Measurements of E-Cloud Instability in the SPS (2001-2008)

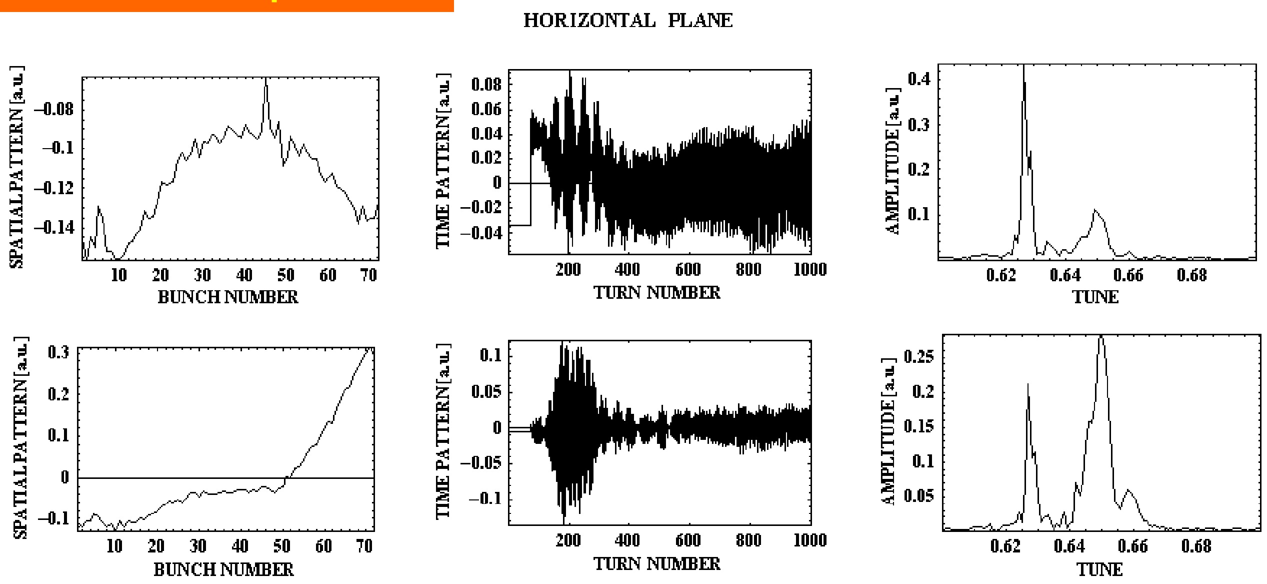
G. Rumolo, in ECM'08 Mini-Workshop, CERN, 20-21 Nov 2008
*with the collaboration of G. Arduini, E. Benedetto, T. Bohl, R. Calaga, K. Cornelis, W. Höfle, E. Métral, G. Papotti, E. Shaposhnikova, B. Salvant, R. Tomás, SPS operators, and many more....

- Observations prior to 2006
- SPS upgrade studies: Scaling law of e-cloud instability with beam energy
- Measurements 2006-2008:
  - First attempt to study experimentally the scaling of the ECI at the SPS in 2006
  - 2007 e-cloud MD campaign
  - 2008 measurements for feedback system
- Conclusions

- **The LHC nominal beam (4 batches with 25 ns spacing and 1.1 10^{11} ppb) in the SPS suffers from:**
  - **The horizontal electron cloud instability is a coupled bunch phenomenon**
    - → It usually affects the last batch(es)
    - → It manifests itself with a correlated bunch-to-bunch unstable motion
    - → It may result in beam loss over hundreds of turns
    - → It can be suppressed with feedback
  - **The vertical electron cloud instability is one of the main single bunch intensity limitations in the SPS.**
    - → It usually affects the tail bunches of the last batch(es)
    - → It manifests itself with uncorrelated unstable motion of these bunches
    - → It results in fast beam loss (few tens of turns)
    - → It can be cured by running with high positive chromaticity after a scrubbing run

Observations prior to 2006.....

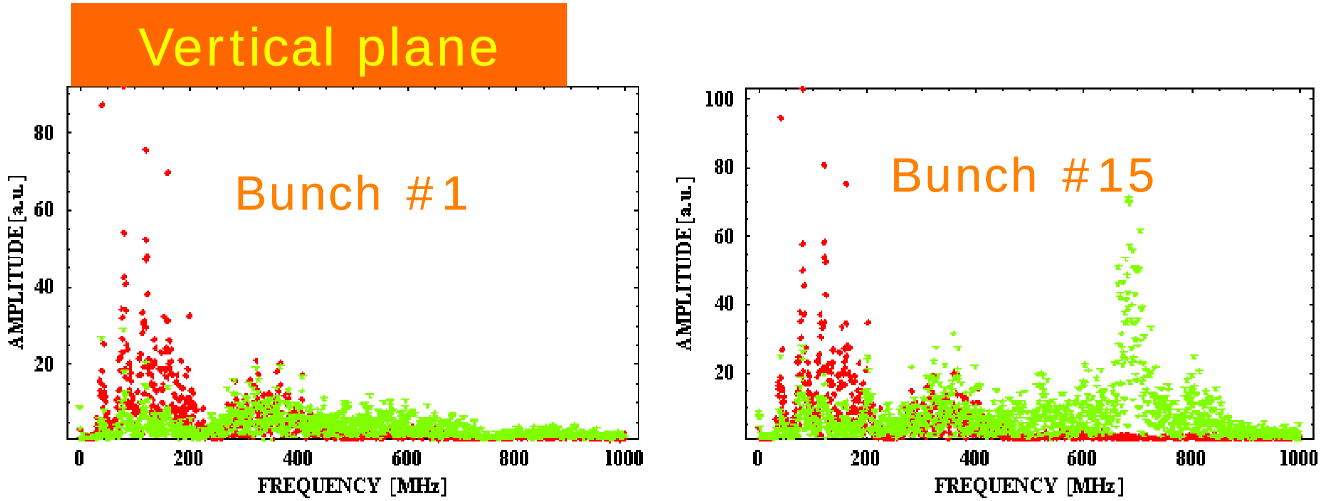
Horizontal plane



$\tau \sim \gamma$

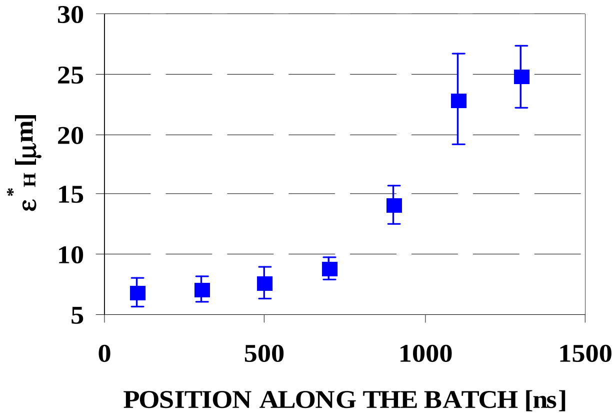
- Low order (~1-2 MHz) CB-mode
- Cures: Transverse feedback (bandwidth 0–20 MHz). Gain due to energy increase is marginal
- The rise time scales with γ and therefore this instability is less critical at higher energy.

