OBSERVATION OF THE ELECTRON CLOUD EFFECT ON PICK-UP SIGNALS IN THE SPS

W. Höfle

Abstract

During the 1999 tests with the LHC type beam with 25 ns bunch spacing in the SPS, the damper (transverse feedback system) pick-up signals were strongly perturbed by the electron cloud effect. The high impedance FET amplifiers used on the electro-static pick-ups detect the deposited charges and allow to observe the threshold as a function of beam intensity as well as the time evolution of the effect along a batch. A magnetic solenoid field of 100 gauss suppressed the effect up to approximately 5×10^{12} protons in 80 bunches. Tests with new electronics are presented, showing how pick-up signals will be made insensitive to the electron cloud effect for the millennium run by processing the signals at a multiple of the bunch frequency.

1 INTRODUCTION

The transverse feedback system, habitually called "damper" in the SPS, is essential in limiting the emittance dilution from transverse injection errors, as well as ensuring beam stability for total intensities above a few 10^{12} charges [1, 2]. The system shares a set of 8 pick-ups, 4 vertical, and 4 horizontal, with the SPS closed orbit system MOPOS. These standard SPS pick-ups are of the electrostatic type ("shoebox-design"). The damper system uses the signals in baseband rendering it insensible to bunch shapes and spacings. High impedance FET head amplifiers installed in the SPS tunnel detect the signals from the pick-up plates.

After having observed perturbed signals on all 8 pick-ups with LHC beam, a number of experiments were carried out between June and August 1999, which show clear evidence of the so called "electron cloud effect" for the LHC beam in the SPS. Results of these experiments are shown in the following together with the remedy for the damper pick-ups, which is to work at a higher frequency for the LHC beam pick-up signal processing.

2 FIRST OBSERVATIONS

8 turns of a 2 μs batch

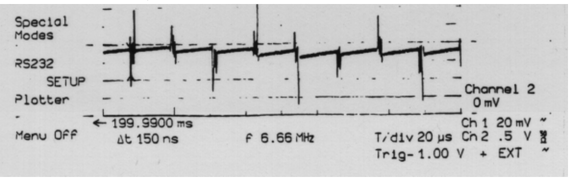


Figure 1: Baseline jumps in September 1998 on a damper pick-up.

In retrospect, the first observations date back to September 1998 when a single LHC batch with sufficiently high intensity was first injected into the SPS. Fig. 1 shows a pick-up signal with 8 turns of the Δ-signal of a short 2 μs batch of LHC beam. Individual bunches are not resolved in this plot. The trace shows a slope between batches and a drop in signal (base-line) during the passage of a batch. Close examination reveals that no such drop occurs during the first displayed passage. Due to its regularity the phenomenon, though unusual, was left practically unnoticed. In December 1998 tests with the LHC beam revealed instability problems, and there were some doubts about the proper functioning of the damper. Back-of-the-envelope calculations showed that pick-up signals for the damper would saturate with the ultimate bunch intensity, due to the high single bunch intensity and the high bandwidth of 100 MHz of the amplifiers used. A set of filters was developed and installed on four pick-ups in the 1998/1999 shutdown to prevent the saturation, and also to equalise distortion by cables up to a frequency beyond 20 MHz, a requirement for the damper bandwidth upgrade [3].

With surprise it was noticed in June 1999 that the problems persisted. Fig. 2 shows a plot of the first 6 turns of LHC beam in the SPS, with two clear base line jumps. Also shown is an enlargement of the second turn where one can see, that the baseline starts to drift about halfway through the batch. It was then quickly established that although fuzzy, there existed a threshold intensity below which no jumps occurred.

top trace: 6 first turns after injection, 20 μs/div
bottom trace: 2^{nd} turn, 1 μs/div

