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Accelerator physics model of expected beam loss along the SNS accelerator facility during normal operation*

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1 INTRODUCTION

The most demanding requirement in the design of the SNS accelerator chain is to keep the accelerator complex under hands-on maintenance. This requirement implies a hard limit for residual radiation below 100 mrem/hr at one feet from the vacuum pipe and four hours after shutdown for hundred days of normal operation. It has been shown by measurements as well as simulation [1] that this limit corresponds to 1-2 Watts/meter average beam losses. This loss level is achievable all around the machine except in specific areas where remote handling will be necessary. These areas have been identified and correspond to collimation sections and dumps where a larger amount of controlled beam loss is foreseen. Even if the average level of loss is kept under 1 W/m, there are circumstances under which transient losses occur in the machine. The prompt radiation or potential damage in the accelerator components can not be deduced from an average beam loss of 1 W/m. At the same time, controlled loss areas require a dedicated study to clarify the magnitude and distribution of the beam loss. From the front end to the target, we have estimated the most probable locations for transient losses and given an estimate of their magnitude and frequency. This information is essential to calculate the necessary shielding or determine the safety procedures during machine operation.

Losses in controlled areas and the cleaning systems are the subject of Section 2. The inefficiency of each system will be taken into account for the discussion on Section 3 where ncontrolled loss is estimated. Section 4 sumarizes our findings and presents a global view of the losses along the accelerator chain.

2 CONTROLLED LOSSES

Controlled losses occur at the choppers, in the LEBT and MEBT lines, at the collimators in the HEBT, Ring and RTBT and in the three dumps along the accelerator. In most of these sections remote handling is necessary and specific shielding and other protection measures should be implemented according to the final radiation levels.

Front end The 1 msec beam pulse from the ion source is chopped in the LEBT at 65 keV. Assuming the LEBT chopper rise time is infinitely fast, 32% would be lost on the LEBT chopper target or in the RFQ. However, due to the $t \leq 50$ nsec rise/fall of the LEBT chopper, only 27.7% of the beam is lost at the end of the LEBT at 65 keV. After acceleration and bunching in the RFQ, a second chopper is located in the MEBT to clean the unbunched beam. Had the MEBT chopper rise time be infinitely fast, 4.3% would be lost on the MEBT chopper target at 2.5 MeV. The actual rise/fall time is about 10 ns and an antichopper is used to compensate partially kicker beam. The beam extinction is better than 10^{-4}.

HEBT transverse collimators To collimate the linac beam we use charge exchange movable carbon foils which strip the H^- to H^+. The H^+ beam is separated from the H^- beam by the magnets and hits the front face of the absorbers downstream. The foils represent the main aperture restriction in the line. Assuming a Gaussian beam profile coming from the Linac, and a foil aperture of 13σ,the tails intercepted by the cleaning system will account for a fraction of 10^4 of the total beam. These losses will be distributed evenly between two absorbers. The position and aperture of the foil and absorbers have been optimized to provide large impact parameters at the absorber. Under these assumptions, the efficiency of the transverse collimations has been estimated to an average of 92.5%. The remaining protons will be spread along the downstream cells and the beginning of the achromat [3].

HEBT Longitudinal collimator In a similar arrangement to the transverse collimation, a mobile stripping foil located in the achromat where dispersion is high, will dump the longitudinal halo onto an absorber located downstream. In this case, the collimator is external to the beam line and there is no protons lost along the line. This system will collimate off momentum particles in the linac beam including large energy spread and energy jitter. The maximum fraction of the beam in the longitudinal tails has been estimated to be 10^{-3} of the total beam [3].

Ring collimation section Losses in the ring are mainly produced by gradual emittance growth produced by space charge and magnet errors. With the introduction of a primary collimator, the incident angle is increased but not enough to reach the front face of the secondary collimators. The losses are produced along the inner surface of the vacuum pipe. The impact angle takes typical values between 0 and 10 mrad. A fraction of $2.0 \cdot 10^{-3}$ of the beam is expected to be in the tails and is intercepted by the collimators with a minimum efficiency of 95%. A preliminary distribution of the losses along the collimation section (superperiod B) has been made with the program ORBIT. Figure 1

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shows the fraction of beam absorbed in every collimator as well as quadrupoles and free drifts in the line [2]. These simulations assume a uniform vacuum pipe wth a 14.0 cm radius. This represents the optimal case and is still under study.