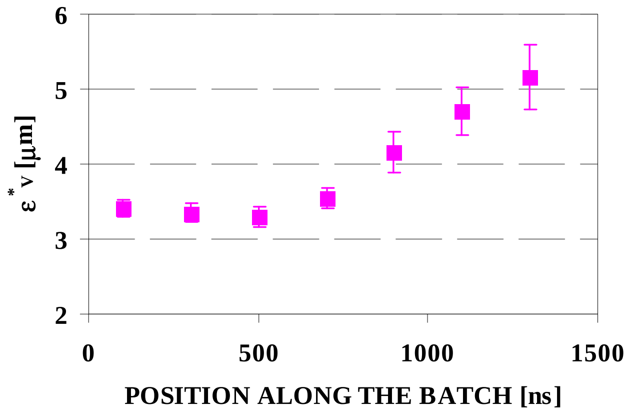
Observations prior to 2006 (II)



- TMCI like instability (~700 MHz) affecting trailing bunches.
- Cures: (ξ_V > 0.4-0.5) ➔ large tune spread.
  - ✓ How far can we go above the nominal intensity ?
  - ✓ Does positive chromaticity significantly affect the beam lifetime ?
- Under conservation of the emittances, constant bunch length and matched voltage, increasing the energy is not beneficial
- Might need to reconsider the optimum longitudinal parameters for the transfer (larger longitudinal emittance?)

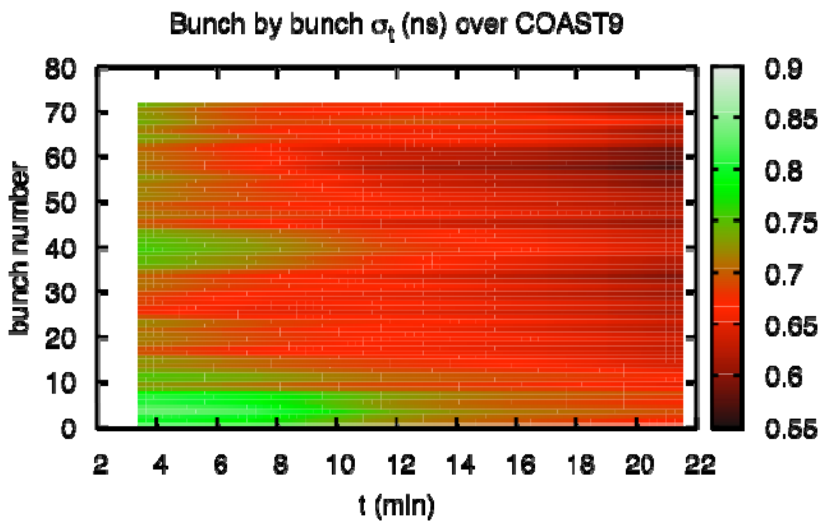
Observations prior to 2006 (III)

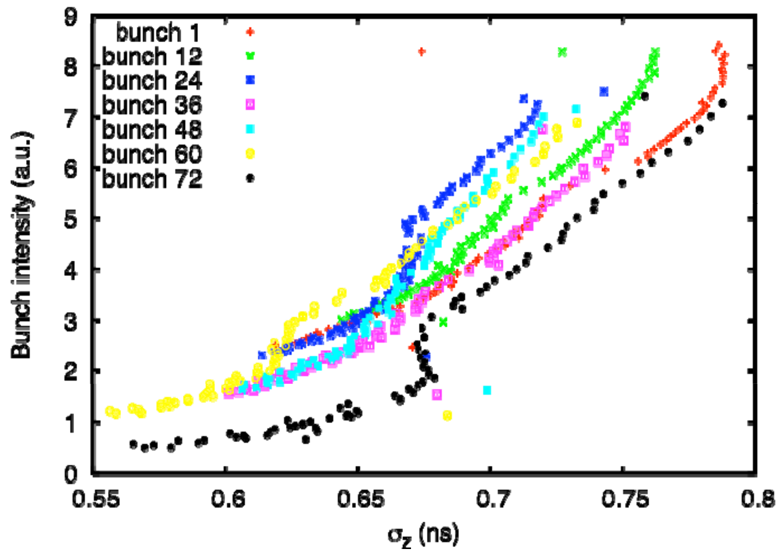




- **Observation of emittance blow up along the batch**
  - ✓ **Tail bunches have larger emittances than those at the head of the batch**
  - ✓ **Both transverse planes affected**
  - ✓ **Effect seems more pronounced in the horizontal plane**
- **Coherent or incoherent effect ?**

OBSERVATIONS PRIOR TO 2006 (IV)

