Transverse Feedback Systems along the Injectors Chain and Outlook for Post-LS2 Performance

W. Hofle

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BE-ABP, BE-RF-CS, BE-RF-PM, BE-BI, BE-OP
Transverse Feedback (TFB, “Damper”)

- Purpose of these feedbacks:
  - Injection oscillation damping (preservation of emittance)
  - Transverse instability damping → simply cannot operate without feedback (PSB H-plane, PS without coupling, SPS, LEIR)
  - Manipulations on bunches (excitation, blow-up and blow-out)

Digital or analog signal processing system, one or more pick-ups and kickers
Coupled bunch or intra-bunch
# Current – and LIU upgrade – scope of TFBs

<table>
<thead>
<tr>
<th></th>
<th>PSB</th>
<th>PS</th>
<th>LEIR</th>
<th>SPS</th>
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<tbody>
<tr>
<td>Injection Oscillation Damping</td>
<td>multi-turn, p⁺ → H- injection 50 MeV → 160 MeV</td>
<td>yes, bunch to bucket transfer 1.4 GeV → 2 GeV (possible larger injection oscillations)</td>
<td></td>
<td>yes, bunch to bucket transfer, injection kicker ripple key in LIU to decrease batch spacing (in particular for ions)</td>
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<tr>
<td>Instability Damping</td>
<td>Horizontal instability → Feedback essential for operation</td>
<td>mitigated also by coupling and chromaticity → LIU relies on mitigation by feedback instead; eCloud CB instability at 26 GeV, flat-top</td>
<td>Instability damping during beam capture after cooling and in ramp optimization</td>
<td>Horizontal and vertical coupled bunch instability (resistive wall impedance and eCloud) → FB essential eCloud intra-bunch instability, scrubbing</td>
</tr>
<tr>
<td>Beam manipulations, measurements</td>
<td>Exciter for optics measurements</td>
<td>Blow-up to shape emittance; Bunch knock-out for 80 b scheme</td>
<td></td>
<td>blow-up to shape emittance, cleaning beam gaps, crystal collimation studies</td>
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</tbody>
</table>

Changes with LIU upgrades highlighted + Exciter for tune measurement (all machines)
# Scope of technology and LIU upgrades

<table>
<thead>
<tr>
<th>Machine</th>
<th>Frequency</th>
<th>Technology and LIU upgrade path</th>
<th>Scope of LIU upgrade</th>
<th>Status of LIU upgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSB 50 MeV (160 MeV) to 1.4 GeV (→ 2 GeV)</td>
<td>13 MHz H-plane most important</td>
<td>electrostatic PU solid state amplifiers strip-line kicker 100 W → 800 W</td>
<td>new head PU amplifier new digital electronics new power amplifiers consolidation (cooling etc.)</td>
<td>under design firmware→ to do under design mostly completed</td>
</tr>
<tr>
<td>PS 1.4 GeV (2 GeV) to 26 GeV/c</td>
<td>&lt;&lt; 50 kHz to 23 MHz</td>
<td>electrostatic PU solid state amplifiers strip-line kicker 800 W → 5 kW</td>
<td>new digital electronics new power amplifiers consolidation (cooling etc.)</td>
<td>done under design mostly completed</td>
</tr>
<tr>
<td>LEIR (Pb) (4.2 -72) MeV/u</td>
<td>up to 100 MHz</td>
<td>currently a copy of the original PSB system</td>
<td>needs for upgrade are under definition</td>
<td>part of 2015 LEIR studies</td>
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<tr>
<td>SPS 14 GeV/c to 450 GeV/c</td>
<td>10 kHz to 20 MHz</td>
<td>strip-line PU for 25 ns digital processing tetrode amplifiers</td>
<td>new PUs (LHC/FT beams) new digital processing consolidation (cabling + power system)</td>
<td>largely done except for ions, improvements and “tuning” + instrumentation !</td>
</tr>
<tr>
<td>SPS</td>
<td>wideband → ~ 1 GHz</td>
<td>vertical, strip-line and slot line kickers digital processing (US LARP / SLAC)</td>
<td>only prototype &amp; proof of principle in LIU baseline (US LARP supported: leading lab: SLAC)</td>
<td>MD use ongoing strip-lines done slot-line under design</td>
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PSB and PS

