Transverse feedback to cure electron-cloud induced and single bunch vertical instability in the SPS

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LARP team
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Joel R. Thompson (Cornell / LBNL), R. de Maria (BNL)
W. Fischer (BNL instability @ transistion)

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Single bunch instabilities: E. Metral, B. Salvant (CERN)

Acknowledgements: T. Bohl

Overview

1. Observation of vertical e-cloud instability in the SPS

2. Study of feasibility of a new wide band feedback system for the SPS

3. Elements needed for a feedback System

4. Studies in 2008

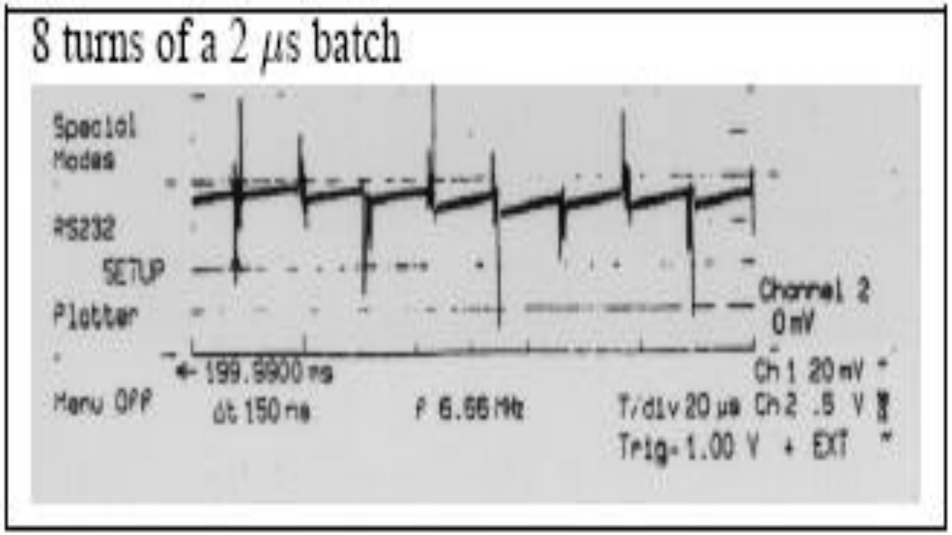
5. Initial results of measurements and simulations

Conclusions / outlook

Excursion to history

SPS 10 years ago

Observation of e-cloud signal on feedback pick-ups (1)

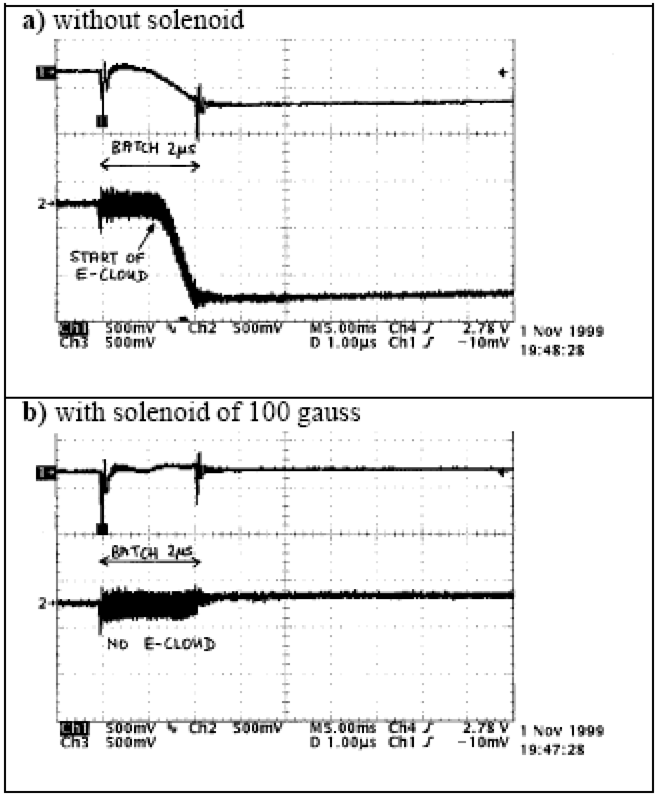


SPS September 1998

Charging up of pick-up plates by electrons perturbs the signals use for the SPS transverse feedback , understood to come from e-cloud in1999 (suppression of the effect by solenoid field)

W. Hofle, in "Chamonix " 2000 Workshop, CERN SL-2000-007 DI
https://ab-div.web.cern.ch/ab-div/Conferences/Chamonix/chamx2k/PAPERS/4_2.pdf

Observation of e-cloud signal on feedback pick-ups (2)



60 - 80 windings
20 A maximum current
5 pick-ups (in series)
power supply in tunnel (1.2 kW)
CW operation with blowers

Suppression of the charging-up on the pick-up by a solenoid (SPS run 1999)

W. Hofle, in "Chamonix " 2000 Workshop, CERN SL-2000-007 DI

https://ab-div.web.cern.ch/ab-div/Conferences/Chamonix/chamx2k/PAPERS/4_2.pdf

Observation of e-cloud signal on feedback pick-ups (3)

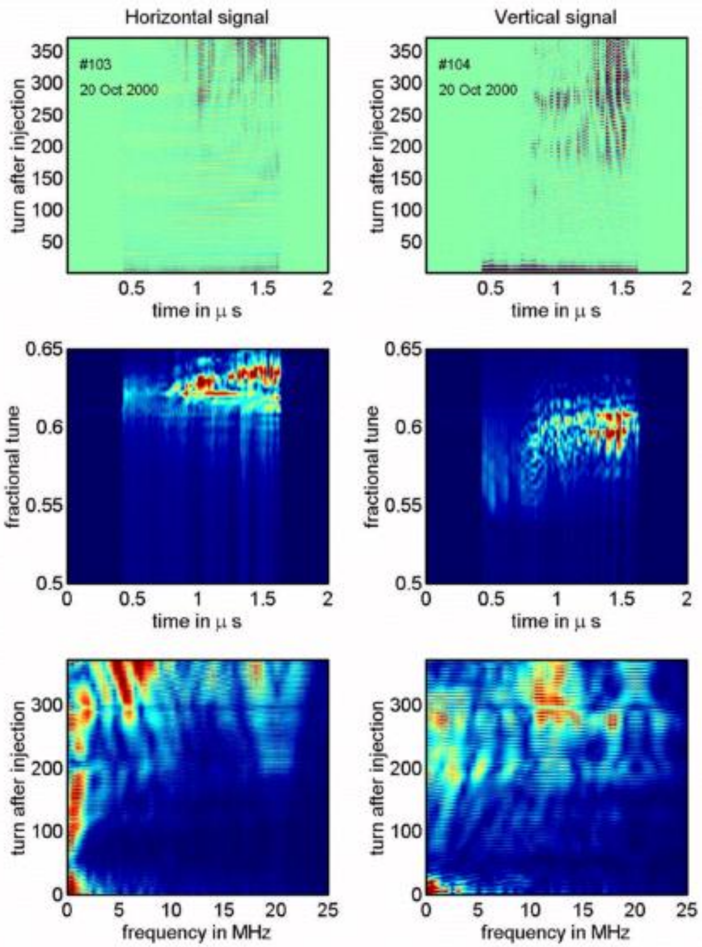
SPS pick-up
(electrostatic, "shoe-box" design)
58 pF, high-impedance FET
amplifiers in tunnel

17 permanent magnets (350 kN)
6-fold symmetry
solenoid field component
not very efficient
small effect on electron cloud

Experiments with permanent magnets to perturb electron movement,
less effect than solenoid

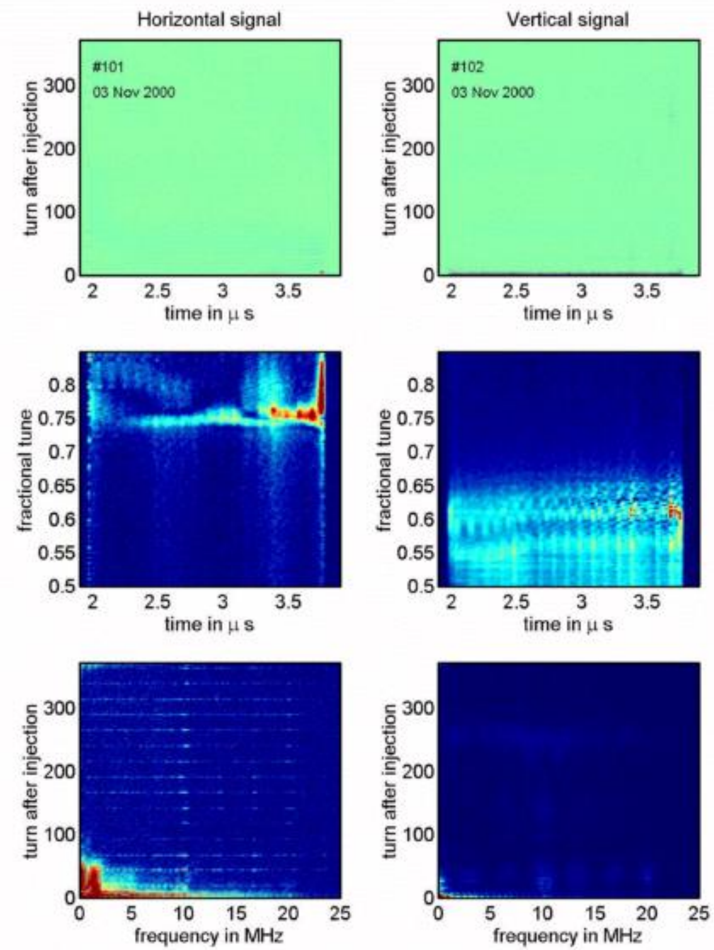
W. Hofle, in "Chamonix " 2000 Workshop, CERN SL-2000-007 DI
https://ab-div.web.cern.ch/ab-div/Conferences/Chamonix/chamx2k/PAPERS/4_2.pdf

Observation with e-cloud instability
(signals of current feedback limited to 20 MHz



FB does not cope with instability

Figure 5: Transverse beam oscillations at injection with tune settings $Q_H = 26.62$ and $Q_V = 26.58$. Orbit variations and synchrotron oscillations are removed by filtering. Pick-ups 2.06 (H) and 2.07 (V) were used with a bandwidth of $\simeq 20$ MHz; 48 bunches spaced 25 ns, 4×10^{12} protons per batch.