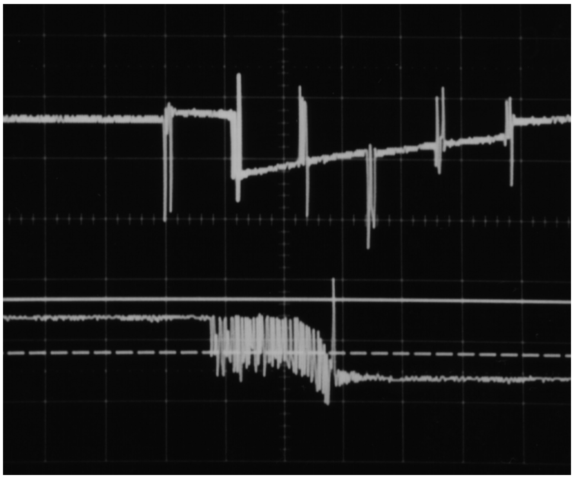


Figure 2: Observation in June 1999: The baseline drift starts during the passage of an LHC batch.

3 A SUMMARY OF THE OBSERVATIONS AND THEIR INTERPRETATION

3.1 Threshold

Fig. 3 shows a series of pick-up signals at injection and 20 ms after injection for different intensities. At 2.9×10^{12} protons per batch no effect is visible. At 3×10^{12} p base line jumps occur at injection. At 4.2×10^{12} p strong regular jumps are visible all the time along the cycle. This shows that there is an overall threshold of between 3.5×10^{12} p and 4×10^{12} p. At 3×10^{12} p the effect is already visible when the beam is oscillating, i.e. at injection or when kicked with the Q-kicker.

During the course of the 1999 run it was observed that the threshold intensity decreased by some 30 % during the fixed target physics run. In autumn, during the ion run, the threshold intensity went back to the original level. During the workshop possible reasons for this were discussed, one being the level of back ground radiation in the SPS accelerator, acting as a “starter”.

3.2 Estimation of the number of charges

The signals on the pick-up plates clearly indicate that charges are generated and collected. The geometry of the pick-ups with two triangular electrodes referenced to ground is complicated. Three insulated surfaces are exposed to beam and the signals on the electrodes only show the net flow of charges, not the individual flow between all three surfaces. Nevertheless it is possible to estimate the number of charges involved.

Taking into account the gain of the amplifiers and the capacitive dividers that load the pick-up plates leads to an estimate of the number of charges detected. At 4×10^{12} protons in a 80 bunch long LHC batch about 10^9 charges are detected per m^2 wall and per bunch. These values were measured 3 ms after injection, when the beam was centered in the pick-up and not oscillating. The drift of the signal started approximately after 30 bunches.

3.3 Influence of bias voltage

The pick-up structure consists of the two pick-up plates, a pick-up ground isolated from the machine ground, and the machine ground. Connecting the pick-up ground to the machine ground did not show any influence. Note that usually the pick-up ground for the damper pick-ups is connected to the ground of the FET amplifier power supply. It was tried to apply a bias voltage to the pick-up electrodes via a resistor of 200 kΩ. There was a strong influence of the bias voltage on the signals detected. Since charges go from one plate to the other or to ground, and leave behind a positive charged electrode, the situation is quite complicated. A set of voltages can be found, where the signals show no base line drift, but these optimum voltages change from day to day. Optimum voltages amounted to a few volts. Above 5 V biasing a saturation effect was visible. The theory is that the applied voltages lead to equal currents to pick-up electrodes and ground, rather than suppressing the effect. In order to suppress the effect separate clearing electrodes and higher voltages would be required.

3.4 Influence of magnetic solenoid field

The tests with bias voltage then led to the tests with a solenoid field. In three interventions in the tunnel a total of 5 pick-ups, 3 horizontal and 2 vertical, were equipped with solenoids. The solenoids were made by winding about 60-80 turns of a standard cable around the pick-ups. A 1.2 kW power supply was connected to the solenoids (all in series) to supply a maximum of 20 A of current. The field was estimated at 100 gauss. Fig. 4 shows horizontal and vertical pick-up signals without and with solenoid field. The base line drift is clearly suppressed by the solenoid. In the horizontal plane spikes (oscillations) from the injection kickers of the SPS, or more likely the ejection kickers of the PS, at the start and the end of the batch can be seen.

