STRAHLSIM, A COMPUTER CODE FOR THE SIMULATION OF CHARGE EXCHANGE BEAM LOSS AND DYNAMIC VACUUM IN HEAVY ION SYNCHROTRONS*

P. Puppel[1,2], P. Spiller[1], L. Bozyk[1,3], and U. Ratzinger[2]
[1]GSI, Darmstadt, Germany; [2]Goethe-Universität Frankfurt, Germany; [3]TU Darmstadt, Germany

Abstract

StrahlSim is a unique code for the simulation of charge exchange driven beam loss and dynamic vacuum effects in heavy ion synchrotrons. Dynamic vacuum effects are one of the most challenging problems for accelerators using intermediate charge state, high intensity heavy ion beams (e.g. AGS Booster, LEIR, SIS18). StrahlSim can be used as a design tool for synchrotrons, e.g. for the estimation of pumping power needed to stabilize the dynamic vacuum. Recently, StrahlSim has been extended to simulate time dependent longitudinal pressure profiles. The new code calculates a self-consistent static pressure distribution along the accelerator and simulates local pressure rises caused by dynamic and systematic beam losses. StrahlSim determines the loss distribution of charge exchanged beam ions and respects the beam energy dependence of the charge exchange cross sections. The beam loss calculated by means of the new time dependent longitudinal pressure profiles has been benchmarked with measured data from the latest SIS18 machine experiments.

INTRODUCTION

The FAIR project at GSI [1] is aiming for highest heavy ion beam intensities of U^{28+} beams with an increase of two orders of magnitude compared to the present intensity levels of U^{73+} beams. Space charge limits and significant beam loss in stripper stages require an operation with intermediate charge state heavy ions. Intermediate charge state ions are exposed to a high probability of charge exchange due to interactions with residual gas particles. Ions which underwent a charge exchange deviate strongly from the magnetic rigidity of the reference ion and hit the vacuum chamber after dispersive elements, where an energy-dependent strong gas desorption takes place. The pressure rise in the accelerator due to this desorption process with a typical η of the order of 10^4 is dependent on the intensity of the ion beam and is referred to as dynamic vacuum.

StrahlSim was developed to determine the loss positions of charge exchanged beam ions and to simulate the beam loss over a synchrotron cycle considering pressure bumps generated by systematic and dynamic beam losses [2]. Losses at injection, Rf-capture and extraction are supposed to be systematic. Dynamic losses are dependent on the actual beam energy, like ionization losses due to collisions with residual gas particles, coulomb and intra beam scattering. However, beam ionization is the most important loss mechanism for high intensity heavy ion beams with intermediate charge states. In order to calculate the number of beam ions which are subject to a charge exchange, the composition and the pressure of the residual gas and the cross sections for ionization at the actual beam energy at every time step in the cycle have to be known. At high beam intensities, the pressure of the residual gas is strongly dynamic and depends on the pressure rise generated by lost beam ions.

So far, StrahlSim used a model which assumes that the beam loss due to ionization depends only on the average pressure inside the machine. This is true for example for the calculation of the transmission or the total pumping speed required to stabilize the dynamic vacuum inside the accelerator. However, this model accounts only for the effective vacuum conductance to the pumps. The real distance of the desorbed gas from the pump, and thereby the real conductance and pumping speed, have not been considered. These parameters are especially interesting in systems which provide either very high localized pumping speeds (e.g. NEG coated vacuum chambers) or which show localized gas desorption. In order to simulate these local effects, a time dependent longitudinal pressure profile must be accounted.

The StrahlSim code was modified to accomplish this request. In the following sections the modeling of longitudinal pressure profiles is summarized and first simulation results are presented.

MODELING OF TIME DEPENDENT LONGITUDINAL PRESSURE PROFILES

The longitudinal pressure profile is modeled using the equation system given in [3]. The pressure change is given by the differential equation

$$V\frac{\partial P}{\partial t} = \frac{\partial}{\partial z}C\frac{\partial P}{\partial z} - SP + Q, \qquad (1)$$

where V is the volume, C the vacuum conductance, S the pumping speed, Q the outgassing and z the longitudinal coordinate along the ring. In [3] this equation is discretized and solved by using the Crank-Nicolson method with fixed boundary conditions. When describing the vacuum system of a synchrotron, the system is closed on itself and periodic boundary conditions have to be applied.

The time evolution is carried out independently for each gas component. In this way, the partial pressures of all

---

* This work is supported by HIC for FAIR.

residual gas components can be calculated using gas specific quantities like vacuum conductance, pumping speeds and outgassing rates. At present, StrahlSim supports hydrogen, nitrogen, oxygen, argon, water, carbon monoxide, carbon dioxide, and methane. Only for the five atoms contained in these molecules, charge exchange cross sections are available.

