FAST COMPRESSION OF INTENSE HEAVY-ION BUNCHES IN SIS-18

Oleksandr Chorniy, Oliver Boine-Frankenheim, Peter Hülsmann, Peter J. Spiller,
GSI, Planckstr. 1, 64291 Darmstadt, Germany

Abstract

At GSI and for the FAIR project short heavy-ion bunches are required for the production and storage of exotic fragment beams as well as for plasma physics applications. In the SIS-18 and in the projected SIS-100 synchrotron longitudinal compression via fast bunch rotation is performed directly before extraction. In order to arrive at the required bunch length the rf cycle has to be optimized for high intensities to avoid the blowup of the occupied longitudinal phase space area. We will discuss experimental and simulation results of the rf capture at injection energy, the rebunching process at the final energy and the subsequent bunch rotation.

INTRODUCTION

Bunch compression with fast beam extraction to the experimental areas is used routinely in the SIS-18. The compression is done via 90^0 fast rotation of the bunch longitudinal phase space distribution. The phase space rotation is initiated by fast jump of RF voltage amplitude.

A first report describing the strategy to obtain high density beams in the SIS-18 was published in 1996 [1]. Early experiments on fast bunch compression with a parallel operation of two RF cavities were done in 1997 [2]. Two ferrite cavities with total available voltage of 32 kV at a frequency of 1 MHz were used. The resulting compressed Ar^{11+} bunch containing $1 \cdot 10^{10}$ particles at the energy 200 MeV/u had the total length of about 350 ns.

For the plasma generation using, the required compressed beams should not exceed 50 ns [3]. In order to calculate the required RF parameters at compression simulation studies were done [3]. The bunch compression should be performed at the voltage amplitude of 200 kV. The layout of the compression system consisting of several magnetic-alloy compressor cavities was described in [4]. Later, due to a restriction of the available resources it was planned to install only one cavity. In 2008 one magnetic alloy compressor cavity with 40 kV voltage amplitude was installed in the SIS-18 and the first test measurements were done at injection energy [5].

The RF system in SIS-18 consists presently of two ferrite cavities and one magnetic alloy bunch compressor cavity. In Table 1 the main parameters of the RF system in the SIS-18 are presented. The ferrite cavities are used for the RF capture and acceleration and the magnetic alloy cavity is used only for the bunch compression. The RF amplitude cycle in the SIS-18 consists of the RF capture with acceleration at h=4, de-bunching to coasting beam, RF recapture at h=1 and bunch compression (Fig. 1). The recapture process is done by a linear ramp of the RF amplitude from 0 till final recapture amplitude.

Table 1: Parameters of SIS-18 RF System

	SIS cavity	**Compressor**
Inductive Load	Ferrites	Magnetic Alloy
Frequency tuning range, MHz	0.85-5.4	0.85-0.9
Peak RF-voltage, kV	16	40
Pulse duration, ms	$>$100	0.5
Voltage rise time, μs	150	10

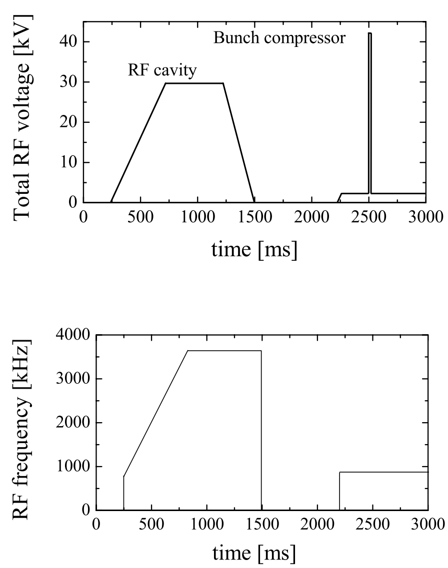

Figure 1: Scheme of the SIS-18 RF cycle with fast bunch compression.

Recently the measurements on the bunch compression at extraction energy using magnetic-alloy compressor cavity were done. Using the measurements results we try to investigate the possible issues and solutions. One of the problem considered here as well is the RF capture in the beginning of the machine cycle. Usually the RF amplitude ramp in the SIS-18 is done simultaneously with acceleration in the beginning of the acceleration ramp. In such situation the RF bucket in the beginning of RF capture should be sufficiently large in order to contain most particle inside. On the other hand the large initial RF bucket produce increase of the longitudinal emittance. If we consider low intensity beams then for the longitudinal emittance conservation it is better to divide RF amplitude ramp and acceleration in two stages. Then, at low energy and high intensities the space charge effects become important in both longitudinal and transverse planes. Here we investigate the effect of RF amplitude ramp in longitudinal plane at constant injection energy with longitudinal space charge field. In this work the space charge factor Σ will be used to define the space charge effects [6].

