BEAM SCRUBBING STRATEGY FOR ELECTRON-CLOUD SUPPRESSION IN THE SPALLATION NEUTRON SOURCE RING*

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Abstract

Electron cloud is still an unsettled issue for the high intensity SNS storage ring. Studies are undergoing, especially on the electron multipacting condition, beam instability threshold, electron density and the electron dose on the wall. It has been simulated that the electron multipacting may generate very large electron dose that the pressure rise might become unacceptable. Chamber sections with high secondary electron yield and/or locations having large numbers of primary electrons, such as the injection region or the collimation area, are likely to have higher pressure rise. Beam scrubbing is proposed as one of the principle mitigations for the electron multipacting problem in the SNS. In this article, experiments of the beam scrubbing on existing machines will be reviewed, and specifics of the SNS ring beam scrubbing will be discussed.

INTRODUCTION

The secondary electron yield (SEY) of the vacuum chamber can be reduced by the beam scrubbing through the electron bombardment, but the required dose is very large [1]. For most machines that encountered electron cloud (EC) problem, beam instability and emittance blowup have already become serious problem before reaching such a high dose rate. Therefore, the beam instability and emittance growth are usually the first consequences of the electron cloud, and the effect of scrubbing was only observed over a long period of time. These machines include the LANL PSR, CERN SPS, and the B-factories.

After several years of struggling with the electron cloud of LHC beam at the CERN SPS, intentional beam scrubbing aiming at the vacuum chamber conditioning has shown clear effect, and the LHC beam requirement has been achieved at the SPS in the first time [2].

With very high beam intensity in SNS storage ring [3], it has been simulated that the electron multipacting may generate very large electron dose on the chamber wall [4]. The pressure may rise to an unacceptable level, due to the electron stimulated gas desorption. Also, chamber sections with high secondary electron yield, and/or locations having large numbers of primary electrons, such as the injection region or the collimation area, are likely to have higher pressure rise.

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Beam scrubbing is, therefore, proposed as one of the principle mitigations for the electron multipacting problem in the SNS. In this article, experiments of the beam scrubbing on existing machines will be reviewed, and specifics of the SNS ring beam scrubbing will be discussed.

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It was shown in [1] that with the electron dose of about $1mC/mm^2$, SEY can be reduced from 2.2 to 1.2 for stainless steel surface. To see how large this dose is, one may look at the one of the most pronounced effect in the beam chamber, which is the vacuum pressure rise.

Usual pumping capability is calculated by

$$M = kSP \qquad (1)$$

where $k = 3.3 \times 10^{22} / m^3$ is the gas molecule density per Torr, S is the average pumping speed, and P is the pressure in $Torr$. Using average pumping speed of $S = 13\ell s^{-1} m^{-1}$, i.e. 13 liters per second per meter, which is close to the situation of RHIC, SPS, PSR, and SNS, the gas molecules pumped out of the chamber are $M = 4.3 \times 10^{20} Ps^{-1} m^{-1}$.

On the other hand, for a typical round chamber with radius of 5 cm, with the dose of $1mC/mm^2$ applied in 24 hours, 2.3×10^{16} electrons will be generated in a 1 meter long chamber per second. Using electron gas desorption rate of 0.1, $N = 2.3 \times 10^{15}$ N_2-equivalent molecules will be produced.

The equilibrium pressure rise will be reached by equating the electron desorption generated molecules with the pumping capability, which is

$$P = N(kS)^{-1} \qquad (2)$$

and one gets $P = 5.3 \times 10^{-6} Torr$. Usually the ion pump will stop work at this pressure level, and vacuum valve will be closed to protect the equipment.

For most machines with electron cloud, the EC induced beam instability and associated emittance blowup have prevented the higher beam intensity, the pressure rise was usually less than $10^{-7} Torr$, therefore, the beam scrubbing effect was not obvious. Only exception is perhaps the RHIC, where electron cloud takes place only in part of the warm sections, which is in total 1,300 m in two rings over the machine circumference of 3,834 m. The pressure rise sometimes was so high that the vacuum valve closed, yet the beam instability had not become a serious problem [5].

In principle, using electron dose as the criterion for the beam scrubbing is not very proper, since the energy of these electrons is very important in terms of scrubbing effect. For example, the electrons with energy less than 20 eV contribute very little in scrubbing, while the ones with 500 eV are probably having the largest effect. Fortunately, similar relation exists also to the projectile electron's energy and the gas desorption rate. Therefore, instead of the complicated procedure of estimating the electron dose on the chamber wall, the pressure rise has emerged as a more useful criterion for the beam scrubbing effect. If the pressure rise induced by the electron cloud is higher, then the beam scrubbing is more effective.

