Electron Cloud and Ion Effects

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Introduction

- Understanding and control of impedances has allowed to design machines with higher and higher brilliance.
- Since several years now ion and electron effects have been observed and are limiting performances of existing machines (ISR, KEK-B, PEP-II, PSR, SPS)
- Understanding of these phenomena (by measurement and simulation) is mandatory for the design of future (high intensity and high brilliance) machines

Outlook

- Electron and ion build-up
  - Positively charged beams
  - Negatively charged beams
- Electron cloud effects
- Ion effects

The original sin

- **Primary electron production**
  - Residual gas ionisation (γ_{beam} >> 1)

$$\frac{d^2 N_{ion}}{ds\, dt} \propto \lambda_{beam}\, \sigma_{ion}\, \rho_{gas}$$

σ_{ion}= 1-100 Mbarn on CO

  - Photo emission (if $E_c \propto \gamma^3/\rho$ > few eV)

$$\frac{d^2 N_{phel}}{ds\, dt} \propto \frac{Z^2_{beam}\, \gamma_{beam}\, \lambda_{beam}}{\rho} Y^*$$

LHC

Y^*=0.02-0.1

  - Beam losses (in proton machines)

$$\frac{d^2 N_{loss}}{ds\, dt} \propto \frac{r_{loss}\, \lambda_{beam}}{C} Y_{ep}$$

LHC PSR

$r_{loss}=10^{-8} - 10^{-6}$; $Y_{ep}^*=100/\gamma^{0.35}$

The original sin

- **Primary electron production**
  - Mainly by Photoemission in lepton machines (ϕ- and B- factories, synchrotron light sources) and very high energy proton machines (LHC, VLHC,…). For the LHC at 7 TeV ~ 10^{15} e^-/m/s. Comparable to B-factories.
  - By Residual Gas Ionisation in high intensity proton machines intermediate energy (CERN PS,CERN SPS,LHC at inj), for LHC and SPS 10^8 – 10^9 e^-/m/s
  - By Beam losses in high intensity proton machines at low energy (PSR), for PSR 10^{14} e^-/m/s
- **Primary ion production**
  - Residual gas ionisation

Electron and ion motion

- **Coasting beams:**
  - (round) beam potential well:

$$V(r) = \frac{Z_{beam} e\lambda_{beam}}{2\pi\varepsilon_0} \begin{cases} -\frac{r^2}{2a^2} + \frac{1}{2} + \ln\left(\frac{r_0}{a}\right) & r \le a \\ \ln\left(\frac{r_0}{r}\right) & r_0 \ge r \ge a \end{cases}$$

Depth of the pot. well a few kV in the ISR

Ion induced pressure instability

  - Electrons (ions) will be trapped in the positively (negatively) charged beam potential and will oscillate with frequency (r<a):

$$f_{e\,x,y} = \frac{c}{2\pi}\sqrt{\frac{r_e \lambda_{beam} Z_{beam}}{2a^2}}$$

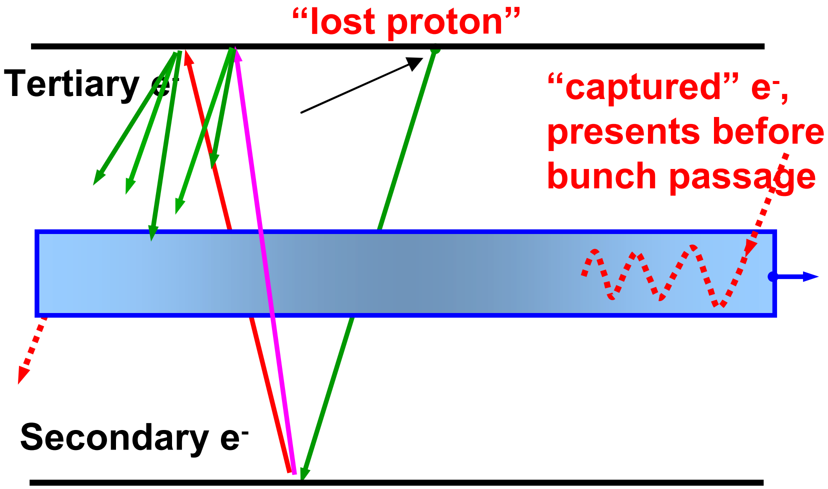
  - …ions (electrons) will be repelled at the walls

Bunched beams (+)

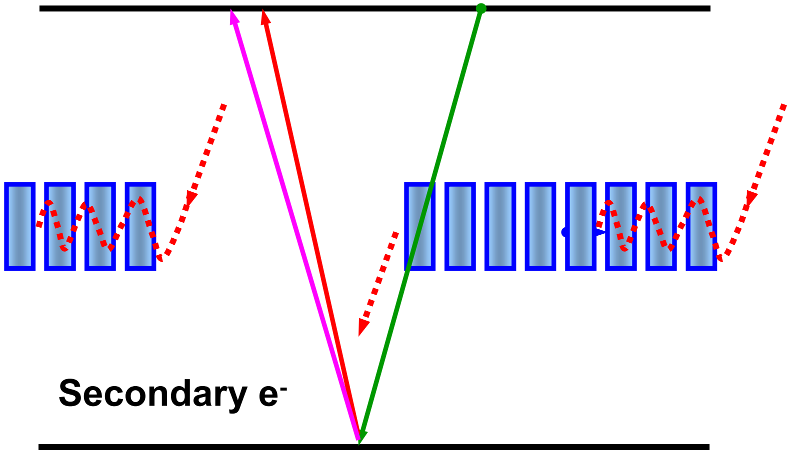
◆ **Electrons, possible schematisations:**

Intense bunch => $1/f_e << \tau_{bunch}$ (PSR)

Trailing edge multipacting



Weak bunch => $1/f_e >> s_{bunch}$ (SPS FT)

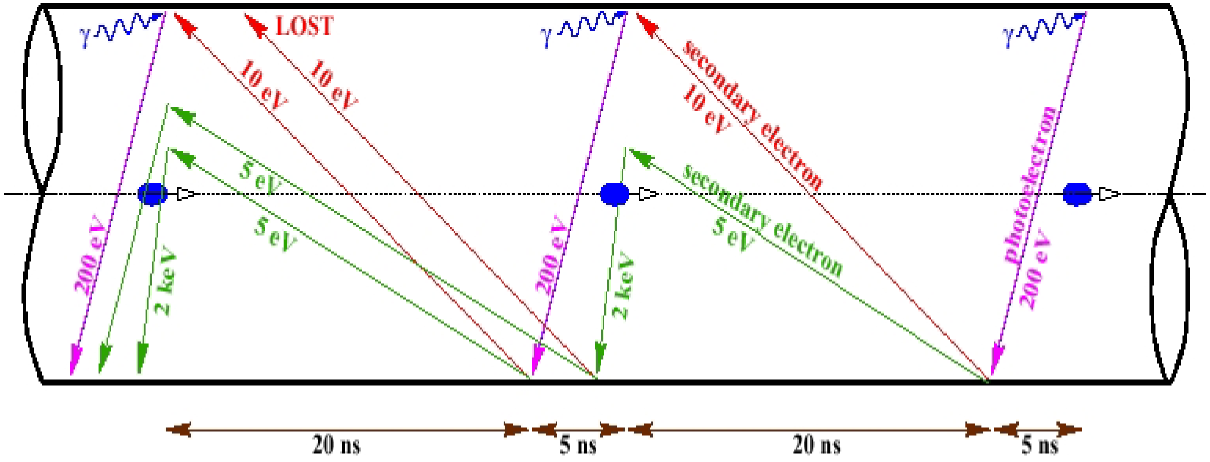


Courtesy of M. Pivi (WEPDO006)

Bunched beams (+)

$\tau_{bunch} < 1/f_e < s_{bunch}$

(LHC, SPS-25 ns)



Interaction electron – beam can be represented by means of single kicks (if r>a)

$$\Delta p = 2 N_b m_e c \frac{r_e}{r}$$

Bunched beams (+)

