ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-FRIXGD1

STATUS AND PROSPECTS IN FAST BEAM-BASED FEEDBACKS

W. Höfle*
CERN, Geneva, Switzerland

Abstract

Fast beam-based Feedback systems play an important role in circular accelerators to mitigate instabilities and reduce the impact of injection oscillations and perturbations on beam quality, both in the longitudinal and transverse planes. The status and prospects of such beam-based feedback systems for circular accelerators are reviewed. This includes progress towards the fundamental limits in noise and feedback gain and the possibilities of modern digital systems to extract large amounts of data that can be used to characterise beam properties. The talk concentrates on machines with hadrons and gives an outlook on possible developments for future accelerator projects under study.

INTRODUCTION

Modern synchrotrons are designed to have a low machine impedance in order to increase the beam intensity threshold above which instabilities will occur. Despite these efforts in the design and due to the ever increasing desire for more beam current, accelerators are still suffering from instabilities both of coupled bunch type, and intra-bunch instabilities characterized by motion within the bunch. Transverse feedback systems have been used since the early days of accelerator design as a means of actively mitigating instabilities. These systems detect with beam position monitors any beam movement and feed back an amplified signal to a deflecting structure applying kicks with the correct phase and timing with respect to the circulating beam in order to counteract the motion. Feedback changes the dynamics of the motion and renders the beam stable [1].

RECAP OF TRANSVERSE FEEDBACK SYSTEMS IN OPERATION

The CERN hadron accelerator chain is an excellent example of the different challenges faced by transverse instabilities for which feedback systems are deployed for mitigation [2]. Table 1 shows some of the parameters of the feedback systems in the CERN Proton Booster Synchrotron (four rings), the CERN Proton Synchrotron (PS) and the Super Proton Synchrotron (SPS) [3, 4]. All these feedback systems underwent upgrades as part of the LHC Injector Upgrade project to increase the intensity delivered to the LHC and hence the luminosity of LHC itself. The last of these upgraded systems, the CERN PS transverse feedback was fully commissioned in 2021 and consisted both in an upgrade of the power system increasing the maximum kick strength as well as new digital signal processing as already deployed in the CERN SPS and PSB [5, 6]. The LHC transverse feedback system came into operation in 2010 [7] and beyond a feedback system, evolved into a versatile tool for diagnostics and beam manipulations [2].

Similar feedback systems are deployed in hadron accelerators worldwide, including ion synchrotrons currently under construction for the FAIR facility in Germany [8], NICA in Russia [9] and HIAF in China [10].

At CERN, after successfully completing the LHC transverse damper (ADT), and demonstrating its use during the entire cycle of LHC from injection through acceleration and with colliding beams during the LHC run 1 [2], research and development has shifted to explore

- possible upgrades to the LHC transverse damper in particular to further reduce the noise in the bunch position detection [11] and to fully exploit the breadth of data available from the feedback systems for characterisation of the beam [12–14]
- develop and test an intra-bunch feedback as part of a possible mitigation of electron-cloud and impedance driven high frequency instabilities leading to transverse motion within the bunches [15, 16]
- research on proposals for HL-Lumi LHC [17] and the future hadron collider (FCC-hh) at CERN [18].

FULL EXPLOITATION OF THE LHC ADT SYSTEM

From the originally envisaged possible upgrade paths for the LHC ADT system [3], increase in kick strength, increase in gain towards 20 MHz (half the bunch repetition frequency) and improved signal-to-noise ratio, all but the first were realised [11, 19]. An increase in kick strength was not necessary as the deployed strength permitted feedback operation, injection damping and beam excitation for measurement purposes beyond expectation [2]. Concerning the increase in gain towards full bunch-by-bunch operation, digital signal processing techniques were deployed during run 1 of LHC and fully used for run 2 for the nominal bunch spacing of 25 ns [19, 20]. The improvement of the signal-to-noise ratio of the beam detection has been achieved through

- increasing the number of pick-ups per beam and plane from two to four [3, 11]
- extensive research and development for the best RF receiver technique for the beam position detection [11]
- many small improvements to eliminate interference and adapt gains to the bunch intensity to optimally use the dynamic range available.

