Beam-Beam Effects with Multipole Interaction Points in eRHIC

Y. Luo, G. Bassi, M. Blaskiewicz, Y. Hao, A. He
C. Montag, V. Ptitsyn, V. Smaluk, F. Willeke, , Brookhaven National Laboratory

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Electron Ion Collider – eRHIC

BROOKHAVEN NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY | Office of Science

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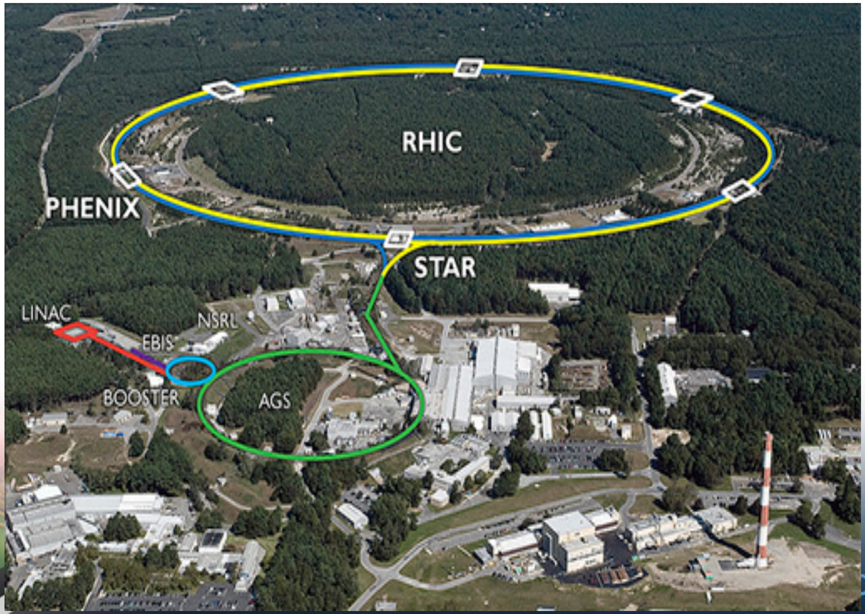
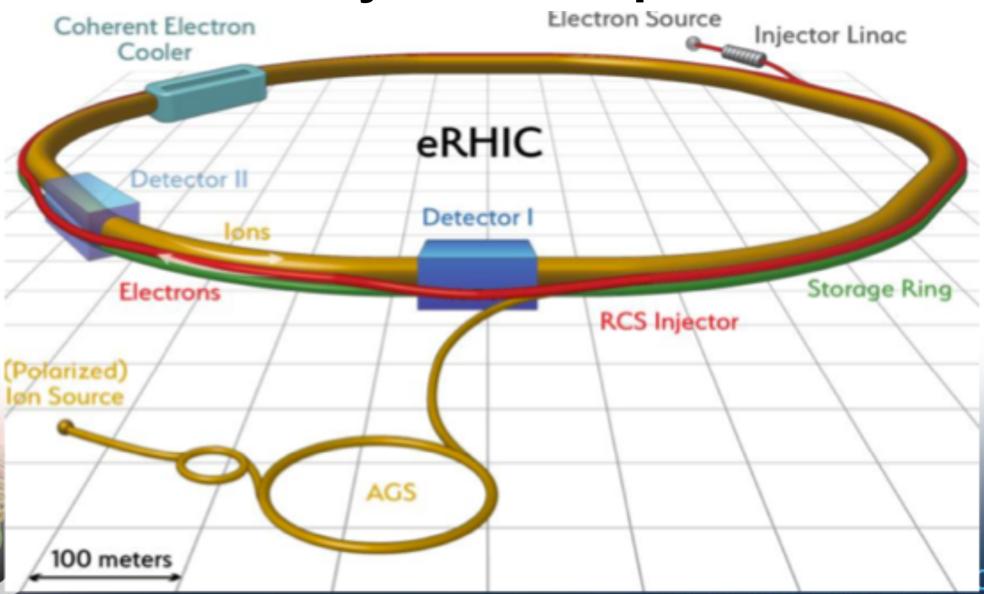
Two Experiments at RHIC

- eRHIC ring-ring design is based on RHIC. RHIC consists of **two rings** with a circumference 3.8 km. Two rings go side by side and intersect horizontally at 6 symmetric points.
- In RHIC, there are **two experiments :** STAR at IP6 and PHENIX at IP8. For the RHIC routine operation, with 111 bunches in each ring, 90% of the bunches collide twice per turn.
- **It is preferable that the eRHIC design is able to deliver collisions to both experiments simultaneously.**



Previous eRHIC BB Studies

- In the previous beam-beam studies for eRHIC ring-ring design, **we focused on 1 collision per turn for each bunch**.
- With 1 IP, the design beam-beam parameters for the electron and proton are **~0.1 and 0.015**, which are based on the KEKB and RHIC experiences. The peak luminosity without cooling is 2.9×10^{33} cm^{-2}s^{-1}.
- In the following **we study the possibility to deliver collisions to both experiments simultaneously with the present eRHIC design beam parameters.**



Machine and Beam Parameters (**v2.1**)

	Unit	Proton	Electron
Circumference	m	3833.845	3833.845
Energy	GeV	**275**	**10**
Bunch population		1.11	3.05
Number of bunches		330	330
Emittance	nm	16/6.1	24.4/3.5
Beta at IP	m	**0.94/0.042**	**0.62/0.073**
Bunch length	cm	7	1
Beam-beam parameter		**0.014/0.005**	**0.092/0.083**
Betatron tune		**31.310/32.305**	**34.08/31.06**
Synchrotron tune		0.002	0.025
Energy spread		0.00065	0.001
Crab cavity RF frequency	MHz	336	336
Crossing angle	mrad	**22**	
Luminosity	10^{33} cm^{-2}s^{-1}	**2.9**	

Locations of 2 Experiments

- Current experiment locations in RHIC:

  STRA at IP6, PHENIX at IP8
- With 2 experiments, another choice may be:

  STAR at IP6, PHENIX moved to IP12
- No. of bunches involved in beam-beam simulation :

