# Performance of the Heavy Ion Storage Ring ESR

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*Abstract*

The progress in storage and cooling of fully stripped or H-like heavy ion beams after two years of commissioning and operation of the ESR [1] is reported. At the time of abstract deadline, various ion-species between $Ne^{+10}$ and $Bi^{+82}$ at energies from 90 to 300 MeV/u have been accumulated by means of rf-stacking combined with electron cooling [3]. The maximum number of stored beam particles is ranging from $5 \cdot 10^6$ for $Bi^{+82}$ to $2 \cdot 10^9$ for $Ne^{+10}$ and $Xe^{+54}$. Very small values for momentum spread, $\delta p/p(FWHM) \approx 6 \cdot 10^{-7}$, and for transverse emittances, $\epsilon \approx 0.05\pi$ mm mrad, have been observed with less than $10^5$ cooled $Bi^{+82}$- and $Ar^{+18}$-ions, respectively. Typical parameters of 1 mA beams are $\delta p/p = 2 - 5 \cdot 10^{-5}$ and $\epsilon \leq 0.5\pi$ mm mrad. At given residual gas pressure of $5 \cdot 10^{-11}$mbar life times of cooled beams are limited only by radiative capture of cooler electrons. Observed values between 10 hours for $Ne^{+10}$- and 10 minutes for $Bi^{+82}$-beams are in good agreement with theoretical expectations.

## 1 BEAM ACCUMULATION

Storage of heaviest ions

Many different ion species could be stored and cooled at energies between 90 MeV/u and 300 MeV/u: $^{20}Ne^{10+}$, $^{40}Ar^{18+}$, $^{84}Kr^{36+}$, $^{129}Xe^{54+}$, $^{163}Dy^{65+}$, and $^{163}Dy^{66+}$, $^{197}Au^{76+}$,to $^{197}Au^{79+}$, and $^{209}Bi^{80+}$,to $^{209}Bi^{82+}$. The success with ions heavier than $^{40}Ar$ was – at least to a large extend – due to increased beam intensities from Unilac and better transmission through SIS [2] with beam transport. Ions with atomic number $\geq 25$ have to be stripped before injection to the ESR. The stripping yield for fully stripped Au- and Bi-ions at 240 MeV/u is nearly 20%, for H-like charge states about 40% .

High beam currents

Currents in the order of mA could be attained by beam accumulation applying rf-stacking combined with electron cooling. By sequential cooling on the injection- and the accumulation-orbit the efficiency of this process could be increased. The total transmission, defined by the beam current increment in the ESR per injection shot divided by the internal SIS current on flat-top, was typically below 15%. Maximum ESR beam currents achieved so far are, for instance, 6 mA for $Ne^{10+}$ at 250 MeV/u and 1.2 mA for $Bi^{82+}$ at 230 MeV/u. Corresponding numbers of stored ions are $2 \times 10^9$ and $5 \times 10^7$, respectively.

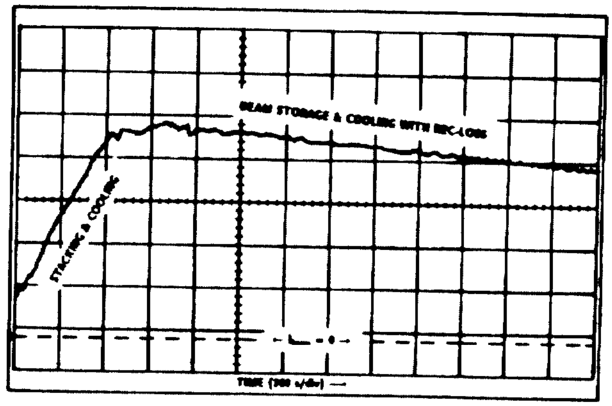

Figure 1: Beam accumulation and storage

Beam currents of highly charged ions were limited mainly by the equilibrium between beam loss by radiative capture of electrons (REC) in the cooler and beam accumulation rate, which is proportional to the primary beam intensity from SIS (see Fig. 1).

Transverse beam stabilization

Electron cooling of $Ne^{10+}$-beams at high currents ($\geq$ 2 mA) led to transverse beam instabilities connected with a dramatic reduction of beam life times. Beam loss was stopped after activating and adjusting the wide band beam stabilization system. It damps coherent beam oscillations with frequencies 1 MHz $\leq f \leq$ 150 MHz in both the horizontal and the vertical directions. Similar oscillations have not been observed yet in beams of higher charged ions, obviously due to beam heating by intra-beam scattering, the rates of which increase approximately proportional to $Z^2$.

Long beam life times

The ion beam life times are determined only by REC in the cooler. The influence of the residual gas at average pressures in the order of $10^{-10}$mbar is negligible. With 1 A electron current in the cooler, the life time of a $Ne^{10+}$-beam is nearly 7 hours. Though REC rates increase proportional to the square of the ionic charge state, we achieved for $Bi^{82+}$ and $Au^{78+}$ comfortable beam life times of about 1 h by applying a rather low electron current of 0.1 A without major reduction of the beam quality. After the latest improvements of the internal jet target, a rather strong reduction of the beam life time has been observed when the target was operated at a thickness of $7 \times 10^{11}$ $N_2$-molecules/cm$^2$. More systematic studies on the influence of target thickness and material on life time and quality of stored beams have to be done in coming beam times.

