Electron cloud detection and clearing in the PS, 4 years of experience

Edgar Mahner, CERN
Thanks to Fritz Caspers, Tom Kroyer, the SPSU Study Team, and many others (RF, OP, VSC, MME)

- Introduction
  - PS electron cloud, first experimental setup in ss98
- Review of PS ss98 results
  - button pickup and stripline signals, start of build-up
  - pressure rise, effect of st.st. clearing electrode and magnetic field
- Second experimental setup in PS ss84
  - 2008: results with enamel clearing electrode
  - 2009: results with a long st.st. clearing electrode
  - 2010: results with fully carbon-coated setup
- Conclusions

Introduction – PS electron cloud

How it started…

- During the 2000 run the electron cloud (EC) effect has been observed in the PS as a baseline distortion of electrostatic pickup signals [1]
- During a MD at the end of the 2006 run instabilities were observed that could be due to an EC build-up [2]
- At intensities higher than nominal, electron cloud instabilities could occur also for the standard LHC beam production scheme in the PS [3]
- Suggestion (G.A. & E.M.) in January 2007 to install some EC diagnostics in the PS
- Simulations (F.Z.) showed that an EC effect can be expected in a straight section, at least if there is a small magnetic dipole field (10 G)

[1] Electron cloud buildup and related instability in the CERN Proton Synchrotron.

R. Cappi, M. Giovannozzi, E. Métral, G. Métral, G. Rumolo, F. Zimmermann; PRST-AB 5, 094401 (2002).

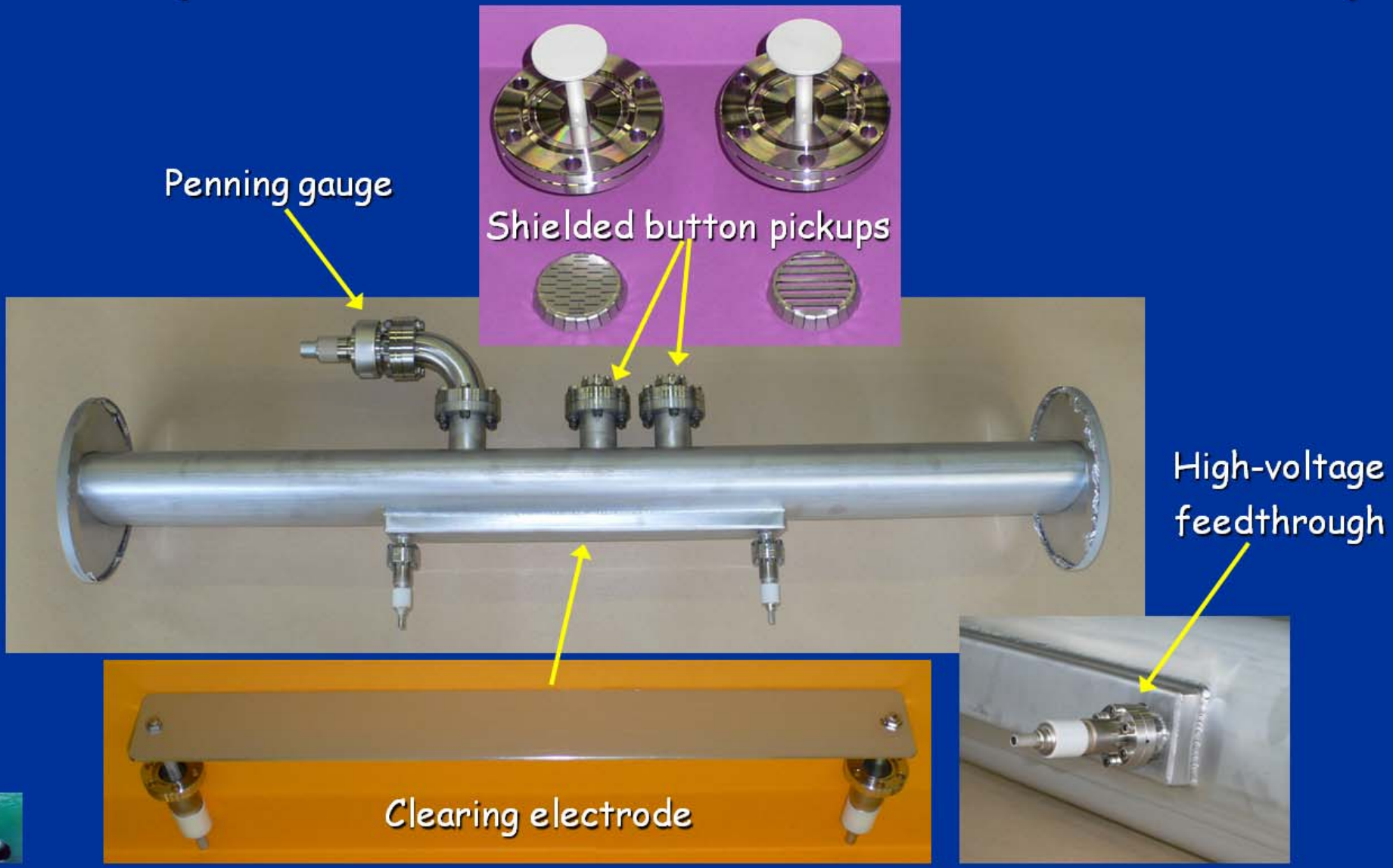
[2] Observations of the high energy instability in the PS.

R. Steerenberg *et al.*, APC 15. December 2006.

[3] Intensity (and Brightness) Limitations in the LHC Proton Injectors.

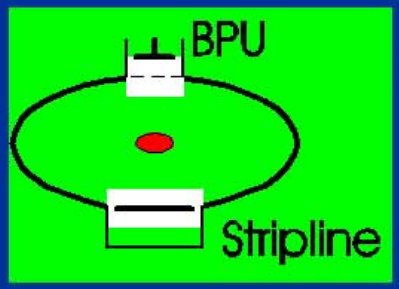
G. Arduini; Proceedings of the CARE-HHH-APD LHC-LUMI-06 Workshop, Valencia, 2006.

