SIMULATION OF DYNAMIC VACUUM INDUCED BEAM LOSS

C. Omet*, P. Spiller, J. Stadlmann, GSI Darmstadt, Planckstr. 1, 64291 Darmstadt, Germany

Abstract

In synchrotrons, operated with low charge state heavy ion beams, strong intensity dependent beam losses have been observed. The origin of these losses is the change of the charge state of the beam ions at collisions with residual gas atoms or molecules. The resulting m/q deviation from the reference beam ion leads to losses behind dispersive elements. At the impact positions, secondary particles are produced by ion stimulated desorption which increases the vacuum pressure locally. In turn, this produced pressure rise enhances the charge change- and particle loss process and may finally cause tremendous beam loss within a very short time (a few turns). A program package has been developed, which links the charge exchange and other beam loss mechanisms to the residual gas dynamics.

INTRODUCTION

The new accelerator facility FAIR at GSI relies on the existing SIS-18 synchrotron as injector. Currently most experiments are performed with highly charged U^{73+}-beams, however, higher intensities will be available using low charged U^{28+}, what is the reference ion for the FAIR project.

Experiments in the SIS-18 have been conducted to test the operation with low charge states. During these experiments, extremely fast and intensity dependent particle losses in connection with a very dynamic behavior of the residual gas pressure have been observed. As the intensities were far below the space charge limit of the machine. The reason for the observed losses is a charge change of the beam particles, which finally degrades the vacuum in connection by ion stimulated desorption. A quantitative explanation of these losses is given in the following.

BEAM LOSS MECHANISMS

Particles of the circulating ion beam in the vacuum of a ring accelerator undergo several effects, which affect their life time. Projectile ionization and eventually radioactive decay leads to a change of the particle's m/q ratio. In dispersive beam transport elements this results in a strong deviation of the trajectory in comparison to the reference ion. Particles, which are subject to these mechanisms or which are Coulomb scattered, will impact at the vacuum tube or acceptance defining devices and produce a gas cloud by desorption processes. For simplification, we do not take into account beam losses by intra beam scattering, resonances or space charge effects at the moment.

* c.omet@gsi.de

Projectile ionization

Beam ions may be ionized by collisions with residual gas particles. Cross sections for these effects in the typical energy range of modern accelerators have been measured or calculated only for a few ion species [1–3]. The sum over the cross sections for all rest gas components results in the charge exchange rate Γ_{PI} as given by

$$\Gamma_{PI} = \beta c \sum_i n_i \sigma_i(E, q), \qquad (1)$$

where β is the relativistic factor, c the speed of light, n_i the particle density of the rest gas component i and the projectile energy E and charge state q dependent charge exchange cross section σ_i.

Coulomb scattering by residual gas particles

Beam particles can be scattered by collisions with residual gas particles. The loss rate for single Coulomb scattering Γ_{CS} can be described by [4]

$$\Gamma_{CS} = \frac{2\pi Z^2 r_p^2 c n_{sc}}{A^2\gamma^2\beta^3}\left(\frac{\langle\beta_x\rangle}{\epsilon_{acc,x}} + \frac{\langle\beta_y\rangle}{\epsilon_{acc,y}}\right), \qquad (2)$$

where $r_p = 1.535 \times 10^{-18}$ m is the classical proton radius, $\langle\beta\rangle$ is the average beta function and ϵ_{acc} the acceptance of the accelerator. A is the mass number and Z the nuclear charge number of the ion. Finally, $n_{sc} = \sum_i Z_i^2 \cdot n_i$ is the Coulomb scattering density, where Z is the nuclear charge number of a particular vacuum component i. However, for low charged ions, the loss rate created by this effect is much smaller than by the projectile ionization.

Radioactive decay

During operation with radioactive nuclei for nuclear structure or neutrino experiments, e.g. a β-decay may change the charge state and momentum of a projectile ion. At high energies, the energy change of the daughter product can be neglected. The corresponding $\Delta p/p$-deviation caused by the charge state change (6) is considerably high. The loss rate by radioactive decay Γ_β is described by

$$\Gamma_\beta = \frac{1}{\gamma\tau} = \frac{\ln(2)}{\gamma t_{1/2}}, \qquad (3)$$

where $t_{1/2}$ is the half-life time of the radioactive particle and γ the relativistic factor.

If we summarize the mentioned loss mechanisms, we find the total loss rate

$$\Gamma_P = \Gamma_{CS}(n_i, \beta) + \Gamma_{PI}(n_i, \beta) + \Gamma_\beta(\beta). \qquad (4)$$

For the number of beam particles N we get

$$\dot{N}_q = -N_q \cdot \Gamma_P(n_i, \beta). \quad (5)$$

Considering only static conditions, the solution is an exponential decay of the particle number.