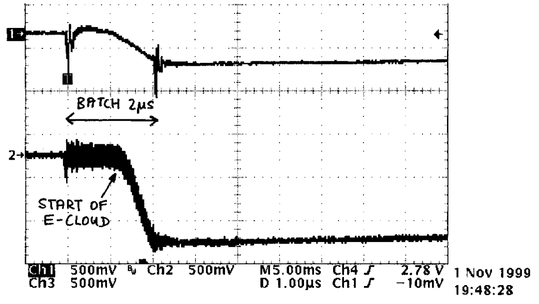
It was also tried out to supply a solenoid like field by placing a total of 17 permanent magnets around a pick-up. Three U-shaped magnets were aligned longitudinal, and then six of these arrangements were placed around the pick-up, with one magnet missing below the pick-up (insufficient space). Although field levels of 100 gauss were measured in the laboratory, the effect on the pick-up signals was disappointingly small. The threshold was only increased by some 25 %. This is explained with the limited effective length of the permanent magnet arrangement, when compared to the wire wound solenoid.

3.5 Correlations

During the search of the origin of the baseline jumps it was tried to correlate the occurrence of this phenomenon with machine and beam parameters. The following observations were made:

- the effect is very violent at injection and also when the beam is transversely oscillating (kicked)
- the effect is very regular and reproducible on a turn by turn and cycle to cycle basis when the beam is *not* oscillating
- no correlation with beam losses at the pick-ups involved was observed
- no correlation with the orbit was seen
- there was no correlation with the presence of lepton beams on the SPS lepton cycles within the super-cycle
- the threshold intensity decreased during the summer 1999
- the threshold intensity increased (went back to the original state of the beginning of the 1999 run) during the ion run (autumn 99)

a) without solenoid



b) with solenoid of 100 gauss

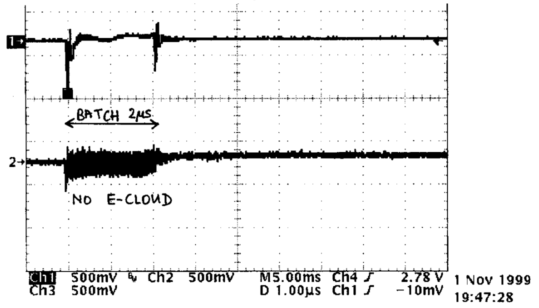


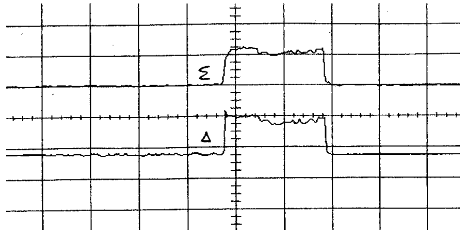
Figure 4: Horizontal (top trace) and vertical (bottom trace) pick-up signals at 4×10^{12} without and with solenoid field.

- at the beginning of August 1999 the vacuum pressure between positions 119 and 216, where the damper pick-ups are located, was decreased by additional sublimators by a factor of 3, to $8 - 9 \times 10^{-10}$ hPa. There was no effect of this pressure reduction on the signals recorded.