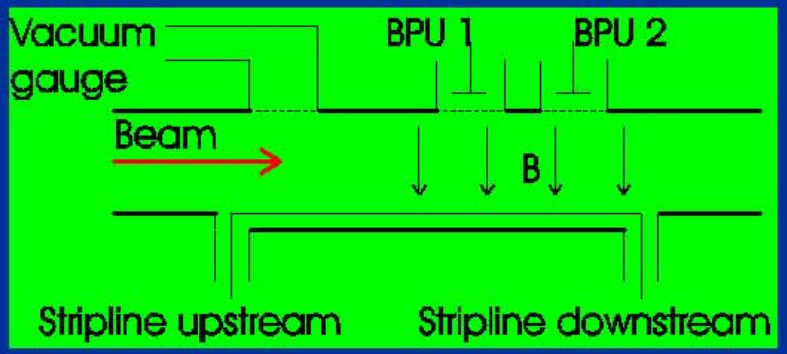
Components of the electron cloud setup



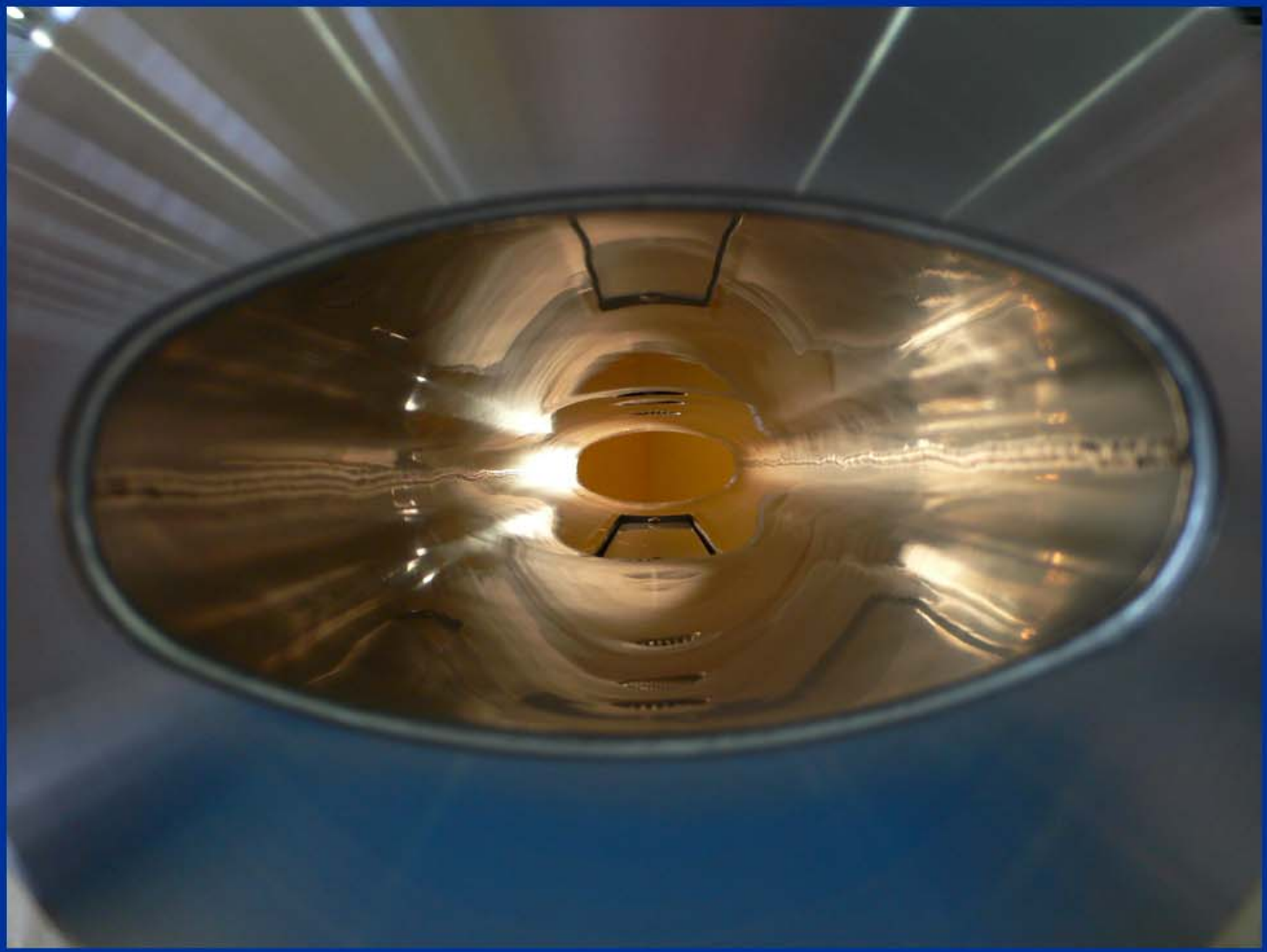
The PS electron cloud experiment in SS98

- PS elliptical vacuum chamber with dimensions 1050 x 146 x 70 mm.
- Special antechamber for clearing electrode without aperture reduction.
- Material: stainless steel 316 LN





How the proton beam sees it…

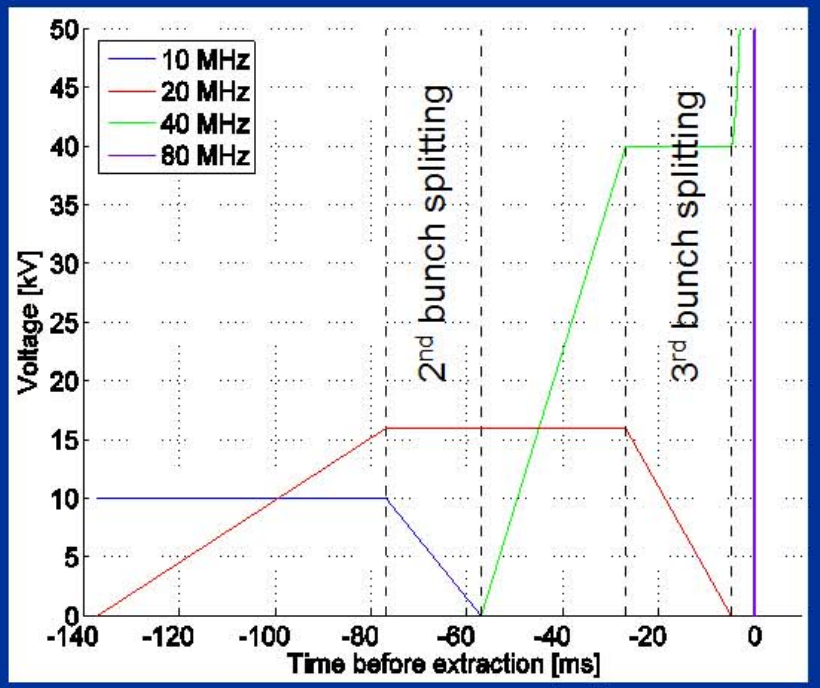


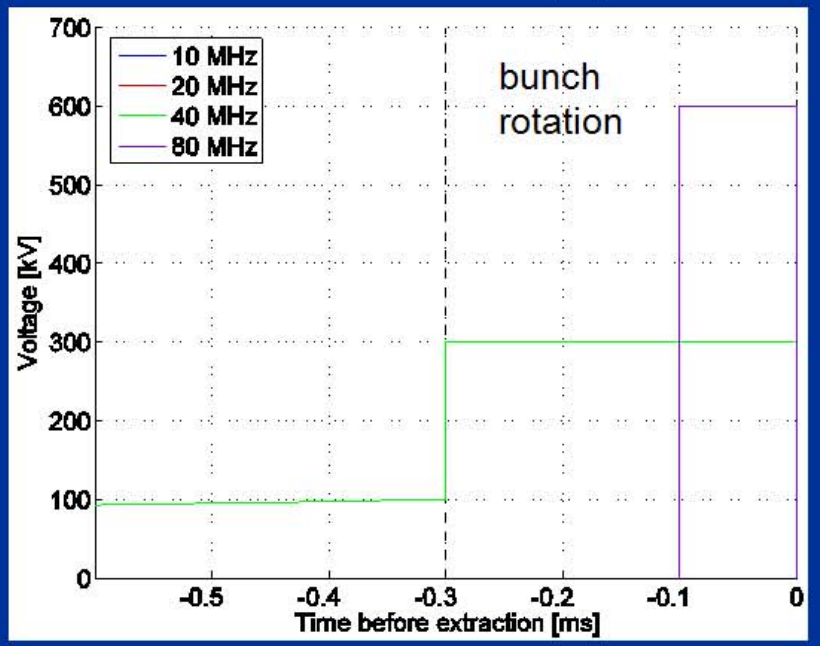
The nominal LHC beam in the PS

- Electron cloud effects are expected in particular shortly before ejection, when the bunches are short

- RF gymnastics:
- C2338 (57 ms before ejection): the second bunch splitting is finished, 36 bunches in the machine, bunch spacing 50 ns.
- C2368 to ~C2390 (27 to ~5 ms before ejection): The third bunch splitting. Afterwards 72 bunches, spacing 25 ns, 4σ length 14 ns.
- C2390 to ~C2395 (5 ms to ~300 μs before ejection): Adiabatic bunch compression to 11 ns.
- Last ~300 μs before ejection: bunch rotation with 40 MHz RF, in the last 100 μs also with 80 MHz RF. Bunch length reduced to 4 ns.
- ~C2395: ejection

- Intensity: 1.15e11 protons per bunch, 828e10 for 72 bunches.
- Transverse emittance (1σ): ~3 μm.





PS ss98 electron cloud experiments **2007**
Machine and beam parameters

TABLE I. Summary of the bunch length evolution during the last milliseconds in the PS cycle.

Operation	Time before ejection	Number of bunches	Bunch spacing	Bunch length (4σ)
Second bunch splitting	57 ms	36	50 ns	
Third bunch splitting	27 to 5 ms	72	25 ns	14 ns
Adiabatic bunch compression	5 to 0.3 ms	72	25 ns	11 ns
Bunch rotation	0.3 to 0.0 ms	72	25 ns	4 ns

TABLE II. The main machine and beam parameters for the PS electron cloud experiment.

PS circumference	628 m
Proton energy	25 GeV
Revolution time	2.1 μs
Number of bunches	72
Bunch spacing	25 ns
Bunch length	4 ns
Bunch population	1.1×10^{11} protons/bunch
Bunch emittance	0.35 eVs
Vacuum chamber aperture (horizontal)	147 mm
Vacuum chamber aperture (vertical)	72 mm

PS ss98 electron cloud experiments 2007
Button pickup and stripline signals (1)

PRST-AB 11,094401 (2008)

