TRANSMISSION OF HEAVY ION BEAMS IN THE AGOR CYCLOTRON*

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Abstract

During the acceleration of intense low energy heavy ion beams in the AGOR cyclotron feedback between beam intensity and pressure, driven by beam loss induced desorption, is observed. This feedback leads to an increase in the pressure in the cyclotron and limits the attainable beam intensity. Calculations and measurements of the pressure dependent transmission for different beams agree reasonably well. Calculation of the trajectories of ions after a charge change shows that the desorption is mainly due to ions with near extraction energies, hitting the outer wall at a shallow angle of incidence. For heavy ions like $^{206}Pb^{27+}$ several charge changes are needed before the orbit becomes unstable. Our calculations indicate that these ions make thousands of turns before finally hitting the wall. Ion induced desorption for relevant ions and materials has been measured; it explains the observations in the cyclotron semi-quantitatively.

INTRODUCTION

The experiments in the framework of the TRIμP program at the KVI required the AGOR cyclotron to produce a wide range of high intensity heavy ion beams, for example ^{206}Pb at 8 MeV/amu and ^{20}Ne at 23.3 MeV/amu. Since issues related with the acceleration of high intensity beams of in particular heavy ions at low energy (e.g. ^{208}Pb at 8 MeV/amu) have not been addressed in the design of AGOR, an upgrade program was initiated which included an investigation of beam transmission of heavy ions at low energies. Experiments showed that the transmission strongly depends on injected beam intensity, which was varied over a few orders of magnitude, with a substantial decrease in transmission at higher injected intensities,and an increase in pressure.

During acceleration beam particles collide with the rest gas atoms leading to beamloss. The observed pressure rise is caused by desorption due to the lost ions which deposit their energy on the walls of the cyclotron vacuum chamber and liberate materials. A positive feedback is created between the pressure rise and beamloss. In this paper we investigate the various components of the beam loss cycle individually, to determine their contribution to the reduced beam transmission.

TRANSMISSION AT LOW INTENSITIES

At low intensities the majority of the vacuum induced beamlosses come from charge changing collisions with the restgas in the cyclotron. The number of beam particles lost depend on the cross-section of interaction, the pathlength of the beam particle and the local density of the rest gas.

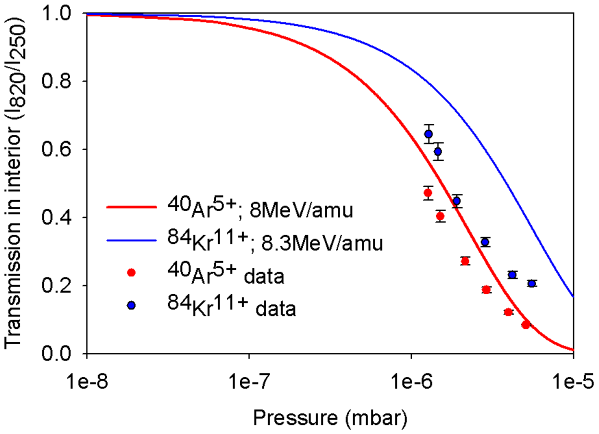

Figure 1: Transmission of $^{84}Kr^{11+}$ and $^{40}Ar^{5+}$ at 8 MeV/amu, comparison of simulations with experimental results.

There are several semi-empirical models which predict the cross sections of ion-atom collisions ([1] and [2]) as a function of the beam energy. Using these semi-empirical models for the cross section, the total transmission is estimated for beams accelerated in the AGOR cyclotron. We compare these calculations to transmission measurements as shown in Figure 1.

We define the transmission as the ratio of the beam current at a radius 820 mm,maximum radius where the read out is not affected by probe efficiency, to the beam current at radius 250 mm. Qualitatively both simulations and experiments show the same exponential dependence on the pressure inside the cyclotron. The overestimation we observe for the calculated values is due to systematic errors in both the pressure measurements and the calculated cross-sections [3].

ORBIT DYNAMICS

Charge changed particles are not accelerated anymore along with the rest of the beam particles due to a change in their charge over mass ratio. Under the influence of the magnetic field, these particles circulate in the cyclotron along a complex trajectory until they eventually, possibly

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after additional charge changes, hit a solid surface and deposit their energy. To simulate the trajectory of these charge changed particles, we first determine the trajectory of the original ions. By solving the equations of motion numerically we calculate the stable closed orbit track for a beam particle at a fixed energy [3]. To simulate a charge change, a change in the charge state (q) of the particle is introduced, at a particular azimuth in the closed orbit. We assume that the charge change process is instantaneous and that there is no change in the radial position and the momentum of the beam particle.

