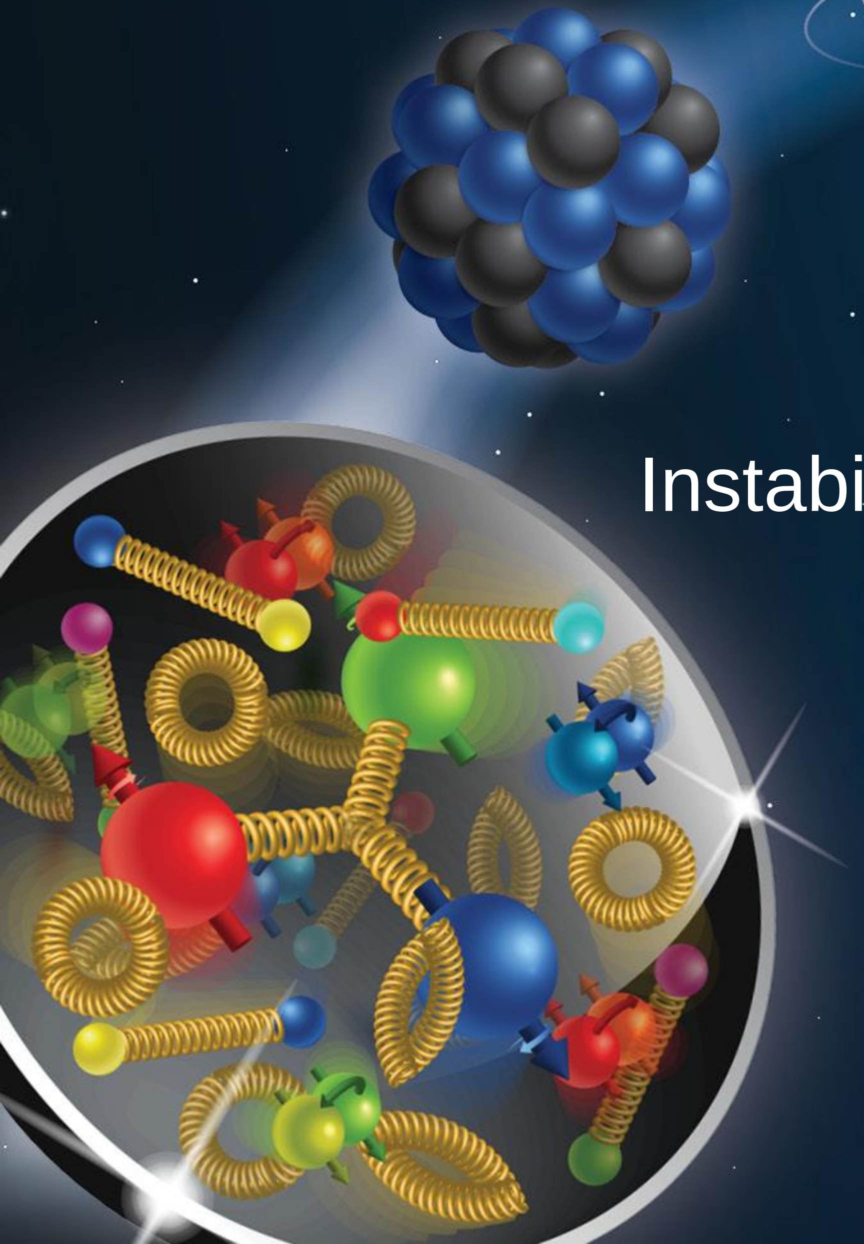

Instabilities and feedback in the EIC

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FCC week

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Electron-Ion Collider

BROOKHAVEN NATIONAL LABORATORY

Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science

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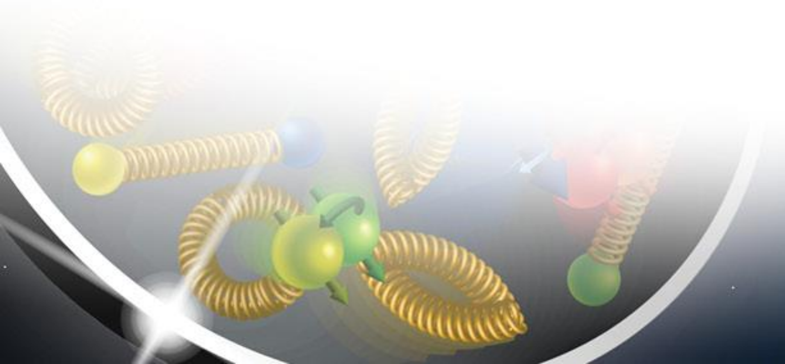
I will endeavor to cite the primary contributors within the talk.

Outline

- Overview of the Complex
- Electron Storage Ring (ESR)
- Hadron Storage Ring (HSR)