SS98 results 2007

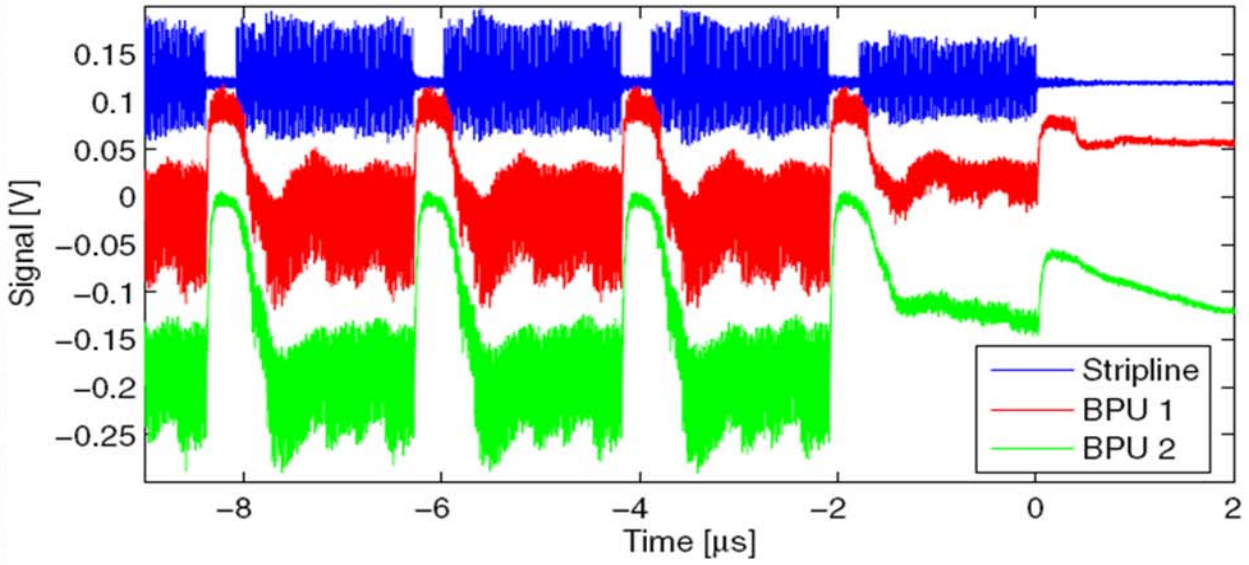


FIG. 4. (Color) Measured signals of the stripline electrode and the button pickups #1 and #2 during the passage of the nominal LHC beam. The last 4 turns before extraction from the PS are shown, the gap between successive recurrences of the same group of 72 bunches is 320 ns. The traces have been stacked vertically for clarity.

The results obtained for the last four turns before extraction of the nominal LHC beam from the PS are displayed in Fig. 4. The beam-induced signal observed on the clearing electrode, which acts essentially as a stripline beam position monitor, was used for synchronization and to monitor the basic beam properties. On both button pickups a clear electron signal was seen when the LHC beam passed. The time t = 0 s was set to the position of the last bunch at the last turn before ejection.

PS ss98 electron cloud experiments **2007**
Button pickup and stripline signals (2)

PRST-AB 11,094401 (2008)

SS98 results 2007

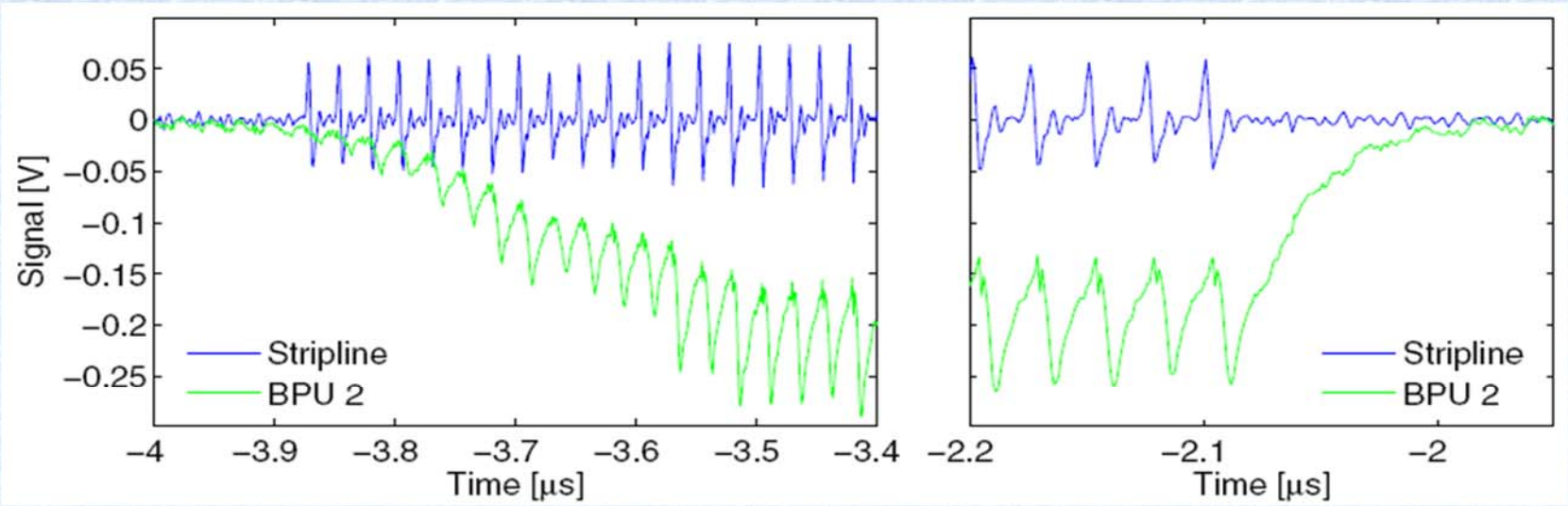


FIG. 5. (Color) Bunch-to-bunch electron cloud buildup (left) and decay (right) measured with button pickup #2 during the second last turn of the LHC beam. The 25 ns gap between successive bunches can be clearly resolved with the stripline electrode.

Measurements during the second last turn, showing the start of the electron cloud buildup with the first of the 72 bunches and decrease behind the last bunches, are displayed in Fig. 5. Every 4 ns (4σ) long bunch can be resolved on the stripline electrode and on the button pickups.

PS ss98 electron cloud experiments **2007**
Start of the build-up

PRST-AB 11,094401 (2008)

SS98 results 2007

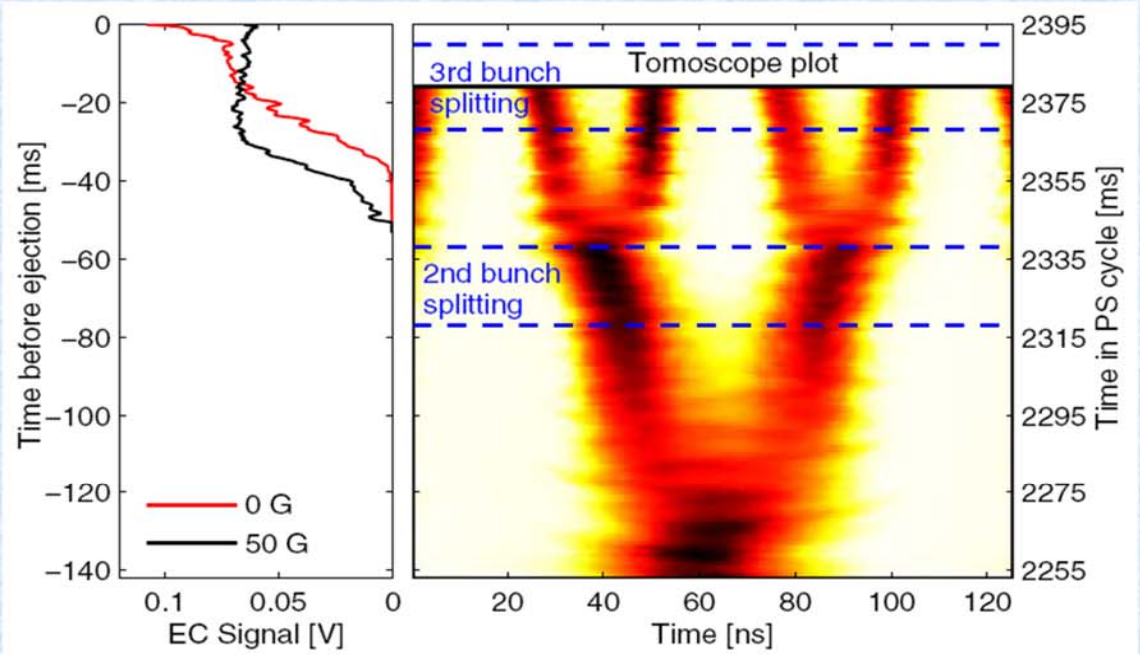


FIG. 7. (Color) The EC signal (left) compared with the bunch length during the rf gymnastics represented in a tomoscope plot (right, courtesy of Steven Hancock.). The EC buildup starts 40 to 50 ms before ejection, right after the second bunch splitting.

Some systematic measurements were performed to determine the exact time when the electron cloud buildup starts to be detectable in our experiment. In Fig. 7 the EC signal on pickup #1 is compared to a tomoscope plot of the longitudinal bunch profile. The EC is observed well before the end of the last bunch splitting (27 to 5 ms before ejection).

