EXPERIMENTAL STUDIES OF BEAM LOSS DURING LOW ENERGY OPERATION WITH ELECTRON COOLED HEAVY IONS IN THE ESR

P. Görgen*, O. Boine-Frankenheim, TEMF, TU-Darmstadt, Darmstadt, Germany
S. Appel, C. Dimopoulou, S. Litvinov, M. Steck, GSI, Darmstadt, Germany

Abstract

At the ESR storage ring at GSI electron cooled heavy ion beams are decelerated to 4 MeV/u and extracted for the HITRAP experiment. We report about cooling measurements of 4 MeV/u coasting beams. We compare the beam parameters with results from beam dynamics simulations. The time slot in which HITRAP accepts beam is 1.5 μs long. For optimum efficiency the beam has to be bunched to this length before extraction. Our measurements show that bunching leads to severe emittance growth for currents below 1 μA and to particle losses for higher currents. The estimated transverse space charge tune shifts during the RF bunching indicate that resonance crossing might be responsible for the observed beam loss. This suspicion is supported by tune measurements which show beam loss when changing the tune by values comparable to the estimated tune shift.

BEAMS FOR HITRAP

The Heavy Ion Trap (HITRAP) [1] experiment at the GSI Helmholtzzentrum für Schwerionenforschung (GSI) facility in Darmstadt, Germany will investigate both rare and stable heavy ions at high charge states. HITRAP is supplied with electron-cooled ion beams decelerated to 4 MeV/u in the Experimental Storage Ring (ESR). After extraction towards HITRAP the ions are further decelerated by HITRAP's linear decelerating structure down to 6 keV/u [2]. Finally the ions are trapped in a penning trap for further cooling and experiments. The penning trap accepts beam for up to 1.5 μs. The revolution period of 4 MeV/u ions in the ESR amounts to about 4 μs. HITRAP therefore requires bunching in ESR in order to capture the entire beam. Before this work RF capture at 4 MeV/u in the ESR sometimes caused particle losses. Our aim was to identify the loss mechanisms and to possibly find a cure.

PARTICLE LOSS AND HEATING MECHANISMS

The tune shift due to transverse space charge was considered the most likely loss mechanism at 4 MeV/u. Remanence effects in the magnets can lead to lattice errors which are more pronounced than at higher energies. The space charge tune shift may then lead to resonance crossing and particle losses even on higher order resonances. To calculate the space charge tune shift we used the following formula [3]:

$$\Delta Q_{v,h} \simeq -\frac{1}{B_f}\frac{r_{\rm i} N}{2\pi E_{v,h}\beta^2\gamma^3}\frac{2}{1+\sqrt{\bar{\beta}_{h,v}E_{h,v}/\bar{\beta}_{v,h}E_{v,h}}} \tag{1}$$

With $\Delta Q_v, \Delta Q_h$ the vertical and horizontal tune shift, $r_{\rm i}$ the ion coulomb radius, N the number of ions, E_h, E_v the 4σ-emittances in the two transverse planes, $\bar{\beta}_h, \bar{\beta}_v$ the average beta functions and $\gamma = (1-\beta^2)^{-1/2}$ the relativistic parameters. B_f is the bunching factor.

Intrabeam Scattering

Apart from resonances, intrabeam scattering (IBS) was considered as the dominant heating process. To investigate intrabeam scattering, the IBS rate formalism of Bjorken and Mtingwa [4] was used. The equations were implemented in the form given in [5]. The implementation was done in the commercial mathematics software Mathematica. As a validation, the results of our implementation for the $\bar{\rm p}$-accumulator lattice matched those given by Bjorken-Mtingwa [4].

MEASUREMENT

The deceleration cycle for HITRAP foresees the supply of ions to ESR at 400 MeV/u. The ions are cooled by either stochastic or electron cooling and decelerated to 30 MeV/u where they are debunched and cooled by electron cooling before the final deceleration step down to 4 MeV/u. At 4 MeV/u the ions are again electron-cooled. When the cooling equilibrium is reached the radio frequency (RF) is switched on for bunching. These measurements employed a simplified cycle starting with 30 MeV/u ions and following the HITRAP cycle from there.

Measurements with Ar^{18+} beams were carried out at 30 MeV/u to determine the beam properties at this more stable machine setting. Measurements with Ar^{18+} and Cr^{23+} beams at 4 MeV/u (the HITRAP extraction energy) followed. At both energies the coasting beam emittance was determined using a residual gas monitor. The momentum spread was obtained from the Schottky signals. The capture process and the bunch dynamics after the RF start were observed using a beam position monitor. The RF was switched on near-instantaneously, the bunches are formed by cooling into the bucket on a time scale of a few hundred ms. The beam current was observed using a beam

* p.goergen@gsi.de

current transformer and when we reached the lower limit of the current transformer of 1 μA we extrapolated from the integrated Schottky signal spectra wherever possible.