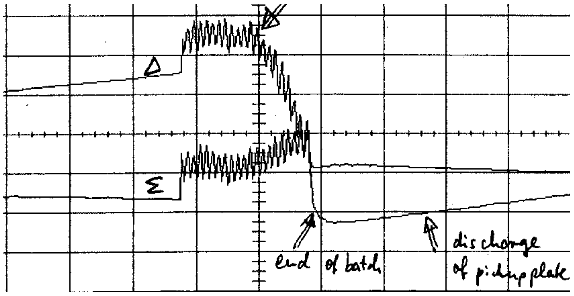
3.6 *Different bunch spacings*

To a limited extent different bunch spacings can be tried out in the SPS. Fig. 5 shows a comparison with three different beams that were available in 1999. The *total* intensity for all three beams is the same. At 5 ns bunch spacing a fast extracted beam with 420 bunches is available from the PS. The bunch intensity was 10^{10} and no signs of the electron cloud were seen. The next Figure shows the LHC batch with 80 bunches and 25 ns spacing. Clearly the baseline drift is visible. A third beam that is available has a bunch spacing of approximately 131 ns. This beam is produced in the PS on h=16, the bunches are fairly long 15-20 ns, but their intensity was very high (2.5×10^{11}). No signs of the electron cloud effect were seen. Note that this last beam cannot be captured in the SPS due to the bunch spacing which is not a multiple of 5 ns. Nevertheless the beam stays bunched long enough with RF off to do measurements of the kind reported here.

a) 5 ns bunch spacing (420 bunches)



b) 25 ns bunch spacing ($\simeq$ 80 bunches, LHC type beam)



c) $\simeq$ 130 ns bunch spacing (PS h=16)

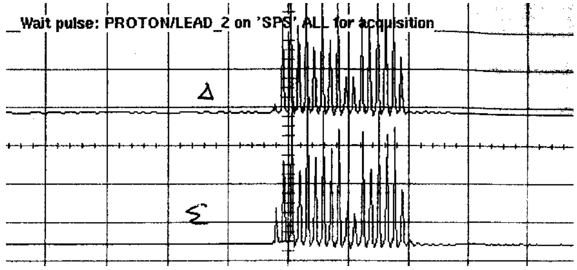


Figure 5: Different bunch spacings (for the same total intensities); scales are 1 μs/div.

3.7 *Are we really looking at electrons?*

During the workshop it was discussed whether we really have evidence of *electrons* in the machine. Could it be ions? Firstly, the influence of the solenoid field clearly shows the presence of charges and excludes an “electronic” artifact.

Initially RF multipacting due to a resonant mode in the pick-up, excited by the 40 MHz beam structure was also considered as a possible cause. Although some resonant modes were found in the pick-up [4], the threshold behaviour of the observed phenomenon is rather untypical for RF multi-pacting where distinct resonances are expected, i.e. distinct beam intensities where this problem would occur. Once the intensity (= field amplitude in resonant mode) is raised above a multi-pacting level, the break down (= charging up of pick-up) should disappear. With the pick-up signals there was a single threshold visible, beyond which baseline jumps increased monotonically.

Would it be ions that are moving around in the chamber we would expect a sensibility to the *average* kicks over several bunches, and we would not expect to see the difference in Fig. 5 between 5 ns and 25 ns bunch spacing.[1] In the following we consider a 3 mm radius round (worst case) batch of 2 μs length with 5×10^{12} protons, i.e. $\simeq 2 \times 10^{-9}$ C on 5ns. Charged particles floating in the vacuum chamber at the border of this beam (worst case) will feel — in the kick model — a transverse momentum transfer of 4×10^{-5} eVs/m within 5 ns. The lightest ions (hydrogen) would travel within 5 ns a distance of about 0.02 mm [2], i.e. a tiny fraction of the beam radius. Therefore even for the worst case momentum transfer, ions could hardly distinguish between a pattern of bunches of 5 ns spacing and 5 times larger bunches (in intensity) and spacing of 25 ns. Basically the effect on ions depends on the *average charge over several bunches*. This is in contrast to our observations of Fig. 5, hence only *light* charge particles, i.e. *electrons*, can be the moving charges.

4 EFFECT ON DAMPER PERFORMANCE - BEAM STABILITY

During the 1999 run the perturbed signals of the damper pick-ups posed a strong limitation for this system for the LHC type beam. With solenoids, a remedy was found up to about 5.5×10^{12} protons per batch of 80 bunches. Beyond that intensity the system performance degraded. It was not possible from our observations to conclude whether the beam instabilities and the blow-up observed [6] were linked to the electron cloud phenomenon or solely a result of the mal-function of the damper due to perturbed signals. Fig. 6 shows a damper signal with a scale of 1 s/div during an MD where the beam was accelerated. At the time of the MD the solenoids could only be used in pulsed mode to avoid overheating. After 2 s they had to be switched off and strong beam oscillations were visible, losses were also observed. After installation of air cooling the solenoids were operated in CW mode and the performance improved. Still slow beam losses were observed, that made it impossible to keep the beam in coast above the electron cloud threshold for a long time.

