PROGRESS IN TRANSVERSE FEEDBACKS AND RELATED DIAGNOSTICS FOR HADRON MACHINES

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Abstract

Today Hadron Accelerators with high intensity and high brightness beams increasingly rely on transverse feedback systems for the control of instabilities and the preservation of the transverse emittance. With particular emphasis, but not limited to, the CERN Hadron Accelerator Chain, the progress made in recent years, and the performances achieved are reviewed. Hadron colliders such as the LHC represent a particular challenge as they ask for low noise electronic systems in these feedbacks for acceptable emittance growth. Achievements of the LHC transverse feedback system used for damping injection oscillations and to provide stability throughout the cycle are summarized. This includes its use for abort gap and injection cleaning as well as transverse blow-up for diagnostics purposes. Beyond systems already in operation, advances in technology and modern digital signal processing with increasingly higher digitization rates have made systems conceivable to cure intra-bunch motion. With its capabilities to both acquire beam oscillations and to actively excite motion, transverse feedback systems have a large variety of applications for beam diagnostics purposes.

INTRODUCTION

Physics at high energy colliders and for Fixed Target experiments at circular accelerators requires high intensity beams to achieve the desired high event rates. In Hadron Colliders such as the Large Hadron Collider (LHC) at CERN [1] at the energy frontier, beams are bunched for acceleration and storage, in the case of the nominal LHC proton beam [1] with bunch intensities in excess of 1×10^{11} protons and 2808 bunches per ring.

As damping by synchrotron radiation is usually small for hadrons in today's colliders the event rate (luminosity) that can be achieved for a given beam intensity is determined much by the transverse beam sizes in collision. Luminosity depends therefore heavily on the preservation of transverse emittance in the injector chain and the collider itself.

Moreover, for the hadron beams for fixed target experiments, preservation of transverse emittance plays an important role as often the beam has to be delivered onto a small target without too many losses.

Transverse feedback systems, also referred to as transverse "dampers" are essential for the preservation of the emittance: firstly they are used to damp injection oscillations caused by kick errors of extraction and injection kickers as well as steering errors during beam transfer; secondly they provide stability against beam transverse dipolar instabilities that can easily develop as a result of the beam interacting with the electromagnetic field it generates in the surrounding vacuum system structure; and thirdly these feedback systems can reduce the effect of external perturbations that shake the beam and cause emittance increase for example by ripple on magnet power converters.

In particular light sources and high current lepton colliders have generally relied on transverse feedback system for many years. For a review of past status see [2, 3] and for an overview of system specifications [4].

RECENT PROGRESS FOR HADRON MACHINES

Recent progress at CERN for hadron machines include the LHC transverse feedback system described more detailed in this paper, as well as a new system for the 26 GeV CERN PS [5] which is part of the LHC Injector Upgrade project (LIU) [6]. In the framework of this project transverse feedbacks in all of the CERN proton injector chain, PSB, PS, and SPS [7] will undergo substantial upgrades. Moreover, LIU includes R&D towards an intra-bunch feedback [8], applicable to PS, SPS and LHC as further summarized below. Progress at other laboratories include demonstration of damping of an e-p transverse instability at the proton rings at the LANL (PSR) in Los Alamos [9] and at ORNL SNS [10]. New feedbacks are also under development for the J-PARC Main Ring (MR) [11] and for FAIR at GSI [12, 13]. Advances in Transverse Feedback Theory include stability analysis [14] and estimation of emittance blow-up at injection in the presence of transverse feedback [15].

PRINCIPLE OF TRANSVERSE FEEDBACK

Initially, transverse feedback systems were realized as purely analog systems. With the advances in digital technologies with high speed analog-to-digital converters (ADCs) and digital-to-analog converters (DACs), today available in the GS/s range and with a high number of bits (14 bit to 16 bit) in the 100 MS/s range, transverse feedback systems mostly rely on digital processing of the signal and field programmable logic employing FPGAs.

Figure 1 shows the principle elements of a transverse feedback system using an embedded digital controller.

The transverse signal from a beam position monitor is digitized after appropriate conditioning which can incorporate a transposition in frequency using mixers, for bunched beams. Digital processing usually includes at least the delay to match the beam time of flight to the electronic delay

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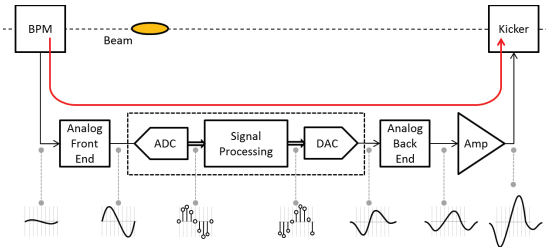

Figure 1: Principle of Transverse Feedback.

between pick-up and kicker and to correctly phase the feedback signal with the beam oscillation at the kicker location. Power amplifiers and kickers are appropriately selected to cover the frequency band of interest and adapted to provide a sufficiently large kick with respect to the size of the oscillations that need to be damped and the beam rigidity.

