SIMULATIONS FOR SNS RING COMMISSIONING

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Abstract

In preparation for SNS ring commissioning, a number of operational issues have been studied using the ORBIT Code and other simulations. These include beam injection without the use of time-dependent painting, detailed tracking through the extraction septum and ring-to-target transfer line (RTBT) with fully correct geometry, a worst case scenario for beam intensity at the target and extraction dump, quadrupole current constraints in the RTBT, quadrupole settings for RTBT fault studies, and studies of H^0, H^-, and circulating beam trajectories in the injection region. All the ORBIT studies incorporated detailed physics models including beam-foil interactions, symplectic single particle tracking, space charge and impedances, and losses due to apertures and collimation.

INTRODUCTION

During the process of commissioning and operating the SNS accumulator ring, many issues require resolution. Simulations using ORBIT [1], MAD [2], and other computational models have proven valuable in addressing many of these issues. We present a number of examples here. The ORBIT results presented here were calculated using detailed precise descriptions of the SNS Ring and RTBT lattices. In particular, a complete set of apertures and collimators is included as well as correct descriptions of the injection and extraction chicane geometries and time dependent kickers for injection painting and extraction. The ORBIT beam dynamics includes symplectic particle tracking, space charge forces, and longitudinal and transverse impedances.

INJECTION WITHOUT 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 the possibility, using the ORBIT code, both at a typical commissioning intensity of 1×10^{13} protons per pulse and at the full intensity of 1.5×10^{14} protons per pulse, of injecting without painting into the ring without incurring excessive beam loss. The controlled loss criterion for the SNS ring is 1×10^{-3}. These studies show that this 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. 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 $<10^{-4}$. 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). 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. 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.

EXTRACTION SEPTUM AND RTBT

In preparation for operation of the SNS accumulator ring and transport of the accumulated beam to the target, we carried out detailed simulations of the extraction process including the full geometry of the extraction septum. As a result we determined the vertical placement of the first quadrupole in the RTBT and demonstrated successful transport of the full intensity beam to the target. ORBIT calculations were carried out for a lattice beginning at the extraction straight section of the ring and proceeding through the extraction septum and the RTBT to the target. The calculations included the detailed geometry of the entire lattice. The extraction kickers, the rotated and tilted septum bend, the vertically displaced first quadrupole of the RTBT, the collimators in the RTBT, the target window, and the apertures throughout the entire lattice were all correctly incorporated. In particular, the 2.48 m, 0.29 radians (16.82°) outward septum bend was included with a downward pitch of 0.0115 radians (0.66°), a clockwise role of 0.0451 radians (2.59°), and a vertical downward displacement of 169 mm relative to the local ring coordinate system. This yields a downward pitch of 0.0020 radians (0.12°) at the septum bend exit relative to the horizontal RTBT line. The distance from the septum bend to the vertically displaced first RTBT quadrupole is 3.6 m. Input for the symplectic ORBIT beam tracker was generated starting from a MAD file of the lattice. The next step was to use ORBIT to track a single reference 1 GeV proton starting on the ring closed orbit through the lattice to the target. In order to transport the reference particle through the lattice with acceptably small orbit deviations in the RTBT, it was necessary to adjust both the strengths of the extraction kicks and the vertical position of the first RTBT quadrupole. The kick strengths were adjusted in order to bring the reference particle to the first RTBT quadrupole at the center of the RTBT, 186.2 mm below the ring. Although the reference trajectory can easily be adjusted in this manner to reach the first RTBT quadrupole at the RTBT center ($y = 0$), the slope of the trajectory is generally not zero ($y' \neq 0$). In our calculation, we obtained $y' = 0.58$ mradians This will lead to deviations of the reference orbit unless the vertical position of the first quadrupole is adjusted to flatten the slope. We accomplished this by adjusting the elevation of the first RTBT quadrupole down by 1.86 mm, reducing the subsequent deviations to less than 0.5 mm. With this accomplished, we demonstrated the propagation of the reference particle to the target with only small deviations (< 0.5 mm) from the RTBT center. As a realistic test of our settings, we then considered an accumulated beam of 795000 macroparticles representing 1.5×10^{14} protons at the beginning of the lattice. We transported this beam to the target including the effects of space charge (3D model), longitudinal and transverse extraction kicker impedance, and losses due to collimation, apertures, and scattering in the beam window. Of the original beam distribution, 93.8% reaches the 20 cm × 7 cm target. The remainder is lost as follows: 2.7% is lost in the target window due to nuclear scattering; 1.1% is lost between the target window and the target; and the remaining 2.4% reaches the target but lands outside the desired footprint. These results are satisfactory and comparable to previous numbers. The results of this test validated our settings for the extraction kick strengths and the position of the first RTBT quadrupole.

