Status of LHC Transverse Feedback System

Summary of Status (1)

Wolfgang Hofle
CERN AB/RF

- 9 HV power converters delivered (15 kV, 14 A)
- Auxiliary power converters for tetrode amplifiers delivered (36 units Ug1, 18 Units Ug2)
- Collaboration with JINR: material for all supports delivered, except alignment jacks, material for kickers delivered, except 1 of 20 tanks which has to be reworked due to bad welding
- one tank (empty) fully vacuum tested and accepted by AT-VAC for installation; one kicker fully assembled, ready for bake-out; worry: find correct bake-out temperature (mixed material assembly copper/stainless steel, bake-out temperature must be high enough for the steel but low enough in order not to damage electrodes); assembly and bake-out of 20 kickers planned for 1st quarter of 2006
Summary of Status (2)

- 200 W driver amplifiers (TCB Thales Belgium); 40 units delivered; excellent RF performance (3 kHz - 20 MHz)

- JINR collaboration: Four amplifiers (each with 2x30 kW tetrodes delivered, one tested); improvements necessary (input matching, re-design of some parts for easy maintainability in the future) => The four delivered amplifiers will be re-worked; 16 such amplifiers still need to be assembled in JINR/Dubna. Delivery of water cooled resistors for these amplifiers is on the critical path. Some technical problems were encountered when testing at CERN: cracks in ceramics due to high water pressure in cooling plates: Re-enforced design under way (a small Swiss company is delivering these devices).

- High power test stand in building 867 operational since Summer 2005 together with interlocks and controls (PLC) equipment; series manufacture of interlock and controls equipment under way.

- Logistics at CERN and JINR require a lot of follow-up: paper work, unclear procedures for reception of material; material must be moved a lot between different sites: cleaning, vacuum testing, installation etc.
Summary of Status (3)

- Infrastructure and installation: Pulling of cables is under way; 18 racks in UX45 (underground), 14 racks on surface plus cabling to pick-ups and tunnel; longest cable (7/8” coax) is ~800 m (!)

- Next installation steps: ~ February - March 2006 start of installation of kickers and their supports in the tunnel; power converters and controls equipment installation at ~the same time; Power amplifiers will only be ready later (manufacturing, testing and installation spread out over the year 2006)

- High speed digital signal processing for the feedback loop late: Damper team concentrates on high power part; other electronics designers in AB-RF-FB section busy with LEIR project and LHC 400 MHz electronics; 2006 will be a difficult year as a considerable fraction of the man power will again be needed to run the RF and damper systems in the CERN accelerator complex (LEIR, AD, Booster, PS, SPS, commissioning of ions in LEIR and PS, SPS beams for CNGS commissioning, LHC test beams, Beams for fixed target Physics program
Transverse multi bunch feedback

Need real-time digital signal processing

Match delays:
\[ \tau_{\text{signal}} = \tau_{\text{beam}} + MT_0 \]

\( T_0 \): beam revolution time

\( M=1 \): very common ->
“One -Turn-Delay” feedback

Need means for phase \textit{and} delay adjustments

- **damping**: of transverse injection oscillations
- **feedback**: curing transverse coupled bunch instabilities
- **excitation**: of transverse oscillations for beam measurements & other applications
Transverse Feedback Systems in Synchrotrons at CERN

Currently *installed* transverse feedback systems in CERN Synchrotrons

<table>
<thead>
<tr>
<th>Accelerator</th>
<th>Digital / analogue processing</th>
<th>Power / kicker / bandwidth</th>
<th>Usage in operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>PS Booster (protons)</td>
<td>multi turn injection from linac analogue beam offset signal suppression, analogue delay (cables &amp; switches)</td>
<td>100 W, 50 Ω stripline Limited to ~13 MHz in operation But built for 100 MHz bandwidth baseband</td>
<td>H-plane: <em>used and required</em> V-plane: beam stable w/o FB</td>
</tr>
<tr>
<td>50 MeV – 1.4 GeV kin. E.</td>
<td></td>
<td>100 W, 50 Ω stripline 100 MHz bandwidth baseband</td>
<td></td>
</tr>
<tr>
<td>AD (anti-proton decelerator)</td>
<td>Copy of booster system</td>
<td>100 W, 50 Ω stripline 100 MHz bandwidth baseband</td>
<td>used only for excitation purposes</td>
</tr>
<tr>
<td>3.57 GeV – 0.1 GeV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SPS (protons, ions)</td>
<td>digital notch filter and 1T-delay (Altera FPGA, 80 MHz clock) commissioned in 2000/2001</td>
<td>tetrode amplifiers with two 30 kW tetrodes in push-pull directly coupled to a kicker (base band); feedback bandwidth ~10 kHz to 20 MHz</td>
<td>H-plane: used in operation V-plane: used in operation <em>used and required for operation</em> above 5x10^{12} protons (max ~5.5x10^{13} ppp accelerated)</td>
</tr>
<tr>
<td>(14 – 450) GeV/c protons FT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(26 – 450) GeV/c LHC beam</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Transverse Feedback Systems in Synchrotrons at CERN

