BEAM TESTS OF THE LHC TRANSVERSE FEEDBACK SYSTEM

W.Höfle, G.Kotzian, E.Montesinos, M.Schokker, D.Valuch (CERN)
V.M. Zhabitsky (JINR)

XXII Russian Particle Accelerator Conference
27.09 - 01.10. 2010, Protvino

BEAM TESTS OF THE LHC TRANSVERSE FEEDBACK SYSTEM

W.Höfle

E.Montesinos

D.Valuch.

G.Kotzian

M.Schokker

LHC Beam Parameters

http://lhc.web.cern.ch/lhc/LHC-DesignReport.html		Injection	Collision
• **Beam Data**			
Proton energy	[GeV]	450	7000
Relativistic gamma		479.6	7461
Number of particles per bunch		$1.15 \cdot 10^{11}$	
Number of bunches		2808	
Longitudinal emittance (4σ)	[eV·s]	1.0	2.5
Transverse normalized emittance	[μm·rad]	3.5	3.75
Circulating beam current	[A]	0.582	
Stored energy per beam	[MJ]	23.3	362
• **Peak Luminosity Related Data**			
RMS bunch length	[cm]	11.24	7.55
RMS beam size in ATLAS and CMS	[μm]	375.2	16.7
RMS beam size in ALICE and LHCb	[μm]	279.6	70.9
Geometric luminosity reduction factor *F*		-	0.836
Peak luminosity for ATLAS and CMS	$[cm^{-2}s^{-1}]$	-	$1.0 \cdot 10^{34}$

LHC Transverse Feedback System

$$L = \frac{N_b^2 K_b f_r \gamma}{4\pi\varepsilon_n \beta^*} F$$

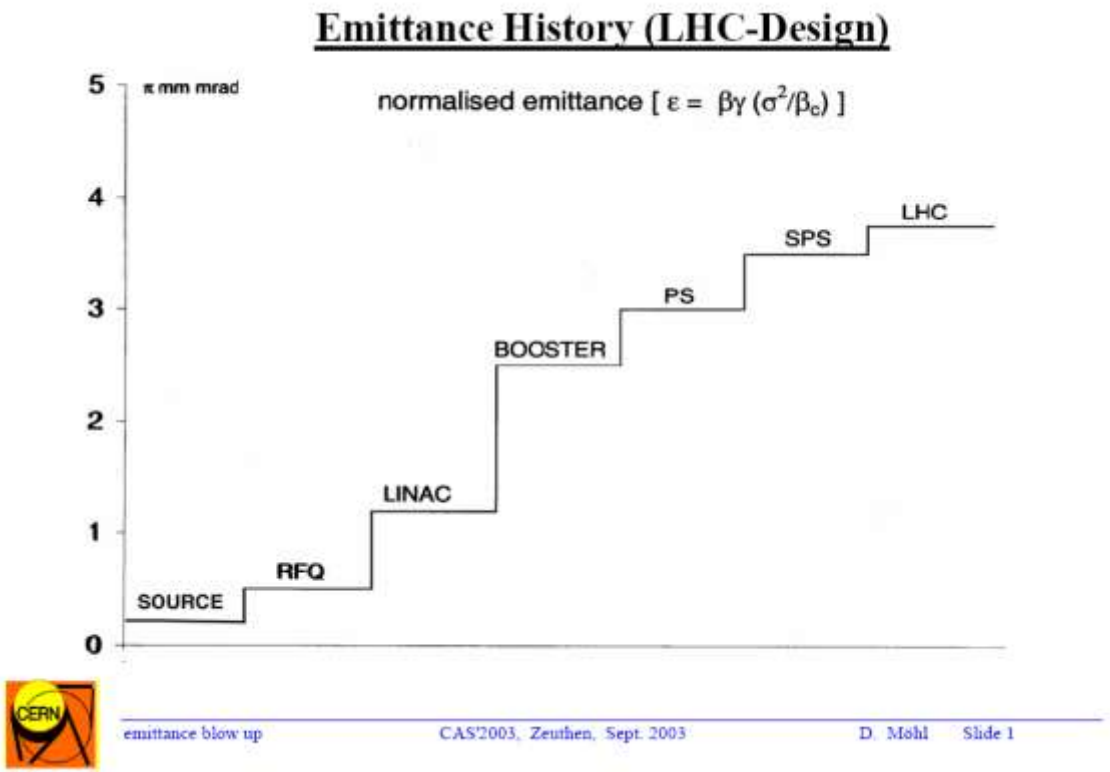
- The LHC will provide high intensity proton and lead ion beams. The ultimate intensities after injection into the LHC will be about
  - $4.8 \cdot 10^{14}$ ($1.7 \cdot 10^{11}$ x 2808 bunches) particles for the proton beam with an energy of 450 GeV,
  - $4.1 \cdot 10^{10}$ ($7 \cdot 10^{7}$ x 592 bunches) ions for the $^{208}Pb^{82+}$ beam with an energy of 177 GeV/u.

  → These intensities can lead to coherent transverse instabilities.
- The theoretical prediction for the instability rise time τ_{inst}, dominated by the resistive wall effect, is about 18.5 ms or 208 turns at injection energy for protons, and a significant contribution of the LHC collimators at collision energy to τ_{inst} is also predicted.
- The LHC Damper will stabilize the beam against coupled bunch instabilities.

Emittance blow-up

$$L = \frac{N_b^2 K_b f_r \gamma}{4\pi\varepsilon_n \beta^*} F$$

$$\varepsilon = \left(1 + \frac{e_{inj}^2}{2\sigma_0^2}\right)\varepsilon_0 \quad \Rightarrow \quad \varepsilon = \left(1 + \frac{e_{inj}^2}{2\sigma_0^2}\left(1 + \frac{\tau_{dec}}{\tau_d} - \frac{\tau_{dec}}{\tau_{inst}}\right)^{-2}\right)\varepsilon_0$$



$$\text{LHC}: \quad e_{inj} \le 3.5\sigma_0$$

$$\tau_d = 40 T_{rev}$$

$$\tau_{inst} > 208 T_{rev}; \quad \tau_{dec} \approx 750 T_{rev}$$

$$\varepsilon_{n0} = 3.5\ \mu\text{m} \cdot \text{rad} \Rightarrow +2.3\%$$

The LHC Damper will stabilize the beam

against coupled bunch instabilities as well as damp the transverse oscillations of the beam originating from steering errors and kicker ripple.

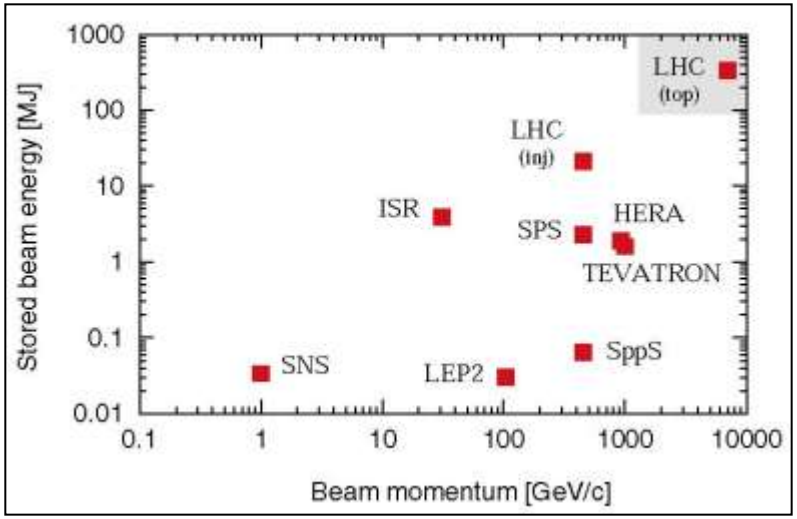
beam momentum & stored energy of colliders

$$L = \frac{N_b^2 K_b f_r \gamma}{4\pi\varepsilon_n \beta^*} F$$

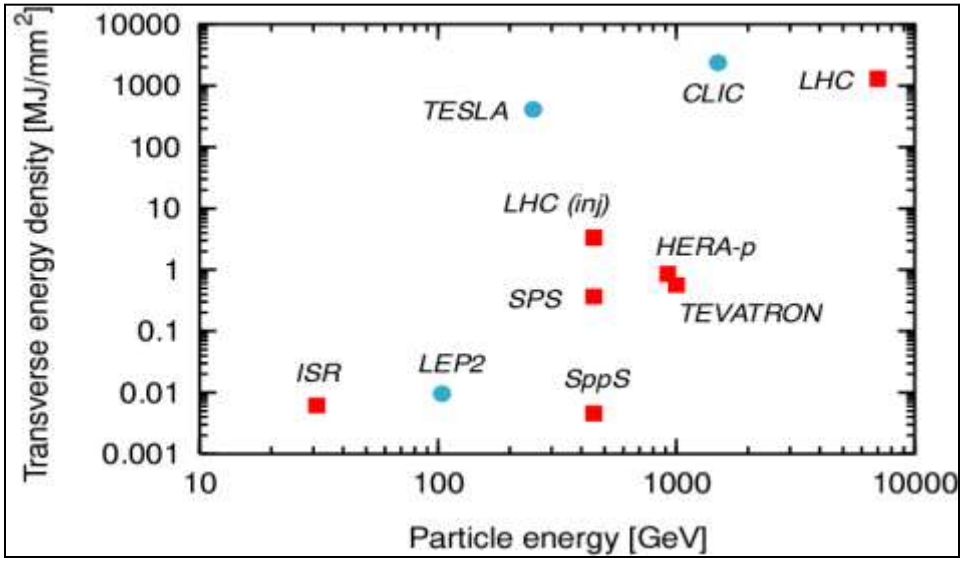
L.Evans. CHIPP APM. 8.09.2008.

E_{beam} = 362 MJ

Enough to melt 500 kg of copper



Energy stored in the accelerator beam, as a function of beam momentum. At less than 1% of nominal intensity LHC enters new territory.



Stored energy density as a function of beam momentum. Transverse energy density is a measure of damage potential and is proportional to luminosity.

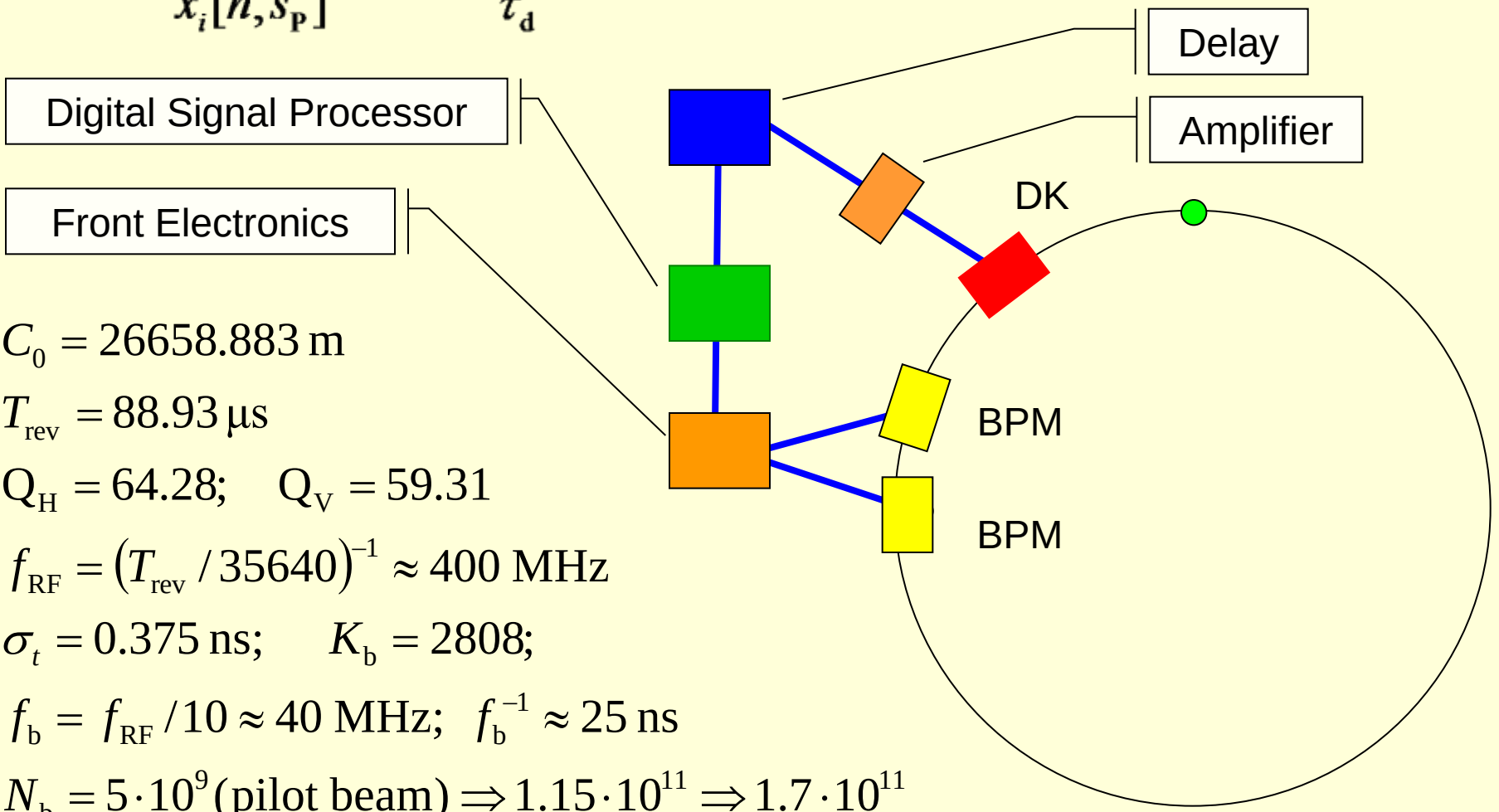
LHC Transverse Feedback System

$$L = \frac{N_b^2 K_b f_r \gamma}{4\pi\varepsilon_n \beta^*} F$$

- The LHC Damper will stabilize the beam
  - against coupled bunch instabilities
  - as well as damp the transverse oscillations of the beam originating from steering errors and kicker ripple.
  - It will also be used for the purposes of tune measurement and for abort gap cleaning.

