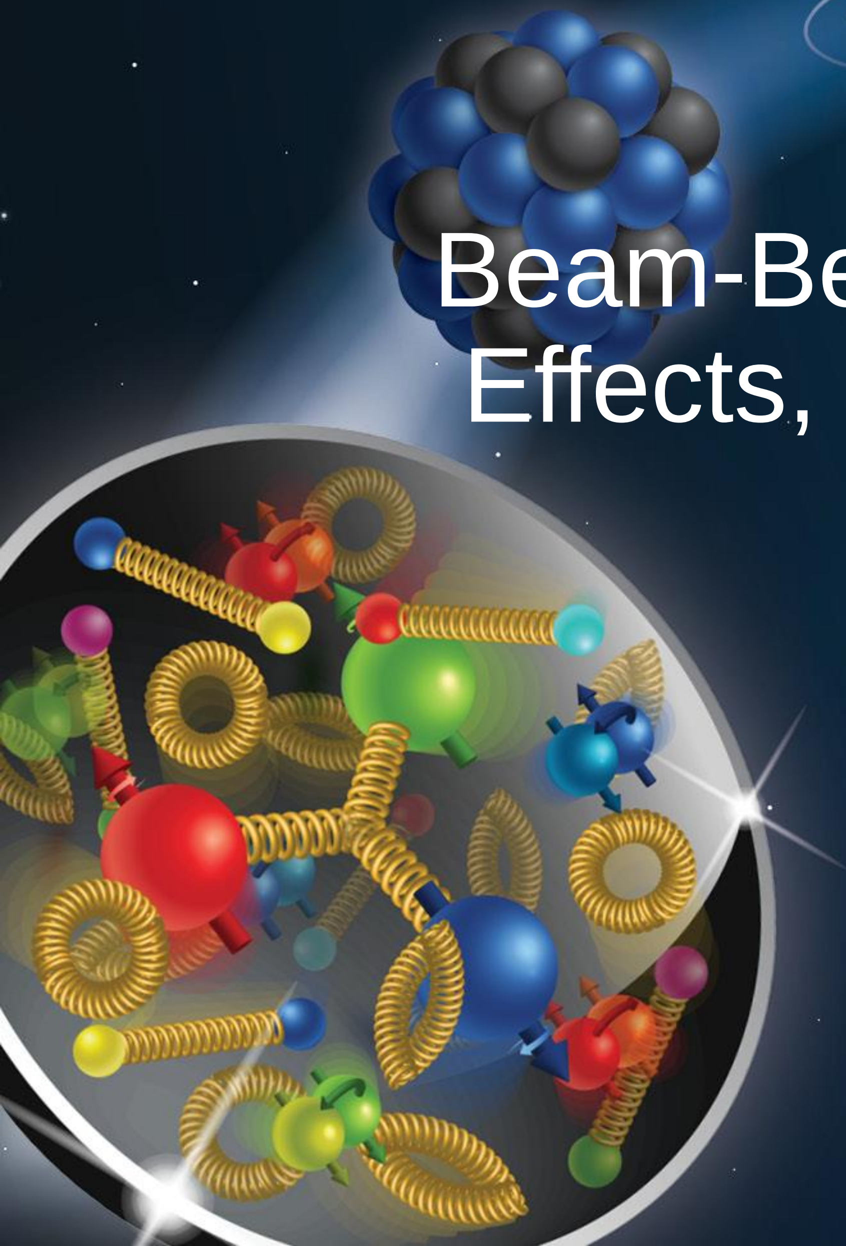
Beam-Beam Effects, Collective Effects, and Dynamic Aperture



Nuclear Physics Accelerator R&D

PI Meeting

Michael Blaskiewicz, BNL

November 13-14, 2018

Electron Ion Collider – eRHIC

BROOKHAVEN NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY | Office of Science

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Beam-Beam Effects, Collective Effects Study, Dynamic Aperture

Funding Source	PI	R&D Report Priority #	R&D Panel Priority Rating	Total $
FY17 Base and Additional	Michael Blaskiewicz	4, 12, 14, 34	High A, B, B-	$517K + $42K

- Benchmarking of realistic EIC simulation tools against available data
- Complete design of an electron lattice with a good dynamic aperture and a synchronization scheme and complete a comprehensive instability threshold study for this design
- Necessity to triple the number of and shorten the bunches in the proton / ion ring
- Electron cloud study

Outline

- Dynamic Aperture
- Beam-Beam
- Collective Effects
- Conclusions

Sources of Lattice Nonlinearity

- The dynamic aperture is limited by lattice non-linearity and beam-beam interactions.
- For eRHIC, **low-β IRs** are used to achieve small beam sizes, which requires **strong focusing** and results in **large chromaticities**.
- **Sextupoles** are needed to compensate chromaticity which is a **dominant source** of the lattice nonlinearity.
- **Nonlinear effects** include: resonances, tune shift with amplitude (tune footprint), phase space deformation (geometric aperture limitation), chaotic behavior (diffusion) and so on.

DA Optimization Approach

Optimization Strategy:

- **Global correction** with several families of sextupoles in the arcs to compensate chromaticity in such a way that nonlinear effects from these sextupoles cancel intrinsically to the largest degree possible.
- **Non-chromatic sextupoles** in dispersion free regions can be used for further nonlinear corrections. This is not yet done.
- **Local correction** in the interaction region will be explored in the future.