Results at 30 MeV/u

At 30 MeV/u the beam was bunched with two different RF voltages. As soon as the RF voltage was switched on an increase in the emittance in both transverse planes together with a decrease in the lifetime by two orders of magnitude was observed. Most of the beam current was lost within ≈ 20 s. Afterwards the lifetime increased again to roughly the initial value. For the different RF settings transverse beam properties were determined. The tune shifts right after bunching were in the regime of -0.02 to -0.1.

Results at 4 MeV/u

After deceleration the coasting beam properties were determined. The horizontal space charge tune shift for the coasting 4 MeV/u beams was calculated to be below $5 \cdot 10^{-4}$. The vertical space charge tune shift was of the same order of magnitude but even smaller.

IBS Rates IBS rates at 4 MeV/u were measured for Cr^{23+} beams. To observe IBS the coasting beam was cooled to equilibrium at different electron currents, then the electron beam was switched off. The beam properties were recorded over some time interval. The aim was to test how well the experimental results match the calculated ones and to verify the calculated IBS rates. The results are shown in Fig. 1. For the simulations the ion current which was below the detection limit was estimated to be between 0.3 μA and 0.9 μA. IBS measurements started at different electron current and thus different beam parameters showed similar agreement to simulations.

Bunching Measurements Cr^{23+} and Ar^{18+} beams were bunched at 4 MeV/u with different RF voltages and the resulting bunch properties were observed. After the switch-on of the RF a sudden increase of the horizontal emittance was observed while the vertical emittance stayed constant or shrank. For the Ar^{18+} beam maximum currents of up to 5 μA were available. Bunching voltages of 100 V led to losses of 40% of the particles. Both particle losses and emittance growth increased with RF voltage. At 400 V 80% of the particles were lost. The number of measurements was not sufficient to establish a detailed relation between RF voltage, emittance growth and amount of loss.

For Cr^{23+}-beams and currents around or below 1 μA, the emittance increases but no particle losses were observed at RF voltages up to 100 V. An example of transverse beam properties after RF start can be found in Fig. 2. After about 200 μs the beam is already bunched but the emittance is still low. The tune shift at this time is in the regime of 0.01. The IBS rate shortly after bunching is calculated as 1.3 s^{-1}. The IBS rate cannot explain the observed emittance increase during bunching which happens at a rate of 5 s^{-1}.

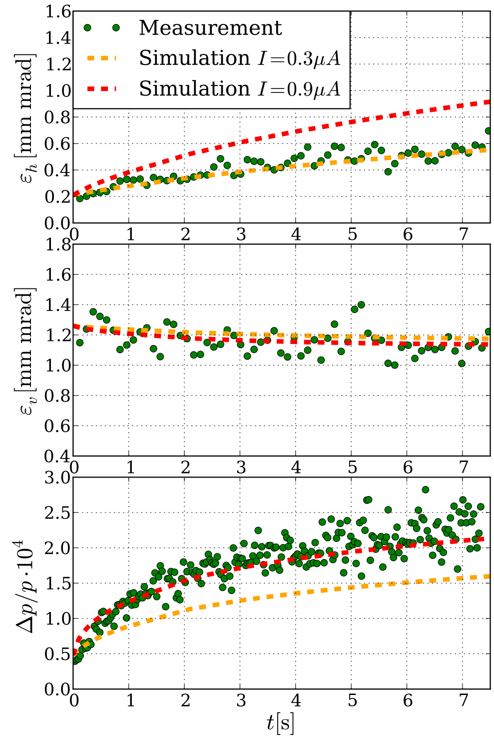

Figure 1: Example of IBS simulations compared with measurement results. The ion current was below the detection limit of 1 μA. The simulations were done estimating it between 0.3 μA and 0.9 μA. We see acceptable agreement with the simulation.

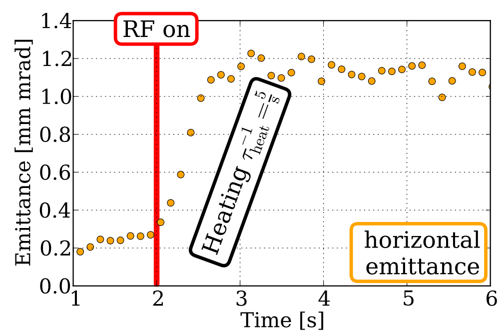

Figure 2: Horizontal emittance around the time of RF start for a $^{52}_{24}Cr^{23+}$ beam at 4 MeV/u and 100 V RF voltage. Signal amplitude on the Residual Gas Monitor (RGM), our remaining measure for current below the limit of the current monitor, does not drop during bunching.

