Beem-Beam Induced Emittance Growth
Simulation of RHIC 2006 pp Run

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Outline

1. LIFETRAC technique and the history
2. Emittance growth simulation in RHIC
3. Comparison to the measurement data
4. A look into shorter bunch options
5. Conclusion and future work
History of the tracking technique and code for Equilibrium Distribution

1. Initial concept was proposed by J. Irwin 1989 (J. Irwin, 3rd ICFA Workshop, Novosibirsk, 1989);

2. Concept was further developed and implemented into beam-beam simulation code “LIFETRAC” by D. Shatilov at INP (D. Shatilov, INP 92-79, Novosibirsk, 1992, in Russian);

3. Same concept, but slightly different method, was developed independently and implemented into beam-beam code “LFM” by T. Chen, et al. at SLAC (T. Chen, et al., Phys. Rev. E49, p2323, 1994);

4. Both codes were tested against multiparticle brute force tracking code “TRS“. They reached good agreement (M. Furman, CBP Tech Note 59, 1995)

5. INP 92-79 tech-note (in Russian) was translated and published in English by D. Shatilov. (D. Shatilov, Particle Accelerators, Vol.52, p65, 1996)
LIFETRAC Tracking Technique  
(Developed for Equilibrium Distribution)

1. Developed to determine beam halo and life time and reduce the required CPU time by 1-2 magnitudes.

2. Beginning from the core region the beam distribution is built step by step in the amplitude space.

3. During each step only those particles fall outside of the given region in amplitude space are tracked.

4. At the end of each step the boundary of the region is moved to larger amplitude where the line of equal distribution density is.

5. The border conditions taken from the previous step connect the distributions of in/out of the region.
How does LIFETRAC Handle
the Underlying Physics

The code is designed to simulate the beam tail/halo without introducing bias towards any one mechanism:

**Resonance overlap**

The beam-beam interaction is treated as a kick. So, it includes all overlapped and isolated resonances.

**Diffusion**

The global expansion of the boundary separating core and halo naturally accommodates diffusion.

**Resonance streaming**

Instead of using simple circular arcs as boundaries LIFETRAC used irregular shaped boundary defined by equal distribution density which naturally stretch out in the direction of Resonance streaming in the $A_x$-$A_y$ plan.
Underlying Physics

**Resonance overlap**

When high-order resonances are wide enough, or close enough, they may overlap which leads to chaotic motion of particles moving from one resonance to another and reach larger amplitude.

**Diffusion**

Particles starting at locations throughout the core slowly diffuse to larger amplitudes where they move as oscillators driven by noise from the beam-beam kick. It may generate non-Gaussian tail.

**Resonance streaming**

Quantum fluctuations drive particles into nonlinear resonances. These particles oscillate around the resonance center located in the $A_x-A_y$ plan satisfying the resonance condition:

$$p Q_x(A_x,A_y) + r Q_y(A_x,A_y) + m Q_s = n$$

where $p$, $r$, $m$ and $n$ are integers.
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### About LIFETRAC Package

<table>
<thead>
<tr>
<th>Original Author</th>
<th>Dmitry Shatilov, BINP SB RAS, Novosibirsk, Russia,</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Purpose</td>
<td>weak-strong simulation of beam-beam effects</td>
</tr>
<tr>
<td>Method</td>
<td>Macro-particle tracking with a special technique</td>
</tr>
<tr>
<td>Particles</td>
<td>Electron-positron, proton-antiproton</td>
</tr>
<tr>
<td>Initial Distribution</td>
<td>Gaussian (by default) or from separate text input file</td>
</tr>
<tr>
<td>Program Language</td>
<td>FORTRAN 90</td>
</tr>
<tr>
<td>Computer Platform</td>
<td>Linux</td>
</tr>
<tr>
<td>Compiler</td>
<td>Intel(R) Fortran Compiler for 32-bit applications, Version 7.1</td>
</tr>
<tr>
<td>Speed (CAD godzilla)</td>
<td>$2.5 \times 10^9$ (part x turn) /node/day</td>
</tr>
<tr>
<td></td>
<td>$10^{11}$ (part x turn) needs 4-10 days on 10 nodes of gadzilla</td>
</tr>
<tr>
<td>Speed (BNL cluster)</td>
<td>$5.3 \times 10^9$ (part x turn) /node/day</td>
</tr>
<tr>
<td></td>
<td>$10^{11}$ (part x turn) needs 19 days on 1 node of cluster.bnl.gov</td>
</tr>
</tbody>
</table>
Advanced Features in LIFETRAC