Optimization Algorithms:

- **Minimizing resonance driving terms** and **detuning terms**.
- **Genetic optimization** (numerically)

Sextupole Layout Scheme in the ESR

- There are 16 focusing and 16 defocusing sextupoles in **16 FODO cells in each arc**. 3 additional focusing and defocusing sextupoles in each dispersion suppressor.
- Sextupoles within one family are separated by 3 cells with a total phase advance π. The first order RDTs are canceled.
- Following sextupole layout scheme in one arc was chosen **based on DA optimization**:

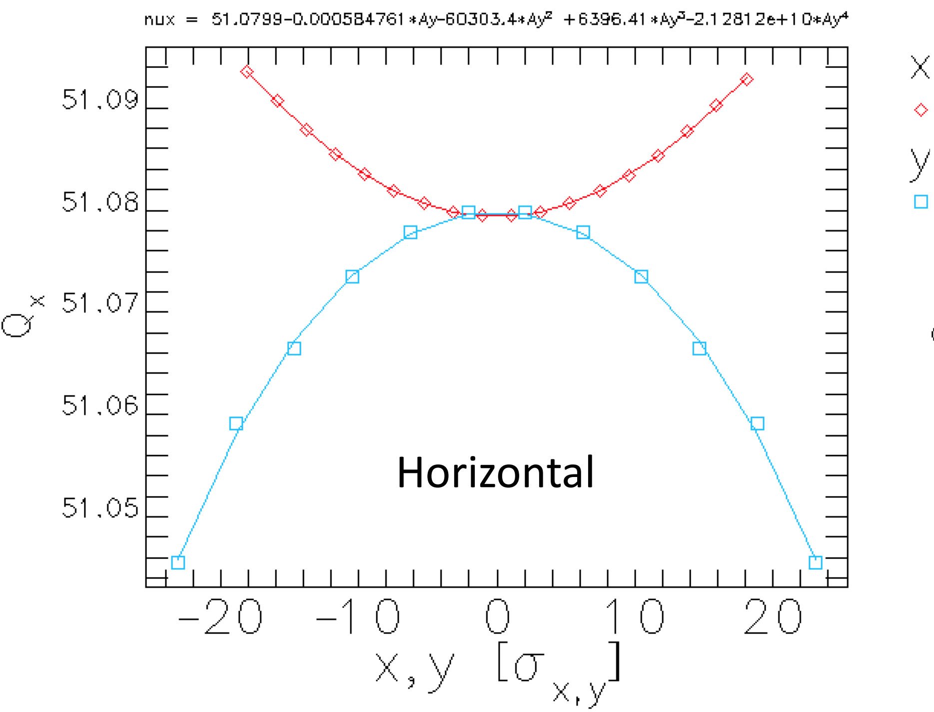
A-B-E-A-B-A-B-C-A-B-C-A-B-E-A-B

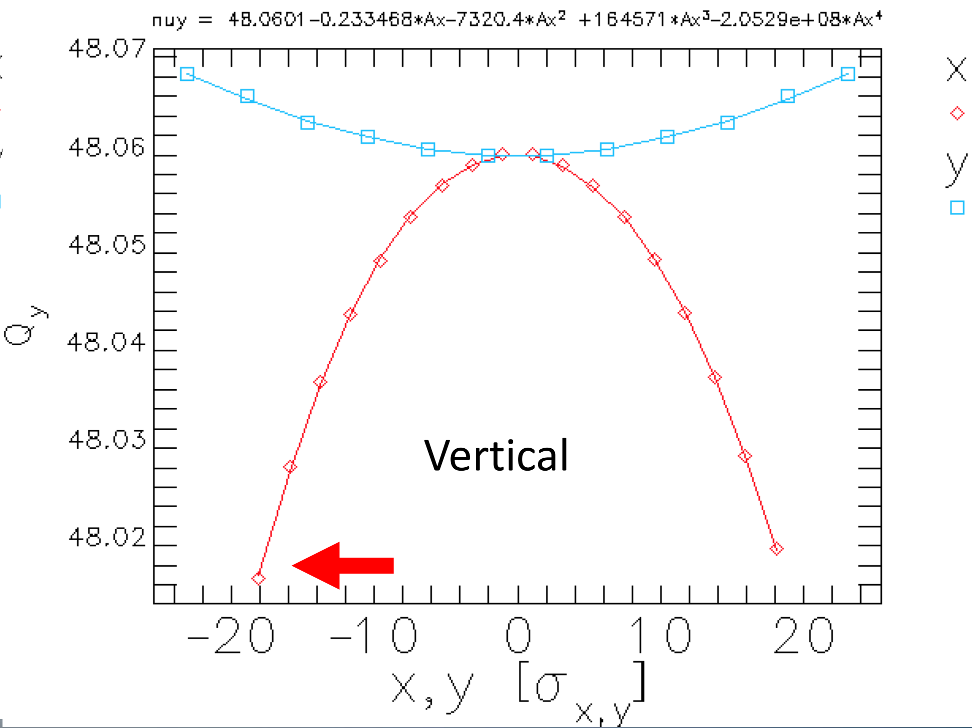
A,B,C means focusing or defocusing sextupoles in one FODO cell, *E* means no sextupole in that cell.

- Since sextupoles in each sextant need to be optimized independently, there are **a total of 36 sextupole families**.

Amplitude Dependent Tunes

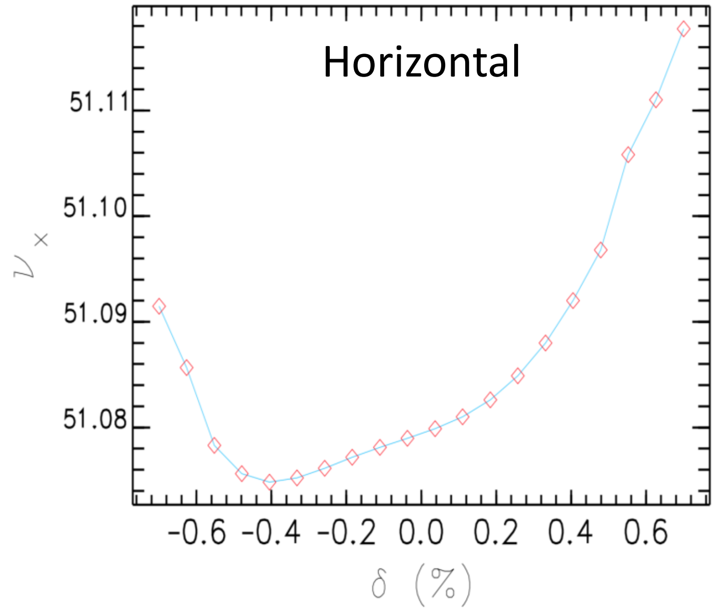
- On-momentum tune variations < 0.05 for particle amplitudes between +/- 20 $\sigma_{x,y}$.
- Second order detuning limits DA for large amplitude particles, which needs further optimization.