WORST CASE BEAM INTENSITY

In order to evaluate design and fault protection requirements at the target and the extraction dump, a scenario for worst case local beam intensity was simulated using ORBIT. A 1.44 MW macropulse was accumulated in the SNS ring under the assumption that the bump magnets were locked full on, so that the entire beam was injected onto the closed orbit resulting in a maximally peaked transverse distribution. The resulting macropulse was then transported alternatively to the target and to the extraction dump. The on-axis injection resulted in a very peaked beam distribution, although spreading due to transverse space charge forces reduced the peak current density by nearly an order of magnitude from 15000 mA/m^2 without including space charge to 1530 mA/m^2 with space charge. The calculated losses due to slow emittance growth were found to be negligible at less than 10^{-4}. However, because the painting was disabled, the number of foil hits during injection averaged 126 for each proton, compared with about 6 foil hits under the usual painting scheme. The resulting beam loss due to large angle Coulomb and nuclear scattering was calculated to be 5.6×10^{-4}, which exceeds the nominal by about a factor of 20. Almost all of this loss occurred in the first 10 meters following the foil. Given the substantial number of foil hits, nearly ¼ the potential maximum, it is quite possible that the foil would not survive. However, assuming that the foil does survive, we carried out calculations extracting and transporting the final distribution both to the target and to the extraction dump.

Losses in the RTBT are insignificant up to the target window. At the target window, which is made from inconel (and which we model as iron) with thickness 4 mm, 2.5% of the protons undergo nuclear inelastic scattering, in which case ORBIT removes them from further consideration by counting them as losses. In reality, this overestimates the beam losses because most of the particles resulting from inelastic nuclear scattering at 1 GeV proceed in the forward direction and remain inside the beam pipe aperture. After subsequent losses, 95.7% of the beam falls inside the target spot of 20 cm × 7 cm. At the window, the peak current density is 1557 mA/m^2 and at the target the peak current density is 623 mA/m^2. Thus, scattering in the target window diffuses the beam significantly, although the peak current density at the target for this worst case distribution is more than a factor of three above the allowable limit of 175 mA/m^2 at 1.44 MW. A similar calculation was taken to extract and transport the beam to the extraction dump. Again, losses are negligible prior to the extraction dump window. Inelastic nuclear scattering in the window, which was taken to be aluminum of thickness 2 mm, is 0.5% of the initial beam. After subsequent losses, 99.1% of the initial beam reaches the dump. The peak current densities are 1187 mA/m^2 at the dump window and 106 mA/m^2 at the dump. The beam size at the extraction dump is still larger than the nominal beam at the linac dump [3], so the small beam should not be a problem for the extraction dump. The beam current density at the window is about three times higher than nominal.

For this extreme scenario, the beam current density at the target and proton beam window clearly exceeds design parameters. In general it is desirable to employ protection mechanisms to prevent excessive beam current densities. Mitigating factors to prevent the on-axis injection scenario include: 1) Stripper foil heating. In the on-axis injection scenario the average proton in the ring passes through the stripper foil 126 times (to be compared to the nominal 6 or 7 times). This will lead to excessive stripper foil heating and eventual failure of the foil. It is not clear how long the foil would survive, but even one second of these high beam current densities could present a problem for the target. 2) Beam loss. As shown in the calculations, the large number of foil traversals will cause high 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 ms 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. 3) Injection kicker magnet ramp monitor. This protection monitor was cancelled as a cost-savings measure, but it could still be implemented .

