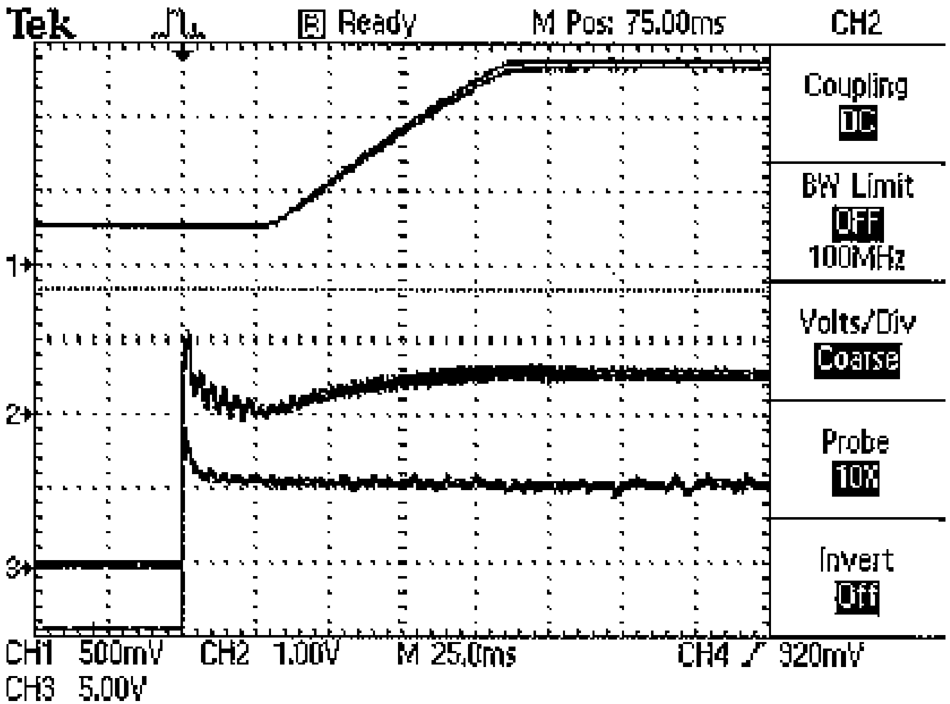
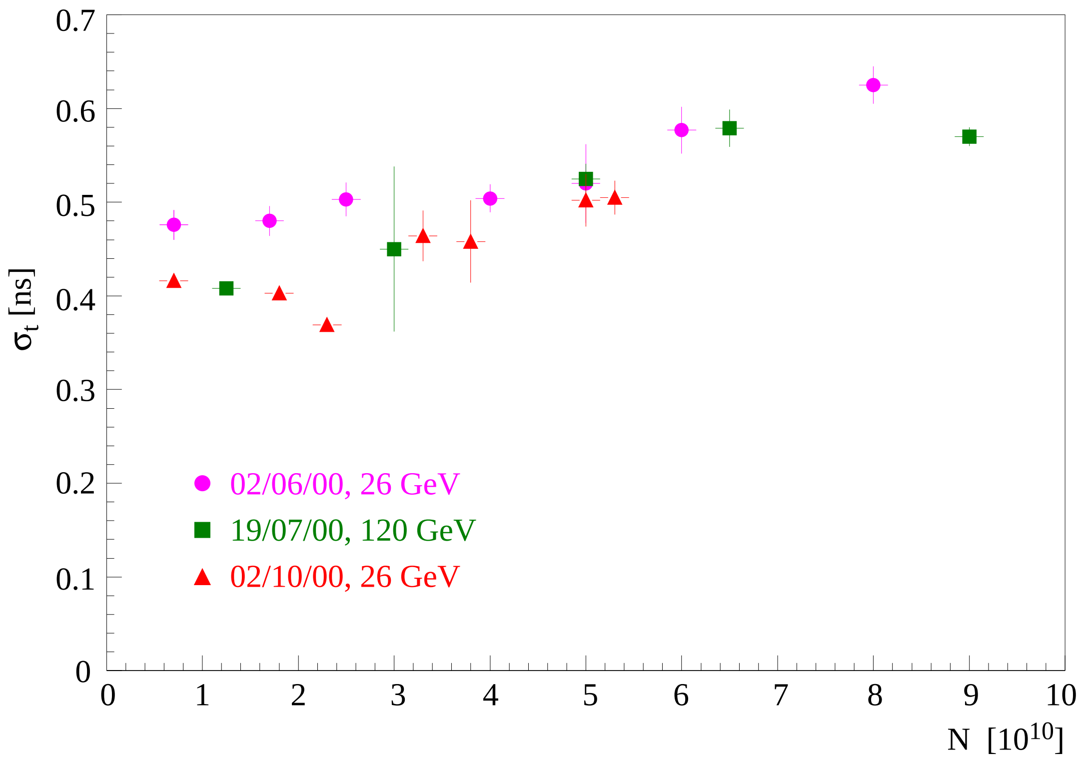
Collective and electron cloud effects: CERN SPS and LHC

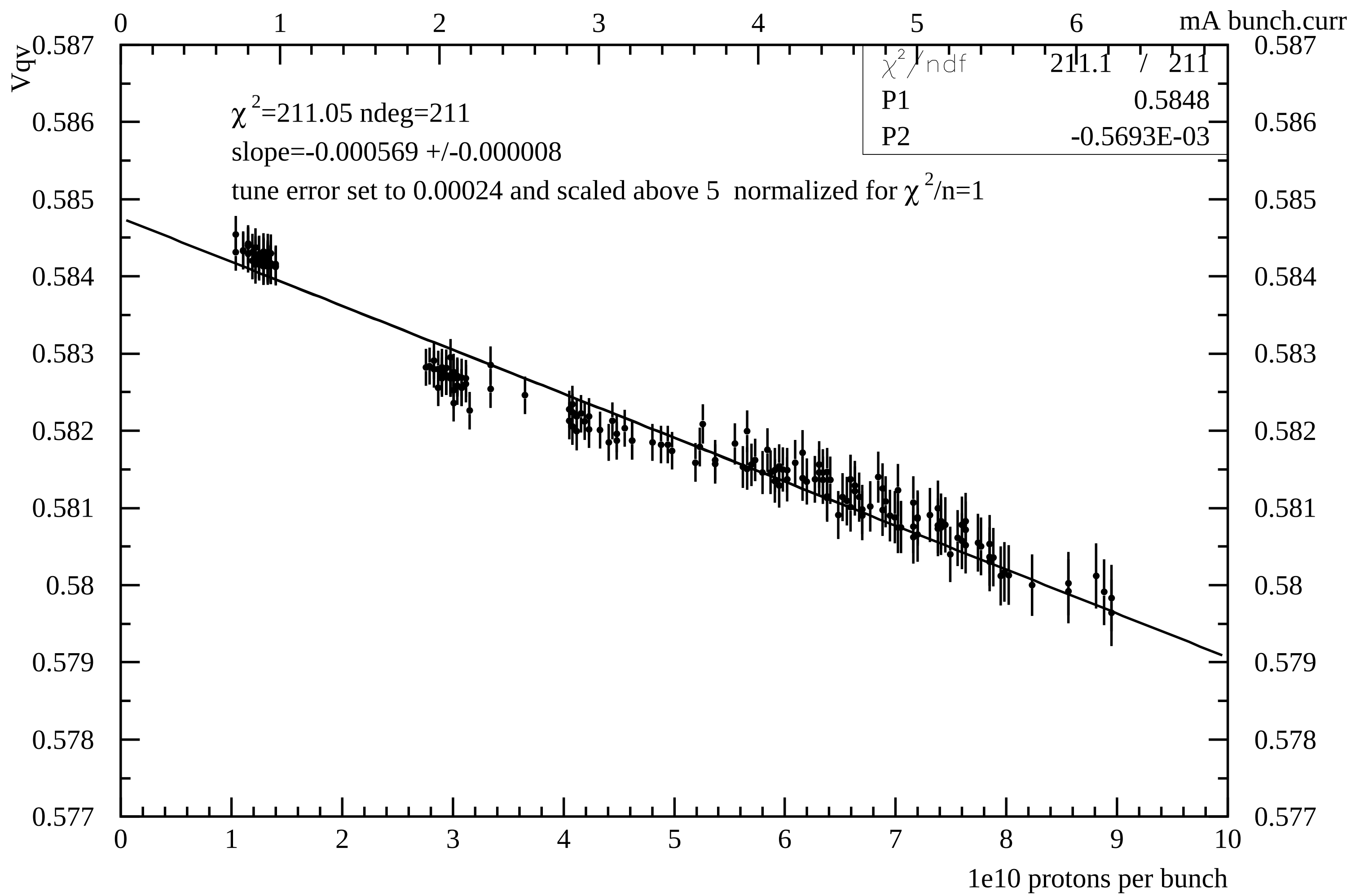
- Impedance measurements in the CERN SPS
- Coherent and Incoherent tune shifts for a flat chamber
- Resistive wall instability: low-frequency effects
- Simulations of electron cloud build-up
- Measurements of elastically reflected low-energy electrons
- Electron-cloud driven instabilities and cures