LHC Transverse Feedback System

$$g = \frac{\Delta \bar{x}_i'[n, s_K]\sqrt{\hat{\beta}_K \hat{\beta}_P}}{\bar{x}_i[n, s_P]} = \frac{2T_{rev}}{\tau_d} = 0.05 \rightarrow \tau_d = 40T_{rev}$$



$C_0 = 26658.883\ \text{m}$

$T_{rev} = 88.93\ \mu\text{s}$

$Q_H = 64.28; \quad Q_V = 59.31$

$f_{RF} = (T_{rev}/35640)^{-1} \approx 400\ \text{MHz}$

$\sigma_t = 0.375\ \text{ns}; \quad K_b = 2808;$

$f_b = f_{RF}/10 \approx 40\ \text{MHz}; \quad f_b^{-1} \approx 25\ \text{ns}$

$N_b = 5 \cdot 10^9\ (\text{pilot beam}) \Rightarrow 1.15 \cdot 10^{11} \Rightarrow 1.7 \cdot 10^{11}$

The LHC Damper

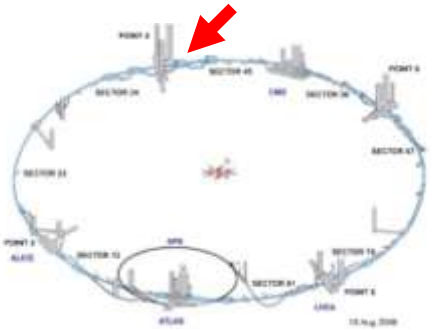
Performance specification

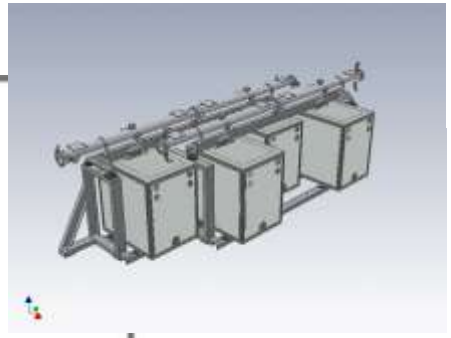
"Electro-static" kickers	base-band
Integrated transverse electric field $\int E_{\perp} ds$ (for 450 GeV/c)	900 kV per turn
Aperture of kickers	52 mm
Number of kickers per beam and plane	4
Length electrodes in kicker	1.5 m
Nominal voltage up to 1 MHz (at β = 100 m)	±7.5 kV
Kick per turn at 450 GeV/c (at β = 100 m)	2 μrad (0.2 σ)
Rise-time 10-90%, V_{max} = ±7.5 kV	350 ns
Rise-time 1-99%, V_{max} = ±7.5 kV	720 ns *)
Frequency range for gain	1 kHz – 1 (20) MHz

*) Rise time fast enough for gap of 38 missing bunches
(900 ns for rise time (0.5 %-99.5 %) in the LHC injection kicker)

The LHC Damper

Installation and Physical layout in Point 4 underground LHC

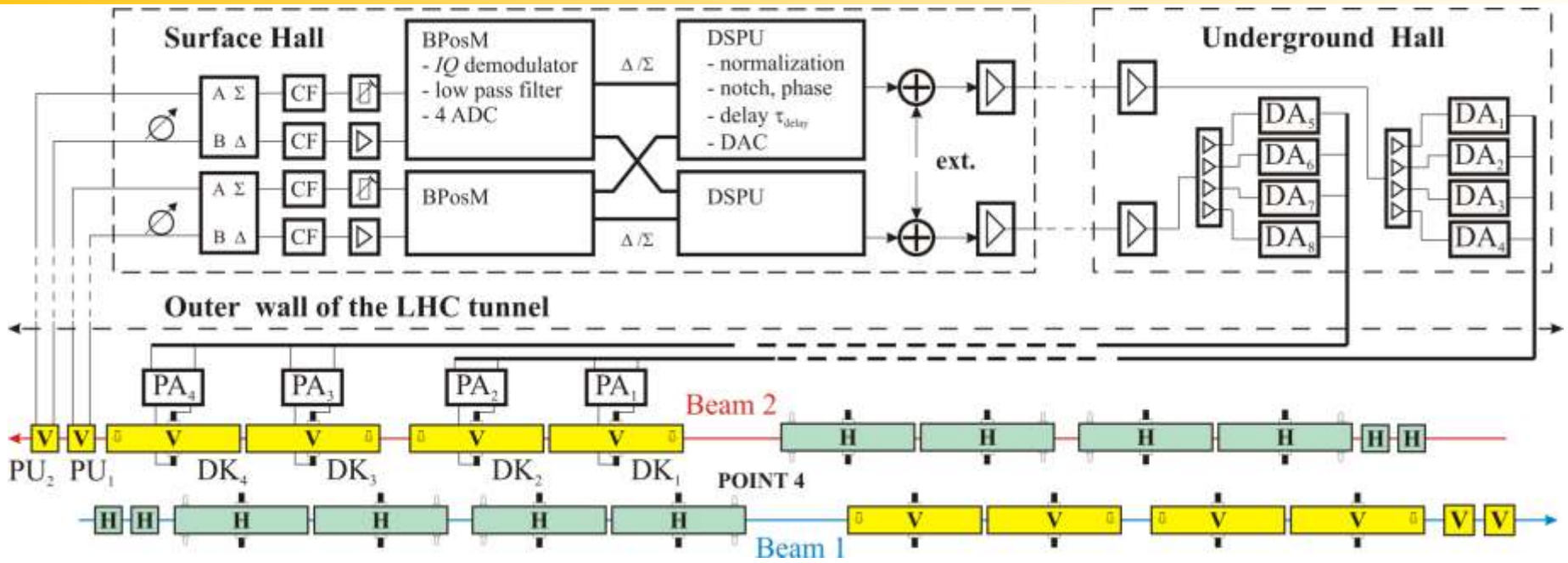




ADT (4 modules) left of IP4 + space for 2 more modules (upgrade)

ADT (4 modules) right of IP4 + space for 2 more modules (upgrade)

The LHC Damper

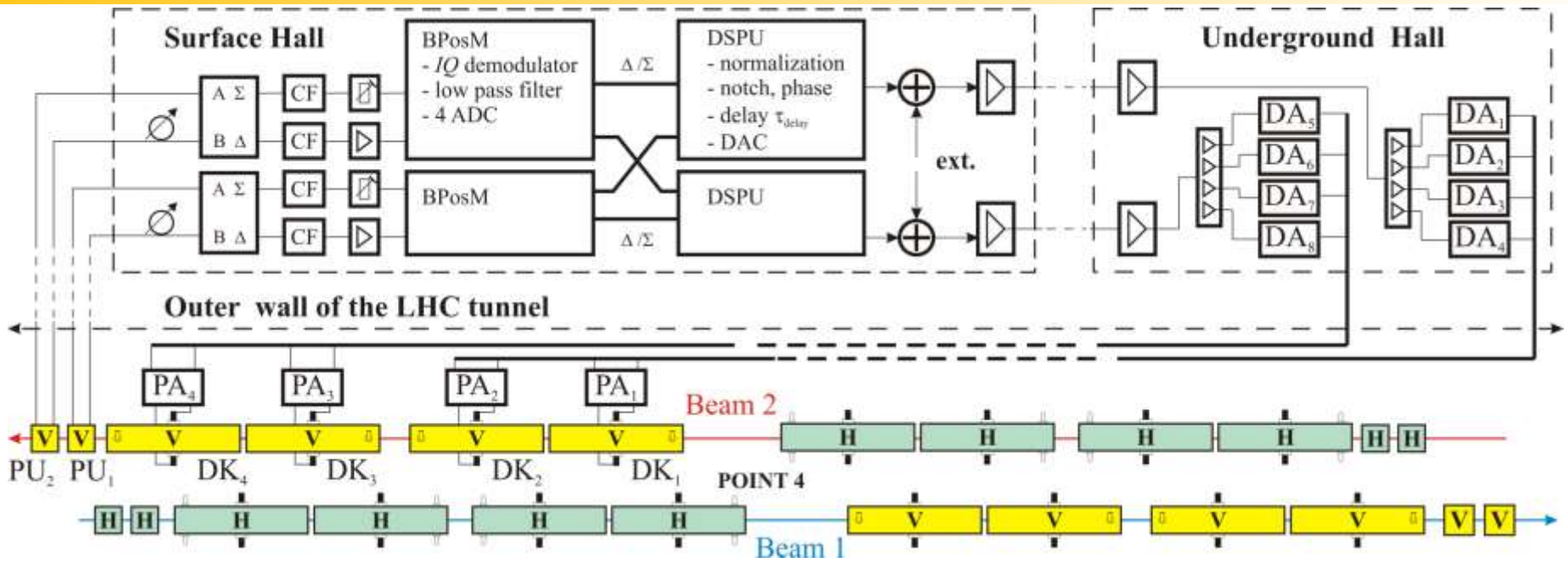


Layout of the LHC Damper

(four independent systems, one per plane (H/V) and beam)
block-diagram of the transverse feedback system for vertical oscillations.

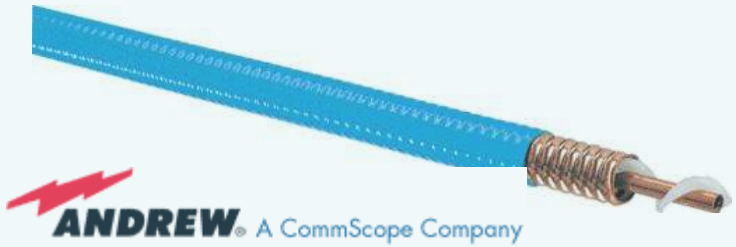
The feedback loop contains all functionalities for transverse damping and controlled bunch excitation as well as many built-in features allowing the user full remote operation and diagnostics.

