Advanced Stacking Methods Using Electron Cooling at the TSR Heidelberg

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Abstract

Using the new method of beam accumulation by stacking with electron cooling intensities were enhanced by factors of several thousands compared with single turn injection. With electron cooler stacking a current of 18 mA (3 \times 10^{10} \text{ particles}) for 1^{2}C^{6+} \text{ ions} (E = 73.3 \text{ MeV}) was achieved.

Introduction

In order to accumulate heavy ions in the Heidelberg Test Storage Ring TSR [1], multiturn injection is used. With the application of multiturn injection, the horizontal machine acceptance can be filled in typically 200\mu s. In order to inject more particles, the already filled phase space must be emptied of particles, which can be accomplished by phase space compression by electron cooling. Phase space needed for a new multiturn injection is thus made available (see fig. 1).

\[ \frac{dI}{dt} = n_s I_m - \lambda I \]  \hspace{1cm} (1)

where \( n_s \) is the repetition rate, \( I_m \) the effectively stored current of a multiturn injection and \( 1/\lambda \) is the beam lifetime. The solution of the differential equation (1) is:

\[ I = I_0 (1 - e^{-\lambda t}) \]  \hspace{1cm} (2)

\[ I_0 = n_s I_m / \lambda \]

The current \( I_m \) depends on the the injector current \( I_e \) with \( I_m = M \cdot I_e \), where \( M \) is the intensity multiplication factor with multiturn injection. The total intensity multiplication factor \( N = I_0 / I_e \) is thus given by:

\[ N = n_s M / \lambda \]  \hspace{1cm} (3)

In the following sections, parameters important for ECOOL-stacking will be discussed.

The Lifetime \( 1/\lambda \)

In order to calculate the intensity multiplication factor \( N \) of ECOOL stacking, the beam lifetime of the ions must be known. The main processes which affect the lifetime of the ions are electron capture in the residual gas and in the electron cooler, as well as stripping reactions and single scattering. Multiple scattering does not play a role since it is compensated by electron cooling. Table 1 shows measured lifetimes. For protons a lifetime without electron cooling of 3 hours was reached whereas with electron cooling the lifetime increased to 36 hours. The cause for this increase by more than one order of magnitude is the compensation of multiple scattering. A lifetime of approximately 15 s was achieved with \( Li^+ \) and \( Be^+ \). The reason for these short lifetimes are stripping reactions in the residual gas. With increasing charge of the ions the cross sections of the capture processes increase. The main processes affecting the lifetime, for example with \( ^{35}Cl^{17+} \text{ ions} \), are electron capture in the residual gas and electron capture in the electron cooler.
Table 1: Measured lifetimes for cooled and uncooled ions.

<table>
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<tr>
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</tr>
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<td>196</td>
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<td>35Cl17⁺</td>
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The Intensity Multiplication Factor $M$

An intensity multiplication factor as large as possible is desirable with ECOOL stacking. The factor $M$ depends on the phase space that is available for the multturn injection (see fig.1). The spatial diameter of the electron cooler compressed phase space during multturn injection is designated by $D_k$. $D_0$ is the maximum beam diameter which should be equal to the electron beam diameter (5 cm) at the position of the cooler. $D_k$ is chosen using the following criterion: $D_k = D_0/2$. The filling of the phase space was investigated under this condition with a simulation program. A value for the emittance of the injected beam from the tandem-postaccelerator combination after three stripping processes of $5 \cdot \pi \cdot \text{mm} \cdot \text{mmrad}$ was used in the calculations. The horizontal tune $Q_z$ of the TSR was selected between 2.6 and 2.9. Investigations of the phase space filling were made for different tunes between 2.6 and 2.9 resulting in an average value of $M = 15$.

The Repetition Rate $n_r$

The repetition rate $n_r$ for the multturn injection depends on the time $T$ which is necessary for the electron cooling to clear the available phase space for the multturn injection ($n_r = 1/T$). $T$ is the time necessary to reduce the beam cross section from $D_0$ to $D_k$. In order to calculate $T$, the damping decrement $\lambda_\perp$ of the electron cooling is needed and defined by the following relation:

$$\frac{dD}{dt} = -\lambda_\perp D$$

(4)

The damping decrement $\lambda_\perp$ was investigated by a Novosibirsk group [2]. They found the following semi-empirical formula for protons:

$$\lambda_\perp = \frac{12 \pi \sqrt{\pi} \frac{\tau}{r} \tau \gamma \eta c^4 \eta}{((\alpha_0 \beta_0) c^2 + \sigma^2_{\perp} + 11 \sigma^2_{\parallel}) \sqrt{\Delta^2 + \sigma^2_{\perp} + \sigma^2_{\parallel}}}$$

(5)

with $\Delta^2 = 2kT_e/m_e$

where:
- $r_\perp$: classical electron radius
- $r_\parallel$: classical proton radius
- $\gamma$: relativistic mass increase (TSR energies, $\gamma = 1$)
- $n_e$: electron density
- $\eta$: ratio of the effective length of the electron cooling to the circumference of the storage ring
- $\alpha_0$: error in the alignment of the electron beam to the ion beam as well as magnetic field errors
- $\beta_0 \cdot c$: particle velocity
- $\sigma_{\perp}$: transverse velocity spread of the ions
- $\sigma_{\parallel}$: longitudinal velocity spread of the ions
- $\Delta^2$: velocity spread of the electron beam
- $k$: Boltzmann constant
- $m_e$: electron mass
- $T_e$: transversal electron temperature; $T_e = 930^\circ\text{C}$ at the TSR.

