Bunch Compression in the Heavy Ion Synchrotron SIS at GSI

K. Blasche, O. Boine-Frankenheim, H. Eickhoff, M. Emmerling, B. Franczak,
I. Hofmann, K. Kaspar, U. Ratzinger, P. Spiller
Gesellschaft für Schwerionenforschung (GSI)
Planckstr. 1, 64291 Darmstadt, Germany

Abstract

Heating matter by heavy ion beams is a central aim of the plasma physics group at GSI. In order to maximize the energy deposition of the beam the total number of ions has to be captured in a single bunch with a pulse length as short as possible. Here we present first experimental results on the pulse compression in the SIS with the existing RF cavities. First the initially four bunches are recaptured adiabatically and then compressed by means of a fast bunch rotation. In the framework of the SIS high intensity upgrade we plan to compress $1 \cdot 10^{11}$ U^{28+} ions at 200 MeV/u to a final bunch length of 50 ns. Here we present simulations of the compression scheme under the influence of the space charge and the impedance of the new RF buncher cavity. The layout of the new cavity, which should operate at a peak voltage of 200 kV, is given.

1 INTRODUCTION

Heavy ion beams can be used to concentrate terawatt power on experimental targets and to produce dense plasma matter. Experiments with dense plasma are of general scientific interest and they also play a more technical role in the development of inertial confinement fusion.

GSI has started a small research program in this field. The explosion of a cylindrical lead target, which was heated by one 300 ns long SIS bunch with $2 \cdot 10^{10}$ argon ions to a temperature of about 0.5 eV was reported in [1]. Further progress is planned for the year 2000, when the new high current injector linac at the front end of the UNILAC will be available. In the best case we expect to compress $1 - 2 \cdot 10^{11}$ U^{28+}-ions within one single short bunch [2]. Effective heating with high intensity beams requires a rather short pulse width of 50 ns, since the deposition of ion beam power has to take place before the plasma matter starts to expand effectively. In Fig. 1 we show for $1 \cdot 10^{11}$ uranium ions at 200 MeV/u impinging on a heavy gold target the specific energy deposition, which depends on the beam spot diameter. The resulting plasma temperature is in the range of 10 eV. The characteristic heating time defines the necessary bunch width.

At present high intensity heavy ion beams with the required bunch width of about 50 ns are not available at the SIS. Therefore a machine development program was started to supplement the present RF system by the installation of additional RF cavities for operation at an RF amplitude of about 200 kV.

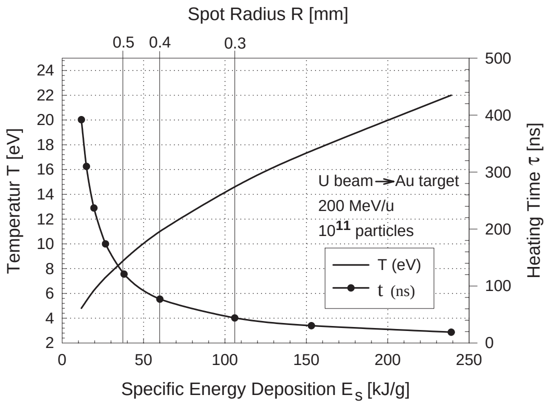

Figure 1: The specific energy deposition, which depends on the beam spot diameter, for $1 \cdot 10^{11}$ uranium ions at 200 MeV/u impinging on a heavy gold target.

2 STATUS OF MACHINE EXPERIMENTS

Bunch compression in the SIS is a two step process : first one has to combine the four bunches, which result from the usual acceleration at harmonic number h=4, into one single bunch, and finally the resulting bunch has to be transformed into a very short bunch, e.g. by a rotation in the longitudinal phase space. For the bunch combination two ways are open, i.e. the straightforward method of adiabatic debunching and subsequent rebunching at harmonic number h=1, and also a two step bunch merging process leading from four bunches via two bunches to finally one single bunch. The debunching and rebunching procedure is in use at the SIS since March 1997. At the end of any adiabatic RF bunching process the pulse length l is determined by the relation $l \sim V^{1/4}$. For a RF voltage of 14 kV the measured bunch length is typically of the order of 500 ns.

A more effective way to produce short bunches is the process of fast bunch compression with a 90^o rotation of the longitudinal phase space ellipse. If an RF voltage jump from V_i to V_f is applied for the fast bunch compression of an ellipse with the initial momentum spread $\Delta p/p_0$ the resulting final bunch length is defined by

$$l_f \sim \sqrt{A/q \cdot (V_i/V_f)} \cdot \Delta p/p_0$$

In contrary to the adiabatic capture process, where the voltage rise time has to be a several times the synchrotron period, at fast compression the final voltage has to be reached as fast as possible. With the existing SIS cavities a rise time of 150 μs can be achieved, which is sufficiently short compared to a synchrotron period of about 1 ms. First machine experiments on fast bunch compression with a parallel operation of both available RF cavities were performed in November 97 in the SIS. The maximum available total RF voltage was 32 kV at a frequency of about 1 MHz.

