Beam-beam Observations in RHIC

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In this talk we focus on observations on luminosity, beam intensity, emittance, and bunch length. Observations on coherent beam-beam and long-range beam-beam will be reported separately.
Introduction

- RHIC consists of two superconducting rings which insect at 6 locations along its 3.8 Km circumference.

- Two beams collide head-on at IP6 and IP8. They are vertically separated at other non-collisional IPs.

- RHIC collides heavy ions and polarized protons. The total maximum beam-beam parameters is 0.003 for Au-Au collision, and 0.018 for p-p collision. In this presentation, we only focus on BB issues in p-p runs.
Beam parameters in the RHIC p-p runs

<table>
<thead>
<tr>
<th>Parameters</th>
<th>100 GeV (2012 run)</th>
<th>255 GeV (2012 run)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No of colliding bunches</td>
<td>...</td>
<td>107</td>
</tr>
<tr>
<td>Ions/bunch, initial</td>
<td>$10^{11}$</td>
<td>1.7</td>
</tr>
<tr>
<td>Trans. emittance, 95%, initial</td>
<td>mm.mrad</td>
<td>20</td>
</tr>
<tr>
<td>$\beta^*$ at IP6 and IP8</td>
<td>m</td>
<td>0.85</td>
</tr>
<tr>
<td>Long. emittance, 95%, initial</td>
<td>eV.s</td>
<td>2.0</td>
</tr>
<tr>
<td>$V_{\text{gap}}$ (28 MHz)</td>
<td>kV</td>
<td>360</td>
</tr>
<tr>
<td>$V_{\text{gap}}$ (197 MHz)</td>
<td>kV</td>
<td>300</td>
</tr>
<tr>
<td>rms bunch length</td>
<td>cm</td>
<td>75</td>
</tr>
<tr>
<td>rms momentum spread</td>
<td>$10^{-4}$</td>
<td>4.5</td>
</tr>
<tr>
<td>Hour glass factor</td>
<td>...</td>
<td>0.80</td>
</tr>
<tr>
<td>Beam-beam parameter $\xi/IP$</td>
<td>$10^{-3}$</td>
<td>0.007</td>
</tr>
<tr>
<td>Peak luminosity</td>
<td>$10^{30}$ cm$^{-2}$s$^{-1}$</td>
<td>46</td>
</tr>
<tr>
<td>Average store luminosity</td>
<td>$10^{30}$ cm$^{-2}$s$^{-1}$</td>
<td>33</td>
</tr>
<tr>
<td>Average / peak luminosity</td>
<td>%</td>
<td>72</td>
</tr>
</tbody>
</table>

...
Working point in p-p is determined by the beam lifetime with BB and the polarization preservation on ramp and at store.

Current nominal working point (28.695, 29.685) is constrained between 2/3 and 7/10. 2/3 is strong 3rd order betatron resonance. 7/10 is 10th order betatron resonance but also a spin depolarization resonance.

Figure of merit in double-spin experiments is \( LP^4 \), where \( L \) and \( P \) are luminosity and polarization.

\[ N_p=2.0\times10^{11}, \text{emit} = 15 \text{ Pi mm.mrad} \]
To mitigate the emittance blowup and bunch lengthening on the ramp, we adopt 9 MHz RF cavities at injection and on the ramp. Between energy and rotator ramps we re-bucket bunches to 28 MHz RF cavities.

197 MHz cavity voltages are added at top energy to achieve a shorter bunch length to increase luminosity. However 197 MHz RF cavities increase beam’s momentum spread.
Observations: General

In this section, we present the general observations with beam-beam interaction:

- luminosity lifetime
- intensity lifetime
- bunch lengthening
- transverse emittance growth

And some statistics will be shown.
Luminosity Lifetime

- Luminosity is determined by

\[ L = \frac{N_p^2 N_b \gamma f_{\text{rev}}}{4\pi \epsilon_{n,\text{rms}} \beta^*} H(\frac{\beta^*}{\sigma_1}) \]

- Empirically, luminosity in RHIC p-p run can be fitted with double exponentials:

\[ L(t) = A_1 \exp(-t/\tau_1) + A_2 \exp(-t/\tau_2) \]

(\(\tau_1, \tau_2\) = (1.5hr, 18.5hr))

Fill 16697, 2012 run

Fills in 250 GeV runs
**Beam intensity**

- With collision at store, we observed a fast beam loss in the first 1-2 hours, followed by a slow loss in the rest store.
- The total beam intensity and single bunch intensity in the store also can be empirically fitted to double exponentials:
  \[ N_p(t) = A_1 \exp(-t/\tau_1) + A_2 \exp(-t/\tau_2) \]

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### Blue ring, Fill 16697, 2012 run

![Graph showing beam intensity over time with data points and fitted curve.](image1)

\[(\tau_1, \tau_2) = (0.5 \text{hr}, 54 \text{hr})\]

### Blue ring, fills in 250 GeV runs

![Scatter plot showing data points from different runs.](image2)
Bunch length

- Bunch intensity and longitudinal profile are measured with wall current monitor (WCM). In RHIC control system, we use averaged FWHM of all bunches.
- We observed that bunch length is reduced shortly after collision, then it slowly linearly increases in the rest of store. The shorten bunch length in the beginning is related to the fast beam intensity loss.
Transverse emittance

- Transverse emittances are measured with ion profile monitor (IPM) and derived from luminosity measurement. IPMs require knowledge of beta function, and need periodic calibration of micro-channel plate channel sensitivity due to aging.
- Emittances are reduced shortly after collision, then they slowly increase in the rest of store. The reduced emittances in the beginning of store are also related to the fast beam loss.
The above plots show luminosity and beam-beam parameter at 10 minutes after beams were brought into collision.

