Electron-Cloud Simulations for SPS and LHC

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(1) Introduction

(2) Model

- primary electrons, secondaries, space charge

(3) Results

- LHC and SPS
- cloud-build up, heat load, instabilities, cures?

(4) Conclusions

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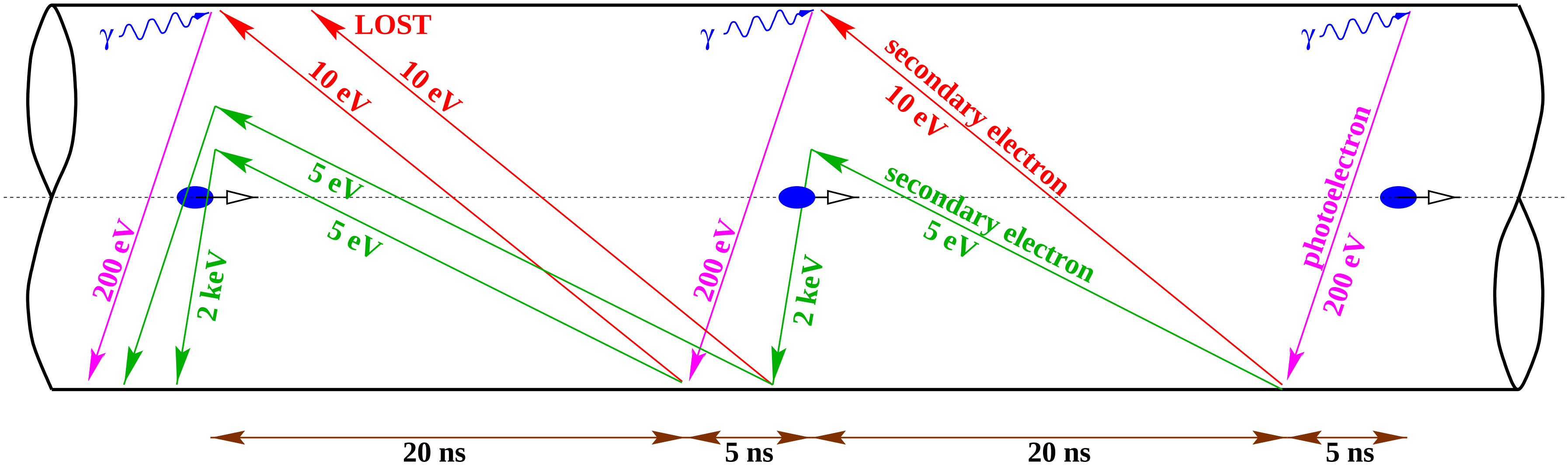
web page: *http://wwwslap.cern.ch/collective/*

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, 1999 KEKB

(1) Introduction



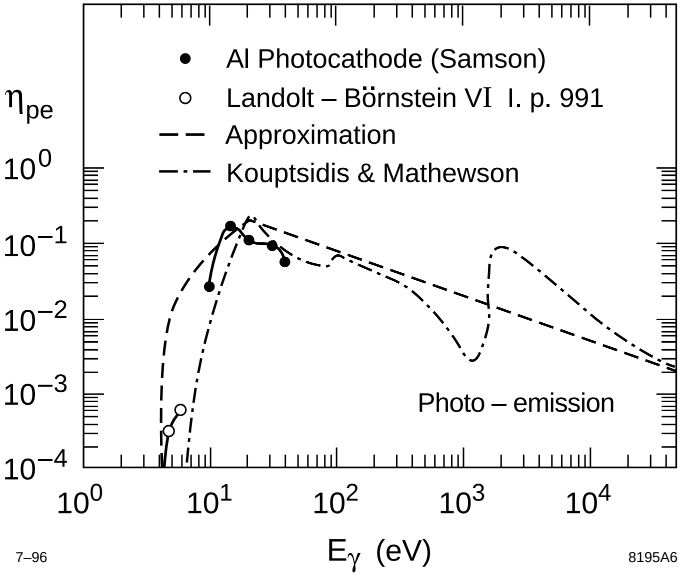
Schematic of electron-cloud build up in the LHC beam pipe.

Primary Electrons

LHC: photoemission from synchrotron radiation

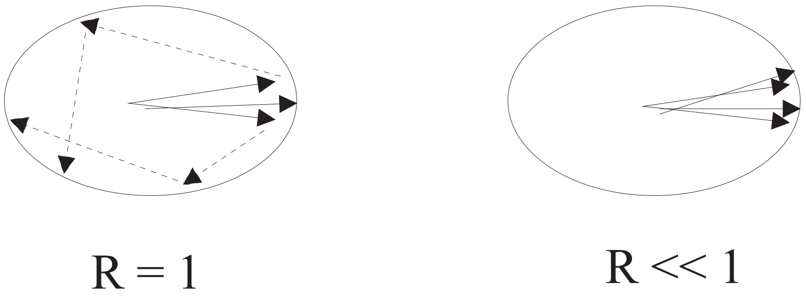
$$N\gamma = \frac{5}{2\sqrt{3}}\alpha\gamma \; \frac{\text{photons}}{\text{radian}} \quad \text{or} \quad 0.025\; \frac{\text{photons}}{\text{proton meter}}$$

critical photon energy: $E_c \sim 45$ 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

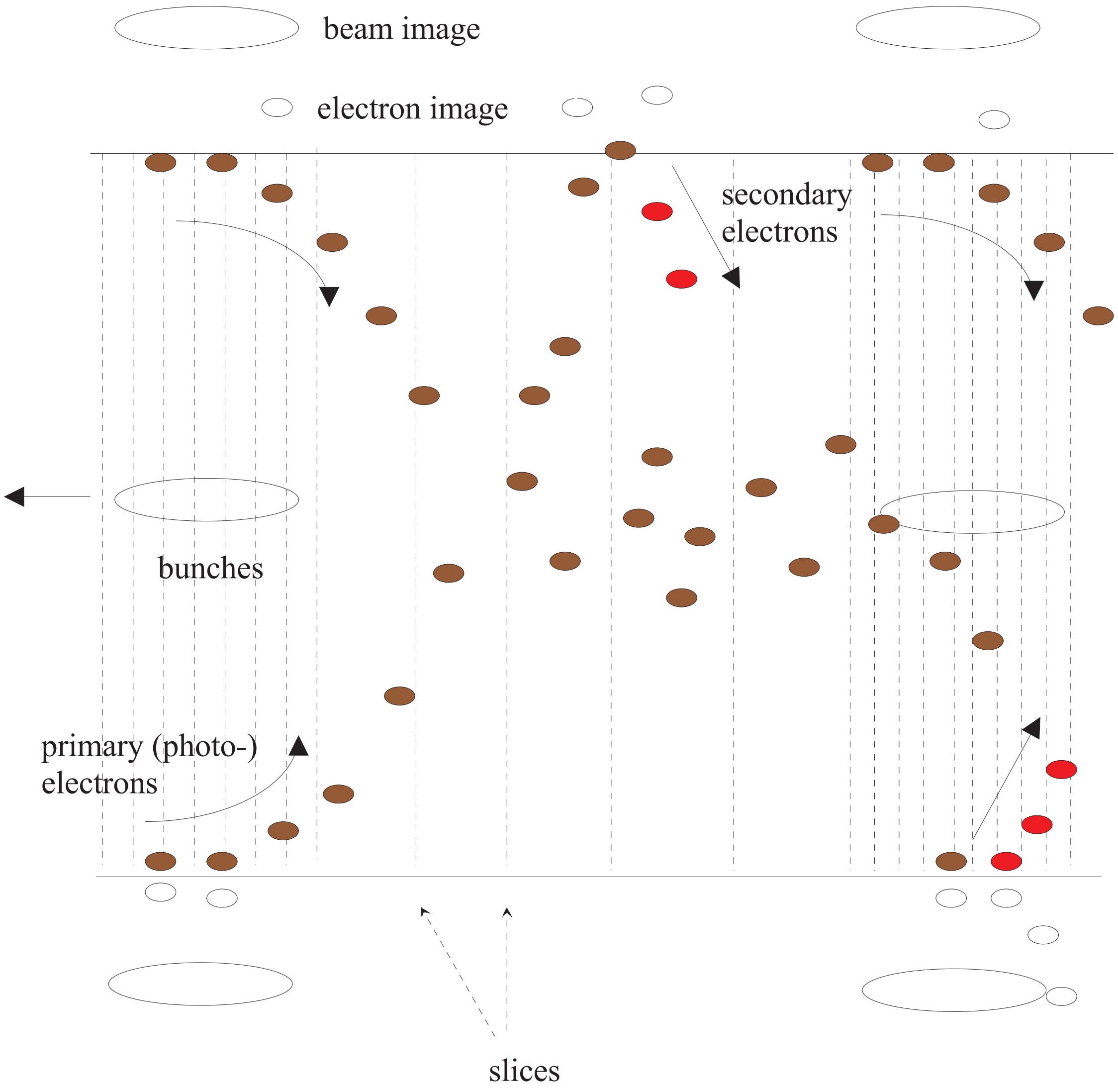
$$\frac{d\lambda_e}{ds} \approx 10^{-3}\ \frac{\text{photo}-\text{electrons}}{\text{proton meter}}$$

SPS: ionization of the residual gas

$$\frac{d\lambda_e}{ds} = \frac{p}{k_B T}\sigma_{ion} \approx 6\ p[\text{Torr}]\ \frac{\text{electrons}}{\text{proton meter}} < 10^{-7}\frac{\text{electrons}}{\text{proton meter}}$$

parameter	symbol	LHC	SPS
beam energy	E	7000 GeV	26 GeV
bunch population	N_b	1.05×10^{11}	$\sim 4 \times 10^{10}$
rms beam sizes	$\sigma_{x,y}$	303 μm	1.5, 1.0 mm
rms bunch length	σ_z	7.7 cm	30 cm
bunch spacing	L_{sep}	7.48 m	7.48 m
vacuum chamber 1/2 height	h_y	18 mm	22.5 mm
vacuum chamber 1/2 width	h_x	22 mm	70 mm
max. secondary emission yield	$\delta_{\max}$	1.0–2.3	≤ 2.0
photon reflectivity	R	2–10%	—
photo-electron yield	Y^*	0.025–0.05	—
primary yield/meter/proton	$d\lambda_e/ds$	$\sim 10^{-3}$ m^{-1}	10^{-7} m^{-1}

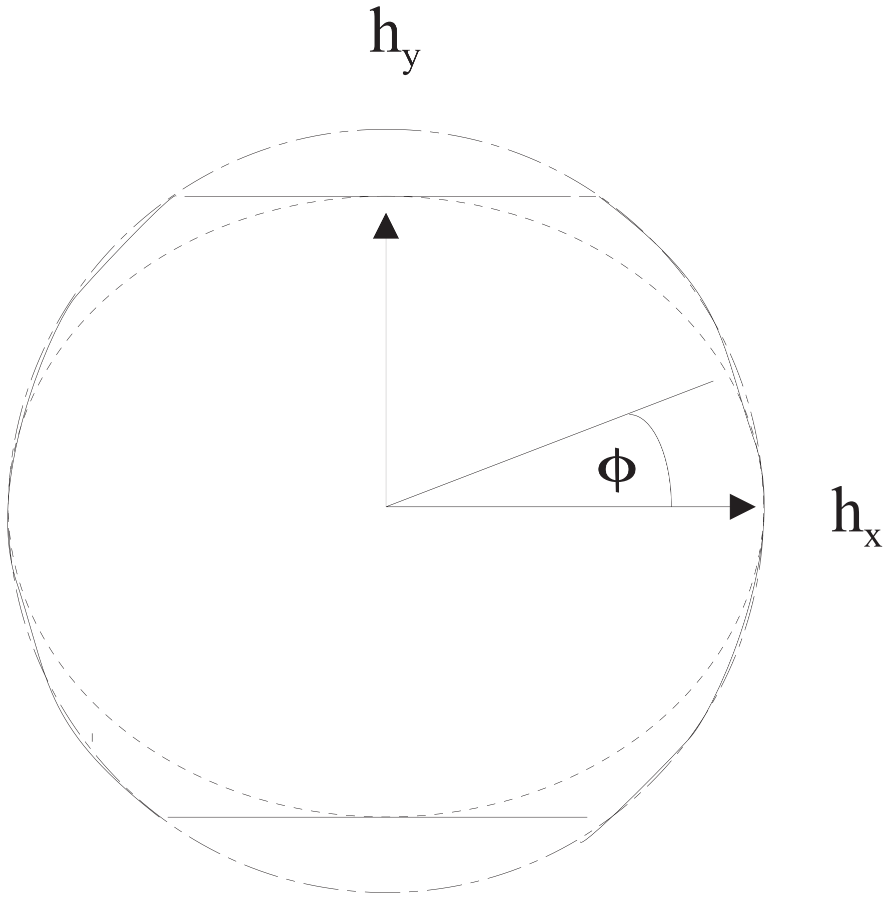
(2) Model


beam image
electron image
secondary electrons
bunches
primary (photo-) electrons
slices

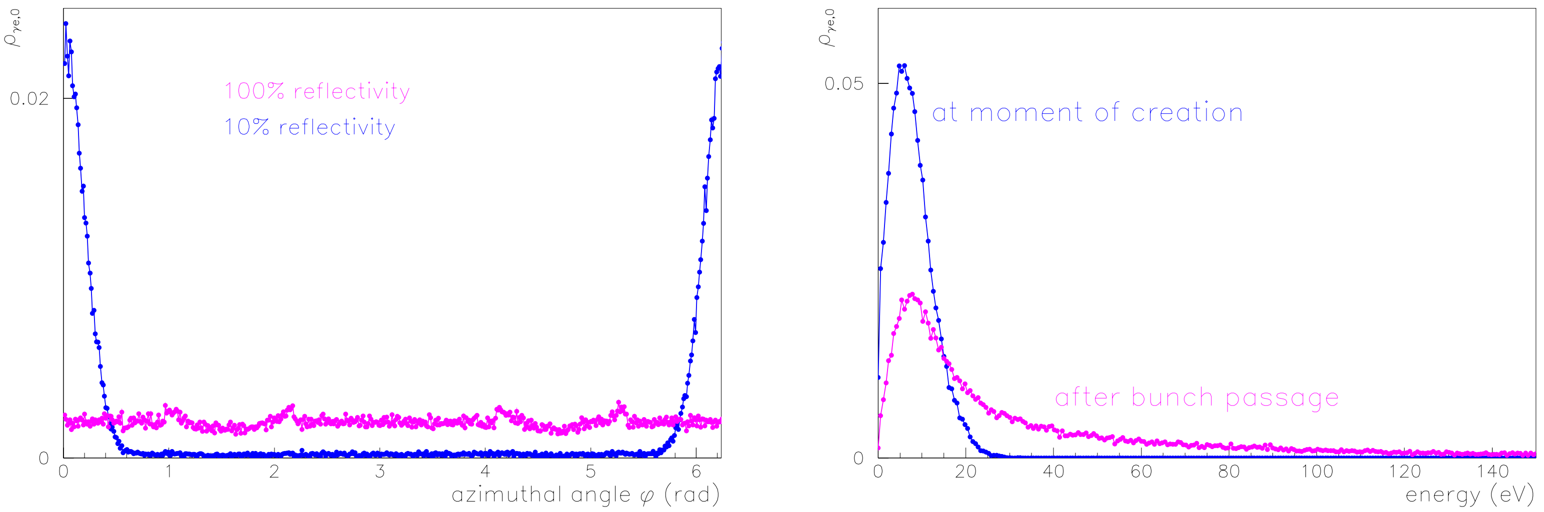
Simulation recipe:

- represent e^- by macro-particles (2000/bunch), split bunches and interbunch gaps into slices
- for each bunch slice, create photoelectrons and accelerate existing e^- in beam and beam-image fields
- if e^- hit the wall → secondary e^-; change macro charge
- at each gap slice the e^- are propagated in the magnetic field; kicks from e^- space-charge and e^- image charges

- energy of lost e^- → heat load
- e^- cloud density → single-bunch wakefield
- force on bunch behind a displaced bunch → multibunch 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°. 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 $E_{max} = 2m_0c^2\ (N_b r_e/b)^2 \approx 200eV$. Random emission angles ϕ and θ ($\theta > \pi/2$).

