Status and prospects in fast beam-based feedbacks

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CERN, Geneva, Switzerland
• Overview and review of activities from the last ten years
• focus on CERN wideband transverse feedback system developments
  • complementary to established coupled bunch feedback systems
• results of original work is referenced, credit given to the original work
• aim is to demonstrate that the technology is sufficiently advanced in order to roll-out an intra-bunch system for short bunches, aka “fast beam-based feedback”
Outline

Recap of transverse feedback systems in operation
Full exploitation of the LHC ADT system
Intra-bunch feedback in hadron synchrotrons
Hardware and technology development
Simulations towards future upgrades and accelerators
Recap of Transverse feedback systems at CERN

- CERN LHC injector chain excellent example for need of beam based feedback systems, 5 synchrotrons with transverse feedback systems
• One or multiple pick-ups, turn by turn, bunch by bunch position with digitization and processing
• widely used in high intensity lepton colliders (B factories) and light sources to provide beam stability
• High intensity hadron machines need feedback for stability as well
• Use in hadron colliders more challenging due to need for low noise systems, i.e. detection of beam oscillations
• LHC collider uses TFB all the time including with stored, colliding beams, (protons and Pb ions) since 2010
• “fast feedbacks” → extend damping to intra-bunch feedback in GHz range
**Injector transverse feedbacks at CERN**

- LHC Injector transverse feedbacks at CERN and studies
  - next “upgrade to digital” opportunity for LEIR

<table>
<thead>
<tr>
<th>Accelerator / energy</th>
<th>Kicker / power per electrode frequency band</th>
<th>Processing used</th>
<th>Last upgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEIR</td>
<td>striplines up to 100 MHz</td>
<td>2 pick-ups</td>
<td>2005</td>
</tr>
<tr>
<td>4.2 MeV/u – 72 MeV/u (kin. E)</td>
<td>100 W, 50 Ω, up to 100 MHz</td>
<td>analog, vector sum</td>
<td></td>
</tr>
<tr>
<td>PS Booster</td>
<td>striplines up to 100 MHz</td>
<td>1 pick-up</td>
<td>2020</td>
</tr>
<tr>
<td>160 MeV – 2 GeV</td>
<td>800 W, 50 Ω</td>
<td>digital</td>
<td></td>
</tr>
<tr>
<td>PS</td>
<td>striplines with impedance transformer</td>
<td>1 pick-up (+spare)</td>
<td>2020</td>
</tr>
<tr>
<td>2 GeV – 26 GeV/c</td>
<td>5 kW, 125 Ω, up to ~ 60 MHz</td>
<td>digital</td>
<td></td>
</tr>
<tr>
<td>SPS</td>
<td>electric field kickers, high impedance</td>
<td>striplines, electro-static</td>
<td>2014</td>
</tr>
<tr>
<td>14, 26 GeV/c – 450 GeV/c</td>
<td>tetrodes, 30 kW, 180 Ω, up to 20 MHz</td>
<td>digital, pick-up pairs</td>
<td></td>
</tr>
<tr>
<td><strong>SPS for wideband feedback study</strong></td>
<td>2 short striplines and 1 Faltin type kicker</td>
<td>1 stripline exponential PU</td>
<td>2008</td>
</tr>
<tr>
<td>26 GeV/c</td>
<td>250 W, 50 Ω, 5 MHz – 1 GHz</td>
<td>Digital up to 4 GS/s (3.2 Gs/s)</td>
<td>to 2018</td>
</tr>
</tbody>
</table>

W. Höfle, FRIXGD1   IPAC’22   June 2022, Bangkok, Thailand
Potentials of a (wideband) feedback system

- active damping of single or coupled bunch instabilities including intra-bunch motion
- no introduction of additional tune spread
- no introduction of additional non-linearities

- technically challenging and complex system → close follow-up required during operation
- imperfections can lead to loss of stabilization (i.e. noise or saturation)

Brute force sampling or band-by-band approach
JPARC intra-bunch feedback

- Intra-bunch oscillation on moderate length bunches (150 ns - 200 ns)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>1568m</td>
</tr>
<tr>
<td>Injection Energy</td>
<td>3GeV</td>
</tr>
<tr>
<td>Extraction Energy</td>
<td>30GeV</td>
</tr>
<tr>
<td>Repetition Period</td>
<td>2.48s</td>
</tr>
<tr>
<td>RF Frequency</td>
<td>1.67-1.72 MHz</td>
</tr>
<tr>
<td>Number of Bunches</td>
<td>8</td>
</tr>
<tr>
<td>Synchrotron Tune</td>
<td>0.002-0.00001</td>
</tr>
<tr>
<td>Betatron Tune (Hor./Ver.)</td>
<td>22.41/20.75</td>
</tr>
</tbody>
</table>

- Commercial electronics iGp12 (Dimtel) adapted to the JPARC main ring
- Pick-up similar to CERN SPS wideband pick-up, good frequency response up to 1 GHz shown

Stripline pick-up with non-uniform electrodes similar to CERN SPS wideband transverse pick-ups
K. Nakamura et al., IPAC’14, THOAA03
CERN PS Example of intra-bunch feedback

