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 ($3 \cdot 10^{10}$ particles) for $^{12}C^{6+}$ ions (E = 73.3 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).

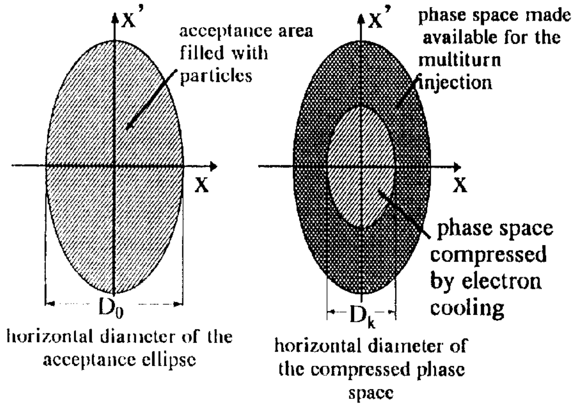

Figure 1: *Schematically the compressed phase space during multiturn injection with electron cooling and the phase space which is available for the multiturn injection is represented.* D_0 *gives the spatial diameter of the acceptance ellipse and* D_k *that of the compressed phase space.*

When this process is repeated several times, a large intensity multiplication factor is obtained. This intensity multiplication factor is defined as the ratio of the stored to the injected current. With the use of this stacking method - called ECOOL stacking hereafter - the stored intensity I increases with time as:

$$\frac{\mathrm{d}I}{\mathrm{d}t} = n_r I_m - \lambda I \tag{1}$$

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

$$\begin{aligned} I &= I_0(1 - e^{-\lambda t}) \\ I_0 &= n_r I_m/\lambda \end{aligned} \tag{2}$$

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:

$$N = n_r M/\lambda \tag{3}$$

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 $^{35}Cl^{17+}$ ions, are electron capture in the residual gas and electron capture in the electron cooler.

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Table 1: *Measured lifetimes for cooled and uncooled ions.*

Ion	Energy [MeV]	Pressure 10^{-11} [mbar]	cooled [s]	uncooled [s]
p	21	8	130000	11000
$^{7}Li^{+}$	13	6	—	18
$^{9}Be^{+}$	7	6	16	16
$^{12}C^{5+}$	52	40	11	10
$^{12}C^{6+}$	73	6	7470	—
$^{16}O^{6+}$	54	20	16	14
$^{16}O^{8+}$	98	50	260	200
$^{28}Si^{14+}$	115	6	540	260
$^{32}S^{16+}$	196	5	450	—
$^{35}Cl^{17+}$	202	6	318	366
$^{63}Cu^{26+}$	510	6	122	—

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 multiturn injection (see fig.1). The spatial diameter of the electron cooler compressed phase space during multiturn 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 $5 \cdot \pi \cdot mm \cdot mrad$ was used in the calculations. The horizontal tune Q_x 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 multiturn injection depends on the time T which is necessary for the electron cooling to clear the available phase space for the multiturn injection ($n_r = 1/T$). T is the time necessary to reduce the beam cross section from D_O 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:

$$\frac{\mathrm{d}D}{\mathrm{d}t} = -\lambda_\perp D \tag{4}$$

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

$$\lambda_\perp = \frac{12\,\pi\sqrt{\pi}\,r_e r_p \gamma n_e c^4 \eta}{\left((\alpha_0\beta_0 c)^2 + \sigma_{v\perp}^2 + 11\sigma_{v\|}^2\right)\sqrt{\Delta_e^2 + \sigma_{v\perp}^2 + \sigma_{v\|}^2}} \tag{5}$$

$$\text{with} \qquad \Delta_e^2 = 2kT_e/m_e$$

where:

r_e	classical electron radius
r_p	classical proton radius
γ	relativistic mass increase (TSR energies, $\gamma = 1$)
n_e	electron density
η	ratio of the effective length of the electron cooling to the circumference of the storage ring
α_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
$\sigma_{v_\perp}$	transversal velocity spread of the ions
$\sigma_{v_\|}$	longitudinal velocity spread of the ions
Δ_e	velocity spread of the electron beam
k	Boltzmann constant
m_e	electron mass
T_e	transversal electron temperature T_e is approximatly 930^oC 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_p is replaced by the classical ion radius r_i, with $r_i = Z^2/A \cdot r_p$. The transverse velocity spread $\sigma_{v_\perp}$ of the ions in the electron cooler can be calculated approximately from the beam diameter D, the β−function in the cooler: β_{ecool} and the ion velocity v_0 : $\sigma_{v\perp} = v_0 \cdot D/(2 \cdot \beta_{ecool})$.
If one considers different bare ions with equal magnetic rigidity one finds that all ion species have the same velocity spread $\sigma_{v\perp}$ after multiturn injection. Since $A \approx 2 \cdot Z$, 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 $3.4 \cdot 10^{13}$ m^{-3} at an electron cooler perveance of $1.6 \mu Perv$. 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 $D_k = D_0/2$, $M = 15$, $p = 6 \cdot 10^{-11}$ mbar and $B \cdot \rho = 0.7$ 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 $^{12}C^{6+}$ beam ($B \cdot \rho = 0.71$ Tm) instabilities were observed between 5 mA and 18 mA. N decreases continously with Z,because of the decreasing lifetime and should approach 10^4 at the atomic number $Z = 25$ ($p = 6 \cdot 10^{-11}$ 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 $M = 1$ 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 10^4 for light ions and for $Z = 20$, a value of $N = 500$ at least should be obtainable.