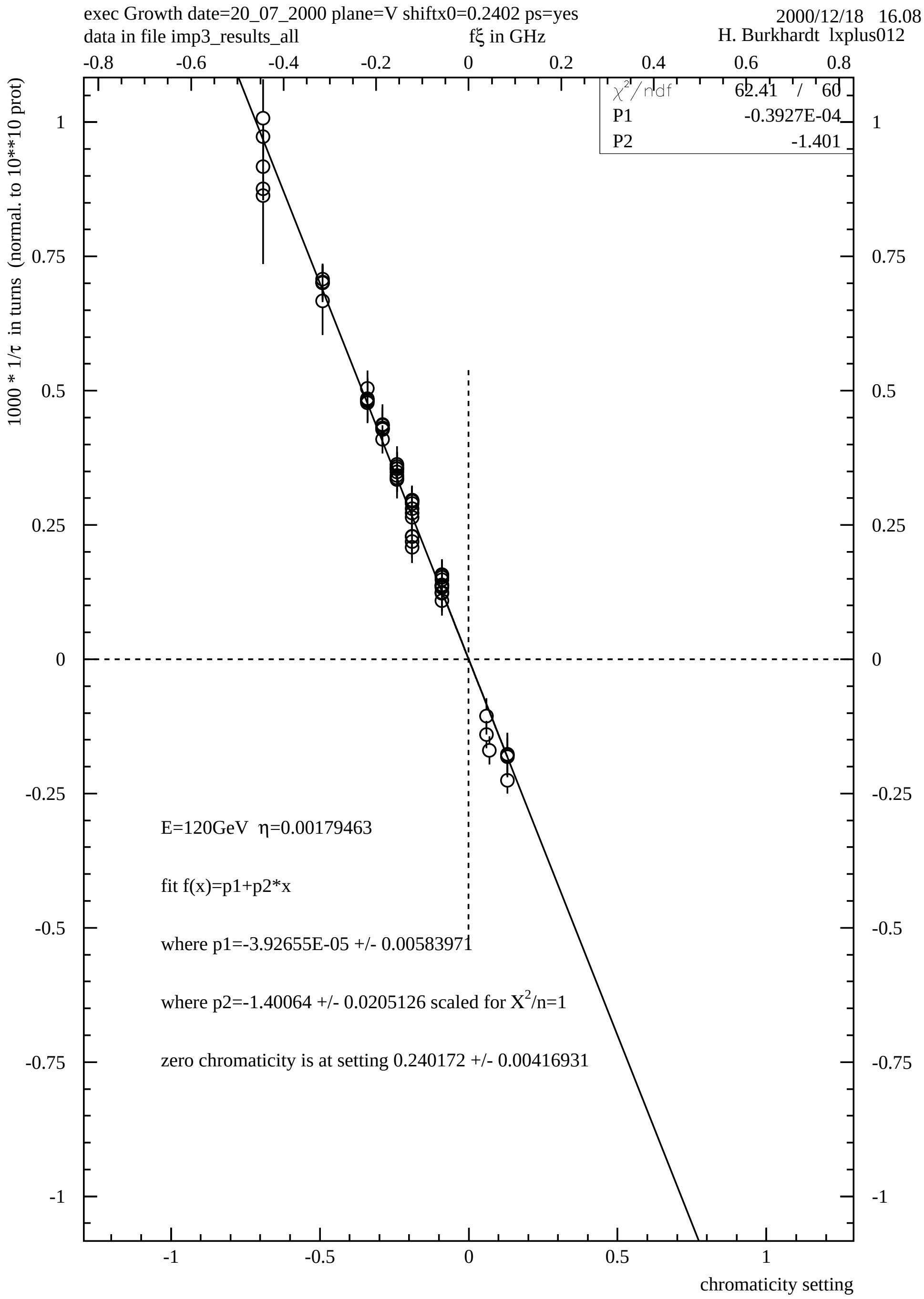
Scope signals illustrating the rf ramp and bunch shortening prior to the SPS impedance measurement. Top trace: rf voltage; medium trace: peak current signal (inversely proportional to the bunch length); bottom trace: dc current signal. The initial decay of both peak and dc currents indicates some beam loss immediately after injection. (G. Arduini et al., PAC2001).



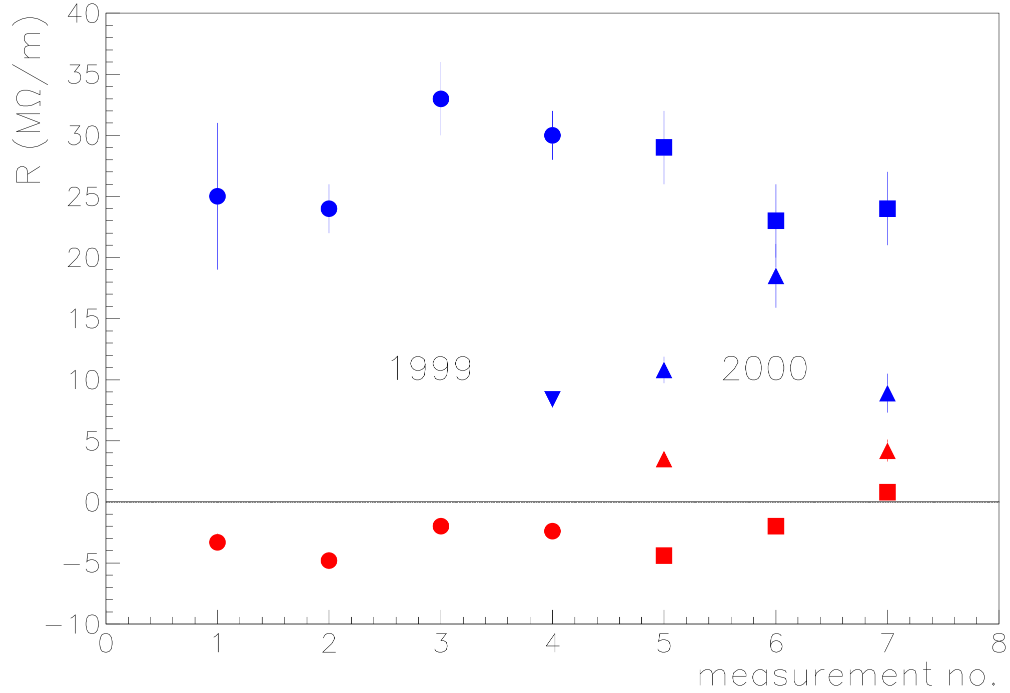
R.m.s. bunch lengths in ns measured as a function of bunch population in 10^{10} for the three SPS study periods in 2000. The values correspond to the standard deviation of a Gaussian fitted to the signal from a wide-band pick up. The vertical error bars reflect the r.m.s. spread of several measurements taken at the same intensity. (G. Arduini et al., PAC2001).



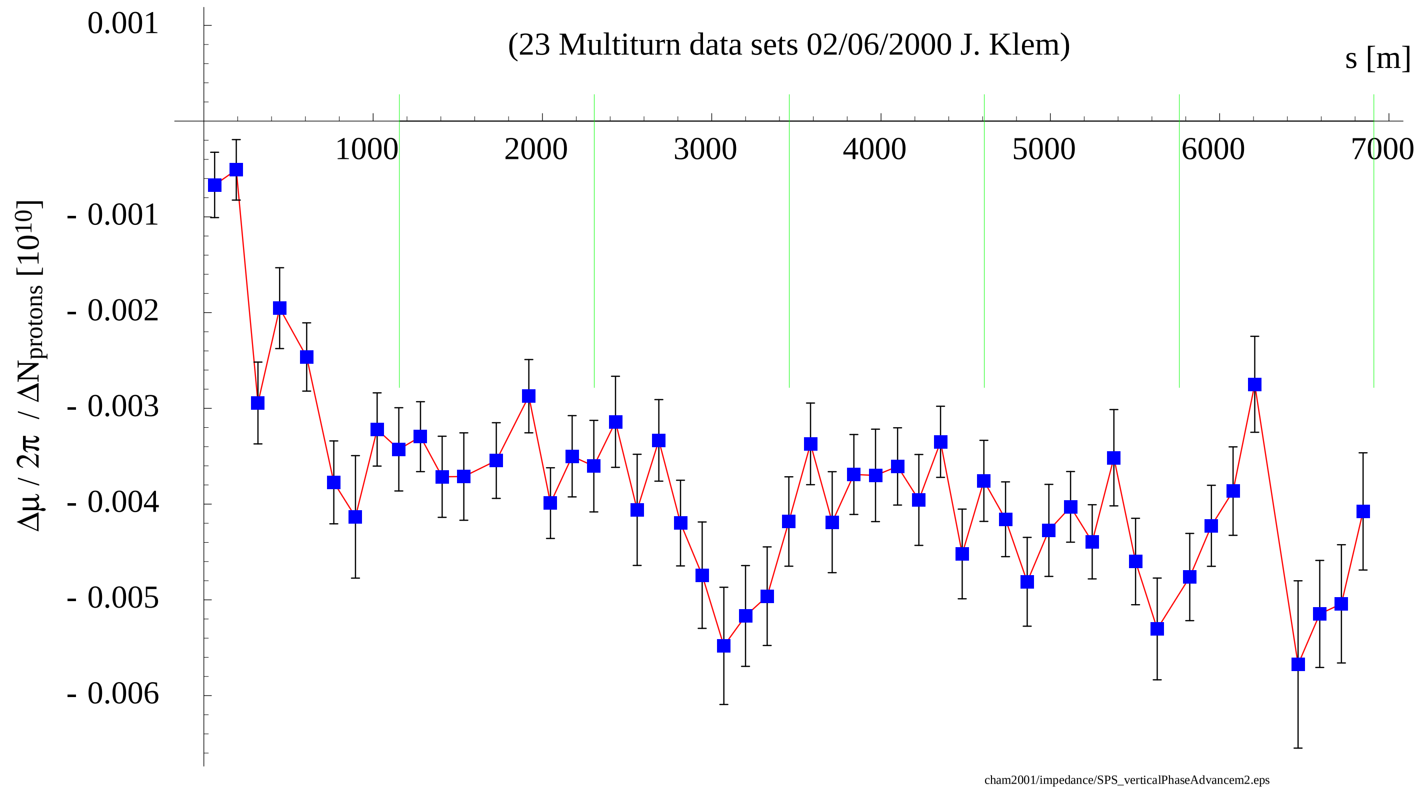
Vertical coherent tune shift versus bunch population measured in the SPS at 120 GeV (19/07/00). (G. Arduini et al., PAC2001).