* Wolfgang.Hofle@cern.ch

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-FRIXGD1

Table 1: Transverse Feedback Systems at CERN in 2021 in the LHC Injector Chain (Power is Per Kicker Electrode)

Accelerator /energy	kicker / power / frequency band	processing used	last upgrade
LEIR 4.2 MeV/u – 72 MeV/u (kin. E)	strip-lines 100 W, 50 Ω, up to 100 MHz	2 pick-ups analogue, vector sum	2005
PS Booster 160 MeV to 2 GeV	striplines up to 100 MHz 800 W, 50 Ω	1 pick-up digital	2020
PS 2 GeV to 26 GeV/c	striplines with impedance transformer 5 kW, 125 Ω, up to ~60 MHz	1 pick-up digital	2020
SPS 14, 26 GeV/c to 450 GeV/c	electric field high impedance/tetrodes 30 kW, 180 Ω	strip-lines, electrostatic, digital, pick-up pairs	2014

As part of the full exploitation of the LHC ADT system and the research on the receiver technology the possible cross-talk of the detected bunch position from intra-bunch motion was extensively studied. The conclusion has been that the used principle to detect the bunch motion at 400 MHz, the 10th harmonic of the bunch repetition frequency and apply the signal in base-band is suitable for the range of parameters of LHC and has no adverse effects [21].

Significant progress has been made in the collection of the full data sets of bunch motion from LHC fills. A system called *Obsbox* was developed at CERN. It collects over serial digital links in real-time beam position data and provides diagnostics of bunch motion, on instabilities, and machine parameters [12,13,20]. As ad-on to the existing VME based electronics it overcomes the limitations of the bus bandwidth of the crate that does not permit a high data throughput. More modern platforms such as MicroTCA [22] can be chosen for transverse feedback systems in the future, however the possibility to extract data with an *Obsbox*-like system remains an integrated solution with unprecedented real-time capabilities and computing power for analysis [13].

COMPARISON WITH TRANSVERSE FEEDBACKS IN LEPTON STORAGE RINGS

Transverse coupled bunch feedback systems in lepton accelerators and storage rings generally use the same type of technologies [23] as employed in hadron accelerators, with some differences motivated by the short bunch lengths and the—in practical terms—fixed revolution frequency:

- the short bunch lengths permit to use for coupled bunch feedbacks pick-ups and kickers that operate in the several 100 MHz to GHz range, leading to small relative bandwidths of the systems, an advantage compared to the broadband systems of hadron machines that need to cover the kHz to multiple MHz range.
- broadband noise in the beam position detection for the feedback has due to the synchrotron radiation damping of the emittances not the same impact as in hadron machines where it easily degrades transverse emittances
- intra-bunch motion caused for example by the TMCI instability does not interfere with the detection of the coupled bunch dipole motion for the very short bunches and is generally not targeted to be suppressed by the feedback system in lepton machines.

INTRA-BUNCH FEEDBACK IN HADRON SYNCHROTRONS

An important research and development program started at CERN in 2008 [2,24,25] to explore the possibilities to mitigate transverse intra-bunch oscillations caused by the electron cloud effect in the SPS by feedback in the GHz frequency range. Prototyping of a system as part of the LIU Injector Upgrade Project in the SPS led to the installation of new wideband kickers [26] in the SPS that were successfully tested with beam.

Initially targeting the vertical ecloud effect in the SPS, both the simulation effort and the system design was extended to cover also the mitigation of impedance driven transverse intra-bunch instabilities, notably the TMCI instability by feedback [27]. To this end simulation codes have been developed as an add on to the macro-particle headtail code to cover active feedback on a slice-by-slice basis [28].

Intra-bunch feedback is an already established technique for bunch lengths longer than around 100 ns [6,29]. For short bunch lengths (< 5 ns), as found in the SPS or LHC, the systems described here are in the R&D stage, but not deployed as operational systems.

