Transverse Feedback Systems in the LHC and its Injectors: Projected Performance and Upgrade Paths

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Abstract

Transverse feedback systems are essential to preserve the small transverse emittances throughout the injector chain and in LHC itself. The striving for higher brilliance beams will put increased demands on the transverse feedback systems in the future. Possible upgrades of the LHC damper will address the low noise performance that is essential for operation in coast, while for the injectors a new generation of sophisticated digital electronics will replace the analogue signal processing as it is still employed in the PS booster today. A particular challenge for the smaller accelerators is the large frequency swing not present in the LHC.

INTRODUCTION

Currently there are transverse feedback systems installed and used in operation in the PS booster and SPS accelerators where they are required to stabilise the high intensity proton beams against coupled bunch instabilities and to damp injection oscillations. Transverse feedback systems in the PS [1] and LEIR accelerators are being installed and commissioned. For the SPS damper an extensive upgrade program was completed as part of the preparations of the SPS as LHC injector [2]. For the LHC a very powerful transverse feedback system (damper) project [2,3] is nearing completion and it is planned to start commissioning in the first year of LHC operation.

OVERVIEW OF CERN TRANSVERSE DAMPER SYSTEMS

Table 1 gives an overview of the transverse feedback systems at CERN that are installed and have been used for many years. Table 2 summarizes the characteristics of the three damper projects that are currently nearing completion. The LEIR system has already been commissioned during the accelerator run in 2006 and the PS and LHC systems are under installation. Tests with new power amplifiers and kickers for the PS transverse feedback have been successfully completed in 2006 and the system was used to excite the beam for the purpose of transverse blow-up. Commissioning of the PS system will continue in 2007.

Table 1: Transverse feedback systems at CERN installed and in operation

Accelerator	Digital / Analogue processing	Power / kicker / bandwidth	operation
PS Booster (protons) 50 MeV – 1.4 GeV (kin. E.)	multi turn injection from Linac 2 analogue beam offset signal suppression, analogue delay (cables & switches)	100 W, 50 Ω stripline limited to 13 MHz in operation but built for 100 MHz bandwidth, baseband	H-plane: **used and required** V-plane: beam stable without feedback
AD (anti-proton decelerator) 3.57 GeV – 0.1 GeV (kin. E).	copy of booster system	100 W, 50 Ω stripline 100 MHz bandwidth baseband	Currently used only for excitation purposes
SPS (protons, ions) (14 – 450) GeV/c protons FT (26 – 450) GeV/c LHC beam	digital notch filter and 1T-delay (Altera FPGA, 80 MHz clock) commissioned in 2000/2001	tetrode amplifiers with two 30 kW tetrodes in push-pull directly coupled to a kicker (base band); feedback bandwidth ~10 kHz to 20 MHz	H-plane: used in operation V-plane: used in operation **used and required for operation** above $5x10^{12}$ protons (max ~$5.5x10^{13}$ ppp accelerated)

Table 2: Transverse damper projects at CERN under installation / commissioning

Accelerator	Digital / Analogue processing	Power / kicker / bandwidth	operation
LEIR (ions: Pb54+) 4.2 MeV/u – 72 MeV/u (kin. E.)	copy of PS Booster System new: remote control of pick-up vector sum	100 W, 50 Ω stripline	2006
PS (protons, ions) 1.4 GeV – 25 GeV (kin. E.)	based on hardware for the LHC damper	3 kW solid state amplifier ~50 kHz to ~30 MHz, 112 Ω stripline (0.9 m length), matching transformers between amplifier and kicker	2006-2007
LHC (protons, ions) protons: 450 GeV/c – 7 TeV/c	digital notch filter and 1T-delay, built-in diagnostics, 14 bit ADC/DAC Altera FPGA, 40 MHz clock new development in progress	tetrode amplifiers with two 30 kW tetrodes in push-pull directly coupled to kicker (base band) similar to SPS system 3 kHz to 20 MHz	2007-2008