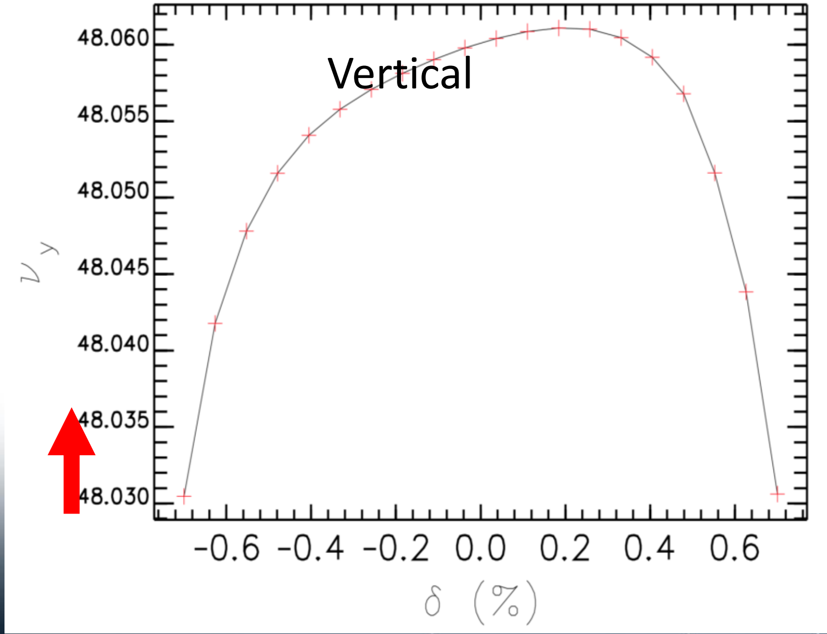




Off-Momentum Tunes

- ***Δp/p*$_0$ = 0.7%** corresponds to **13 (*Δp/p*$_0$)$_{rms}$** for electron ring.
- The tune variations are < 0.05 for $\Delta p/p_0$ between +/-0.7%.
- Off momentum DA is limited by vertical tune reaching the integer resonance.
- Longitudinal injection bumps the stored beam within 5σ of the septum. For a 2mm septum at a dispersion of 1 meter an injected beam of +/- 2σ just fits.





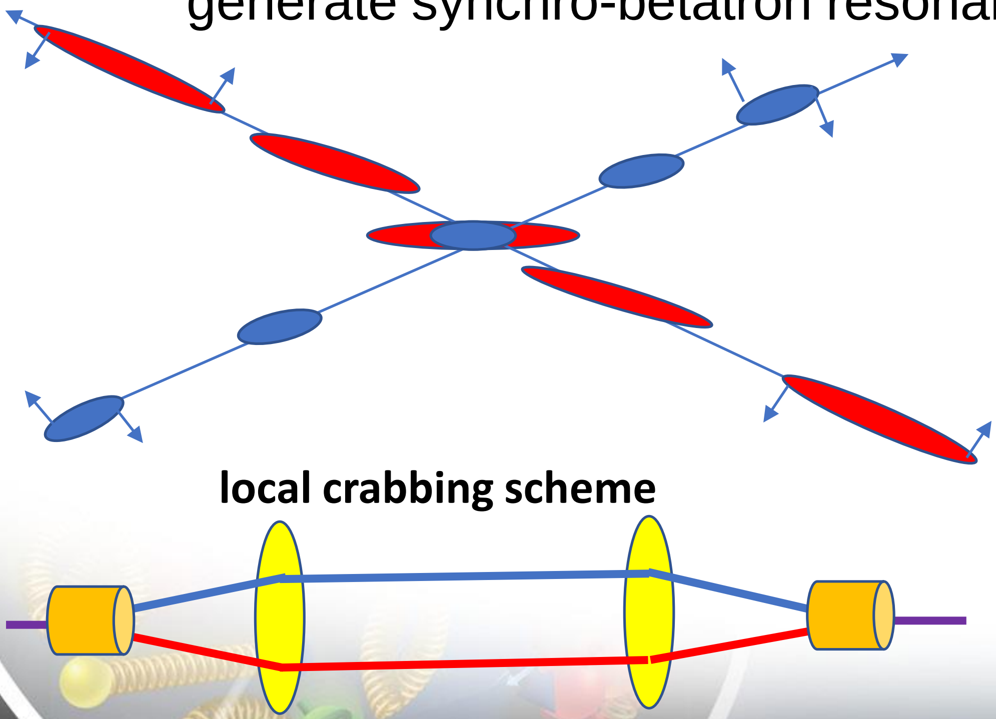
Beam-Beam Related Machine & Beam Parameters (v5.1)

