I. Electron-Cloud Investigations (11.11.99)
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II. Electron-Cloud Simulations (18.11.99)
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web page: http://wwwslap.cern.ch/collective/
Electron-Cloud Simulations

(1) Introduction

(2) Model

– primary electrons, secondaries, space charge

(3) Results

– LHC, arcs & straights, SPS
– cloud-build up, heat load, instabilities, cures?

(4) Conclusions

(1) Introduction

Schematic of electron-cloud build up in the LHC beam pipe.
Brief History

- **1977** beam-induced multipacting observed with Al chamber in ISR → *pressure rise*
- in **1980s** some concern for LHC
- **1989** electron cloud effect at KEK photon factory → *increased vertical beam size, coupled oscillation, low threshold current, broad distributions of sidebands; clearing gap does not help*
- **1996** experiments at BEPC (IHEP-KEK collaboration)
- **1997** crash programs for PEP-II (*simulations, TiN coating,...*) and LHC
- **1998–99** electron cloud in the SPS
Primary Electrons

*LHC*: photoemission from synchrotron radiation

\[
N_\gamma = \frac{5}{2\sqrt{3}} \alpha_\gamma \frac{\text{photons}}{\text{radian}} \quad \text{or} \quad 0.025 \frac{\text{photons}}{\text{proton meter}}
\]

critical photon energy: \( E_c \sim 45\ \text{eV} \)

Measured photoemission yields for aluminum vs. photon energy.
Reflectivity

Electron yield per absorbed photon is $Y^* = Y/(1 - R) \sim 0.05$ with $Y$ the photoelectron yield per incident photon and $R$ photon reflectivity. Hence, for the LHC we estimate

$$ \frac{d\lambda_e}{ds} \approx 10^{-3} \text{ photo - electrons per proton meter} $$

**SPS: ionization of the residual gas**

$$ \frac{d\lambda_e}{ds} = \frac{p}{k_B T} \sigma_{ion} \approx 6 \ p [\text{Torr}] \text{ electrons per proton meter} < 10^{-7} \text{ electrons per proton meter} $$
<table>
<thead>
<tr>
<th>parameter</th>
<th>symbol</th>
<th>LHC</th>
<th>SPS</th>
</tr>
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<tbody>
<tr>
<td>beam energy</td>
<td>$E$</td>
<td>7000 GeV</td>
<td>26 GeV</td>
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<tr>
<td>bunch population</td>
<td>$N_b$</td>
<td>$1.05 \times 10^{11}$</td>
<td>$\sim 4 \times 10^{10}$</td>
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<td>rms beam sizes</td>
<td>$\sigma_{x,y}$</td>
<td>303 $\mu$m</td>
<td>1.5, 1.0 mm</td>
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<td>rms bunch length</td>
<td>$\sigma_z$</td>
<td>7.7 cm</td>
<td>30 cm</td>
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<tr>
<td>bunch spacing</td>
<td>$L_{sep}$</td>
<td>7.48 m</td>
<td>7.48 m</td>
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<tr>
<td>vacuum chamber 1/2 height</td>
<td>$h_y$</td>
<td>18 mm</td>
<td>22.5 mm</td>
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<tr>
<td>vacuum chamber 1/2 width</td>
<td>$h_x$</td>
<td>22 mm</td>
<td>70 mm</td>
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<tr>
<td>max. secondary emission yield</td>
<td>$\delta_{\text{max}}$</td>
<td>1.0–2.3</td>
<td>$\leq$ 2.0</td>
</tr>
<tr>
<td>photon reflectivity</td>
<td>$R$</td>
<td>2–10%</td>
<td>—</td>
</tr>
<tr>
<td>photo-electron yield</td>
<td>$Y^*$</td>
<td>0.025–0.05</td>
<td>—</td>
</tr>
<tr>
<td>primary yield/meter/proton</td>
<td>$d\lambda_e/ds$</td>
<td>$\sim 10^{-3}$ m$^{-1}$</td>
<td>$10^{-7}$ m$^{-1}$</td>
</tr>
</tbody>
</table>
Simulation recipe:  

