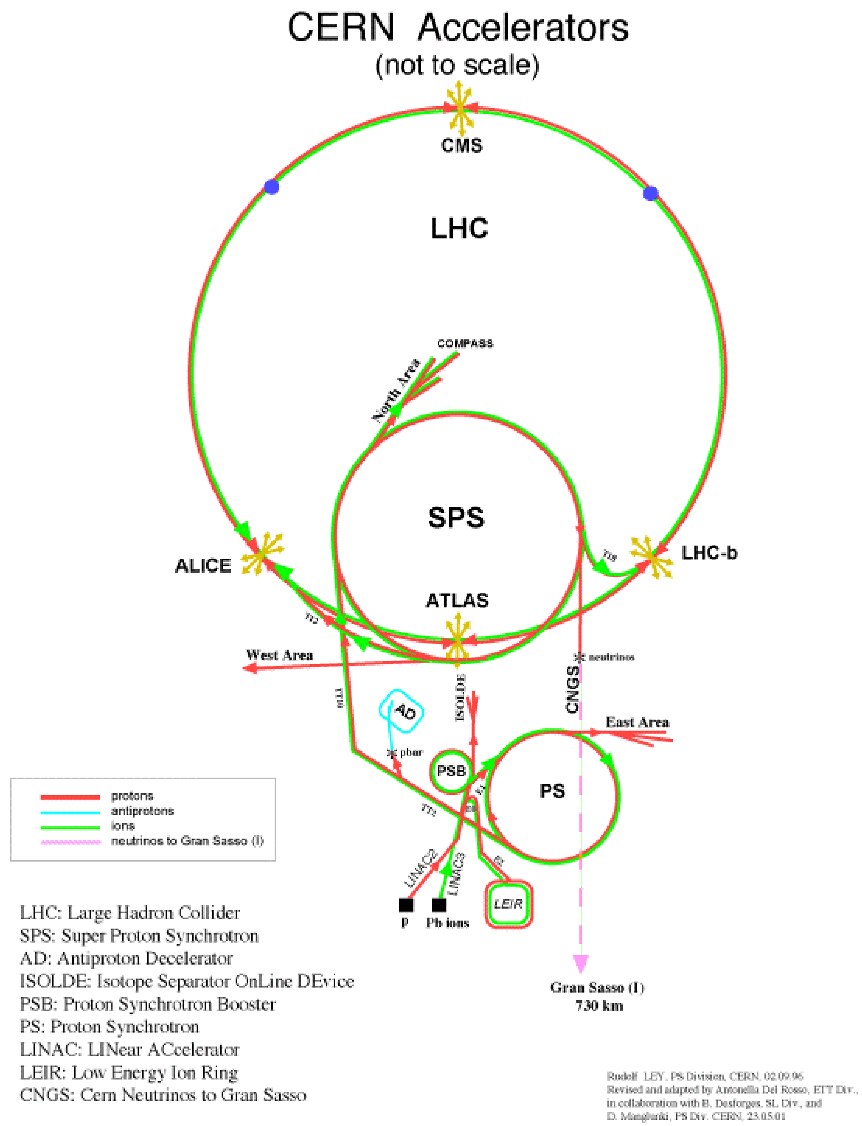
Beam Observations with Electron Cloud in the CERN-PS & SPS Complex

G. Arduini – AB Department

Acknowledgements: T. Bohl, K. Cornelis, W. Höfle, J.-M. Jimenez, E. Métral, G. Rumolo, F. Zimmermann

Outline

- The LHC and Fixed Target Beams
- Electron multipacting in the PS Complex and SPS
- Effects on the Beam
- Electron Cloud Instability in the SPS – LHC Beam
- Electron Cloud Instability in the PS – ”quasi-LHC Beam”
- Electron Cloud Build-up with Fixed Target beam in the SPS
- Electron Cloud Lifetime
- ECI in the SPS with fixed target + LHC beam operation
- Cures for ECI
- Summary and Conclusions



Electron multipacting and its effects have been observed in the SPS since 1999 when the first injection tests of the nominal LHC beam started.

Since then investigations have been conducted in the PS & SPS complex for the LHC beam and the high intensity fixed target beam.

	PS @ extr.	SPS	
Momentum [GeV/c]	26	26	450
Revolution period [μs]	2.1	23.07	23.05
Tunes (H/V)	6.25	26.185/26.13	
Gamma transition	6.1	22.8	
Max. n. of batches	1	4	
n. bunches/batch	72	72	
Nominal N_{bunch} [10^{11} p]	1.15	1.15	
Bunch spacing [ns]	24.97	24.97	24.95
Full bunch length [ns]	4-16*	4	<2
Batch spacing [ns]	-	224.7	224.6
r.m.s. $\varepsilon^*_{H,V}$ [μm]	3	3	3.5
ε_L [eV s]	0.35	0.35	<0.8

* Bunch compression within ~100 turns ~ 200 μs

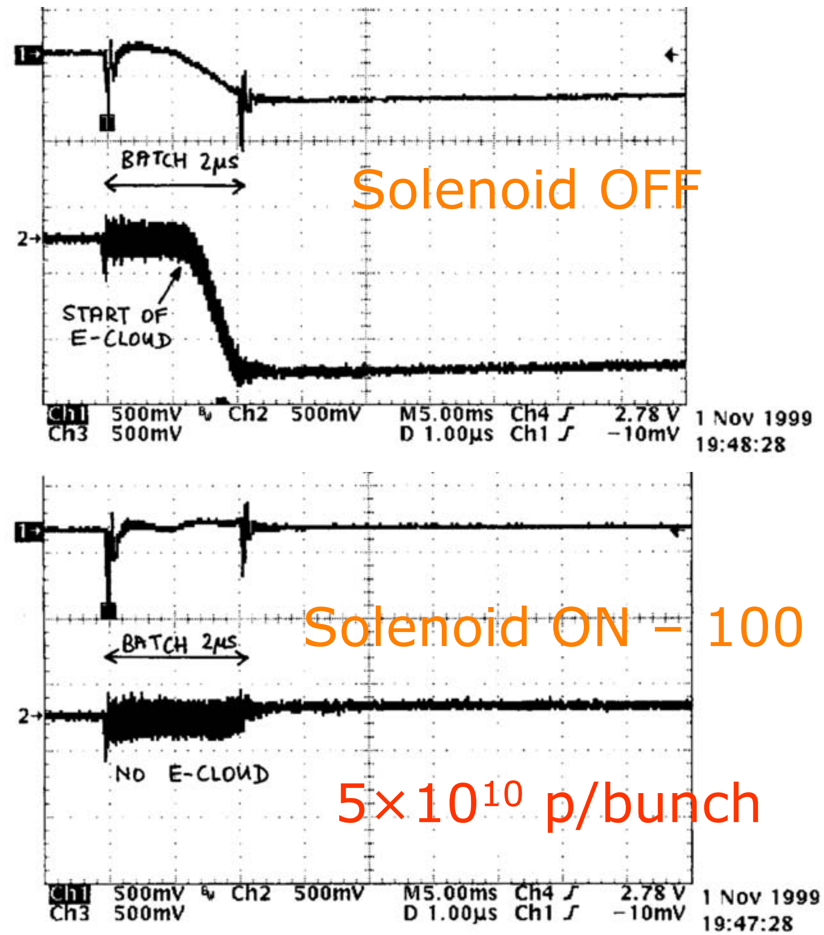
Fixed Target Beam

	SPS	
Momentum [GeV/c]	14	400
Revolution period [μs]	23.07	23.05
Tunes (H/V)	26.62/26.58	
Gamma transition	23.2	
Max. n. of batches	2	
n. bunches/batch	2100	
Nominal N_{bunch} [10^{11} p]	0.1 – 0.2	
Bunch spacing [ns]	5.00	4.99
Full bunch length [ns]	4	<3
Batch spacing [ns]	1050	1048
r.m.s. $\varepsilon^*_{H,V}$ [μm]	<10/<7.5	<12/<12
ε_L [eV s]	0.2	0.6 - 2

Dynamic Pressure increase (> factor 100 – mainly in the arcs) – close to interlock level (10^{-5} mbar). Threshold $N_{bunch}=2\text{-}3\times10^{10}$ p after SD.

SPS –LHC beam

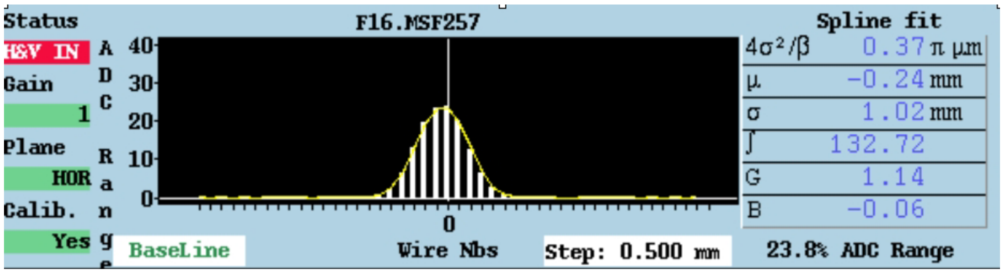
Baseline distortion of TFB electrostatic PUs, preventing reliable TFB operation (W. Höfle)



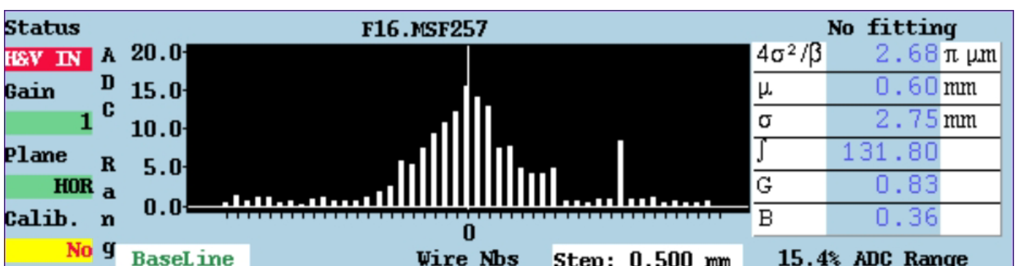
Electron multipacting

Single passage phenomenon: also in PS-SPS transfer line (SEM Wires – E. Métral)

τ_{bunch}=16 ns



τ_{bunch}=4 ns



LHC beam

This prevents emittance measurements on the LHC beam with SEM in the PS-SPS transfer line ➔ OTR (Optical Transition Radiation) beam profile monitors.

All measurements compatible with electron cloud build-up along the LHC bunch train.

Seed electrons=residual gas ionization (~10^8 e^-/m^3).