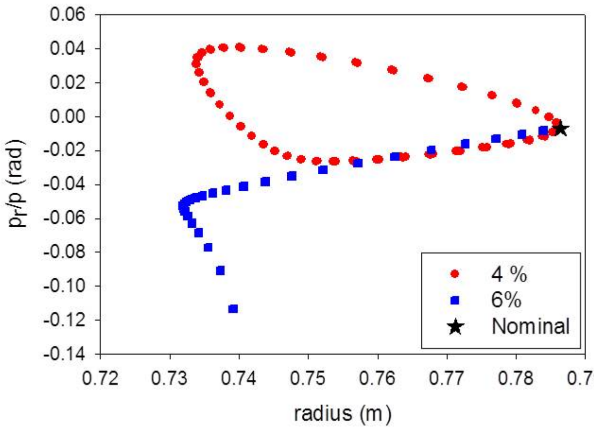

Figure 2: Phase diagram of particles at the azimuth of charge change (215°) at a relative energy of 13.5/18 for ^{129}Xe^{26+} for different percent change in charge state (nominal orbit is before charge change).

We use a percent change in charge state ($\frac{\Delta q}{q}$) so that our results are applicable to all ion beams, irrespective of their initial charge state. The resulting trajectory of the particle is tracked by integrating the equations of motion using a realistic fieldmap for the primary beam. A single charge change results in a change in the radius of curvature from the stable orbit. This is equivalent to giving the particle a kick in the radial betatron amplitude of the same order. The orbit center shifts from the closed orbit center and the particles starts precessing in an off-centered band.

In Figure 2 the phase space trajectory is plotted for charge change at a closed orbit with an relative energy of 13.5/18, where 18 MeV/A denotes the energy of the extracted beam and 13.5 MeV/A corresponds to the energy at that orbit. The phase space diagrams plot the radial momentum (p_r) as a function of radius (r) at an azimuth of 215° while the particle precesses in its off-center track. For this relative energy and a $\frac{\Delta q}{q}$ of 4%, the phase space diagram is a closed loop indicating that the particle track is stable and hence it will precess for a large number of turns (greater than 100). The particle orbit becomes unstable only for $\frac{\Delta q}{q}$ larger than 6%. For the ^{129}Xe^{26+} beam this corresponds to $\Delta q > 1$. Simulations showed that the minimum percent change in charge state required for the beam trajectory to become unstable decreases as we go towards the extraction regions [3]. Thus, particles having a single charge change near the extraction energy have a greater probability of becoming unstable and hitting the periferal walls of the cyclotron.

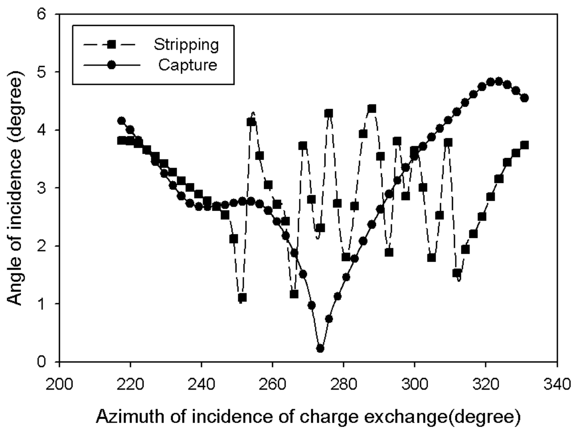

Figure 3: Angle of incidence after unit charge change for closed orbit at a relative energy of 17.46/18 for ^{129}Xe^{26+}.

To determine the impact parameters of the lost particles on the walls of the cyclotron, the simulations are terminated at a radius of 905 mm which is roughly the location at which the walls of the extraction elements are located. The angle of incidence for these impacting particles is small, varying between 0° and 5° (Figure 3).

DESORPTION EXPERIMENT

In order to get a better insight in the desorption induced by charge changed particles in the cyclotron, quantitative measurements of desorption yields for various materials and ions under well controlled conditions were performed with extracted beams in a dedicated experimental setup as shown in Figure 4. The base pressure in the cyclotron during acceleration of heavy ion beams is about 3 × 10^{-7} mbar. To mimic these operating conditions the experimental setup is pumped down to a pressure of about 2 × 10^{-7} mbar in the target chamber. The custom made bellows allows the target surface to rotate between 1° and 8°. The

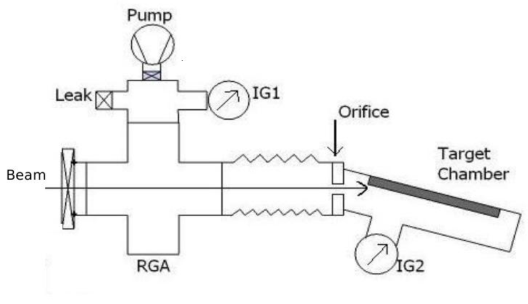

Figure 4: Experimental setup schematics as seen in top view. (IG - ionization gauge; RGA- rest gas analyser)

ionization gauges and the rest gas analyzer measure the pressure rise due to beam incidence, from which we calculate the desorption yield.