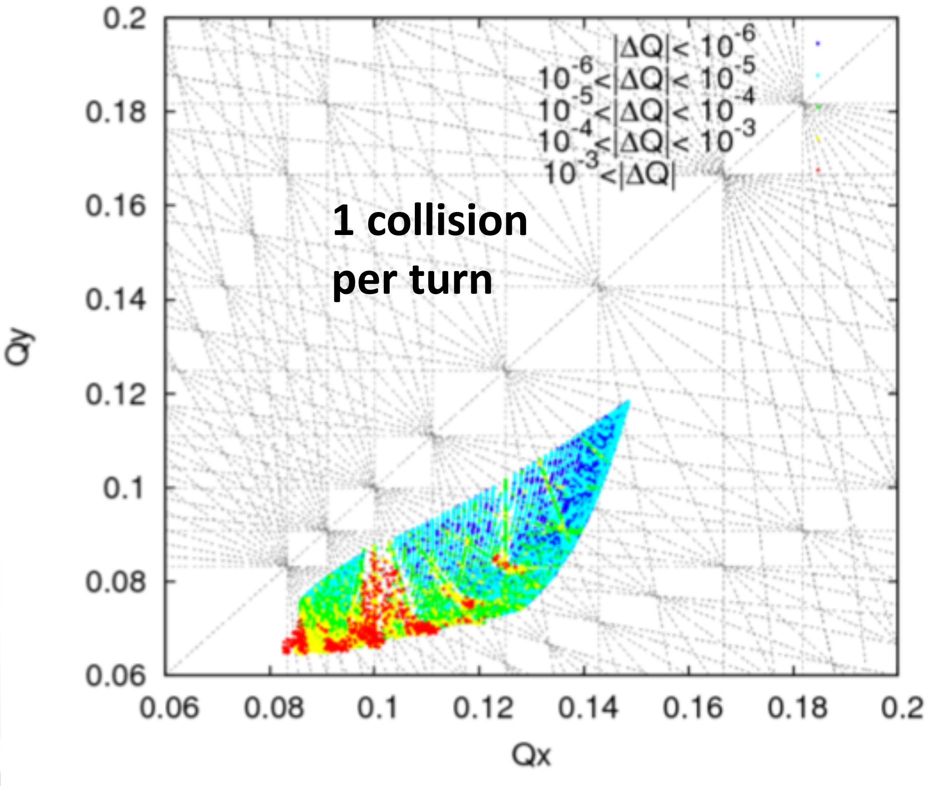
  1 collision: 1 * 1 bunches

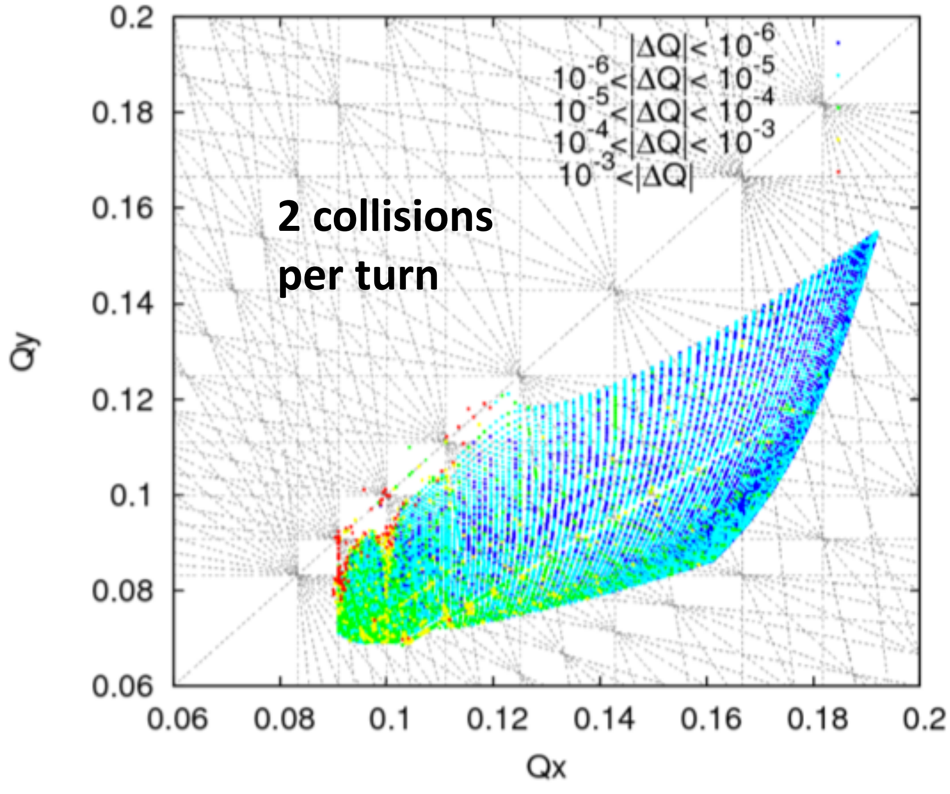
  2 collisions at IP6 and IP12 : 1 * 1 bunches

  2 collisions at IP6 and IP12 : 3 * 3 bunches
- Both **weak-strong and strong-strong** BB simulation done.
- We assume uniform betatron phase advances along the rings.