- In all cases a necessary condition for multipacting is SEY>1
  - Exponential growth of an electron cloud until space charge fields associated with e-cloud cancel the beam field
- Simple but not strict condition for multipacting (based on kick approx.):

$$N_b = \frac{r_0^2}{r_e s_b} \equiv N_{th} \qquad [Gr\ddot{o}bner]$$

- Good representation of reality when kick approximation is valid (PS/SPS/LHC)

Bunched beams (+)

- The electron cloud properties depend on the matching of:
  - the electron energy distribution resulting from the interaction with the beam potential (determined by bunch intensity, beam size, bunch length and spacing) and on the geometry of the vacuum chamber

with

  - SEY (E), dependent on the the surface properties of the vacuum chamber. Basic characterization given by δ_{max} and ε_{max} where δ_{max}=SEY (ε_{max})

➔ SIMULATIONS AND BENCHMARKING

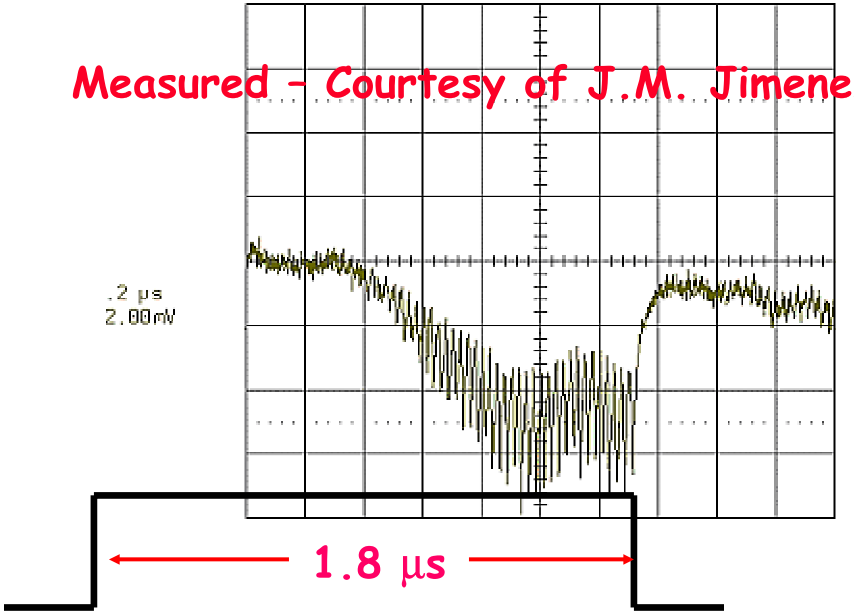
Electron cloud build-up
Single – passage!!!

SPS straight section

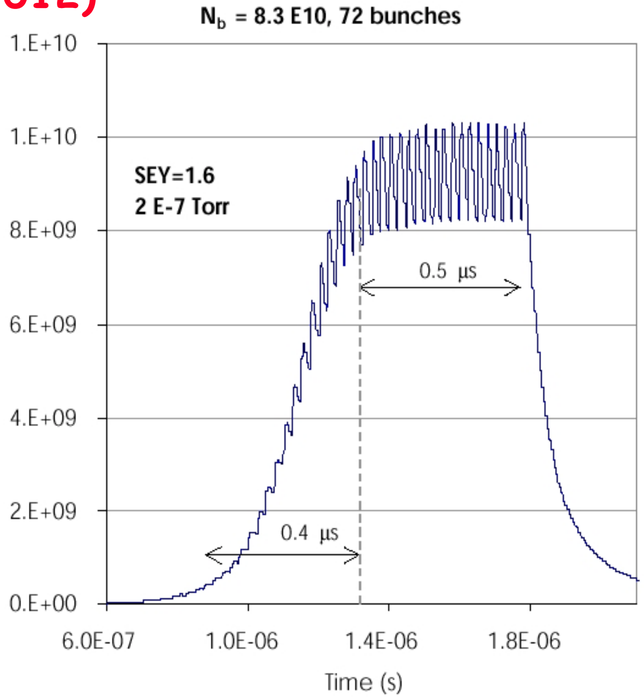
LHC beam – 72 bunches

$N_b=8.3\times10^{10}$ p – 25 ns spacing

0.2 μs/div


Measured – Courtesy of J.M. Jimenez

Simulation – Courtesy of A. Rossi (WEPDO012)



Bunch spacing

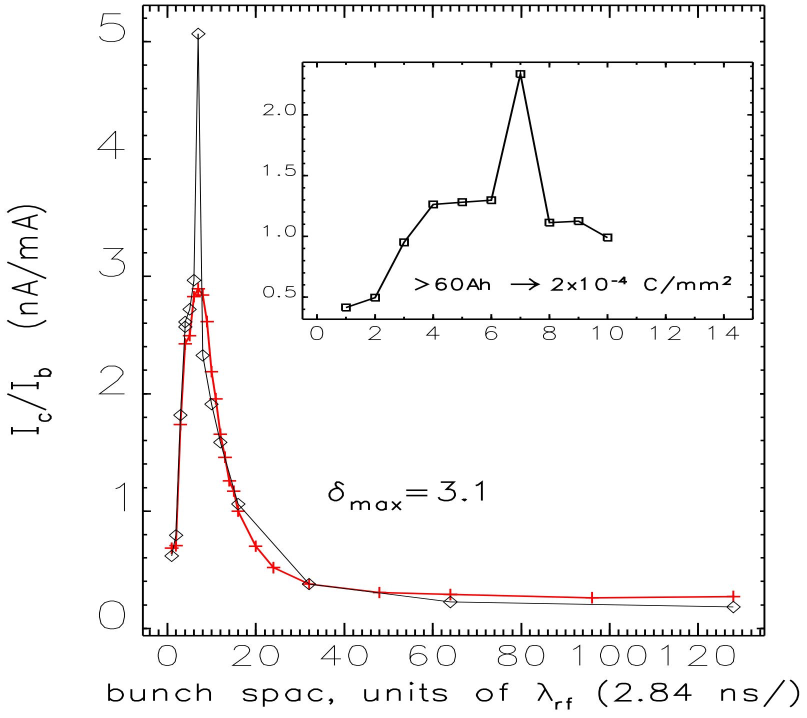
LHC beam in the SPS:

- 25 ns ➔ $N_{b\ th} = 3\text{x}10^{10}$ p
- 50 ns ➔ $N_{b\ th} = 6\text{x}10^{10}$ p

- In agreement with Gröbner criterion

➔ 75 ns spacing possible initial scenario for LHC compatible with luminosity in all Expts.