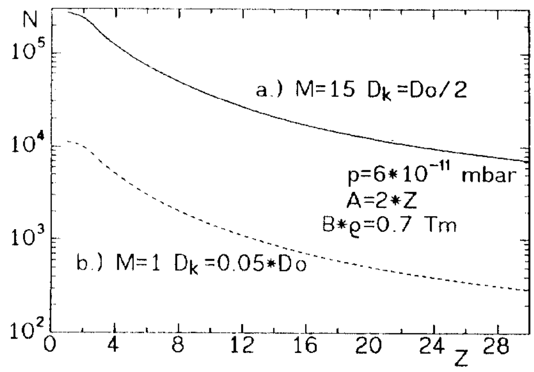

Figure 2: *a) Calculated intensity multiplication factor N with* $A = 2 \cdot Z$, $M = 15$, $p = 6 \cdot 10^{-11}$ *mbar* $D_k = D_0/2$. *b) calculated with the following parameters:* $M = 1$, $p = 6 \cdot 10^{-11}$ *mbar,*$D_k = 0.05 \cdot D_0$.

Experimental Results

Stacking experiments were carried out with the condition that the electron velocity was equal to the ion velocity, for example with $^{32}S^{16+}$ ($B \cdot \rho = 0.7$Tm) 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 multiturn 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 bringing the ions closer to the detuned electron velocity (fig. 4). In table 2 the achieved intensities are listed for various ions, as well as the applied injection scheme: MU labels multiturn injection only, EC is ECOOL stacking and EC+RF is a combination of ECOOL and RF stacking. There is also listed whether an equilibrium has been reached between the injection rate and particle loss (EQ) or if an instabilility (IN) occured with the given current. One sees that with $^{9}Be^{+}$ and $^{7}Li^{+}$ only a relatively low current can be stored because ECOOL stacking can't be attempted with these ions due to the small lifetime and cooling force.

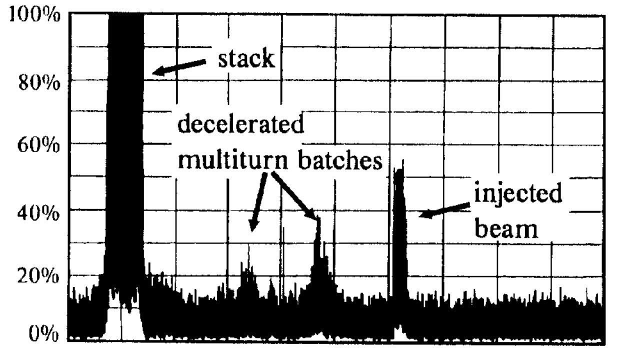

Figure 3: *Schottky-noise spectrum illustrating the process of beam accumulation of multiturn batches by deceleration and cooling with the electron beam.*

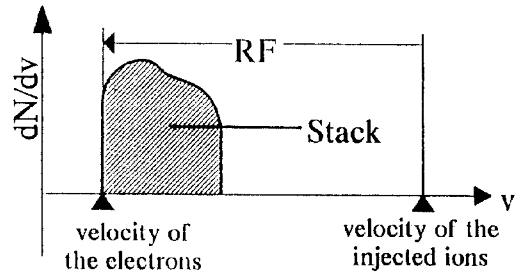

Figure 4: *Schematic description of the combination of ECOOL and RF stacking*

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

Ion	Energy [MeV]	Intensity [μA]	Injection Method	Limitation
p	21	2400	EC	IN
$^{7}Li^{+}$	13	4	MU	-
$^{9}Be^{+}$	7	6	MU	-
$^{12}C^{6+}$	73	18000	EC+RF	IN
$^{32}S^{16+}$	195	1500	EC	EQ
$^{35}Cl^{15+}$	157	400	EC	EQ
$^{35}Cl^{17+}$	202	650	EC	IN
$^{63}Cu^{26+}$	510	110	EC	EQ

Acknowledgement

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References

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