Weak-strong Simulation: Tune Footprint

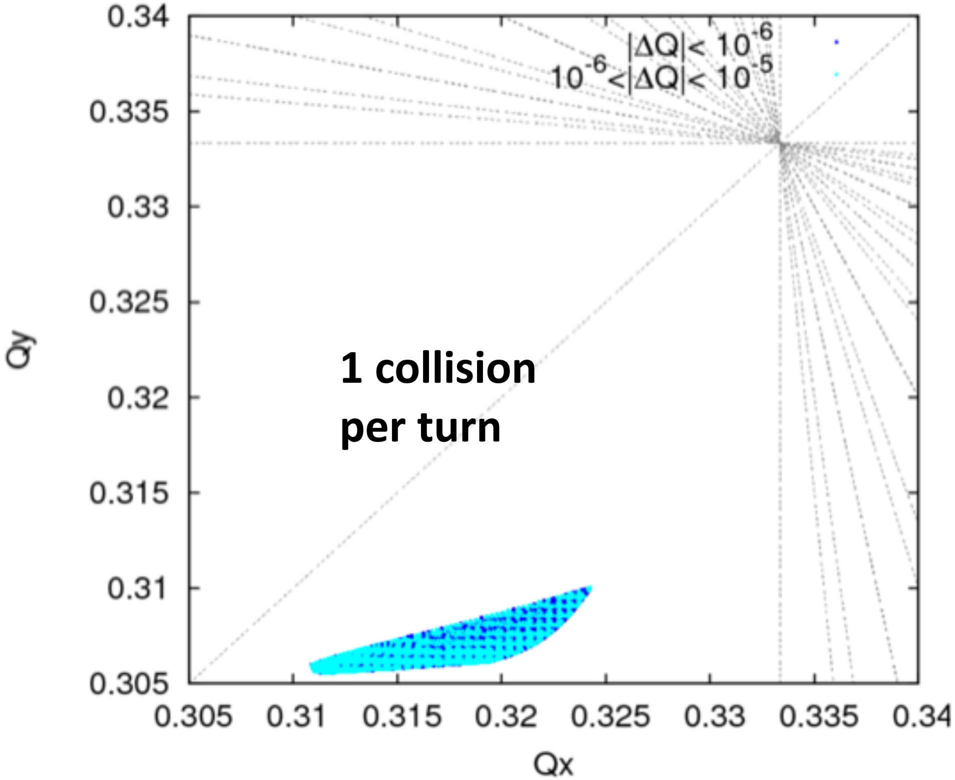
Electron ring

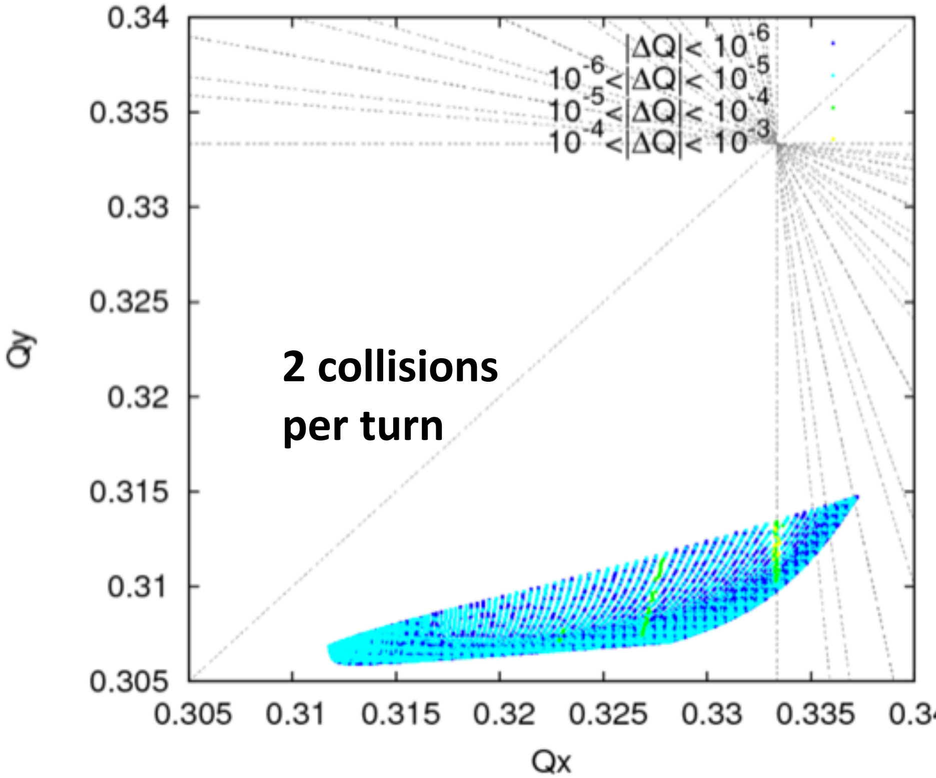




The electron tune footprint is doubled with 2 collisions per turn. Its tune footprint moves to the 5th resonance line.

Proton ring

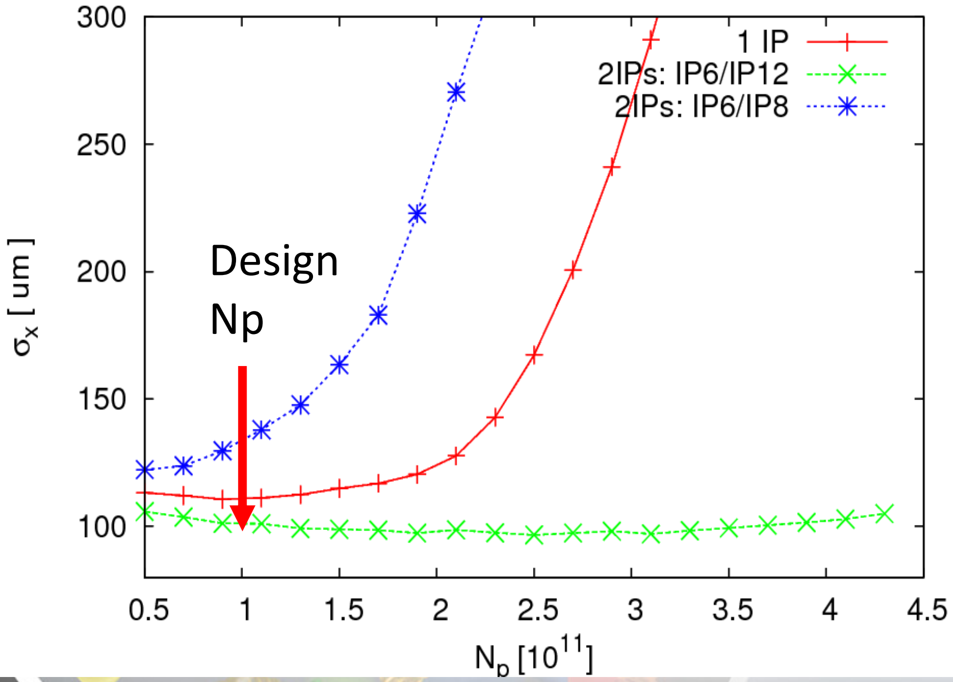




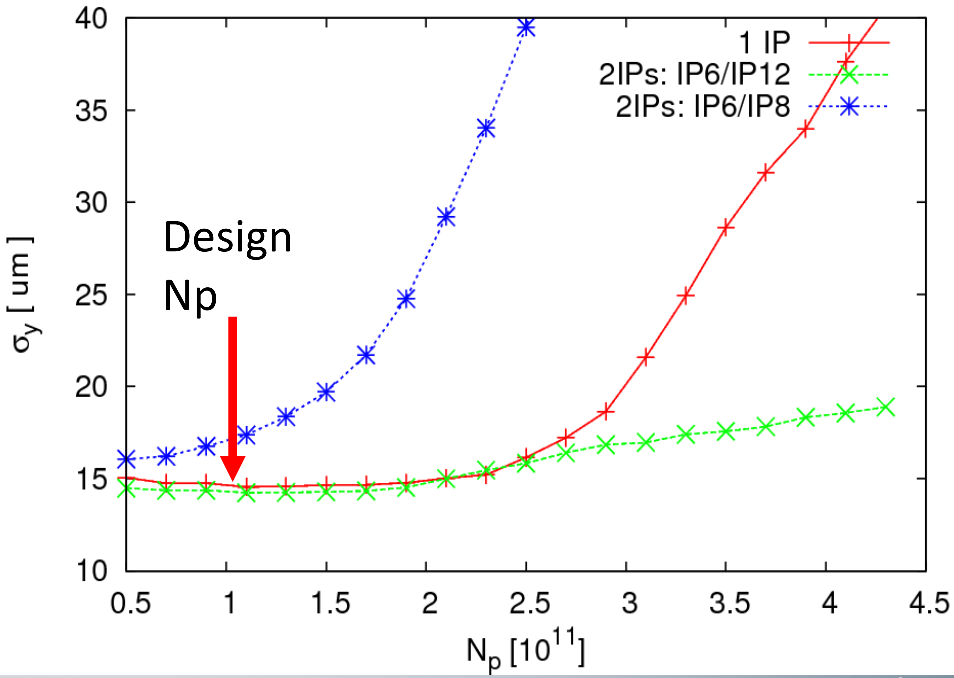
The proton tune spread with 2 collisions per turn is doubled.
Its tune footprint even crosses the 3th order betatron resonance which is problematic.

Weak-strong Simulation: Np Scan

In this study : **the proton bunch is assumed rigid**, **the electron bunch is represented by 10k macro-particles and they are tracked up to 50k turns**. The SR damping and excitation are included.