AD, LEIR AND PS BOOSTER TRANSVERSE FEEDBACK SYSTEMS

The AD, LEIR and PS booster transverse feedback systems employ similar technology, share common hardware for the power amplifiers and a similar scheme for the delay compensation using switched cable delays. The bandwidth of the power amplifiers and the strip line kickers would allow operation up to 100 MHz. In practice the bandwidth is limited to a lower value, 13 MHz in the case of the PS booster. In the PS booster the system is essential to provide stability in the horizontal plane where for a high intensity proton beam coupled bunch instabilities develop. In AD the system is used today only for excitation purposes. At its conception it was planned to be used for the very small emittance pbar beams after cooling, but in practice this mode of operation is currently not necessary. In LEIR the transverse feedback systems have been used during cooling. Future operation of LEIR will show where improvements need to be made.

For all three systems (AD, LEIR and PS booster) a constant consolidation effort is necessary. This includes in particular rebuilding power amplifiers (spares). A major improvement in the future could be the employment of digital processing for the beam offset suppression and the automatic delay compensation. This should be studied in the context of a future upgrade of the LHC injector chain with the construction of Linac4 and the PS2 accelerator. As it is likely that the PS booster will continue to be required for many years, taking the protons from Linac4 to the new PS, its transverse feedback systems will certainly need to be upgraded.

PS AND SPS SYSTEMS

PS Transverse Feedback Systems

Commissioning of the new PS transverse feedback system [1] was started in 2006 and will continue in 2007. Strip-line kickers and a wide band high power (3 kW) solid state amplifier provide a flat gain over the required bandwidth of 20 MHz for bunch-by-bunch operation. Experience gained with this new system over the next years will help with the design of a possible transverse damping system for PS2. The digital electronics will be based on the LHC system. A special scheme is required to compensate the loop delay during acceleration due to the strongly varying revolution frequency [1].

SPS Transverse Feedback Systems

The SPS has operated for more than two decades with a transverse feedback system which has undergone a number of upgrades and modifications. The latest upgrade dedicated to the LHC beams was completed in 2002. It employs a digital notch filter and 1T-delay on a single FPGA [4]. The feedback system had been instrumental in achieving the nominal transverse emittances of the LHC beam in the SPS. Unforeseen difficulties with the electron cloud instabilities were overcome. However, the system is working at its limits in particular in the horizontal plane where the electron cloud effect causes a strong coupled bunch instability. On the road towards ultimate LHC intensity it has to be checked if a further upgrade of this system is required.

LHC TRANSVERSE FEEDBACK SYSTEM

LHC Transverse Feedback System on day 1

The expected performance of the LHC transverse damper system is well documented in the LHC Design Report [2]. For the power system it is essentially a scaled copy the SPS system working in baseband. The correction signal is applied to a set of four kickers (per plane and beam) with tetrode amplifiers installed directly under the kicker tanks in the accelerator tunnel. At low frequency the amplifiers, each of which employs two 30 kW RS 2048 CJ tetrodes, work on a relatively large impedance (~1 kΩ) leading to a large kick voltage. At higher frequency the capacitance of the kicker plates shunts the impedance and consequently less kick strength is available. The estimated performance is summarized in Tables 3 and 4.

Table 3: LHC Damper expected performance from 3 kHz up to 1 MHz

	β=100 m performance	Optics 6.500 performance
	Kick per turn in σ	Kick per turn in σ @ β in m
ADTH beam 1	0.2 σ	0.271 σ at β=183 m
ADTH beam 2	0.2 σ	0.274 σ at β=189 m
ADTV beam 1	0.2 σ	0.301 σ at β=227 m
ADTV beam 2	0.2 σ	0.331 σ at β=275 m

Table 4: LHC Damper: Estimate of maximum capabilities [450 GeV/c and 7 TeV]

	100 kHz	1 MHz	10 MHz	20 MHz
ADTH 450 GeV/c 7 TeV	0.42 σ 0.11 σ	0.38 σ 0.10 σ	0.12 σ 0.03 σ	0.044 σ 0.011 σ
ADTV 450 GeV/c 7 TeV	0.46 σ 0.12 σ	0.42 σ 0.12 σ	0.14 σ 0.04 σ	0.049 σ 0.012 σ

Table 3 shows in the centre column the baseline performance assuming 7.5 kV kick voltage at 1 MHz and a betatron function of 100 m at the location of the kickers. In practice the beta-functions will be higher as shown in the last column. Table 4 shows the performance as it drops off towards higher frequencies.