BUNCH COMPRESSION IN THE SIS-18 AT EXTRACTION ENERGY

Recently, measurements of the bunch compression at extraction energy in the SIS-18 were done in order to identify the issues restricting the final bunch length. Beam and RF system parameters during the measurements on recapture and consecutive compression are presented in Table 2. The maximum space charge factor obtained during the measurements was too low to produce significant effects on compression process [7, 8]. Thus, these effects were not included in the simulations study and in the tomography reconstruction which will be discussed in this section.

Table 2: Beam and RF System Parameters during the Measurements of Bunch Compression

Ion	U^{73+}
Extraction energy, MeV/u	295
Final recapture amplitude, kV	1-16
Recapture time, ms	6
Compression amplitude, kV	38
Σ in the compressed bunch	0.01

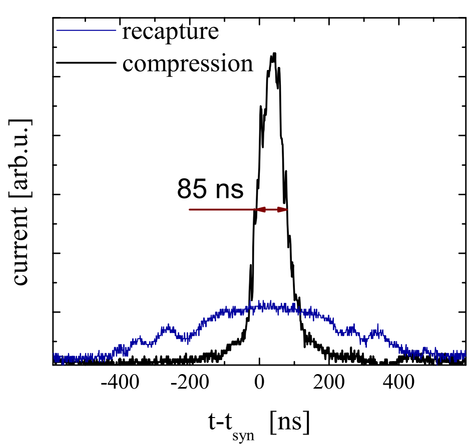

Figure 2: Measured longitudinal bunch profiles before and after compression.

In Fig. 2 the longitudinal beam profiles before and after compression are presented. The profile before compression is measured in the end of the recapture with the final recapture amplitude of 1 kV. The compressed bunch length for the measurement presented in Fig. 2 is 85 ns(FWHM). The measurements were repeated for different recapture amplitudes and the resulting compressed bunch lengthes were measured (Fig. 3).

In general, the performance of the fast bunch compression can be proved by checking the validity of the relation:

$$\frac{\tau_{recap}}{\tau_{compr}} = \sqrt{\frac{V_{compr} + V_{recap}}{V_{recap}}}, \tag{1}$$

where τ_{recap} and τ_{compr} are the length of the recaptured and compressed bunches respectively, V_{recap} is the final recapture amplitude and V_{compr} is the amplitude provided by the compressor cavity. Since the recaptured bunch profile was significantly distorted it was not possible to obtain the recaptured bunch length properly. The reason for this distortion was the mismatch of the RF frequency with respect to the beam energy at the start of recapture.

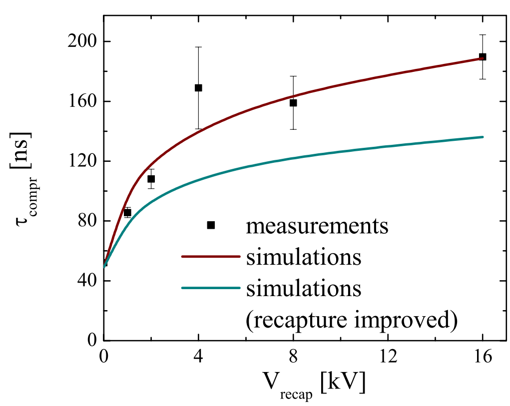

Figure 3: Comparison of the compressed bunch lengthes from measurements and simulations. The simulations were done for two cases: under the same conditions as in the measurements and under improved conditions, where the frequency offset was removed and the recapture time was increased.

To understand the measurements the numerical simulations of the recapture and compression were performed. Simulations were done using a longitudinal PIC code developed at GSI [9]. In Fig. 3 the compressed bunch length as a function of the recapture final amplitude is presented. Simulations were done for two cases. In first case the simulations were done with the same RF precapture parameters as in the measurements. Also in first simulation the RF frequency offset was added. The value for this frequency offset cannot be obtained from the measurements, thus we assume the offset which corresponds to one rms energy deviation. As one can see the simulation data matches well to the experimental data. This shows that the voltage seen by the beam from bunch compressor was close to 38 kV. In the second case the simulations were done without RF frequency offset and with increased recapture time of 40 ms. With improved recapture parameters the simulations show that the compressed bunch length can be decreased.