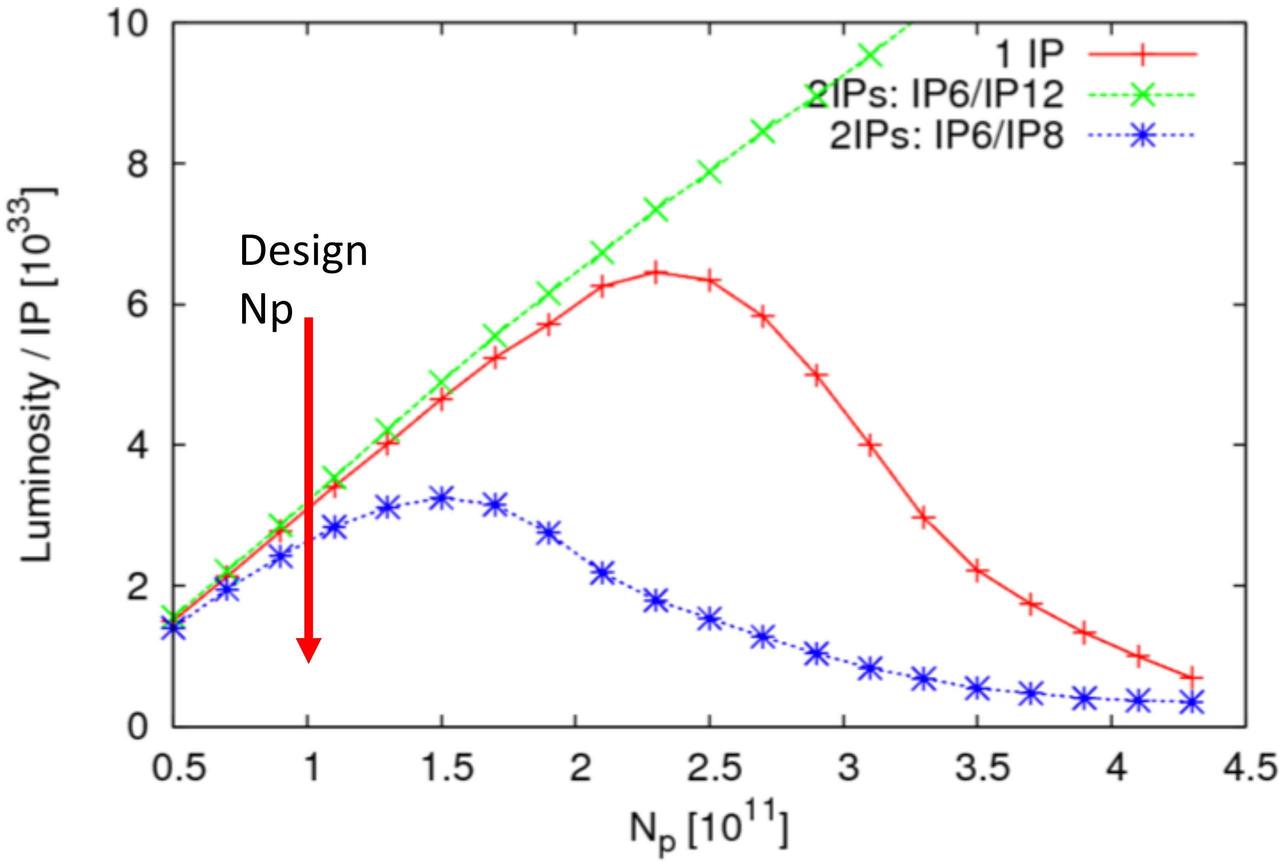


Electron horizontal size



Electron vertical size

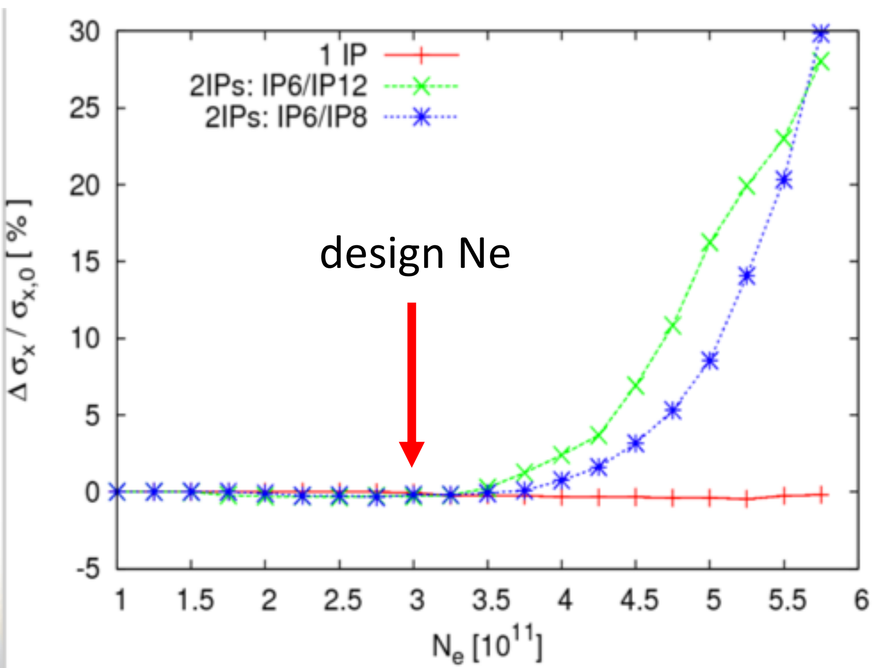
Luminosity after 50k turns

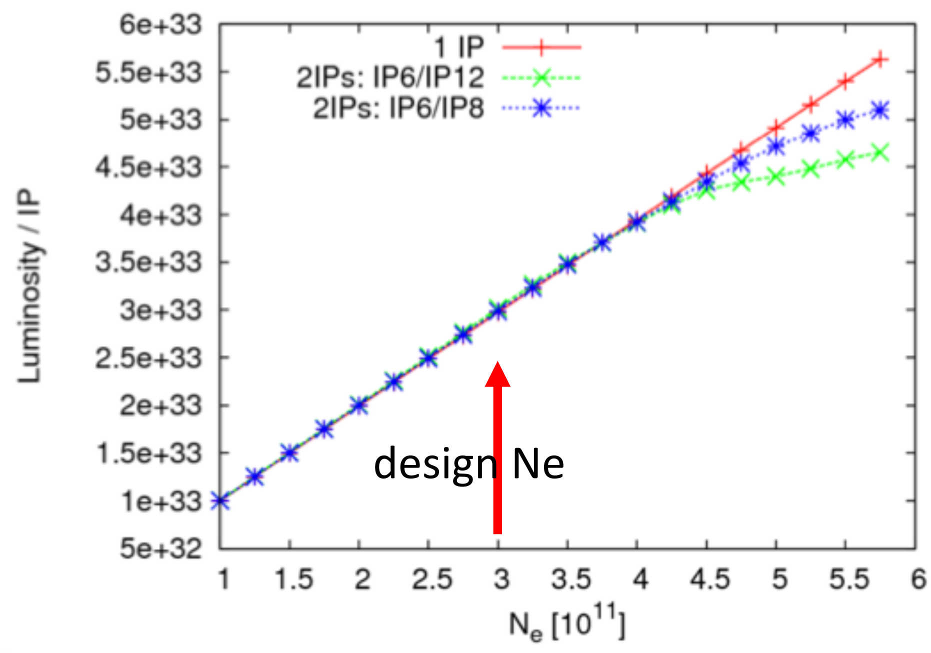


With 1 collision per turn , the beam-beam limit is about Np~2.0e11, which is twice the design Np. **With 2 collisions at IP6 and IP8, the beam-beam limit happens at Np~1.0e11**. It is not understood that **the beam-beam limit happens at Np~4.0e11 with 2 collisions at IP6 and IP12 from weak-strong simulation**.

