DECELERATION OF CARBON IONS AT THE HEAVY ION STORAGE RING TSR

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Abstract

To evaluate the beam quality obtained after deceleration of $^{12}C^{6+}$ ions at the heavy ion Test Storage Ring (TSR), considering the possible sources of beam heating is important. In our experiments at the TSR, we inject $^{12}C^{6+}$ ions at 73.3 MeV and decelerate them to 9.7 MeV in a cycle that includes two steps in which beam cooling is applied. In this study we discuss the influences of intrabeam scattering (IBS) on the circulating ions during deceleration. We additionally present results on the deceleration efficiency and lifetime measurements of $^{12}C^{6+}$ ions in the energy range 9.7 - 73.3 MeV .

INTRODUCTION

The heavy ion storage ring TSR, at the Max-Planck-Institut für Kernphysik (MPIK) in Heidelberg, operates for accelerator, atomic and molecular physics experiments. The storage ring has a circumference of 55.42 m, and it receives heavy ions from a 12 MV tandem van-de-Graaff and a normal conducting RF linac combination. Light positive ions and negative ions with mass to charge ratio $\frac{A}{|q|} \leq 9$ are provided by a high current injector. At TSR the experiments mainly performed at the injection energy. In addition, the widely tunable range of the RF resonator enables the possibility to accelerate and decelerate ions. To ramp the magnetic fields at TSR, Digital-Analog Converter(DAC) and DSP driven synthesizer cards developed by MPIK. The generated functions to ramp the magnetics can be calculated from the rigidity by assesing the measured saturation effects of the TSR magnets. With some minor additional corrections to the calculated dipole magnets ramp and one quadrupole family ramp, decelerating a $^{12}C^{6+}$ ion beam from 73.3 MeV to 9.7 MeV, corresponding to a rigidity decrease from 0.71 Tm to 0.26 Tm is possible. In the deceleration process, an increase of bunch length, momentum spread and beam emittance occurs. To avoid beam loss during deceleration due to these effects, electron pre-cooling of the injected bunched ion beam is necessary.

INTRABEAM SCATTERING EFFECTS DURING DECELERATION

To decelerate a heavy ion beam, cooling at the injection energy is required, resulting in a dense ion beam such that IBS effects must be considered. Immediately before starting the deceleration cycle, electron cooling is switched off and the ion beam sizes increase due to IBS. The blow up rate of a bunched beam due to IBS can be expressed by [1]:

$$\frac{1}{\sigma_i}\frac{d\sigma_i}{dt} = c_i \cdot \frac{Z^4}{A^2}\frac{N}{\beta^3}\frac{1}{\epsilon_x\epsilon_y \Delta p/p \cdot h \cdot l_{eff}}, \tag{1}$$

where i (i=x,y,$\frac{\Delta p}{p}$) corresponds to the horizontal, vertical and longitudinal coordinates of the beam. N is the number of ions with charge state Z, mass A, and velocity β. The number of bunches in the storage ring is h and l_{eff} is the effective bunch length. c_i are lattice dependent functions which depend slightly on the ion energy. The horizontal emittance and vertical emittance scales are computed as $\epsilon_x \propto \sigma_x^2$, $\epsilon_y \propto \sigma_y^2$, where σ_x and σ_y are the horizontal and vertical beam widths, respectively. If in the IBS process σ_x, σ_y, and the momentum spread $\Delta p/p$, l_{eff} are proportional to each other as in $\epsilon_x\epsilon_y l_{eff}\Delta p/p \propto \sigma_i^6$, we obtain three uncoupled differential equations for all three degrees of freedom [2] [3]:

$$\frac{1}{\sigma_i}\frac{d\sigma_i}{dt} = \frac{D_i}{\sigma_i^\gamma}. \tag{2}$$