MACHINE EXPERIENCES

In this section, existing machines' practice and study experiences will be reviewed. The relation between the electron dose, associated pressure rise and the scrubbing effect seems to approximately agree with the prediction.

PSR

In the PSR, detected peak electron flux on the wall, in a high intensity study, is $0.14 mA/cm^2$ [6], but in normal operation, it was more like $0.014 mA/cm^2$. This flux takes place at about 40 ns in the 357 ns revolution time in each turn, and in 300 turns of the usual 1,800 injection turns. For 20 Hz repetition rate, the average electron current on the wall is $0.034 nA/mm^2$. Therefore, the accumulated dose in 24 hours is $2.9 \mu C/mm^2$. For the round chamber radius of 5 cm, the pressure rise is, using equation (2), 1.6×10^{-8} *Torr*. The observed pressure rise in PSR is from 2 to 4×10^{-8} *Torr*, approximately agreeable with the calculation.

In a period of longer time, the scrubbing effect, nevertheless, was obvious [7].

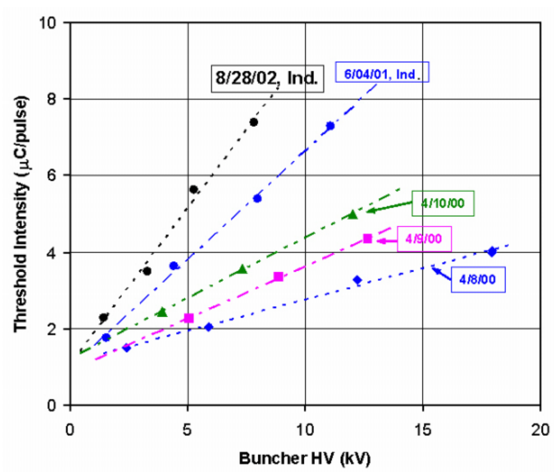

Fig.1. Instability threshold intensity curves during 2000-2002 operations. The data for 2001 and 2002 also include the effect of inductive inserts, which cause an ~30% increase in the slope of the curves for those dates.

Fig.1 shows the PSR beam scrubbing effect in terms of instability threshold vs. RF voltage. Excluding other factors, such as the inductive inserts, there is a factor of 2 improvement during the period.

In Fig.2, the prompt electron signals and ion pump pulse during 2002 operation are plotted. The electron signal diminished rapidly at first and more slowly after a few weeks, and tends to reach a plateau after 3 months.

Among other indicators of the beam scrubbing effect, the electron signal at the extraction transfer line did not change much, and it offers now the strongest electron signal at the PSR, presumably because of lack of scrubbing.

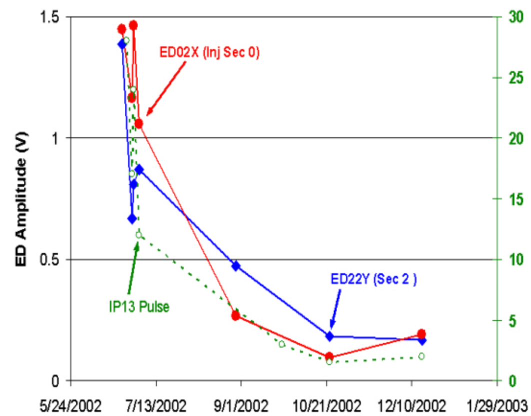

Fig.2. Prompt electron detector signals and ion pump pulse for 8 µC beam pulse as a function of time in the run cycle.

SPS 2000

In 2000, a beam scrubbing of 2.5 days was tested in the SPS, with modest pressure rise and the electron dose [8]. The bunch intensity was 0.43×10^{11} proton, and 72 bunches (1 batch) was injected. The collected electrons by a pick up showed that about 10^{11} electrons hitting the wall in a meter long pipe for 1 batch of beam passing. Using the electron gas desorption rate of 0.1, with the revolution frequency of $43 kHz$, this implies that $4.3 \times 10^{14} s^{-1} m^{-1}$ N_2 -equivalent molecules were produced. For the duty cycle of 45%, total electron dose in 24 hours is about $0.1 mC/mm^2$, the observed typical pressure rise was $< 7 \times 10^{-7}$ *Torr*, close to the calculated pressure rise, 5.3×10^{-7} *Torr*. As the result of the beam scrubbing, the pressure rise was reduced by a factor of 5 in the first 24 hours for the same beam.