FB ok

: Transverse beam oscillations at injection with tune settings $Q_H \simeq 26.74$ and $Q_V = 26.58$. Orbit variations hrotron oscillations are removed by filtering. Pick-ups 2.06 (H) and 2.07 (V) were used with a bandwidth of Iz; 72 bunches spaced 25 ns, 6×10^{12} protons per batch.

High frequency observation of electron cloud

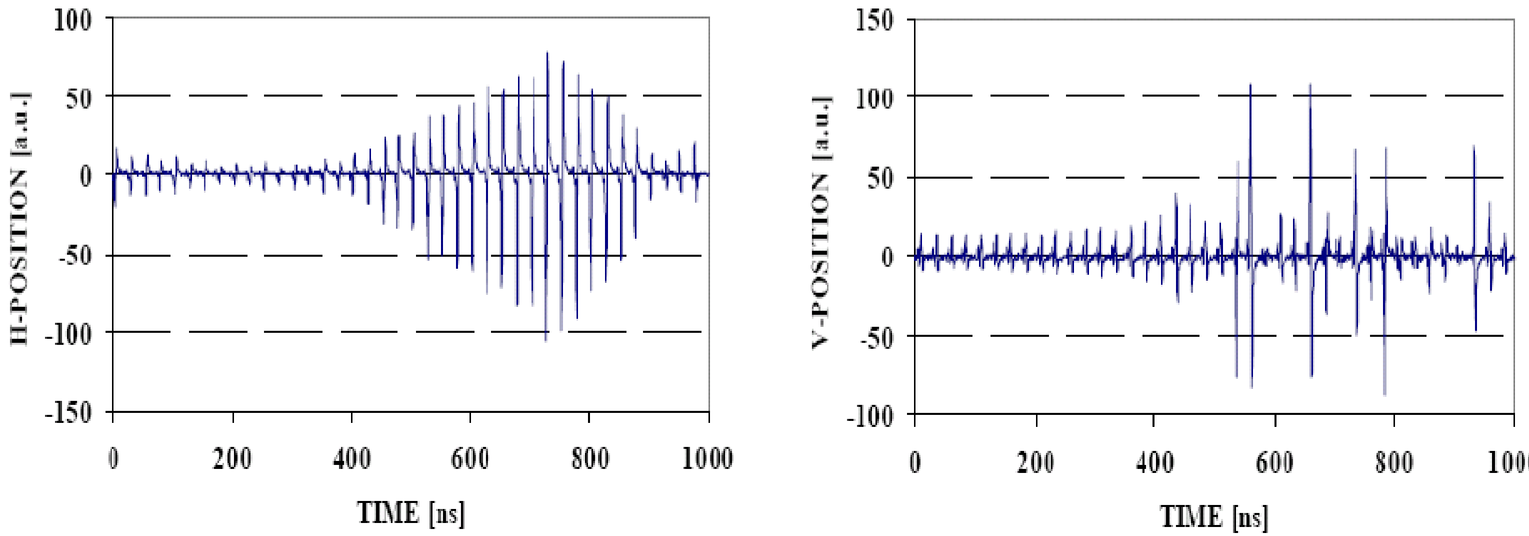


Figure 6. Snapshot of the horizontal (left) and vertical (right) position of the first 48 bunches of the LHC bunch train. $N_b = 0.8\times10^{11} > N_{th} \sim 0.2\text{-}0.3\times10^{11}$.

From G. Arduini et al, Proceedings E-cloud 2004

Observation of oscillations with strip line coupler (head tail monitor) along batch:

- horizontal plane: coupled bunch behavior, strong correlation between bunches, low frequency (~ 1 MHz), taken care of by the present transverse feedback system
- vertical plane: some bunches oscillate with large amplitude, single bunch oscillations, weak correlation between adjacent bunches, controlled by current transverse feedback *and* high chromaticity, emittances at the limit for nominal LHC beam (blow-up at tail of batch)

High frequency observation of electron cloud instability (2)

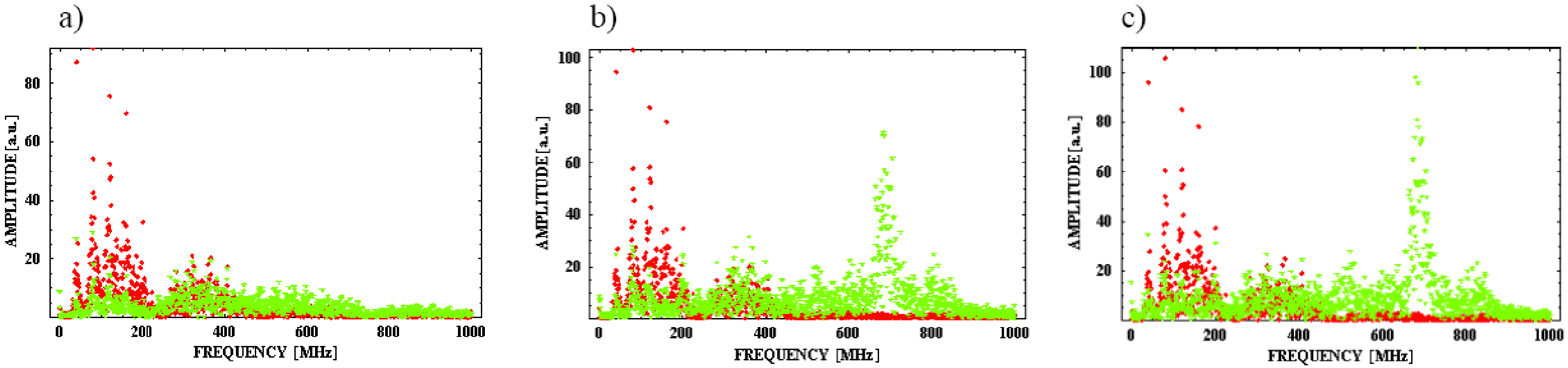


Figure 17. Fourier spectra of the sum (red) and delta (green) signals from a wideband vertical pick-up for the leading (a) bunch of the LHC bunch train and for bunch number 15 (b) and 39 (c). $N_b= 0.8\times10^{11} > N_{th}=0.2\text{-}0.3\times10^{11}$.

From G. Arduini et al, 31st Advanced ICFA Beam Dynamics Workshop on Electron-Cloud Effects, Napa, CA, USA, 19 - 23 Apr 2004, pp.31-47, CERN-2005-001

Vertical activity at 700 MHz for the trailing bunches correlated with vertical blow-up in tail of batch, clear signature of e-cloud induced instability; note absence of activity for sum signal at this frequency

LARP Initiative for SPS e-cloud FB

Interest expressed in 2007 by J. Byrd (LBNL, Berkeley) and J. Fox (SLAC) to collaborate on transverse feedbacks in the frame work of LARP

Research on SPS e-cloud FB identified as an interesting option for CERN, can lead to a construction project for a new feedback system
in the framework of the future upgrade of the SPS (see E. Shaposhnikova)

SLAC and LBL well placed to contribute owing to their past experience with high frequency feedbacks as in PEP II feedbacks (500 MS/s processing) and Los Alamos PSR e-p instability damping,
50 MHz-300 MHz analog bandwidth

Since the first contacts were established the US team is enlarging:

SLAC: J. Fox, M. Pivi, J.J. Xu, L. Wang
LBNL: J. Byrd, J. Thompson, M. Furman, J.-L. Vay, M. Venturini
R. de Maria (Toohig Fellow, based at BNL),
W. Fischer (BNL) expressed interest for RHIC

2. Feasibility of feedback system

Possible show-stoppers for a feedback system:

