LHC TRANSVERSE FEEDBACK SYSTEM:

FIRST RESULTS OF COMMISSIONING

V.M. Zhabitsky

XXI Russian Particle Accelerator Conference

28.09 -03.10.2008, Zvenigorod

LHC Transverse Feedback System: First Results of Commissioning

- **CERN**
  - W.Hofle, E.Montesinos, P.Baudrenghien, F.Killing, I.Kojevnikov, G.Kotzian, R.Louwerse, V.Rossi, M.Schokker, E.Thepenier, D.Valuch

- **JINR**
  - **LHC Damper**

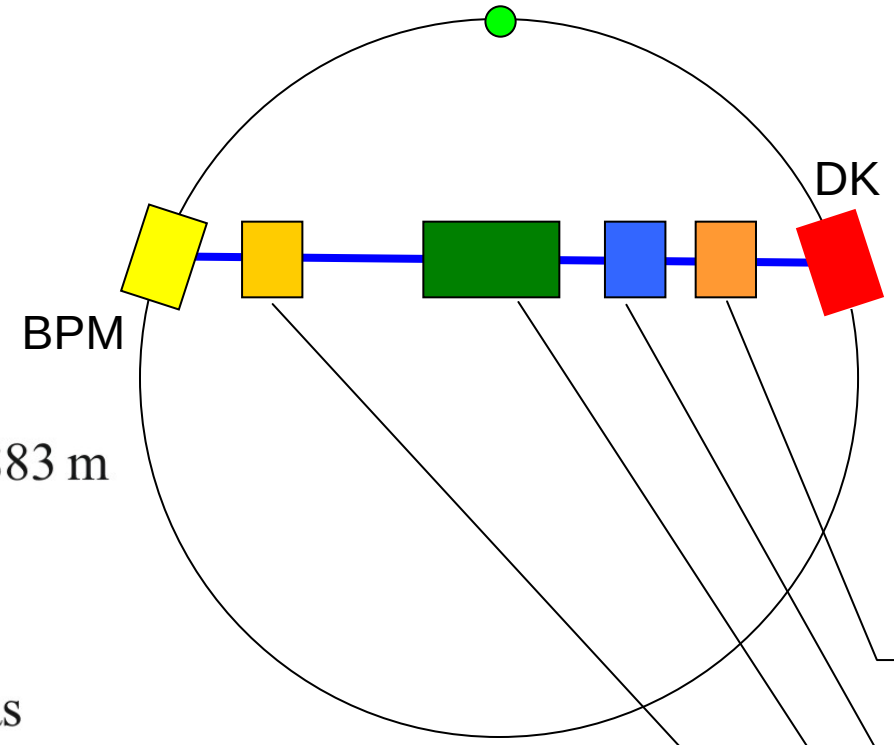
    V.M.Zhabitsky, N.I.Lebedev, E.V.Gorbachev, N.V.Pilyar, S.V.Rabtsun, A.A.Makarov, R.A.Smolkov

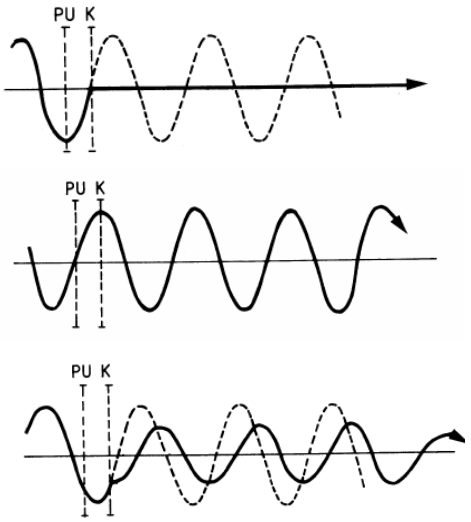
LHC Transverse Feedback System

- The LHC will provide high intensity proton and lead ion beams. The ultimate intensities after injection into the LHC will be about
  - $4.8 \cdot 10^{14}$ particles for the proton beam with an energy of 450 GeV,
  - $4.1 \cdot 10^{10}$ 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, and a significant contribution of the LHC collimators at collision energy to τ_{inst} is also predicted.
- <u>The LHC Damper will stabilize the beam</u>
  - 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.

The LHC Transverse Feedback System





$C_0 = 26658.883\ \text{m}$

$Q_H = 64.28$

$Q_V = 59.31$

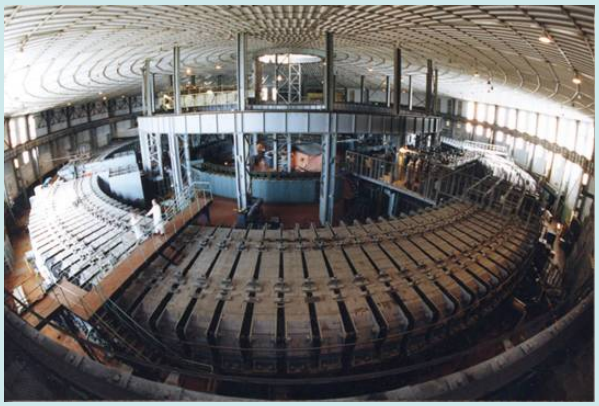
$T_{rev} = 88.93\ \mu\text{s}$

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

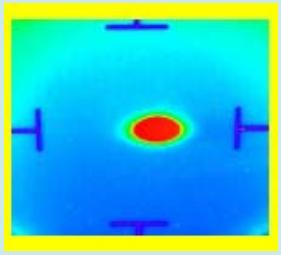
$K_b = 2808;\ \sigma_t = 0.375\ \text{ns}$

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

- Amplifier
- Delay
- Digital Signal Processor
- Front Electronics

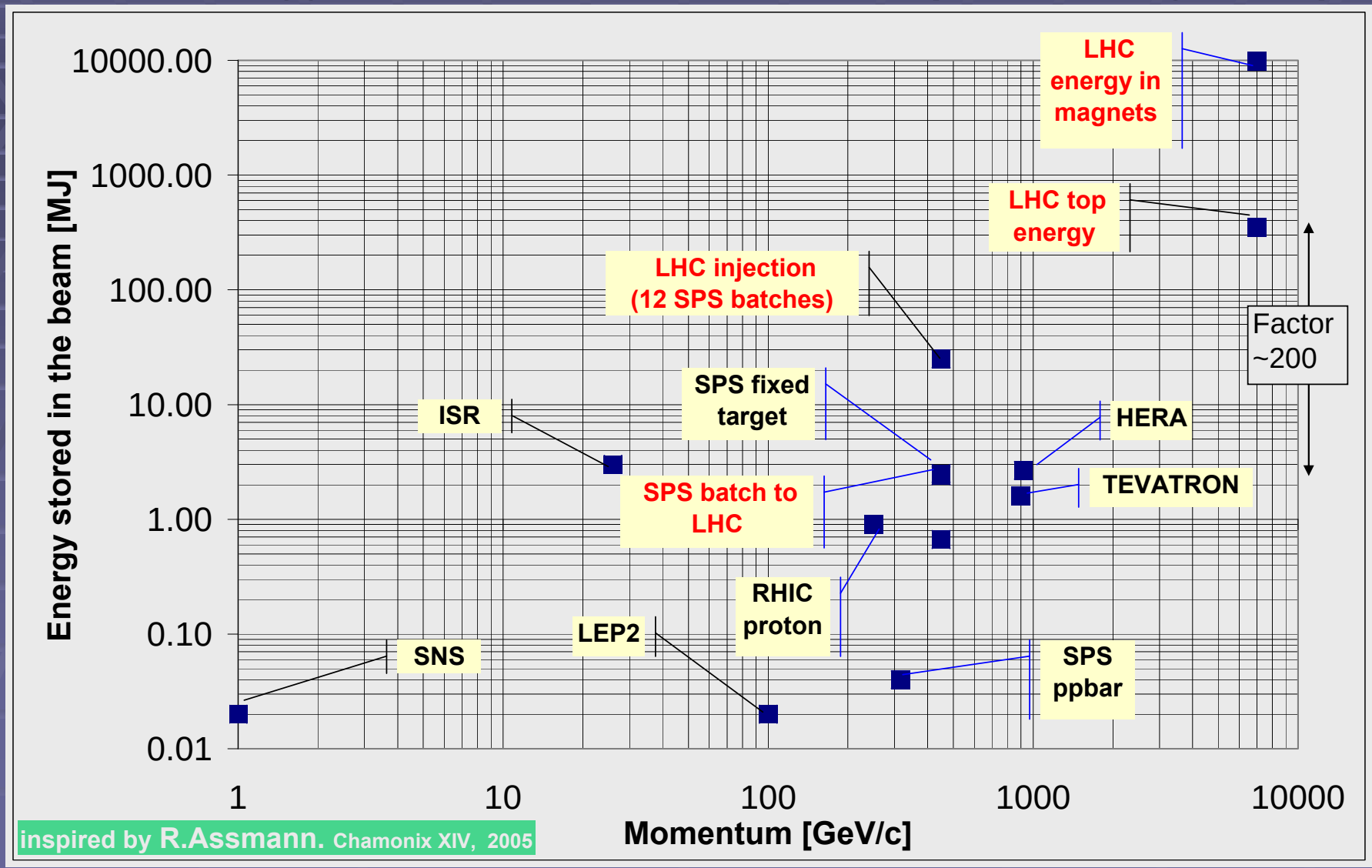


Synchrophasotron
(operated in 1957 - 2002)