Overview

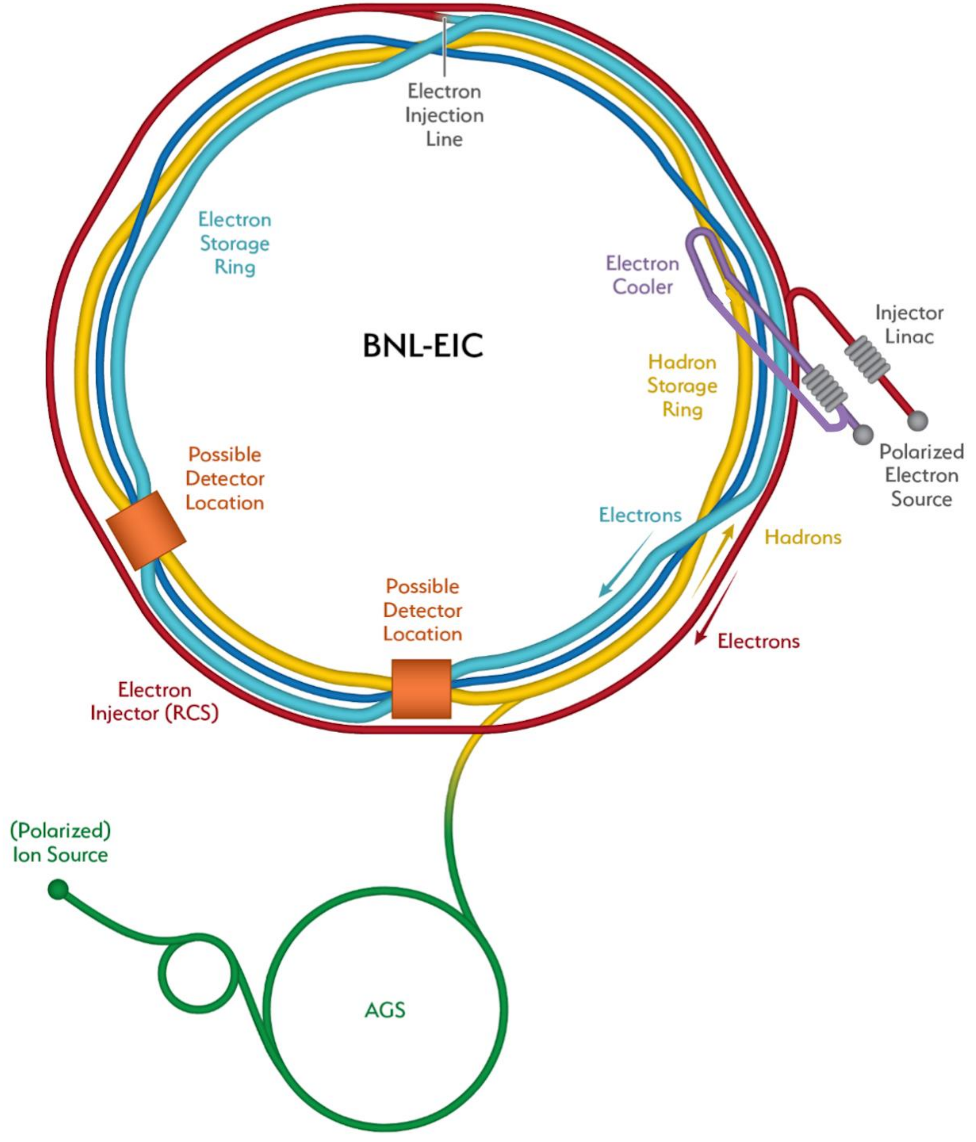
The Yellow (CCW) RHIC ring serves as the HSR.

Electrons are accelerated via a LINAC and the RCS.

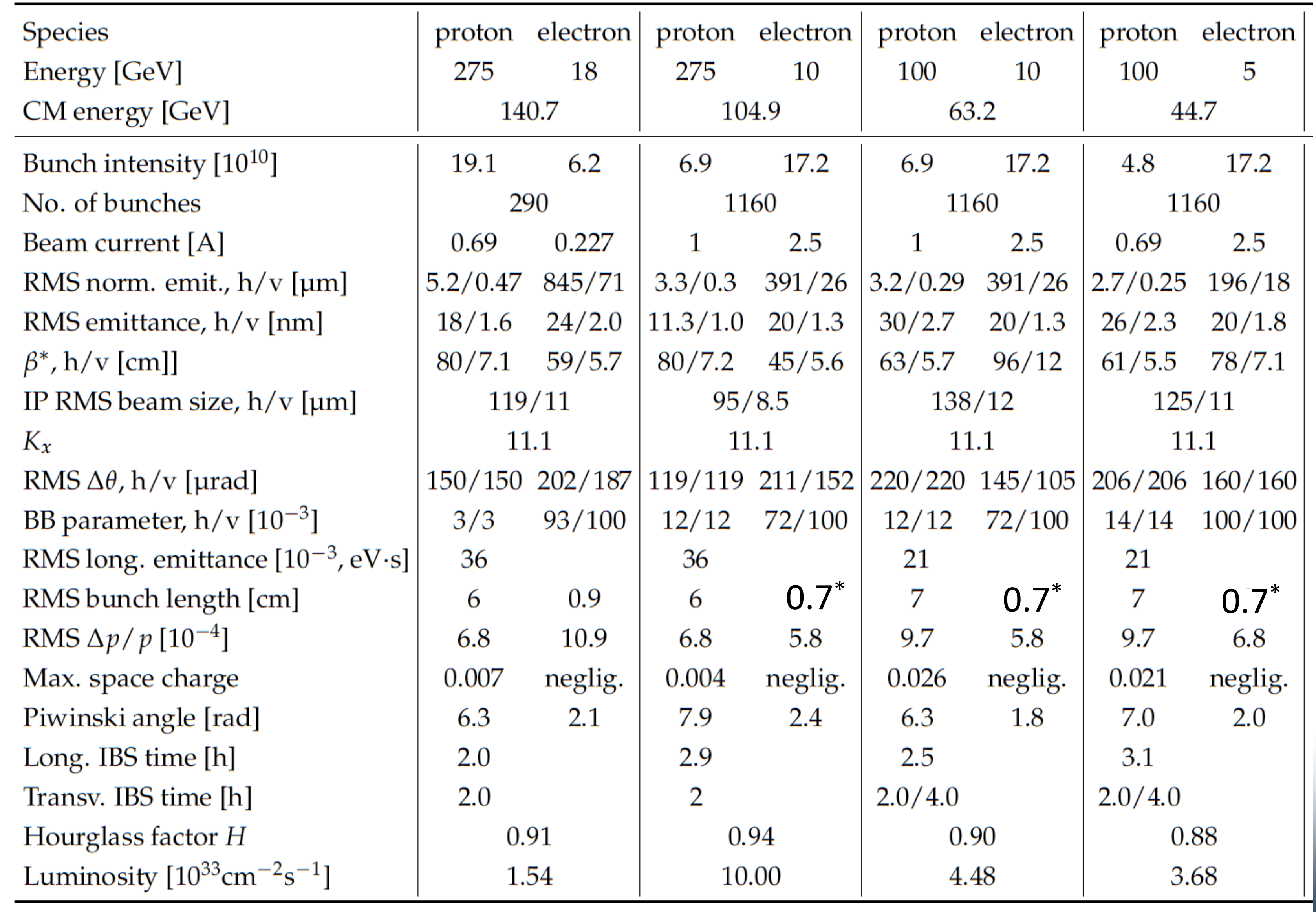
Use swap out injection into the ESR.