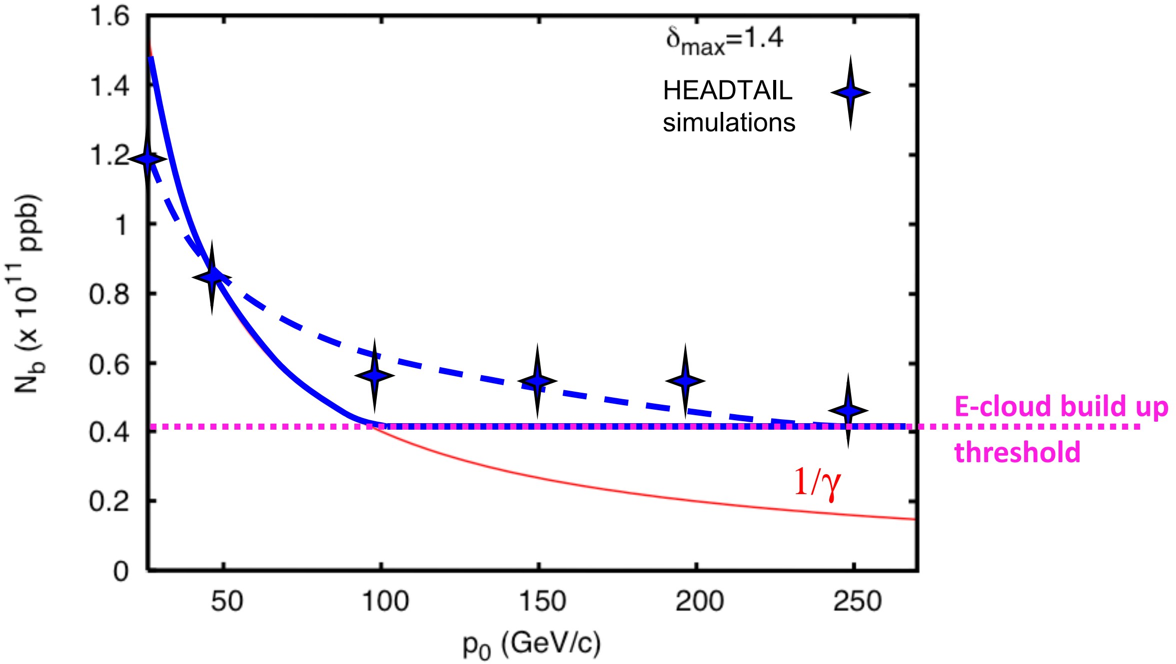




- **Bunch shortening along the batch during a coast**
  - ✓ **Trains of LHC beams stored over several minutes in the SPS show that bunches at end of the train tend to lose more and to become shorter**
  - ✓ **There is an effect of chromaticity**
- **Is it an incoherent effect due to electron cloud ?**
  - ✓ **However, correlation intensity-length for different bunches along the train does not seem to depend on the bunch position**

- **In the framework of the PS2/SPS Upgrade studies, the possibility to inject into the SPS with a higher energy (50-60 GeV/c) poses the following question:**
  - **How does the electron cloud single bunch instability scale with energy, conserving the specifications and assuming unchanged production scheme ?**
  - **Answer not straightforward because**
    - → Higher energy means more rigid, therefore **more stable**, beam
    - → At higher energy the beam gets **transversely smaller**, which enhances the pinch of the electrons as the bunch goes through them
    - → The matched voltage is lower at higher energy, which translates into a **lower synchrotron tune** (destabilizing)
  - **Detailed HEADTAIL simulation study was carried out to find out the correct scaling law with energy**
  - **Experimental verification at the SPS was first attempted in 2006, and then continued throughout all 2007**

HEADTAIL prediction using model with self-consistent e-cloud



For δ_{max}=1.4 the instability threshold is found to decrease with γ up to ~100 GeV/c, then it levels off at the value of the build up threshold

$\rightarrow$ Conservation of longitudinal emittance, bunch length and normalized transverse emittances.

$\rightarrow$ Bunch always matched to the bucket !

First experiment at the SPS trying to prove the scaling law of e-cloud instability (2006)

• On the 24.10.2006 we used a 20.4 s LHC cycle in which 5 batches with 48 bunches were injected over 10.8 s in the SPS and then ramped to 450 GeV/c

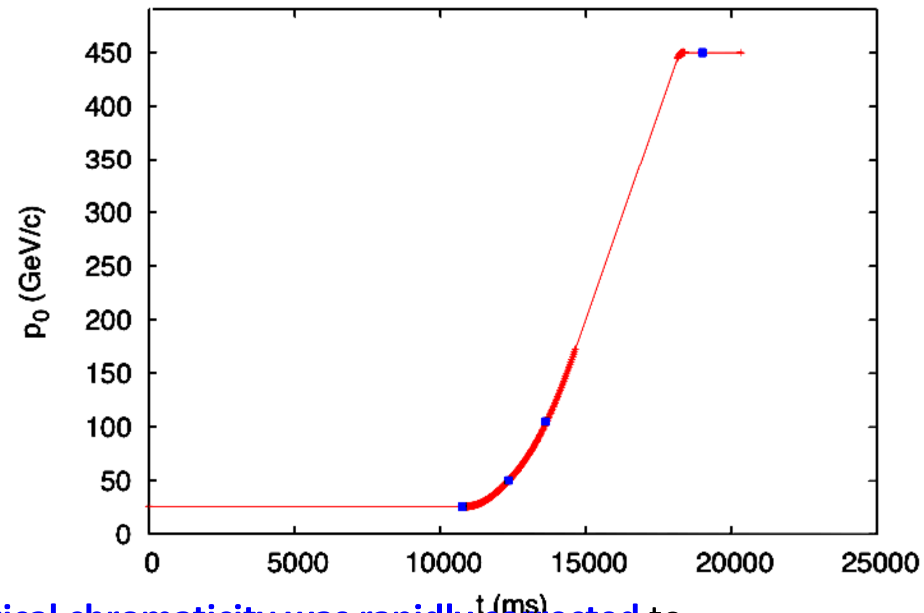
• Measurement points are:

→ 26 GeV/c, 10770 ms,
  beam dump @ 10850 ms

→ 50.2 GeV/c, 12360 ms,
  beam dump @ ?

→ 105 GeV/c, 13630 ms,
  beam dump @ 13670 ms

→ 450 GeV/c, 19000 ms,
  beam dump @ 19060 ms

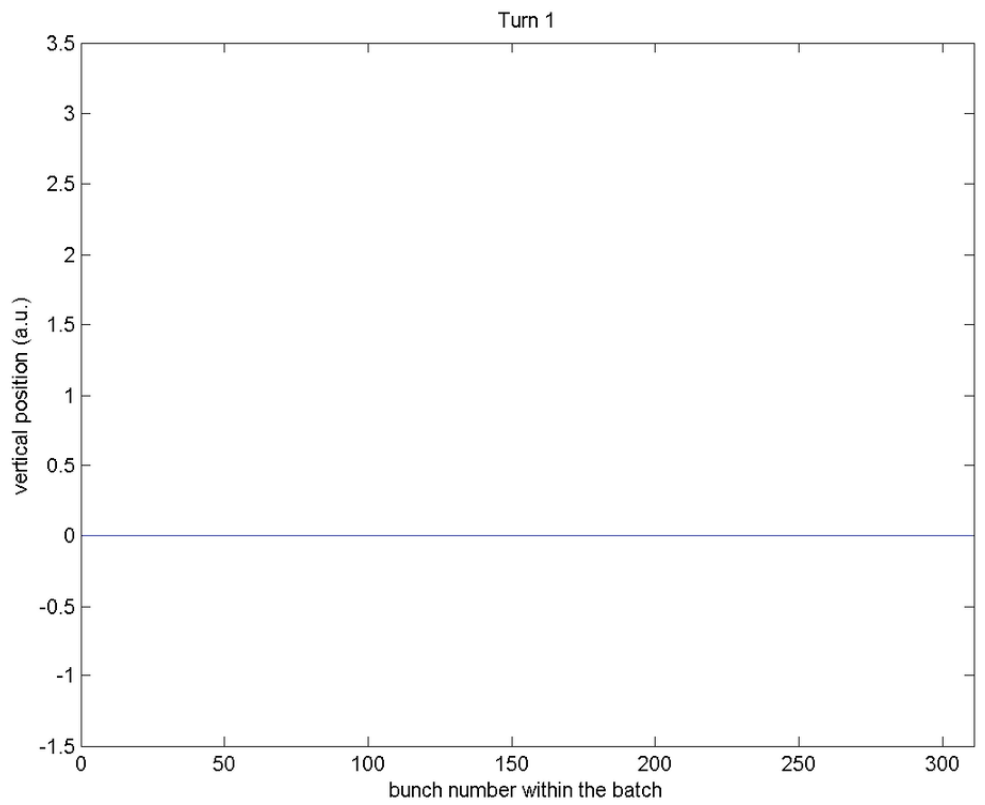


At these measurements points the **vertical chromaticity was rapidly corrected** to observe the beam electron cloud induced instability

