STUDIES PERFORMED IN PREPARATION FOR THE SPALLATION NEUTRON SOURCE ACCUMULATOR RING COMMISSIONING

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Abstract

The Spallation Neutron Source accumulator ring will compress 1.5×10^{14}, 1 GeV protons from a 1 ms bunch train to a single 695 ns proton bunch for use in neutron spallation. Due to the high beam power, unprecedented control of beam loss will be required in order to control radiation and allow for hands-on maintenance in most areas of the ring. A number of detailed investigations have been performed to understand the primary sources of beam loss and to predict and mitigate problems associated with radiation hot spots in the ring. The ORBIT particle tracking code is used to perform realistic simulations of the beam accumulation in the ring, including detailed modeling of the injection system, transport through the measured magnet fields including higher order multipoles, and beam loss and collimation. In this paper we present the results of a number of studies performed in preparation for the 2006 commissioning of the accumulator ring.

INTRODUCTION

We present here the results of recent computational studies using the ORBIT code [1], performed in preparation for commissioning and operation of the SNS accumulator ring. These studies are of a practical nature, seeking to answer questions regarding the impact of scenarios that may occur during operation. In particular, we independently examine four separate issues. The first regards the potential effect of errors in the injection chicane kicker strengths on the painted beam. To examine this issue we assume 1% strength errors in combination to provide a worst case scenario. The second question we examine also involves the injection kickers. We study the maximum possible beam intensity delivered to the target by assuming that the injection kickers are stuck full on, thus painting directly onto the closed orbit throughout injection. As a third study we assess the possibility of operating without the injection kickers altogether. This could simplify operation in the initial testing of the ring and, if feasible, could provide a means to operate even at high intensity if one or more kickers fail. Finally, we consider the effect of higher order multipole fields on the beam during accumulation. We use the actual data measured for the SNS ring magnets. In all these calculations we use the ORBIT code with symplectic single particle tracking, space charge, the dominant transverse and longitudinal ring extraction kicker impedances, the ring RF focusing, foil scattering, apertures for collimation and loss, and injection painting as appropriate. In all the full intensity calculations we paint a beam of 1.5×10^{14}, 1 GeV protons in 1060 turns. For low intensity calculations we paint a beam of 1.0×10^{13} protons over 150 turns.

INJECTION BUMP MAGNET ERRORS

The SNS injection region contains four horizontal and four vertical kickers for painting the beam. It is of interest to determine the effect of errors in the kicker strengths on the injected beam properties. The present study assumes errors of ±1% in the kicker amplitudes, with the signs of the errors chosen to give a worst possible case. Figure [1] shows the total emittance profiles at the outer 0.1% of the beam edge for four different cases. The red curve was produced by a calculation in which a simplified painting routine replaces the injection chicane. The green curve uses the injection chicane, but only with dipole fields in the chicane bend magnets. The blue curve includes the multipole field contributions in the chicane bends. These contributions are significant in the inside bends, which are specially shaped to direct stripped electrons to a collector. Finally, the pink curve is the same as the blue curve except for the ±1% in the kicker amplitudes. Thus, the effect of the kicker errors shows up as the difference between the blue and the pink curves. This difference turns out to have little effect on beam losses, which calculations show remain below 10^{-4} of the beam.

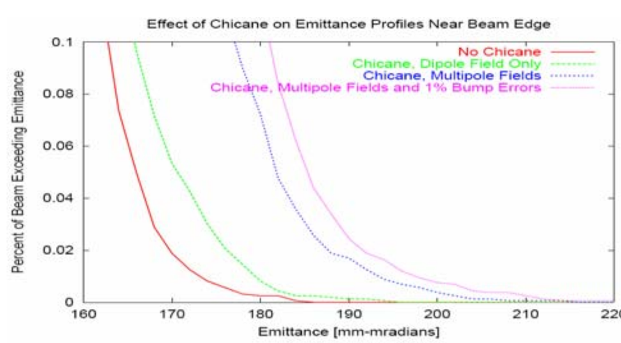

Figure 1: Emittance distributions of the simulated injected SNS beam with no chicane (red), chicane with dipole fields only (green), chicane with multipole components included (blue), and chicane with ±1% errors in the kicker strengths.

