LHC Injectors Upgrade

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LHC Injectors Upgrade

Performance of upgraded SPS damper in view of crab cavity tests Complementarity to High Bandwidth Transverse Feedback

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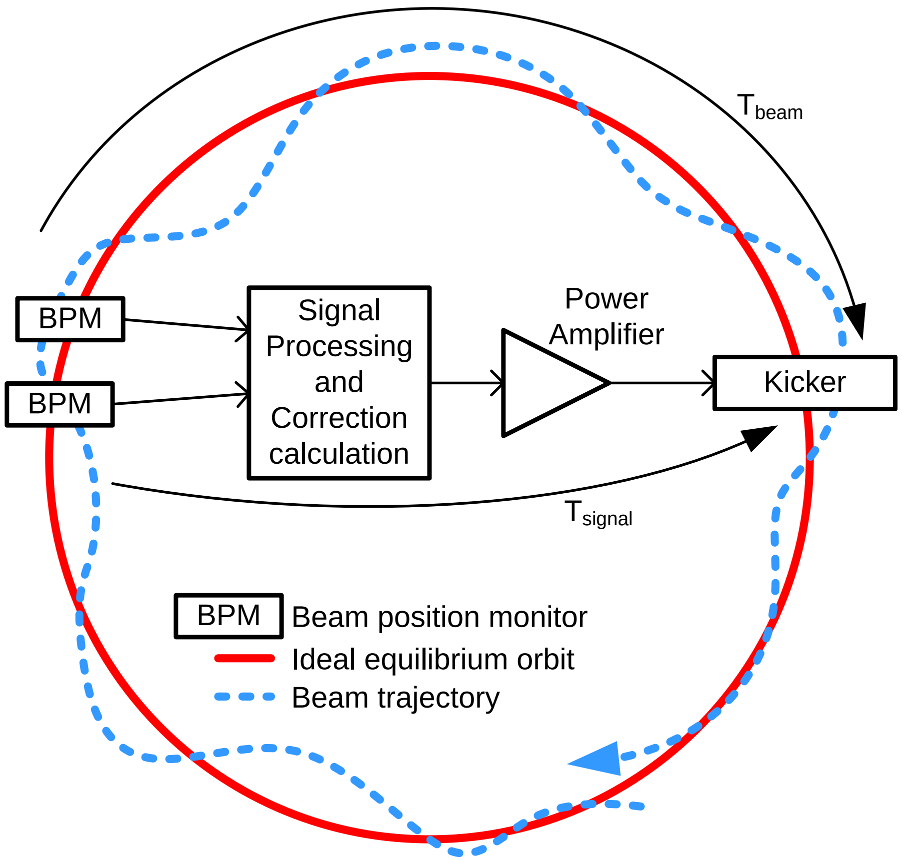
CERN BE-RF-FB

Acknowledgement: A. Butterworth, F. Killing, G. Kotzian, T. Levens,
E. Montesinos, A. Rey, D. Valuch
G. Ledey, S. Mutuel (FSU-BE03)

Reminder: Principle of Transverse Feedback

- One or multiple pick-ups
- Signal detection, signal processing, amplifiers, kickers
- All LHC injector synchrotrons use transverse feedback systems, PSB, PS, LEIR (ions), SPS, in case of SPS since 1970’s
- Challenging in Hadron Colliders due to need for low noise systems
- LHC: transverse feedback system since 2010 at all times with high intensity bunches, during injection, acceleration and in collision
- Feedback correction applied as correction in quadrature with position signal of oscillation
- Matching of time of flight for wideband system



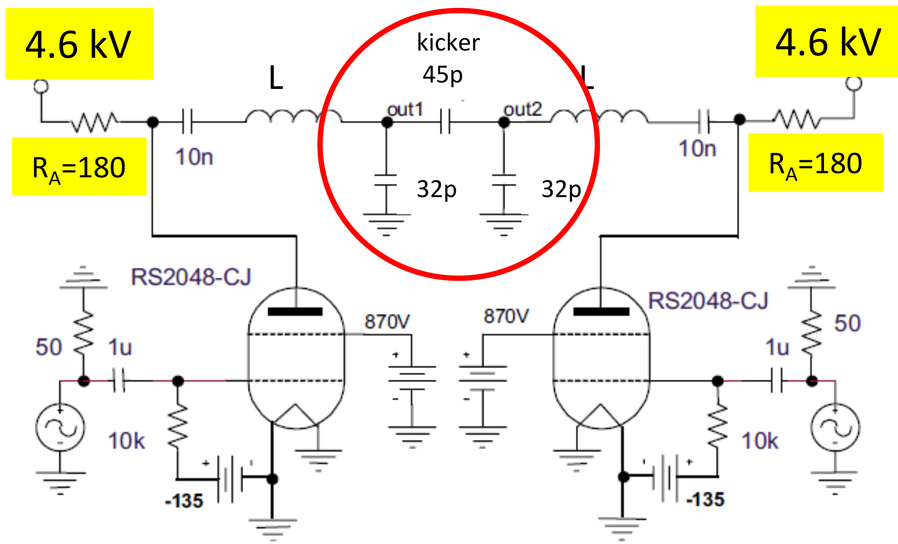
$$T_{signal} = T_{beam} + n\,T_{rev}$$

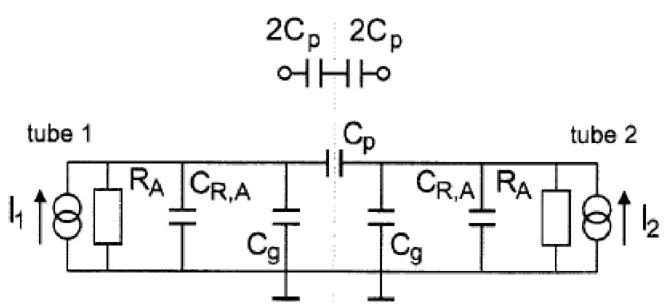
Existing SPS Transverse Feedback System

- Last upgrade 1997-2000 in preparation of the SPS as LHC injector
- damping of injection errors and cure of resistive wall impedance driven coupled bunch instability (threshold ~5×10^{12} protons total intensity)
- operates since 2001 between lowest betatron frequency and 20 MHz (V & H plane) to damp all possible coupled bunch modes at 25 ns bunch spacing
- handles large injection errors of the order of several mm
- Tetrode amplifiers with two tubes driving kicker plates in push-pull configuration installed in tunnel under kicker tanks
- 200 W drive power per tetrode 3 kHz to 20 MHz
- Served as starting point for the design of the LHC damper (ADT) kickers and power system
- Technology of electronics of system used in SPS until 2012 dates from late 1990’s

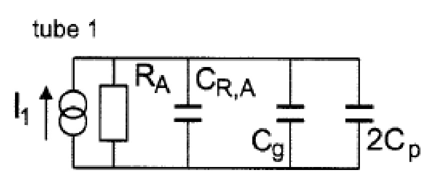
Tunnel with kicker tank and tetrode amplifier in SPS LSS2

Existing Transverse Feedback System





f < 25 MHz
series resonance
with L at 37 MHz



kicker effective capacitance:
C_g+2C_p = 122 pF

not all circuit elements shown,
e.g. matching at input

200 W drive power in 50 Ω

3 dB @ 4.5 MHz
R_A = 180 Ω, C_{eff} = 200 pF

Tube: RS 2048-CJC (V-plane) or
TH561 (H-plane),
max current 15A to 16A
class AB

operational RF voltage 2.6-2.9 kV
phase corrected → 20 MHz

Existing Feedback: Kick Strength

Accurate kick strength evaluation with HFFS: example V-plane

- +/- 2.6 kV @ 100 kHz, L=1536 mm, gap d=38 mm

$$V_{\perp} \approx 2 \times V \frac{L}{d} \rightarrow 215\,\text{kV (exact from HFSS-15)}$$

$$\Delta p_{\perp} = V_{\perp} \cdot e / c = 7.2 \times 10^{-4}\ e\text{Vs/m}$$

integrated kick strength over the entire structure
→ 41.375 V (transverse) for +/-1 V on kicker plates

- +/- 1.83 kV @ 4.5 MHz

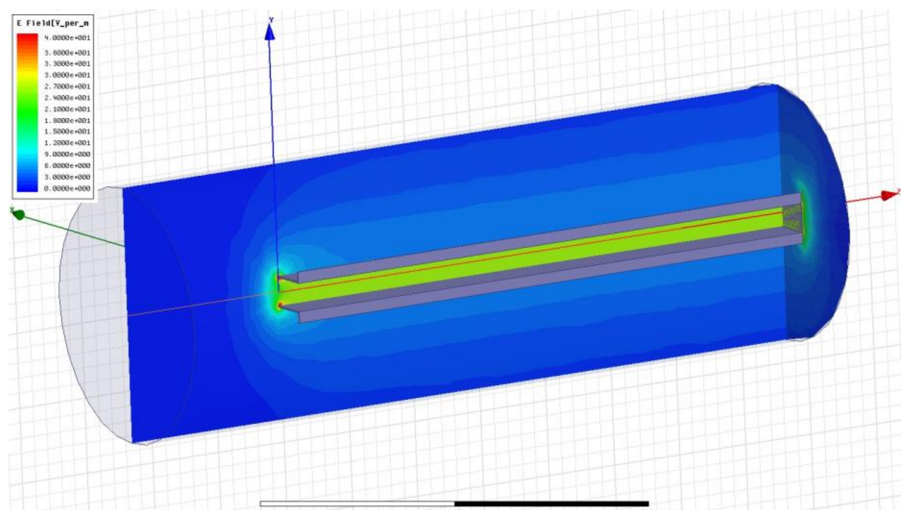
$$V_{\perp} \approx 152\,\text{kV}$$

$$\Delta p_{\perp} = 5.0 \times 10^{-4}\ e\text{Vs/m}$$

- +/- 0.572 kV @ 20 MHz

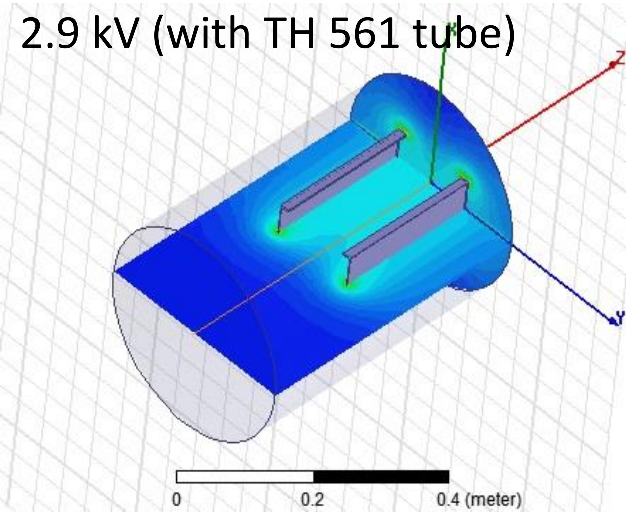
$$V_{\perp} \approx 46\,\text{kV}$$

$$\Delta p_{\perp} = 1.58 \times 10^{-4}\ e\text{Vs/m}$$



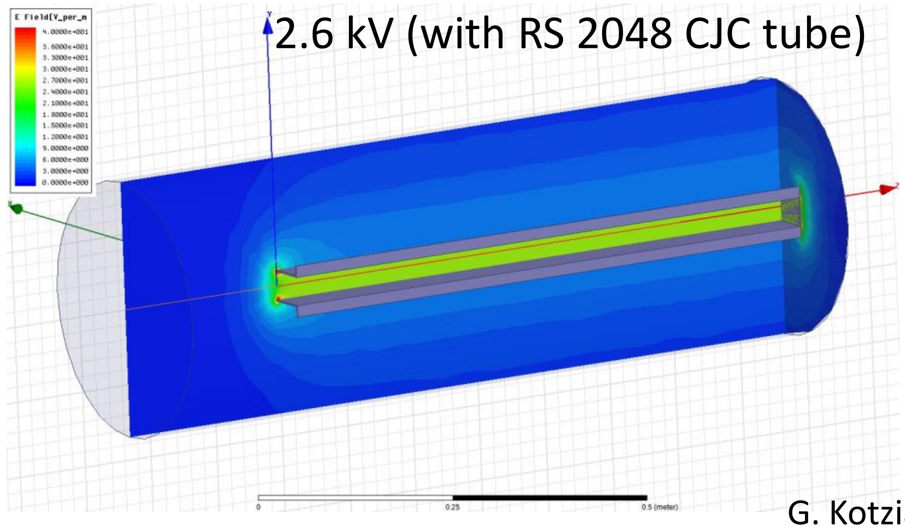
Feedback kickers: Kick Strength

2.9 kV (with TH 561 tube)



