

TRANSVERSE FEEDBACK SYSTEM FOR THE CERN FCC-hh COLLIDER

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Abstract

For the future hadron Collider (FCC-hh) being studied at CERN a strong transverse feedback system is required to damp coupled bunch instabilities. This system is also planned to be used for injection damping. Based on the LHC transverse feedback design, we derive requirements for power and kick strength for this system and consider different options of bunch spacing, 25 ns and 5 ns, and injection energy. Operation at high gain and close to a half integer tune is being considered and constrains the layout and signal processing. Requirements for the pick-up resolution are high in order to keep the emittance increase small. The performance is evaluated using numerical simulations based on the headtail code. Future areas of research and development and possible prototype developments are outlined.

INTRODUCTION

The international Future Circular Collider (FCC) study includes a proton-proton collider option with 100 TeV c.m. collision energy and circumference close to 100 km [1]. With bunch intensities of 10^{11} protons per 25 ns a strong transverse feedback system similar to the already operating feedback in LHC will be needed to damp injection errors and to cure transverse instabilities caused by the resistive wall impedance essentially dominated by the beam screen impedance [2]. Different options have been proposed for the injection energy ranging from 450 GeV up to 3.3 TeV, the latter having become the baseline and 1.3 TeV the alternative option retained [3].

In the following we will first review the considerations that have led to the specifications for the LHC transverse damper. Based on these a set of parameters for the FCC-hh transverse feedback is derived by scaling and confirmed using simulation results. Areas for further study are then summarized including alternative approaches.

LHC TRANSVERSE FEEDBACK

The LHC transverse feedback (ADT) uses a set of four kickers per plane and beam with tetrode amplifiers working in push-pull mode installed directly under the kicker tanks [4, 5]. The kicker plates represent a capacitive load to the tetrode amplifier permitting a high impedance design with which large kick voltages can be applied in the low frequency regime while permitting operation up to 20 MHz with lower voltages. This design is adapted to high energy accelerators in which large kick strength and high gain are needed at low frequency, both for injection error damping of

the separately injected batches and for mitigation of instabilities with the fastest growth rates for the low order coupled bunch modes.

The maximum kick strength needed is determined by the size of the injection error, the desired damping time, instability growth time and the permissible emittance increase at injection. The relative emittance increase at injection due to filamentation of an injection error a_{inj} can be expressed as [5]

$$\frac{\Delta\epsilon}{\epsilon} = F \cdot \frac{a_{inj}^2}{2\sigma^2} \quad (1)$$

where F is called *blow-up factor* and σ is the beam physical size at the reference β taken to define the injection error a_{inj} . For injection errors not too large compared to the beam physical size, the blow-up factor F can be expressed by [5]

$$F = \left(1 + \frac{\tau_{dec}}{\tau_d} - \frac{\tau_{dec}}{\tau_{inst}}\right)^{-2} \quad (2)$$

where τ_{dec} , τ_d , and τ_{inst} are the decoherence, damping and instability time constants. The instability risetime τ_{inst} is the worst case risetime, i.e. of the lowest order coupled bunch mode for a given tune working point for a linear optics without any active damping effect. The damping time τ_D is the active damping time in the absence of instability for a linear optics and related to the feedback gain $\tau_D = 2T_{rev}/g$ where g is the fraction of detected oscillation corrected every turn and T_{rev} is the revolution time. The decoherence time τ_{dec} is defined in this simplified model, as the time constant with which an injection reduces due to optics non-linearities (Q' , octupoles, etc.), in the absence of instability and active damping, leading to an emittance increase.

Figure 1 shows a convenient display of this relation for LHC. The design target of LHC has been for the damper for a maximum emittance increase of 2.5 % due to injection errors corresponding to a limit for the blow-up factor of $F = 4.2 \times 10^{-3}$ for an injection error of 4 mm at a reference $\beta = 183$ m [4]. With the chosen nominal damping time of 40 turns, the blow-up stays within the acceptable limit with a good safety margin for a range of intensities with instability growth time as fast as 160 turns. The maximum kick strength of $2 \mu\text{rad}$ at 450 GeV injection energy assumes $\beta = 100$ m at the kickers and is achieved with a kick voltage of 7.5 kV for each of the four units over an aperture of 52 mm and a kicker length of 1.5 m [4]. The spacing of injected batches determines the minimum needed rise time to full voltage and hence the frequency up to which the maximum kick strength must be made available. In the system design for the LHC ADT with the high impedance tetrode amplifiers the capacity to ground of the kicker plates and the anode resistor

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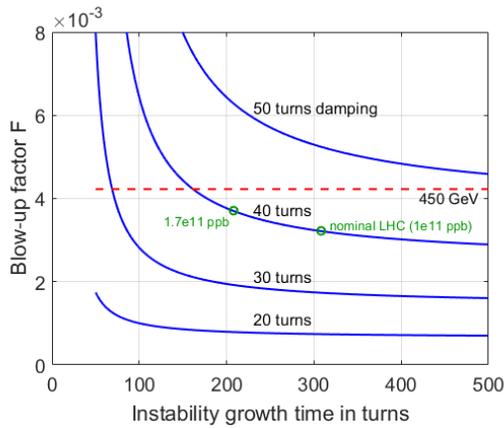


Figure 1: Blowup factor for different damping times as a function of instability growth time for nominal LHC (1×10^{11} protons per bunch) and limit for blow-up factor (red dashed line); $\tau_{\text{dec}} \approx 750$ turns assumed.