The only clear sign of **vertical instability** was observed at 26 GeV/c

⇒ the beam would go unstable at the end of the third batch

⇒ beam losses observed

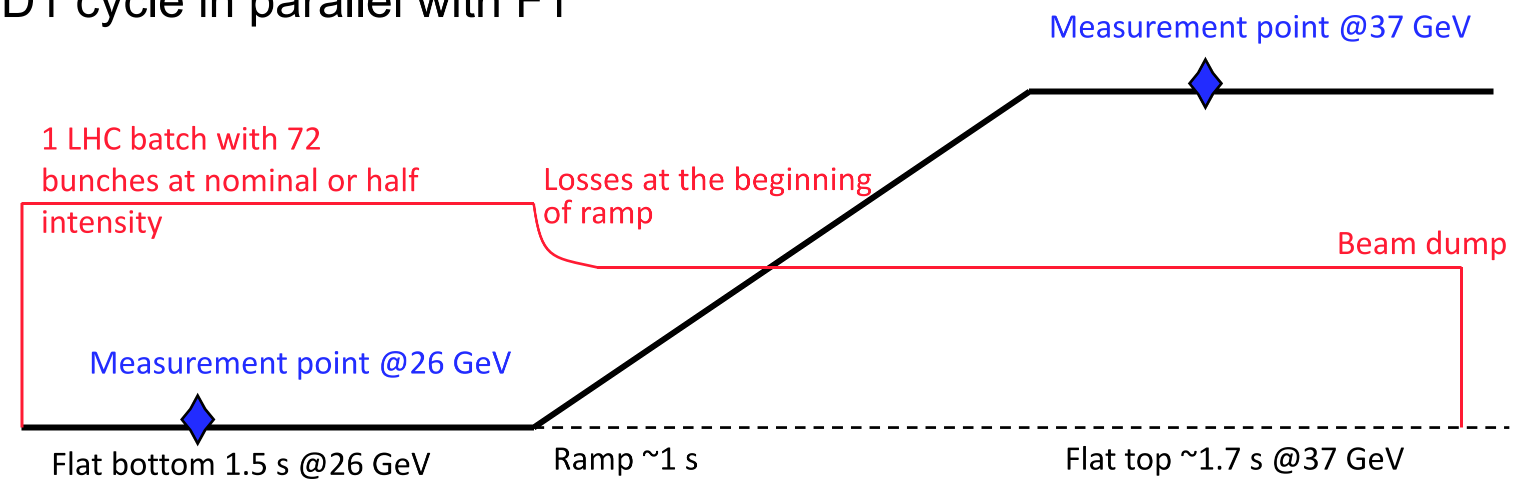


MDs in 2007 (I)

26 and 37 GeV/c before the scrubbing run

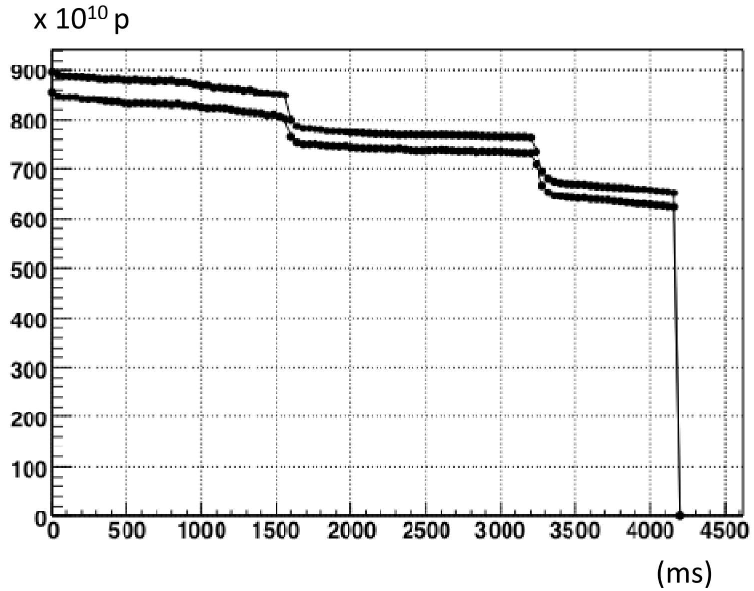
- Vertical chromaticity was lowered at the measurement points, till the beam (1 batch nominal LHC) becomes unstable. Look for *Q´* threshold for instability
  - $\rightarrow$ *Q´=-0.19* at 26 GeV/c (setting value)
  - $\rightarrow$ *Q´=0* at 37 GeV/c (setting value)
- The damper gain was kept to nominal value all along the cycle

MD1 cycle in parallel with FT



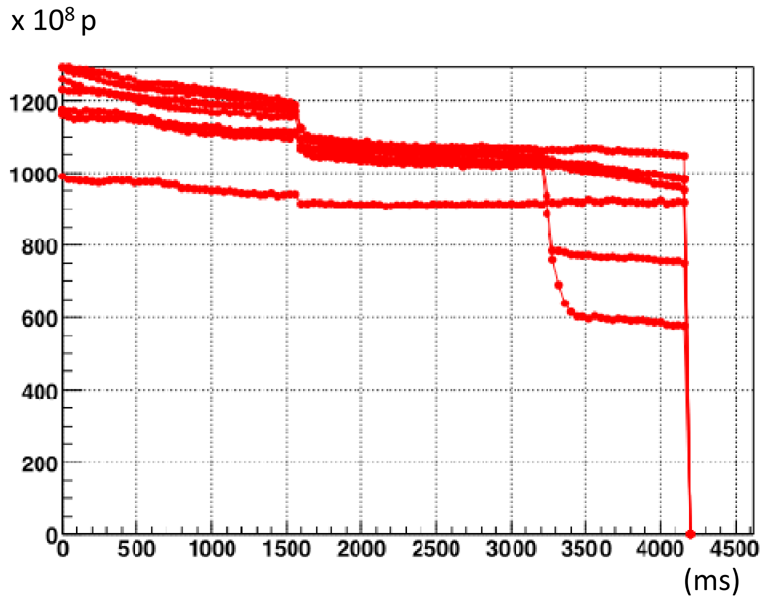
MDs in 2007 (II)

Example of instability @ 37 GeV/c



Here Q'_V was trimmed to 0 at 3500 ms.