Two different approaches can be taken for an intra-bunch feedback, slice-by-slice sampling with processing and feeding back of the signal synchronised with the beam passage at the kicker or a frequency domain approach with separate paths for the feedback for different internal modes. The signal paths for the different bands can be separated in the analog domain before digitization or in the digital domain by mode decomposition [30,31].

Slice-by-Slice Approach to Feedback

Similarly to the simulations described above that are carried out on a slice-by-slice basis by tracking particles in the time domain and applying feedback kicks on a turn by turn basis, a real system can act in the same way. Signals from

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-FRIXGD1

the transverse pick-ups are digitised at a high sampling rate, in the case of the SPS prototype system at a maximum rate of 4 GS/s [32] with upgrades proposed to 8 GS/s [33]. Signal processing on this stream of data is applied to compute a correction that is fed to the beam via broadband kickers at a later passage of the beam.

Amongst the type of processing that is required we have to distinguish processing that is intended to remove the variations that are not caused by betatron oscillations (closed orbit variations) from the processing needed to phase- and time-align the feedback action with the beam. All signal processing techniques can be carried out in the digital domain, although in some cases analog corrections can be complementary and present the advantage of maximising the available dynamic range for digitization.

An example for this are analog means to correct the closed orbit using precision attenuators before the hybrid that generates the signal to be digitized [34].

Correction of the imperfection in phase of pick-ups, cables and kickers can also be well compensated by analog means, especially at the lower end of the frequency spectrum where strong variations of phase with frequency would require very long digital filters. For this purpose, analog equalizers were developed for the SPS prototype system [35].

When treating intra-bunch motion with FIR filters that take into account multiple previous turn samples, special attention has to be paid that they still cover in frequency all synchrotron sidebands characteristic to the internal modes that are targeted [36–38]. This usually limits the FIR filters to a small number of taps.

Band-by-Band Approach to Feedback

The frequency band in which instabilities are occurring can be split in several bands and assigned separate kickers optimised for the respective frequency range.

For the SPS wideband feedback prototype system two type of kickers have been produced, a short strip-line to cover the lower frequencies up to several 100 MHz and a broadband structure that provides gain to beyond 1 GHz [26]. Low-Q cavity type kickers were also considered for higher frequencies but not implemented [39].

For separating the different bands before digitization an approach similar to the multi-band Instability monitor (MIM) developed for the LHC [40] can be used. Bandpass filters on a strip-line pick-up single out the different bands and the oscillation can then be detected within this band with a better signal-to-noise ratio by separate analog down-conversion followed by digitization. The MIM could be extended to include I,Q detection of the signal preserving phase information needed for use in a feedback system. Presently this monitor only uses a diode based amplitude detection scheme.

The band-by-band approach can also be looked at from a different angle: It is equivalent to expanding the internal bunch motion into modes with a chosen set of basis functions. With more processing power becoming available on FPGA's it will be possible to decompose the motion into a basis matching the internal modes that actually develop without feedback. As part of the SPS wideband feedback study such a model based approach was also explored [30, 31]. These new feedback techniques that can be derived from this model based approach await implementation on a new electronics platform better suited than the prototype system. Such a new future platform can profit from the increase in sampling rate now available, in the 6–8 GS/s [33] range.

Application in View of LHC Crab Cavities

One of the future applications of the band-by-band approach will be the planned crab cavity feedback for High-Lumi LHC (HL-LHC). Here the aim of the intra-bunch part of the feedback is to mitigate the effect of amplitude noise in the crab cavity Low Level RF system (LLRF) that leads to a headtail oscillation of the bunch. The accelerator Physics studies show that a feedback system can significantly suppress the headtail noise component. As a kicker, in this case, the very same crab cavity can be used, because the initial noise introduced will be filtered by the cavity transfer function and thus can be mitigated by a cavity of similar bandwidth as kicker [41].

HARDWARE AND TECHNOLOGY DEVELOPMENT

Pick-ups

Feedback systems in hadron colliders can profit from developments needed for FELs for beam stabilisation and for linear colliders for final focus feedback and feed forward systems. Here significant progress has been made towards sub-micron resolution using both strip-line systems and cavity BPMs [43–46]. A recent study relevant to beam position detection for feedbacks explores the different techniques and pick-ups available [47].

