BROADBAND FEEDBACK SYSTEM FOR INSTABILITY DAMPING IN THE SNS RING*

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Abstract

The transverse feedback system in the Accumulator Ring of the Spallation Neutron Source (SNS) is intended to damp broadband (≈40-120 MHz), coherent betatron motion due to e-p interaction. The SNS feedback system is based on an analog delay-line model with some signal conditioning and tuning parameters implemented digitally. This system provides a simple setup with two primary knobs, phase and gain, as well as an equalizer. This simplicity comes at the cost of some flexibility normally found in a standard mode-by-mode design, namely mode-by-mode phase, and gain control. In this paper we discuss the design, tuning, evaluation, and operation of the SNS feedback damper, and discuss the tradeoffs implicit in the design of the system.

INTRODUCTION

Table 1 lists parameters of the SNS ring running in 1.4 MW neutron production operation. The purpose of the ring is to accumulate $\approx 10^{14}$ protons over 1 ms, about 1000 turns, to deliver a short intense pulse of protons to the neutron production target. This millisecond long cycle is repeated at 60 Hz. Since the early days of the design of the SNS ring, e-p instability due to the interaction of electrons in the vacuum vessel with the proton beam has been a serious concern necessitating the inclusion of many mitigation measures [1].

Table 1: SNS Ring Parameters for 1.4 MW Operation

Parameter	Value
Energy	939.5 MeV
Revolution Period	955 ns
RF 1st (2nd) harm	6.5(3.5) kV
Circumference	248 m
Bunch Length(FW)	650 ns
Charge	25μC
δ p/p Inj(Ext)	$10^{-4}(10^{-3})$
Pipe Radius	$\geq$ 10cm
η	-0.2173
$\nu_{H,V}$	6.205, 6.165

The nature of e-p interaction leads to a broadband spectrum of coherent transverse betatron oscillation, in the case of SNS this spectrum has been observed in the range ≈≈40-120 MHz [2, 3]. The frequency spectrum evolves throughout a cycle, typically broadening toward higher frequencies as accumulation progresses. During dedicated study cycles in 2008, the e-p instability was induced in 8.5,10 and 20 μC/pulse beam at low repetition rate by changing various parameters such as storage time and 2nd harmonic RF cavity voltage. During these studies experimenters observed beam loss, and high frequency beam oscillation of several cm [3], but only in configurations specially tuned to produce the instability.

Broadband motion attributed to e-p has been seen in the SNS ring during normal operation, high frequency oscillation has only produced peak amplitudes < 1.5 mm during normal operation. This motion has not limited high intensity operation, up to the design power of 1.4 MW (24 μC/pulse), achieved in the Fall of 2015. The broadband transverse damper system in the SNS Accumulator ring was designed to address broadband betatron oscillation due to e-p interaction spanning the range from ≈40-120 MHz. Despite the fact e-p has not lead to operation limiting losses, the damper system has been used to suppress motion due to e-p interaction.

The state-of-the-art in broadband transverse damping typically makes use of a separate processing channel for each mode, or equivalently each time-slice of the bunch within the resolution of the system, e.g. JPARC, CERN SPS, among others [4, 5]. Each channel consists of a separate FIR filter used to tune the phase and gain of the feedback signal based on the history of that mode, or slice, over several turns.

The SNS system forgoes the complexity associated with such a design, instead using a delay-line model with certain digital signal processing elements to ease system setup. The feedback system is tuned for all modes simultaneously using a single gain, and phase knob. This simplicity comes at the cost of decreased flexibility with respect to tuning the phase and gain of each mode independently.

DAMPER SYSTEM

Figure 1 shows a schematic of the SNS damper system including: the stripline pickup and kicker, Low-level RF(LLRF), ADC, FPGA with processing blocks, DAC and power amplifiers.

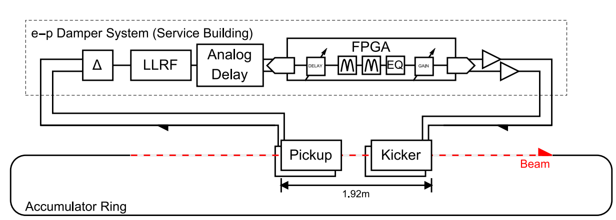

Figure 1: Schematic layout of the damper system.