Weak-strong Simulation: Ne Scan

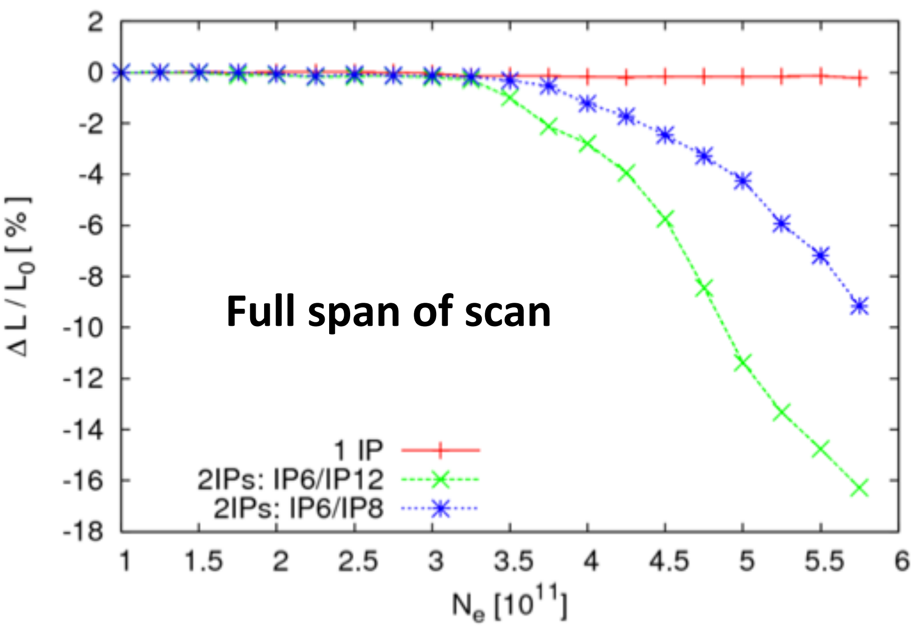
In this study, **the electron bunch is assumed rigid**, **the proton bunch is represented by 10k macro-particles and they are tracked up to 1 M turns**.

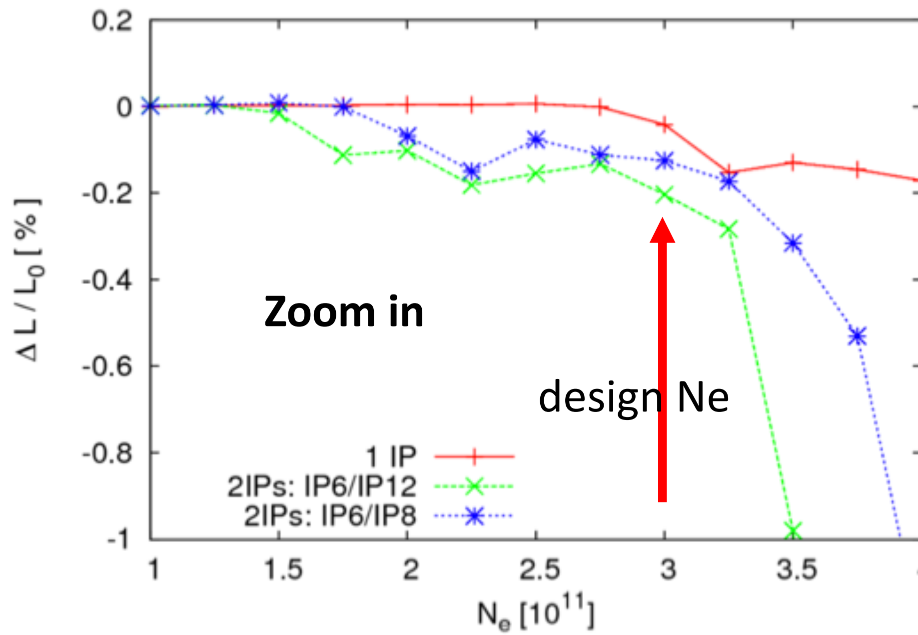




Left plot: relative proton beam size change in 1 M turn.
Right plot: Luminosity / IP after 1 M turn.

Relative luminosity change in 1 M turn





For 1 collision per turn, the luminosity drops only 0.05% in 1 M turn weak-strong tracking; However, for 2 collisions per turn, the drops are much bigger and earlier.

Strong-strong Simulation

- **Weak-strong BB simulation is not consistent**. We need to do strong-strong BB simulation too.
- For eRHIC strong-strong BB simulation we are using **BeamBeam3D** (Dr. Qiang) and **BBSS** (Dr. Ohmi).
- However, for this study involving multi-bunches, we wrote a strong-strong code with **SimTrack**. The code is benchmarked with BeamBeam3D with 1 collision per turn case.
- The purpose of strong-strong simulation here is :

1) to identify coherent beam-beam instability,

2) to find the beam-beam limit

- For each case we do **2-d bunch intensity scan**. Beam-beam parameter is closely linked to bunch intensities.

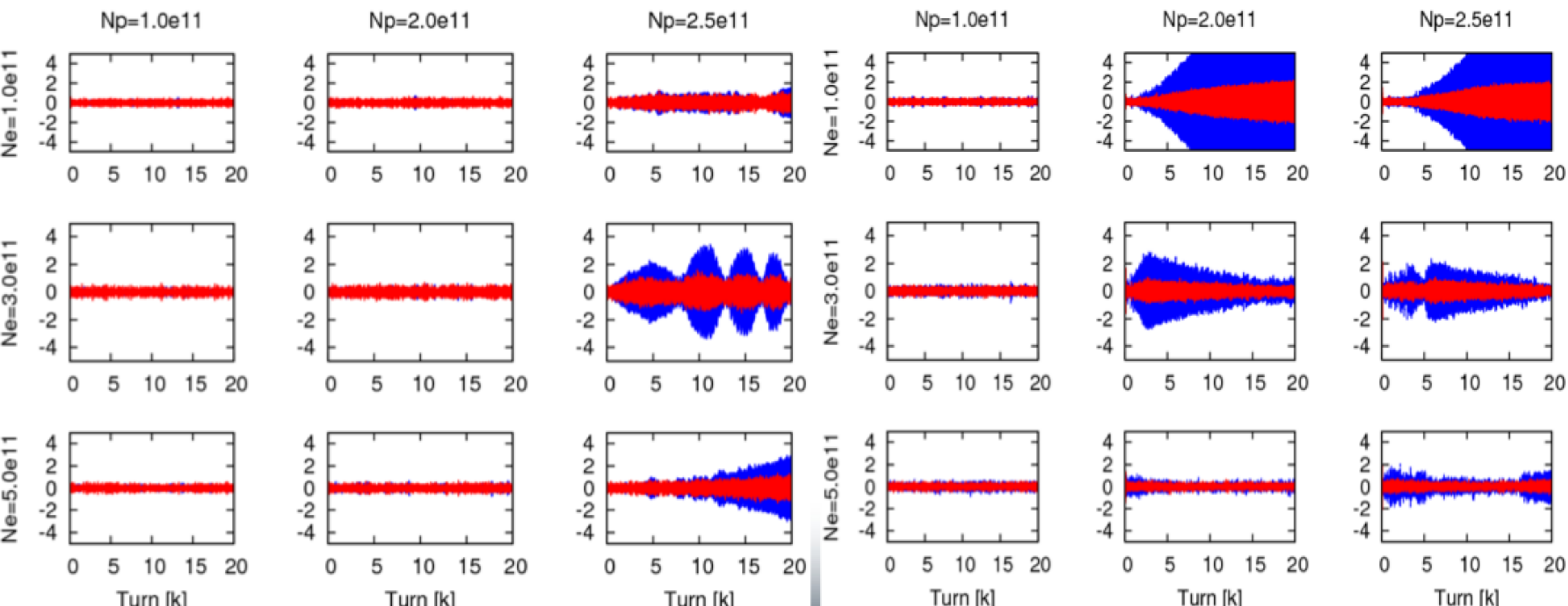
  Electron bunch intensity: [1e11, 5e11], the design is 3e11