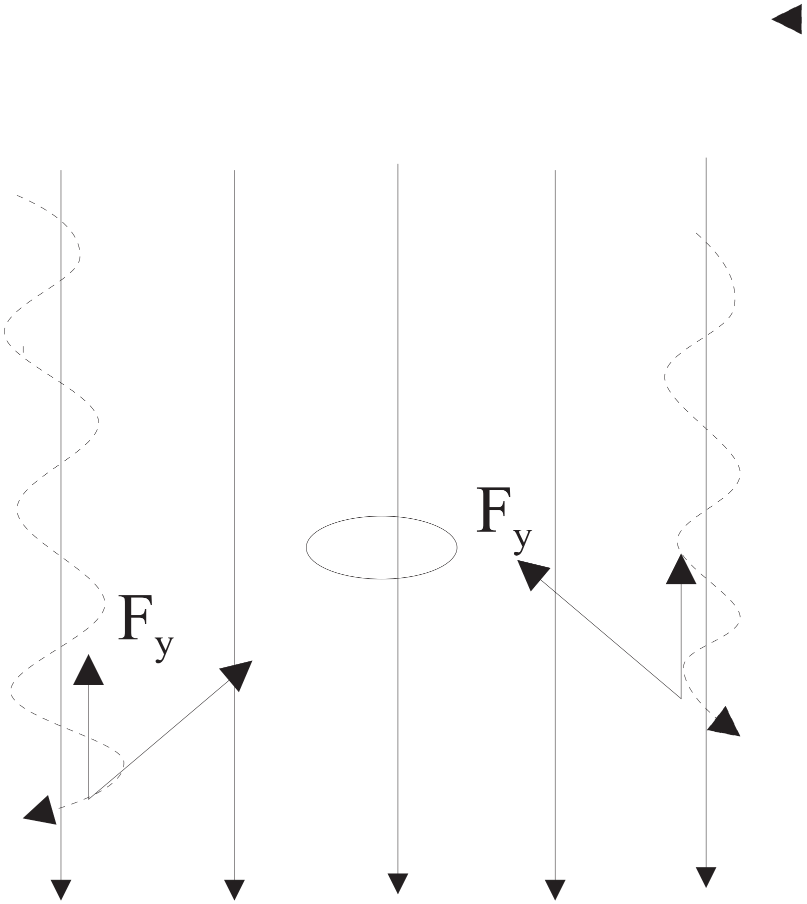
Electron Motion

simulations can be performed for

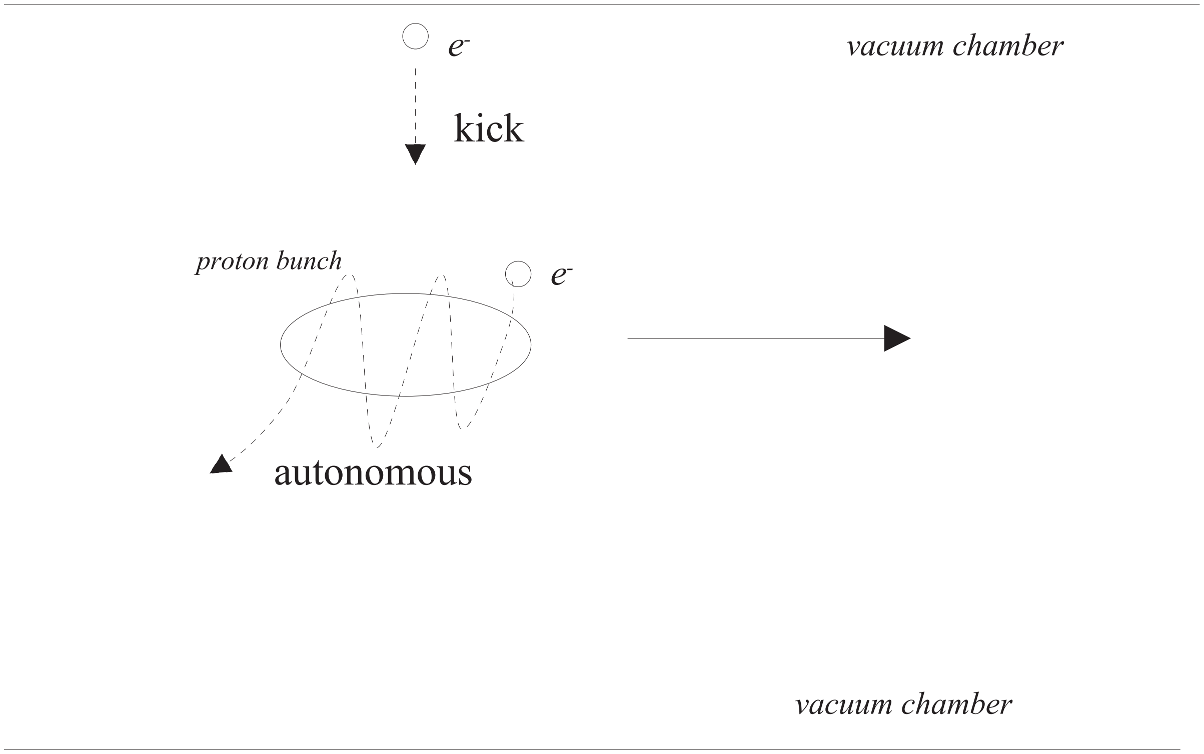
- drift space
- strong dipole field: only vertical motion, vertical kick from passing bunch, horizontal kick averages to zero due to large number of cyclotron oscillations/bunch

$$\frac{eBc}{m_e c^2}\frac{2\sigma_z}{2\pi} \approx 120 \text{ (LHC)},\ 12 \text{ (SPS at 26 GeV)}$$

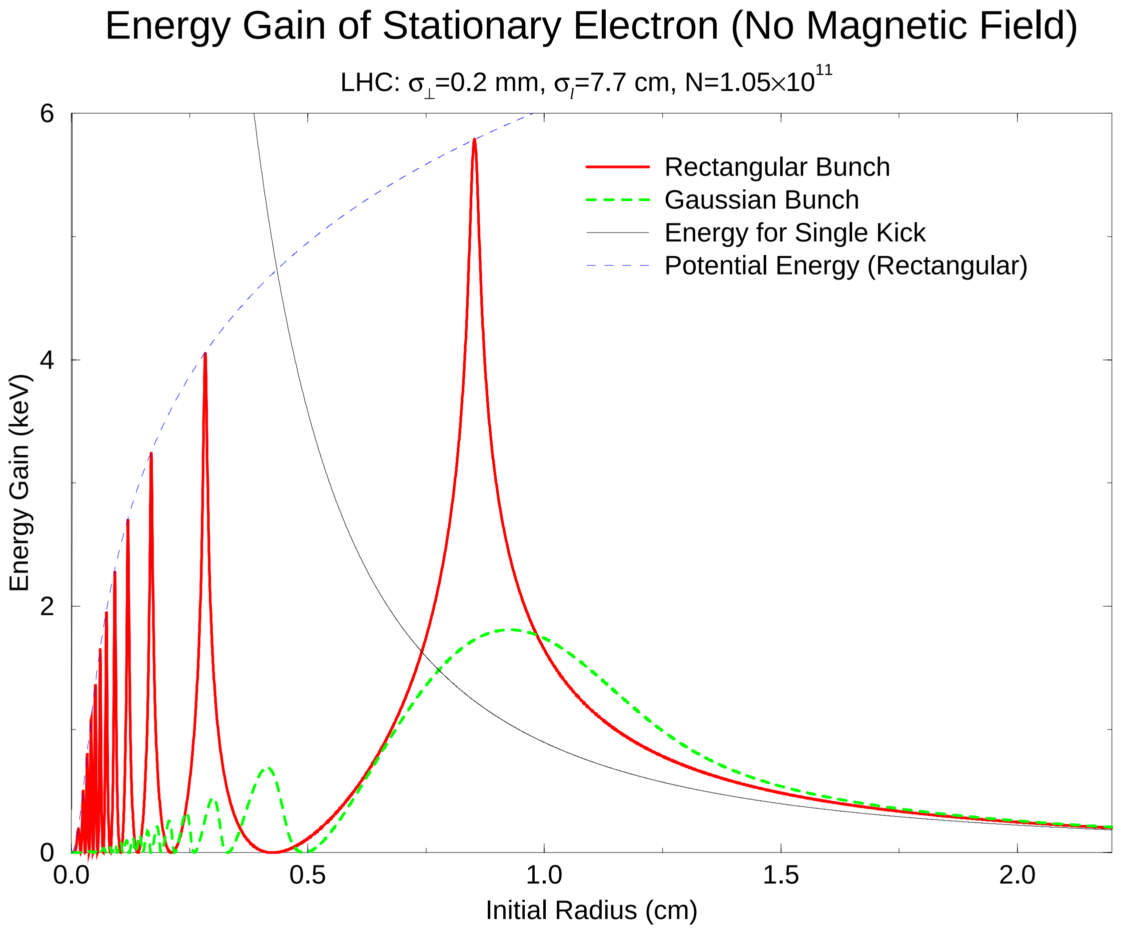
- weak dipole & solenoid fields
- quadrupole, or arbitrary field (Runge-Kutta, O. Brüning)



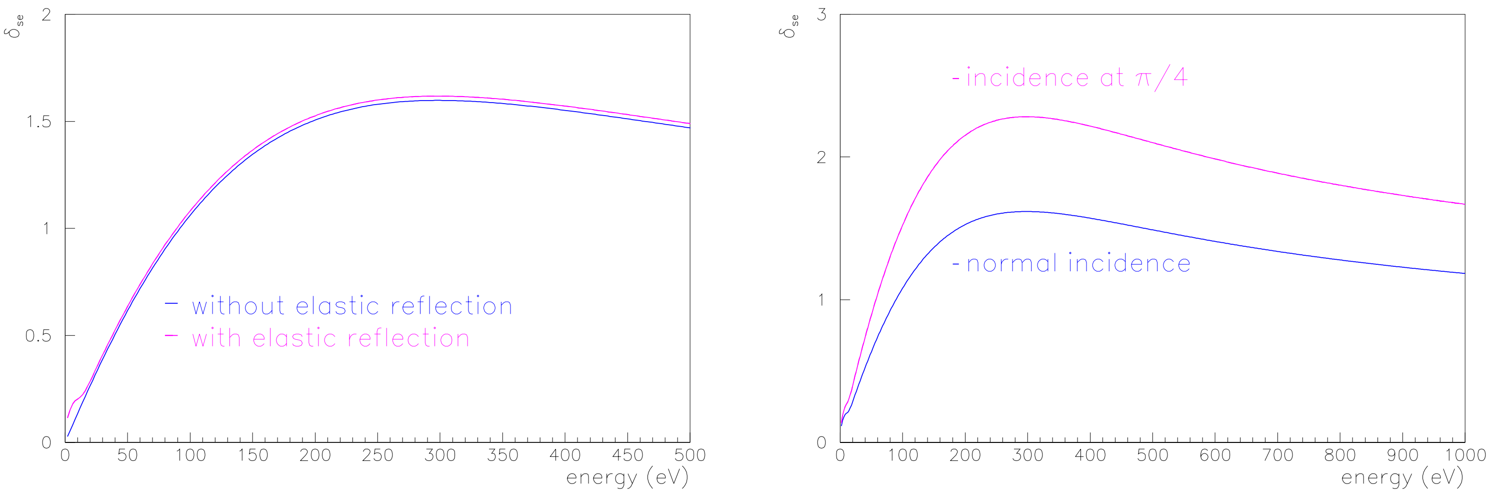
The electrons spiral in the 8.4-T field with a typical radius $\rho = p/(eB)$ of 6μm for 200 eV, and 26μm for 4 keV. A net vertical kick is applied; the $E \times B$ longitudinal drift is ignored.



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 $\delta_{\rm max} = 1.6$ and $E_{\rm max} = 300$ eV. Left: with and without elastic reflection. Right: for two different angles of incidence.

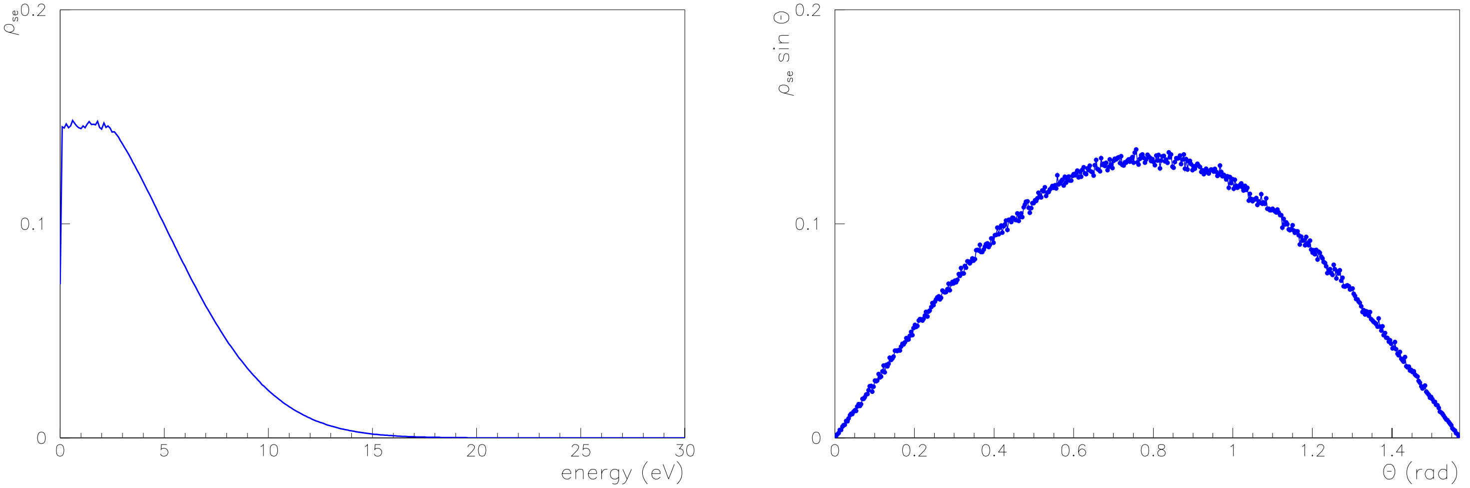
Analytical expression for secondary emission yield [H. Seiler, J. Appl. Phys. 54 (11) (1983)]:

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

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

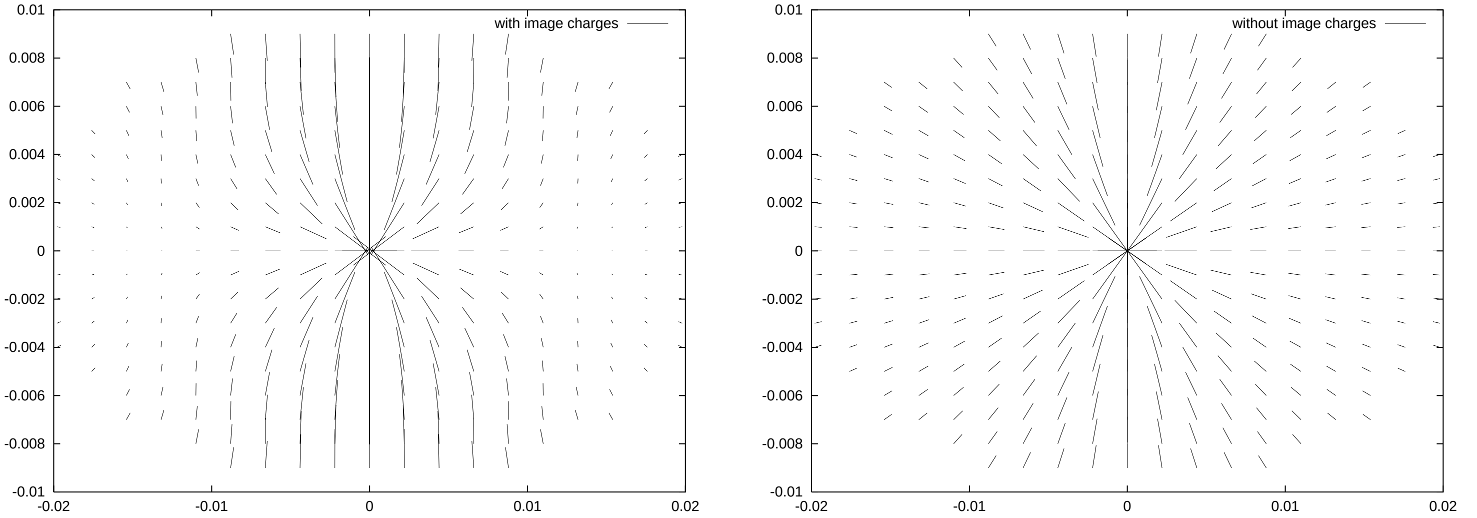
$$\delta_e = \delta_{e,\infty} + (\hat{\delta}_e - \delta_{e,\infty})\ \exp\left(\frac{-(E-E_e)^2}{2\Delta^2}\right)$$

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 θ w.r.t. surface normal, assuming $dN/d\Omega = \cos\theta$.

