1.1 Beam-beam experience in RHIC

Christoph Montag
Mail to: montagc@bnl.gov
Brookhaven National Laboratory, Upton, NY 11973, US

1.1.1 Introduction

The Relativistic Heavy Ion Collider RHIC consists of two superconducting storage rings that intersect at six locations around the ring circumference. Two of these interaction regions are currently equipped with experiment detectors, namely STAR at the "6 o'clock" interaction point (IP), and PHENIX at "8 o'clock". The two beams collide only at these two interaction regions, while they are vertically separated by typically 6-10mm at the other IPs. Together with the separator dipoles located at roughly 10m from the IP, and a distance between bunches of 30m, this avoids any parasitic beam-beam collisions. RHIC is capable of colliding any ion species at magnetic rigidities up to $B \cdot \rho = 830 T \cdot m$, corresponding to 250 GeV for proton beams, or 100 GeV/n for fully stripped gold ions.

1.1.2 Achieved beam-beam parameters in RHIC

The beam-beam parameter for two identical ion beams can be written as

$$\xi_1 = \frac{Z_1}{A_1} \frac{N_2 Z_2 r_p \beta_1^*}{4\pi \gamma_1 \sigma_2^2},$$

where the subscripts "1" and "2" refer to the "weak" and the "strong" beam, respectively. Z and A denote the charge state and number of nucleons of the ions, N the number of ions per bunch, and r_p the classical proton radius. β^* and γ are the β-function at the interaction point and the relativistic Lorentz factor, while σ denotes the rms beam radius. With the total bunch charge in RHIC limited to about $Z \cdot N = 2 \cdot 10^{11}$ proton charges regardless of ion species, the highest beam-beam parameters are reached during collisions of (polarized) proton beams. Not surprisingly, performance limitations due to the beam-beam effect were encountered during polarized proton operations only, while for all other ion species the luminosity was limited by other effects. As Table 1 shows, a maximum total beam-beam parameter of 0.018, or 0.009 per interaction point, has been achieved with polarized proton beams at RHIC. The corresponding number for gold-gold collisions, 0.0025, is about a factor 3 smaller than for protons.

Table 1: Latest machine parameters relevant to beam-beam interactions, for Au-Au and p-p collisions.

Parameter	Unit	Au-Au	p-p
relativistic γ, injection	…	10.5	25.9
relativistic γ, store	…	107.4	106.6
no of bunches, n_b	…	111	111
ions per bunch, N_b	10^9	1.3	170
Number of nucleons, A	…	197	1
Charge state, Z	…	79	1
β -function at IP, β^*	m	0.7	0.7
emittance $\varepsilon_{N\,x,y\,95\%}$	mm·mrad	10	15
chromaticities (ξ_x,ξ_y)	…	(+2,+2)	
harmonic no h, store	…	7×360	360
Number of IPs	…	2	2
Avg. beam-beam parameter per IP	…	0.002	0.0075
Max. beam-beam parameter per IP		0.0025	0.009

1.1.3 Luminosity lifetimes at different beta*

While the proton bunch intensities have been practically equal for several years, the β -function at the IP has been decreased from 1.0m in Run-8 to 0.7m in Run-9 to increase the luminosity. This resulted in the expected peak luminosity increase, but the luminosity lifetime suffered considerably, as illustrated in Figure 1. During the course of Run-9, several attempts were made at understanding and improving this situation [1]. After re-loading the Run-8 lattice configuration restored the luminosity lifetime, it finally became clear that the luminosity lifetime reduction was related to the lower beta-star value of 0.7m in conjunction with the beam-beam effect.
Tracking studies with a 4-D beam-beam model and all known lattice nonlinearities have shown that the dynamic aperture drops from 4.9σ at β^*=0.9m to 4.1σ at β^*=0.7m, which is a significant reduction [2]. However, since a 4-D beam-beam model is not realistic in the case of RHIC with its rms bunch length of about 1m, these dynamic aperture simulations are only valid in a relative sense when two lattice configurations are compared.
It is important to note here that the situation at 250 GeV is expected to be significantly better for several reasons. First of all, the multipole errors in the low-β triplet quadrupoles were minimized during construction for the full RHIC proton energy of 250 GeV. Since the Run-9 experience demonstrates that these multipole errors are the main source of beam lifetime degradation, these smaller errors at the higher energy should result in better beam lifetimes for the same lattice configuration. Furthermore, the transverse beam size at 250 GeV is a factor 1.6 smaller than at 100 GeV due to adiabatic damping. With this smaller size, the beam therefore samples smaller magnetic field nonlinearities in the triplets.