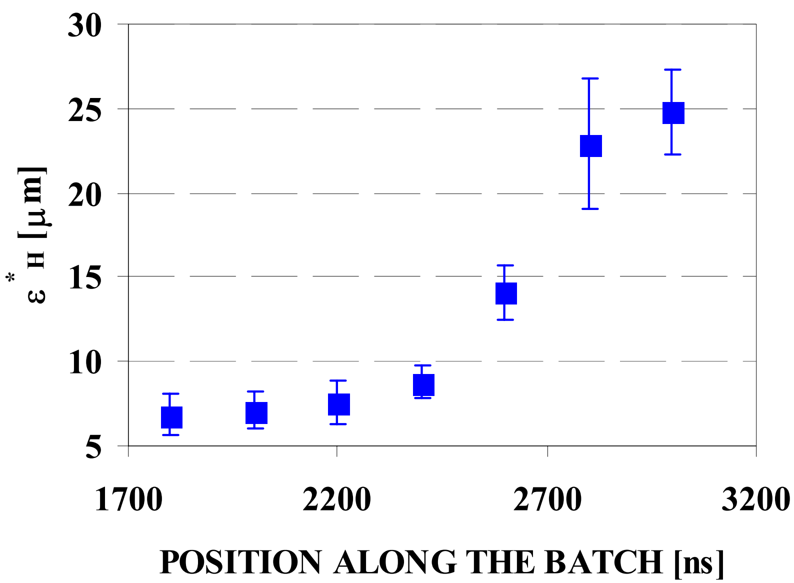
Electron cloud build-up to densities 10^{11}–10^{12} e^-/m^3.

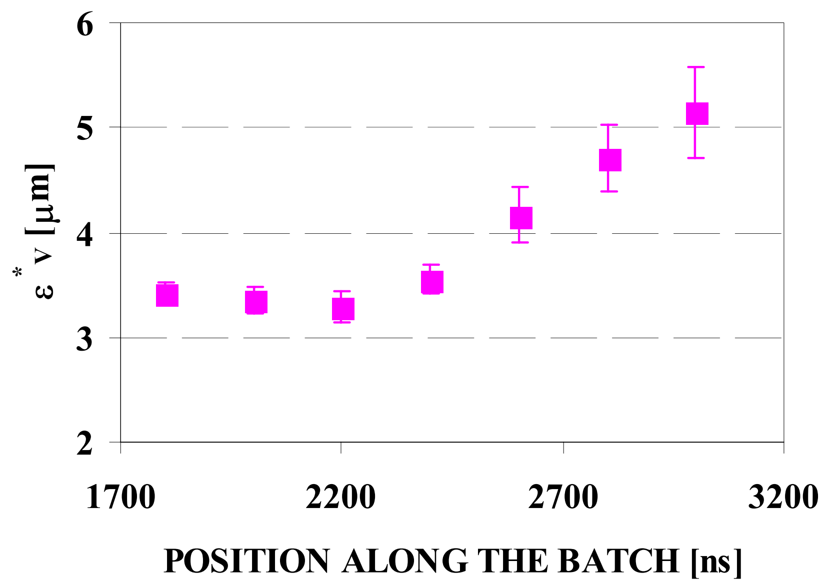
Effects on the beam

H & V emittance blow-up affecting mainly the tail of the batch and occurring at injection above threshold.

48 bunches - $N_{bunch} = 8 \times 10^{10} > N_{th} = 2\times10^{10}$

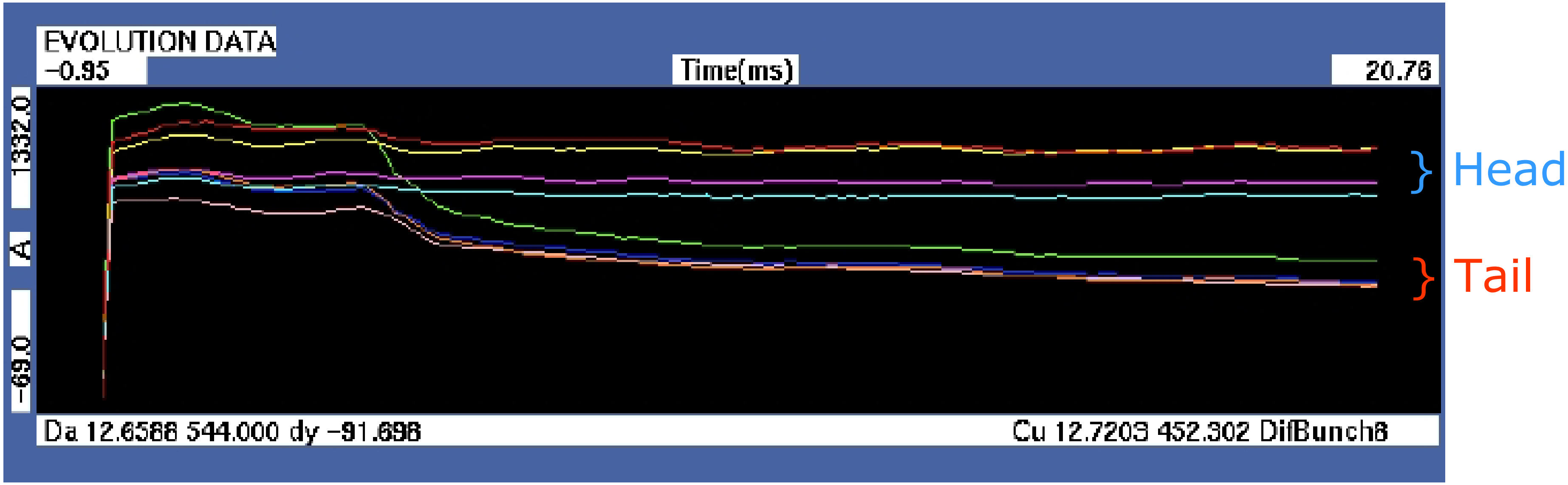
Linear machine: $\xi_{H,V}$ =(ΔQ/Q)/(Δp/p)= 0.03, Coupling corrected (CTA ~ 0.001), Det. with amplitude compensated by means of machine octupoles. TFB ON.





SPS - LHC beam

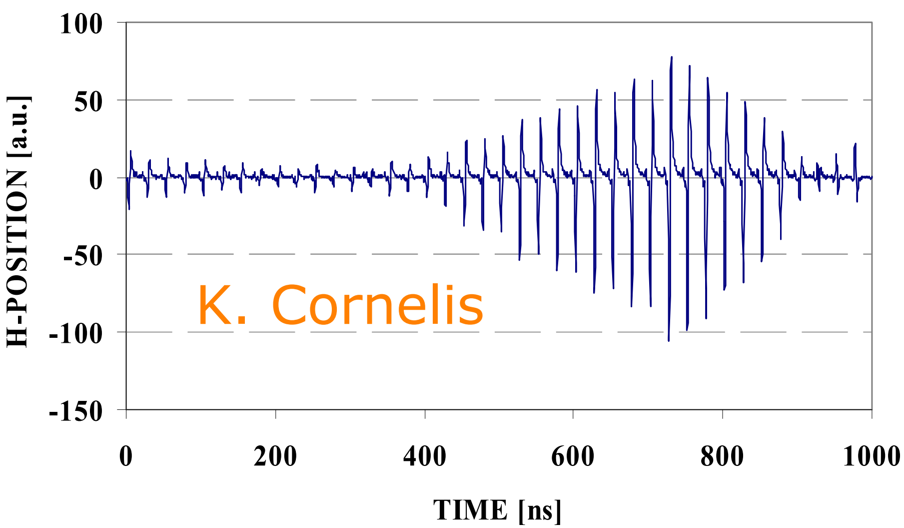
Beam losses, a few ms after injection, mainly affecting the tail of the batch.



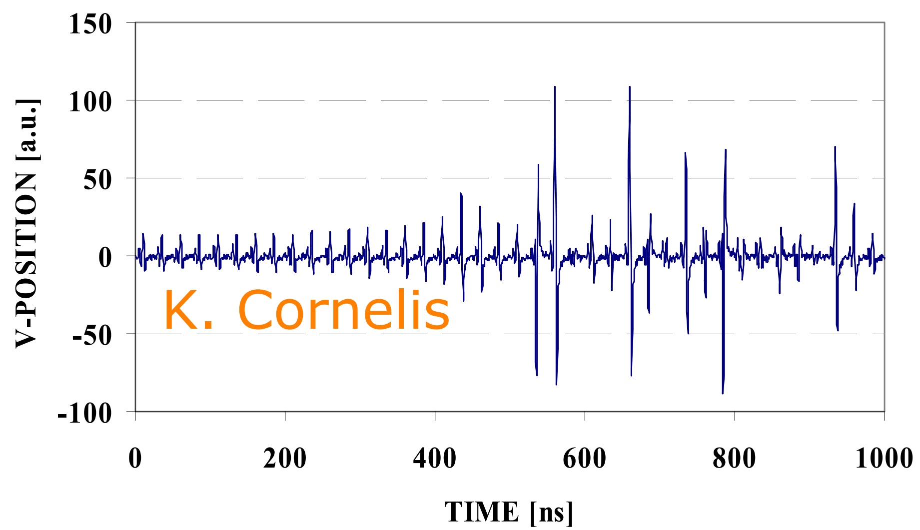
SPS - LHC beam

ECI develops for $N_{bunch}>N_{th}$ from the tail and progress to the head of the batch and it is responsible for beam losses and transverse emittance blow-up. For a single batch with nominal bunch population all the bunches except the first 10-15 are affected. The characteristics of the instability are significantly different in the H and V planes in the SPS.

H-plane – Coupled bunch inst.



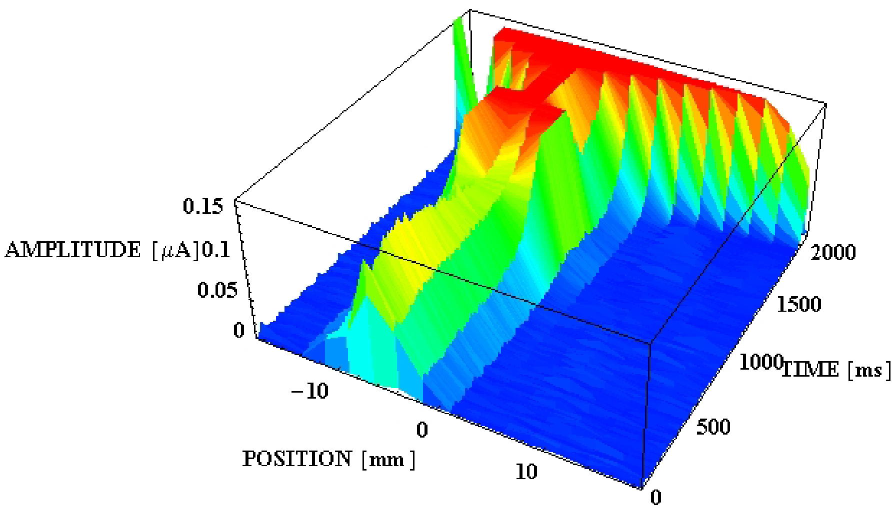
V-plane – Single bunch inst.