For low noise performance it is essential to start with a large signal, i.e. a pick-up that has a high value of transfer impedance. Two coupler type pick-ups per plane and beam with a length of 150 mm and a peak Z_T at 500 MHz of 6.46 Ω provide a peak signal in time domain of close to 100 V on each electrode for the nominal bunch (1.15×10^{11} protons/bunch). The objective is to achieve a resolution of 1 μm (at pick-up beta values of 100-200 m) and keep betatron oscillations of the beam below this level.

Assuming a 1 μm rms oscillation of the beam the available power for signal processing on the surface, for nominal intensity in a 40 MHz band around 400 MHz, amounts to 433 pW. This compares to 0.16 pW of thermal noise (T=290 K). Hence there is a large margin. A digitization with 14 bit (16384 discrete levels) will be sufficient (assuming 1 μm corresponds to 4 steps) to cover an aperture of +/- 2 mm. It is important to centre the beam physically in the pick-ups, possibly to be achieved by means of the planned slow orbit feedback.

Possible upgrades of the LHC damper

Possible upgrades of the LHC damper could be targeted in different directions:

- increased kick strength
- increased gain and kick strength for higher frequencies (towards 20 MHz)
- improved signal/noise performance

Increased kick strength may be required due to larger injection errors or insufficient kick strength at top energy. Upgrade possibilities are to push the current system to its ultimate limits by applying a high voltage pulse to the power amplifiers to boost the kick voltage for a short time (~ 100 ms). Up to 40% more kick strength above the base line specification of 7.5 kV at 1 MHz seems to be within reach. Increased beta function values at the location of the kickers can also push the effectiveness on the beam, but the scaling is only $\beta^{1/2}$. Space has been left in the machine and contracts could be quickly placed for a 50% upgrade by installing more kickers, power amplifiers and associate electronics, however, at an expense of some 4 MCHF.

Increased gain at high frequency will require new kickers and power amplifiers adapted in their frequency response to the kind of instabilities which may dominate growth rates at higher frequencies. As the beam intensity in LHC will be increased the characteristics of the impedances and their effects on the beam will become clearer and an adequate upgrade program to achieve the highest intensities could be planned. Impedance sources that can be more important than originally estimated include the electron cloud effect and the collimators.

Improved signal to noise ratio may be necessary to achieve better performance during coast. A first step of improvement would be to better adapt the layout of the equipment. Currently the RF signals from the pick-ups are transmitted by coaxial cable some 700 m through the accelerator tunnel and to the surface. This layout was originally chosen to maximise the access to equipment during machine commissioning and operation and minimise the risk of deterioration of signal quality due to ionizing radiation on the electronics. By relocating the equipment and upgrading cabling, an improvement of up to 18 dB in the signal to noise ratio could be achieved.

Increasing the beta function values at the pick-ups provides another possibility to increase the S/N ratio. In particular the vertical beta function at BPMC7L4.B2 for beam 2 has dropped to 87 m in optics 6.5, somewhat short of the originally specified 100 m.

Using additional pick-ups or averaging the signal from the pick-ups over several turns can also improve the S/N ratio. Averaging needs to take into account the betatron phase advance between the pick-ups and over one turn. Assuming the noise from subsequent beam passages (different pick-ups, and different turns) is uncorrelated the gain in S/N ratio from averaging follows a square root law, i.e. doubling the number of pick-ups improves the S/N by a factor $2^{1/2}$. Coupler pick-ups at quadrupoles Q8 and Q10 around IP4 could be used but no infrastructure (cabling, electronics) is foreseen in the LHC baseline plan. Adjustment of the betatron phase can employ digital processing, e.g. digital Hilbert Filter [4, 5].

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