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**

- **JINR**
  - LHC Damper
  - V.M.Zhabitsky, N.I.Lebedev, E.V.Gorbachev, N.V.Pilyar, S.V.Rabtsun, A.A.Makarov, R.A.Smolkov
• 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 $^{208}\text{Pb}^{82+}$ beam with an energy of 177 GeV/u. These intensities can lead to coherent transverse instabilities.

• The theoretical prediction for the instability rise time $\tau_{\text{inst}}$, 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 $\tau_{\text{inst}}$ is also predicted.

• 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.
The LHC Transverse Feedback System

\[ C_0 = 26658.883 \text{ m} \]
\[ Q_H = 64.28 \]
\[ Q_V = 59.31 \]
\[ T_{\text{rev}} = 88.93 \mu\text{s} \]
\[ f_b = f_{\text{RF}} / 10 = 40 \text{ MHz}; \quad f_b^{-1} = 25 \text{ ns} \]
\[ K_b = 2808; \quad \sigma_t = 0.375 \text{ ns} \]
\[ N_b = 5 \cdot 10^9 \text{(pilot beam)} \Rightarrow 1.15 \cdot 10^{11} \Rightarrow 1.7 \cdot 10^{11} \]
Synchrophasotron
(operated in 1957 - 2002)

LHC:
\[ C_0 = 26658.883 \, \text{m} \]
1232 main dipole
392 main quadrupole magnets

7 TeV
- 8.33T, 15 m
- 11850A
- 7MJ
\[ \varepsilon = \left( 1 + \frac{e_{\text{inj}}^2}{2\sigma_0^2} \right) \varepsilon_0 \]

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

**Emittance History (LHC-Design)**

[Diagram showing normalized emittance with various stages labeled: SOURCE, RFQ, LINAC, BOOSTER, PS, SPS, LHC.]

- **LHC**: \( e_{\text{inj}} \leq 3.5\sigma_0 \)
- \( \tau_d = 40T_{\text{rev}} \)
- \( \tau_{\text{inst}} > 208T_{\text{rev}} \); \( \tau_{\text{dec}} \approx 750T_{\text{rev}} \)
- \( \varepsilon_{n0} = 3.5 \mu\text{m} \cdot \text{rad} \Rightarrow +2.3\% \)
- \( \varepsilon_n = 3.75 \mu\text{m} \cdot \text{rad} \)
### Performance specification

<table>
<thead>
<tr>
<th>“Electro-static” kickers</th>
<th>base-band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated transverse electric field [E_\perp ds] (for 450 GeV/c)</td>
<td>900 kV per turn</td>
</tr>
<tr>
<td>Aperture of kickers</td>
<td>52 mm</td>
</tr>
<tr>
<td>Number of kickers per beam and plane</td>
<td>4</td>
</tr>
<tr>
<td>Length electrodes in kicker</td>
<td>1.5 m</td>
</tr>
<tr>
<td>Nominal voltage up to 1 MHz (at (\beta = 100) m)</td>
<td>±7.5 kV</td>
</tr>
<tr>
<td>Kick per turn at 450 GeV/c (at (\beta = 100) m)</td>
<td>2 (\mu)rad (0.2 (\sigma))</td>
</tr>
<tr>
<td>Rise-time 10-90%, (V_{\text{max}} = \pm 7.5 \text{ kV})</td>
<td>350 ns</td>
</tr>
<tr>
<td>Rise-time 1-99%, (V_{\text{max}} = \pm 7.5 \text{ kV})</td>
<td>720 ns *)</td>
</tr>
<tr>
<td>Frequency range for gain</td>
<td>1 kHz – 1 (20) MHz</td>
</tr>
</tbody>
</table>

*) 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!
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) 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

Beam Position Monitor in Cryomodule

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

Pick-up Signal Processor Crate

Outer wall of the LHC tunnel

Beam 2

H H H H H H H

POINT 4

DK 1 DK 2 DK 3 DK 4

PU 1 PU 2

Beam 1

PA 1 PA 2 PA 3 PA 4

DA 1 DA 2 DA 3 DA 4

Underground Hall

SerDes

FPGA

-normalization

-notch

-phase

-delay $\tau_{\text{delay}}$

32 tap FIR

DAC

Interpolator

40.08 MHz/80.16 MHz

Hybrid

ADC

CF

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Σ A

Δ B

Sigma delta modulator

Differential amplifier

Delay line
The LHC Damper

The illustration shows a schematic of the LHC Damper system, including the beam position unit and its components. The diagram includes labels and connections for various elements such as SerDes, FPGA, DAC, and ADC. The diagram also indicates the interaction between the Underground Hall and the Surface Hall through the beam position unit.

D. Valuch

30.09.2008 RuPAC 2008
The LHC Damper

Digital Signal Processor Unit

30.09.2008
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

CERN. 21 December 2006.

CERN. 21 December 2006.
A fragment of an assembly drawing of a vertical kicker:
1 - vacuum tank (wall thickness: $\delta = 14$ 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
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 $\approx 4 \cdot 10^{-12}$mbar·l/s/cm², $S=2 \cdot 10^4$cm², $P=30$ l/s for hydrogen).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Required</th>
<th>Achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface smoothness</td>
<td>1.6 μm</td>
<td>0.4 μm</td>
</tr>
</tbody>
</table>

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.
“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 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.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Required</th>
<th>Achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lowest frequency</td>
<td>1 kHz</td>
<td>1 kHz</td>
</tr>
<tr>
<td>Highest frequency</td>
<td>20 MHz</td>
<td>20 MHz</td>
</tr>
<tr>
<td>Nominal - 3dB bandwidth</td>
<td>3 kHz – 1 MHz</td>
<td>2 kHz - 0.95 MHz</td>
</tr>
<tr>
<td>Nominal voltage up to 1 MHz</td>
<td>±7.5 kV</td>
<td>±7.8 kV</td>
</tr>
<tr>
<td>Gain, dB</td>
<td>34</td>
<td>34.3</td>
</tr>
<tr>
<td>Gain ripple</td>
<td>±0.7 dB</td>
<td>±0.5 dB</td>
</tr>
<tr>
<td>Rise-time 10-90%, $V_{\text{max}} = 7.5$ kV</td>
<td>350 ns</td>
<td>410 ns</td>
</tr>
<tr>
<td>Rise-time 1-99%, $V_{\text{max}} = 7.5$ kV</td>
<td>720 ns</td>
<td>760 ns</td>
</tr>
</tbody>
</table>
Beam stability is achieved for a damping rate
\[
\frac{T_{\text{rev}}}{\tau_d} = \frac{1}{2} g(\omega) \cos(\varphi(\omega)) > \frac{T_{\text{rev}}}{\tau_{\text{inst}}}
\]

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 \(f_{\text{HP}} = 500\) MHz (blue, solid) and tetrode anode voltage (green, dashed)
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.
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

Ready to work !!!