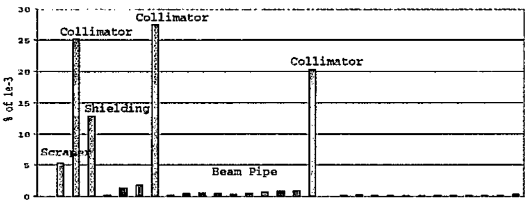

Figure 1: Loss distribution along the collimation straight section. Data given in fractional loss assuming a total loss of $1.9 \cdot 10^{-3}$.

RTBT collimators The RTBT collimators are provided to protect the target and RTBT line against extraction kicker malfunction [3]. After collimation of the beam inside the ring, the extension of the beam is well defined at the RTBT line. Under nominal conditions, the beam passes through the line without touching the vacuum pipe. A failure of one of the fourteen extraction kickers will produce an orbit deviation along the RTBT line but no beam hits the vacuum pipe and the beam impacts the target at the nominal location. In the event of a failure of two kickers, approximately 10% of the beam hits the collimator with no further losses downstream. The losses are equally distributed between the two absorbers. In the rare case of more than two kicker failures, the whole pulse is dumped onto the two collimators. We estimate the average beam losses in the RTBT collimator by the probability of kicker failure and the fraction of beam collected at each scenario. Nevertheless, we have to draw attention to the fact that prompt losses are high and very localized. The design of the collimators has been done to resist two whole consecutive pulses after which the machine should be stopped and the kickers fixed.

Location	Frect. Loss	Power [W]
LEBT chopper	$2.8 \cdot 10^{-1}$	36
MEBT chopper	$4.3 \cdot 10^{-2}$	215
Linac dump	$1.0 \cdot 10^{-5}$	20
HEBT x-y-coll. (2)	$3.0 \cdot 10^{-4}$	600
HEBT z-coll.	$1.0 \cdot 10^{-3}$	2000
Injection dump	$1.0 \cdot 10^{-2}$	20000
Ring coll. (3)	$1.9 \cdot 10^{-3}$	3800
RTBT coll. (2)	$1.0 \cdot 10^{-5}$	20

Table 1: Summary of the controlled losses.

3 UNCONTROLLED LOSSES

RFQ The transmission in the RFQ structure is expected to be of the order of 80%. The other 20% of the beam will be lost along the cavity. We consider these losses uncontrolled because no special protection or shielding is provided. However, we do not expect any activation at this low energy ($E \leq 2.5$ MeV) and the area is assumed to fulfill the requirements for hands-on maintenance. In addition, this is an area with controlled access during operation. For simulation purposes, we consider the loss homogeneously distributed along the RFQ inner surface ($\approx$4 m).

Warm Linac The main sources of loss in the linac are ionization and magnetic stripping as well as halo growth due to mismatch and space charge. Due to the level of loss we are interested in, and the large number of free input parameters in the beam dynamics simulation, the net amount of losses and their location is difficult to predict by simulation. We extrapolate our experience from other Linacs as LANSCE to predict the most probable loss locations and to confirm the required beam loss limit of 1W/m.

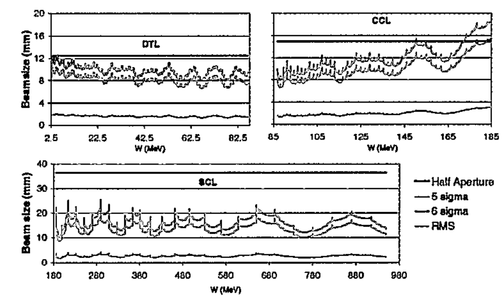

Figure 2: Envelope of the beam along the DTL, CCL and SCL. The minimum aperture of the vacuum pipe in every structure is indicated for comparison.

The comparison between the beam envelope and the vacuum pipe along the SNS linac is shown in Fig. 2 [5]. From this plot we can imply that localized losses may occur at the beginning of the DTL, at the end of the CCL and at the transition of between CCL and SCL. From experience in LANSCE and LEDA, we know that losses typically occur at locations where a change in transverse focusing or RF frequency introduce a mismatch. In the SNS linac there is a frequency transition between the DTL and CCL where we expect losses above the average.

Cold Linac For the superconducting linac the bore radius aperture is much larger than the nominal beam. In addition, the vacuum pressure is one order of magnitude lower than in the warm linac (=10^{-9} compared to $5 \cdot 10^{-9}$). Simulations and stripping calculations give a negligible amount of losses. On the other hand, one should be very cautious with our expectations as there is no experience with superconducting proton linacs up to now. Measurements in the high energy end of the LANSCE linac, indicated unexplained losses up to 0.6W/m that have not been predicted by simulation [1]. On top of this, it is foreseen to continue operating with a missing klystron in the superconducting linac. This operating mode creates a mismatch and populates the transverse tails of the beam [6] leading to exceptional losses downstream from the missing cavity. Studies are in progress to establish the importance of these losses in the SNS cold linac. In the case of mismatch or abnormal emittance growth, beam loss will be concentrated in the warm quadrupole sections where the aperture is smaller and the beam reaches its maximum extent. This assumption is supported by measurements made at LANSCE CCL where residual radiation at quadrupoles was found to be up to a factor 100 larger than the average.