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The pickup and kicker are both 0.49 m long stripline pickups [6]. The pickup and kicker are 1.92 m apart, a betatron phase advance of about 0.3 rad. The response of the combined pickup-kicker configuration extends from about 25-180 MHz, with a peak response at 105 MHz, corresponding to the range of observed e-p activity in the SNS ring. Electronics in the ring service building are connected to the electrodes by 70 m of cabling in each direction, which contributes a total of 560.1 ns of delay to the system.

LLRF comprises a 300 MHz low-pass filter, amplification, and a 180° hybrid for each plane. Variable attenuators on the input to the difference hybrids provides a way to tune out the signal due to the closed orbit from the difference signal. Also included in the LLRF is a a cascaded set of binary delay lines to add upto 15.75 ns of additional delay with a precision of 250 ps, and several amplification stages as needed.

The digitizer comprises a 10-bit ADC, and a 12-bit DAC with up to 2 GSPS driven by a dedicated clock synched to the ring RF 10 MHz reference line. The digitizer clocks are driven at frequency such that each revolution contains an integer number of samples.

The FPGA provides several DSP functions: two notch filters at the revolution frequency implemented as two-tap FIRs (the second filter is used to reverse the effect of the first filter on the signal phase), an EQ which equalizes the magnitude response and corrects for phase dispersion in the cabling, and a coarse ≈8 ns digital delay necessary to tune the system.

After equalization, the addition of signal delay, and scaling by a gain multiplier, the difference signal is finally amplified and returned to the kicker. The horizontal and vertical planes have two and four 100W Intertronic/Eltac amplifiers [8, 9] dedicated to each electrode, respectively, for hardware details see [6].

Feedback Signal The difference signal used to damp beam motion is the product of the position and the beam current in the time domain. The inclusion of the beam current in the feedback signal has some consequences for the operation of the system during the accumulation cycle increasing the effective gain as the beam current increases.

The proper phase relative to the beam is attained primarily through delay. As the signal traverses the feedback system, including operator added delay, the betatron phase of the beam advances by the $\Psi_{p-k} \approx 0.3$ rad (there is a small difference between the two planes because of the two tune values) between the pickup and kicker and by an additional 2π Q radians per turn. By waiting N turns such that $\Psi_{p-k} + 2\pi NQ = (2j+1)\pi/2$, where j is any integer, the angular feedback kick can be applied when the measured betatron amplitude has rotated in the phase space to an angular deflection. The integer number of turns, N, delay must necessarily be larger than the total minimum delay in the system, which is dominated by the cabling, and the two turns of delay introduced by the notch filters. Table 2 shows the delay budget. Based on these numbers and the revolution period of 955 ns, we must have $N \geq 3$ in the SNS ring.

Table 2: Main Contributions to Delay

Source	Delay (ns)
2×70 m Cable	560.1
Electronics Pipeline	631.1
Comb Filters	955.0
Total	2146.2

Damping Production Beam

The data presented in this section was taken parasitically during normal 1 MW operation. Oscillation amplitude is on the order of 1 mm, and does not cause any measurable beam loss. However the broadband spectral content, which increases in frequency and amplitude as accumulation proceeds is unambiguous.

Figure 2 shows the power spectrum of difference signal of several modes of horizontal betatron motion in the lower sideband for both damped and undamped cases. The undamped beam shows clear activity at the fractional tune of ≈ 0.2, which is suppressed to within the background, about 25 dB, for the most active modes. The reference value for the log scale on each pane of Fig. 2 is the maximum power for that pane. Plotting the power in the damped difference signal at the betatron peak relative to the undamped reference value at each mode, Fig. 3 shows the effectiveness of the damper on the lower sideband across modes 10-120 at turns 600, and 900 of the accumulation cycle. Taken by itself, Fig. 3 can be easy to misinterpret. For instance, the decreased damping at higher modes at turn 600 is not due to the damper, but rather the lack of betatron motion at these modes when the damper is off. (A positive value on this figure would indicate the damper was driving certain modes.)

Figure 4 complements Fig. 3 showing the same information as Fig.2 but integrated over each sideband (upper sidebands are also included in this image), using a sliding window of 32 turns throughout the accumulation cycle to produce a spectrogram. It is more difficult to determine exactly how well the damping is working, but it is more obvious that the betatron motion due to e-p is suppressed over the entire band.

Tuning the System

The plots presented in the previous section illustrate the operation of the damper, but are difficult to evaluate in real time for the purpose of tuning the beam. Typically the preceding plots are produced after the system has been tuned. To tune the system we typically integrate the power contained in the difference signal in the entire band from 10-300 MHz, as shown in Fig 5.

