DECCELERATION OF HIGHLY CHARGED IONS IN THE ESR

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Abstract

Heavy ions are accelerated to energies around 300 MeV/u for efficient stripping to high charge states. After injection into the storage ring ESR the highly charged ions can be decelerated to a minimum energy around 10 MeV/u for atomic physics experiments. Electron cooling provides small beam emittances and momentum spread which is beneficial for efficient deceleration and high resolution experiments with the decelerated ion beam. The possibility of decelerating the heavy ion beam by means of the friction force of the electron beam has been demonstrated.

1 INTRODUCTION

At the GSI accelerator complex [1] beams of ions up to the heaviest species are available. After acceleration to energies of several hundred MeV/u in the synchrotron SIS the ions can be injected into the storage ring ESR. Stripping targets between the synchrotron and the storage ring allow a choice of the charge state. Even completely stripped ions of the heaviest species are available with sufficient yield.

A variety of atomic physics experiments request bare ions at low energy in order to minimize Doppler broadening of spectral distributions. Therefore the highly charged ions are produced at high energy and decelerated to the required energy. Tuning and variation of the ion beam energy after deceleration allow the measurement of resonances and excitation functions. Internal experiments with the decelerated beam can be performed with the electron cooler or the internal gas jet as target for the ion beam.

The decelerated highly charged ions can also be extracted slowly employing a charge changing reaction [2]. The extraction time is variable in the range from minutes to hours depending on the density of the electron beam or the gas target which determines the rate of charge change. In addition equipment for resonance extraction or excitation by rf noise is installed.

2 TECHNICAL LIMITATIONS FOR RAMPING OF THE ESR

Beam acceleration and deceleration in the storage ring ESR was considered from the beginning. The power supplies were designed for fast ramping, particularly the power supplies for the ring magnets can be operated at a ramping rate of 1 T/s. At present magnetic bending fields exceeding 1.2 T are ruled out by inappropriate power supplies for correction coils in the main dipole magnets, The necessary bipolar power supplies for deceleration starting from higher dipole fields will be furnished by the end of the year.

The rf system consisting of two identical ferrite-loaded cavities is designed for adequately fast ramping in the frequency range 0.8-5.6 MHz. This covers with harmonic number h=2 the range from the full energy (corresponding to 10 Tm) down to 12 MeV/u. For even lower energies the harmonic has to be changed to a higher number.

The electron cooling system was designed for operation in the energy range from a few keV up to a maximum electron energy of 320 keV. Presently its maximum accelerating voltage for breakdown safe operation is 240 kV corresponding to an ion energy of 440 MeV/u. The accelerating voltage of the electron cooling system can be increased at a rate of 50 kV/s, ramping down, however, is limited by the capacitance of the high voltage platform and the load resistance. The high load resistance (about 400 MΩ) which is presently installed results in a time constant of about 10 s. This limits the ramping rate if cooling immediately after deceleration is required. The electron current can be chosen independently of the electron energy. At lower energies the current is limited by the gun perveance ($P = 1.9\ \mu$P), if all gun electrodes are operated at negative potential with respect to ground, which is the preferred mode for stable electron beam operation.

3 RAMPING PROCEDURE

The highly charged ions, mostly bare or hydrogen-like, are injected at an energy around 300 MeV/u. The ESR has a momentum acceptance of $\Delta p/p \simeq \pm 1.5$ %. Within an acceptance of $\Delta p/p \simeq \pm 1.0$ % the tune deviates by less than $\Delta Q = \pm 0.02$ from the the values $Q_h = 2.28$ and $Q_v = 2.29$ on the central orbit. After singleturn injection the ions are circulating at a momentum deviation of about $\Delta p/p$ = +1.0 % with respect to the central orbit. Beam accumulation by a combination of rf stacking and electron cooling results in a stack on an inner orbit (corresponding to $\Delta p/p \simeq -0.5$ %) with respect to the central orbit. Both after singleturn injection and after stacking the cooled beam is moved with the rf system to the central orbit and recooled by electron cooling to prepare the beam bunches for deceleration. This results in beams with transverse emittances below 1π mm mrad. After adiabatic capture with the rf the two bunches have a length of less than 50 ns and a momentum spread $\delta p/p \lesssim 1 \times 10^{-4}$.