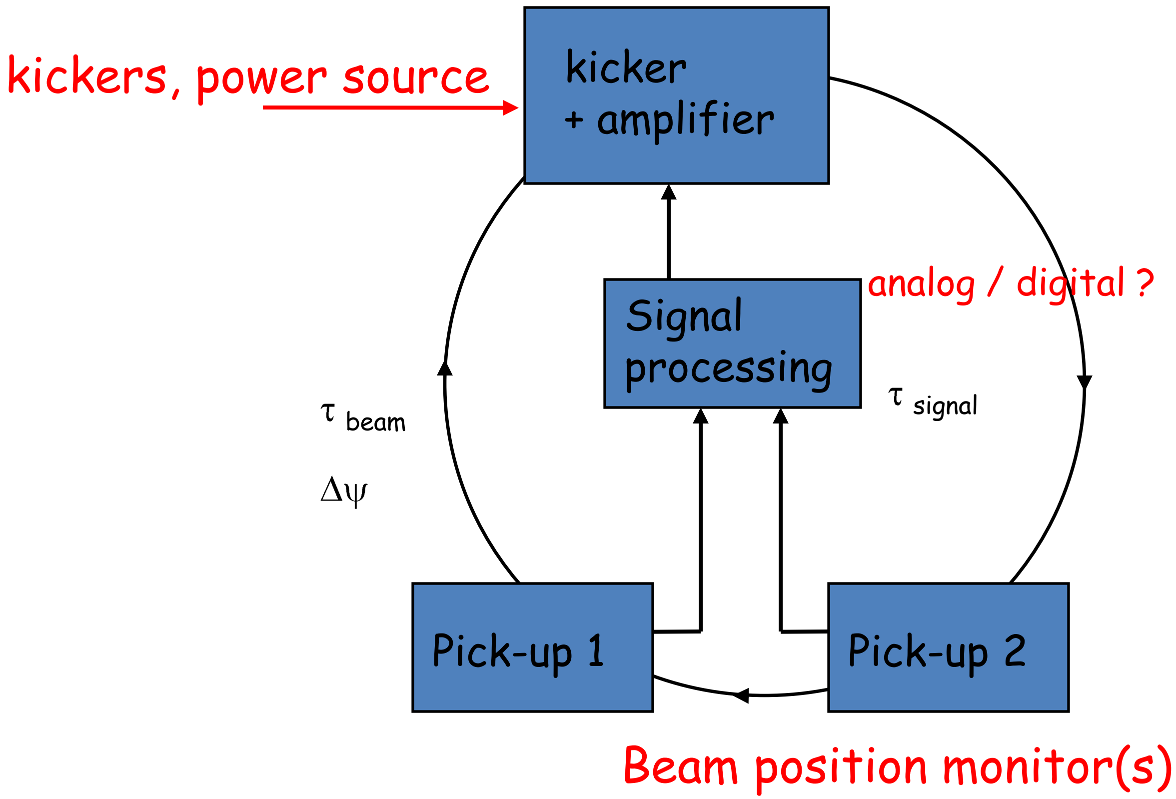
1) Emittance growth may be dominated by incoherent effects which cannot be damped

2) Required power is excessive due to the fast growth rates, i.e. a FB might even require distributed kickers for stability if growth rates are faster than 10 turns research on low-noise front-ends crucial

1) Feasible but not robust enough:

- adjustment of loop delay will be very delicate for the high frequency high bandwidth system (GHz !),
- mix-up with longitudinal motion possible if bunches not absolutely stable longitudinally ?
- Suppression of common mode signal crucial to avoid amplifier saturation and a good usage of the dynamic range available (digitization),
- we may require to split the system into several bands in order to be able to cover the entire frequency range -> overlap of bands becomes delicate

3. Elements of feedback system



3. Elements of feedback system

Pick-ups: Strip-line or exponential couplers, strip-line pick-ups: notch in response, exponential couplers need correction of non-linear phase with frequency

Signal processing: direct sampling at 2.5 GS/s and 8 bit proposed by SLAC, R&D required

Use of optical notch filter using fiber for one turn delay (?), LBNL has experience

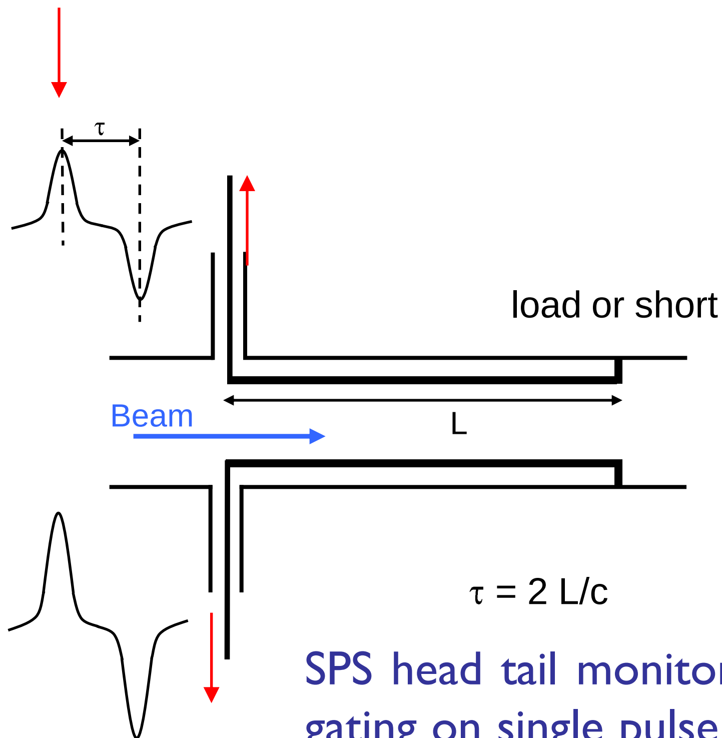
If instability rather narrow-band (100 MHz) with center frequency moving from ~200 MHz to ~ 1 GHz during acceleration -> down conversion to IF may be an option for the processing; however I suspect it's really broadband

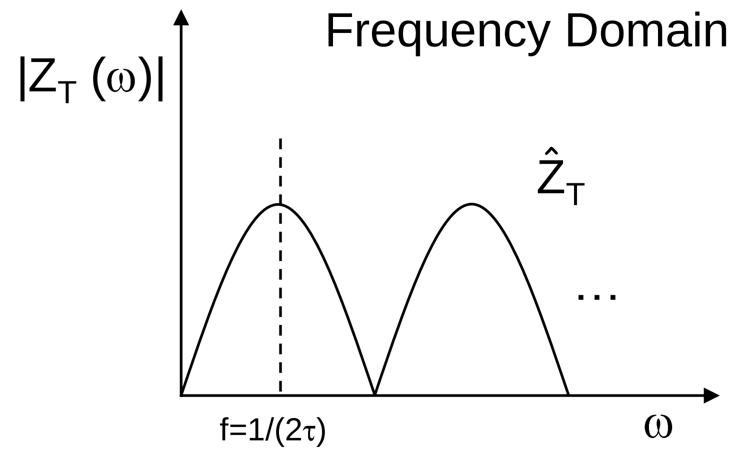
Use of delay stabilized cables (small delay variation with temperature etc.) necessary

Power sources: solid state amplifiers commercially available moderate power is sufficient split into several frequency bands, watch for quality of amplifiers (need good linearity)

Kicker structures: Simple strip-line preferred by SLAC/LBNL, travelling wave structures for better use of available power ? Strip-line wide band enough for required frequency range ? split frequency range ! Exponential coupler an option for kicker ?
Look at stochastic cooling systems !

Coupler type pick-ups





$\tau = 2\,L/c$

$$Z_T\,(\omega) = \hat{Z}_T\; j\,\sin(\omega\tau/2)\; e^{-j\omega\tau/2}$$

SPS head tail monitor (R. Jones, AB-BI) uses direct sampling and gating on single pulse in time domain to effectively remove notch in frequency response, current software developed by
R. Steinhagen, can be used for MDs, software good for logging,
is this signal treatment also useful for a FB system ??
matching of the SPS head tail monitor not very good for higher frequencies, we observed some ringing

