# Investigation of the Afterglow Mode with the Caprice ECRIS for the GSI Heavy–Ion–Synchrotron Operation

K. Tinschert, J. Bossler, R. Lang, K. Langbein*, H. Schulte, P. Spädtke
Gesellschaft für Schwerionenforschung mbH, Planckstrasse 1
D-64291 Darmstadt, Germany
*Physikalisch–Technische Beratung, Kraichgaustr. 2
D-76698 Ubstadt–Weiher, Germany

## Abstract

The Caprice–type ECRIS of the High Charge State Injector (HLI) of GSI predominantly has been operated in DC mode so far to deliver high duty cycle beams for the experimental area of the LINAC (UNILAC). The increasing demand of the Heavy Ion Synchrotron (SIS) for high intensities of heavy ion beams at very low duty cycle favours the application of the afterglow mode by pulsed operation of the ECRIS in these cases. Experiments with O, Ar, Xe and mainly with Pb were performed at the new ECR injector setup (EIS) which is a copy of the HLI injection beam line. Different RF pulse lengths and repetition rates were compared to optimise the respective afterglow intensities. For Pb two different types of ovens were investigated and modifications of the extraction system were applied. Thus peak intensities in the afterglow for $^{208}\text{Pb}^{27+}$ of up to 200 e$\mu$A could be obtained. Stable operation for time periods of several days could be achieved at reduced intensity level. Operational experiences are reported under the aspect of adaption to SIS injection.

## Introduction

Two preaccelerators are feeding the heavy ion Universal Linac (UNILAC) at GSI which in turn delivers the ion beam simultaneously to an experimental area with high duty cycle (typ. 5 ms; 50 $s^{-1}$) and to the Heavy Ion Synchrotron (SIS) (typ. 300 $\mu$s; 1 $s^{-1}$). As the High Charge State Injector (HLI) mainly has been used for the high duty cycle operation so far its ECRIS is working in DC mode. Pulses of adequate timing for acceleration are produced with an electrostatic chopper. This method takes advantage of the high beam stability of the ECRIS when working in DC mode.

In order to satisfy the requirements of many experiments at high energies the SIS increasingly demands high intensities of heavy ions. Due to the low duty cycle of SIS injection the afterglow mode of ECRIS operation fits well to these requirements. This special RF pulsed operating mode was first investigated at CEN Grenoble [1, 2]and routinely applied at the Lead Injector of CERN [3] for several years now. It is characterized by a peak with a sharp increase of the ion current for highly charged ions just after the cut off of the RF pulse. The width of the peak top typically does not exceed several hundred $\mu$s and is followed by a decay slope which can have various shapes.

## Experimental setup

The experiments reported here have been performed at the new ECR Injector Setup (EIS) [4]. In order to obtain resultswhich can directly be transferred to the low energy injection beam line of the HLI it is equipped with the same CAPRICE ion source, an identical analyzing system and the same kind of beam diagnostics. To enable variable and improved ion beam matching between ion source extraction and analyzing system an additional solenoid lens is integrated there. The analyzing system consists of a high resolution split dipole magnet spectrometer with a deflection angle of 135° and a quadrupole singlet at its object side to adapt the vertical matching [5]. As the afterglow phenomenon has a very specific time dependence a computer controlled multiple timing generator has been used. It provides a master clock from which the signals for all timing dependent devices are derived. Thus the length and repetition rate of the RF pulse can easily be changed during full operation while the gate pulse for the beam diagnostic tools (e.g. current integration window for Faraday cups) can be varied simultaneously. So it is possible to measure the ion current within the RF pulse or in the afterglow regime at any precisely defined instant of the pulse cycle. This procedure is also applied when recording a charge state spectrum.