As previously mentioned, both the gain and delay are set for all modes simultaneously. To set the working values for phase and gain we minimize the total power contained

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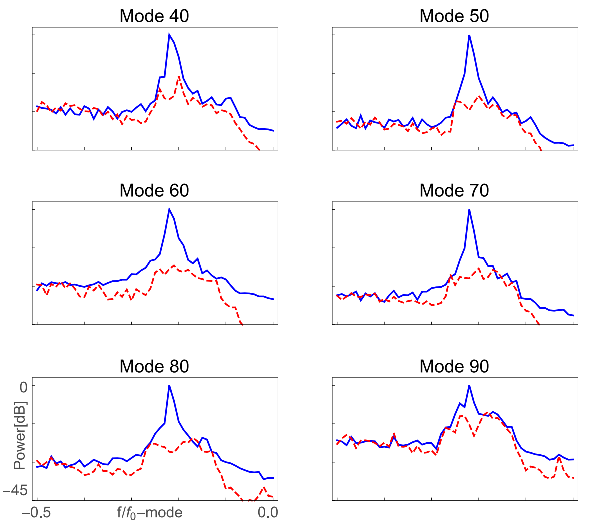

Figure 2: Power spectrum of several modes with damper off(blue, solid), and on(red, dashed) at turn 600 during the accumulation cycle during 1MW operation.

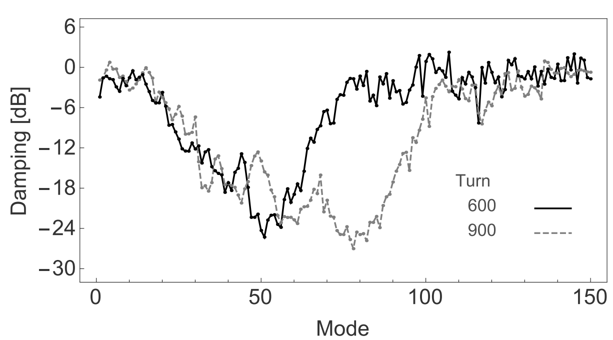

Figure 3: Ratio of damped to undamped power in the horizontal difference signal at the betatron peak for many modes at turns 600, and 900 of the accumulation cycle.

in the difference signal in the band from 10-300 MHz at extraction, in practice the oscillation power tends to grow monotonically throughout the cycle so this metric is effective at minimizing oscillation throughout the cycle. Figures 6, and 7 show the total oscillation power at extraction in the band 10-300 MHz as a function of digital gain multiplier, and ns of delay respectively. Detail regarding the activity in each mode is lost in this view, but it is clear that the damper improves the overall oscillation as gain is increased, but eventually begins to cause growth. Small delays, δ, from the optimal delay likewise cause growth in oscillation at extraction.

Design Limitations

Because each mode oscillates at the same tune, it is not necessary in principle to independently adjust the phase for each mode, the betatron motion itself provides the phase advance needed to properly apply the negative feedback. The downside to this method is that one must wait several complete revolutions for a phase advance near an odd multiple of

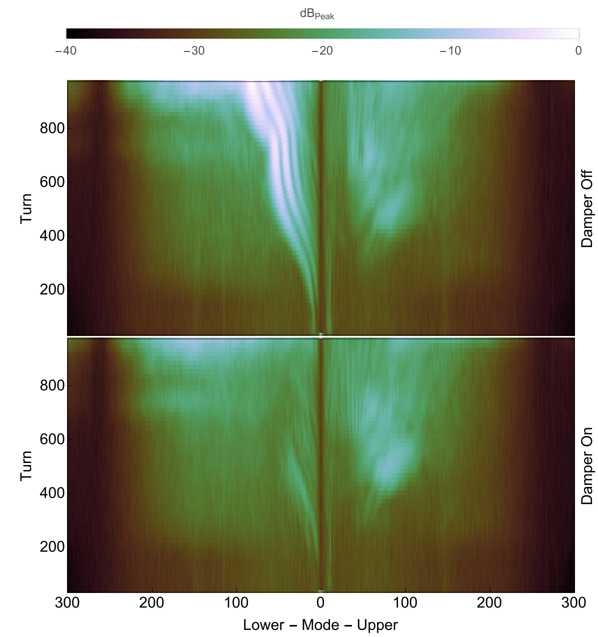

Figure 4: Power spectrum of several modes with damper off(blue), and on(red) at turn 600 during the accumulation cycle during 1MW operation.

