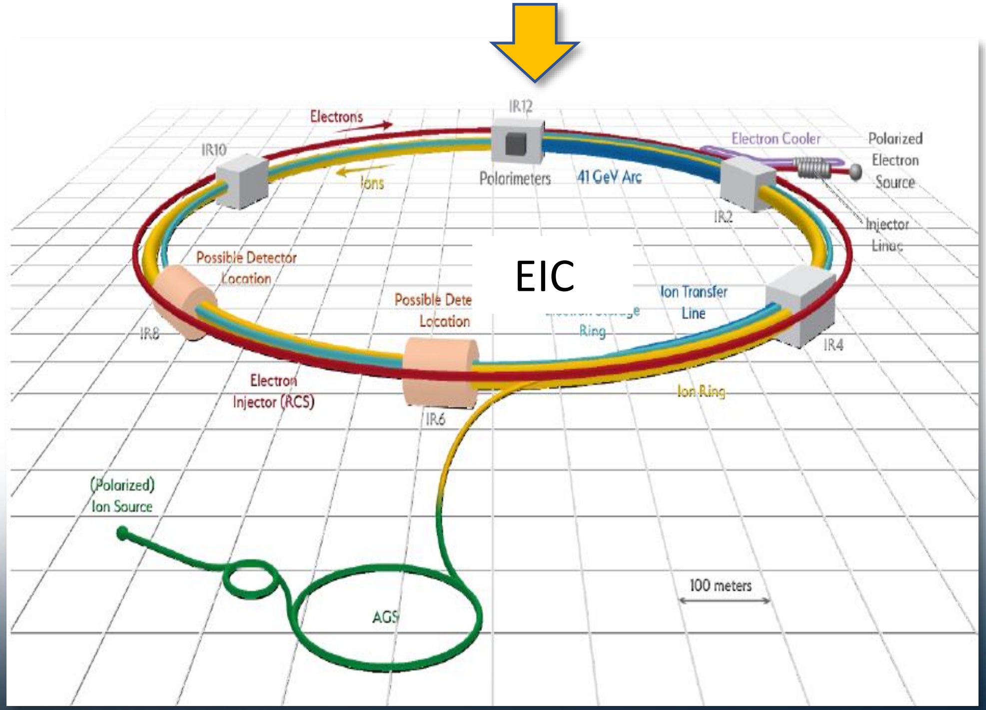
Conceptual design scope and expected performance meets or exceed NSAC Long Range Plan (2015) and the EIC White Paper requirements endorsed by NAS (2018).



Electron-Ion Collider

EIC Design Overview

- **Design based on existing RHIC Complex**
  - RHIC is well maintained, operating at its peak
  - RHIC accelerator chain will provide EIC Hadrons
  - EIC constructed in Collaboration with Jefferson Lab
- **Hadron storage Ring (HSR ← RHIC rings) 40-275 GeV**
  - Superconducting magnets
  - 1160 bunches, 1A beam current (3x RHIC)
  - bright vertical beam emittance 1.5 nm
  - strong cooling (coherent electron cooling)
- **Electron Storage Ring (ESR) 2.5–18 GeV**
  - large beam current, 2.5 A → 9 MW S.R. power
  - S.C. RF cavities
  - Need to inject polarized bunches
- **Electron rapid cycling synchrotron (RCS) (0.4- 18) GeV**
  - 1 Hz
  - Spin transparent due to high periodicity



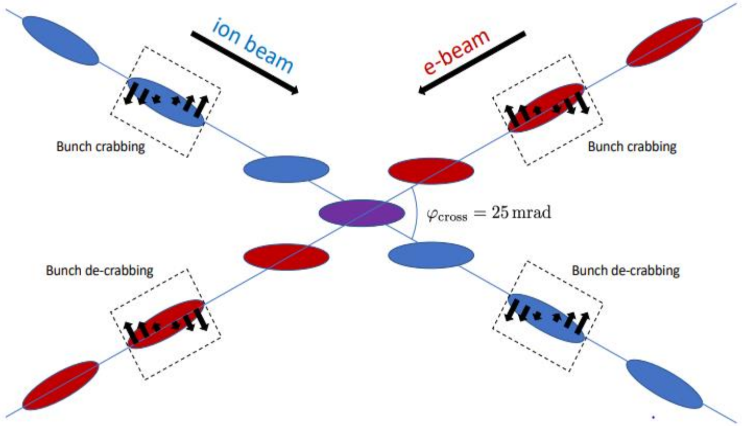
Design Parameters for Highest Luminosity e-p Collision

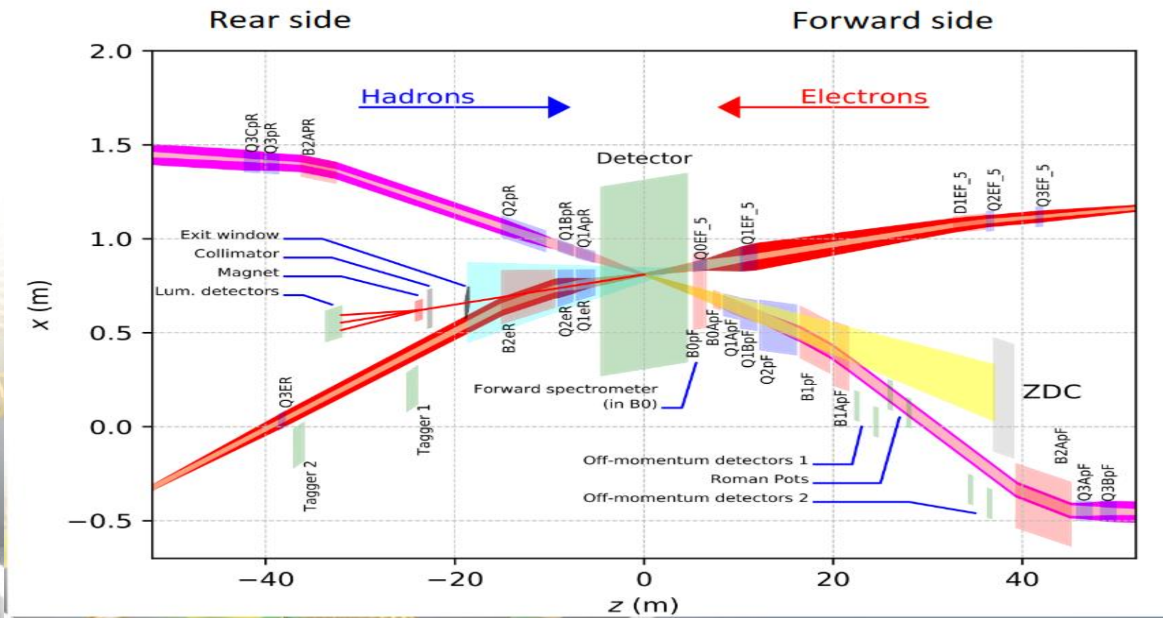
- Beam-beam parameters of unequal species chosen for each beam chosen as they would collide with own species.
- **Hadron beam parameters** differ from present RHIC by smaller vertical emittance, “flat beam”,10x bunches, 3 times more average beam current, shorter bunch length
- Two hours IBS growth time requires strong hadron cooling at store. Flat beam generated at injection energy with electron cooling.
- **Electron beam parameters** resemble a B-Factory: high beam current, large beam-beam tune shift ~0.1.

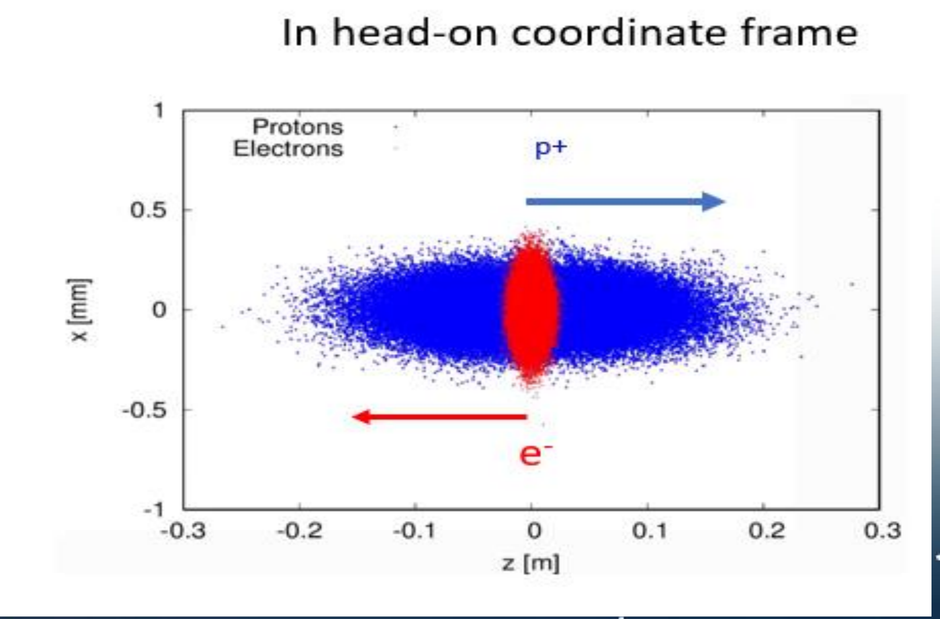
Parameter	proton	electron
Ring circumference [m]	3833.8451	
Particle energy [GeV]	275	10
Lorentz energy factor γ	293.1	19569.5
Bunch population [10^{11}]	0.688	1.72
RMS emittance (H,V) [nm]	(11.3, 1.0)	(20.0, 1.3)
β^* at IP (H, V) [cm]	(80, 7.2)	(45, 5.6)
RMS bunch size σ^* at IP (H, V) [μm]	(95, 8.5)	
RMS bunch length σ_l at IP [cm]	6	0.7
Beam-beam parameters (H, V)	(0.012, 0.012)	(0.072, 0.1)
RMS energy spread [10^{-4}]	6.8	5.8
Transverse tunes (H,V)	(29.228, 30.210)	(51.08, 48.14)
Synchrotron tune	0.01	0.069
Longitudinal radiation damping time [turn]	-	2000
Transverse radiation damping time [turn]	-	4000
Luminosity [10^{34}cm^{-2}s^{-1}]	1.0	

Large Crossing Angle Collision with Crab Cavities

- **Full crossing angle 25mrad**. Crab cavities are needed in both rings to compensate geometric luminosity loss. Local closed crabbing scheme is adopted.
- **List of crab cavities**: four 197 MHz and two 394 MHz crab cavities on each side of IR6 in the HSR, and two 394MHz crab cavities on each side of IR6 in the ERS.

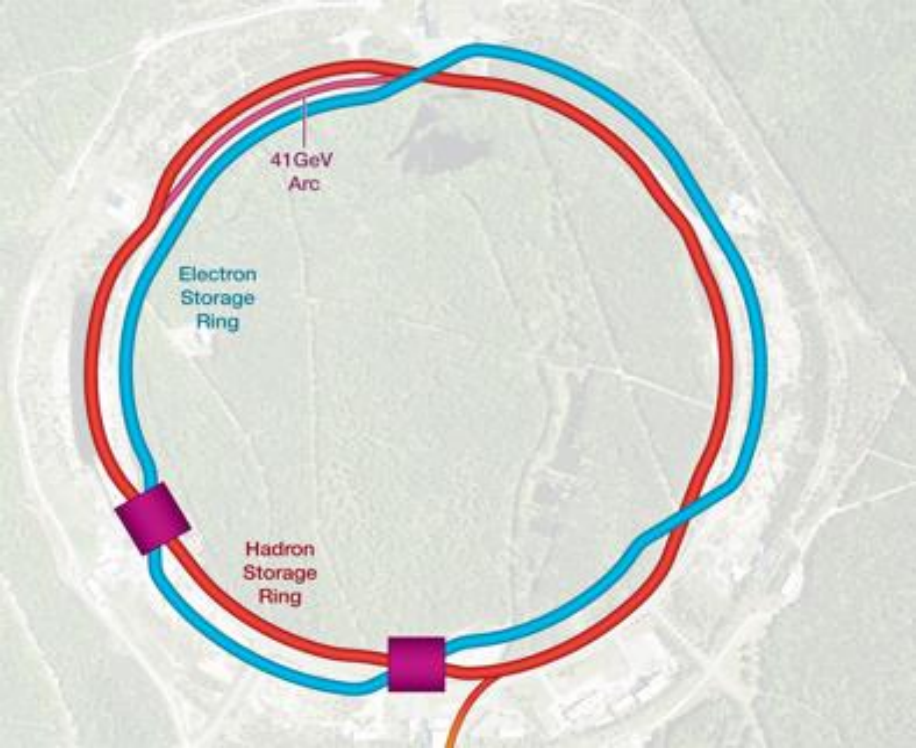


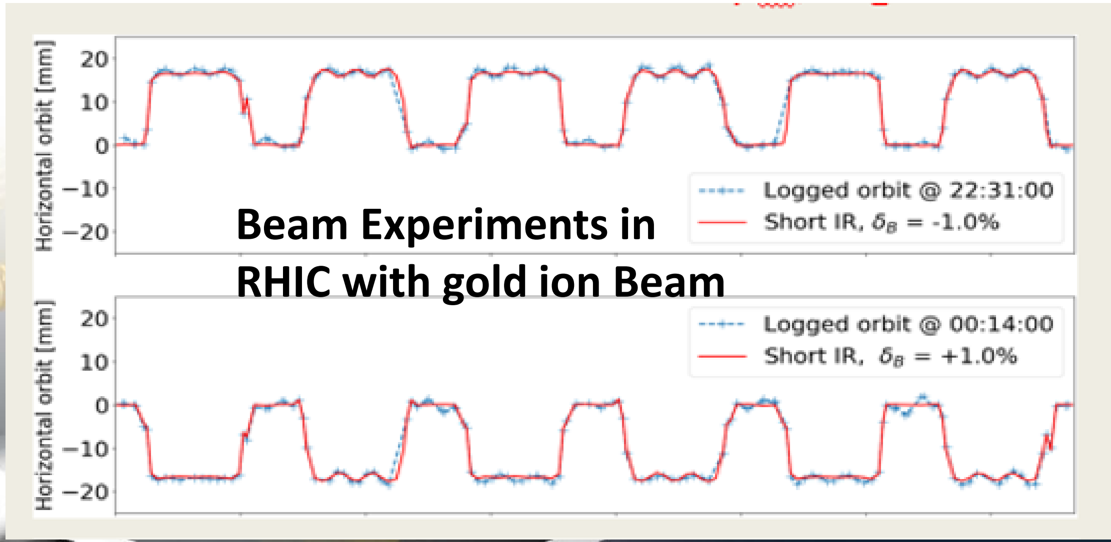




Collision Synchronization

- Hadron Storage Ring SR needs to operate over a wide energy range, e.g. 41 GeV – 275 GeV for protons
- Collison synchronization accomplished by Hadron path length change.
- Between 100 and 275 GeV (protons), this can be done by a radial shift off the beam orbit
- For lower energies, use an inner instead of an outer arc as a shortcut. 90 cm path length difference corresponds to 41 GeV proton beam energy.