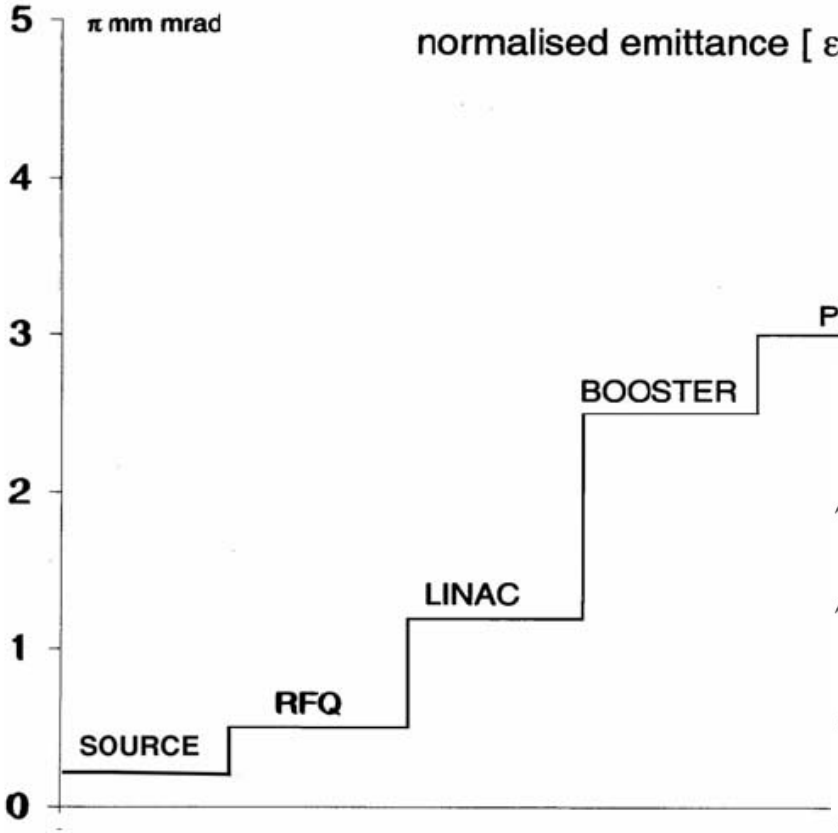
LHC: C_0 = 26658.883 m
1232 main dipole
392 main quadrupole magnets

Livingston type plot:
Energy stored in the beam (and magnets)



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

Emittance History (LHC-Design)



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

$$\tau_{\mathrm{d}} = 40T_{\mathrm{rev}}$$

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

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

$$\varepsilon_{\mathrm{n}} = 3.75\,\mu\mathrm{m}\cdot\mathrm{rad}$$

emittance blow up CAS'2003, Zeuthen, Sept. 2003 D. Möhl Slide 1

The LHC Damper

Performance specification

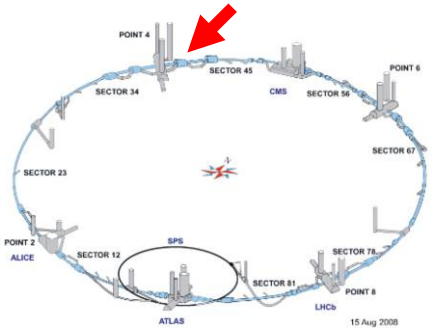
"Electro-static" kickers	base-band
Integrated transverse electric field $\int E_{\perp} ds$ (for 450 GeV/c)	900 kV per turn
Aperture of kickers	52 mm
Number of kickers per beam and plane	4
Length electrodes in kicker	1.5 m
Nominal voltage up to 1 MHz (at β = 100 m)	±7.5 kV
Kick per turn at 450 GeV/c (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

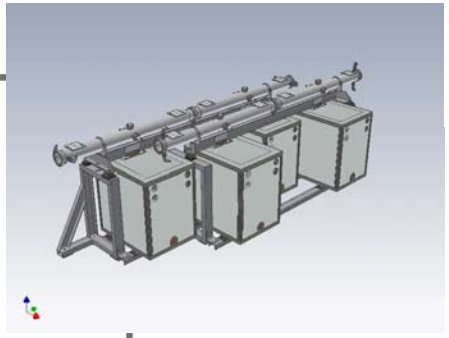
*) Rise time fast enough for gap of 38 missing bunches
(900 ns for rise time (0.5 %-99.5 %) in the LHC injection kicker)

All LHC Damper systems must operate on day ONE !

The LHC Damper

Installation and Physical layout in Point 4 underground LHC





Underground hall for LHC ADT

cavern

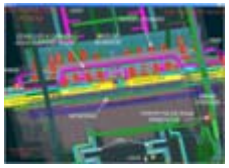
ADT (4 modules) left of IP4 + space for 2 more modules (upgrade)

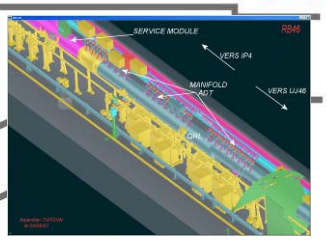
ADT (4 modules) right of IP4 + space for 2 more modules (upgrade)