Kickers

As an example of an advanced kicker design Fig. 1 shows the Faltin type kicker developed for the SPS wideband feedback [26]. A bandwidth of 1 GHz was achieved. For future designs of feedback systems synergies with developments for stochastic cooling systems can be explored [48] and low-Q cavity type kickers deserve a fresh look.

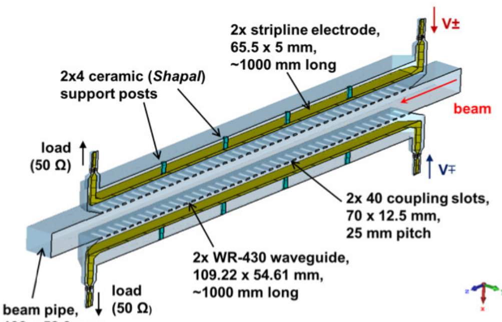

Figure 1: Faltin type kicker built for the SPS [42].

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-FRIXGD1

Electronics Development

Future consolidation project proposals at CERN include the Low energy ion ring (LEIR) transverse feedback system, the last transverse feedback system at CERN not yet profiting from a fully digital system. Due to the significant change in revolution frequency during acceleration from 4.2 MeV/u to 72 MeV/u kinetic energy for Pb54+ ions, a system with constant sampling frequency using the MicroTCA platform is one of the options being explored. Equipped with power amplifiers covering frequencies up to 100 MHz, the analog part of the system is also suitable for tests for higher frequency applications. The relatively long bunch length makes it ideal to study intra-bunch feedback. Funding for the consolidation is motivated by the obsolescence of hardware, however this project can serve as a starting point to introduce fixed frequency sampling into the LHC injector chain transverse feedbacks as is already widely used for the longitudinal feedback and beam control systems at CERN [49, 50].

RESULTS FOR INTRA-BUNCH FEEDBACK WITH BEAM IN THE SPS

A particular recent highlight of the SPS intra-Bunch feedback has been the demonstration that it can suppress at 26 GeV/c injection energy at low chromaticity a headtail instability and permit higher intensities to be injected and stored. Fig. 2 shows as a result the intensity that can be maintained with no feedback at all, with coupled bunch feedback only and with the additional intra-bunch feedback. These tests were carried out with the so called Q22 optics that shows a lower instability threshold and has been a fall-back option for the LIU project of the SPS [16]. With the Q20 optics actually used the design intensities are achievable without intra-bunch feedback.

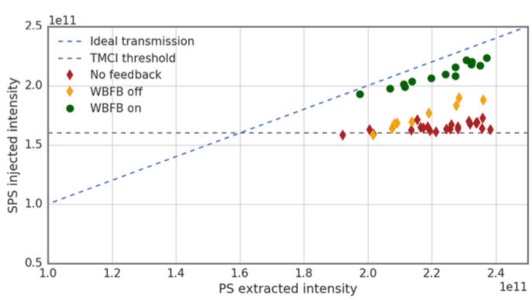

Figure 2: SPS Results at 26 GeV/c with Q22 optics [16].

R&D TOWARDS FUTURE ACCELERATORS AND COLLIDERS

The case of the FCC-hh is a typical example of a future accelerator project to which the R&D for the intra-bunch feedback directly applies.

Simulations showed [18] that a classical system as was developed for LHC can serve as injection oscillation damper and at the same time provide transverse feedback for the fastest growing coupled bunch modes at low frequency. A base band system is proposed that can continue to use as in LHC tetrode amplifiers that offer the possibility to directly apply RF signals in base-band to a kicker structure with high RF voltages in the multi kV range. In order to cope with the increased needed kick strength such a system can be split over more units. This system can be complemented by a second system operating at higher frequency and providing feedback also for intra-bunch motion. Suitable kicker structures would include short strip-lines or structures derived and used in stochastic cooling systems.