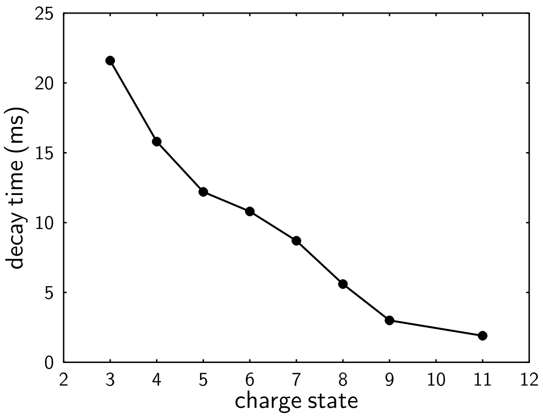

Fig. 1: 1/e decay times of the afterglow peak for different Ar charge states (RF pulse: 20 ms, rep. rate: 20 $s^{-1}$)

The current of the spectrometer is incremented in small equidistant steps (≈ 2300 per spectrum) while the analyzed beam current is recorded with the predefined timing of the gate pulse. In order to maintain the same ion beam optics for all mass/charge ratios the other magnetic elements in the beam line are simultaneously varied in linear dependence to the spectrometer. By this way a spectrum of the true charge state distribution (CSD) can be obtained within several minutes.

The shape of the RF pulse is not restricted to a simple rectangle but may be composed of different parts. It is also possible to append a further postpulse to the main RF pulse within the afterglow regime and a constant RF level can be added to the complete signal. Thus a great flexibility of RF pulse modulation is possible.

## Results for gases

Basic investigations started with the noble gases Ar and highly enriched $^{136}$Xe because they are easy to handle and they provide very stable operating conditions. The extraction voltage was 15 kV in both cases. Fig. 1 shows the dependence of the 1/e decay times of the afterglow pulse for different Ar charge states. The ion source was operated with Ar + He as auxiliary gas. The RF pulse length was set to 20 ms at a repetition rate of 20 $s^{-1}$. The decay times are clearly decreasing with increasing charge states. The functional dependence is very similar to that previously observed for the CSD of Pb [3]. To study the correlation between the decay time of the afterglow pulse and the lifetime of the plasma and to investigate a possible influence of electrons accelerated by the extraction potential a simple experiment was carried out. A CCD–camera is usually looking through the 0° beam line of the spectrometer magnet and the extraction aperture directly into the plasma chamber. For the actual experiment the CCD–camera was replaced by a highly sensitive photomultiplier with fast signal readout to a digital storage oscilloscope. The decay time of the multiplier signal representing the integral photon intensity from the plasma is in the order of 20 ms. This number coincides with the decay time of the total ion current measured in a Faraday cup directly behind the extraction. This total ion decay time may be a superposition of the sum of all charge states extracted from the plasma. No difference was found for the time constant of the multiplier signal measured with and without extraction voltage. So this time constant is not affected due to the presence or absence of accelerated electrons.

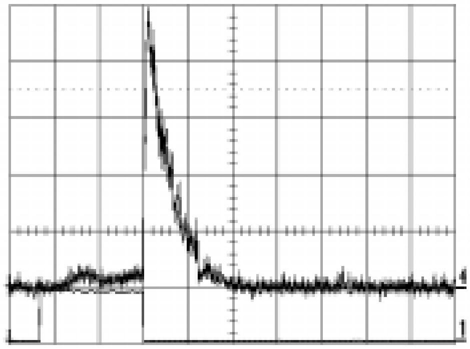

Fig. 2: Afterglow for $Xe^{18+}$ (trace 4, vertical scale: 10 e$\mu$A/div); trace 1 shows the RF pulse (time base: 5 ms/div)

Using isotopically enriched $^{136}$Xe with $O_2$ as auxiliary gas the afterglow of the charge state q = 18 was studied as it is the relevant one for HLI operation. Fig. 2 shows a typical afterglow of $Xe^{18+}$ with very low intensity during the RF pulse and smooth decay slope of the afterglow. The influence of the RF pulse length $t_p$ on the afterglow intensities was studied for $Xe^{18+}$ as well. The integration window for the ion current remained fixed (0.8 ms). It was set on top of the afterglow peak. The afterglow was optimized for $t_p$ = 10 ms and $t_p$ = 50 ms, respectively. In each case $t_p$ was varied online while keeping all other parameters constant. In the first case the ion current decreases with increasing $t_p$ and drops rapidly towards shorter $t_p$ (see Fig. 3). This rapid drop is also abserved in the second case, however, between $t_p$ = 12 ms and $t_p$ = 50 ms no significant decrease of intensity appeared. As high charge states are generated by successive single ionization by electron impact a specific minimum time is required to get a sufficient population of high charge states. Ob-