Table 1: Composition of the outgassed and desorbed gases used for the simulation. 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%

The vacuum system is discretized in elements with a length of about 0.1 m, while the sampling points do not have to be equidistant. This property eases the creation of vacuum elements from a given ion optical lattice. For each of these elements, the aperture, the surface type, the surface temperature, the outgassing rate and the pumping speed can be set independently. For cryogenic surfaces the pumping speed depends on the surface temperature, and for NEG coated elements the pumping speed decreases with increasing saturation of the NEG.

During the simulation for each vacuum element, the number of ions performing a charge exchange within this element is computed. The charge exchanged ions are distributed according to the in prior calculated loss distribution, which is generated for each element by tracking simulations. The loss distribution stores the positions, where the particles after a charge exchange are stopped, and whether an ion catcher [4, 2] is hit or not.

The gas desorption induced by the impact of charge exchanged ions is modeled by increasing the outgassing rates at the positions where the ions hit the chamber or an ion catcher. The amount of desorbed gas depends on the desorption rate of the material and the electronic energy loss of the incidenting ions [5].

Systematic effects, leading to a pressure rise in the machine are e.g. beam loss at injection, extraction and during Rf-capture. The position and the relative amount of injection and extraction losses can be specified. Gas desorption induced by these losses are modeled by increased localized outgassing rates over the time period of injection and extraction respectively. Currently Rf-losses are distributed equally over the whole ring. However, a localized loss at one or more positions, limiting the momentum acceptance of the accelerator, would be easy to implement.

INITIAL STATIC PRESSURE PROFILE

Before a dynamic simulation starts, the static pressure profile along the accelerator is determined by StrahlSim. At the beginning, the pressure in the vacuum system is set to a uniform start value along the ring. Then the pressure is changed due to outgassing and pumping until the relative change of every partial pressure in each element is below a certain threshold (usually 0.1%). When this limit is reached the pressure distribution is considered to be static. For the calculation, a total outgassing rate for stainless steel of 2.5×10^{-12} mbar l/s is assumed. The outgassing rate for each gas component results from the composition given in table 1. These numbers were measured during a machine experiment in SIS18 in March 2010. The data were acquired by three mass spectrometers, which are positioned in different sectors along the ring.

It is important to note that by using this technique the static pressure is not a free parameter for the simulation, but determined by the configuration of the vacuum system and calculated by StrahlSim.

Figure 1 shows the static pressure profile for SIS18 calculated with StrahlSim. The average pressure was determined to 2×10^{-11} mbar which is close to the measured pressure of about 4×10^{-11} mbar. The measured pressure data are taken at 12 positions distributed along the ring (not situated in NEG coated chambers [4]). Therefore, the measured values are expected to be higher than the true average pressure.

Furthermore, figure 1 shows the added partial pressures of argon and methane. These gas species are of particular interest, since they are not pumped by NEG coated surfaces and therefore dominate the pressure in the NEG regions. The calculation shows that the pressure does not drop below 10^{-12} mbar.

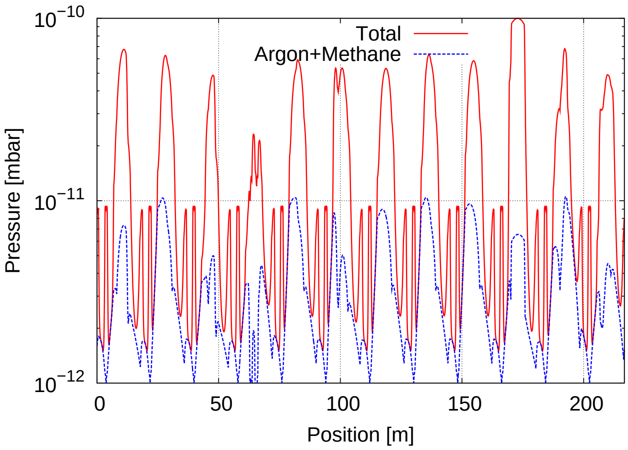

Figure 1: Static pressure profile along the SIS18 ring calculated by the StrahlSim code. The absolute pressure minima are situated within the NEG coated regions and are dominated by the partial pressures of argon and methane, which are not pumped by NEG coated surfaces.

DYNAMIC PRESSURE AND BEAM LOSS SIMULATION RESULTS

During machine experiments with U^{28+} beams in March 2010 the particle numbers have been measured over many SIS18 cycles. Figure 2 shows measured data in comparison with two simulations with different parameters carried out with the new StrahlSim code. It can be seen that the simulation is in agreement with the measurement.

For both simulations, the same initial vacuum properties were used with a desorption yield $\eta = 25500$ particles per incidenting ion at 11.4 MeV/u. At higher energies, the desorption yield is scaled with the electronic energy loss calculated with ATIMA [6]. The composition of the desorbed gas used for the simulation is given in table 1.

