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THE FUTURE OF THE E-P INSTABILITY IN THE SNS ACCUMULATOR RING *

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Abstract

Concerns about the e-p instability drove many decisions during the design of the accumulator ring for Oak Ridge's Spallation Neutron Source. To date, these decisions seem justified since e-p activity has been observed at the mm scale as a broadband transverse excitation but it has not been a limiting factor (or even a contributor to normal losses) during operation up to the design power of 1.4 MW. (This motion is attributed to e-p based on the broad, evolving spectrum 80-100MHz, and a fast rise time on the order of 10's - 100's of turns when RF buncher voltage is significantly reduced [1, 2].) However, the proton power upgrade (PPU) [3] will increase beam energy from 1.0 GeV to 1.3 GeV to allow 2.0 MW operation on the first target station, and eventually the Second Target Station project (STS) [4] will require an increase in beam current in the ring of about 50% above current operation resulting in 2.8 MW beam. This paper explores the potential for e-p induced beam instability during PPU and STS operation, the predicted effectiveness of existing e-p mitigation measures in the SNS ring, and potential experiments to test these predictions within current operational limitations.

SNS UPGRADES AND THE E-P INSTABILITY

The threshold number of protons, N_p, for e-p instability in a bunched beam may be expressed [5] as:

$$N_p \geq \frac{\pi}{2}\frac{R}{r_e}\left(\frac{64}{9\pi^2}\frac{m_p}{m_e}\gamma_p\beta_p\right)^2\left(\frac{b(a+b)}{R^2}\right)Q_\beta{}^2 \times \left(\frac{(1-f_e)}{f_e}\right)^2\left(\frac{\Delta Q_e}{Q_e}\right)^2\left(\eta\frac{\Delta p}{p}\right)^2 F \quad (1)$$

with

$$\left(\eta\frac{\Delta p}{p}\right)^2 F = \frac{\eta e V BW f_0}{\pi\gamma_p\beta_p{}^2 m_p h}\left(1-\cos(\pi BW f_0)\right) \quad (2)$$

in terms of the machine radius (R), the classical electron radius (r_e), the proton and electron mass (m_p,m_e), the proton's relativistic factors (γ_p, β_p), the horizontal and vertical beam radii (a, b assumed equal for electrons and the protons), the betatron tune of the proton beam (Q_β), the neutralization factor (f_e), the transverse oscillation frequency, and frequency spread of the electrons (Q_{β_e} and ΔQ_e), the phase slip factor ($\eta = 1/\gamma_T^2 - 1/\gamma_p^2$) the relative momentum spread of the protons ($\Delta p/p$), buncher voltage (V), revolution frequency (f_0), RF harmonic number (h), filling factor (F), and fractional bunch width (BW). We assume RF bunching dominates to calculate $\Delta p/p$, and that f_e, $\Delta Q_e/Q_e$ are roughly constant, based on experience at Los Alamos Proton Storage Ring, a close analog to the SNS case.

For the PPU project the SNS accumulator ring will be operated at 1.3 GeV instead of the current design energy of 1.0 GeV. The only changes to the ring lattice will be the replacement of two of the injection chicane magnets. From the relation given in eq. 1 the threshold intensity (N_p) depends on energy only through γ_p, β_p, η, and f_0 and is proportional to the factor $\gamma_p\beta_p\eta$. Evaluating N_p (1.0 GeV) / N_p (1.3 GeV) = 1.17 i.e., the instability threshold is 17% higher at 1.0 GeV compared to 1.3 GeV. Interpreting these numbers in light of the equation given, the threshold decreases because the SNS ring is operated below transition, and as the beam energy increases the phase slip factor, and thus the frequency spread of betatron oscillation decreases faster than the beam stiffness increases.

This estimate of the relative change in instability threshold is very rough and does not include the effect of changing space charge effects which we have considered to be constant. The scaling given here will need to be verified with experimental measurements of the threshold intensity at various energies. The e-p instability threshold is notoriously difficult to predict. For instance, the development of instability is highly dependent on longitudinal profile [6].

ACTIVE SUPPRESSION OF THE E-P INSTABILITY

Up to 1.4 MW the e-p instability has not been an operational limitation, but the spectral signature of e-p activity is clearly visible in BPM data, accounting for roughly a 0.5 mm, localized displacement of the beam centroid. During operation this instability can be controlled with RF bunching cavities, but can be induced by lower buncher voltage, especially the bunch flattening 2^{nd} harmonic station [6]. Running in this configuration, a transverse instability with a spectrum that shifts upward, and increases in bandwidth as it grows, with a growth rate on the order of 10-100's of turns ($\tau_{rev} = 1\mu s$) can be observed, characteristics consistent with the e-p instability [7, 8].

Many features designed to mitigate e-p instability (TiN vacuum vessel coating, large ring apertures (10 cm), ded-

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icated collimation region) will provide no additional safeguard under different operating scenarios. Here we consider the future efficacy of existing, active suppression measures. We assume that SNS operates very near the e-p threshold when evaluating the potential efficacy of the following active measures to suppress e-p instability.

RF Bunching

Linac beam is accumulated in the ring over 1000 turns with an injected $\Delta p/p \approx 8\times10^{-3}$ and a width of about 70% of the circumference of the ring, into a stationary h=1 bucket with some 2^{nd} harmonic before being extracted to the target with $\Delta p/p \approx 2\times10^{-2}$, currently two turns after the last injected linac pulse. The longitudinal mismatch causes the injected beam to tumble with a synchrotron period of 1000-2000 turns, depending on the voltage. As the early injected beam rotates, the bunch becomes highly peaked without the second harmonic (though the maximum extent of the bunch in phase is defined by the most recently injected bunch), this peaked beam can lead to the development of the e-cloud that leads to e-p instability [9].