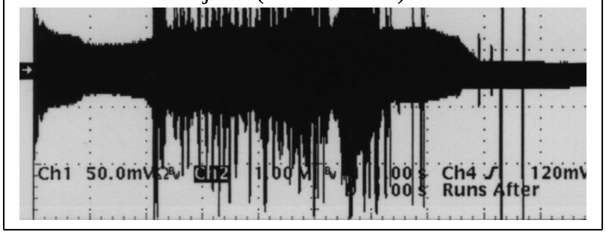

Solenoid off at inj+2s (scale: 1s/div)

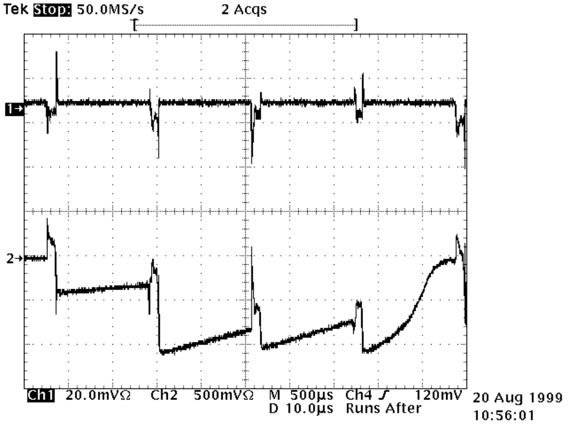
Figure 6: Effect on damper performance of switching off the solenoid.

5 OBSERVATIONS AT MULTIPLES OF THE BUNCH FREQUENCY - A REMEDY FOR THE DAMPER

5.1 Mixing Σ and Δ signals

It quickly became clear during summer 1999 that we could not rely on the solenoids for the damper. The fields were too low, and with increasing intensity it was unclear whether solenoid fields strong enough could be generated in the pick-up, given the space constraints.

a) without solenoid



b) with solenoid of 100 gauss

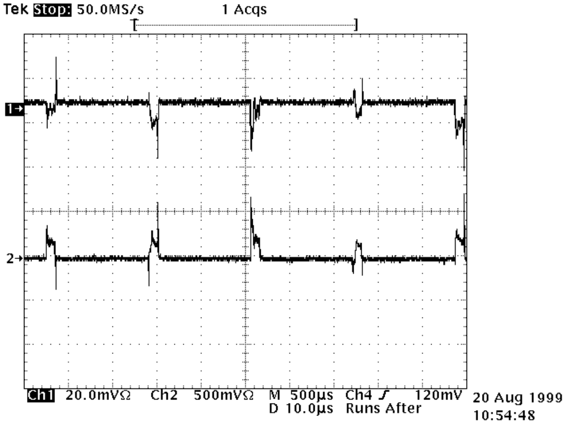


Figure 7: Comparison of base-band signal with high impedance FET amplifiers (bottom traces) and 200 MHz detection by mixing Σ and Δ signals (top traces) of a horizontal pick-up with and without solenoid. The 200 MHz detected signal is “electron-cloud free”.

A possible alternative to base-band processing is to work at a multiple of the bunch frequency, similar to the closed orbit system of the SPS. For the LHC beam the bunch frequency is $f_b \simeq 40$ MHz and all envelope information of bunch by bunch oscillations repeats every 40 MHz. To provide a signal for the damper we can mix the Δ-signals (beam position) with a multiple of 40 MHz down to base-band for further processing.

Depending on the length of the arrival time window of

---

[1] The following line of argumentation was developed by J. Tückmantel.