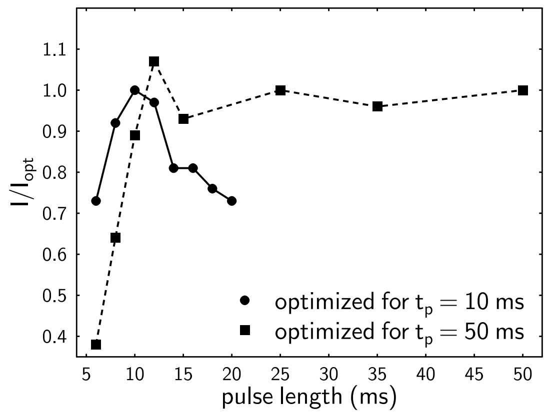

Fig. 3: Afterglow peak currents of $Xe^{18+}$ versus RF pulse length $t_p$; the ion source was optimized to maximum intensities for $t_p = 10$ ms and 50 ms, respectively; ion currents are normalized to the current obtained for the respective $t_p$.

viously for $Xe^{18+}$ $t_p = 12$ ms is the minimum time to achieve a stationary confinement of its population and it seems not to be advantageous to make the RF pulse much longer than this specific time.

## Results for Pb

For $Xe^{18+}$ the enhancement of the afterglow intensity with respect to the optimized intensity for DC operation is a factor of 2–3. An even stronger enhancement can be achieved for high charge states of Pb. The main interest concentrated on $^{208}Pb^{27+}$ because it was scheduled for a beam time period for SIS. The ions were extracted from the ion source with 20 kV. Two alternatives have been compared for material evaporation: The conventional GSI high temperature oven which has to be operated at its lower limit of temperature regime and a type of micro oven. This micro oven is similar to that one which is successfully used for $^{208}Pb^{27+}$–production at CERN's Lead Injector [3].

Previous experiences with the GSI standard oven during DC operation of the CAPRICE with Pb showed that the decoupling of electric heating and passive heating becomes difficult in the required temperature range of about 600 °C. Therefore experiments started using the micro oven which may have the advantage of a reduced passive heating but at the expense of a much smaller material content. The samples for all experiments were made from highly enriched isotopic $^{208}Pb$ metal. In every case when starting with a new oven charge the ion source was prepared with an operating period of several days running only with the auxiliary gas $O_2$ for cleaning and conditioning. To optimize the afterglow for $^{208}Pb^{27+}$ high microwave pulse power of up to 1.5 kW is necessary requiring a reduction of the RF duty cycle in order to keep the average power below the limit acceptable for the ion source. A repetition rate of 5 $s^{-1}$ turned out to be useful and was applied for most of the measurements. The RF pulse length $t_p$ was varied between 20 ms and 70 ms to estimate the minimum time necessary to obtain maximum intensity in the afterglow. The standard pulse length of 50 ms used at CERN could be reduced to 35 ms in the present investigations without reduction of intensity and stability. With the micro oven it was possible to obtain ion currents of up to 100 e$\mu$A in the afterglow of $Pb^{27+}$, however, a long time stability exceeding a few hours could not be achieved.

The second series of measurements was performed with the high temperature oven with a slightly modified arrangement: In order to reduce heating by fast electrons from its front the oven was equipped with a set of two aperture rings of $Al_2O_3$ leaving a hole of only 3 mm diameter. Furthermore the thermal shielding of the oven was improved by using a coaxial copper tube which completely encloses the oven. The first investigations showed that it is possible to reduce passive heating in pulsed mode substantially by keeping the current of the source coil at the injection side within certain limits. Applying these precautions similar performance was achieved as with the micro oven. After an operation period of several days while repeatedly optimizing the parameters a very stable mode was found for the afterglow characterized by good pulse to pulse reproducibility and a good long time stability. When optimized for high intensity the afterglow of $Pb^{27+}$ showed a sharp cut off instead of a smooth decay. This cut off which occured at variable delay times after the RF pulse (see Fig. 4) depending on optimization of the ion source