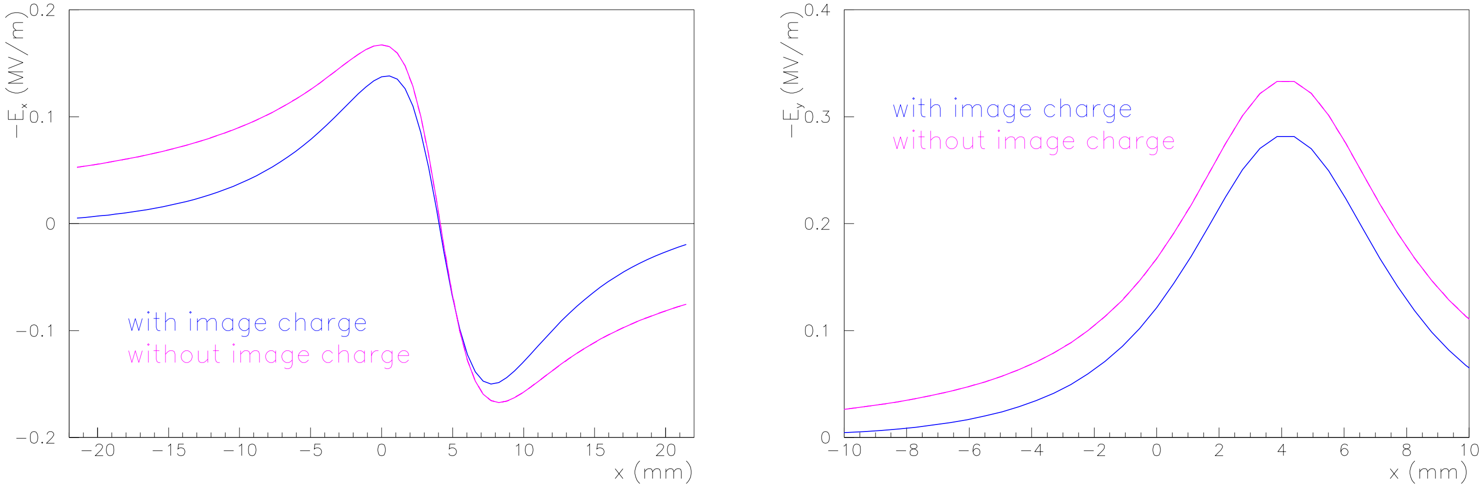
Beam Field and Image Charges



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

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

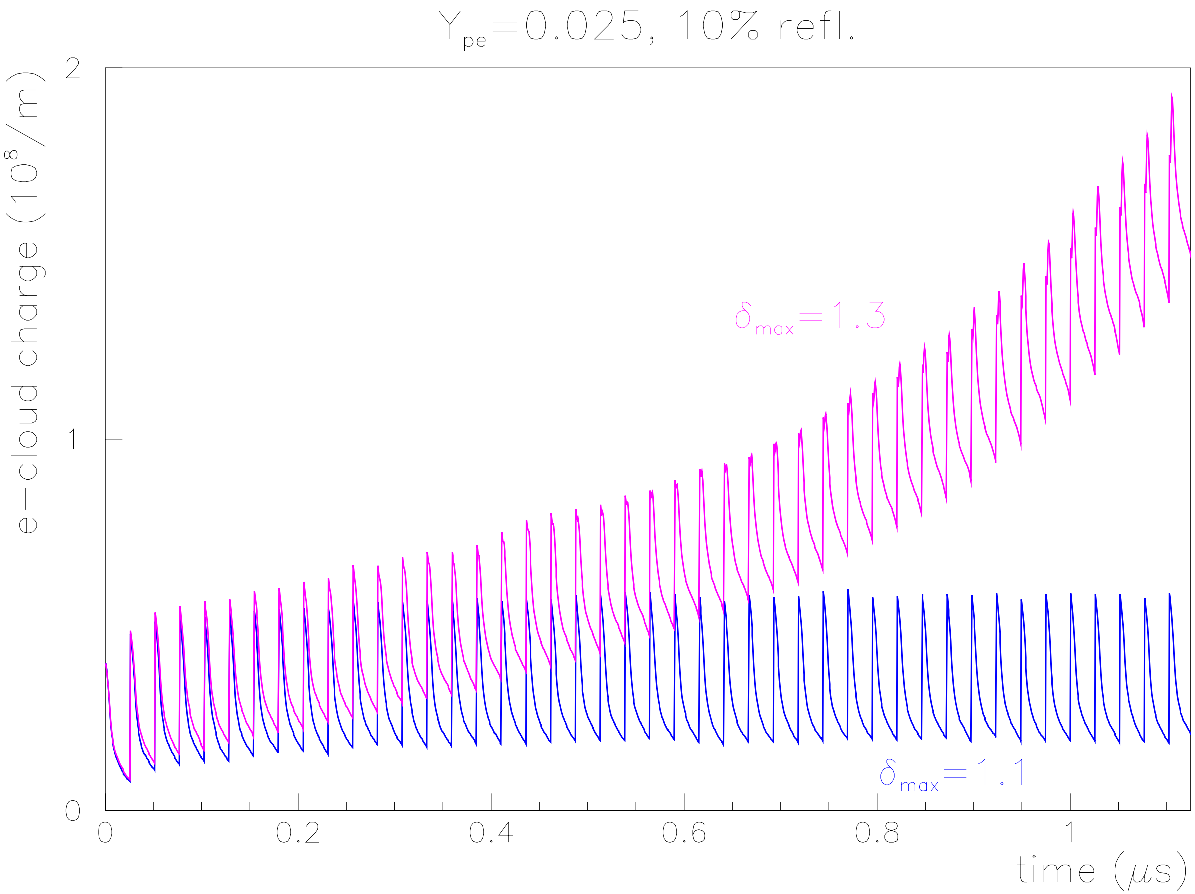
where $z = x + iy = g\ \mathrm{cosh} q = g\ \mathrm{cosh}\ (\mu + i\phi)$ test position, $z_0 = x_0 + iy_0$ $= g\mathrm{cosh} q_0 = g\mathrm{cosh}(\mu_0 + i\phi_0)$ source, $g = \sqrt{a^2 - b^2}$, $\mu_c = \tanh^{-1}(b/a)$.



Horizontal (left) and vertical average electric beam field vs. horizontal position, for an elliptical chamber with 22×10 mm half apertures, and a beam offset of +4.3 mm in both transverse planes.

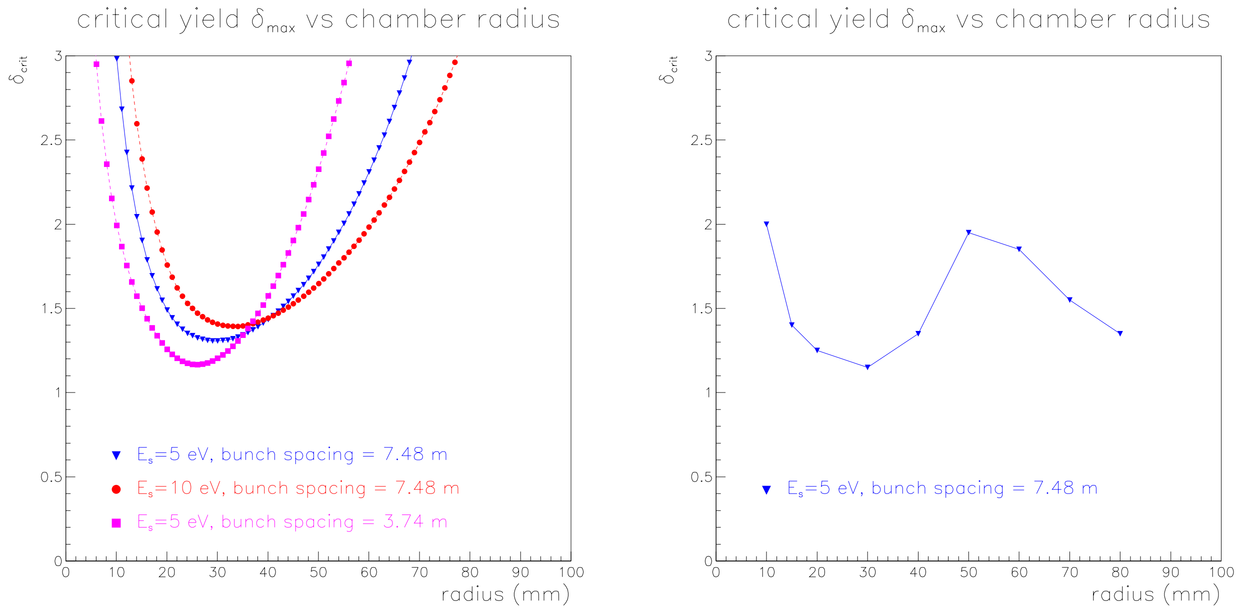
(3) Results

- e^- cloud build up for LHC and SPS
- electron distribution
- LHC heat load
- multibunch instability
- single-bunch instability
- reliefs and cures: fill patterns,...

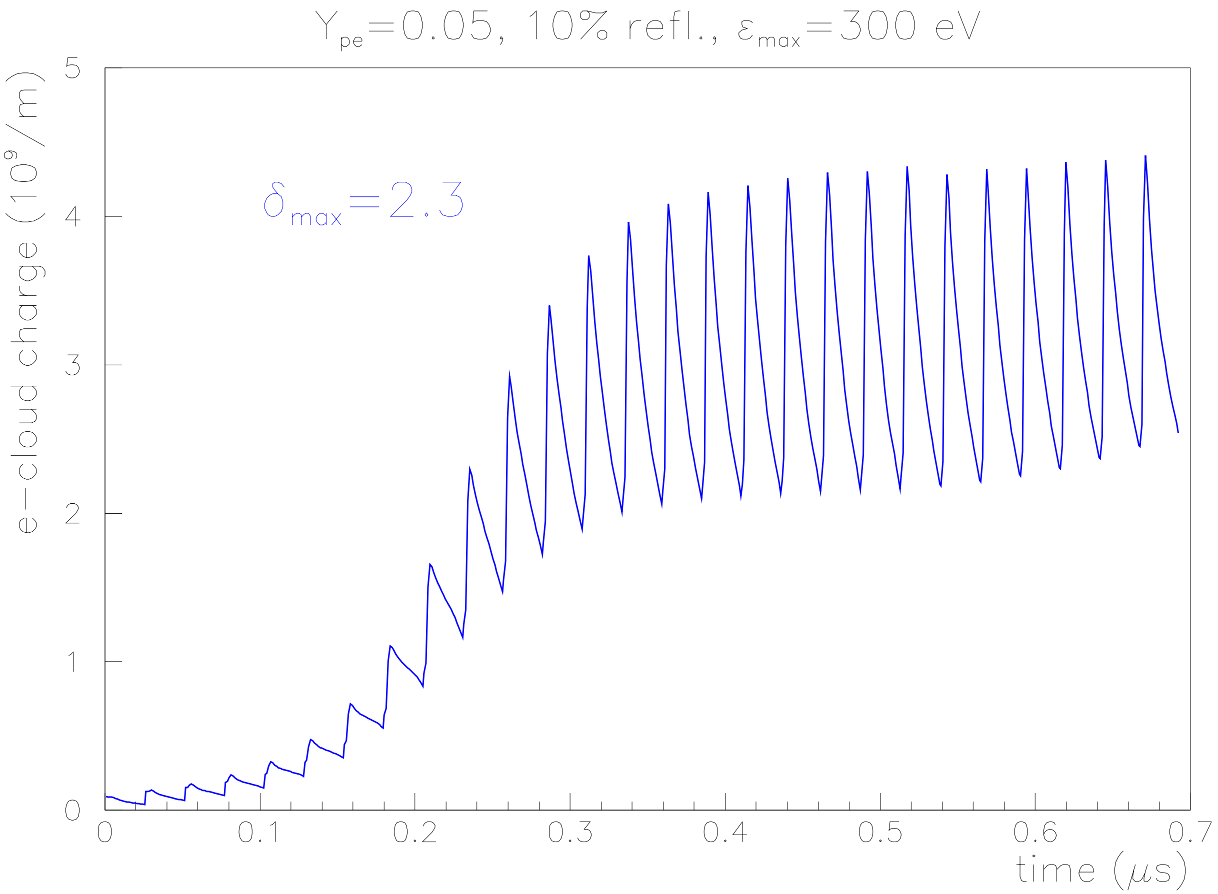


Electron charge per meter in an LHC dipole chamber vs. time along bunch train, comparing $\delta_{\rm max} = 1.1$ and $\delta_{\rm max} = 1.3$. Critical yield is between these values. Other parameters: $\epsilon_{\rm max} = 450$ eV, $R = 0.1$, and $Y^* = 0.025$.

Dependence on Beam Pipe Radius

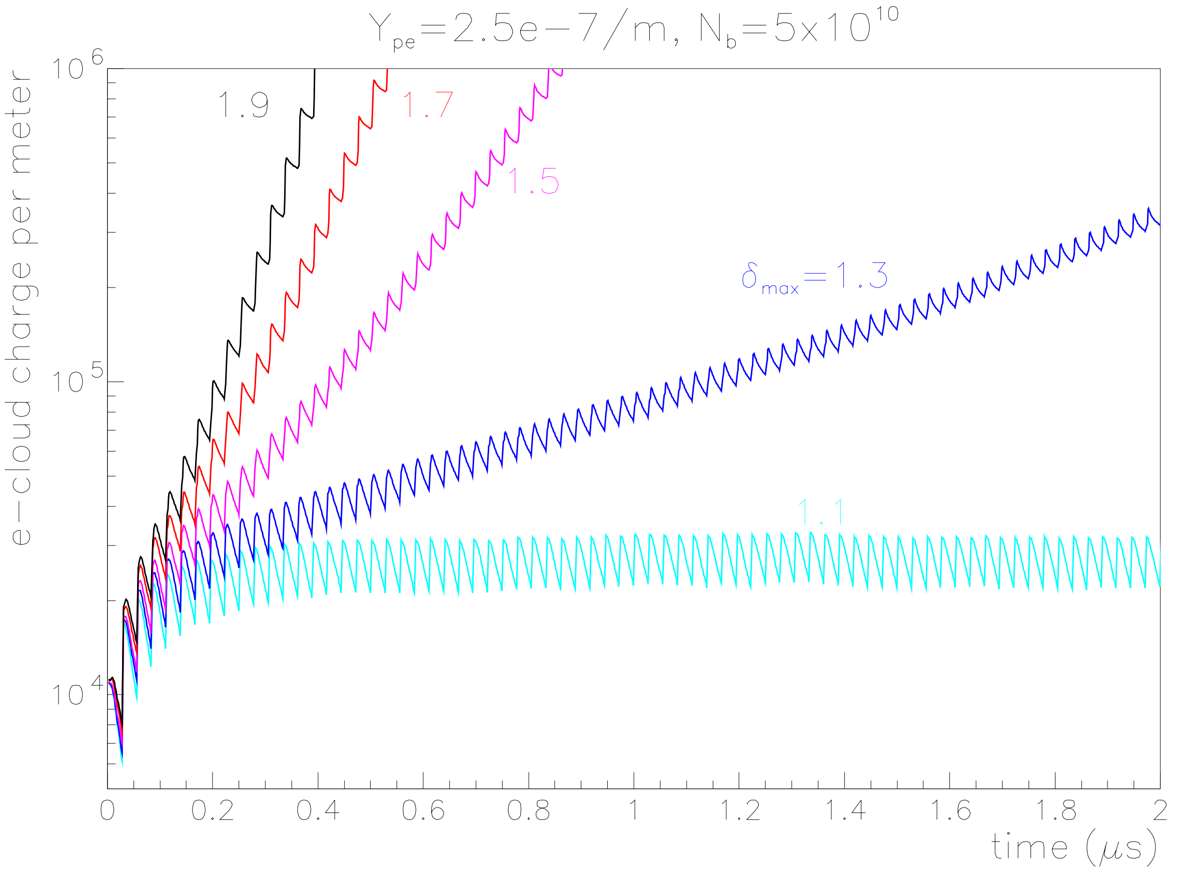


Critical yield as a function of round-chamber radius in a dipole field. Left: numerical evaluation of the above equation for $x = 0$, considering two different values of the characteristic emission energy E_s and of the bunch spacing $l_{sep} = ct_{sep}$; right: simulation for nominal bunch spacing.



