INJECTION AND ACCELERATION OF Au^{31+} IN THE BNL AGS*

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Abstract

Injection and acceleration of ions in a lower charge state reduces space charge effects, and, if further electron stripping is needed, may allow elimination of a stripping stage and the associated beam losses. The former is of interest to the accelerators in the GSI FAIR complex, the latter for BNL RHIC collider operation at energies lower than the current injection energy. Lower charge state ions, however, have a higher likelihood of electron stripping which can lead to dynamic pressures rises and subsequent beam losses. We report on experiments in the AGS where Au^{31+} ions were injected and accelerated instead of the normally used Au^{77+} ions. Beam intensities and the average pressure in the AGS ring are recorded, and compared with calculations for dynamic pressures and beam losses. The experimental results are used to benchmark the StrahlSim dynamic vacuum code and will be incorporated in the GSI FAIR SIS100 design.

INTRODUCTION

Partially stripped ions experience a number of effects that can limit the beam intensity. With low charge states space charge effects are reduced but electron stripping is enhanced. With high charge states electron stripping cross sections are small but electron capture cross sections increase, as do space charge effects. Charge exchange processes lead to beam losses, and the subsequent ion-impact desorption to dynamic pressure increases that further enhance the charge exchange processes. Such charge exchange effects limit machines like the GSI SIS18 [3], BNL AGS Booster [2, 4], and CERN LEIR [5], and their understanding is important for future machines like the GSI SIS100 [6–8].

Currently the GSI SIS18 operates with U^{73+}. For the FAIR project it is planned to operate both the SIS18 and the SIS100 with U^{28+}. An upgrade program is under way for the SIS18 [1]. The energy ranges of SIS18 and AGS Booster are close, so are the energy ranges of SIS100 and the AGS. Charge exchange effects in SIS18 and the AGS Booster have been compared previously [2], and the AGS can serve as a test bed for the SIS100. When running as an injector for RHIC Au^{77+} ions are injected and accelerated in the AGS. The AGS Booster accelerates Au^{31+} ions which are stripped in the Booster-to-AGS (BtA) transfer line. These could also be injected directly into the AGS.

In RHIC an experimental program is forming for Au-Au collisions at energies below the normal injection energy [10]. At these energies luminosities are much reduced compared to the high energy operation due to the increased beam size, space charge effects, intrabeam scattering, and large field errors in the superconducting magnets. Under these conditions an increase in the available beam intensity could be beneficial, in particular with beam cooling or in top-off mode. If Au^{31+} ions could be accelerated with small losses in the AGS, a stripping stage and the associated beam losses can be eliminated and more fully stripped Au ions are available for injection in RHIC.

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Table 1: Main parameters of the AGS vacuum system.

parameter	unit	value
avg. static pressure, p_0	Torr	2×10^{-8}
dominant residual gas	...	H_2O (92%)
other residual gases	...	H_2, CO, CO_2 (8%)
circumference	m	807.1
number of ion pumps	...	240
pumping speed (N_2)	$l{\cdot}s^{-1}$	100
pipe conductance (N_2),	$l{\cdot}m{\cdot}s^{-1}$	190

EXPERIMENTAL SETUP

The AGS vacuum system has 240 ion pumps distributed around the circumference (one per dipole). Vacuum components are not baked resulting in an average static pressure of 2×10^{-8} Torr (the average pressure quoted is 3 times the average of the pressures measured in the pumps, see Ref. [9] and below). There are 7 locations with elevated pressure (C5 and E15 - ionization profile monitors; C15 and C20 - polarimeters; D20, I20 and J20 - rf) where the pressure up to 10^{-7} Torr. The dominant residual gas is H_2O (about 92%), the remaining components are about equal parts of H_2, CO, and CO_2. The general readout frequency of the pressure data is 0.2 Hz. For the experiments a faster readout of 2 Hz was implemented at 1 gauge and 3 ion pumps in each of the 24 vacuum sectors, and in addition at 3 ion pumps in each of the 7 locations with elevated pressure. The main parameters of the AGS vacuum system are summarized in Tab. 1.

In normal Au operation Au^{31+} is accelerated in the Booster, and a stripping foil in the Booster-to-AGS transfer line creates Au^{77+} that is injected and accelerated in the AGS. For the experiments the stripping foil in the BtA transfer line was removed, and the line after the stripping foil was re-tuned to account for the changed rigidity. To test the beam lifetime at injection the rf was switched off, for acceleration it was switched on. The ramp rate for acceleration was 1.25 T/s.

MEASUREMENTS

In the experiments the beam lifetime and the vacuum pressure were observed as a function of a number of parameters:

- beam intensity (0.1 ... 3×10^9 Au^{31+} ions)
- injection energy (50.5, 62.0, 100.8 MeV/nucleon)
- energy in acceleration (100.8 ... 700 MeV/nucleon)
- background pressure (20 ... 140 nTorr)

Of the pressure gauges and pumps with fast readout about one quarter showed some response to injected beam. The lifetime can be fitted well to an exponential function. In Fig. 1 the intensity and pressure in 3 pumps is shown as a function of time in one of the measurements with a beam energy of $E_{kin} = 100.8$ MeV/nucleon.