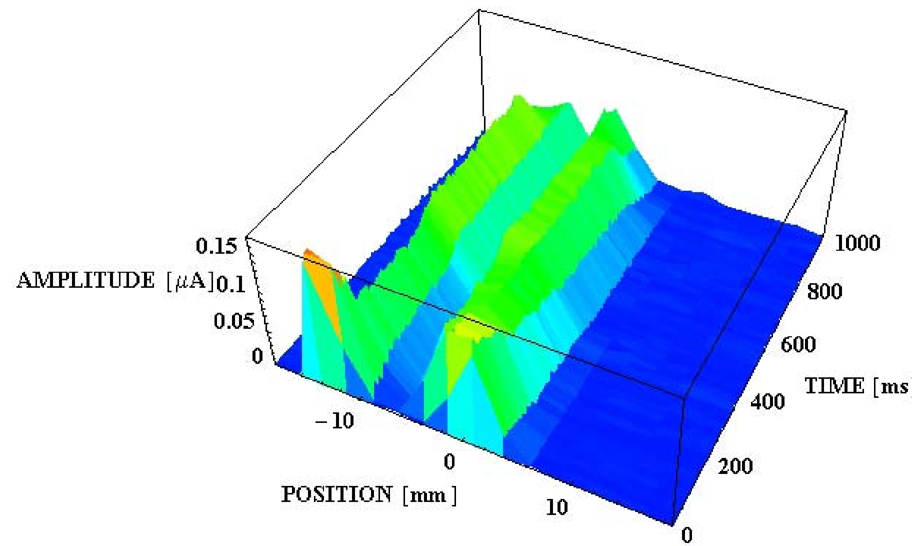
LHC beam

About 70 % of the SPS circumference is filled with bending magnets and N_{th} is lower in dipole field regions than in field-free sections ➔ the behaviour of the electron cloud in the arcs determines the characteristics of the ECI in the SPS with LHC beam.

$N_{th}=0.2\times10^{11}$ p $<N_{bunch}<0.5\times10^{11}$ p



$N_{th}<0.5\times10^{11}$ p $<N_{bunch}<1.1\times10^{11}$ p



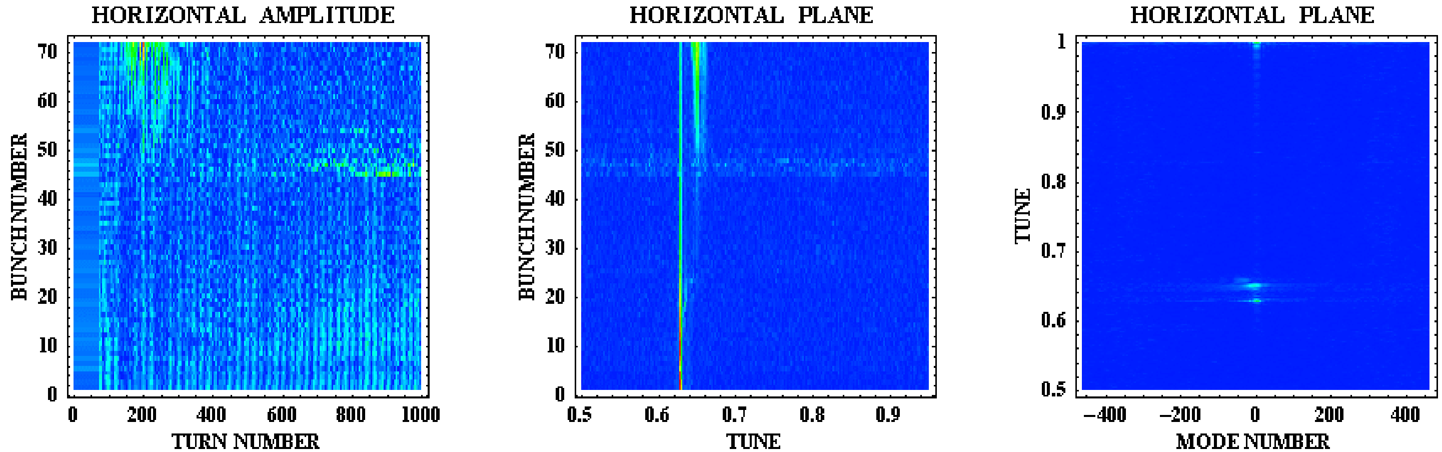
Above 1.1 $\times10^{11}$ a third central stripe appears

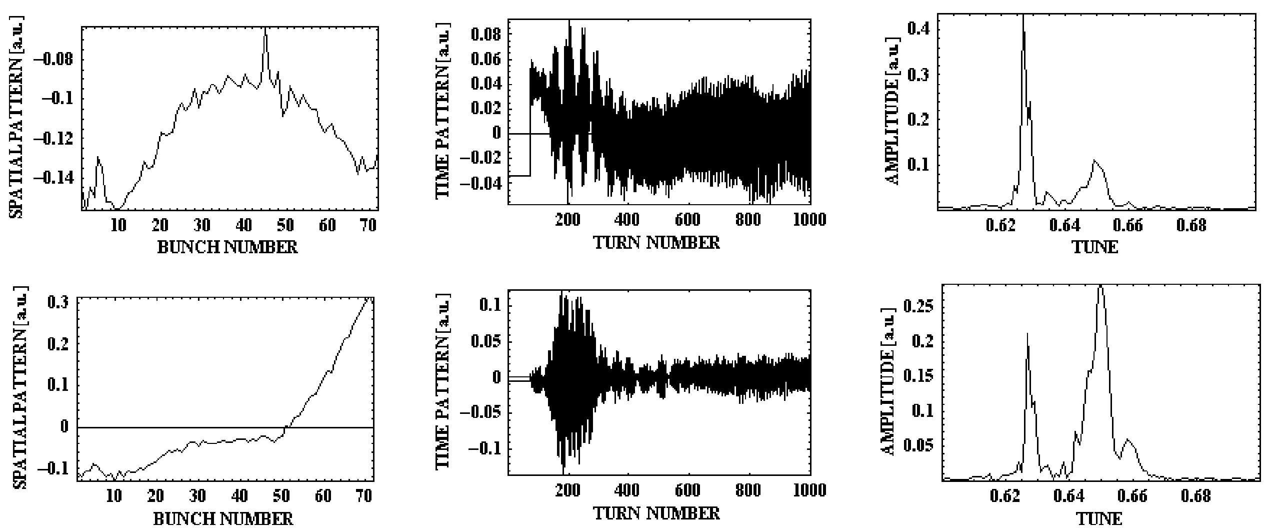
J.-M. Jimenez' talk for more details !!!

Horizontal Instability in the SPS
LHC beam

$N_{bunch}=0.3\times10^{11}$ p > $N_{th}=0.2\times10^{11}$ p – Linear machine - TFB OFF

Bunch-by-bunch centroid position meas.



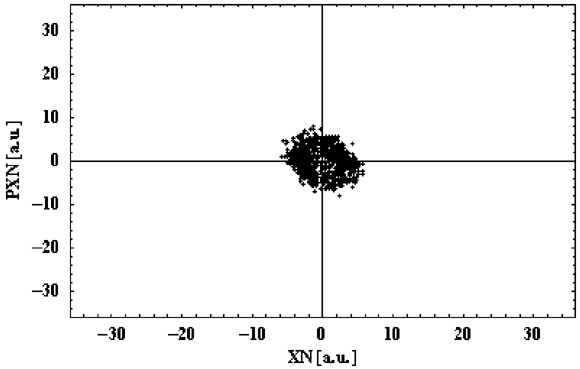


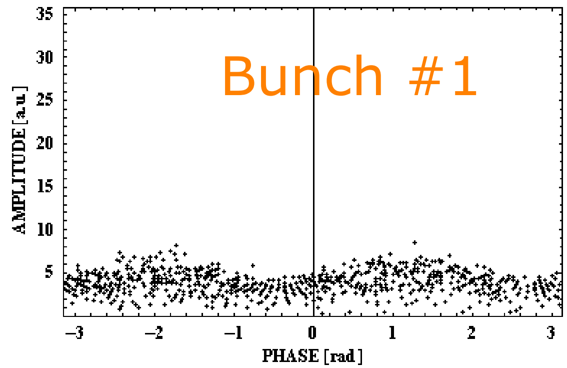
- One central electron stripe
- $\tau_{ECI}\sim40$ turns
- e-cloud saturates > bunch 50
- Second mode (+0.025) appearing in the tail of the batch

SVD analysis in time domain (Y. Ohnishi et al. – EPAC2002)

Horizontal Instability in the SPS
LHC beam

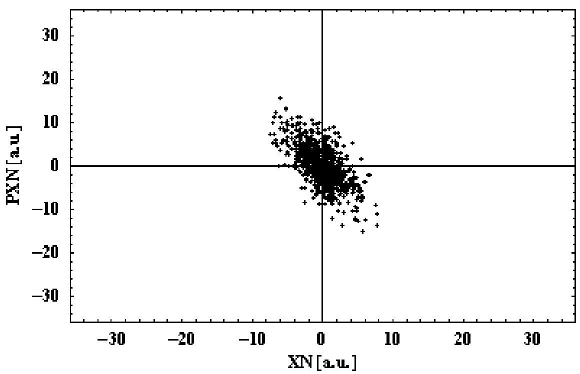
$N_{bunch}=0.3\times10^{11}$ p > $N_{th}=0.2\times10^{11}$ p – Linear machine - TFB OFF

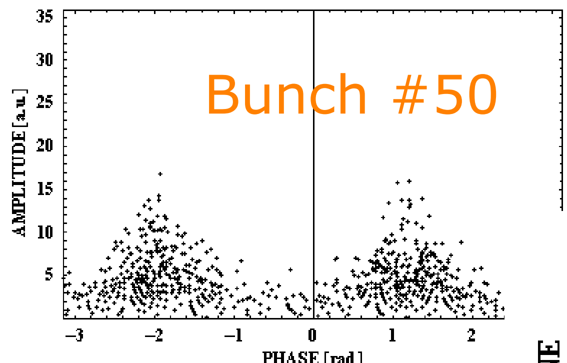




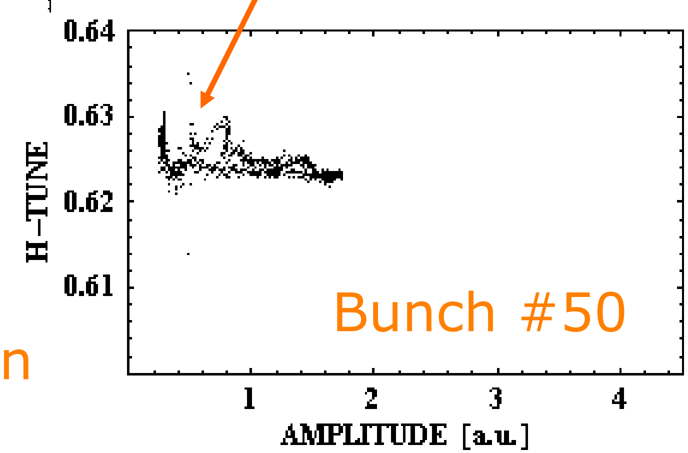
{50}

- β-beating due to the electron cloud building-up along the batch?