PS ss98 electron cloud experiments **2007**
Effect of st.st. clearing electrode

PRST-AB 11,094401 (2008)

SS98 results 2007

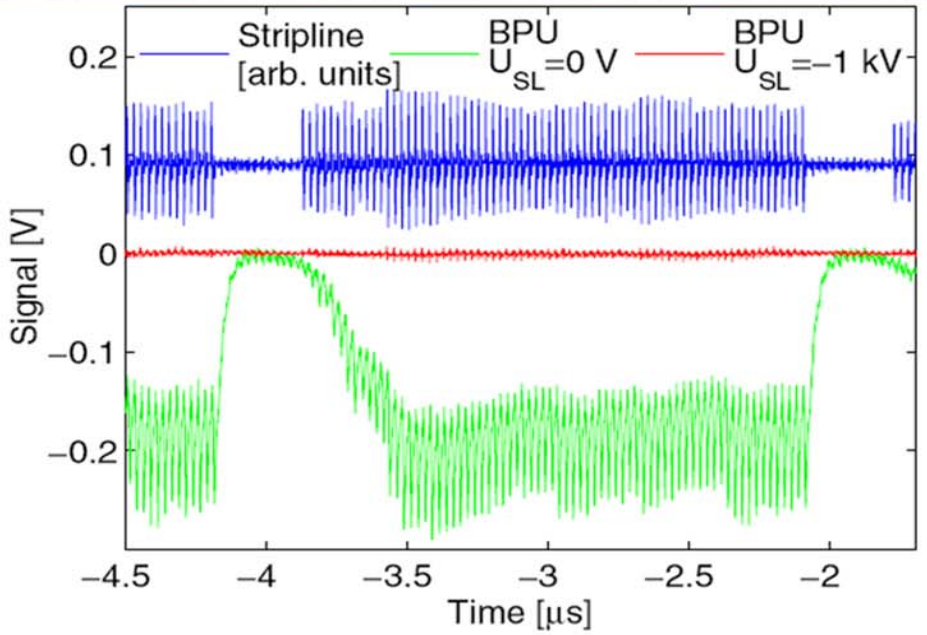


FIG. 8. (Color) The electron cloud was suppressed below the detection limit for large enough clearing voltages, e.g. $U_{SL} = -1$ kV, data from BPU 2 are plotted.

For large enough positive and negative clearing voltages $|U_{SL}| > 300$ V, the EC signals decreased below our detection limit. The case of U_{SL} = - 1 kV is depicted in Fig. 8.

PS ss98 electron cloud experiments 2007
E-cloud suppression: PU signal (t, U_{SL})

PRST-AB 11,094401 (2008)

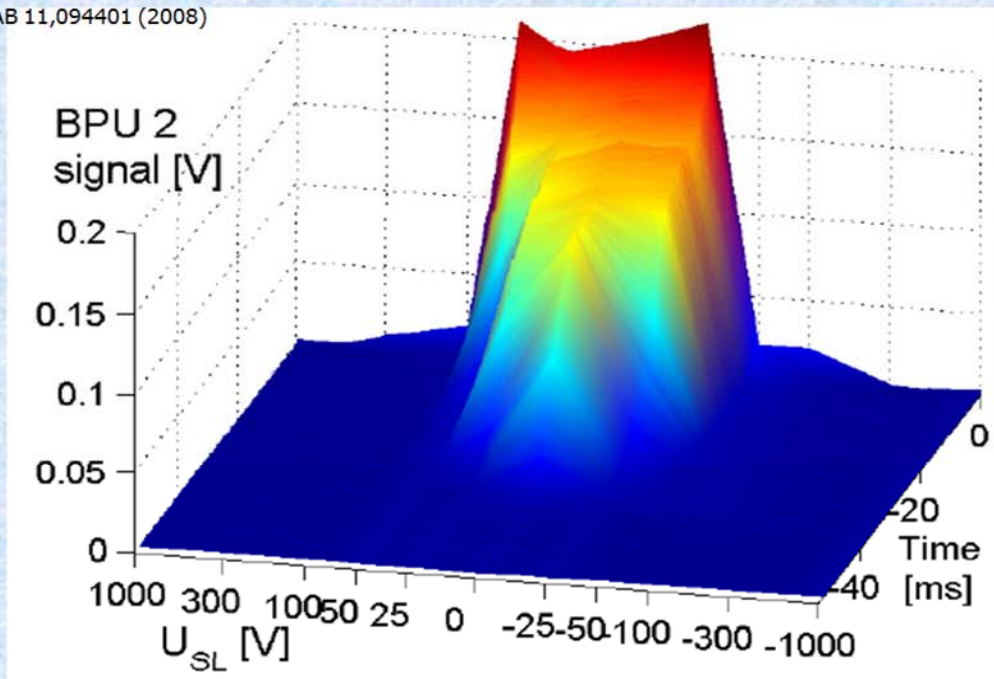


FIG. 9. (Color) Electron cloud button pickup #2 signal measured in SS98 for the nominal LHC beam. The color-coded signal height varies as a function of applied voltage on the clearing electrode and with time, no magnetic field was applied. The last 50 ms before ejection are shown.

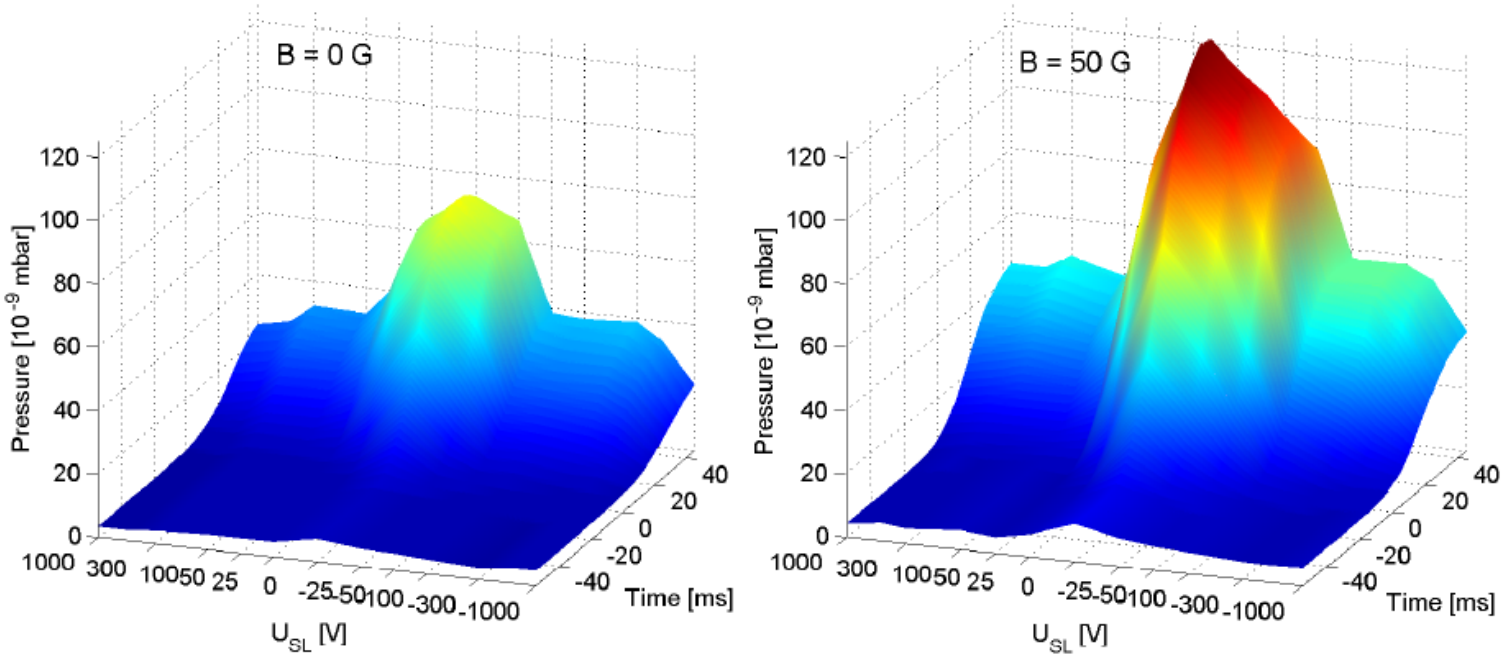
SS98 results 2007

The pickup signals have been measured for clearing voltages ranging from -1000 V to +1000 V.

Figure 9 shows the EC signal on pickup #2 averaged over the last 12 of 72 bunches in the PS machine as a function of clearing voltage.

