IMPROVED PERFORMANCE OF THE HEAVY ION STORAGE RING ESR

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Abstract

The operation of the heavy ion storage ring ESR has been continuously improved. The energy range of decelerated highly charged ions could be extended down to 3 MeV/u. Electron cooling is available over the full energy range from injection to the final energy. Stochastic cooling has been established as a powerful pre-cooling method for fragment beams in combination with final electron cooling which allows a considerable reduction of the total cooling time. The isochronous mode of the focussing structure allows studies of the performance of electron cooling above transition energy. Experiments with a cooled beam above transition energy showed strong heating due to microwave instabilities.

INTRODUCTION

The heavy ion storage ring ESR was designed as a versatile accelerator equipped with beam cooling [1]. Even after more than ten years of operation not all options have been fully exploited and they are still being perfected. The high energy needed to efficiently produce the heaviest ions as bare or few electron ions contradicts to experimental requirements, which prefer low energy in order to reduce Doppler effects. The highest resolution in spectroscopic experiments can be achieved with low beam velocity, thus deceleration of highly charged ions has been continuously developed towards lowest energies.

The possibility of injecting rare isotope beams from the fragment separator FRS requires fast cooling of the hot, short-lived nuclei. Consequently, a stochastic cooling system was installed for pre-cooling of fragment beams with a cooling time constant of less than a second [2]. The standard cooling technique for experiments with stored beams is electron cooling, which presently allows cooling of ion beams in the energy range 3-420 MeV/u [3]. For mass measurements of short-lived nuclei the focussing structure can be adjusted to provide isochronous revolution of the ions in a momentum acceptance of a few permille [4]. In the following, the latest improvements in various operational modes will be reported.

DECELERATION

The heavy ion beams are accelerated in the synchrotron SIS to the energy required for efficient production of highest charge states by a stripping foil installed between the synchrotron SIS and the storage ring ESR. The injection energy into the ESR is chosen due to the availability of beam cooling immediately after injection. The electric circuits of the stochastic cooling system are presently optimized for a beam energy of 400 MeV/u and this energy is close to the maximum energy at which the electron cooling system can be operated reliably. Therefore, great flexibility for cooling of the injected beam is warranted. Starting from the injection energy of 400 MeV/u the ions are decelerated by synchronous ramping of the magnetic field and the frequency of the rf system. The deceleration of the beam is achieved by proper control of the sequence of reference values for all ring components. The typical ramp rate is about 0.15 T/s. At an intermediate energy of 30 MeV/u electron cooling is applied to compensate the beam quality degradation due to phase space dilution during the deceleration process. Deceleration to lower energies is subsequently performed in a second ramping sequence with a reduced rate of 0.05 T/s.

In earlier experiments a clear limitation at a minimum energy of about 10 MeV/u had been found [5]. It could be confirmed that this minimum energy was limited by the magnetic field of the electron cooling system, which was initially operated in a static mode. The constant magnetic field of the electron cooling system caused an amplitude of the closed orbit distortion increasing inversely proportionally to the beam momentum. Therefore the control system was programmed to allow time dependent control of the magnetic system. The magnetic field of the electron cooler is presently reduced synchronously with the main ring magnets. At lower energies the electron beam is guided by a magnetic field of only 0.015 T.

In the first attempt with variable cooler guiding field, a beam of bare uranium was used for deceleration tests. After fine corrections of the tunes and of the ion beam orbit, the ion beam could be decelerated to the design minimum energy of 3 MeV/u. This minimum energy after deceleration is limited by the frequency range of the rf system. The rf harmonic at the beginning of the deceleration cycle is $h = 2$, at 30 MeV/u the rf amplitude is adiabatically decreased to zero and then the beam is recaptured at harmonic $h = 4$ supported by electron cooling. For this harmonic the minimum rf frequency of 0.9 MHz corresponds to a minimum beam energy of 3 MeV/u. Changing to a higher harmonic might allow even further deceleration, but will make the operation more complex. Deceleration to lower energies will be ultimately limited by remanent fields and hysteresis effects in the magnets and by the lifetime of the beam in the residual gas.

Deceleration to lowest energies (below 10 MeV/u) is presently associated with considerable intensity losses which exceed the losses observed previously for deceleration to energies in the range 20-50 MeV/u [5]. Starting with a few times 10^7 U^{92+} ions at the injection energy of 400 MeV/u a number of 10^6 ions could be decelerated to

5 MeV/u. After deceleration to 3 MeV/u only 10^5 ions were detected. Nevertheless, for both final energies it was possible to cool the decelerated ion beam with an electron current of 5 mA at the electron energy corresponding to the ion energy. Application of higher electron currents resulted in fast beam losses. These losses might be caused by crossing a resonance, as during cooling of the beam its energy was slightly changed, with corresponding changes of the beam orbit in the ring acceptance. The total time for cooling the decelerated beam with an electron current of 5 mA was a few seconds.

