Beam-Beam Simulations at SLAC

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SLAC/ACD

4/9/2009
Computational Challenges

- Computationally:
  - LHC: 4 IPs, 120 parasitics
  - Non-linear lattice, 1000s of elements
- "Predictive power": can one go beyond DA?
- Beam lifetimes, emittance growth, ...
- Code + computing capabilities approach realistic time scales
- Appreciable differences in approximations used
The PLIBB Code

- Used for Tevatron, RHIC, LHC
- Full tracking code, highly parallel
  - MAD-X lattices
  - handles all elements in RHIC, LHC lattices
  - Embedded scripting language
- Fully 6D throughout, uses differential algebra
- Creates fast tracking kernels in different approximations (Thick lenses, thin lenses: drift-kick, 4th order, 6th order)
- Symplectic lumping: absorb quadrupoles + bends between interesting elements into single 3rd order integrable Hamiltonian
- Weak-strong beam-beam, current wire, electron lens (multi-bunch, soft gaussian, strong-strong)
Particle Tracking on Graphics Cards (with D. Yershov)

GPUs:
- Many ALUs, many lightweight threads
- Maximum benefit for data-parallel, branchless code (ray tracing, texture mapping...)
- Beam dynamics: Ray tracing in 6 dimensions
Symplectification

- Symplectic integrators: correct integration of a ‘nearby’ Hamiltonian.
- Roundoff errors will introduce non-Hamiltonian terms, even with symplectic integrators.
- Integers: Lower accuracy, no rounding error
- Resolution required $\sqrt{\frac{\varepsilon N}{\lambda_{\text{Compton}}}}$
- (Skeel, 1999:) Pinning $\nu$-bit mantissa floating-point number to a $2^\mu \otimes 2^\mu$ lattice in $[-q_{\text{max}}, q_{\text{max}}] \otimes [-p_{\text{max}}, p_{\text{max}}]$

$$q := (q + (.75 \cdot 2^{\nu-\mu} q_{\text{max}}))$$

$$p^{n+\frac{1}{2}} = p^n + [\Delta F^n]_p$$

$$q^{n+1} = q^n + \left[\frac{2\Delta}{m} p^{n+\frac{1}{2}}\right]_q$$

(1)
Symplectic Lattice: Toy Example

Kinetic energy vs. turn number for plain and lattice single-precision arithmetic (Simplified model: Storage ring in $4 \times 4$ smooth approximation, single $1/r$ (‘current wire’) perturbation)
PLIBB module gputrack

- general, table-driven Drift/Kick kernel running on GPU
- Leapfrog, 6th + 8th order Yoshida implemented
- PLIBB precalculates coefficients
- LHC fits onto GPU texture memory
- Tracks particles in batches of 128
- Full speed gain realized
Tracking Through the LHC Lattice

![Graph showing tracking through the LHC lattice](image)
Multi-Bunch

- Run `plibb` one CPU/bunch/beam,
- put ‘trap door’ elements in IPs
- only pairwise communication needed
- sequence is fixed by communicators
- pipelining, synchronized by update of
  - Full strong-strong: $\rho, \varphi$ (expensive: 2D convolution solver in PLIBB)
  - $x_{avg}, y_{avg}, \sigma_x, \sigma_y$
Electron Lens Tracking Studies

- Model used: LHC 7TeV, IPs 1,2,5,8
- 8/30 parasitic crossings per IP
- Design emittances
  - \( N = 1.05 \cdot 10^{11} \), \( N = 1.3 \cdot 10^{11} \), \( N = 1.7 \cdot 10^{11} \)
- Position single electron lens at location, \( s = -103m \) (\( \beta \) crossing)
- \( \sigma_x \approx \sigma_y \approx 1.02\text{mm} \)
Possible E-Lens Configuration

Figure 1: Electron lens configuration for compensation of beam-beam effects.
**Electron Lens Element**

Modeled as current distribution \( I(r) r dr \) within \( R \) (possibly confined by solenoidal external fields)

\[
\delta x'_\perp = k \frac{I_{encl} R^2}{r^2_{\perp}}, \quad r_{\perp} > R
\]

\[
\delta x'_\perp = 2 \pi k r_{\perp} r^2_{\perp} \int_0^{r_{\perp}} I(r') r' dr', \quad r_{\perp} \leq R
\]

\[
k = \frac{e_p \mu_0}{\gamma_p} \left( 1 \pm \frac{1}{\beta_e} \right)
\]

Has been implemented in plibb as a generalized current element.