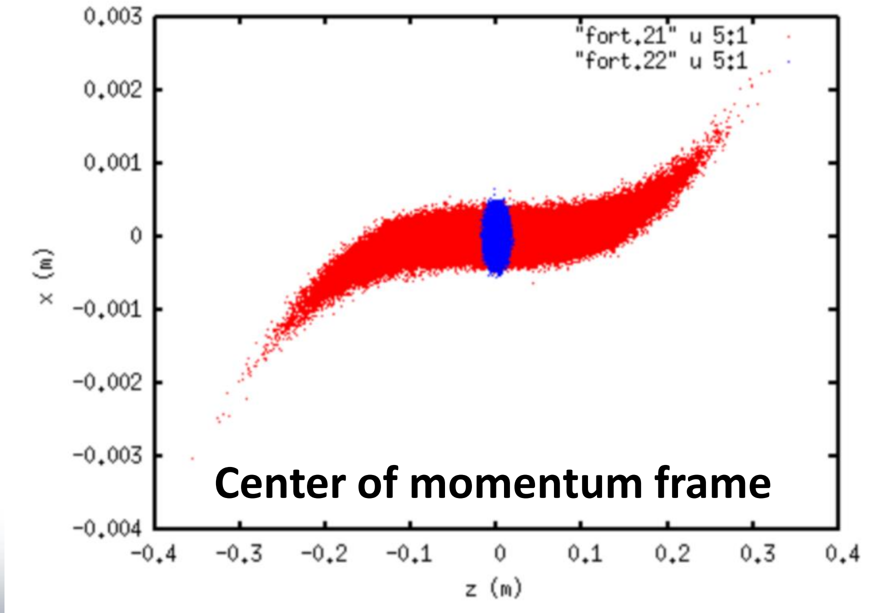
Table 4.9: Machine and beam parameters for the beam-beam interaction study.

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}]	1.05	3.0
rms emittance (H,V) [nm]	(13.9, 8.5)	(20.0, 4.9)
β^* at IP (H, V) [cm]	(90, 5.9)	(63, 10.4)
rms bunch size σ^* at IP (H, V) [μm]	(112, 22.5)	
rms bunch length σ_l at IP [cm]	7	1.9
rms energy spread [10^{-4}]	6.6	5.5
Transverse tunes (H,V)	(29.310, 30.305)	(51.08, 48.06)
Synchrotron tune	0.01	0.069
Longitudinal radiation damping time [turn]	-	2000
Transverse radiation damping time [turn]	-	4000
No. of bunches	660	660
Luminosity [$\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	(4.39)	

Crabbed Collision

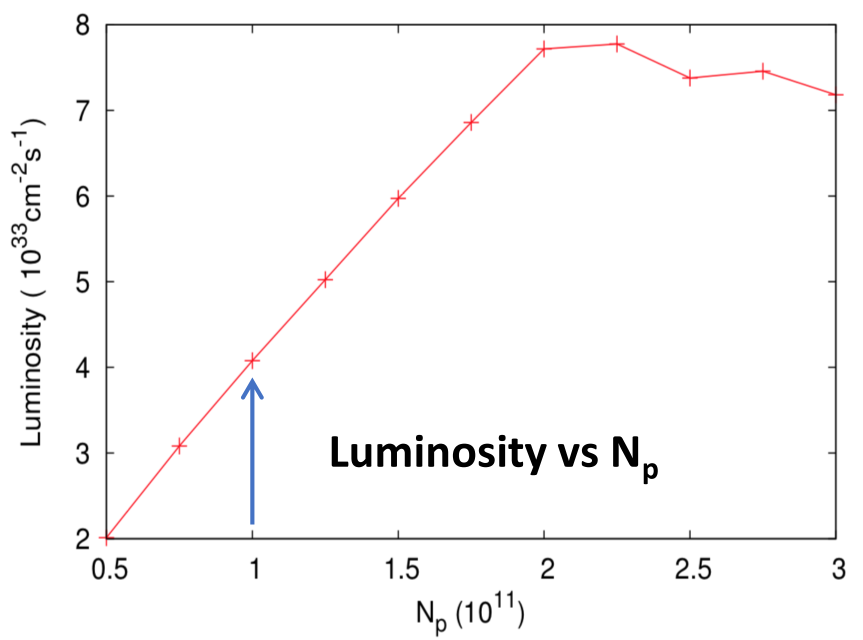
- To compensate geometric luminosity loss, crab cavities are used to tilt both beams in the x-z plane to recover head-on collision at IP.
- Finite wave length of crab cavities causes protons in the bunch head and tail to be poorly crabbed. Beam-beam interaction may generate synchro-betatron resonances.