A possible application of the intra-bunch feedback was explored for Hi-Lumi LHC. Here at low chromaticity a head-tail instability develops with a spacial signature as shown in Fig. 3. intra-bunch feedback in the range up to 1 GHz was shown to cure this instability in simulations [17]. An Intra-bunch system for LHC is currently not foreseen and the luminosity upgrade of LHC relies on a combination of high chromaticity and octupole settings to keep instabilities at bay, in addition to the classical coupled bunch feedback already in operation for more than one decade. Due to the

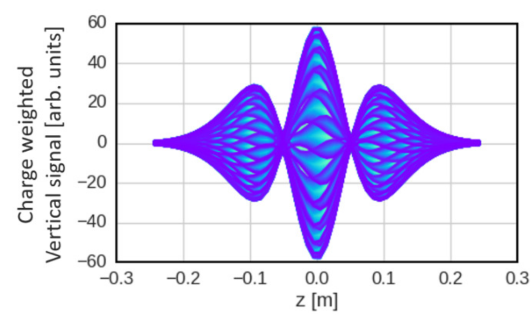

Figure 3: Intra-bunch motion in spacial domain [17].

potential of intra-bunch feedback systems for future colliders, R&D needs to continue. A path that has been explored is to move the R&D to accelerators that offer more time for machine studies. A particular interesting proposal has been to use DAFNE (LNF at INFN Frascati) as an accelerator test facility in the future with a project proposal that includes transverse feedback R&D [51].

SUMMARY AND OUTLOOK

With the commissioning of the LHC and its sophisticated transverse feedback system it has been shown that feedback systems of this kind are both feasible and indispensable for modern hadron colliders. Intra-bunch feedback on short bunches has made significant advances during the last decade and its feasibility was demonstrated in the SPS. It can now be included in future accelerators at the design stage. The principle aim of colliders and accelerators in operation is to serve the (physics) clients. There is limited time and resources for new hardware developments and tests in these facilities that are not directly aimed to improvements in the very same accelerator. For the intra-bunch feedback developed at the SPS this leaves open the question on where the R&D and the practical beam tests can continue. It is unquestionable that research efforts need to continue in the area of transverse feedback systems in view of the future accelerator projects such as FCC-hh and FCC-ee at CERN.

ACKNOWLEDGEMENT

The author would like to thank the members of the international collaboration for the R&D project conducted in the time frame of 2008 to 2018 for the intra-bunch feedback at the SPS. The CERN transverse damper team has made significant progress in LHC and its injectors, conceptually as well as for the hardware implementation and software. Here my special thanks go to G. Kotzian, M. Söderén and D. Valuch for their long standing contributions.

REFERENCES

[1] M. Lonza, and H. Schmickler, "Multi-bunch Feedback Systems", Proceedings of the CAS-CERN Accelerator School: Advanced Accelerator Physics, Trondheim, Norway, 19–29 August 2013, edited by W. Herr, CERN–2014–009, pp. 503–546, CERN, Geneva, Switzerland, 2014.

[2] W. Höfle, "Progress in Transverse Feedbacks and Related Diagnostics for Hadron Machines", in *Proc. IPAC'13*, Shanghai, China, May 2013, paper FRXCA01, pp. 3990–3994.

[3] W. Höfle, "Transverse Feedback Systems in the LHC and its Injectors: Projected Performance and Upgrade Paths", CERN-2007-002, pp. 177–179, CERN, Geneva, Switzerland, 2007.

[4] J. Coupard, *et al.* (Ed.), "LHC Injectors Upgrade", Technical Design Report, Vol. I: Protons, CERN-ACC-2014-0337, CERN, Geneva, Switzerland, 2014.

[5] A. Blas, and G. Kotzian, "Upgraded Transverse Feedback for the CERN PS Booster", in *Proc. HB'18*, Daejeon, Korea, Jun. 2018, pp. 256–259. doi:10.18429/JACoW-HB2018-WEP2PO001

[6] G. Sterbini, A. Blas, and S. S. Gilardoni, "Beam-based Performance of the CERN PS Transverse Feedback", in *Proc. HB'14*, East Lansing, MI, USA, Nov. 2014, paper MOPAB10, pp. 40–44.