Horizontal kicker (BDH)

2.6 kV (with RS 2048 CJC tube)



G. Kotzian

Vertical kicker (BDV)

plane	Length/gap mm/mm	Δp eVs/m	kV transverse	µrad at 26 GeV/c
H	2x 2396/142	$3.3x10^{-4}$	98	3.8
V	2x 1536/38	$7.2x10^{-4}$	215	8.3

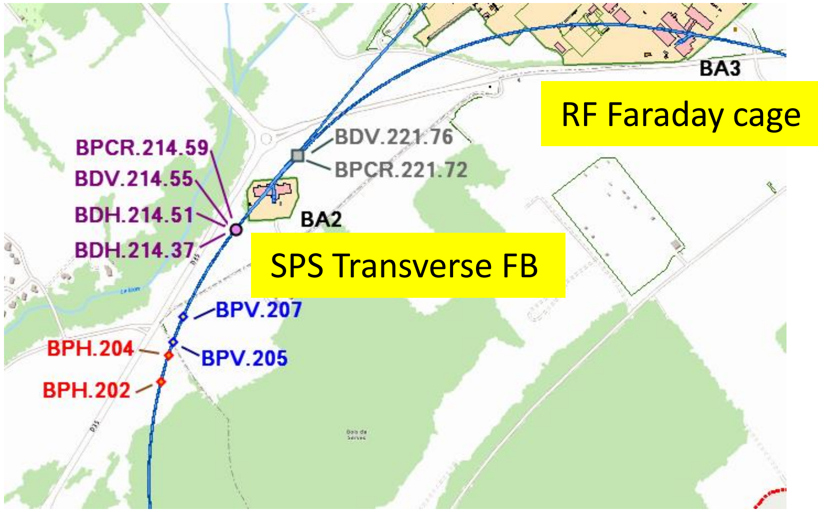
- damps ~5 mm injection error (β=100 m) at 26 GeV/c in 20 turns (gain=0.1) in V-plane
  - 26 GeV/c: kick per turn 8.3 µrad (→ 0.54 mm at β=100 m) in V-plane
  - regularly running at 0.5 ms damping time (20 turns)
  - resistive wall growth rate for lowest mode: 0.5 ms to 1 ms

Scope and Motivation for SPS damper upgrade under LIU *Why in LS1 ?*

- sharing pick-ups with Orbit System (MOPOS) from Beam Instrumentation Group incompatible with MOPOS upgrade foreseen
- requirements for single bunch damping for protons used for LHC p-ion Physics (closer spaced proton bunches, 100 ns)
- ions injection damping with fixed frequency scheme, closer spaced batches
- individual bunch damping for crab cavity studies not possible with previous system (sampling was not synchronous with bunch in previous system)
- LHC doublet scrubbing beam incompatible with previous system
- controls with G64 chassis and MIL-1553 are obsolete (MMI) → new controls for power system and LLRF, new RF function generators

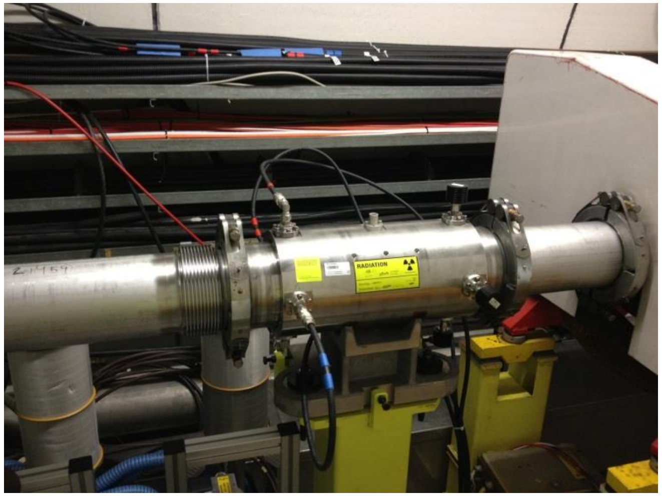
→ implement this LIU upgrade already in LS1

Pick-ups dedicated for transverse FB

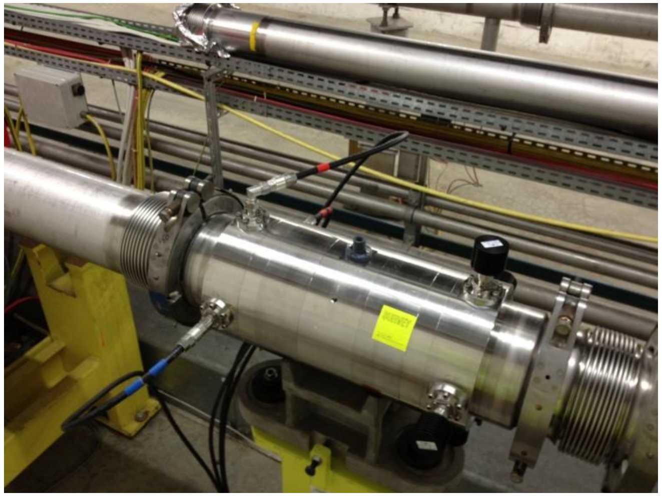


- 2 BPCR (H/V) for LHC type beams (couplers maximum Z_T @ 200 MHz)
- 2 BPH electrostatic PU (pFixedTarget)
- 2 BPV electrostatic PU (pFixedTarget)

BDH / BDV kickers unchanged

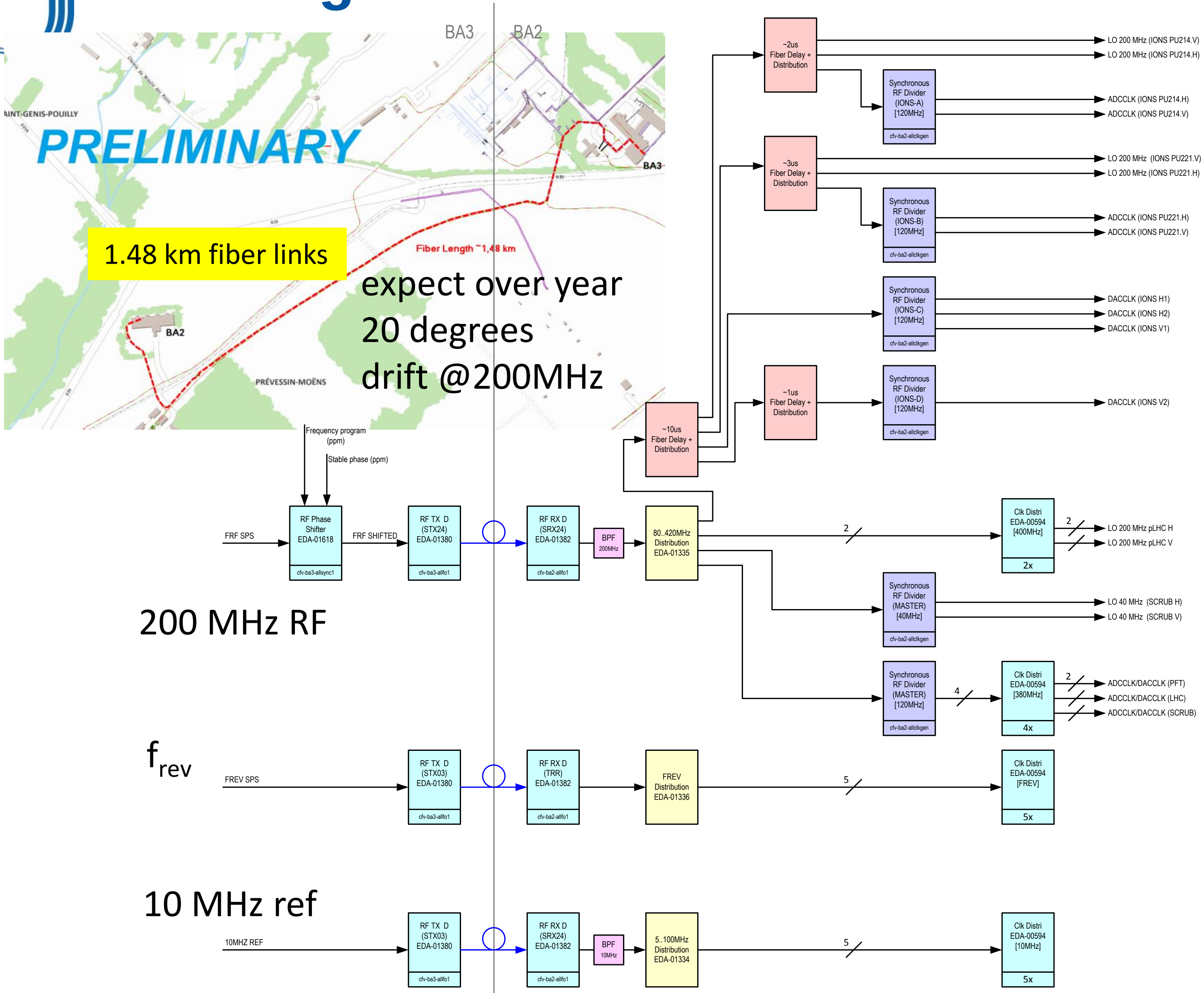


BPCR.214



BPCR.221

New Signal Transmission BA3 → BA2



Ions (for implementation in 2015): 4 different delays for pick-up and kicker (ADC/DAC) clocks

200 MHz LO

40 LO

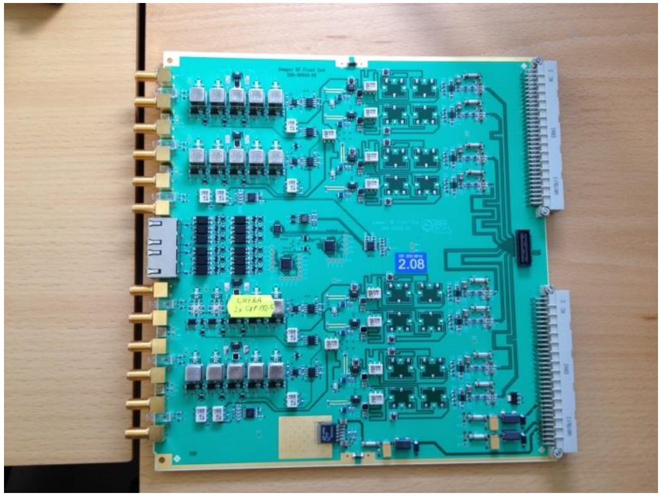
120 MHz ADC/DAC

+ inj. Pulse (copy of SPS→CPS)