[2] This also justifies the application of the kick model. For an electron we would get about 40 mm — large against the beam radius — thus the kick-model is excluded here. Electrons so close to the beam would oscillate several times across the beam (see also [5]) and thus get in the end much less momentum transfer.

the electrons *between* bunches the signals will not be influenced by the electron cloud phenomenon. Also working at higher frequencies and discarding the low frequencies allows to load the pick-up with 50 Ω providing a rapid path for discharge.

Fig. 7 shows experiments with mixing of Σ and Δ signals. A balanced level 7 mixer (mini-circuits ZAD-1) was used and signals were amplified and band-pass filtered. The sum signal was sent through a limiter to supply a constant signal level. The top traces show the 200 MHz detected signal, and the bottom traces the corresponding baseband signals for the *same pick-up* on the *same turn*, with and without solenoid. 200 MHz signals are always clean.

5.2 Mixing using an RF reference

Due to dynamic range and bandwidth issues it is more advantageous to do the mixing with a locally generated fixed RF, that is always present and independent of the beam intensity. A system to generate such a beam synchronous signal was set-up using an optical fiber link for the 200 MHz and the revolution frequency signal transmitted from BA3 (Faraday cage) to BA2, the location of the damper. We succeeded in generating all multiples of 40 MHz up to 200 MHz at a fixed energy (at the injection energy of 26 GeV). During acceleration dephasing has to be controlled, e.g. by programming the phase of the 200 MHz reference sent from BA2. This is foreseen for the run in the year 2000.

Fig. 8 shows the results of the observations on pick-up 2.06. Filters were produced to look at the modulation at 40, 80, 120, and 160 MHz. Concerning the electron cloud no evidence of a disturbance at any multiple of 40 MHz was seen. We do see a signal dip in the batch somewhere where we expect that the electron cloud avalanche starts. This can be explained by particle loss (signal is proportional to intensity and position). The typical drift of the signal seen for baseband signals is absent.

6 POSSIBLE EXPERIMENTS WITH DAMPER PICK-UPS IN 2000

Having four spare pick-ups with high impedance amplifiers we can envisage to do more systematic investigations. Possible directions could be

- tests with solenoid fields
- record the evolution of threshold during the year
- do more experiments with respect to time structure to understand the bunch to bunch build-up

Our priority will be the detection scheme and its operation during the full LHC acceleration cycle, to ensure the proper functioning of the damper with the LHC beam. Due to fear from interferences from the main 200 MHz RF-system — in case of a movement of the damper system to BA3 — a frequency other than 200 MHz will be used. Presently the prototyping work aims at a frequency of 120 MHz.

7 ACKNOWLEDGEMENTS

I would like to acknowledge help and collaboration from our colleagues at the PS for providing the different beams for the MD studies, SL-OP, in particular G. Arduini, and K. Cornelis for the help in MDs, SL-BI for collaboration and sharing with us the pick-ups. Help of the LHC-VAC group which provided the cooling for the solenoids, is also acknowledged. Thanks to F. Zimmermann for stimulating discussions on the subject, and T. Linnecar for support in MDs. For building the necessary hardware, and the many modifications for MDs during the 1999 run, many members of SL-HRF have contributed. In particular I would like to thank R. Louwerse, and J.-F. Malo for their work. Special thanks to J. Tückmantel for his contributions, during the MDs and the writing up.

8 REFERENCES

[1] W. Höfle, “Towards a transverse feedback system and damper for the SPS in the LHC era”, CERN SL-97-017 (RF), 1997.

[2] W. Höfle, “Transverse Damping and Fast Instabilities”, Proceedings of the Workshop on LEP-SPS performance — Chamonix IX, Chamonix, January 25–29, 1999, 86–91.

[3] P. Collier (Ed.), “The SPS as Injector for LHC Conceptual Design”, CERN SL-97-007 (DI), 1997.

[4] W. Höfle, Presentation 3.7, These Proceedings.

[5] F. Zimmermann, Presentation 4.6, These Proceedings.

[6] G. Arduini, Presentation 4.4, These Proceedings.