H^- Stripping We have estimates of the stripping losses which will account for a significant fraction of the average 1W/m along the linac especially in the low energy range where the stripping cross sections are larger. These calculations agree with measured data [4]. The vacuum stripping losses for the H^- beam depending on the energy are shown in figure 3. The losses, expressed in watt per meter assume a generic vacuum composition for warm sections and mainly hydrogen for the cold sections.

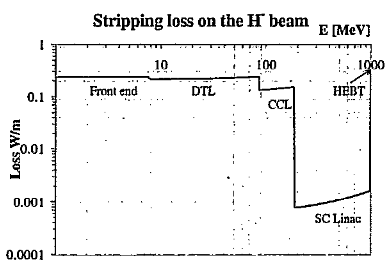

Figure 3: Residual gas stripping loss for H^- beam from the front end to the HEBT transfer line.

HEBT Along the HEBT, the sources of uncontrolled loss are residual gas and magnetic stripping. These losses are homogeneously distributed along the line and inside the magnetic fields. At 1 GeV the cross section of H^- stripping is $9.14 \cdot 10^{-19}$ cm^2 and $1.30 \cdot 10^{-19}$ cm^2 for Nitrogen and Hydrogen respectively. With a vacuum of $5 \cdot 10^{-8}$, the fractional stripping losses account for $\approx 2.8 \cdot 10^{-5}$ along 170 meters or $1.6 \cdot 10^{-7}$ per meter. Magnet strength is chosen so that the magnetic stripping is at the 10^{-8}per meter level much lower than the vacuum stripping loss.

Injection Section The main source of loss in the injection section is the nuclear scattering of the beam in the Carbon foil. Besides, we need to consider the magnetic stripping of the H^- beam in the second dipole of the injection chicane INJB2. The losses produced at the injection foil are dominated by nuclear scattering. The average number of foil crossing per proton has been estimated by simulation to be ≈ 7 in nominal conditions. Yet, if the beam emittance increases or deviates from a Gaussian distribution, this number increases up to 12 crossings per proton. For a carbon foil of 300 μg/cm^2, the fractional loss at the foil due to nuclear scattering will be $\approx 3.7 \cdot 10^{-5}$ under nominal conditions and up to $\approx 6.3 \cdot 10^{-5}$ for an exceptional large beam. For the magnetic stripping we assume a magnetic field of 0.25-0.3 Tesla. For this magnetic field, $1.3 \cdot 10^{-7}$ of the beam will be lost along the effective magnetic length of the dipole ($\approx$ 1 meter).

Ring Along the arcs and in the injection, extraction and RF straight sections we expect spurious losses arising from the inefficiency of the collimation system. This accounts for $1.0 \cdot 10^{-4}$ arising from the inefficiency of the ring collimator system and is in general homogeneously distributed in phase-space. We assume that this halo is spread according to the dispersion, phase advance and aperture along the 218 meters of the ring outside the collimation system.

RTBT The losses along the RTBT line expected during normal operation are negligible. The only potential source of loss is the residual beam coming from the RTBT collimators expected to be $\leq$ 10% of the incident beam. As in the HEBT, the loss will be localized in the two or three cells downstream from the collimators. These losses are of the order of $10 \cdot 10^{-8}$. One should include in this section the losses in the target window due to nuclear scattering.

4 SUMMARY

Figure 4 shows the total amount of uncontrolled losses expected during normal operation along the accelerator chain. In this paper, we only evaluate expected beam loss under

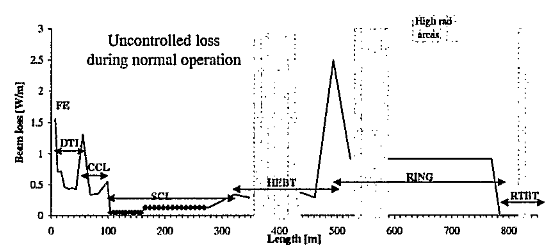

Figure 4: Uncontrolled loss distribution along the accelerator chain from the front end to the target. High radiation areas are excluded from the plot. Dots in the SCL indicate that the loss occurs only in the 1.6 m warm section.

normal operation. Loss incurred due to system failure will be the subject of future studies. Also, an average beam power of 2MW has been assumed.

5 REFERENCES

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