ACCELERATOR VACUUM

Target ionization

Residual gas molecules can be ionized by a beam projectile. Cross sections for the target ionization σ_B can be described for energies $> 2\,\mathrm{MeV/u}$ by the Bethe-Formula [5]

$$\sigma_B = 4\pi a_0^2 \frac{\alpha^2}{\beta^2}\left[M_i^2\left(\ln\frac{\beta^2}{1-\beta^2} - \beta^2\right) + C_i + \gamma_i\frac{\alpha^2}{\beta^2}\right],$$

where a_0 is the classical atom radius and α the fine structure constant. M_i, C_i and γ_i are target specific parameters, which were determined empirically in [5]. For particles with charge states $q > 1$, the target ionization cross section σ_{TI} scales [6] with $\sigma_{TI} = q^2 \exp(-\lambda|q|\frac{\alpha^2}{\beta^2})\sigma_B$, where λ is an empirically determined target specific parameter [3]. The production rate of ionized molecules Γ_{TI} is calculated analogous to (1).

Ion impact induced desorption

Particles with a trajectory modified by the above mentioned effects will most probably hit the vacuum tube under grazing incidence. Thereby, molecules attached loosely to the wall's surface are desorbed at rates of $\eta_\angle \approx 5 \times 10^3 \ldots 1 \times 10^6\,\mathrm{molecules/ion}$.

Ionized rest gas molecules accelerated in the beam potential to energies of a few keV or less will hit the vacuum tube under nearly perpendicular angle of incidence, leading to moderate desorption rates in the range of $\eta_\perp \approx 0.1 \ldots 10\,\mathrm{molecules/ion}$.

For stainless steel, the most common desorbed gases are CO and H_2. Since the physics behind the desorption effect itself is not understood in all details, detailed investigations of the GSI UHV group using the ERDA technique [7] have been conducted. It could be shown that blank Copper or Silicon surfaces have a very low desorption rate. Furthermore, different measurements have indicated that η depends on the electronic energy loss $(dE/dx)^2$ of the ion in matter. However, no material with $\eta \approx 0$ has been found so far.

Dynamic vacuum stabilization concepts

The residual gas pressure dynamics can be stabilized by strong pumping and a dedicated ion catcher system. Catchers can be designed such that they control most of the ionized or scattered particles and confine the produced desorption gases. It is essential to prevent the desorbed gases from reaching the beam axis and enhance the charge exchange rate. Assuming a properly designed lattice cell and careful positioning, a catcher system will not reduce the acceptance of the machine.

For a successful catcher system design, the distribution of the beam impacts onto the vacuum chamber must be known. A changed charge state q from the reference charge q_0 is equivalent to a momentum deviation $\Delta p/p$ of

$$\frac{\Delta p}{p} = \frac{q_0}{q} - 1. \quad (6)$$

The calculation of the impact position can be done using the transfer matrix method for linear beam optics. The number of particles hitting the catchers N_c and the wall N_w defines the catching efficiency θ with

$$\theta_q := \frac{N_c}{N_w + N_c}. \quad (7)$$

For an exact estimation of θ, a longitudinal resolved pressure (and therefore charge exchange) distribution is needed. Only few vacuum calculation codes do exist for the pressure range of interest. Most of them add vacuum conductance values for a given lattice (what could be wrong [8]) and become numerically unstable at extreme pumping speeds, very low pressures or very small conductance values. To overcome these problems, the Monte-Carlo-algorithm given in [9] has been used. Calculation of the pressure profile by this algorithm is reduced to a simple molecular raytracing through the ion optic elements.

Dynamic vacuum calculation

Key parameters for the calculation of the residual gas pressure dynamics in ring accelerators are the equilibrium partial pressures $p_{i,0}$ and the effective pumping speed S. Volume, surface, etc. can be extracted from geometry. As the pressure in an accelerator is usually in the regime of molecular flow ($p < 1 \times 10^{-7}\,\mathrm{mbar}$), the dependence of the pumping speed on the residual gas pressure can be neglected. It is sufficient to assume an averaged pressure because all mentioned loss mechanisms are linear in pressure. The time dependent density n of each vacuum component i can be expressed by

$$\dot{n}_i = -\dot{N}_q\left[\eta_{\angle,i}\left(1-\theta_q(E)\right) + \eta_{c,i}\theta_q(E)\right] + \\ +\eta_{\perp,i}\Gamma_{TI}(n_i,\beta) + G_i - P_i, \quad (8)$$

where η_c is the desorption rate of the catcher system, G the outgassing rate and P the effective pumping rate of the vacuum system. Equations (5) and (8) describe a system of coupled differential equations, which is solvable by numerical methods.

SIMULATION CODE ”STRAHLSIM“

All mentioned effects for the calculation of the beam life time including ion optics, longitudinally resolved pressure calculation and typical synchrotron cycles with their systematic losses have been implemented in the program

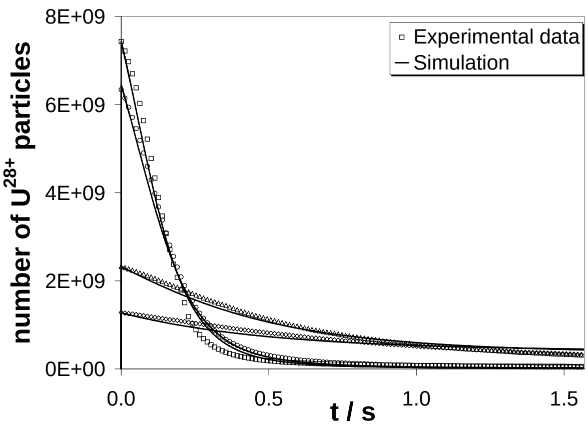

Figure 1: Measured and calculated number of U^{28+}-particles in the SIS-18.