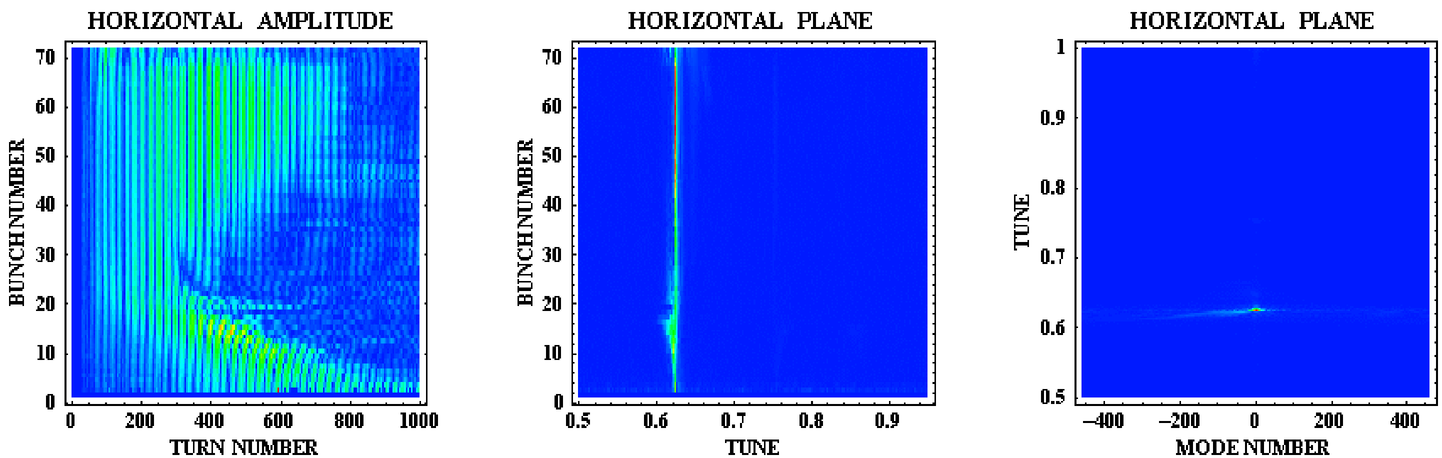
Injection

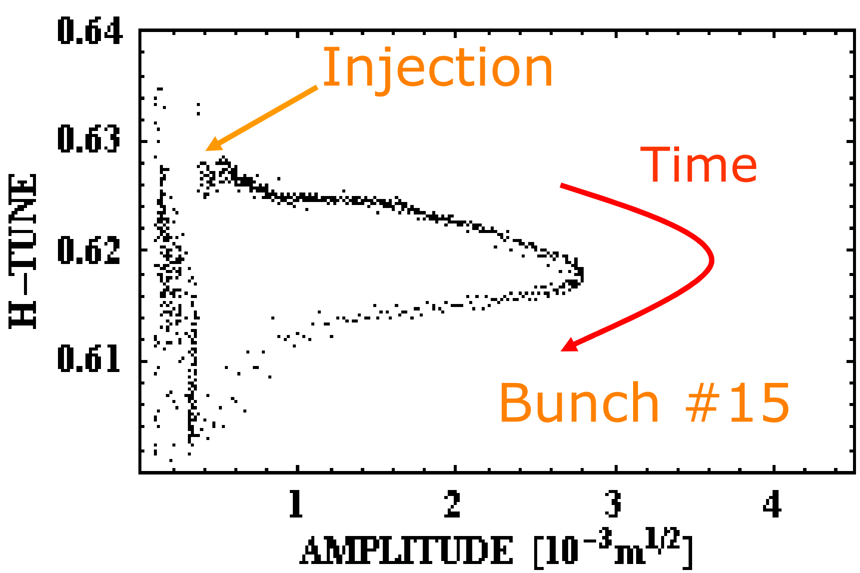


Detuning with amplitude of oscillation

Horizontal Instability in the SPS
LHC beam

$N_{bunch}=0.5\times10^{11}$ p > $N_{th}=0.2\times10^{11}$ p – Linear machine - TFB OFF

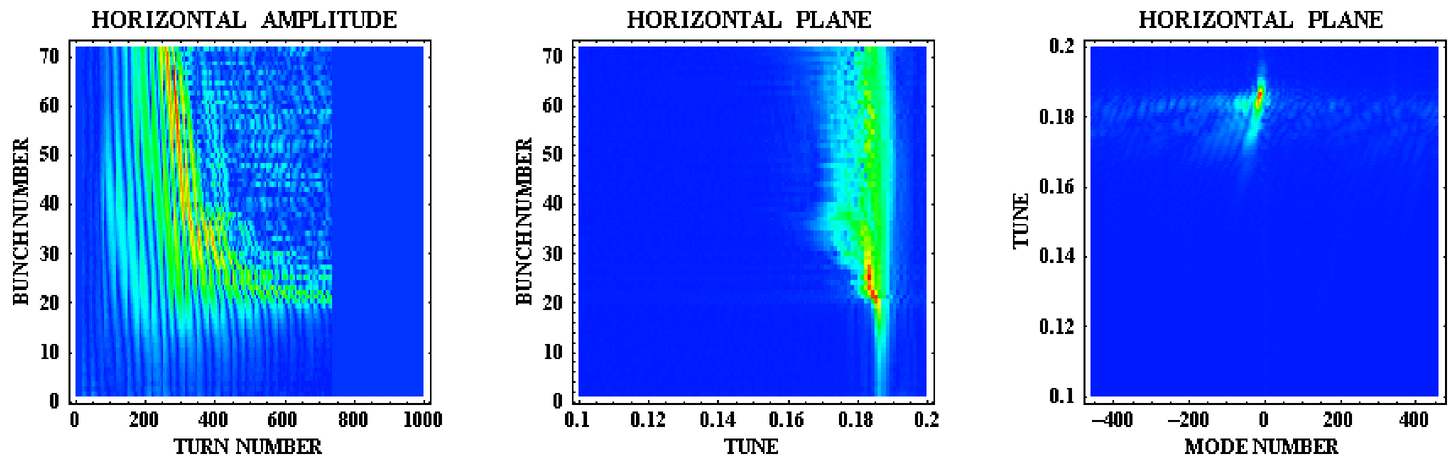


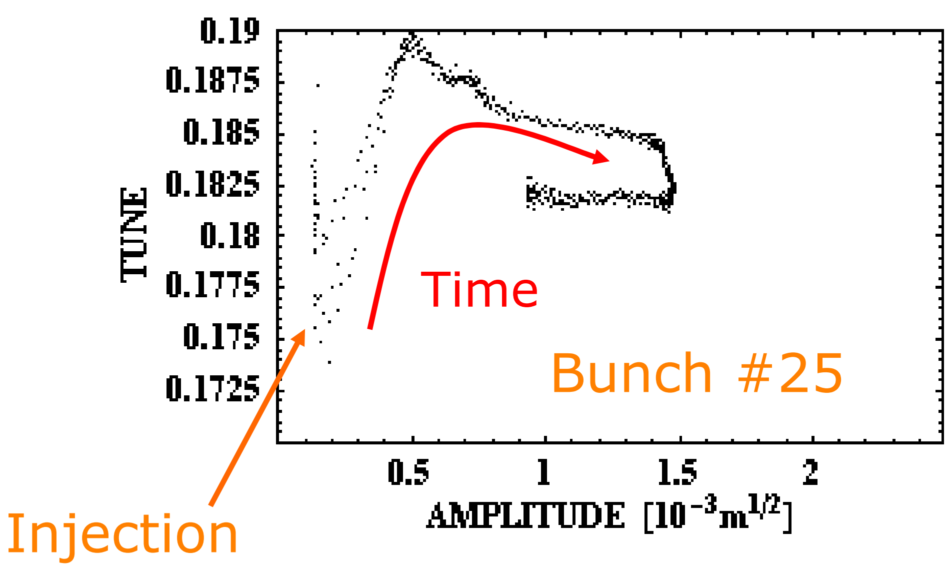


- 2 symmetric electron stripes (depletion of the central area)
- τ_{ECI}>40 turns
- e-cloud saturates>bunch 15-20
- No net separation among modes
- Negative detuning
- Non-linear forces coupling bunches

Horizontal Instability in the SPS
LHC beam

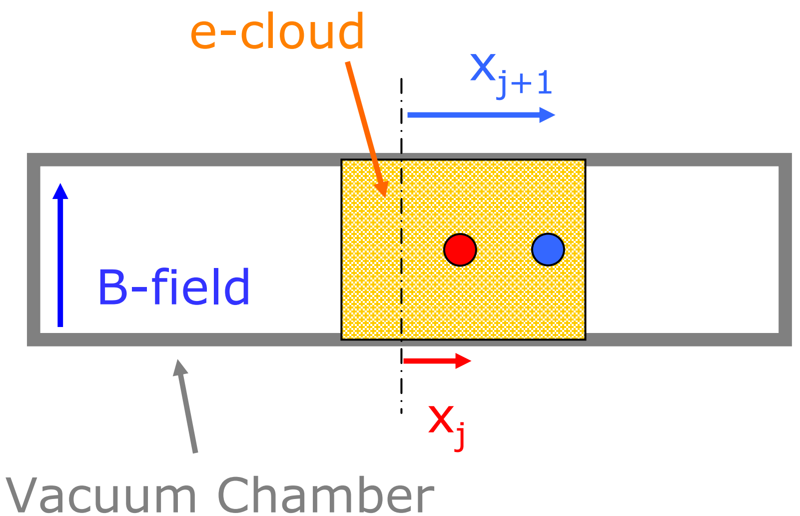
$N_{bunch}=1.1\times10^{11}$ p > $N_{th}=0.8\times10^{11}$ p – Linear machine - TFB OFF





- Three electron stripes
- τ_{ECI}~40 turns
- e-cloud saturates>bunch 15
- Positive detuning for low amplitudes and negative detuning for higher amplitudes
- Non-linear forces coupling bunches

For $N_{th}<N_{bunch}<5\text{-}6\times10^{10}$ p e-cloud ~ vertical ribbon of uniform density starting from a given bunch n.