Exponential coupler

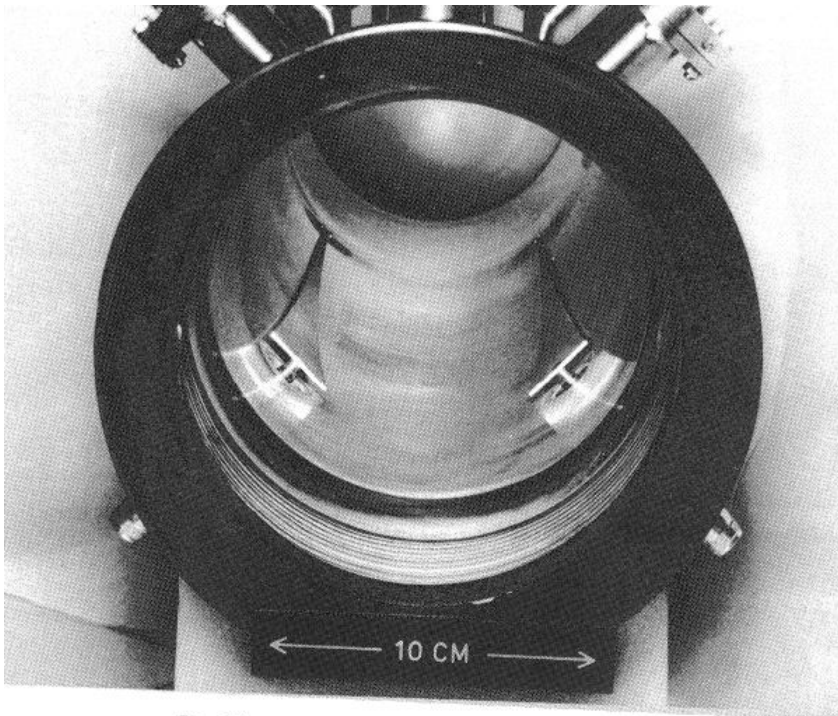
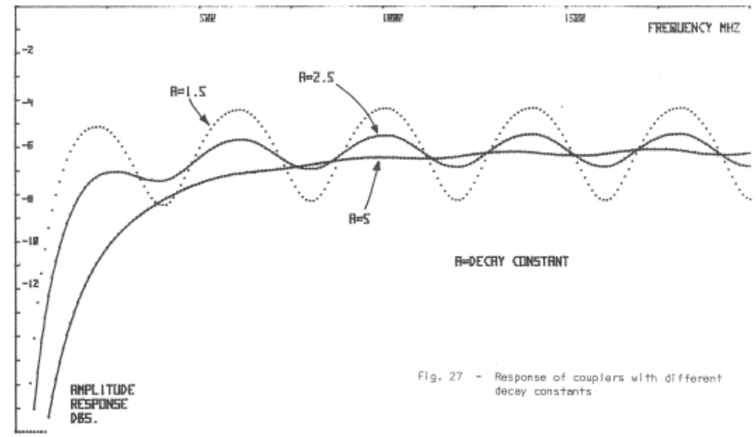


Fig. 31b - Interior of directional coupler pick-up

Four such couplers installed in SPS (four electrodes at 45 degrees) can be used for MDs, hybrids and cables checked and their transfer functions measured in March 2008 (R. de Maria, Gerd Kotzian)



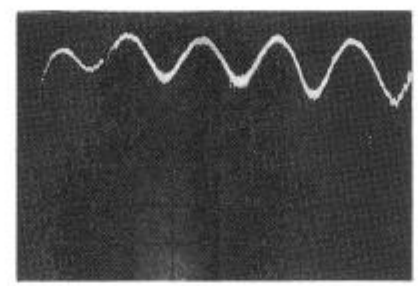
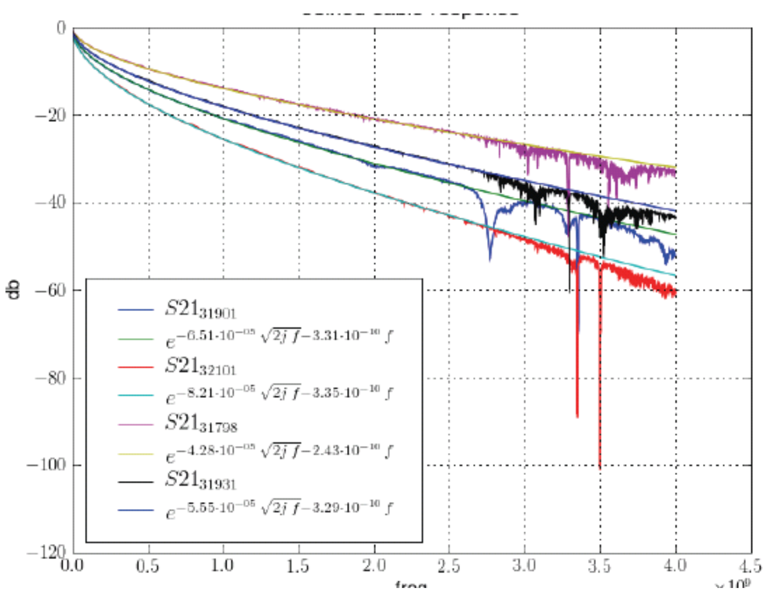


Fig. 37 - Frequency response of sum signal from directional coupler pick-up
200 MHz/div 2.5 dB/div

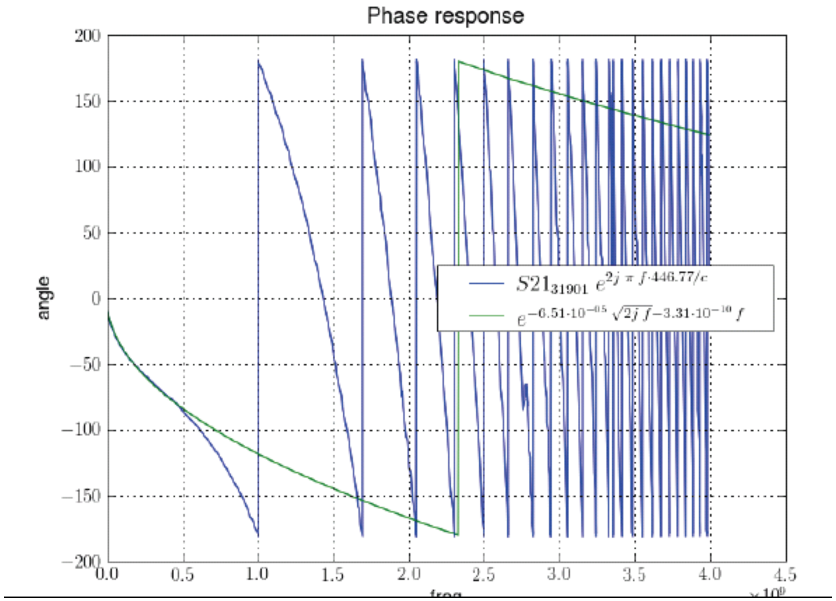
Developed for SPS by T. Linnecar,
Reference: CERN-SPS-ARF-SPS/78/17

Signals perturbed by
beam pipe cut-off frequency
(~1.6 GHz)

Measurement on 7/8” cables used for exponential coupler



GHz



GHz

Attenuation of cables (air dielectric, 7/8”) used today (G. Kotzian, R. de Maria)

For feedback system one needs a perfectly linear phase !

Phase response of cable, strongly nonlinear with frequency, above 500 MHz, cannot be fitted with phase term ~sqrt(f) beyond 500 MHz (G. Kotzian, R. de Maria)

4. Objectives of Studies

Use LHC type beam, but also single bunch beam (include TMCI instability observed on single bunch (E. Metral, B. Salvant) into the study of a feedback), SPS Studies Working Group strongly recommends to TMCI, some LHC upgrade scenarios involve bunch intensities beyond ultimate bunch LHC intensity in the SPS

Clearly establish frequency spectrum of instability using both the exponential coupler and the head tail monitor

Observed signal is always *position x intensity* -> disentangle longitudinal and transverse motion !

Establish growth rates and spectrum as function of beam parameters, energy (!)….

Attempt to excite beam using second kicker and measure its response

Analyze data collected with head tail monitor and exponential coupler and compare with simulations, correct for transfer functions of pick-up, cables and hybrids

Show in simulations with head-tail code whether the instability can be damped by feedback and what bandwidth and gain are required.

Establish feasibility, power required, bandwidth and frequency as basis of a system design study in 2009

5. First Results

MD results from scrubbing run (11th June 2008 and 4th August), ***see talk by R. de Maria,*** some plots on the next slides show occurrence of high frequency oscillations within the bunch

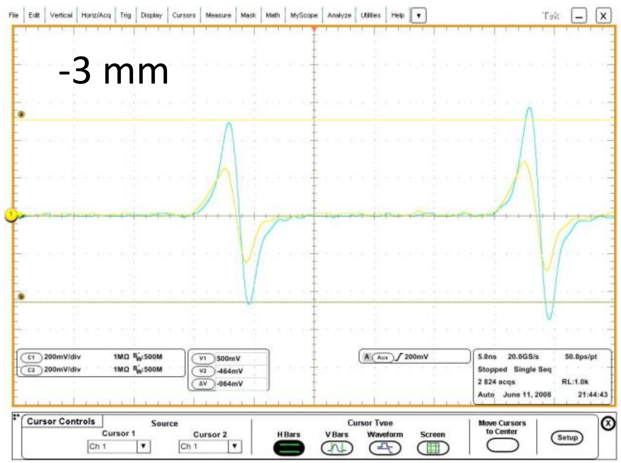
In June MD it was observed that the Δ signal is not flat zero for a centered bunch; (exponential coupler), some doubts about the linearity of phase with amplitude of the hybrids used in the tunnel to combine the signals existed; three hybrids were used, two to sum signals from two plates and a third to generated the Σ and Δ signal; reflections due to imperfect matching of pickup and hybrids can spoil the signal

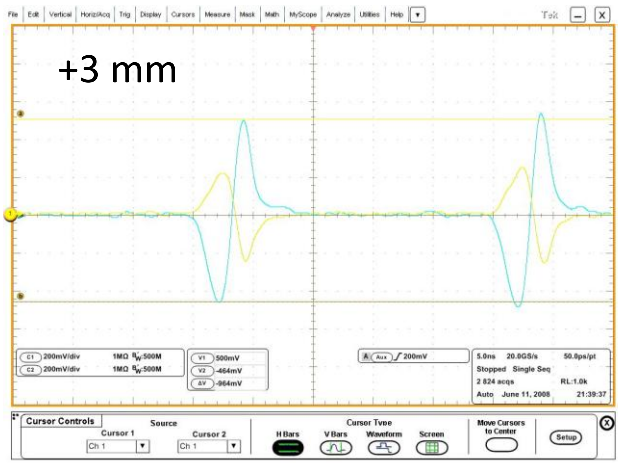
Finally it was decided to modify the installation in order to combine signals from two strips with resistive combiners, not generate Σ and Δ with a hybrid, and have just the sums of the two pairs of electrodes available on the surface.