Advanced Photon Source



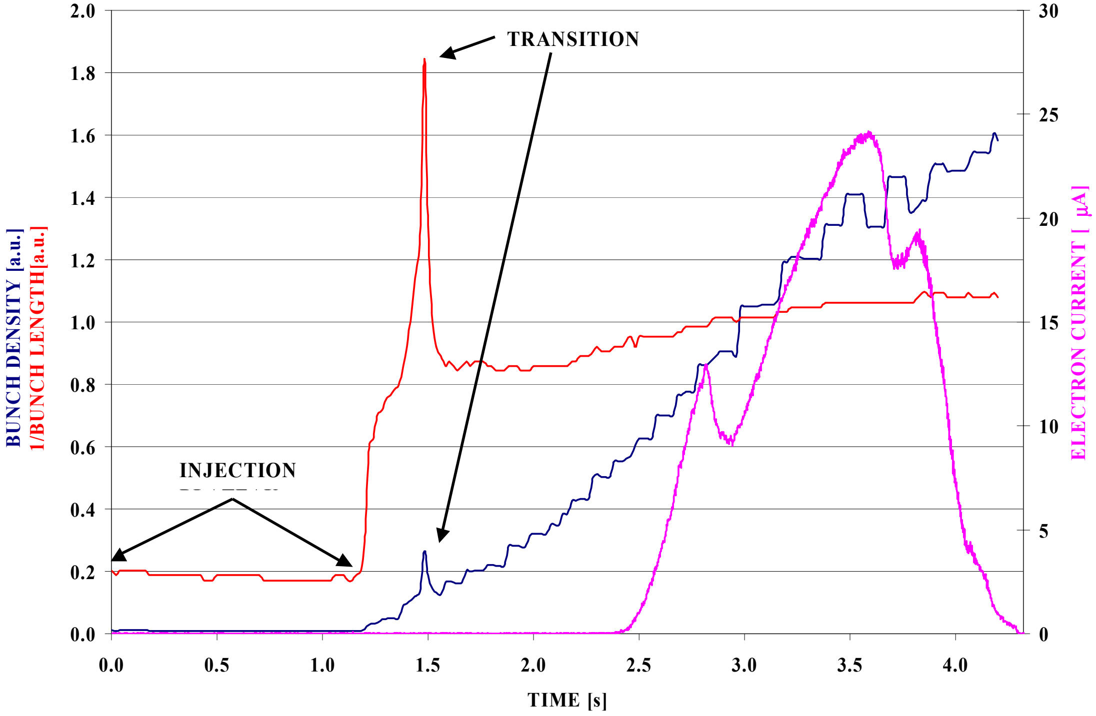
Courtesy of K. Harkay

Beam size dependence

BIM observed also with Fixed Target beam in the SPS

(but only @ E > 100 GeV)

- 2 trains
- 5/11 SPS each
- 2100 bunches each
- 5 ns spacing
- $N_{b\ th} = 5 \times 10^9$ p
- 1/22 SPS gap

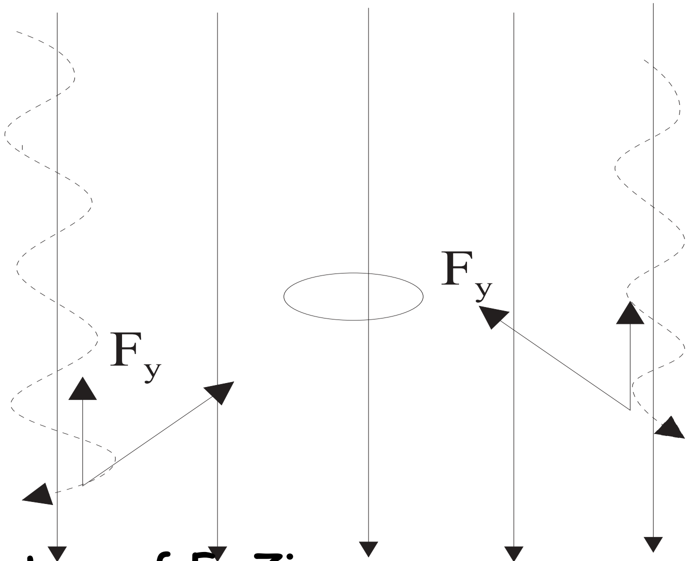


e^--cloud in dipoles

Measured in the SPS (WEPDO002)

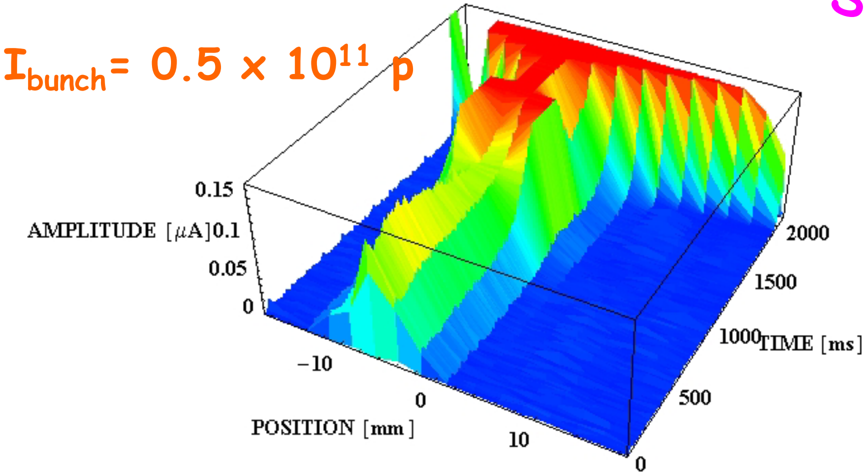
Only V motion during wall-to-wall transit because $T_{cycl} << \tau_b$.

No net ⊥ component

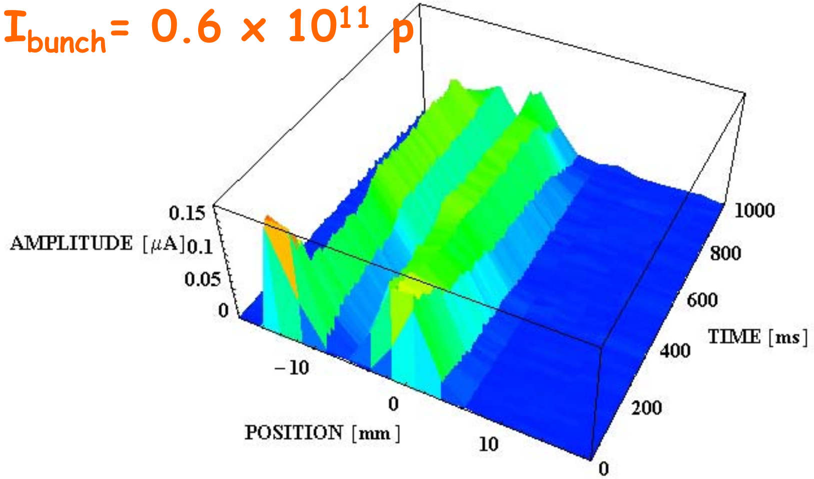


Courtesy of F. Zimmermann

$I_{bunch} = 0.5 \times 10^{11}$ p



$I_{bunch} = 0.6 \times 10^{11}$ p



Arcs vs. Straight Sections

- Qualitative agreement with simulations
- Recently measured third central stripe at N_b > 1.1 x 10^{11} p as predicted by simulations
- Distance between stripes simulated ~ 2 x measured
- Might require reconsidering parametrization SEY(E)

THZGB001 – WEPDO005

- Measurements in the SPS
  - dynamic pressure increase
  - electron cloud strip monitor in variable magnetic field

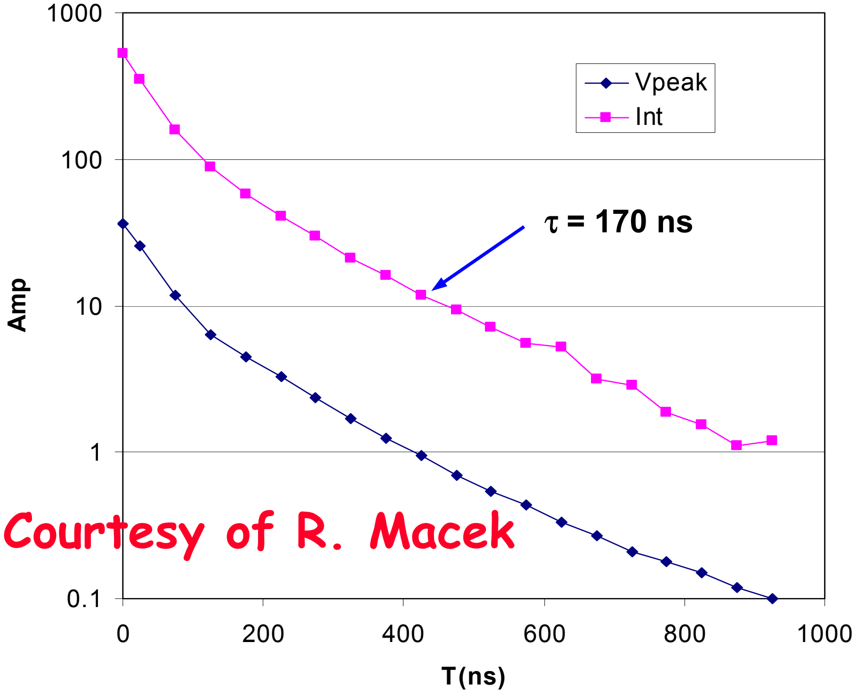
  indicate that the threshold for BIM in the straight sections is ~ 2.5 that in the arcs.
- Higher neutralisation density in the arcs due to the different e^- cloud distribution w.r.t. beam ?