B-field freezes H-motion of the electrons ➔ no distortion of the e-cloud distribution ➔ e-cloud can couple only subsequent bunches.

Linear coupling force F:

$$F = -\frac{e\rho_{ec}}{\varepsilon_0}\left(x_{j+1} - x_j\right)\chi(j-n)$$

F depends on N_{bunch} via ρ_{ec} ➔ mild dependence on N_{bunch} above threshold. Only the number of bunches affected increases with N_{bunch}.

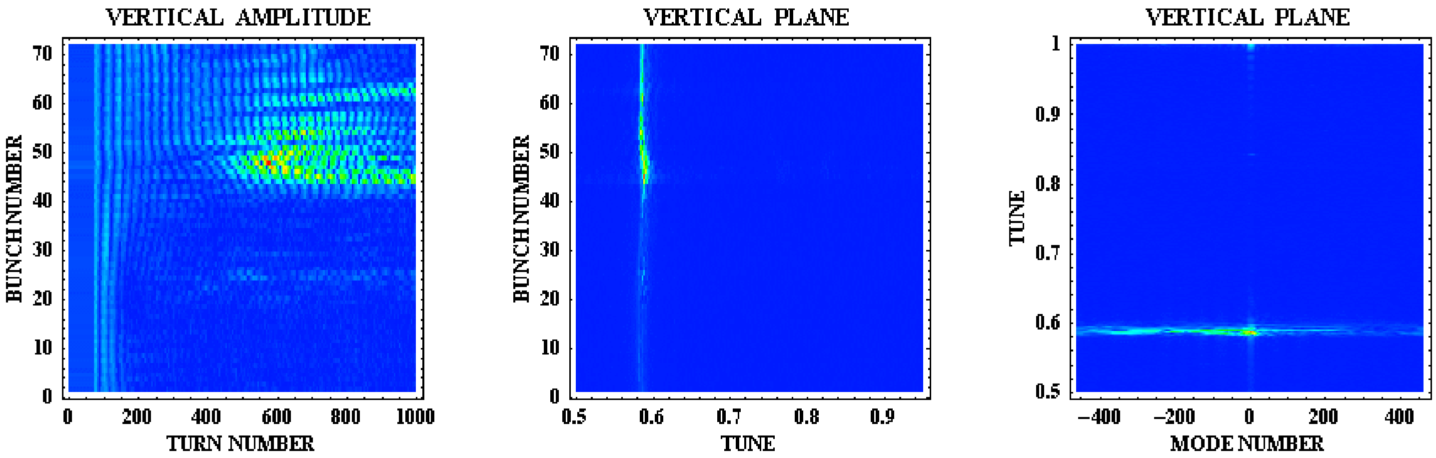
Coupling range can be longer than bunch spacing and one bunch can couple to a few trailing bunches.

For $N_{bunch}>5\text{-}6\times10^{10}$ p> N_{th} the above approx. is no more valid ➔ non-uniform density ➔ non linear behaviour of the coupling force

Vertical Instability in the SPS
LHC beam

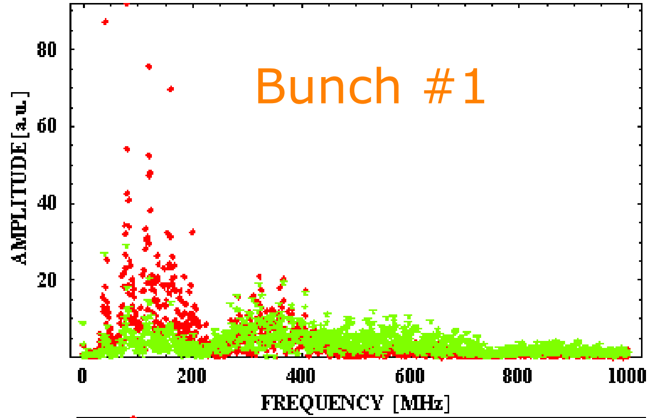
- Mainly affecting the tail of the batch
- τ_{ECI} decreasing with increasing N_{bunch} (max. amplitude of oscillation in ~600 turns for $N_{bunch}=3\times10^{10}$ p and in 300 turns for 5×10^{10} p).
- Sidebands close to the tune line - separation close to Q_s~0.004.

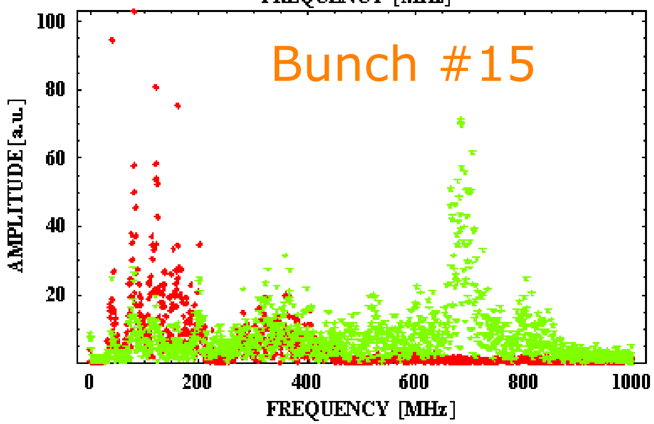
$N_{bunch}=0.3\times10^{11}$ p > $N_{th}=0.2\times10^{11}$ p – Linear machine - TFB OFF

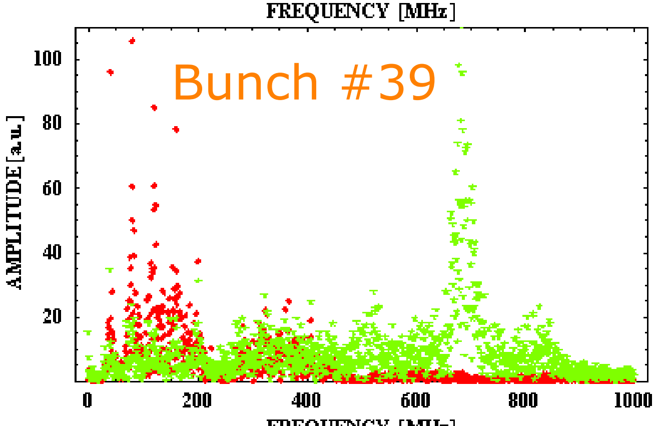


The observed continuum in the mode spectrum (up to the max. observable frequency – 20 MHz) is compatible with an uncorrelated dipolar motion of the bunches.

Vertical Instability in the SPS
LHC beam







$N_{bunch}=0.8\times10^{11}$ p > $N_{th}=0.2\times10^{11}$ p – Linear machine - TFB OFF

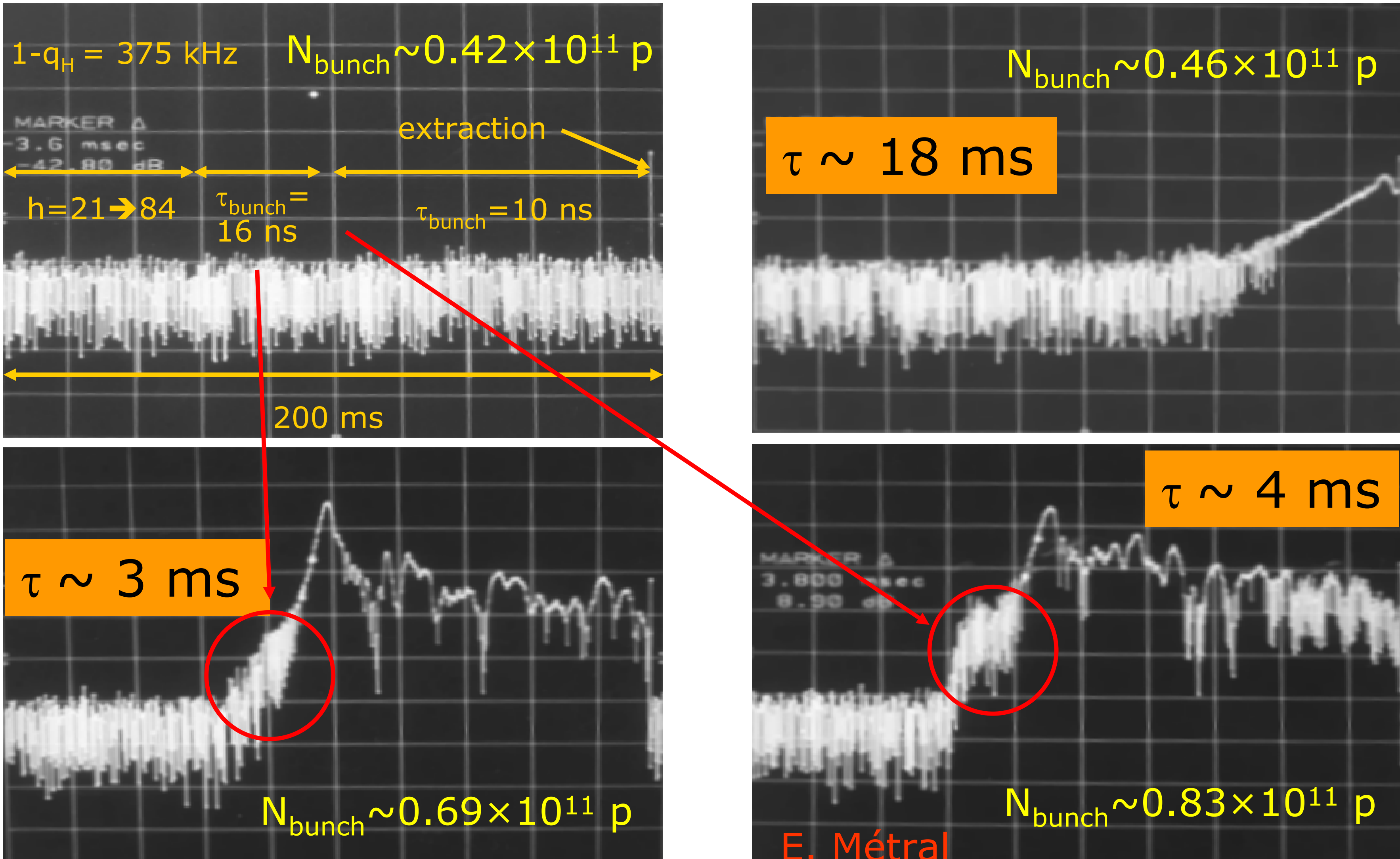
Spectrum of vertical Sum and Delta signals from a strip-line coupler for different bunches along the LHC bunch train.