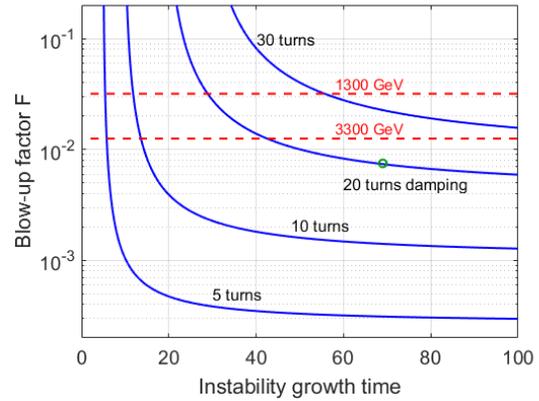


Figure 2: Blowup factor for different damping times as a function of instability growth time for FCC-hh; the instability risetime assumed is 69 turns [2] for the more critical vertical plane at a fractional tune of $q \approx 0.31$ at the baseline injection energy of 3.3 TeV [2].

determine this maximum frequency, chosen to be 1 MHz, which is compatible with a minimum spacing of batches of just under $1 \mu\text{s}$ [4]. With the demonstrated operational performance [6–8] over run 1 and run 2 of LHC, the concept and engineering of the LHC ADT make it a first choice for a baseline system for FCC-hh.

FCC-hh TRANSVERSE FEEDBACK

Similar to the LHC ADT system [5] the FCC-hh damper will use a set of pick-ups, and digital signal processing for phase adjustment and closed orbit suppression. For FCC-hh different injection energies have been considered. In Fig. 2 the blow-up factor F is plotted as a function of the instability growth time for different damping times and a constant normalized emittance as well as a constant injection error as specified in Table 1. The instability growth times however are faster at lower energy and faster damping is required for coupled bunch instability damping. Table 1 shows a comparison of the specifications for LHC and the baseline FCC-hh [9] with the currently chosen batch spacing of 430 ns [10]. For LHC the specified damping time was 40 turns and the achieved damping time in run 1 was 13 turns [7].

Numerical Simulations of Blow-up at Injection

Equation (1) is valid for small injection errors and Gaussian beams and assumes a simplified approach to both instabilities and the blow-up by decoherence, both being described by their respective growth and decay times. In order to more accurately simulate the actual blow-up expected and the instability growth rates a numerical code was developed [11] to implement the feedback and a machine model of the FCC-hh with its known impedance [2]. Figure 3 shows the simulated blow-up at injection for different feedback damping times and constant injection error along the batch and in addition for 40 turns damping and an injection error as expected from the injection kicker ripple. The simulations

show that emittance growth as low as 5 % can be achieved with a damping time of 40 turns at $Q' = 14$ at zero octupoles leaving margin to run with non-zero octupoles. Attention must be paid to the injection kicker ripple and its impact on the bunches on the edge of a batch [12].

Damping Coupled Bunch Instabilities at 3.3 TeV

Figure 4 summarizes the coupled bunch instability growth rates for the nominal 25 ns bunch spacing requiring feedback up to 20 MHz, half the bunch repetition frequency. The plot shows the computed growth rate from an analytical model

Table 1: Parameters of Baseline FCC-hh Transverse Feedback System Scaled from LHC

Parameter	LHC	FCC-hh	
energy (inj.)	0.45	3.3	TeV
trans. emittance (norm.) inj.	3.5	2.2	μm
bunch spacing	25	25	ns
batch spacing	925	430	ns
max feedback frequency	20	20	MHz
power bandwidth	1	2.35	MHz
inj. error	4	1	mm
reference β	183	200	m
decoherence time	750	300	turns
max emittance increase	2.5	5	%
instability growth	310	69	turns
max damping time feedback	40	20	turns
blow-up factor F (limit)	4.2	12.5	$\times 10^{-3}$
minimum β at kickers	100	100	m
total kick at inj. energy	2	0.5	μrad
voltage per kicker (1.5 m)	7.5	2.5	kV
# kickers per plane/beam	4	22	
minimum space (staggered)	13.5	67.5	m
with overhead	18	100	m