### Current transverse feedback system projects at CERN

<table>
<thead>
<tr>
<th>Accelerator</th>
<th>Digital / analogue processing</th>
<th>Power / kicker / bandwidth</th>
<th>Planned commissioning and usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEIR (ions: Pb^{54+}) 4.2 MeV/u – 72 MeV/u</td>
<td>copy of PS Booster System</td>
<td>100 W, 50 Ω stripline</td>
<td>2005 damping during e-cooling may be necessary</td>
</tr>
<tr>
<td>PS (protons, ions) 1.4 GeV – 25 GeV (kinetic E)</td>
<td>synergy with LHC Damper</td>
<td>3 kW pulsed, 200 W CW, 50 Ω stripline with ~30 MHz bandwidth in baseband, lower cut-off ~50 kHz? upgrade possible with magnetic kicker (0.9 m length, 12.5 W, but bandwidth considered too limited); H-plane magnetic kicker built already</td>
<td>2006 injection damping and feedback will be beneficial in particular for high intensity CNGS beams and LHC beams. Currently horizontal instabilities are cured by introducing coupling to the vertical plane which constrains the tunes</td>
</tr>
<tr>
<td>LHC (protons, ions) pProtons: 450 GeV/c – 7 TeV/c</td>
<td>digital notch filter and 1T-delay, built-in diagnostics 14 bit ADC/DAC Altera FPGA, 80 MHz clock new development in progress</td>
<td>tetrode amplifiers with two 30 kW tetrodes in push-pull directly coupled to kicker (base band) similar to SPS system 3 kHz -&gt; 20 MHz</td>
<td>2007 injection damping feedback loop closed during ramp switch off during physics?</td>
</tr>
</tbody>
</table>
LHC Transverse Feedback ("LHC Damper")

LHC Damper will be installed in point 4 of LHC along with the accelerating 400 MHz RF system
Nominal LHC filling pattern: 2808 bunches

- Basic bunch spacing is 25 ns (every 10th bucket of 400 MHz RF)
- Running-in with 75 ns bunch spacing possible
- Trains of 72 bunches created in PS accelerator
- Up to 4x72 bunches accelerated in SPS and injected into LHC
- $1 \mu s$ gap between batches injected into LHC
Performance specification (1)
(LHC Design Report)

Beam parameters and requirements for nominal intensity:

- **Injection beam momentum**: 450 GeV/c
- **Static injection errors**: 2 mm (at $\beta_{\text{max}}=183$ m)
- **ripple (up to 1 MHz)**: 2 mm (at $\beta_{\text{max}}=183$ m)
- **resistive wall growth time**: 18.5 ms
- **assumed de-coherence time**: 68 ms
- **tolerable emittance growth**: 2.5%
- **Overall damping time**: 4.1 ms (46 turns)
- **bunch spacing**: 25 ns
- **minimum gap between batches**: 995 ns
- **lowest betatron frequency**: $>2$ kHz
- **highest frequency to damp**: 20 MHz
Performance specification (2)

Equipment performance specification:

choice: electrostatic kickers ("base-band")
aperture 52 mm

kickers per beam and plane 4
length per kicker 1.5 m
nominal voltage up to 1 MHz at $\beta=100\text{m}$ +/- 7.5 kV
kick per turn at 450 GeV/c 2 $\mu$rad

rise-time 10-90%, $\Delta V= +/- 7.5$ kV 350 ns
rise-time 1-99%, $\Delta V= +/- 7.5$ kV 720 ns

must provide sufficient gain from 1 kHz to 20 MHz

noise must be less than quantization noise due to 10 bit / $2\sigma$

rise time fast enough for gap of 38 missing bunches
Overview of one Damper system

Power amplifiers and kickers from JINR/Russia
Overview of LHCADT system components and responsibilities (“PBS”)

LHCADT is part of the RF system. Shown is one system (horizontal)
All LHCADT systems planned to work on day “One”

Shown is one “system”. There are four independent systems, one per plane (H/V) and beam.
The LHC Transverse Damping System (high power part)

- 20 electrostatic kickers
- 40 wideband amplifiers, i.e. 40 tetrodes (RS2048 CJC, 30 kW)
- 20 amplifier cases

Transverse Feedback ("LHC Damper")

W. Hofle
CERN AB/RF

Module
LHC optics at injection in IR4
(beams do not cross!)