Losses occur due to an instability

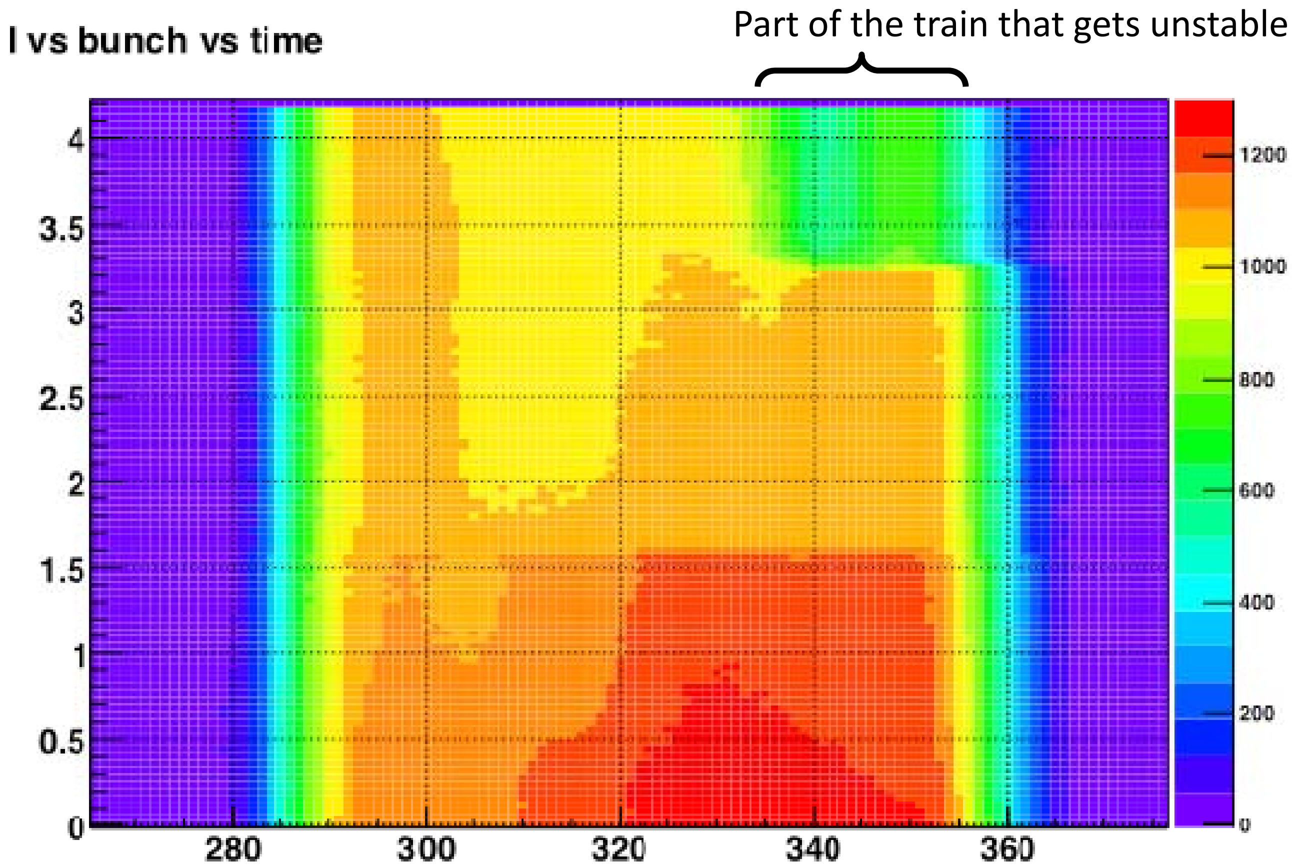


The Fast BCT shows the time evolution of 7 bunches along the batch (1,11,21,31,41,51,61,71).

Losses affect the bunches in the tail of the train

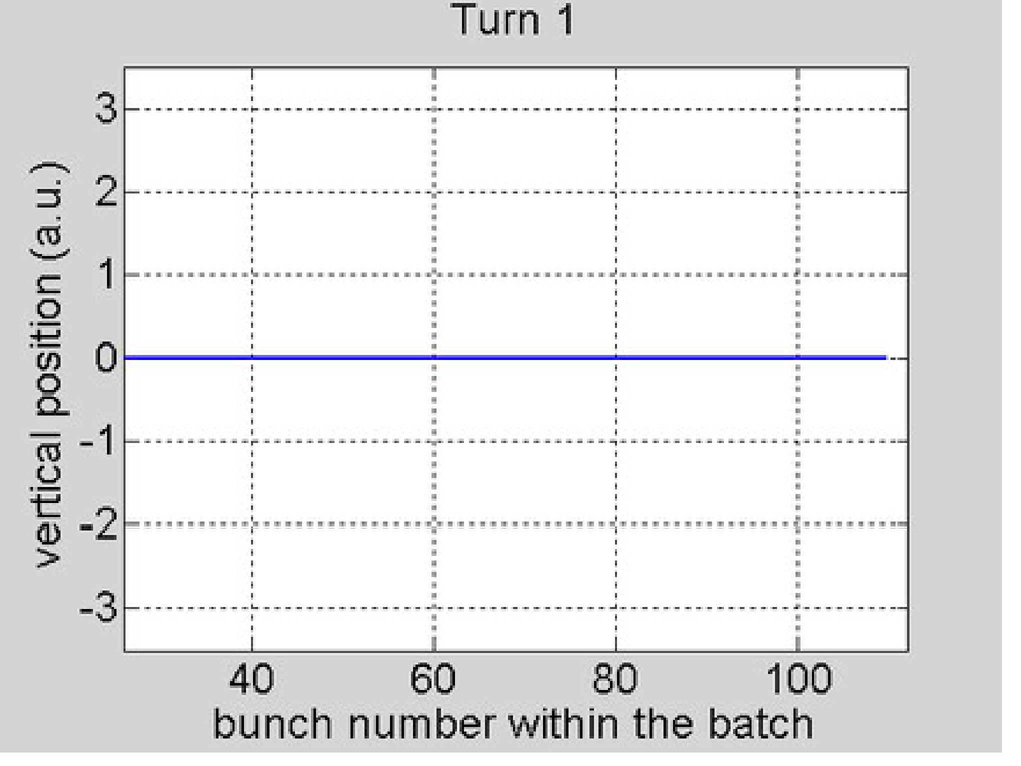
MDs in 2007 (III)

Example of instability @ 37 GeV/c



MDs in 2007 (IV)