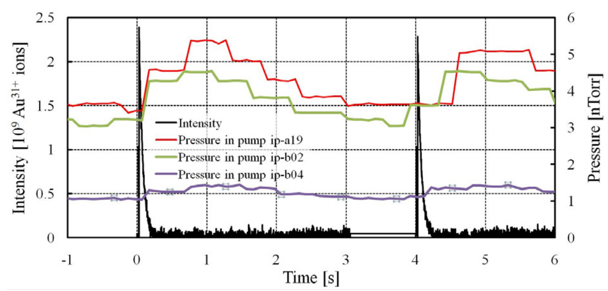

Figure 1: Time-dependent intensity of injected Au^{31+} beam ($E_{kin} = 100.8$ MeV/nucleon) and pressure readings from 3 vacuum pumps.

Figure 2 shows fitted beam lifetimes as a function of the beam intensity and for the 3 kinetic energies tested (50.5, 62.0, and 100.8 MeV/nucleon). The data are consistent with a beam lifetime independent of the intensity in the range tested, and for all 3 beam energies tested. The static background pressure is high enough so that desorption after beam loss from charge exchange processes changes the pressure only by a small amount (see Fig. 1), not further deteriorating the beam lifetime.

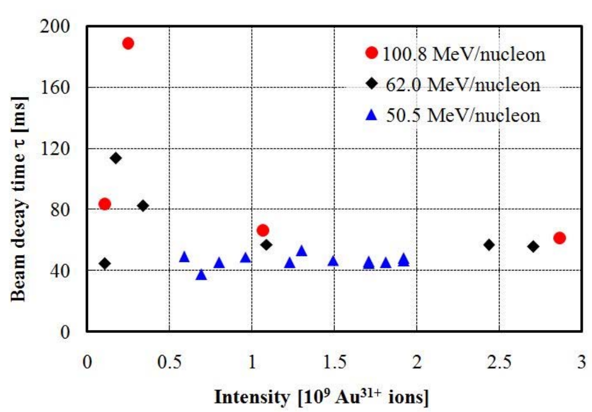

Figure 2: Fitted beam decay times as a function of beam intensity for three different beam energies.

In addition to beam lifetime and dynamic pressure measurements at injection acceleration was attempted to further explore the beam energy dependence of the beam loss rate. In Fig. 3 one such acceleration is shown for the initial energy of $E_{kin} = 100.8$ MeV/nucleon and a ramp rate of 1.25 T/s. No significant difference in the beam lifetime is found compared to the non-accelerating case.

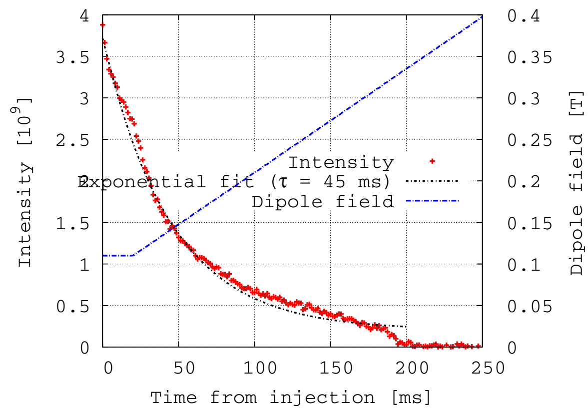

Figure 3: Acceleration of Au^{31+} beam from an energy of $E_{kin} = 100.8$ MeV/nucleon with a ramp rate of 1.25 T/s. The beam lifetime is not noticeably different from the the non-accelerating case.

In another test the average ring pressure was changed through a pressure bump at an ionization profile monitor that can leak CO_2 gas into the beam pipe. Figure 4 shows the fitted beam lifetime as a function of the inverse average ring pressure, showing a linear dependence.

With these data data, and assuming electron stripping as the dominant charge exchange process, the electron stripping cross section σ_{es} can be obtained as

$$\sigma_{es} = \frac{1}{\tau}\frac{1}{\beta c}\frac{k_B T}{p} \tag{1}$$

where τ is the beam lifetime, β the relativistic factor, c the speed of light, k_B the Boltzmann constant, T the absolute temperature, and p the pressure. With the τ and p values shown in Fig. 4 an electron stripping cross section of 2×10^{-22} m^2 is obtained. Mainly due to the uncertainty in the pressure value from both the error of the pressure measurement in the pump and the error in translating these into the average ring pressure this value has an error of at least a factor of 2.

COMPARISON WITH CALCULATIONS

As the pressure gauges are situated near pumps, the average pressure visible for the beam is larger than the measured pressure by some amount. A longitudinal pressure calculation with StrahlSim [11] shows that the measured average pressure is a factor of ≈ 3.3 lower than the real average pressure. Total ion loss cross sections for Au^{31+} have been calculated by V. Shevelko [12] with the relativistic LOSS-R code, which are shown together with the electron capture cross section by Schlachter [13] in Fig. 5.