The LHC Damper



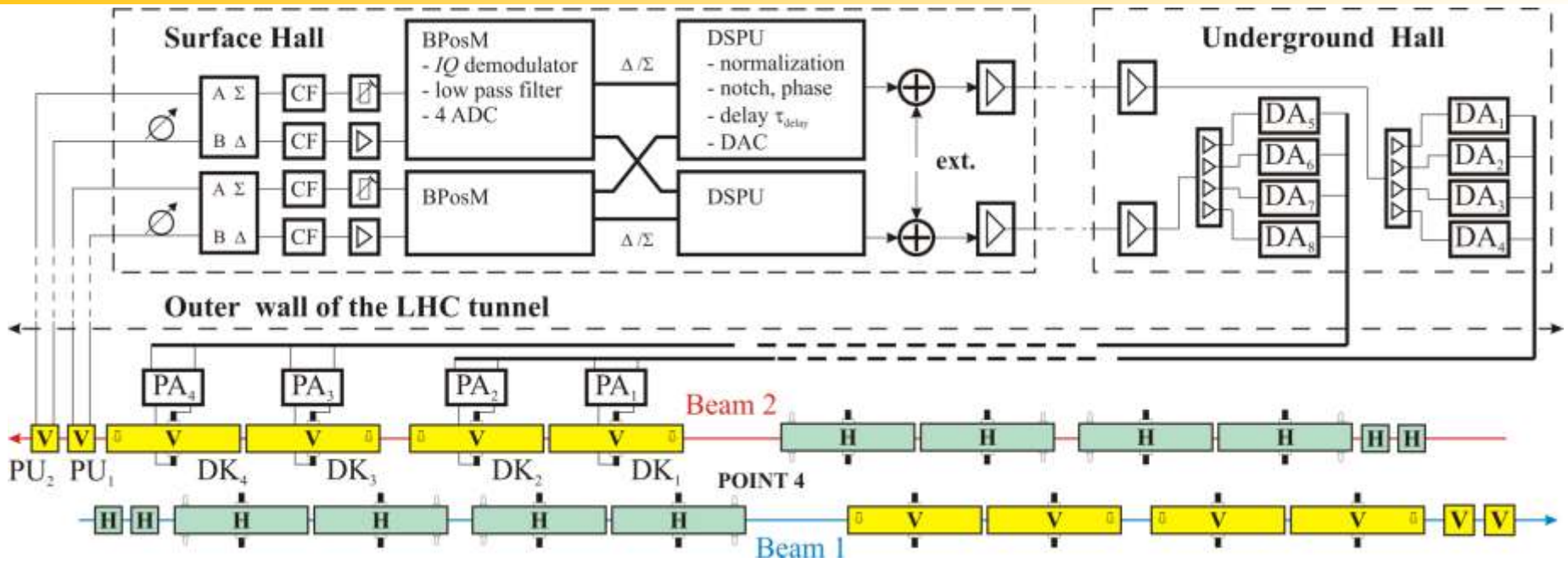
Beam Position Monitor in Cryomodule

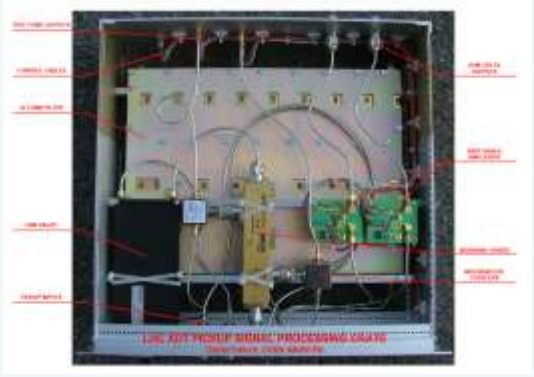
7/8 inch coaxial cable
(coaxial lines of 450-650 m)



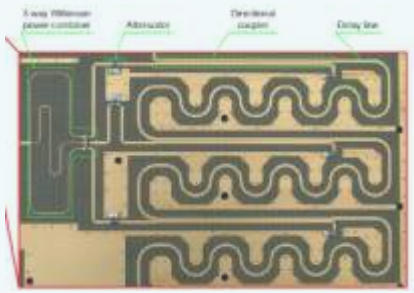
The LHC Damper

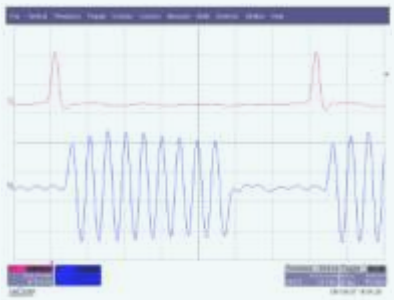
The LHC Damper





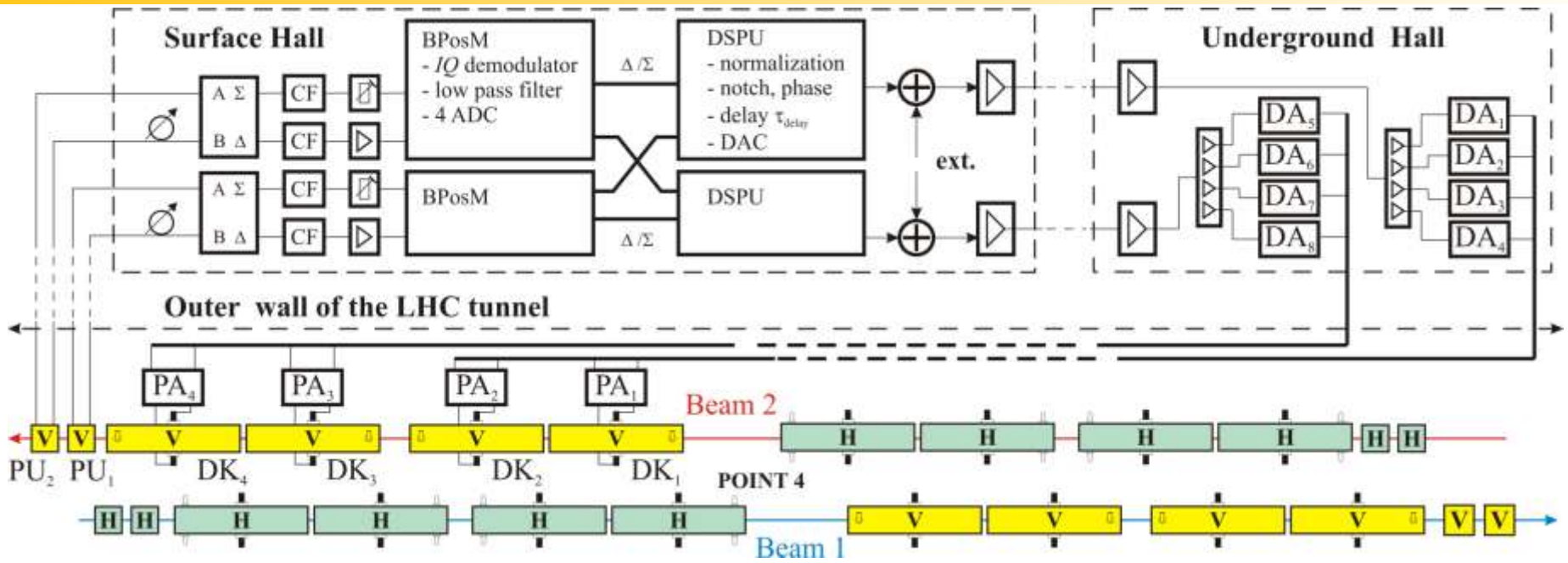
Pick-up Signal Processor Crate



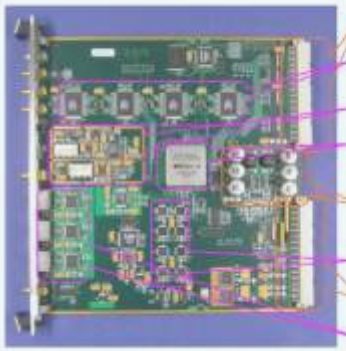


Comb Filter

The LHC Damper

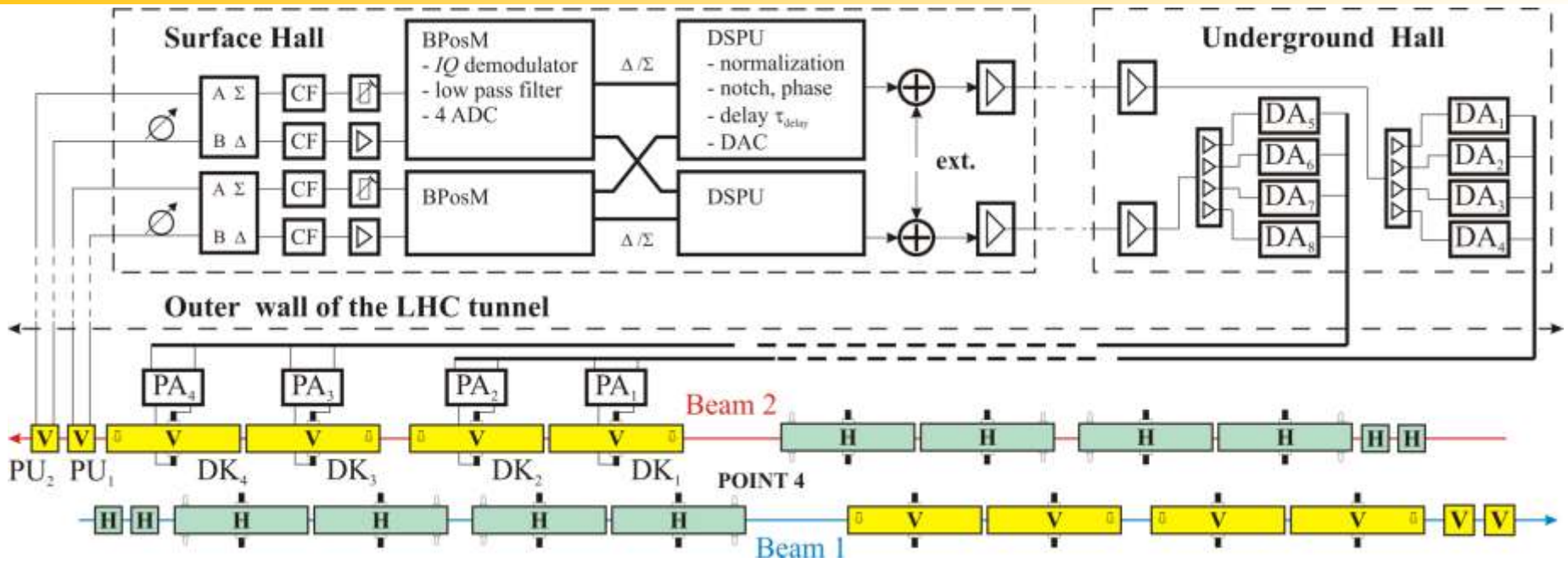


Beam Position Module



Digital Signal Processor Unit

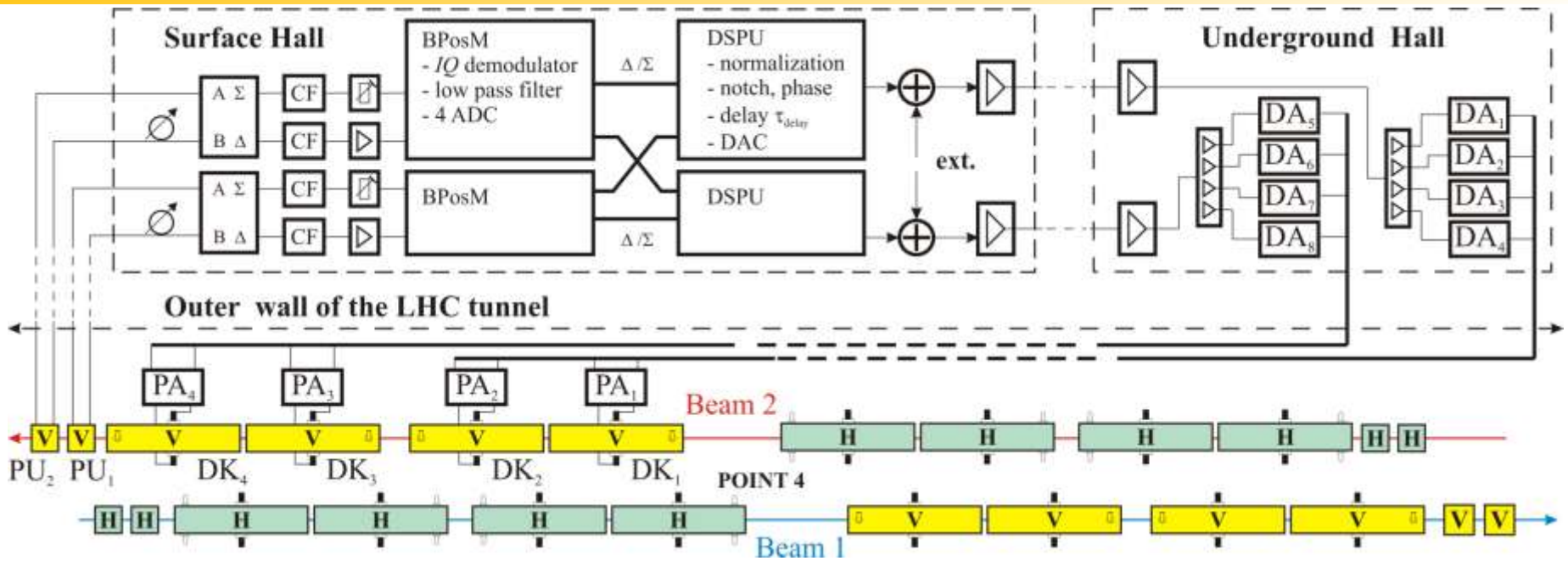
The LHC Damper



THALES The Thales Communications (Belgium)

200 W solid state driver amplifier:
43 dB gain,
very flat, 3 kHz – 20 MHz.

The LHC Damper



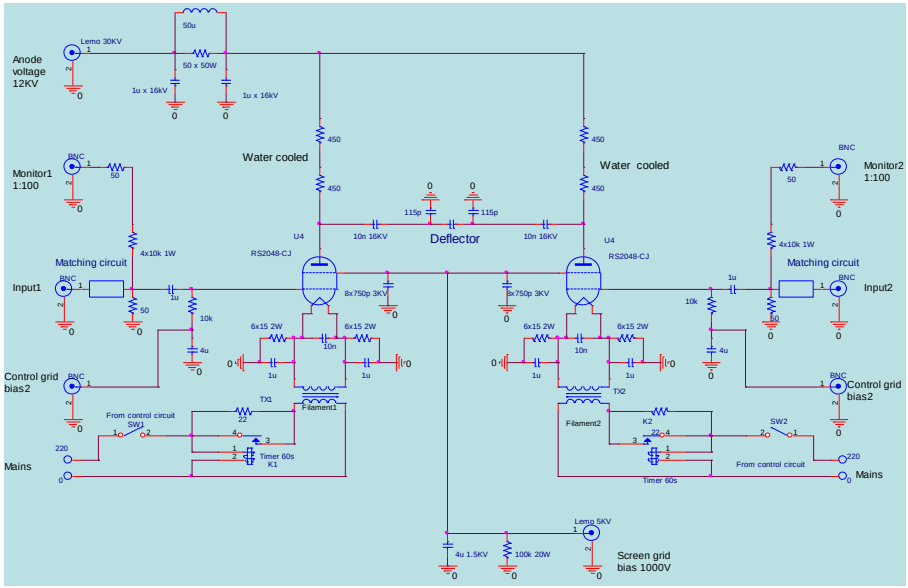
Electrostatic Kickers and Wideband Power Amplifiers in the LHC tunnel

The LHC Damper

N.I.Lebedev, Leading engineer.