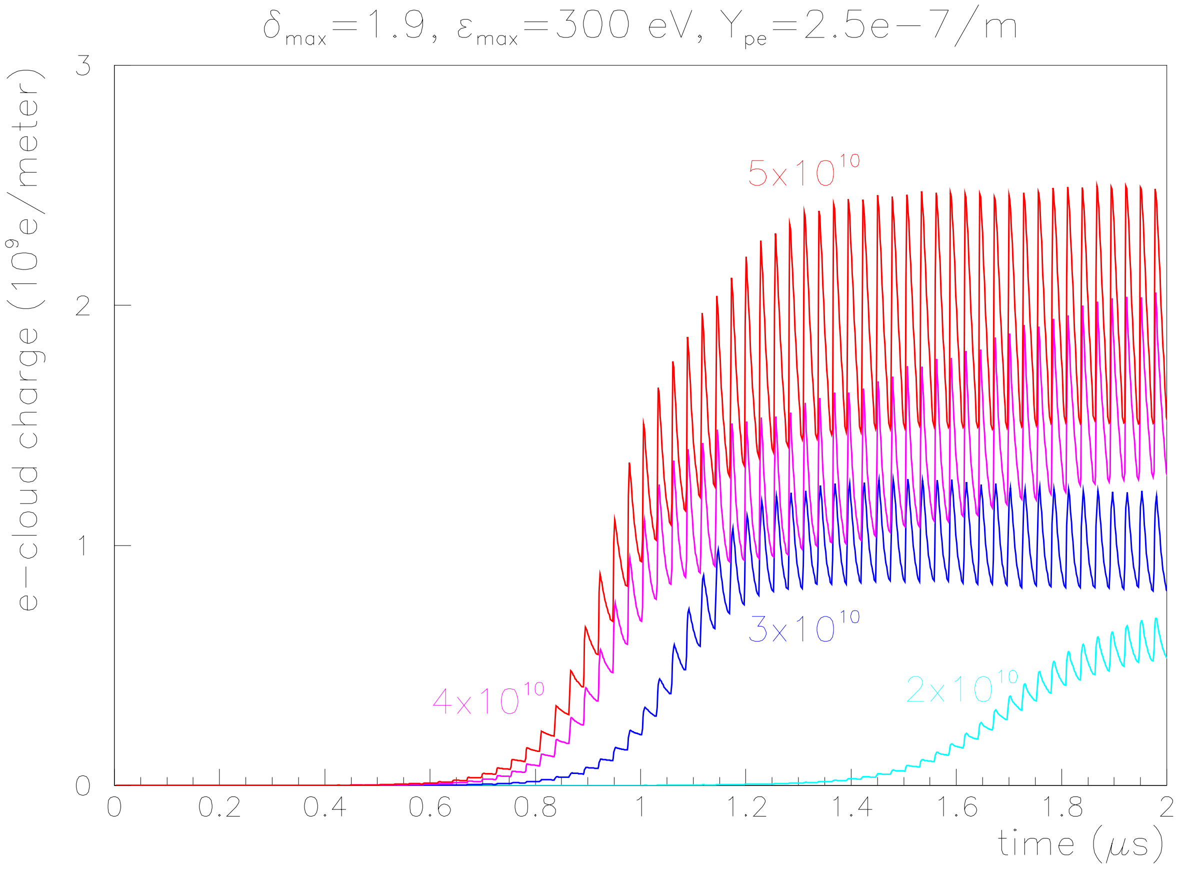
Electron charge per meter in an LHC dipole chamber vs. time along bunch train for large secondary emission yield $\delta_{\max} = 2.3$. Build-up saturates due to electron-cloud space charge. Other parameters: $\epsilon_{\max} = 300$ eV, $R = 0.1$, $Y^* = 0.05$.

e^- cloud build up in the SPS

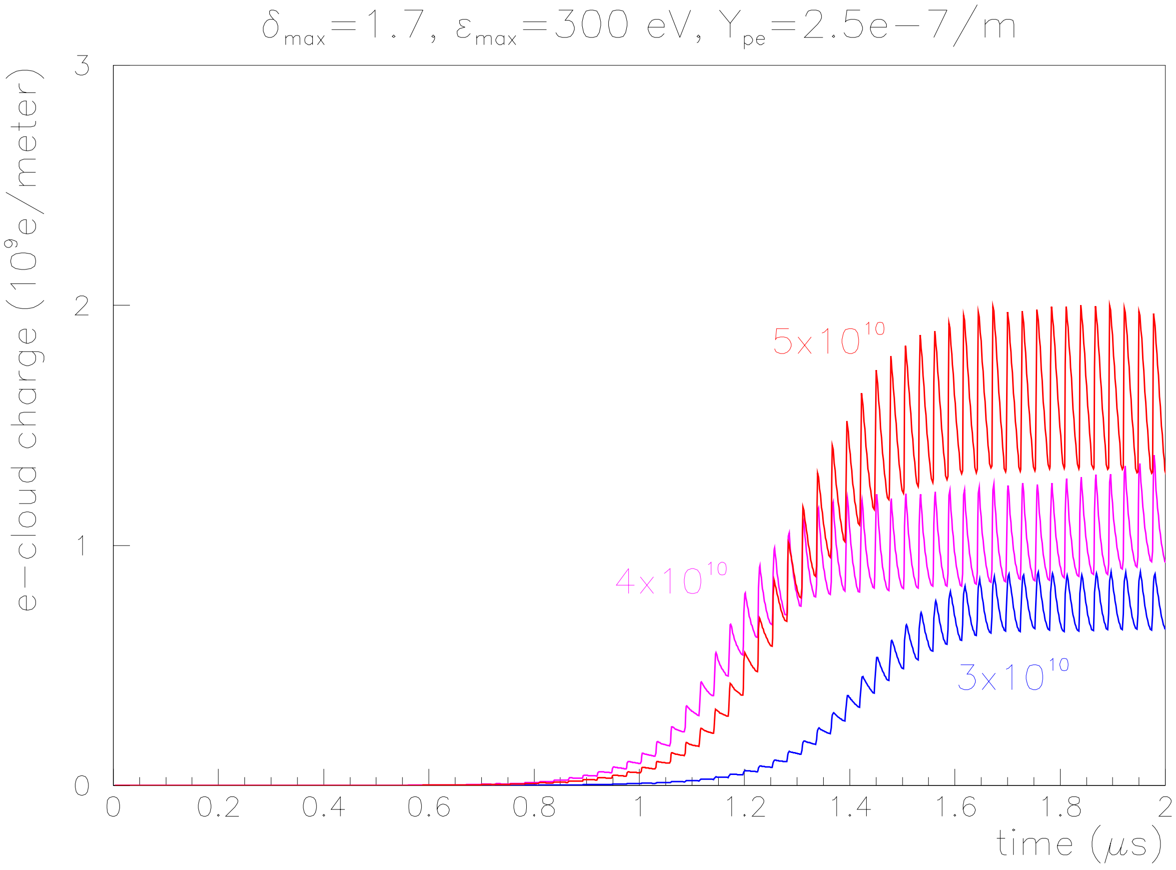


e^- cloud build-up in the SPS for $N_b = 5 \times 10^{10}$. The colors refer to different values of the maximum secondary emission yield $\delta_{\max}$.

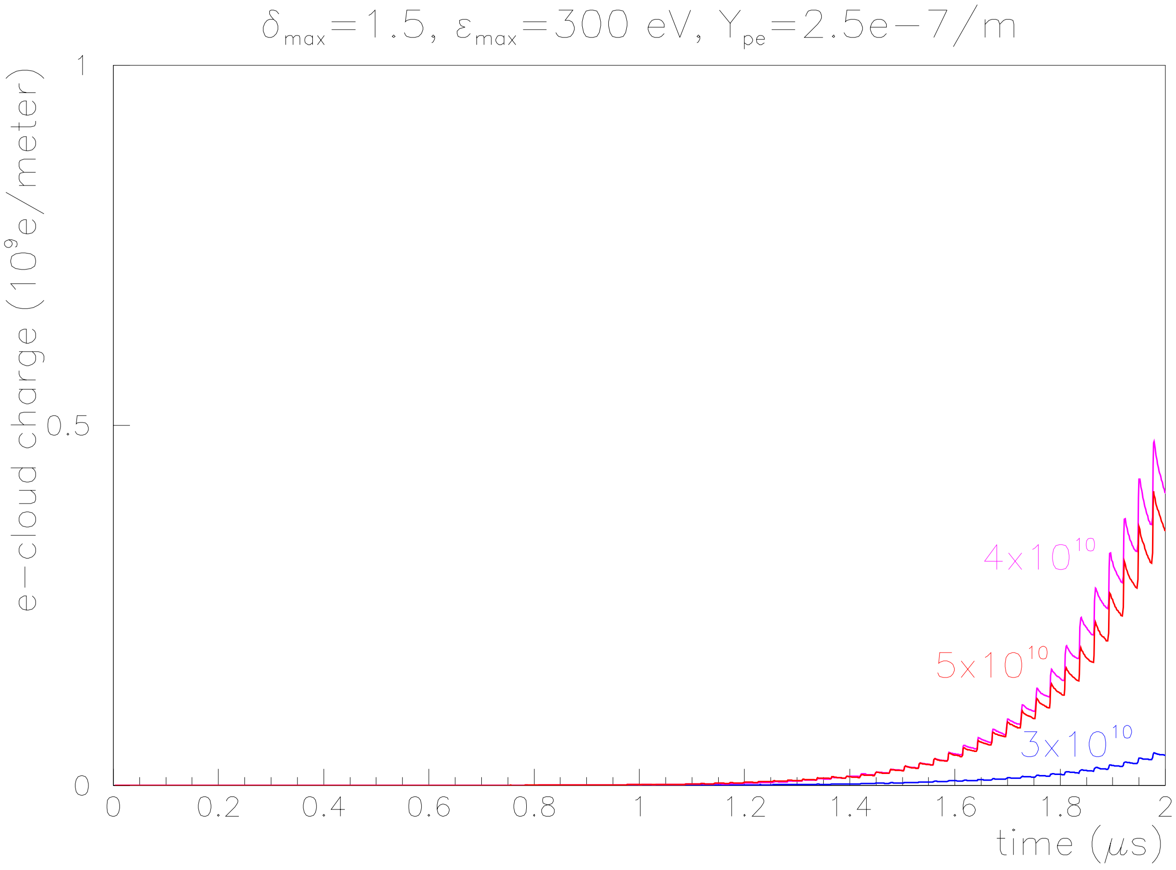
Critical yield $\delta_{\max}$ between 1.1 and 1.3, similar to LHC.



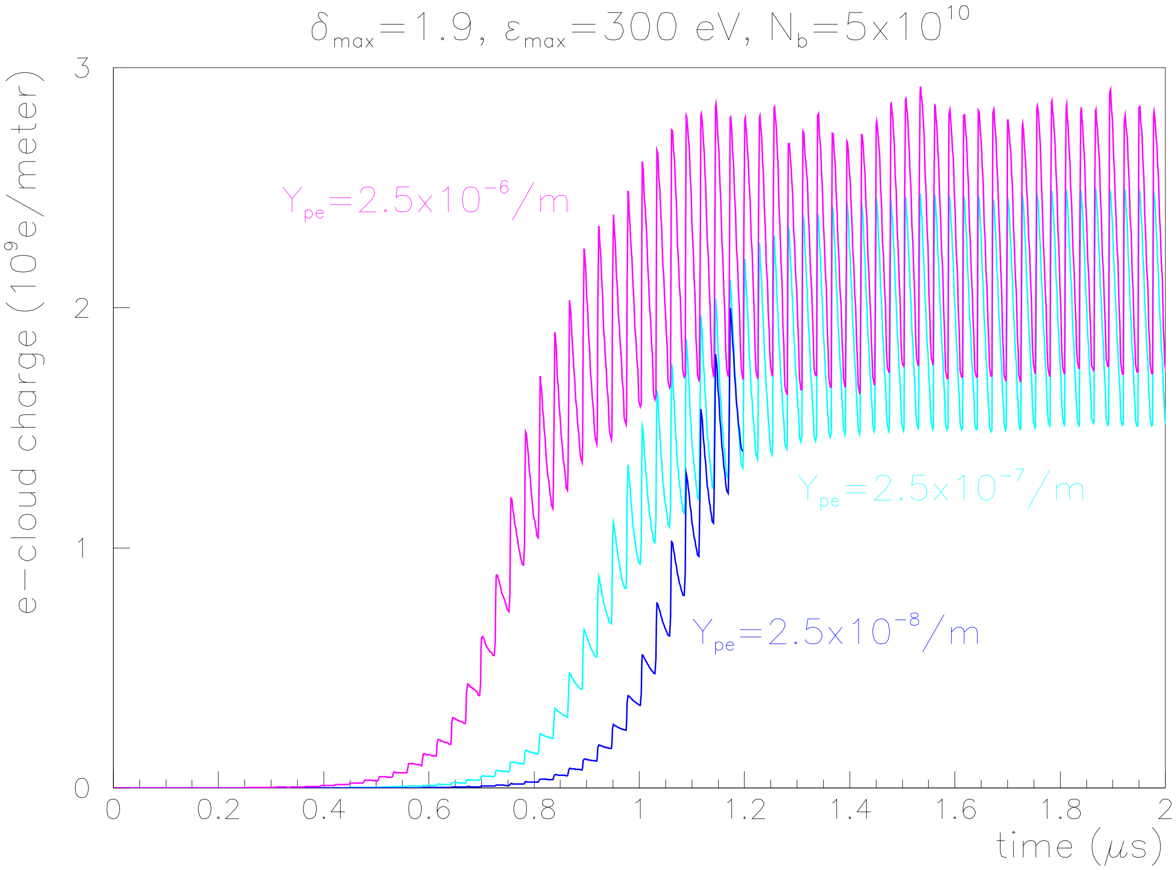
e^- cloud build-up in the SPS for 4 different bunch populations and $\delta_{\rm max} = 1.9$. The growth saturates for a few 10^9/m electron charge, consistent with pressure rise and damper pick-up data.



e^- cloud build-up in the SPS for 4 different bunch populations and $\delta_{\rm max} = 1.7$. The growth saturates for an electron charge of a few 10^9/m, again consistent with pressure rise and damper pick-up data.



e^- cloud build-up in the SPS for 4 different bunch populations and $\delta_{\rm max} = 1.5$. The growth does not saturate.



Electron-cloud build up in the SPS for three different rates of primary electron creation, corresponding to vacuum pressures of 5, 50 and 500 nTorr. $N_b = 5 \times 10^{10}$, $\epsilon_{\rm max} = 300$ eV, $R = 1$, $\delta_{\rm max} = 1.9$.

How large is the actual e^- cloud in the SPS?