In simplified IBS model γ=6 [3] for a bunched ion beam and the heating term:

$$D_i \propto c_i \frac{Z^4}{A^2}\frac{1}{\beta^3}\frac{N}{h}. \tag{3}$$

If the velocity of circulating the ion beam is not changed the solution of equation 2 is given by:

$$\sigma_i(t) = (\sigma_{i,0}^\gamma + \gamma D_i t)^{\frac{1}{\gamma}}, \tag{4}$$

where $\sigma_{i,0}$ is the initial beam width. In figure 1, the measured horizontal beam width of a $^{12}C^{6+}$ bunched ion beam at the injection energy of 73.3 MeV is shown as a function of time. For bunching, a resonator voltage of 186 V was applied. By fitting the experimental data, we obtained $\bar{\gamma} = 5.9$, which is approximately close to the theoretical value of $\gamma = 6$. As shown in figure 1, the horizontal profile can be described well with simplified IBS model if the ion beam velocity is constant. To investigate the velocity dependence of IBS we make the following ansatz for the heating term:

$$D_i(t) = \frac{\tilde{D}_i}{\beta^\kappa(t)}, \tag{5}$$

where κ=3. In the deceleration cycle the ion velocity is changed linearly:

$$\beta(t) = \beta_0 + \alpha t, \tag{6}$$

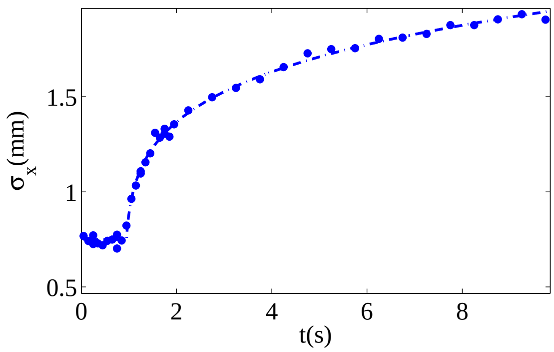

Figure 1: Measured horizontal beam width σ_x of a $^{12}C^{6+}$ bunched ion beam (73.3 MeV, 50μA) as a function of time after 1.5 s. The dashed line through the data is a fit using equation 4 where γ is the fit parameter.

where β_0 is the initial velocity of ions. The parameter α can be determined as follows:

$$\alpha = (\beta_f - \beta_0)/T, \tag{7}$$

where T is ramping time and β_f is the final velocity of ions. To assess the beam width during deceleration the equation (2) can be solved with (5) and (6):

$$\sigma_i(t) = \left(\sigma_{i,0}^{\gamma} + \frac{\gamma \tilde{D}_i \left(\beta_0^{1-\kappa} - (\beta_0 + \alpha t)^{1-\kappa}\right)}{\alpha(\kappa - 1)}\right)^{\frac{1}{\gamma}} \tag{8}$$

In figure 2, the experimental and computed horizontal beam width during deceleration as a function of time is shown. Computed σ_x from equation (8) for different values of κ are shown as red and green lines, measured σ_x are shown as colored dots. After injection, the ion beam was electron cooled, resulting in a horizontal beam width of $\sigma_x = 0.65$ mm. At the time t=4 s electron cooling was switched off and the ion beam was decelerated in 7 s to the final energy of 9.7 MeV. After reaching the final energy at t=11 s, electron cooling was switched on again, yielding in fast reduction of the horizontal beam width σ_x. Because the IBS heating term D_i (in equation (3)) is higher at the final energy, the equilibrium beam width at 9.7 MeV is larger comparing to at the initial energy of 73.3 MeV. The heating term $\tilde{D}_i$ and the parameter γ were both determined by the IBS measurement obtained at the initial energy of 73.3 MeV [3]. As displayed in figure 2, the computed σ_x values are below than the measured beam widths, especially at low velocities. Obviously, some term in equation (8) is missing to describe the real measured beam widths. From equation (8), the conclusion follows that the beam width for very weak intensities ($\tilde{D}_i \rightarrow 0$) would be constant during deceleration, which is, however, not correct. Deceleration of beams can be described by Liouville's theorem, which postulates that the phase space area occupied by noninteracting particles is conserved during deceleration. Thus the theorem leads to an increase of the ion beam size during deceleration even without any IBS effects. Accordingly, in the non-relativistic approach, the change of the ion beam size σ_i is given by:

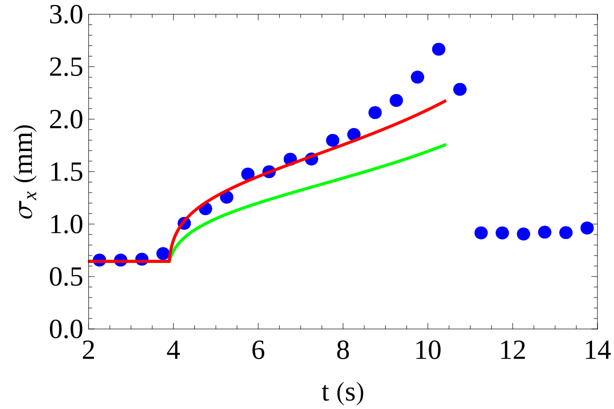

Figure 2: Experimental and computed horizontal beam width σ_x of a $^{12}C^{6+}$ ion beam (28 μA.) as a function of time during deceleration. Deceleration starts at t=4 s. Two cooling steps were applied at t=0 s and t= 11 s. The final energy is 9.7 MeV. The red and green lines are computed beam width with equation (8) for $\kappa = 3.25$ and $\kappa = 3$, respectively.

$$\sigma_i(t) = \tilde{\sigma}_i \sqrt{\frac{\beta_0}{\beta(t)}}, \tag{9}$$

where $\beta(t)$ is the ion velocity at the time t and $\tilde{\sigma}_i$ is the beam width at t=0 s. Equation (9) is the boundary value for $\tilde{D}_i \rightarrow 0$ of the equation 8, for which we are looking. To consider IBS time dependent beam width $\tilde{\sigma}_i$ in equation (9) will be replaced by the beam width $\sigma_i(t)$ in equation (8):

$$\sigma_i(t) = \left(\sigma_{i,0}^{\gamma} + \frac{\gamma \tilde{D}_i \left(\beta_0^{1-\kappa} - \beta(t)^{1-\kappa}\right)}{\alpha(\kappa - 1)}\right)^{\frac{1}{\gamma}} \sqrt{\frac{\beta_0}{\beta(t)}}. \tag{10}$$

According to equation (10), the beam width during deceleration was computed. The result is shown in figure 3 as a red line. The IBS heating term $\tilde{D}_i$ and γ were determined at the injection energy of 73.3 MeV [3]. The equilibrium beam width $\sigma_{i,0}$ was found from the measured beam widths between t=2-4 s. As demonstrated in figure 3, the calculation of the beam width during deceleration using only IBS data, measured at the injection energy, is now consistent with the observation. As shown in the next section, the number of ions decreases slightly in the deceleration cycle, whereas this particle loss is not considered in equation (10). Further calculation shows that after taking into account the small particle loss during deceleration, there is no significant deviation to equation (10). Assuming the number of particles as a constant, for particle losses which less than 15%, approximating the measured beam width in deceleration cycle with equation (10) is possible.

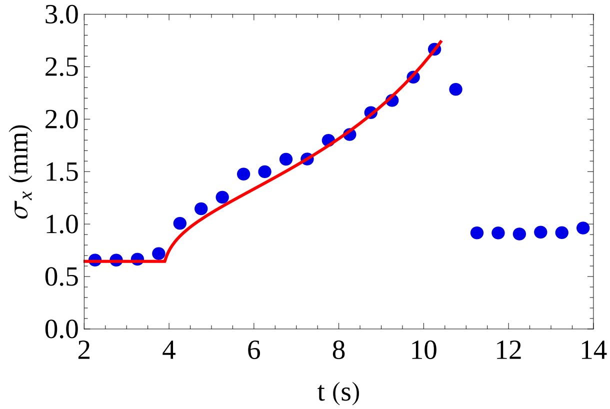

Figure 3: Development of σ_x of a $^{12}C^{6+}$ ion beam (I=28 μA) as a function of time during deceleration. Computed σ_x for $\kappa = 3$ is shown as red line.