E.V.Gorbachev, Leading engineer.

A.A.Makarov, Leading designer.

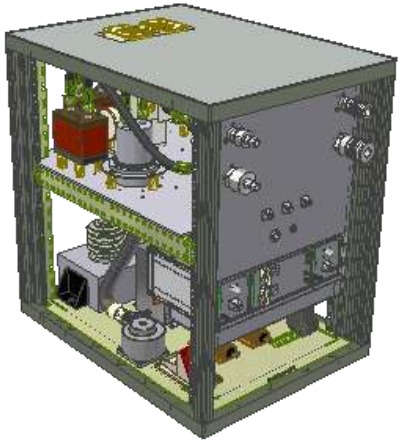


R.A.Smolkov, Leading engineer.

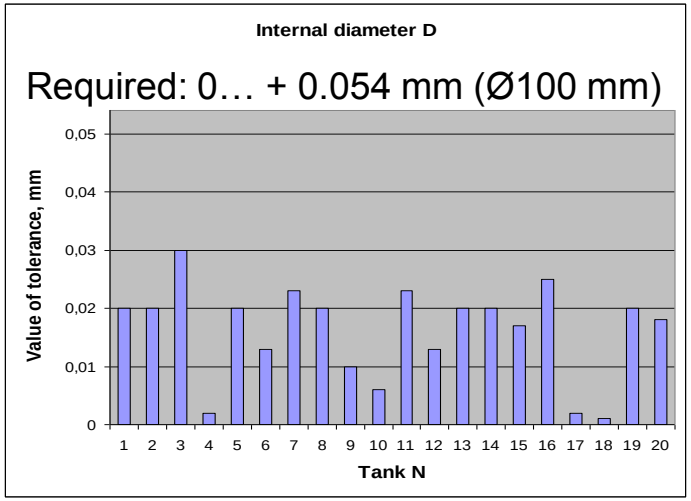
N.V.Pilyar, Leading engineer.

"Push-pull" wideband power amplifier:

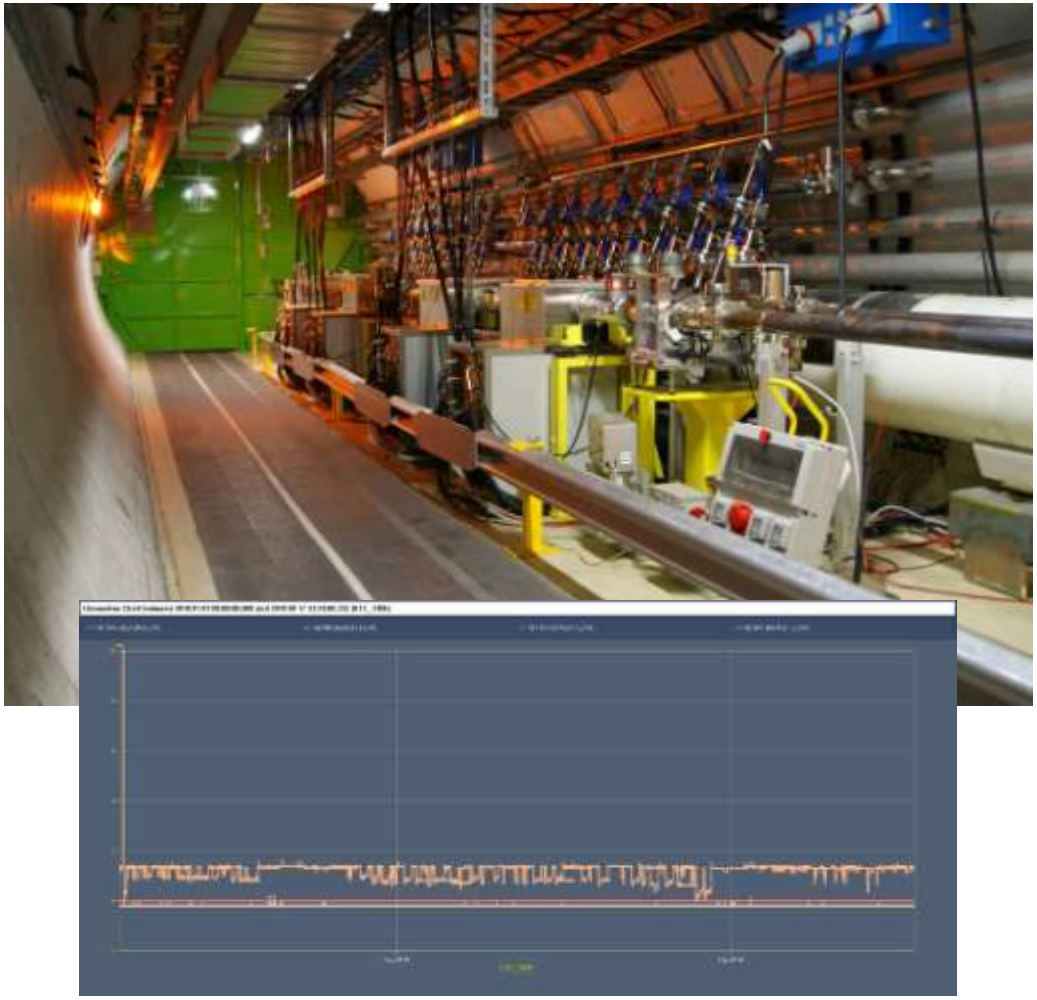
- Class of operation: AB
- Input amplitude: ±150 V
- Output amplitude: ±7500 V
- Bandwidth: 1 kHz – 1 (20) MHz
- Power elements: two 30 kW "Thales" RS 2048-CJC tetrodes



The LHC Damper



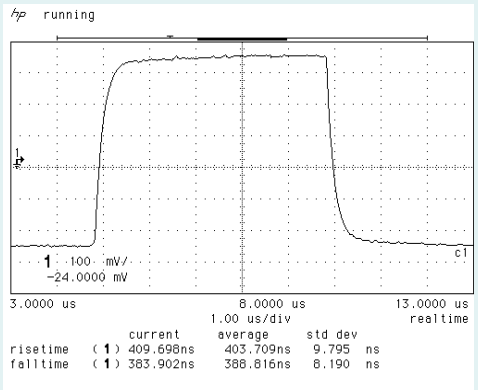
Parameter	Required / Achieved
Surface smoothness (L_K=1.6 m; Ø100 mm)	1.6 μm / 0.4 μm

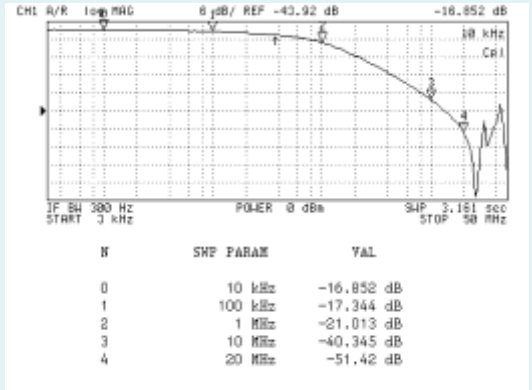


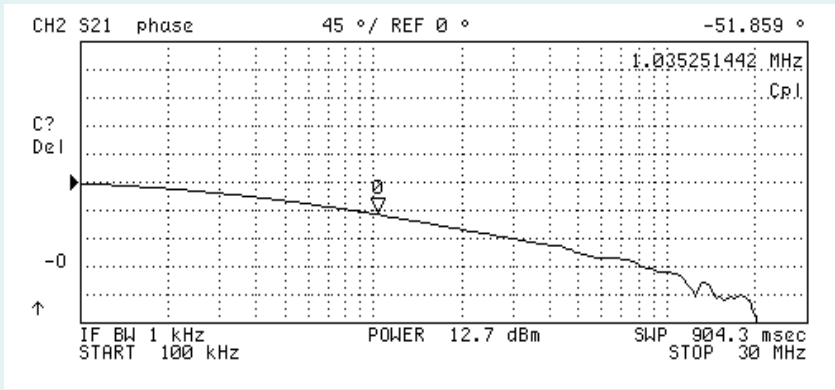
The vacuum pressure values are between 8.0×10^{-10} and 1.0×10^{-9} mbar.

The LHC Damper

Parameter	Required	Achieved
Lowest frequency	1 kHz	1 kHz
Highest frequency	20 MHz	20 MHz
Nominal - 3dB bandwidth	3 kHz – 1 MHz	2 kHz - 0.95 MHz
Nominal voltage at 1 MHz	±7.5 kV	±7.8 kV
Gain, dB	34	34.3
Gain ripple	±0.7 dB	±0.5 dB
Rise-time 10-90%, V_{max} = 7.5 kV	350 ns	410 ns
Rise-time 1-99%, V_{max} = 7.5 kV	720 ns	760 ns







The measured characteristics of the amplifier in the frequency range from 1 kHz to 30 MHz correspond globally to the design specifications.

The available peak voltage of 11 kV at 100 kHz has exceeded the design value 10.5 kV.

The LHC Damper

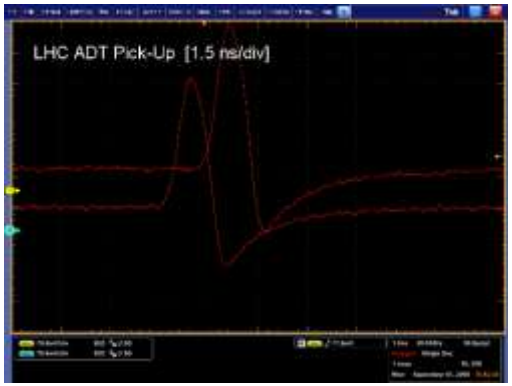
First Beam Tests:

- 16 kickers (JINR) and front-electronics (CERN) were successfully checked for first beams in the LHC.

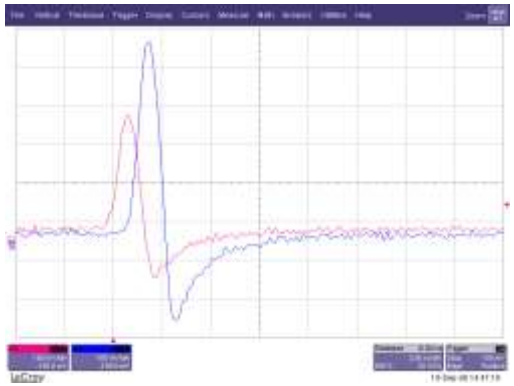
- Tune measurements with excitation (scanning) of the beam 2 (about $2 \cdot 10^9$ protons in the single bunch) by kickers with power amplifiers of the LHC Damper.
(23:52. 11 September 2008)

Signals from the LHC Damper pick-up for the first shots:

beam 1. 7 September 2008.