(1) from pressure rise [O. Gröbner] :

pressure balance reads $S_{eff}P/(k_BT) = Q$, where S_{eff} pumping speed in volume per meter per second, $Q = \alpha\dot{\lambda}_e$ total flux of molecules per unit length (α: desorption yield per electron) and $P = k_BTN/V$.

$$\frac{d\lambda_e}{ds} = \frac{T_{rev}}{\alpha k_B T} S_{eff}P$$

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

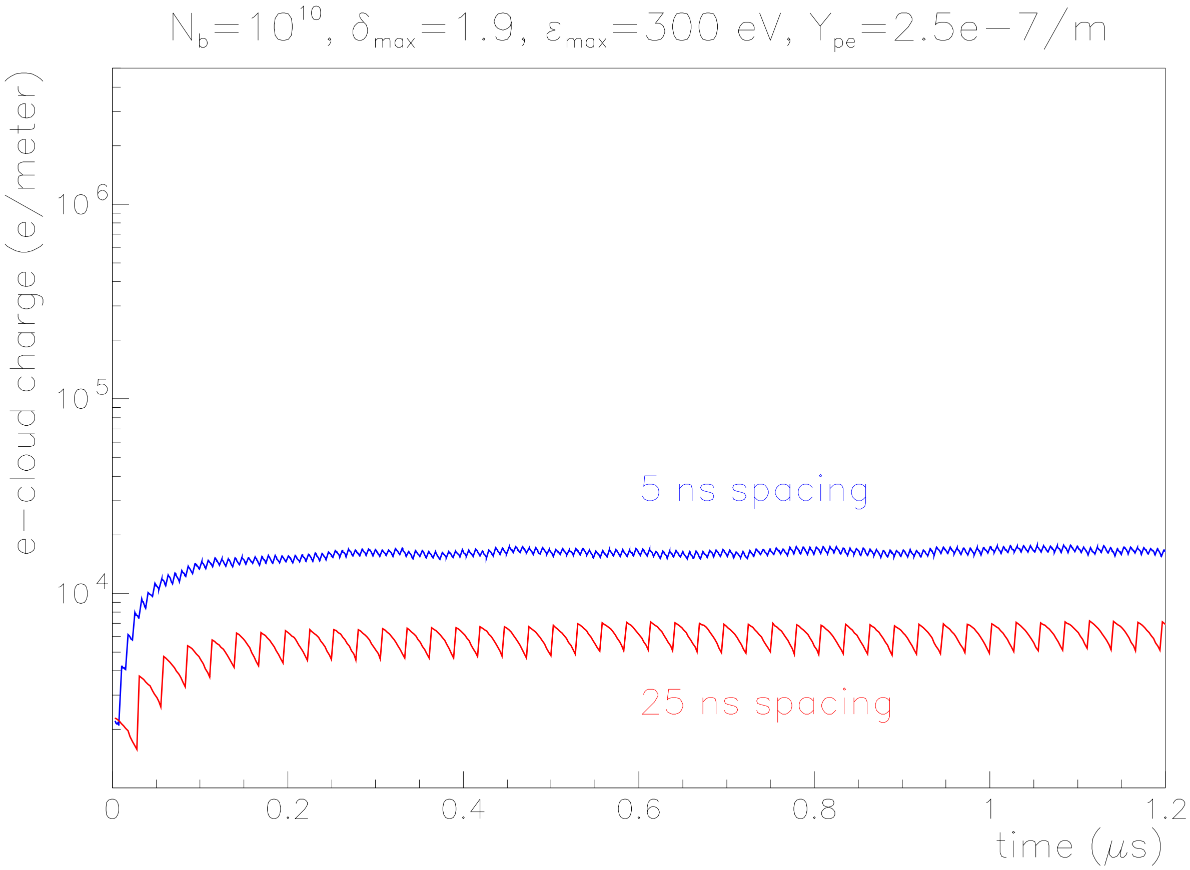
$$\frac{d\lambda_e}{ds} \approx 10^{10} \frac{\text{electrons}}{\text{bunch} - \text{train meter}}$$

(2) from damper pick-up measurements [W. Hoefle]:

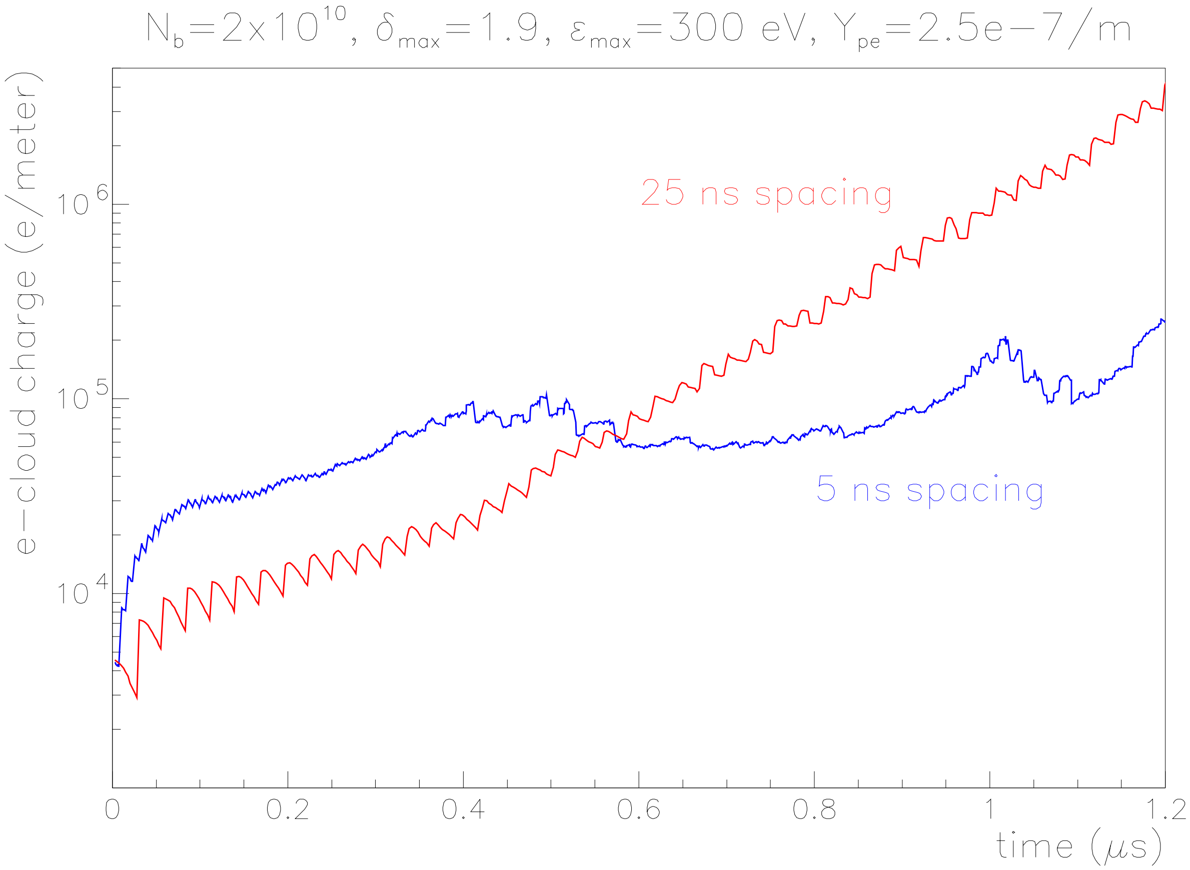
a few 10^8 electrons per bunch passage are deposited on the pick-up; this amounts to $10^9 - 10^{10}$ per train, or, with an effective pick-up length of about 10 cm,

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

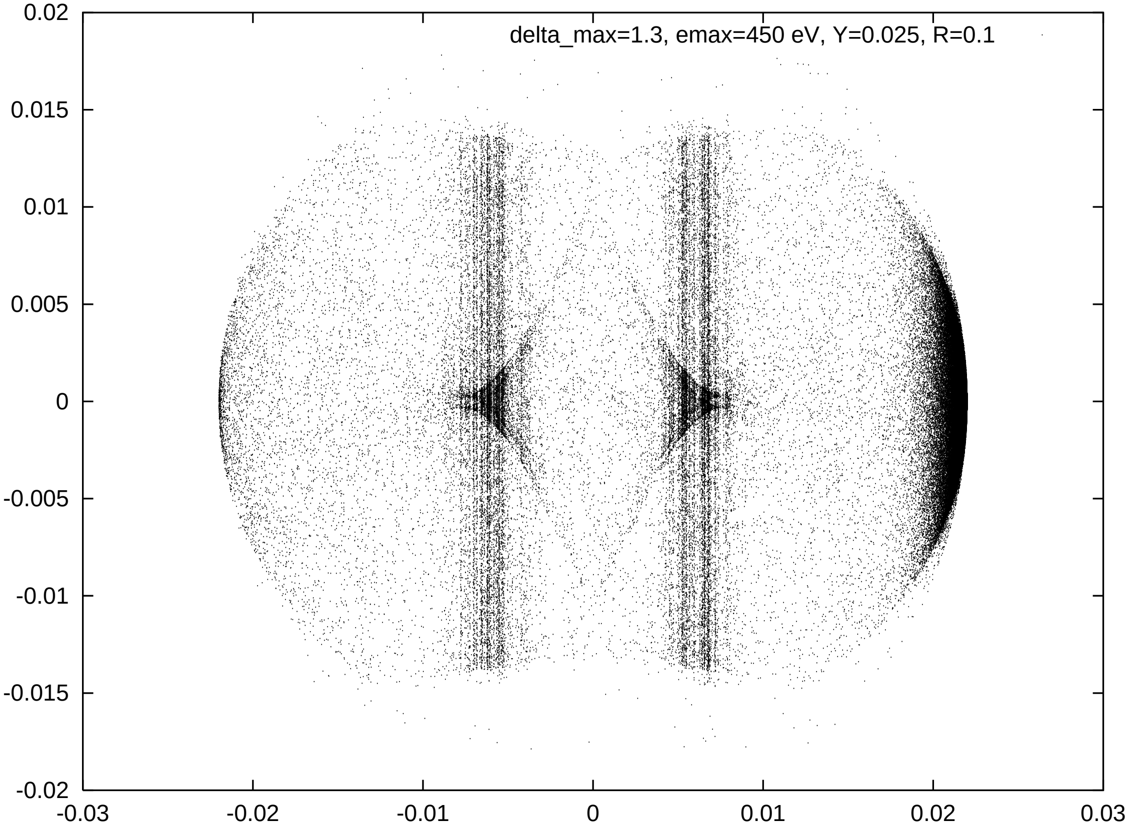
The two estimates are consistent.



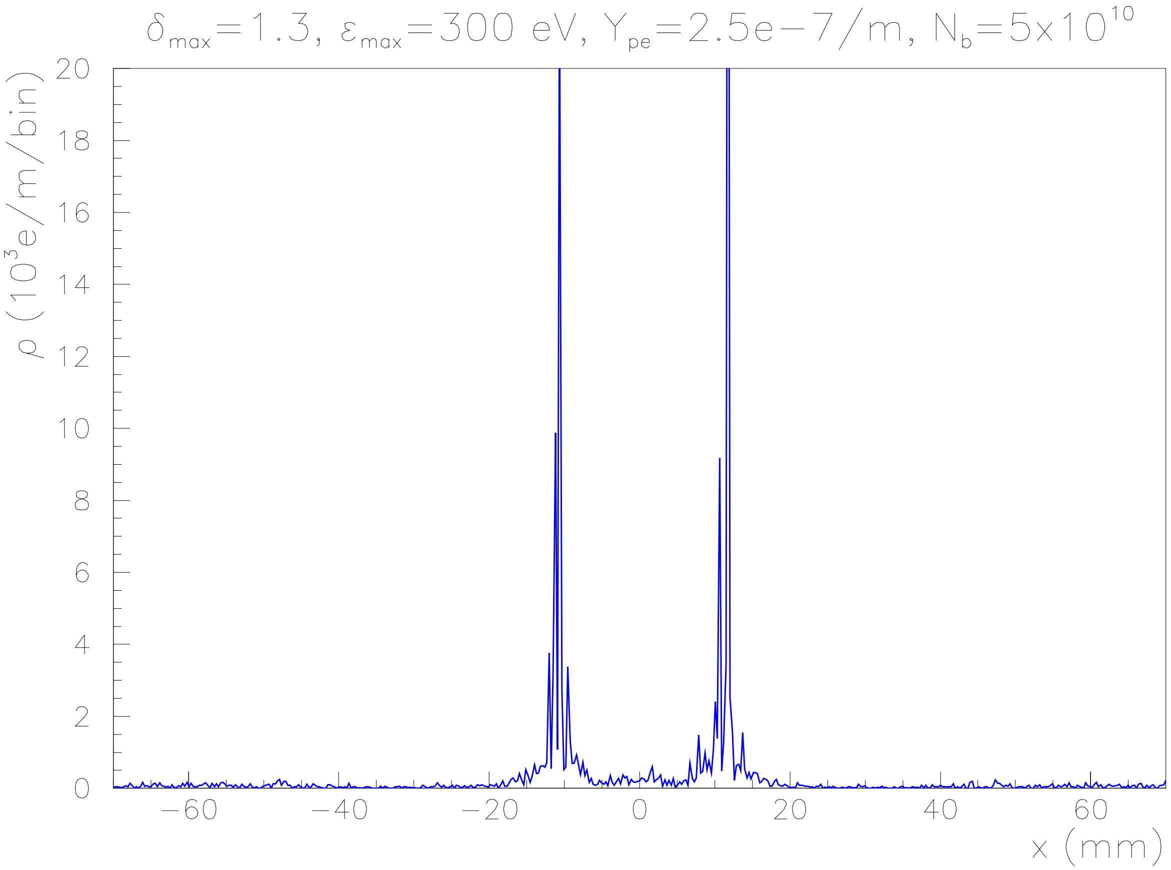
Electron-cloud build up in the SPS for a bunch population of $N_b = 10^{10}$, comparing bunch spacings of 5 ns and 25 ns. Other parameters: $\epsilon_{\max} = 300$ eV, $R = 1$, $\delta_{\max} = 1.9$, and $p = 50$ nTorr.



Electron-cloud build up in the SPS for a bunch population of $N_b = 2 \times 10^{10}$, comparing bunch spacings of 5 ns and 25 ns. Other parameters: $\epsilon_{\rm max} = 300$ eV, $R = 1$, $\delta_{\rm max} = 1.9$, and $p = 50$ nTorr.



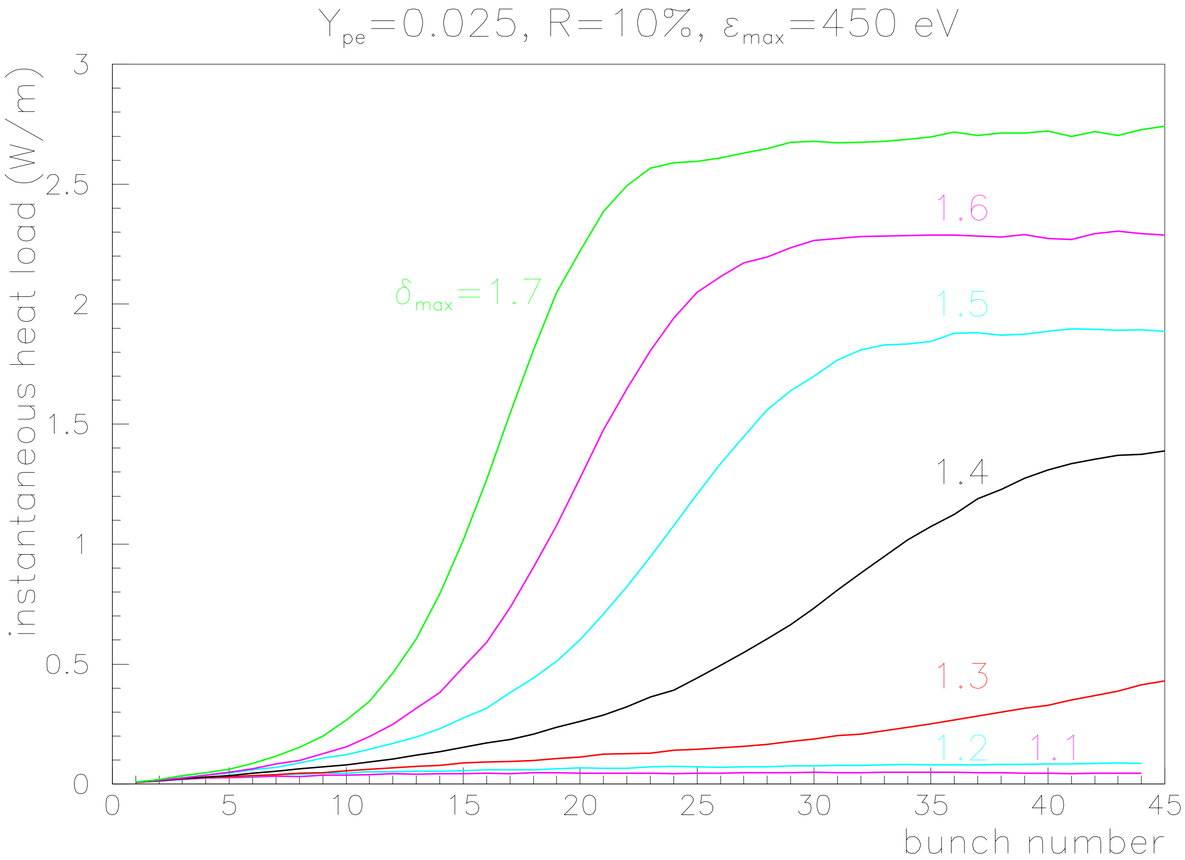
Snap shot of transverse electron cloud distribution in an LHC dipole chamber after 60 bunches with the design current. Vertical stripes indicate regions with large secondary emission. Parameters: $\delta_{\max} = 1.3$, $\epsilon_{\max} = 450$ eV, $R = 0.1$, and $Y^* = 0.025$.