ACS klystrons

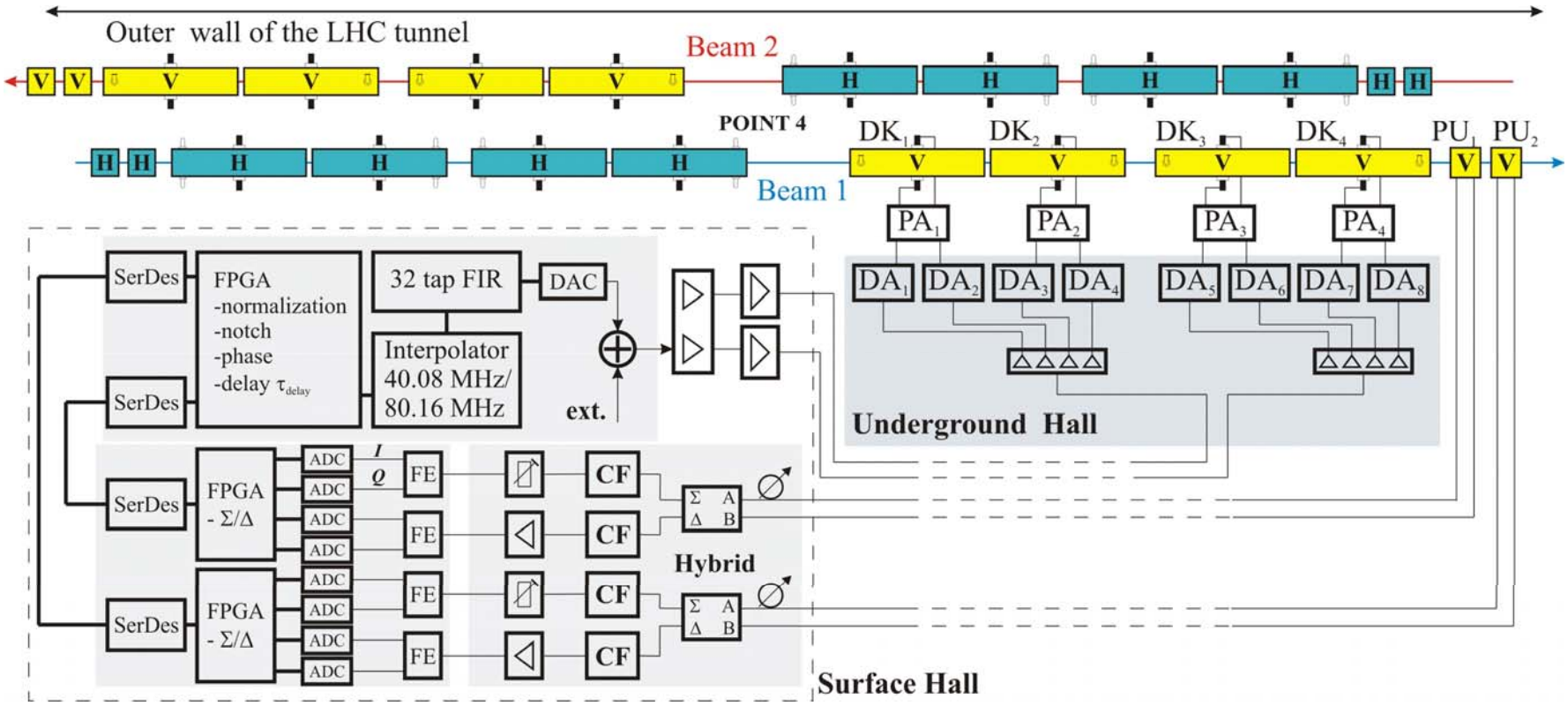
Outer wall of the LHC tunnel

Beam 2 ACN ADT ACS ACS ACS ACS ADT ACN Beam 1





The LHC Damper

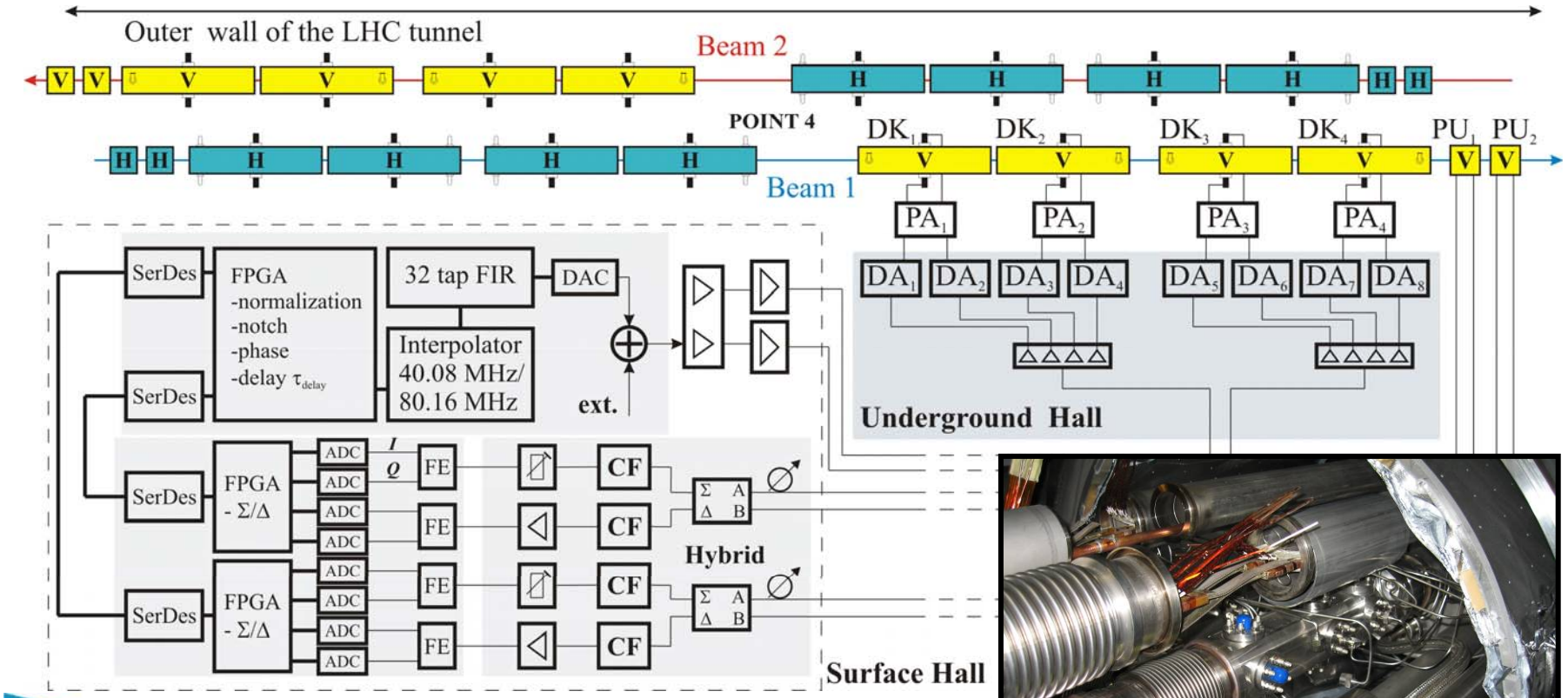


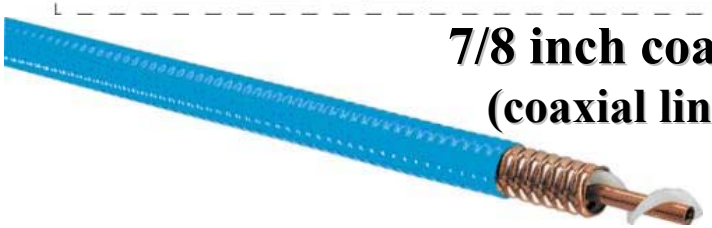
Layout of the LHC Damper

(four independent systems, one per plane (H/V) and beam) and 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



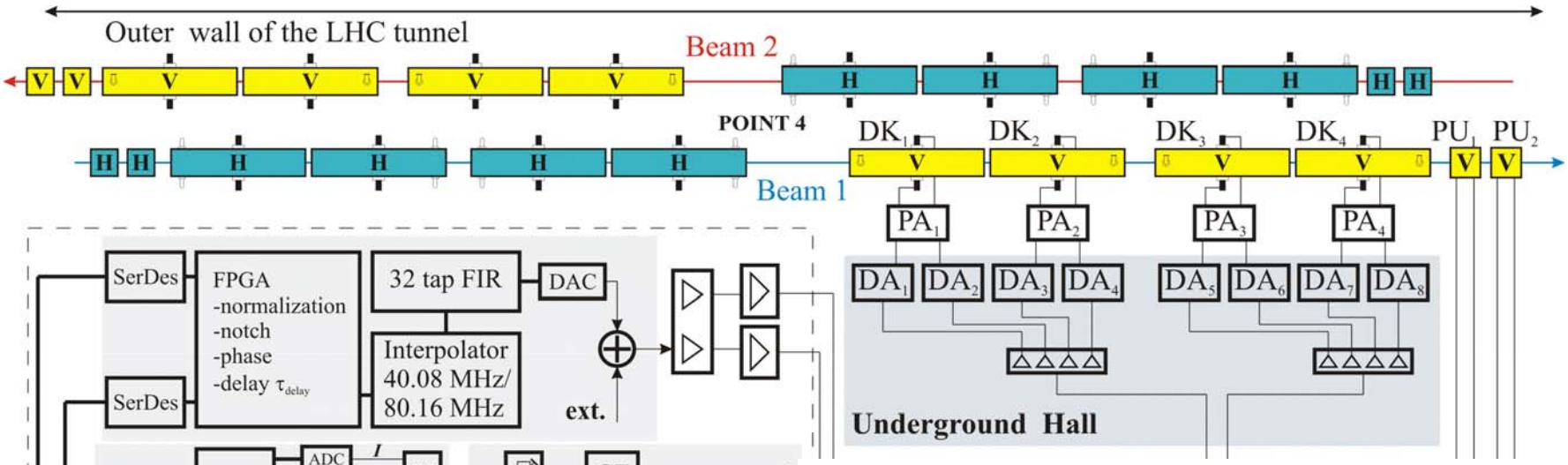


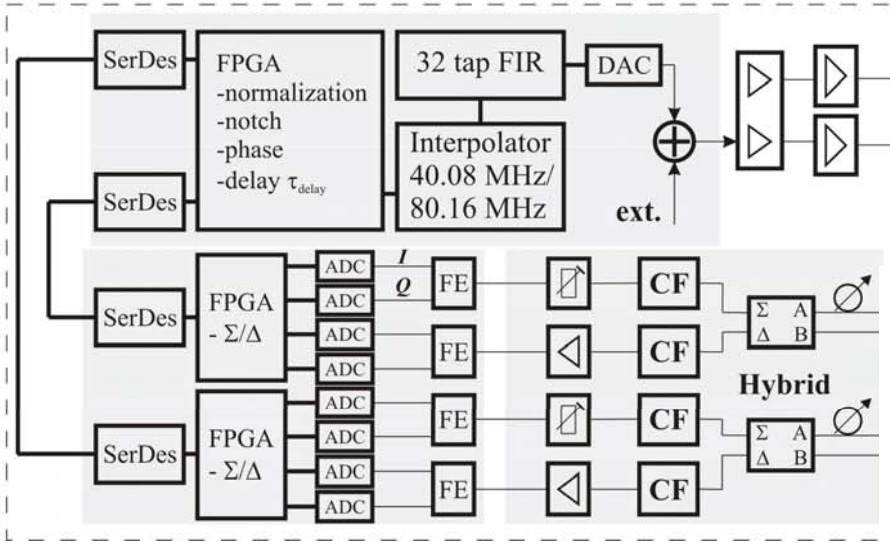
7/8 inch coaxial cable
(coaxial lines of 570-650 m)