Different \( I(r) \) distributions available:

- Cut-off Gaussian
- Fermi-Dirac
- Flat top (\( \equiv \) Wire, using correct form factor)
BB tune footprints
BB tune footprints w/Gaussian Electron Lens Element

Gaussian E-Lens

- All IPs, no parasitics
- Single elens, L*Ieff 15Am, cutoff=4sigma
- Single elens, L*Ieff 12Am, cutoff=4sigma
BB tune footprints w/ quasi-flat Electron Lens Element

(Almost) Flat E-Lens

- All IPs, no parasitics
- Single elens, L*Ieff 10Am, cutoff=1.2
- Single elens, L*Ieff 8Am, cutoff=1.2
- Single elens, L*Ieff 6Am, cutoff=1.2

fractional tune

fractional tune

0.308 to 0.322

0.3 to 0.312

Beam-Beam Simulations at SLAC

LHC Electron Lens Tracking Studies

Parameters
3D tune ‘footprint’
Electron Lens Tracking Results (I)

Electron Lens Compensation of LHC Increased Currents: $N_0=1.3\text{e}11$

- uncompensated
- 12.0Am, 1.6$\sigma$
- 10.0Am, 2.0$\sigma$
- No Sextupoles, 10.0Am, 2.0$\sigma$

Graph showing the ratio $N_i/N_0$ vs. number of turns for different compensation scenarios.
Electron Lens Tracking Results (II)

Electron Lens Compensation of LHC Increased Currents: $N_0=1.7\times10^{11}$

- uncompensated
- uncompensated, local RF kicks
- 10.0 Am, 2.0σ
- 12.0 Am, 3.0σ
- 16.0 Am, 3.0σ

$N_i/N_0$ vs. Turns
Electron Lens Tracking Results (III)

Electron Lens Compensation of LHC Increased Currents: $N_0=1.3e11$

- uncompensated
- 12.0Am, 1.6σ
- 10.0Am, 2.0σ
- No Sextupoles, 10.0Am, 2.0σ
- Fit to $\exp(b+a*t**1/2)$
### Parameters

<table>
<thead>
<tr>
<th>Label</th>
<th>( N_0 \cdot 10^{-11} )</th>
<th>( \int l_{\text{eff}} , dl ) [Am]</th>
<th>( r_{\text{max}} / \sigma )</th>
<th>( \tau )</th>
<th>(( \Delta \log N ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>job1</td>
<td>1.3</td>
<td>0</td>
<td>n/a</td>
<td>5h19m ± 4m</td>
<td>.24%</td>
</tr>
<tr>
<td>job5</td>
<td>1.3</td>
<td>-12</td>
<td>1.6</td>
<td>5h14m ± 5m</td>
<td>.22%</td>
</tr>
<tr>
<td>job6</td>
<td>1.3</td>
<td>-10</td>
<td>2.0</td>
<td>7h53m ± 9m</td>
<td>.29%</td>
</tr>
<tr>
<td>job7(^a)</td>
<td>1.3</td>
<td>-10</td>
<td>2.0</td>
<td>11h53m ± 7m</td>
<td>.56%</td>
</tr>
<tr>
<td>job2</td>
<td>1.7</td>
<td>0</td>
<td>n/a</td>
<td>1h37m ± 3m</td>
<td>.53%</td>
</tr>
<tr>
<td>job0(^b)</td>
<td>1.7</td>
<td>0</td>
<td>n/a</td>
<td>1h40m ± 6m</td>
<td>0.43%</td>
</tr>
<tr>
<td>job3</td>
<td>1.7</td>
<td>-10</td>
<td>2.0</td>
<td>2h20m ± 5m</td>
<td>0.61%</td>
</tr>
<tr>
<td>job4</td>
<td>1.7</td>
<td>-10</td>
<td>3.0</td>
<td>2h18m ± 1m</td>
<td>0.57%</td>
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<tr>
<td>job9</td>
<td>1.7</td>
<td>-16</td>
<td>2.0</td>
<td>2h02m ± 1m</td>
<td>0.41%</td>
</tr>
</tbody>
</table>

\(^a\)No sextupoles, \(7 \cdot 10^5\) turns  
\(^b\)RF kicks treated locally
Conclusions + Future Work

- Timescales of minutes are accessible to simulations
- Codes show similar + plausible behavior for LHC e-lens
- Differences need to be explained: bugs, approximations, lattices?
- **Benchmarking is needed**
- RHIC electron lens may be an ideal study object
Backup + Orphaned Slides
Possible E-Lens Configuration

Figure 1: Electron lens configuration for compensation of beam-beam effects.
RHIC Wire Compensation

\[ \Delta \phi_{x,y} = 6 \, \text{deg} \quad (\beta^* = 1\text{m}) \]
Past workshop; BTF Measurements

Simulation vs Measurement (BTF data courtesy W. Fischer, N. Abreu)
Past workshop; BTF Measurements
From N. Abreu’s workshop presentation:

- **\( \sigma_y = 6.9 \text{ mm} \)**

- **Yellow Ring: 50 Amps**

- **Yellow Ring: 5 Amps**