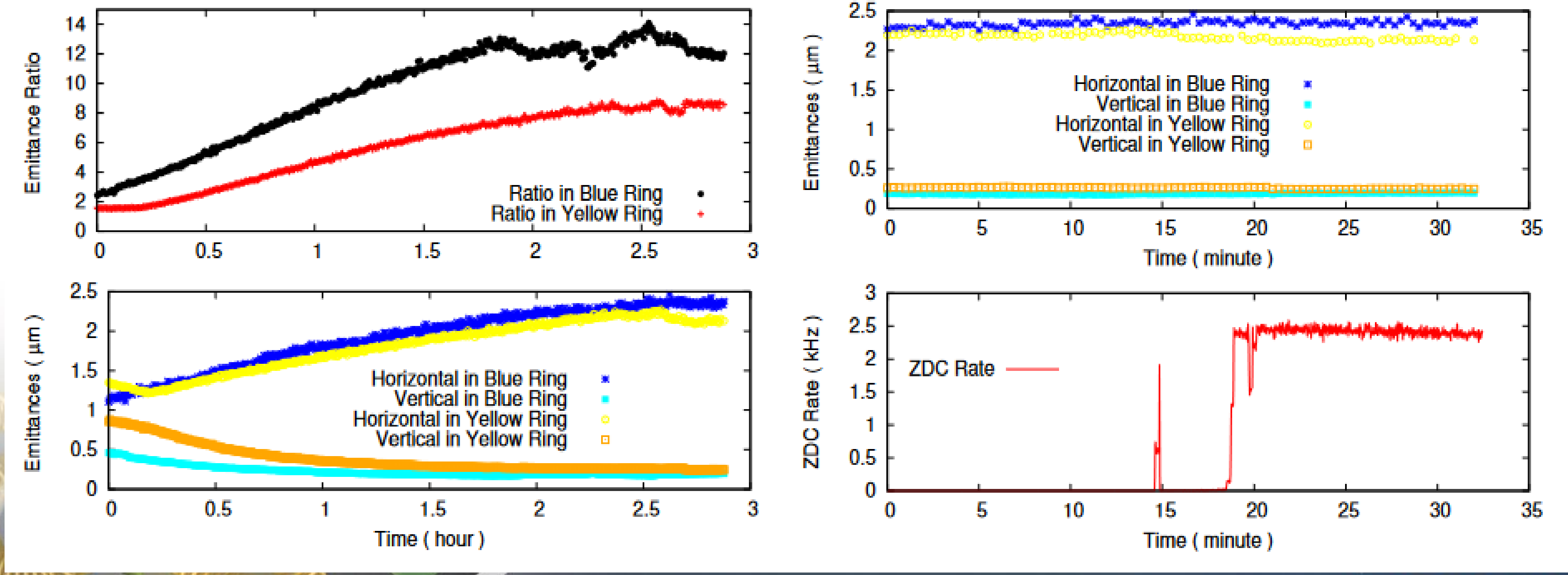
Beam Experiments in RHIC with gold ion Beam

Circumference change at various proton energies

E_{tot} [GeV]	γ	$1-\beta$ $[10^{-3}]$	C [m]	ΔC [mm]	$\langle \Delta R \rangle$ [mm]
41.0	43.70	0.26189	3832.9153	-908.7	–
100	106.58	0.04402	3833.7506	-73.4	-11.7
133	141.75	0.02488	3833.8240	0.0	0.0
275	293.09	0.00582	3833.8971	73.1	11.6

Flat beam experiments in RHIC

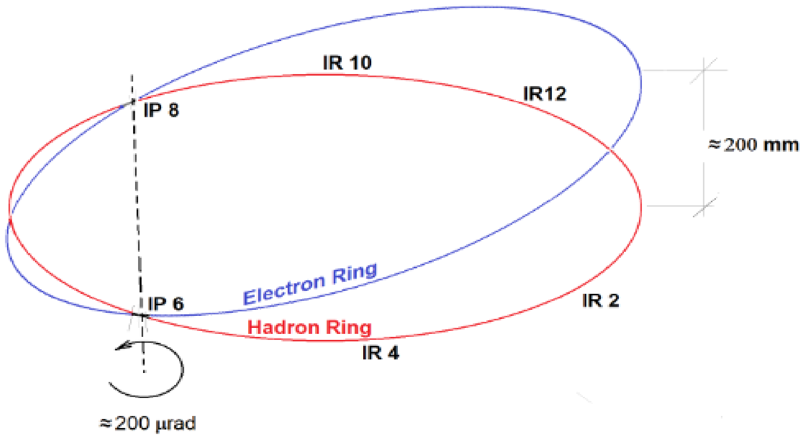
- Large emittance ratio for hadron beams required for high luminosities and equal transverse divergencies at IP. Electron beam naturally features this large ratio.
- Experiments demonstrated 11:1 transverse ratio in RHIC with gold ion beam at 100 GeV/nucleon **with vertical stochastic cooling and fine decoupling**. Demonstrated flat beam collision with beam-beam parameter ξ=0.005.
- There is an experiment in preparation to get this emittance ratio at γ=26 and then accelerate it to γ=106.



n Collider

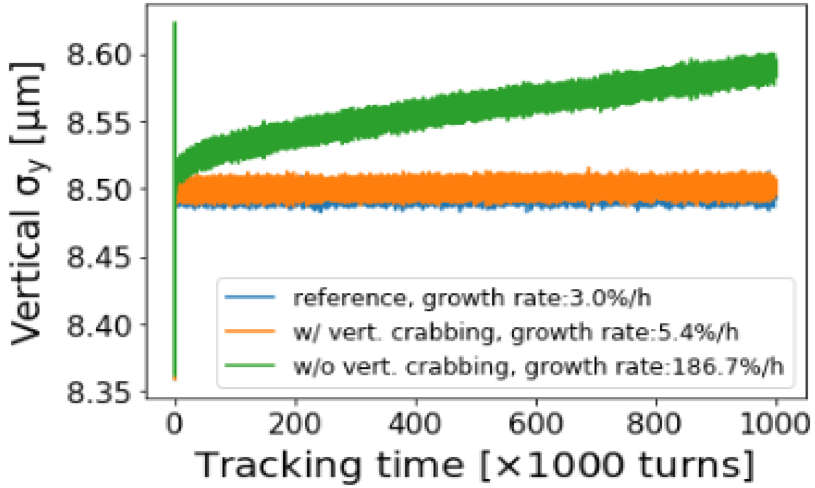
Tilted ESR Plane w.r.t HSR Plane

Idea:
Vertical beam excursions may be detrimental to polarization. Rotate the ESR reference plane about a line through IP6 and IP8 by 200 μrad to keep the ESR in one plane and to avoid vertical beam excursions at the crossing points.



Impact:
1) This equivalently introduces an $x-y$ axis rotation of about 4~mrad to both HSR and ESR before and after beam-beam.
2) These rotation angles introduce vertical crab dispersion at the IP and must be compensated together with the detector solenoid.

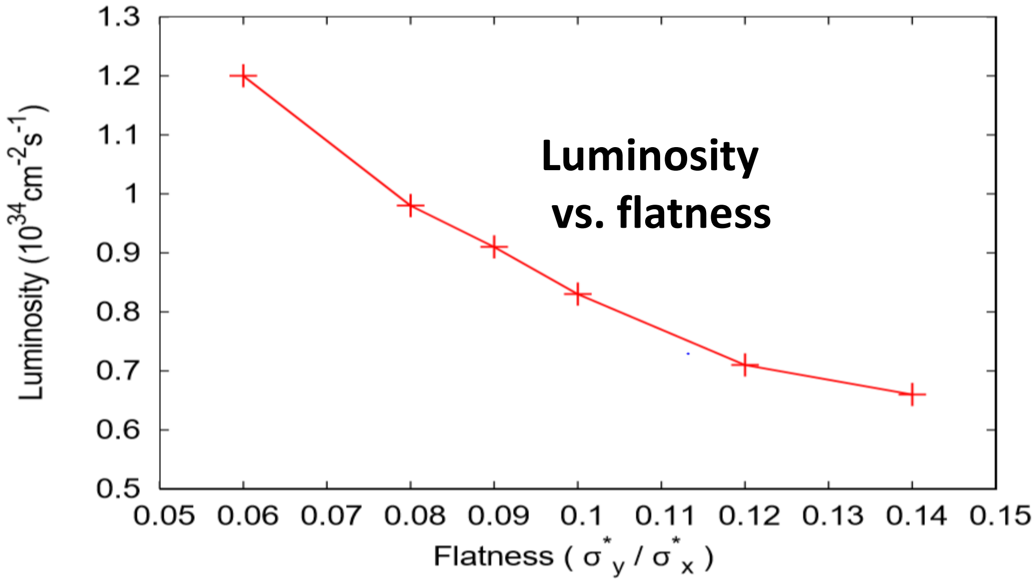
Weak-strong simulation

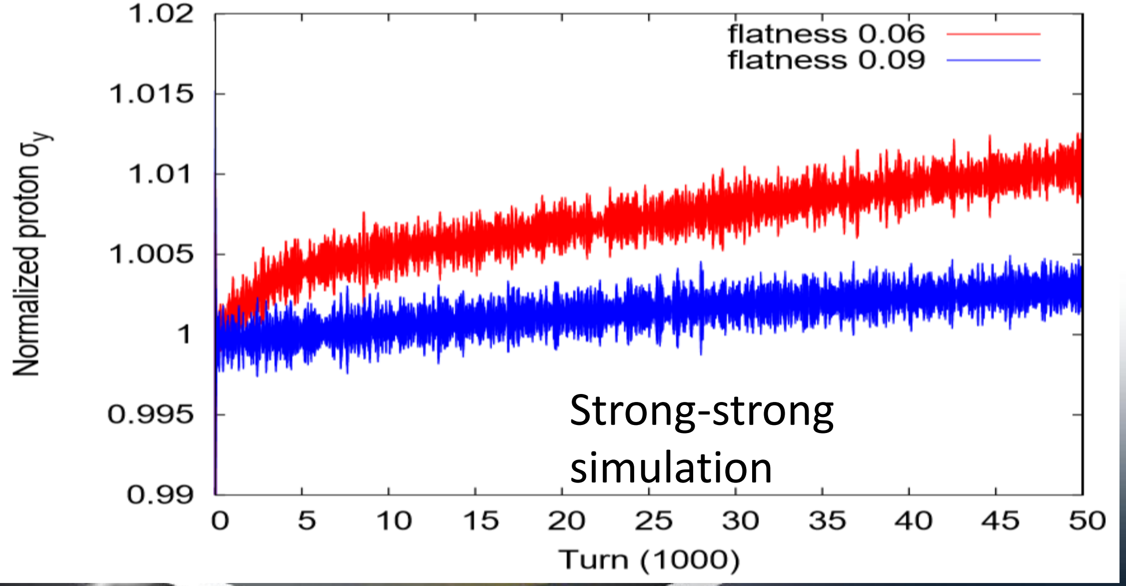


Electron-Ion Collider

Flatness and BB Performance

- **Key design parameters for BB performance**: BB parameter, flatness, working points, etc.
- **Flatness (σ^*_y / σ^*_x) at IP affects overall BB performance: DA and emittance growth.**
- Flatness 0.09 was chosen for the EIC e-p collision to achieve the maximum design peak luminosity 1×10^{34} $cm^{-2}s^{-1}$ and to maintain a relatively low proton emittance growth rate.