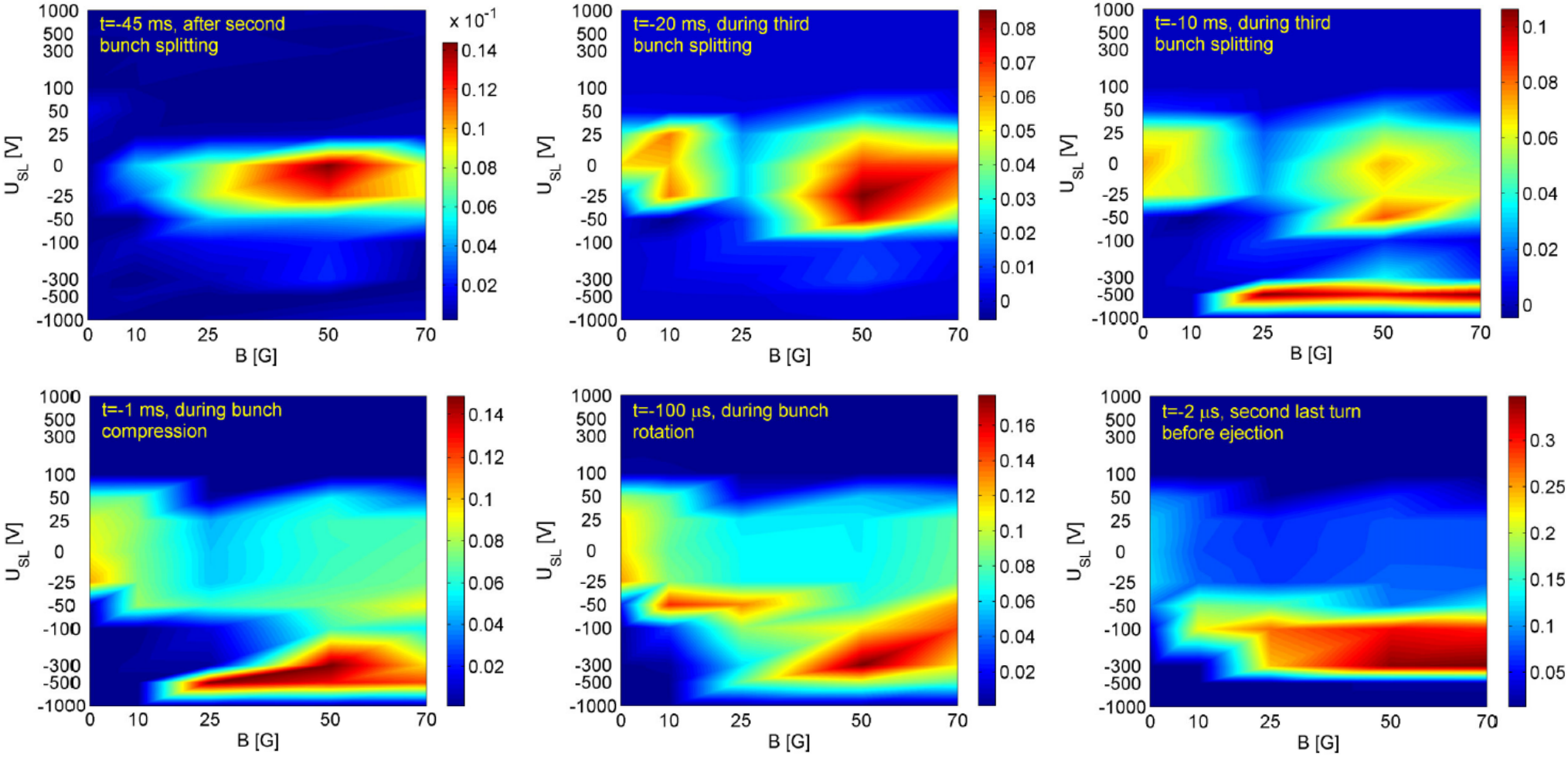
The data cover the last 50 ms before the proton beam is ejected from the PS.

PS ss98 electron cloud experiments **2007**
Pressure rise: Gauge signal (t, U_{SL}, B)



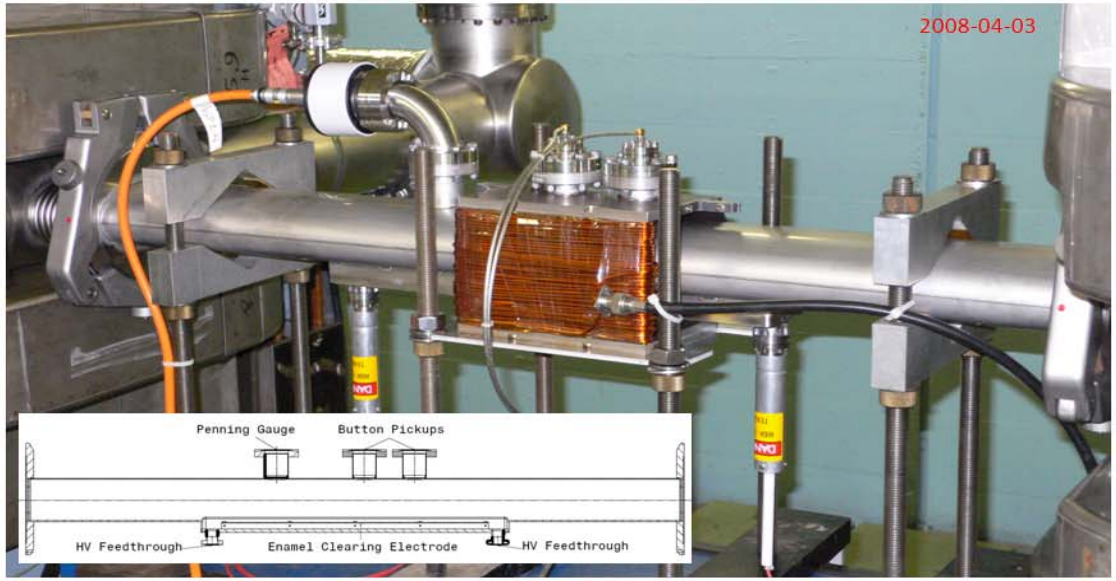
VIDEO 2. Vacuum pressure rise as a function of the stripline clearing voltage U_{SL} and time in the PS cycle. Even for large clearing voltages a pressure rise can be observed, though the Δp is delayed, as the pressure bump originates from the vacuum chamber outside the clearing electrode. With magnetic field the pressure rise is stronger and starts earlier. This video shows the time evolution of the vacuum pressure for $B = 0$.

PS ss98 electron cloud experiments **2007**
E-cloud suppression: PU signal (t, U_{SL}, B)

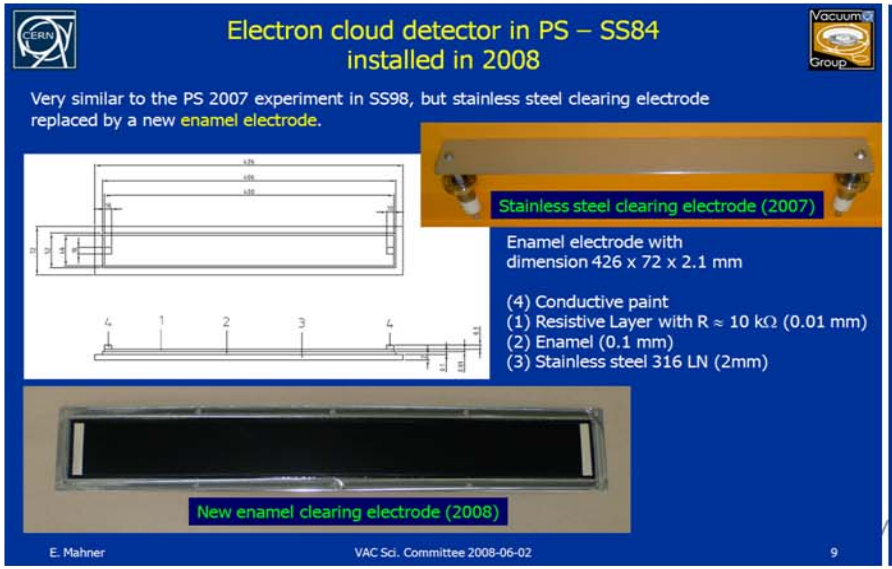


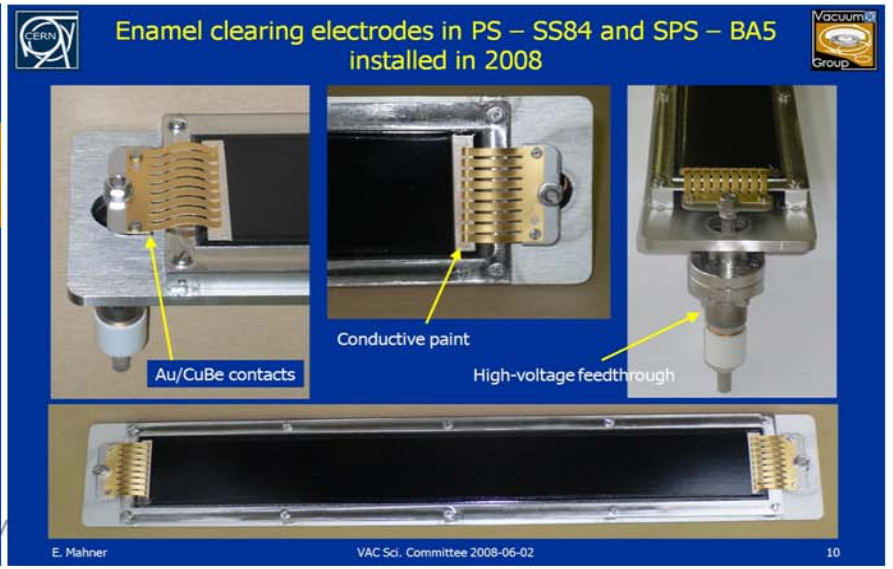
VIDEO 1. Electron cloud signal on pickup #1 measured for various clearing electrode voltages (-1 kV $\leq U_{SL} \leq +1$ kV) and magnetic dipole fields (0 G $\leq B \leq$ 70 G). Measurements were taken continuously during the last 50 ms before beam extraction at $t = 0$ ms. This video shows the time evolution of the pickup signal.