[7] W. Höfle, G. Kotzian, M. Schokker, and D. Valuch, "LHC Damper Beam Commissioning in 2010", in *Proc. IPAC'11*, San Sebastian, Spain, Sep. 2011, paper MOPO012, pp. 505–507.

[8] T. Rueckelt, M. Alhumaidi, and A. M. Zoubir, "Realization of Transverse Feedback System for SIS18/100 using FPGA", in *Proc. IBIC'13*, Oxford, UK, Sep. 2013, paper MOPC29, pp. 128–131.

[9] D. Dinev, "Coherent instabilities in the booster and collider of the heavy ion accelerator complex NICA", *Phys. Part. Nuclei* vol. 44, pp. 623–656, 2013. doi:10.1134/S1063779613040047

[10] J. Liu *et al.*, "Transverse impedances and collective instabilities in a heavy ion accelerator", *Phys. Rev. Accel. Beams,* vol. 21, no. 6, p. 064403, 2018. doi:10.1103/PhysRevAccelBeams.21.064403

[11] D. Valuch, and V. Stopjakova, "New Generation of very Low Noise Beam Position Measurement System for the LHC Transverse Feedback System", presented at the 13th International Particle Accelerator Conf. (IPAC'22), Bangkok, Thailand, Jun. 2022, paper TUPOST007, this conference.

[12] L. R. Carver *et al.*, "Usage of the Transverse Damper Observation Box for High Sampling Rate Transverse Position Data in the LHC", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 389–392. doi:10.18429/JACoW-IPAC2017-MOPAB113

[13] M. Söderén, and D. Valuch, "Low Latency, Online Processing of the High-Bandwidth Bunch-By-Bunch Observation Data From the Transverse Feedback System in the LHC", in *Proc. 24th International Conference on Computing in High Energy and Nuclear Physics (CHEP 2019)*, EPJ Web of Confererences, vol. 245, 01036, 2020. doi:10.1051/epjconf/202024501036

[14] G. Kotzian, M. Söderén, P. S. Solvang, and D. Valuch, "Reconstruction of Transverse Phase Space from Transverse Feedback Data for Real Time Extraction of Vital LHC Machine Parameters", presented at the 13th International Particle Accelerator Conf. (IPAC'22), Bangkok, Thailand, Jun. 2022, paper TUPOST037, this conference.

[15] J. D. Fox *et al.*, "Control of Intra-Bunch Vertical Motion in the SPS with GHz Bandwidth Feedback", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 2365–2368. doi:10.18429/JACoW-IPAC2018-WEPAL079

[16] W. Höfle *et al.*, "Impact of a Wideband Feedback Prototype System on TMCI in the SPS", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 1208–1211. doi:10.18429/JACoW-IPAC2018-TUZGBD4

[17] K. Li, *et al.*, "Studies on potential use and needs of a wideband feedback system for the HL-LHC", CERN-ACC-Note-2018-0058, CERN, Geneva, Switzerland, 2018.

[18] W. Höfle, J. Komppula, G. Kotzian, K. S. B. Li, and D. Valuch, "Transverse Feedback System for the CERN FCC-hh Collider", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 1997–2000. doi:10.18429/JACoW-IPAC2018-WEPAF072

[19] W. Höfle, F. Dubouchet, G. Kotzian, and D. Valuch, "Performance of the LHC Transverse Damper with Bunch Trains", in *Proc. IPAC'13*, Shanghai, China, May 2013, paper WEPME043, pp. 3022–3024.

[20] M. Söderén, J. Komppula, G. Kotzian, S. Rains, and D. Valuch, "ADT and Obsbox in LHC run 2, plans for LS2", Proceedings of the 9th LHC Operations Evian Workshop, Evian Les Bains, France, 30 Jan - 1 Feb 2019, pp. 165-171, CERN-ACC-2019-059, CERN, Geneva, Switzerland, 2019.