Strong cooling maintains the ion emittance.

The Blue ring is left largely intact.



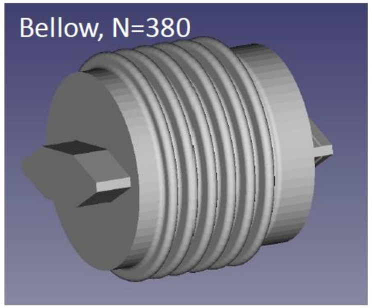
Machine Parameters (CDR Table 3.3*)

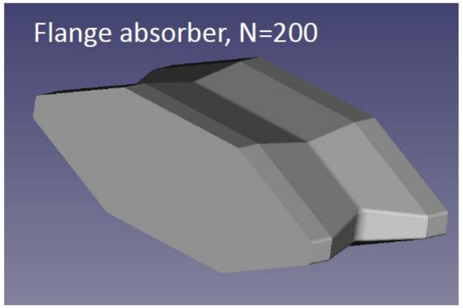


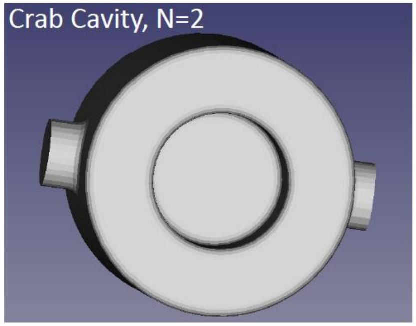
Species	proton	electron	proton	electron	proton	electron	proton	electron
Energy [GeV]	275	18	275	10	100	10	100	5
CM energy [GeV]	140.7		104.9		63.2		44.7	
Bunch intensity [10^{10}]	19.1	6.2	6.9	17.2	6.9	17.2	4.8	17.2
No. of bunches	290		1160		1160		1160	
Beam current [A]	0.69	0.227	1	2.5	1	2.5	0.69	2.5
RMS norm. emit., h/v [μm]	5.2/0.47	845/71	3.3/0.3	391/26	3.2/0.29	391/26	2.7/0.25	196/18
RMS emittance, h/v [nm]	18/1.6	24/2.0	11.3/1.0	20/1.3	30/2.7	20/1.3	26/2.3	20/1.8
β^*, h/v [cm]]	80/7.1	59/5.7	80/7.2	45/5.6	63/5.7	96/12	61/5.5	78/7.1
IP RMS beam size, h/v [μm]	119/11		95/8.5		138/12		125/11	
K_x	11.1		11.1		11.1		11.1	
RMS $\Delta\theta$, h/v [μrad]	150/150	202/187	119/119	211/152	220/220	145/105	206/206	160/160
BB parameter, h/v [10^{-3}]	3/3	93/100	12/12	72/100	12/12	72/100	14/14	100/100
RMS long. emittance [10^{-3}, eV·s]	36		36		21		21	
RMS bunch length [cm]	6	0.9	6	0.7*	7	0.7*	7	0.7*
RMS $\Delta p/p$ [10^{-4}]	6.8	10.9	6.8	5.8	9.7	5.8	9.7	6.8
Max. space charge	0.007	neglig.	0.004	neglig.	0.026	neglig.	0.021	neglig.
Piwinski angle [rad]	6.3	2.1	7.9	2.4	6.3	1.8	7.0	2.0
Long. IBS time [h]	2.0		2.9		2.5		3.1	
Transv. IBS time [h]	2.0		2		2.0/4.0		2.0/4.0	
Hourglass factor H	0.91		0.94		0.90		0.88	
Luminosity [$10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	1.54		10.00		4.48		3.68	

ESR Impedance

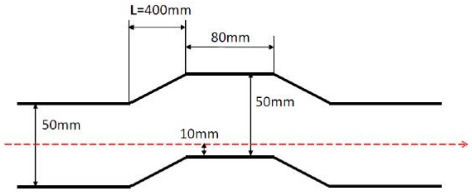
- The ESR reaches currents of 2.5 A. bunch charge of 28 nC (PEP-II e^+ 3.2A,14 nC, 1cm, 3.1 GeV)
- With a 591 MHz RF system $\sigma_s \approx 1$cm, $I_{peak} \approx 340$A.
- Wall heating is an issue
- We have rough designs for main components and wakefield calculations.
- The resulting wakefields are not too different to the scaled results from NSLS – II used previously.