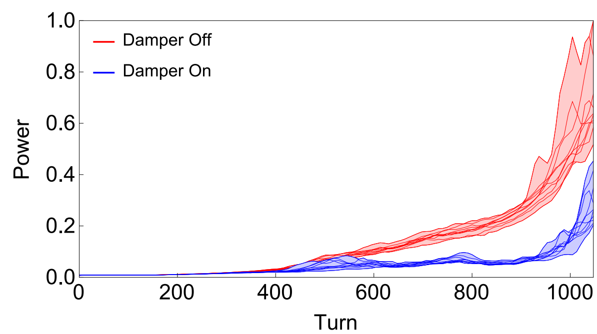

Figure 5: Total power in the horizontal difference signal in the frequency range 10-300 MHz throughout the accumulation cycle.

$\pi/2$, this delay between sensing and affecting beam motion reduces the effectiveness of the damper by, among other things, decreasing the maximum gain that can be applied before the system is driven. This delay can be reduced by reducing the minimum delay due to cabling and system latency to less than a single turn, or by changing the tune such the timing condition is satisfied in the smallest number of turns possible. Because the comb filters add a full turn of delay to the system, even if additional delay is kept to less than a single turn, the minimum delay in the current design is two turns.

The lack of mode-by-mode gain control is also a concern. In reality, for some gain multiplier in the signal processing chain, the effective gain depends on the magnitude of the transfer function of the entire system across all relevant frequencies.

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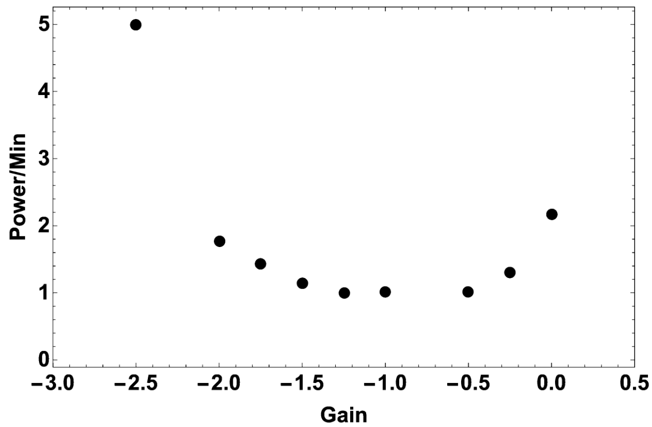

Figure 6: Total power in the horizontal difference signal at extraction from 10-300 MHz as a function of gain.

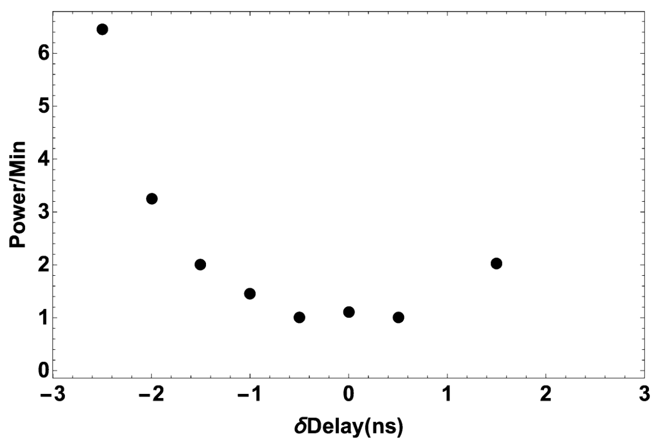

Figure 7: Total power in the horizontal difference signal at extraction from 10-300 MHz as a function of delay.

For a system which acts on n frequencies ω_n, the effective gain on the signal at each frequency is given by the response function of the system $|H(\omega)|$ multiplied by the digital gain multiplier, which is a constant, g. (I am assuming that the phase response is perfect for the sake of argument.) If the maximum gain that can applied to any frequency is some constant value g_{max}, then for each frequency we must have $g \times |H(\omega_n)| \leq g_{max}$. This means that some modes may be limited by the gain needed to maintain this condition for all modes simultaneously, a fact exacerbated if g_{max} is not independent of mode.