Analogue Hardware developed in LS1 (1)

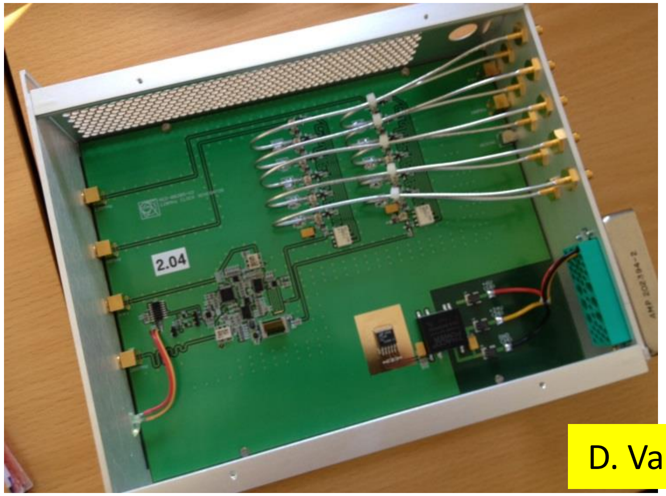
LHC beam: 25 ns bunch spacing:

- 200 MHz bandpass filters (Σ and Δ)
- programmable gain/attenuation
- down mixing (I,Q) to base-band
- ADC protection
- sampling @120 MS/s (on digital board)



Mixers for down conversion

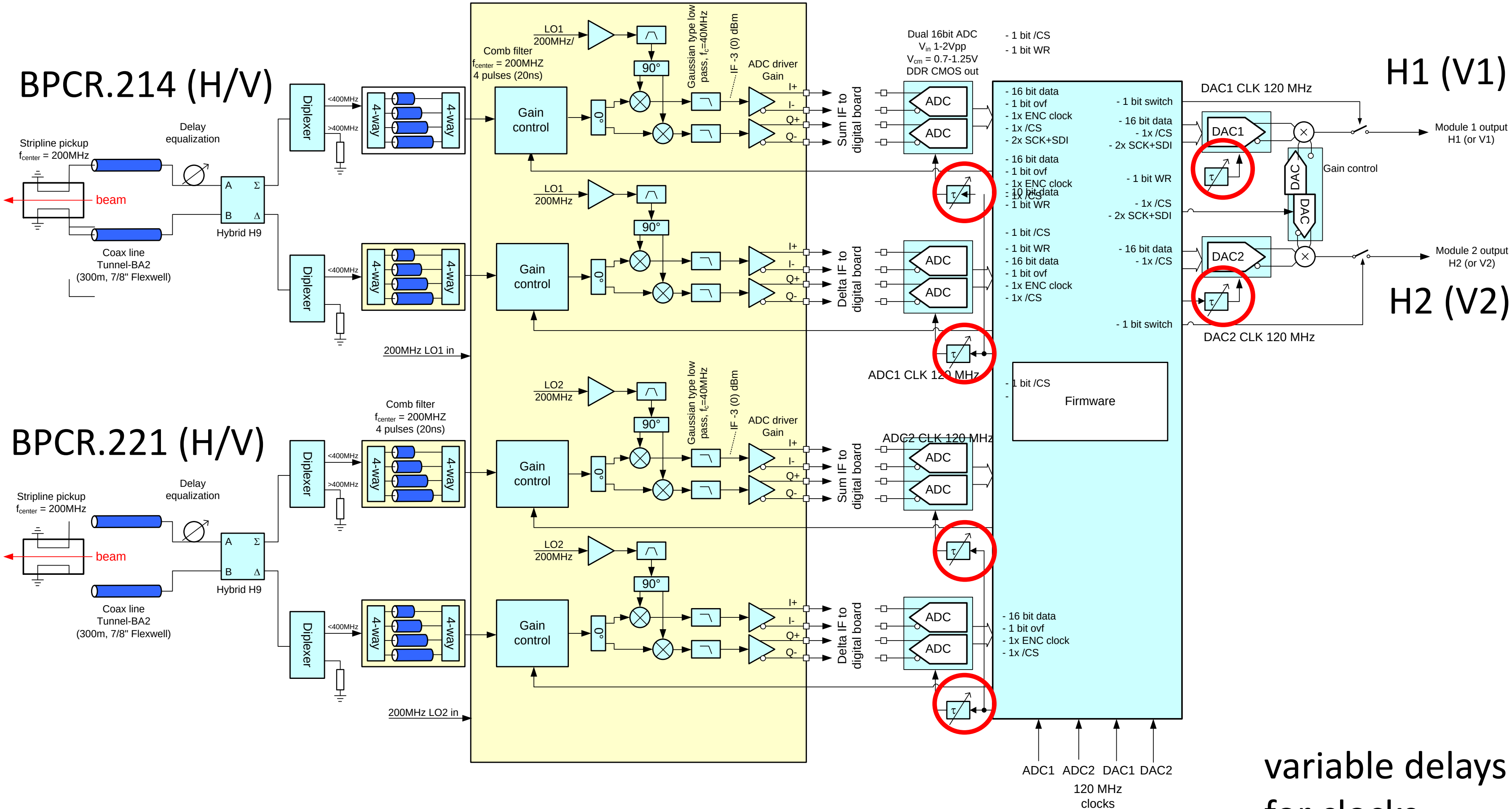
200 MHz filters during production in CZ



D. Valuch

Clock generation board (all beams)

Signal processing LHC 25 ns beam

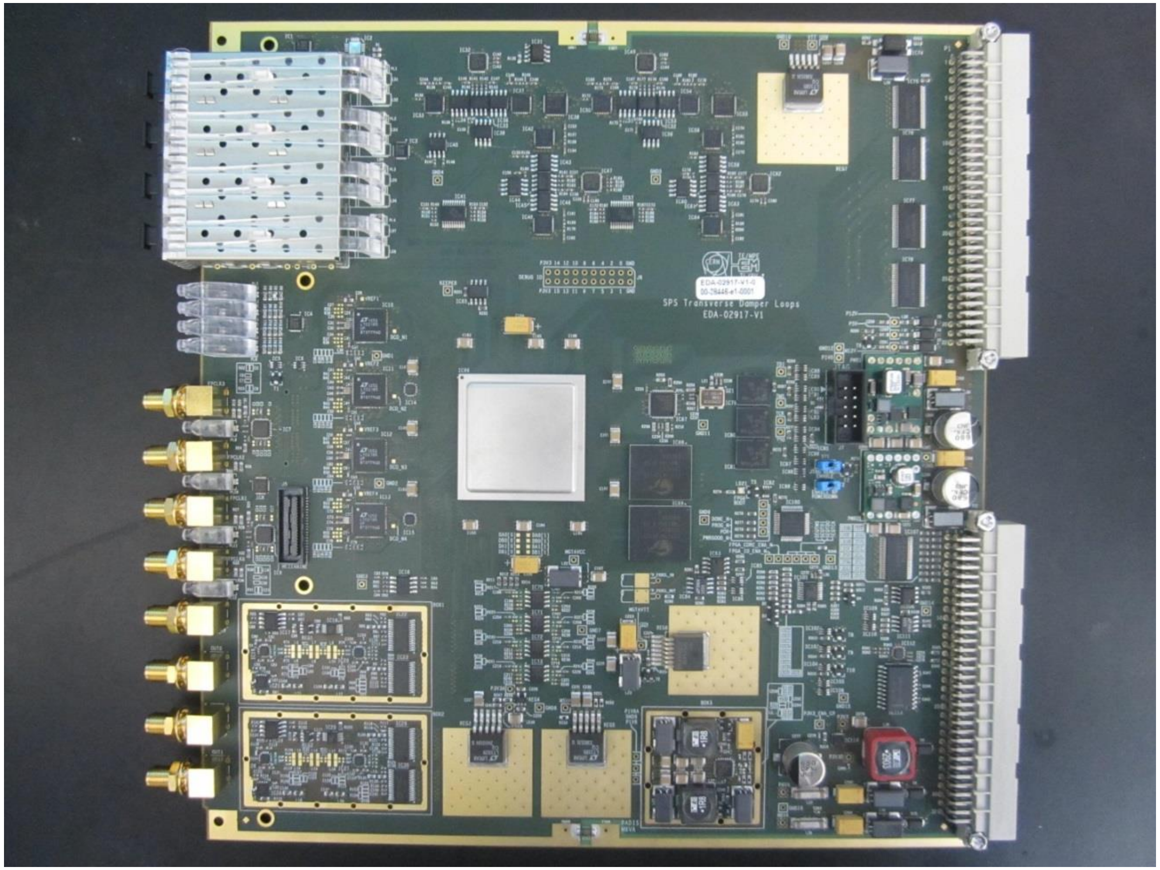


analogue front-end
(here for LHC beam)

Digital Board

variable delays
for clocks
ADC/DAC
(120 MHz)

Digital Hardware developed in LS1



8 ADCs
4 DACs

output
gain control
via DAC a la
LHCADT

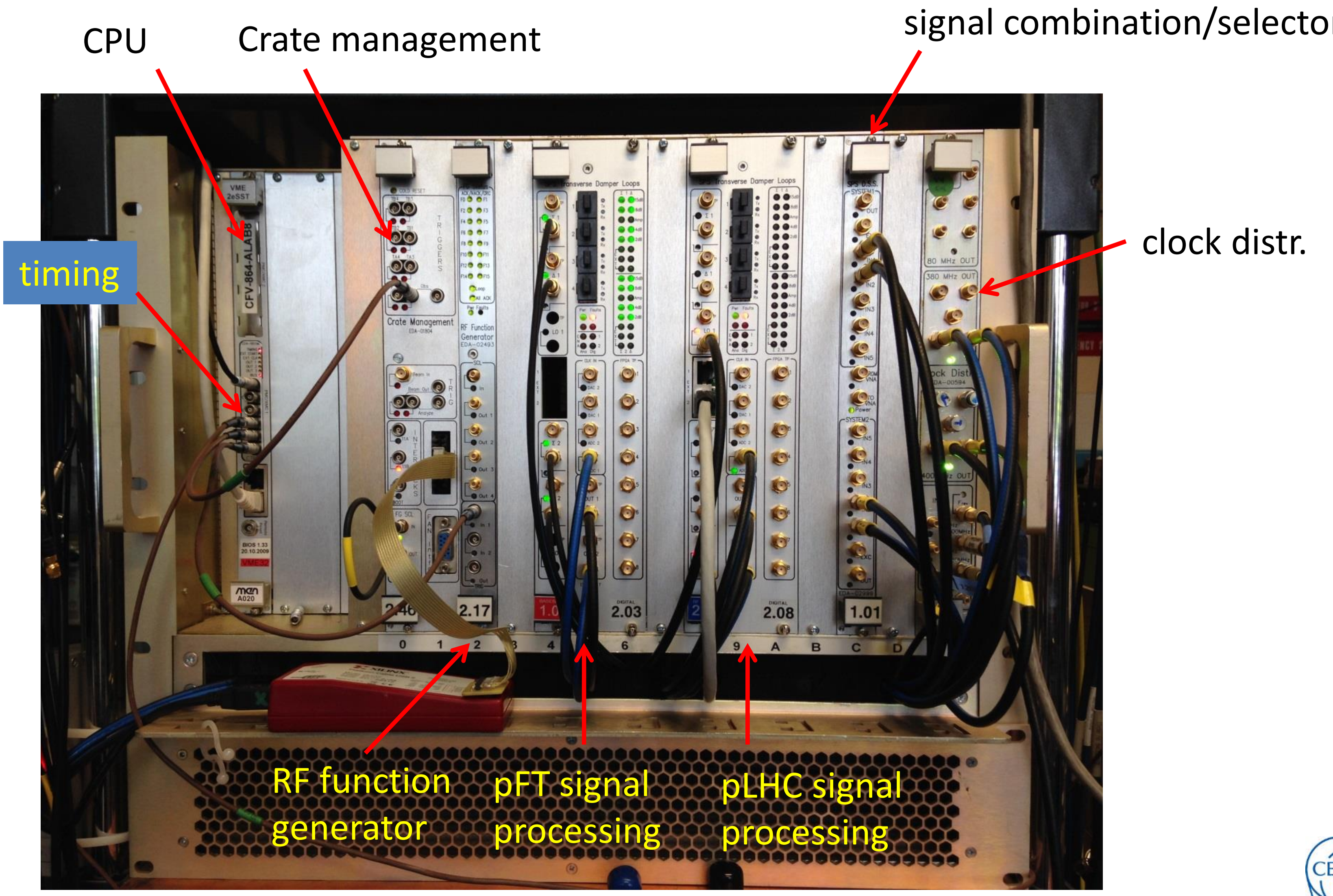
Board will be used
for ADT (independent
gain control on DACs)