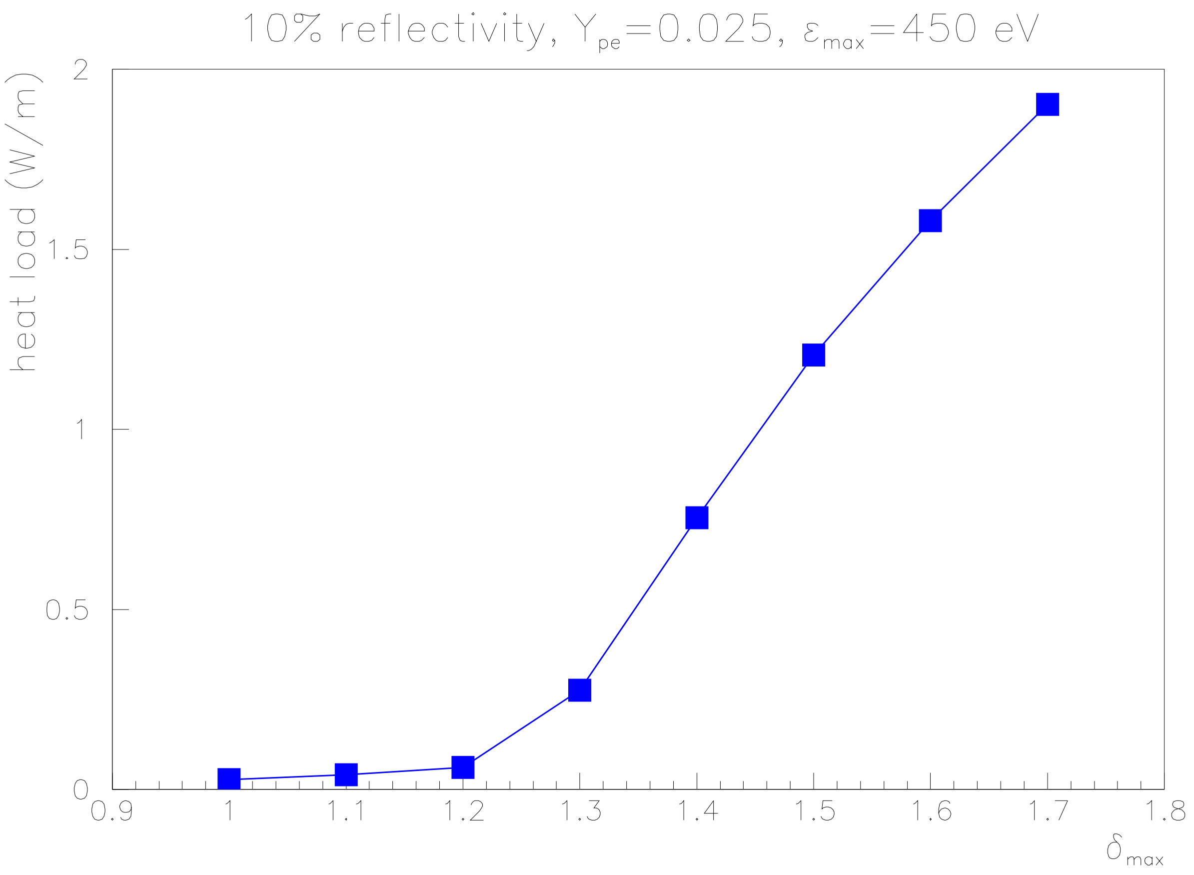
Projected horizontal electron charge density after 60 bunches in an SPS dipole chamber. Vertical peaks correspond to regions with large secondary emission. Parameters: $\delta_{\text{max}} = 1.3$, $\epsilon_{\text{max}} = 300$ eV, $R = 1$, pressure 50 nTorr, and 500 bins.

Heat load from incident electrons is a concern for LHC:

- *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
- → *heat load from electron cloud must be smaller than* $0.6\ W/m$



Instantaneous heat load in W/m vs. bunch number for LHC dipole chamber. Parameters: $\epsilon_{\rm max} = 450$ eV, $R = 0.1$, and $Y^* = 0.025$.



Heat load in LHC dipole chamber vs. maximum secondary emission yield $\delta_{\rm max}$. Parameters: $\epsilon_{\rm max} = 450$ eV, $R = 0.1$, and $Y^* = 0.025$. The curve changes slope near the critical yield $\delta_{\rm max} \approx 1.3$.

Parameters

variable	LHC initial	LHC final	SPS
δ_{max}	2.3	1.1	
ϵ_{max}	300 eV	450 eV	
$d\lambda_e/ds$	1.4×10^{-3} m^{-1}	7×10^{-4} m^{-1}	10^{-7} m^{-1}
Y	0.05	0.025	—
N_b	1.05×10^{11}	1.05×10^{11}	4×10^{10}

Simulated LHC heat loads

magnet	initial[†]	final[‡]
arc dipole	5000 mW/m	42 mW/m
D1 dipole*, 1 beam	2020 mW/m	15 mW/m
2 beams	7580 mW/m	90 mW/m
triplet quadrupole*, 1 beam	14 mW/m	6 mW/m
2 beams	32 mW/m	14 mW/m
drift with 3 cm aperture*, 1 beam	7500 mW/m	460 mW/m
2 beams	>16000 mW/m	630 mW/m

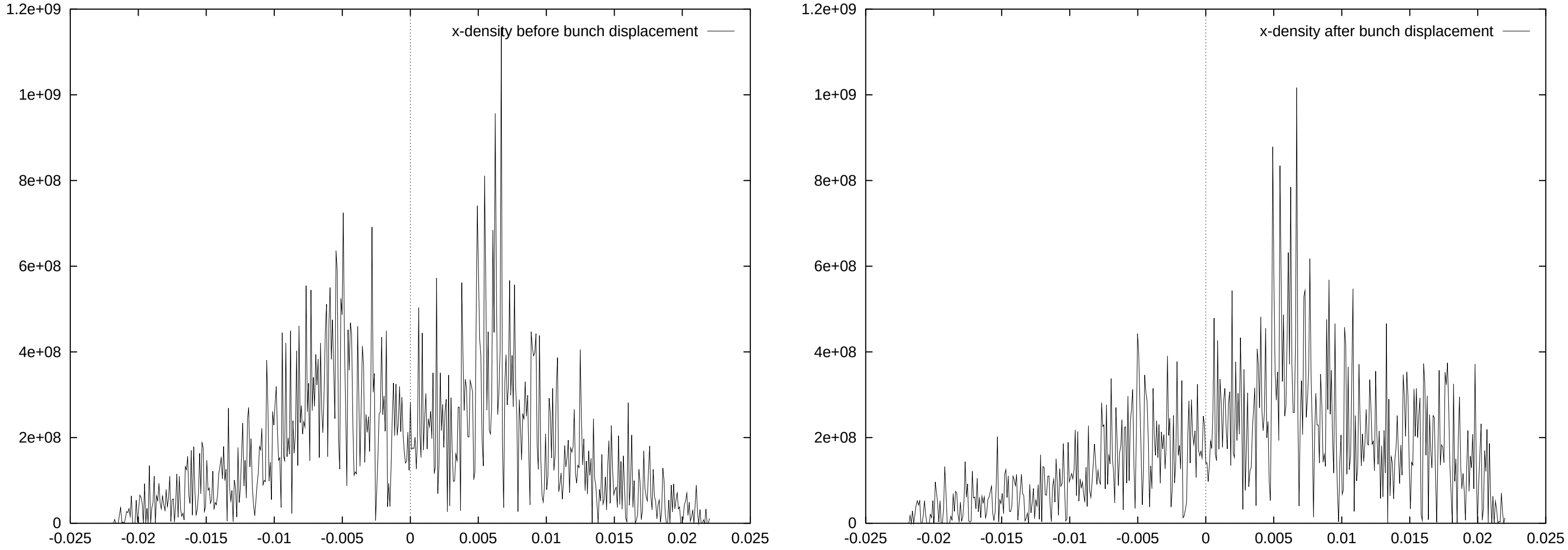
*with transverse offsets of 4–5 millimeters.

[†] with $\delta_{\max} = 2.3$, $\epsilon_{\max} = 300$ eV, $Y_{pe} = 0.05$.

[‡] with $\delta_{\max} = 1.1$, $\epsilon_{\max} = 450$ eV, $Y_{pe} = 0.025$.

Multibunch Wake

Electron cloud couples motion of subsequent bunches.



Projected horizontal electron charge density in an LHC bending magnet before the 41st bunch in the train is horizontally displaced by 1 cm [left] and just prior to the arrival of the 42nd bunch [right]. The horizontal axis is in units of meters; the vertical coordinate is the charge (in units of e) per bin and per grid point. Other parameters: 500 grid points, $\delta_{\max} = 1.7$, $R = 1$, $Y^* = 1$.

Effective wake and instability

electron cloud can couple motion of subsequent bunches
→ instability

- after stationary cloud is established, displace 1 bunch transversely by Δx or Δy
- calculate kick that the disturbed e^- exerts on the next bunch → short-range dipole wake field $W_1(L_{sep})$

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

where $r_i = (x_i^2 + y_i^2)^{1/2}$, l_b simulated length of bending magnet, and Q_i charge of ith macro-electron.

- assume uniformly filled ring with M bunches and a short-range wake

  → complex frequency shift of μth mode is (see Alex Chao's book)

$$\Omega_{y\ (x)}^{(\mu)} - \omega_{\beta,y\ (x)} = \frac{N_b r_p c^2}{2\gamma C \omega_\beta} W_{1,y\ (x)} e^{i2\pi(\mu+Q_{y\ (x)})/M}$$

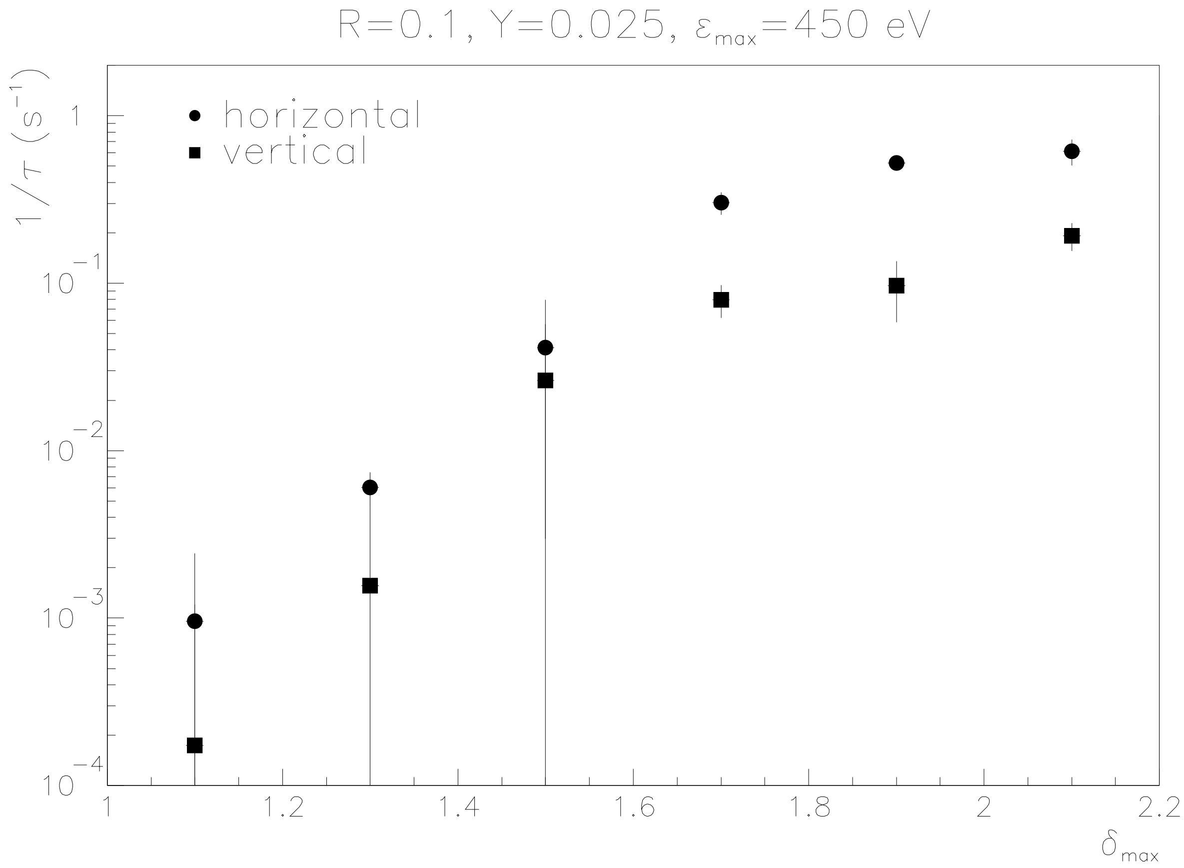
  and shortest rise time

$$\tau \approx \frac{4\pi\gamma Q_{y\ (x)}}{N_b r_p c W_{1,y\ (x)}}$$

- with clearing gaps growth is not exponential but

$$y_n \sim \frac{1}{n!}(t/\tau)^n\ \hat{y}_0$$

  for nth bunch in a train; τ is the same as above



Multibunch instability growth rate as a function of maximum secondary emission yield $\delta_{\rm max}$ for the LHC. Other parameters: $\epsilon_{\rm max} = 450$ eV, $R = 10\%$, and $Y_{pe} = 0.025$.

Single-Bunch Instability

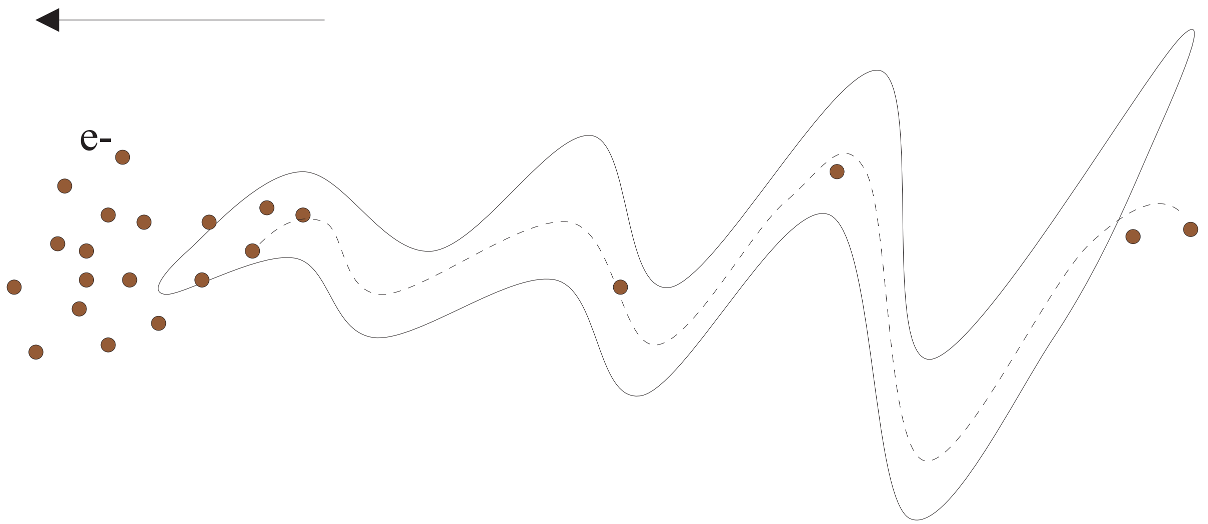


Illustration of a single-bunch instability driven by the electron-cloud.