(2) Model

- represent electrons by macro-particles (2000/bunch), split bunches and interbunch gaps into slices
- for each bunch slice, create photoelectrons and accelerate existing electrons
- if $e$ hit the wall → secondary electron; change charge of macro-particle
- at each gap slice the electrons are propagated in the magnetic field; kicks due to electron space-charge and image charges
- energy of lost electrons → heat load; force on bunch behind a displaced bunch → wakefield
Solid line describes the actual cross section of the beam screen. Sometimes we approximate it by the inscribed ellipse, *e.g.*, for accurate modeling of image charges.
Initial photoelectron distribution. Left: azimuthal density for 10% and 100% photon reflectivity. Unreflected photons are limited to an outward cone of rms angle $11.25^\circ$. Right: energy distribution at moment of emission (Gaussian with peak at 7 eV and rms value 5 eV) and after bunch passage. The bunch imparts a maximum momentum of $E_{max} = 2m_0c^2 \left( N_br_e/b \right)^2 \approx 200eV$. Random emission angles $\phi$ and $\theta$ ($\theta > \pi/2$).
Electron Motion

simulations can be performed for

- drift space
- strong dipole field: only vertical motion, vertical kick from passing bunch, horizontal kick averages to zero due to large number of cyclotron oscillations/bunch

\[ \frac{eBc}{m_e c^2} \frac{2\sigma_z}{2\pi} \approx 120 \]

- quadrupole, or arbitrary field
  Runge-Kutta integration, implemented by O. Brüning

- wire and coaxial chambers for multipacting tests (O. Brüning)
The electrons spiral in the 8.4-T field with a typical radius \( \rho = p/(eB) \) of 6\( \mu \)m for 200 eV, and 26\( \mu \)m for 4 keV. A net vertical kick is applied; the \( E \times B \) longitudinal drift is ignored.
Depending on its initial position when a bunch passes by, an electron may either receive a single kick or perform many oscillations in the bunch potential.
Maximum energy gain vs. initial particle radius for nominal LHC parameters (S. Berg). Autonomous and kick regions.
Secondary emission yield vs. primary electron energy $E_p$, for \( \delta_{\text{max}} = 1.6 \) and \( E_{\text{max}} = 300 \text{ eV} \). Left: with and without elastic reflection. Right: for two different angles of incidence.

$$\delta_{se}(E_p, \theta) = \delta_{\text{max}} \times 1.11 \times x^{-0.35} \frac{1 - e^{-2.3x^{1.35}}}{\cos \theta}$$

with $\theta$ the angle of incidence w.r.t. surface normal and $x = E_p / E_{\text{max}}$. Additional yield from elastic reflections:

$$\delta_e = \delta_{e,\infty} + (\hat{\delta}_e - \delta_{e,\infty}) \exp \left( \frac{-(E - E_e)^2}{2\Delta^2} \right)$$

with $\hat{\delta}_e = 0.1$, $\delta_{e,\infty} = 0.02$ and $\Delta = 5$ eV.
Initial distribution of secondary electrons. Left: density vs. energy. Right: density $dN/d\theta$ vs. polar angle $\theta$ w.r.t. surface normal, assuming $dN/d\Omega = \cos \theta$. 
**Beam Field and Image Charges**

Electric field pattern for a beam centered in an elliptical chamber with [left] and without [right] image charges. Field (M. Furman):

\[
\mathcal{E} \approx \frac{2}{\bar{z} - \bar{z}_0} + \frac{4}{g} \sum_{n=1}^{8} e^{-n\mu_c} \left[ \frac{\cosh n\mu_0 \cos n\phi_0}{\cosh n\mu_c} + i \frac{\sinh n\mu_0 \sin n\phi_0}{\sinh n\mu_c} \right] \frac{\sinh n\bar{q}}{\sinh \bar{q}}
\]

where \( z = x + iy = g \cosh q = g \cosh (\mu + i\phi) \) test position, \( z_0 = x_0 + iy_0 = gcoshq_0 = gcosh(\mu_0 + i\phi_0) \) source, \( g = \sqrt{a^2 - b^2}, \mu_c = \tanh^{-1}(b/a) \).

