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EXPLORATION OF BEAM FAULT SCENARIOS FOR THE SPALLATION NEUTRON SOURCE TARGET*

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Abstract

The Spallation Neutron Source (SNS) accelerator systems will provide a 1 GeV, 1.44 MW proton beam to a liquid mercury target for neutron production. In order to ensure adequate lifetime of the target system components, requirements on several beam parameters must be maintained. A series of error studies was performed to explore credible fault scenarios which can potentially violate the various beam-on-target parameters. The response of the beam-on-target parameters to errors associated with the phase-space painting process in the ring and field setpoint errors in all the ring-to-target beam transport line elements were explored and will be presented. The plan for ensuring beam-on-target parameters will also be described.

INTRODUCTION

The Spallation Neutron Source (SNS) accelerator consists of a 2.5 MeV H- Injector, a 1 GeV Linear Accelerator, an Accumulator Ring and associated transport lines [1]. The linac provides an average macropulse current of 26 mA which is accumulated over 1060 turns by charge-exchange injection in the accumulator ring. The ring intensity reaches 1.5×10^{14} protons at which point the current is extracted in a single turn and transported to the target via the Ring-to-Target Beam Transport (RTBT) line [2]. With a repetition rate of 60 Hz, the SNS provides 1.44 MW average beam power to the liquid mercury target [3] for spallation neutron production. The baseline SNS beam parameters are summarized in Table 1.

Table 1: Baseline SNS Parameters

Parameter	Baseline Value
Beam Power on Target	1.44 MW
Accumulated Protons	1.5×10^{14}
Accumulated Turns	1060
Repetition Rate	60 Hz
Beam Energy	1 GeV
Target Cross-section	404mm x 104 mm
Beam spot width x	200mm x 70 mm

In order to ensure adequate lifetime of target system components, requirements on several beam-on-target parameters must be maintained. These various requirements are summarized in Table 2. At the target shroud face the nominal proton beam spot size is $200\times70\text{mm}^2$. For the baseline parameters shown in Table 1, the normal peak single pulse density is 1.9×10^{16} protons/m^2, the time-averaged peak current density is 0.18 A/m^2, the time-averaged beam current density over the nominal spot size is 0.103 A/m^2, and 93% of the beam power is within the nominal footprint. Of primary concern is the peak single pulse proton density. If the peak density increases by more than 25% above nominal (2.3×10^{16} protons/m^2) the beam must be shut off within two 60 Hz pulses. Another requirement demands that 90% of the total beam power remain within the nominal beam spot. In an off-normal condition in which more that half the beam power lies outside the nominal beam spot the beam must be shut off within two 60 Hz pulses. In normal operation, the time-averaged peak current density on the target remains below 0.18 A/m^2. In an off-normal condition in which the time-averaged peak current increases by 10% (0.20 A/m^2), the beam should be shut off within 10 seconds. In addition, tolerances on the beam centroid are noted in the table.

Table 2: Beam on Target Requirements

Requirement	Normal Condition	Off-Normal Condition	Fault Duration
Peak single pulse density	$< 1.9\times10^{16}$ proton/m^2	$> 2.3\times10^{16}$ proton/m^2	≤ 2 pulses
Peak time averaged current density	≤ 0.18 A/m^2	> 0.20 A/m^2	10 sec
Power within nominal spot	$\geq 90\%$	$< 50\%$	≤ 2 pulses
Centroid tolerance	± 2 mm		

A series of error studies was performed to explore credible fault scenarios which could potentially violate these beam-on-target parameters. The following faults were considered in this study: i) phase-space injection painting errors in the accumulator ring, ii) ring extraction kicker misfires, iii) RTBT dipole errors, iv) RTBT quadrupole errors and v) RTBT dipole corrector errors. These various fault scenarios are discussed in turn.

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THE RING-TO-TARGET BEAM TRANSPORT LINE

The RTBT is described in [2]. The line begins in the ring extraction region. The extraction system [4] consists of 14 fast kicker magnets to deflect the beam vertically into the extraction septum magnet, which then directs the beam into the RTBT. The RTBT lattice consists of 30 quadrupoles, one dipole and 19 dipole correctors. Two collimators provide protection of the target system from large amplitude particles. The beta-functions are increased in the last quadrupoles to achieve the large beamsize required by the target. A 10m drift takes the beam from the last quadrupole to the target face. Two meters upstream of the target is a 4 mm thick Inconel Proton Beam Window which separates the accelerator vacuum from the target environment.