Effect of magnetic fields

- Solenoids are successfully used to trap the electrons generated at the wall and keep them far from the beam (KEKB, PEP II)
- Electrons might also be trapped in non-uniform magnetic fields like quadrupoles, sextupoles (WEPDO007) and insertion devices
- This could explain the long decay time observed in the e-cloud signal after the batch passage.

Decay time

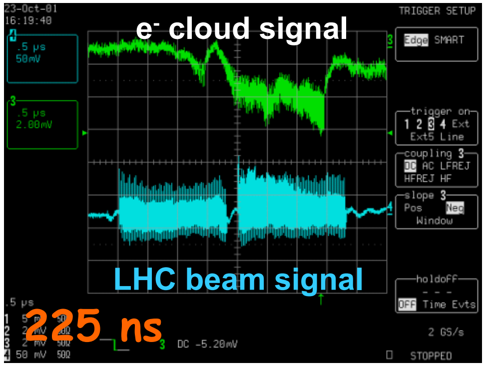
PSR: e^- signal after extraction

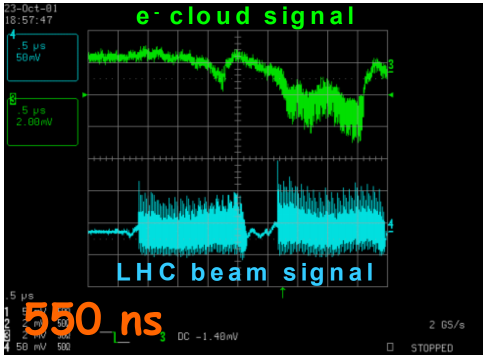


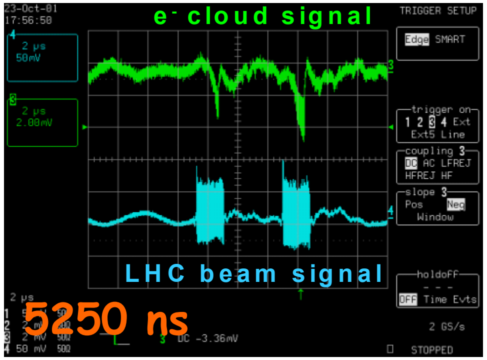
Courtesy of R. Macek

SPS

LHC beam







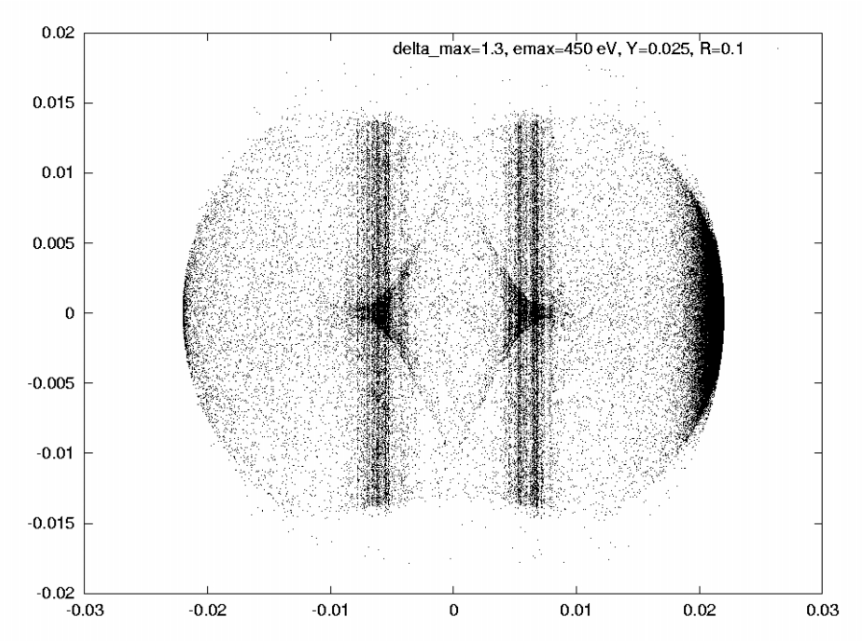
Both results indicate high reflectivity for electrons at few eV

Courtesy of J.M. Jimenez

Cures for e^--cloud build-up

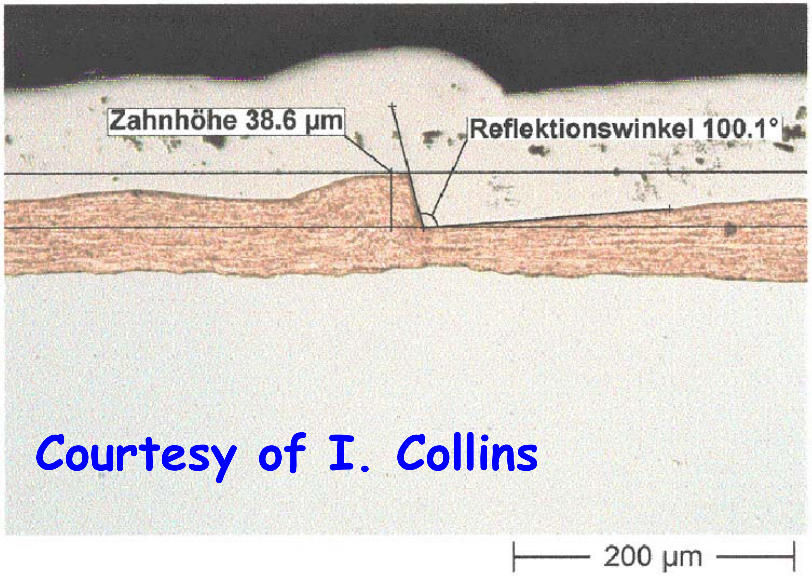
- Reduction of SEY possible by:
  - Glow-discharge tretaments (ISR)
  - TiN coating (PEP-II LER Arc chambers, PSR)
  - TiZrV NEG coating (LHC warm sections) – WEPDO012
  - Electron bombardment. Observed at APS, PSR and recently at CERN SPS (~ 12 days with LHC beam):
    - Threshold increased from 0.4×10^{11} p to 0.8×10^{11} p in the arcs and from 0.6×10^{11} p to > 1.4×10^{11} p in the straight sections
    - In situ SEY: δ_{max} 2.3 ➔ 1.6

Cures for e^--cloud build-up



- ◆ Reduction of photon reflectivity and of photoemission yield

- ◆ Antechamber slot (PEP-II)
- ◆ 'Dose effect': photon bombardment reduces Y*
- ◆ Ribbed surface (LHC)



Courtesy of I. Collins

Bunched beams (-)

- Electron cloud can develop also with negative beams though with much smaller amplitude (experimental evidence in APS + results of simulations)
- Ions are trapped in the beam potential if

$$A > A_{crit} = \frac{N_b s_b r_p}{2n\sigma_x\left(\sigma_x + \sigma_y\right)}$$

and oscillate with frequency f_{ion}

$$f_{ion\,x,y} = \frac{c}{2\pi}\sqrt{\frac{r_p \lambda_{beam} Z_{beam} Z}{\sigma_{x,y}\left(\sigma_x + \sigma_y\right)A}}$$

