# SIMULATION OF THE LONG TERM BEAM INTENSITY PERFORMANCE OF THE NEG-COATED SIS18*

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## *Abstract*

The StrahlSim code has been developed to simulate dynamic vacuum effects and charge exchange beam loss in the GSI and FAIR heavy ion accelerators. The code accounts for charge exchange cross sections at the actual beam energy, it determines the loss positions of charge exchanged ions, and the pressure rise caused by desorption due to the impact of these ions onto the vacuum chamber. Recently, the modeling of time dependent longitudinal pressure profiles has been implemented in StrahlSim. Thereby, localized pressure bumps during a cycle and the lifetime of NEG-coated surfaces depending on their distance from the local pressure bumps, and the corresponding influence on the beam performance resulting from the saturation process can be simulated. The new code was applied to SIS18 considering two scenarios: 1) the currently available $U^{28+}$ intensity of $2\times10^{10}$ extracted particles per cycle, and 2) the proposed FAIR booster operation with $1.5\times10^{11}$ extracted particles per cycle. The simulations show, that the beam scrubbing effect, which is also accounted by the code, is crucial for a stable booster operation of SIS18, as it stabilizes the dynamic vacuum over long term operation. Already for the currently available beam intensity, the beam scrubbing effect is important, as it prevents an exceeding saturation of the NEG near the injection septum.

## INTRODUCTION

In order to provide high intensity heavy ion beams, the FAIR project [1] relies on the use of intermediate charge state heavy ions. SIS100, the main synchrotron of the FAIR accelerator complex, is supposed to accumulate $5 \times 10^{11}$ $U^{28+}$ ions per cycle. The existing SIS18 will work as booster for SIS100 and is supposed to accelerate $1.5\times10^{11}$ $U^{28+}$ ions per cycle. Four SIS18 cycles will be accumulated in SIS100. A major upgrade program, which is still ongoing, is performed to increase the beam intensities of SIS18 [2].

The use of intermediate charge state heavy ions is necessary to avoid intensity losses in stripping stages, and to increase the space charge limit. However, the operation with such intermediate charge state ions may suffer from significant beam loss due to charge exchange processes. Beam ions are ionized by collisions with residual gas particles and deflected differently with respect to the reference ion in dispersive elements. At collisions with the vacuum chamber or other inserts, a high-energy desorption process takes place, which leads to a local pressure rise in the machine. This effect can be self amplifying and is referred to as dynamic vacuum. In order to minimize the amount of desorbed gas, a dedicated ion catcher system has been installed in SIS18 [3]. The catcher system is able to catch about 68 % of the charge exchanged uranium ions[1] and has a very low desorption yield, three orders of magnitude lower than that of a standard stainless steel vacuum chamber.

In order to minimize the static residual gas pressure and to remove the desorbed gases as fast as possible, all dipole and quadrupole chambers of the SIS18 were coated with the non-evaporable getter (NEG) material TiZrV. The NEG-coating provides a high pumping speed of approximately 7 l/s·cm$^2$ for heavy gases like carbon monoxide and carbon dioxide [4]. Unfortunately, the NEG-coated surfaces saturate over time, depending on the amount of absorbed particles. The maximum capacity was measured to be about $10^{15}$ particles per cm$^2$. Since the hydrogen molecules diffuse into the getter material, it has to be noted that hydrogen does not contribute to the saturation. Chemically inert gases like argon and methane are not pumped at all.

A natural effect which counteracts the desorption problem is beam scrubbing. Measurements by Mahner et al. [5] show that the desorption yield decreases with an increasing number of heavy ions bombarding the surface of a vacuum chamber. After a bombardment of $10^{12}$ ions per cm$^2$, the desorption yield from a stainless steel vacuum chamber drops by two orders of magnitude, and is finally comparable with the low desorption yield from the ion catchers.