T. Levens, D. Valuch
G. Kotzian (firmware)

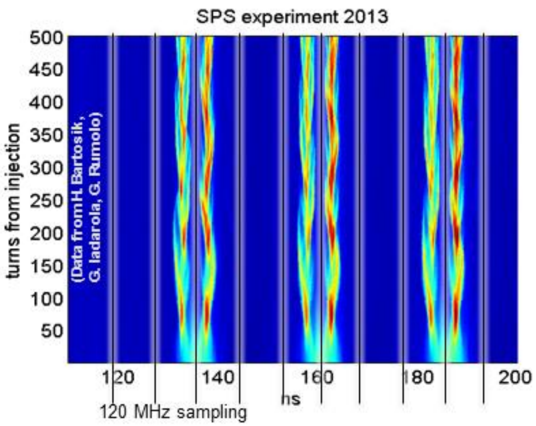
New development !

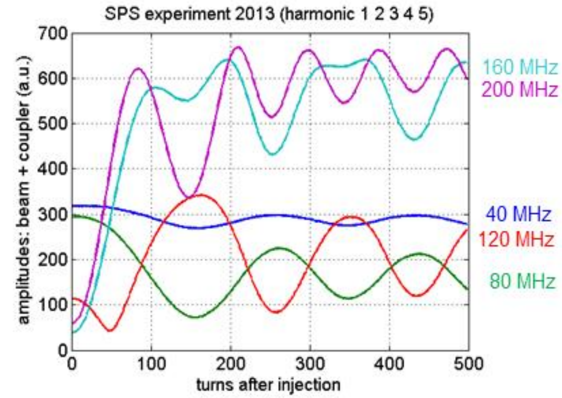
- eight installed for SPS start-up
- separate boards for H- and V-plane and beam type (pFT, pLHC, pSCRUB, Ions)
- tested up to beyond 120 MHz clock frequency, Xilinix ARTIX 7 FPGA
- features ADCs and DACs with four different clock domains for delay adjustment

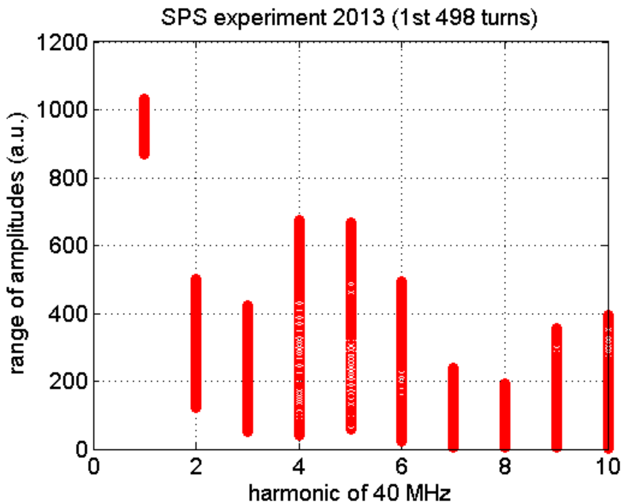
Feedback electronics uses LHC RF VME standard

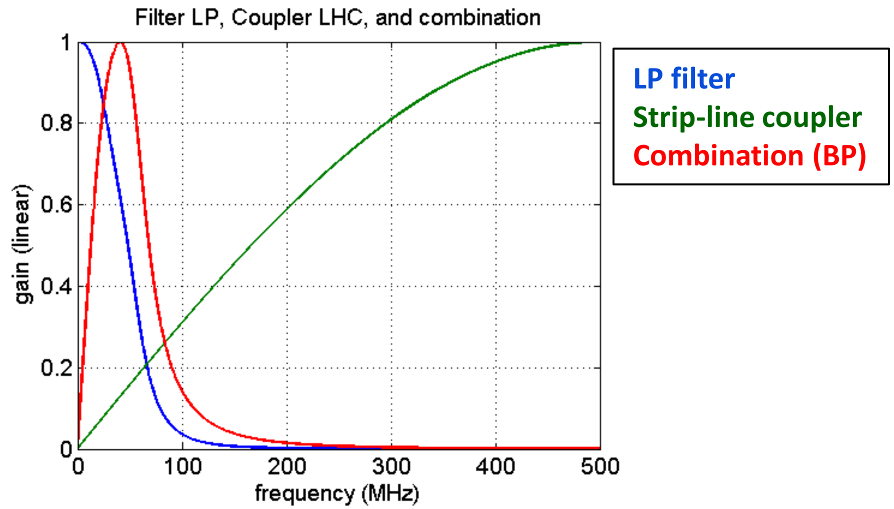


Scrubbing Doublet Beam









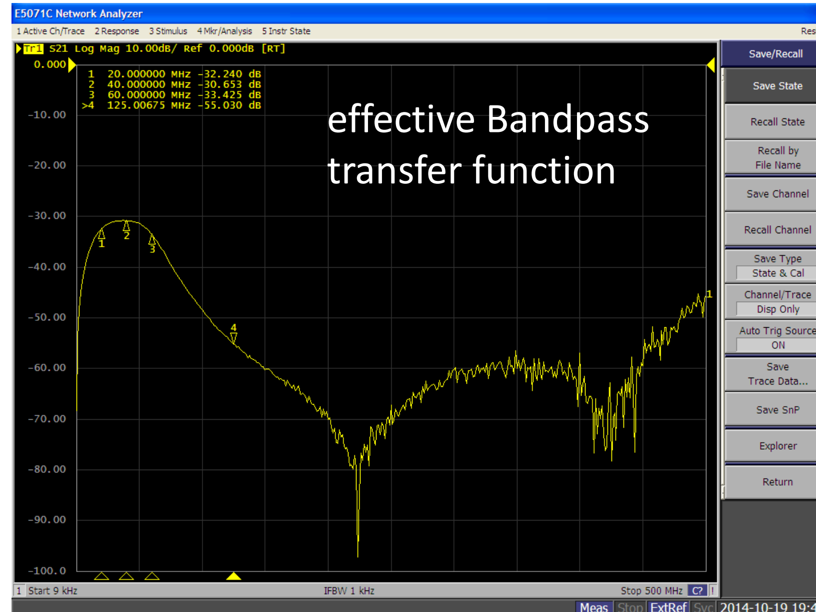
Scrubbing beam position detection:

- Bandpass formed by LP and strip-line coupler response
- Synchronous sampling at 120 MHz
- Compute position from 3 samples → digital down conversion

Position detection: doublet beam

Scrubbing beam position detection:

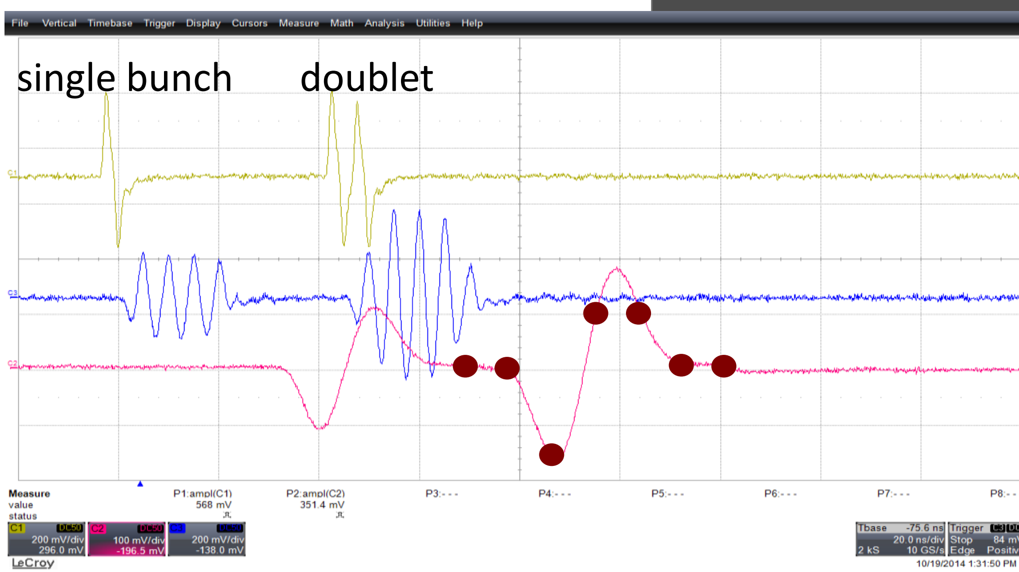
- Long bunches injected on unstable phase
- Bunch splits into doublet
- 200 MHz component low at injection and phase changing → cannot use pLHC 200 MHz demodulation, damper must work from turn 0
- 40 MHz component stable during
- After splitting could switch to pLHC 200 MHz demodulation