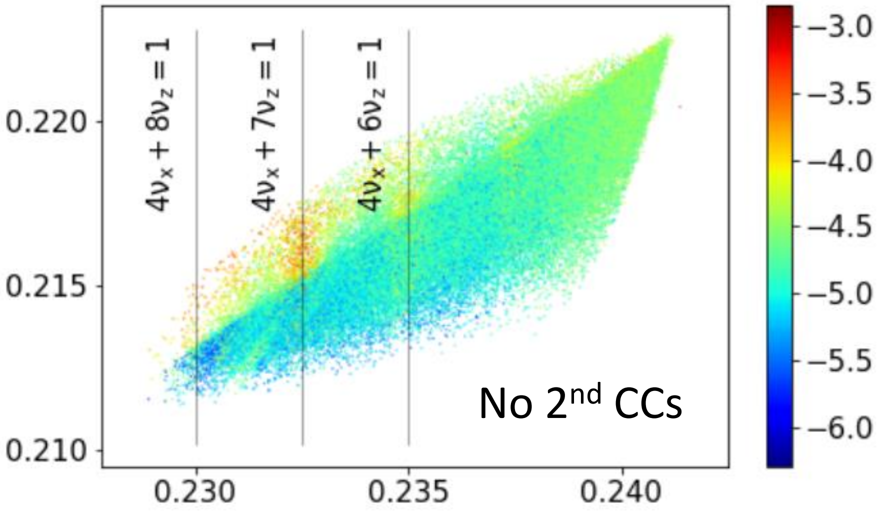


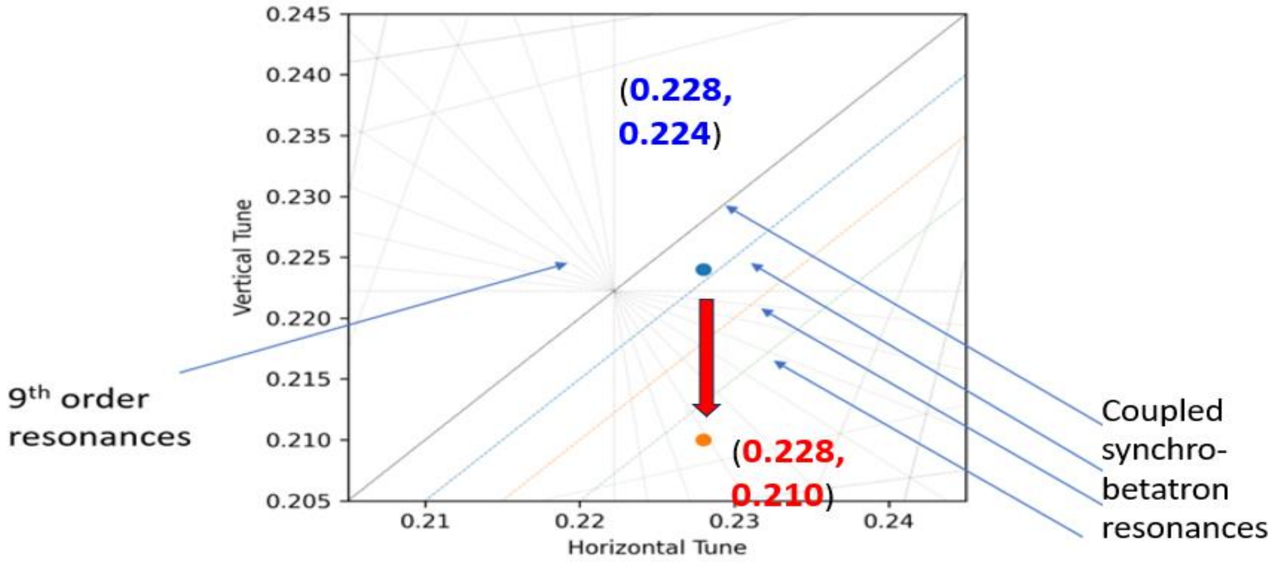
Weak-strong simulation

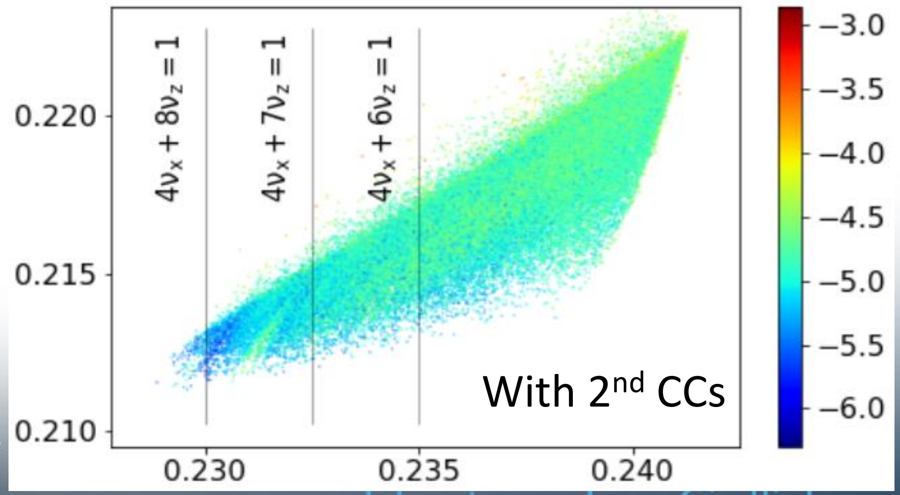
flatness	ID	proton beta*x,y [cm]	proton horizontal growth rate [%/hour]	proton vertical growth rate [%/hour]
0.06	43-47	90/5.4	-0.68+/-1.10	14.57+/-7.1
0.08	33-37	90/7.2	-0.52+/-0.37	2.6 +/-1.9
0.09	49-53	90/8.1	0.16+/-0.94	2.7+/-3.1
0.10	28-32	90/9.0	0.09+/-0.86	1.2+/-2.6
0.12	one seed	90/10.9	0.05	0.87
0.14	59-63	90/12.6	-1.2+/-2.5	0.27+/-8.9
0.09	91-95	80/7.2	0.11+/-0.75	3.3+/-3.2

Synchro-Betatron Resonances with Crossing Collision

- Synchro-betatron resonances have been observed in many BB simulation studies.
- **Tunes: ESR (0.08,0.14,0.069), HSR (0.228,0.210,0.01)**
- Two kinds of synchro-betatron resonances are identified: mQ_x+pQ_s and $2Q_x-2Q_y+pQ_s$.
- **Mitigation measures:**
  1) working point optimization
  2) second harmonic crab cavities







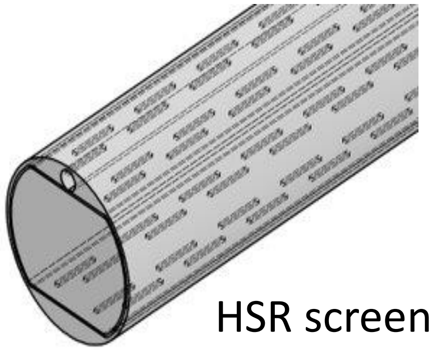
Wake Field and Impedance Budget

- We are calculating the impedance of RCS, ESR & HSR components using CST, GdfidL and ECHO 2D & 3D codes.
- Iterations on the vacuum component design and impedance optimization for RCS, ESR & HSR in progress.
- The transverse and longitudinal broadband impedances of RHIC had been measured with tune shift vs bunch current
- Beam-induced heating simulations performed by the CST code. The obtained results are used for Finite Element Analysis (ANSYS) for thermal studies.
- Impedance modeling is continuing.

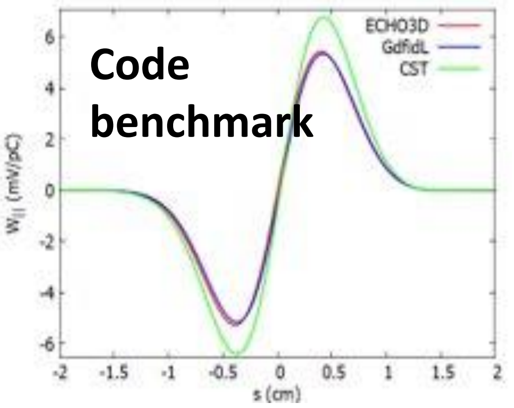
Work Plan:

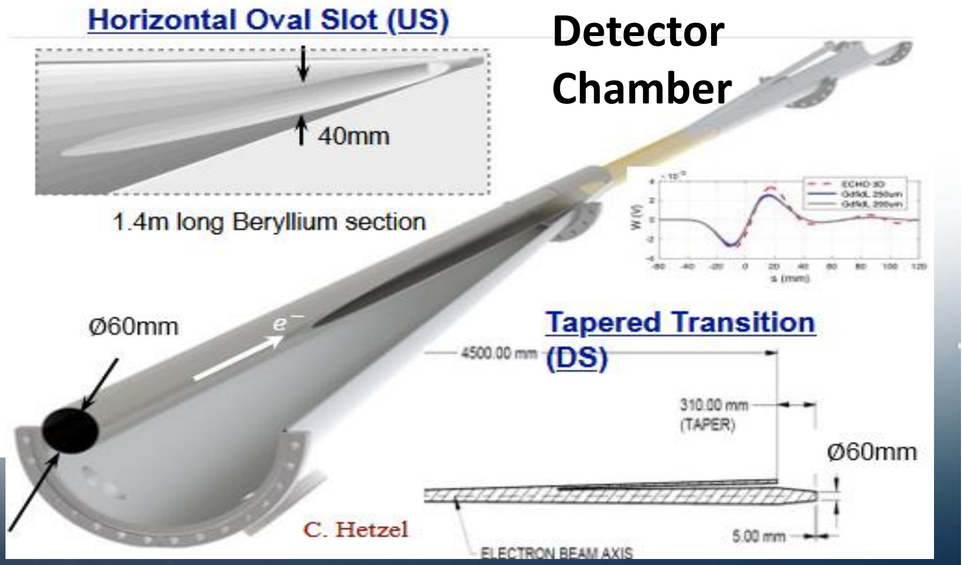
- Define maximum allowed HOM of RF cavities.

- Continue to calculate/optimize impedance budget /wake field for the RCS, ESR, HSR.



HSR screen with pumping slots





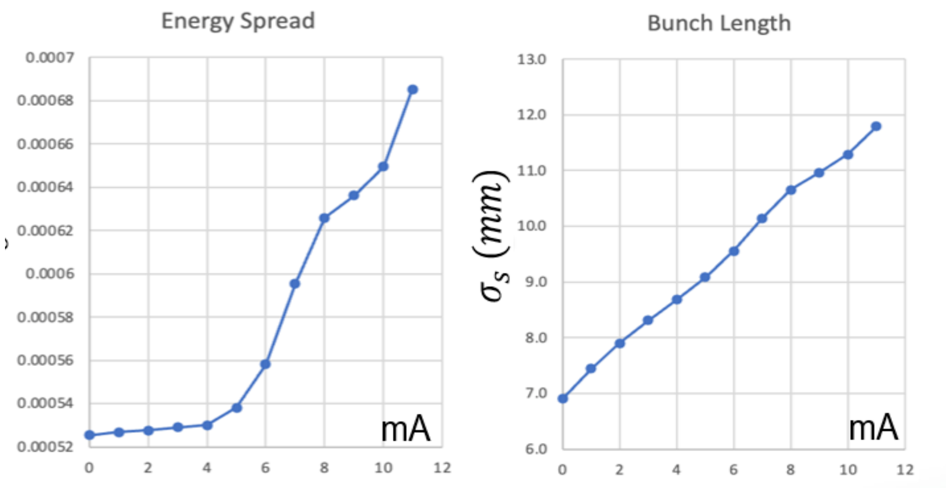
Instabilities in the EIC

- **ESR**: single-bunch instability threshold is above the requirement for stable operation. Beam-beam interaction provides a large tune spread to Landau damp the transverse coupled-bunch instability and ion instability.
- **HSR**: coupled bunch instabilities are also stabilized by WS-BB though the impedance estimate is less well developed.
- **In both ESR and HSR** there needs to be strong RF feedback on the crab cavities to reduce the apparent impedance.
- **RCS**: using the ESR impedance, there is a fast head-tail instability at low energy. There are some questions with bunch merging. Dampers are likely to be needed but considerations are preliminary.