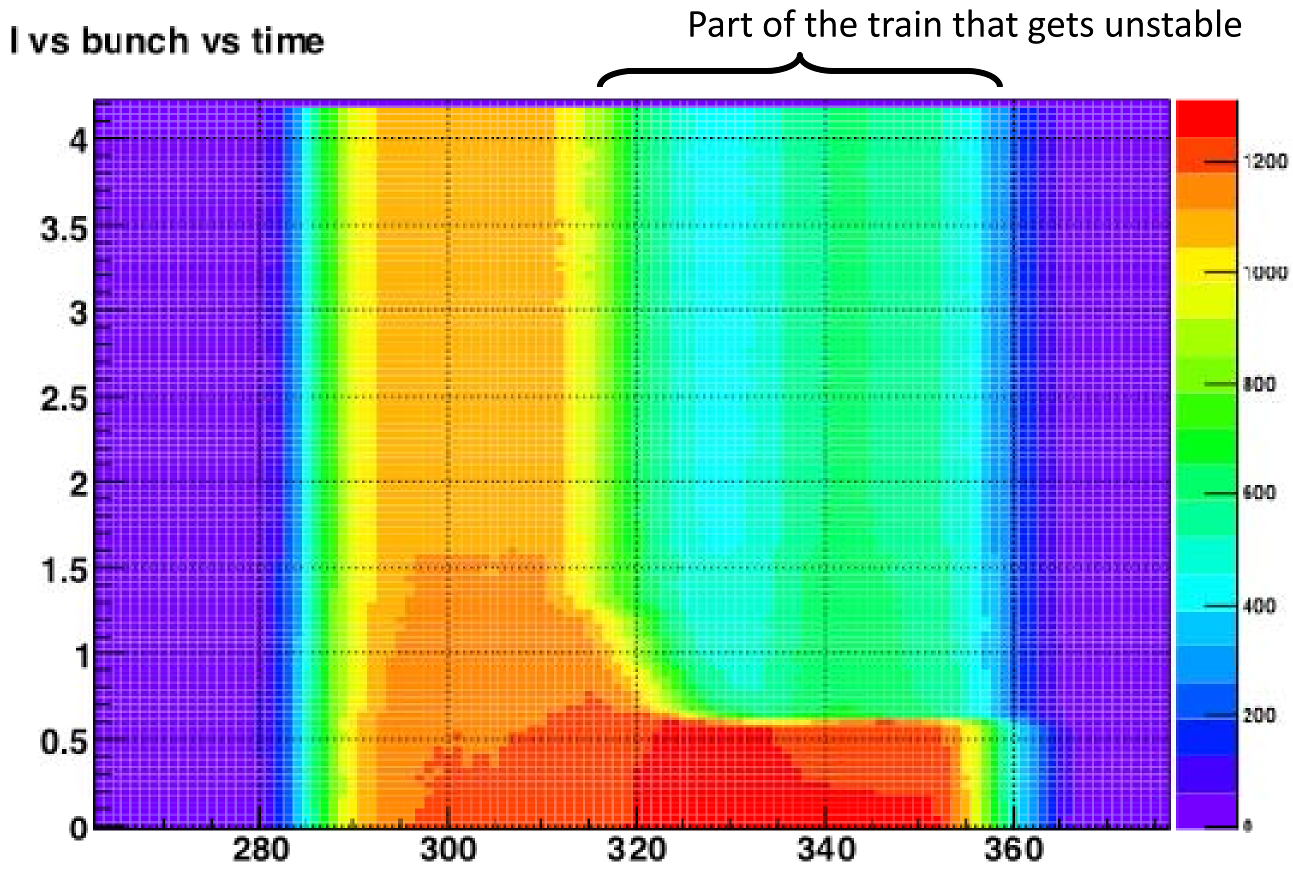
Example of instability @ 37 GeV/c



- No real correlation visible between the motion of the unstable bunches
- Seems a single bunch instability affecting the very last bunches of the train

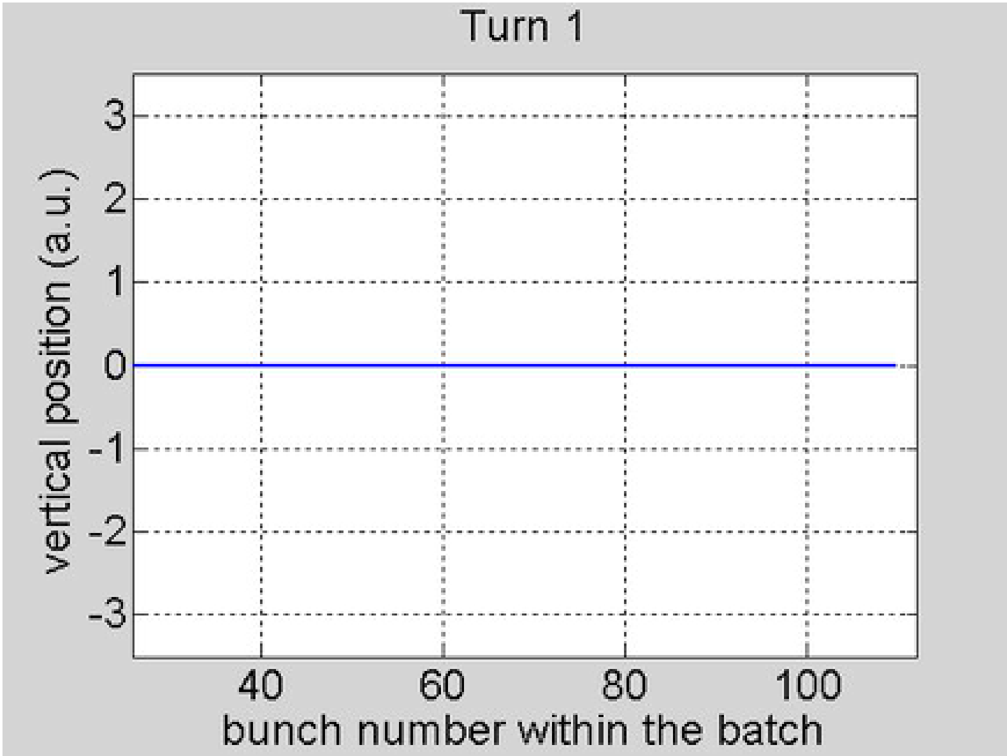
MDs in 2007 (V)

Example of instability @ 26 GeV/c



MDs in 2007 (V)