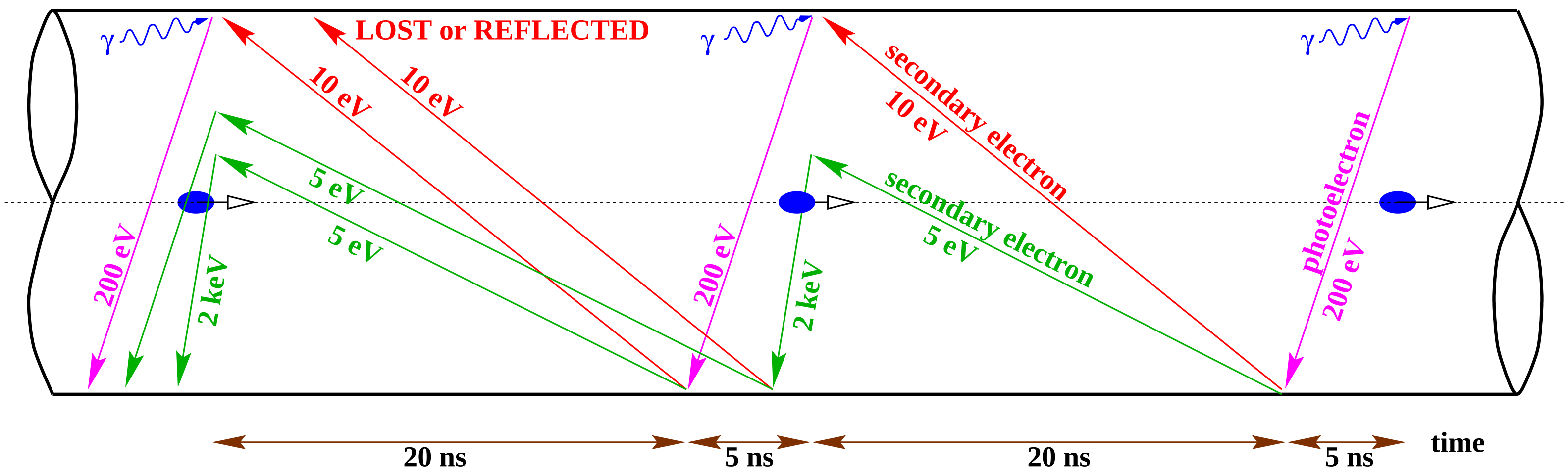
Growth rate of vertical head-tail mode (in units of 10^{-3} turns^{-1}) measured as function of chromaticity $\xi = Q'/Q = \frac{\Delta Q}{Q} / \frac{\Delta p}{p}$ in the SPS at 120 GeV on 19/07/2000 (G. Arduini et al., PAC2001).



Impedance values $R_{\perp}^{(\Delta Q)}, x(y)$ inferred from all SPS measurements in 1999 (first 4) and 2000 (the last 3), by fitting to a broadband resonator with frequency $\omega_r/2\pi = 1.3$ GHz and $Q = 1$. Triangles are the $R_{\perp}$ values obtained from the growth rate measurements; squares and circles represent $R_{\perp}^{\Delta Q}$ inferred from the coherent tune shift. The 6th measurement was performed at 120 GeV, all others at 26 GeV (G. Arduini et al., PAC2001).

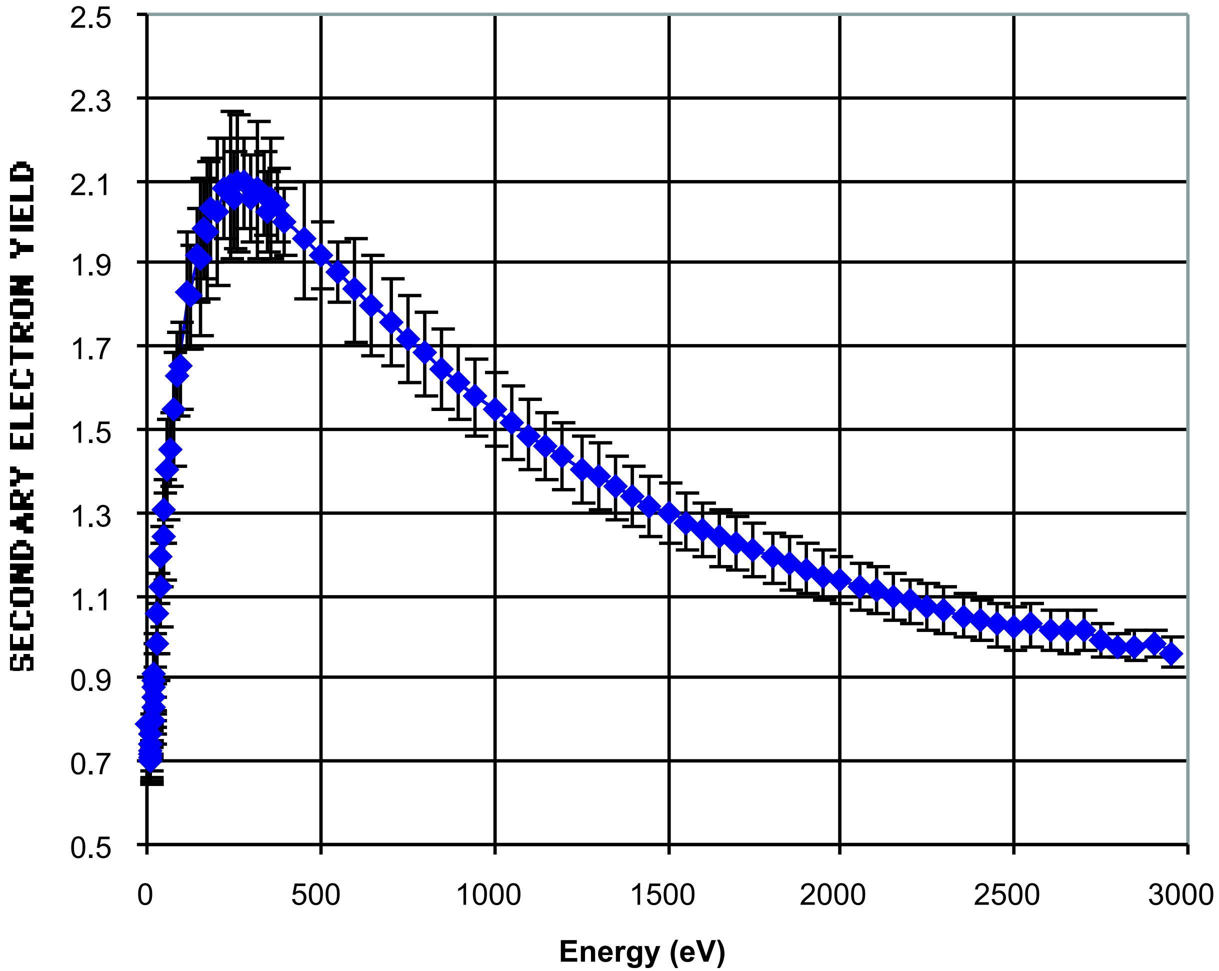


Change of the accumulated vertical phase advance around the SPS ring with bunch intensity, suggesting local impedance contributions (steps) in the injection, rf and extraction area, located roughly at 1000, 3000 and 6000 m (G. Arduini et al., PAC2001).

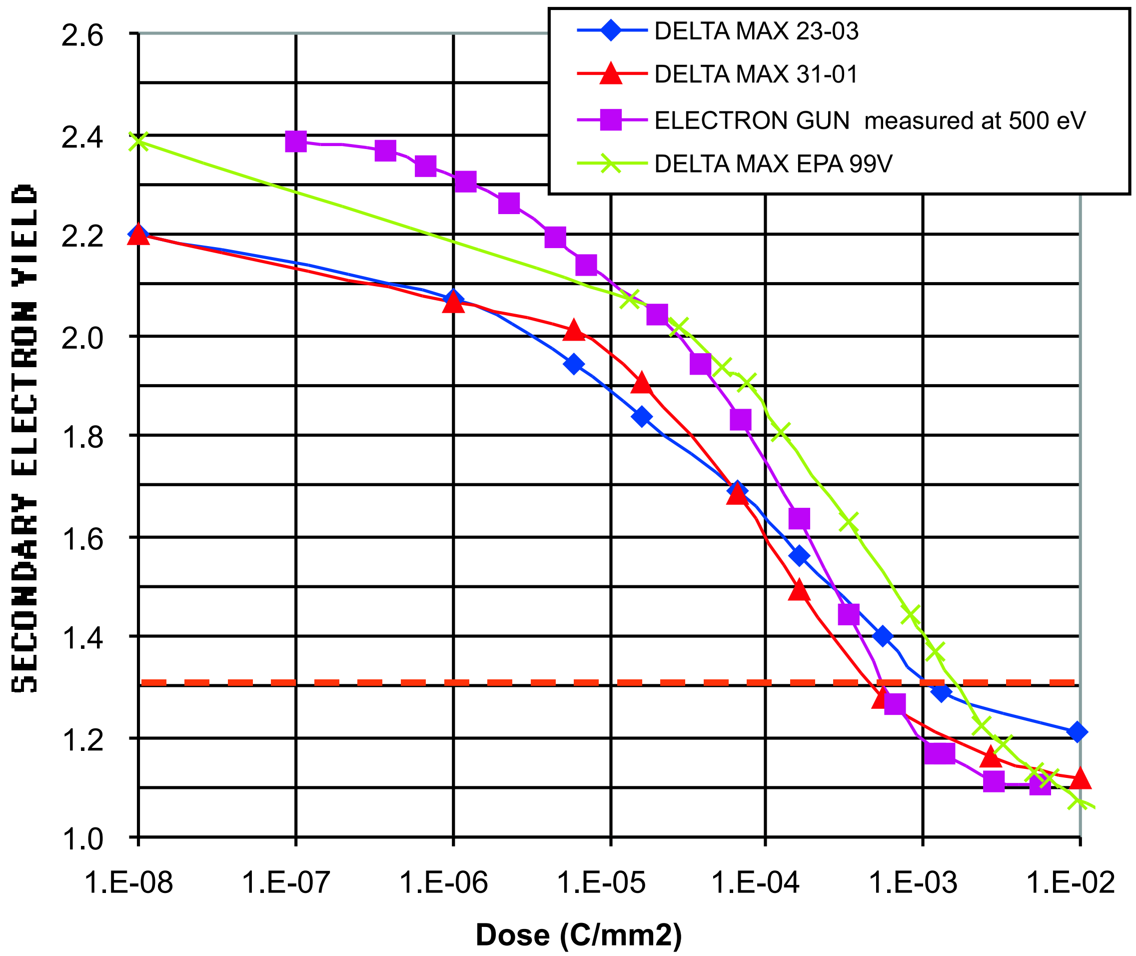


- In the LHC above 3.5 TeV, photoelectrons created at the pipe wall are accelerated by proton bunches up to 200 eV and cross the pipe in about 5 ns. Slow secondary electrons survive until the next bunch. This may lead to an electron cloud build-up with implications for *beam stability*, *emittance growth*, and *heat load on the beam screen*.
- In the LHC at 7 TeV each proton generates 10^{-3} photoelectrons/m, while in the SPS the primary yield is dominated by *ionization of the residual gas* and, at 20 nTorr, it is only 10^{-7} electrons/m.
- The electron cloud build-up is a *non-resonant single-pass effect* and may take place also in the *transfer lines* and in the *LHC at injection*.