DECELERATION EFFICIENCY

To obtain information about the ion loss in the deceleration cycle, the number of ions by measuring the voltage on a capacitive pick-up is determined. The integral of this signal over one RF period scales with the number of ions in the bunch [4]. Because several injections were needed to evaluate the ion number at different time in the deceleration cycle and since the injection intensity fluctuated in the range 55±9 μA, measuring the number of particles at injection by determining the counting rate of the residual gas beam profile monitor was required. The ratio of the number of particles $N(t)$ during the deceleration cycle and the number of particles N_0 of the injected ions is shown in figure 4 as a function of time. Beam is injected at t=0 s and electron pre-cooled for 1.5 s. Deceleration starts at t=1.5 s and lasts 7 s. The final energy was achieved at t=8.5 s. During deceleration of the beam the initial intensity was 55 ±9μA and the resonator voltage for bunching was 232.5 V. As shown in figure 4, a small, almost linear particle loss occurs. 83 % of the ions reach the final energy of 9.7 MeV. In the intensity range of 8 μA -120 μA the ϵ of the deceleration process was measured. ϵ is defined as the ratio of the final number of particles N_f, reaching the final energy of 9.7 MeV, to the initial number of particles N_0: $\epsilon = \frac{N_f}{N_0}$. The results has no significant dependency on the injected ion intensity as shown in figure 5. Determined efficiency $\bar{\epsilon}$=87.5% in the intensity range of 8 μA-120 μA.

LIFETIME

Ion losses occur in the deceleration process. In order to compare these with those resulting from the ion interaction with the residual gas, lifetime measurements were performed in the energy rangy of 9.7-73.3 MeV. In these experiments the ion beam was injected and then decelerated to the various energies where the lifetimes were determined. In all measurements which are shown in figure 6 no

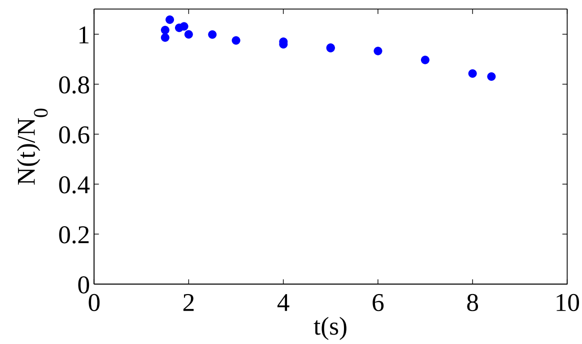

Figure 4: Measured number of particles $N(t)$, normalized to the injected particle number N_0, during deceleration of a $^{12}C^{6+}$ ion beam from E=73.3 MeV to E=9.7 MeV. Deceleration starts at t=1.5 s. At t=8.5 s the final energy was reached.

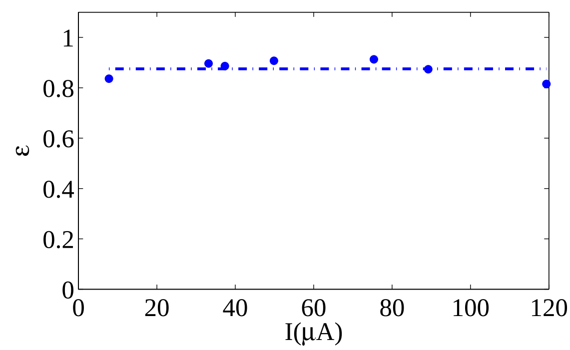

Figure 5: Measured deceleration efficiency as a function of the injected ion intensity.

electron cooling was applied. Obviously, the lifetime decreases with decreasing energy. For uncooled bare $^{12}C^{6+}$ ions, we have to consider two loss mechanisms: multiple scattering and electron capture in the residual gas. The partial lifetime τ of the beam with respect to a certain process is given by $\tau^{-1} = \sigma\rho v$, where σ is the relevant cross section, ρ the density of the residual gas atoms or molecules of atomic charge number Z_{gas}, and v the ion velocity. Because of the loss cross section for electron capture in the residual gas scales with a power of about 4 of Z_{gas}, the concentration of heavier atoms in the residual gas is most important for the lifetime of the beam. After bakeout of the storage ring to $250°$, the residual gas composition is of typically 93 % hydrogen. Other molecules contain 2 % carbon, 1 % nitrogen 6 % oxygen and the heaviest component is 0.3% argon. In figure 6, the partial lifetimes of electron capture and multiple scattering are shown as blue and green dashed lines, respectively, both calculated for p=$7 \cdot 10^{-11}$ mbar. The total lifetime of these resulting from two processes is displayed with a solid red line. As indicated in figure 6, multiple scattering dominates at higher energies of 70 MeV and at low energies around 10 MeV electron capture is the determining process for the final energy of 9.7 MeV when the lifetime has the minimum value