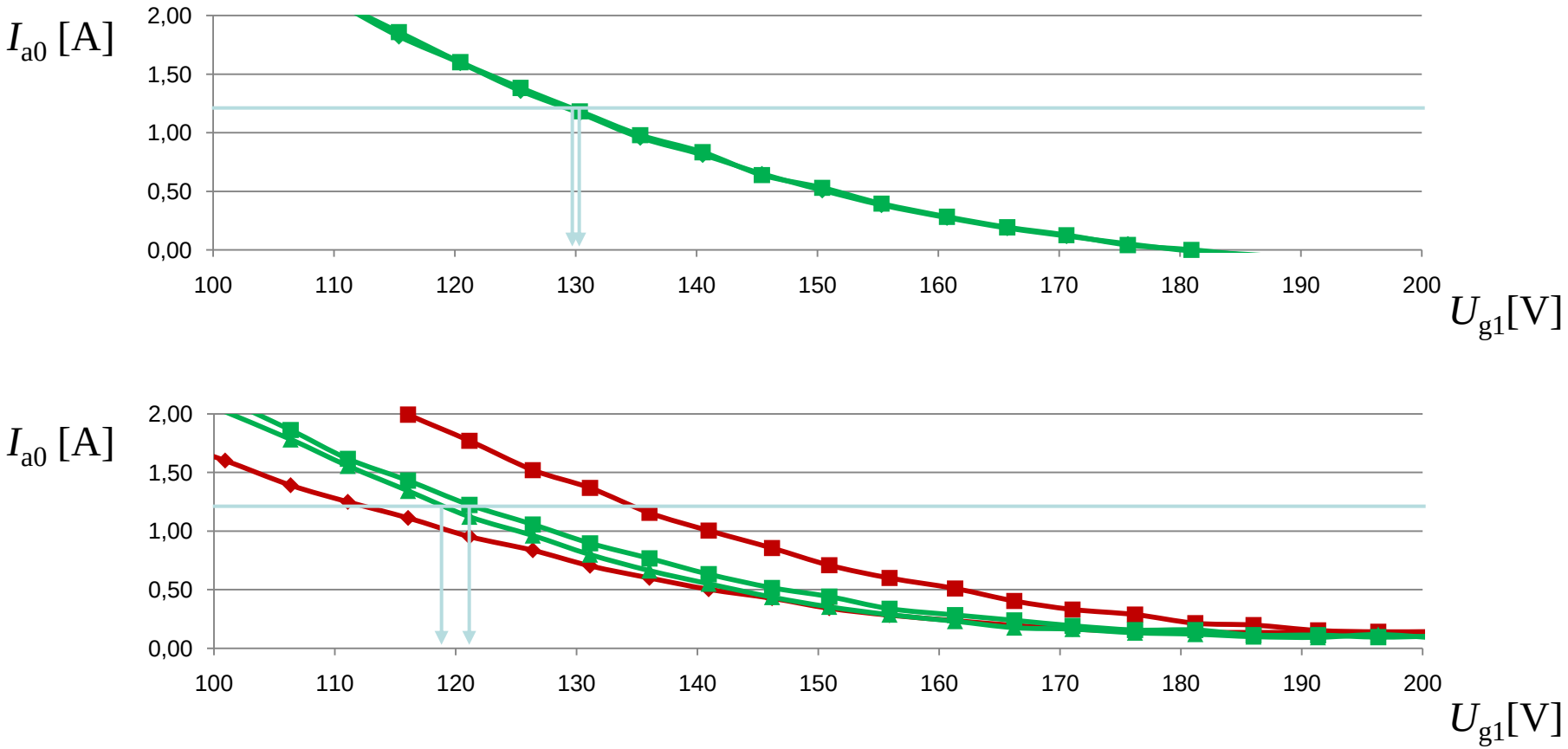


beam 2. 10 September 2008.



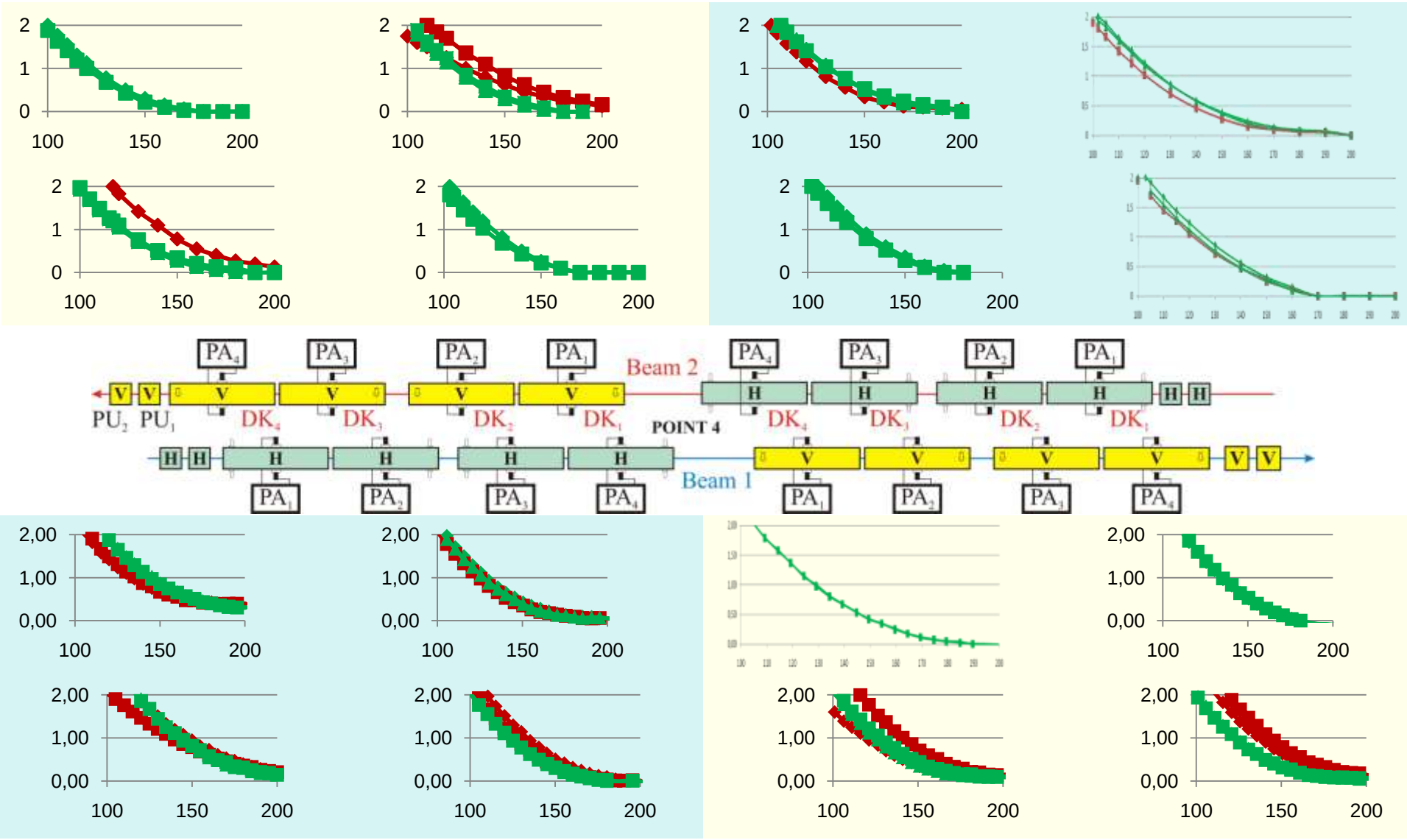
Hardware Tuning

Wideband Power Amplifiers: tetrodes rearrangement



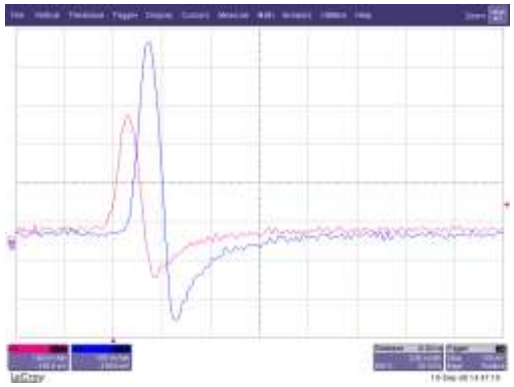
Green curves = new situation. Red curves = previous tetrodes (removed)

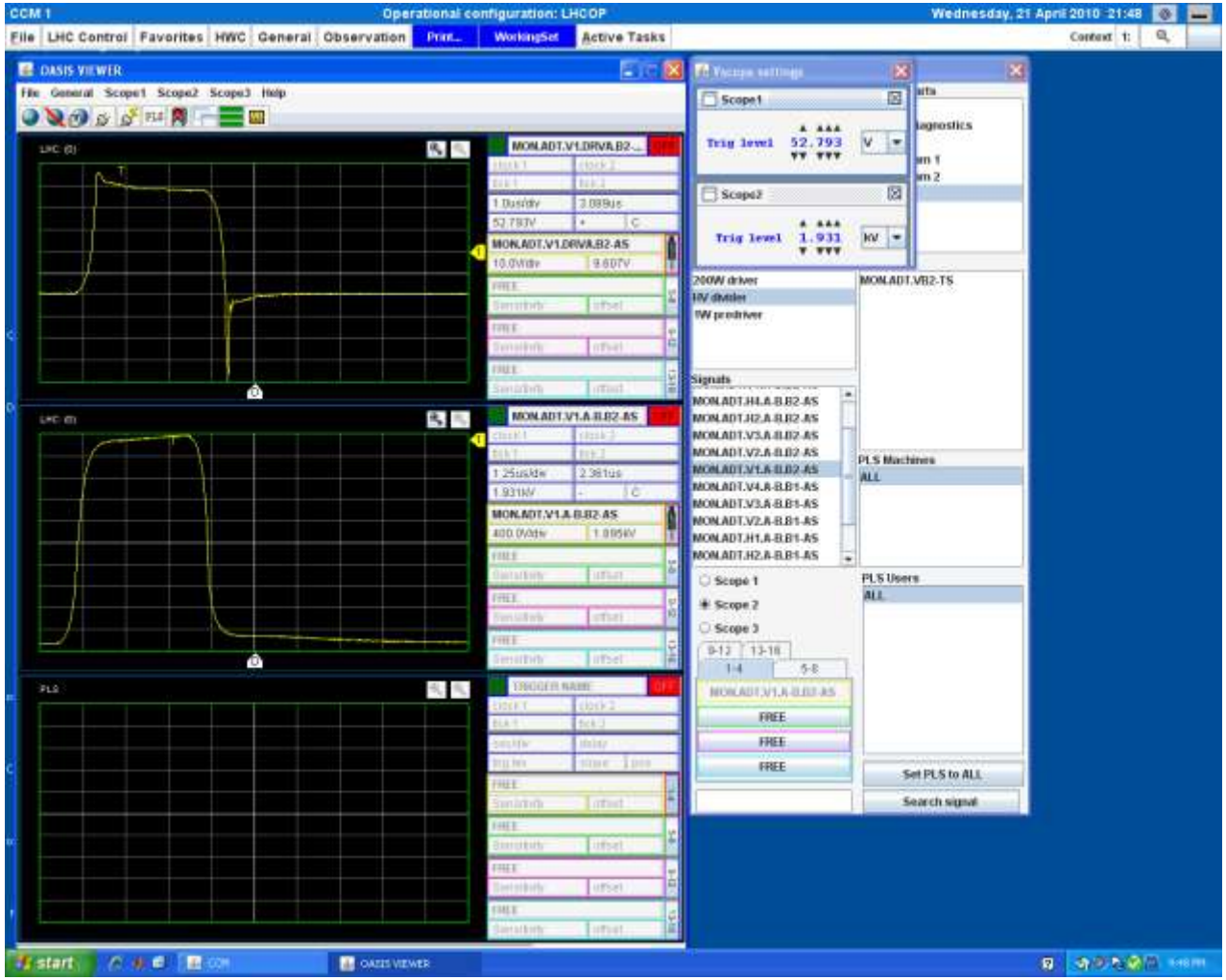
Wideband Power Amplifiers: tetrodes rearrangement



All amplifiers now have similar pair of tetrodes for $I_{a0}(U_{g1})$ characteristics