PS electron cloud experiments **2008**
Second setup in SS84 (enamel clearing electrode)



PS ss84 (2008)
2nd electron cloud setup in the PS
316LN st.st. vacuum chamber with shielded button pickups,
enamel clearing electrode,
shielded vacuum gauge, dipole magnet.





PS electron cloud experiments **2008**
Detection

- Bias voltage on pickup (U_{pu} = +60 V)
- No voltage on stripline (U_{SL} = 0 V)
- No magnetic field (B = 0 *G*)

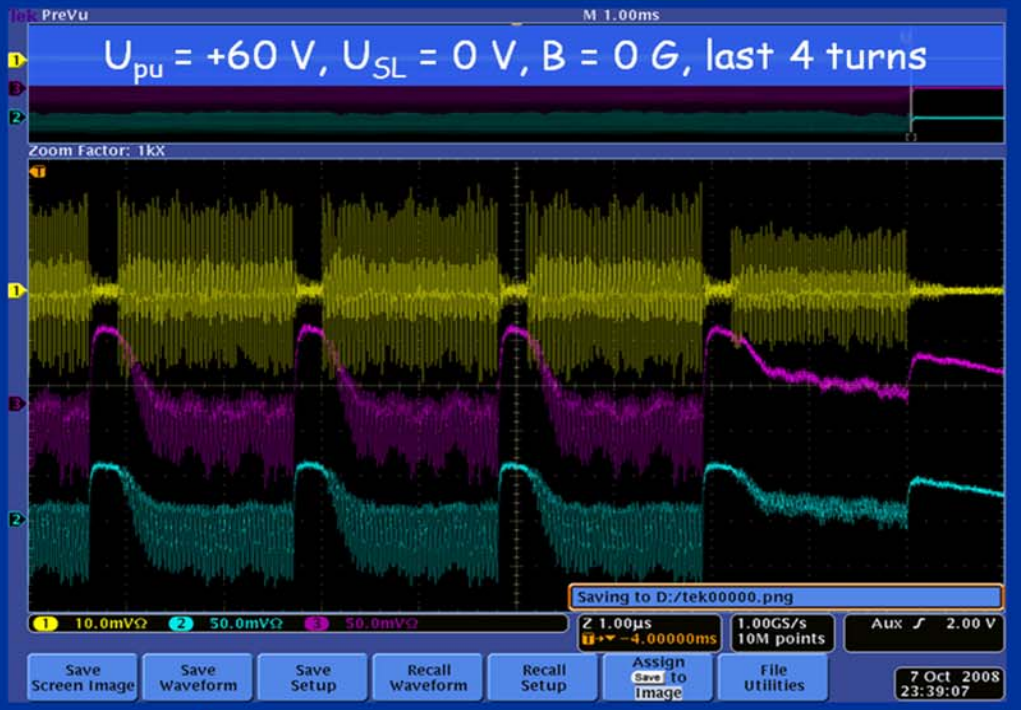
- **Yellow**: Beam signal from stripline
- Blue: pickup 1 (low transp.)
- Magenta: pickup 2 (high transp.)

- Triggered at extraction, looking at the last 4 turns
- Sampling rate: 1 *GS/s*
- Full time span: 10 μs

- On the pickups one can see when the LHC25 beam is passing SS98.

- During the last turn the stripline and pickup signals are different: orbit offset after firing of the extraction kicker

SS98 results 2008



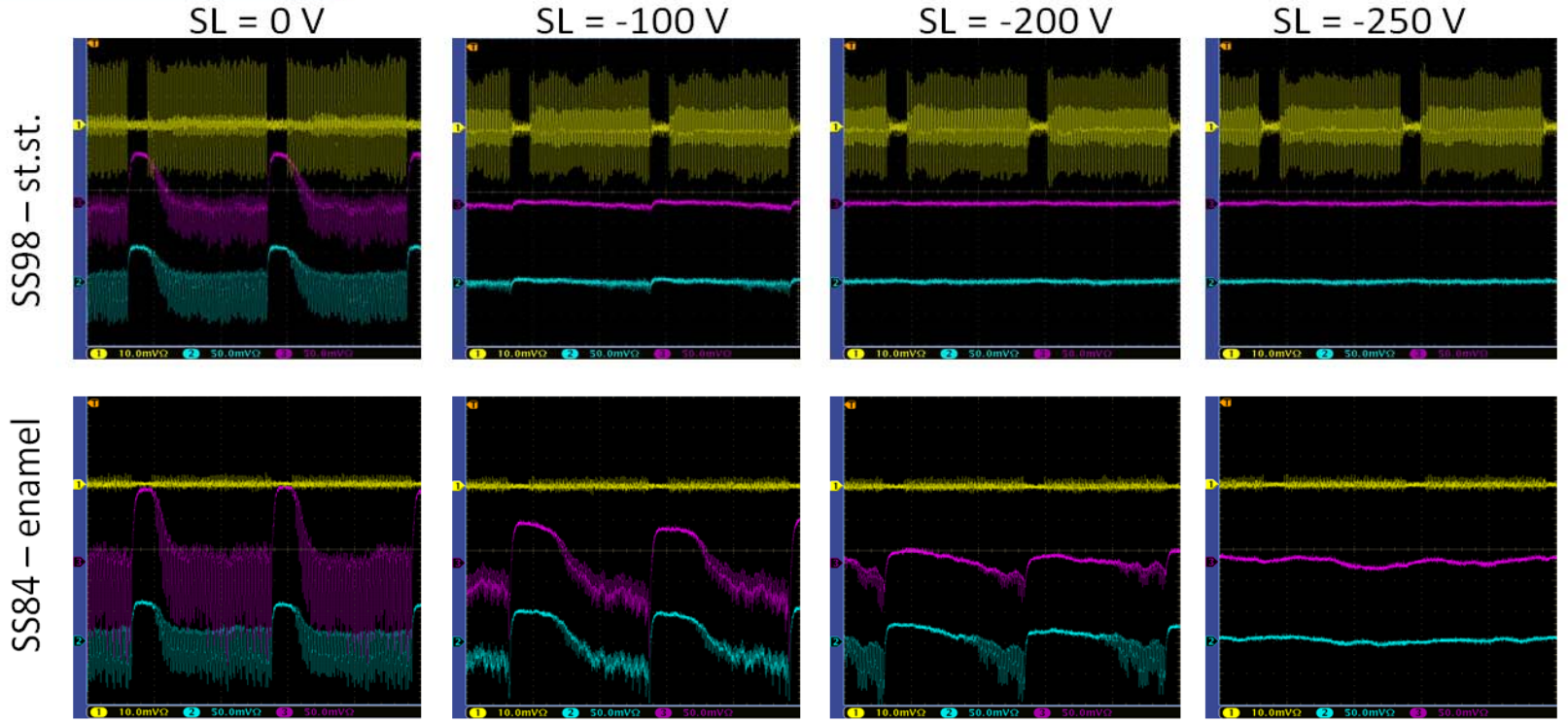
7. October 2008
LHC 25ns, 72 bunches, 908 x 10^{10} p