A. Blas and team
Motivation for upgrades:
- Increased kick strength
- Replacement of obsolete hardware
Consolidation and infrastructure
PSB and PS dampers, and LEIR

- Completed → improved reliability, increased availability
  - New PLC power control in all machines
  - New water distribution in all machines
  - New power supplies for solid state amplifiers in all machines
  - New Oasis monitoring systems (digitizers + software)
  - New and additional racks and cabling renovation (PSB / PS)
PSB & PS damper signal processing
2015 Hardware - Achievements

- Development for PSB and PS dampers
  - Based on longitudinal PS 1TFB electronics
  - LHC RF VME standard
- Features
  - Fully digital processing with analog input/output
  - FPGA based with custom firmware for PSB and PS dampers
  - Automatic delay compensation during acceleration

Hardware completed in 2015
PS (PSB) Damper Signal Processing  
- Firmware -

Features

- PU selection
- Loop betatron phase setting from the tune value as a function of time (1 degree precision)
- Removal of revolution line (closed orbit variation)
- Automatic delay adjustment to the particle time of flight (1 ns precision and jitter free)
- Blow-up signal generation with:
  - 9 individual excitation vectors
  - 3 possible excitation gaps programmed in revolution angles (bunch suppression for 80 bunch scheme)
  - Fractional harmonic of the excitation selected with a function generator
- Digital summation of tune measurement and external blow-up signals
LEIR, PSB, PS Dampers “To Do’s”

- New power amplifiers for the PS and PSB
  - 136 RF power units of 400 W are required
- New power impedance matching transformers for the PS kickers
- Fesa Class for the PSB new electronics
- Working set and synoptic for the new PSB and PS damper electronics
- Upgrade of the control crates in PSB
- New head amplifiers for the pick-ups in the PSB (R2E !)

Critical Path:
Manpower available for amplifier development and production follow-up shared between several projects within the RF group
Path for PSB-PS amplifier development

PSB

- 400 W 25 Ω
- 400 W 50 Ω
- 800 W 50 Ω
- Kicker plate 50 Ω 200 V RMS
- 600 W 60 dB 50 Ω Att.

PS

- 400 W 25 Ω
- 400 W 50 Ω
- 800 W 25 Ω
- 800 W 50 Ω
- 1600 W 25 Ω
- 1600 W 50 Ω
- 3200 W 50 Ω
- 6400 W 50 Ω 100 Ω
- Kicker plate 100 Ω 800 V RMS
- 6400 W 100 -> 50 Ω
- 1500 W 60 dB 50 Ω Att.

PS Ring

- 16x

Single N connector!
Status of amplifier development

- Development of 400 W RF amplifier basic building block is advancing
  - in-house development
  - support structure for the manufacturing and assembly of the many units required and being put in-place, critical for completion
  - alternative solutions reviewed within BE-RF in December 2015, retained in-house development (performance, cost & schedule); back-up plan for PSB amplifiers identified based on another development

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<tr>
<th></th>
<th>PS amplifiers</th>
<th>PSB amplifiers</th>
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<tbody>
<tr>
<td>Quantity</td>
<td>6 x 5 kW</td>
<td>20 x 800 W</td>
</tr>
<tr>
<td></td>
<td>= 96 x 400 W units</td>
<td>= 40 x 400W blocks</td>
</tr>
<tr>
<td>+ kicker matching</td>
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Status of amplifier development

Basic building block, 400 W, 25 Ohm output impedance

- Development advancing, prototype performance ok
- Based on LDMOS transistor BLF574
- Innovative matching transformers
- 3C95 ferrite core
- Transformer ratio: 1.5625 : 6.25 : 25
Performance of upgraded PSB Damper

• 800 W power requirement per kicker plate requested for optics measurements
  • nota bene: scaling today’s kick strength with 100 W per kicker plate from 1.4 GeV to 2 GeV requires less than 800 W
• injection of H- from LINAC4 at 2 GeV completely different than current transverse phase space painting at 1.4 GeV → learning curve after LS2 to be expected
  • main improvements for injection damping and instability damping from new digital signal processing and new head amplifiers
• Bandwidth
  • power amplifiers: aim for highest bandwidth achievable (above current 13 MHz used) compatible with 800 W requirement
  • Signal processing bandwidth: defined by clock frequency chosen (64 x \( f_{\text{rev}} \), frequency swing during acceleration)
Towards performance of upgraded PS Damper: Achievements