Example of instability @ 26 GeV/c



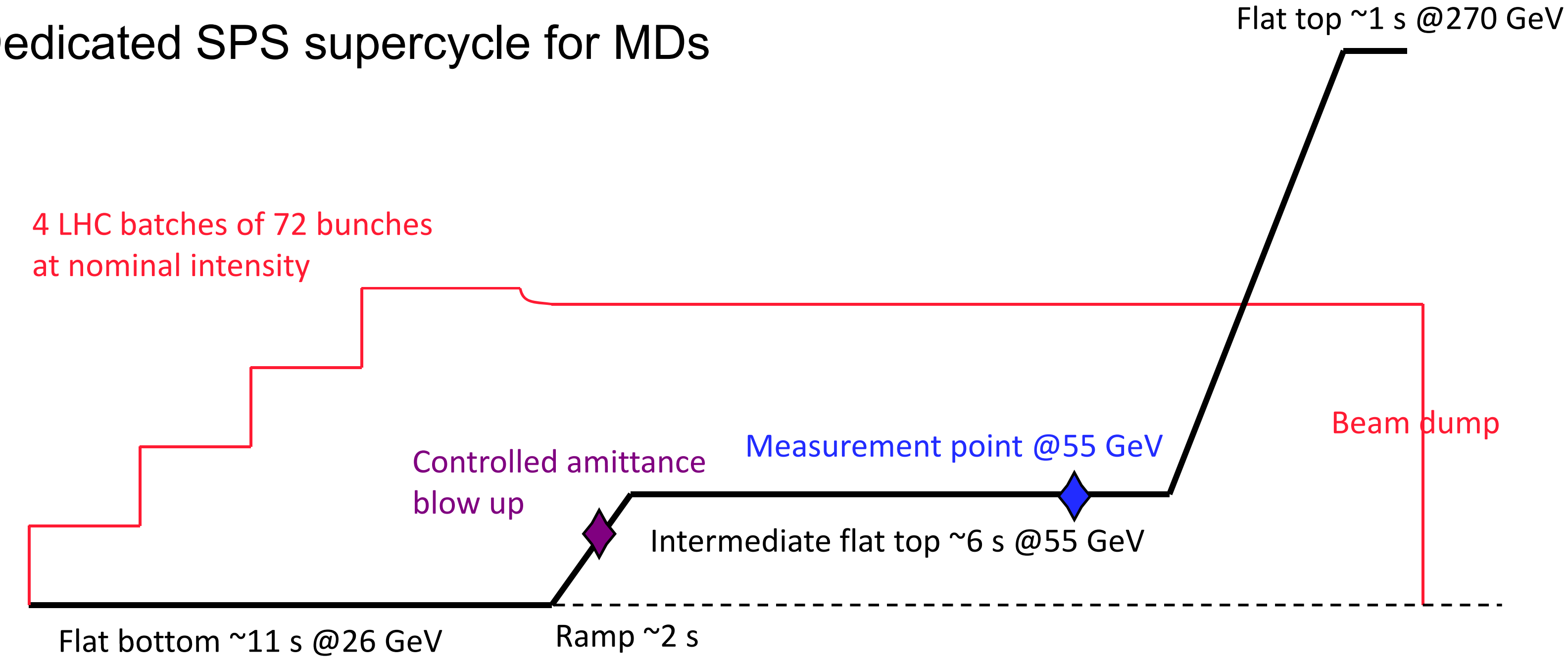
- The coherent motion seems to start at the tail and propagate over the train
- Suspected coupled bunch instability with high mode number

MDs in 2007 (VI)

Study on the 55 GeV/c plateau

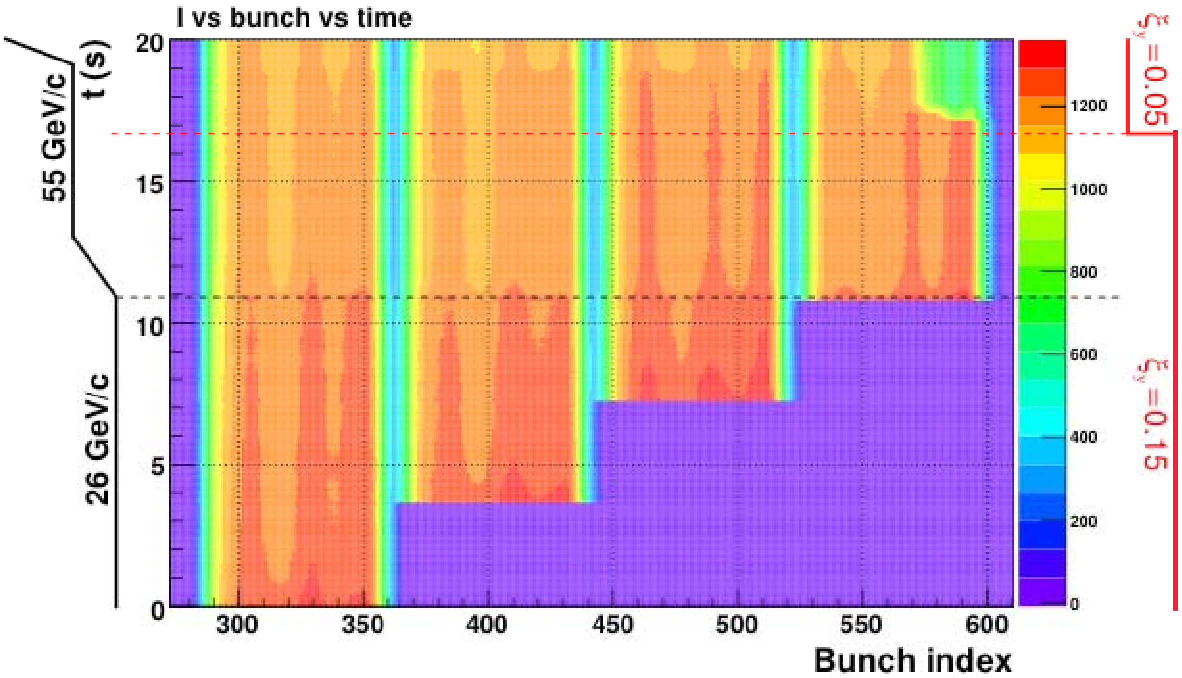
• Vertical chromaticity was lowered at the measurement point, till the beam becomes unstable. Try to stabilize by increasing the transverse emittance (excitation made with the damper).