Work Plan:

- Demanding RF feedback requirements to reduce crab cavity impedance
- Reduction of Landau damping from beam-beam tune spread when coherent beam-beam motion is included.
- interplay of beam-beam and wake fields started

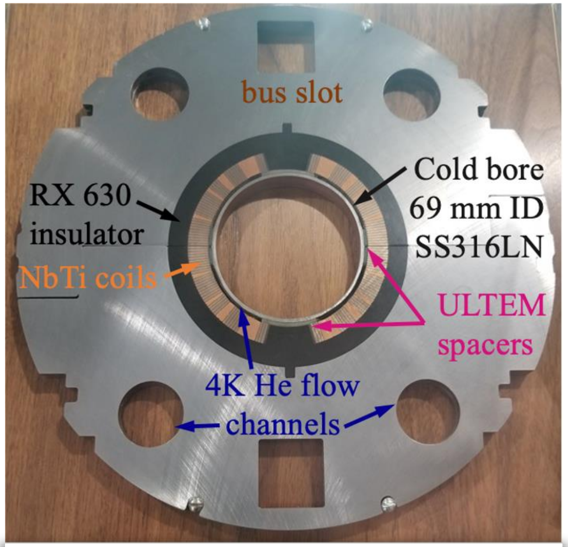
Microwave Instability in ESR 5 GeV: $I_{th} > I_0$



Instability simulation results for HSR

Parameter	41 GeV	100 GeV	275 GeV
number of bunches	1260	1260	1260
protons per bunch [10^{10}]	3	10	10
RF voltage ($h = 2520$) [MV]	2	5	6
RF voltage ($h = 7560$) [MV]	6.7	16.7	20
rms beam radius [mm]	0.83	0.65	0.38
$\sigma(p)/p$ [10^{-4}]	9.9	8.6	5.7
σ_s [cm]	5.5	5.5	5.5
Z_{sc} [MΩ/m]	44	12	4.6
β_{crab} [m]	50	500	1300
ΔQ_{bb}	0.0029	0.0040	0.0014
ΔQ_{sc}	0.013	0.0047	0.0007
$Im(\Delta Q)$	0.00013	0.0017	0.0016

HSR Vacuum System Upgrade



RHIC arc dipole cross section

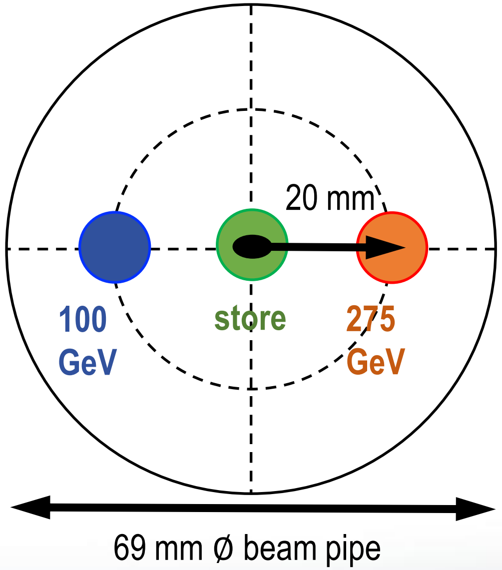
MOTIVATION

The **4.5 K stainless steel beam pipe of RHIC SC magnets** features **unacceptable:**

- High RF surface resistance → excessive **resistive-wall heating**
- High secondary electron yield (SEY) → **electron cloud buildup**

The **demanding EIC HSR** beam parameters:

- High bunch charge (0.69e11 ppb)
- High stored current (3x higher than RHIC)
- Short bunch spacing (10 ns)
- Short bunch (10x smaller than RHIC)
- Large beam offsets in collision
  (up to +/-20 mm in 69 mm-diam pipe)



Large radial orbit offsets for collision beams in arc magnets

HSR Vacuum System Upgrade

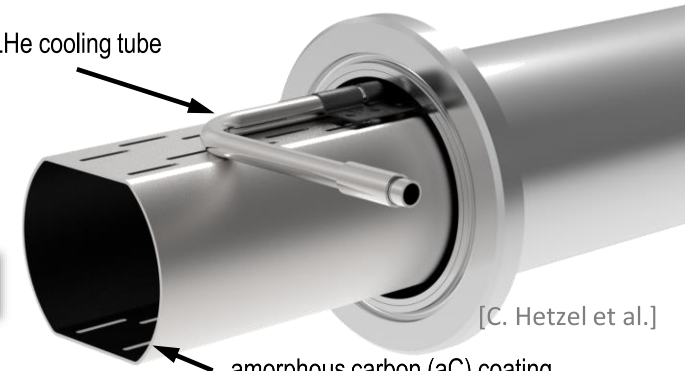
BASELINE SOLUTION (Inspired on solutions for LHC and HL-LHC.)

✓ **Install beam screens inside existing SC magnet bores**

- Copper cladded stainless steel
- High RRR reduces resistive wall heating
- Temperature control by active cooling (4.5 → 9K)
- aC coating reduces the SEY of the surface
- Pumping slots for improved dynamic pressure

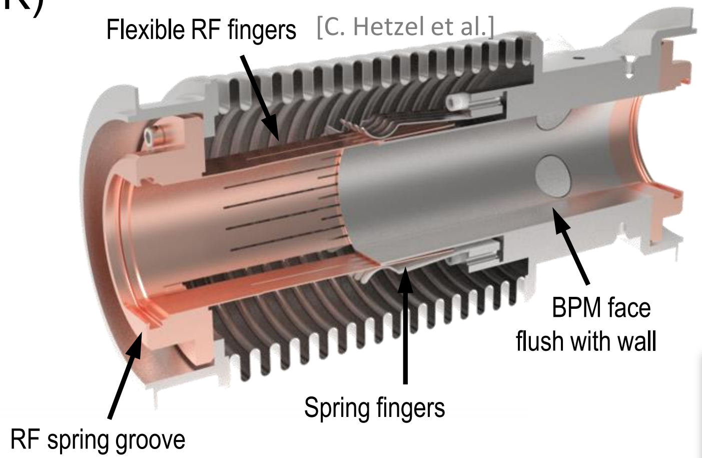
✓ **Redesigned interconnect**

- Impedance-driven requirement
- Replace bellows by RF shielded bellows
- Shield existing stripline BPMs
- Integration of new BPMs and screens



HSR beam screen

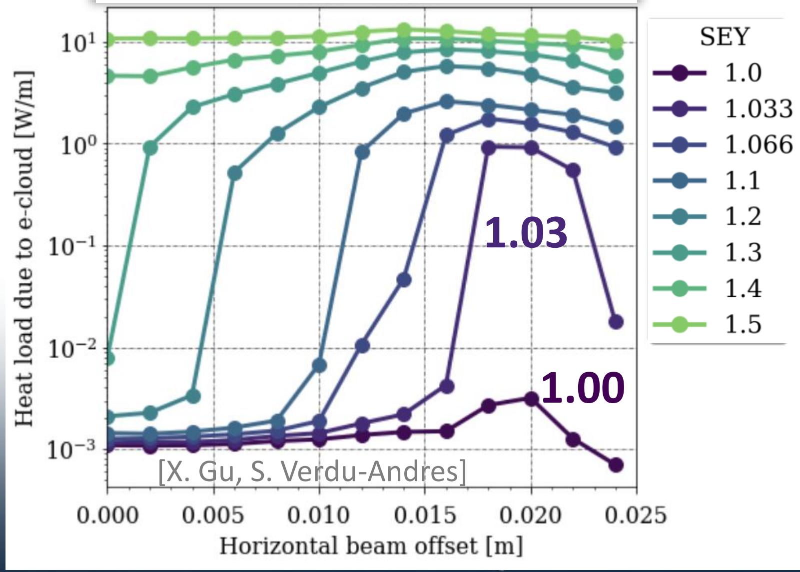
HSR RF shielded bellows



CHALLENGES

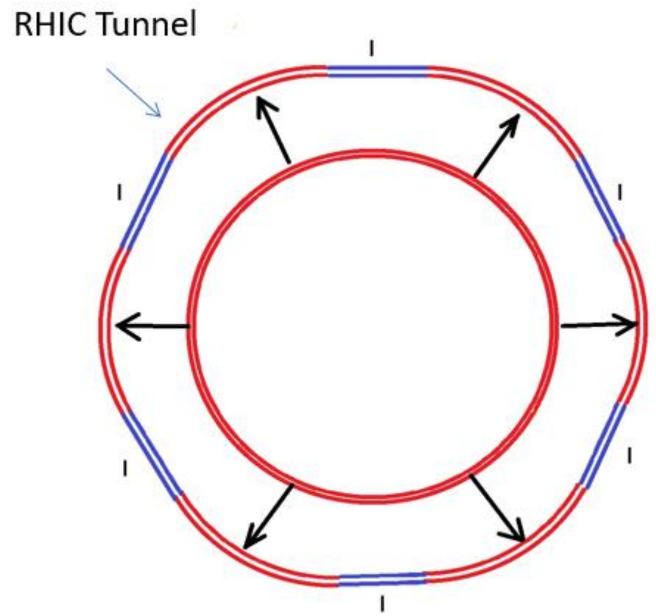
- Ongoing work to determine optimal randomized pattern of pumping slots in the screen that mitigates high-Q narrow-band resonances.
- Low SEY required to suppress e-cloud buildup motivates the study of scrubbing beams and mitigation strategies like hybrid filling schemes.

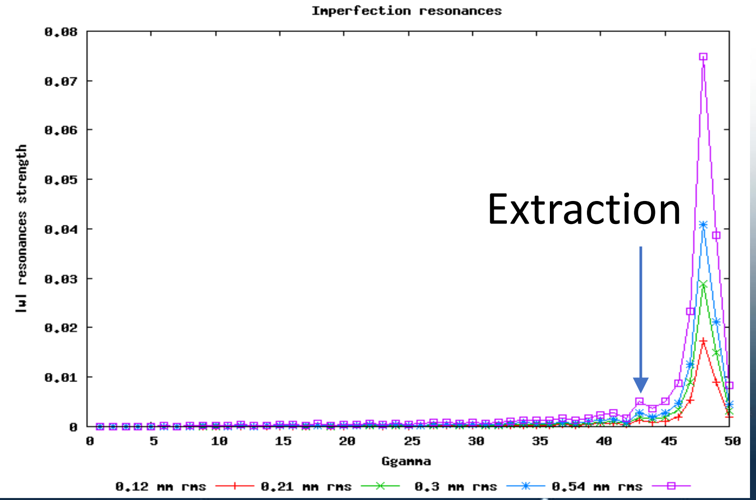
Proton beam for highest luminosity scenario through HSR arc sextupole



Electron Polarization Preservation In RCS

- Both the **strong intrinsic and imperfection resonances** occur at:
  - K = nP +/- Qy
  - K = nP +/- [Qy] (integer part of tune)
- To accelerate from 400 MeV to 18 GeV requires the spin tune ramping from
  - **0.907 < GY < 41.**
- If we use a periodicity of P=96 and a tune with an integer value of 50 then our first two intrinsic resonances will occur outside of the range of our spin tunes
  - K1 = 50+ν_y (ν_y is the fractional part of the tune)
  - K2 = 96 – (50+ν_y) =46-ν_y
  - Also our imperfection will follow suit with the first major one occurring at K2 = 96 – 50 = 46
- **Simulation**: At 200 mm-mrad RMS normalized emittance, we can tolerate beyond 2% field errors and still maintain above 95% polarization transmission.
- **Issue to control**: Imperfection spin resonances → vertical RMS orbit 0.5 mm to keep losses < 5%.



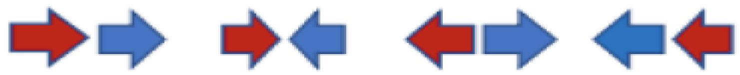


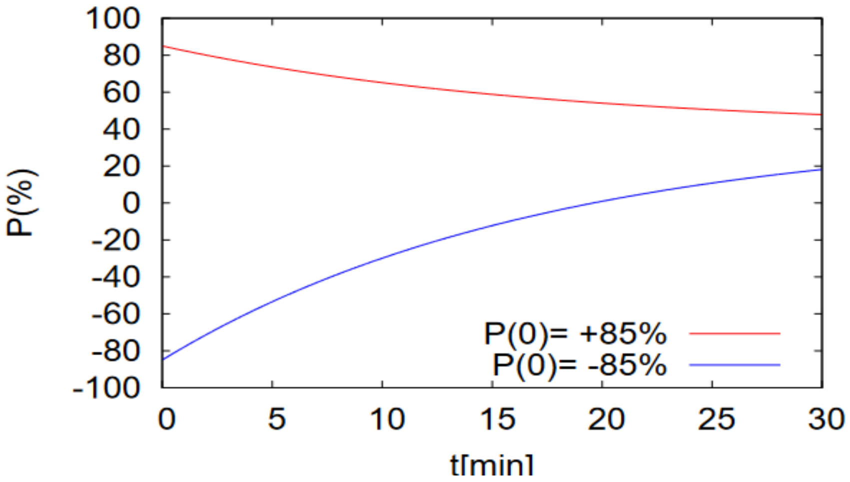
Electron Polarization In ESR

- **Experiments requirements**:
  1) high average polarization > 70% ,
  2) longitudinal polarization with both helicities in the store,
  3) beam energies 5, 10, 18 GeV
- Self-polarization and spin diffusion processes reduce polarization
- **All bunches in ESR to be replaced in a few minutes to achieve 70% average polarization.**
- High initial polarization of 85% from RCS at 1 Hz injection rate.
- Spin rotators on both sides of IP to change polarization from vertical to longitudinal directions → spin matching in rotators
- **Need tight orbit control** to achieve P_∞= 30% at 18 GeV ESR lattice.