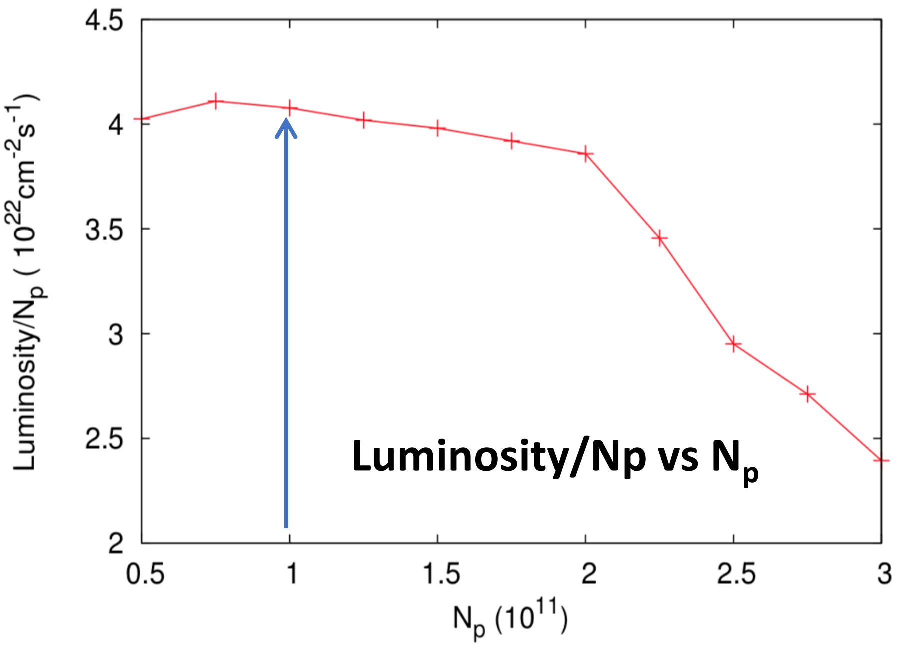




Beam-beam Limit

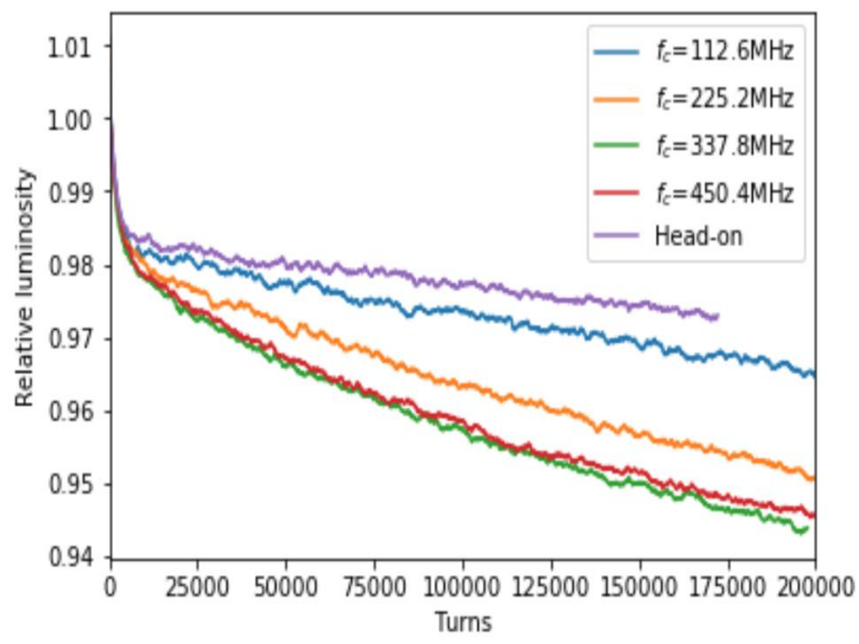
- When the beam-beam limit is reached, due to the coherent motion and/or emittance blowup, the luminosity will not increase linearly with the bunch intensity.
- For current eRHIC design, based on strong-strong simulation, the design beam-beam parameter is at about half the beam-beam limit.

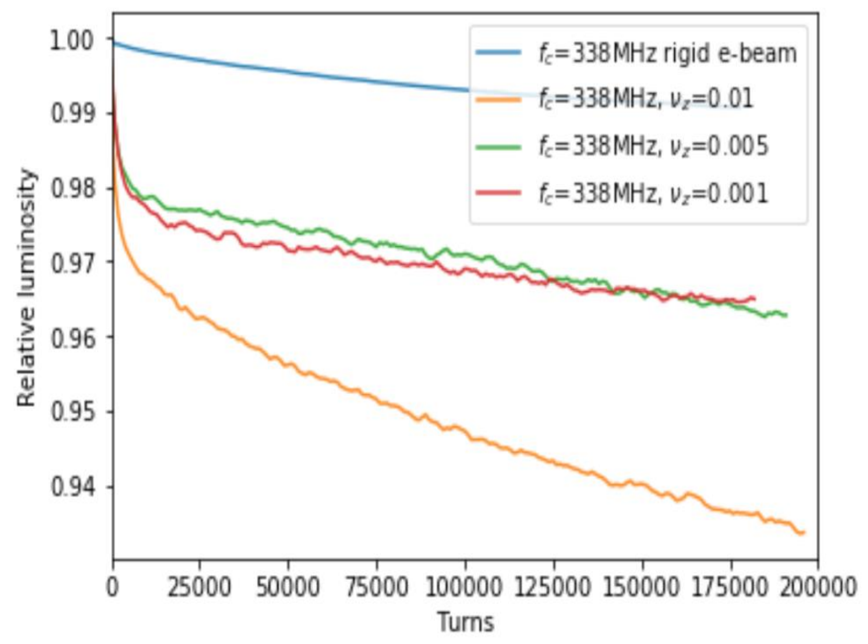




Parameter Dependence of Luminosity Degradation with Crabbed Collision

- ❑ With self-consistent strong-strong simulation, we found that the luminosity degradation rate depends on proton crab cavity frequency, proton synchrotron tune, proton bunch length. The protons grew.
- ❑ Following plots show the luminosity dependence on the crab cavity frequency (Left) and the synchrotron tune of the proton ring (Right).





Modified Weak-Strong Beam-Beam

To understand the mechanism of proton emittance growth we have modified the code.

First we run a strong-strong calculation long enough to let initial transients fade.

There are then three options:

- Continue running in strong-strong mode
- Use the same initial conditions for the electron bunch on every turn. This removes any dependence on the electron tunes but retains the possibility of two stream instabilities
- Use the same trajectory and beam size of the electron bunch each turn. With fixed electron dynamics all forces are periodic at the revolution frequency

Electron Storage Ring Stability [1,2]

- The electrons may require a longitudinal damper for narrow band CBMs
- Broad band longitudinal instabilities and all transverse instabilities are Landau damped.

Parameter	5 GeV	10 GeV	18 GeV
RF voltage ($h = 7200$) [MV]	20	20	62
RF voltage ($h = 3 * 7200$) [MV]	6.6	6.4	0
γ_T	31	31	41
V_{synch} [MV]	1.3	5.0	38
$\sigma(p)/p_{lattice}$ [10^{-4}]	8.2	5.5	10
N_e [10^{10}]	31	31	6.3
$\sigma(p)/p$ [10^{-4}]	8.6	6.4	10
σ_s [mm]	22.5	23	8.8