PU signal

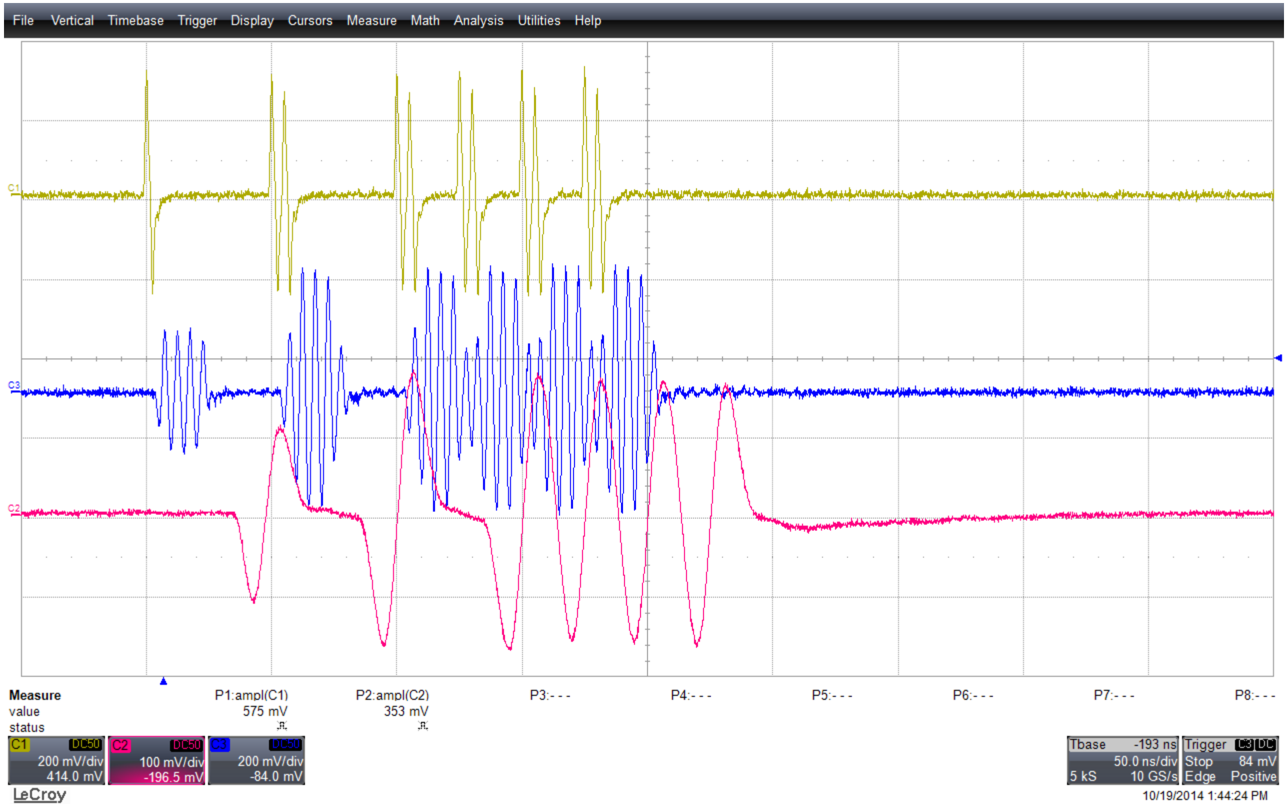
200 MHz BP filtered

40 MHz BP filtered
(120 MHz sampled)



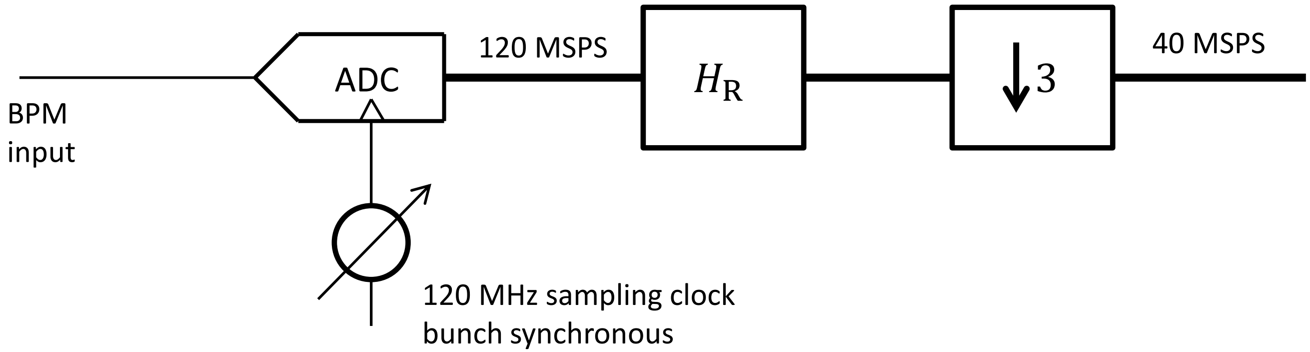
Performance Doublet beam: bunch train

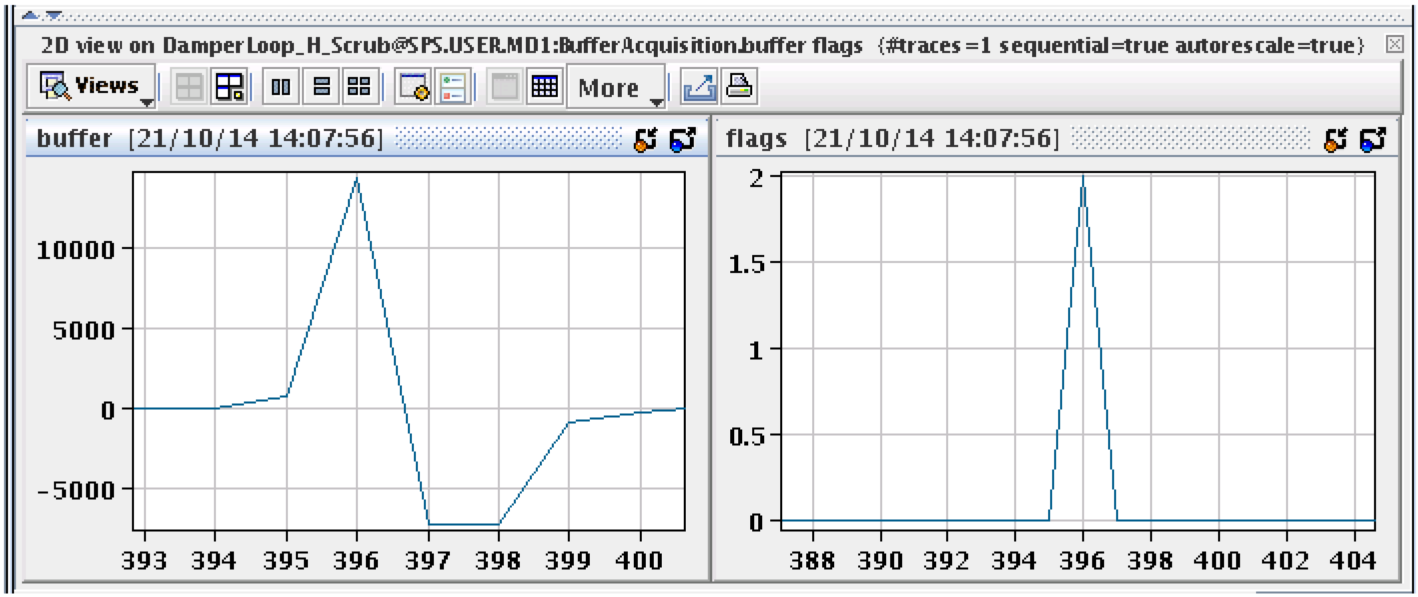
Analog signals before digitization:



25 ns spaced doublets

Doublet beam: phasing ADC clocks

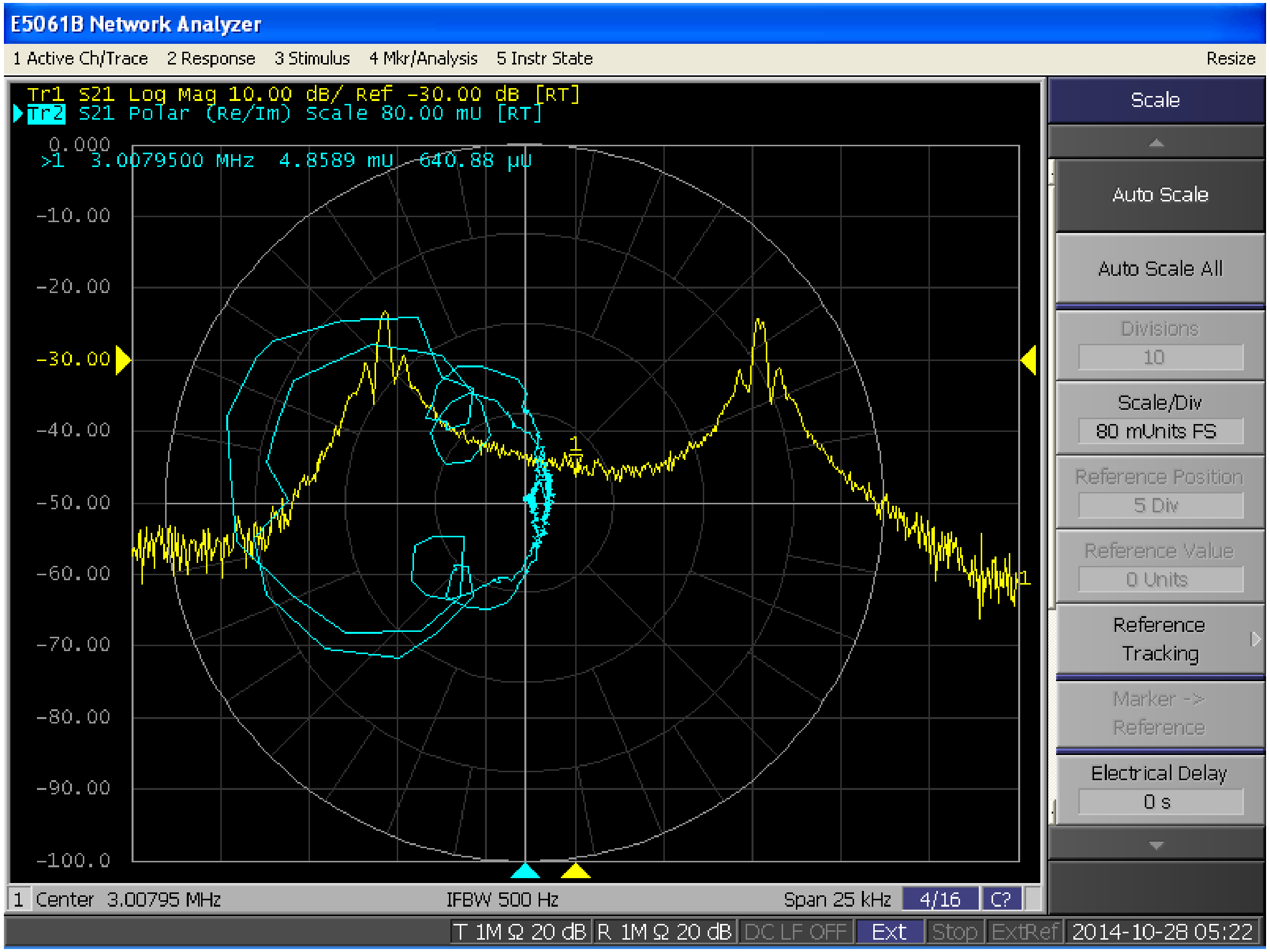




$h_R[n] = [1.0, -0.5, -0.5]$

tagging of bunch[0]