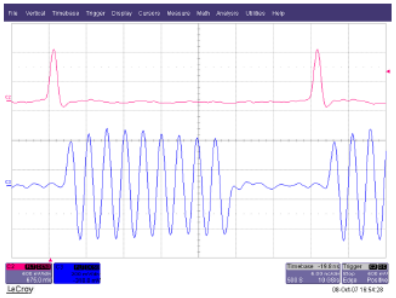
Beam Position Monitor in Cryomodule

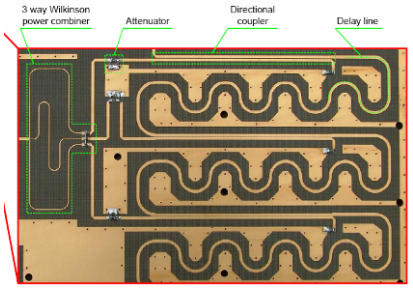
ANDREW A CommScope Company

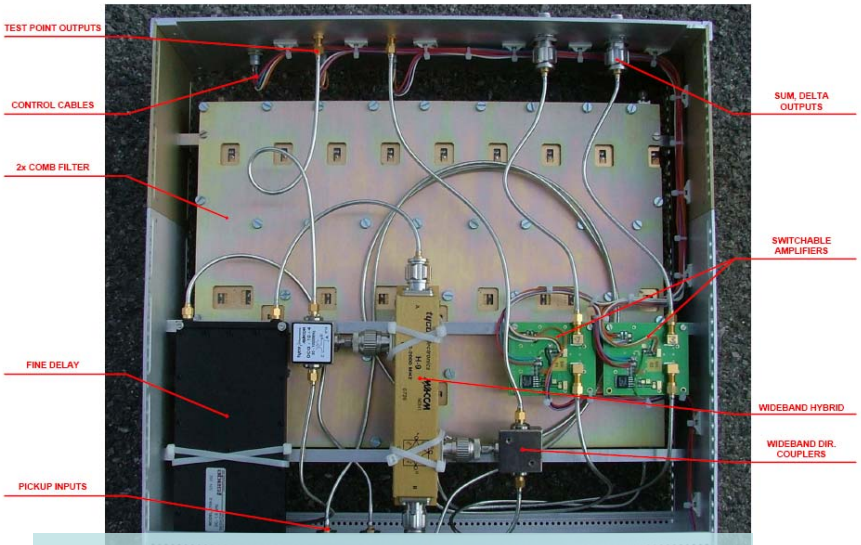
The LHC Damper





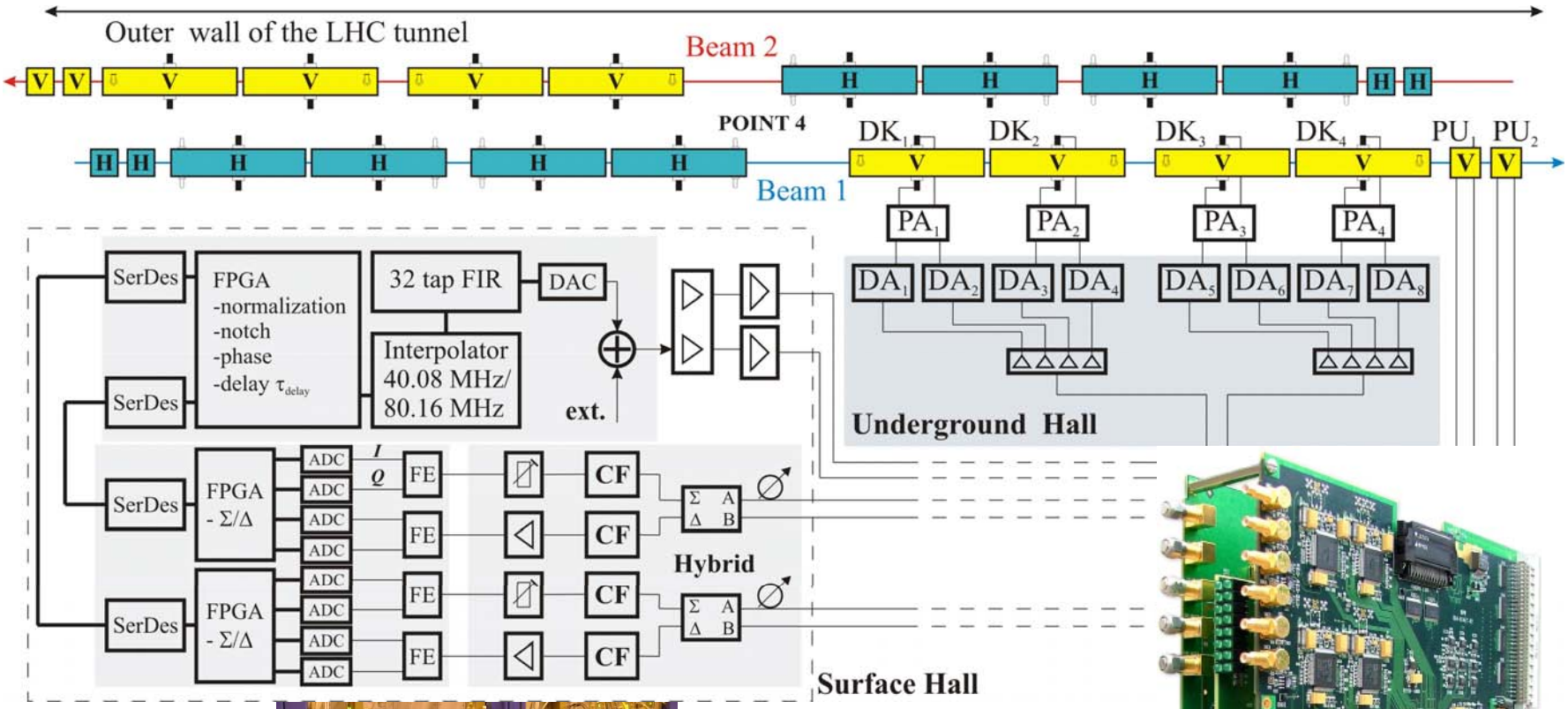






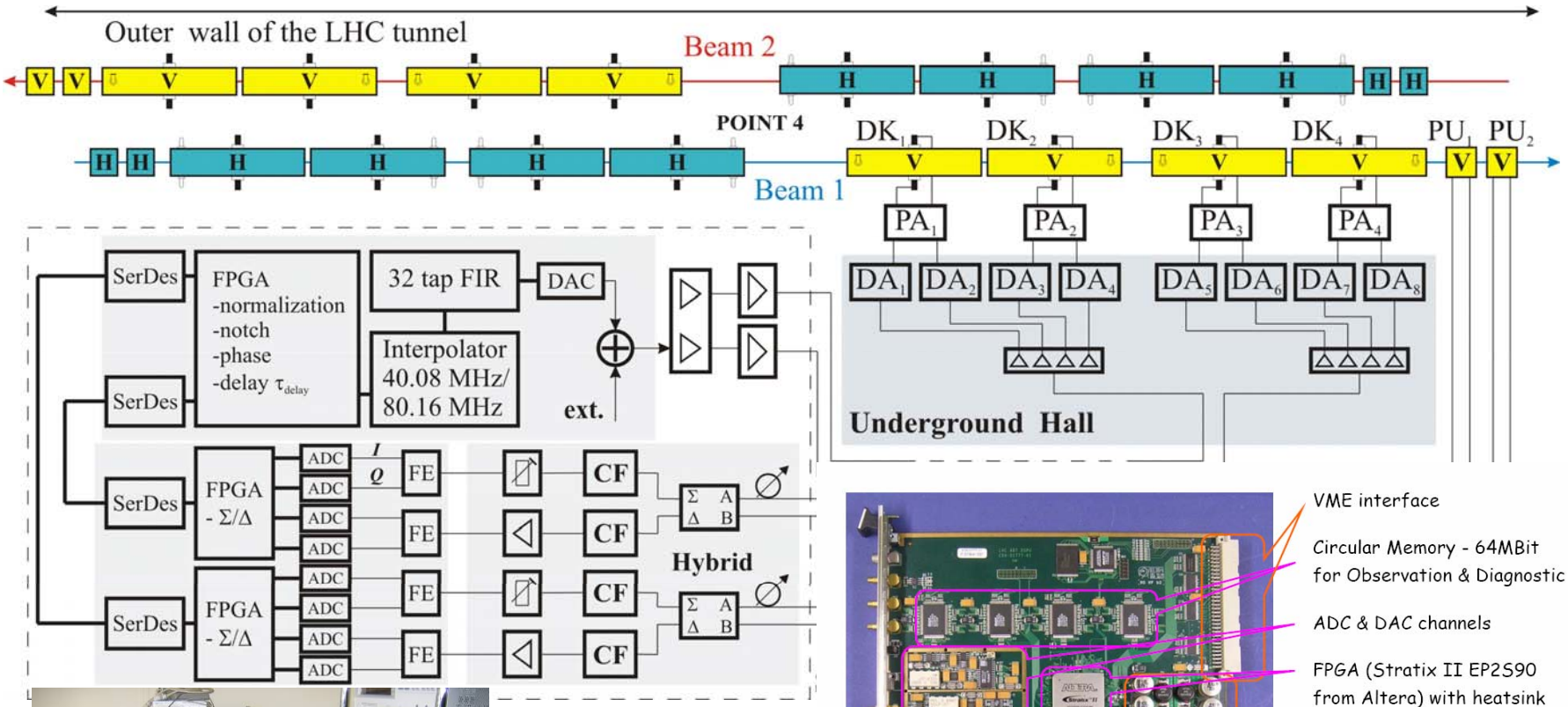
Pick-up Signal Processor Crate

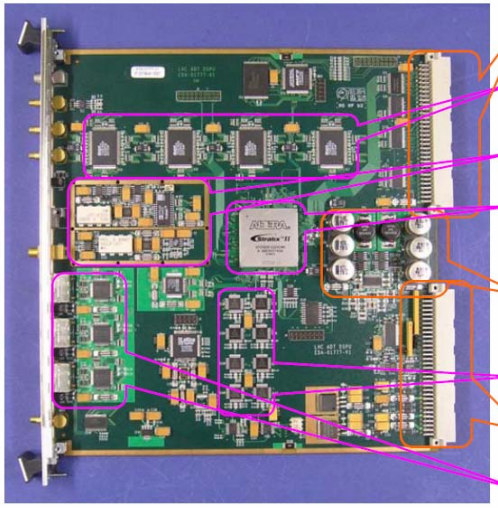
The LHC Damper



Beam Position Unit

The LHC Damper





VME interface