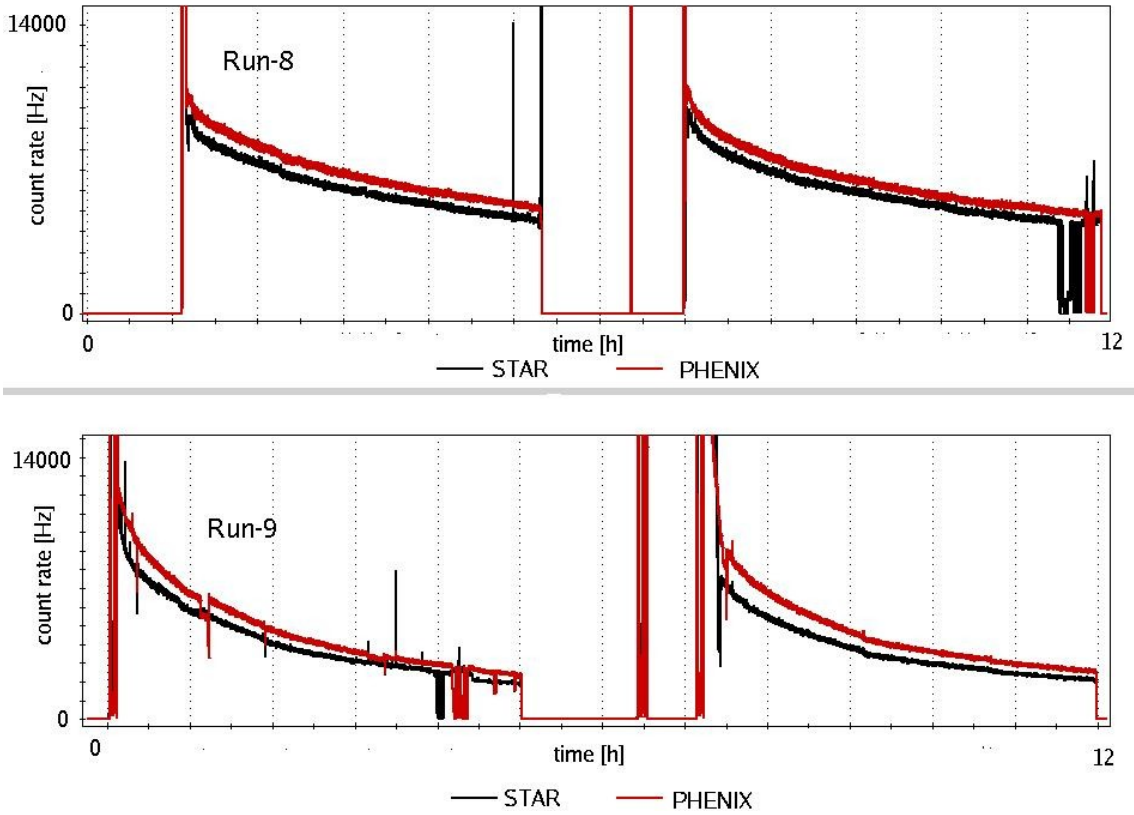

Figure 1: ZDC interaction rates at the two RHIC experiments during Run-8 and Run-9.

1.1.4 Strong-strong effects

With the fractional polarized proton tunes of both beams between 2/3 and 7/10, and a beam-beam parameter of 0.0075 per IP, coherent beam-beam effects, which in previous years manifested themselves only in dedicated experiments [3], are now observed during regular operations. Since the available tune space between these resonances is not sufficient to suppress these π -modes by means of separating the tunes of the two rings, this effect limits the attainable beam-beam parameter and therefore the luminosity of RHIC. The amplitude of these π -modes may depend on the betatron phase advance between the two beam-beam collision points. Designing a lattice with betatron phase advances of $(2n+1)\cdot\pi$ between IPs 6 and 8 is expected to result in a significant reduction of the π -mode amplitudes, thus allowing for higher beam-beam parameters and therefore resulting in higher luminosity.

1.1.5 Unequal RF frequencies

When RHIC was providing deuteron-gold collisions during Run-3, the machine was initially set up with equal beam rigidities at injection. The resulting unequal RF frequencies led to pseudo-random beam-beam interactions and in turn to unacceptably

short beam lifetimes despite the transverse separation of the beams in the interaction regions [4]. To avoid these detrimental effects, RHIC was subsequently set up with equal relativistic γ , and therefore equal RF frequencies at injection and throughout the entire energy ramp.

1.1.6 Future Improvements

To overcome the present limitations posed by the beam-beam effect, several countermeasures are being studied. A near-integer working point shows improved dynamic aperture in simulations [5]. However, actual operation at tunes close to the integer turned showed intolerably high background levels caused by 10 Hz orbit oscillations whose amplitude is enhanced by roughly a factor five compared to the regular working point near 2/3 [6]. A fast global orbit feedback system currently under development is expected to eliminate these orbit oscillations, and therefore reduce background levels significantly [7].
To allow for higher beam-beam parameters, an electron lens will be installed to compensate the nonlinear beam-beam kick of one RHIC interaction point, thus reducing the total beam-beam tuneshift parameter [8]. In turn, bunch intensities can be increased to result in the same total beam-beam parameter as in the present configuration. This is expected to increase the luminosity by a factor up to two.
Systematic experimental studies of the effect of the betatron phase advance between the two interaction points on coherent beam-beam oscillations (π -modes) will be conducted in the near future as part of the head-on beam-beam compensation project.
Since the predictive power of dynamic aperture calculations with respect to machine performance is limited, beam lifetime simulations are currently being developed. For realistic results, effects such as intrabeam-scattering, orbit jitter, tune modulations, etc. need to be included in these simulations, which are therefore very challenging in CPU-time intensive.
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1.1.7 References

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