In a theoretical description [3] of the cooling process $\lambda_\perp$ depends on the ion charge $Z$ and mass number $A$ as follows:

$$\lambda_\perp \sim Z^2/A$$

This means that the cooling decrement $\lambda_\perp$ can be estimated for ions when the classical proton radius $r_\parallel$ is replaced by the classical ion radius $r_i$, with $r_i = Z^2/A \cdot r_\parallel$. The transverse velocity spread $\sigma_{\perp}$ of the ions in the electron cooler can be calculated approximately from the beam diameter $D$, the $\beta$-function in the cooler: $\beta_{cool}$ and the ion velocity $v_0$:

$$\sigma_{\perp} = v_0 \cdot D/(2 \cdot \beta_{cool})$$

If one considers different bare ions with equal magnetic rigidity one finds that all ion species have the same velocity spread $\sigma_{\perp}$ after multturn injection. Since $A \approx Z$, the cooling decrement as well as $n_r$ scale with $Z$ ($\lambda_\perp \sim Z, n_r \sim Z$). If the ions have a magnetic rigidity of 0.7 Tm, the electron density is $3 \cdot 10^{13}$ m⁻³ at an electron cooler perveance of 1.6 μPerv. With this, one obtains for $D_k = D_0/2$: $n_r \approx 0.15 \cdot Z$ Hz.

The Total Multiplication Factor $N$

Calculated values for the total intensity multiplication factor $N$ are shown in curve a of figure 2 for bare ions ($A = 2 \cdot Z$) with $D_k = D_0/2$, $M = 15$, $r = 6 \cdot 10^{-11}$ mbar and $B = 0.7$ Tm. For light ions one finds an intensity multiplication factor of the order of $10^5$. This factor certainly cannot be reached since instabilities will occur. For example, with a $^{12}$C⁶⁺ beam ($B = 0.71$ Tm) instabilities were observed between 5 mA and 18 mA. $N$ decreases continuously with $Z$ because of the decreasing lifetime and should approach $10^2$ at the atomic number $Z = 25$ ($r = 6 \cdot 10^{-11}$ mbar, $D_k = D_0/2$, $M = 15$). These intensity multiplication factors should in principle be achievable for an optimum setup of the machine parameters when no instabilities occur. A lower limit for $N$ can be estimated if a value of $\lambda_\perp = 1$ and the value $n_r$ for $D_k = 0.05 \cdot D_0$ are substituted into equation (4). Curve b of figure 2 shows the results of these calculations. $N$ should reach a value of $10^3$ for light ions and for $Z = 20$, a value of $N = 500$ at least should be obtainable.
Experimental Results

Stacking experiments were carried out with the condition that the electron velocity was equal to the ion velocity, for example with $^{32}$S$^{16+}$ ($B \cdot p = 0.7 T_m$) a factor $N \approx 4000$ was obtained. Besides the above described ECOOL stacking experiment, where the electron velocity is set equal to the ion velocity, other variations of the ECOOL stacking are used in the Heidelberg Test Storage Ring. In those experiments, the electron velocity is selected slightly lower than the ion velocity (typically $\Delta v/v = -0.5\%$). The ions will thus be pulled inwards because of the dispersion available at the injection point and the distance between the stack and the electrostatic septum (accumulated particles) will increase. Figure 3 shows a Schottky spectrum that was taken during this accumulation process. The successively injected multturn batches are decelerated by the electron beam to the stack position. ECOOL stacking can also be combined with RF stacking. With this method, a current of 18 mA for $^{12}$C$^{6+}$ ions ($E = 73.3$ MeV) was reached. The modulated frequency of the RF cavity decelerates the ions in this case filling the longitudinal phase space and bring-

![Figure 2](image_url)

**Figure 2:** a) Calculated intensity multiplication factor $N$ with $A = 2 \cdot Z$, $M = 15$, $p = 6 \cdot 10^{-11}$ mbar $D_k = D_0/2$. b) calculated with the following parameters: $M = 1$, $p = 6 \cdot 10^{-11}$ mbar, $D_k = 0.05 \cdot D_0$.

![Figure 3](image_url)

**Figure 3:** Schottky-noise spectrum illustrating the process of beam accumulation of multturn batches by deceleration and cooling with the electron beam.

![Figure 4](image_url)

**Figure 4:** Schematic description of the combination of ECOOL and RF stacking.

Table 2: Achieved intensities for a few ion species with different methods of injection.

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<tr>
<th>Ion</th>
<th>Energy [MeV]</th>
<th>Intensity [$\mu$A]</th>
<th>Injection Method</th>
<th>Limitation</th>
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Acknowledgement

We gratefully acknowledge the skillful and enthusiastic work of the technicians of the Max-Planck-Institute.

References