Measurements with a single bunch show now a very good quality of the signal

Implementation of a feedback system in the headtail code (Joel R. Thompson, summer student (Cornell / LBNL)
reported also by ***M. Venturini*** at this workshop

Pick-up performance with hybrids



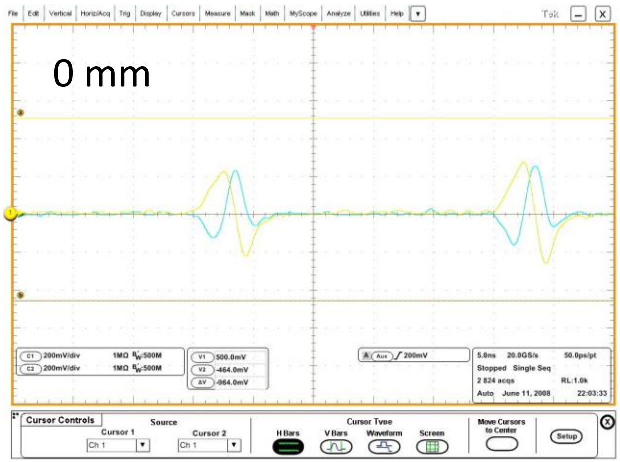


Σ-signals (yellow)

5 ns/div

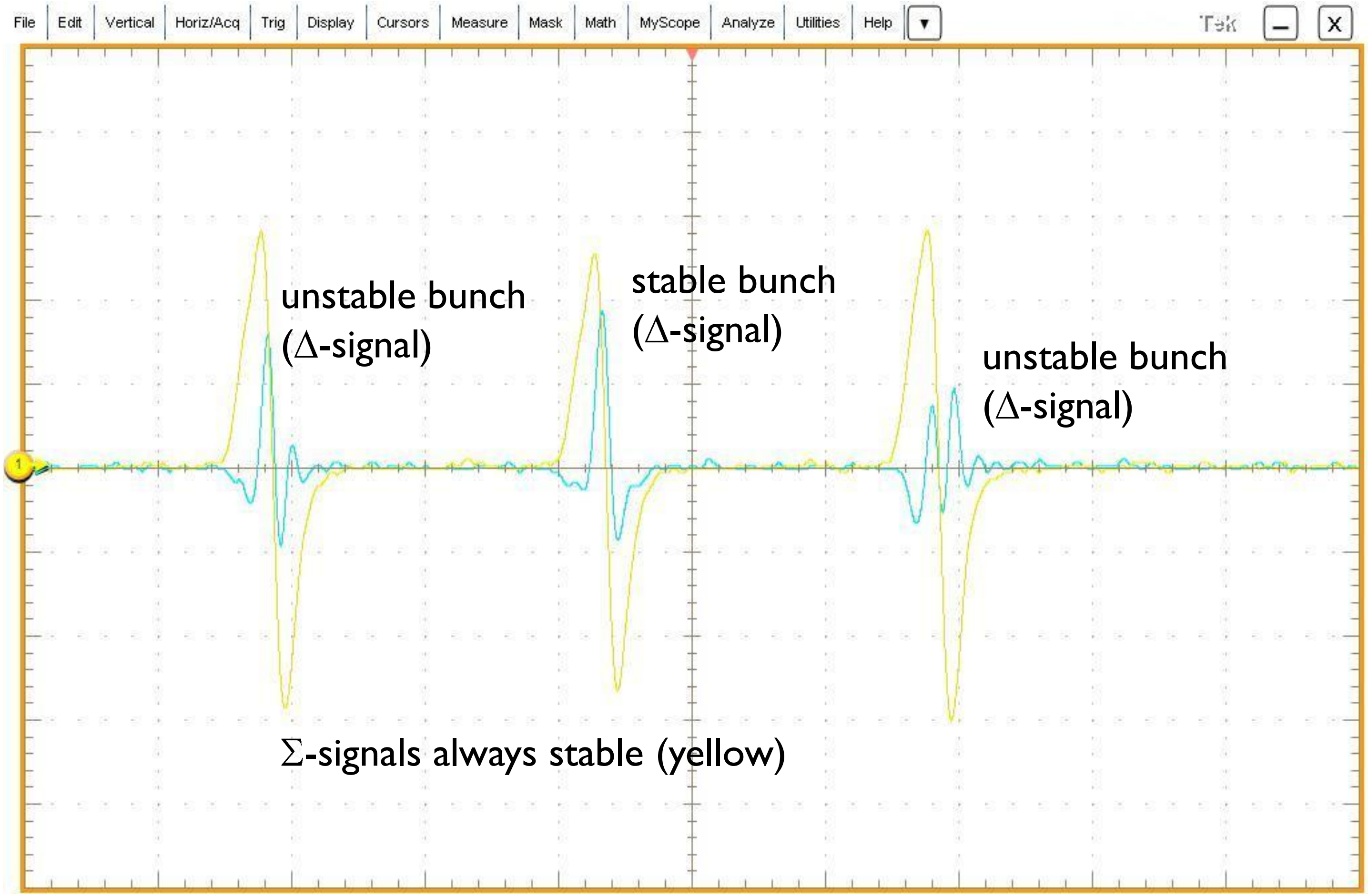
Δ-signal (blue)

Different attenuation used for sum and delta



Δ-signal does not cancel
very well for a centered beam -
subsequently exchanged hybrids
with resistive combiners
A, B were available for August MD

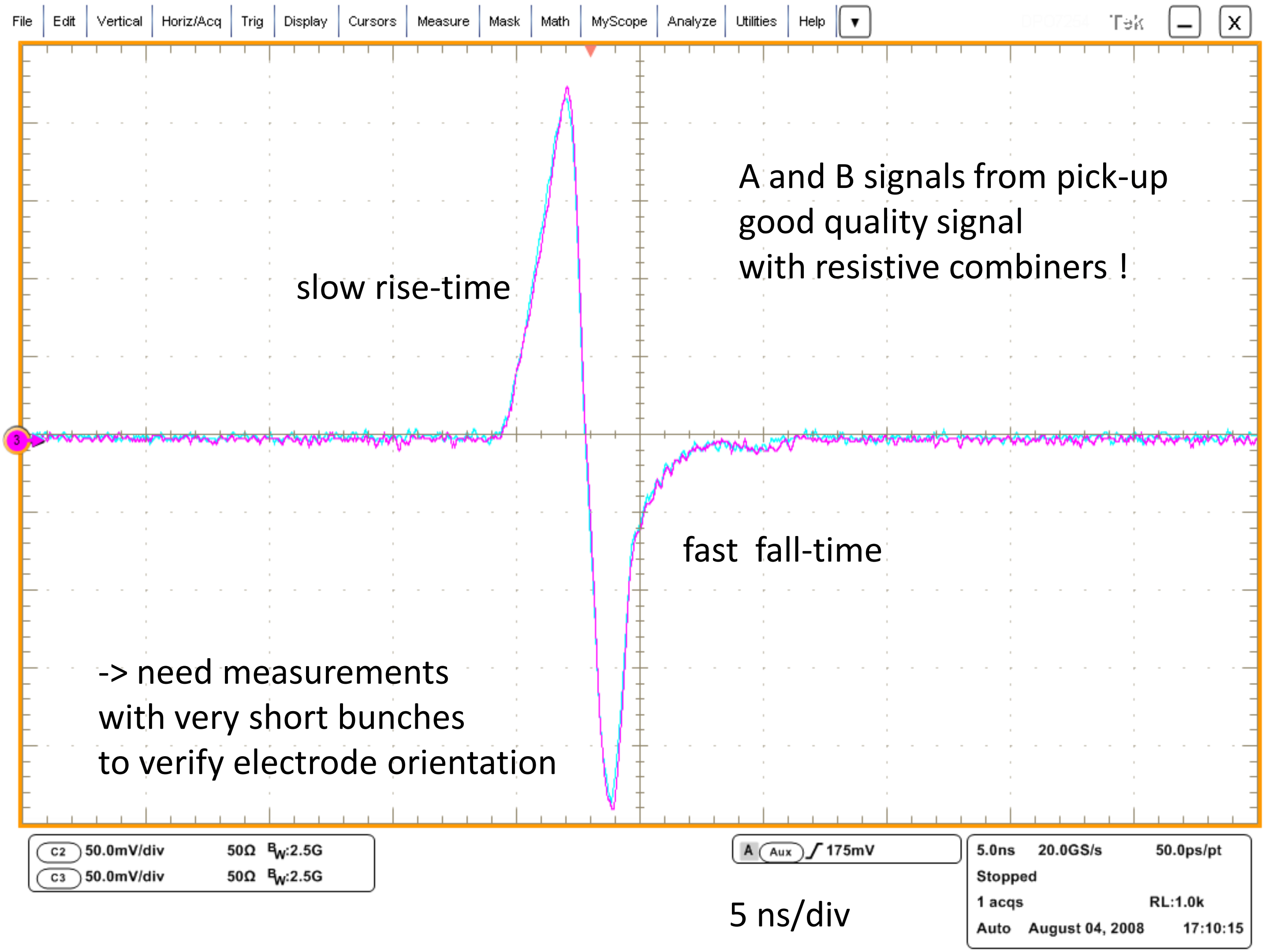
5x72 bunches injected; 25 ns bunch spacing; machine well scrubbed with four batches shown are the last three bunches of the 5th batch, vertical pick-up, shortly after injection evidence of single bunch multi-100 MHz transverse instability,