 Beam 1
 high horizontal beta left of IP4
 high vertical beta right of IP4

 Beam 2
 high horizontal beta right of IP4
 high vertical beta left of IP4
Integration of the damper equipment in the LHC tunnel has been done jointly by the CERN and JINR teams.
Maximum achievable performance

LHCADT performance in LHC optics version 6.4 compared to original assumptions (at \(450 \text{ GeV/c}\)), assuming 7.5 kV maximum kick voltage

<table>
<thead>
<tr>
<th></th>
<th>(\beta=100) m performance</th>
<th>Optics 6.4 performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADTH beam 1</td>
<td>(0.2 \sigma)</td>
<td>(0.277 \sigma) at (\beta=193) m</td>
</tr>
<tr>
<td>ADTH beam 2</td>
<td>(0.2 \sigma)</td>
<td>(0.273 \sigma) at (\beta=187) m</td>
</tr>
<tr>
<td>ADTV beam 1</td>
<td>(0.2 \sigma)</td>
<td>(0.309 \sigma) at (\beta=239) m</td>
</tr>
<tr>
<td>ADTV beam 2</td>
<td>(0.2 \sigma)</td>
<td>(0.316 \sigma) at (\beta=250) m</td>
</tr>
</tbody>
</table>

Estimate of maximum capabilities (usage as beam exciter, abort gap cleaning etc.), assumes optics 6.4 as in table above, \(450 \text{ GeV/c}\) and running with \(~15\) kV DC for tetrode anode voltage

<table>
<thead>
<tr>
<th></th>
<th>100 kHz</th>
<th>1 MHz</th>
<th>10 MHz</th>
<th>20 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADTH</td>
<td>(0.47 \sigma)</td>
<td>(0.43 \sigma)</td>
<td>(0.14 \sigma)</td>
<td>(0.05 \sigma)</td>
</tr>
<tr>
<td>ADTV</td>
<td>(0.47 \sigma)</td>
<td>(0.43 \sigma)</td>
<td>(0.14 \sigma)</td>
<td>(0.05 \sigma)</td>
</tr>
</tbody>
</table>
Physical layout in point 4 underground LHC

ADT racks
(driver amplifiers, PLC controls, fast interlocks)

ADT (4 modules)
left of IP4

ADT (4 modules)
right of IP4

Beam 1

Beam 2
Transverse Feedback ("LHC Damper")

Kicker design

- Prototype kicker delivered and tested with power amplifier at CERN; series production has started in Russia

- Vacuum testing planned at CERN for November 2005; installation in LHC tunnel in February 2006, vacuum interconnection in March 2006, progress depends on advance with cryoline in LSS4
LHC Transverse Feedback ("LHC Damper")

Testing of power amplifier

Prototype manufactured and tested in 2001: +/- 10 kV achieved, 1 kΩ load in amplifier

Production series design and manufacturing 2002-2006

Nonlinear phase vs frequency will be compensated in low-level (kicker is a capacitive shunt at high frequencies)

![Gain vs Frequency Graph]

Gain, dB

- Classic
- Cascode (1 channel)
- Simulation
- Test

Frequency, MHz
4 wideband power amplifiers were assembled and tested successfully at the specialized test stand of the LPP (JINR) in December 2004 – September 2005.

An amplitude of ±7.5 kV was obtained on the deflector which corresponds to the required magnitude. The measured characteristics of the amplifiers in the frequency range from 10 kHz to 10 MHz correspond globally to the computer simulation data and to the design specifications.
Assembly of deflector at CERN for bake-out procedure. 5 December 2005.
LHC Transverse Feedback ("LHC Damper")

Power amplifier and test stand at CERN operational since July 2005

Two power amplifiers and their kickers

Control racks with 200 W driver amplifiers and PLC controls with interlocks
Experience from the SPS damper with in-house developed driver amplifiers showed that the driver amplifier is one of the most critical items with respect to performance and reliability. For the LHC damper industry developed a custom design amplifier inspired by the design of the SPS amplifiers; 40 amplifiers have been manufactured and tested.

43 dB gain, very flat 3 kHz - 20 MHz
200 W solid state driver amplifier (2)

200 W output power max CW

3 kHz to 20 MHz at up to 100 W achieved:
- +/- 0.5 dB gain ripple
- +/- 5 degree phase variation from linear phase
- constant group delay < +/- 0.1 ns
  (also from amplifier to amplifier)
- < -30 dBc 3rd harmonic distortion

Fulfills spec for interference and noise (10 mV rms and spikes limited to 50 mV peak)
LHC ADT Low level electronics

- System will be based on experience gained with SPS Damper
- Two coupler type pick-ups with betatron phase advance of ~90 degrees will be installed (BDI group)
- Spectrum repeats every 40 MHz (25 ns bunch spacing) → analogue down mixing with a multiple of 40 MHz to baseband, LO probably 320 MHz
- One of the horizontal pick-ups is installed at zero dispersion and it will be possible to use this pick-up and a Hilbert transformer (FIR filter) for the phase adjustment if wanted; Hilbert filter tested in SPS but not used in operation (reduced phase stability margin at very high gain)
- FPGA technology for implementing most of the functions digitally (notch filter, fine delay adjustment, betatron phase adjustment by two pick-ups or Hilbert filter and single pick-up use)
- Electronics development on the critical path because of accumulated delays (manpower); outsourcing is still an option (estimate: 500 kCHF, 9 month + lead time due to CERN purchasing rules)
Synergy between LHC-1-Turn longitudinal feedback and transverse damper - use same hardware

FPGA code done (V. Rossi); board layout under way

P. Baudrenghien
planned to launch FPGA coding early 2006, further synergy with PS transverse damper project and later longitudinal PS 1-T cavity feedback (2008)
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