Circular Memory - 64MBit for Observation & Diagnostic

ADC & DAC channels

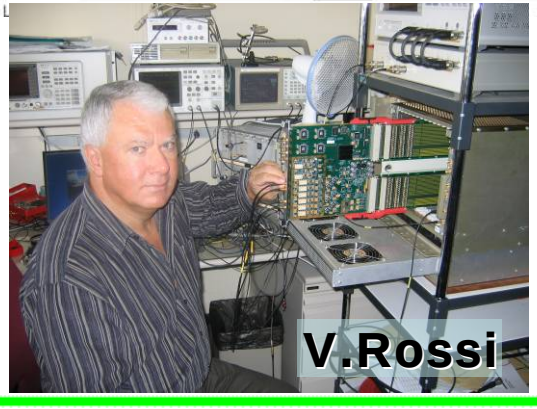
FPGA (Stratix II EP2S90 from Altera) with heatsink

Dual-voltage synch-switching regulator for FPGA core & IO

Dual channel Prog. Delay

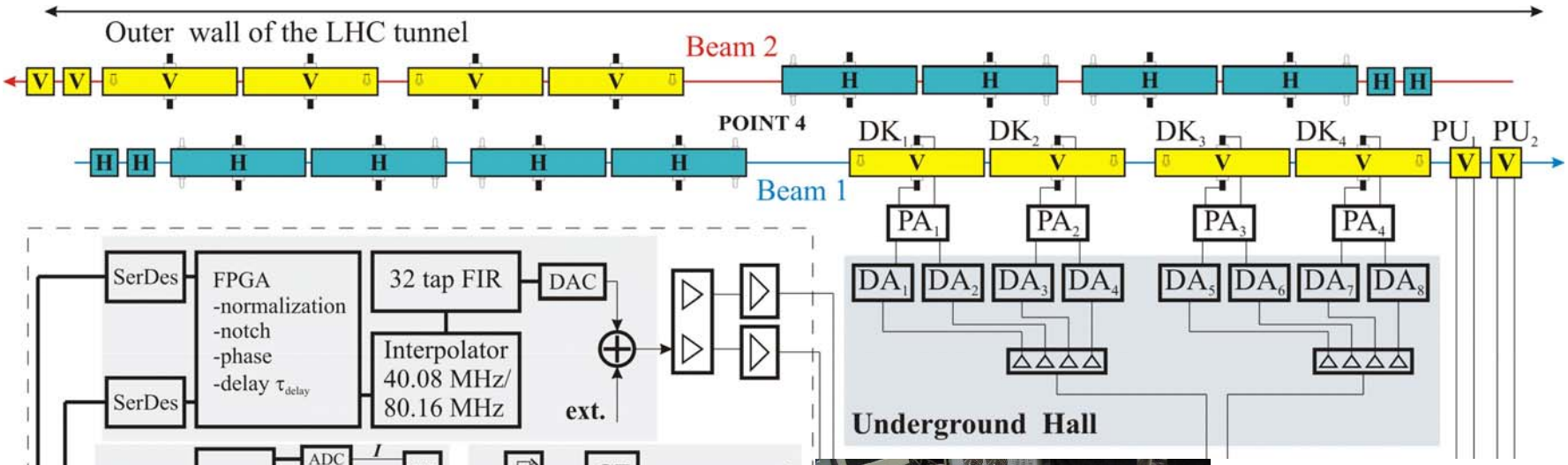
Backplane interface

Serdes channels



Digital Signal Processor Unit

The LHC Damper

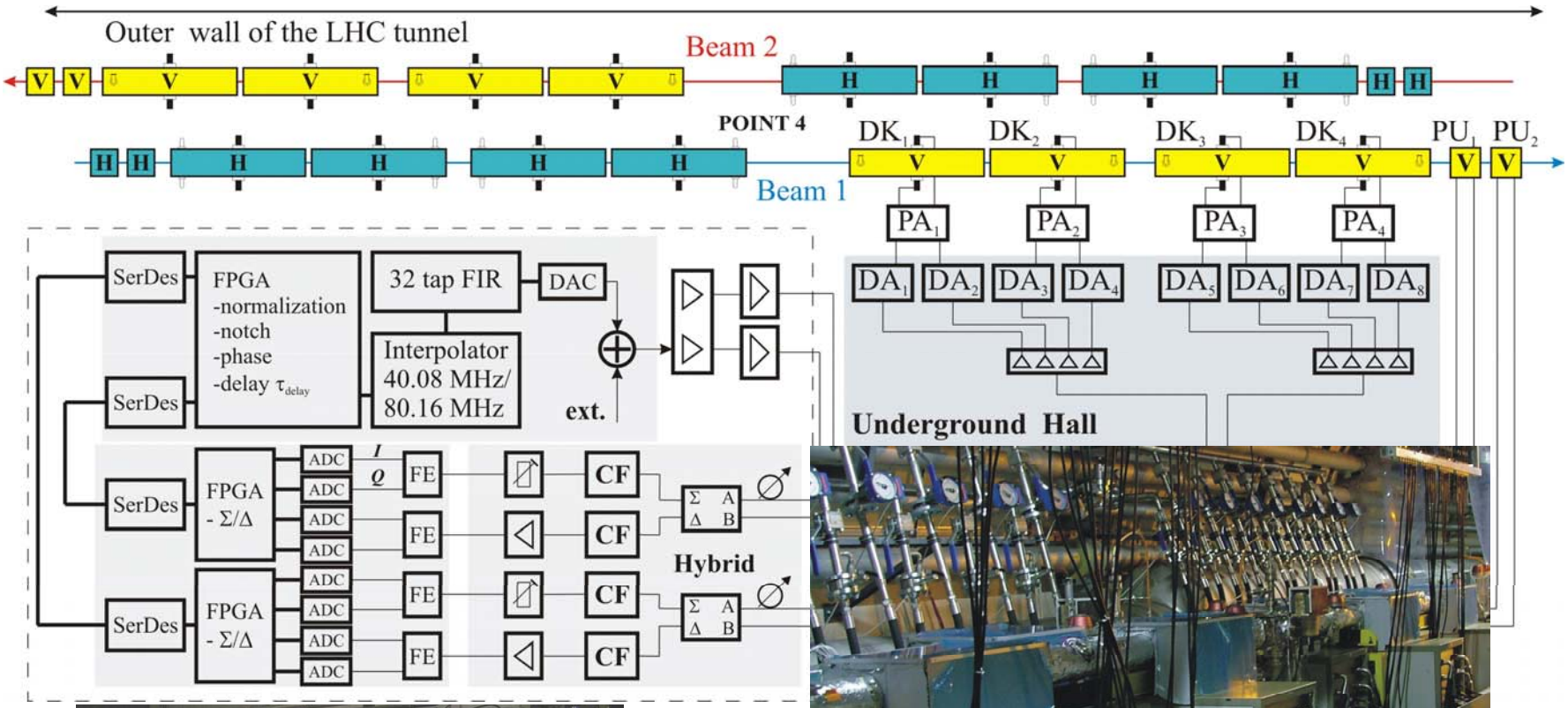


THALES

The Thales Communications (Belgium)