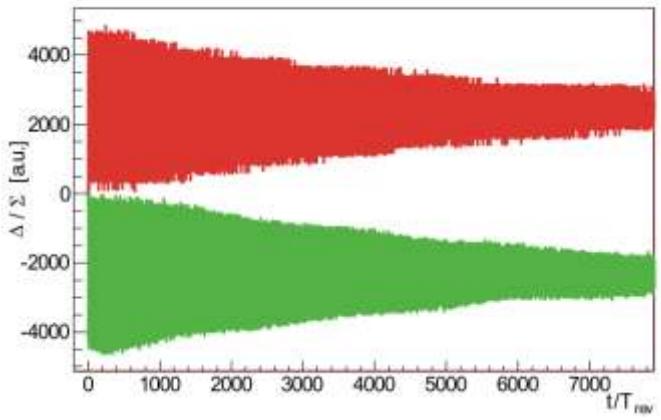
Hardware Tuning

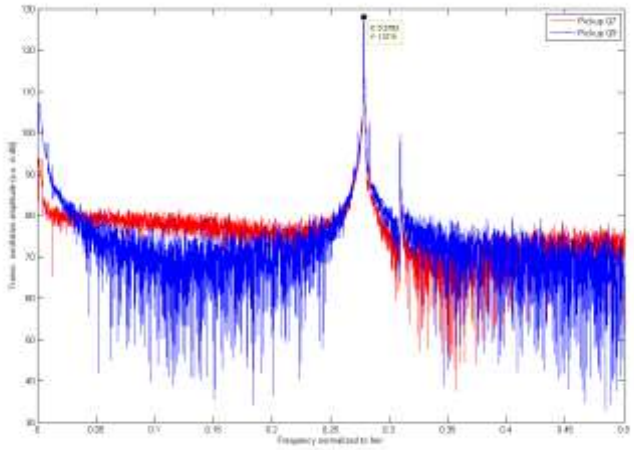


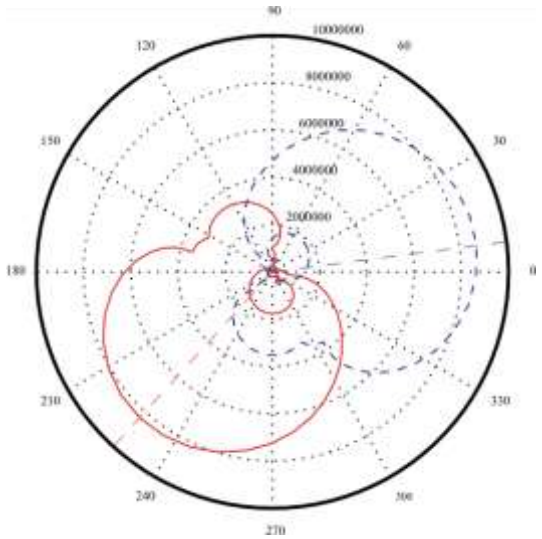


Hardware Tuning

Measurements of betatron phase advances between pick-ups





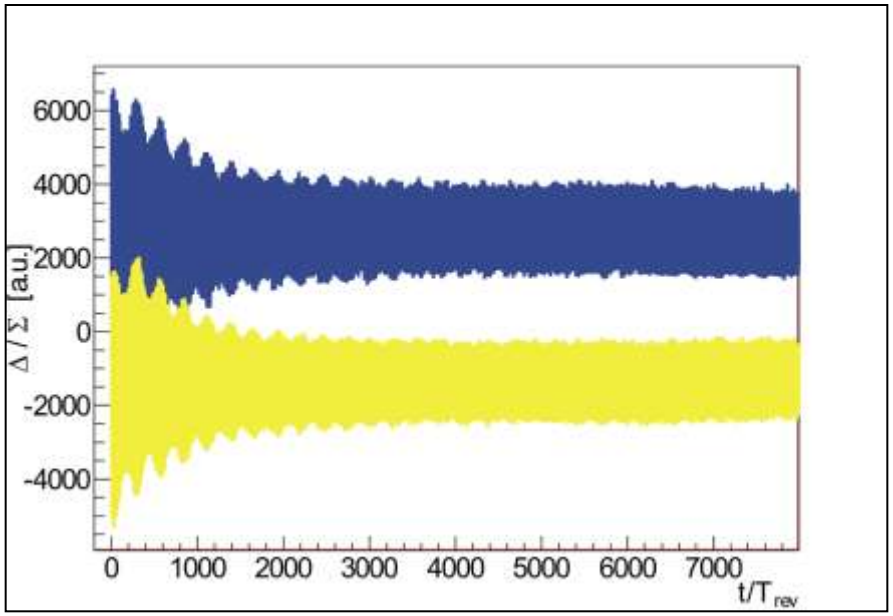


Position of pick-ups (left or right of point 4) for beam 1 (B1) or beam 2 (B2)	Phase advance, degrees	Delta with respect to 90°
H.B1, left of 4, $Q9 \rightarrow Q7$	115	25
H.B2, right of 4, $Q9 \rightarrow Q7$	107	17
V.B1, right of 4, $Q7 \rightarrow Q9$	56	34
V.B2, left of 4, $Q7 \rightarrow Q9$	137	47

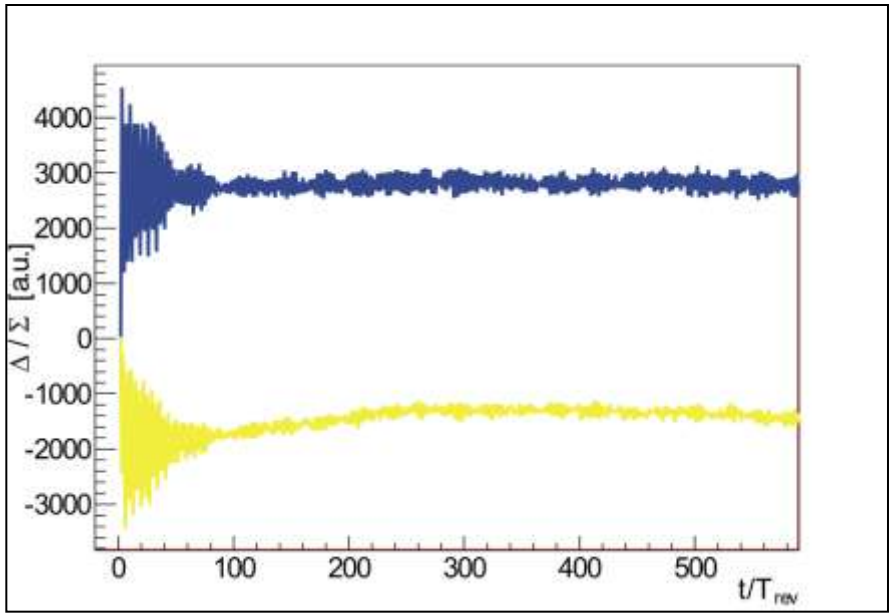
Measured phase advances between pick-ups

Beam Tests

Single Bunch Operation: Damping of Injection Errors



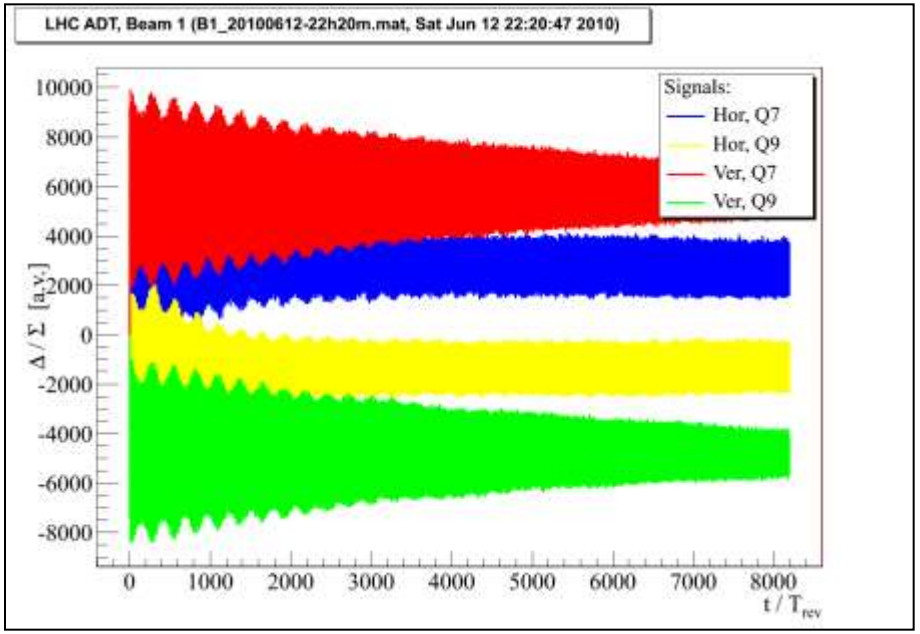
Damper OFF



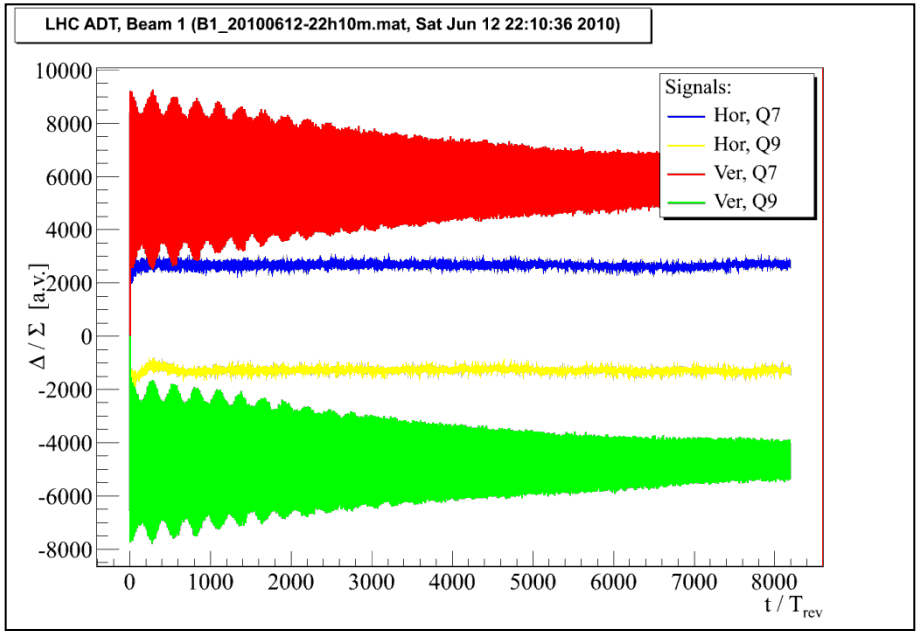
Damper ON

Beam Tests

Single Bunch Operation: Damping of Injection Errors



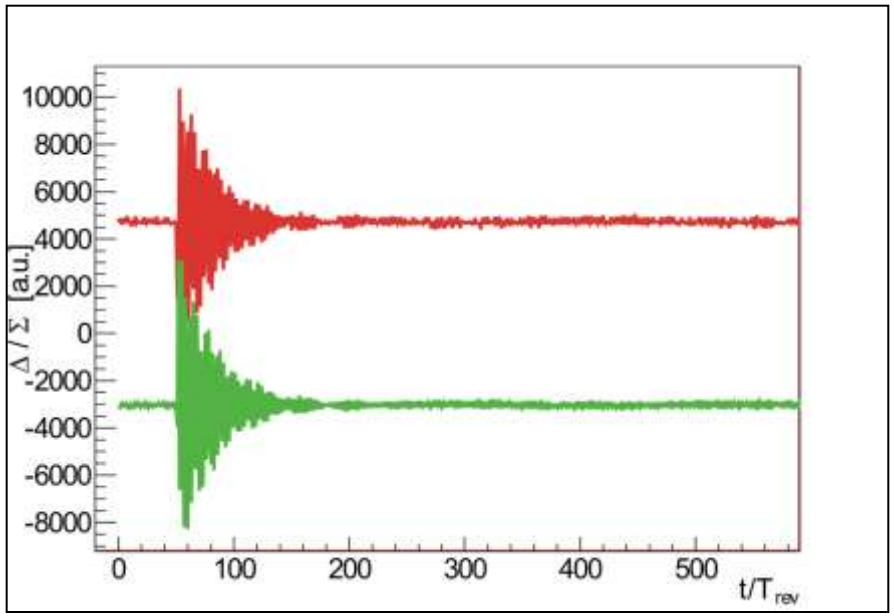
Damper OFF



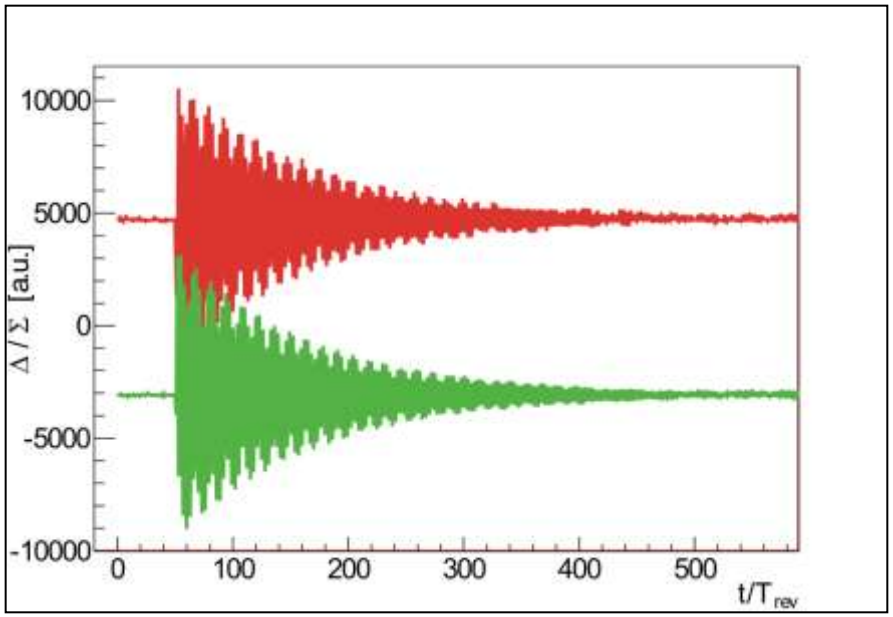
Damper ON for horizontal oscillations

Beam Tests

Single Bunch Operation (450 GeV):
Damping of Vertical Oscillations induced by the *Q*-kicker