Available tune space between 2/3 and 7/10 is about 0.03. There is still some room to push beam-beam parameter and increase luminosity.
Explanations & Modeling

In this section we will present

1) Mechanism of particle loss
   - which particles lost
   - how they get lost

2) Calculate IBS contributions to
   - emittance growth
   - bunch lengthening
   and compare them to observations
Beam-beam determined beam decay

- Beam decays without and with collision: the left plot. Beam lifetime got worse immediately after beams were brought into collision.
- Bunch decays with 1 and 2 collisions: the right plot. 1-collision bunches had better intensity lifetime as 2-collision bunches.
- We conclude: beam-beam is the dominated factor for beam loss at store.
Longitudinal profiles in the store

With WCM, we can calculate each bunch’s particle distribution and particle migration in the longitudinal plane.

- 1-collision bunches have larger bunch width and larger particle population in the bunch tail than 2-collision bunches.
- We conclude: particle with larger $\delta p/p$ are less stable with beam-beam.
Particle leakage vs. particle loss

Particle leakage pattern (out of [-5ns, 5ns])

- Intensity loss proportional to particle leakage in the longitudinal plane.
- However, there was no de-bunching beam from WCM.
- Considering particles in the bunch tail having large off-momentum deviation, we conclude: particles lost in transverse plane due to limited off-momentum DA.
- Beam-beam reduces off-momentum DA.
With 197MHz RF the maximum \( dp/p_0 \) for the center bucket \([-2.5\text{ns}, 2.5\text{ns}]\) reaches \( 5\times10^{-4} \). And for the tail particles out of \([-6\text{ns}, 6\text{ns}] \) (full width), \( dp/p_0 \) is bigger than \( 6\times10^{-4} \).

- Off-momentum DA calculation shows 1) off-momentum DA drops with BB than without BB; 2) for particles with \( dp/p_0 > 6\times10^{-4} \), DA < 5 sigmas and they may get lost.

- We believe that the early fast particle loss is caused by large \( dp/p_0 \) particles left from re-bucketing and adding 197MHz RF voltage and it takes 1.5-2 hours to clean them up.
Emittance and bunch length w/o BB

Without beam-beam and 197 MHz RF voltages:

- Beam loss rate was below 1%/h during entire store.
- No emittance and bunch length reductions at the beginning of store.
- Emittance growth bigger than without beam-beam.

Therefore, the beam-beam effects limited transverse emittance growth at store through reduced transverse dynamic aperture.
Intra-beam Scattering (IBS) effects

- We estimate the emittance and bunch length growth from IBS after 1.5 h.
- For example: initial inputs based on Blue ring, Fill 16697. Use real bunch intensity to calculate IBS effects. Assume 90% particles in center Gaussian distribution.
- Emittance and bunch length growth are largely consistent with IBS.
Observations: Limits

In this section, we focus on operational limits we met in the previous RHIC p-p runs due to particular reasons:

- 3Qx and 3Qy resonances
- chromatic effects with low $\beta^*$
- 10 Hz orbit oscillation
3Qx and 3Qy resonances

- We had used mirrored working points of two rings on both sides of diagonal in tune space (to suppress coherent modes). However, after the 2006 run we have to place working points of two rings below diagonal to avoid 3Qx resonance to obtain better store beam lifetime.

- In the 2012 100 GeV run, we observed 3Qy caused beam loss when the bunch intensity is higher than 1.7e11.

- The main source of 3Qx,y resonances are located in IR6 and IR8. A lot of efforts have been put in to correct 3Qx,y RTDs. Currently they are corrected with IR bump method using local IR sextupoles.
Chromatic effects with low beta*

- Low beta* lattices reduce dynamic aperture due to IR nonlinear field errors and nonlinear chromatic effects.

- 100 GeV run: in 2009 we used beta*=0.7m, we observed a poor beam lifetime. In 2012 we increased beta* to 0.85m which gave 16 hour beam lifetime.

- 250 GeV run: we achieved beta*=0.65m. Potential to go lower.

- The main sources of Q” are from triplets in IR6 and IR8. Phase advance adjustment between them may help. And we found lower integer tunes have smaller chromatic effects.

- We are interested in and working on LHC’s ATS design for RHIC.

Chromaticities vs. beta*

Each section’s contributions to Q’’ and Q’’’
**10 Hz orbit oscillation**

- Horizontal 10 Hz orbit in RHIC due to mechanical eigenfrequencies of triples, driven by cryo flow.

- In 2008 we tested a near-integer working point (0.96, 0.95) which was abandoned due to 10 Hz orbit oscillation.

- A 10 Hz feedback was developed and the peak-to-peak amplitude of 10 Hz orbit oscillation was reduced from 3000 μm to 250 μm in triplets, and luminosity lifetime was improved some.

- We plan to revisit the near-integer tunes in the beam experiments.
Summary

- Beam-beam effects on beam lifetime, emittance and bunch length growth in RHIC have been reported and explained.

- The main reason of particle loss in the store is the limited transverse dynamic aperture. Beam-beam interaction, 3Qx,y resonances, and nonlinear chromaticities reduce the dynamic aperture.

- To further increase luminosity, we plan to further increase bunch intensity, reduce beta*. We are implementing nonlinear chromaticity and 3Qx,y resonance corrections. We are also improving the longitudinal emittance from injectors and sources and on the energy ramp.