Transverse single bunch instability (~700 MHz) affecting only the trailing bunches (after bunch 15)

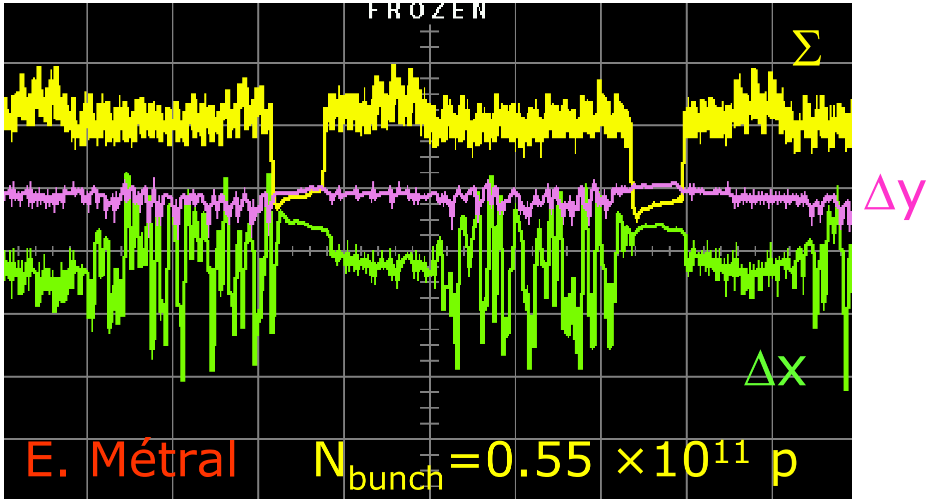
V electron motion is not frozen by the dipole field ➔ electron cloud is pinched during the bunch passage and couples the head and the tail of the bunches.

Horizontal Instability in the PS
Modified LHC beam

Adiabatic bunch compression 16 ns → 10 ns (normally not done)



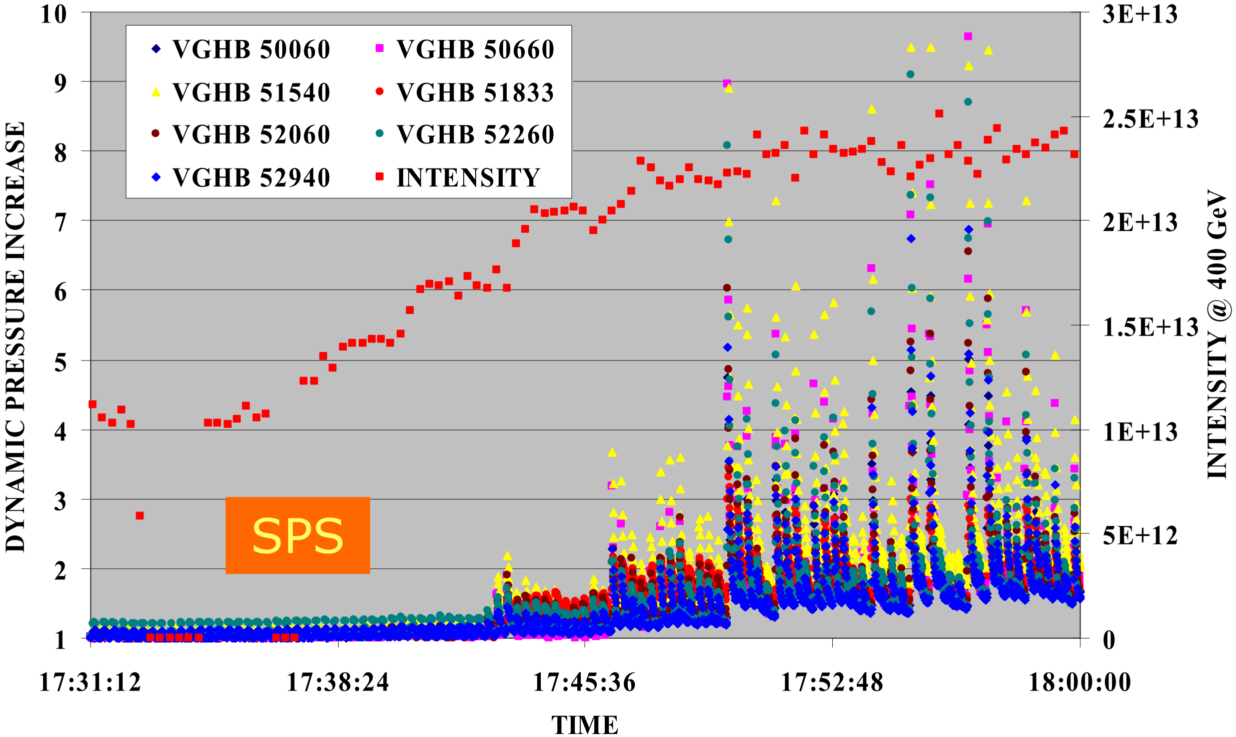
Modified LHC beam



- N_{th}~0.4-0.5 $\times 10^{11}$ p/bunch close to the threshold for the onset of the electron cloud build-up
- Mild (or no) dependence of the growth time on N_{bunch} (as in the SPS)
- Single bunch effect (differently from SPS)? ➔ not evident

- No V-ECI observed but it could have a longer growth time than H-ECI at the intensities considered (as observed in the SPS)
- Beam size blow-up: ×10-20 (H) and ×2 (V)
- Observations under conditions which are different from those for the production of the LHC beam. The LHC beam is extracted once the bunches are splitted and compressed, but we might be just at the edge. At the highest intensity some activity is observed already for τ_{bunch}=16 ns. Important to investigate what happens at higher intensities.

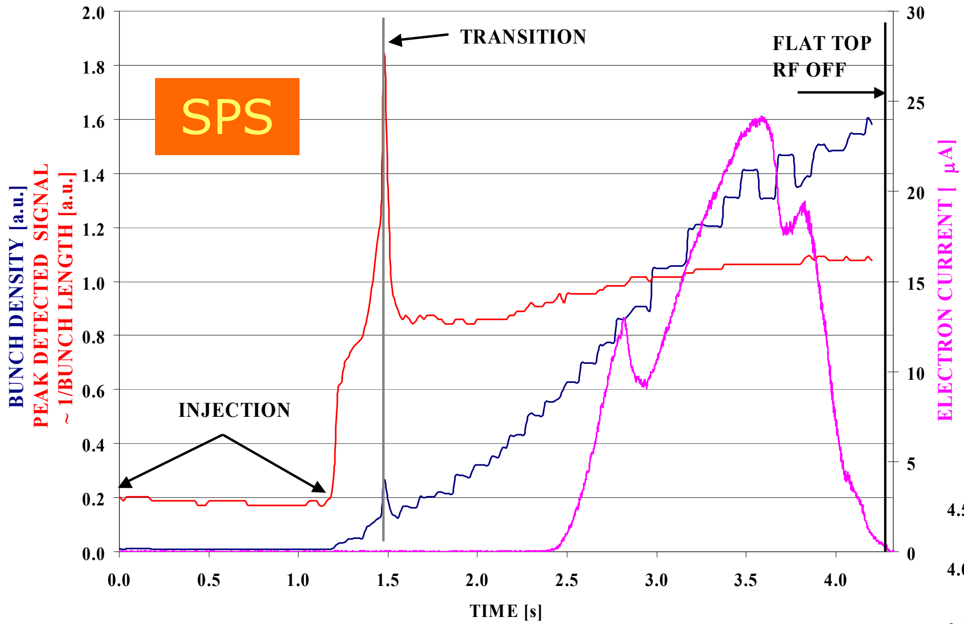
Fixed target beam and electron-cloud



- e-cloud is visible not only with LHC beams, but also with fixed target beam in an unconditioned SPS machine.

Beam	**N_{th} [10^{11} p/bunch] in the arcs**
LHC-25ns (1 batch) @ injection	**0.2**
Fixed Target (2 batches) @ ~100 GeV/c	**0.05**