  Proton bunch intensity: [0.5e11,2.5e11],the design is 1e11

Simulation Results (I)

- **First we compare two cases**: **with 1 collision/turn, 2 collisions/turn at Ip6 & IP12.**
- With 1 collision per turn, coherent motion observed when Np >= 2.5e11.
- With 2 collisions per turn at IP6 and IP12, coherent motion is observed when Np >= 2.0e11.

center motion <x> : blue-proton, red->electron



1 collision/turn

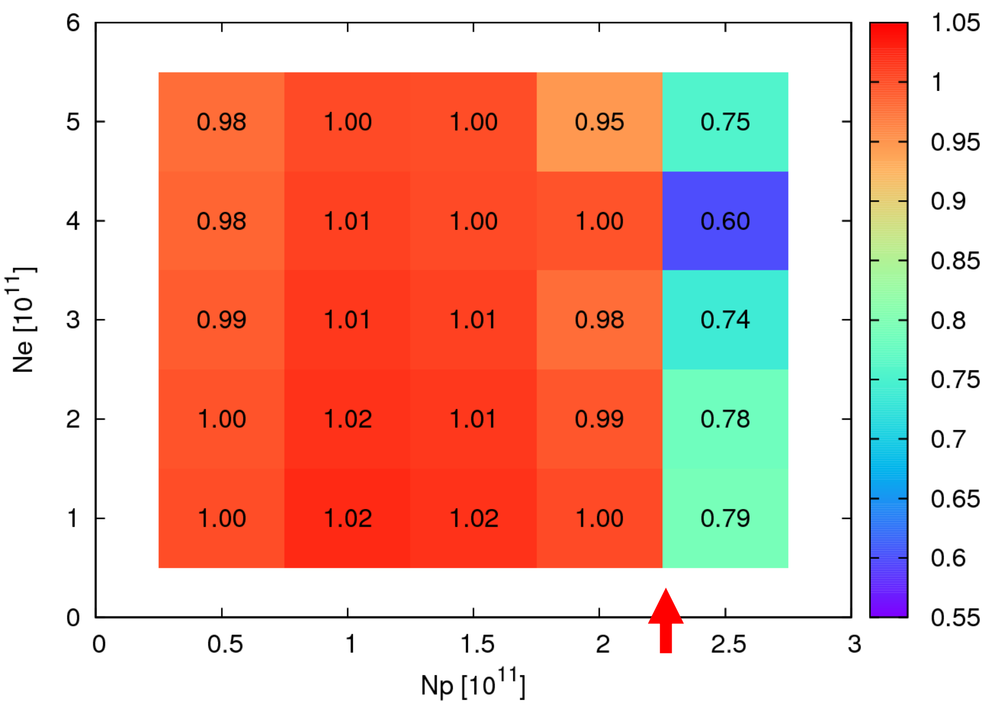
2 collisions/turn : IP6 & IP12

Simulation Results (II)

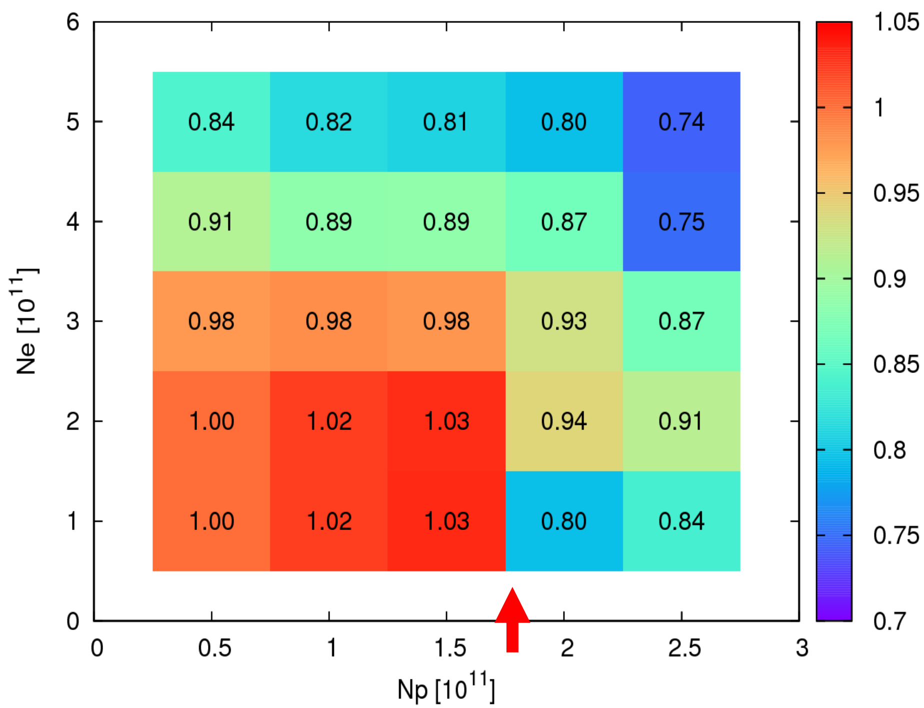
Define $$\kappa = \frac{L(N_p, N_e)}{L(N_{p0}, N_{e0})} \frac{N_{p0}}{N_p} \frac{N_{e0}}{N_e}$$

If there is no emittance blow-up when increasing bunch intensity, κ will remain constant.

