Detailed Electron Cloud Modeling Using CMAD

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Electron cloud in a nutshell

- Photons and beam residual gas ionization produce primary e-
- Number of electrons may increase/decrease due to surface Secondary Electron Yield (SEY) $\rightarrow$ number of secondary electrons per incident electron.
- Bunch spacing determines the survival of the electrons
Electron cloud in a nutshell

- Especially strong effect and possible consequences:
  - Single-bunch and Coupled-bunch instability
  - Emittance increase
  - Luminosity reduction
  - Vacuum pressure and excessive power deposition at walls (load on LHC cryogenic system)

- In summary: the electron cloud effect (ECE) is a consequence of the strong coupling between the beam and its environment:
  - many ingredients: beam energy, bunch charge and spacing, secondary emission yield, chamber size and geometry, chromaticity, photoelectric yield, photon reflectivity, …
The electron cloud has been observed / is expected at:

- PSR
- B-factories PEP-II, KEK-B
- DAΦNE
- CesrTA
- LHC complex, SPS, PS2
- Super-B
- Linear Collider (LC) Damping Rings (DR)
Simulation Efforts (LC)

Color code:
- Cloud Generation/Build-up code
- Instability code

- KEK: PEI and PEHTS K. Ohmi
- LBNL: POSINST M. Furman, M. Pivi, J. Qiang, M. Venturini et al., WARP/POSINST J. L. Vay et al.
- SLAC: CMAD M. Pivi, CLOUD_LAND L. Wang, POSINST

Other used codes: ORBIT (SNS), QuickPIC (USC), COUD_MAD (SLAC), MICROMAP (GSI) ..
ILC DR simulations history: 2006

ILC DR “OCS2” 6.7km Ring design

Single-Bunch instability threshold (blue bar – see also picture on the right) and simulated ring averages cloud density according to SEY values assumed.
Single-bunch instability mechanisms

- Depending on cloud density beam instability:
  - Beam break-up rise time $\tau$ shorter than synchrotron period: $\tau < T_s$
  - Transverse mode coupling instability: $\tau \sim T_s$
  - Head-Tail* slower growth rate: $\tau >> T_s$

*Damping by synchrotron oscillation

See F. Zimmermann: *Review of Single Bunch Instabilities driven by Ele. cloud*
• Motivations for CMAD:
  – Include real lattice and sampling the ring beta functions variation (ILC DR demanding …)
  – Parallel simulations to deal with many lattice elements and many turns (>1000)
  – Study incoherent emittance long-term growth below threshold: “real or numerical?”
  – 2D forces
  – Cloud build-up (not there yet) and instability in the same code
  – Use for benchmark with other codes
Simulation code

- Tracking the beam \((x,x',y,y',z,\delta)\) in a MAD lattice by 1\(^{\text{st}}\) order and 2\(^{\text{nd}}\) (2\(^{\text{nd}}\) order switch on/off) transport maps
- MAD8 or X “sectormap” and “optics” files as input
- Apply beam-cloud interaction point (IP) at each ring element
- Parallel bunch-slices based decomposition to achieve perfect load balance
- Beam and cloud represented by macroparticles
- Particle in cell PIC code 9-point charge deposition scheme
Simulation code

- 2D Beam-Cloud forces – FFT $O(N \log(N))$ open space and conducting boundary
- 3D electron cloud dynamics Leap-Frog with Boris-rotation including magnetic fields
- Define at input a cloud density level $[0<\rho<1]$ for each magnetic element type
Beam-cloud forces: electric field calculation

- Electric field computed near beam ~10-20 beam sigma
  - Open space: use Green function method and Fast Fourier Transform FFT in a double gridded domain (Hockney)

Solution of Poisson equation:

\[ \phi(x, y) = \int dx' dy' G(x - x', y - y') \rho_c(x', y'), \]

with

\[ G(x - x', y - y') = -\frac{1}{2} \ln[(x - x')^2 + (y - y')^2], \]

and convolution of Fourier transforms

\[ \phi_F = \mathcal{F}^{-1} \rho \]

- or metallic conducting boundaries at grid domain edges, using FFT method
Open space: Beam Vertical electric field using 300000 macroparticles (middle of LHC beam)
Beam-cloud forces: electric field calculation

Conducting boundaries: Beam Vertical electric field (middle of LHC beam)
Beam-cloud forces: electric field calculation

Open space: e- Cloud Vertical Electric field using 100000 macroelectrons (middle of LHC beam)
Conducting boundaries: e- Cloud Vertical Electric field (middle of LHC beam)
Bunch-slice parallel decomposition

Computation in parallel - pipeline

Each processor deals with the bunch-slice, then send cloud information to the next in the pipeline. The last processor print out the beam information. At each turn, 1 processor gathers all particles and give RF-kick.
Scalability of parallel computation

- At the moment, the code can use a number of processors up to the number of bunch slices, typically ~70-100.
- Gain ~53 with 70 processors

Computing time (at NERSC) with number of processors, example for 1 LHC turn/100 elements, for simulation parameters: 70 bunch slices, 300,000 macroparticles, 100,000 macroelectrons, 122x122 grid size
Review of recent codes benchmarking