[21] G. Kotzian, W. Höfle, and D. Valuch, "Sensitivity of the LHC Transverse Feedback System to Intra-Bunch Motion", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 1916–1919. doi:10.18429/JACoW-IPAC2017-TUPIK093

[22] https://www.picmg.org/openstandards/microtca/

[23] T. Nakamura, "Transverse and Longitudinal Bunch-by-Bunch Feedback for Storage Rings", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 1198–1203. doi:10.18429/JACoW-IPAC2018-TUZGBD2

[24] J. R. Thompson, J. M. Byrd, W. Höfle, and G. Rumolo, "Initial Results of Simulation of a Damping System for Electron Cloud-Driven Instabilities in the CERN SPS", in *Proc.*

PAC'09, Vancouver, Canada, May 2009, paper FR5RFP076, pp. 4713–4715.

[25] J. D. Fox *et al.*, "Feedback Techniques and SPS Ecloud Instabilities – Design Estimates", in *Proc. PAC'09*, Vancouver, Canada, May 2009, paper TH6REP078, pp. 4135–4137.

[26] J. M. Cesaratto *et al.*, "A Wideband Slotted Kicker Design for SPS Transverse Intra-bunch Feedback", in *Proc. IPAC'13*, Shanghai, China, May 2013, paper WEPME061, pp. 3073–3075.

[27] K. S. B. Li *et al.*, "Modelling and Studies for a Wideband Feedback System for Mitigation of Transverse Single Bunch Instabilities", in *Proc. IPAC'13*, Shanghai, China, May 2013, paper WEPME042, pp. 3019–3021.

[28] J. Komppula, W. Höfle, and K. S. B. Li, "Simulation Tools for the Design and Performance Evaluation of Transverse Feedback Systems", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 1912–1915. doi:10.18429/JACoW-IPAC2017-TUPIK091

[29] K. Nakamura *et al.*, "Transverse Intra-bunch Feedback in the J-PARC MR", in *Proc. IPAC'14*, Dresden, Germany, Jun. 2014, pp. 2786–2788. doi:10.18429/JACoW-IPAC2014-THOAA03

[30] O. Turgut, J. E. Dusatko, J. D. Fox, C. H. Rivetta, and S. M. Rock, "Identification of Intra-bunch Transverse Dynamics for Model-Based Control Purposes at CERN Super Proton Synchrotron", in *Proc. IPAC'16*, Busan, Korea, May 2016, pp. 3145–3148. doi:10.18429/JACoW-IPAC2016-THOAA01

[31] C. H. Rivetta, T. Mastoridis, and J. D. Fox, "Identification of the Inter-Bunch and Intra-Bunch Beam Dynamics Based on Dynamic Modal Decomposition (DMD)", in *Proc. IBIC'21*, Pohang, Rep of Korea, Sep. 2021, pp. 473–477. doi:10.18429/JACoW-IBIC2021-FROA01

[32] J. D. Fox *et al.*, "Control of Intra-Bunch Vertical Instabilities at the SPS - Measurements and Technology Demonstration", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 2005–2007. doi:10.18429/JACoW-IPAC2017-TUPIK119

[33] J. E. Dusatko, and J. D. Fox, "Ultra-Wideband Transverse Intra-Bunch Feedback: Beginning Development of a Next Generation 8 GSa/s System", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 2001–2004. doi:10.18429/JACoW-IPAC2018-WEPAF073

[34] G. Kotzian, W. Höfle, R. J. Steinhagen, D. Valuch, and U. Wehrle, "Evaluation of Strip-line Pick-up System for the SPS Wideband Transverse Feedback System", in *Proc. IBIC'13*, Oxford, UK, Sep. 2013, paper WEPC12, pp. 690–693.

[35] J. Platt *et al.*, "Equalizer design techniques for dispersive cables with application to the SPS wideband kicker", *Nucl. Instr. M.*, vol .868, pp. 93–97, 2017. doi:10.1016/j.nima.2017.06.029

[36] G. Kotzian, "Possibilities for Transverse Feedback Phase Adjustment by Means of Digital Filters", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 1924–1927. doi:10.18429/JACoW-IPAC2017-TUPIK095

[37] K. Li, and J. Komppula, "Implementation of Transverse Dampers in Beam Stability Analyses", Proceedings of ICFA mini-Workshop on Mitigation of Coherent Beam Instabilities in Particle Accelerators (MCBI 2019), Zermatt, Switzerland, September 2019, pp. 211–215, CERN-2020-009, CERN Geneva, Switzerland, 2020.