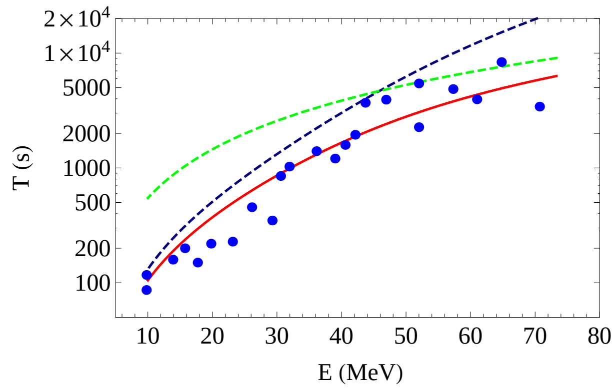

Figure 6: Measured lifetime of the $^{12}C^{6+}$ beam for different energies. The green dashed line is the lifetime taken into account multiple scattering, whereas the blue dashed line represents the electron capture lifetime. The red solid line is the total lifetime calculated for p=$7 \cdot 10^{-11}$ mbar.

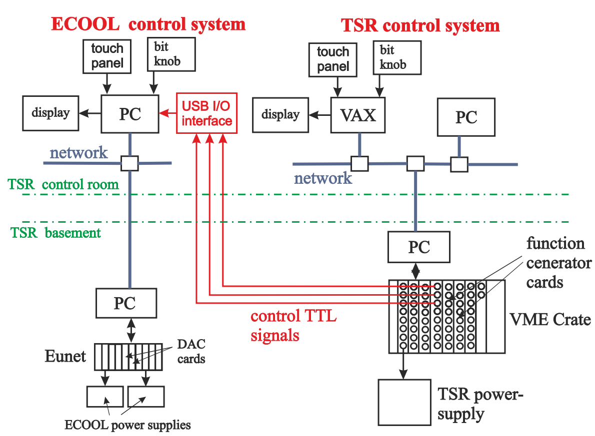

Figure 7: Schematic drawing of the TSR and ECOOL control system modification to enable electron cooling at various energies in the deceleration cycle.

of about 100 s was measured. Consequently, the losses during the deceleration time of 7 s coming from the interaction with the residual gas much less than 1 % and are, thus negligible.

MODIFICATION OF THE CONTROL SYSTEM

In the deceleration cycle, at least two cooling steps at the initial and final energy, when the experiment takes place, are necessary. This means the electron cooler has to operate at different settings during the deceleration cycle, requiring an extension of the electron cooler control system. To enable a cooler operation at different settings an USB I/O card is added to the ECOOL user interface computer (compare figure 7), containing the database of the electron cooler settings. The I/O card is connected via an USB bus with the ECOOL computer. An additional three control cables connect the I/O card with three function generators of the TSR control system. Those create the ramps controlling the TSR power supplies and three TTL control signals for the ECOOL computer. If one of the three control signals changes its value, the ECOOL computer loads a new data base, according to the TTL values of the three control signals. Eight different data bases of the electron cooler settings can be loaded because 3 digital control signals are used.

CONCLUSION

Experiments to decelerate $^{12}C^{6+}$ ions from 73.3 MeV to 9.7 MeV (1 MeV/u), which corresponds to a rigidity decrease from 0.71 Tm to 0.26 Tm, were conducted where a reduction of the beam energy was by a factor of > 7. To achieve an efficiency of 87.5% from deceleration, an electron pre-cooling is required. The cooling results in a dense ion beam where IBS effects have to be taken into account to describe the development of the ion beam width during deceleration. We proposed the approximated equation (10) to explain the beam width during the deceleration process which is consistent with the observation.

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