SPS 2002

In 2002, it was decided to have a dedicated beam scrubbing run for SPS, which lasted 10 days [8]. The bunch intensity was raised to between 1×10^{11} to 1.4×10^{11} protons, with 1 to 4 batches injected. The pressure rise was pushed to as high as 5×10^{-6} *Torr*, barely below the valve close threshold. Various patterns of the beam injections with increasing bunch intensity were used to maximize the beam scrubbing effect. The duty cycle was about 45% in first 24 hours, and the accumulated electron dose, estimated from the pressure rise, was about $0.5 mC/mm^2$. Correspondingly, the pressure rise for the same beam was reduced by a factor of 100 in 24 hours.

Table1: Beam scrubbing parameters comparison, with the electron dose, associated pressure rise and result in 24 hours of period

	Dose	Pres. Rise	Result
PSR	0.003	2e-8	Ins. thre. modest incr.
SPS00	0.1	7e-7	PR reduced, factor 5
SPS02	0.5	5e-6	PR reduced, factor 100
	$mC/mm2$	Torr	

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SNS Electron cloud and counter measures

With 2.08×10^{14} protons in the SNS ring of the $2\,MW$ operation, large numbers of electrons may be produced by the bunch tailing edge multipacting. Simulation [4] shows that the peak electron flux at the beam tail may reach $5mA / cm^2$. Given the flux duration of 70 ns over 945 ns per turn, assuming that the electron cloud takes place in the last 100 turns of total 1,200 injection turns, with 60 Hz operation cycle, the electron dose on the wall is $1.6mC / mm^2$ in 24 hours. For the SNS chamber with radius of 10 cm, the pressure rise of $1.7 \times 10^{-5}\,Torr$ is calculated using equation (2), which is well above the vacuum valve close threshold, $5 \times 10^{-6}\,Torr$. As the result, there is a possibility that the SNS ring will encounter difficulties for full power operation without a proper beam chamber conditioning.

In addition to conventional electron cloud induced problems, such as the beam instability, the vacuum valve may close due to high pressure rise. The later is different from the former that it may happen locally at a few locations. In general, a high pressure rise in a limited length of pipe affects not much the beam stability and emittance.

For the counter measure, the SNS ring chamber is coated by TiN alloy, several electron collectors will be placed at the most troublesome locations, such as the injection area, and also solenoids will be installed between the collimators [3]. In addition, SNS ring has reserved empty ports to later install high throughout pumps if needed in the future.

For further electron cloud suppression in the SNS ring, the beam scrubbing is proposed. In the following, some possible scenarios are discussed.

Scenarios of beam scrubbing

To prepare for the worst case scenario, the beam scrubbing fits this need very well as one of the principle mitigations for the electron multipacting problem in SNS ring.

1. First scenario is that at the early commissioning, the electron multipacting may take place, and at one or more locations, the local pressure rise might be too high to tolerate. For beam scrubbing, the beam may be injected until the local pressure rises to about $5 \times 10^{-6}\,Torr$, and to run the machine until the pressure rise reduces, then increase the injection turns, and/or increase the Linac beam current. It is possible that the locations with highest pressure rise are scrubbed more than others, which means that more time is needed to conditioning the whole ring.

2. The second scenario is that in the early operation, the electron cloud induced beam instability may prevent the higher intensity operation, similar to PSR's situation. In the proposed operation mode, which is similar to the PSR, the Linac beam will be injected by 1,200 turns, followed by prompt beam extraction. The electron cloud is likely to develop at the end of the injection, probably the last 100 turns within the total 1,200 turns of the beam accumulation. At the end of the injection, 0.5 ms to 1 ms additional store time may increase the electron dose by about factor of 20. According to the PSR experience, the conditioning period may be reduced by the same factor. There is no major stopper in this scenario. Existing RF power supply, which is a resonance type and hence cannot hold up the voltage for too long, can support this period of time with tolerable voltage drooping. Beyond this store time, a $250K upgrade of the power supply system can extend the store time much longer [9]. It is of interest to know, of course, if the beam loss, etc. can be tolerable.

SUMMARY

Review of existing machine cases has shown consistent relation between the electron dose, pressure rise, and the beam scrubbing effect. The pressure rise caused by the electron cloud is a good indicator of the effective electron dose, and it can be used in the beam scrubbing operation.

The SPS dedicated beam scrubbing experiment has changed the conventional thinking about mitigation of the electron cloud effects, which is to directly counteract the EC induced beam instability and emittance blowup. One now can see a strong role for conditioning the beam pipe to reduce the beam induced electron multipacting. With hindsight, more attention should be given to beam scrubbing as part of the mitigation strategy.

For the very high power SNS ring, therefore, the beam scrubbing has been proposed as one of the principle mitigations for the electron multipacting problem.

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