Bellow, N=380


Flange absorber, N=200

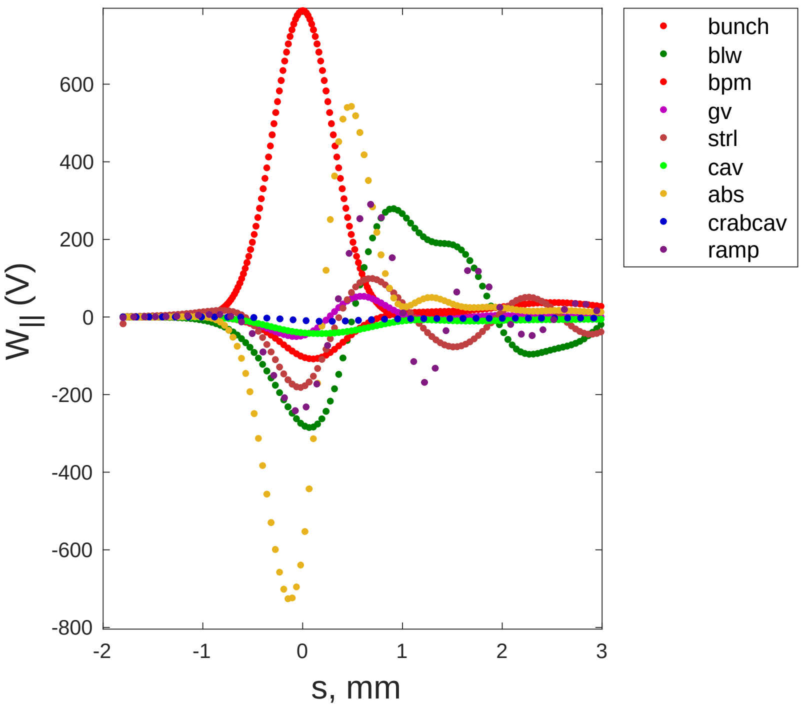

Crab Cavity, N=2

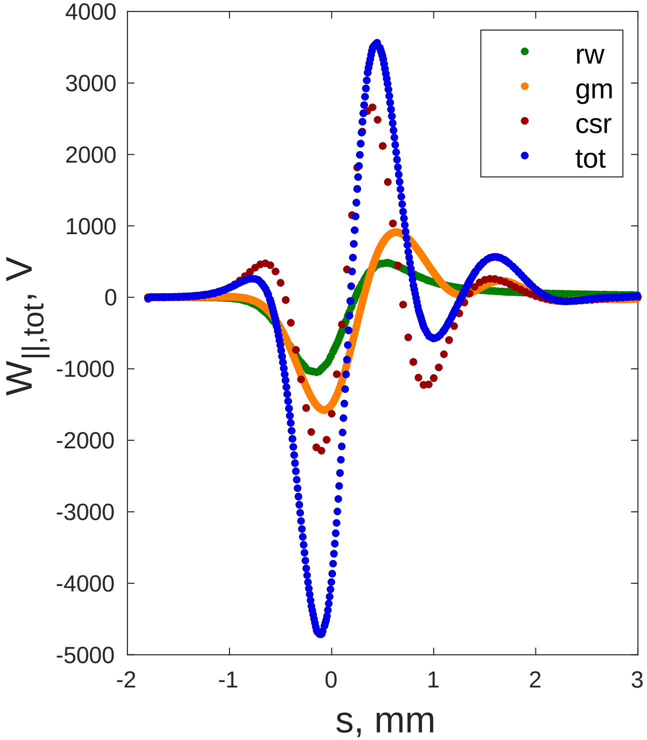
SKEKb Collimator, N=16



G. Wang, σ_s=2mm

- Longitudinal short range wakes (Blednykh, Wang)