At the final energy the horizontal beam emittance was measured with a residual gas ionization beam profile monitor and the momentum spread was determined by Schottky noise analysis (Fig. 1). The horizontal emittances were 0.9×10^{-6} m at 5 MeV/u and 0.7×10^{-6} m at 3 MeV/u, The momentum spreads were 2.4×10^{-4} at 5 MeV/u and 1×10^{-4} at 3 MeV/u. At the lowest energy of 3 MeV/u the beam lifetime was determined from the decrease of the Schottky noise power with time. The lifetime of 6 s was dominated by electron capture in the residual gas. Although the pressure was as low as 3×10^{-11} mbar, tiny leaks may have spoilt the vacuum.

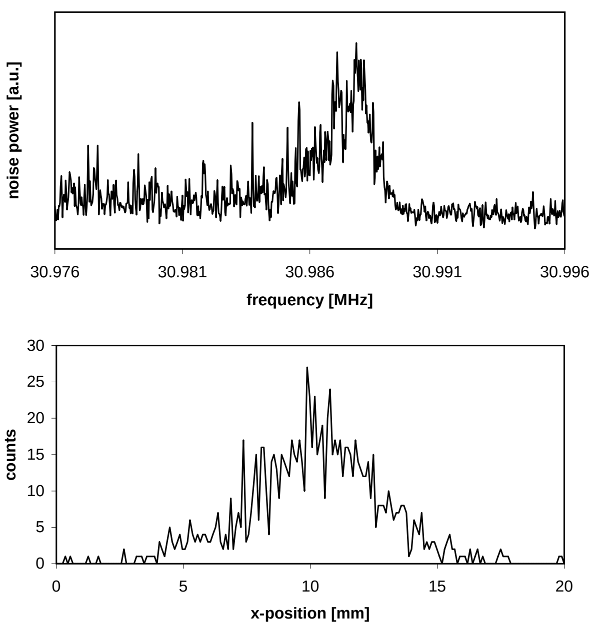

Figure 1: Measurement of a bare uranium beam at 3 MeV/u cooled with an electron current of 5 mA. The longitudinal Schottky spectrum measured at the 140^{th} harmonic of the revolution frequency corresponds to a momentum spread of 1×10^{-4}. The residual gas ionization monitor measured a beam width of 5 mm.

Various improvements of deceleration are still envisaged. First tests to increase the ramping speed, which presently is about 0.1 T/s, to 1 T/s were successful [6]. This will allow experiments with short lived radioactive beams. By optimization of the deceleration cycle, the number of decelerated ions should be increased. This optimization should also allow the application of larger electron currents for cooling at the final energy, thus reducing the cooling time and the emittance and momentum spread of the stored beam. Finally, recent experiment demonstrated considerable improvements of the vacuum conditions. By reduction of heavier residual gas components, the beam lifetime was increased by more than an order of magnitude.

STOCHASTIC COOLING

The ESR stochastic cooling system has been commissioned over the past years. An important step forward was the first stochastic cooling of hot secondary beams from the fragment separator FRS. A fragment beam was injected into the ESR and pre-cooled by the stochastic cooling system for six seconds. After turning the stochastic cooling system off, electron cooling was used to finally obtain a very well cooled beam with an excellent separation of different components of the fragment composite.

A two-fold benefit resulted from stochastic pre-cooling. The fragments were well cooled after less than ten seconds, and, when the beam was ready for experiments, the intensity of the fragments was about an order of magnitude larger than without stochastic pre-cooling.

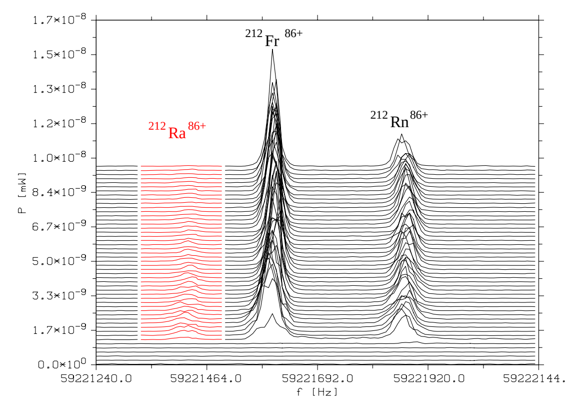

Figure 2: Waterfall diagram of the Schottky noise of a fragment beam with stochastic pre-cooling and subsequent electron cooling. The signal from $^{212}Ra^{86+}$ could not be detected with electron cooling only.

As an example Fig. 2 shows a waterfall diagram with peaks in the Schottky noise spectrum of three isobars in the same charge state, $^{212}Ra^{86+}$, $^{212}Fr^{86+}$ and $^{212}Rn^{86+}$. The lines appeared as soon as the stochastic cooling system had been turned off and electron cooling reduced the momentum spread. The separation between traces is 1.28 s. The mass difference between the ions can be inferred directly from their position in the Schottky spectrum. The half-life of the $^{212}Ra^{86+}$-ion at rest is 13 s. The fast stochastic precooling allowed a measurement of the half-life of this isotope by Schottky noise analysis. Without the application of stochastic pre-cooling the signal of the $^{212}Ra^{86+}$ component was not detectable as the electron cooling time for the hot fragment beam was longer than the lifetime of the nucleus.