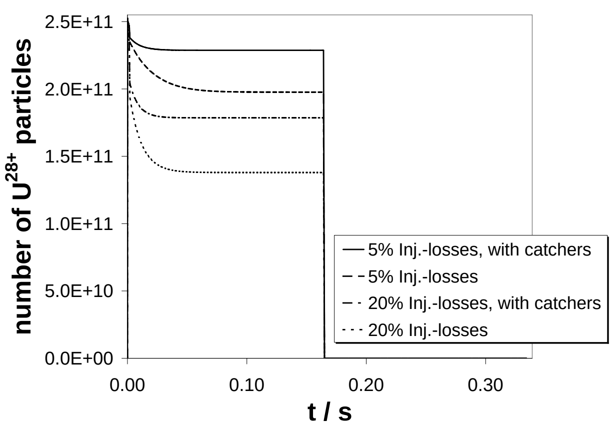

Figure 2: Calculated beam life time of an U^{28+}-beam in the SIS-18 after finishing the upgrade project.

package "STRAHLSIM“. A benchmarking of the physics model was performed by comparing the simulation results with the experimental data for SIS-18. A very good agreement with the experimental data could be achieved, as shown in figure 1. Furthermore, a comparison with the beam loss during an AGS Booster cycle with low charge state Au^{32+} ions was conducted [10].

SIS-18 Upgrade

SIS-18 will be upgraded for highest beam currents required for the FAIR project. The dynamics of the residual gas pressure was simulated with STRAHLSIM. To minimize the losses in SIS-18 during acceleration, the simulations have shown that beside the injection losses of the multi turn injection, a large distributed pumping speed and an effective catcher system are required.

Injection losses produce a very high pressure bump in the range of several orders of magnitude during a few μs, which has to be removed as fast as possible. For this purpose, NEG coating of the magnet chambers is foreseen, which delivers a distributed pumping speed a factor of 100 higher than presently available. A dedicated catcher system will be installed to control the charge change generated beam losses of U^{28+} and to confine the desorbed gases. The effect of all upgrade measures is shown in figure 2 for different injection efficiencies (20% is a current value, 5% is the goal for the future).

SIS-100 lattice design

A new lattice design concept has been developed for the SIS-100. Each cell in the SIS-100 lattice has been designed as a charge separator for the charge state 29+ of the reference ion U^{28+}. The catcher positions were optimized using STRAHLSIM such that the acceptance of the machine is not reduced [11].

Beta beams

Within the framework of the beta beams project, beam loss and pressure calculations for the CERN PS, SPS and the planned RCS have been performed [12]. To protect the PS magnets from impact of the beta beam decay products, a new lattice structure for a PS replacement was proposed [13].

REFERENCES

[1] R. E. Olson et al. Electron Stripping Cross Sections For Fast, Low Charge State Uranium Ions. Report, University of Missouri-Rolla, 2004.

[2] R. E. Olson et al. Projectile Electron Loss and Capture in MeV/u Collisions of U28+ with H2, N2 and Ar. *Journal of Physics*, B:4539–4550, 2004.

[3] N. Madsen. Vacuum changes during accumulation of Pb54+ in LEIR. Note PS/DI 99-21, CERN, 11 1999.

[4] N. Madsen. Beam Evolution in the Antiproton Decelerator (AD) under the influence of Residual Gas and Intra Beam Scattering. Note PS/DI/Note 99-06, AD Note 047, CERN, 1999.

[5] F. Rieke et al. Ionization Cross Sections of Gaseous Atoms and Molecules for High-Energy Electrons and Positrons. *Physical Rev.*, A(6):1507–1519, 10 1972.

[6] G. H. Gillespie. Impact ionisation scaling cross sections for fast highly stripped ions colliding with H2 and He. *Phys. Lett.*, A(93):327–332, 1983.

[7] M. Bender et al. Understanding of Ion Induced Desorption Using the ERDA Technique. In *these Proceedings*, 2006.

[8] C. W. Oatley. The flow of gas through composite systems at very low pressure. *British Journal of Applied Physics*, 8:15, 1957.

[9] G. B. Bowden. RF Accelerator Pressure Profile by Monte Carlo. Linear collider collaboration tech note, Stanford University, 5 2002. SLAC-TN-03-055, LCC-0078.

[10] A. Smolyakov et al. Comparison of the present and planned operation of the SIS18 and the AGS Booster with intermediate charge state heavy ions, 11 2005. GSI-Acc-Report-2005-11-001.

[11] J. Stadlmann et al. Ion Optical Design of the Planned Heavy Ion Synchrotron SIS100. In *these Proceedings*, 2006.

[12] M. Benedikt et al. Estimation of decay losses and dynamic vacuum for the Beta-Beam accelerator chain. In *these Proceedings*, 2006.

[13] M. Kirk et al. Proposal for a replacement of the CERN PS with optimized collimation, 2005.