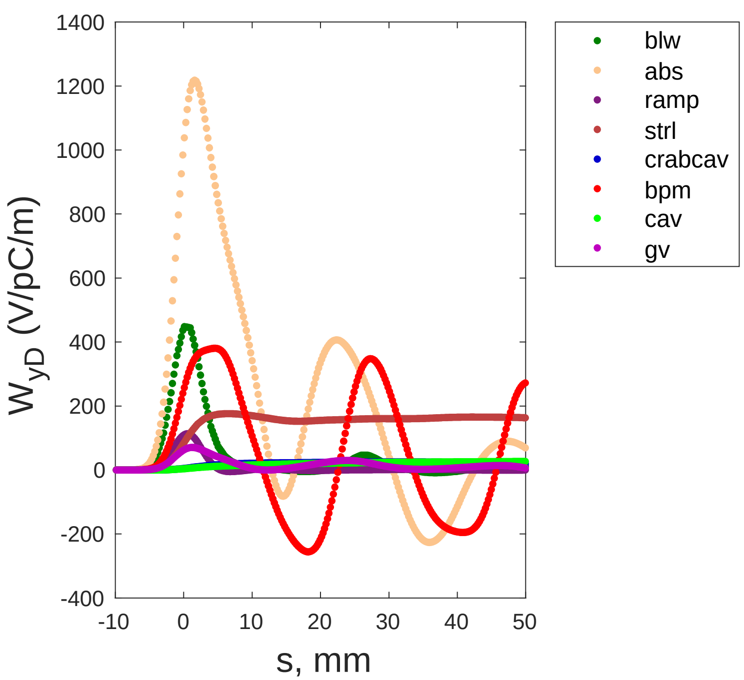


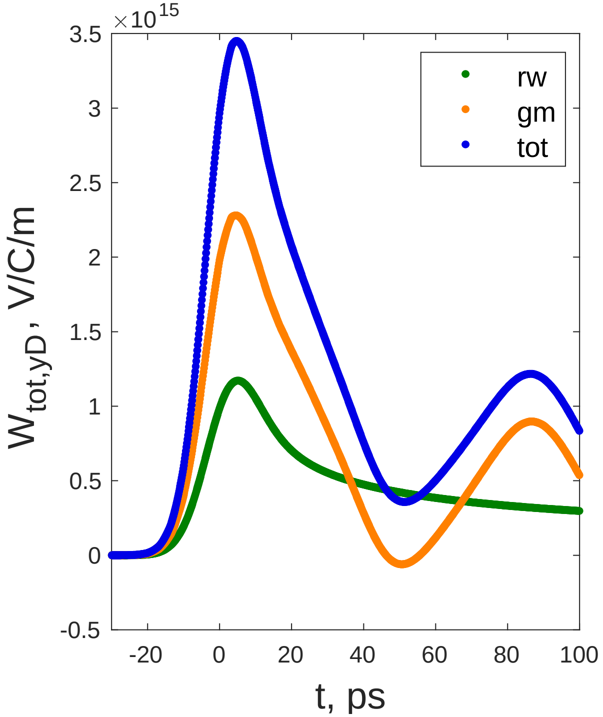


- The contributibutors to the geometric wake in order of size are synchrotron radiation absorbers (abs), bellows (blw), ramped collimator (ramp), stripline swap out kickers (strl), beam position monitors (bpm), gate valves (gv), RF cavities (cav), and crab cavities.

Vertical short range wakes (Wang, Blednykh)

- Vertical aperture is 36 mm, horizontal is 80 mm.





- Here too the synchrotron radiation absorbers dominate.

Long range wakes and HOMs

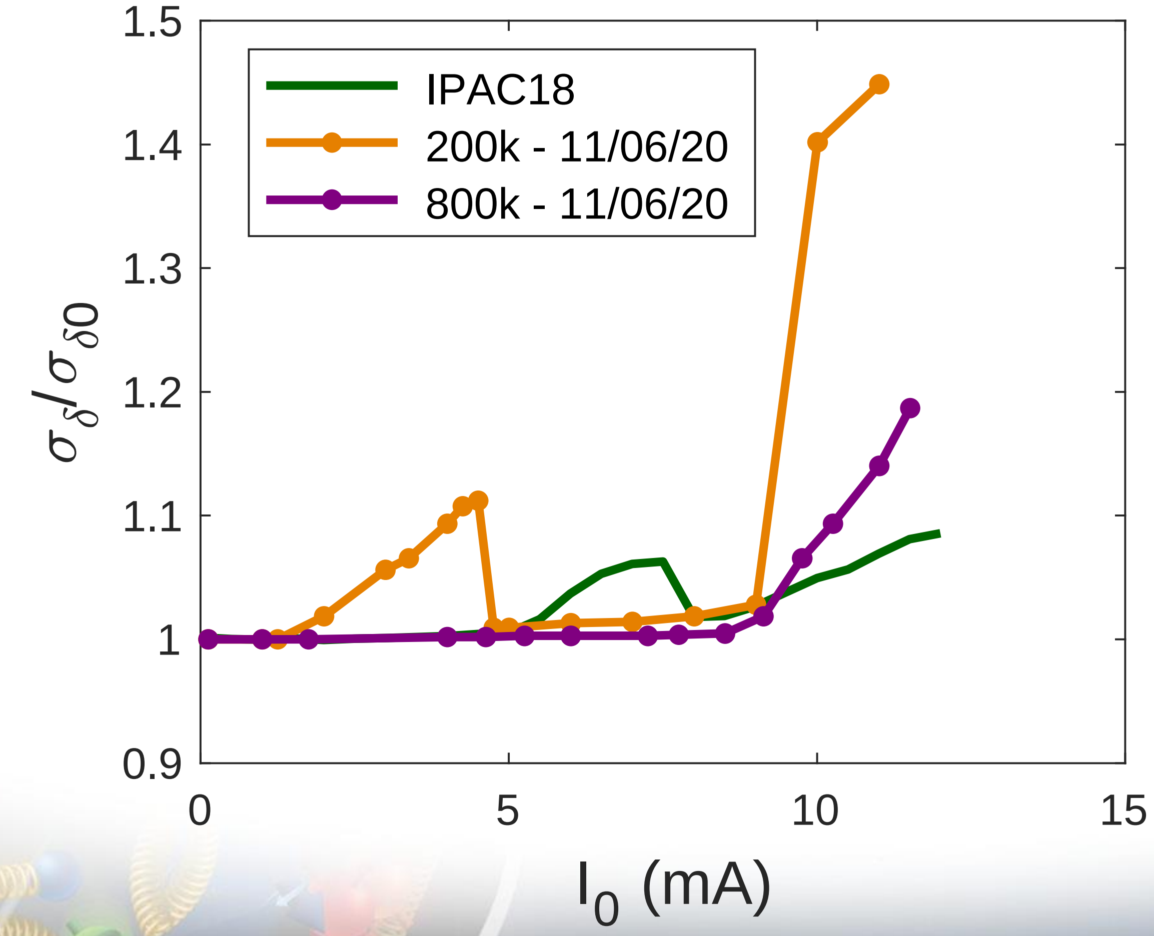
- The dominant transverse long range wake is the resistive wall. We use a copper alloy with resistivity $\rho = 1.33\rho_{Cu}$.
- The $1/\sqrt{t}$ long range behavior of the wake is difficult to simulate effectively. We use $W(t) = W_0 \exp(-\alpha t)$. Parameters are chosen to have the same CBM growth rate as resistive wall, but at $5f_{rev}$. This simply changes the coupled bunch mode number. Similar considerations by A. Burov?
- HOMs in the RF cavities and crab cavities dominate the longitudinal component.
- These are still being designed but appear to be OK.