Before deceleration the electron beam is switched off, then the bunched ion beam is decelerated by synchronous ramping of the ring magnets and the frequency of the rf system. The best efficiency was obtained for a ramping rate of 0.15 T/s which is also in accordance with the maximum slope for the electron beam accelerating voltage. Minor corrections for eddy current effects are applied to the frequency of the rf system. Typical rf voltages with harmonic h=2 are around 1 kV. The magnetic field of the electron cooler is kept constant, therefore also the corresponding corrections with the ring magnets. This is caused by the fact that the electron cooler was designed for operation at a constant magnetic field of sufficiently high strength (larger than 0.1 T) independent of the beam energy. For improved deceleration the magnetic field has already been reduced to 0.07 T which provides still satisfactory cooling. Preparations have been made for the future to ramp the magnetic field of the electron cooler and to further reduce the magnetic field at low beam energy.

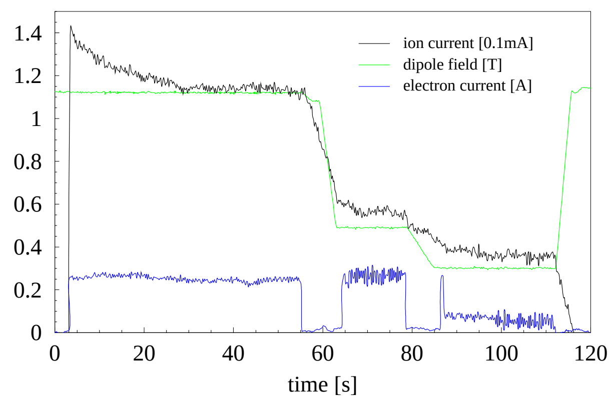

Figure 1: Cycle for deceleration of U^{92+} from 300 MeV/u to 15 MeV/u with intermediate cooling at 30 MeV/u.

The fine correction of tune and orbit at the end of the deceleration ramp have been found experimentally. During the ramp the set values are linearly changed with time from the initial to the final values. With a continuous ramp the beam can be decelerated from the injection energy to an energy of 25 MeV/u. After introduction of an additional plateau for cooling at an intermediate energy between 30 and 50 MeV/u further deceleration to an energy of 12 MeV/u was achieved (Fig. 1). For the second part of the deceleration ramp even a smaller ramp rate was chosen in order to minimize beam losses. The lowest energy of 12 MeV/u is limited by the rf system operated at the second harmonic.

For lower ion energies the harmonic has to be changed. First attempts to debunch the beam and rebunch it with harmonic h=4 and simultaneous electron cooling were successful. However, the beam was lost below 9 MeV/u, most likely because of crossing a betatron resonance. The efforts to achieve even lower energies with bare heavy ions will be continued aiming at energies around 3 MeV/u.

4 IMPORTANCE OF COOLING

As the beam emittance grows adiabatically during deceleration it is of crucial importance to start with the best beam emittance that can be achieved. The typical beam quality for a Kr^{36+} beam decelerated to various energies and cooled by an electron beam of fixed density ($n_e = 6 \times 10^6$ cm^{-3}) is shown in Fig. 2. The momentum spread for the coasting beam was measured by Schottky noise analysis, the horizontal emittance was determined with a residual gas ionization beam profile monitor. For fixed ion energy the momentum spread and the horizontal emittance grow with the intensity of the ion beam. This effect is well known and can be attributed to intrabeam scattering in the dense beam. At energies of about 250-300 MeV/u a dependence proportional to $N^{0.3}$ for the momentum spread and proportional to $N^{0.6}$ for the transverse emittance was measured. Horizontal and vertical emittances are usually of similar value.