The StrahlSim code has been developed to simulate beam loss due to charge exchange processes and the corresponding pressure evolution in a synchrotron. The new code version has been extended for the simulation of longitudinal time dependent pressure profiles [6]. The real distance and vacuum conductance from the locations of the desorption to the pumps is considered. The locations of beam loss and desorption are determined by tracking simulations of the charge exchanged ions. The intensity of the charge exchange processes depends on the pressure profile and the energy of the beam ions at a given time in the machine cycle. The number of lost ions hitting the vacuum chamber and the number of particles absorbed by the

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[1] This number is valid for the main charge exchange process $U^{28+} \rightarrow U^{29+}$.

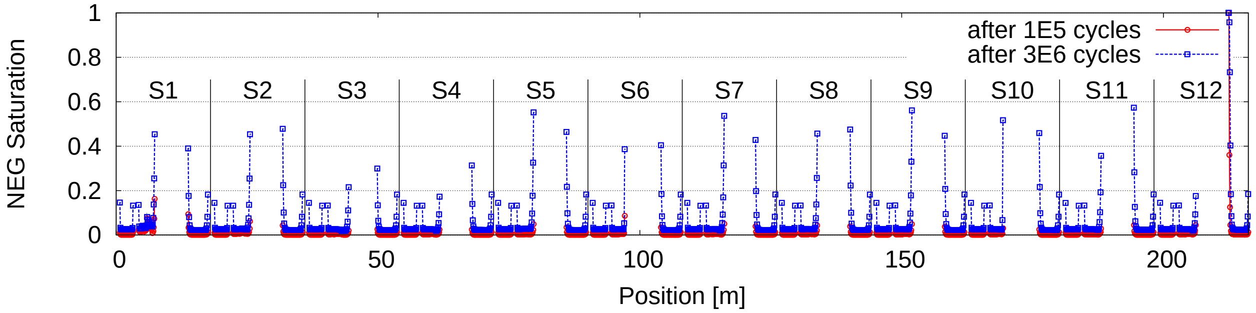

Figure 1: Simulated saturation of the NEG-coated surfaces for the currently available beam intensity including beam scrubbing. A minor saturation can be noticed in sector 12 behind the injection septum (210 m).

NEG-coated surfaces are recorded. Taking the beam scrubbing effect into account, the influence of the saturation of the NEG on the beam survival can be calculated.

In this study the StrahlSim code was used to extrapolate the beam performance for different scenarios. In the first scenario the currently available beam intensity of SIS18 has been considered: $2 \times 10^{10}$ $U^{28+}$ ions are accelerated from 11.4 MeV/u to 200 MeV/u with a ramp rate of 4 T/s. This corresponds to a cycle time of 1.4 s. In the second scenario the future booster mode was simulated. Here $1.75 \times 10^{11}$ $U^{28+}$ ions are injected into SIS18 and accelerated with a ramp rate of 10 T/s. Four of these cycles form a booster cycle, which takes 1.33 s, corresponding to a repetition rate of 3 Hz.

Table 1: Composition of the outgassed and desorbed gases used for the simulations. These numbers where measured during machine experiments in March 2010.

| Gas component | Outgassing | Desorption |
|---|---|---|
| Hydrogen | 88% | 40% |
| Nitrogen | 0% | 0% |
| Oxygen | 0% | 0% |
| Argon | 1% | 0% |
| Water | 4% | 0% |
| Carbon monoxide | 2% | 25% |
| Carbon dioxide | 1% | 10% |
| Methane | 4% | 25% |

## MODELING OF THE NEG-SATURATION AND THE BEAM SCRUBBING

Before the simulation of the dynamic phase is started, a static pressure profile is calculated. This static pressure profile is obtained by evolving the vacuum system until an equilibrium between outgassing and pumping is reached. The composition of the static residual gas, measured during machine experiments, is shown in Table 1. Figure 2 shows the static pressure profile along the circumference of SIS18 calculated by the StrahlSim code. The calculated static pressure is in a good agreement within a factor of two with the measurement. Since argon and methane are not pumped by the NEG-coated vacuum chambers, these gases are of particular interest. Therefore, the partial pressures of argon and methane are explicitly plotted in Fig. 2. The calculated static pressure is about $2 \times 10^{-11}$ mbar.