Simulations

- So far we have been using an updated version of TRANFT, which was used for NSLS-II and evolved into the code used to simulate stochastic cooling with great accuracy.
- The updates involve the inclusion of long range wakes to simulate coupled bunch modes while tracking only a few bunches. Beam-beam has been upgraded too.
- Suppose a symmetric fill with $M=P^*n$ bunches with n small (5 or so). One tracks n adjacent bunches. On a given turn adjacent sets of n have identical longitudinal profiles. Transverse profiles are phase advanced by $\exp(i2\pi s/P)$ with $s=0,1,..P-1$, allowing for any transverse CBM.
- With these assumptions it is straightforward to update wakes of the form $W(t)=\mathrm{Re}[(W_r+iW_i)\exp(-a_r t-ia_i t)]$
- One needs to slightly modify longitudinal resonant frequencies $f_{res} \approx (K/P)f_{rev}$ to drive allowed modes.

ESR Instabilities

- Single bunch thresholds at 10 GeV are well beyond 2 mA (Blednykh).



ESR Instability

- Simulations show that weak-strong beam-beam tune spread Landau damps resistive wall transverse instabilities.
- We envision a damper for operation without ions and are looking into the limitations of damping with ions present.
- Beam-beam damps the ion instability for reasonable vacuum (Blaskiewicz NAPAC19).
- HOMs of the crab cavities and the main RF lead to an instability. We need a longitudinal damper. A 0.3 mm residual oscillation appears achievable and poses no threat to the ions. (Podobedov BNL-215885-2020)

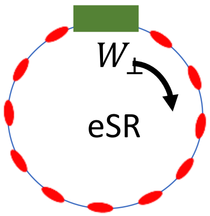
Coupled Coherent Dipole Motion (Rui Li)

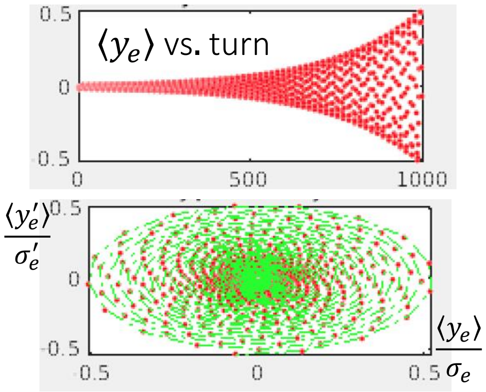
(Interplay of coherent beam-beam with transverse coupled-bunch instability)

TRANFT uses weak-strong beam beam for Landau damping.

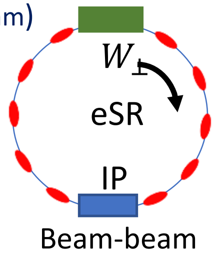
We are exploring the limitations in this.

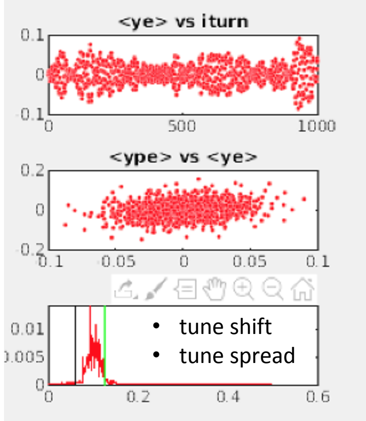
Transverse Coupled-Bunch Instability (TCBI)





TCBI is Landau damped by nonlinear beam-beam tune spread (for on-axis opposing beam)





- tune shift
- tune spread

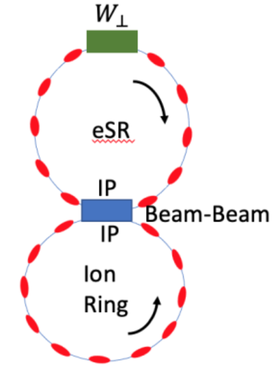
Beam-beam Parameters in EIC:

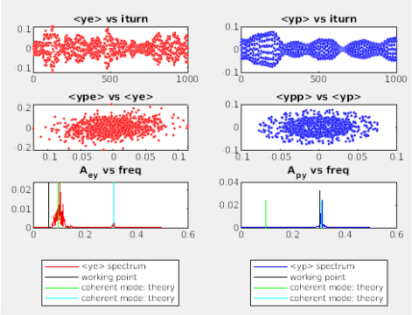
$\xi_e = 0.1$

$\xi_p = 0.012$

Round-beam and soft-Gaussian beam-beam model for initial study

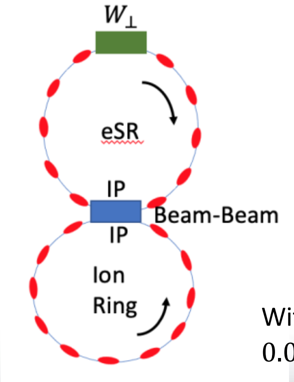
TCBI and coherent beam-beam (CBB) dipole coupling