- 2-Dimensional coupled optics;
- 3-Dimensional, beam-beam kick computed using interpolated formulae;
- Non-Gaussian transverse density of the strong bunches (superposition of up to 3 Gaussian distributions with different emittances);
- Chromatic modulation of beta functions;
- Longitudinally sliced strong bunch for transformation through main IPs;
- RF cavity;
- Non linear elements for beam-beam compensation;
- Beam tail treatment (by applying more weight on core particles and less weight on tail particles);
- Optics error;
- Noise can be introduced as a short kick at each turn;
- Macro particle of weak beam (~10,000 particles);
- Parallel computation.
LIFETRAC Specifics

1. Originally developed for e+e- colliders where the equilibrium is reached within a few dumping times. Then the code is extended to un-equilibrium cases.

2. The beam-beam parameter is an input (not a result). The number of particles and charge/macro-particle are calculated through

\[ \xi_{x,y} = \frac{r_p}{2\pi \gamma} \frac{N_p \beta_{x,y}}{\sigma_{x,y}(\sigma_x + \sigma_y)} \]

3. 3D=2D (transverse) + 1D (longitudinal)

4. Statistics are over all macro-particles and all turns within macro-steps. (N_{mac-part}*N_{turn}<2*10^9)
1. Novosibirsk B-factory with flat beam
   Confirmation of reduction on resonance width with increased monochromatization parameter

2. Novosibirsk B-factory with parasitic crossing

3. Novosibirsk $\phi$-factory with round beam

4. HERA electron beam

5. Tevotron, FNAL proton and antiproton
   Lifetime and Emittance growth simulation

6. RHIC polarized proton run 2006
   Emittance growth simulation

(The list is limited to my knowledge only)
### Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lattice (RHIC Blue ring)</td>
<td>2006 100GeV proton</td>
</tr>
<tr>
<td>Blue tunes (x, y)</td>
<td>28.691, 29.690</td>
</tr>
<tr>
<td>Yellow tunes (x, y)</td>
<td>28.697, 29.687</td>
</tr>
<tr>
<td>Chromaticity (x, y)</td>
<td>2m, 2m</td>
</tr>
<tr>
<td>Beta* IP 6, 8, 10, 12, 2, 4</td>
<td>1, 1, 10, 10, 10, 10 [m]</td>
</tr>
<tr>
<td>Blue Initial Emittance x, y</td>
<td>$15\pi$mmrad (95% norm)</td>
</tr>
<tr>
<td>Yellow Initial Emittance x, y</td>
<td>$15\pi$mmrad (95% norm)</td>
</tr>
<tr>
<td>Initial RMS Beam Length</td>
<td>1m</td>
</tr>
<tr>
<td>dE/E</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>Aperture x, y, z</td>
<td>$8.5\sigma$, $8.5\sigma$, $10.6\sigma$</td>
</tr>
<tr>
<td>Beam-beam parameter simulated</td>
<td>0.0–0.018</td>
</tr>
<tr>
<td>Initial particle distribution</td>
<td>Gaussian</td>
</tr>
<tr>
<td>Number of macro-particles (in core)</td>
<td>$10^4$</td>
</tr>
<tr>
<td>Number of macro-steps simulated</td>
<td>$10^2$</td>
</tr>
<tr>
<td>Number of turns per macro-step</td>
<td>$10^5$</td>
</tr>
<tr>
<td>Total turns simulated</td>
<td>$10^7$</td>
</tr>
<tr>
<td>Total RHIC time simulated</td>
<td>2.13 mins</td>
</tr>
</tbody>
</table>
Tune Scan

Emittance [cm-rad] after $10^5$ turns

This working point is used in all the beam-beam simulations.
Emittance Growth from Simulation