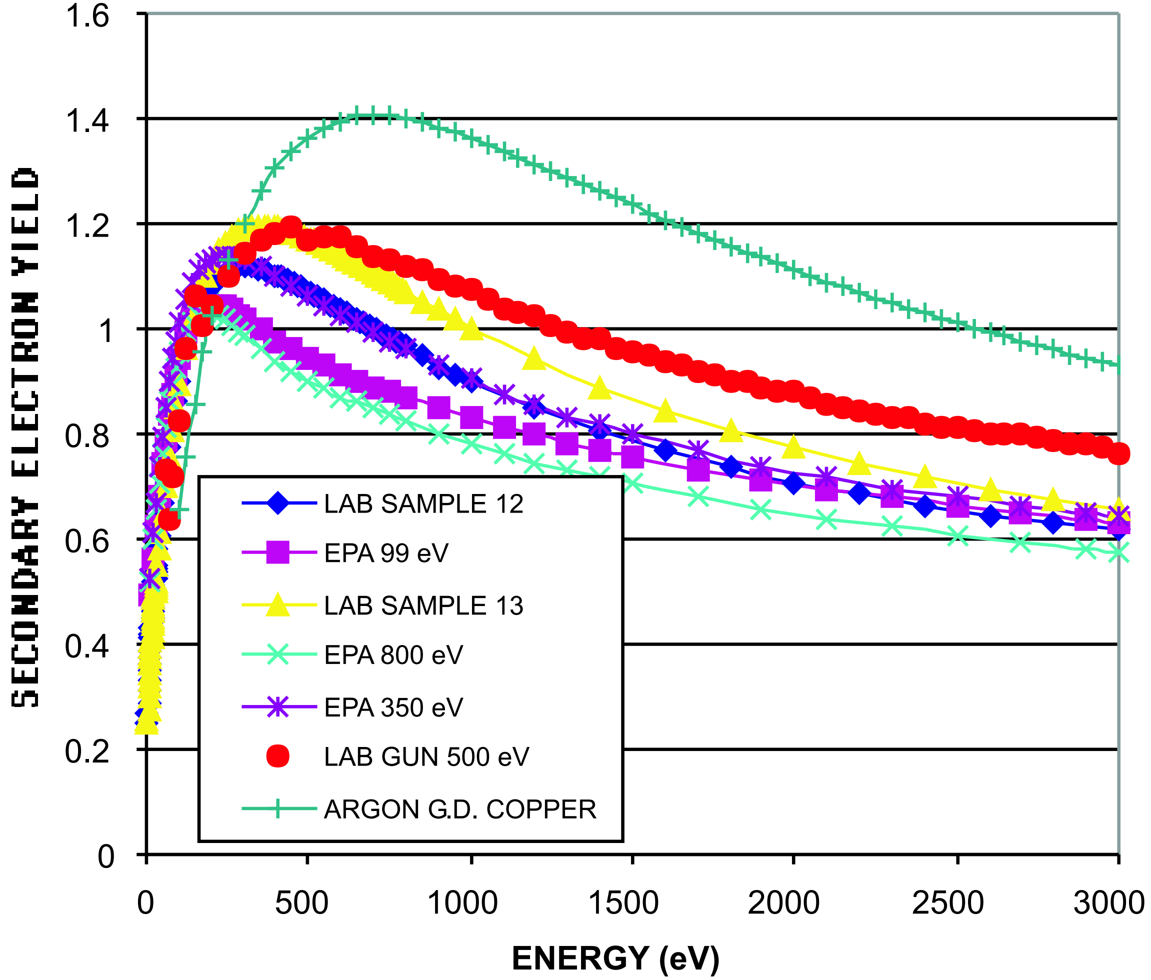
- Electrons form a time-dependent cloud extending up to the pipe wall:
  - in field free regions this cloud is almost uniform
  - in the dipoles, electrons spiral along the magnetic field lines and tend to form two stripes at about 1 cm away from the beam axis
- Depending on the *bunch spacing*, a significant fraction of secondary electrons is *lost* in between two successive bunch passages. A minimum gain is thus required for cloud amplification and this corresponds to a *critical secondary electron yield*, typically around $\delta_{\rm max} = 1.3$ for nominal LHC beams
- Electron bombardment is also an effective solution to reduce secondary emission. Lab measurements indicate that *the required electron dose is of a few* $\rm mC/mm^2$. The dose accumulated in 55 hours of SPS operation with LHC beam in April 2000 is $\underline{0.5\ \rm mC/mm^2}$
- Electron scrubbing in the LHC will take about *one week at* 0.2 W/m (limited cryogenic power), using a special proton beam with *reduced intensity* or *increased bunch spacing*, possibly with *weak satellite bunches*. Surface conditioning is also possible by photon scrubbing



Average Secondary Electron Yield versus primary electron energy for 25 ‘as received’ copper samples (courtesy N. Hilleret, 2001).



Measured reduction of Secondary Electron Yield with incident electron dose for copper samples (courtesy N. Hilleret, 2001).



SEY versus primary electron energy for 6 fully conditioned copper samples (10 mC/mm^2) (courtesy N. Hilleret, 2001).

Magnitude of e^- cloud in the SPS

(1) from pressure rise [O. Gröbner]:

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

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

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

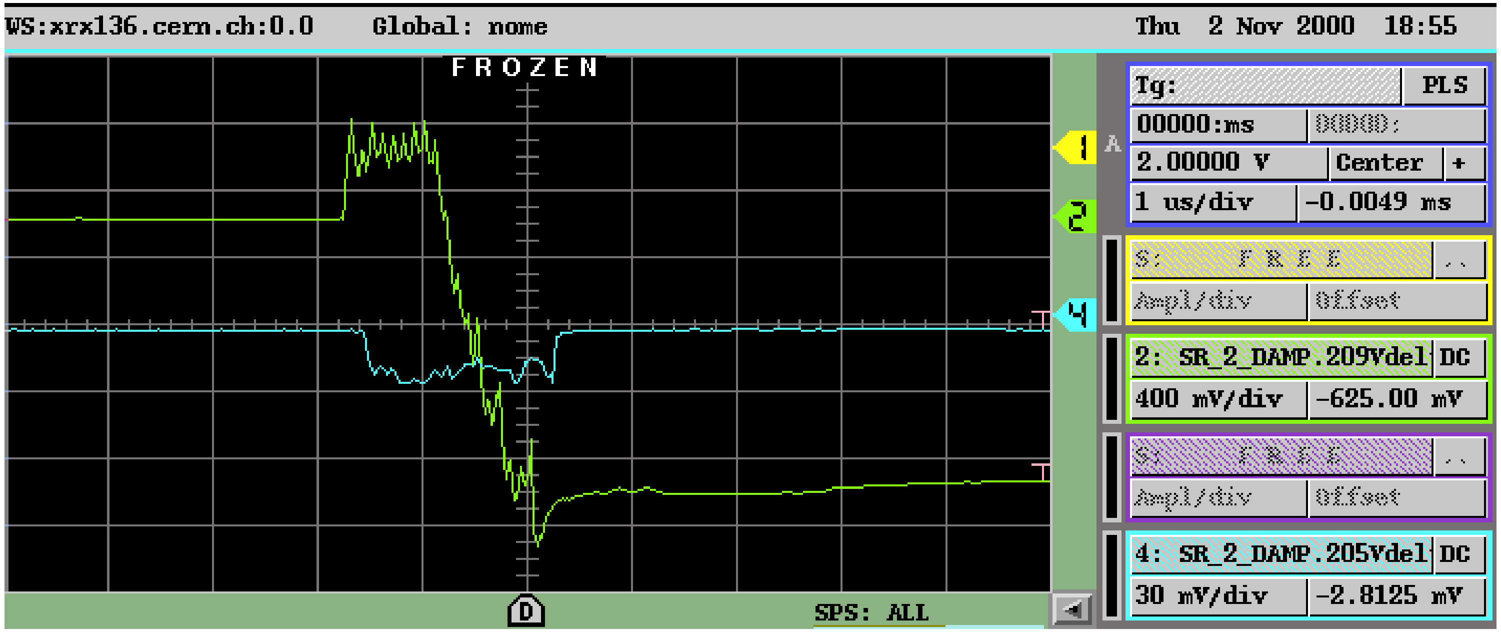
$$\frac{d\lambda_e}{ds} \approx 10^{10} \frac{\text{electrons}}{\text{bunch} - \text{train meter}}$$

(2) from damper pick-up signal [W. Höfle]:

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,

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

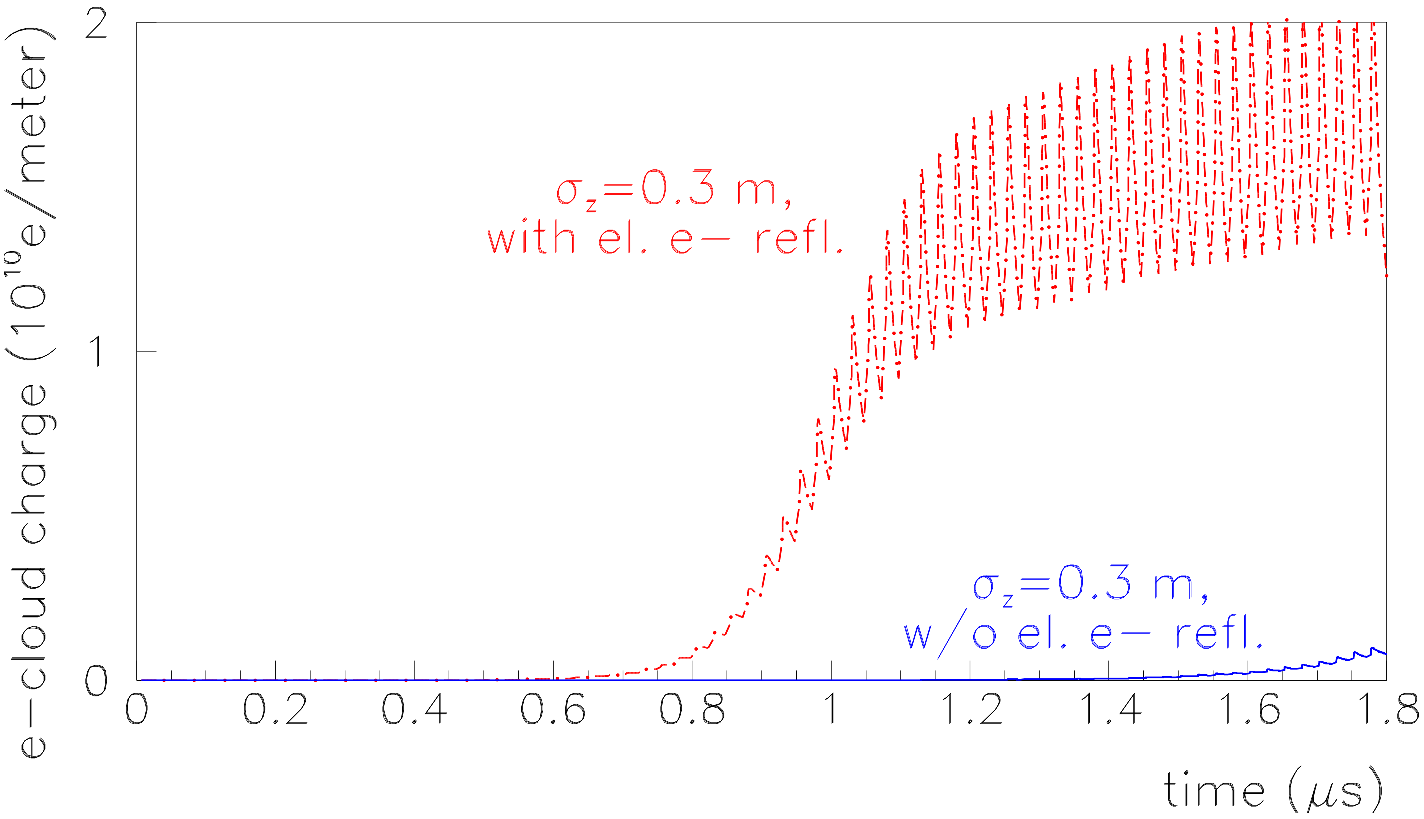
The two estimates are consistent.



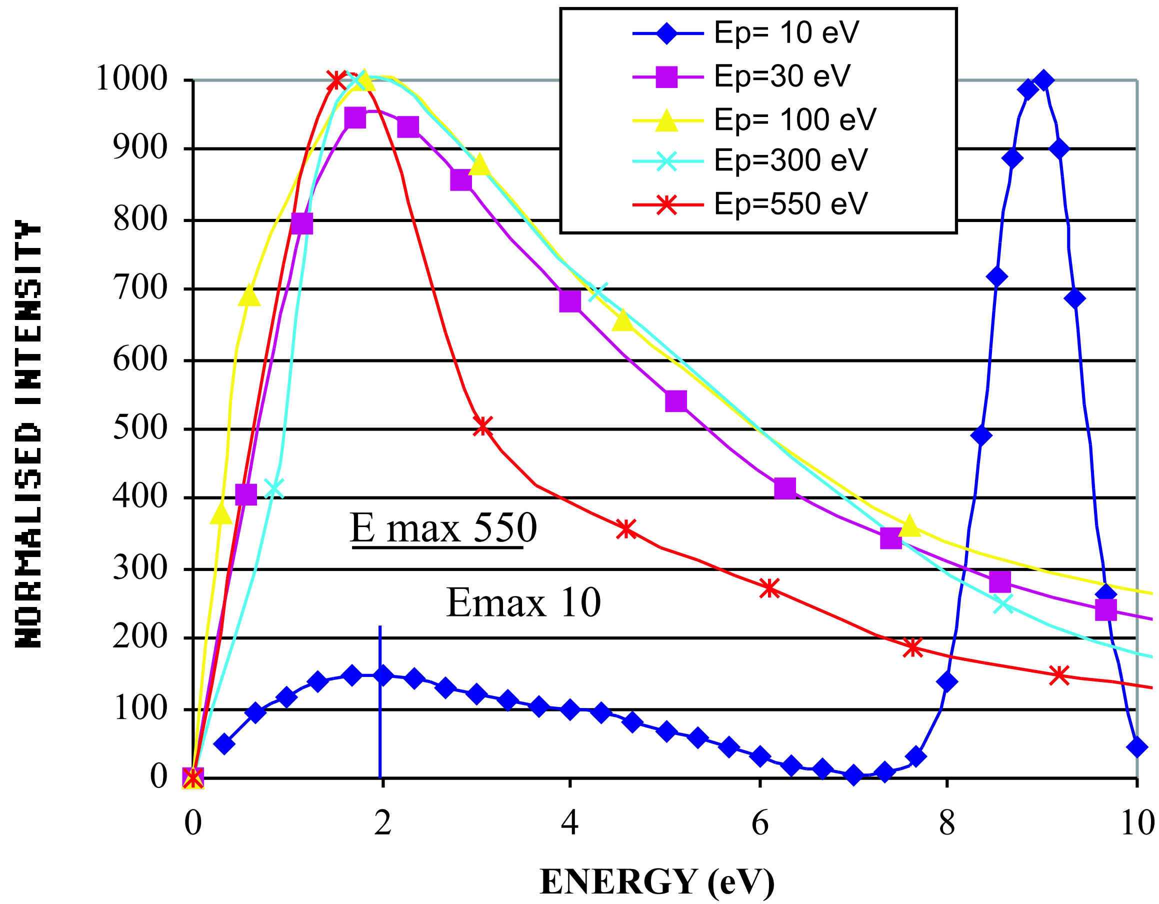
Sum and difference signal on damper pick-up during the passage of an LHC batch in the SPS ($1\mu s$/div) (courtesy W. Hofle, 2001).

symbol	LHC (init.)	LHC (fin.)	SPS	PS
E [GeV]	7000	7000	26	26
N_b	10^{11}	10^{11}	10^{11}	10^{11}
$\sigma_{x,y}$ [mm]	0.3	0.3	3.0, 2.3	2.4, 1.3
σ_z [cm]	7.7	7.7	30	30
$\beta_{x,y}$ [m]	80	80	40	15
$h_{x,y}$ [mm]	22, 18	22, 18	70, 22.5	70, 35
$\delta_{\max}$	1.9	1.1	1.9	1.9
$\epsilon_{\max}$ [eV]	240	170	300	300
R [%]	10	5	100	100
$d\lambda_e/ds$ $[10^{-6}\ \mathrm{m}^{-1}]$	1230	615	0.25	0.05

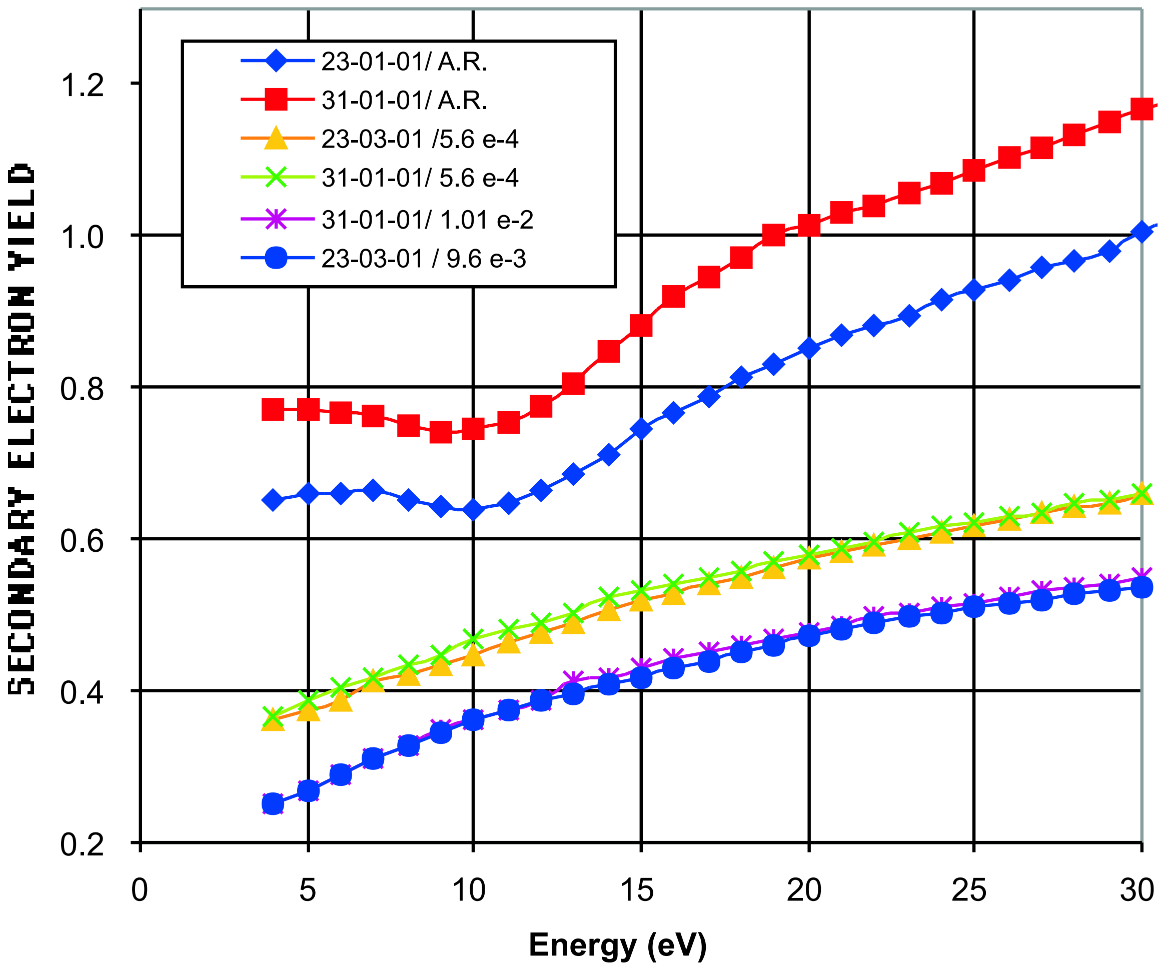
Simulation parameters for LHC, SPS, and PS (F. Zimmermann, Chamonix 2001).