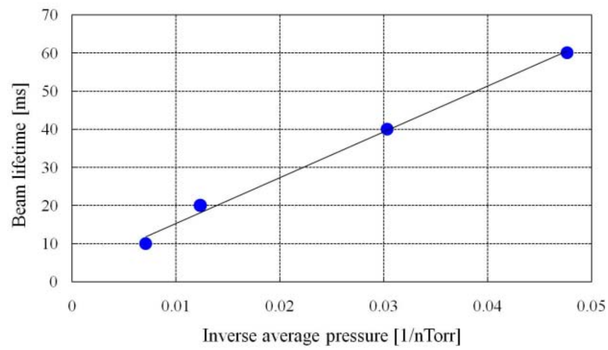

Figure 4: Fitted beam decay times as a function of inverse average ring pressure, at a beam energy of $E_{kin} = 100.8$ MeV/nucleon. Note that the dominant residual gas is H_2O but CO_2 was leaked to increase the pressure.

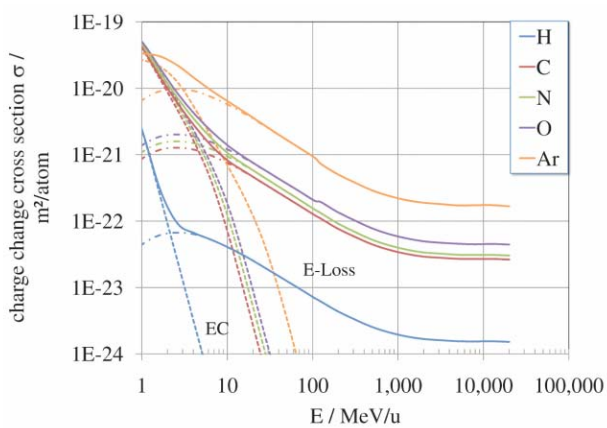

Figure 5: Calculated charge change cross sections for Au^{31+} for various target atoms [12, 13].

For an energy of 100 MeV/nucleon, the calculated electron loss cross section for H_2O is 2.15×10^{-22} m^2, in good agreement with the measured one (see above). The beam life time, calculated with these parameters then also shows good agreement with the experiment (Fig. 6).

To calculate the ion stimulated desorption rate, the measured ring averaged pressure rise of $\Delta p \approx 1 \times 10^{-9}$ Torr

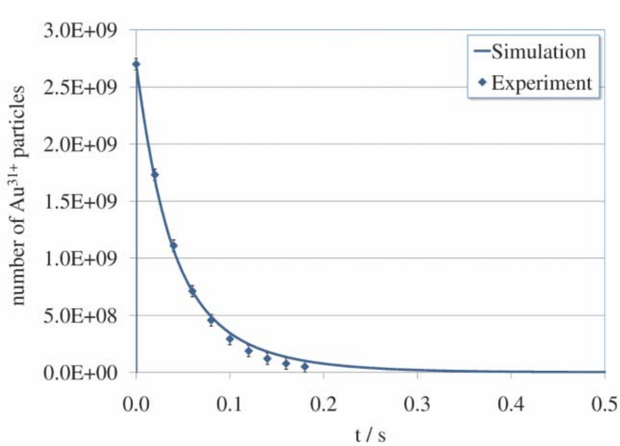

Figure 6: Calculated and measured time dependent intensity for Au^{31+} at injection.

during a single injection cycle with $N = 3.6 \times 10^9$ lost particles have been taken into account together with the accelerator volume of $V = 9.5$ m^3. With

$$\eta = \frac{\Delta p V}{N k_B T}, \qquad (2)$$

we obtain for the desorption coefficient $\eta \approx 3 \times 10^4$ molecules/ion, which is higher than the expected desorption coefficient of $\eta \approx 4 \times 10^3$ molecules/ion estimated from SIS18 experiments with U^{28+} at 11.4 MeV/nucleon using a $(dE/dx)^2$ scaling of the incident ions. The discrepancy can be explained by the fact that the AGS is an unbaked machine, whereas the SIS18 is baked.

SUMMARY

Au^{31+} ions were injected and accelerated in the AGS instead of the usually used Au^{77+} ions. In the tests the injection energy, the beam energy, and the background pressure were varied, and acceleration was attempted. In all cases the beam lifetime is dominated by electron stripping processes due to the relatively high static pressure of 2×10^{-8} Torr. Only a small dynamic pressure rise was observed in a few gauges and pumps, and the measured beam lifetime was independent of beam energy and beam intensity in the ranges tested.

The electron stripping cross section obtained from the measured beam lifetime is 2×10^{-22} m^2, compared with the calculated cross section of 2.15×10^{-22} m^2. However, due to the uncertainty in the pressure measurement, the measured electron stripping cross section has an error of at least a factor of 2. An ion-impact desorption coefficient η for lost beam ions of 4×10^4 is estimated for the unbaked AGS vacuum system.

AGS operation with Au^{31+} ions for RHIC would only be possible after an AGS vacuum upgrade.

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