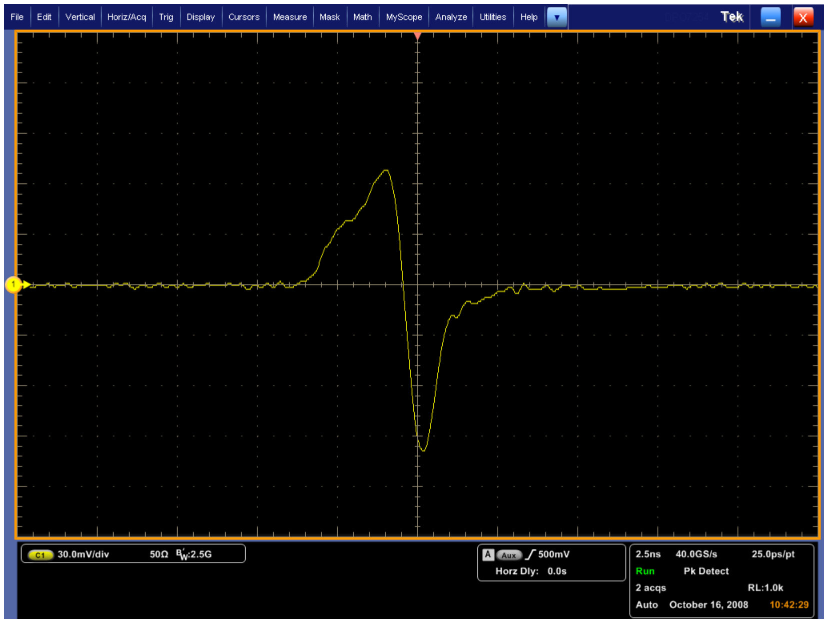
Instability at injection of 5th batch, analysis ongoing

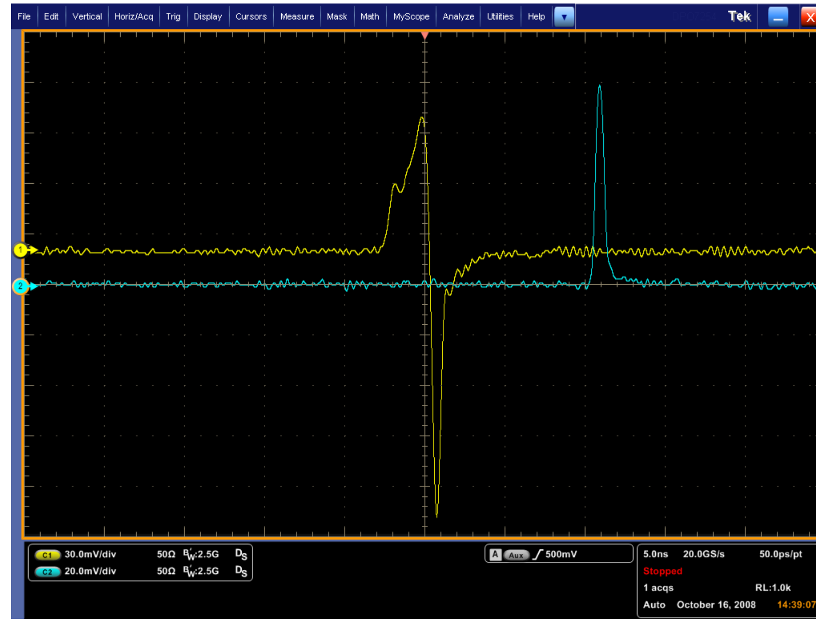
10 ns/div

Single bunch signals after modification of pick-up connection
(stable bunch with ~7 $x10^{10}$ protons per bunch)



Single bunch signals after modification of pick-up connection
(stable short bunch with ~5 x10^9 protons per bunch)