- Compare with Head-Tail (CERN) and WARP (LBNL)
  http://conf-ecloud02.web.cern.ch/conf-ecloud02/CodeComparison/modelinst.htm
  (CERN page)

- Head-Tail has been benchmarked with other codes, ex. PEHTS (KEK), with good results.
Review of recent codes benchmarking

- Compare with Head-Tail (CERN) and WARP (LBNL)
  http://conf-ecloud02.web.cern.ch/conf-ecloud02/CodeComparison/modelinst.htm

(CERN page)

1 beam-cloud IP/turn, SPS with cloud density 1e12 m^-3. "New 2006 simulations results"
Codes benchmarking

- Compare with Head-Tail (CERN) and WARP (LBNL)

(CERN page)

![Graph showing fractional vertical emittance growth vs. number of turns with different beam densities.](image)

Upt to 100 beam-cloud IP/turn. LHC with cloud density 1e12 to 1e14 m^-3. 2008 simulations results. **Constant beta function.** Magnetic free region.
Codes benchmarking
SPS simplified lattice

MADX input SPS simplified lattice beam-cloud IP kicks in ~250 dipoles. Synchrotron tune 5.92e-3. Qx' = Qy' = 0.

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>26</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch population</td>
<td>1.15e11</td>
</tr>
<tr>
<td>Synchrotron tune</td>
<td>0.00592</td>
</tr>
<tr>
<td>Emittance (m)</td>
<td>1e-7</td>
</tr>
<tr>
<td>σz</td>
<td>0.24</td>
</tr>
<tr>
<td>dp</td>
<td>0.003887</td>
</tr>
<tr>
<td>α</td>
<td>1.63539</td>
</tr>
<tr>
<td>Qx', Qy'</td>
<td>0</td>
</tr>
</tbody>
</table>

Benchmarking proposed by F. Zimmermann; Simplified lattice by R. Thomas.
Codes benchmarking
SPS simplified lattice

Tracking the beam in the linear lattice and beam-cloud kicks in dipoles only, assume e-cloud in field free regions is cured (no beam-cloud interaction in drift).

[CMAD run 3.5 hours at rate 13 sec/turn on Franklin/NERSC machine with 64 processors]
Codes benchmarking SPS simplified lattice

Tracking the beam in the linear lattice and beam-cloud kicks in dipoles only, assume e-cloud in field free regions is cured (no beam-cloud interaction in drift).

[CMAD run 3.5 hours at rate 13 sec/turn on Franklin/NERSC machine with 64 processors]
Slow emittance growth below threshold.

Simulations indicate that below the instability threshold a slow (< synchrotron period) persistent emittance blow-up takes place.

Emittance growth vs cloud density LHC at injection - from E. Benedetto (CERN thesis), G. Rumolo, F. Zimmermann
ILC DR Structure and layout

- Arcs consist of a total of 192 FODO cells
- Flexibility in tuning momentum compaction factor, given by phase advance per arc cell:
  - 72° phase advance: $\alpha_p = 2.8 \times 10^{-4}$
  - 90° phase advance: $\alpha_p = 1.7 \times 10^{-4}$
  - 100° phase advance: $\alpha_p = 1.3 \times 10^{-4}$
- No changes in dipole strengths needed for different working points.
- Racetrack structure has two similar straights containing:
  - injection and extraction in opposite straights
  - phase trombones
  - circumference chicanes
  - rf cavities
  - "doglegs" to separate wiggler from rf and other systems
  - wiggler
### Major Parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>5 GeV</td>
</tr>
<tr>
<td>Circumference</td>
<td>6476.440 m</td>
</tr>
<tr>
<td>RF frequency</td>
<td>650 MHz</td>
</tr>
<tr>
<td>Harmonic number</td>
<td>14042</td>
</tr>
<tr>
<td>Transverse damping time</td>
<td>21.0 ms</td>
</tr>
<tr>
<td>Natural rms bunch length</td>
<td>6.00 mm</td>
</tr>
<tr>
<td>Natural rms energy spread</td>
<td>1.27×10⁻³</td>
</tr>
</tbody>
</table>