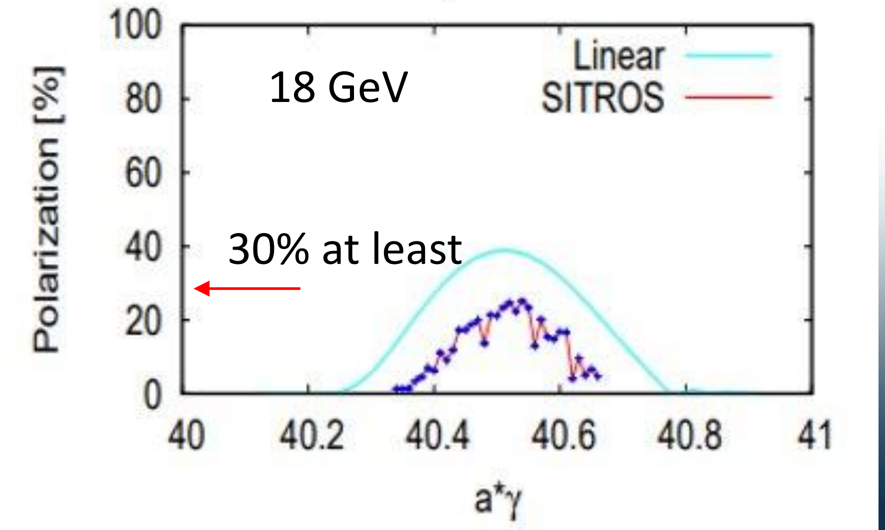
18 GeV Lattice	P_{bks}	τ_{bks} [min]	τ_{dep} [min]	P_∞*	$T_{\uparrow\downarrow}$[min]	$T_{\downarrow\downarrow}$[min]	T_{tot}[min]
V6.1 1IP	87.5%	36.2	26.0	35.8%	11.8	4.1	6.1
V6.1 2IP	85.9%	36.3	20.6	28.4%	8.6	3.8	5.3

Random spin pattern

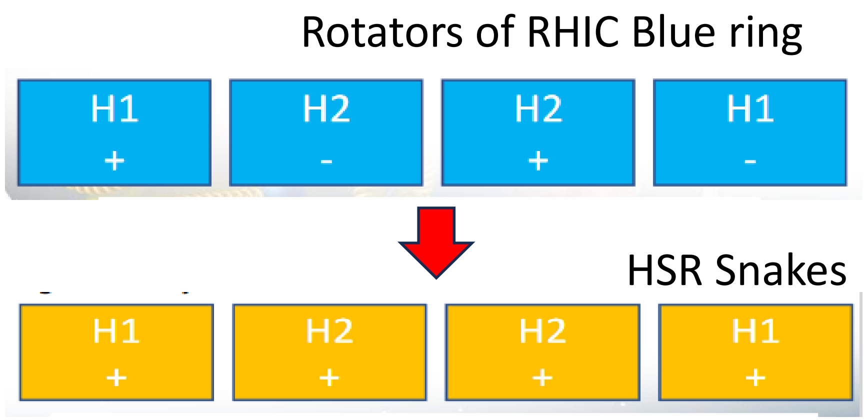




$$P(t) = P_\infty \left[1 - \exp^{-t/\tau_p}\right] + P(0)\exp^{-t/\tau_p}$$



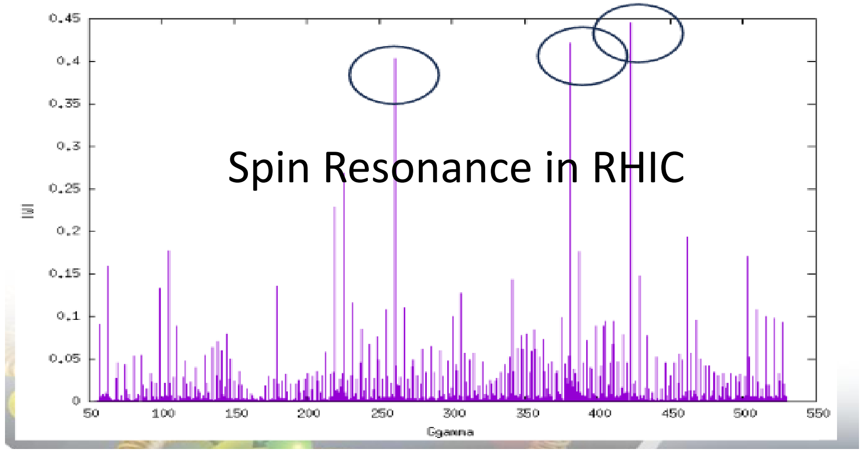
Hadron Beam Polarization

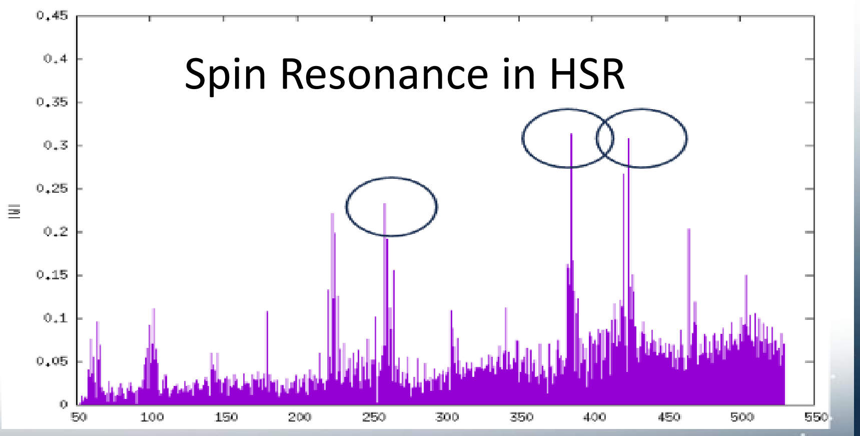


- **HSR requirement**: 70% polarization for proton and 3Helion+2
- 3He+2 polarization simulations show that **number of Snakes must be increased from present 2 to 6** to over full energy range. Additional Snakes can be transferred from RHIC Yellow rotators.
- The HSR lattice requires significant changes to the 6-folded symmetry of the RHIC yellow ring, which impacts the intrinsic spin resonance structure.
- **Simulation results**:

  1) protons using 6 snake show that polarization is maintained in the HSR for < 1 mm-mrad emittance beam (nominal: 0.5 mm-mrad rms)

  2) However, for He3 we see losses at 0.5 mm-mrad emittance beam.
- Spin tracking studies are still on-going as are studies and lattice design is still evolving.





Dynamic Aperture of ESR

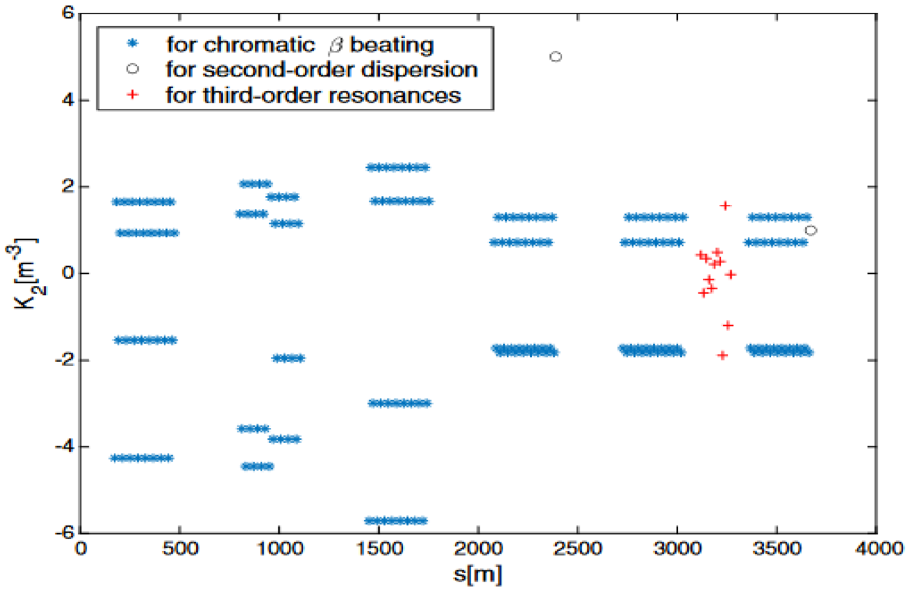
- ESR needs 20-25 nm horizontal emittance from 5 GeV to 18 GeV for optimum luminosity. 60° FODO cells at 10 GeV and 90° FODO cells at 18 GeV.
- **Dynamic aperture requirement**: 10 σ in all three dimensions. Most challenge case is: 18 GeV with two interaction regions, $(\Delta p/p_0)_{rms} = 10^{-3}$.
- **Strategies for DA improvement**:

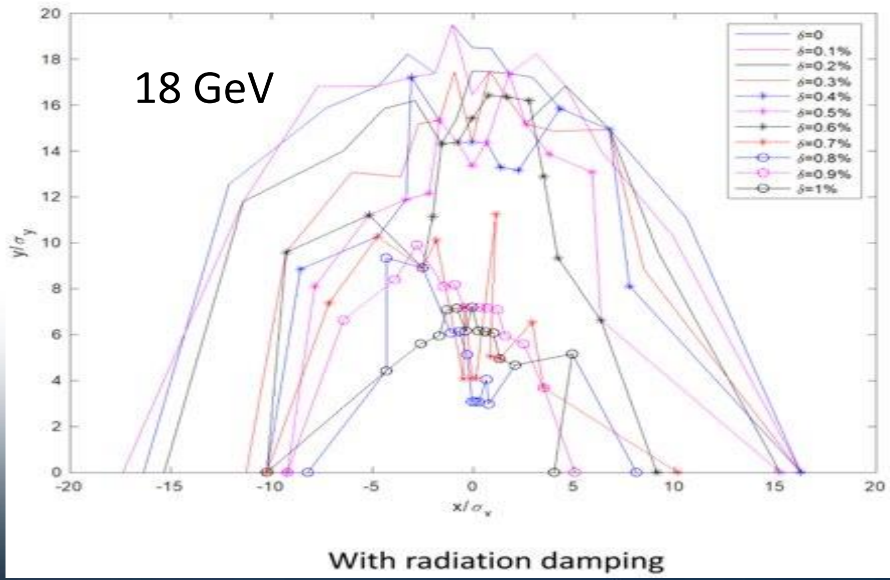
  - grouping of arc sextupoles

  - minimize off-momentum tune spread

  - minimize $W_{x,y}$ functions (semi-local scheme)

  - using harmonic sextupoles for $dD_x/d\delta$, RDTs
- APS quads and sextupoles found their new life in ESR and their field errors were included in DA studies.

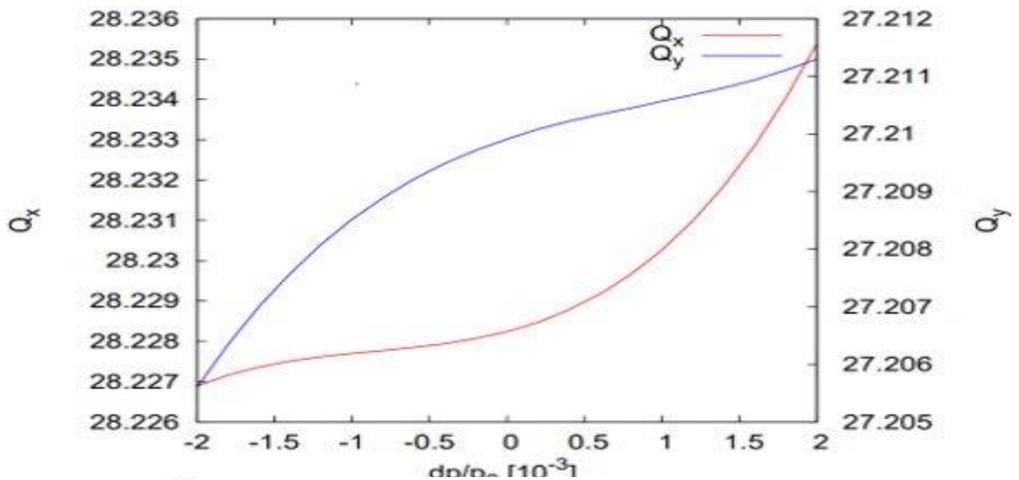


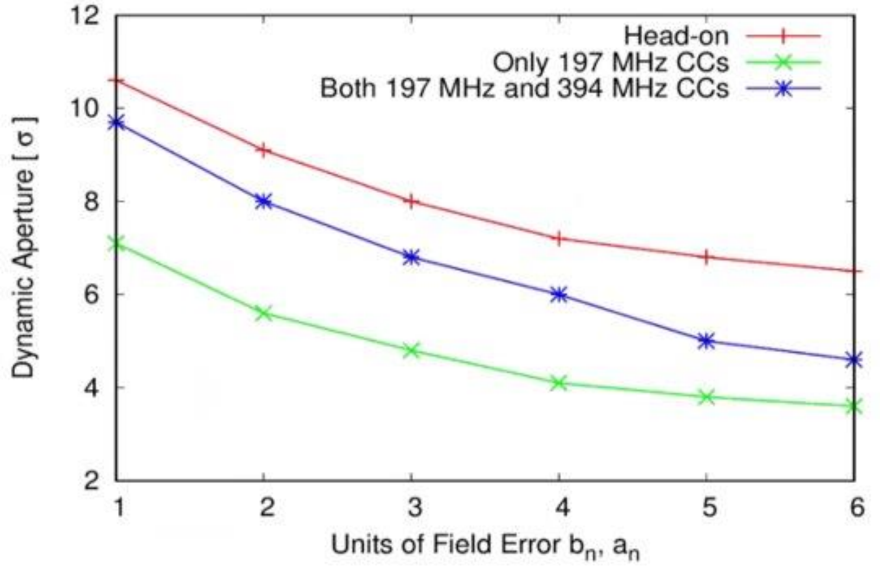


Dynamic Aperture of HSR

- **Requirement:** DA with beam-beam should be better than 5σ to guarantee sufficient proton beam lifetime.
- **Chromatic correction**: second order chromaticities below 800 with two families of chromatic sextupoles. More sextupole families is possible if needed (e.g., 2-IR lattice).