- 5 kW per kicker plate expected to damp +/- 3 mm error at 2 GeV in less than 30 turns → improvement to the current 800 W
- 5 kHz lower cut-off frequency for injection damping for optimal performance desired
- 23 MHz for damping injection kicker ripple
- 20 MHz for coupled bunch instability damping (half bunch repetition frequency for 25 ns bunch spacing); also intra-bunch damping
LEIR
LEIR: Overview of current TFB system

Similar to PSB system
Summary of 2015 LEIR damper study

LEIR TFB essentially a copy of the original system deployed in PSB
Generally satisfactory performance with bunched and un-bunched beam

Improvements requested

• Programmable phase and gain settings along cycle
• FFT diagnostics of loop signals
• Monitoring point between pick-up and the critical Beam-Orbit-Suppression System (BOSS) in the signal chain
• Replacement of the BOSS (Beam Orbit Suppression System) if needed
  • leverage on development for SPS wideband feedback
  • feasibility of a digital system to be studied

Based on 2015 observations, further studies to be carried out in 2016:
• on reduced stability margin at extraction (possible source: delay error)
• monitoring signals before BOSS unit (to track down spurious signals observed)
SPS
Coupled bunch feedback → 20 MHz

G. Kotzian, W. Hofle, D. Valuch and team
Motivation for SPS damper LIU upgrade

- Incompatibility of sharing pick-ups with beam instrumentation orbit system after LS2 BI upgrades
- Obsolete hardware with limited observation capabilities for instabilities → bring system up to LHC ADT standards
- Obsolete controls (G64) hardware and MIL 1553 phasing out in LS1
- Incompatibility of hardware with requirement to damp scrubbing doublet beam → defined urgency of upgrade in 2014
- Requirement to damp single bunches in view of crab cavity tests with good efficiency and a low noise system
- Requirement to provide damping for ions and improved damping for protons for injection damping at short batch spacings
- Possibility to adapt frequency response to needs by using a digital system

Priority established: FT & LHC p beams, then ions; progress limited by available man power (same team also working on LHC ADT)
• 2 BPCR (H/V) for LHC type beams (couplers maximum ZT @ 200 MHz)
• 2 BPH electrostatic PU (pFT)
• 2 BPV electrostatic PU (pFT)
• 2 kickers for each plane (BDH, BDV)

new dedicated BPMs installed in LS1 (BI group)
re-cabled with 7/8-inch smooth wall coaxial cables during LS1; cabling clean-up in BA2
BDH / BDV kickers unchanged
SPS Feedback kickers: Kick Strength

2.9 kV (with TH 561 tube)

2.6 kV (with RS 2048 CJC tube)

<table>
<thead>
<tr>
<th>plane</th>
<th>Length/gap mm/mm</th>
<th>Δp eVs/m</th>
<th>kV transverse</th>
<th>μrad at 26 GeV/c</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>2x 2396/142</td>
<td>3.3x10^{-4}</td>
<td>98</td>
<td>3.8</td>
</tr>
<tr>
<td>V</td>
<td>2x 1536/38</td>
<td>7.2x10^{-4}</td>
<td>215</td>
<td>8.3</td>
</tr>
</tbody>
</table>

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 mrad (→ 0.54 mm at b=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
SPS damper overview (one plane of two)
SPS Transverse damper LIU Upgrade: Achievements 2014/2015 and plans

2014 commission start after LS1
• 6 new pick-ups
• new electronics
• new controls
• p-FT, pLHC, p-scrub damped

2015 and 2016
• complete electronics and commission for ions
• understand instabilities observed (scrubbing beam), increase to full bandwidth of 20 MHz for scrubbing beam
• optimize gain, delay
• software interfaces (GUI)
• observation box for signal acquisition
SPS damper after LS1 - commissioning

- Successful setting-up for p-FT, LHC type beams and scrubbing doublets after LS1 with new digital hardware
- Ion injection damping using hardware for protons
  - Limitations due to frequency modulation scheme for ions
- Improvements in hardware and tuning as well as instrumentation ongoing
- User interface development ongoing