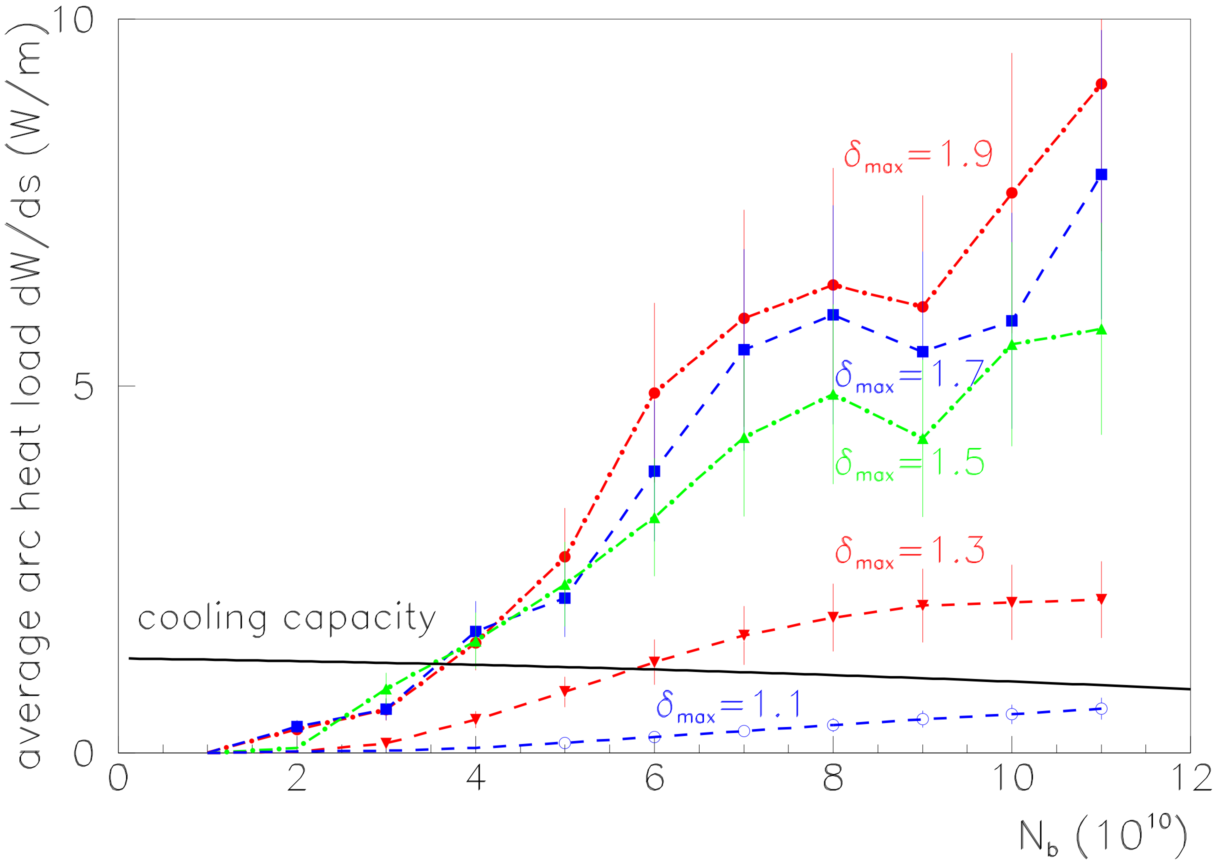
Simulated electron-cloud build up for an SPS dipole chamber, with and without elastic electron reflection. Saturation at $\lambda_{e,\mathrm{sat}} \sim N_b/L_{\mathrm{sep}} \approx 1.3 \times 10^{10}\ \mathrm{m}^{-1} \rightarrow$ 'neutralization' density $\rho_{\mathrm{sat}} \approx N_b/(\pi h_x h_y L_{\mathrm{sep}}) \approx 3 \times 10^{12}\ \mathrm{m}^{-3}$. (F. Zimmermann, PAC 2001).



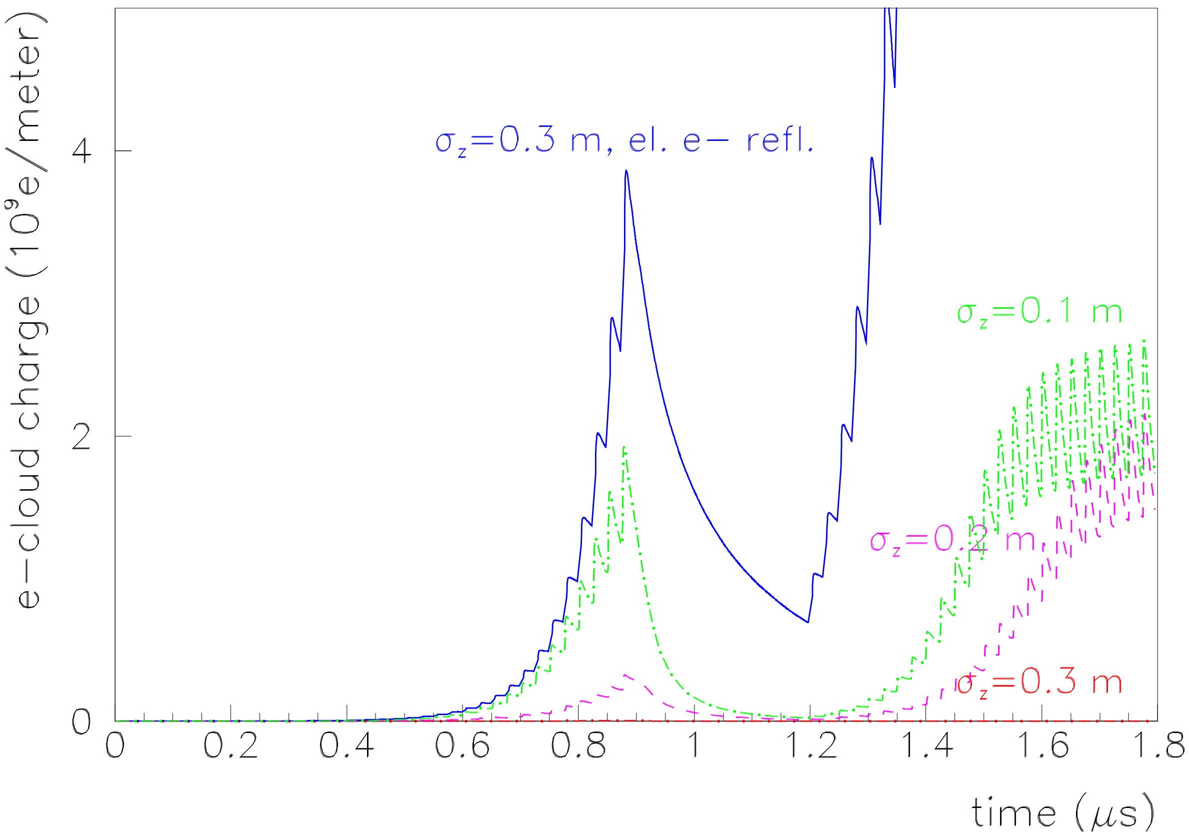
Secondary electron energy distribution below 10 eV for conditioned copper and different primary electron energies (courtesy N. Hilleret, 2001).



Secondary Electron Yield at primary energies lower than 30 eV for several copper samples (courtesy N. Hilleret, 2001).