[38] J. Komppula, X. Buffat, G. Kotzian, K. Li, and D. Valuch, "MD4036: New ADT signal processing for large tune acceptance", CERN-ACC-Note-2019-008, CERN, Geneva, Switzerland, 2019.

[39] J. M. Cesaratto *et al.*, "SPS Wideband Transverse Feedback Kicker: Design Report", CERN-ACC-NOTE-2013-0047 (also SLAC-R-1037), CERN, Geneva, Switzerland, 2013.

[40] T. E. Levens, T. Lefèvre, and D. Valuch, "Initial Results from the LHC Multi-Band Instability Monitor", in *Proc. IBIC'18*, Shanghai, China, Sep. 2018, pp. 314–318. doi:10.18429/JACoW-IBIC2018-TUPC09

[41] P. Baudrenghien *et al.*, "Crab Cavity RF Noise Feedback and Transverse Damper Interaction", CERN-ACC-Note-2019-0006, CERN, Geneva, Switzerland, 2019.

[42] M. Wendt, I. A. Alonso Romero, S. J. Calvo, W. Höfle, O. R. Jones, and E. Montesinos, "A Broadband Transverse Kicker Prototype for Intra-Bunch Feedback in the CERN SPS", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 1812–1815. doi:10.18429/JACoW-IPAC2017-TUPIK053

[43] G. B. Christian *et al.*, "A Sub-micron Resolution, Wideband, Stripline BPM System for Driving Bunch-by-bunch Feed-back and Feed-forward Systems at ATF", in *Proc. IPAC'14*, Dresden, Germany, Jun. 2014, pp. 1358–1360. doi:10.18429/JACoW-IPAC2014-TUPME009

[44] K. G. Nakamura *et al.*, "Development of Wideband BPM for Precise Measurement of Internal Bunch Motion", in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, pp. 937–939. doi:10.18429/JACoW-IPAC2015-MOPTY001

[45] T. Bromwich *et al.*, "Progress Towards Nanometre-Level Beam Stabilisation Using a Cavity BPM System at ATF2", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 1986–1988. doi:10.18429/JACoW-IPAC2017-TUPIK112

[46] B. Keil *et al.*, "First Beam Commissioning Experience With The SwissFEL Cavity BPM System", in *Proc. IBIC'17*, Grand Rapids, MI, USA, Aug. 2017, pp. 251–254. doi:10.18429/JACoW-IBIC2017-TUPCF17

[47] M. Wendt, "Direct (Under)Sampling vs Analog Downconversion for BPM Electronics", in *Proc. IBIC'14*, Monterey, CA, USA, Sep. 2014, paper WEIYB1, pp. 486–494.

[48] G. Zhu *et al.*, "Stochastic Cooling Pickup/Kicker Developments for the High-precision Spectrometer Ring in the HIAF Project at IMP", *IEEE Trans. Nucl. Sci.*, Vol. 68, No. 1, January 2021, pp. 9–20.

[49] G. Hagmann *et al.*, "The CERN SPS Lowlevel RF: The Cavity-Controller", presented at the 13th International Particle Accelerator Conf. (IPAC'22), Bangkok, Thailand, Jun. 2022, paper TUPOST023, this conference.

[50] M. E. Angoletta *et al.*, "Beam commissioning of the New Digital Low-level RF System for CERN's AD", presented at the 13th International Particle Accelerator Conf. (IPAC'22), Bangkok, Thailand, Jun. 2022, paper TUPOST025, this conference.

[51] A. Drago *et al.*, "Intra-bunch feedback system developments at DAFNE", in *Proc. of the Joint INFN-CERN-ARIES Workshop on Electron-Cloud Effects*, La Biodola (Isola d'Elba), Jun. 2018, pp. 223–227, CERN-2020-007, CERN, Geneva, Switzerland, 2020.