Beside beam dynamics measurements important machine parameters like the behavior of the RF system at a fast voltage jump e.g. the RF phase stability could be studied. Especially the bunch current oscillation was observed over many revolutions of the longitudinal phase space. The typical evolution of the ring current at fast bunch compression is shown in Fig. 2.

In order to use the total available RF voltage most effectively the prebunching amplitude was taken as low as possible. This yields a certain amount of nonlinearities acting on the beam particles in the edges of the initial bunch. Without any prebunching about half of the beam current is not being captured in the RF bucket and forms a dc offset socket. However the captured fraction of particles is compressed to a very short bunch with a width of less than 100 ns.

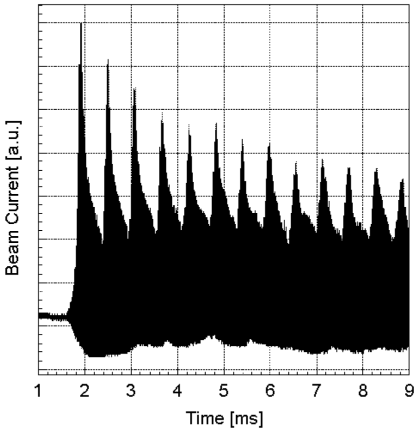

Figure 2: Evolution of the ring current after a fast voltage jump starting from a coasting beam.

In order to measure the fraction of non-captured particles it was necessary to extract the bunch at the time of maximum compression. A fast beam current transformer just before the experimental area of the plasma physics group could be used to determine the longitudinal bunch profile (Fig. 3).

With respect to the space charge coupling to the longitudinal impedances of the RF cavities a debunched beam behaves most sensitive. Therefore it is planned to avoid the coasting beam phase after acceleration and envisage a bunch merging process [3] to generate the single bunch.

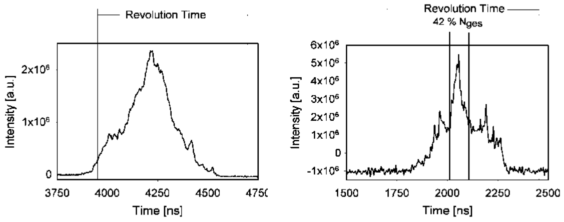

Figure 3: Beam transformer signal of an extracted single bunch after adiabatic (left picture) and fast (right picture) compression respectively.

3 MACHINE THEORY

We employ a Particle-In-Cell (PIC) code [4] to simulate the compression of $1 \cdot 10^{11}$ U^{28+} in the SIS. The code typically tracks 50000 macro particles self-consistently in the electric fields caused by space charge and the RF cavity. The two subsequent bunch merging steps ($4 \rightarrow 2$, $2 \rightarrow 1$) have to be performed under the influence of the beam loading field induced in the SIS RF cavities and acting back on the beam. Here we assume that the total shunt impedance seen by the beam on $h = 1$ is $R_s = 10$ kΩ. For the final merging step the RF amplitude V_i on $h = 1$ has to be much larger than the beam loading voltage. The simulation shows that above V_i=20 kV the resulting bunch is sufficiently centered for the following fast bunch rotation.

A bunch rotation immediately following the merging process would be inefficient due to the high RF amplitude V_0 needed on $h = 1$ for the last merging step. This can be easily seen by reconsidering that the compression ratio for a fast bunch rotation caused by an RF amplitude jump from V_i to V_f is $l_i/l_f = (V_f/V_i)^{1/2}$, with the initial and the final bunch lengths l_i, l_f. After the merging we therefore reshape the bunch in longitudinal phase space by two subsequent 180^0 RF phase jumps. The first jump is used to stretch the bunch in the linear part of the RF potential. The bunch is rotated back by means of the RF potential with the original RF phase. We simulate this process for V_i=20 kV with our PIC code. Here we stretch the bunch for 150 μs with the phase shifted RF amplitude. The original phase is applied for 200 μs, before the bunch is compressed by means of an RF jump to 200 kV.

The complete scenario is given schematically in Fig. 4. In Fig. 5 the resulting compressed bunch is shown. About 80 % of the beam ions can be collected in a pulse of $\tau_{\mathrm{FWHM}} = 53$ ns duration. The bunch is slightly shifted backwards due to the influence of the beam loading.