In our experiments we have used heavy ion beams with nearly the same charge over mass ratio and final energy as that of the $^{206}\mathrm{Pb}^{27+}$ at 8.5 MeV/amu beam used by TRIμP. For the targets we have concentrated on materials present in the cyclotron vacuum chamber: copper, aluminum, stainless steel and a gold coated copper target.

Observations and Results

Since we were interested in the desorption yields for shallow angles of incidence, the angular dependence of desorption was examined in detail.

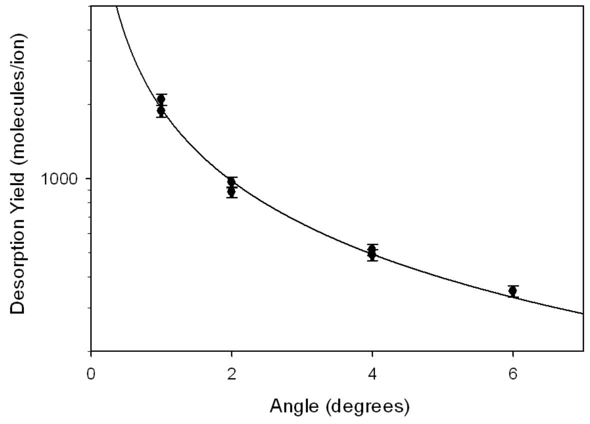

Figure 5: Dependence of desorption yield on the angle of incidence for $^{129}\mathrm{Xe}^{16+}$ 8MeV/amu on a copper target, incident intensity 200 nA.

As an example, Figure 5 shows the desorption yield for Xenon for different angles of incidence for the same beam power indicating a dependence on the inverse of the angle of incidence.

Existing models for desorption predict a scaling with the electronic stopping power on incidence. For perpendicular beam incidence on target, the most widely accepted model is the thermal spike model, according to which the desorption yield scales with $\left(\frac{dE}{dx}\right)^2$ [4]. Other models predict a stopping power scaling with $n = 1.5$ (shock wave model [5]). The results obtained from our experiments (Figure 6) are not consistent with either of those models, suggesting that desorption caused by shallow angle ion beam incidence does not solely depend on the energy deposited at the surface. The average desorption yield is significant, releasing about 10^3 molecules per ion incident at 2°. This is roughly of the same order as desorption yields from other experiments [3].

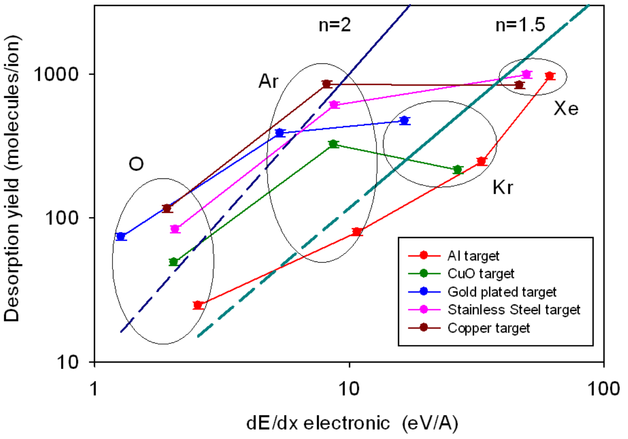

Figure 6: Dependence of desorption yield on the surface stopping power (compared to different models) for mass 28, incident intensity 200 nA, all beams on target at 2°

SUMMARY

In a bid to reduce ion-induced desorption in AGOR, the beamloss feedback cycle was investigated in detail. Experiments showed that primary beamloss due to charge changing collisions could be explained by existing models.These charge changed particles precess in an off-centered trajectory until after subsequent charge changes they eventually hit the walls. We identified that the ions with near extraction energy and small impact angle chiefly contribute to desorption. From the desorption experiment the average yield for ion-induced desorption at shallow angles of incidence was also determined. Using these results we can make a rough prediction of the increase in pressure and thereby the beam loss during heavy ion beam transmission.

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