The scheme can be extended to using several pick-ups and kickers. For bunched beams there can be several samples per bunch or a single sample depending on the desired system bandwidth with respect to the bunch length. Kicker structures include matched strip lines (often 50 Ω) with solid state power amplifiers, or for large kick strengths tetrode amplifiers working on a high impedance with short connection to a kicker deflecting with the electric field only [16].

COUPLED BUNCH INSTABILITIES

The interaction of the beam with the electromagnetic fields induced in the surrounding accelerator structures is well described by the beam coupling impedance. For both longitudinal and transverse coupled bunch instabilities Sacherer [17] developed more than 35 years ago the theory that links the complex tune shift of individual modes of oscillation of the beam to the beam coupling impedance.

Coupled bunch modes

In the transverse plane, for a bunched beam these modes of oscillation can be characterized by three indices representing the degrees of freedom, the coupled bunch mode number n, the head-tail mode number m and a radial mode number p. Beam pick-ups, sensitive to the dipole moment of oscillation can only detect higher mode oscillations in the case of higher order coupled bunch and head-tail mode number, but cannot distinguish radial modes as their dipole moments do not change as time evolves. Consequently, higher order radial modes cannot be treated by feedback systems built to correct with angular kicks. They will not be further considered here.

A coupled bunch mode with mode number n for M equally distributed bunches and head tail mode number m, $m = 0$ being the rigid dipole mode, will appear in the spectrum at frequencies

$$f_{\mathrm{nmk}} = (n + kM) \cdot f_0 \pm f_\beta + m f_{\mathrm{s}} \qquad (1)$$

where f_0 denotes the revolution frequency, f_β the betatron frequency and f_{s} the synchrotron frequency. The spectrum repeats every frequency interval of $M f_0$, with k integer $-\infty < k < \infty$ in Eqn. (1). In the case of a single bunch instability the spectrum repeats every revolution frequency interval.

Growth rates

For the classical dipolar coupled bunch instability, growth rates readily follow from the real part of the effective transverse impedance $Z_{\mathrm{T,eff}}$, obtained from the impedance by sampling at the relevant frequencies and weighting with the bunch spectrum and beta functions. For a particular mode the growth rate $1/\tau$ normalized to the beam revolution time T_0 is proportional to the total beam current I_{DC} and $1/\gamma$

$$\frac{T_0}{\tau} \propto \frac{I_{\mathrm{DC}}}{\gamma} Z_{\mathrm{T,eff}} \ . \qquad (2)$$

Complex impedance models have been developed for accelerators to compute growth rates taking into account all known machine impedances, for example for the CERN SPS [19].

Mitigation by transverse feedback

In order to cover by a multi-bunch transverse feedback all rigid dipole oscillations it is sufficient to restrict the operating range to a frequency band at any one of the bunch harmonics kMf_0. A bandwidth of half the bunch frequency is sufficient and lower or upper sideband of a bunch harmonic can be used. For an overview see for example [18]. Due to the long bunch lengths in Hadron machines the choice for transverse feedback systems is often to work in “base-band” or at a low harmonic of the bunch frequency in order to have a constant kick strength over the bunch length.

DESIGN AND PERFORMANCE OF THE LHC DAMPER

Due to relatively large transverse injection errors that were expected (±4 mm at $\beta = 183$ m) and the strong instabilities predicted in the low frequency range due to the resistive wall impedance a relatively high kick strength had been specified for the LHC damper providing at least 2 μrad of deflection at 450 GeV/c, corresponding to a kick of $\simeq 3 \times 10^{-3}$ eVs/m. The design has been inspired by the SPS transverse feedback system using high power tetrode amplifiers mounted directly in the accelerator tunnel under the kicker tanks. Four kickers, each 1.5 m long, provide the required kick strength per beam and plane [16, 20].

Table 1 summarizes the principle design parameters [16], which have all been achieved or exceeded. In practice losses at injection limit the acceptable injection errors to well below 1 mm easing the requirements for the transverse feedback. The high kick strength installed has permitted to damp injection oscillations up to a factor four faster than in the original design and was also a key to the

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success for a number of applications, in which the transverse damper is used as an exciter, described further below.

Table 1: LHC Transverse Damper: Beam Parameters and Design Requirements [16].