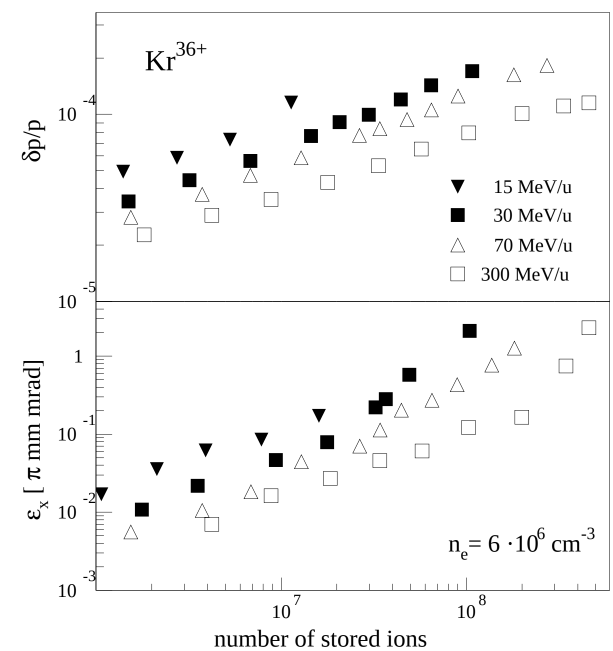

Figure 2: Momentum spread and horizontal emittance of a Kr^{36+} beam at various energies cooled with an electron beam of density $n_e = 6 \times 10^6$ cm^{-3} as a function of the number of stored ions.

For the lower energies in Fig. 2 the dependence of the transverse emittance on the particle number appears to be stronger, particularly at particle numbers $N \geq 10^7$. It is not clear whether this is an artifact by the beam profile monitor or due to an additional heating mechanism, e.g. influence of a betatron resonance. From the measurement also the expected increase of the emittance at lower beam energy, proportional to the inverse of the beam momentum $(\beta\gamma)^{-1}$, is evident. This is caused by the intrabeam scattering rate which is inversely proportional to the normalized six-dimensional beam emittance, whereas the cooling rate is virtually constant for fixed electron density, independent of the beam velocity.

For deceleration the ion beam has to be bunched. This corresponds to an increase of the line density of the beam which causes increased intrabeam scattering. Consequently the transverse emittance for the same total number of particles is larger if the beam is bunched. With the typical bunching factor of 5-10 the emittance grows by a similar factor.

5 BEAM LOSSES DURING DECELERATION

Unlike acceleration beam dynamic effects during deceleration are more adverse with respect to losses. The emittances are growing, space charge effects are stronger at lower energy and also all kinds of manufacture errors or inaccurate control of components have an increased influence. The typical efficiency of deceleration is shown in Fig. 3 for a Kr^{36+} beam decelerated from 300 MeV/u to 15 MeV/u and a Pb^{82+} beam decelerated from 300 MeV/u to 46 MeV/u. For small particle numbers ($N \leq 10^7$) the beam is decelerated with an efficiency better than 90 %. Unavoidable losses due to interaction with the residual gas or recombination with electrons in the cooler are not corrected for. For the lower intensities the deceleration procedure performs well. With increasing particle number the relative losses are increasing. Particles with larger emittances are lost due to closed orbit errors which bring the beam close to the acceptance or due to chromaticity effects causing beam loss at betatron resonances. Particularly the vertical emittance of the beam can be crucial as the vertical acceptance of the storage ring is considerably smaller than the horizontal one.