Tune Measurements Still it remained to be shown that the small space charge tune shift at 4 MeV/u is sufficient to put the beam onto nearby resonances and thereby cause heating and particle loss. For this reason the machine behaviour around the 4 MeV/u standard working point setting of $(Q_h, Q_v) = (2.27, 2.32)$ was investigated. Beams were decelerated to 4 MeV/u, debunched and cooled, then the tune was moved to different settings and beam lifetime was measured. The lifetimes are shown color-coded in Fig. 3.

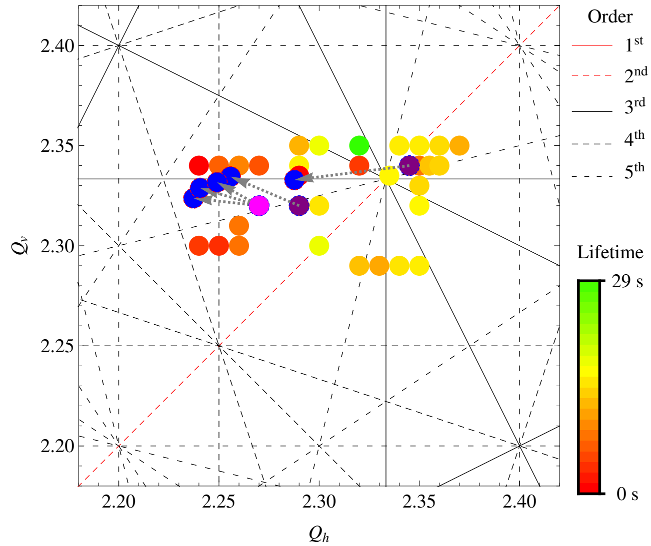

Figure 3: Resonance diagram showing color-coded lifetimes at different tune settings around the 4 MeV/u standard tune in ESR (shown in pink at (2.27, 2.32)). Set and corresponding measured tune values are shown connected by an arrow. Recovery of machine tunes from set tunes was impossible with our data. Resonance lines up to fifth order are also shown.

While moving the tune around, sudden particle losses were observed even during small changes in the tune of the order of 0.01. The losses are very likely to be caused by resonance crossing.

Remanence effects can lead to differences between the set tune and the machine tune. To be sure about the actual tune, the fractional part of the machine tune at different tune settings was measured. The measured tunes are shown in Fig. 3. We see that the measured tune of the standard working point with setting $(Q_h, Q_v) = (2.27, 2.32)$ is in fact somewhere near (2.25, 2.33), the crossing point of a third and fourth order resonance, namely the two resonance lines corresponding the resonance condition [3] $aQ_h + bQ_v = n$ with (a, b, n) equal to (0,3,7) and (4,0,9).

INCREASING BUNCH LENGTH

A method of counter-acting the space charge of bunched beams is to increase the bunch length and thereby decrease the peak current. Space charge tune shift is inversely proportional to the bunch length. The maximum bunch length acceptable to the HITRAP experiment amounts to a fraction of 0.375 of the ESR circumference. Neglecting longitudinal space charge and assuming constant momentum spread the bunch length is proportional to $U_{\mathrm{RF}}^{-0.5}$. Figure 4 shows measured bunch lengths at different RF voltages and a fit to $a \cdot U_{\mathrm{RF}}^{-0.5}$. The lower voltage limit of the RF electronics corresponds to about 5 V. Cavity electronics modification may allow for bunch lengths up to the HITRAP limit, reducing the tune shift by a factor of 4. Barrier buckets could permit further reduction of space charge and tune shift by providing a more even distribution of the charge in the bucket.

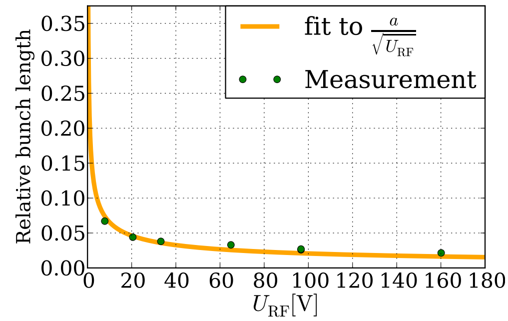

Figure 4: Bunch length for the Cr^{23+} beam at 4MeV/u over RF voltage together with a fit to the theoretical idealization $a \cdot U_{\mathrm{RF}}^{-0.5}$. Cooler parameters were constant. The maximum permissible bunch length corresponds to the top frame of the figure.

CONCLUSION

At 4 MeV/u we observed particle losses and horizontal heating during RF capture which increase with RF voltage. The tune shift in the horizontal direction after bunching is in the regime of -0.01. In our measurements a tune change by this value was often followed by particle losses. We excluded IBS as the main source of heating by comparing the calculated IBS rates to the observed heating rates. We conclude that, very likely, the space charge tune shift is the source of the observed heating and particle losses. In the lifetime measurements tune settings which were significantly more stable than the standard tune at 4 MeV/u were found. Using a more optimized tune together with the lowest bunching voltage possible might allow for bunching of higher numbers of ions.

REFERENCES

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