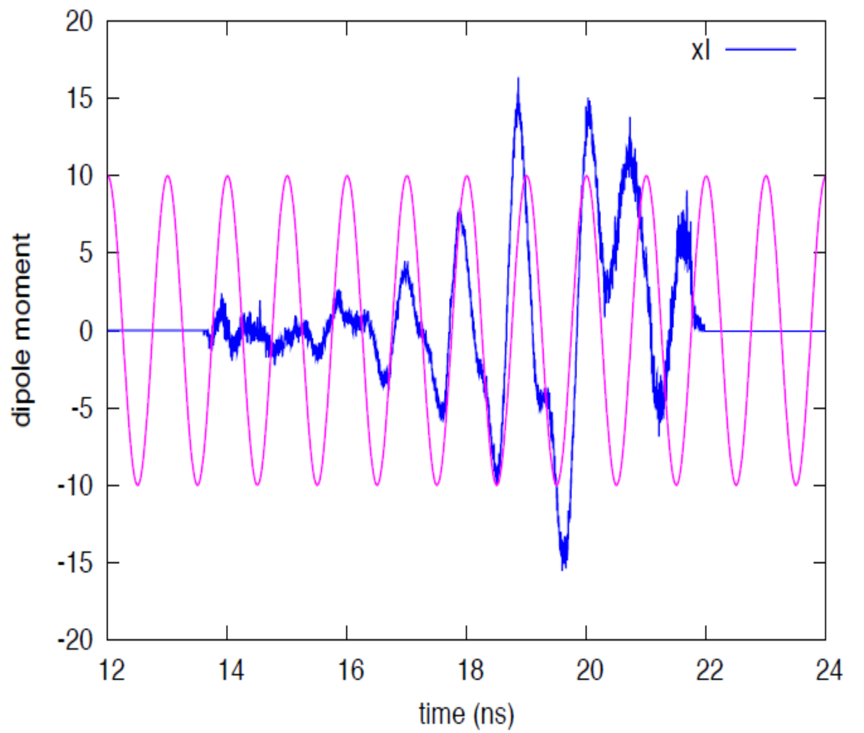
Impedance Type	R_{sh}	Q	f_{res}
BB longitudinal	51 kΩ	2	20 GHz
BB transverse	1.4 MΩ/m	2	20 GHz
NB longitudinal	360 kΩ	80	856 MHz
NB transverse	10.8 MΩ/m	80	1.0 GHz

Electron Storage Ring Fallback

- The third harmonic RF system is challenging.
- Increasing the 10 GeV energy spread to 1.0×10^{-3} and the 5 GeV spread to 1.2×10^{-3} allows us to operate at nominal bunch currents with no third harmonic system.
- This places additional stress on the lattice design.
- If we increase energy spread by increasing the strength of the reverse bends, we increase radiative losses.
- This will reduce the allowed electron current at 10 GeV.
- Increasing bunch length using RF modulation is being considered.

Proton Instabilities Depend on Unknown Narrow Band RHIC Impedance

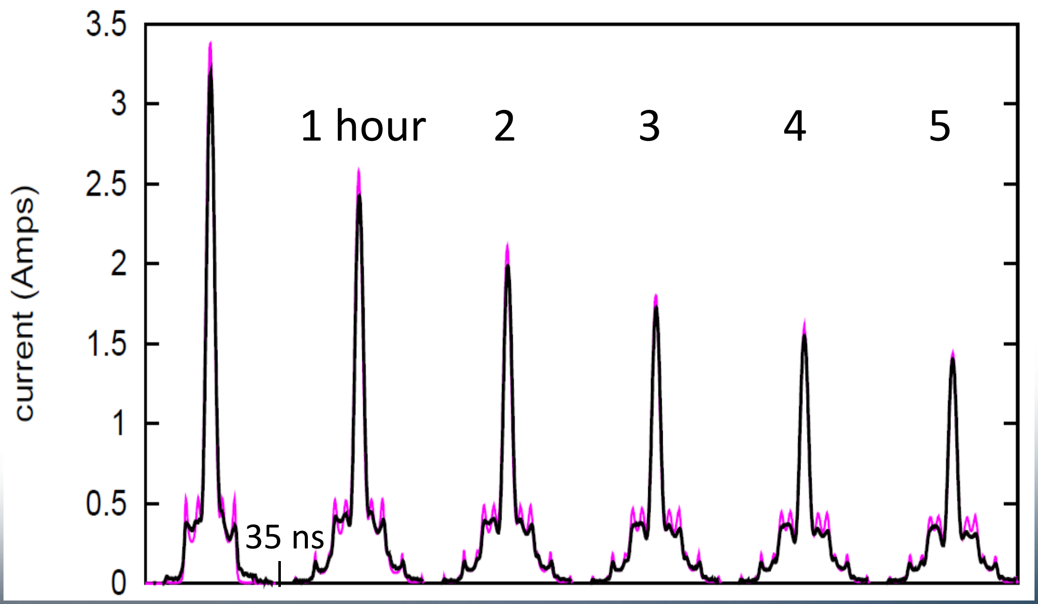
- Transverse dipole mode at injection due to assumed narrow band impedance.
- The magenta sine wave is at the resonant frequency of the HOM.
- The number of macroparticles was varied between 10^5 and $2x10^6$.
- No significant difference was seen.
- We might need narrow band dampers for the protons.