Approximate growth rate:

$$\frac{1}{\tau} \approx 4\pi n_{\rm cloud} \frac{N_b^{1/2} r_e^{1/2} r_p \sigma_z^{1/2} \sigma_x \beta_y c}{\gamma \sigma_y^{1/2} (\sigma_x + \sigma_y)^{3/2}}$$

Growth Rate Estimates

$$\frac{1}{\tau}\,[\mathrm{s}^{-1}] \approx \begin{cases} 2\times10^{-8}\ n_{\mathrm{cloud}}[\mathrm{m}^{-3}] & \text{SPS at 26 GeV} \\ 6\times10^{-10}\ n_{\mathrm{cloud}}[\mathrm{m}^{-3}] & \text{LHC at 450 GeV} \\ 1\times10^{-10}\ n_{\mathrm{cloud}}[\mathrm{m}^{-3}] & \text{LHC at 7 TeV} \end{cases}$$

where n_{cloud} denotes the electron density near the beam.

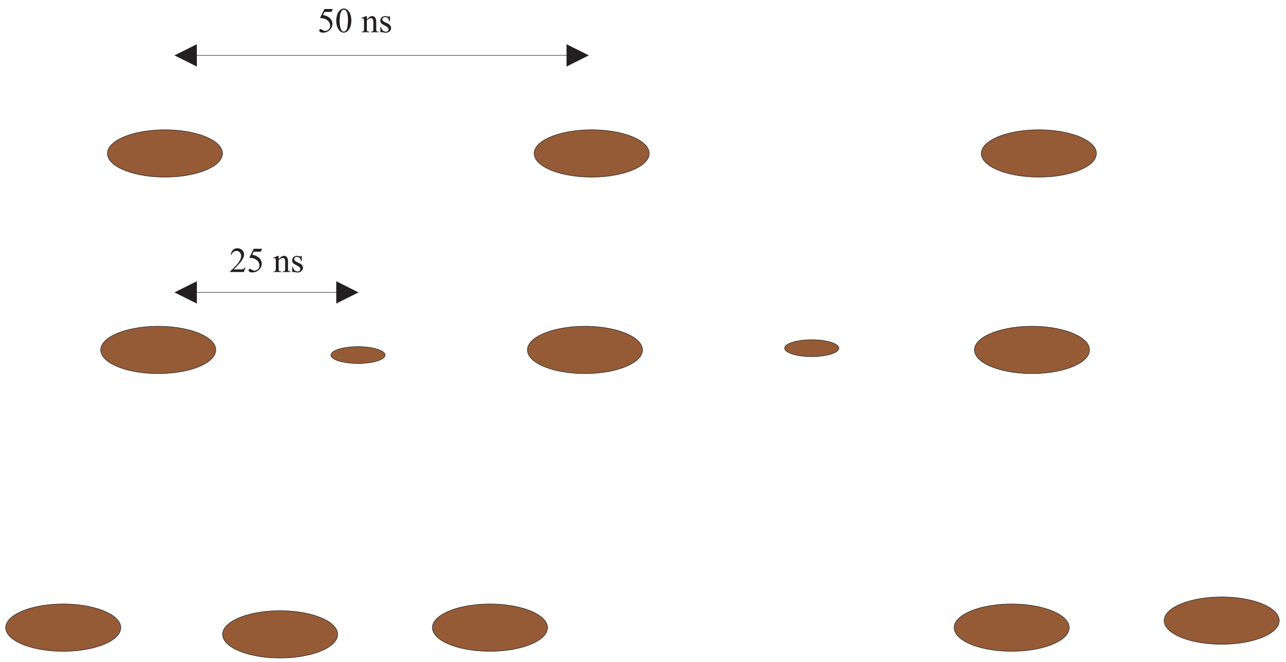
E.g., for the SPS with $n_{\mathrm{cloud}} \approx 10^{11}$ m^{-3}: $\tau \approx 500$ μs.

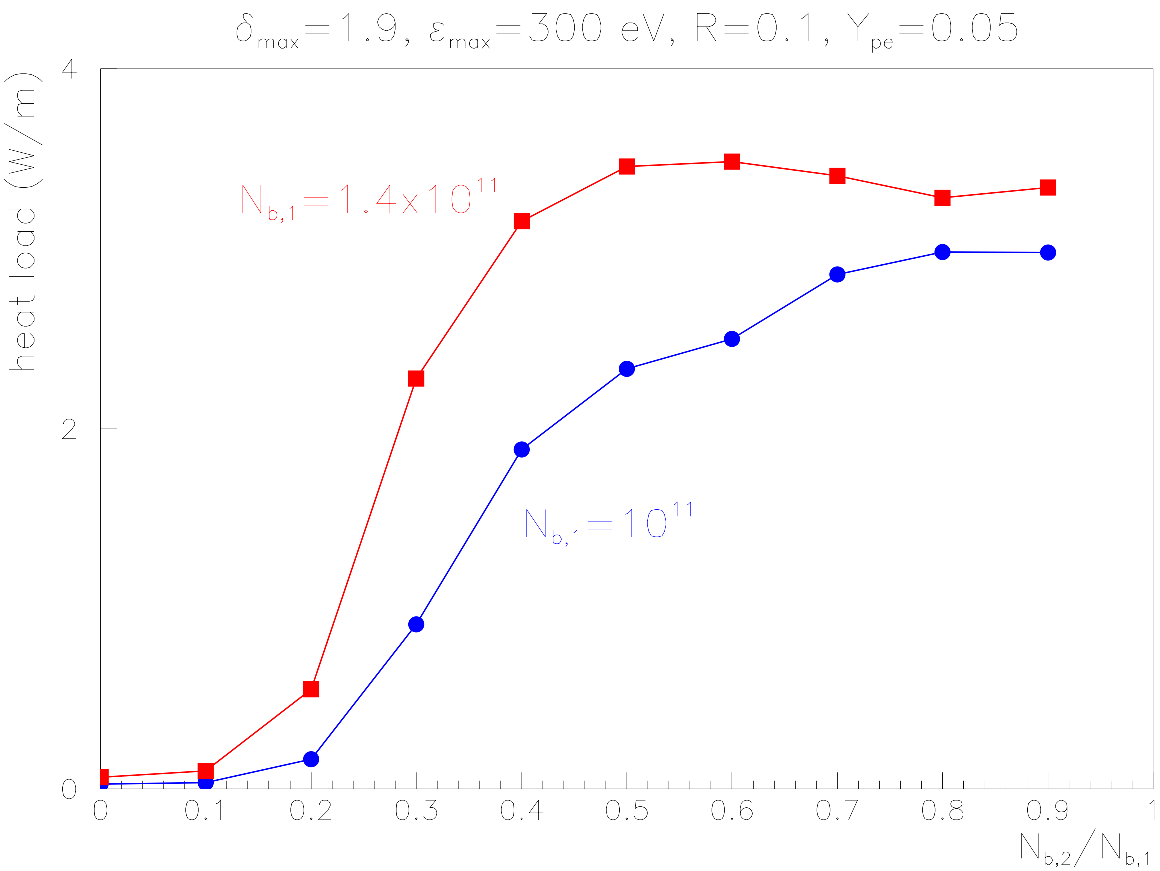
Similar instability due to ionization electrons created by the bunch itself: $\tau \approx 50$ ms at 10 nTorr ($\propto 1/$pressure).

Growth rate will be modified by synchrotron oscillations and chromaticity! (V_{rf}, Q',...)

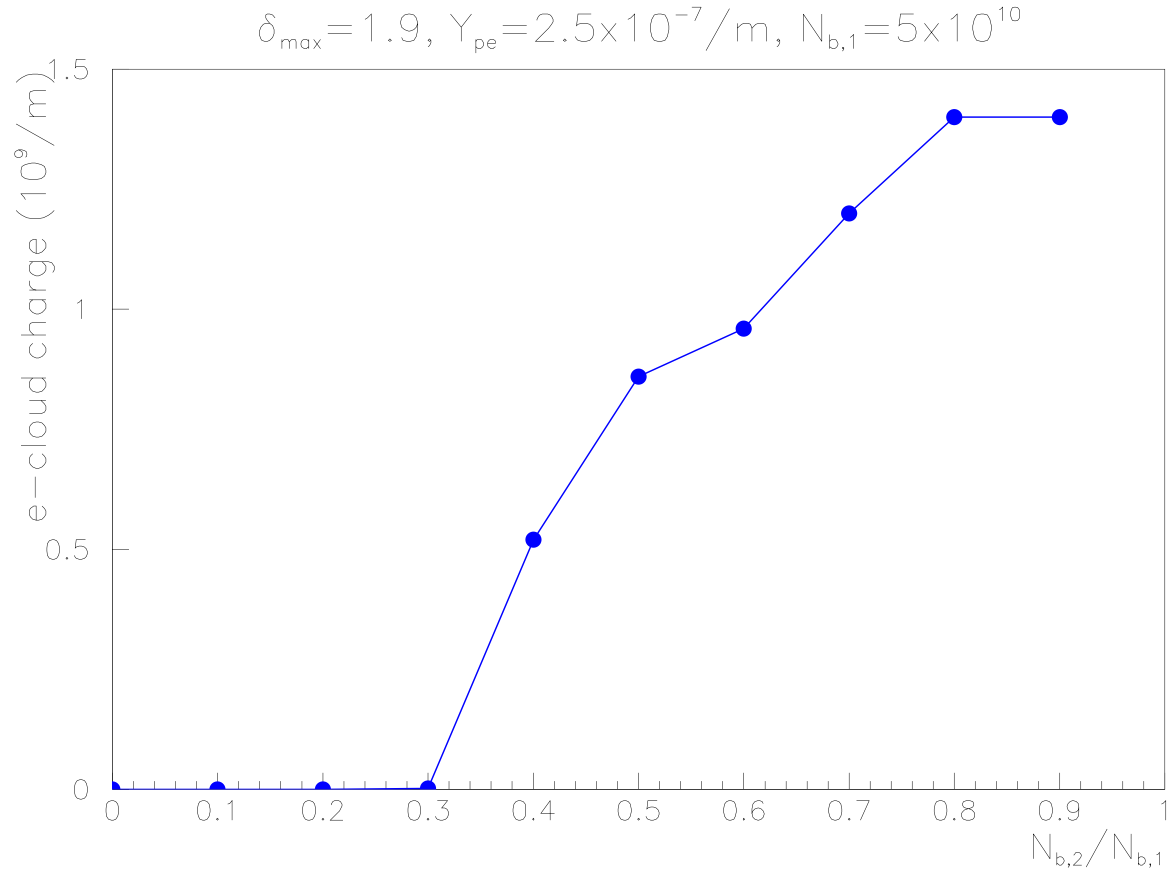
Possible Cures

Double bunch spacing or gaps in the train:



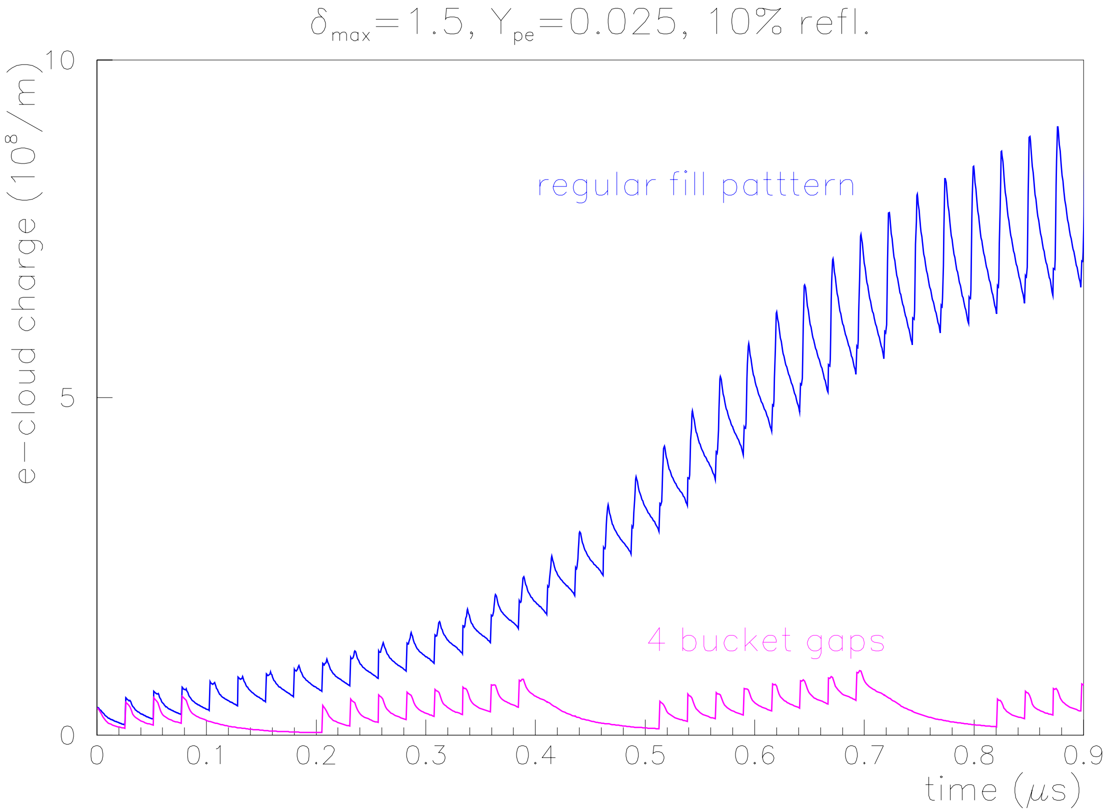


Heat load in an LHC dipole for twice the nominal bunch spacing and intermediate low-current bunches as a function of charge ratio $N_{b,2}/N_{b,1}$, for 2 values of $N_{b,1}$. $\epsilon_{\rm max} = 300$ eV, photon reflectivity $R = 10\%$, $\delta_{\rm max} = 1.9$, and $Y_{pe} = 0.05$.



Electron-cloud charge in the SPS after bunch no. 60 for twice the nominal bunch spacing and intermediate low-current bunches as a function of charge ratio $N_{b,2}/N_{b,1}$ for $N_{b,1} = 5 \times 10^{10}$ and $\delta_{\max} = 1.9$.

Gaps in the LHC Bunch Train

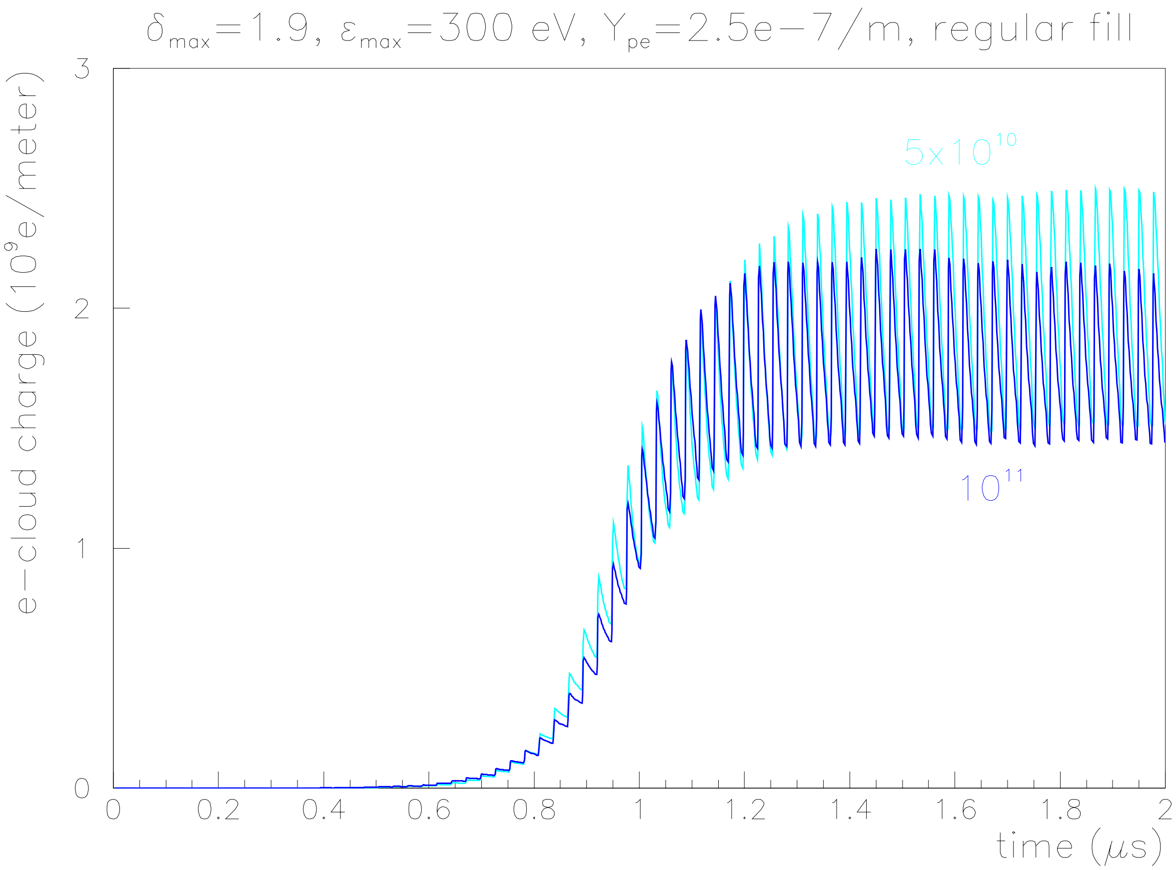


Suppression of charge build-up by gaps in the LHC bunch train; here a gap of 4 missing bunches after every 8 bunches.