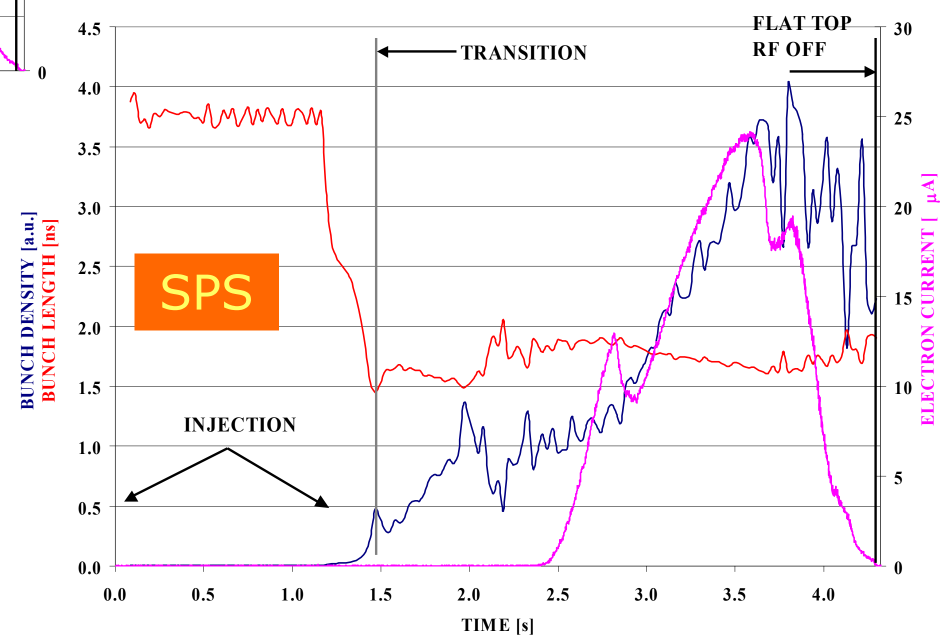
Fixed target beam and electron-cloud



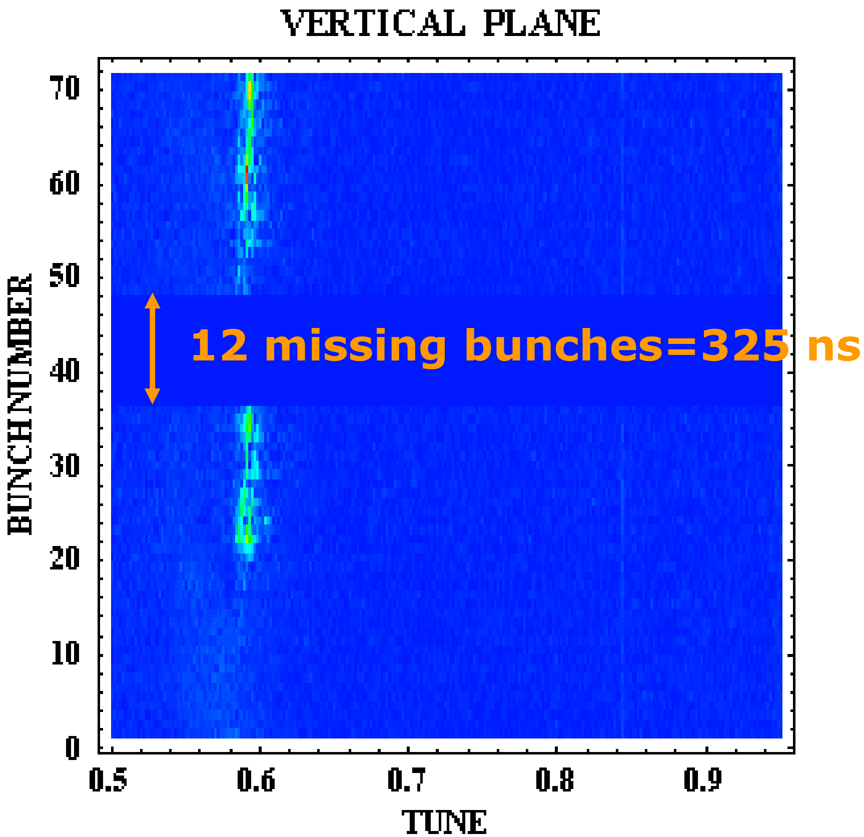
- e-cloud visible only at at high energy
- Qualitatively correlation with bunch density ~ P.D.S./(σ_H σ_Y), although electron flux reduction at the end of the ramp is not explained

- Better correlation with $1/(\sigma_H \sigma_Y \sigma_t^4)$ where σ_t is the measured average bunch length.

  Peak detected signal ~ inverse of the bunch length of the ***shortest*** bunch



You will never forget it….



LHC beam in the SPS

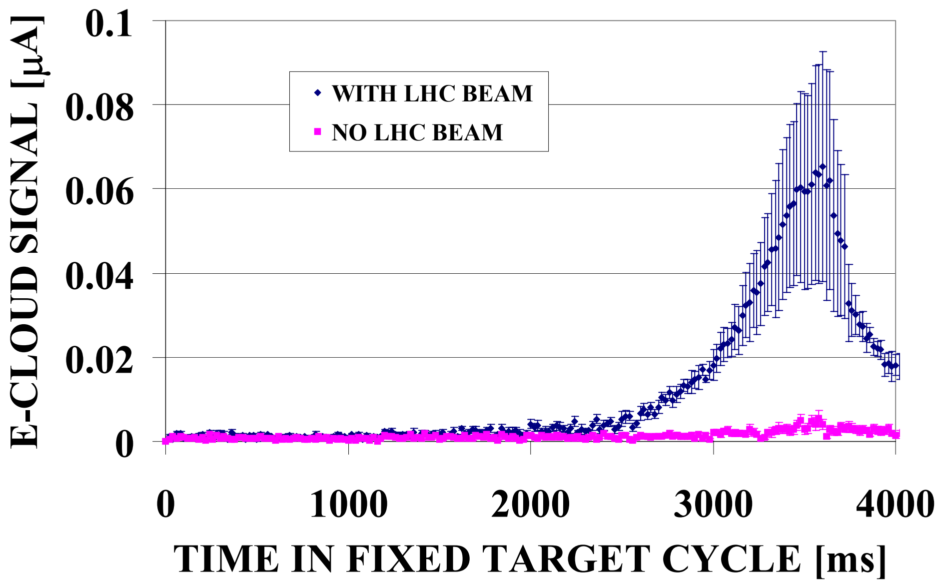
$N_{bunch}=0.3\times10^{11}$ p > $N_{th}=0.2\times10^{11}$ p

Linear machine - TFB OFF

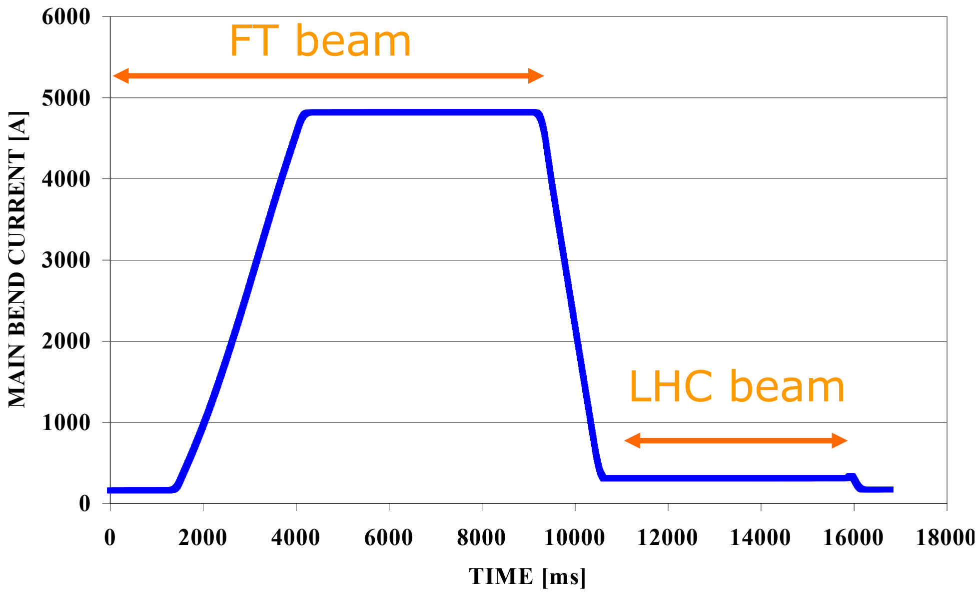
Holes of a few bunches are not sufficient to reset the electron cloud. After a hole the instability restarts earlier. Compatible with observations done with e-cloud monitors.

You will never forget it….

But e-cloud survival can be even longer (seconds) and "couple" beams in different cycles, even in a "conditioned" machine.



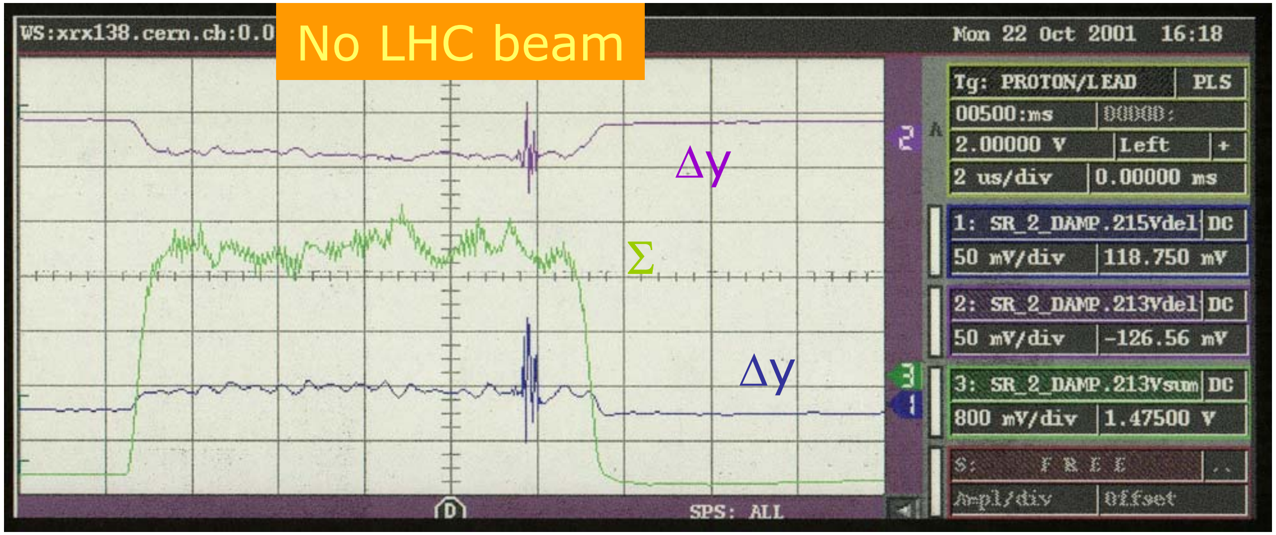
Standard SPS super-cycle

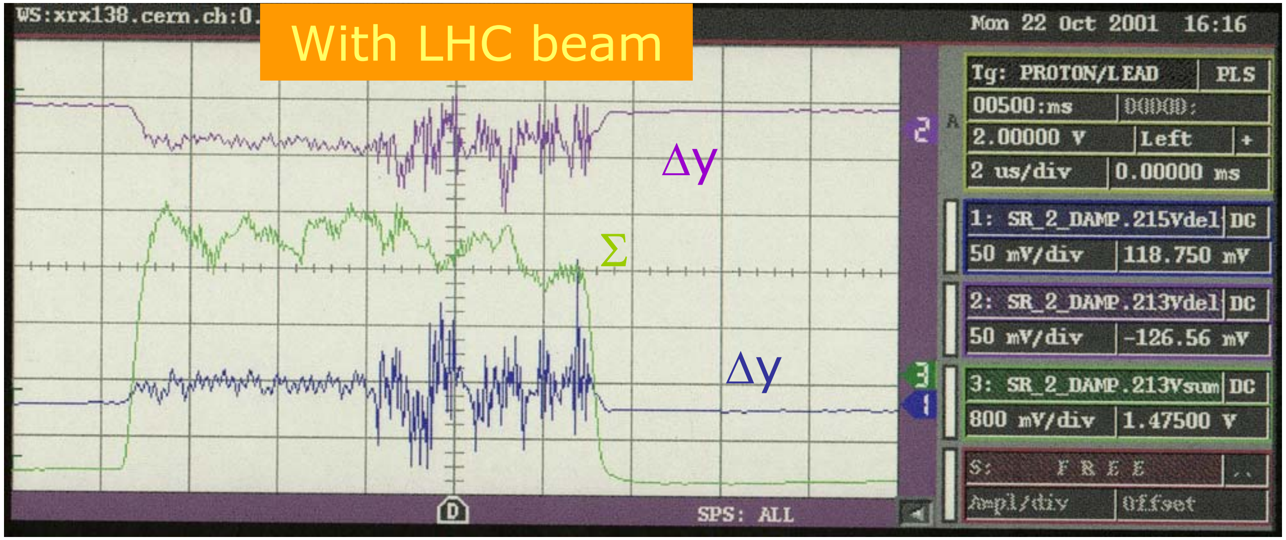


Enhancement of the e-cloud signal induced by the FT beam due to the presence of the LHC beam in the preceding cycle.