Central to the discussion of faults and machine errors is the consideration of the aperture throughout the machine. The collimation system [5] in the ring consists of three actively cooled absorbers which form the limiting apertures for the ring with admittance of 300 πmm-mrad in each plane. The collimation system includes an adjustable scraper which is expected to reside at 200 πmm-mrad. The collimators in the RTBT have 300 πmm-mrad horizontal admittance and 400 πmm-mrad vertical admittance.

RING INJECTION PAINTING FAULTS

In order to minimize space-charge and other collective effects in the accumulator ring, phase-space painting is utilized in all three planes [6]. Transverse painting is accomplished by a set of injection bump magnets that sweep the closed-orbit at the injection point during the accumulation cycle.

Several painting faults have been considered, i) injection onto the closed-orbit (corresponding to a failure mode in which the bump magnets are "stuck" at full scale excitation), ii) failure of the horizontal injection bump magnets, iii) failure of the vertical injection bump magnets, and iv) failure of both sets of bump magnets. In each case increasing levels of ring quadrupole gradient errors (up to a maximum of 25% beta function errors) were explored.

The case of injection onto the closed-orbit is potentially dangerous because a high-current-density beam is produced. Particle-in-cell simulations using ORBIT [7] show that indeed the current density on the target can reach 0.47 A/m^2 (or a single pulse density of 4.9x10^{16} protons/m^2) producing an off-normal pulse. However, this fault is accompanied by loss of ~0.5% of the beam in the ring, which is a factor of ~5 greater than nominal conditions. This condition is readily detected with loss monitors that trip the Machine Protection System (MPS). Furthermore, this is an unsustainable fault condition since the closed orbit remains in the injection foil, increasing the foil heating by more than an order of magnitude – a condition that leads to the rapid disintegration of the foil.

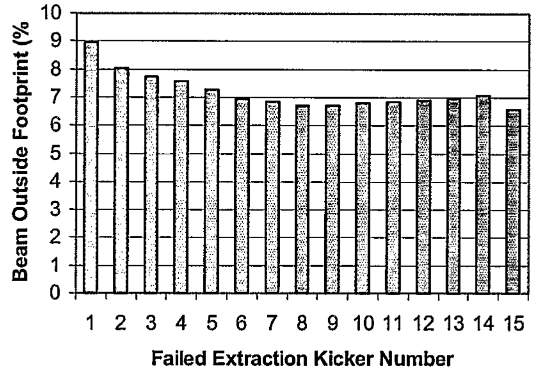

Figure 1: Fraction of beam outside the nominal target footprint for single extraction kicker failures. Number 15 shows the nominal value.

The other faults mentioned are important to consider as they have the potential for painting larger beams which could in principle violate "beam-in-footprint" requirements. It is found that in all the fault scenarios involving failure of the injection bump system the ring losses are orders of magnitude larger than nominal conditions and are therefore readily detected by loss monitors. In the case of horizontal or vertical injection bump failure, ~15% of the beam is lost, whereas for failure of both sets of injection bump magnets ~40% of the beam is lost. In none of these injection-bump failure cases are off-normal target pulses produced. Finally, it should be noted that the injection kicker waveform is monitored for proper operation by the MPS system, providing further protection against this class of failures.

EXTRACTION KICKER MISFIRES

The RTBT transport line optics are designed to achieve an integral multiple of π phase advance between the ring extraction straight and the target in order to minimize the displacement at the target if one or more kickers fails to fire. In addition, the RTBT collimation system is designed to protect the target from faults in which two or more extraction kicker magnets fails to fire. The extraction kicker misfires are not capable of modifying the current density, but may displace the beam centroid.

Figure 1 shows the fraction of beam outside the nominal target footprint as a function of extraction kicker number for single kicker failures. In nominal conditions about 6.5% of the beam lies outside the nominal footprint, whereas all faults respect the 10% requirement, and are therefore incapable of producing off-normal conditions.

DIPOLE ERRORS

There are two high-field dipoles in the transport line, the extraction septum magnet and the 16.8 degree bend magnet. It was found that for 0.1% field errors in either of these dipoles, more than 10% of the beam was lost on the RTBT collimators – a situation which is easily detected by loss monitors. Even for these rather large dipole errors, an off-normal condition is never produced.

The impact of dipole corrector faults has been assessed by investigating the beam-on-target parameters for the case of full-scale powering of single correctors. It is found that single corrector failure is incapable of generating an off-normal condition.