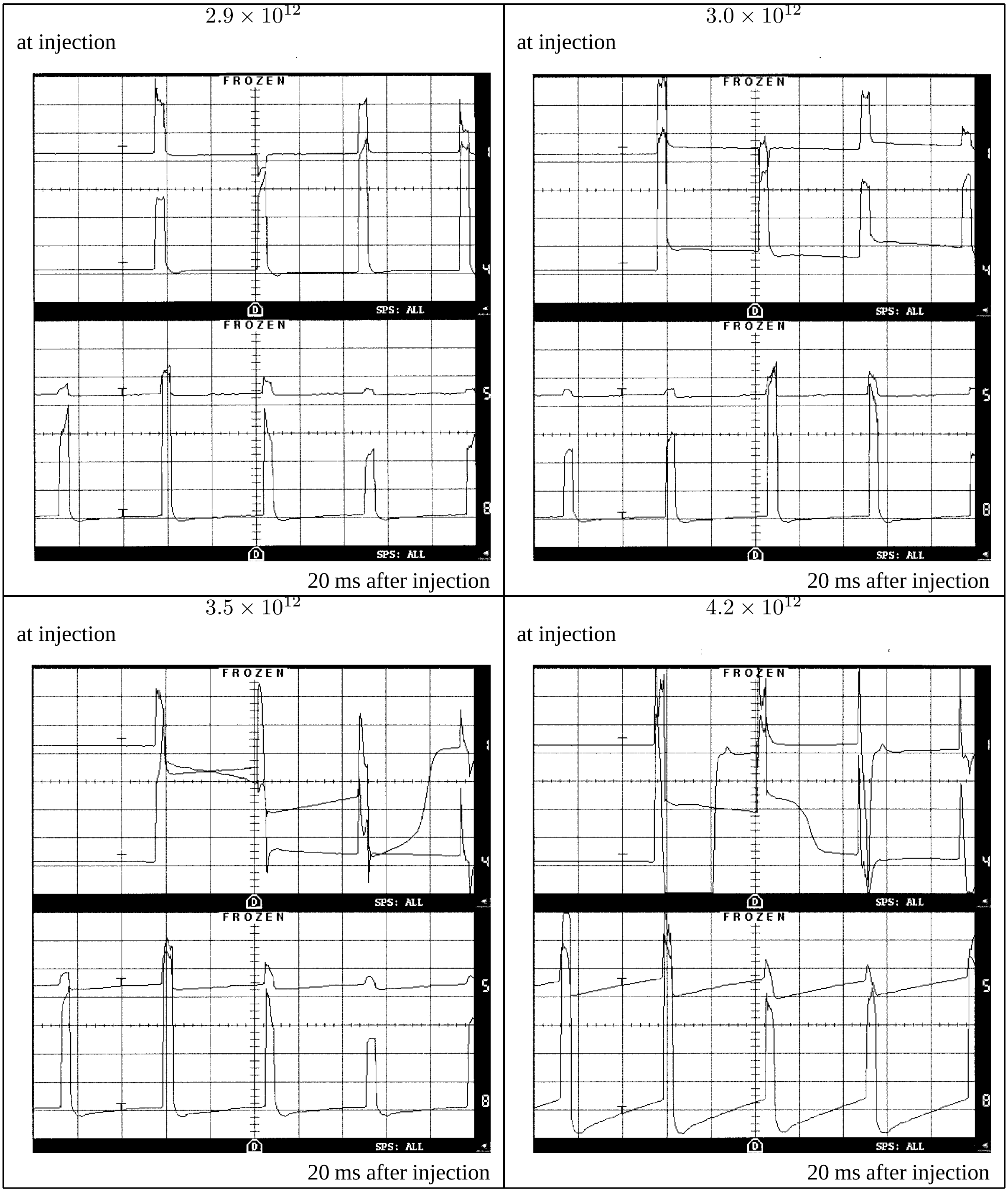


Figure 3: Four different intensities showing threshold, and the evolution at injection and 20 ms after injection; shown are Σ (top trace) and Δ-signals (bottom traces); scales are 10 μs/div.