Dedicated SPS supercycle for MDs



MDs in 2007 (VII)

Study on the 55 GeV/c plateau

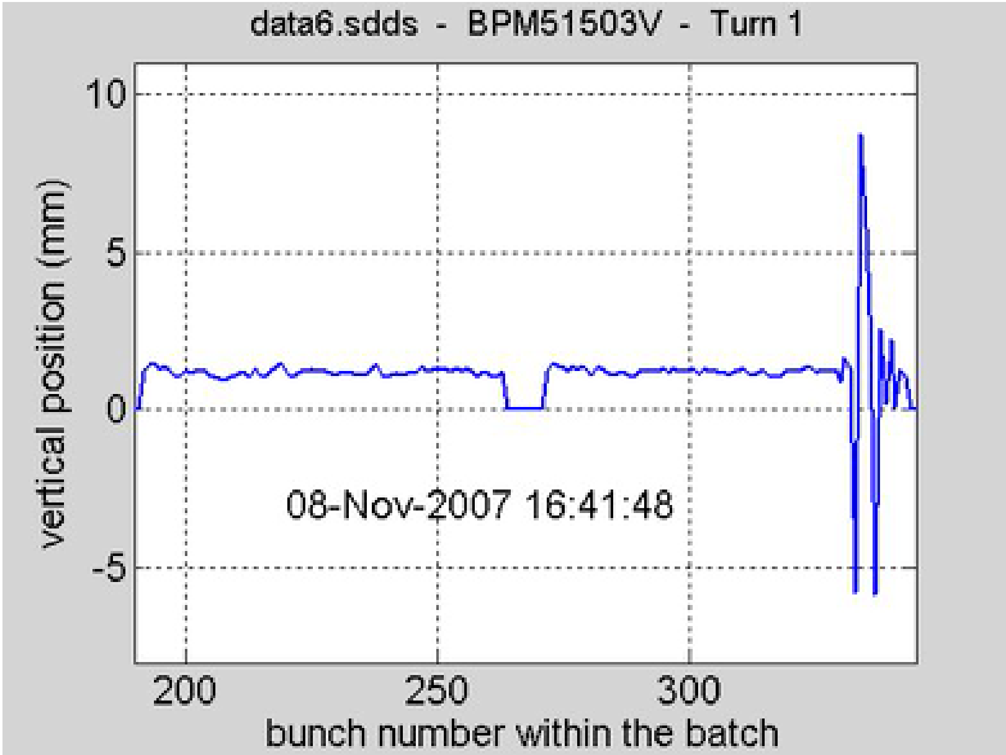


Without emittance blow up:

⇒ An instability caused beam loss at the tail of the fourth batch, when vertical chromaticity was lowered to 0.05 toward the end of the intermediate plateau at 55 GeV/c

MDs in 2007 (VII)

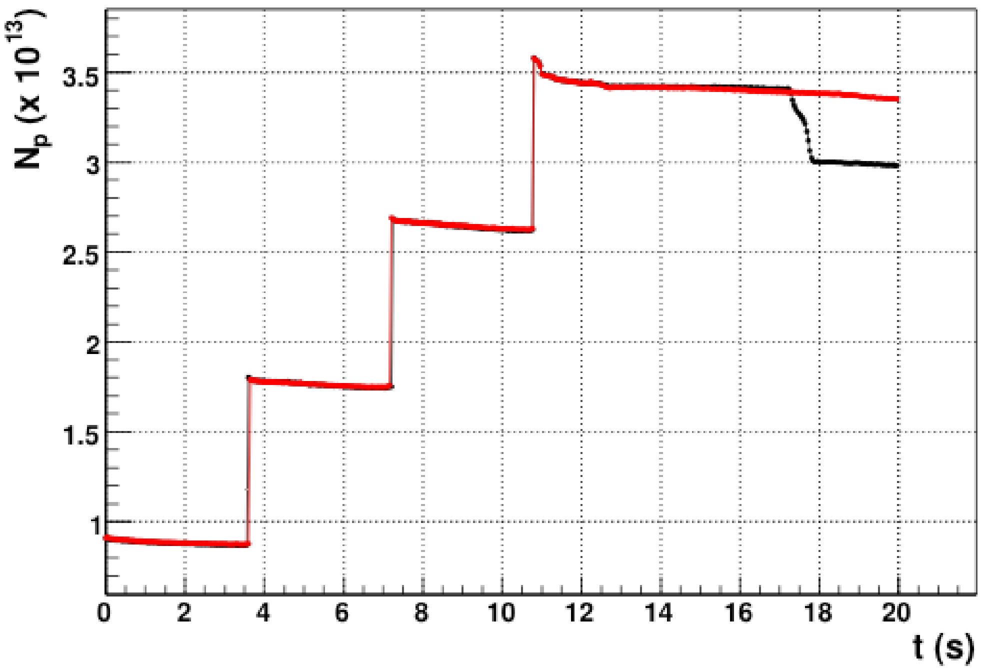
Study on the 55 GeV/c plateau



- The unstable coherent motion appears at the end of the bunch train
- It is a typical electron cloud instability

MDs in 2007 (VIII)

Study on the 55 GeV/c plateau



The transverse emittance blow up can suppress this instability!!

⇒ The black trace is the BCT signal from a cycle w/o emittance blow up, the red trace from a cycle w blow up

MDs in 2008

Hunting for the e-cloud instability at 26 GeV/c

- To develop the idea of designing a feedback system to suppress the electron cloud instability (see talks by J. Fox, W. Höfle) , SPS data are needed to characterize the electron cloud instability along the bunch (head-tail Δ signal)

- First attempt was made during the scrubbing run

  $\rightarrow$ Toward the end of the scrubbing run 5 batches could be injected into the SPS

  $\rightarrow$ Measurements were made at 26 GeV/c with low chromaticity

  $\rightarrow$ Losses at the end of the fifth batch were observed and some data were saved with the exponential pick-up (see talk by R. de Maria)

- There was a dedicated slot during the long MD in mid August

  $\rightarrow$ Up to four batches could be injected into the SPS due to the length of the flat bottom

  $\rightarrow$ Time left for the instability measurement was very short, only few msec before start of the ramp

  $\rightarrow$ No clear electron cloud instability, off line analysis shows coherent motion (R. de Maria's talk)

Summary

- The horizontal electron cloud instability is mainly of coupled bunch type in the SPS.
- The single bunch electron cloud instability appears in the SPS in the vertical plane for nominal LHC beams (25 ns spacing, nominal intensity, 4 batches)

  $\rightarrow$ A scrubbing run helps cleaning the machine and reducing electron cloud formation

  $\rightarrow$ Running with high chromaticity (0.4-0.5) can suppress the instability

- Lots of measurements of this instability have been done over the years

  $\rightarrow$ The unstable vertical signal exhibited a peak at ~700 MHz

  $\rightarrow$ The instability has been observed on plateaus at 26, 37 and 55 GeV/c

  $\rightarrow$ The fact that it can be damped by blowing up the transverse emittance (@55 GeV/c) has been the experimental proof of the unfavourable scaling law of the e-cloud instability threshold with the beam energy.

  $\rightarrow$ The evolution of the unstable intra-bunch signal can be used for feedback studies and probably more work is required on that.

- There are some indications of incoherent emittance growth leading to degraded lifetime for bunches in the tail of a train due to electron cloud.