QUADRUPOLE FAULTS

Quadrupole faults have the potential to both increase the current density on the target and place beam outside of the nominal footprint. The RTBT beamline contains 30 quadrupoles, powered by 19 supplies. The impact of quadrupole errors was investigated by transporting the nominal extracted beam distribution through the RTBT to the target (including scattering in the proton beam window) while each quadrupole (or string of quadrupoles as determined by power supply configuration) was swept from zero to 50% higher than its nominal operating gradient. The detailed vacuum chamber geometry was included to accurately model the losses in the beamline. The losses were tallied and the beam-on-target parameters recorded at each quadrupole setting.

Figure 2 demonstrates the results for the "beam-in-footprint" requirement. Shown is the fraction of the beam which is lost in the RTBT at that power supply current for which the "beam-in-footprint" off-normal condition (of 50% of the beam power lying outside the nominal beamspot) is just met. The solid bars show the beam fraction lost up to and including the last quadrupole, and the light bars show the beam fraction lost between the last quadrupole and the target. To generate an off-normal beam pulse requires, in most cases, the loss of much of the beam in the beamline – a condition which is readily detected by loss monitors. Exceptions to this rule are the last few quadrupoles in the line (power supplies 16 through 19), which are capable of violating the "beam-in-footprint" condition without generating losses in the beamline proper. For these cases, dedicated hardware current monitors will be deployed.

Figure 3 shows the maximum target current density achievable by tuning single power supplies from zero to 50% above nominal current with all others at their nominal currents. It is noted that eleven power supplies have the capability of violating the peak single pulse density requirement (which corresponds to 0.22 A/m^2 time averaged current density). In many of these cases detectable beamloss is predicted. Again, some quadrupoles (particularly near the end of the RTBT) do not produce detectable beamloss and so dedicated hardware current monitoring will be used.

FAULT PROTECTION STRATEGY

To ensure required target parameters the following approach will be taken. First, the proper operation of the ring injection painting, extraction and RTBT beamline will be certified by measurement of beam profiles in the RTBT, both in wire scanner arrays as well as at a Harp located immediately downstream of the last quadrupole in the RTBT beamline. Once the beam profiles and trajectory are certified, software current limits will be placed on each RTBT power supply to avoid accidental mistuning. The power supply status is read prior to each 60 Hz beam pulse and factored into the beam permit for the next pulse. In addition, the MPS has power supply status inputs in hardware to ensure that a power supply has not tripped. Critical magnetic elements such as the last quadrupoles in the line will have dedicated current monitoring hardware providing an enable signal to the MPS. As shown above, the beamloss monitoring system, which is also linked to the MPS in hardware, provides protection against most target violating conditions since such conditions are typically accompanied by substantial beamloss in the RTBT.

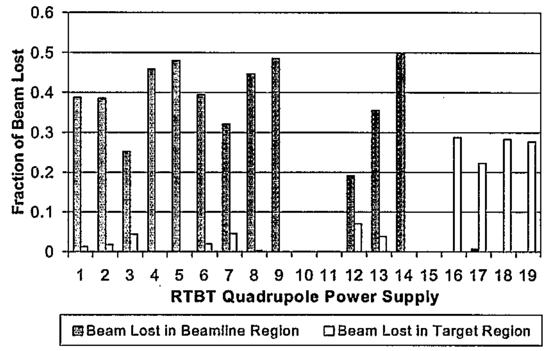

Figure 2: Fraction of beam lost in RTBT at the power supply setting which produces an off-normal "beam-in-footprint" condition.

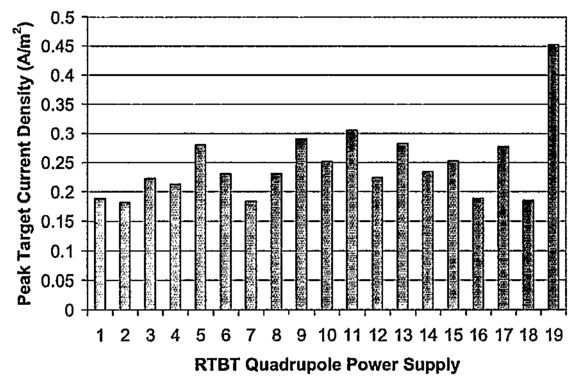

Figure 3: Peak current density achievable by tuning each power supply individually, leaving the others at nominal strength.

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