If the impedance seen by the beam on $h = 1$ can be reduced well below 5 kΩ the bunch merging followed by the RF phase gymnastics can be avoided. We can simply debunch the beam and rebunch adiabatically on $h = 1$ with V_i=2 kV. The following RF jump to 200 kV leads to a similar result. Above 5 kΩ the longitudinal instability together with RF phase instability during the adiabatic recapture leads to a rapid blow-up of the longitudinal phase space.

For our scenario we assumed an initial momentum spread after acceleration of $\Delta p/p_0 = \pm 5 \times 10^{-4}$ of the equivalent coasting beam. For the fast bunch rotation the scaling is $l_f \sim \Delta p/p_0$. We might still get a major improvement of the bunch lengths if we find and remove all sources of longitudinal phase space blow-up during injection and acceleration and incorporate the SIS electron cooler in our scenario. First theoretical results on the electron cooling of the low energy coasting beam after injection into the SIS look promising, further more detailed investigations are necessary.

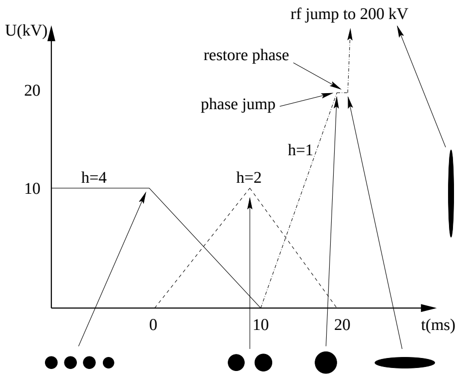

Figure 4: The bunch compression scenario for the SIS under the presence of a high shunt impedance ($R_s \approx 10$ kΩ) on $h = 1$.

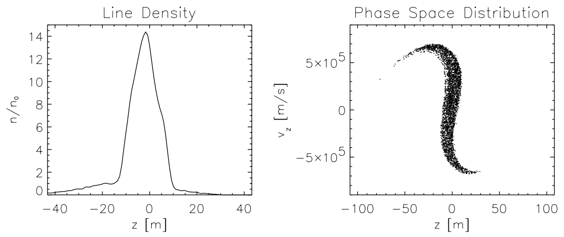

Figure 5: Line density and the longitudinal phase space plot of the final bunch.

4 MACHINE DEVELOPMENT PROGRAM

At first it is planned to check and improve the steps, which are essential for an effective bunch compression scheme at intensities of 10^{11} heavy ions:

- Optimization of RF capture and acceleration in order to provide the minimal initial momentum spread $\Delta p/p_0$. It will be also checked, if electron cooling in the SIS can help to reduce the momentum spread.
- Test of the $4 \rightarrow 2 \rightarrow 1$ bunch merging process.
- Test and improvement of the fast bunch rotation in the SIS.

According to theory we expect with the available total voltage V_f=40 kV a pulse width $\tau \simeq 90$ ns for heavy ion beams, if we assume the measured momentum spread of $\Delta p/p_0 = 0.0005$ (FWHM). It is planned to verify the theoretical results with further machine experiments.

In addition, a new RF system is under study, which shall operate at a total RF voltage of about 200 kV. The corresponding parameter list is summarized in Table 1. The frequency tuning range around 800 kHz is matched to the operating energy of 200 MeV/u, which is foreseen for SIS operation with short bunches. The duty cycle is very low compared to the standard RF system. Several modifications of the SIS cavities are under study in order to approach the high RF voltage of about 50 kV for each cavity:

- Galvanic RF coupling at an adequate position on the inner conductor will be used to match the anode voltage of the tube to the RF voltage of the cavity.
- Either NiZn-ferrite or metallic glass materials may be used as high permeability inductive load.
- A longitudinal instead of the usual circular magnetic bias field may be used.

Table 1: Parameters for a new RF system

		SIS RF	New RF
Resonator		push-pull	single gap
Total length	(m)	2.9	1.1
Tuning range	(MHz)	0.85-5.4	0.75-1.0
RF amplitude	(kV)	16	50
Duty cycle	(%)	100	0.1
Peak power	(kW)	40	800
Mean power	(kW)	40	0.8
Impedance	(kΩ)	3.2	1.6

Acknowledgment : For supporting the measurements we thank P. Moritz and the plasma physics group.

5 REFERENCES

[1] GSI Sc. Report 1997 (1998) 125

[2] GSI Report GSI-96-07 (1996)

[3] I. Bozsik *et al.*, Proc. of *Computing in accelerator design and operation*, Berlin 1983 (128)

[4] C.K. Birdsall, A.B. Langdon, *Plasma Physics via Computer Simulation*, IOP Publishing 1991