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Electron-Cloud Simulations
Horizontal (left) and vertical average electric beam field vs. horizontal position, for an elliptical chamber with $22 \times 10$ mm half apertures, and a beam offset of $+4.3$ mm in both transverse planes.
Horizontal electric space-charge field of electron cloud vs. horizontal position after 8 bunches. Parameters: \( \delta_{\text{max}} = 2.0, Y_{pe} = 0.2, R = 10\%, \epsilon_{\text{max}} = 300 \text{ eV} \).
(3) Results

- electron cloud build-up
- electron charge distributions
- heat load in dipoles, drifts, quadrupoles
- instability rise time
- reliefs and cures
## Simulated LHC heat loads

<table>
<thead>
<tr>
<th>Magnet Type</th>
<th>Initial (mW/m)</th>
<th>Final (mW/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>arc dipole</td>
<td>5000</td>
<td>42</td>
</tr>
<tr>
<td>D1 dipole*, 1 beam</td>
<td>2020</td>
<td>15</td>
</tr>
<tr>
<td>2 beams</td>
<td>7580</td>
<td>90</td>
</tr>
<tr>
<td>triplet quadrupole*, 1 beam</td>
<td>14</td>
<td>6</td>
</tr>
<tr>
<td>2 beams</td>
<td>32</td>
<td>14</td>
</tr>
<tr>
<td>drift with 3 cm aperture*, 1 beam</td>
<td>7500</td>
<td>460</td>
</tr>
<tr>
<td>2 beams</td>
<td>&gt;16000</td>
<td>630</td>
</tr>
</tbody>
</table>

*with transverse offsets of 4–5 millimeters.
## Parameters

<table>
<thead>
<tr>
<th>variable</th>
<th>LHC initial</th>
<th>LHC final</th>
<th>SPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta_{max}$</td>
<td>2.3</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>$\epsilon_{max}$</td>
<td>300 eV</td>
<td>450 eV</td>
<td></td>
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<tr>
<td>$d\lambda_e/ds$</td>
<td>$1.4 \times 10^{-3} \text{ m}^{-1}$</td>
<td>$7 \times 10^{-4} \text{ m}^{-1}$</td>
<td>$10^{-7} \text{ m}^{-1}$</td>
</tr>
<tr>
<td>$Y$</td>
<td>0.05</td>
<td>0.025</td>
<td></td>
</tr>
<tr>
<td>$N_b$</td>
<td>$1.05 \times 10^{11}$</td>
<td>$1.05 \times 10^{11}$</td>
<td>$4 \times 10^{10}$</td>
</tr>
</tbody>
</table>
Electron charge per meter in an LHC dipole chamber vs. time along bunch train, comparing $\delta_{\text{max}} = 1.1$ and $\delta_{\text{max}} = 1.3$. Other parameters: $\epsilon_{\text{max}} = 450$ eV, $R = 0.1$, and $Y^* = 0.025$. 

$Y_{\text{pe}} = 0.025$, 10% refl.
Electron charge per meter in an LHC dipole chamber vs. time along bunch train for large secondary emission yield $\delta_{\text{max}} = 2.3$. Build-up saturates due to electron-cloud space charge. Other parameters: $\epsilon_{\text{max}} = 300$ eV, $R = 0.1$, $Y^* = 0.05$. 
Snap shot of transverse electron cloud distribution in an LHC dipole chamber after 60 bunches. Parameters: \( \delta_{\text{max}} = 1.1 \), \( \epsilon_{\text{max}} = 450 \) eV, \( R = 0.1 \), and \( Y^{*} = 0.025 \).
Snap shot of transverse electron cloud distribution in an LHC dipole chamber after 60 bunches with the design current. Vertical stripes indicate regions with large secondary emission. Parameters: $\delta_{\text{max}} = 1.3$, $\epsilon_{\text{max}} = 450$ eV, $R = 0.1$, and $Y^* = 0.025$. 

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Snap shot of transverse electron cloud distribution in an LHC dipole chamber after 40 bunches with half the design current per bunch. Vertical stripe indicates region with large secondary emission. Parameters: $\delta_{\text{max}} = 1.7$, $\epsilon_{\text{max}} = 300$ eV, $R = 1.0$, and $Y^* = 1.0$. 