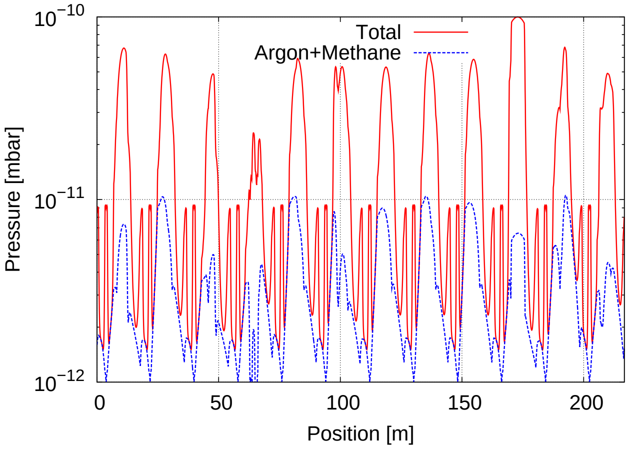

Figure 2: Static pressure profile along the SIS18 circumference calculated by the StrahlSim code. The absolute pressure minima are situated within the NEG-coated regions and are dominated by the partial pressures of argon and methane (which are not pumped by NEG-coated surfaces).

There are other beam loss mechanisms than charge exchange that lead to (local) pressure rises in the machine. First, there is systematic beam loss at injection and during Rf-capture. Desorption driven by the systematic losses does also create a pressure rise, which then again increases the intensity of charge exchanges. The composition of the desorbed gases is summarized in Table 1. Since the loss distribution of the charge exchanged ions depends only on the lattice structure, it is calculated at the beginning of the simulation[2]. The intensity distribution is then scaled with the pressure profile and the energy-dependent beam loss cross sections at each time step during the simulation.

For the simulation, the accelerator is discretized into elements with a length of about 10 cm. The number of ions

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[2] The influence of the adiabatic dampening of the emittance on the loss distribution is negligible.

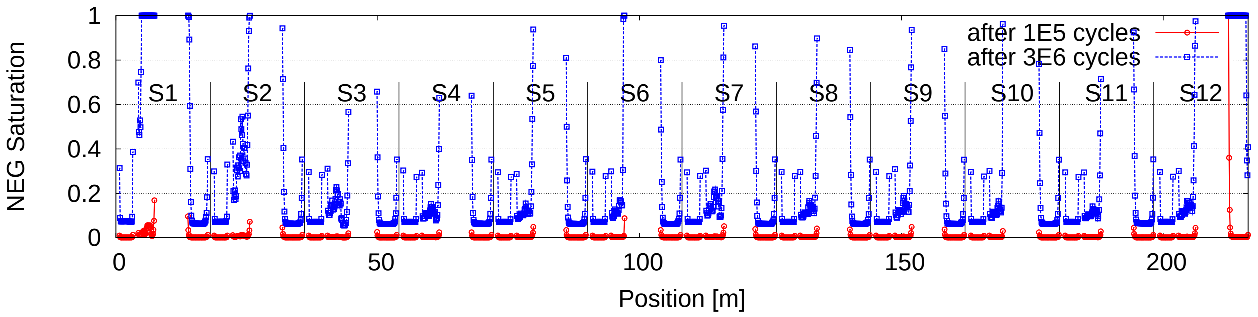

Figure 3: Simulated saturation of the NEG-coated surfaces for the currently available beam intensity without beam scrubbing. After $3 \times 10^6$ cycles a considerable saturation takes place behind the injection septum (210 m) as well as in sectors 1 and 2.

incidenting in each element is counted, whereby it is distinguished between electron loss (incident on the inner side of the ring) and electron capture (incident on the outer side of the ring). The area of beam impact is crucial for the calculation of the number of ions per area, and is determined by the average vertical beam size multiplied by the length of the element. In order to simulate the beam scrubbing effect, the desorption yield of each element is scaled with the number of incidented ions divided by the impact area. The scaling for a standard stainless steel vacuum chamber was taken from [5].

The amount of gas pumped by each NEG-coated surface is integrated over time. The saturation of the NEG-coated surfaces causes a decrease of the pumping power. The pumping speed is scaled linearly with the number of pumped particles. Hydrogen does not contribute to the saturation. After $10^{15}$ particles per cm$^2$ are pumped, the pumping speed drops to zero.