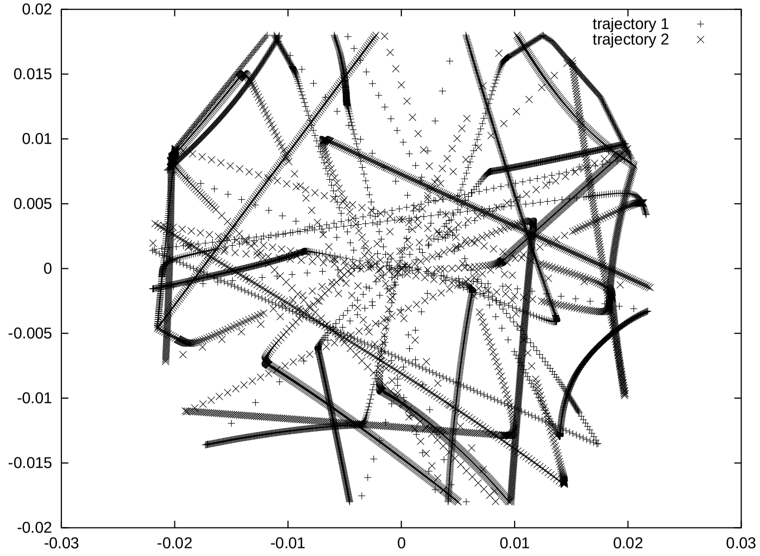


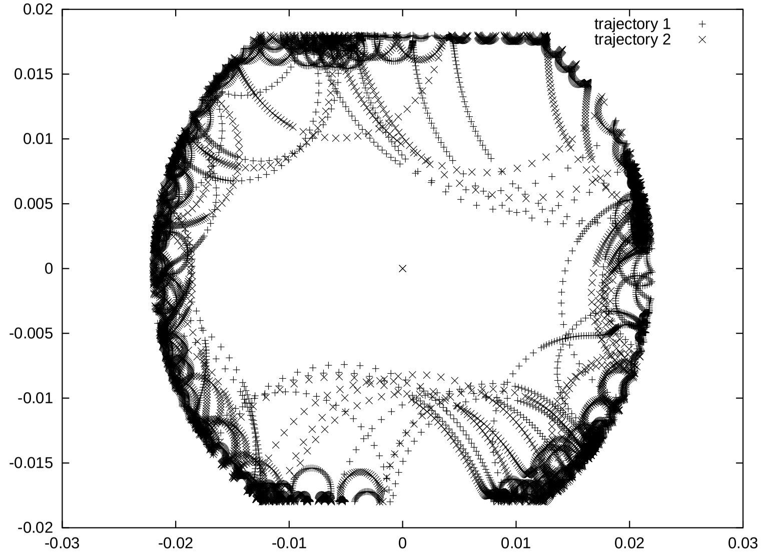
Simulated heat load in the LHC arcs and available cooling capacity of the cryogenics system, vs bunch population N_b, for different maximum SEY $\delta_{\max}$ at $\epsilon_{\max} = 240$ eV, with photon reflectivity $R = 5\%$, photoemission yield $Y = 5\%$, 25-ns bunch spacing, and including elastic electron scattering on the chamber wall. (F. Zimmermann, Chamonix 2001).



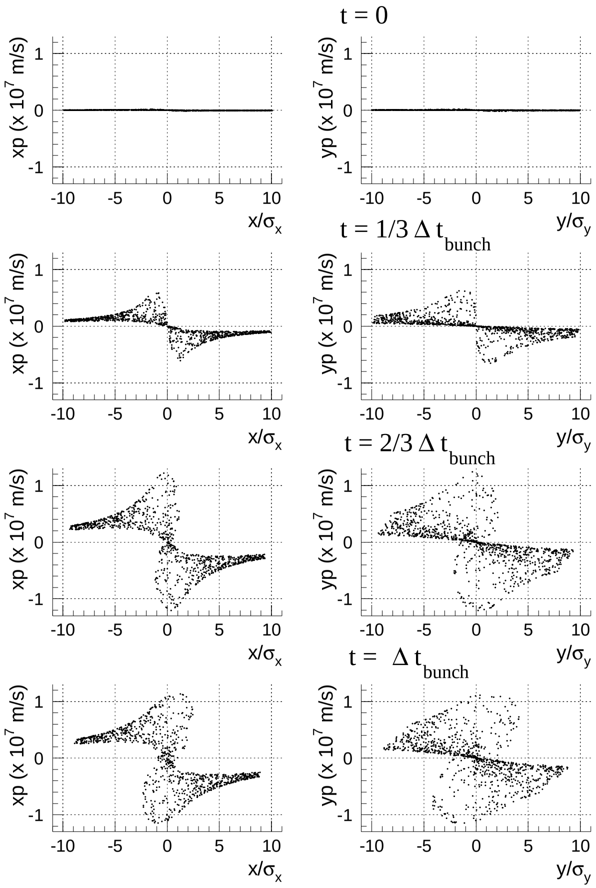
Time evolution of the electron line density during the passage of an LHC batch through an SPS dipole chamber with a 12-bunch hole after 36 bunches, for various values of the rms bunch length and with or without elastic electron scattering. At the end of the batch, the top curve has approached a value of 1.4×10^{10} m^{-1}. (F. Zimmermann, Chamonix 2001).

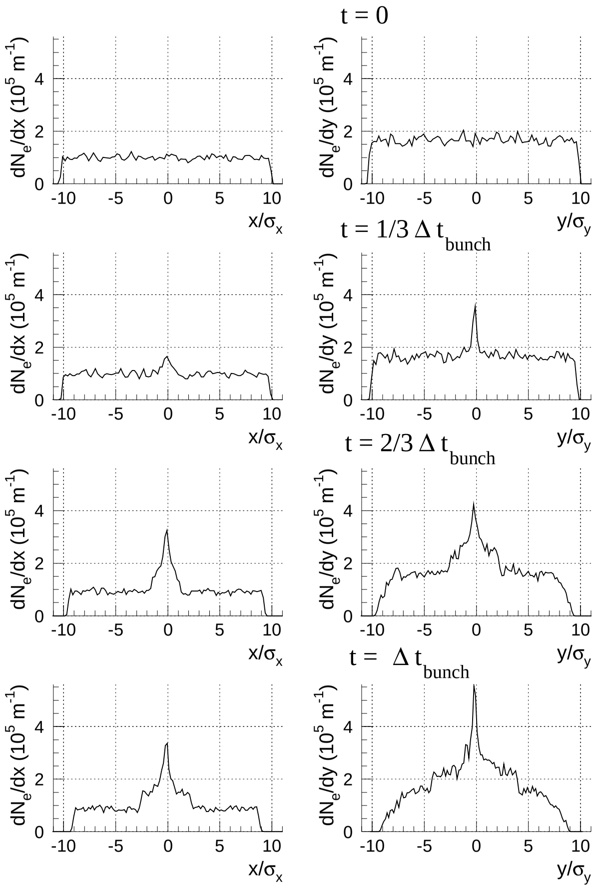
Effect of a weak solenoid





Sample transverse electron trajectories in a field-free region (left) and in a 50-G solenoid (right). (F. Zimmermann, Chamonix 2001).





Snapshots of the horizontal and vertical electron phase space (left) and their projections onto the position axes (right). (G. Rumolo, Chamonix 2001).

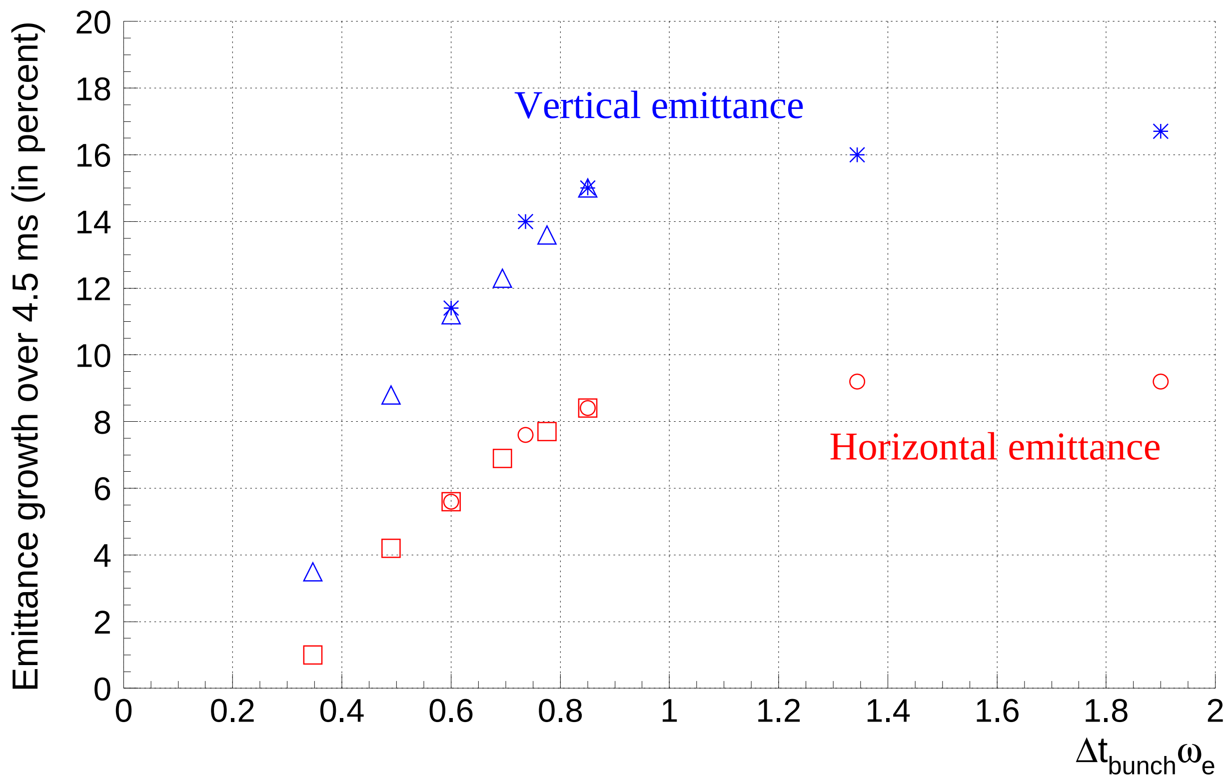
Electron-Cloud driven Single-Bunch Instability

- adapt FBII theory
  $1/\tau \approx 4\pi\rho_e N_b^{1/2} r_p r_e^{1/2} \sigma_z^{1/2} \sigma_x \beta c / (\gamma \sigma_y^{1/2} (\sigma_x + \sigma_y)^{3/2} \propto N_b^{3/2} \sigma_z^{1/2} / L_{\rm sep} / \sigma_y^{1/2}$ (F. Zimmermann, CERN-SL-Note-2000-004).

- 2-particle model with length
  $W_0 = \approx 8\pi\rho_e C/N_b \approx 8C/(\pi L_{\rm sep} h_x h_y)$ (for $\sigma_z \omega_e > c\pi/2$); rise time estimates for BBU, HT and FHT instabilities (K. Ohmi & F. Zimmermann, PRL 85, 3821).

- wake field simulation & either TMCI calculation or threshold for fast blow up (K. Ohmi, et al., HEACC'01).
  $N_{b,\rm thr} \approx 5.3 Q_R \gamma Q_s (\omega_R \sigma_z / c)^2 / (c R_s / Q) / \beta_y / r_e \propto Q_s \omega_R^2 \sigma_z^2 / \rho_e$

- various simulation codes microbunches, soft Gaussian, PIC codes (G. Rumolo et al, K. Ohmi, PAC'01).