RTBT QUADRUPOLE LIMITS

A detailed study has been conducted to determine limiting constraints on the quadrupole strengths in the RTBT. The RTBT contains 30 quadrupole magnets powered by 19 separate power supplies. Quadrupoles 1, 2, 3, 4, 12, 13, 14, 15, 16, 17, 26, 27, 28, 29, and 30 each have independent power supplies. In addition, there are 4 families, each driven by a single power supply. These families are: quadrupoles {5, 7, 9, 11}, {6, 8, 10}, {18, 20, 22, 24}, and {19, 21, 23, 25}. We first conducted a survey using MAD in order to determine the effect of changing the quadrupole strengths on the beam size. This was done by individually varying the quadrupole strengths corresponding to each power supply by ±5% from their reference values and then observing the resulting horizontal and vertical fractional beam size changes. Then a whole series of ORBIT calculations were carried out in which the quadrupole strengths corresponding to each power supply were varied independently, one power supply at a time. Strengths were both increased and decreased until one of three things occurred: 1) beam loss > 1×10^{-3} occurs upstream of the target window; 2) < 90% of the total beam reaches the 20 cm × 7 cm target footprint; or 3) the maximum beam current density on target exceeds that of the reference case by > 10%. In case of 2) or 3), we assume that the target current requirements are violated and place a constraint on the appropriate quadrupole or quadrupole family. In case of 1), we assume that the losses are detected by the BLMs in the RTBT and that the MPS will trip the beam. In this case, we place no constraint on the appropriate quadrupole strength. Only for six of the nineteen power supplies does beam loss occur in the RTBT for smaller field change than is required to violate target beam distribution constraints. For the remaining thirteen power supplies, target distribution requirements are violated before upstream beam loss occurs. For these cases, we consider the percent of change in the field from the reference value at the point of violation of the target requirements. These values vary from 7% on QH4 and QH28 to 40% on QH26.

RTBT FAULT STUDY SETTINGS

We have carried out computational studies using ORBIT in order to establish quadrupole magnet settings to facilitate beam spills for fault studies in the SNS RTBT. To conduct the fault studies, it is desired to spill the beam in the vicinity of Q24 and independently in the region between Q27-Q30. In these studies, it is desired to spill the entire beam in the RTBT so that no beam reaches the target. The strategy pursued here for losing beam at a given location is to alter the fields in one or several upstream quadrupole magnets, thus changing the focusing of the beam. For the nominal settings no beam is lost in the RTBT prior to the target window. In order to spill beam in the vicinity of Q24, we have essentially two knobs which might prove effective: quadrupole families Q18-Q24 even and Q19-Q25 odd. We made several attempts to induce such losses by exercising these knobs. In spite of varying the quadrupole strengths from zero to 125% of the nominal values in these families, either singly or in combination, significant losses in the vicinity of Q24 are not obtained. The reasons for this are two: each of these quadrupole families extends about 35 meters, mostly upstream of Q24. Thus, it is impossible to localize the beam distortion with either of these knobs. The second reason is the placement of the second RTBT collimator between Q22 and Q23. With its small aperture, this collimator casts a significant shadow on Q23 and Q24. In our studies the highest beam fraction lost on Q24 is less than 10%. However, we did learn that setting the family Q19-Q25 odd to 75% the nominal strength leads to only 0.5% loss, all in the second collimator. We use this to advantage to spill beam in the vicinity of Q27-Q30. This is done by setting Q19-Q25 odd to 75%, Q27 and Q29 to 0%, and Q26, Q28 and Q30 to their maximum settings. In this case, 99.7% of the beam is spilled before the target window with over 90% in the desired region. Thus, it is not possible to spill the beam near Q24, but easy to do so between Q27 and Q30.

INJECTION CHICANE AND DUMP

During commissioning, the highest beam losses occurred in the injection dump region. Analysis indicates that these losses are due to incompletely stripped H^0 and H^- particles. These two components are supposed to be stripped at a secondary foil upstream of the final (fourth) chicane bend. However, the original injection design was modified to move the primary stripping foil upstream into the second injection chicane bend to facilitate the magnetic stripping of excited H^0. Because of this, the H^0 and H^- beam components are farther apart at the secondary stripping foil and at the entrance to the injection dump than originally planned. To understand and remediate this, analysis was carried out using a simple MathCad model to track the various beam components from the injection septum in the HEBT line to the downstream end of chicane bend 4. The field strengths in the injection septum and the four injection chicane bends were varied to provide specified injected beam angle entering chicane 2, specified injected and circulating beam angles at the first stripper foil, and to close the circulating beam orbit. With these 5 knobs, we searched for prospective chicane settings to take the unstripped beam to the injection dump while closing the circulating beam bump. Preliminary results indicate that increasing the bend in the injection septum by 1 mradian and increasing the secondary foil width by 1 mm on the outside edge may solve the injection dump loss problem.

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