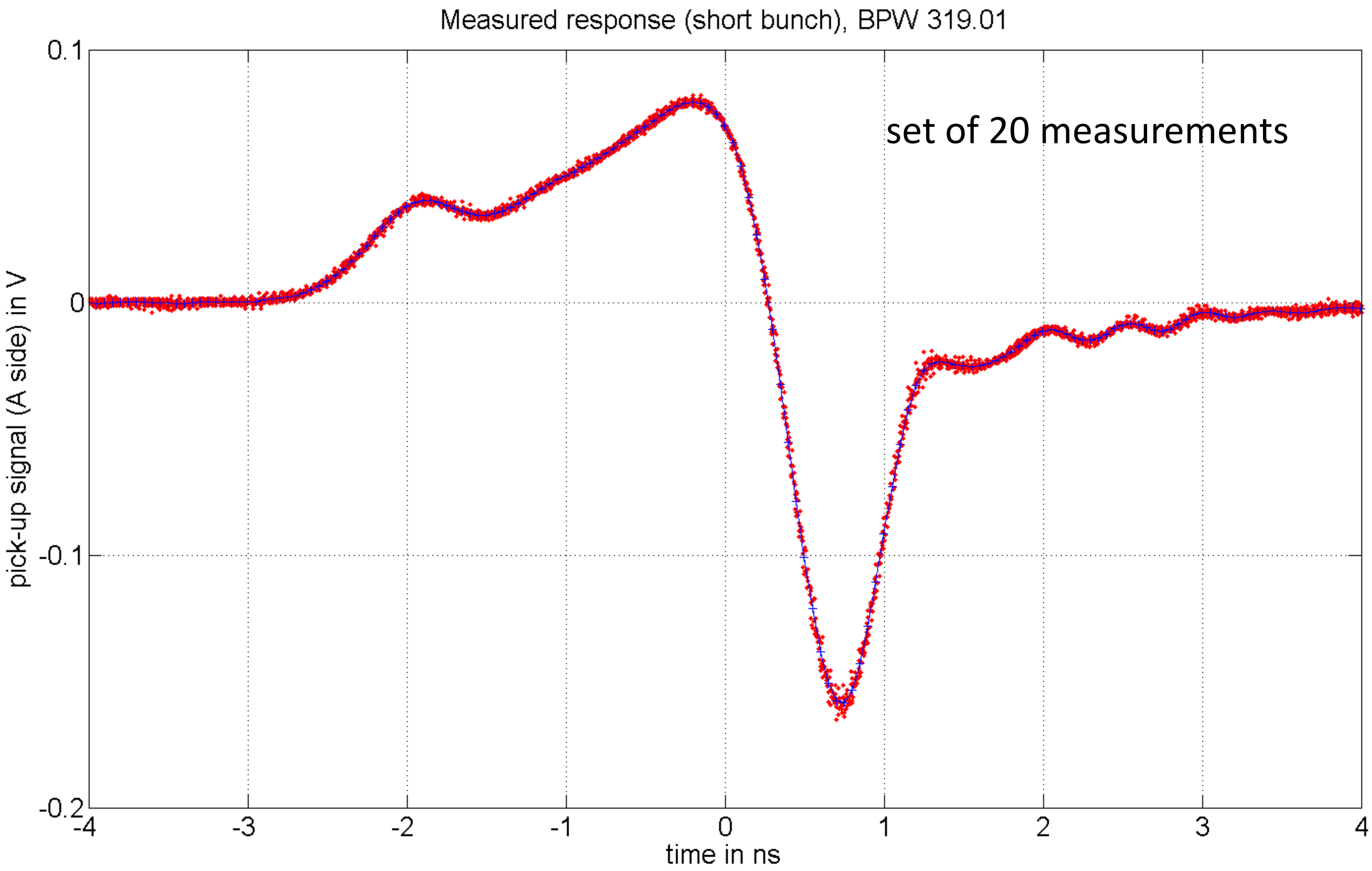




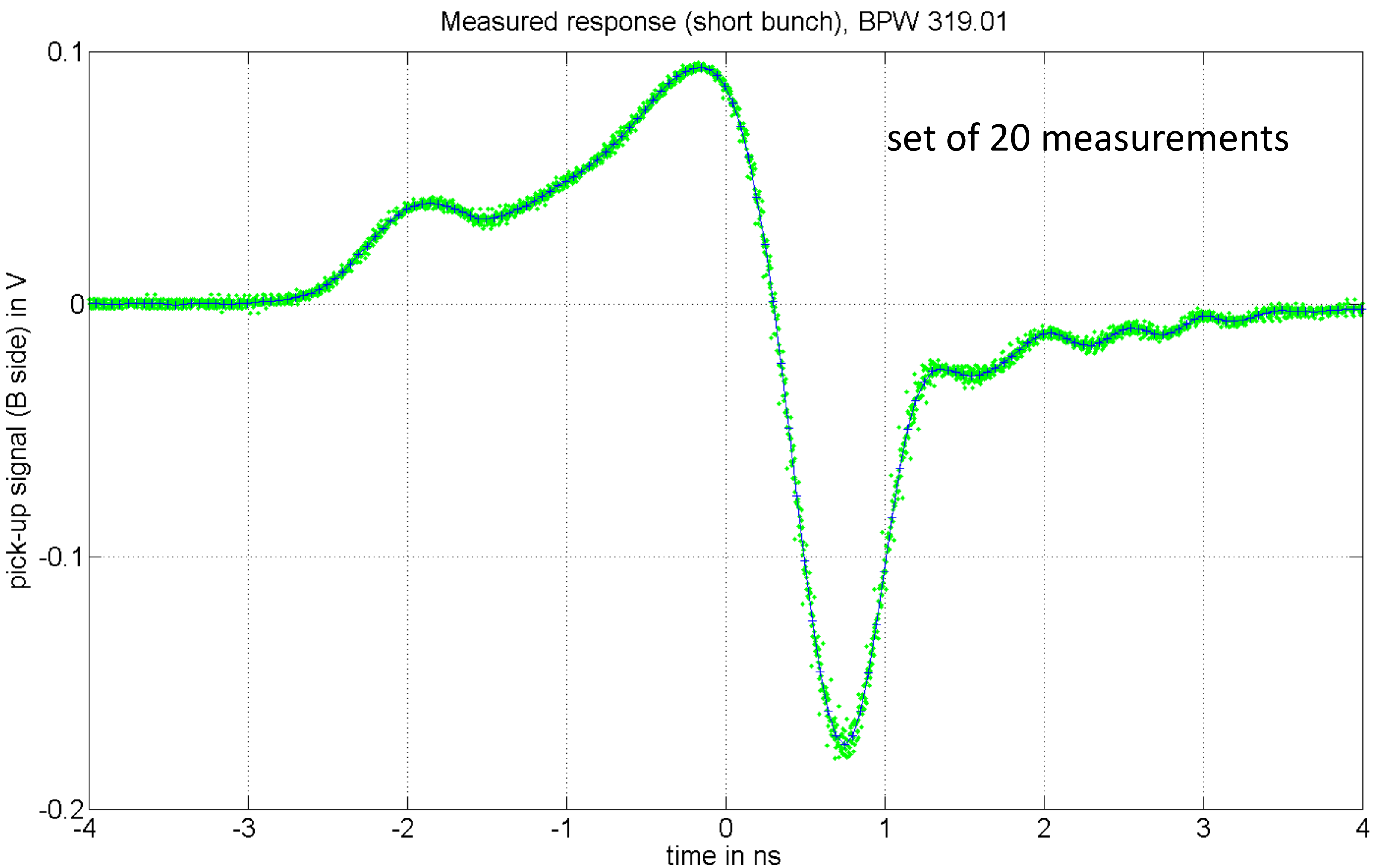
2.5 ns/div
Injection, 26 GeV/c
(longer bunch)

5 ns/div
450 GeV/c
(shorter bunch)

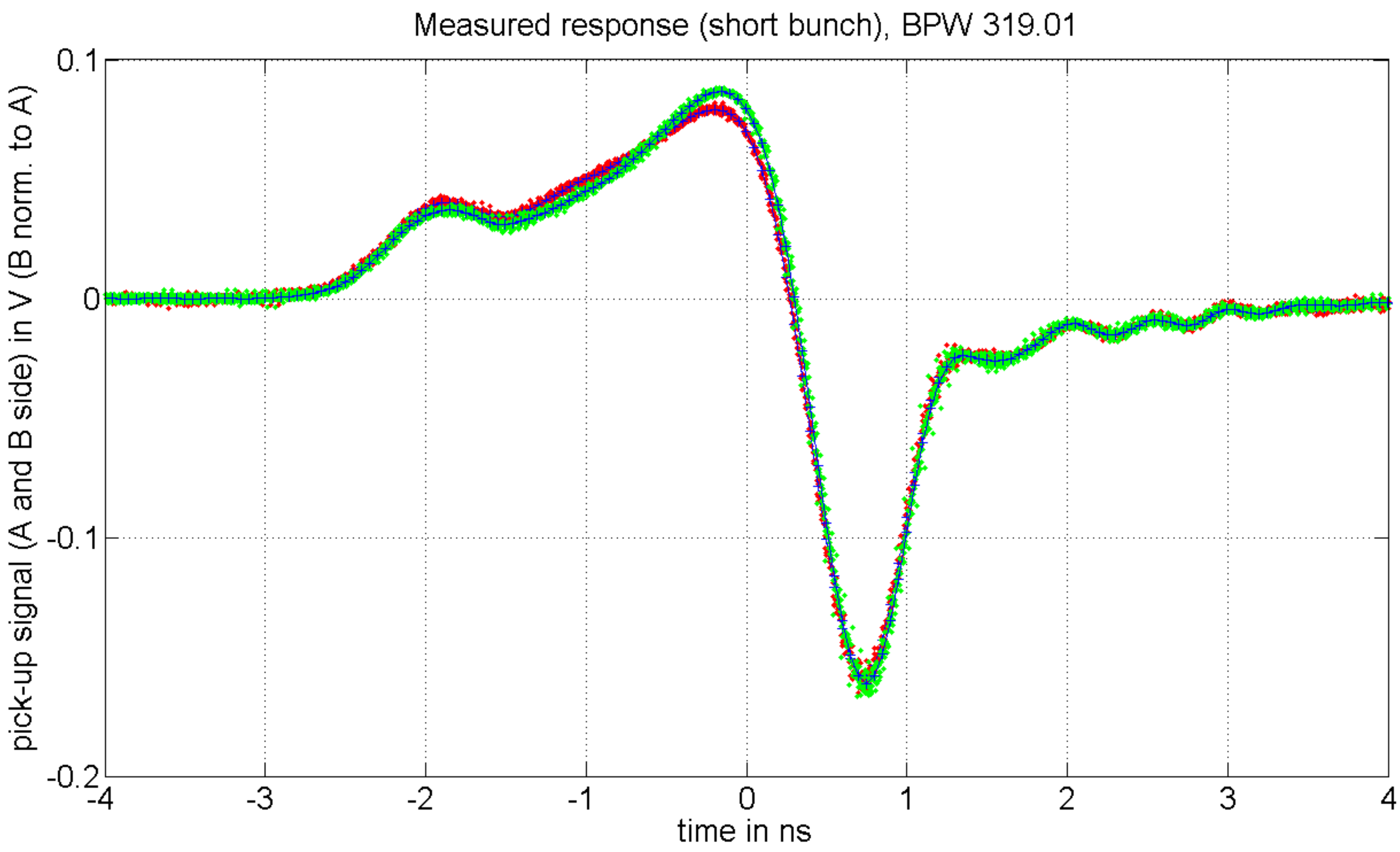
Single bunch signals after modification of pick-up connection
(stable bunch with ~5 x10^9 protons per bunch)



Single bunch signals after modification of pick-up connection
(stable bunch with ~5 x10^9 protons per bunch)