MAXIMUM INTENSITY FAULT STUDY

In order to evaluate design and fault protection requirements at the target and at the extraction dump, we have performed a maximum intensity fault study. The calculations were carried out to produce a worst case peak intensity beam by assuming that the injection kickers were stuck full on to paint the entire beam onto the closed

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orbit. We injected 1.5×10^{14}, 1 GeV protons in 1060 turns and transported the resulting beam alternatively to the target and to the extraction dump. Because the closed orbit passed through the foil during the entire injection process, the average number of foil hits per proton was 126, nearly 25% of the maximum possible. This led to the result that of the total fraction of the beam lost during accumulation, 5.6×10^{-4}, almost all was lost because of large angle scattering in the foil. There were no other significant losses in the ring. In transporting the beam to the target, the next significant losses 2.5%, occurred at the target window due mostly to nuclear inelastic scattering. Because of wide angle scattering in the window, an additional 0.9% was lost between the window and the target. Finally, 95.7% of the beam fell within the 7 cm × 20 cm target area. Most important, for this peaked beam the maximum current density inside the target spot was 623 mA/m^2, as shown in Fig. [2], more than three times the specified limit of 180 mA/m^2. For transport to the extraction dump, the respective losses were 0.5% in the dump window, 0.3% between the window and the dump, 99.1% of the beam reaching the dump, and a peak current density of 106 mA/m^2 at the dump.

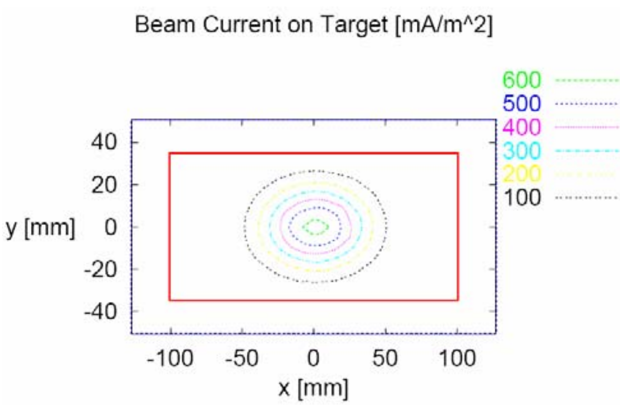

Figure 2: Beam current contours on the target. The red rectangle indicates the 7 cm × 20 cm target area.

Of all the results of these studies, the main cause of concern is the peak current density at the target. There are, however, some potential mitigating factors. The large number of foil traversals will lead to excessive heating and failure of the foil. It is not clear exactly how long the foil would survive, but at 20 times the nominal beam on foil intensity it would fail quickly. The large number of foil traversals will also increase beam loss in the ring injection area. This beam loss can be monitored, and the beam loss monitors can be set to trip off the beam if the beam loss becomes higher than a pre-determined set point. The loss monitor system has a fast loss mode with a 10 μs rise time. If the threshold is set to twice the nominal value, then the injection process would be terminated quickly midstream, thus lowering the beam density at the target. Previous designs included an injection kicker magnet ramp monitor. This protection monitor was cancelled as a cost-savings measure, but it could still be implemented.

RING OPERATION WITHOUT INJECTION KICKERS

For first beam injection into the ring it is desirable to turn off the injection kickers to simplify the setup as much as possible. It is also desirable to explore the limitations of operating the ring without the injection kickers in the event that one or more kicker units fail. We have investigated this possibility, using ORBIT, both at a typical intensity for commissioning of 1×10^{13} protons per pulse and at the full intensity of 1.5×10^{14} protons per pulse, of injecting a pulse without painting into the ring without incurring excessive beam loss. The results of these studies are shown in Table 1. For optimized painting, the 99.9% emittance, outside of which only 0.1% of the beam lies, is at 162π mm-mr. Normally, the limiting aperture comes from the adjustable scrapers in front of the collimation section, which are usually set at about 180π mm-mr. When the scrapers are withdrawn, the collimators present the limiting aperture at about 290π mm-mr. Thus, less than 10^{-4} of the beam is lost for optimized painting. The studies show that injection without painting is not possible for the nominal offset of 40 mm horizontally and 46 mm vertically between the closed orbit and the injection foil, even when the scrapers at the beginning of the collimation section are completely withdrawn. Table 1 shows that the 99.9% emittance for the nonscraped beam in this case lies at about 400π mm-mr, and over 90% of the beam is lost. However, it is possible to change the closed orbit using the dipole corrector magnets. By doing this, it is estimated that the closed orbit can be moved closer to the foil by a maximum of 12 mm horizontally and 15 mm vertically, thus reducing the offset between closed orbit and foil to 28 mm horizontally and 31 mm vertically. In this case, controlled losses of $<10^{-4}$ can be obtained at 1×10^{13} protons per pulse by withdrawing the corner (45° angle) scrapers. For full beam intensity of 1.5×10^{14} protons per pulse, removal of all the scrapers also results in losses of $<10^{-4}$. This is consistent with the result that the 99.9% emittances of the nonscraped beam lie in the vicinity of 200π mm-mr. As a realistic scenario for closed orbit adjustment using the dipole corrector magnets, we also considered an intermediate case of 34 mm horizontal and 38.5 mm vertical offsets between the closed orbit and foil (half the maximum bump, namely 6 mm horizontally and 7.5 mm vertically). In this case, it is necessary to remove the beam scrapers entirely, which results in $<10^{-4}$ beam loss at 1×10^{13} protons per pulse and 0.13% beam loss at 1.5×10^{14} protons per pulse. It is interesting that the nonscraped beam 99.9% emittances for these two cases are 280π mm-mr and 298π mm-mr, respectively, which is close to the limiting aperture posed by the collimators. Thus, through a combination of closed orbit adjustment using the dipole corrector magnets and retraction of the collimation beam scrapers, it is feasible to inject a 1×10^{13}