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

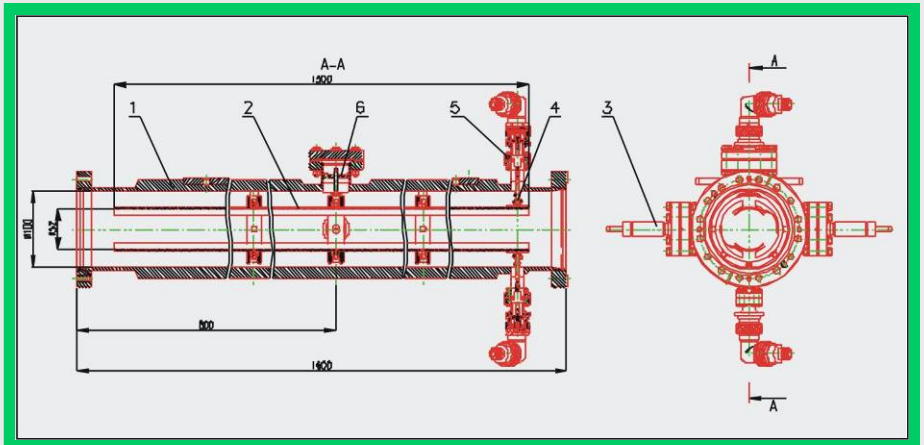
The LHC Damper



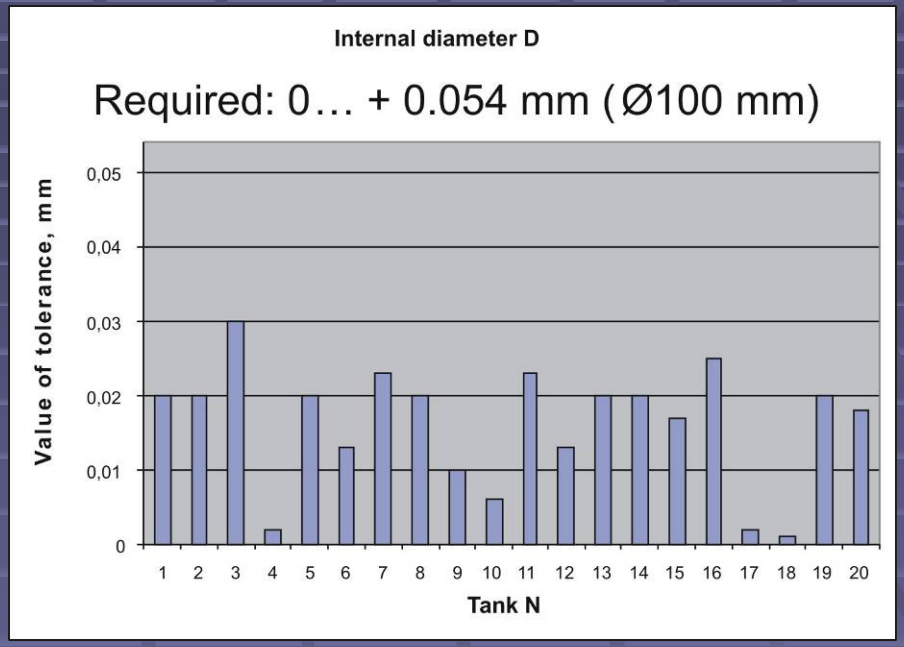

CERN. 21 December 2006.

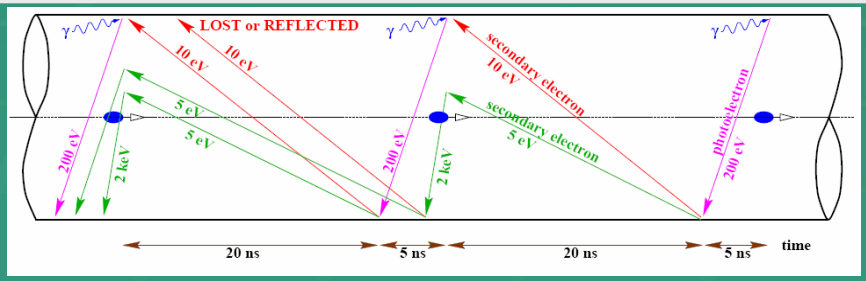
Electrostatic Kickers and
Wideband Power Amplifiers in the LHC tunnel

The LHC Damper



A fragment of an assembly drawing of a vertical kicker:
1 - vacuum tank (wall thickness: δ = 14 mm),
2 - electrodes, 3 - input of a signal,
4 – coupler, 5 – feedthrough for coupler,
6 - device of fixing of the electrode module.



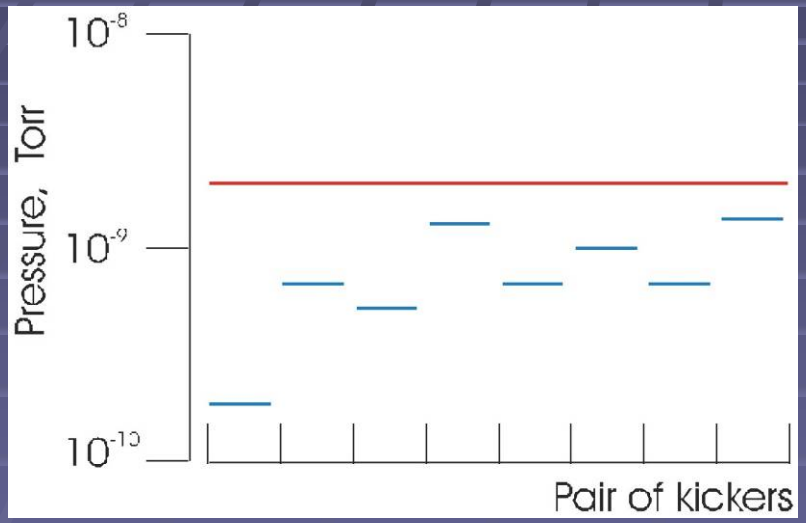


Electron cloud's problem: F. Ruggiero (CERN).
Chamonix XI, 15 – 19 January 2001

S.Rabtsun. Leading Designer.

The LHC Damper

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



The obtained pressure limits of outgassing (stainless steel 304L) were from $2.0 \cdot 10^{-10}$ Torr to $1.7 \cdot 10^{-9}$ Torr.
All data (blue lines) are better than the expected limit of $2 \cdot 10^{-9}$ Torr (red line: bake-out 200°C, 24 h, surface ougassing rate≈$4 \cdot 10^{-12}$mbar·l/s/cm², S=$2 \cdot 10^4$cm², P=30 *l*/s for hydrogen).

NEG pumps around the kickers are used in the LHC tunnel.

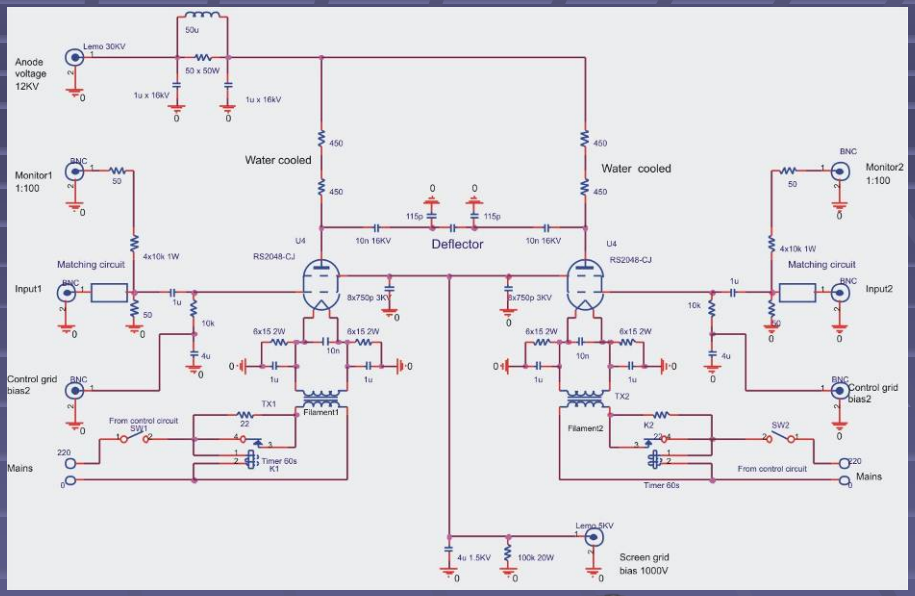
During hardware and beam commissioning the vacuum at the kickers was better than 10^{-11} mbar.

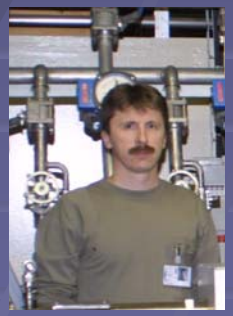
The LHC Damper

N.I.Lebedev,
Leading engineer.