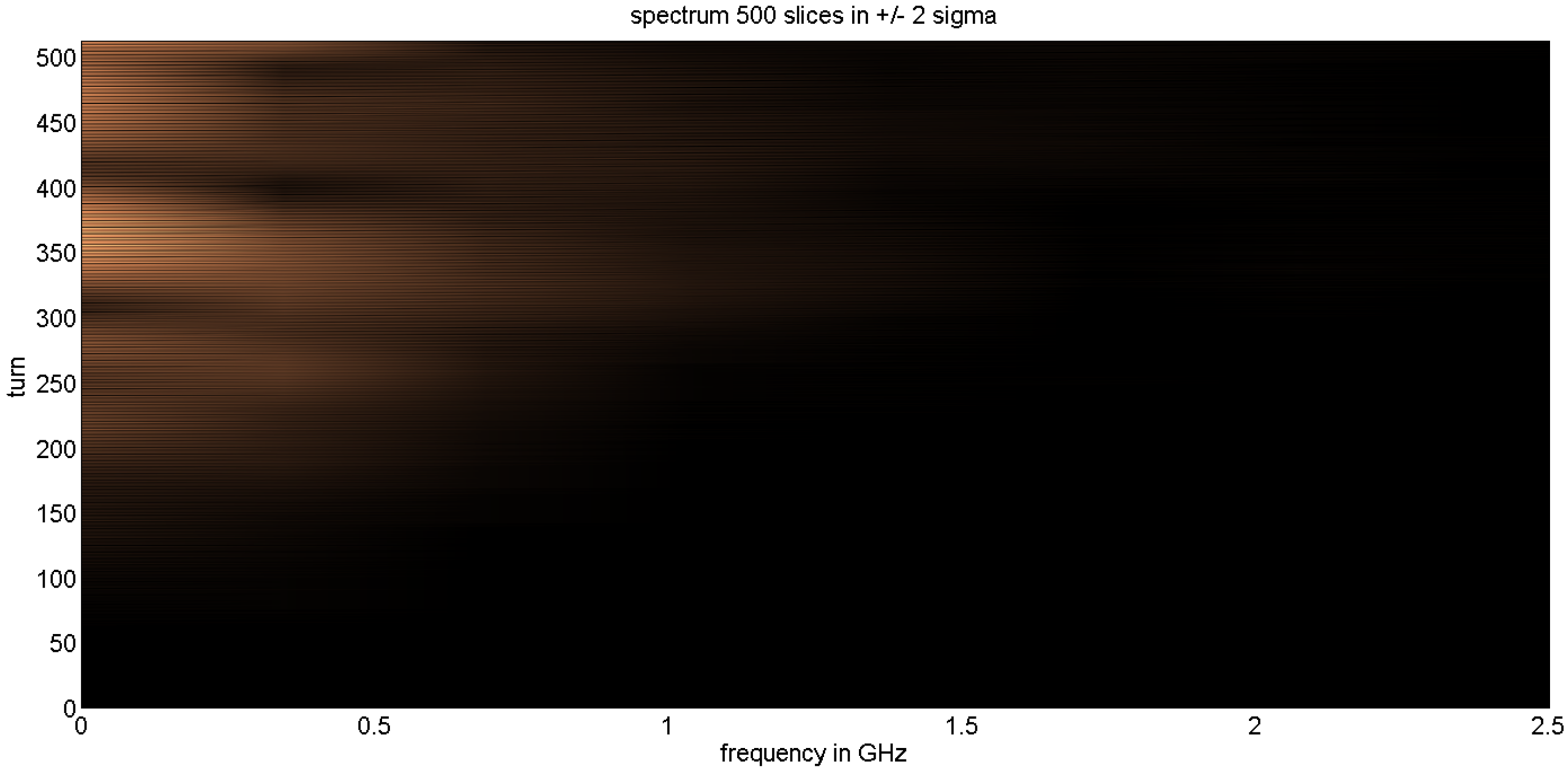


Single bunch signals after modification of pick-up connection
(stable bunch with ~5 x10^9 protons per bunch)



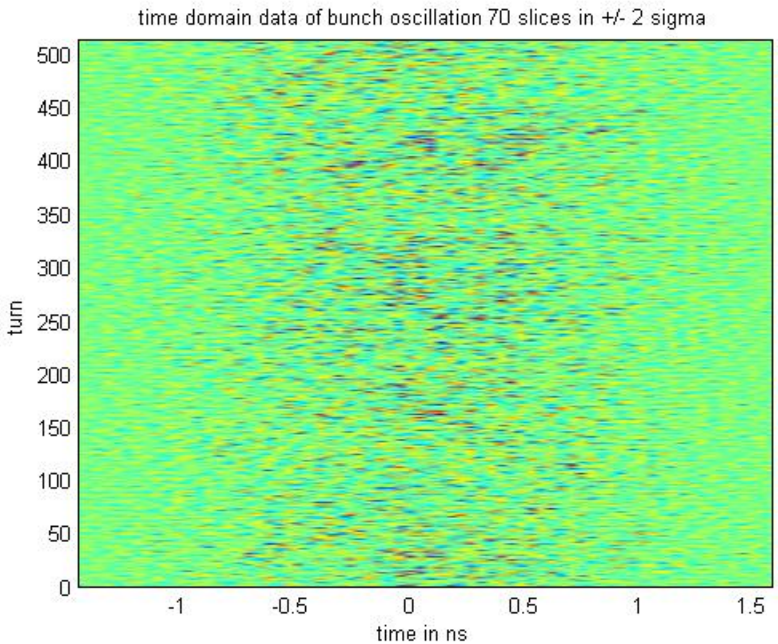
Single bunch signals after modification of pick-up connection
(stable bunch with ~5 x10^9 protons per bunch)

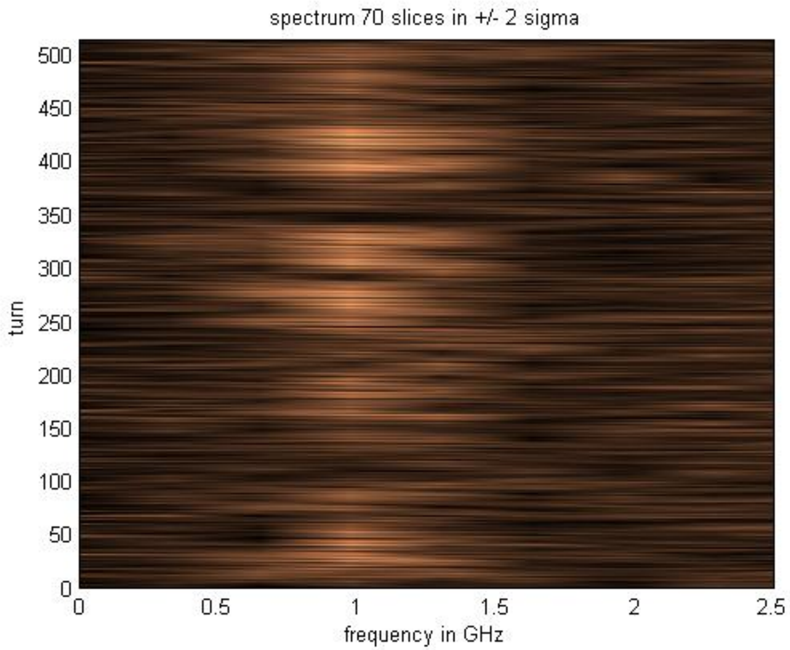
First Results (simulations)



no feedback, spectrum extends to ~ 1GHz (Headtail, G. Rumolo, J. R. Thompson et al.)

First Results (simulations headtail)





Time domain data and spectral plot for a feedback with moving average as band limiting filter (31 samples, 1.3 ns), time domain: only "noise" visible, spectral domain: noise below 1GHz visibly suppressed as expected - amplitudes are very low, is it sufficient to prevent blow-up ?

(J. R. Thompson et al.)

Preliminary conclusions from head tail simulations

dipole feedback alone insufficient

spectrum covers several 100 MHz

feedback with a bandwidth of up to ~500-800 MHz keeps the bunch stable

probing the frequency limit with higher precision requires to take tails
of bunch into account, possibly by smoothing these for the analysis (initially truncated at +/- 2 σ)

in any case bunch is relatively short, so we do not understand the origin
of the narrow spectrum at 700 MHz measured earlier with the head tail monitor,
this may have come from the characteristics of the head tail monitor
or it may be due to the oscillations being coherent bunch-to-bunch –
note that head tail only simulates a single bunch here, not a train, to be followed-up

interesting question to check: can a high frequency feedback alone control the instability
(for example lower cut-off at 200 MHz) ? If not, how much gain for the dipole is required ?

Plans for simulations and experiments

Increase treated bunch frame from +/- 2 σ to +/- 3 σ to increase frequency resolution

Include y' in the output data for analysis

avoid quadrupolar longitudinal oscillations by better matching (constant slice spacing wanted !)

possibly extend bunches by interpolation in the tail, since the tail cannot be modeled well by headtail (too few, or chance of zero, macro particles in a slice)

probe required bandwidth limits for the feedback (upper and lower bandwidth) by introducing FIR filters in the feedback path

probe required gain for the feedback

compare data without FB with measurements, continue analysis of MD data
Next years MD should be planned for June 15-17, 2009 when SPS is not well scrubbed
During August 2008 MD we were below onset of instability at injection,
not easy to capture instability during the ramp, focus on 1st MD with LHC beam in SPS 2009 !

Preparations for Beam Transfer Function measurements

Connection changed on 2nd pick-up from horizontal to vertical (pick-up 321.01)

Now two pick-ups are available in the Faraday cage for beam transfer function measurement

Requires amplifier in the 100-1000 MHz

Pick-up 319.01 backwards installed (relict of ppbar era)

Pick-up 321.01 forward installed

Pick-up response will be compared, backward / forward, note that signal is always extracted at the up-stream port, backward and forward refer to the orientation of the strip, forward = wide end is up-stream

Note: pick-ups good up to cut-off frequency of TE11 mode (~1.64 GHz) of beam pipe; we see ringing above this frequency

Conclusions and outlook

Instrumentation in the SPS is available to investigate frequency spectrum and growth rates, exponential coupler favored

Further MDs planned for 2009, including beam transfer function
Measurements -> need amplifiers for this !
analysis of data in partnership with US labs

Need the experimental data to establish feasibility of feedback system and to specify key components, such as pick-ups, kickers, power sources and the signal processing

Promising first results, experimentally and in simulations

Continue with experiments, analyze data taking into account transfer function of cables and pick-up

Continue simulations

The aim is to propose a solid system design in 2009