protons per pulse and probably a full intensity beam into the ring with acceptable loss, even in the absence of the injection kicker magnets.

Table 1: Beam Losses Without Injection Kickers.

Case (Closed Orbit Bump Size)	**Scrapers In**	**Corner Scrapers Out**	**All Scrapers Out**	**Remove Aperture: 99.9% $\varepsilon_x + \varepsilon_y$ {mm-mr}**
Optimized Painting 1.5×10^{14}	**$<10^{-4}$**			**162**
Disabled Painting: 1.0×10^{13}				
0-0 mm			**92.1%**	**390**
6-7.5 mm		**14.2%**	**$<10^{-4}$**	**280**
12-15 mm	**15.9%**	**$<10^{-4}$**		**190**
Disabled Painting: 1.5×10^{14}				
0-0 mm			**97.4%**	**404**
6-7.5 mm		**79.1%**	**0.13%**	**298**
12-15 mm		**52.9%**	**$<10^{-4}$**	**212**

THE EFFECT OF HIGHER ORDER MULTIPOLE COMPONENTS

Magnetic field surveys have been performed on all of the SNS accumulator ring quadrupole and dipole magnets. Though most of the multipoles are negligibly small, a significant sextupole component has been observed in one family of quadrupole magnets; these magnets have been sorted in the ring in a manner which minimizes the effect of this error [2]. Additionally, two of the injection chicane dipoles contain significant multipole components. Using ORBIT, we simulate the full beam accumulation for the 1.4 MW SNS beam with the full nonlinear lattice, including the measured multipoles through octupole in order for all quadrupole magnets in the ring, and for the two relevant injection chicane magnets. The simulations are performed for the working point (6.40, 6.30), which is near a sextupole resonance, and for a natural chromaticity beam. The results of the simulation are shown in Figure 3, where the emittance distribution for the beam simulated with the magnetic multipoles is shown along with the emittance distribution of the beam simulated without the magnetic mutipoles. We observe only negligible difference in the two emittance distributions, and therefore conclude that the measured multipoles do not cause significant emittance growth in the beam. The simulation was also repeated for the 2 MW accumulation scheme, with similar findings.

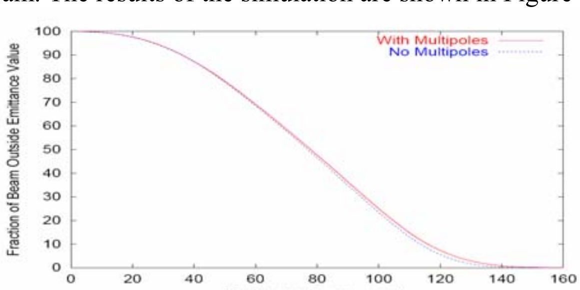

Figure 3: Emittance distribution for beams simulated with and without the quadrupole and injection chicane measured multipoles.

CONCLUSIONS

A number of detailed investigations have been performed to understand various ring physics and operating issues. We have demonstrated that likely errors in the injection kicker strengths should not significantly increase beam losses. We have also shown that the target current density limit can be seriously exceeded in a worst case scenario in which the injection kickers are locked full on, and have discussed ways to mitigate this possibility. We have demonstrated that it is possible to operate the ring without using the injection kickers by retracting the adjustable beam scrapers. Finally, we have shown that inclusion of the higher order multipole fields in the ring magnets does not cause any significant degradation of the beam quality. These calculations were all carried out using the ORBIT particle tracking code.

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[2] D. Raparia et al., Proceedings of the 2004 European Accelerator Conference, (Lucerne, 2004) 1574.