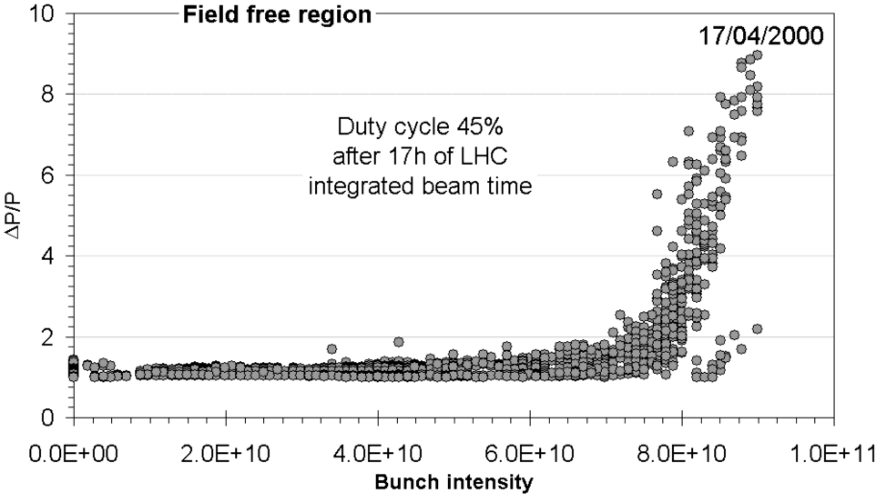
- As the trapping proceeds the beam potential is partly neutralised and lighter ions will be trapped until complete neutralisation is achieved (ion ladder)
- Cure: Clearing gap >> $1/f_{ion}$

Electron Cloud Effects

- **Historically first ECE observed at the CERN ISR (1977)**
  - Coasting beam
  - Background spikes in the experiments
  - Electrons bouncing at frequencies f_e
  - Proton beam oscillating at 40-60 MHz ~ f_e
  - Cure: clearing electrodes and more powerful vacuum pumps

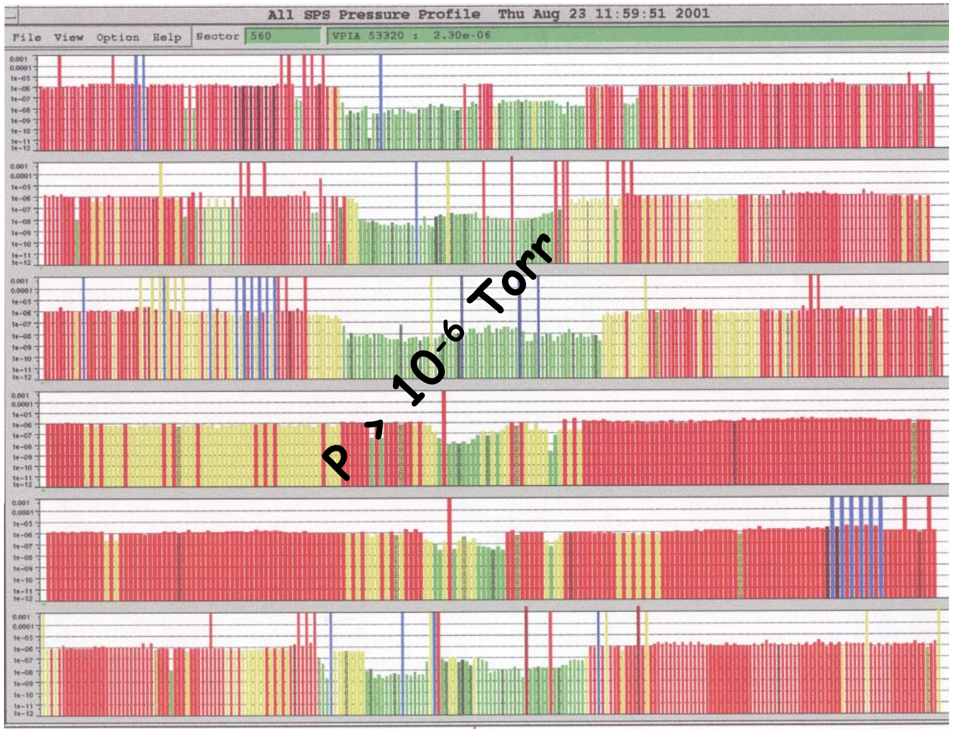
Electron Cloud Effects

- Non linear pressure increase (SPS-LHC beam) from molecular desorption induced by electron bombardment
- Observed also at KEKB, PEP-II and APS


Field free region

17/04/2000

Duty cycle 45%
after 17h of LHC
integrated beam time


All SPS Pressure Profile Thu Aug 23 11:59:51 2001

Sector 560

VPIA 53320 : 2.30e-06

P ~ 10^{-6} Torr

Courtesy J.M. Jimenez

Electron Cloud Instabilities

Fast Single (S) and Coupled (C) bunch instabilities are observed together with other ECE

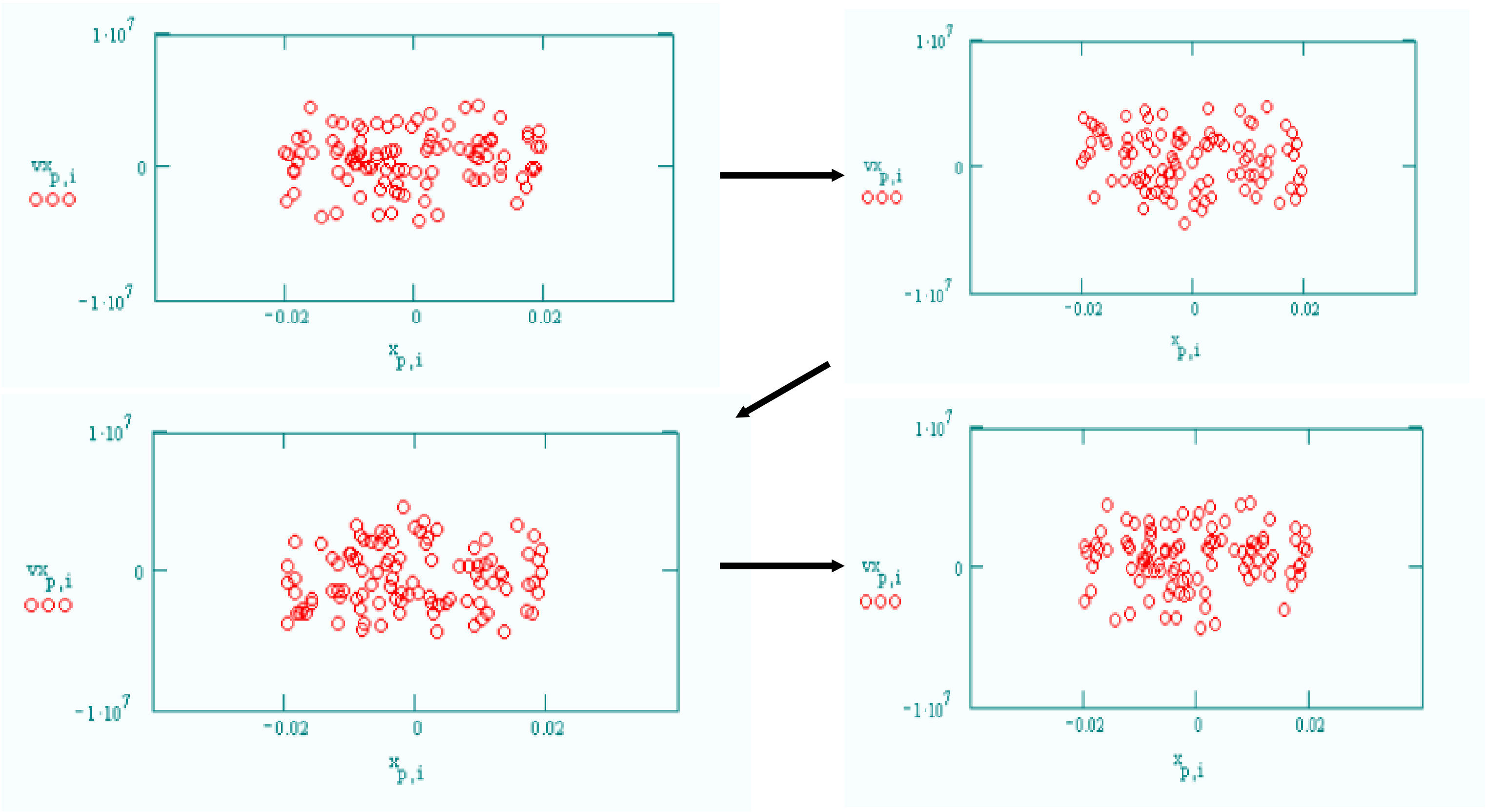
Machine	H-plane	V-plane
PS–LHC beam	S, $\tau \sim 1000$	--
PSR	--	S, $\tau \sim 100$
SPS–LHC beam	C, $\tau \sim 50$	S, $\tau \sim 500\text{-}100$ Decrease with N_b
KEKB LER	C, $\tau \sim 200\text{-}50$ Decrease with N_b	C, $\tau \sim 300\text{-}70$ Decrease with N_b S
PEP II LER	S	--