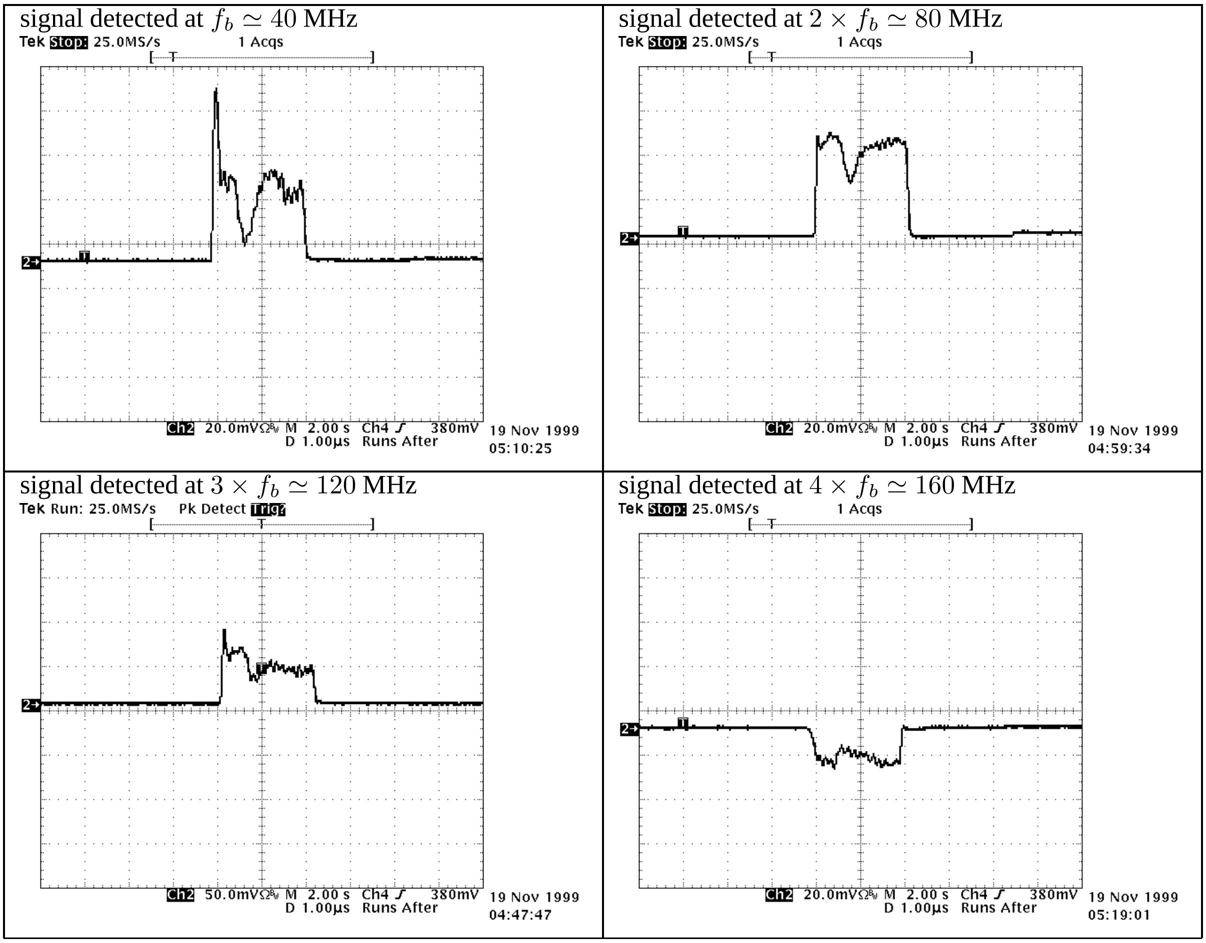


Figure 8: Mixing of pick-up signals from the horizontal PU 2.06 loaded with 50 Ω impedance, using a bunch synchronous RF reference signal.No electron cloud effect is visible; scales are 1 μs/div.