- CERN PS transverse feedback
  - Example of intra-bunch instability mitigated by transverse feedback
  - within bandwidth of upgraded coupled bunch system
  - permits to run LHC beam without using the traditional coupling between H, V for instability mitigation
  - Instabilities also seen at transition crossing (up to 800 MHz) for very high intensity single bunches that could benefit from increased bandwidth of a wideband system → possible use case for bandwidth increase
CERN LHC transverse damper (aka ADT) power system

- kicker length: each kicker 1.5 m
- max voltage: 10.5 kV
- 2 μrad kick to 450 GeV beam
- gain up to beyond 20 MHz
- 16 kickers
- 32x30 kW tetrode amplifiers
- bandwidth up to 20 MHz

LHC transverse Feedback (ADT) kickers and amplifiers in tunnel point 4 of LHC, RB44 and RB46

Measured ADT frequency response. Green: bare power amplifier, blue: power amp + kicker.

Built in collaboration with JINR, Dubna, Russia; fully commissioned in 2010 with beam
W. Höfle et al. IPAC’11, MOPO012
Upgrades to LHC ADT and instability observation

• increase in kick strength not needed
• Improved signal-to-noise ration in position detection
  • novel receiver technique for bunch-by-bunch detection (I,Q sampling)
  • combining data from four pick-ups (double the initial number) per beam and plane
• frequency response shaping by digital filters, flat response to 20 MHz possible and used operational in parts of the cycle
• full exploitation of the diagnostics possibilities offered by the data from the feedback → “obsbox”, data recording
• installation of an intra-bunch feedback not base-line of HL-LHC upgrade
  • feasibility checked in simulation
• diagnostics of intra-bunch motion with multi-band instability monitor
Sampling and bandwidth

- reminder on sampling and bandwidth
  - motivated by appearance of single bunch instabilities
  - used operationally for LHC squeeze
  - and 25 ns spacing tests
  - relevant to all feedbacks

Condition for $h(nT_b) = 0$ → symmetry of roll off
LHC ADT improvements - receiver

- LHC ADT improvements, new receiver developed
  - potential to be used to extract band-by-band intra-bunch motion
  - Application possible to head tail feedback needed for crab cavities in HL-LHC

400 MHz, analog down conversion, total of 12 ADCs used
Interleaved sampling with 4 ADCs of the $\Delta$ signal at effective rate of 480 Ms/s

D. Valuch, V. Stopjakova,
IPAC’22, TUPOST007
• Analysis → tune determination from phase advance
ADT ObsBox for data recording from feedback

- data recording from feedback systems

<table>
<thead>
<tr>
<th></th>
<th>Level-1 Rate (Hz)</th>
<th>Event size (Bytes)</th>
<th>Readout Bandw. (GB/s)</th>
<th>HLT Out MB/s (Events/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALICE (Pb-Pb)</td>
<td>500</td>
<td>$5 \times 10^7$</td>
<td>25</td>
<td>1250 ($10^2$)</td>
</tr>
<tr>
<td>ALICE (p-p)</td>
<td>$10^3$</td>
<td>$2 \times 10^6$</td>
<td>25</td>
<td>200 ($10^2$)</td>
</tr>
<tr>
<td>ATLAS</td>
<td>$10^3$</td>
<td>$1.5 \times 10^6$</td>
<td>50</td>
<td>$\approx 1000 (10^3)$</td>
</tr>
<tr>
<td>CMS</td>
<td>$10^5$</td>
<td>$10^6$</td>
<td>100</td>
<td>$\approx 1000 (10^3)$</td>
</tr>
<tr>
<td>LHCb</td>
<td>$10^6$</td>
<td>$5 \times 10^4$</td>
<td>50</td>
<td>700 ($1.2 \times 10^4$)</td>
</tr>
<tr>
<td>ADTObsBox</td>
<td>$10^4$</td>
<td>$10^5$</td>
<td>2</td>
<td>1280 ($10^4$)</td>
</tr>
</tbody>
</table>

M. Söderén, D. Valuch
EPJ Web of Conferences 245, 01036 (2020)
CHEP 2019,
https://doi.org/10.1051/epjconf/202024501036
Bunch-by-bunch observation

- Addressed by Obsbox System in LHC

L. Carver et al.
IPAC’17, MOPAB113

user trigger or through events such as detected instabilities
Instabilities in need of damping by feedback

- example of within bunch oscillation and needed bandwidth
band-by-band observation

• Multi-band instability monitor (MIM)
  • amplitude (peak) detection per band versus time