Electron Cloud Instability in the SPS
Fixed target beam

FT beam ($\sim 1.7\times10^{13}$p$\rightarrow N_{bunch}\sim 0.08\times10^{11}$p)–500ms after inj.-TFB ON

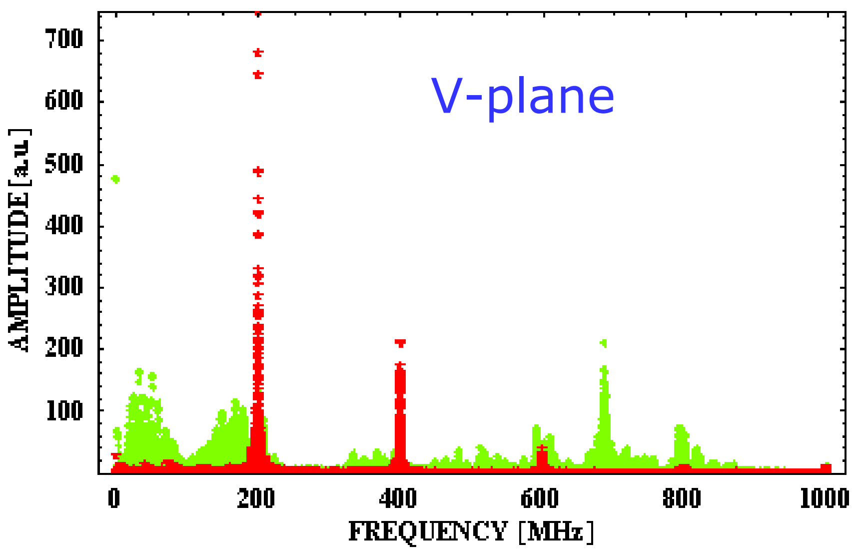


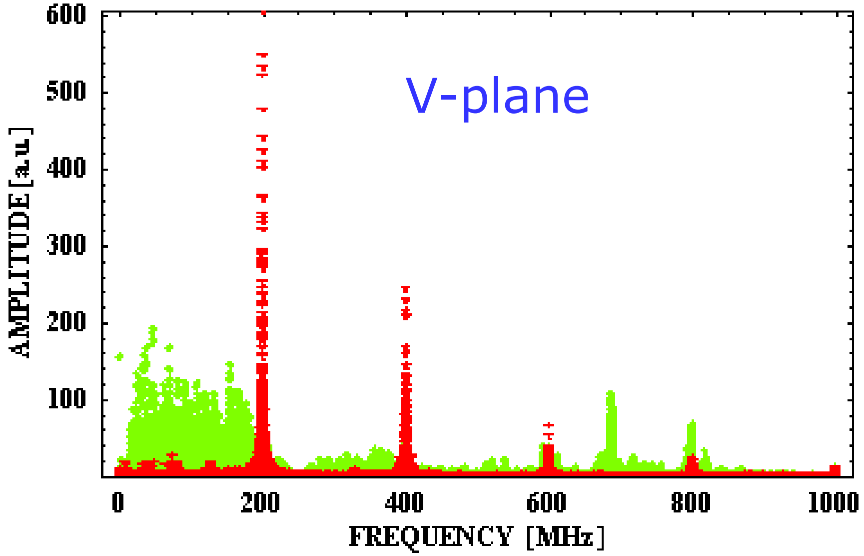


- In the presence of LHC beam, losses occur at flat-bottom on FT beam.
- A vertical instability is affecting the tail of FT batch if the LHC beam is injected in the preceding cycle.
- Inhibiting injection of the LHC beam eliminates this effect in the following FT cycle.

FT beam (~1.4×10^{13}p → N_{bunch}~0.07×10^{11}p)–100ms after inj.-TFB ON

Spectrum of Σ and Δ signals from strip-line coupler





High order coupled-bunch modes (max. 50 MHz but sometimes up to the highest=100MHz). Low frequency modes (up to ~20 MHz) are damped by the TFB.

Still visible single-bunch modes ~700 MHz.

Growth times are of several thousand turns.

- FT beam in parallel to LHC beam operation:
  - In the H-plane only low order coupled bunch modes (<10 MHz) can occur because the e-cloud motion is frozen in that plane. These modes are damped by the TFB.
  - In the V-plane coupled-bunch instabilities up to the highest modes are also observed, very likely because of the lower bunch charge and tighter bunch spacing resulting in bouncing period longer than the bunch spacing. Measured rise-times are much longer than those observed for the nominal LHC beam.
- Dedicated operation with FT beam:
  - For the conditions explored up to now ($N_{bunch}<0.1\times10^{11}$ p) ECI is not a serious problem for the FT beam: even in an "unscrubbed" SPS machine electron cloud build-up occurs mainly at high energy when the beam is stiffer.
  - But other undesirable effects have been noticed: sparking of the electrostatic septa.

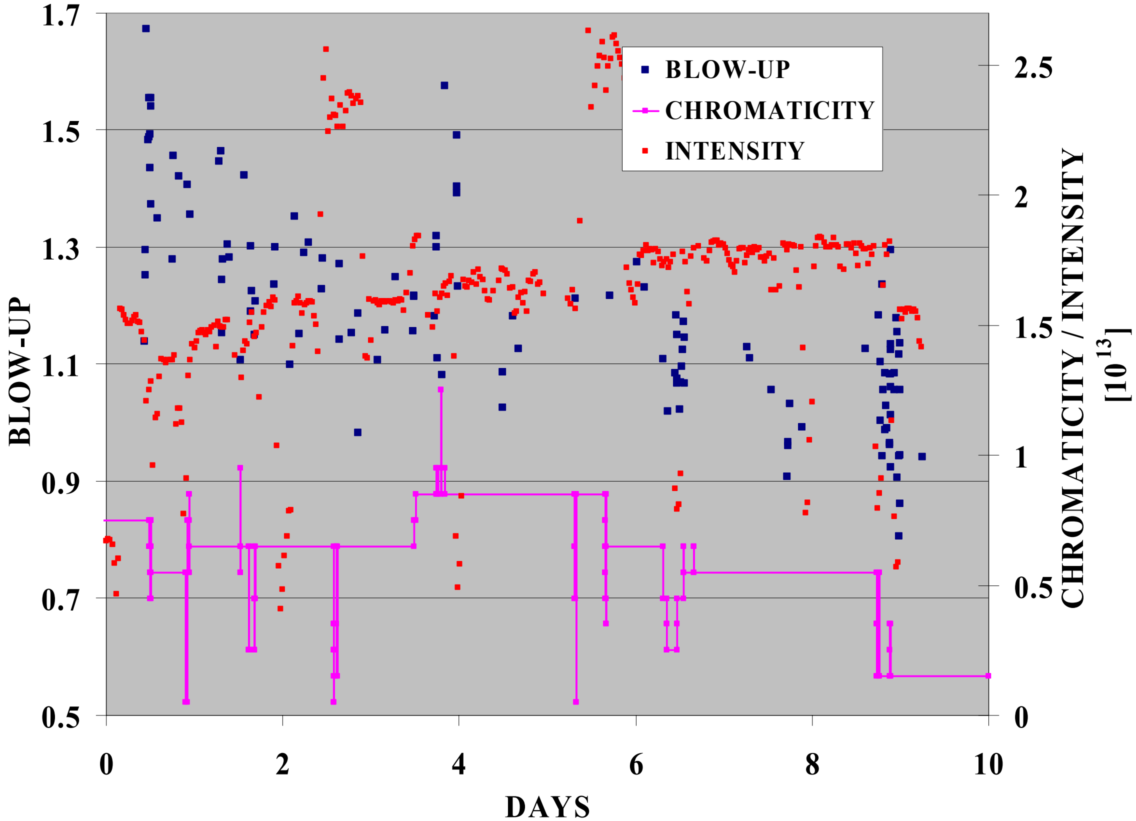
Cures for ECI

- In the horizontal plane where only (PS?) coupled-bunch modes are observed the TFB is sufficient to fight ECI. Whenever a TFB is not available (PS) "strong" octupoles can cure ECI.

- In the vertical plane:
  - Single bunch instabilities (LHC beam in the SPS) can be cured with high chromaticity $\xi=(\Delta Q/Q)/(\Delta p/p) \sim 0.5 - 1$
  - Coupled-bunch instabilities (FT beam || LHC beam in the SPS) can be cured with octupoles.

Cures for ECI

- Of course eliminating the cause of the ECI is even better …➔ Scrubbing (see J.M. Jimenez talk). Although an electron-cloud free environment cannot be achieved.



Reduction of the V-emittance blow-up along a 15 s injection plateau during the SPS scrubbing run in 2002.

Note:the intensity is increasing and the V-chromaticity is reduced.

Summary and Conclusions

- Electron cloud effects have been observed in the PS Complex and SPS initially with LHC beams
- Fast instabilities are the most dramatic effect on the beam. Their nature is the result of the behaviour of the electron cloud in the bending magnets which are filling >70 % of the circumference of these machines.
- Electron cloud build-up has been observed in the SPS also for Fixed Target beam, but for the moment only at high energy and for an "unscrubbed" machine.
- Evidence that the electron-cloud can survive seconds after the LHC beam passage ➔ ECI can develop on the FT beam if this is injected in the following cycle.
- Cures have been found to control the ECI and to reduce electron multipacting
- LHC beam with nominal intensity and longitudinal emittance and with transverse emittances close to nominal ($\varepsilon_H^* = \varepsilon^*_{nominal}$ and $\varepsilon_V^* \sim 1.2\ \varepsilon^*_{nominal}$) has been accelerated up to the SPS extraction energy in 2003.