The graph illustrates the growth of emittance over time for different values of \( \Delta \nu \). Each line represents a different \( \Delta \nu \) value, with the legend indicating the specific values used:

- \( \Delta \nu = 0.000 \)
- \( \Delta \nu = 0.001 \)
- \( \Delta \nu = 0.002 \)
- \( \Delta \nu = 0.003 \)
- \( \Delta \nu = 0.004 \)
- \( \Delta \nu = 0.006 \)
- \( \Delta \nu = 0.008 \)
- \( \Delta \nu = 0.010 \)
- \( \Delta \nu = 0.012 \)
- \( \Delta \nu = 0.014 \)
- \( \Delta \nu = 0.016 \)
- \( \Delta \nu = 0.018 \)

The emittance growth is measured in units of mm-mrad.
Beam Distributions in \((A_x, A_y)\) Plane

\[ \nu_{bb} = 0.004 \]

\[ \nu_{bb} = 0.006 \]

\[ \nu_{bb} = 0.010 \]

\[ \nu_{bb} = 0.012 \]

\[ \nu_{bb} = 0.015 \]

\[ \nu_{bb} = 0.018 \]
1. All fills in 2005 and 2006 runs are evaluated;
2. Based on the ZDC coincident rates measured during 4 hours of early store (from 1.5 to 5.5 hours after the acceleration ramp event “accramp”) at PHENIX and STAR;
3. The 95% normalized beam emittances
4. “Peak Luminosity” = Luminosity at 1.5 hours;
5. “Luminosity lifetime” = average Luminosity lifetime over 4 hours;
6. “Emittance growth rate” = average growth rate over 4 hours.
7. “Beam-beam parameter” = measured at the beginning of the 4 hour period (not averaged).
Emittance Growth Rate

Measurement & observation (S.Y. Zhang)

The bunch intensity in 2006 is much higher than in 2005, but the collision points were reduced from 3 to 2. The largest beam-beam parameters are both limited to 0.012.
The simulation result is slightly higher than the experiment.

**Experiment:**

The measured emittance was averaged over 4 hours of beam store from 1.5 hours to 5.5 hours after the acceleration ramp event (accramp). The beam-beam parameter was measured at the beginning of the 4 hour period (not averaged). Thus, the average value of beam-beam parameter over the 4 hour period could in fact be lower if the effect of beam intensity drop and the beam emittance growth were included.

**Simulation:**

Tracks the initial 2.13 minute after the beams are brought to perfect head on collision, when the intensity drop and emittance blow up are both the strongest. This may account for the higher emittance growth rate predicted by the simulation as compared with the calculation based on ZDC measurements.
RHIC RF System Upgrade

First step:

Use a 9MHz RF system to match the beam injected from AGS into RHIC.

Use the existing 28MHz RF system for store.

$L_{RMS}=58\text{cm}$, $dp/p=0.06\%$, $V_{rf}=0.3\text{MV}$, $f_{rf}=28\text{MHz}$, $f_s=44\text{Hz}$

Second step:

Use a 56MHz superconducting cavity for store.

$L_{RMS}=30\text{cm}$, $dp/p=0.11\%$, $V_{rf}=2\text{MV}$, $f_{rf}=56\text{MHz}$, $f_s=161\text{Hz}$
Emittance growth rate as function of $\sigma_{RMS}$ from polynomial curve fit:

$$\frac{d\varepsilon}{\varepsilon} = 0.01324 \sigma_{RMS}^3 - 0.0727 \sigma_{RMS}^2 + 0.101 \sigma_{RMS} - 0.003$$
1. The simulations of RHIC 2006 run and the measurement from ZDC are in reasonably good agreement.

2. Magnet nonlinearities and noises are not included so far.
   A) Can’t directly tack MAD nonlinear model as input.
   B) There is a plan to build a more advanced model or, at least, include the magnet errors in the form of global noise matrix.

3. The cooling effect could be investigated in the form of damping. (Currently looking into related issues)

2. Simulations on emittance growth vs. bunch length gave encouraging result. However, we need more detailed studies with the conditions of proposed RF upgrades.
   Currently in the progress of setting up models for simulations with
   A) 28MHz RF system
   B) 56MHz RF system
   C) RF system for 250GeV protons