PS electron cloud experiments 2008
Clearing

Comparison of stainless steel and enamel clearing electrodes

SS98-84 results 2008

LHC 25ns, 72 bunches, 900 x 10^{10} p, 7.10.2008

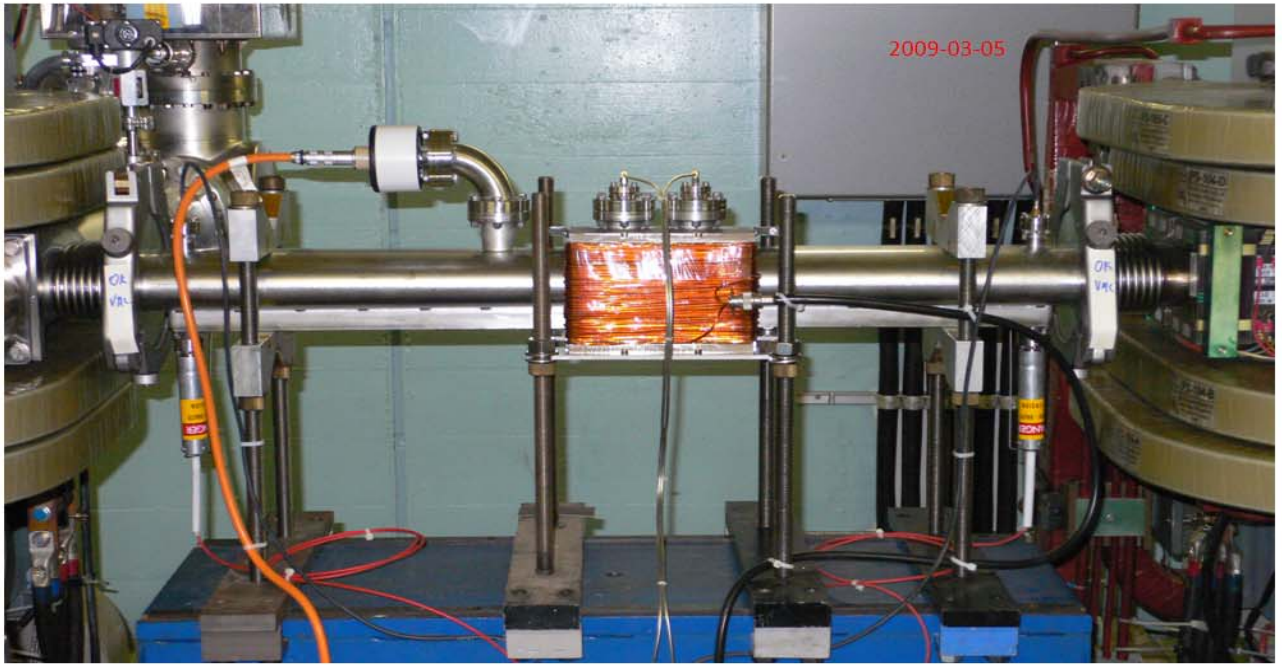


PAC'09, Caspers, Mahner, Kroyer, Wendel

For positive voltages, the stainless steel and enamel clearing electrode behave very similar -> electron cloud suppressions is obtained for U_{SL} > 300 V.
For negative voltages, the stainless steel and enamel clearing electrode behave a bit different for U_{SL} < 300 V (see above). For higher stripline voltages (>500 V) the enamel electrode is as efficient as the stainless steel.

EM (AEC'09)

PS electron cloud experiments **2009**
Third setup in SS84 (long st.st. clearing electrode)




st.st. clearing electrode with HV feedthroughs


antennas for μw transmission

PS ss84 (2009)

3rd electron cloud setup in the PS (2nd setup with enamel removed from the ring)

316LN st.st. vacuum chamber with shielded button pickups, shielded vacuum gauge, dipole magnet.

New idea: 2 st.st. antennas for a short distance μw transmission measurement with the possibility to switch electron cloud activity on/off using a 1m long st.st. clearing electrode, the vacuum chamber is not coated.

EM (AEC'09)

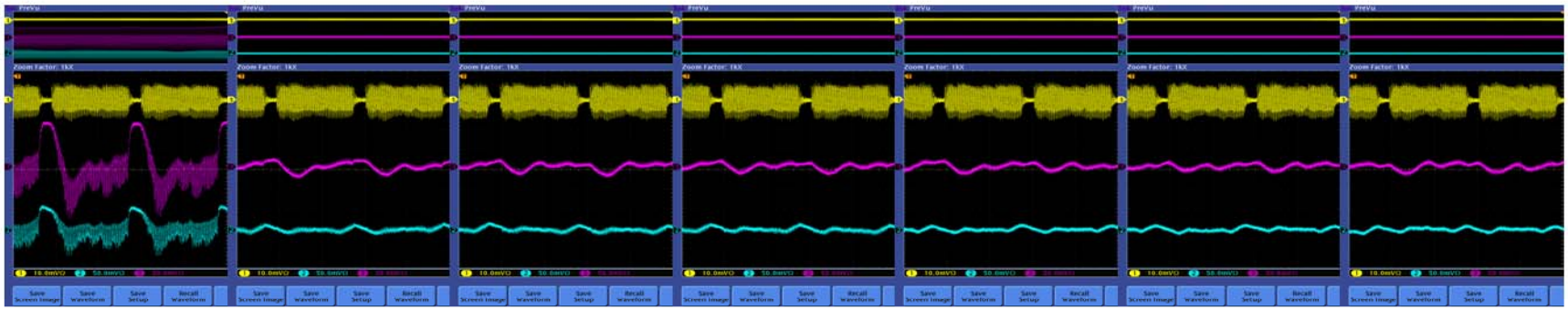
PS electron cloud experiments **2009**
Clearing

Electron cloud clearing in PS μw transmission experiment

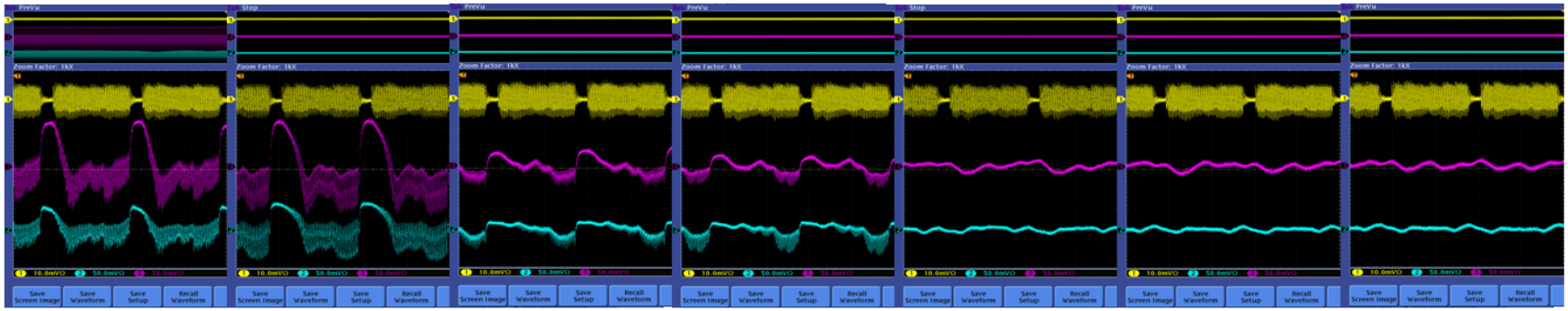
SS84 results 2009

LHC 25ns, 72 bunches, 900 x 10^{10} p, 23.09.2009

SL = 0V | 50V | 100V | 150V | 200V | 500V | 1000V



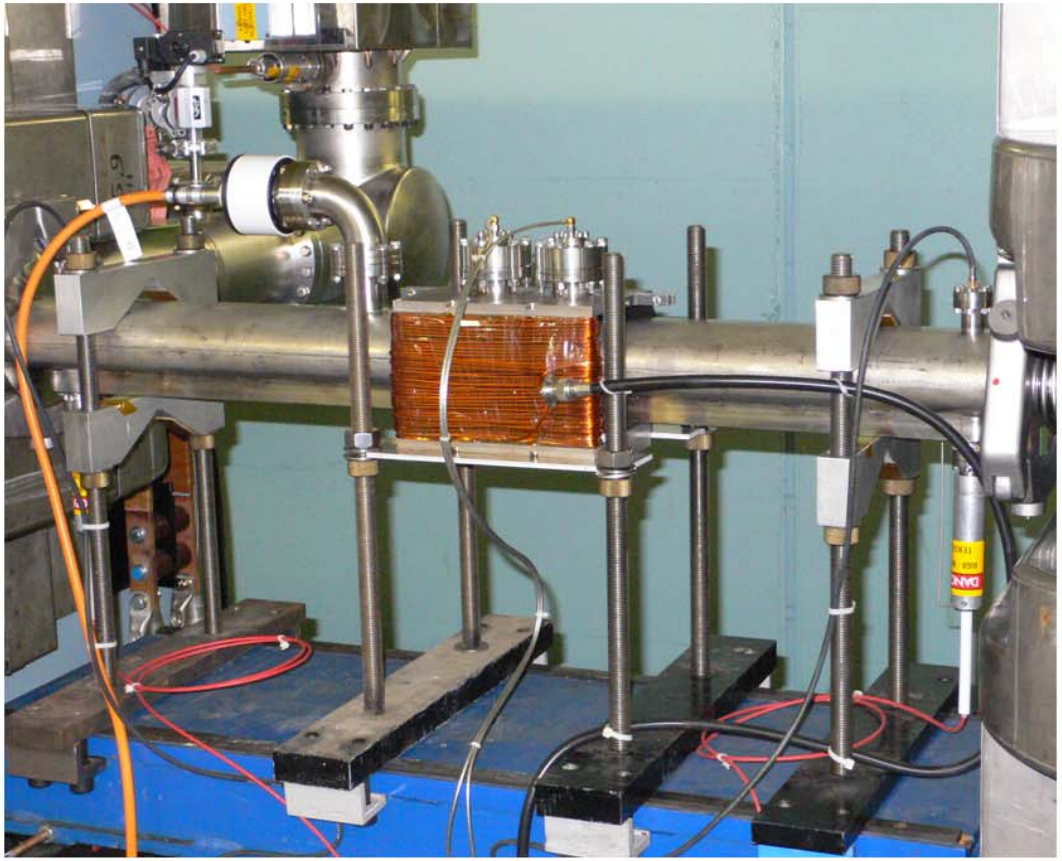
SL = 0V | -50V | -100V | -150V | -200V | -500V | -1000V