This is partially compensated by the fact that our system is designed with a peak response that coincides with the peak of e-p activity as seen in the SNS ring, and an equalizer that allows some tuning of the response function. Still, independent gain control remains the major advantage of mode-by-mode systems. A similar argument can be applied to independent mode-by-mode phase control.

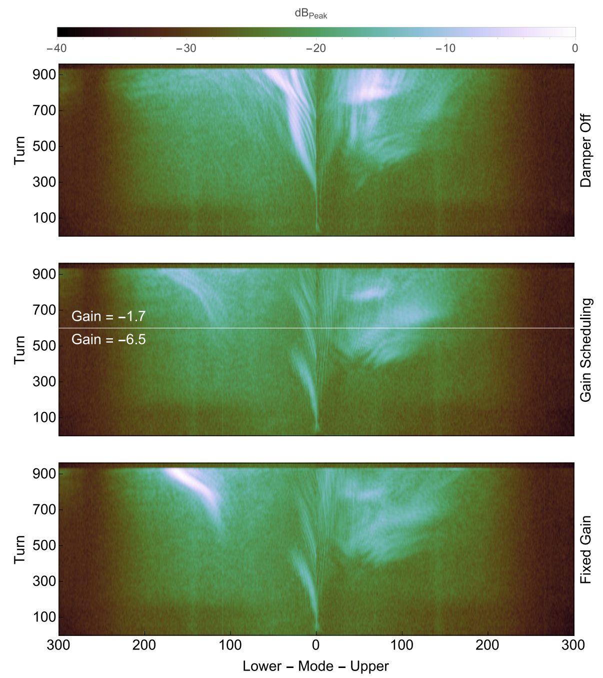

Figure 8: Power spectra for three cases to show the benefit of gain scheduling in the horizontal plane. For the damper on configurations gain is initially set about three times higher than the optimal value determined by minimizing oscillation power at extraction.

The consequences of this design decision can be seen in Fig. 8, which shows three cases: damper off, damper on but with a gain set too high, and damper on with gain scheduling to reduce the gain by 6 dB at turn 600. In the case where the damper is on with no gain scheduling, some of the higher modes, modes not even noticeable with the damper off, are driven by the system late in the cycle. A generalized gain schedule is easy to implement digitally, but this feature was not initially included in the SNS damper design so this experiment was performed using a TTL switch and a delay generator.

DISCUSSION

Because no losses due to e-p have been observed during normal operation, the damper system is not currently used during neutron production. In the future there are several circumstances which may necessitate the use of the damper system. Venting the ring for maintenance can affect contamination of the beam pipe, increasing the secondary electron yield. Though normal operation should eventually scrub the contamination from the beam pipe to at least the levels observed now, a swift return to full power could see losses due to e-p interaction, which the damper system could suppress.

Additionally, future plans for the SNS call for a doubling of the average power from 1.4 MW to 2.8 MW, through a combination of an increase in beam energy from 1.0 GeV to 1.3 GeV, and an increase in beam current while maintaining

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the same accumulation time of ≈1000 1 μs machine turns. Alone, this increase in beam intensity could lead to increased broadband e-p activity, but part of this plan includes so-called 'smart chopping'.

Smart chopping involves reducing the injected pulse length throughout accumulation. This allows pulses long enough to occupy more of the extraction gap to be injected early in the cycle, as long as the resulting synchrotron motion before extraction is enough to compress the tails in time to within the allowed pulse length. The late injected pulses must be short enough to accommodate the extraction gap without the help of synchrotron rotation. Since longitudinal shape is one of the parameters that strongly affects e-p, it is possible that the addition of smart chopping may also increase e-p activity [7].

As a final possibility, note that to-date the damper has not been included as part of the neutron production setup tuning, additionally, all studies shown here have been done with production beam. It is possible that including the damper in this tuning procedure could allow for previously unusable regions of the parameter space to be explored, e.g. lower 2^{nd} harmonic RF cavity settings lead to a longitudinal distribution that increases e-p activity, but may also lower the momentum spread enough to reduce losses in dispersive regions, if the coherent oscillations could be controlled. This has not yet been explored for the SNS.

The hybrid approach presented here solves some of the problems inherent in a strictly analog system with respect to ease of tuning, but forgoes the complexity of other state-of-the-art, mode-by-mode dampers, and as a result suffers with respect to control of independent modes. Despite these limitations, this delay-line based system has proven effective in reducing broadband oscillation in the SNS ring.

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