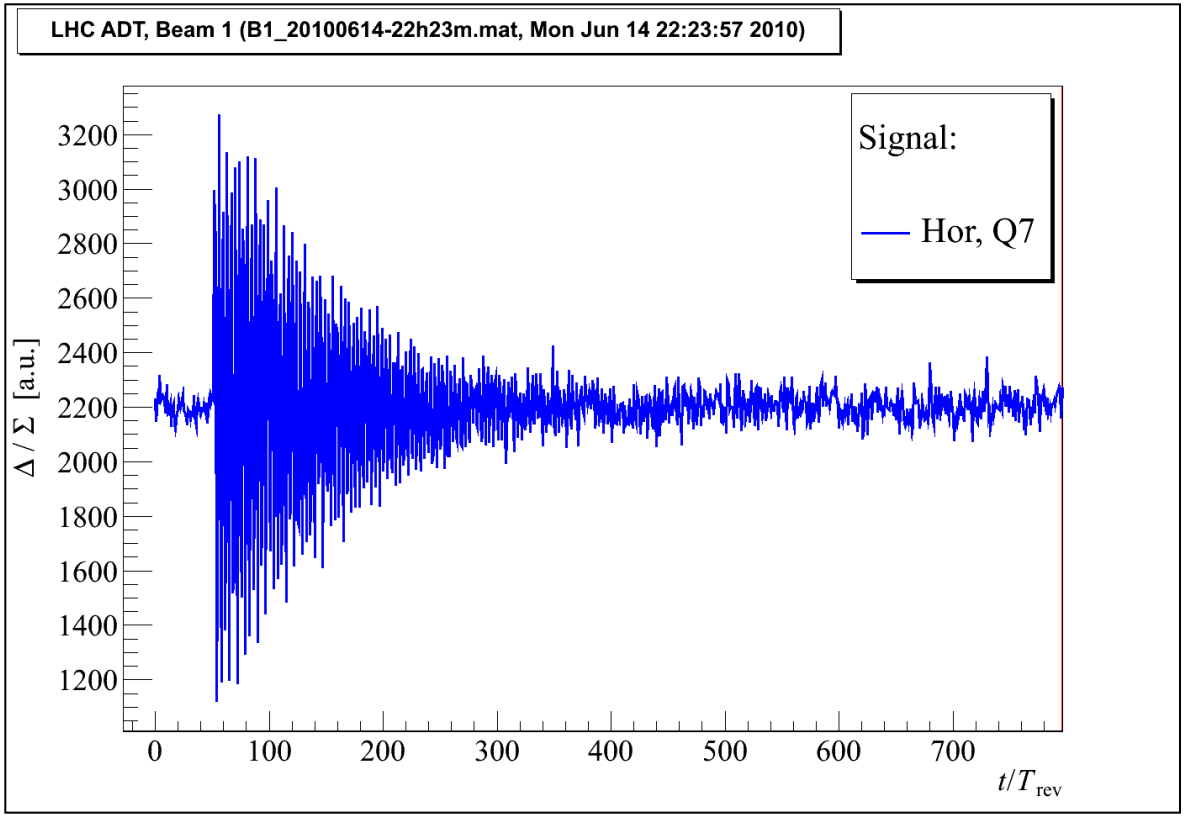
High Gain



Lower Gain

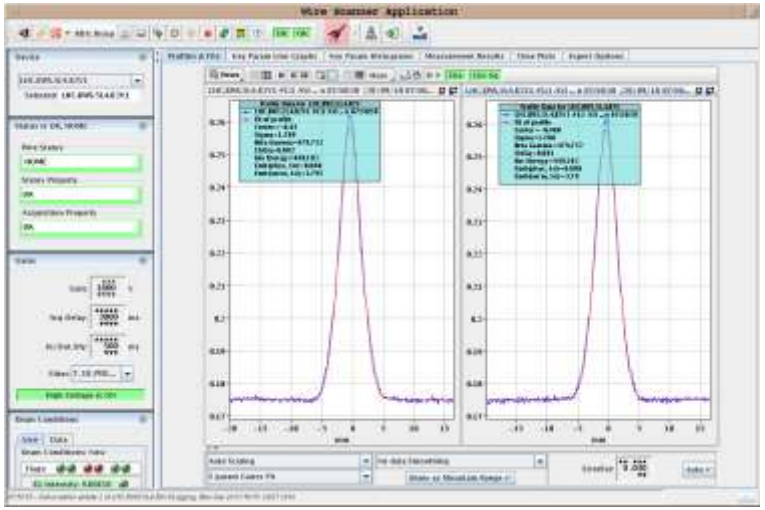
Beam Tests

Single Bunch Operation (3.5 TeV):
Damping of Transverse Oscillations induced by the *Q*-kicker



LHC Damper: Emittances

$\varepsilon_n < 3.5\,\mu m$



Beam / plane	ε_n , μm, @20.09 / 7:47
B1H	2.4
B1V	2.8
B2H	2.7
B2V	3.8

19.05.2010 / 22:30 : Test ramp with orbit FB and transverse damper on B2 V plane

Beam	ε_0, μm	ε, μm	Growth, %
H.B1	1.053	1.747	66
H.B2	1.009	1.603	59
V.B1	1.334	1.787	34
V.B2	1.305	1.487	14

damper on (at low gain)
in the ramp (3.5 TeV)

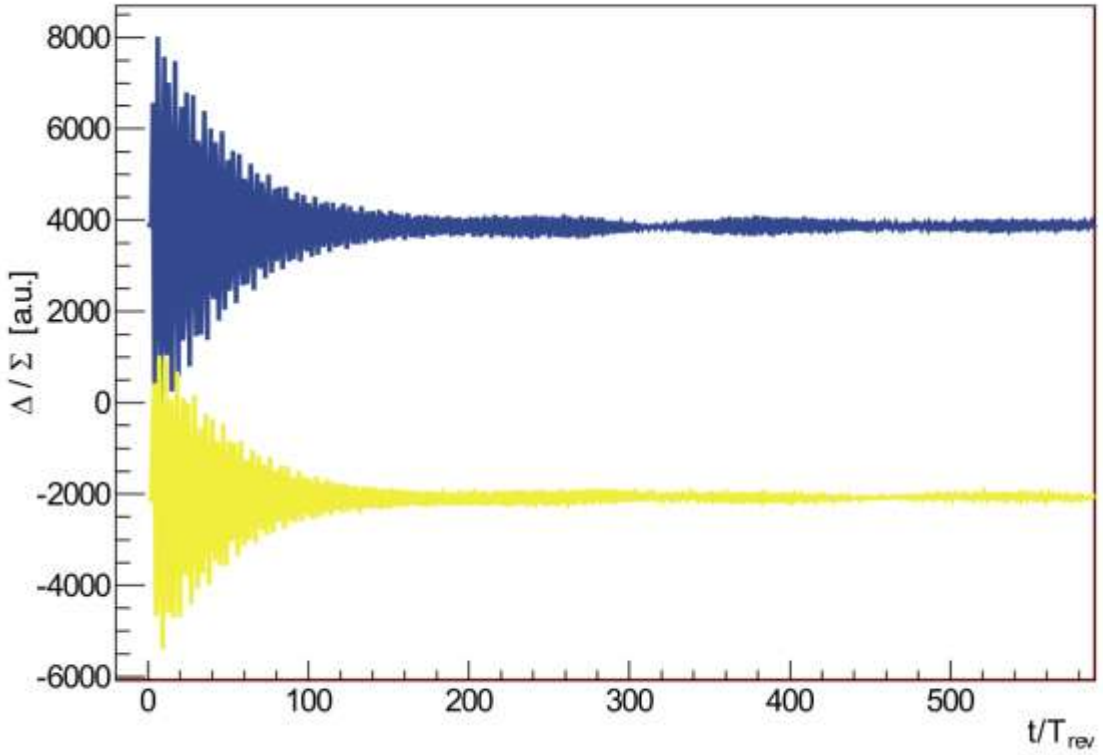
Beam Size evolution

5 – 6 May 2010

Damper on

The LHC Damper

150 ns Bunch Train Operation



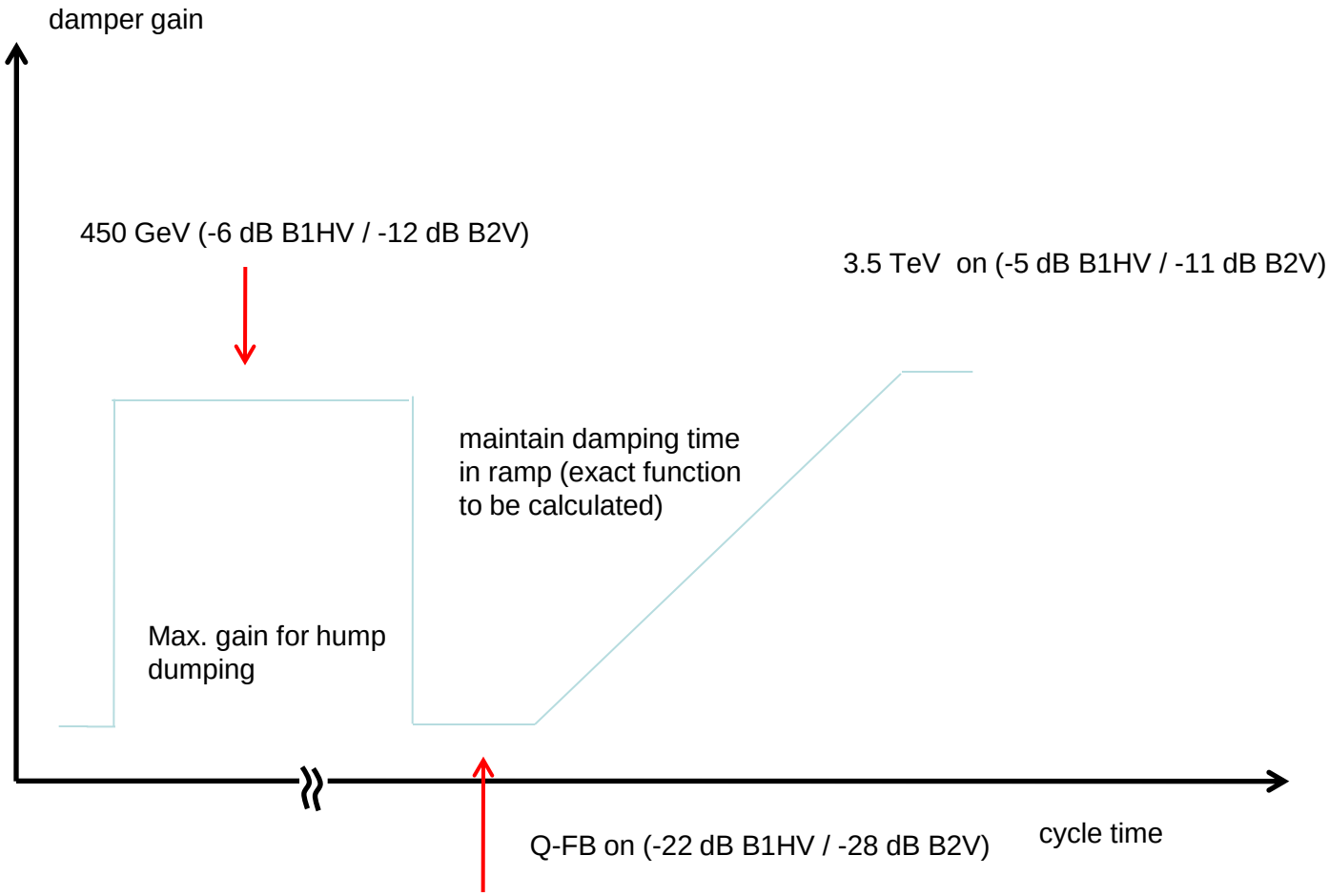
The LHC Damper specification:

- <1.3·10^{11} protons per bunch of length >1 ns at a saturation of ±2 mm
- an amplitude resolution of about 1 μm