- **1 collision per turn has more emittance stable region than 2 collisions per turn.**



1 collision/turn

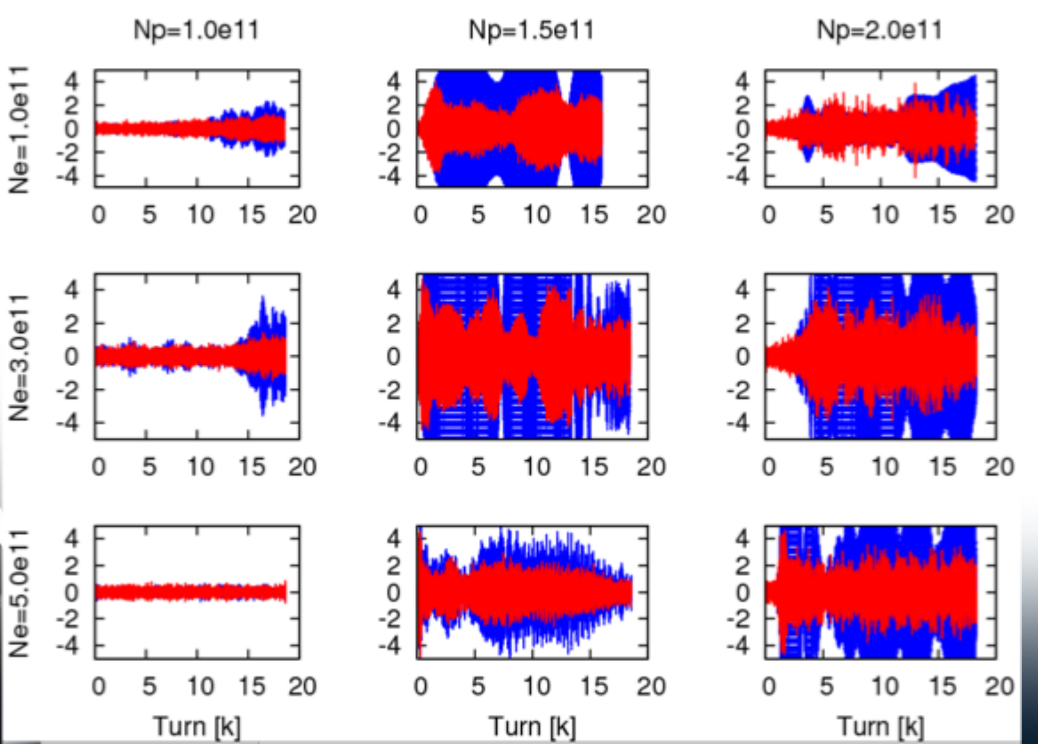


2 collisions/turn : IP6 & IP12

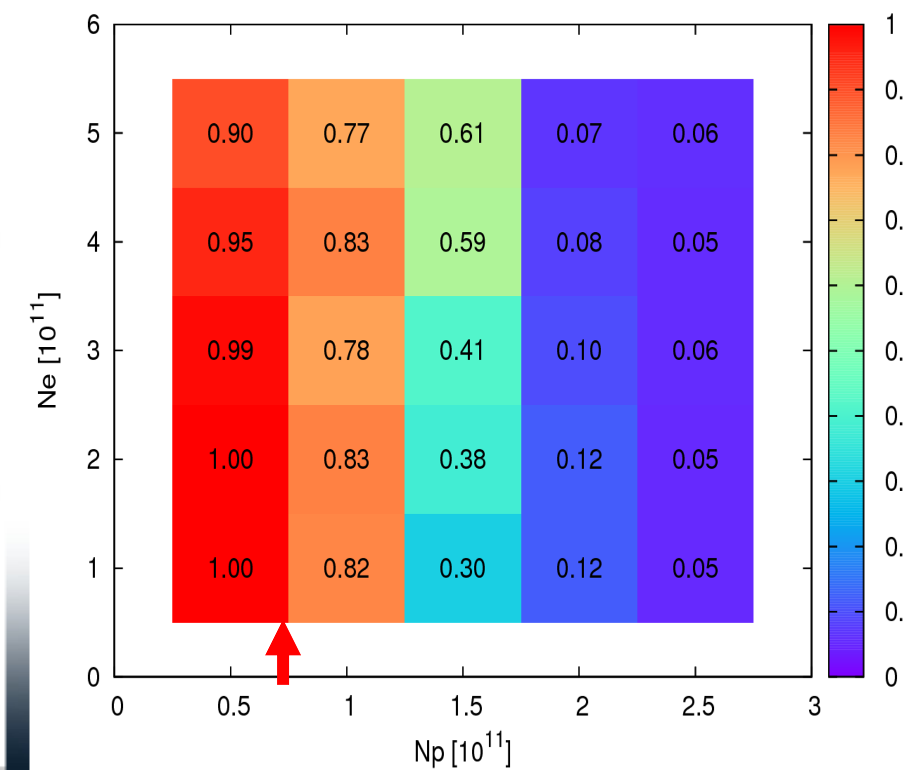
Simulation Results (III)

- **The third case: 2 collisions/turn at IP6 and IP8**
- For this case, we need to track 3 proton bunches and 3 electron bunches, since they collide with each other.
- With 2 collisions per turn at IP6 and IP8, coherent motion seen at Np>=1.0e11, which gives **the smallest emittance-stable region**.

center motion <x>



luminosity factor κ



Conclusion from Simulation Studies

- With the design machine and beam parameters, **coherent BB instabilities** are observed with 2 collisions per turn, not matter 2 collisions at IP6 & IP8, or at IP6 & IP12.
- With 2 collisions per turn, the **beam-beam limit**s are reduced more than half comparing to 1 collision per turn. The worst case is 2 collisions at IP6 and IP8.
- Conclusion: **with current design lattice and beam parameters, we can not have 2 collisions per turn for both electron and proton beams without reduction in luminosity per IP.** Therefore we should avoid 2 collisions per turn in eRHIC filling pattern design.