## 2 BEAM-COOLING

### Very cold ion beams

For cooled, low intensity $Kr^{36+}$– and $Bi^{82+}$–beams extremely small values for the momentum spread have been observed. $\delta p/p \approx 6 \times 10^{-7}$ was measured in a beam of less than 1000 stored $Bi^{82+}$–ions, $\delta p/p \approx 1 \times 10^{-6}$ for about 10 000 $Kr^{36+}$–ions. Typical $\delta p/p$–values for medium beam currents up to 1 mA are $1 \times 10^{-5}$ for $Ne^{10+}$ to $4 \times 10^{-5}$ for $Bi^{82+}$, depending weakly on the electron current in the cooler. Transverse beam emittances have not been measured as frequently as the momentum spread. Evaluation of particle spectra from the position sensitive detectors delivered values between $0.1\pi$ mm mrad and $0.5\pi$ mm mrad.

### Multi charge operation

Due to its large momentum acceptance of about $\pm 1.8\%$ the ESR is capable to store and cool simultaneously two charge states of Kr–ions or three charge states of Au– and Bi–ions.

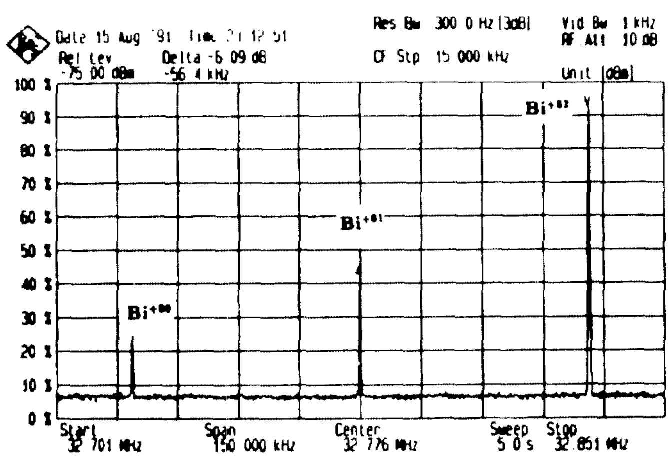


Figure 2: Longitudinal Schottky spectrum of three charge states of Bi–ions at 230 MeV/u stored and cooled simultaneously in the ESR. Charge states from left to right: 80+, 81+, and 82+.

Fig. 2 shows longitudinal Schottky bands from three different charge states of Bi–ions at 240 MeV/u. The lower charge states are populated by sequential REC in the cooler and are held at exactly the same velocity by electron cooling. Therefore, the relative frequency differences are determined only by orbit length differences due to charge differences:

$$\frac{\Delta f}{f_q} = -\frac{\Delta C}{C_q} = \frac{1}{\gamma_t^2}\frac{\Delta q}{q}$$

As charge states are exactly known and frequencies can be measured with high accuracy, the transition point for the ESR lattice, $\gamma_t$, can be derived precisely from multicharge spectra. $\gamma_t = 2.67$ is determined from Fig. 2. It should be noted that $\gamma_t$ is also the important calibration factor for the planned measurements of masses of exotic nuclei.

### Cooling of radioactive beams

First storage and cooling of radioactive beams from the FRS has been demonstrated with fragments of $^{20}Ne$ at 250 MeV/u. A Schottky spectrum measured immediately after injection and cooling to equilibrium is given in Fig. 3.

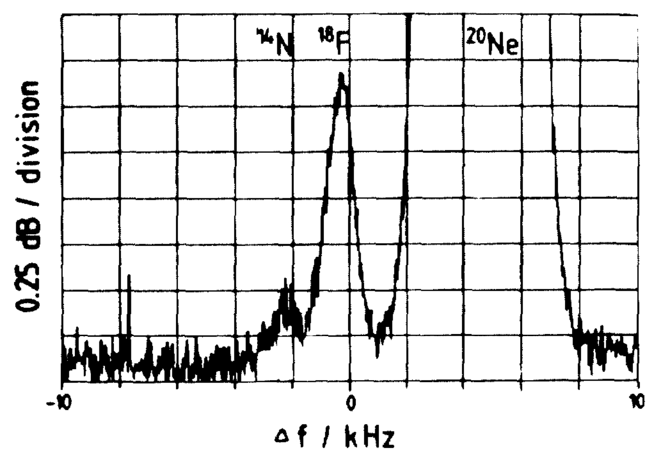


Figure 3: Schottky spectrum of stored and cooled $^{20}Ne^{10+}$ (cut peak, mostright) and isotonic fragments $^{18}F^{9+}$ (middle) and $^{14}N^{7+}$ (left) at 250 MeV/u. The spectrum was measured near 83.4 MHz, i. e. at the 49th harmonic of the revolution frequency.