Electron Cloud Instabilities

- The electron-cloud couples the motion of subsequent bunches and/or of different slices of a bunch.
- In field-free regions:
  - H/V symmetry (a part from vacuum chamber geometry)
  - The electron cloud is 'pinched' during the bunch passage in both planes
  - Expect single and coupled bunch instabilities in both planes
- In the arcs (if $T_{cycl} << \tau_b$):
  - No H-motion of the e-cloud in the time scale of the wall-to-wall traversal
  - E-cloud pinched only vertically
  - Expect single bunch instabilities ONLY in the V-plane
  - Expect coupled-bunch instabilities in both planes

Electron Cloud Instabilities

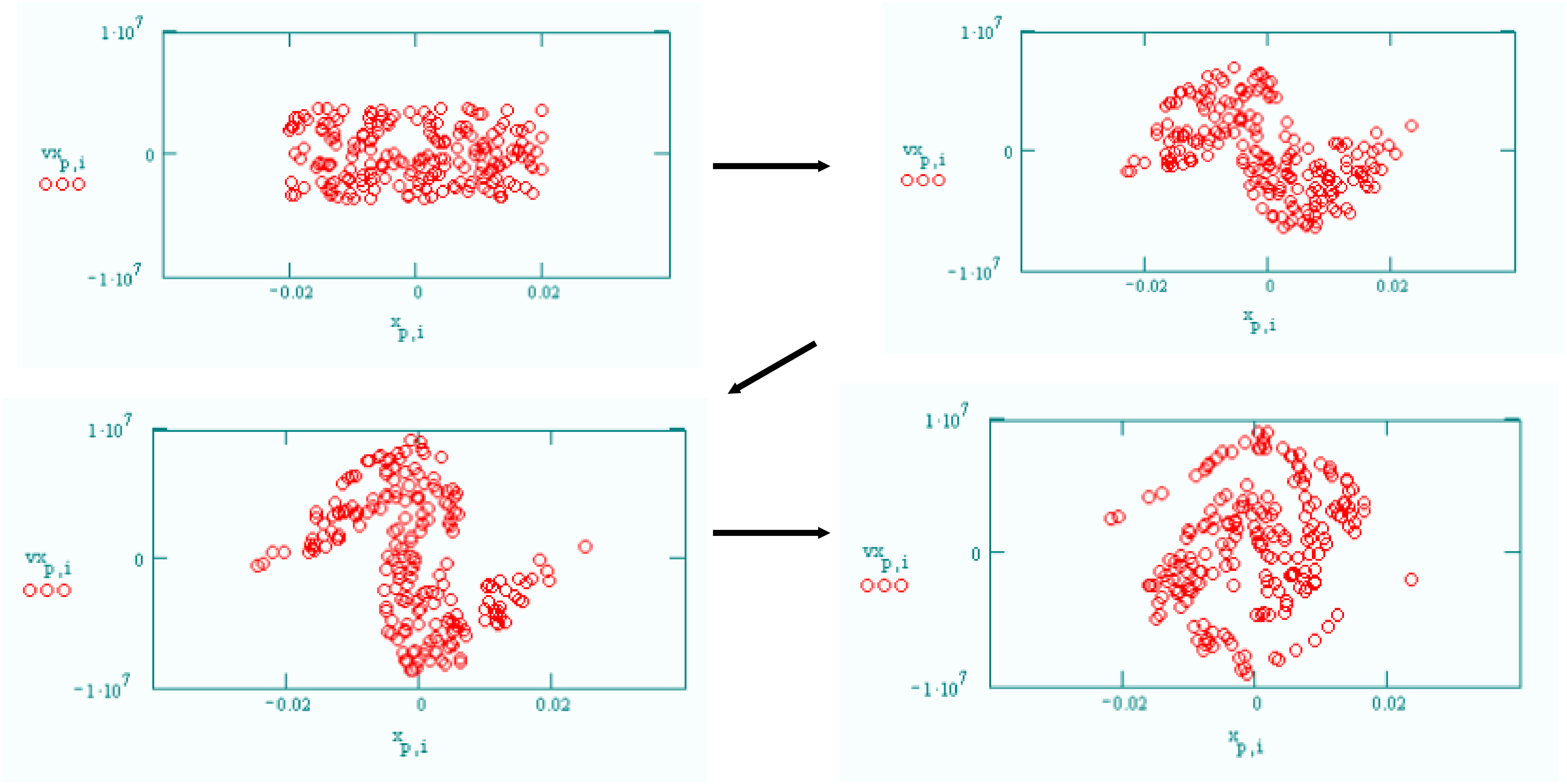
- H plane (phase space during bunch passage - SPS)



Courtesy of K. Cornelis

Electron Cloud Instabilities

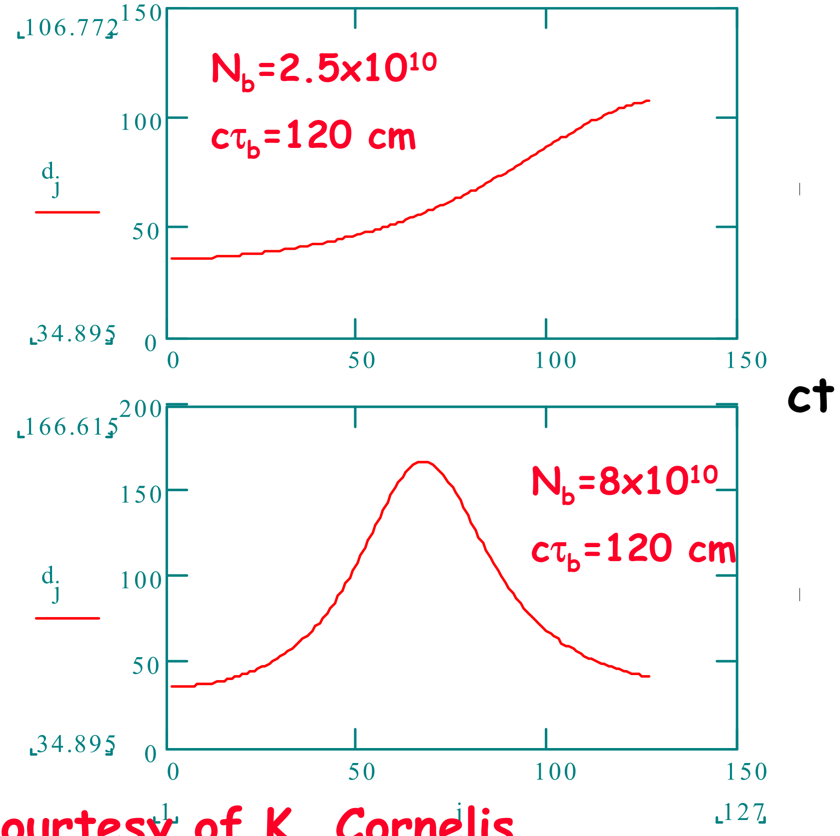
- V plane (phase space during bunch passage - SPS)