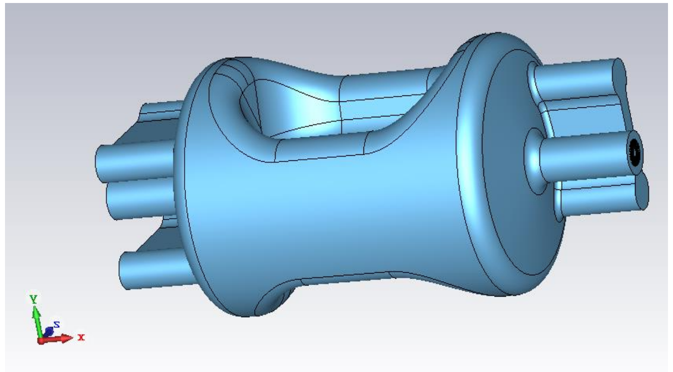
- **DA calculation results:** With 1 unit of IR field errors bn / an, DA is about 6σ with beam-beam and 197 MHz crab cavities. Second harmonic crab cavities required to limit dynamic aperture reduction due to crab crossing to 1 to 2σ, thus relaxing IR magnet tolerances.
- **Work Plan**:
  - Determine nonlinear field tolerances for HSR IR magnets
  - Build a complete HSR tracking model.

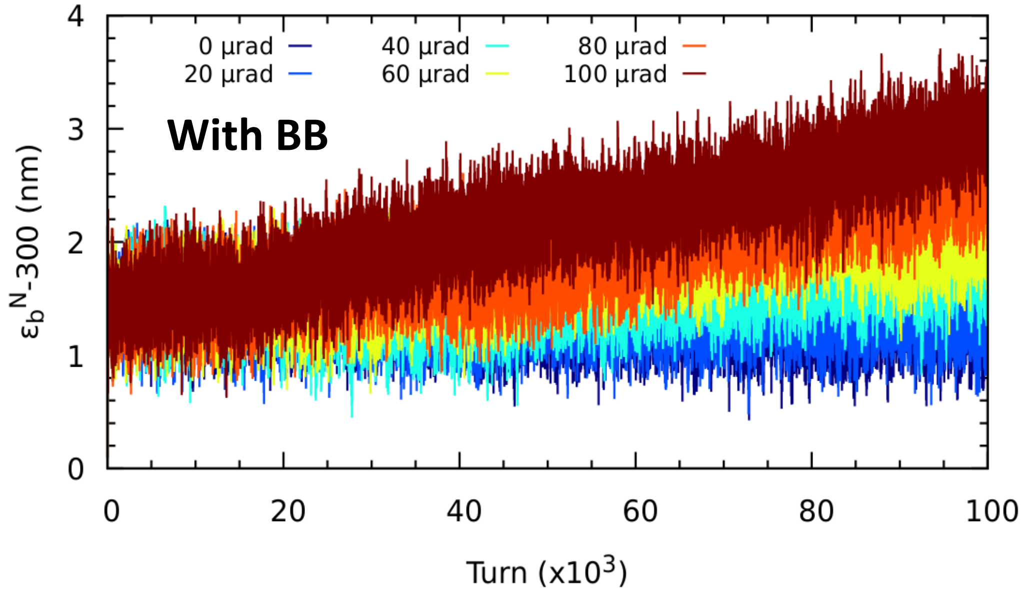


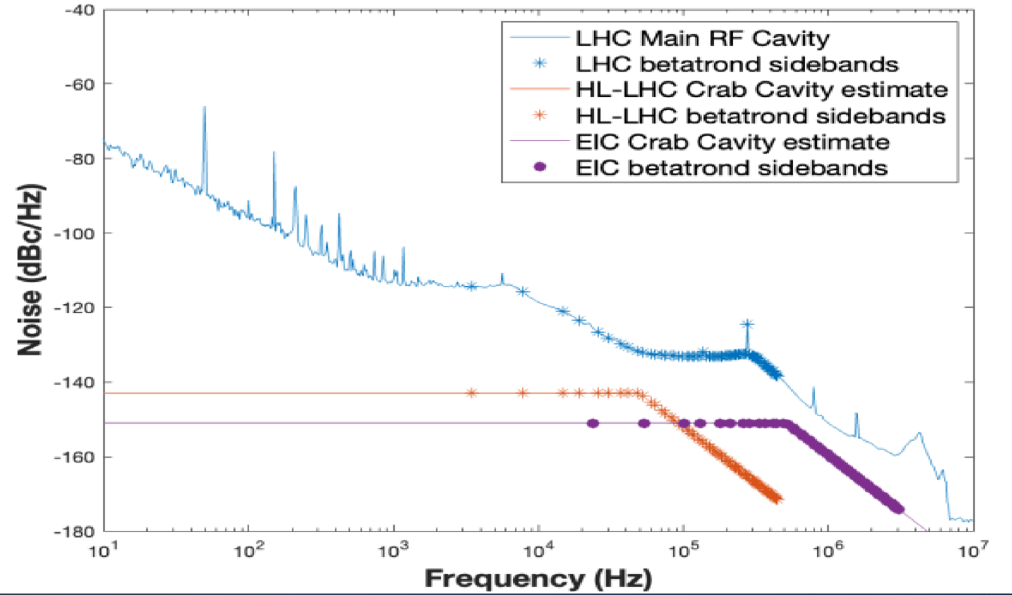


Crab Cavity Noises

- Numerical simulations confirmed horizontal growth predicted by analytical calculation.
- We observed vertical emittance growth with both phase noises and beam-beam.
- **Tolerances:** To have proton beam size growth rate less than 10%/hour in both planes, RMS of pink phase noises should be no more than 1urad.
- **Possible countermeasures:** LLRF phase feedback, fast one-turn beam feedback, high precision pickup~1 um, etc.

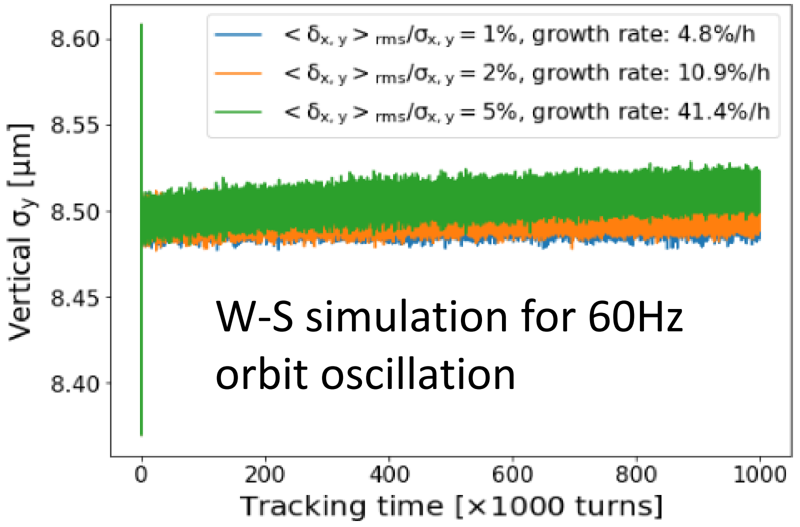






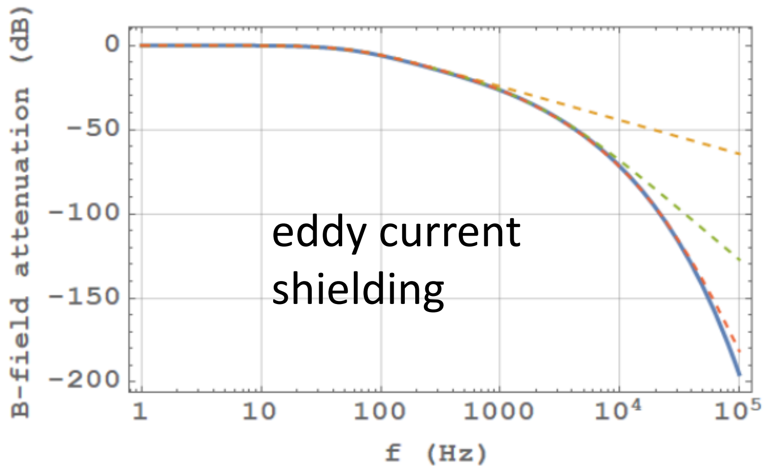
Power Supply Current Ripples

- Power supply current ripples, especially that from main dipoles of the ESR will introduce orbit oscillations, which will cause a sizeable proton emittance growth through beam-beam interaction.
- W-S BB simulation: to have proton beam size growth less than 10%/hour, orbit oscillation at IP should be less than 2.5% $\sigma_{x,y}$ for low frequency band (<8 kHz), and less than 10^{-4} $\sigma_{x,y}$ for high frequency band.
- The tolerance of dipole power supply current ripple at low frequency band is about 0.5-1.5 ppm depending on the magnets. The high-frequency ripple is less worrisome due to very significant eddy current shielding.



Orbit oscillation at IP with 100ppm dipole field errors

Lattice v. 5.6 configuraton	x-orbit rms (microns), uncorrelated dipoles	x-orbit rms (microns), dipole strings
6 GeV/100 GeV, 1 IP	178	46.6
6 GeV/100 GeV, 2 IP	193	141
10 GeV/275 GeV, 1 IP	80.6	30.7
10 GeV/275 GeV, 2 IP	132	192
18 GeV, 1 IP	88.8	50.4
18 GeV, 2 IP	100	63.5

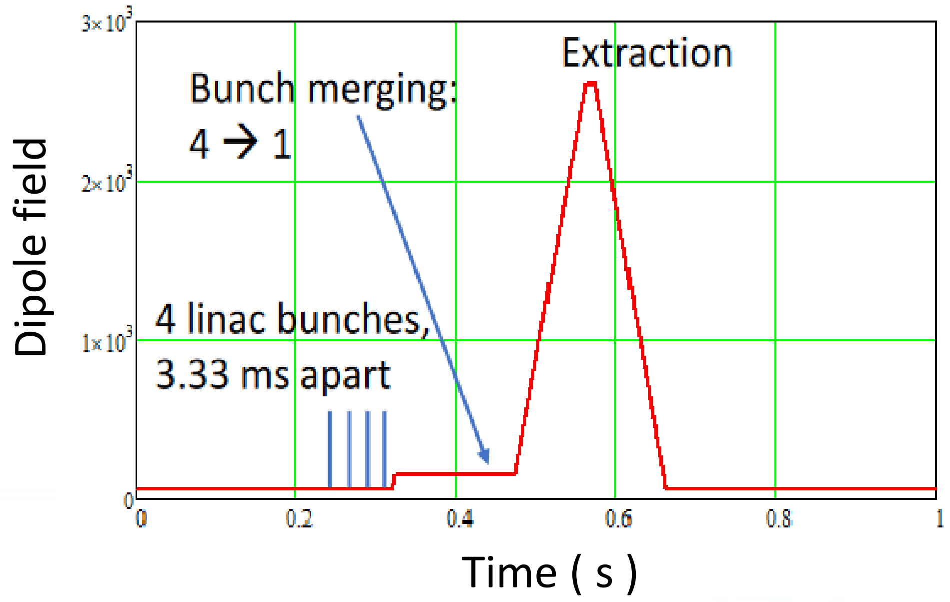


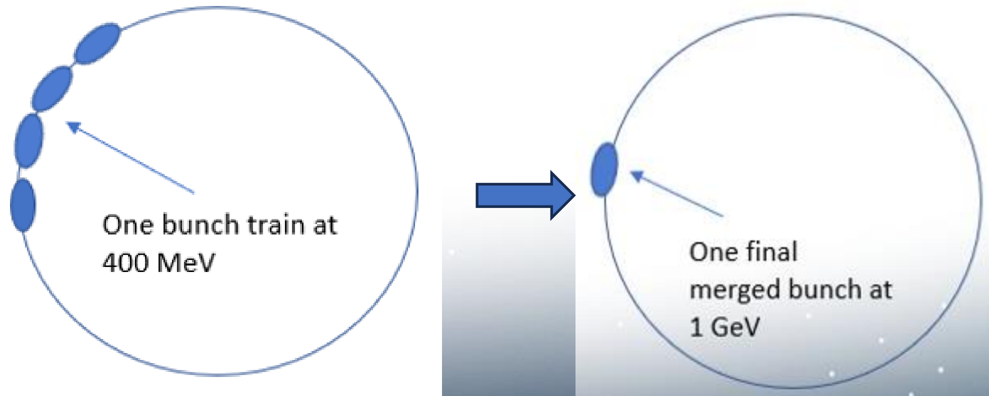
Bunch Merging & Emittance Preservation in RCS

- **RCS energy range**: 400 MeV to 18 GeV .
- Cycling rate of 1 Hz to replace ESR e-bunches to maintain average polarization 70% during collision.
- 4->1 bunch merging takes place at beam energy 1 GeV: 4 * 7nC/bunch -> 28 nC/bunch
- After bunch merging, RMS longitudinal emittance is **$\sigma_E \times \sigma_t$=2.5e-4 eV-s.**

- Equilibrium ESR rms emittances:
  5 GeV: 8.0e-5 eV-s
  10 GeV: 1.4e-4 eV-s
  18 GeV: 5.9e-4 eV-s

- **Work Plan**:
  We need to examine its impacts on dynamic aperture and beam-beam performance with synchrotron radiation damping in the ESR.





Low Fields and Eddy Currents in RCS

- Low dipole field in the RCS:

  400 MeV : 57 G , 18 GeV : 2.5 kG

  Large ratio of maximum and minimum fields is 45 !

  Quad fields are also small at injection: 80 G tip field.
- RCS beam spends its longest period of time (200 ms) at 1 GeV : dipole field: 140 G (still quite low). This is where we need the best field quality during bunch merging.
- **Eddy currents** during ramp induce large multipoles in dipoles.