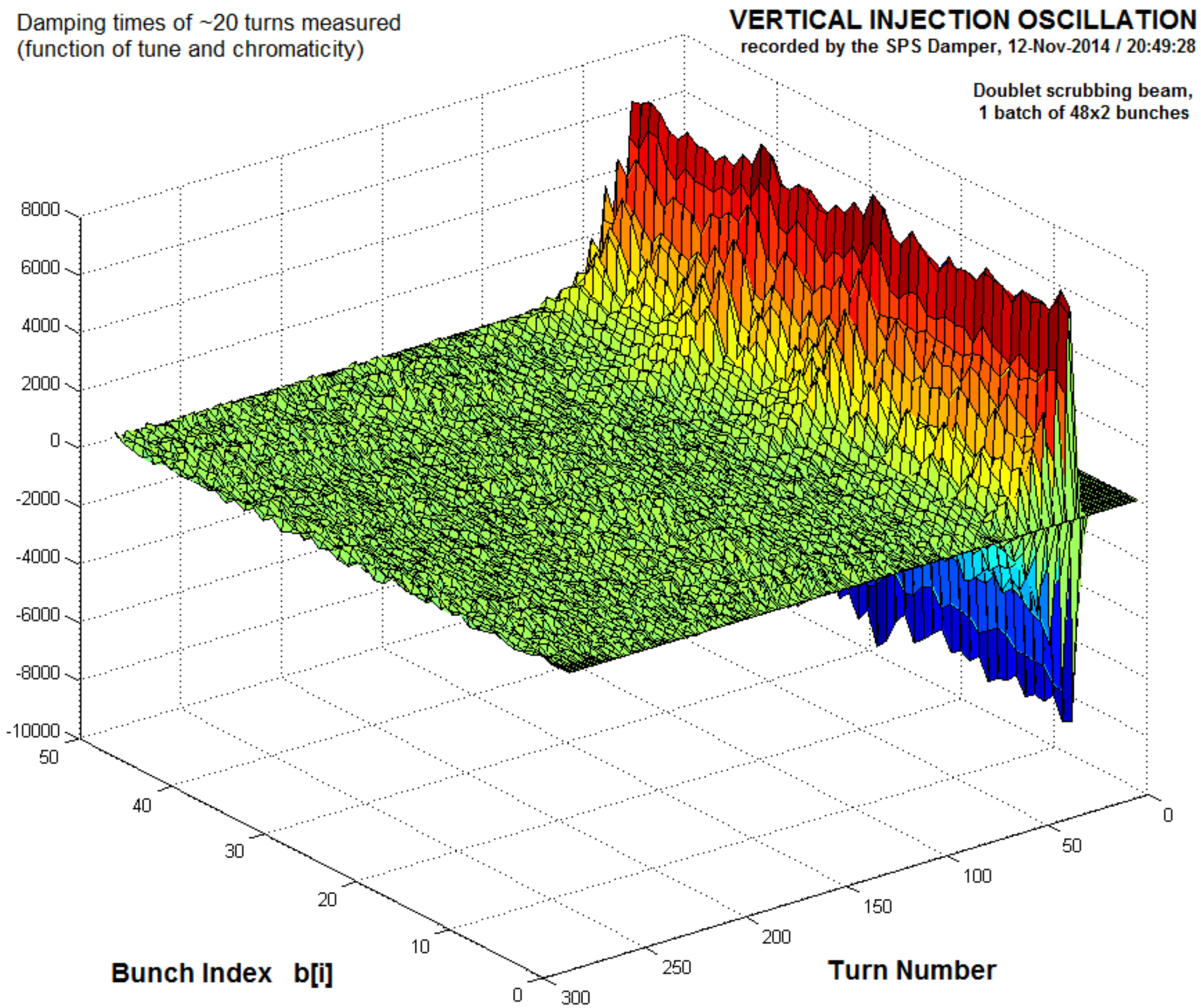
Setting-up: open loop BTF measurement



Commissioning
SPS Start-up
In 2014

- open loop BTF measurement: H damper, example fixed beam, NWA, remotely
- Sweep across two betatron lines (example ~ 3 MHz)
- adjustments using phase setting and loop delay
- synchrotron sidebands visible

Performance for Doublet beam - first results



batch of
48 doublets

- bunch-by-bunch position data available in internal memory
- damping time of 20 turns reached as in previous system
- commissioned for three types of beams, pFT, pLHC, pDoublet → optimization ongoing

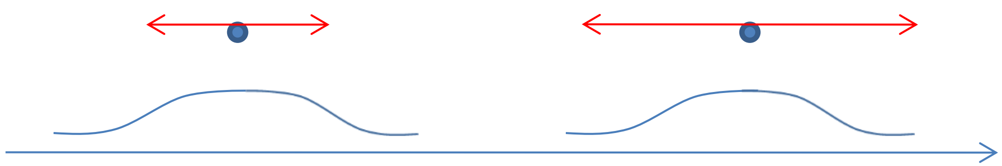
Plans for single bunch damping

Relevance for crab cavity tests with single bunches

issue: full kick strength only available for frequencies up to < 5 MHz
→ need to play some "tricks" as for LHCADT

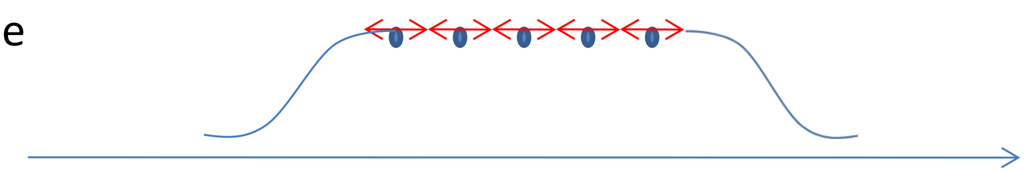
Dense spacing 100 ns | Truly isolated bunches 250 ns

scheme for large spacing



best for isolated bunches

what we propose

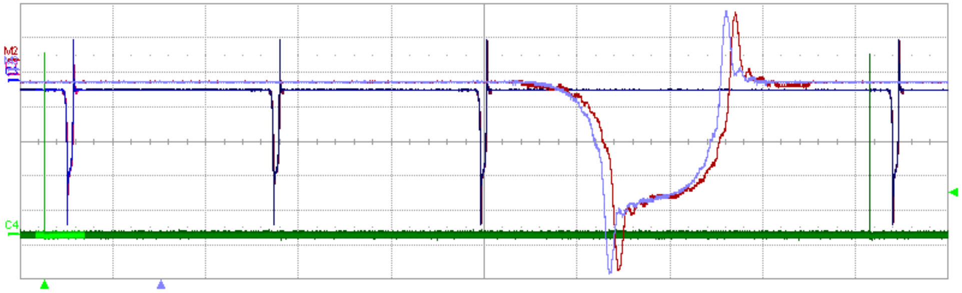


Full kick strength available with peak hold

Single bunch damping example: LHC ADT

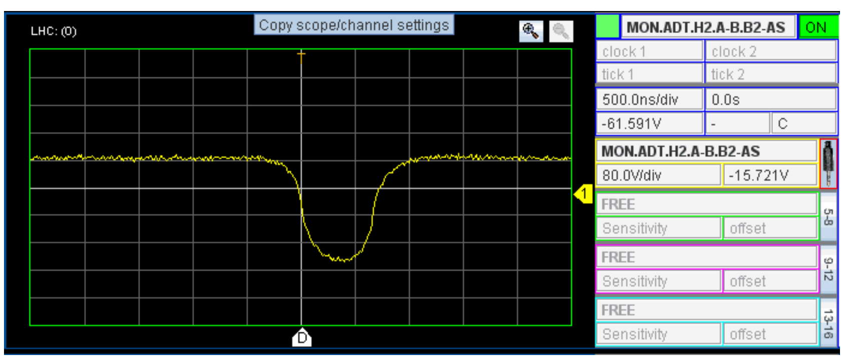
drive signal (200 W level):

zoom: 500 ns/div



10 μs/div

kick voltage (power amplifier return, kV level):



500 ns/div

large bunch spacing:
peak hold (25 x 25 ns = 625 ns)
pre-distortion of drive signal to compensate for phase response of power amplifiers

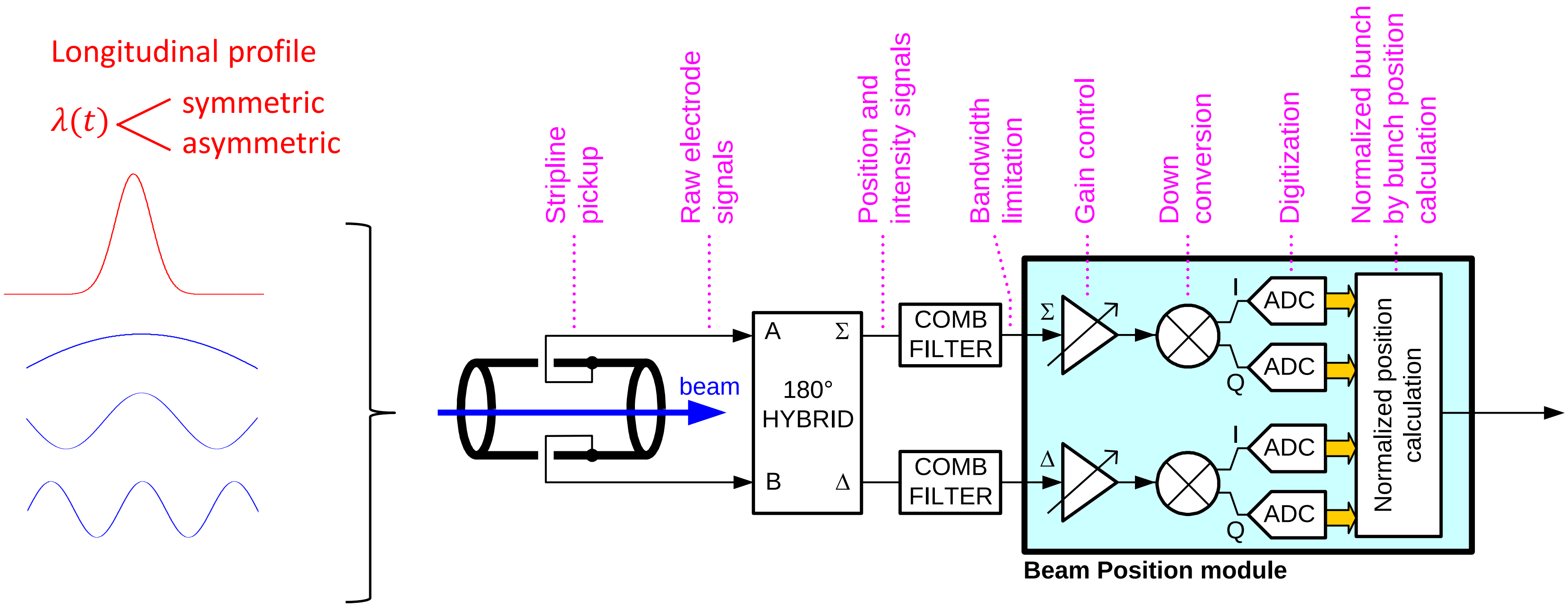
50 ns, 75 ns operation:
peak hold for 2-3 samples

25 ns operation:
without peak hold

Easier in SPS as frequency up to which full kick strength available four times larger than in LHC ADT case

Diagnostics potential for headtail motion

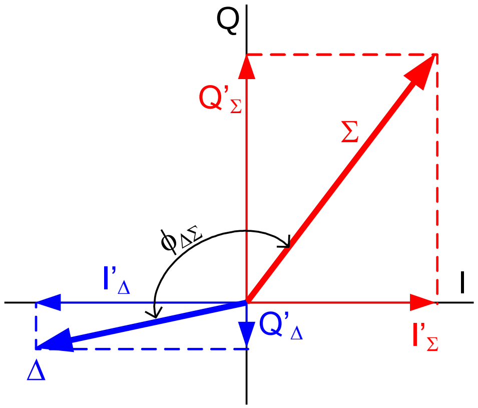
Relevance for crab cavity and instability studies !