Intrabeam Scattering and Emittance Growth

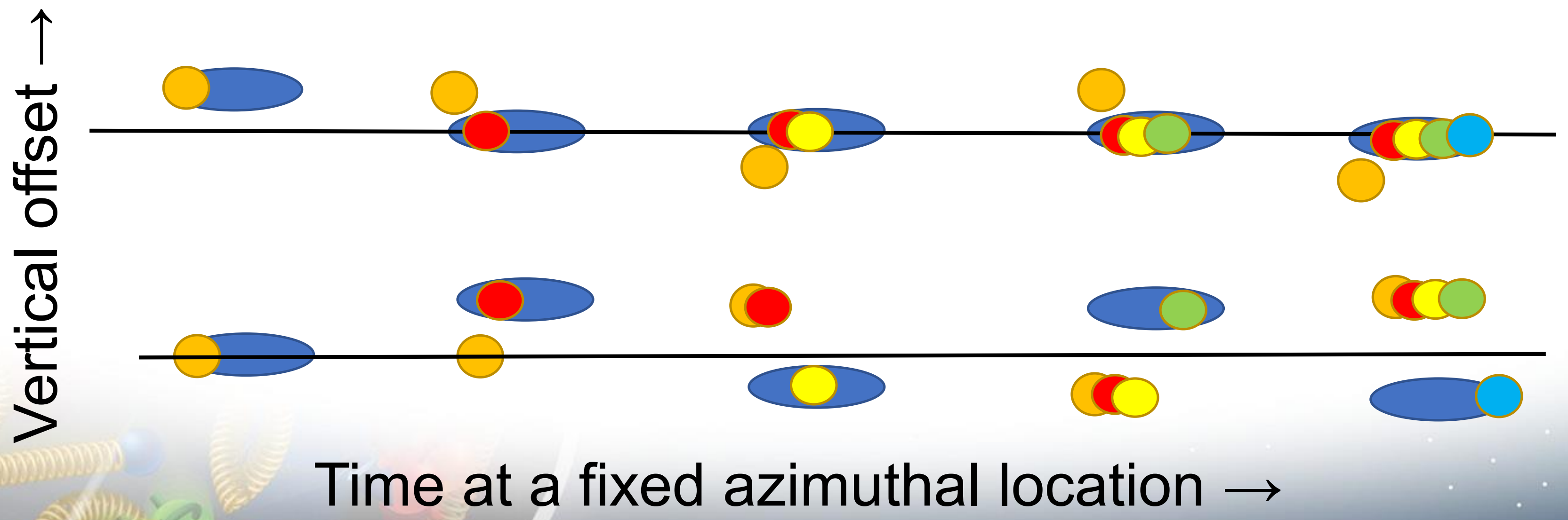
- We have Betacool and various other codes based on the Piwinski and/or Bjorken-Mtingwa formalisms.
- Recently implemented fully coupled Piwinski [4]
- Betacool and uniform Piwinski used most so far.
- When action diffusion rates are important (like in spin diffusion) we have subroutines to evaluate the relevant integrals [5].

- Data (black) and simulation (magenta) of Au with IBS in RHIC over 5 hours.
- Uniform lattice Piwinski model.
- No free parameters.



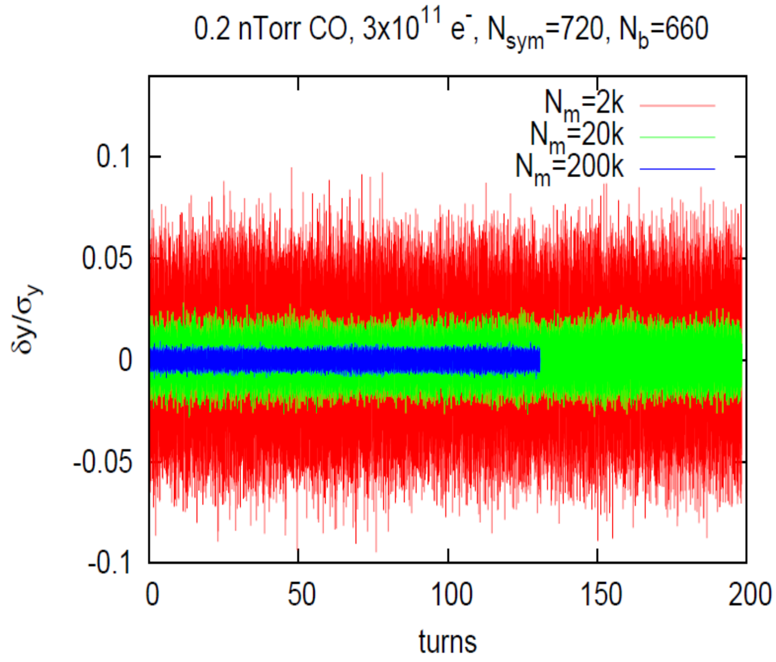
Fast Beam Ion Instability [6,7]

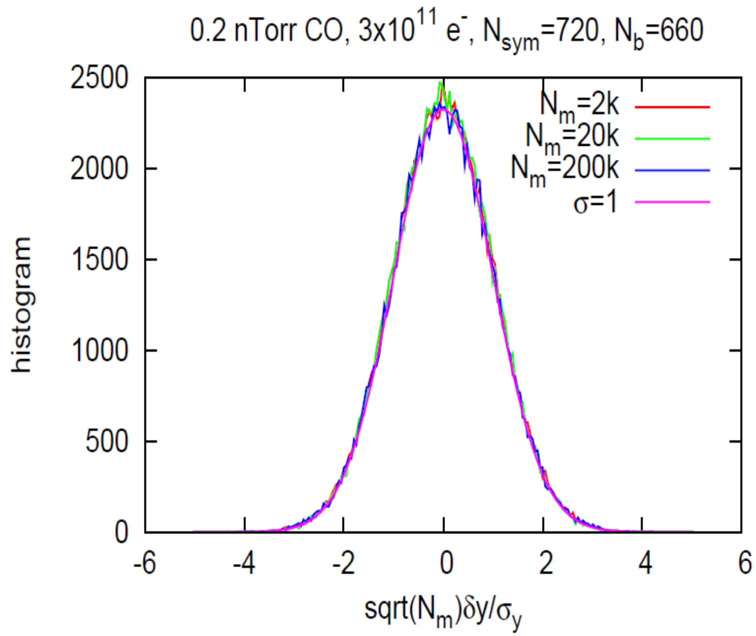
- Suppose the first bunch is offset.
- Its ion cloud will kick subsequent bunches and be kicked by them.
- The second plot shows what happens ¼ betatron oscillation downstream



Fast Beam Ion Instability

Initial results for eRHIC including beam-beam tune spread.





The plot on the right shows that between 2k and 200k particles the RMS fluctuation in the electron centroid is just statistical.

Now suppose $\langle \delta y^2 \rangle = \frac{\sigma_y^2}{N_m} + \sigma_{real}^2$ We need $\sigma_{real} < 10^{-4}\ \sigma_y$

Planning experiments at NSLS-II

Cryogenic Limits in the Hadron Ring [8]

We need to coat the vacuum chamber with copper to reduce resistive heating below 1 W/m.

A mole employing magnetron sputtering is under development.

A niobium cavity with an insert to test the surface conductivity of the coating at cryogenic temperatures is being used to test deposition techniques.