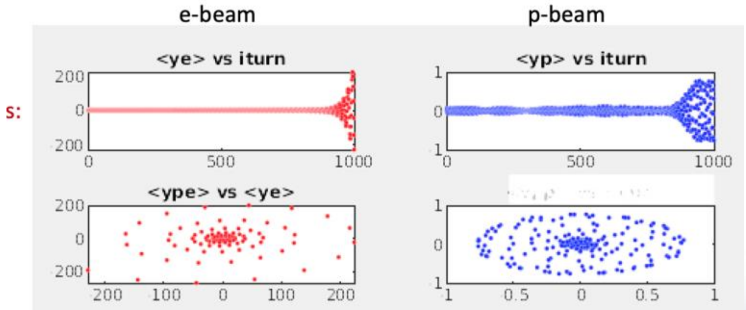




- Coherent BB modes manifested
- TCBI is Landau damped

TCBI and CBB dipole coupling (an extreme case)





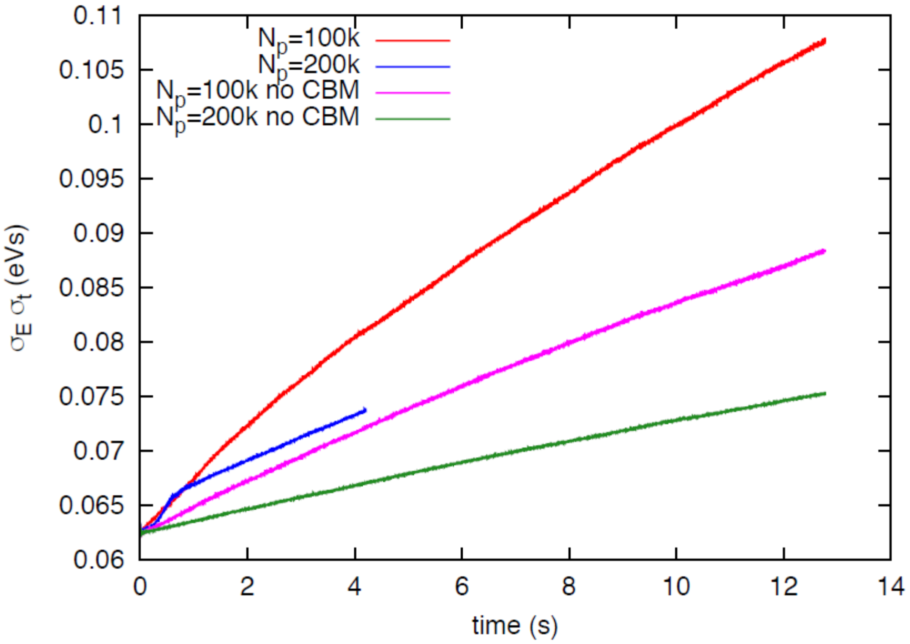
With a smaller e-beam beam-beam parameter ($\xi_e = 0.05, \xi_p = 0.012$) and a bigger transverse wake

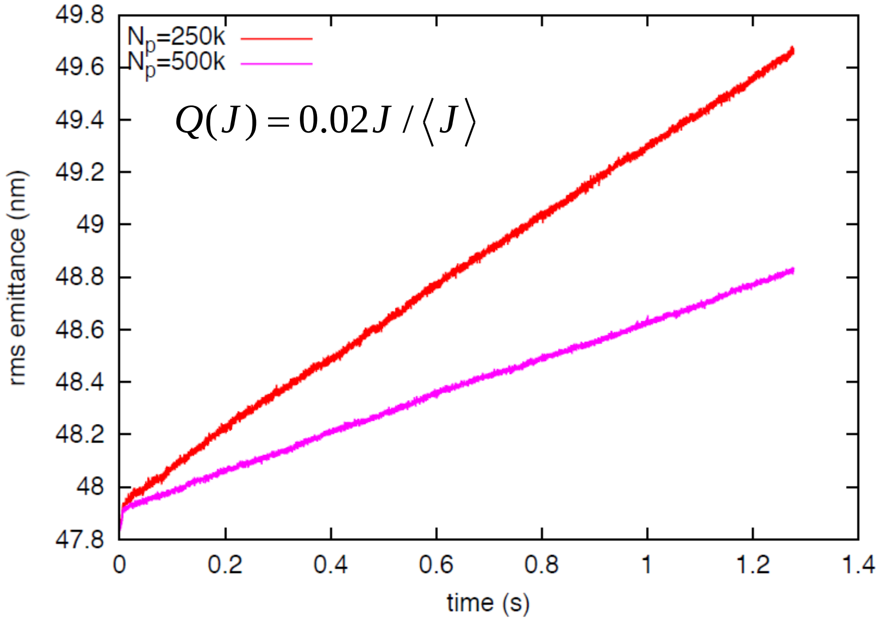
Instabilities in the Hadron Ring

- Ions do not have radiation damping and stability is due solely to frequency spread.
- Our simulations use no more than a few 10^6 macroparticles per bunch so our granularity is high and we always see emittance growth even with stable beams.
- This is like stochastic cooling in reverse and the growth rates for stable beams scale like $1/N_{macro}$.
- Therefore, we vary the number of macroparticles and look for the correct scaling.
- Similar things have been done before.