Injection beam momentum	450	GeV/c
Static injection errors ($\beta = 183$ m)	2	mm
ripple ($\beta = 183$ m)	2	mm
resistive wall growth time	14	ms
decoherence time	68	ms
tolerable emittance growth	2.5	%
overall damping time	4.7	ms (53 turns)
standard bunch spacing	25	ns
lowest betatron frequency	> 2	kHz
highest frequency to damp	20	MHz
Electro-static kickers	base band	
aperture of kickers	52	mm
number of kickers per plane and beam	4	
length of kicker plates	1.5	m
nominal voltage up to 1 MHz	± 7.5	kV
kick per turn at 450 GeV/c up to 1 MHz	2	μrad

Beam Position Detection and Noise

For collider operation low noise electronics for the detection of beam oscillations is mandatory. In the case of LHC a set of coupler type pick-ups is used with I/Q detection of an RF signal burst at 400 MHz of Σ and Δ signals from individual bunches [21]. With 16 bit digitization a resolution in the μm range, single shot, single bunch, has been obtained. The LHC damper beam position electronics also features a normalization with the bunch intensity and can be calibrated using orbit bumps against the standard LHC BPMs. In this way the signals from the feedback provide detailed quantitative information on beam oscillations, bunch-by-bunch.

Using a set of N pick-ups has been proposed [7, 13] as a means to average out noise uncorrelated between pick-ups thus gaining a factor $\sqrt{N}$ in Signal-to-Noise Ratio. In the case of LHC the number of pick-ups per beam and plane for the transverse feedback will be doubled from two to four, helping to improve the S/N ratio. Moreover, new electronics will be deployed during the 2013-2014 long shutdown (LS1), with the expectation to push the resolution down to below 1 μm.

Platform for Signal Processing

The LHC Low Level RF (LLRF) system and the transverse feedback system signal processing share a common hardware platform [22]. Custom developed VME 32X boards are housed in a VME crate featuring also a dedicated back plane for the distribution of clock signals and beam synchronous timing and triggers. The VME front-end processors are used for control of the feedback parameters and serve as gateway to the middle ware of the LHC control system. Application software operated from the central control room is used to change parameters, monitor the system and acquire data from the internal buffers of the VME hardware. Processing of feedback loop critical data is done on FPGAs, clocked by beam synchronous clocks.

The FPGA based signal processing includes FIR filters to adjust the feedback phase, and to correct, as well as shape the frequency response in amplitude and phase as desired [23, 24]. Output signals are generated by 14 bit DACs with a gain adjustment in the range of 72 dB via the reference supplied to the DAC, without loss of resolution.

Pushing the Performance

Initially commissioned to damp injection errors in 2010 with 40 turns damping time [26], the performance was very quickly pushed to achieve faster damping rates. This had become necessary as external perturbations, likely caused by noise from power converters in the magnet system, caused unwanted emittance increase. The feedback has been shown to efficiently counteract such perturbations [27, 28]. Operation at 10 turns damping time at the 450 GeV injection plateau became standard procedure since.

Single bunch instabilities with bunch trains during the squeeze motivated flattening the frequency response of the damper to achieve bunch independent treatment. This mode of operation has also helped to improve injection damping of the 25 ns spaced beam [29].

APPLICATIONS BEYOND DAMPING

Built-in Observation Capabilities

Built in observation capabilities permit diagnostics of injection oscillations and instability analysis. Figure 2 shows

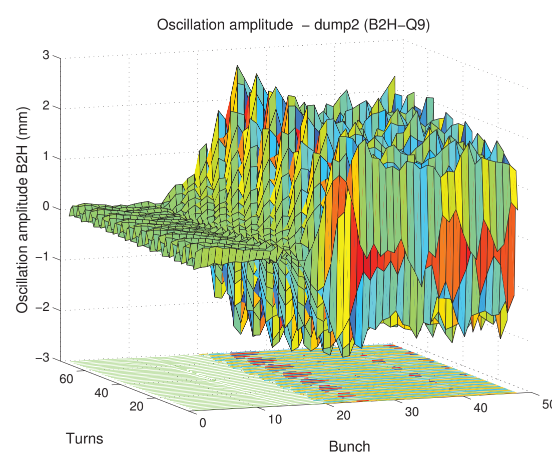

Figure 2: Injection of a batch of 48 bunches spaced 25 ns in LHC without transverse feedback at low chromaticity [30].

as an example the oscillations in LHC in the horizontal plane of a train of 48 bunches spaced 25 ns prior to a beam dump [30]. This beam injected without transverse feedback was heavily unstable at low frequency, with a signature compatible with an electron cloud triggered coupled bunch instability developing along the batch.

Tune Measurement

The tune measurement in LHC relies on residual oscillations of the beam and a very high sensitivity of detection [31]. It is perturbed by the operation of the transverse feedback system: Larger oscillations are damped, and the noise injected by the feedback system increases the noise floor of the tune detection system [32]. Therefore, alternative methods to measure the tune are being explored such as the direct computation of tune from the transverse damper in-loop signals [34], as has been already demonstrated at electron machines [33].