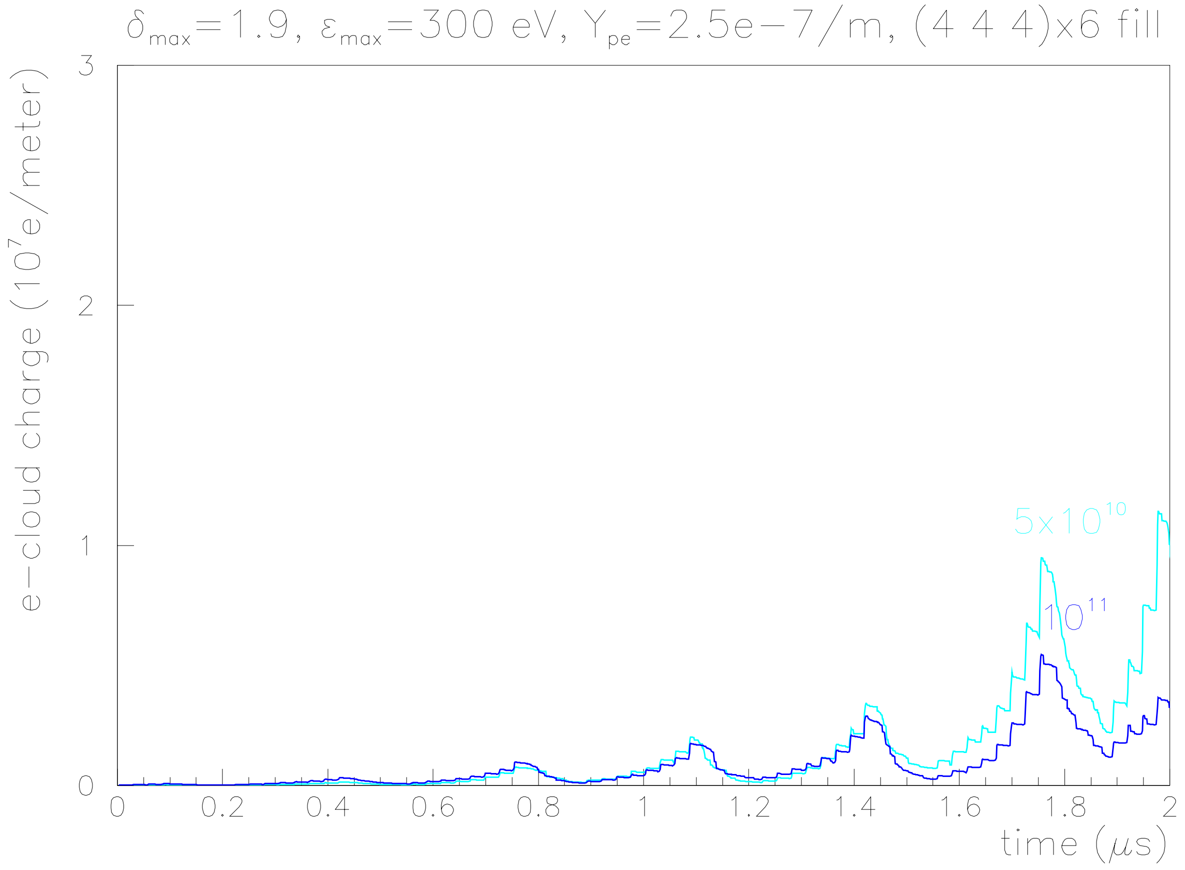
Heat load reduction in LHC dipole

δ_{max}	regular fill	six gaps per train
1.1	41 mW/m	16 mW/m
1.3	222 mW/m	26 mW/m
1.5	564 mW/m	60 mW/m
2.3	5000 mW/m	890 mW/m

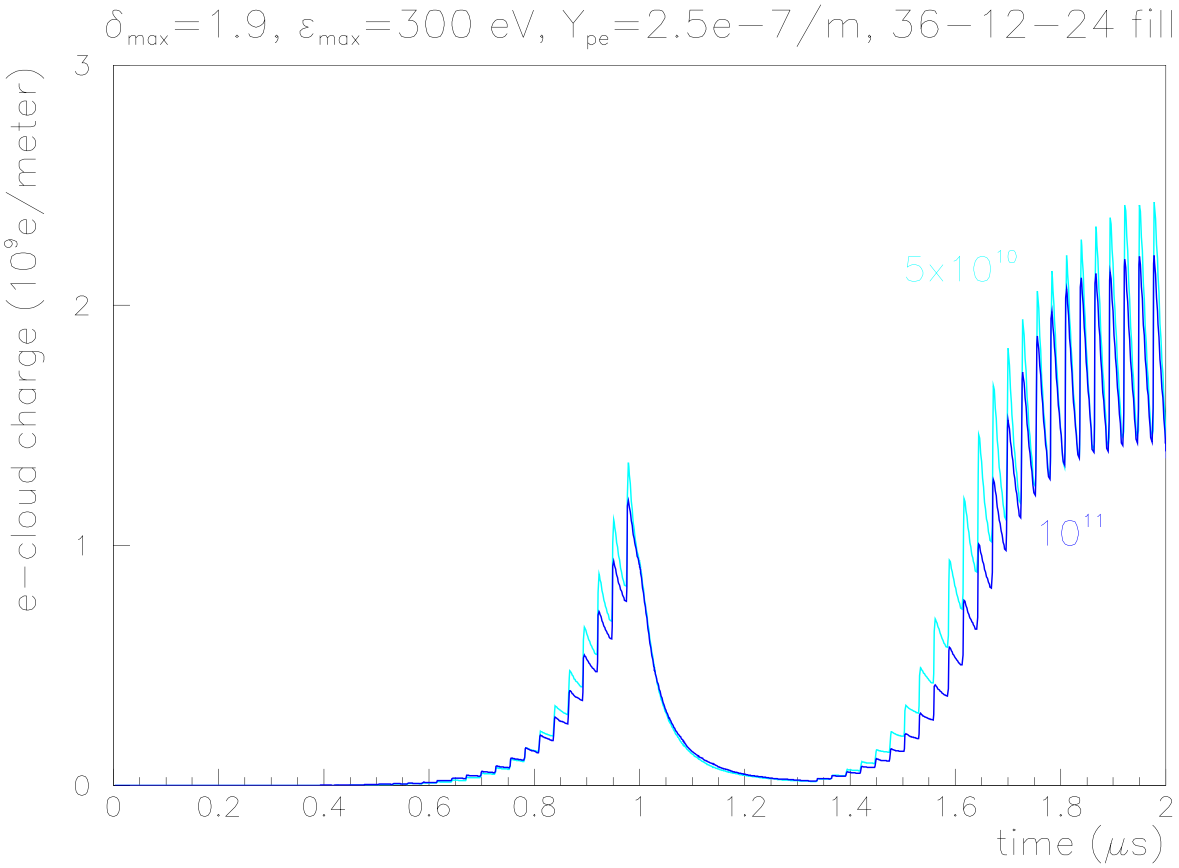
SPS Fill Patterns



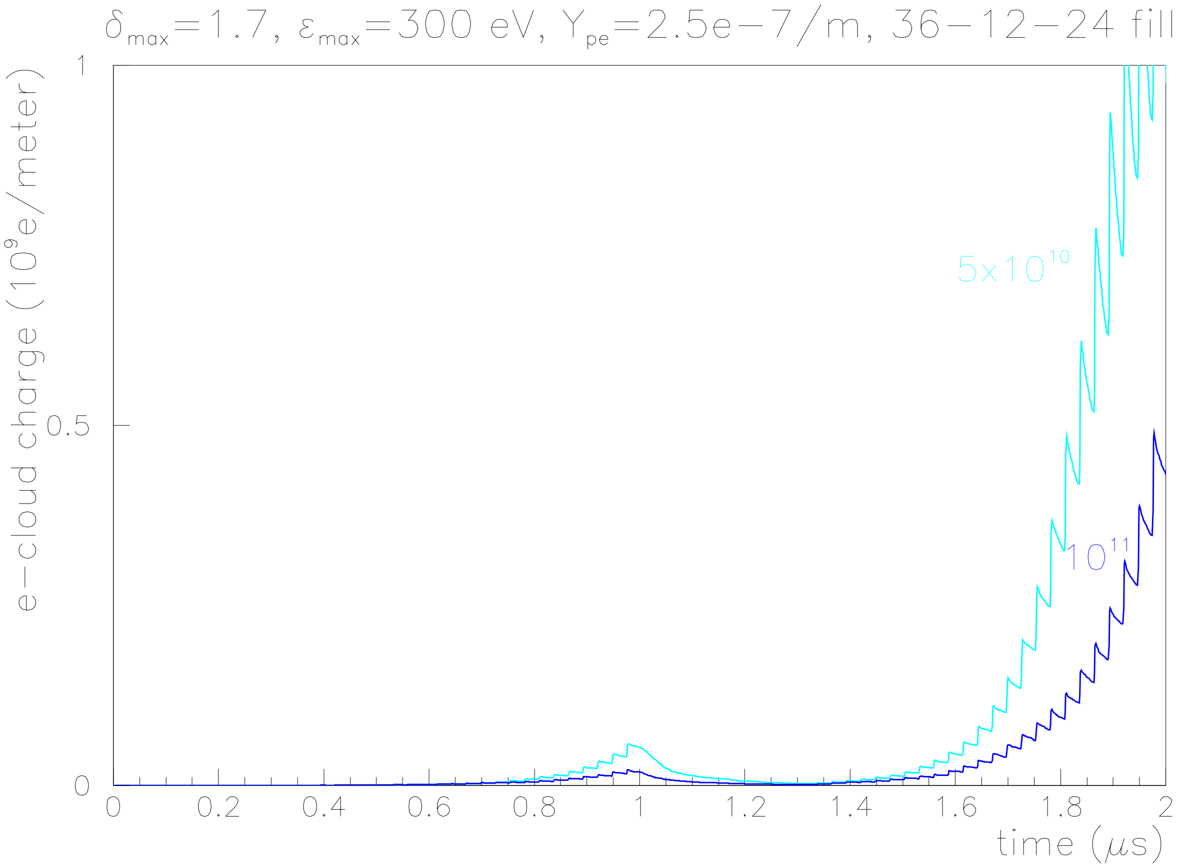
Electron cloud build up in the SPS for bunch populations of $N_b = 5 \times 10^{10}$ and 10^{11} (almost no difference!) and regular fill.



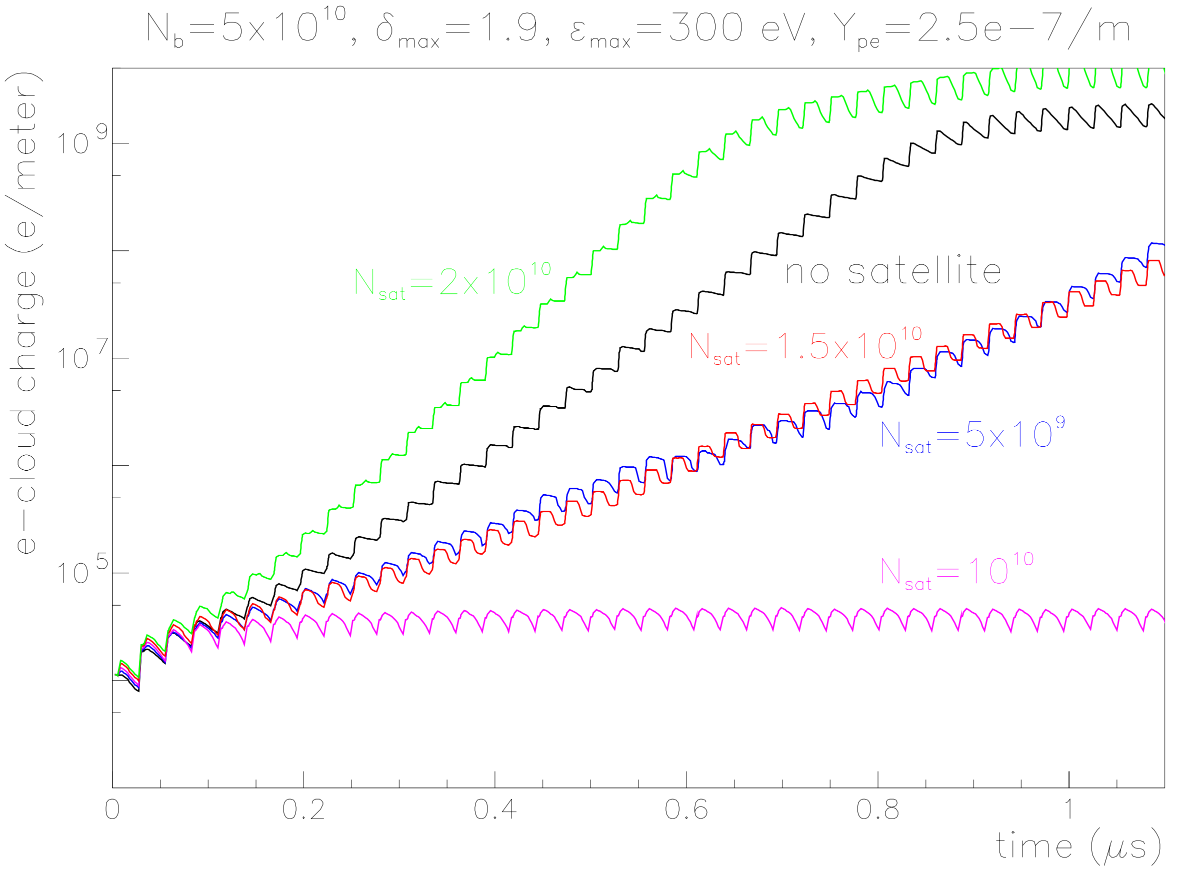
Electron cloud build up in the SPS for bunch populations of $N_b = 5 \times 10^{10}$ and 10^{11} and a fill pattern of 6× (4 bunches, 4 empty buckets, 4 bunches).



Electron cloud build up in the SPS for bunch populations of $N_b = 5 \times 10^{10}$ and 10^{11} (almost no difference!), $\delta_{\max} = 1.9$, and a fill pattern of 36 bunches, 12 empty buckets, 24 bunches.



Electron cloud build up in the SPS for bunch populations of $N_b = 5 \times 10^{10}$ and 10^{11} (almost no difference!), $\delta_{\rm max} = 1.7$, and a fill pattern of 36 bunches, 12 empty buckets, 24 bunches.



Electron-cloud build up in the SPS for satellite bunches of various intensities, following 3 ns behind the main bunches. Parameters: $N_b = 5 \times 10^{10}$, $\epsilon_{\rm max} = 300$ eV, $R = 1$, $\delta_{\rm max} = 1.9$, and $p = 50$ nTorr.

Summary I

- electron cloud effects depend on properties of vacuum chamber: $\delta_{\rm max}$, $\epsilon_{\rm max}$, $(R,\, Y_{pe})$
- critical yield for multipacting is $\delta_{crit} \approx 1.3$ for both LHC and SPS
- SPS observations are consistent with electron cloud and $\delta_{\rm max} \approx 1.9$

Summary II

- electron cloud causes pressure rise, slow multibunch instability, single-bunch beam break up, and heat load (at LHC)
- weak solenoids for LHC field free regions?
- emittance growth from single-bunch break up should depend on rf voltage and chromaticity
- gaps in the bunch train or doubling the bunch spacing or satellite bunches may help during surface conditioning