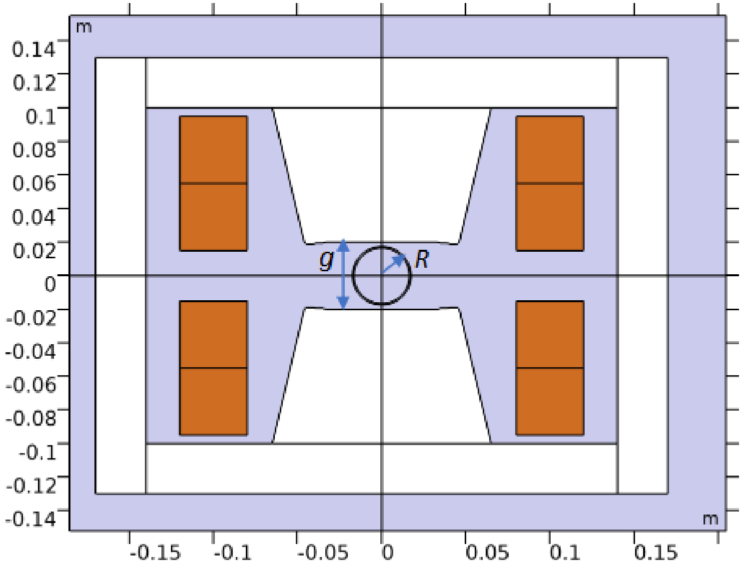
$$B_S(t) = \frac{S(t)}{2}\left(y^2 - x^2\right) \qquad S(t) = \frac{\pi^4}{15}\frac{\dot{B}(t)tR\mu_0}{\rho}\frac{R^2}{g^4} \approx 2.3\ \frac{\mathrm{T}}{\mathrm{m}^2}$$

- **RCS magnet R&D program just started**:
  - Test dipole magnet:

    measure low-field behavior, repeatability, hysteresis
  - Stray field in RHIC tunnel:

    expecting significant fields due to HSR and ESR at full energies

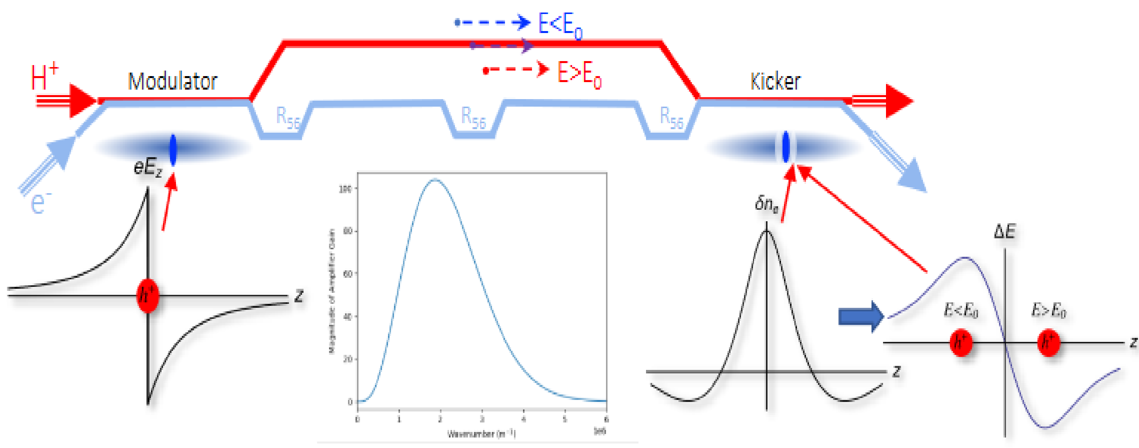
RCS dipole magnet concept

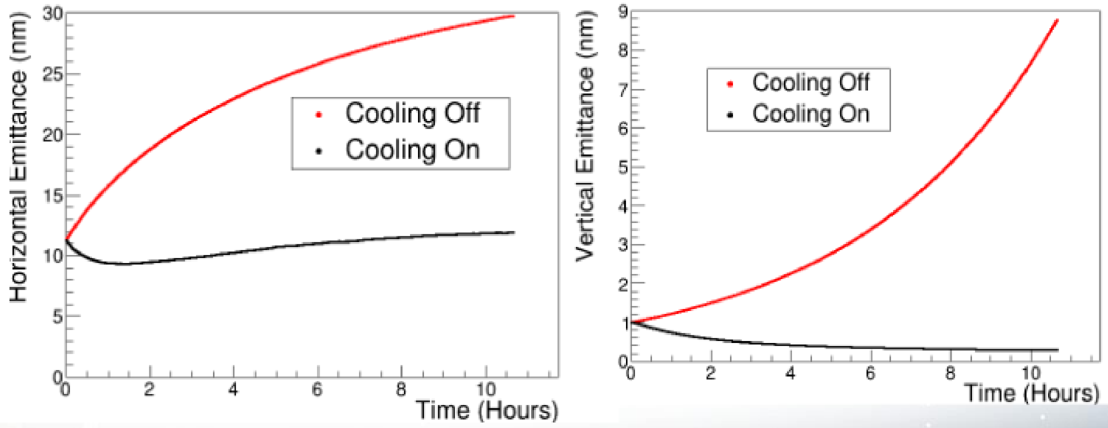


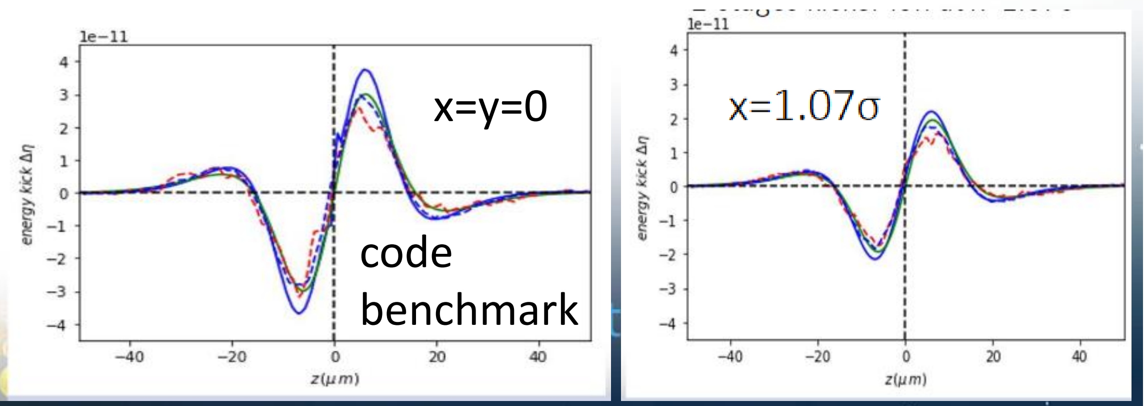
RCS vacuum chamber: Copper tube, R = 17.5 mm, t = 1 mm.

Strong Hadron Cooling

- IBS longitudinal and transverse (horizontal) growth time is 2-3 hours. Beam-beam growth time (vertical) is > 5 hours. The cooling time shall be equal to or less than the diffusion growth from all sources. The integrated luminosity with cooling is 10 x larger than without SHC.
- **Baseline for high energy hadron cooling is coherent electron cooling approach**, with the bandwidth range raised from ~GHz to tens of THz.
- This team made significant progress on the EIC SHC design:
  - 3D simulation tools have been developed.
  - ERL design shows we can get good beam quality.
  - Beam noise have been studied and within specifications
  - Schottky signal modification for e-h misalignment diagnosis
- **Another scenario**: storage ring cooler feasibility studies progress well.
- Final pick due to early next year. Both needs significant R&D.







Summary

- Beam dynamics challenges in the EIC design are presented.
- We have made good progress on the majority of accelerator physics topics. Some issues have been identified but most look straightforward.
- Crab cavity noise and feedback requirements are beyond the state of the art, much work is being done.
- Final decision on which method to adopt for strong hadron cooling for the EIC will be made next year.

Acknowledgement

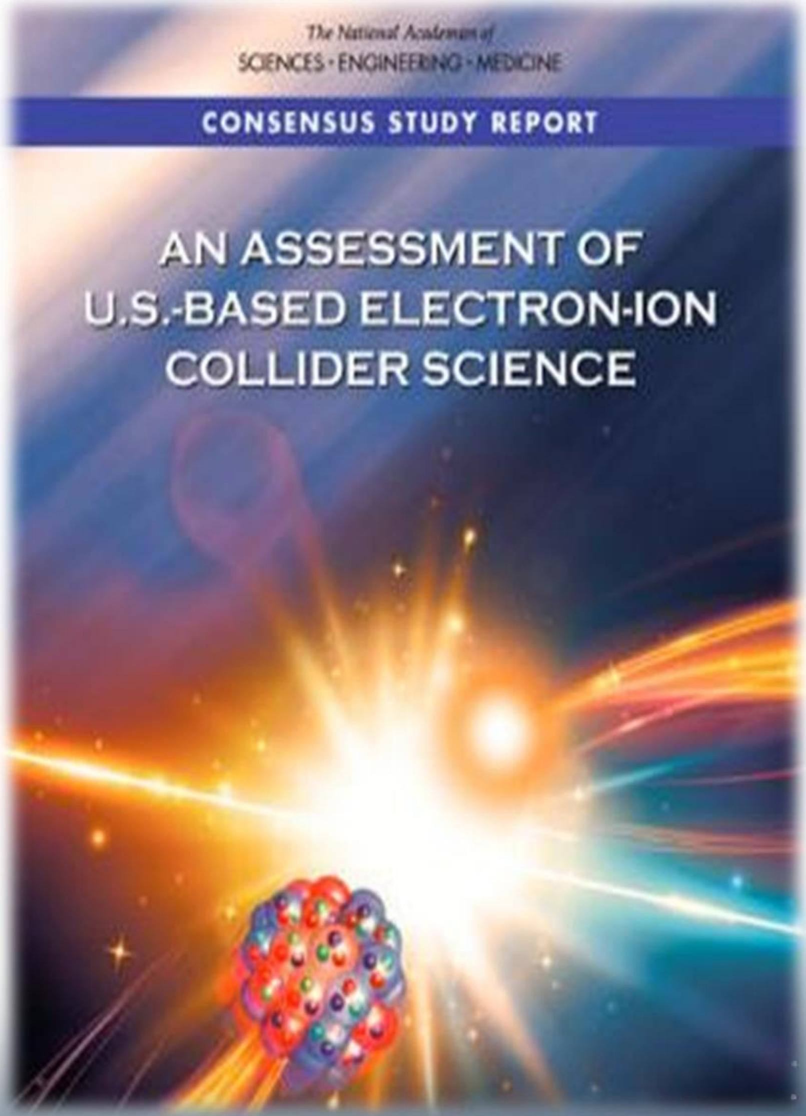
M. Blaskiewicz, A. Blednykh, C, Montag, D, Marx, S. Nagaitsev, V. Ranjbar, V. Ptitsyn, S. Verdú-Andrés, E. Wang, F. Willeke for generous help during preparation of this talk.

EIC Physics

An EIC can uniquely address three profound questions about nucleons — neutrons and protons — and how they are assembled to form the nuclei of atoms:

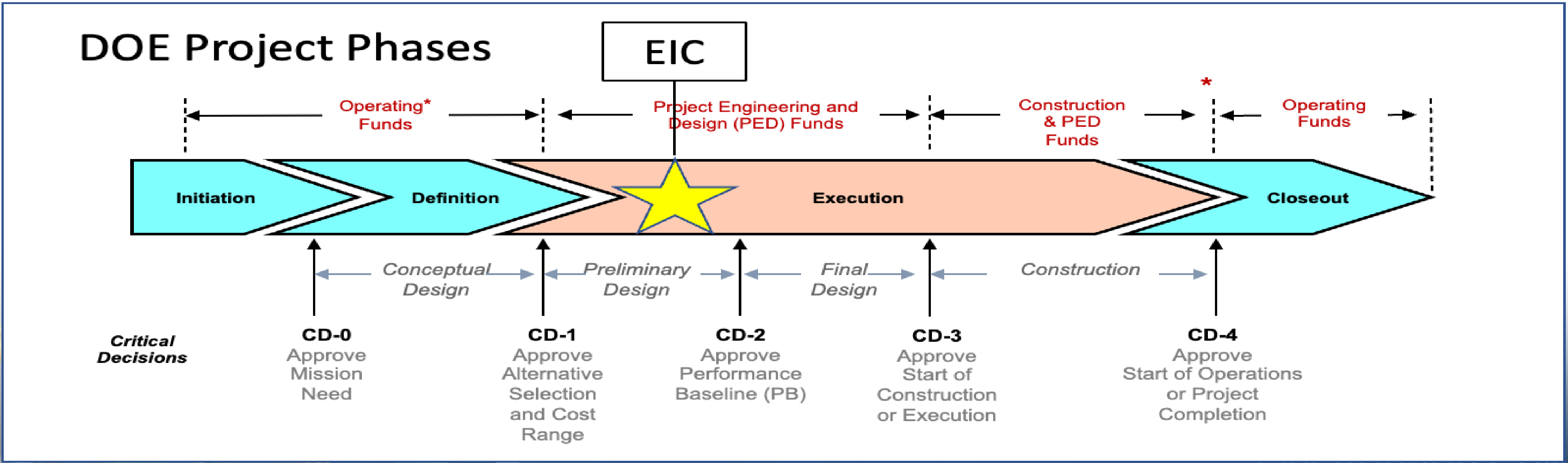
- **How does the mass of the nucleon arise?**
- **How does the spin of the nucleon arise?**
- **What are the emergent properties of dense systems of gluons?**

* National Academies of Sciences, Engineering, and Medicine, "An Assessment of U.S.-Based Electron-Ion Collider Science." The National Academies Press, Washington DC, 2018. https://doi.org/10.17226/25171.