BTF measurements (open loop) as part of setting-up
SPS Ions damping: 1st tests in 2015

- Special requirement for ions: Frequency Shift Keying (FSK) for ion operation
- Delay error up to 166 ns
- Planned compensation by delaying RF clock from BA3 to align in time the RF clock and beam signals from pick-ups, and for the kickers → under development
- Operation in 2015 without clock compensation allowed already improvements in the batch spacing

**Emittances OK**

Damping at 225 ns batch spacing

Damping at 150 ns batch spacing
SPS
High Bandwidth Transverse Feedback
(aka Wideband Feedback)
few MHz to 1 GHz
High Bandwidth Transverse Feedback

- Intra bunch feedback on short bunches
  - Damping of impedance driven (TMCI) and ecloud instabilities shown in simulation
  - Motivated by ecloud instability, LIU and US LARP support a prototype proof-of-principle development for a vertical system for the SPS with a target bandwidth of 1 GHz

![Mode Spectra without feedback](image-url)
High Bandwidth Transverse Feedback Hardware & Simulation of performance

- Digital hardware for 4 GS/s supplied by SLAC
  - Commissioned in single bunch MDs
  - Planned for experiments with 25 ns trains for 2016

- Kickers
  - Initially used exponential pick-up (BPW) from 1970’s with 4x100 W
  - Two new kicker designs launched
  - Short strip-lines (3 dB @ 700 MHz) developed, built and installed
  - Slotted line kicker design ongoing (higher frequency reach beyond 1 GHz)

Simulation with CERN Headtail code
Kicker designs

Short strip-line kicker
- Two kickers installed in the SPS with four 250 W solid state power amplifiers for 2016 operation
- First kicker used in 2015 machine development experiments
- One spare available

Slotted line kicker
- Design to be completed
- Construction of prototype
- Experimental evaluation of shunt impedance in lab in 2016
- Decision on installation at Project Review in 2016
Proposed slotted kicker: action on beam

Horizontal deflection, 1800 mm downstream, to a 50 ns long rectangular kicker pulse

 Beam trajectory

response faster than 5 ns kicker can target individual bunches @ 5 ns spacing!

enormous value beyond high bandwidth feedback

Simulation: M. Wendt
MD results with new kicker in 2015

April 2015 SPS MD - Grow/Damp measurements

- Grow/damp SPS Measurement - Damping G=4 (left) G=16 (right)
- Intensity $2 \times 10^{11}$ with low chromaticity Q26 lattice (special beam)
- $\nu_y = 0.185 \ nu_s = 0.006$
- Feedback gain is switched to promote instability, then damp it
- Quantifies damping from increased gain of system, compare to models
High Bandwidth Transverse Feedback
- Priorities for 2016 -

- Full use of installed new strip-line kickers
  - Tackle challenge of Q20 optics (controller design)
  - Demonstrate experimentally intra-bunch motion damping (4 GS/s) – on a bunch train with new SLAC supplied firmware (USLARP support)
  - Demonstrate damping on a bunch train with new SLAC supplied firmware
  - Possibility to drive kickers with existing SPS coupled bunch damper hardware being considered with tests in 2016
- Kicker Design
  - Advance slot-line kicker design and manufacturing
- Review in autumn 2016
  - Performance of the prototype system with beam
  - Future use of the installed system
  - Possible extensions (full fledged system) in SPS adapted to LIU needs
  - Explore the possible continuation of R&D for other accelerators and studies (PS, LHC, FCC) based on experience gain with the SPS system
Conclusions: Transverse Feedbacks

• LEIR:
  • MD effort needed to define final scope of a possible upgrade
  • Control of parameters and closed orbit suppression identified as most critical items and being addressed

• PSB:
  • Infrastructure consolidation well advanced or completed
  • New digital processing hardware built, firmware under design, pick-up head amplifiers under design
  • New 800 W power amplifiers on critical path

• PS:
  • Consolidation and new electronics completed, software to complete
  • New power amplifiers on critical path (5 kW)

• SPS
  • Coupled bunch feedback upgrade essentially completed; ions damping and some rebuilding of hardware (spares, performance improvement) under way
  • High bandwidth damper: critical tests and review planned for 2016