Besides a strong band from the primary $^{20}Ne$ (cut peak), two weak bands from the isotonic fragments $^{18}F$ and $^{14}N$ are visible. The total intensity fraction of fragments was about $2 \times 10^{-3}$, the spectrum is exponentially averaged from roughly 2000 single spectra measured within 20 minutes. As in the case of different ionic charge states, all nuclei are cooled to the same velocity. Using the experimental value for $\gamma_t$ mentioned above, differences in $A/Z$ can be determined with an absolute error in the order of $10^{-5} A/Z$. The life time of the positron emitter $^{18}F$ is about 100 min. Therefore, in a spectrum measured 12 h after the injection, the $^{18}F$-band had disappeared. Compared to the short cooling times for primary beams, which are typically $\leq 1$ s, the electron cooling of hot $^{20}Ne$–fragments to equilibrium required 10 s to 20 s.

Attempts failed to get similar spectra for the short living $^{19}Ne^{10+}$ decaying by positron emission into $^{19}F$. However, the unambigeous detection was possible by applying one of the position sensitive detectors for counting the rates and measuring the transverse distribution of the daughter nuclei $^{19}F$. The measured laboratory decay time $\tau_{lab} \approx 22$ s is in good agreement with the well known 17 s in the rest frame.

Up to now the experimental area in the target hall can be supplied with radioactive beams only by using the ESR as beam transport line. For this purpose the beam has to be led from FRS over a full ESR turn to the slow extraction beam line (TT-line). A first successful test of this transport has been made with a $^{20}Ne$-beam heated up in the FRS production target.

# 3 EXPERIMENTS

Internal Target

Late in 1991, the thickness of the internal gas jet target [4] could be increased to $6 \times 10^{12}$ atoms/cm$^2$ for argon and $1 \times 10^{12}$ atoms/cm$^2$ for $N_2$. The improvement was mainly due to better aligned and sharper skimmers between differential pumping stages of the jet inlet part.

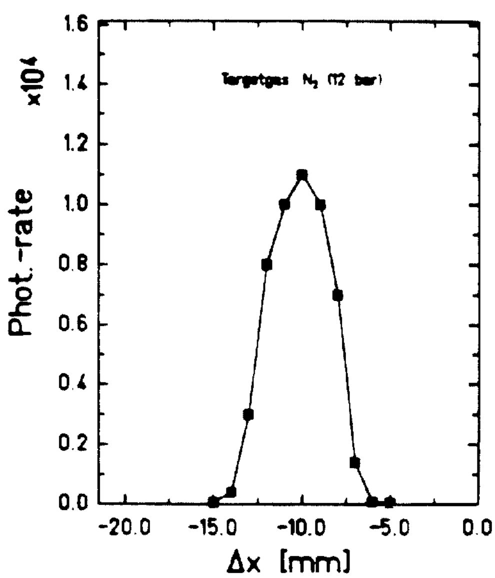


Figure 4: Photon and charge exchange rates vs. ion beam position. Ion beam: $Bi^{82+}$, 230 MeV/u

The jet diameter at the point of interaction with the ion beam was determined by variing the horizontal position of the cooled ion-beam at the positon of the internal target. The production of photons and stripped ions by scattering processes between the ions and the target molecules was measured to evaluate both the mean position and the thickness of the target (see Fig. 4). By this procedure also the diameter of the target region could be determined to be less than 5 mm, as the diameter of the ion beam was measured by position sensitive particle detectors. The target thickness is varied by controlling the inlet pressure at the Laval nossle. There is a strong indication that the gas jet becomes the more a cluster jet the higher the inlet pressure and the heavier the gas. Therefore, for having better control of this gas–cluster transition, we are considering heating and cooling of the target gas a the inlet.

Internal experiment operation

A fraction of approximately 70% of the beam time in 1991 has been used for internal experiments or for testing experimental equipment. The main topics of the experimental program were:

- dielectronic recombination of Li-like $Bi^{80+}$-ions using the electron-cooler as a free electron target
- x-ray-spectroscopy at the internal target using the photon/particle coincidence technique
- measurements of the bound -$\beta^-$-decay of $^{163}Dy^{66+}$ to $^{163}Ho^{67+}$
- first attempts to measure the hyperfine transition of H-like $Bi^{82+}$-ions

Without internal target, the fraction of beam storage time used for experiments, $\delta_{exp}$ (duty factor), is in the order of 90% for $Ne^{10+}$. $\delta_{exp} \approx 50\%$ was attained for $Bi^{82+}$ by applying reduced cooling electron current of 0.1 A. For the investigation of hyperfine structure excitation of $^{209}Bi^{82+}$–ions by a tunable laser even $\delta_{exp} \approx 100\%$ could be reached by running the experiment in parallel to beam accumulation.

# 4 REFERENCES

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