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Electron-Cloud Simulations
Projected horizontal electron charge density after 60 bunches in an LHC dipole chamber. Vertical peaks correspond to regions with large secondary emission. Parameters: $\delta_{\text{max}} = 1.3$, $\epsilon_{\text{max}} = 450$ eV, $R = 0.1$, $Y^* = 0.025$, and 500 bins.
Heat load from incident electrons is a concern

- *LHC cryogenics system designed for maximum beam-screen heat load of 1 W/m*
- resistive heating by beam: 0.2 W/m
- synchrotron radiation: 0.2 W/m
- \( \rightarrow \) *heat load from electron cloud must be smaller than 0.6 W/m*
Azimuthal distribution of heat load in units of W per m$^2$ for an LHC dipole chamber. Parameters: $\delta_{\text{max}} = 1.3$, $\epsilon_{\text{max}} = 450$ eV, $R = 0.1$, $Y^* = 0.025$, and 500 bins.
Instantaneous heat load in W/m vs. bunch number for LHC dipole chamber. Parameters: $\epsilon_{\text{max}} = 450$ eV, $R = 0.1$, and $Y^* = 0.025$. 
Heat load in LHC dipole chamber vs. maximum secondary emission yield $\delta_{\text{max}}$. Parameters: $\epsilon_{\text{max}} = 450$ eV, $R = 0.1$, and $Y^* = 0.025$. The curve changes slope near the critical yield $\delta_{\text{max}} \approx 1.3$. 
Critical Yield and Beam Pipe Radius

Critical yield as a function of round-chamber radius in a dipole field. Left: numerical evaluation of Stupakov’s equation

\[
\delta_{\text{max}} > \delta_{\text{crit}}(x) = \left( \int_{-a}^{a} dy \ h(W(x, y)) \frac{a}{y_0(x)} \frac{n_e(x, y, t_{sep})}{n_0(x)} \right)^{-1},
\]

for \( x = 0 \). Right: simulation for nominal bunch spacing.
$e^-$ cloud build-up in the SPS for $N_b = 5 \times 10^{10}$. The colors refer to different values of the maximum secondary emission yield $\delta_{\text{max}}$. Charge build-up already for $\delta_{\text{max}} = 1.3$. 

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Electron-Cloud Simulations
$e^-$ cloud build-up in the SPS for 4 different bunch populations and $\delta_{\text{max}} = 1.9$. The growth saturates for a few $10^9$/m electron charge.
$\delta_{\text{max}}=1.9$, $\varepsilon_{\text{max}}=300\ \text{eV}$, $Y_{\text{pe}}=2.5\times10^{-7}/\text{m}$

$e^-$ cloud build-up in the SPS for 4 different bunch populations and $\delta_{\text{max}}=1.9$. The growth saturates for a few $10^9/\text{m}$ electron charge.
How large is the actual $e^-$ cloud in the SPS?

(1) from pressure rise [O. Gröbner]:
pressure balance reads $S_{\text{eff}}P/(k_BT) = Q$, where $S_{\text{eff}}$
pumping speed in volume per meter per second, $Q = \alpha \dot{\lambda}_e$
total flux of molecules per unit length ($\alpha$: desorption yield
per electron) and $P = k_BT N/V$.

$$\frac{d\lambda_e}{ds} = \frac{T_{\text{rev}}}{\alpha k_BT} S_{\text{eff}}P$$

With $P = 100$ nTorr, $\alpha \approx 0.1$ and $S_{\text{eff}} \approx 20$ l s$^{-1}$ m$^{-1}$:

$$\frac{d\lambda_e}{ds} \approx 10^{10} \frac{\text{electrons}}{\text{bunch} - \text{train} \text{ meter}}$$
(2) from damper pick-up measurements [W. Hoefle]: a few $10^8$ electrons per bunch passage are deposited on the pick-up; this amounts to $10^9 - 10^{10}$ per train, or, with an effective pick-up length of about 10 cm,

$$\frac{d\lambda_e}{ds} \approx 10^{10} \frac{\text{electrons}}{\text{bunch - train meter}}$$

The two estimates are consistent.
Effective wake and instability

electron cloud can couple motion of subsequent bunches → instability

- after stationary cloud is established, displace 1 bunch transversely by $\Delta x$ or $\Delta y$