ELECTRON COOLING ABOVE TRANSITION ENERGY

The special ion optical mode of the ESR which is used for isochronous mass measurements has a transition energy $\gamma_t = 1.37$. The beam energy of 340 MeV/u at which the particles circulate with a revolution frequency which is independent of their momentum can be significantly exceeded with cooled beams. This allows studies of cooled ion beams above transition energy.

A beam of bare krypton ions was injected at an energy of 380 MeV/u. Electron cooling was applied and the reduction of momentum spread and emittance could be clearly observed. The time for cooling with an electron current of 0.25 A was about 10 s, which is also the typical cooling time at this energy with the standard ion optical mode. The energy of the electron beam was varied and the changes of the ion revolution frequency were monitored by Schottky noise detection. The momentum slip factor $\eta = \gamma^{-2} - \gamma_t^{-2} = (df/f)/(dp/p)$ was determined using the relation between changes of the electron energy dE and the relative momentum change $dp/p = (\gamma/(\gamma+1))dE/E$. The measured value $\eta = -0.019$ was only valid in the vicinity of the injection orbit. It was observed that for larger momentum deviations the η-value varied considerably, even changing sign.

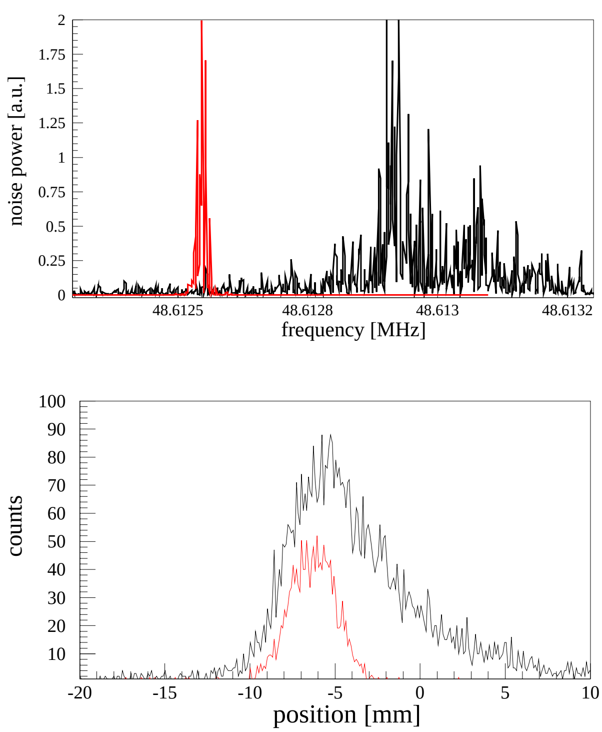

Figure 3: Distribution of cooled beams above transition energy observed by Schottky noise analysis and with a beam profile monitor. With both methods the low energy particle are on the right hand side of the spectrum. Distributions for two particle numbers are shown, $N = 5 \times 10^5$ in red, $N = 1 \times 10^8$ in black.

The measured η-value around the orbit of the cooled beam allows the determination of the momentum spread from frequency spectra. However, the small absolute value of η results in a strong compression of the frequency spread. Therefore a significant contribution to the frequency spread comes from fluctuations of the dipole field due to power supply ripple. The current ripple $\delta I/I$ of the main dipole power supply causes a frequency spread $\delta f/f = \gamma_t^{-2} \cdot \delta I/I$, with a typical value $\delta I/I = 1 \times 10^{-6}$ a frequency spread of $\delta f/f = 5 \times 10^{-7}$ is expected. For intensities below 5×10^6 stored ions a constant frequency spread of this value was observed, which is due to power supply ripple.

At larger beam intensities strong longitudinal self bunching was observed. For ion beam intensities above 10^7 stored ions the frequency spread increased almost linearly with intensity. For intensities in the 10^8 range the Schottky spectra exhibited a strong tail due to low energy particles (Fig. 3). This low energy tail was also observed in the beam profile monitor. The dispersion function at the beam profile monitor location is about 40 m, this agrees with the measured extension of the low energy tail in the horizontal beam profile. The strong increase of the momentum spread with intensity at higher intensities is attributed to the onset of microwave instabilities heating up the beam. The measured momentum spread agrees well with the theoretical threshold value for microwave instabilities.

It should be mentioned that attempts to repeat the cooling experiment for an increased beam energy, i.e. at a more negative value of η, failed. No significant cooling effect could be observed. The change of magnetic rigidity may have resulted in a change of the ion optical values due to higher order field components which must be corrected in future experiments. From these first attempts it can be concluded that electron cooling above transition energy is feasible, but more delicate.

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