TUNE MEASUREMENT IN THE SNS RING*

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Abstract

Minimization of beam loss and activation in the Spallation Neutron Source Ring is highly dependent on proper control of the tune footprint. The major contributors to tune spread are space charge, chromaticity, and uncompensated fringe fields. In addition to the challenge of accurate measurement in the presence of large tune spread, large dynamic range will be required to permit measurement through the accumulation cycle. Measurement of the tune footprint of this high-intensity fast-cycling accumulator ring will be accomplished with a variety of tune measurement systems. System design is greatly facilitated by tracking simulations. We present preliminary simulation results, as well as details of the overall system design and its planned implementation.

1 INTRODUCTION

The SNS Ring is an accumulator ring. The Ring accumulates microbunches injected from the linac, where the RF frequency is 805MHz and the bunching frequency is 402.5MHz. Due to momentum spread, after a small number of turns the microbunch charge diffuses, the microbunches coalesce, the 402.5MHz structure is lost, and the bunch has the character of a 645ns pulse with a repetition rate of 945ns. The response of a BPM to this bunch structure has been studied in detail [1]. With a millisecond of injection and a 1.058MHz revolution frequency, the charge will grow by a factor of 1000 during an accumulation cycle. At cycle end, the bunched beam current will be 52A. Measurement of tune in the presence of this large dynamic range will be challenging.

The concept of betatron tune in such a machine is somewhat different from tune for instance in a storage ring, where tune can be defined by a single number. Protons injected late in the accumulation cycle are not in the machine long enough for their tune to be defined with any significant precision. Protons injected early in the cycle may see their tune environment modified considerably by space charge as accumulation proceeds. The relevant concept for tune in an intense accumulator is tune footprint. The tune footprint is not constant, but varies through the accumulation cycle.

2 TUNE FOOTPRINT

There is significant tune spread as a result of space charge, chromaticity, and uncompensated fringe fields [2]. The effect of space charge tune spread becomes progressively more dominant as accumulation proceeds. Combined tune spread [3] due to space charge and chromaticity is shown in Fig. 1 for several beam intensities at the end of 1060-turn accumulation:

1) red color – intensity $N=0.1*10^{14}$ (mainly chromatic tune spread),
2) pink color - intensity $N=1.0*10^{14}$,
3) green color - $N=2.0*10^{14}$.

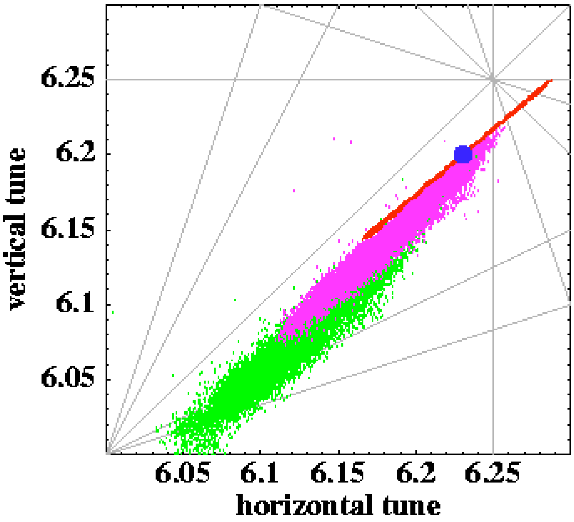

FIGURE 1. Tune footprint for working point (6.23, 6.20) for 3 intensities at the end of accumulation.

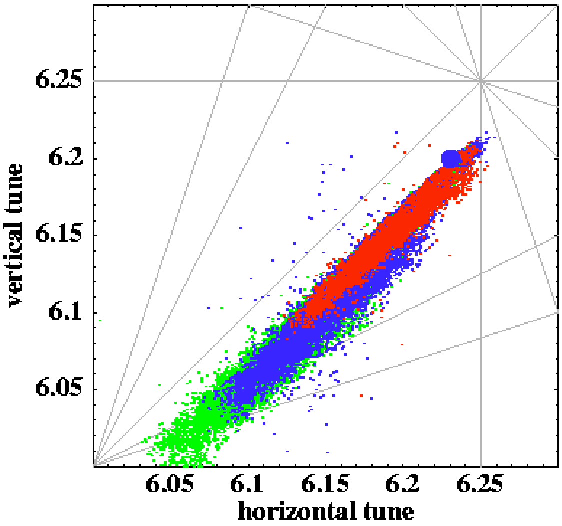

FIGURE 2. Tune footprint for working point (6.23, 6.20) for $N=2*10^{14}$ at three steps during accumulation.

Figure 2 shows tune spread after 263 (red), 526 (blue) and 1060 (green) turns. Note that after 263 turns there is already significant tune depression due to the space charge as the painted beam size is still relatively small.