- calculate kick that the disturbed $e^{-}$ exerts on the next bunch → short-range dipole wake field $W_1(L_{sep})$

\[
W_1(L_{sep}) = \sum_i \frac{2y_i Q_i}{N_b r_i^2(\Delta y)} \left( 1 - \exp \left( -\frac{r_i^2}{2\sigma^2} \right) \right) \frac{C}{l_b}
\]

where $r_i = (x_i^2 + y_i^2)^{1/2}$, $l_b$ simulated length of bending magnet, and $Q_i$ charge of $i$th macro-electron.
Projected horizontal electron charge density in an LHC bending magnet after about 40 bunches; left: before the 41st bunch is horizontally displaced by 1 cm; bottom: just prior to the arrival of the 42nd bunch. The horizontal axis is in units of meters; the vertical coordinate is the charge (in units of $e$) per bin and per grid point. Parameters: 500 grid points, $\delta_{\text{max}} = 1.7$, $R = 1$, $Y^* = 1$. 

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Electron-Cloud Simulations
• assume uniformly filled ring with $M$ bunches and a short-range wake

$\rightarrow$ complex frequency shift of $\mu$th mode is (see Alex Chao's book)

$$\Omega^{(\mu)}_{y}(x) - \omega_{\beta,y}(x) = \frac{N_{b}r_{p}c^{2}}{2\gamma C \omega_{\beta}} W_{1,y}(x) e^{i2\pi(\mu+Q_{y}(x))/M}$$

and shortest rise time

$$\tau \approx \frac{4\pi \gamma Q_{y}(x)}{N_{b}r_{p}c W_{1,y}(x)}$$

• with clearing gaps growth is not exponential but

$$y_{n} \sim \frac{1}{n!} (t/\tau)^{n} \hat{y}_{0}$$

for $n$th bunch in a train; $\tau$ is the same as above
Rise time estimates

in 1997 we found for an LHC dipole chamber with $\delta_{\text{max}} = 1.5$, $R = 1$, $Y^* = 1$, $\epsilon_{\text{max}} = 300$ eV:

$$W_{1,x} \approx 2.5 \times 10^6 \text{ m}^{-2}$$

$$W_{1,y} \approx 3.0 \times 10^5 \text{ m}^{-2}$$

translating into the rise times

$$\tau_x \approx 50 \text{ ms}, \quad \text{and} \quad \tau_y \approx 400 \text{ ms}$$

Much larger $\tau$’s for ‘final’ LHC parameters:

$$\tau_x \approx 450 \text{ s}, \quad \text{for} \quad \delta_{\text{max}} = 1.1$$
**Summarizing...**

- electron cloud effects depend on properties of vacuum chamber: \( \delta_{\text{max}}, R, Y_{pe}, \epsilon_{\text{max}} \)
- final \( \delta_{\text{max}} \) should be smaller than critical yield \( \delta_{\text{crit}} \approx 1.3 \)
- heat load is largest in field-free regions
- SPS observations consistent with electron cloud
- simulations reproduce multipacting studies
Challenge:

going from initial to final LHC parameters

surface cleaning by electron bombardment (N. Hilleret): \( \delta_{\text{max}} = 2.4 \rightarrow 1.2 \) for electron dose of 1 mC/mm\(^2\)

Constant heat load of 200 mW/m & average e energy of 200 eV → only 35 hours scrubbing time (C. Benvenuti).
Possibilities:

- lower beam energy \( (n_\gamma \text{ and } E_c \text{ drop}) \)
- reduced bunch charge (heat load \( \propto N_b^3 \))
- increased bunch spacing
- solenoid fields (10 G) for field-free regions
- clearing electrodes (10 V)
- satellite bunches, fill patterns, gaps in bunch trains
Gaps in the Bunch Train

Suppression of charge build-up by gaps in the bunch train; here a gap of 4 missing bunches after every 8 bunches.
# Heat load reduction in LHC dipole

<table>
<thead>
<tr>
<th>$\delta_{\text{max}}$</th>
<th>regular fill</th>
<th>six gaps per train</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>41 mW/m</td>
<td>16 mW/m</td>
</tr>
<tr>
<td>1.3</td>
<td>222 mW/m</td>
<td>26 mW/m</td>
</tr>
<tr>
<td>1.5</td>
<td>564 mW/m</td>
<td>60 mW/m</td>
</tr>
<tr>
<td>2.3</td>
<td>5000 mW/m</td>
<td>890 mW/m</td>
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