Proton results

- Measured broad band impedances for RHIC are $Z/n=5\Omega$, $Z_y=10\text{M}\Omega/\text{m}$. Modeled as Q=2, 5GHz resonators.
- Poorly known, narrow band modes are the main concern. Behavior at injection with 2.75e11 p/bunch shown below.

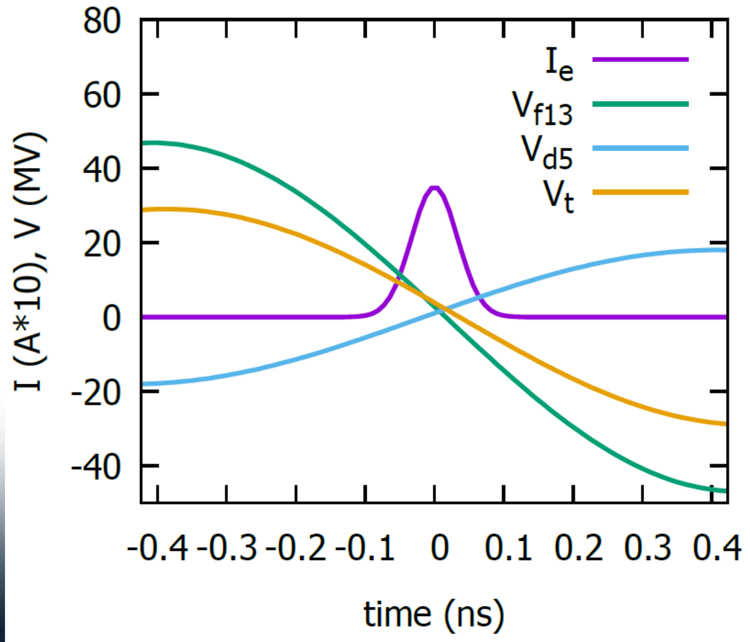




- Everything looks better at storage energy
- Measurements of the narrow band impedance are planned.

RF Studies

- We have done extensive studies of the RF beam dynamics in the ESR
- Multi-bunch, multi-particle simulation codes with full dynamics as well as reduced dynamics have been employed (Bassi, Mastoridis,Xin)
- Analytic estimates based on coupled bunch theory with and without mode coupling and employing iterative solutions to accurately model narrow spectral features agree well with the simulations.
- We employed the reverse phase mode, used at KEKB, in the ESR. Beam is stable at 5,10 and 18 GeV with radiation damping alone. 10 GeV parameters are shown.

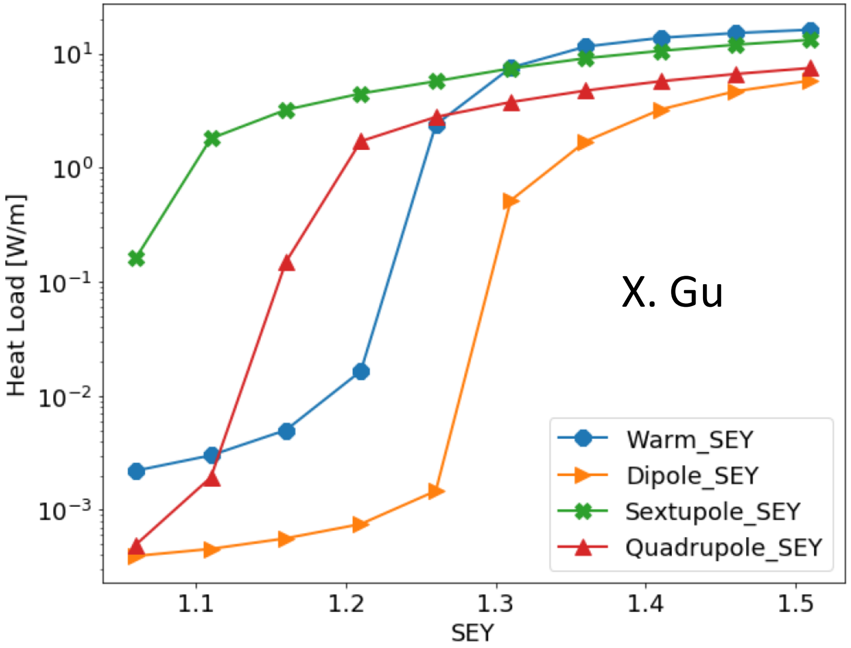


Electron Cloud Considerations

- The electron partition numbers are sensitive to orbit offsets so the hadron revolution frequency does not vary with energy. The hadron orbit circumference does change.
- This enhances already dangerous resistive heating.
- The cryo system cannot be overwhelmed.
- We will use copper clad stainless steel sleeves to reduce Joule losses with an amorphous carbon coating to suppress electron clouds (S. Verdu-Andres)

Electron Cloud Considerations

- Estimates of copper resistivity include the effect of impurities, magnetic field and phonons.
- When combined with the beam offsets we find a maximum heat deposition of 0.37 watts/meter.
- Detailed ANSYS thermal modeling shows we can tolerate 0.55 watts/meter
- There is little overhead for electron clouds.
- We need amorphous carbon coating.
- Working closely with CERN.
- Sextupoles require attention.



X. Gu

Summary

- Instabilities and collective effects for the EIC are tractable.
- All the necessary computational tools exist to estimate instabilities and other collective effects.