Because of the long computing time, the simulation of several million cycles is impossible. Thus, an extrapolation scheme for the effect of beam scrubbing and the saturation of the NEG-coated surfaces had to be applied. After a given number of cycles, the number of pumped particles and the number of incidented ions within each element is multiplied by an extrapolation factor. Before this extrapolation is applied, the vacuum system is evolved to its equilibrium state. In other words, in case of shorter breaks between the cycles, the effect of higher starting pressures at the beginning of the following cycles is neglected. Thus, the obtained results may slightly underestimate the NEG saturation.

## SIMULATION PARAMETERS

So far, two scenarios are considered. In the first scenario, SIS18 cycles with the presently achieved beam intensity of $3.2 \times 10^{10}$ injected U$^{28+}$ ions per cycle with injection losses of 20 % and Rf-capture losses of 10 % are assumed. These numbers were measured during machine experiments in March 2010. The currently possible ramp rate is 4 T/s, which implies a cycle time of 1.4 s. For the beam scrubbing and the saturation of the NEG-coated surfaces an extrapolation factor of $10^5$ has been used after each cycle. In order to investigate the influence of the beam scrubbing effect, simulations with and without this effect have been performed.

The second scenario considers the booster mode of SIS18. Four SIS18 cycles will be accumulated in SIS100 over 1 s, which requires an operation of SIS18 with a repetition rate of 3 Hz. For the simulation, an extrapolation factor of $2.5 \times 10^4$ was used after every four SIS18 cycles. For the booster mode an initial beam loss of 3 % and a Rf-capture loss of 2 % has been assumed. As recently shown [2], a total systematic beam loss of about 5 % and an average of $1.5 \times 10^{11}$ extracted particles over four booster cycles is feasible. An operation with initial losses of 3 % in the booster mode is the goal for the optimization of the multiturn injection process into SIS18. During machine experiments in June 2010, multiturn injection of about $3 \times 10^{10}$ U$^{28+}$ ions into SIS18 over 20 turns with an efficiency of 98 % was demonstrated [7].

Both scenarios are based on the same setup for the vacuum system.

## SIMULATION RESULTS

In each of the simulated scenarios, the long term beam performance develops differently depending on the beam scrubbing effect. As described before, in case of beam scrubbing, the number of incidented ions is accounted for the cleaning process of the vacuum chambers. Systematic losses at injection may also have a strong influence on the pressure evolution within a SIS18 cycle. From machine experiments it is known that injection losses occur within the injection channel, and after injection into the ring close to the back side of the injection septum (longitudinal position of about 210 m in sector 12). Beam scrubbing should efficiently clean the injection loss positions, as for a given machine setting, the loss positions should be fixed.

Figure 5 shows the long term beam loss in a cycle for scenario 1 depending on the number of cycles. With beam scrubbing (left plot), already after $10^5$ cycles the dynamic (charge exchange) beam losses decrease considerably. The corresponding saturation of the NEG-coated surfaces can

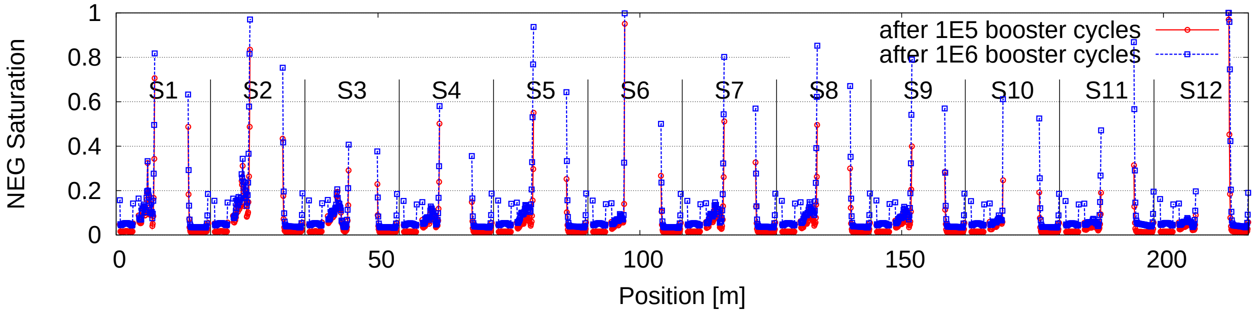

Figure 4: Simulated saturation of the NEG-coated surfaces for the proposed booster operation including beam scrubbing. Saturation takes place in all sectors. However, the amount of saturation is not critical.