In Figs. 1 and 2 depressed tunes are obtained using 1-turn tune ORBIT [4] diagnostic algorithms implemented in UAL [5]. Less noisy tune footprints are obtained by performing tune analysis over several turns. Figure 3 shows a slightly different working point of the SNS. In this figure the variation due to the chromatic contribution to the combined tune spread (space charge plus chromatic) is shown for three different values of momentum spread [3].

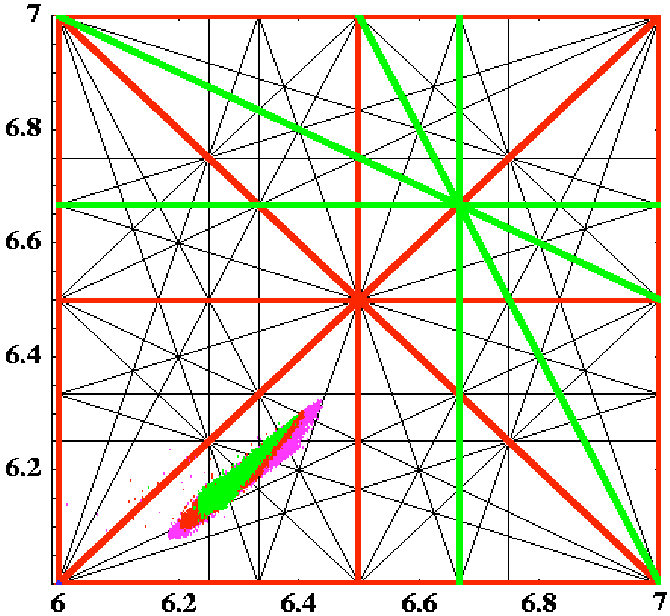

FIGURE 3. Tune footprint for working point 6.4, 6.3 for dp/p=0 (green), 0.07 (red) and 1% (pink).

3 TUNE MEASUREMENT OPTIONS

There are many possibilities [6] for measuring coherent and incoherent tune and tune shift in the SNS Ring. The first and most common method is to measure coherent (dipole) tune/tune shift from impulse excitation. Beam is excited with a transverse kick and coherent motion is observed on a position monitor during many machine turns. Analyzing the spectrum one gets coherent tune. The coherent tune shift is then the difference in tune measured at vanishing and high beam intensities. We intend to measure coherent tune and tune shift in this manner.

A second approach is to measure incoherent tune from injection oscillations. While the signal from the microbunches results from coherent injection oscillations, it is a measure of incoherent tune in the present context, where we are considering the tune of the accumulated bunch. As accumulation proceeds the coherent oscillations of the microbunches effectively sample the incoherent tune of the accumulated bunch. The measurement is complicated by the fact that injection timing is deliberately asynchronous to the 402.5MHz bunching frequency to minimize emittance growth due to space charge, so that turn-to-turn injection oscillations are not coherent. This has been studied in some detail [1], and it has been shown that FFT analysis will be satisfactory to provide tune information. Details of the planned data acquisition are presented elsewhere [7].

A third method is to measure incoherent tune from Schottky signals. The Schottky spectrum reveals the range of individual (incoherent) tunes of the particles – as a result, one gets both tune shift and tune spread. Schottky measurements are commonly used in storage rings for measurement of tune, chromaticity, and emittance, and a variety of other measurements. Several difficulties present themselves when one considers using Schottky in a fast accumulator. The foremost difficulties are probably the spectral energy from the injected beam and the high intensity. Given these difficulties, and the fact that incoherent tune is more easily available from other sources, there is no plan for Schottky measurements in the SNS Ring.

A fourth method is to measure incoherent tune from quadrupole mode oscillations. This method was specifically developed to measure incoherent tune shift for high intensity beams. It is based on the excitation of envelope (quadrupole) oscillation with a quadrupole pick-up. This method was pioneered at CERN (1996) [8] and successfully implemented at GSI, Germany [9] and HIMAC, Japan [10], and is discussed extensively in a recent workshop [11]. Incoherent tune shift due to the space charge is extracted by knowing the analytic relation between envelope frequency and individual particle frequency in the presence of the space charge. First, one needs to excite quadrupole beam envelope oscillations with a quadrupole kicker. Then the envelope frequency is measured with a quadrupole pick-up. The possibility of installing a quadrupole kicker and pickup in the SNS Ring is under active consideration.

A fifth approach is to measure incoherent tune from resonance crossing. This is an approximate method that can be applied even for bunched beams. This method does not require any special equipment and can be an operational way to measure tune shift/spreads.