Courtesy of K. Cornelis

Electron Cloud Instabilities

- E-cloud density vs. time (SPS)



Courtesy of K. Cornelis

- Non-conventional wake-fields: strongly depending on the position along the bunch from where they get excited (WEPDO003).
- Work to take into account that in TMCI formalism [Perevedentsev]
- 'Negative' synergy between space charge, machine impedance and ECI in the SPS (WEPDO003).
- Hints of similar synergy ECI – beam beam for B-factories [Ohmi]

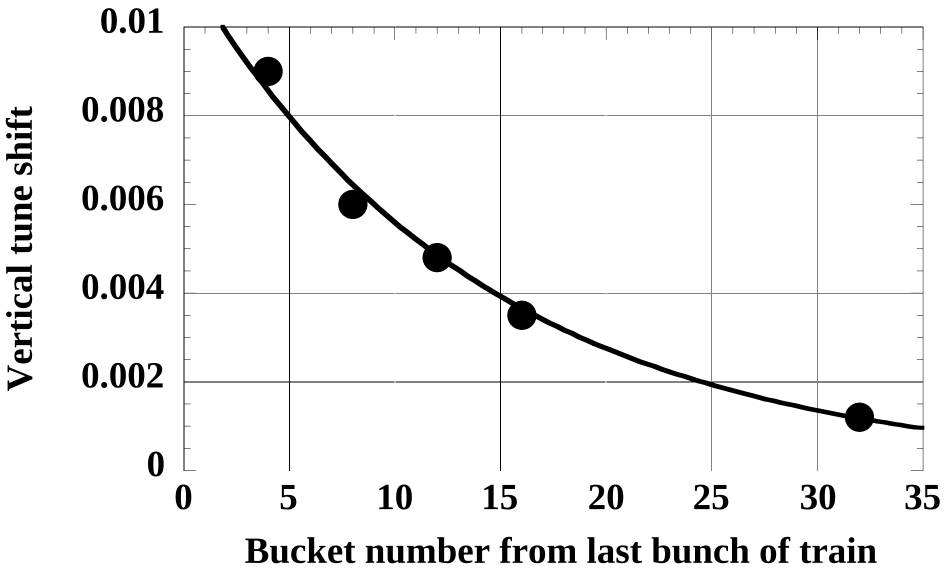
Electron Cloud Instabilities

- This qualitative model explains observations in PSR, SPS and KEKB (WEPDO008)
- PS behaviour due to effect of combined function magnets on e-cloud ? [Rumolo]
- PEP II ?

- CURES:
  - High Positive Chromaticity (above transition)
  - Transverse bunch-to-bunch feedback

Tune shifts

- Coherent and incoherent tune shifts are induced by the e-cloud along a train.
- Indirect measure of the e—cloud density
- Witness bunch injected after bunch train can be used to measure the decay of the cloud (KEKB)



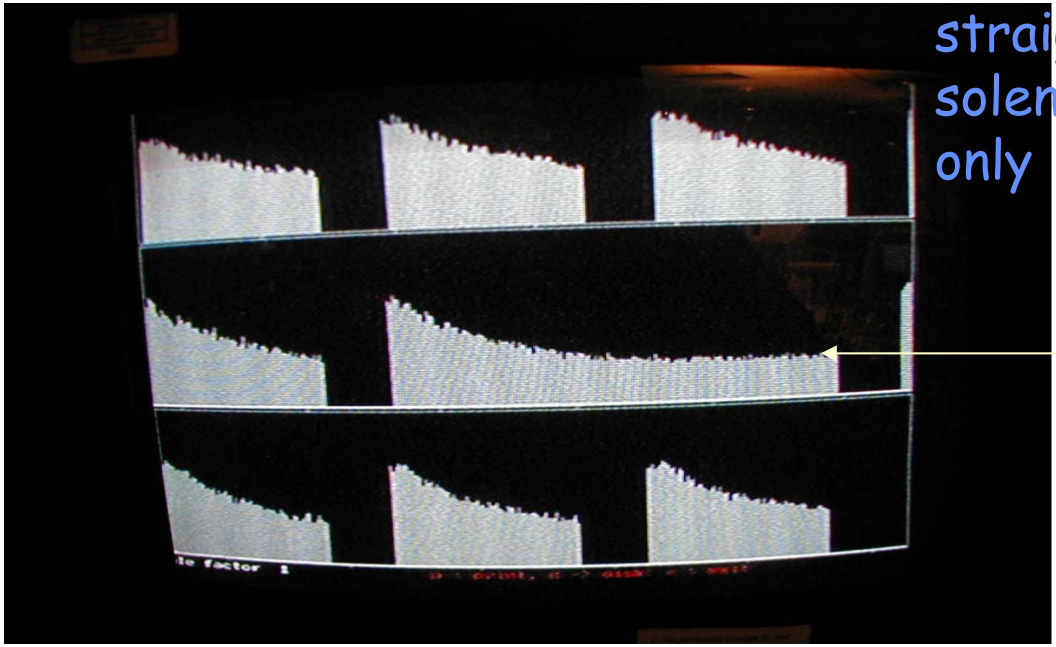
Courtesy of H. Fukuma

Blow-up and Lumi. reduction

- Single bunch instabilities are the main responsible of beam blow-up and Luminosity reduction in B-factories

PEP II →

Luminosity versus Bunch Number
Pattern: by-4 with 8-1 additional big gaps (July 2000)



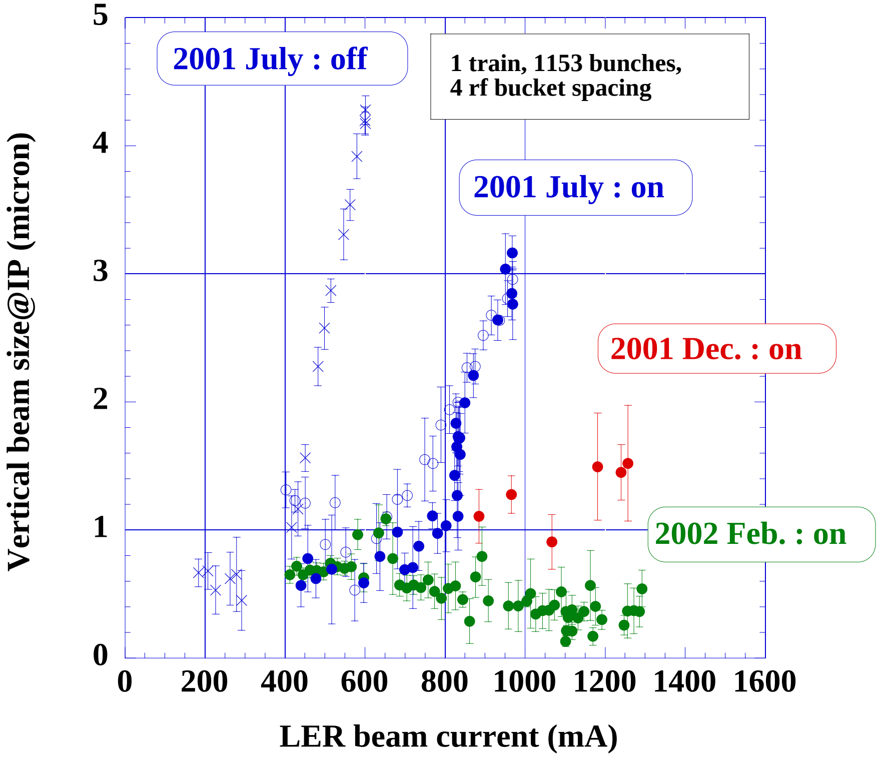
≈ one straight solenoid only

40%

Courtesy of F.-J. Decker

Blow-up and Lumi. Reduction (cures)