be seen in Fig. 1. The NEG-coated surfaces around the injection section (end of sector 12) and the NEG in sector 1 (where ions, which underwent a charge change in sector 12, hit the vacuum chamber) do not show considerable saturation. The initial saturation of the NEG in sector 12 does not increase from $10^5$ to $3 \times 10^6$ cycles. Thus, this scenario shows a stable long term performance. The increasing saturation of the NEG at the beginning and the end of all NEG-coated chambers is due to the pumping of gas, diffusing from the not-coated parts of the machine into the NEG-chambers.

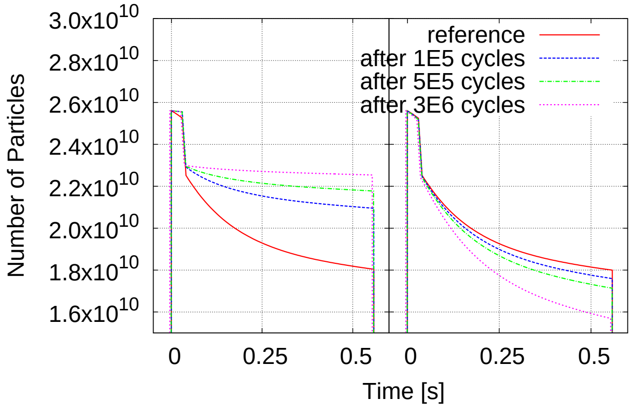

Figure 5: Beam loss after a different number of performed cycles for the currently available beam intensity with beam scrubbing (left) and without beam scrubbing (right).

The same scenario without beam scrubbing looks quite different. Without beam scrubbing, the surfaces are not cleaned and the desorption yield does not decrease. This leads to a saturation of the NEG behind the injection septum (sector 12) as can be seen in Fig. 4. The NEG in front of the septum is not affected due to a limited vacuum conductance and a rather high pumping power of conventional pumps between the septum and those NEG-coated surfaces. Due to the saturation of the NEG behind the septum, the desorbed gases cannot be removed efficiently anymore. At this location, many ions undergo a charge exchange process and hit the collimator and the vacuum chamber in sector 1. The NEG close to the loss position saturates as well, as can be seen clearly in Fig. 4. An avalanche-like effect takes place and leads to the saturation of the NEG, starting at the injection section and progressing downstream the machine. This behavior is consistent with measured beam loss patterns on the ion catchers in sectors 12 to 3.

Figure 6 shows the beam loss for the booster mode of SIS18 with and without the consideration of beam scrubbing effects. As can be seen, the beam scrubbing in the simulation stabilizes the booster operation at rather high transmission values after already $2.5 \times 10^4$ cycles. The corresponding saturation of the NEG surfaces is shown in Fig. 4. The scrubbing at injection in sector 12 circumvents the saturation of the NEG within this sector due to the reduction of the desorption yield by a factor of $10^{-2}$. The losses in the sectors 1 and 2 are smaller compared to the injection losses. It takes a longer time for the beam scrubbing to be efficient, which leads to a higher saturation of the NEG-coated surfaces in these sectors.