### Phase advance per arc cell (approximate)

<table>
<thead>
<tr>
<th>Angle</th>
<th>72°</th>
<th>90°</th>
<th>100°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momenta compaction factor</td>
<td>2.80×10⁻⁴</td>
<td>1.73×10⁻⁴</td>
<td>1.29×10⁻⁴</td>
</tr>
<tr>
<td>Normalised natural emittance</td>
<td>6.53 μm</td>
<td>4.70 μm</td>
<td>4.27 μm</td>
</tr>
<tr>
<td>RF voltage</td>
<td>31.6 MV</td>
<td>21.1 MV</td>
<td>17.2 MV</td>
</tr>
<tr>
<td>RF acceptance</td>
<td>2.35%</td>
<td>1.99%</td>
<td>1.72%</td>
</tr>
<tr>
<td>Synchrotron tune</td>
<td>0.061</td>
<td>0.038</td>
<td>0.028</td>
</tr>
<tr>
<td>Horizontal tune</td>
<td>64.750</td>
<td>75.200</td>
<td>80.450</td>
</tr>
<tr>
<td>Natural horizontal chromaticity</td>
<td>-76.5</td>
<td>-95.1</td>
<td>-106.9</td>
</tr>
<tr>
<td>Vertical tune</td>
<td>61.400</td>
<td>71.400</td>
<td>75.900</td>
</tr>
<tr>
<td>Natural vertical chromaticity</td>
<td>-75.6</td>
<td>-93.4</td>
<td>-103.5</td>
</tr>
</tbody>
</table>
### Magnet counts and Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arc dipole length</td>
<td>2.00 m</td>
</tr>
<tr>
<td>Arc dipole field</td>
<td>0.273 T</td>
</tr>
<tr>
<td>Number of arc dipoles</td>
<td>192 (1 per arc cell)</td>
</tr>
<tr>
<td>Total number of 2 m dipoles</td>
<td>200</td>
</tr>
<tr>
<td>Total number of 1 m dipoles (in chicanes)</td>
<td>48</td>
</tr>
<tr>
<td>Total number of quadrupoles</td>
<td>690</td>
</tr>
<tr>
<td>Maximum quadrupole gradient</td>
<td>12.0 T/m</td>
</tr>
<tr>
<td>Total number of sextupoles</td>
<td>384</td>
</tr>
<tr>
<td>Maximum sextupole gradient</td>
<td>215 T/m²</td>
</tr>
<tr>
<td>Wiggler peak field</td>
<td>1.6 T</td>
</tr>
<tr>
<td>Wiggler period</td>
<td>0.400 m</td>
</tr>
<tr>
<td>Wiggler unit length</td>
<td>2.45 m</td>
</tr>
<tr>
<td>Wiggler total length</td>
<td>215.6 m</td>
</tr>
</tbody>
</table>
Arc Cell

Arc Cell
ILC Damping Ring (DCO): 90 deg arc cell
Windows NT 4.0 version 8.23 dl

\[ \beta (m) \]

\[ s (m) \]

\[ \beta_x \]

\[ \beta_y \]

\[ D_x \]

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ILC DR flat beams

- To minimize the truncation errors in our simulation with flat beams [1], we select $>>$ more mesh points in the horizontal direction compared to the vertical one so that at least grid size $H_x \sim 10 \ H_y$.
  - Example in case of $\sigma_x/\sigma_y = 150:1$, we use a transv. grid $300\times20$.

Simulations SR camera at injection
DR Simulations

- Tracking the beam and applying beam-cloud kicks everywhere except magnetic-free: assume e-cloud in field free Drift regions is mitigated. Note high synchrotron tune 0.038.
- Horizontal emittance small increase
- In the case 8e11, also beam losses of 40%
Incoherent emittance blow-up below threshold:
Next: include radiation damping and quantum excitations …
Dynamic aperture

- Next to include in simulation: variation of the dynamic aperture with e-cloud density

- 90° phase advance per arc cell.
- Red ellipse shows maximum particle coordinates for injected positron beam.
- Solid black line shows on-energy dynamic aperture.
Summary

- Benchmarking for single-bunch instability codes looks from good to excellent.
- More confirmation of incoherent emittance blow-up below threshold
  - Setting up for longer simulations at lower cloud density
- Instability threshold for ILC DR new lattice is at cloud density about \( \sim 4 \times 8 \times 10^{11} \text{ m}^{-3} \).
- Next: benchmarking CesrTA
- Next to include in simulations: dynamic aperture vs cloud density.
Special Thank to Frank Zimmermann; K. Sonnad, J-L. Vay, T. Raubenheimer, M. Furman, A. Kabel, G. Rumolo, NERSC computing and consulting (!), K. Ohmi, A. Wolski et many other colleagues...
\[ y = 39261x + 0.5972 \]
\[ R^2 = 0.9872 \]

\[ y = 42162x + 0.1597 \]
\[ R^2 = 0.9881 \]
LC DR flat beam

- In case of very flat beams, the discretized Poisson equation:

\[
\frac{\phi_{i-1,j} + \phi_{i+1,j} - 2\phi_{i,j}}{H_x^2} + \frac{\phi_{i,j-1} + \phi_{i,j+1} - 2\phi_{i,j}}{H_y^2} = -2\pi \rho_{ci,j}
\]

- The truncation errors are of the order of $H_x^2$ and $H_y^2$. If we use the same number of mesh points per $\sigma$ in both directions, in case of very flat beams, the truncation errors in the $H_x$ horizontal direction completely dominates [1].

- To minimize the errors in our simulation with flat beams, we select $>>$ more mesh points in the horizontal direction compared to the vertical one so that at least $H_x \sim 10 \, H_y$.

  - Example in case of $\sigma_x/\sigma_y = 150:1$, we use $300 \times 20$ grid.

ILC DR synchrotron oscillations

Synchrotron tune 0.038
Slicing the beam

- Bunch sliced either uniformly in $z$, or with each slice containing same number of macroparticles, preferred for processors load balance. The methods should coincide in the limit slices $\gg 1$. Main difference with other codes, in the following simulations.