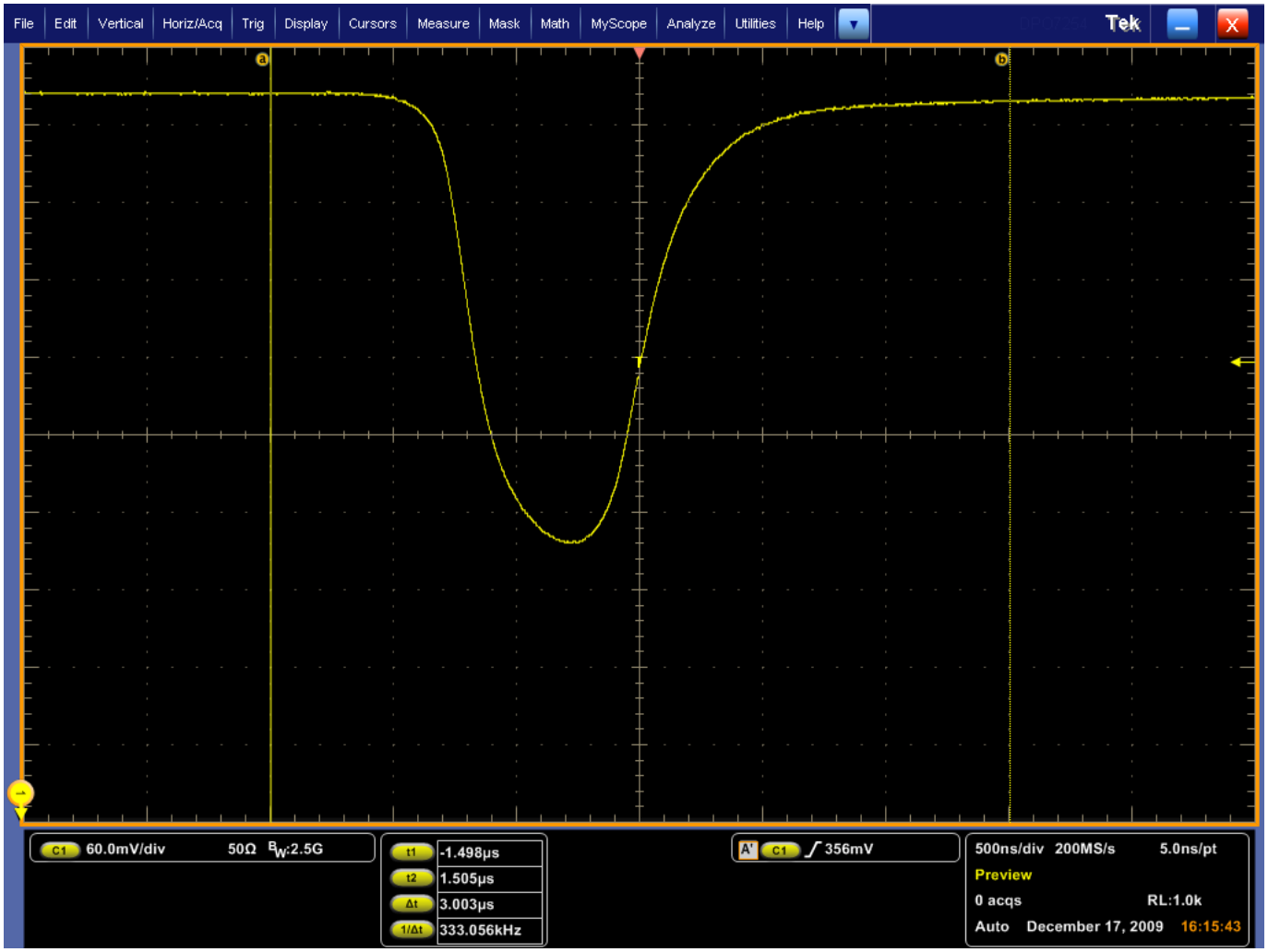
Pilot ramp

22.09.2010

- Damper functions at injection-ramp



Abort Gap Cleaning



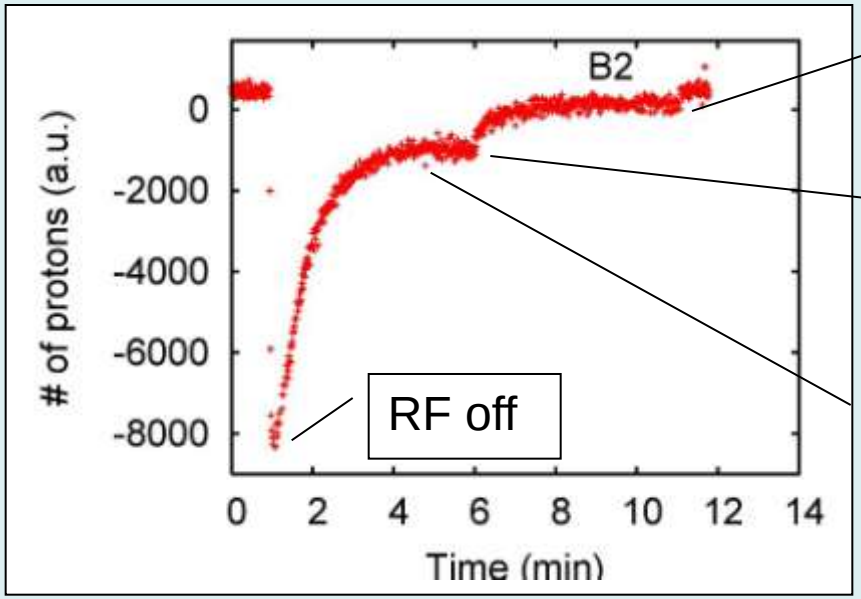
Cleaning pulse shape used in 2009 beam tests

Abort Gap Cleaning

EXPERIMENTAL RESULTS: 15-16 December 2009

Cleaning of a coasting beam:

- 4 bunches of $2.5 \cdot 10^{10}$ protons
- RF switched off
- After 5 minutes, started cleaning using stepped frequencies around Q_v



Beam dumped
→ gap had not been completely emptied.

cleaning starts
→ synchrotron light production decreased proportionally to the gap population

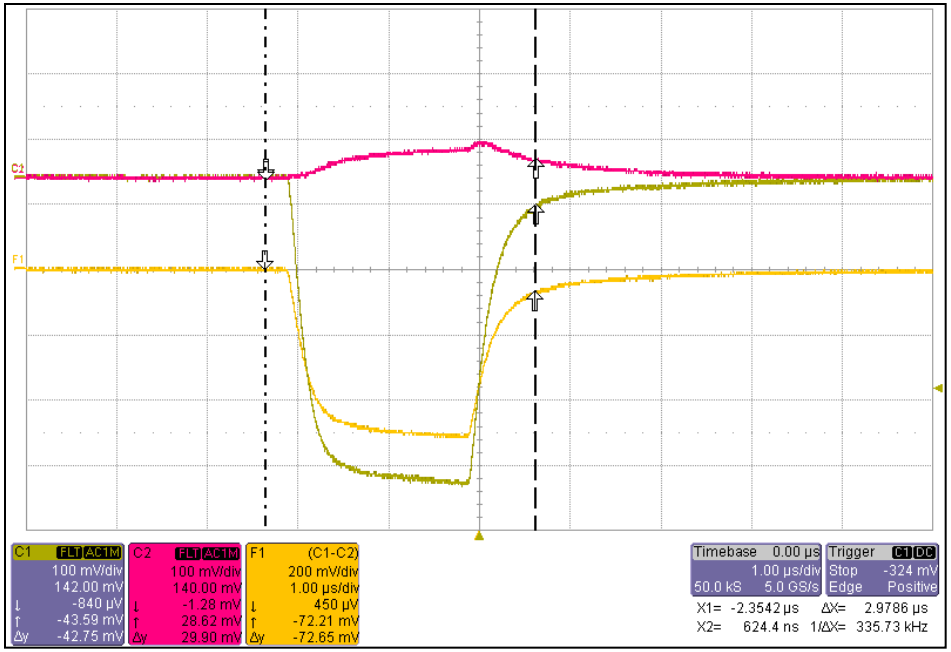
gap population equilibrium

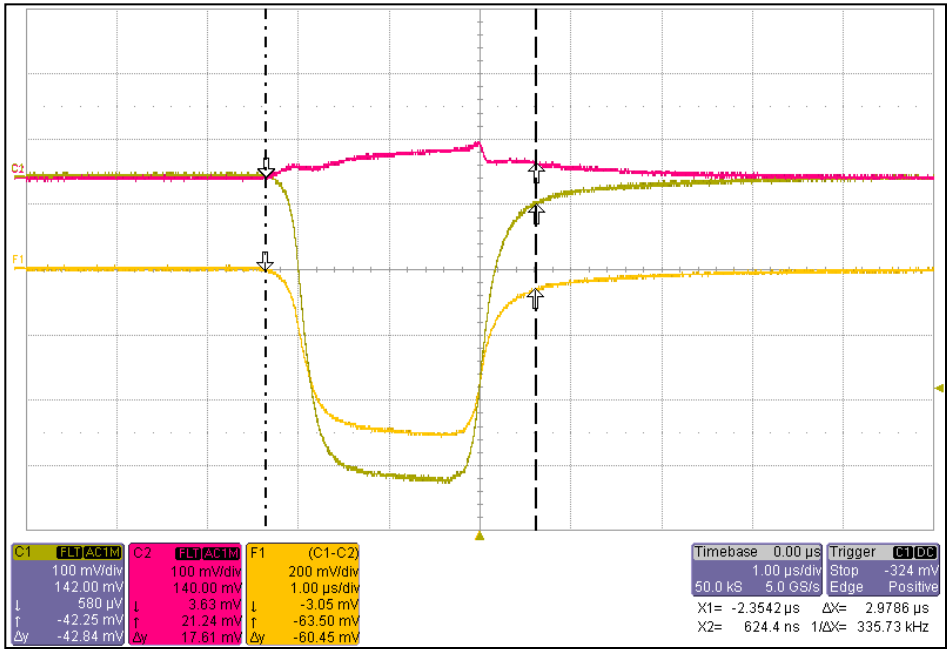
Abort Gap Monitor signal during coasting beam cleaning experiment.

T.Lefevre et al. “First Operation of the Abort Gap Monitors for LHC”. IPAC-2010, 23-28 May 2010, Kyoto, Japan, pp.2863 - 2865.

Abort Gap Cleaning

22.02.2010; V4.B2 (#16) W.Hofle & D.Valuch



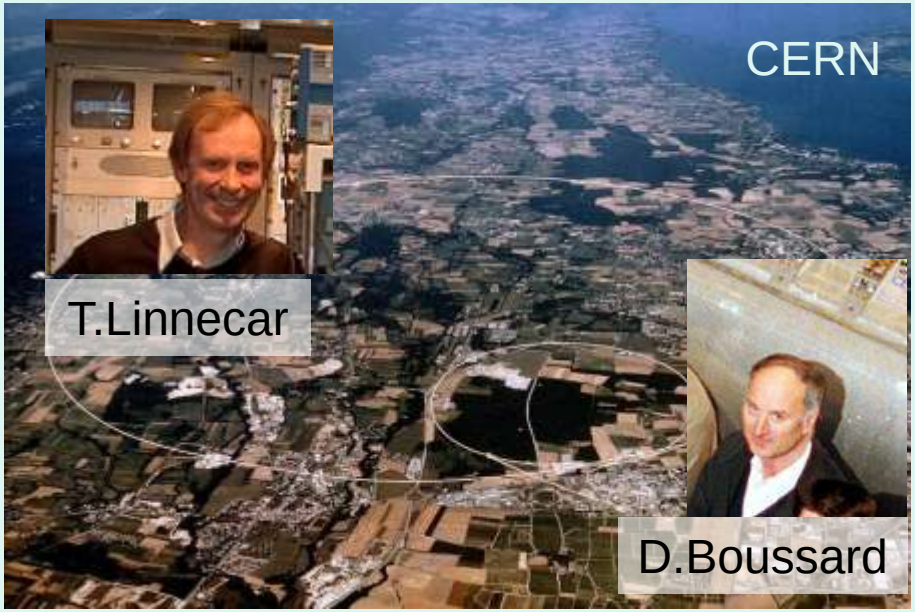


Abort gap cleaning pulse (full steam) seen @ switching matrix
left without phase compensation, right with phase compensation
red trace: non-active tube, olive: active tube, yellow: difference
2 us window modulated @ 3 kHz (gives the slope at flat top)

CONCLUSIONS

- Beam tests and commissioning of the LHC transverse feedback system have been successfully completed.
- All of the 16 damper kickers, 16 wideband power amplifiers and 8 low-level subsystems have been operating continuously since.
- **The LHC Damper is now routinely used during injection, ramping and collisions for active damping.**


V.P. Sarantsev, I.N. Ivanov, 1991


CERN
T.Linnecar
D.Boussard


JINR