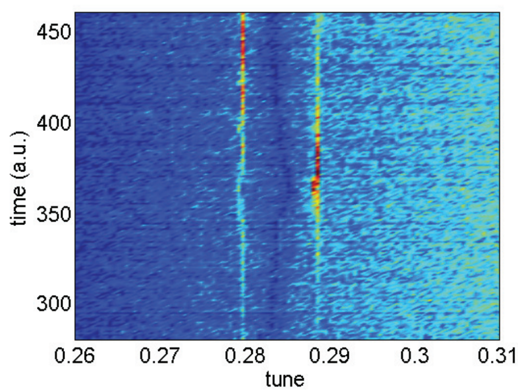

Figure 3: Time evaluation of FFT of beam oscillations (average over six bunches).

Figure 3 shows the average of the FFTs (2048 turns) of six bunches observed within the transverse feedback loop. The tune is seen as a trench bordered by narrow lines representing beam oscillations driven by multiples of the 50 Hz line frequency from noise supposedly penetrating the circuits of magnets.

Abort Gap and Injection Cleaning

In a high energy collider with super-conducting magnets it is extremely important to maintain a gap in the circulating beam, free of particles, in order to be able to fire the kickers of the beam abort system without creating any additional losses that can quench or damage a magnet. In RHIC abort gap cleaning using transverse kickers has been successfully used [35].

Following machine tests in the SPS abort gap cleaning using the transverse damper was proposed for LHC [36, 37]. A pulse, amplitude modulated close to the betatron frequency is gated within the abort gap and used to drive the beam to the aperture limit defined by the collimation system.

In order to cover the possible range of tunes the excitation frequency is swept in steps across the tune of the beam. This procedure has been tested in simulation [38] put in operation at the injection plateau in 2011 using the vertical dampers [39, 40], and is available on demand at collision energy since 2012 [41].

Subsequently the same technique was proposed and deployed to clean the injection slot ($\simeq 11\ \mu$s) prior to the injection of a new batch of beam with the horizontal dampers. This procedure has been indispensable for the injection of high intensity long bunch trains as it substantially reduces losses during the firing of the injection kicker [42].

Transverse Excitation and Blow-up

The transverse damper kickers are also used operationally for transverse blow-up. Noise generated in the feedback loop is applied to the power chain and can be gated on individual bunches [43]. An important application of this technique has been the generation of "loss maps", the mapping of losses around the accelerator using the BLM system of LHC. These loss maps are required for collimation set-up and alignment verifications. Using the transverse damper for loss maps has much increased the operational efficiency when compared to the traditional method used, the crossing of the third order resonance [44].

Blow-up and excitation with the transverse feedback has also been used for the LHC quench tests at the end of run 1 in February 2013 [45]. In addition to an excitation with noise the feedback was also used with flipped sign as positive feedback to produce a rapidly growing oscillation driving a very low intensity bunch directly into the cold aperture of a magnet [46].

MITIGATION OF TRANSVERSE INTRA-BUNCH MOTION BY FEEDBACK

In accelerators such as the CERN SPS and LHC, beam intensities are limited amongst other effects also by transverse instabilities, both in the single bunch and multi-bunch case. In the single bunch case it is the transverse mode coupling instability (TMCI) and in the multi-bunch case at 25 ns bunch spacing the electron cloud driven instability (ECI) that pose severe limitations [25].

Common to these two instabilities is the appearance of intra-bunch motion. Feedback techniques with GHz bandwidth to cure these instabilities are being proposed [48, 49] and have been shown to work for the SPS in simulations for both cases, ECI [48, 50], and TMCI [51]. Results have been confirmed with independent codes and realistic feedback models [52, 53, 54].

Intra-bunch motion has been successfully excited in an initial system test in the SPS [55] and first closed loop experiments with a completed prototype feedback system [56] in the SPS were successful [8]. The time evolution of intra-bunch motion was observed as parameters of the feedback were changed [8]. Engineering these feedback systems is challenging in many respects, covering a bandwidth in the GHz range with novel kickers [57] and power systems, and high speed digital techniques in the multi-GS/s range [56].

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SUMMARY AND OUTLOOK

Challenges for the future include the full exploitation of the diagnostics offered by the signals within the feedback loop for purposes of tune measurement and instability diagnostics. Transverse Feedback systems have much profited from the availability of highly integrated fast digital logic in the form of FPGAs, which has become the standard technology used. The requirement to have precise time control and synchronization drives the design of custom made electronics for these feedback system. Developments also profit from the ADCs and DACs clocked at and beyond 100 MHz with 14-16 bit readily available. These advances in technology have shown to permit operating these digital systems in hadron colliders with stored beam during collisions. Advances with high speed ADCs and DACs also drive the development of novel intra-bunch transverse feedbacks.

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