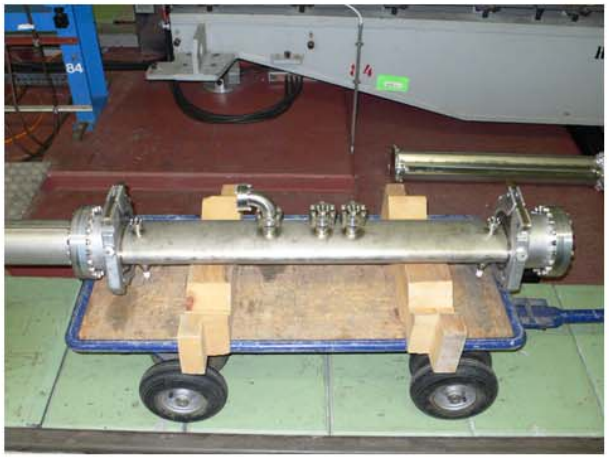


- ✓ Clear electron cloud detection with pickups (magenta + blue traces).
- ✓ Ecloud suppression with long st.st. clearing electrode (yellow trace).
- ➢ The μw transmission measurement is presently under commissioning (F. Caspers *et al.*)

EM (AEC'09)

PS electron cloud experiments **2010**
Fourth setup in SS84 (carbon coated chamber)





PS ss84 (2010)

4th electron cloud setup in the PS (3rd setup removed from the ring)

316LN st.st. vacuum chamber with shielded button pickups, shielded vacuum gauge, dipole magnet.

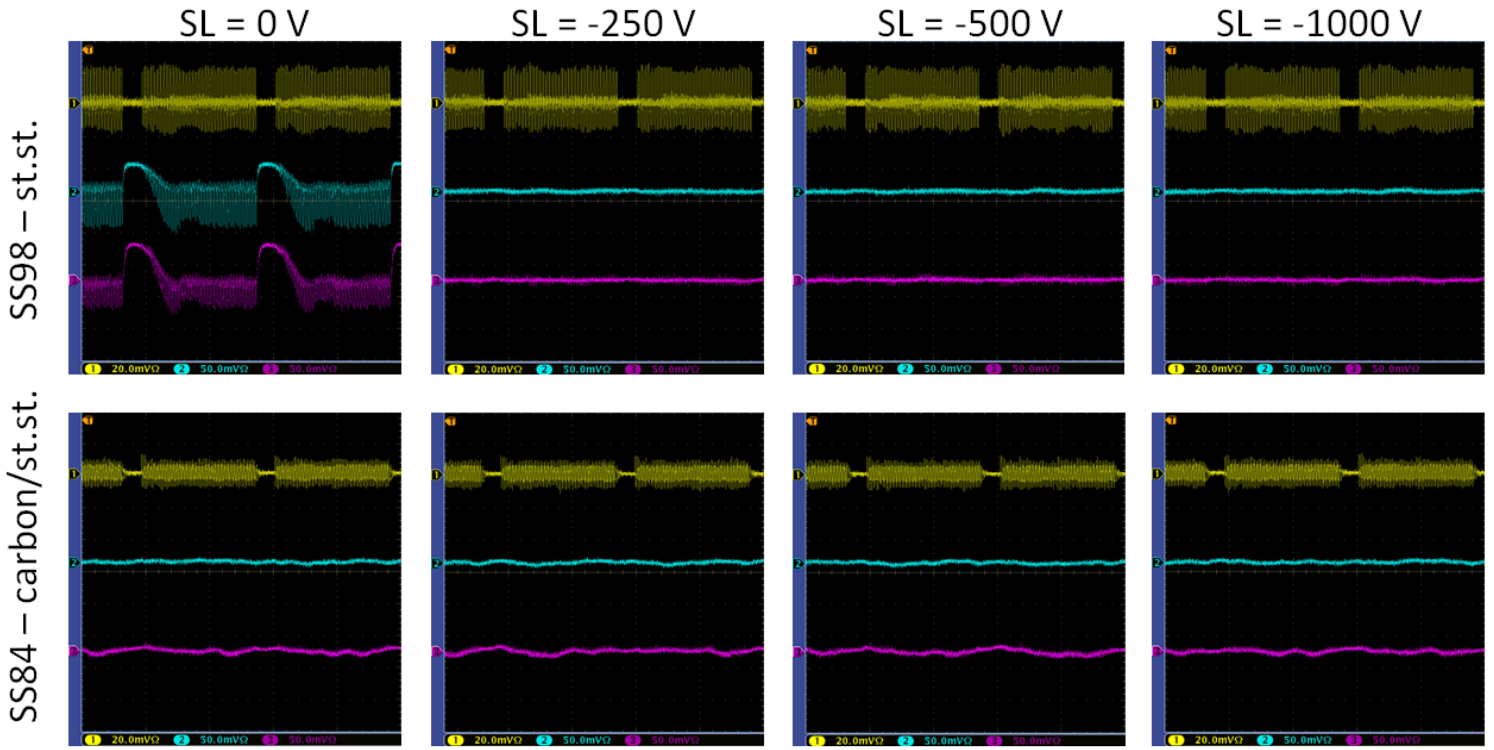
New: the vacuum chamber + st.st. clearing electrode (1 m long) are coated with amorphous carbon, setup contains 2 antennas for a short distance μw transmission measurement

PS electron cloud experiments 2010
SS98 Clearing – SS84 Suppression

Comparison bare with carbon-coated stainless steel PS chamber

SS98-84 results 2010

LHC 25ns, 72 bunches, 900 x 10^{10} p, 3.6.2010

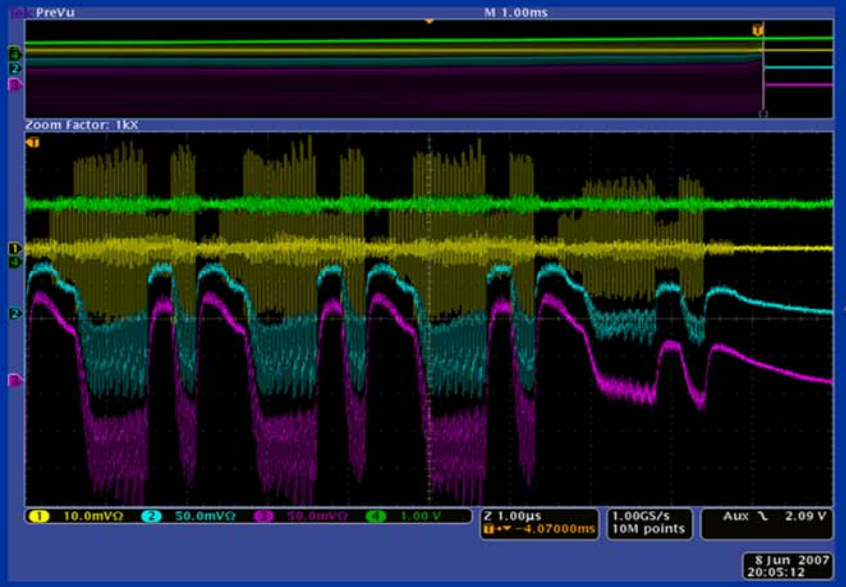


- ✓ SS98 – st.st: clear electron cloud detection + suppression with clearing electrode
- ✓ SS84 – carbon: no electron cloud detected + no influence of clearing electrode
- ✓ SS84 carbon coated st.st. vacuum chamber works (very) well for EC suppression in the PS
- ➢ 2011: study "long-term behaviour" of installed carbon coated chamber

PS experience…
…another attractive clearing electrode feature

Intensity dependence…

- A change in bunch intensity or missing LHC25 bunches in the PS are clearly visible on the button pickups in SS98.



A sensitive detector for electron cloud driven instabilities in the PS

E. Mahner, T. Kroyer, F. Caspers, CERN APC 6. July 2007 32

Apart from electron cloud suppresion, bunch-to-bunch intensity variations detected in the PS for the nominal LHC beam with 25ns bunch spacing.

Conclusions

- Dedicated PS electron cloud detector operational in ss98 since 2007
  - comprises two shielded pickups, one shielded Penning gauge for fast vacuum logging, a dipole magnet, and a stainless steel stripline electrode for electron cloud clearing.
- Since June 2007 clear signs of EC found in the PS with nominal LHC beam
  - fast vacuum pressure rise, characteristic signal on the shielded button pickups,
  - develops during the last 40 to 50 ms before ejection, when the bunches are shortened by the rf gymnastics.
- EC can be suppressed by putting a sufficiently large voltage of either polarity onto the clearing electrode. First enamel clearing electrode tested in ss84 in 2008.
  - The functionality of enamel technology as clearing electrode material has been clearly demonstrated. Enamel electrode, compared to st.st., acts very similar in terms of EC suppression.
  - CERN development was stopped and priority was given to low SEY coatings
- First carbon coated PS ss84 EC experiment successfully tested in 2010