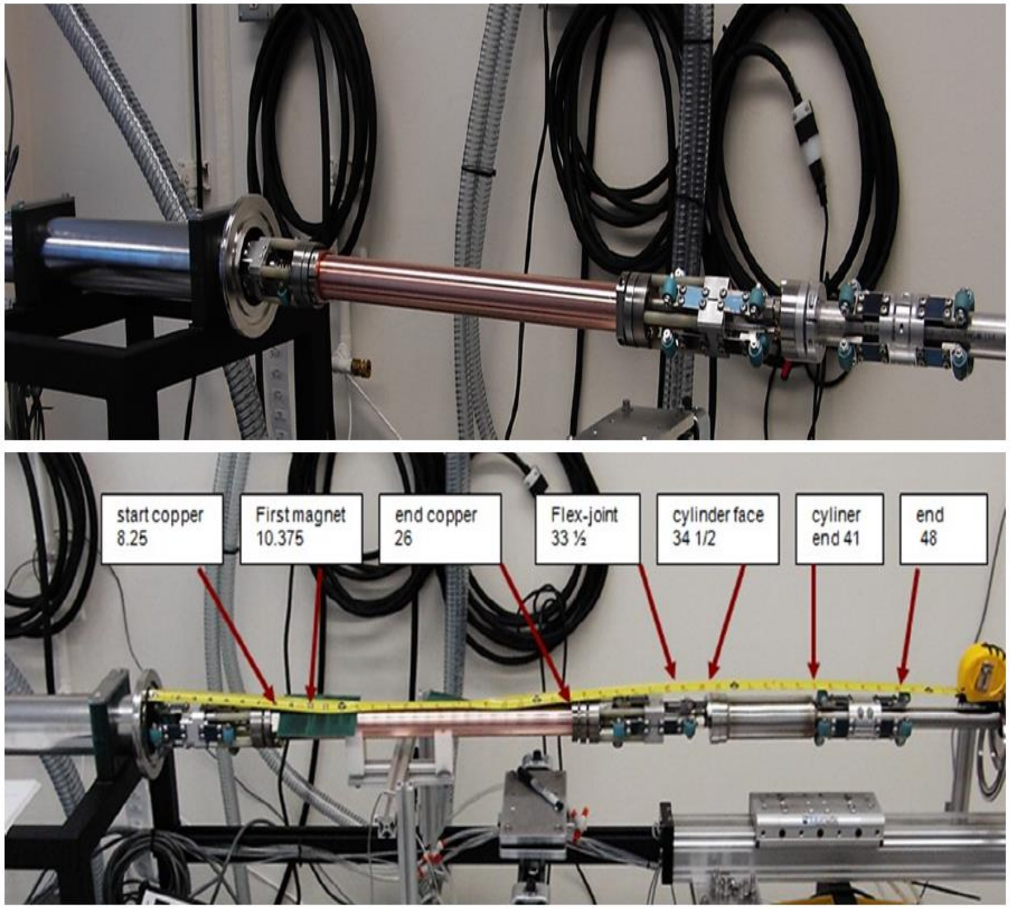


Figure 6.206: Magnetron coating mole: Top: 50 cm long cathode magnetron. Bottom: the 50 cm long cathode magnetron assembly; the magnetron carriage has spring loaded guide wheels that cross bellows and adjust for diameter variations keeping the magnetron centered.

Costs and Schedule

Lab Base R&D	FY10+FY 11	FY12+FY13	FY14+FY15	FY16+FY17	Totals
a) Funds allocated				516,927	516,927
b) Actual costs to date				516,927	516,927

Activity	Start Date	End Date	
Beam Dynamics Study	May 1, 2016	September 30, 2018	✓
Design Choice Validation Review	April 6, 2017	April 7, 2017	✓

Conclusions

- We have studied the dynamic aperture with 60° per cell.
- On-momentum dynamic aperture is OK. We have enough momentum aperture for longitudinal injection.
- We need to develop a 90° per cell lattice.
- We have a factor of two safety margin for collective strong-strong beam effects
- Slow emittance growth due to finite crab cavity wavelength was found. We have developed simulation tools to isolate the cause of this growth and are beginning a systematic campaign. Reducing luminosity by 20% is the worst case scenario.
- Traditional instabilities are under control if we design at the state of the art.
- FBII appears to be OK. If it is unavoidable the noise in the damper is the primary concern and a concerted effort will go into low noise design.
- For electron clouds we expect the secondary electron yield at no more than 1 so that safety is guaranteed.

References

[1] M. Blaskiewicz, TRANFT User's Manual, BNL-77074-2006-IR

[2] M. Blaskiewicz, NAPAC13, froaa2

[3] Handbook of Accelerator Physics and Engineering, Chao, Tigner *eds.*, World Scientific 1999, pg 113.

[4] A. Piwinski, DESY 90-113 (1990), also CERN 92-1, p 226 (1992).

[5] Zenkevich, Boine-Frankenheim and Bolshakov NIMA, v561, p 284, (2006)

[6] Stupakov, Raubenheimer & Zimmermann PRE **52**, 5499 (1995). Also R&Z PRE **52**, 5487

[7] R. Nagaoka, ICFA Newsletter #69, p 227 (2016) *and references therein*

[8] A. Hershcovitch *et. al.* IPAC2014 thpri114 *and references therein*

Modified Weak-Strong BB Simulation

- To understand the sources of emittance growth and luminosity degradation and to determine their realistic growth/degradation rates, we are starting modified weak-strong simulations.
- In strong-strong mode these simulations assume the initial electron phase space is always the same, as if from a linac.
- In weak-strong mode the electron bunch parameters during the collision are the same on every turn, unaffected by the ions.

The procedure is as follows:

- First perform a strong-strong simulation to extract average trajectories and beam sizes of the electron bunch.
- Next perform weak-strong or strong-strong simulations with this information to calculate proton emittance growth.
- These results are then compared with true strong-strong simulations to find the key processes and parameters.