Finally, incoherent tune can be found from the Beam Transfer Function. In a BTF measurement the beam is excited by a kicker driven by a sinusoid swept across the betatron resonance, and the response is the amplitude of the resulting betatron oscillation. The intent for the SNS Ring is to use a resonant pickup (to enhance sensitivity) resonated in the difference mode (to enhance sensitivity of the difference mode signal relative to the much larger sum mode signal) above the coherent spectrum of the bunch (to enhance sensitivity to the BTF stimulus relative to other information present in the coherent spectrum). Coherent energy due to injection oscillations of the 402.5MHz microbunches will be present, and cannot be escaped. The frequency of kicker and pickup will probably be about 50MHz.

4 SIMULATION METHOD AND RESULTS

For evaluating the BTF approach to tune measurement we have been employing the same simulation model used in the SNS Ring beam dynamics studies. The model is based on the open UAL infrastructure[5], allowing one to create realistic scenarios including the complex combination of several physical effects and dynamic processes. In the UAL infrastructure, various physical effects or algorithms are represented by pluggable and collaborative C++ shared libraries exchanging data via Common Accelerator Objects (e.g. Bunch, Twiss, etc.). Then the overall tracking scenario can be considered as the propagation of the Bunch object through the sequence of different algorithms (e.g. the TEAPOT symplectic integrator, ORBIT space charge kick, ZLIB Taylor map, etc.) associated with the corresponding accelerator element. Following this generic approach, the tune measurement system has been implemented as another tracking application with two new diagnostics elements: kicker and BPM. The kicker excites the propagated bunch during each turn of the injection painting and delegates it to the next tracking module. The BPM element calculates the center of bunch and writes the turn-by-turn data into the external file. This application allows one to measure the BPM response to the kicker deflection at a single predefined frequency. Then the tune footprint measurement is represented by a set of several simulation runs, each with a different predefined excitation frequency. Values of FFT signals determine the boundary of the tune footprint. Figure 6 shows preliminary FFT results for the tune spread due to chromaticity.

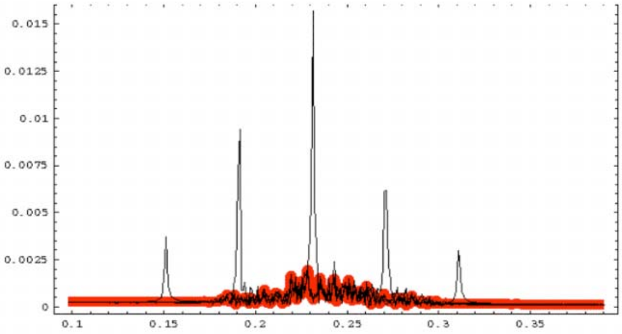

FIGURE 6. Model-based ‘measurement’ of the tune spread due to chromaticity.

These preliminary results confirm the measurement approach. This method is now being applied to measure full non-linear tune footprint with space charge, as shown in figures 1 and 2. To facilitate future activities, the model will be enhanced with the new very efficient tracking engine and additional diagnostics extensions.

These calculations were done at baseband with a non-resonant pickup, when in fact the kicker and pickup will operate at about 50MHz, and the pickup Q will approach 100. Kicks in the above modeling were about a factor of 100 stronger than what will be required with the resonant pickup. The observed BTF at 50MHz will show broadening of the revolution line due to a comparatively large relativistic slip factor η, as well as asymmetric chromatic broadening of the betatron sidebands. The chromatic contribution to the frequency spread is quantitatively expressed as [12]

$$\Delta f = f_0 \ \Delta p/p \ [(n \pm \nu)\,\eta \ \pm \xi]$$

where for the SNS Ring we have revolution frequency f_0~1MHz, momentum spread Δp/p~.01, harmonic number n~50, tune ν~.23, slip factor η~.2, and chromaticity ξ~8. From figure 7 below it can be seen that the effects of slip and chromaticity approximately cancel for the lower betatron line at 50MHz, and result in an additional broadening of about 170Khz (or tune of .17) at the upper line.

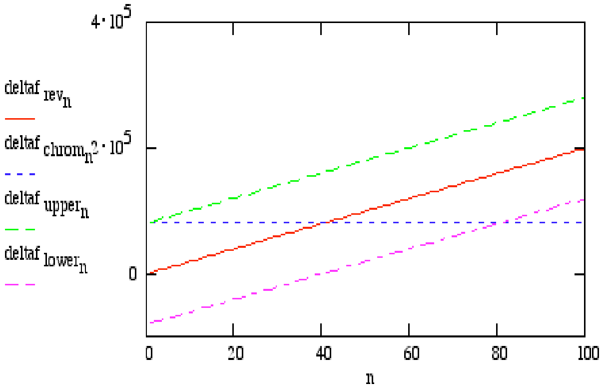

FIGURE 7. Effect of Δp/p and ξ on upper and lower sideband widths.

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