Measured response of each band

![Image of measured response of each band](image_url)
Beam position detection sensitivity to intra-bunch motion with down modulation at 400 MHz

\[ I_{\Sigma}(t) = k_{\Sigma} \left[ q \lambda(t) \cdot c(t) \right] \ast g(t) \]
\[ Q_{\Sigma}(t) = k_{\Sigma} \left[ q \lambda(t) \cdot s(t) \right] \ast g(t) \]

\[ I_{\Delta}(t) = k_{\Delta} \left\{ \left( \frac{x(t)}{d_x} \cdot q \lambda(t) \right) \cdot c(t) \right\} \ast g(t) \]
\[ Q_{\Delta}(t) = k_{\Delta} \left\{ \left( \frac{x(t)}{d_x} \cdot q \lambda(t) \right) \cdot s(t) \right\} \ast g(t) \]

\[ X_N = \frac{I_{\Delta}I_{\Sigma} + Q_{\Delta}Q_{\Sigma}}{I_{\Sigma}^2 + Q_{\Sigma}^2} + j \frac{Q_{\Delta}I_{\Sigma} - I_{\Delta}Q_{\Sigma}}{I_{\Sigma}^2 + Q_{\Sigma}^2} \]

bunch centroid  head tail motion

study relevant for planned crab cavity noise feedback

G. Kotzian et al.,
IPAC’17, TUPIK093
Intra-bunch feedback developments

- Push to shorter bunch lengths to GHz range
- Band-by-band versus brute force sampling
  - Separation of kickers for different bands
  - Mode decomposition after direct sampling
- O. Turgut et al., IPAC’16, THOAA01, C.H. Rivetta et al. IBIC’21, FROA01

Cavity options:
- 400 MHz: H=1.0 m
- 1.2 GHz: H=0.6 m

Low Q for bunch-by-bunch modulation (25 ns, 40 MHz)

J. Cesaratto
CERN-ACC-Note-2013-0047
SLAC-R-1037
Kickers built for SPS wideband feedback

• Built and installed in SPS

Invented originally for stochastic cooling by L. Faltin at CERN:
optimised design for SPS:
J. Cesaratto, IPAC’13, WEPME061
M. Wendt et al.: as built see IPAC’17 TUIK053
SPS Wideband feedback kicker

• Technology for Faltin kicker

1. Feedthrough (5 kW)
2. Electrode (Cu)
3. Supports (shapal)
4. Body & cover (316 LN / 304 L)
5. Supports

Transverse shunt impedance 3-8 kΩ (vertical) up to 1 GHz (for 1 m)
Slotline kicker SPS (Faltin-type)

- GHz bandwidth kicker

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

installed in SPS enormous value beyond high bandwidth feedback

Simulation: M. Wendt
IPAC’17 TUIK053

17/06/2022
SPS Wideband Feedback processor - technology

- Prototype system could be used to excite beam and in feedback mode

- 4 GS/s ADC/DAC with proposal to move to 8 GS/s
- reconfigurable controller on FPGA board
- synchronised to SPS RF clock at 26 GeV/c
- careful phase and amplitude equalization in analog receiver
- possibility to remove slowly varying offset before digitization

Overall System Block Diagram: Feedback and Excitation Systems

J. Dusatko, IPAC’18, WEPAF073
G. Kotzian, IBIC’13, WEPC12
• Grow damp experiments with intra-bunch feedback
Demonstration in SPS

• Demonstration in SPS, Q22 and Q26 optics

Q26, $2 \times 10^{11}$ per bunch, injection transient with feedback on

Q20 optics chosen for LIU upgrade
→ Injection energy well above transition, consequently TMCI instability threshold raised to above intensities needed for transfer to LHC
→ wideband feedback not baseline

J. D. Fox, IPAC’17, TUPIK119

W. Höfle et al.
IPAC’18, TUZGBD4
• Modelling studies

K. S. B. Li, IPAC’13, WEPME042
J. Komppula et al., IPAC’17, TUPIK091
Modelling Studies for LHC

• study for wideband feedback for LHC

K.S.B. Li
CERN-ACC-Note-2018-0058
Study for LHC

- study for wideband feedback for LHC

600 MHz feedback
Conclusion

• SPS Wideband feedback prototyping demonstrated that intra-bunch feedback is practically feasible in the GHz range at rates of multiple Gs/s
• design estimates for systems in SPS and LHC were made
• these fast feedbacks are a power tool for diagnostics as well
• technology waiting for an opportunity of an instability becoming limiting
• when designing pick-ups and kickers future bandwidth upgrades should be folded in
• kicker and pick-up design synergies with stochastic cooling systems to be explored, exploration of cavity type kickers and pick-ups interesting
• potential candidate for next project at CERN is LEIR, the low energy ion ring (consolidation, new digital system needed)
  • synergies possible with ion facilities under design and construction (FAIR, HIAF, ...)

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A. Alesini, S. Caschera, A Gallo, INFN-LNF, Frascati, Italy
M. Tobiyama, KEK, Tsukuba, Japan
Wideband feedback system for LIU-SPS with SLAC

courtesy K. Li

• The project is essential to acquire expertise on:
  • How to numerically model and study wideband feedback systems for mitigation of intra-bunch coherent motion
  • Prototyping of high speed electronics (4Gs/s digital signal processing system) & exploration of control algorithms

The fast synchrotron motion in the Q20 optics of the SPS is especially challenging due to the required extended controller bandwidth

• Experience has been gained using different filter types to balance flat phase response and effective noise suppression for single and multi-bunch control
• Root-locus analysis to study closed loop transfer functions, time-domain behaviour, stability
  → Expected to be less challenging for LHC/HL-LHC (lower Qs)
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