E.V.Gorbachev,
Leading engineer.

A.A.Makarov,
Leading designer.





R.A.Smolkov,
Leading
engineer.

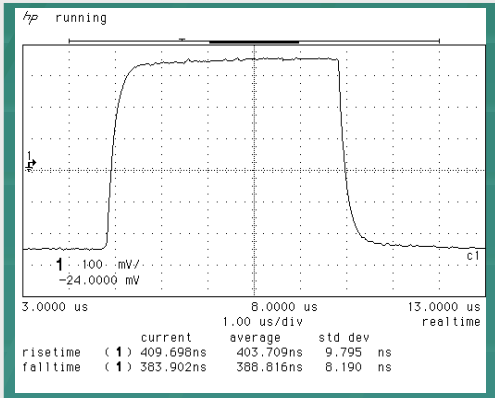
N.V.Pilyar,
Leading
engineer.

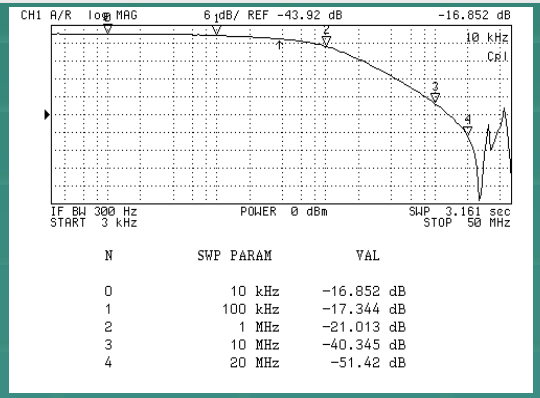
"Push-pull" wideband power amplifier:

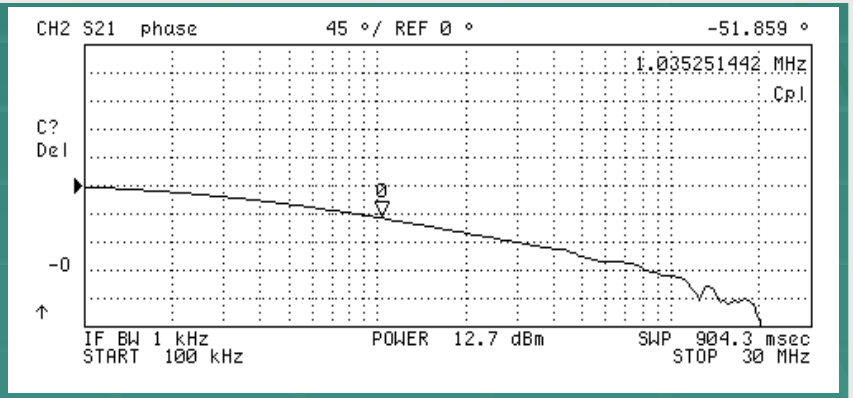
- Class of operation: AB
- Input amplitude: ±150 V
- Output amplitude: ±7500 V
- Bandwidth: 1 kHz – 1 (20) MHz
- Power elements: two 30 kW "Thales" RS 2048-CJC tetrodes

The LHC Damper

Parameter	Required	Achieved
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 up to 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.
An amplitude of ±7.8 kV was obtained on the deflector which is higher the required magnitude of ±7.5 kV.

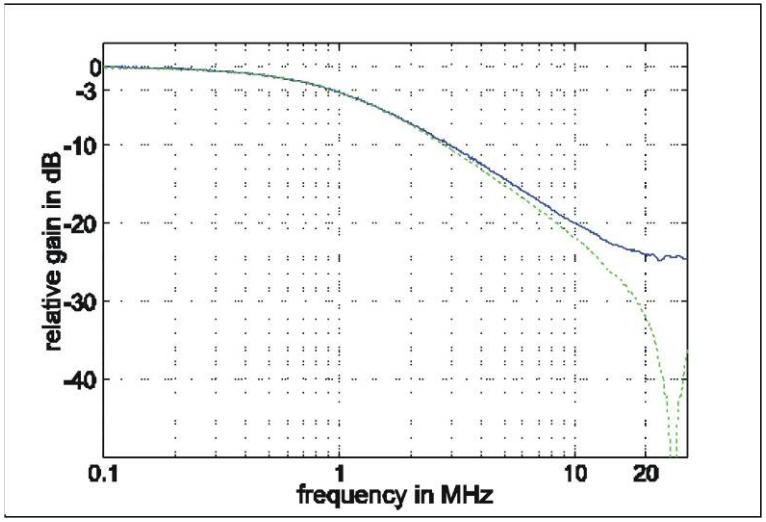
The LHC Damper

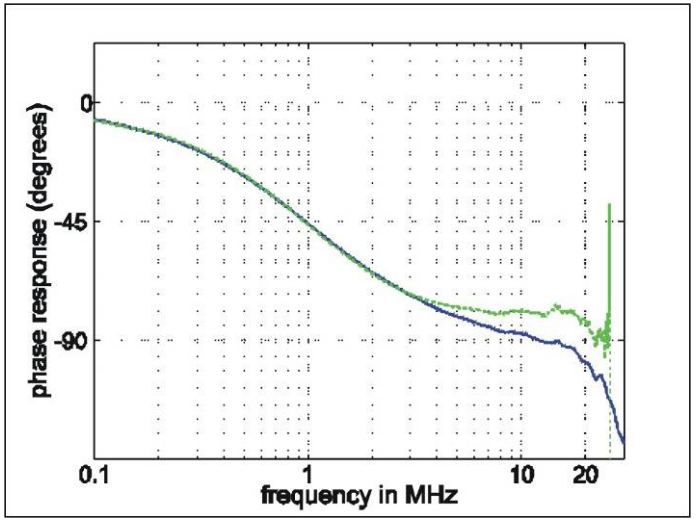
Beam stability is achieved for a damping rate

$$\frac{T_{\mathrm{rev}}}{\tau_{\mathrm{d}}} = \frac{1}{2} g(\omega)\cos(\varphi(\omega)) \quad > \quad \frac{T_{\mathrm{rev}}}{\tau_{\mathrm{inst}}}$$

where $g(\omega)$ and $\varphi(\omega)$ are gain and phase transfer characteristics of the feedback loop.

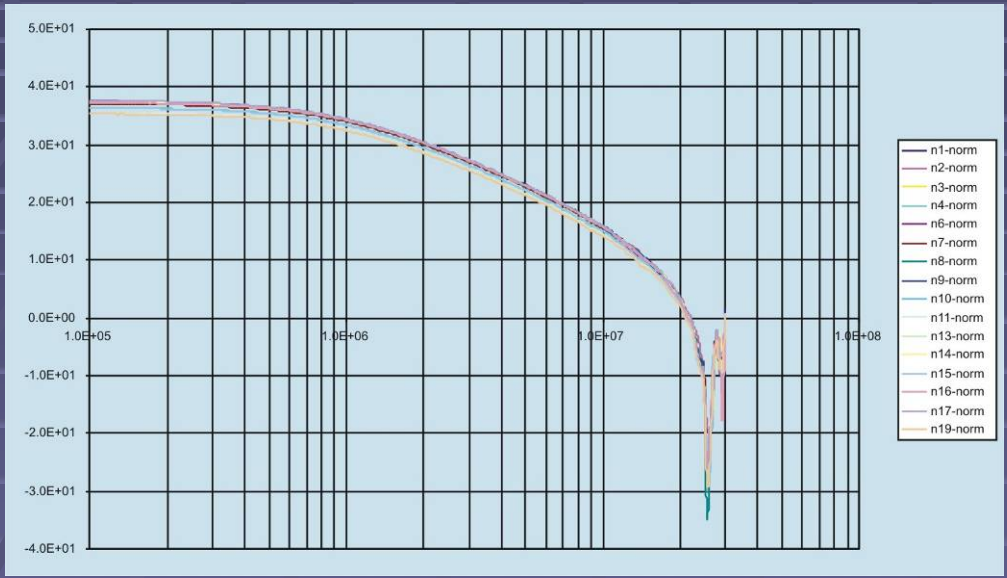
Due to the LHC specifications, the gain transfer function of the feedback loop is constant starting from 1 kHz and decreases by 3 dB at 1 MHz.