EIC Project History and Plans

CD-0, Mission Need Approved	December 2019
DOE Site Selection Announced	January 2020
CD-1, Alternative Selection and Cost Range, Approved	June 2021
CD-3A, Long Lead Procurement	**January 2024**
CD-2/3, Performance Baseline/Construction Start	**April 2025**
RHIC Shut Down	**June 2025**



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Challenges in EIC BB Interaction

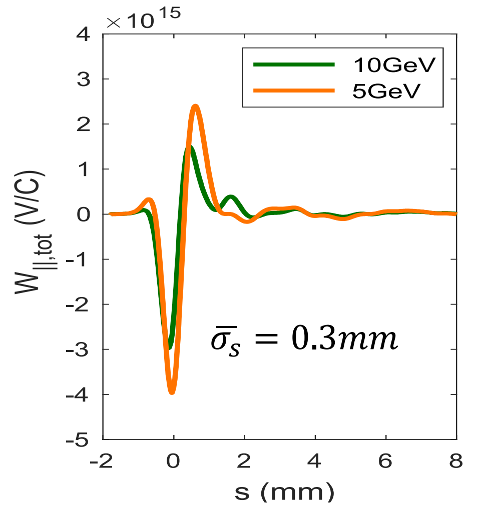
- **High beam-beam parameters**
  Proton BB parameter~0.015, Electron BB parameter~0.1
  combination not demonstrated in early electron-ion collider
- **Large crossing angle**
  full crossing angle is 25mrad in IR6
- **Crossing angle collision with crab cavities**
  crab cavities had been used in KEK-B, not used in hadron collider yet
  crab dispersion leakage, interference between detector solenoid and crab cavities
  crab cavity multipoles, voltage and phase noises of crab cavities
- **Flat beam at IP and large transverse emittance ratio**
  need very strict coupling control, vulnerable vertical emittance growth with BB
- **Synchro-betatron resonances:**
  large crossing angle, large synchrotron tunes (0.01 in HSR, 0.069 in ESR)
- **Near-integer electron tunes:**
  electron bunch pinch effect → larger proton BB parameter

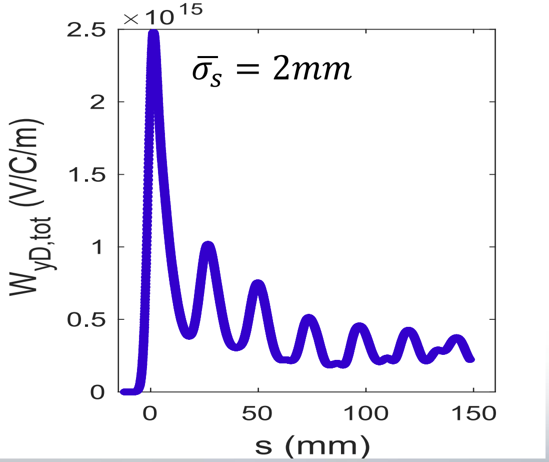
ESR Impedance Budget (CD-1)

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	-	✓
Coherent Synchrotron Radiation	CSR	-	✓

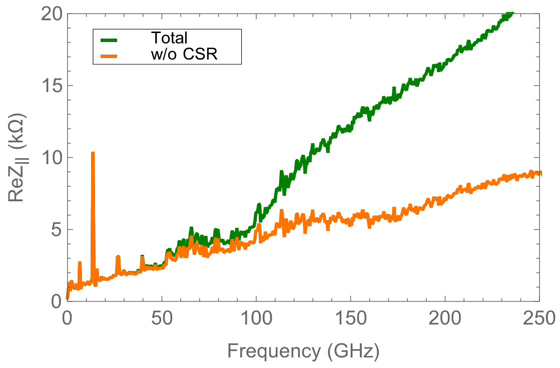
1 - SKEKB design
2 - NSLS-II design

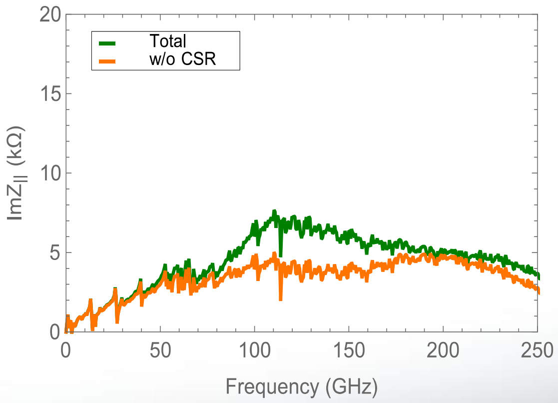
✓ - Included into the total W(s)





- FFT of the total longitudinal wake field at 5GeV



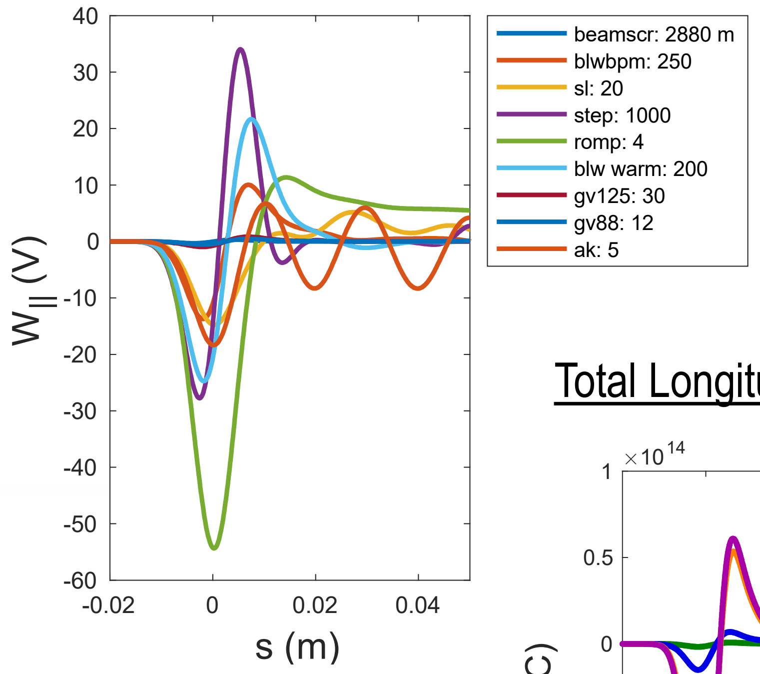


- The strong resonance peak at 14GHz corresponds to 494 BPM.

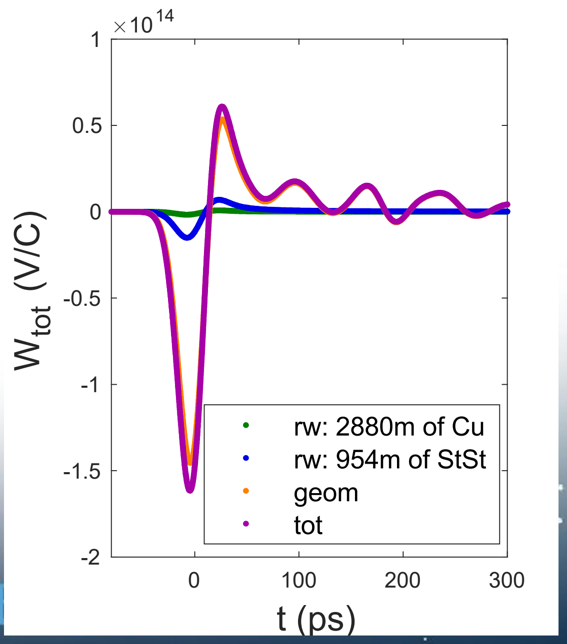
HSR Impedance Budget

- Status of Impedance Simulations:
  - Beam Screen
  - Cold BLW + BPM: 250
  - Cold BLW + Pump Ports: 250
  - Warm BLW: 200
  - Arcs: 2880m of Cu
  - Warm Straight Sections: 120mm diam StSt with NEG coating (1um), L=954m
  - RF System + Tapered Transitions: TBD
  - Collimators: 3
  - Septums: 2 low Energy by-pass, 4 SHC, 1 Inj. 1 Extraction
  - Flange Joints (Steps): 1000
  - IR: 1
  - Abort Kickers: 5
  - Injection Kickers (SL): 20
  - Polarimeters: 2 pCarbon & hJet
  - Roman Pots: 4
  - Tune Monitors: Bunch-by-Bunch Feedback 1H&1V
  - GV 88mm & 125mm: 12 & 30

σ_s = 4 mm



Total Longitudinal Wakefield



Dampers for Instabilities in the EIC

Per Mike Blaskiewicz:

- We might need a longitudinal one in the ESR during store. Not sure, but maybe.

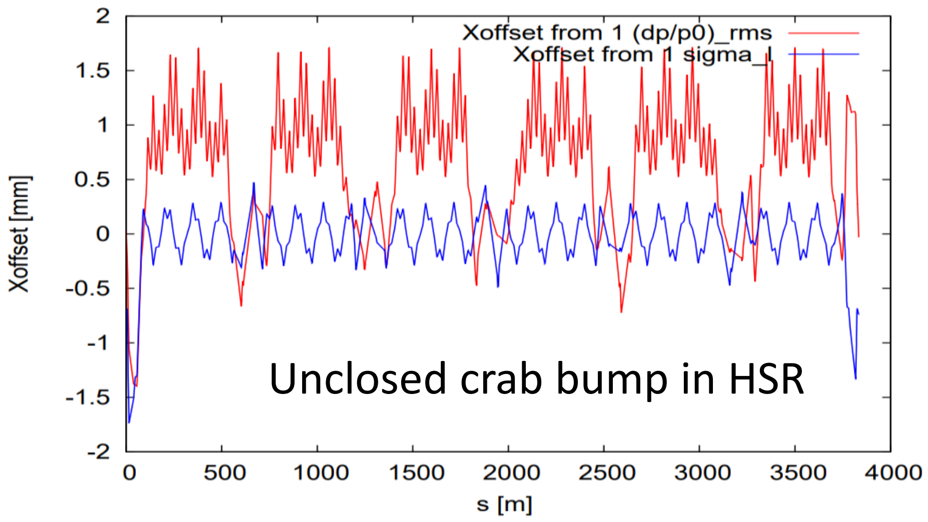
- During injection and ramp in the HSR, we might need a damper to damp instabilities driven by the crab cavity fundamental mode.

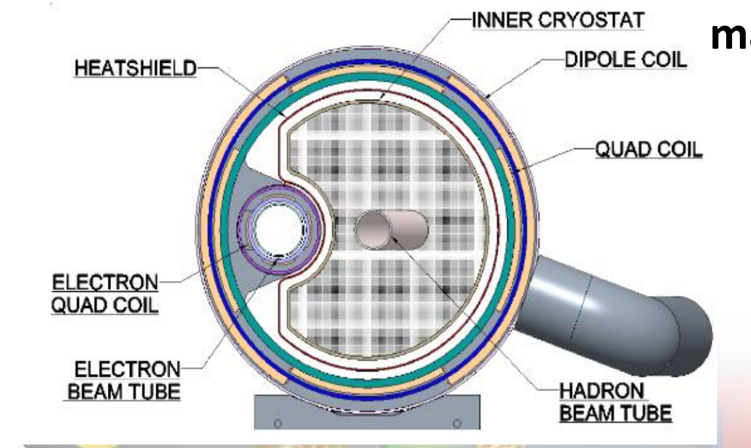
- When we do vacuum scrubbing in the ESR, we will probably need a transverse damper and a longitudinal damper.

Further studies are ongoing.

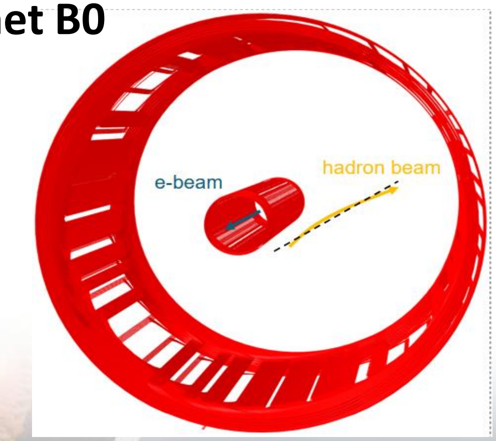
Machine Imperfection

- **Optics Imperfections**: Twiss parameters at IP and crab cavities, phase advances between IP and crab cavities, crabbing bump closure, detector solenoid effect, vertical crab dispersion at IP, crab dispersion leakage, etc.
- **Machine Imperfections**: misalignment and roll errors of magnets, magnetic nonlinear field errors, multipoles in crab cavities, nonlinear fields in arc dipoles (important for radially shifted design orbits), etc.





Common magnet B0



$$(B_yL)^M + i(B_xL)^M = B(R_r)L\left[10^{-4}\sum_{n=0}^{N_{max}}(b_n^M + ia_n^M)\frac{(x+iy)^n}{R_r^n}\right]$$