Bunch Filling Scheme

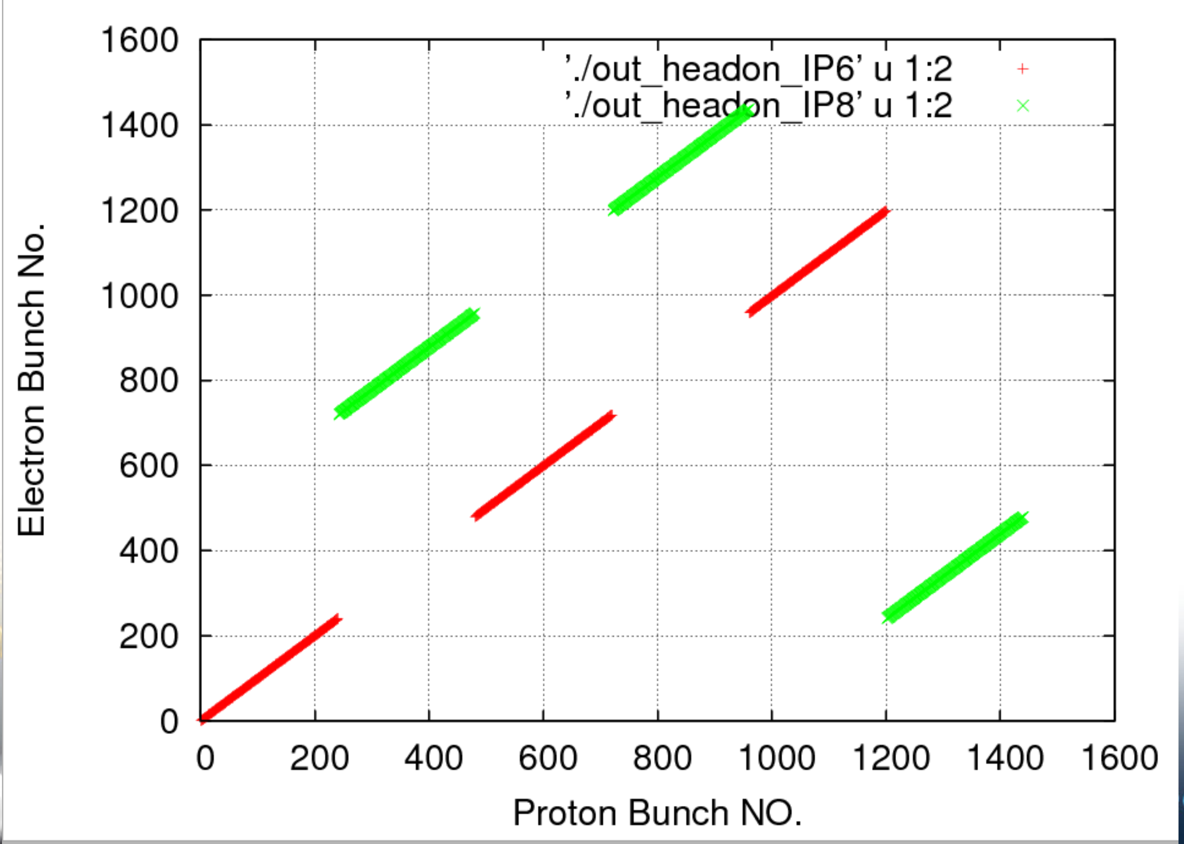
- To delivery collisions to two experiments simultaneously and to avoid 2 collisions per turn for both beams, we (Mike Blaskiewicz, et al.) came up a solution : **bunch shift filling scheme.**

- **How this works:**

- **RF System**:
  - proton ring: 112MHz, 1440 buckets, bucket width 2.66m
  - electron ring: 560MHz, 7200 buckets, bucket width 0.53m
- **Filling Patterns**:
  - proton: 1 bunch / bucket, 1440 bunches
  - electron: 3*(240*5 + 3 + 239*5 + 2) = 7200 buckets, 1437 bunches
- **PHENIX experiment moved south** by 0.53m (1 electron bucket width)

Programming Test: with the bunch shift scheme,

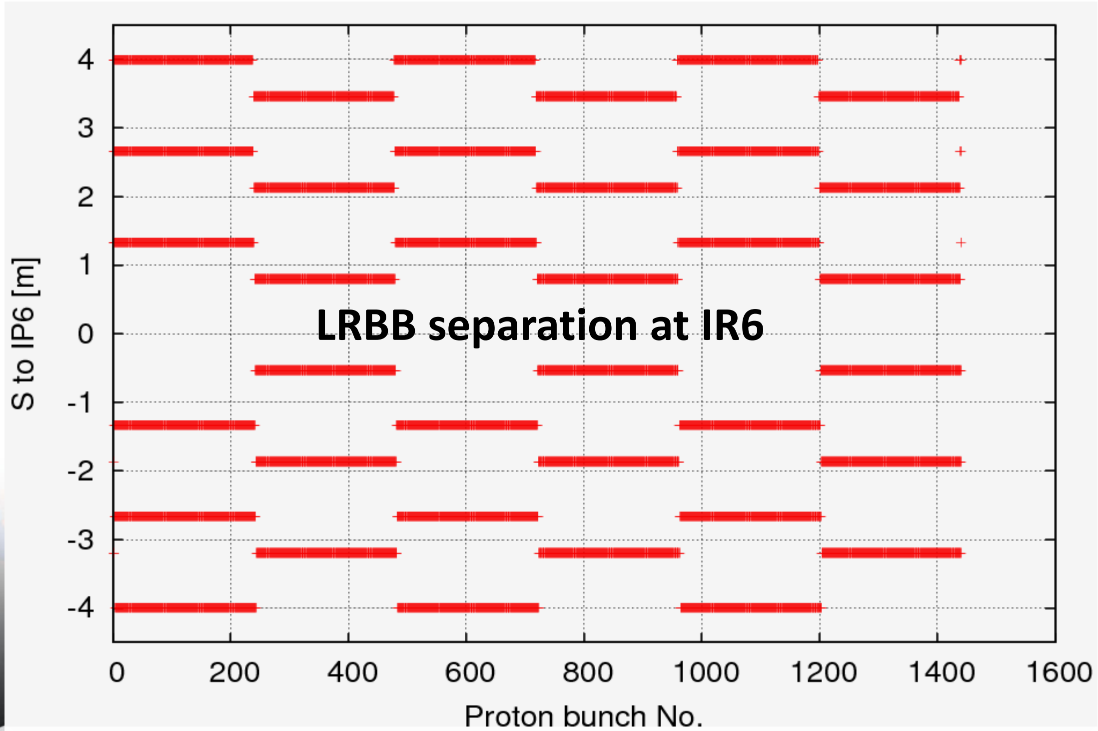
- Each bunch only collides once per turn at IP6 or IP8 .
- There are **720 collisions at IP6** (STAR) each turn, **717 collisions at IP8** (PHENIX).
- The luminosity per experiment is half of that with only 1 experiment.



- Assumption:
  1) Proton bunches go counter-clockwise, electron bunches clockwise.
  2) Proton bunch 1 and electron bunch 1 collide at IP6.

Long-range (LR) BB Interaction

- The common beam pipe at the experiment IRs is +/-4.5m.
- With 1 experiment per turn: each bunch has **6 LR BB** interactions. The nearest one to IP is at **1.33m.**
- With 2 experiments and bunch shift scheme: each bunch has **12 LR BB** interactions on average. The nearest one to IP is at **0.53m**.



LR BB Effect

- Here we evaluate the LR BB effect with the bunch shift scheme.
- From the following table, the minimum separation with 2 experiments are $82\sigma_p$ and $71\sigma_e$.
- Therefore, **the LR BB effect is negligible for eRHIC design**.

	1 experiment	2 experiments
Number of LR BB	6	12
Nearest distance to IP [m]	1.33	0.53
Horizontal separation d [mm]	29.26	11.66
Local beam sizes (σ_p, σ_e) [mm]	(0.212, 0.291)	(0.142, 0.165)
Separation in beam size ($\frac{d}{\sigma p}, \frac{d}{\sigma e}$)	(**138 , 101**)	(**82 , 71**)

Summary

- It is preferable to delivery collisions to both STAR and PHENIIX experiments simultaneously for the eRHIC design. The previous studies were abased on 1 collision per turn for both beams.
- Both weak-strong beam-beam simulations show that we can not have 2 collisions per turn for both electron and proton bunches, with the current eRHIC machine and beam parameters without losing luminosity per IP.
- To deliver luminosity simultaneously to two experiments, a new bunch filling pattern bunch shift scheme is adopted. The integrated luminosity for each experiment will be half of that with 1 experiment operation. The long-range BB effect is checked and found negligible.