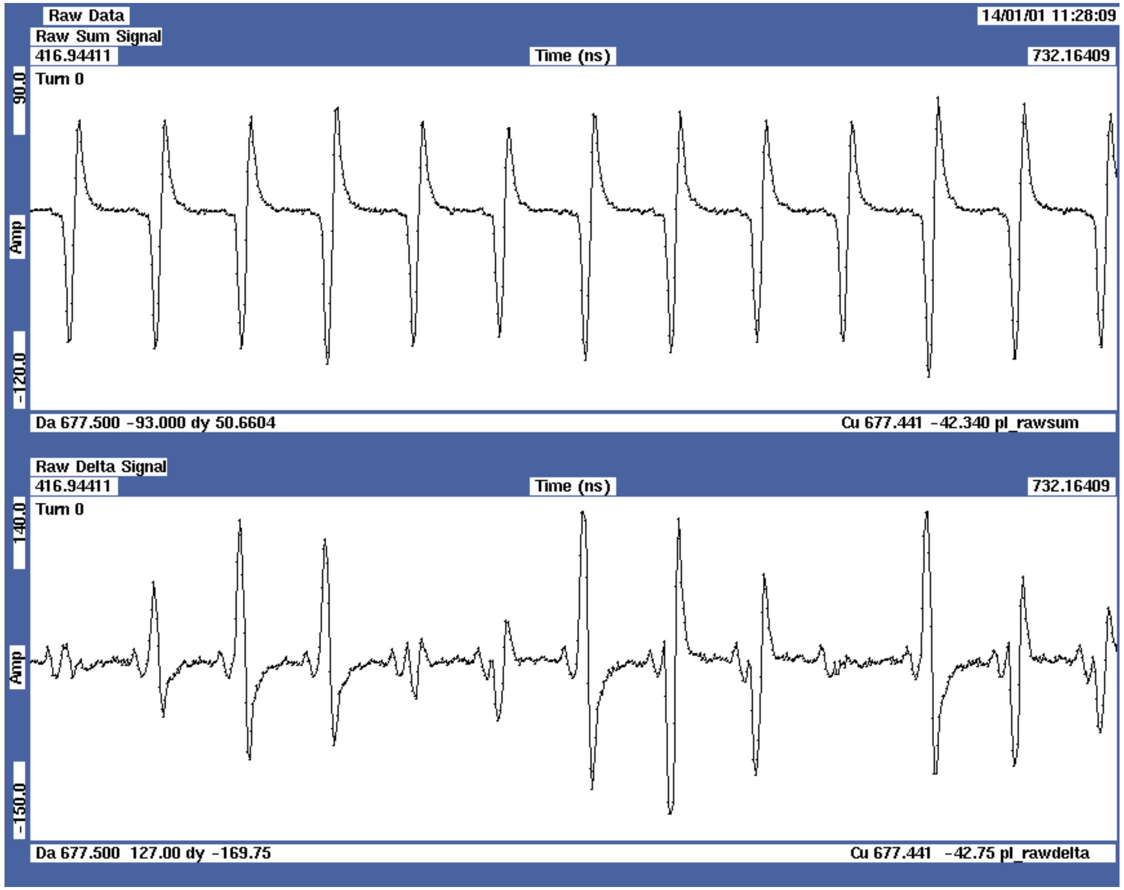


Emittance growth vs. no. of electron oscillations inside bunch for the SPS, comparing variations of σ_z and N_b (different symbols). (G. Rumolo, Chamonix 2001).

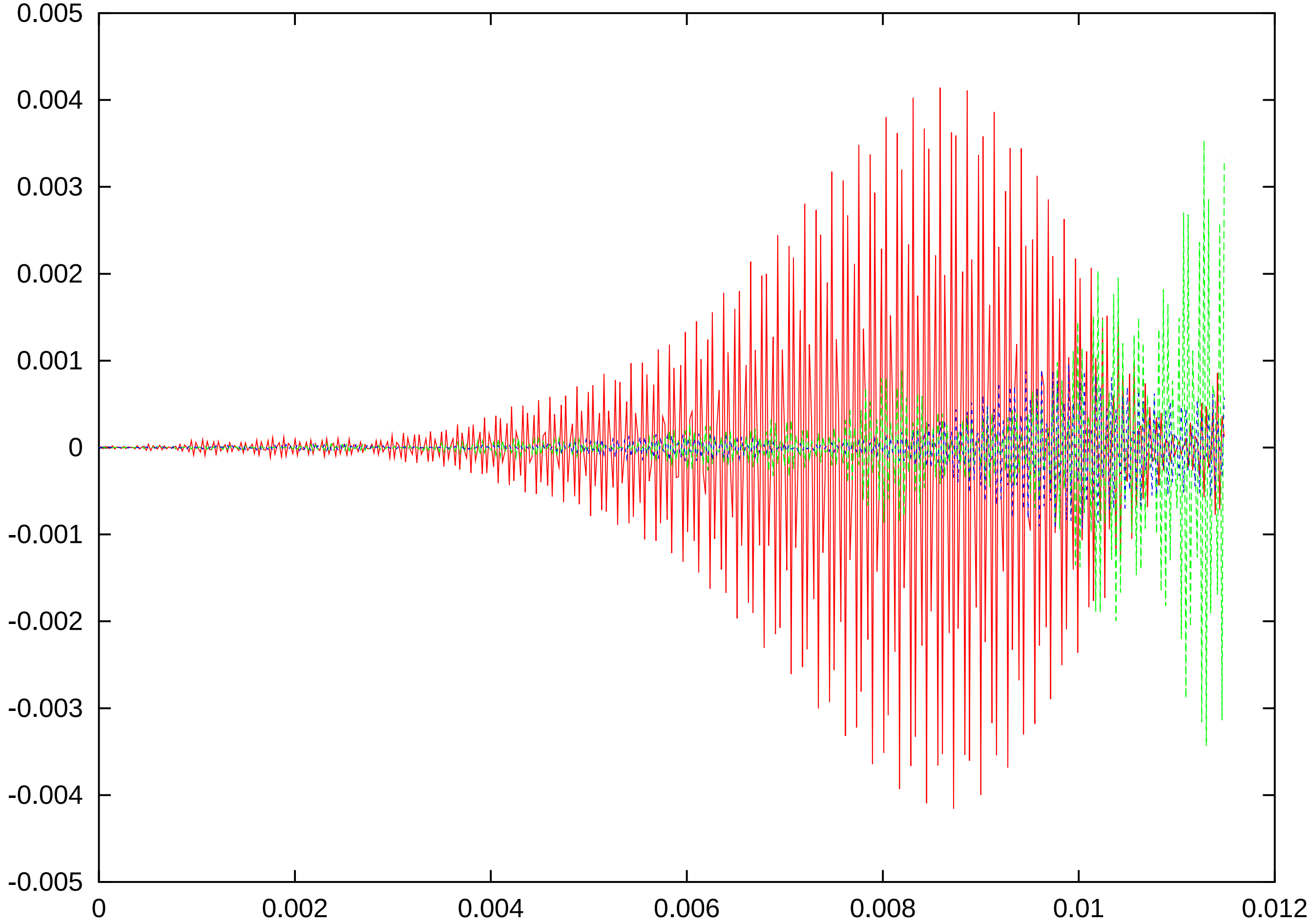
Estimated electron-cloud driven TMCI thresholds

accelerator	PEP-II	KEKB	PS	SPS	LHC	PSR	SNS
e^- osc./bunch $n_{osc} \equiv \omega_e \sigma_z / (\pi c)$	0.8	1.0	1	0.75	3	34	970
TMCI threshold ρ_e [10^{12} m^{-3}]	1	0.5	5	0.25	3	(0.6)	(0.5)
density ratio $\rho_{e,sat}/\rho_{e,thresh}$	**19**	**4**	0.35	**11**	**4**	(92)	(27)

(F. Zimmermann, PAC 2001)



Detail of the sum (top) and delta (bottom) signals at the SPS provided by the wide-band transverse pick-up in the vertical plane. Head-tail motion inside the bunches is visible. (G. Arduini, PAC'01). Wake period determined from measured head-tail motion: $\lambda_{e^-,\mathrm{wake}} \approx \sigma_z$ (K. Cornelis, Chamonix'01).



PIC code simulation of the vertical centroid position for an SPS bunch over 500 turns: broad-band impedance, e-cloud + broad-band impedance, and broad-band impedance + space charge. (G. Rumolo et al, PAC'01).

Cures

- reduce number of electrons
  antechamber (PEP-II), surface coating (PEP-II, PSR), sawtooth chamber (LHC), bunch length (PS, SPS), surface scrubbing (LHC), N_2 discharge (SPS),...

- suppress/modify electron propagation
  weak solenoids (KEKB, PEP-II), clearing electrodes (ISR), special filling schemes (PEP-II), satellite bunches

- raise instability thresholds
  octupoles (KEK PF, BEPC), large chromaticity (BEPC, KEKB, SPS), TMCI feedback? (VEPP-4M), lattice detuning, bunch length

Conclusions and recommendations

- We have *experimental evidence* for an electron cloud effect in the SPS with LHC type beams (25 ns spacing).
- SPS vacuum observations *clearly indicate a reduction of pressure rise after electron scrubbing,* but this is not (yet) accompanied by a corresponding increase of threshold intensity for beam instability and emittance growth $\Longrightarrow$ *accumulate more electron dose in 2001*
- Further lab measurements are required to clarify the issue of *low energy reflected electrons* to be used in SPS and LHC simulations. LHC scrubbing scenarios should be further investigated: *solenoids to be foreseen in cold straight sections?*

- Electron cloud impedance has been measured in qualitative agreement with simulations. The interplay between conventional and electron cloud impedance remains to be understood
- Special bypass will be installed in the SPS for *in situ measurements of SEY and heat load* (possibly in cold conditions), in addition to 'Rosemberg' electron probes
- Beam observations will profit in 2001 of better feedback performance, that should enable us to *suppress dipole beam instability*
- It will be necessary to coordinate lab measurements, SPS and LHC diagnostics, vacuum and beam observations