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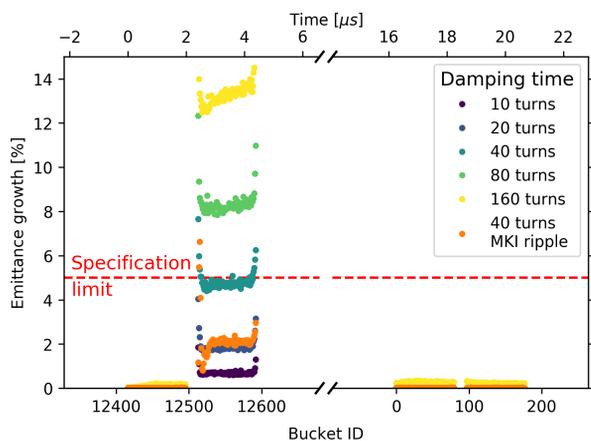


Figure 3: Simulated blow-up for an injected batch into FCC-hh at 3.3 TeV [12]; the fractional tune is ≈ 0.31) and the full impedance model of the FCC-hh [2] has been taken into account; $Q' = 14$ and zero octupoles.

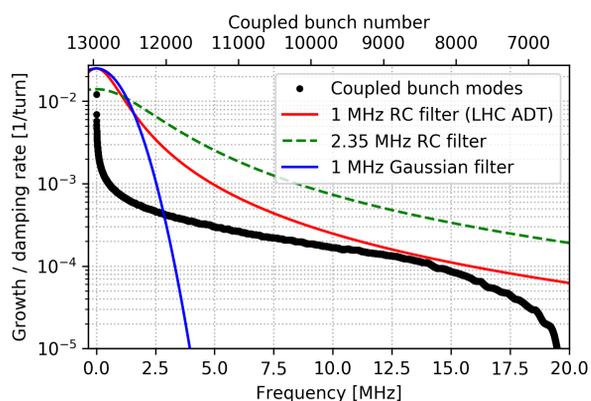


Figure 4: Instability growth rates and damping times as function of frequency with different damper power system characteristics; feedback phase assumed corrected for all frequencies by means of an equalizer circuit or digital processing.

for a fully filled machine. The damping rate is sufficient for 1 MHz and 2.35 MHz power bandwidth (1-pole roll-off). Damping has also been verified by numerical simulation for both injection and collision energies with complete accelerator parameters and filling patterns [12].

OPTIONS AND FUTURE RESEARCH

Alternative Bunch Spacing of 5 ns

The alternative bunch spacing of 5 ns requires an additional damping system to cover the coupled bunch modes between 20 MHz and 100 MHz [12]. This is conveniently realized by a stripline kicker system with solid state power amplifiers. More research is required to define the system parameters and a suitable optimized kicker structure.

Feed Forward and Optimal Control Approach

A completely different alternative approach is to use a set of kickers that can be driven from pulsed generators to correct for the systematic part of the injection error [12]. The individual kicker systems are triggered at different times and each apply kicks of different length and amplitude. In combination they correct the major part of the injection error including any ripple from injection kickers. All of the systematic part of the injection error could thus be corrected in the shortest possible time applying optimal control [13]. An adaptive algorithm can maintain optimal control by adjusting parameters for subsequent injections. Any residual injection error is damped by a classical damper system then requiring only small amounts of power. A possible prototype system could be developed and tested in the SPS in the future.

Intra-bunch Feedback System

As part of the LHC injector upgrade project LIU, an intra-bunch feedback has been prototyped and tested successfully with beam [14]. Possible applications for FCC-hh are mitigating the TMCI and the slow headtail instability [11, 12]. It has also been shown that the Falin type kicker developed for the SPS [15] can be scaled to the FCC-hh aperture increasing its the frequency reach from 1 GHz to 4 GHz [16].

Emittance Increase from Noise

For LHC, the current use of two pick-ups per plane and the excellent performance of the position detection have shown to limit the emittance increase to acceptable levels. Mitigation of perturbations by external noise sources with the feedback is as expected [17]. The use of more than two pick-ups for transverse feedback systems to average out pick-up noise has been previously proposed [18] and is being pursued at the LHC. Improvements can be achieved using more sensitive pick-up electronics and by combining signals from several pick-ups and turns. The future refined design of the FCC-hh transverse feedback system will leverage on the experience gained at the LHC in the future run 3 with more pick-ups and better electronics.

CONCLUSION

A scaled version of the LHC transverse feedback system using tetrode amplifiers can fulfill the basic requirements for the baseline FCC-hh. Due to the higher injection energy, the scaled system from LHC is correspondingly larger and requires more space and power than the LHC system. Future research is proposed to explore alternative approaches using systems to correct adaptively the systematic part of the injection error using modern solid-state technology. Research is also proposed for alternative options such as a 100 MHz bandwidth system for 5 ns spacing, and a high bandwidth system with a potential to cure intra-bunch motion.

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