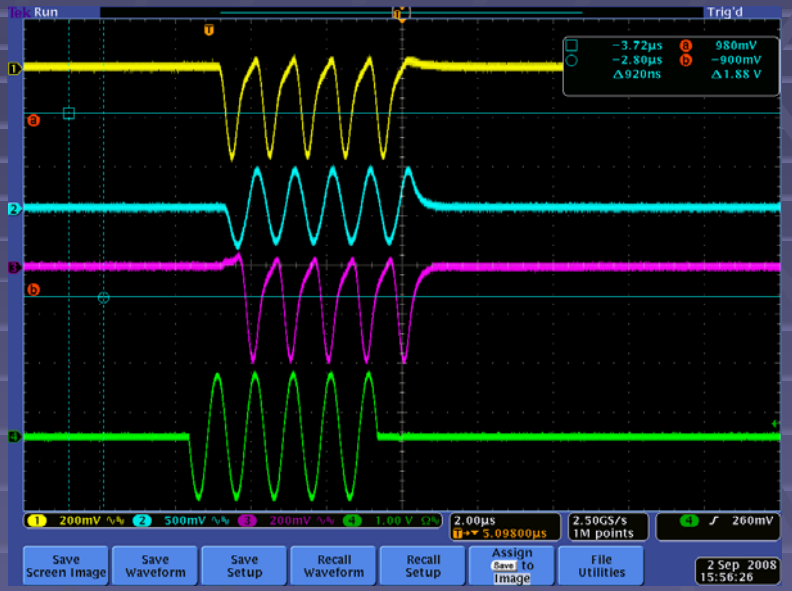




Frequency characteristics for kicker voltage measured via the HOM port and recalculated from high pass with a cut-off of f_{HP} = 500 MHz (blue, solid) and tetrode anode voltage (green, dashed)

The LHC Damper





The 16 amplifiers were tested at full DC anode voltage of 12kV, 7A of DC current per amplifier and with 0dBm signal source.

Input circuit, amplitude and phase characteristics of all 16 amplifiers were stored in pictures and data files.

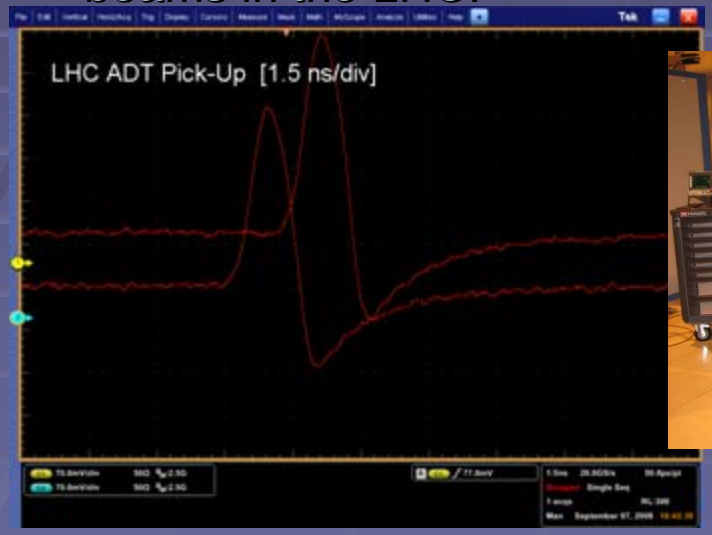
The LHC Damper

Hardware commissioning:

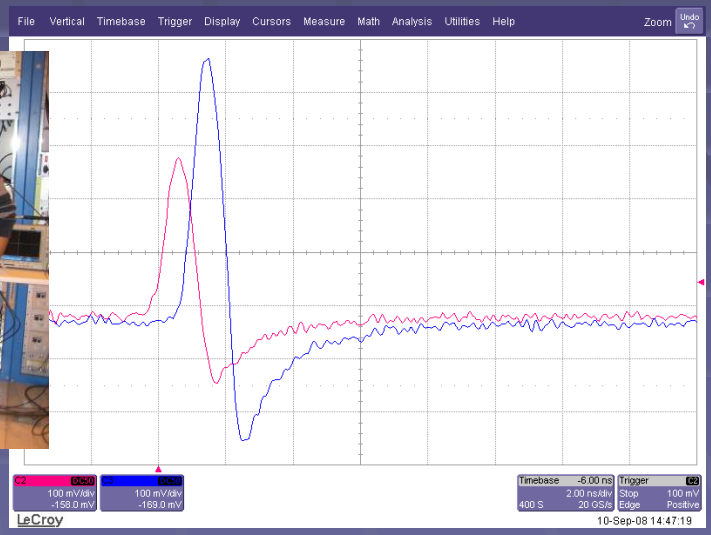
- all extensive tests required were completed in full volume and in time; the design specifications have all been met, the available peak voltage 11kV at up to 100kHz has exceeded the design value 10.5kV at kickers.

Beam commissioning:

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



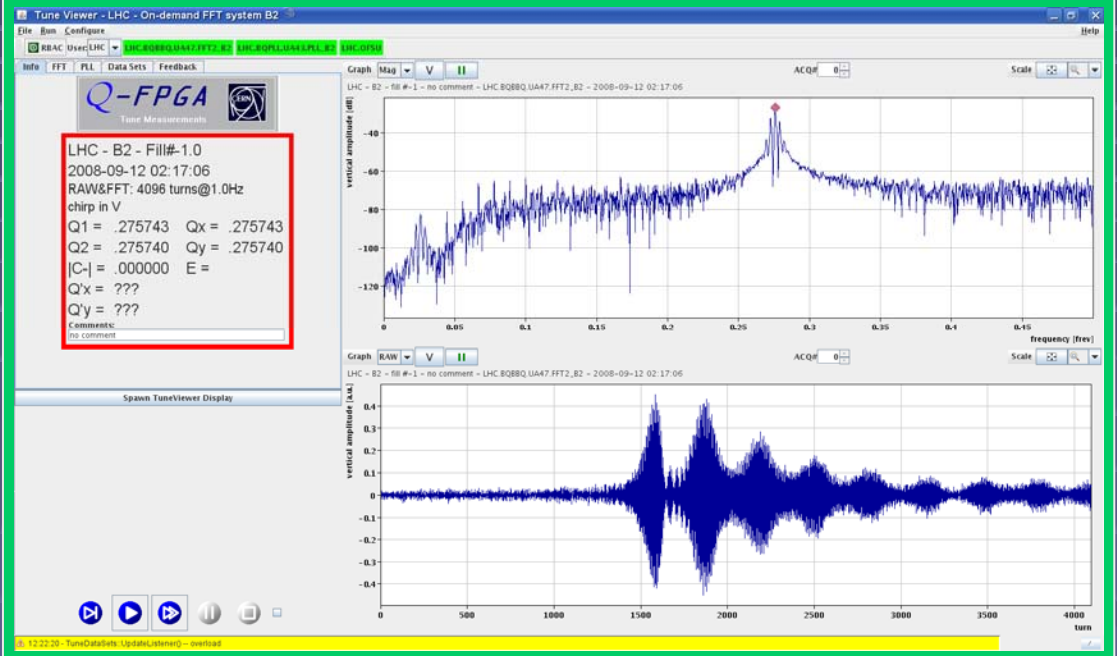
Signals from the LHC Damper pick-up for the first shot of beam 1. 7 September 2008.



Signals from the LHC Damper pick-up for the first shot of beam 2. 10 September 2008.

The LHC Damper & Tune Measurements

- **Tune measurements were the first operational option for the LHC Damper when it was used as exciter after obtaining the circulating beam 2 on 22:23, 11 September 2008.**
- **Beam was scanned by sweeping-frequency generator as external signal source in the feedback loop at half the level of the maximum power of the wideband power amplifiers.**

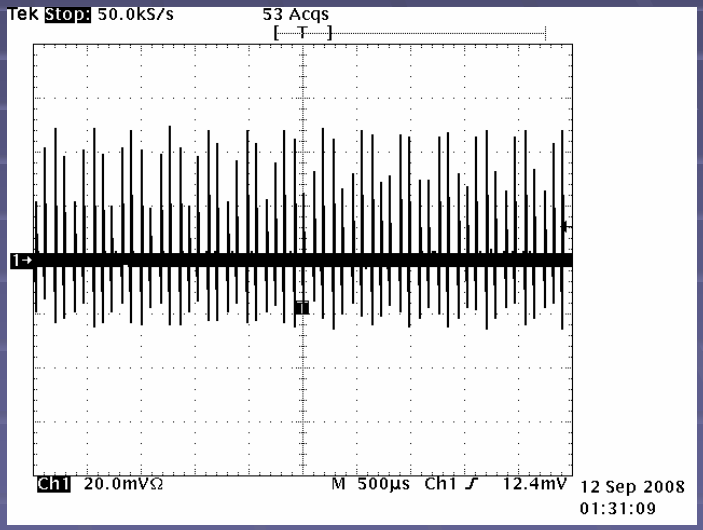


A Tune Measurement using “Chirp” Excitation (courtesy AB/BI). The bottom trace shows the vertical beam response; the top trace is the spectrum of the signal with the vertical tune peak.

The LHC Damper commissioning plans

- low-level damper hardware deployed to be ready to close the loops on all dampers;
- transverse position measurement checked
- getting ready to close the loops.

40 MHz sampling clock adjustment started on beam 2 damper pick-ups shortly after first beam capture



Vertical oscillations on beam 2, @Q7, seen by damper pick-up signal processing

The LHC Damper