- Solenoids proved to be very effective in reducing multipacting and therefore blow-up (particularly at KEKB) ➔



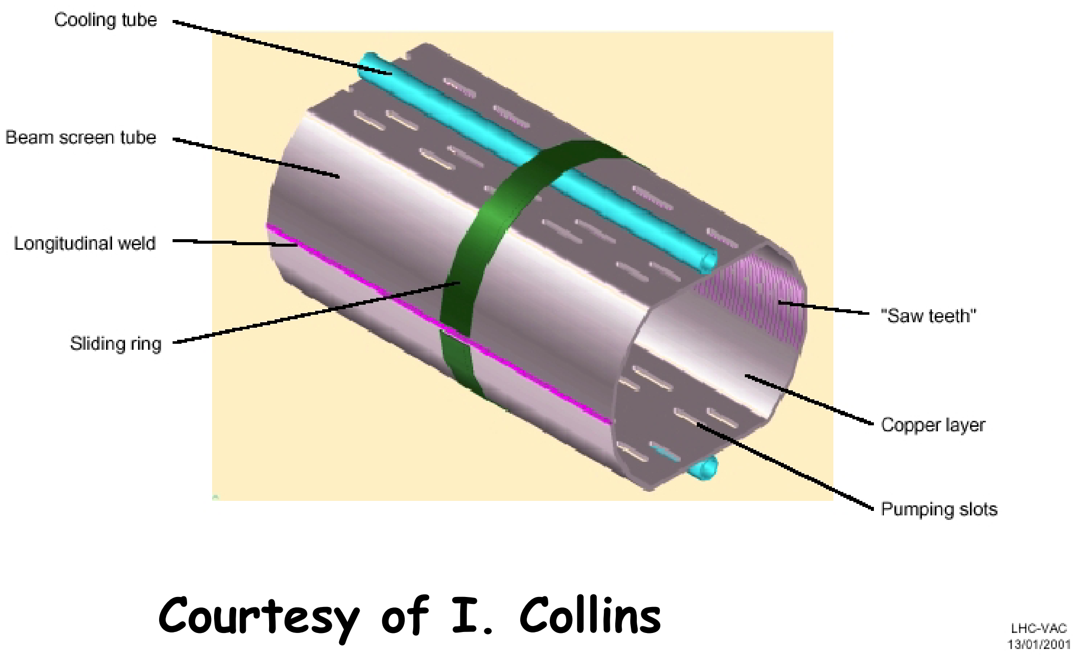
- Special filling pattern taking into account the e-cloud decay time are also used in operation at PEP-II to equalise luminosity

Courtesy of H. Fukuma

Heat Load

- Main concern for high energy SC machines (e.g. LHC)
- Implemented all the the 'realistic' actions to reduce Y* and SEY
- Careful evaluation of implications of 'stripe' position measurements on Beam Screen design.

LHC beam screen



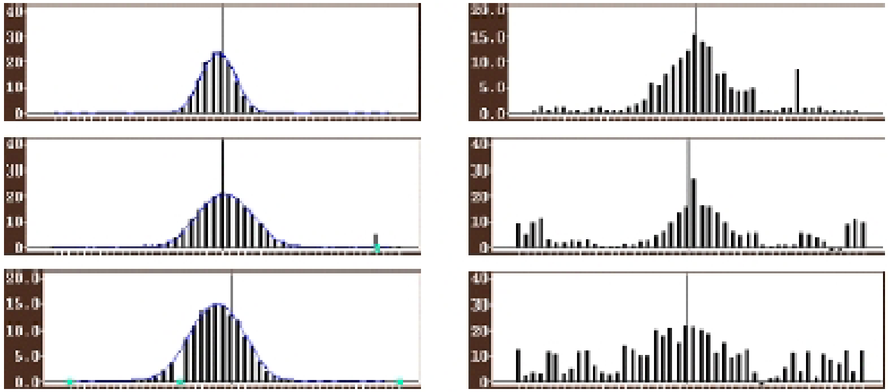
Courtesy of I. Collins

- A lot of measurements

Effects on Instrumentation

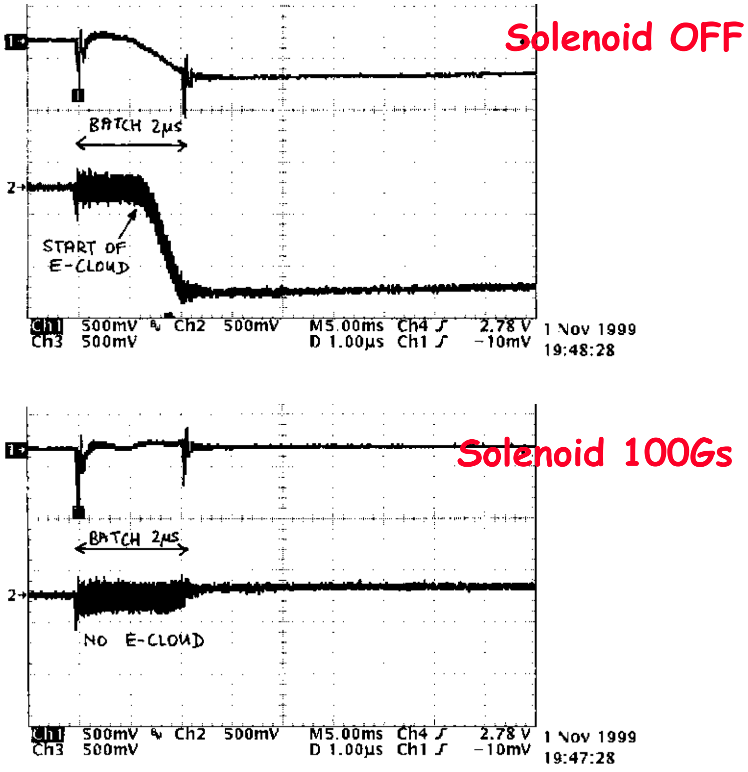
- SEM grids – PS-SPS transfer line – with LHC beam

τ_b= 16 ns τ_b= 4 ns



Courtesy of M. Giovannozzi

- Electrostatic pick-ups



Courtesy of W. Höfle

Ion Effects

- Ion effects pertains negatively charged beams (except Ion Induced Pressure Instability)
- Mode numbers around f_{ion} are excited → beam blow-up or ions expelled from beam potential.
- Cure: gaps in the bunch train

- Nevertheless:….

Fast Beam Ion Instability

- For high brilliance beams the focussing force exerted by the ions on the beam is strongly enhanced and an ion instability may develop as a result of the ion build-up along the bunch train (single-turn phenomenon) and therefore also in the presence of a clearing gap.

Multi-bunch beam break-up

(Raubenheimer, Zimmermann):

$$y_b(s,z) \propto \exp\left(\sqrt{\frac{s}{c\tau_{FBII}}}\,\frac{z}{l_{train}}\right)$$

$$\frac{1}{\tau_{FBII}} \propto \frac{\rho_{gas}\sigma_{ion}\beta_y N_b^2 n^2 s_b^{1/2}}{\gamma_{beam}\sigma_y^{3/2}\left(\sigma_x+\sigma_y\right)^{3/2} A^{1/2}}$$

Fast Beam Ion Instability

- Observed at ALS, KEKB HER, ESRF, PLS, Spring-8 but only when operated with poor vacuum
- It manifests as coupled-bunch instability and blow-up (V-plane only)
- Intrinsic Landau damping from:
  - Non linearity beam-ion force
  - Different ion spaces
  - Dependence on beam size
- Concern for linear colliders and high brilliance light sources. Implications for the vacuum system evaluated for TESLA and NLC (seems to be feasible)
- Other cures (TFB, additional short gaps)

Summary

…Each little bucket space has more unique features than we ever expected to know. Starting from ion clearing gap the symmetry is broken, creating phase changes, tune changes, different densities in the electron cloud and other variations along the bunch train…..

(from F.J. Decker et al. PAC2001, p. 1963)