In simulation 1, 2.9×10^{10} U^{28+} particles (2.0 mA current before multiturn injection) are injected. The injection losses, determined by comparing this number, to the number of particles measured directly after injection, are 12.4 %. The Rf-losses where also determined from transformer measurements (7.5 %). In simulation 2, the number of injected ions was 3.2×10^{10} particles (2.2 mA current before multiturn injection) with injection losses of 20 % and Rf-losses of 10% respectively.

Even though the number of injected ions is larger in simulation 2, simulation 1 shows more extracted particles: 2.02×10^{10} compared to 1.83×10^{10}. This results clearly from dynamic vacuum effects. The lower current in measurement 1 leads to a more efficient stacking with lower losses than in measurement 2, and therefore to a lower pressure rise. The minimization of the pressure rise at injection due to injection losses is crucial to establish a stable operation with high intensity intermediate charge state heavy ions, as needed for the SIS18 booster operation for FAIR.

Figure 3 shows the simulated pressure evolution along the SIS18 circumference obtained in simulation 2. The injection takes place at 211 m. The pressure rise due to injection losses is indicated by bright colors. At this position, many beam ions are subject to a charge exchange during and right after injection. The charge exchanged particles hit the ion catcher and the vacuum chamber in sector 1, which leads to a time shifted pressure rise at 4.5 to 12.5 m. The charge exchanged ions at this position cause a pressure rise at about 28 m (sector 2). The simulation shows that there are no dynamic vacuum effects downstream sector 3 (50 m). Continuous pressure measurements during the machine experiments show a systematic pressure rise only at injection and in sectors 1, 2, and 3, which is in agreement with the simulation. The overall pressure rise at 0.03 s in figure 3 is due to the Rf-losses.

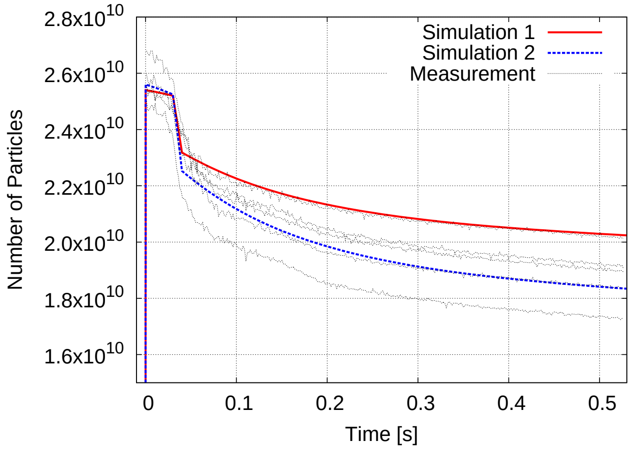

Figure 2: Simulated and measured number of particles over many SIS18 cycles with U^{28+} beams.

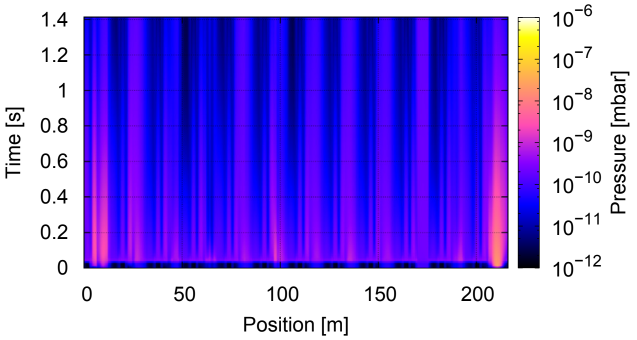

Figure 3: Simulated pressure evolution along the circumference for one SIS18 cycle. The injection losses can be noticed at 211 m where also the injection septum is located.

SUMMARY AND OUTLOOK

The new StrahlSim code with time dependent longitudinal pressure profiles is able to reproduce the measured beam loss in a SIS18 cycle, and is consistent with the measured systematic pressure rise in the machine.

The code will be used in the near future to estimate the saturation of the NEG coated surfaces and the corresponding change in beam performance of SIS18. Obviously the NEG surfaces close to the major beam loss positions will saturate faster. This effect could not be reproduced with the old StrahlSim version.

Furthermore, the code will be used to verify the stability of high intensity uranium beams in SIS100.

REFERENCES

[1] ”FAIR Baseline Technical Report”, http://www.gsi.de/fair/reports/btr.html (2006).

[2] C. Omet, Dissertation, TU Darmstadt, Germany (2009).

[3] V. Ziemann, Vacuum 81, 866–870 (2007).

[4] P. Spiller et al., ”Acceleration of Intermediate Charge State Heavy Ions in SIS18”, These Proceedings.

[5] A.W. Molvik et al., PRL 98, 064801 (2007).

[6] H. Geissel et al., NIM in PR B 195, 3–54 (2002).