Transverse oscillation → Movement of centre-of-charge → Normalized transverse position $x[n]$

pattern
- even symmetric
- odd symmetric

Normalized beam position



Phase rotation in digital part to alig
Sum and Delta in I, Q; required
angle measured during set-up

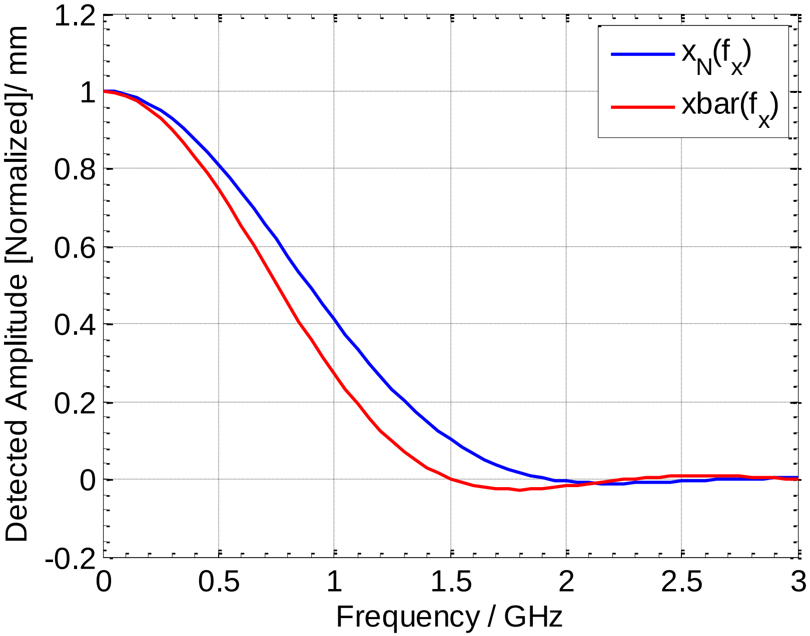
normalized
transverse position
as computed

$$x_N = \frac{I_\Delta I_\Sigma + Q_\Delta Q_\Sigma}{I_\Sigma^2 + Q_\Sigma^2}$$

center of gravity
oscillation amplitude

$$\bar{x} = \int_{-\infty}^{\infty} x(t)\lambda(t)\, dt$$

LHC ADT case (f scales 1/bunch length)



- The normalization scheme **sees the symmetric (even) oscillation** patterns (needed for the closed loop feedback)
- Damper sensitivity to symmetric intra-bunch motion is a function of the longitudinal beam spectra
- For the anti-symmetric case no oscillation amplitude is detected, **odd modes not visible to the damper, provided bunch is symmetric in shape**

LHC vs SPS feedback: 400 MHz → 200 MHz, bunchlength

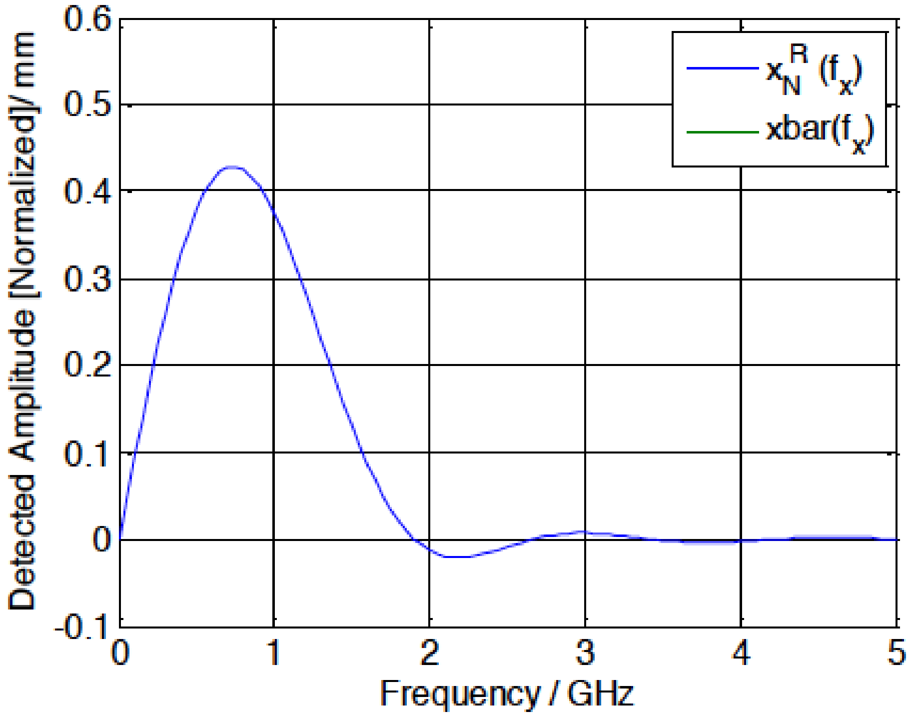
G. Kotzian, EDMS 1404633

Headtail oscillation detection

different combination
of Sum and Delta I,Q components
indicates headtail motion

$$x_N{}^R = \frac{Q_\Delta I_\Sigma - I_\Delta Q_\Sigma}{I_\Sigma^2 + Q_\Sigma^2}$$

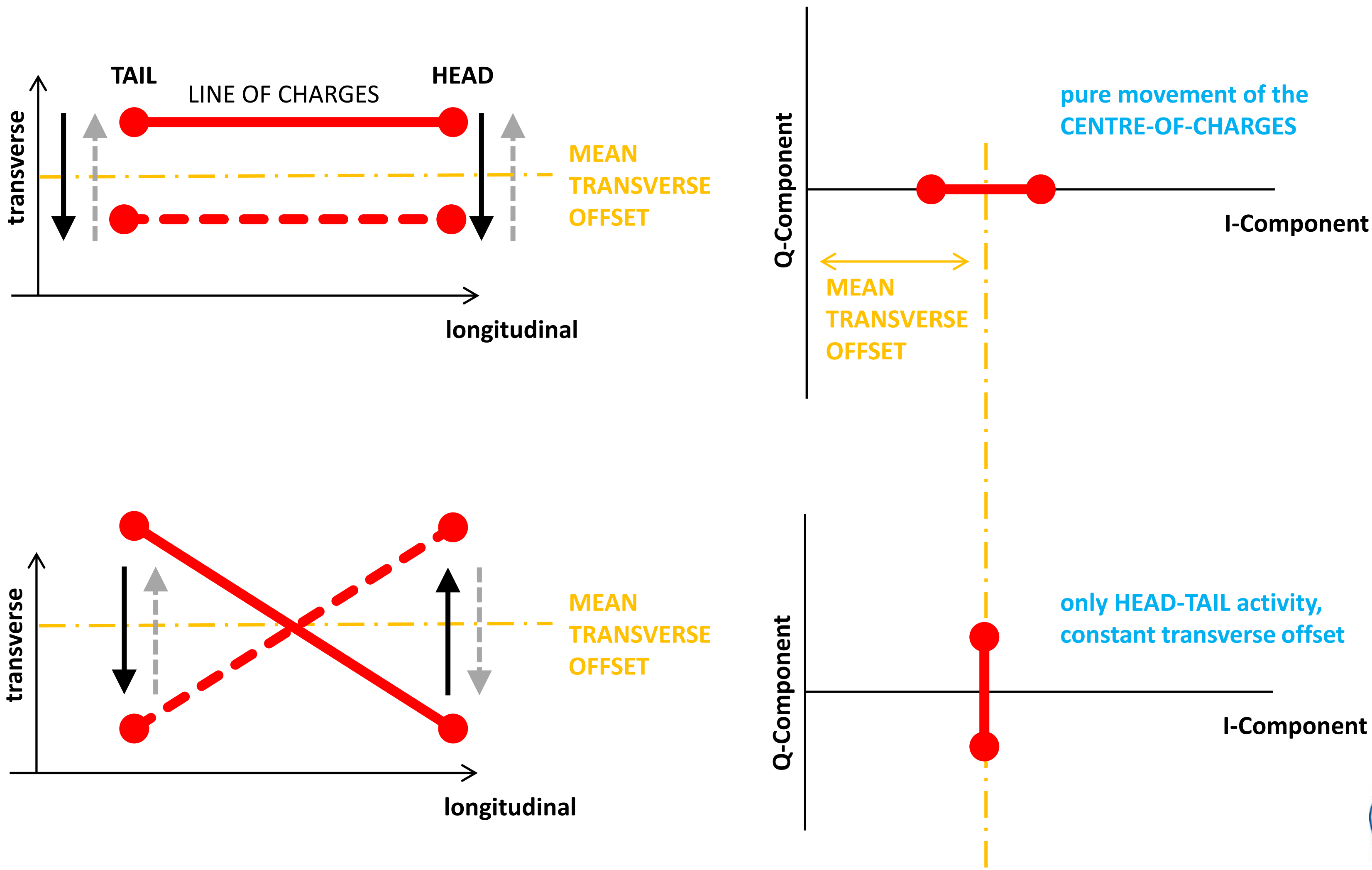
LHC ADT case (f scales 1/bunch length)



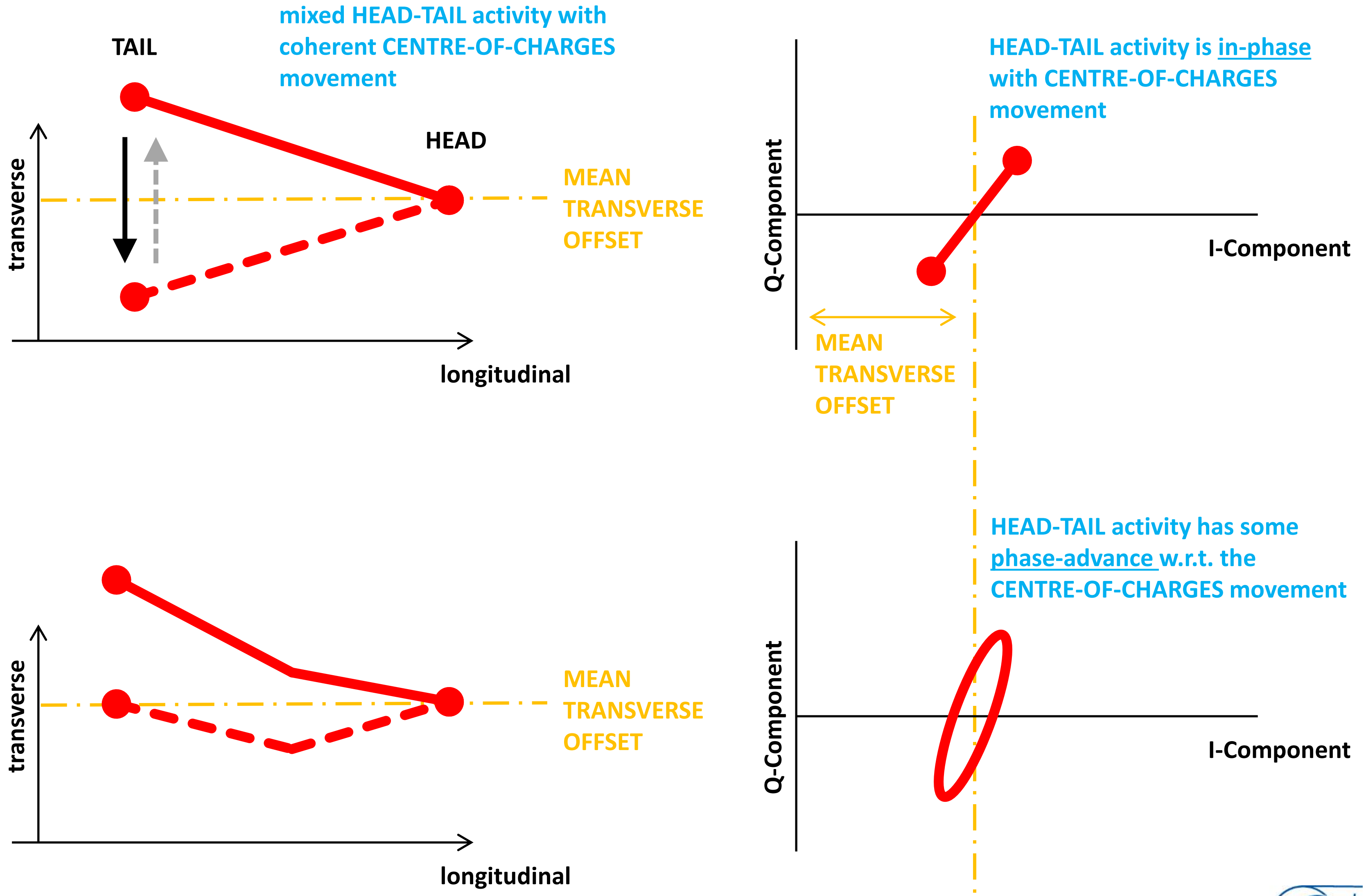
- This algorithm **can detect odd-mode** oscillations
- Algorithms cannot resolve the original oscillation frequency, and absolute oscillation amplitude accurately
- However, **can detect activity** and **distinguish between symmetric** (even) **and asymmetric** (odd) **modes of every bunch → valuable diagnostics !**