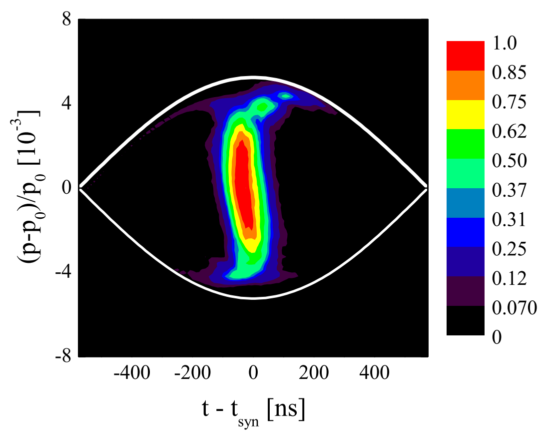

Figure 4: Phase space of the compressed bunch profile which corresponds to result in Fig. 2.

Presently, it is planned to develop the online tomography diagnostics for the reconstruction of the longitudinal phase space in bunched beams. It will be based on the tomography code developed at CERN [10]. The code was applied to the presented measurements in the SIS-18. The resulting phase space of compressed bunch presented in Fig. 4. As it can be seen the phase space distribution of the bunch has small offset from the bucket center and also non-symmetric tails distribution. The source of the distortion will be identified in future measurements.

RF CAPTURE AT LOW INTENSITIES

In addition to improving the recapture at extraction energy, the length of the compressed bunch can be improved by choosing properly the RF manipulations in the beginning of the machine cycle. Presently, the RF amplitude ramp and acceleration is done simultaneously. By comparing the coasting beam momentum spread at injection and at extraction energy it was obtained that the normalized longitudinal emittance was increased by a factor of 1.7. This significantly increases the length of the compressed bunch. In order to avoid the longitudinal emittance blowup along the cycle, the RF amplitude ramp and acceleration must be done in two consecutive steps. We consider here RF amplitude ramp at constant energy. For this case the first question is the amplitude ramping time which does not produce the longitudinal emittance increase. The second question which will be important at higher intensities in SIS-18 at injection energy is the influence of the longitudinal space charge field. The experimental and theoretical studies concerning the optimization of the RF capture using iso-adiabatic amplitude ramp with low intensity beam were done in Refs. [10, 11]. Here we will use a linear rf amplitude ramp.

The ramping time may induce an emittance increase if this time is relatively short compared to the synchrotron period. Recently the measurements were done in order to identify the reasonable RF amplitude ramping time which does not produce the longitudinal emittance increase. The measurements results were accompanied by the numerical simulation studies of RF capture at constant energy with low intensity beams. Beam and RF amplitude parameters during the measurements on RF capture are presented in Table 3. The RF amplitude was raised linearly with time.

Table 3: Beam and RF Parameters along the Measurements with on the RF Capture at Constant Injection Energy

Ion	Ar^{18+}
Injection energy, MeV/u	11.4
Initial RF amplitude, kV	0.1
Ramping time, ms	3-20
Final RF amplitude, kV	6
Σ in the captured bunch	0.05

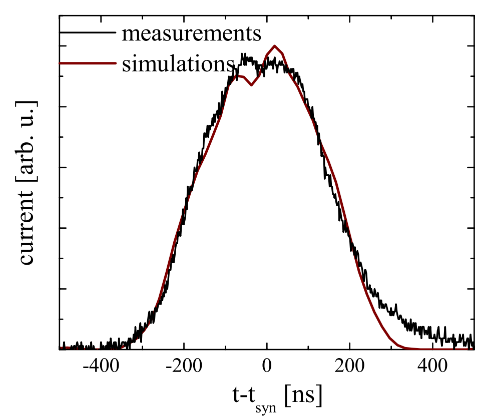

Figure 5: Comparison of the longitudinal beam profiles after RF capture in measurements and in simulations.

In Fig. 5 the longitudinal beam profile after the RF capture with 3 ms amplitude ramping time is shown as well as longitudinal beam profile produced by simulations. In order to define the most appropriate ramping time where the bunch will have the shortest bunch length the measurements and simulations were done for longer ramping times. The comparison of the measurement and simulation results is presented in Fig. 6. The rms bunch length vs ramping time are presented. The agreement between measurement and simulations data allows us to choose the value of the ramping time to be 20 ms.