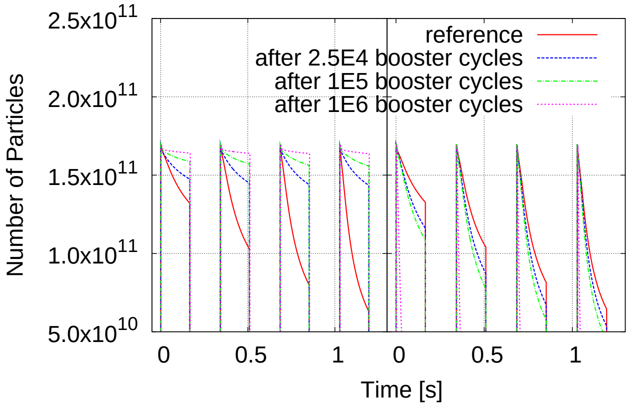

Figure 6: Beam loss as a function of the performed cycles for the proposed SIS18 booster operation with beam scrubbing (left) and without beam scrubbing (right).

The simulation of the same scenario without beam scrubbing shows a dramatic decline in beam performance (Fig. 6) and the saturation of almost all of the NEG in SIS18 within $10^6$ booster cycles (Fig. 7). These simulations indicate that beam scrubbing is an invaluable effect for the operation of a NEG-coated synchrotron with very high inten-

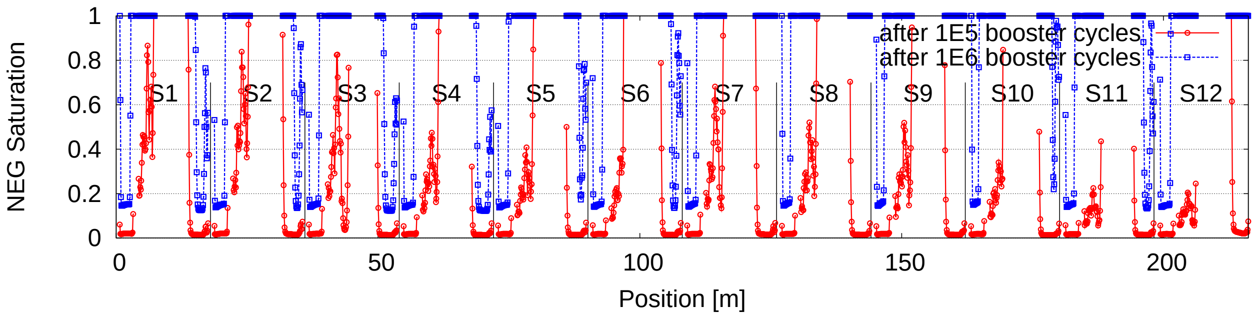

Figure 7: Simulated saturation of the NEG-coated surfaces for the proposed booster operation without beam scrubbing. The simulation shows a dramatic amount of saturation along the ring.

sities of intermediate charge state heavy ions. Beam scrubbing may stabilize the dynamic vacuum in the machine for a long term operation.

## SUMMARY

The StrahlSim code was used to simulate the long term beam performance of SIS18 considering the saturation of the NEG-coated surfaces. For the currently available beam intensities of $U^{28+}$ ions, the simulation shows, that a stable long term operation is feasible, under the assumption of an efficient beam scrubbing. Without beam scrubbing a saturation of the NEG-coated surfaces close to the injection septum and in sector 1 is supposed after $3 \times 10^6$ cycles. This saturation causes a higher pressure in these sectors and will lead to an ongoing saturation of the NEG in the subsequent sectors.

In the second scenario, which addresses the planned booster mode, beam scrubbing is even more important to guarantee a stable long term operation. Without beam scrubbing a saturation of the NEG surfaces all over the machine can be observed after about $10^6$ booster cycles.

The beam scrubbing seems to be a stabilizing effect, that is invaluable when operating a NEG-coated synchrotron with very high intensities of intermediate charge state heavy ions.

It is worth to note, that a beam scrubbing scenario, with injection losses creating over long term a drastic decrease of the initial pressure rise, is equivalent to the installation of a low desorption ion catcher for the multiturn injection process. Such a system is currently under investigation at GSI. The simulations show that such a system would strongly contribute to a stable booster operation.

Due to some presently needed numerical approximations, the results may be slightly optimistic with respect to an uninterrupted continuous booster operation. Furthermore, the beam scrubbing rates used, apply for clean UHV surfaces and are based on a high performance quality assurance at UHV preparation and installation. The scrubbing of polluted surfaces may take sufficiently longer, and will lead to a much stronger saturation of NEG surfaces.

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