It is well known, that increasing the buncher voltage, despite increasing the mismatch, creates a more stable beam, which has been attributed to the increased transverse tune spread that comes from increasing $\Delta p/p$ in a machine with non-zero chromaticity [10]. Additionally, a second harmonic can be used to flatten the longitudinal distribution with the primary purpose of modifying the development of the e-cloud that drives the e-p instability. This dependence on the longitudinal shape of the beam has been studied in simulation, and experiment [8, 11]. The effect of the buncher on the spectrum of broadband motion is shown in fig. 1.

The RF buncher design consists of 40 kV of h=1, and 20 kV of h=2 RF but each harmonic is currently run at 8 kV during production. We will attempt to make a very rough estimate of the increase in accumulated proton threshold before e-P still available with the existing RF system. Here we assume that it is necessary to maintain the 1:1 ratio of h=1 to h=2 voltage to achieve a similar current profile, that is for the second harmonic to counteract the bunch shortening induced by the bunch rotation from the first harmonic station. We can achieve up to a 150% increase in voltage, and thus threshold charge assuming the trend we currently observe continues. Even assuming SNS currently operates near the threshold value, this would provide sufficient damping to maintain stability with the estimated 17% decrease in threshold at 1.3 GeV even as charge is increased 50% to reach STS beam power. This estimate is made assuming that the relationship between increasing the RF amplitude and an increased e-p threshold holds, but this relationship may break down above some amplitude, a situation which will need to be considered in simulation, or through more experimental investigations.

Transverse Feedback

In case the RF bunching cavities should prove inadequate, SNS has a broadband transverse feedback system developed

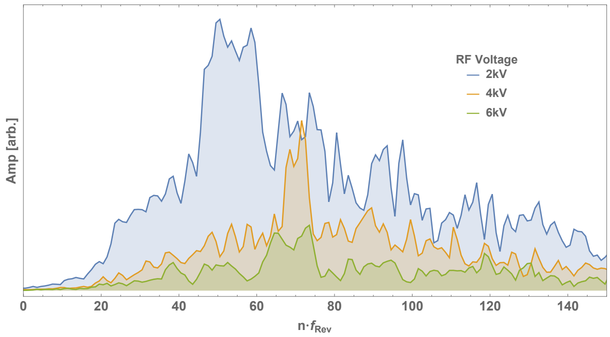

Figure 1: The spectral content of the lower sidebands at extraction for several values of the buncher voltage showing a reduction in oscillation power as the voltage is increased.

expressly to actively suppress e-p induced oscillation over the bandwidth observed in early experimental investigations and simulations. This system is documented extensively in [2]. Data showing the effect of the transverse feedback system on mm scale broadband oscillations we attribute to e-p interaction taken during operation at 1.2 MW are shown in fig. 2. The motion shown in fig. 2 causes no operational problems even without the damper, but can be enhanced by reducing the RF buncher voltage as demonstrated in fig. 1. Although the transverse feedback system is designed to suppress e-p, we hope we can avoid running with active feedback for two reasons: 1) predictions about the strength of the e-p oscillation, and the effectiveness of a feedback system for the type of broadband spectra associated with e-p are very difficult to make, and 2) the necessity of another active system for routine operation introduces a failure point that we hope to avoid, especially if the RF system, which is a part of routine operation in order to maintain the extraction gap, will suffice.

CONCLUSIONS

We estimate the PPU energy upgrade to the SNS accelerator complex will lower the e-p threshold in the ring by about 17%. This estimate makes several assumptions which may prove wrong: that the effect of space charge will be roughly the same as the energy is increased, and can be held constant for the planned increase in intensity; that the neutralization factor, and fractional tune spread of the electron cloud are roughly constant. We plan to carry out experiments to: test assumptions of e-p threshold scaling with energy, verify linear behavior of threshold with increased buncher voltage, and benchmark threshold intensity for current operation.

If these assumptions are at least approximately true, the existing margin in the RF bunching system should be sufficient to raise the estimated e-p threshold above the operating intensities for both PPU and STS. The damper system is available to provide additional suppression of e-p induced transverse motion if needed.

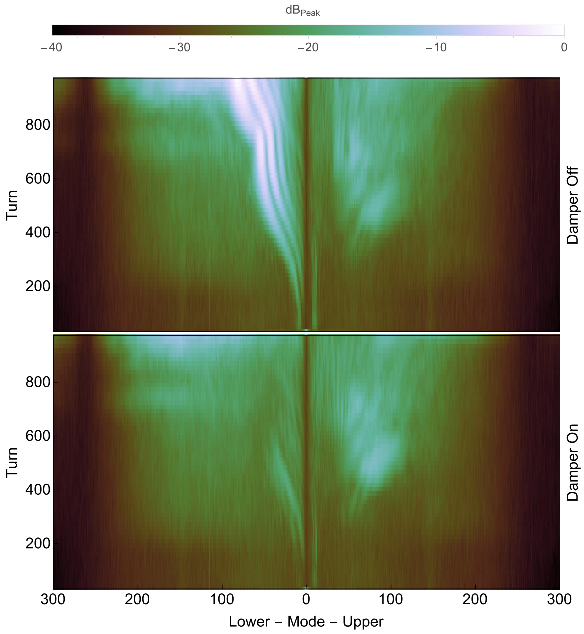

Figure 2: The spectral content of the upper and lower sidebands with the damper system on and off. With a revolution frequency of 1 MHz the excitation attributed to the e-p instability spans 40-100 MHz and is clearly suppressed by the damper system. Figure reproduced from [2].

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