In order to extrapolate these results to other beam and RF conditions the concept of the adiabaticity parameter can be used. The adiabaticity parameter μ_c for the rf amplitude ramp can be defined as:

$$\mu_c = \frac{R}{h \cdot v_m} \frac{1}{T_{ramp}}, \quad (2)$$

$$v_m = \sqrt{5}\eta\beta c \frac{dp}{p_0}_{rms}, \quad (3)$$

where R is the radius of synchrotron, h harmonic number, η momentum compaction factor, βc is the velocity of the synchronous particle in the laboratory frame, $\frac{dp}{p_0}_{rms}$ is the rms momentum spread in the coasting beam in the beginning of RF capture. Using the simulations studies it was checked that the longitudinal emittance increase depends only on adiabaticity parameter. The proper adiabaticity parameter was obtain as 0.02. This value will be used in future machine operations in order to obtain properly ramping time for RF capture at constant energy. The recapture ramping time at extraction energy will also be calculated using this adiabaticity parameter value.

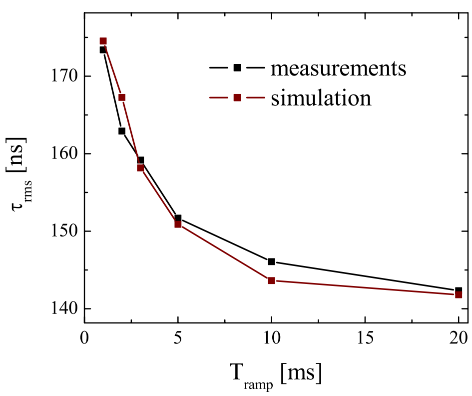

Figure 6: Comparison of the longitudinal rms bunch lengthes after RF capture in measurements and in simulations.

RF CAPTURE IN THE PRESENCE OF LONGITUDINAL SPACE CHARGE FIELD

In this section the effect of longitudinal space charge field on the longitudinal emittance during RF capture at constant energy will be discussed. Presently no significant deviation between the measurements and the simulations ignoring the space charge field were observed. In the future it is planned to increase the intensity by one order of magnitude. Using simulations with longitudinal space charge fields we observed intensity effects. The simulations were done with U^{28+} as the reference ion for the future operation in the SIS-18.

Table 4: Beam Parameters at Injection for Future SIS-18 Operation

Ion	U^{28+}
Injection energy, MeV/u	11.4
Momentum spread of coasting beam	$\pm 5 \cdot 10^{-4}$
Number of particles in the ring	$1.5 \cdot 10^{11}$
Σ in the captured bunch	1.7

In Fig. 7 the captured bunch profiles from the simulations are presented. The beam parameters were taken as in Table for the planned parameters for SIS-18 operation with U^{28+}. The amplitude ramping time for this case was 15 ms with final amplitude 5 kV in order to have bunching factor 0.33. For comparison the simulation result without space charge is presented. In this case the ramping time was 15 ms with final amplitude 2 kV. The RF amplitude in low intensity case lower since no space charge has to be compensated in order to obtain bunch with bunching factor 0.33.

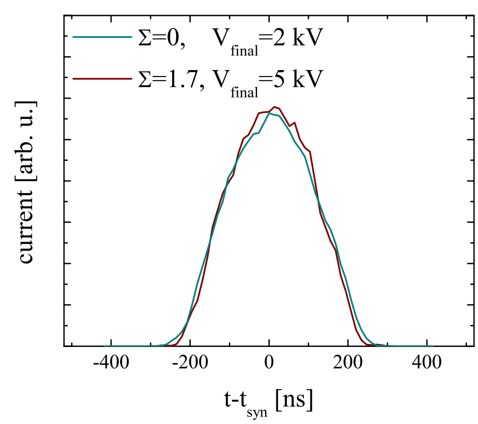

Figure 7: Simulation beam profiles after RF capture with and without the longitudinal space charge field.

The simulation were done for different amplitude ramping times and different number of particles in the ring. In Fig. 8 the simulations results are presented for the normalized longitudinal emittance after RF capture. The area restricted by the emittance equal to 1 corresponds to the optimized RF capture, i.e. with minimum longitudinal emittance at the end of RF capture. In Fig. 8 it can be noticed that with higher intensity the longitudinal space charge field tends to improve the RF capture in a sense that the RF capture can be performed faster without increase of the longitudinal emittance.