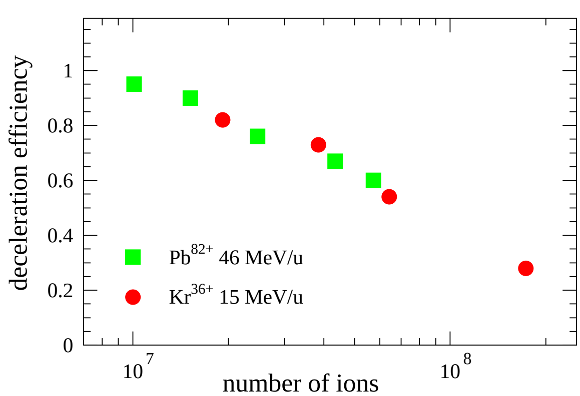

Figure 3: Efficiency for deceleration from 300 MeV/u injection energy to the energy indicated in the legend.

The main closed orbit distortion during deceleration is expected from the magnetic field of the electron cooling system. As the magnetic field of the electron cooler is kept constant during deceleration the closed orbit distortion is increasing inversely proportional to the magnetic rigidity of the ion. A vertical correction in the cooler section has to be applied in order to reduce beam losses during deceleration. The vertical deflection of the ion beam in the toroid which is a second order effect is supposed to produce a vertical kick which has to be compensated by ring correction elements.

6 DECELERATION WITH THE ELECTRON BEAM

The electron beam provides at small relative velocities between ions and electrons a longitudinal force which increases linearly with the relative velocity. The q^2-dependence of the cooling force on the ion charge q results in a strong force for highly charged ions. If the electron energy is ramped at a speed which allows the ion beam to follow the electron velocity and to stay within the acceptance of the ring a continuous energy change of the ion beam can be achieved. This is favorable at low ion energy as the cooling force usually is more effective because of the reduced importance of imperfections. The permanent cooling also results in a small transverse emittance. By ramping the electron energy and the magnetic field of the ring elements synchronously a U^{92+} beam was decelerated with a 0.25 A electron beam from 15 MeV/u to 11 MeV/u within 6.7 s (Fig. 4). This corresponds to a deceleration rate of 1.3 eV/u per revolution.

This scheme applies to a coasting beam and, moreover, the ion beam is kept cooled permanently during this procedure, thus allowing to explore the lower limit for deceleration of heavy ion beams. At low energy it can offer advantages compared to the usual technique employing the rf system, particularly if the beam emittances are dominated by intrabeam scattering. With higher electron currents deceleration or energy tuning of a coasting beam can be performed correspondingly faster. A current increase by a factor of 2 - 3 seems feasible for future experiments.

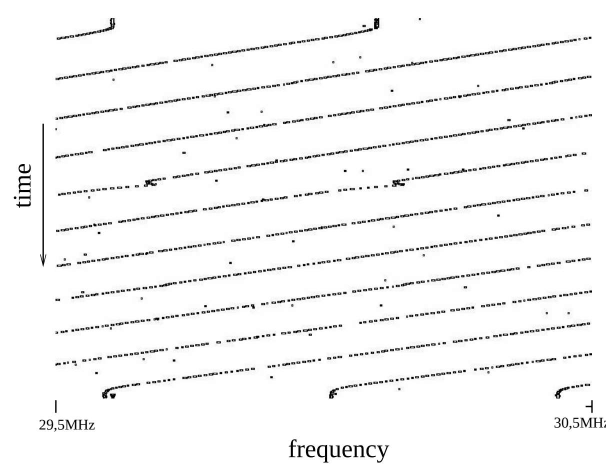

Figure 4: Schottky signal in a 1 MHz band around 30 MHz during deceleration with a 0.25 A electron beam. The time for deceleration of a U^{92+} beam from 15 MeV/u to 11 MeV/u was 6.7 s.

7 REFERENCES

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[2] T. Winkler, K. Beckert, H. Eickhoff, B. Franzke, F. Nolden, H. Reich, M. Steck, Proc. of the 6^{th} Europ. Part. Acc. Conf., Stockholm, 559 (1998).