LHC vs SPS feedback: 400 MHz → 200 MHz, bunchlength

Visualization of bunch motion



Visualization of bunch motion

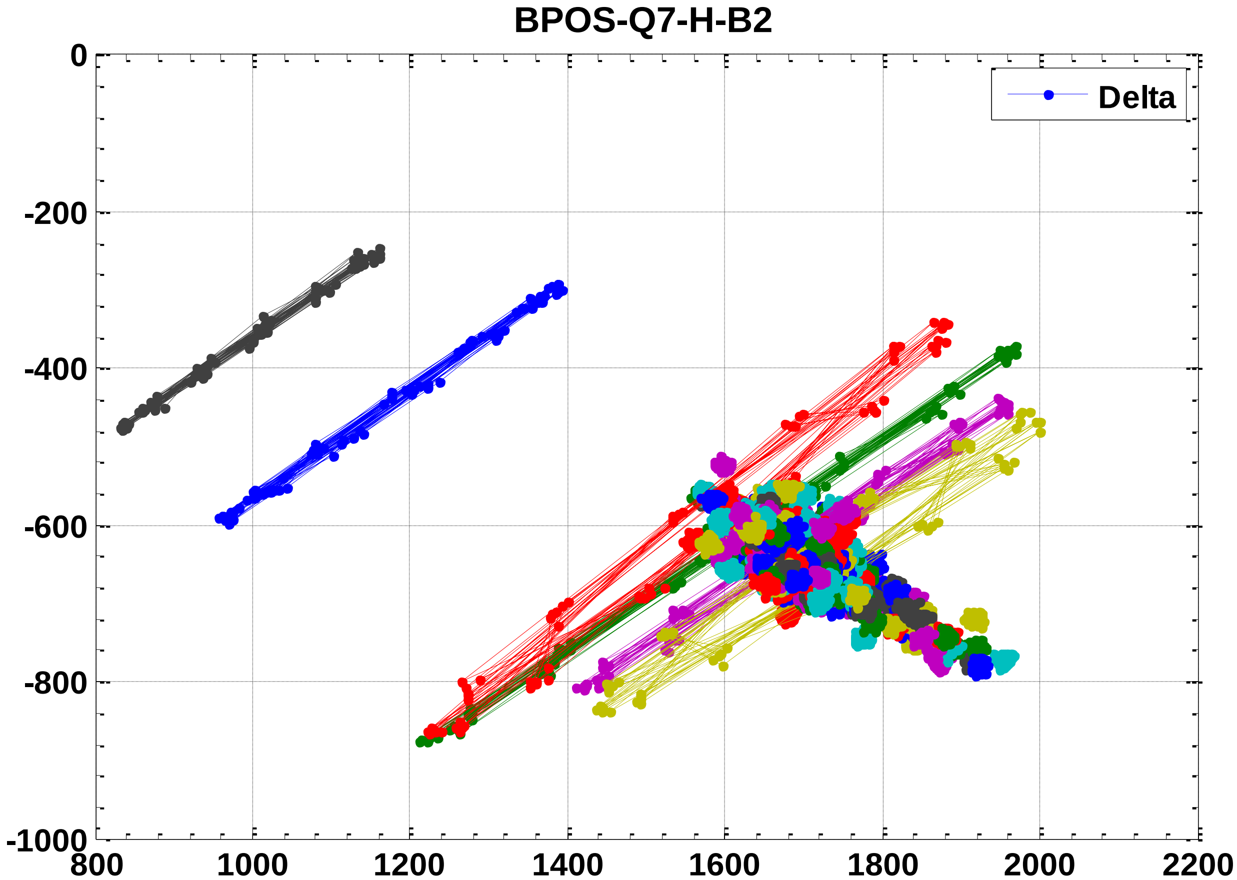


→ extend to include influence of long. motion and non-symmetric bunches in analysis

Visualization of bunch motion

Rapid identification of

- quiet bunches
- bunches with transverse center of mass motion
- bunches with head tail motion
- bunches with combination of center of mass and headtail motion with correlation



example from LHC scrubbing run

Added value of upgraded SPS damper to crab cavity tests in SPS

- Efficient damping of single bunches will become possible
- Studies with stored beams and a state-of the art low noise damper should serve as test bad for the LHC case with respect to noise issues
- Similarity of SPS damper and LHCADT permits to investigate interplay between transverse feedback and crab cavities
- Diagnostics potential of damper hardware in area of headtail motion analysis

Above is possible before LS2 as a result of realizing the SPS damper upgrade in LS1

→ significant effort which will pay off for crab cavity tests between LS1 and LS2

Complementarity of Feedbacks

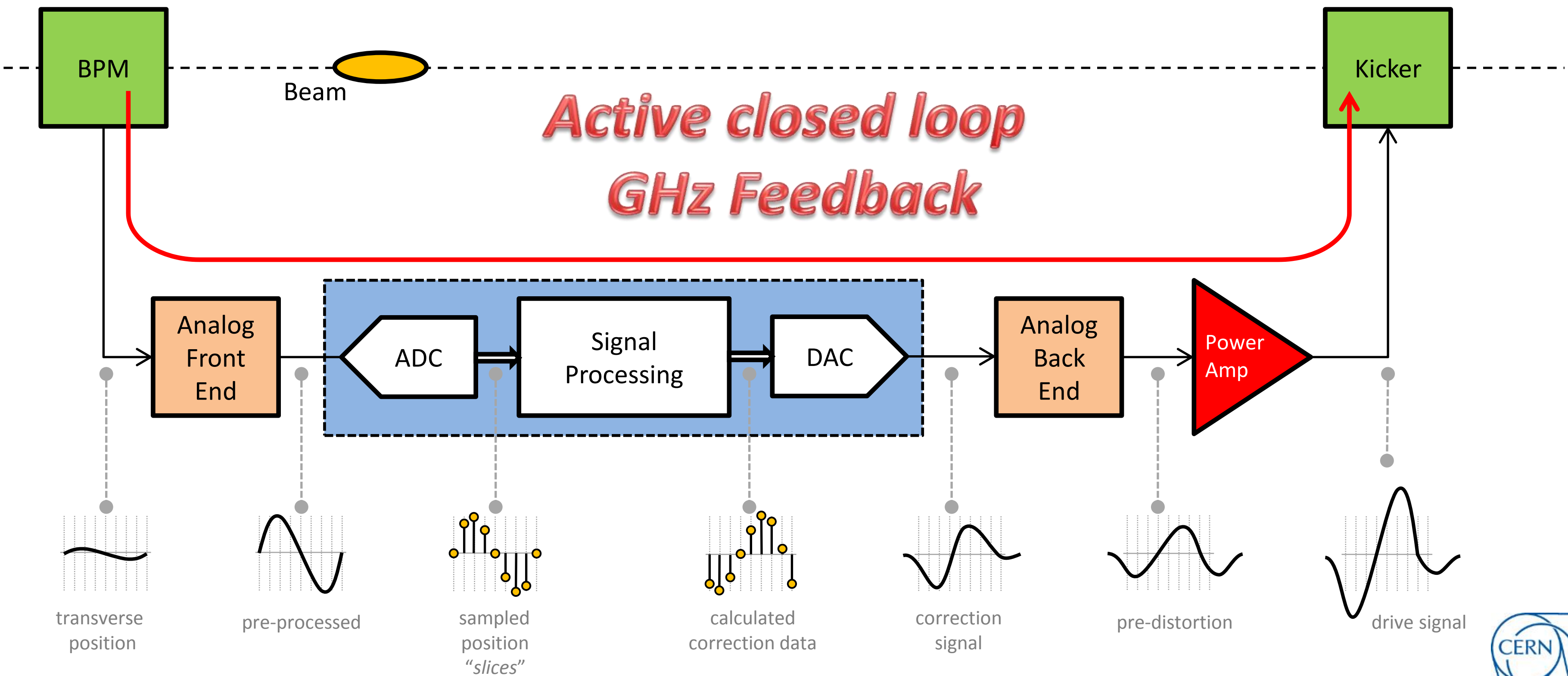
- Upgraded BA2 Damper
  - detects center of mass oscillations of bunches, feedback in “base-band”
  - LIU upgrade successfully implemented:
    - dedicated new standard SPS pick-ups (BPCR coupler)
    - New eletcronics, bunchlet scrubbing beam
  - kHz to 20 MHz, high kick strength (good for mm’s of oscillation) high kick strength
  - Headtail “intergral” diagnostics possible
  - LL electronics could drive wideband kicker (up-converted signal)

- BA3 Proposed High Bandwidth Feedback (V-plane)
  - New approach: Intra-Bunch System similar to stochastic cooling in some way
  - advanced Digital Technology 4-8 GS/s
  - ~5 MHz to >~ 1 GHz, not so high kick strength
  - addresses intra-bunch motion, diagnostics potential by direct sampling
  - potential to damp intra bunch motion inside doublets → interesting with respect to requirement to provide a high quality doublet beam for LHC scrubbing
  - kicker and Amplifier development crucial for success
  - applicable to other accelerators including colliders such as FCC and LHC.

HBTFB - High Bandwidth Transverse Feedback

- **Wideband feedback** system (GHz bandwidth) for SPS
- Intra-bunch **GHz transverse feedback** system
- Help **stabilize beam** against Ecloud and TMCI effects
- Under development with **LARP**

supported by:
US-LARP (SLAC, LBNL)
LNF-INFN (kicker study)
CERN SPS LIU Project



Summary

- SPS damper was consolidated with respect to power system and controls
- completely new electronics developed, installed and commissioned
- required Performance reached including for critical doublet beam
- upgrade opens possibilities to use the system for tests with crab cavities including diagnostics for headtail motion.
- diagnostics potential complementary to monitors and feedback that directly sample in time domain at high sampling rate
- Implementation of electronics for LHC ion beams before LS2

LHC Injectors Upgrade

THANK YOU FOR YOUR ATTENTION!

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