This effect can be qualitatively explained as following. In space charge dominated beams the relevant velocity is not the maximum particle velocity but the coherent velocity of space charge waves c_s, defined as in [13]. The value

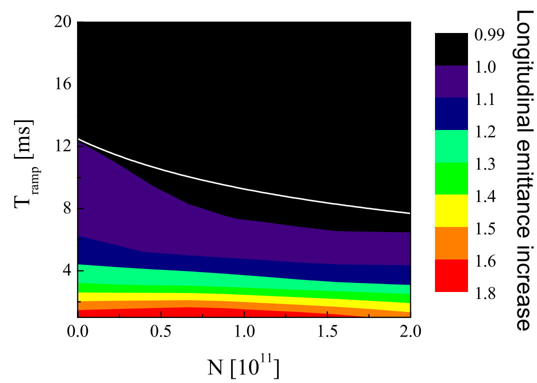

Figure 8: The simulation results for the normalized longitudinal emittance. The simulation scan was done for different amplitude ramping time and different number of particles in the ring. White line is the analytical expression Eq. 5.

of c_s increases with the number of particles. We assume here that for moderate intensities the relevant velocity can be calculated as the average of the maximum particle velocity and the velocity of space charge waves. Therefore the expression for the adiabaticity parameter can be rewritten as compared to Eq. 2:

$$\mu_c = \frac{R}{h \cdot \sqrt{v_m^2 + c_s^2}} \frac{1}{T_{ramp}}. \quad (4)$$

The proper ramping time as intensity function then can be obtained using the expression:

$$T_{ramp} = \mu_c \frac{R}{h} \frac{1}{\sqrt{v_m^2 + c_s^2}}. \quad (5)$$

The result of this expression is presented on a diagram as a white line. As one can see it agrees well with the simulation data. The discrepancy can be explained by the uncertainty in definition of a maximum particle velocity in the beam.

CONCLUSIONS

The present performance of the bunch compressor in the SIS-18 is in good agreement with the expected values for the compressed bunch. The compressed bunch length can be further improved by tuning the rf frequency during recapture and by a proper choice of recapture scheme. Additionally, the RF amplitude ramp and RF frequency ramp in the beginning of machine cycle should be divided in two consecutive steps. The measurements and simulations on the proper choice of the amplitude ramping time using linear ramp were done. Using simulation results a simple analytical model to describe the influence of longitudinal space charge field on the RF capture was found. It was shown that longitudinal space charge will reduce the longitudinal emittance increase during RF capture.

REFERENCES

[1] R. W. Müller and P. Spiller, ”Strategy for Achieving High Target Power Density with a Modified SIS 18 and the NEw High Current Injector (U^{28+})”, GSI Report, 1996

[2] P. Spiller, K. Blasche at al., ”Generation of High Power Heavy Ion Beams at GSI”, PAC procc., pp.1788-1790 (1999)

[3] K. Blasche, O. Boine-Frankenheim et al., ”Bunch Compression in the Heavy Ion Synchrotron at GSI”, Europ. Part. Acc. Conf., Stockholm, Sweden, 1998, pp. 1347-1349

[4] P. Hülsmann at al., ”The Bunch Compressor System for SIS 18 at GSI”, Proc. of EPAC 2004, pp.1165-1167

[5] P. Hülsmann at al. ”Bunch Compression for FAIR”, Proc. of PAC 2009

[6] O. Boine-Frankenheim and Tripti Shukla, ”Space charge effects in bunches for different rf wave forms”, Phys. Rev. ST Accel. Beams 8, 034201 (2005)

[7] G. Franchetti, I. Hofmann, and G. Rumolo, ”Effect of space charge on bunch compression near the transition”, Phys. Rev. ST Accel. Beams 3, 084201 (2000)

[8] E. Shaposhnikova, ”Nonlinear bunch motion in an accelerator with reactive impedance”, CERN-SL-96-047-RF

[9] O. Boine-Frankenheim, I. Hofmann, G. Rumolo, ”Simulation and observation of the long time evolution of the longitudinal instability in a cooler storage ring”, Phys. Rev. Lett. 82, 3256 (1999)

[10] S. Hancock, ”A simple algorithm for longitudinal phase space tomography”, CERN/PS/RF/Note 97-06, 1997

[11] H. Damerau at al. ”Emittanzeoptimierter Hochfrequenz-Einfang bei niedriger Strahlintensitat”, GSI report nr. SIS08012.HF

[12] O. Chorniy, ”Experimental study of adiabatic RF capture in single and in double harmonics buckets in the SIS-18”, GSI report 2009

[13] O. Boine-Frankenheim, ”rf barrier compression with space charge”, Phys. Rev. ST Accel. Beams 13, 034202 (2010)