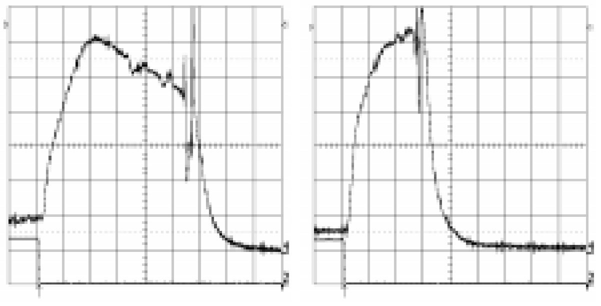

Fig. 4: Afterglow peaks of $Pb^{27+}$ with cut off at different time delays (trace 4, vertical scale: 20 e$\mu$A/div, time base: 0.2 ms/div)

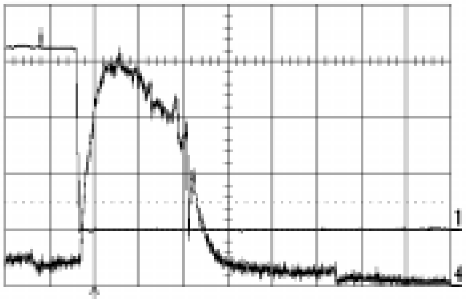

Fig. 5: Afterglow peak of $Pb^{27+}$ obtained with the large extraction aperture (trace 4, vertical scale: 50 e$\mu$A/div, time base: 0.5 ms/div)

parameters which was also observed with the ECR4 at CERN [3]. The most effective parameter to influence the length of the afterglow until its cut off is the tuning of the RF coupling to the ion source by plunger adjustment. The optimum adjustment for suitable afterglow pulse length and intensity does not necessarily coincide with minimum reflected power. Furthermore it was confirmed that optimization of source parameters for maximum afterglow intensity leads to strongly reduced intensity within the main pulse.

For 100 hours a very stable run was performed only with some short phases of instabilities which, however, recovered without retuning the ion source in most cases. During a period of 60 hours of this run definitely no instability occured.

In many cases sharp spikes are visible in the course of the afterglow pulse (see Fig. 4) indicating that very high intensities of extracted ions can appear during very short time periods. In order to investigate whether these high intensities can be extracted under stable conditions the extraction system was modified. The aperture of the plasma outlet electrode was enlarged from 10 mm to 15 mm diameter. In fact a further considerable enhancement of afterglow intensity could be achieved. Fig. 5 shows an afterglow peak for $Pb^{27+}$ which attains 200 e$\mu$A peak intensity. At a slightly reduced intensity level of 175 e$\mu$A a very stable operation was possible. Fig. 6 contains two examples showing the ion current in the afterglow of $Pb^{27+}$ continuously recorded over a time period of 8 hours each. The upper diagram was obtained with the small plasma electrode at a 100 e$\mu$A level and contains a typical period of minor instabilities. The lower diagram of Fig. 6 was recorded with the large plasma electrode at extremely stable conditions at an intensity level of 175 e$\mu$A. Pulse to pulse variations were well below 5 %, long time drifts did not exceed 5 % during this run as well. The material consumption is estimated to be less than 0.5 mg/h.

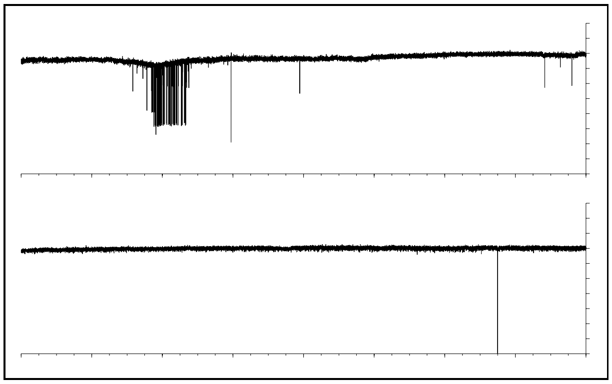

Fig. 6: Afterglow current of $Pb^{27+}$ versus time continuously recorded over 8 hours; upper diagram: run with the 10 mm extraction aperture (full scale: 125 e$\mu$A); lower diagram: run with the 15 mm extraction aperture (full scale: 250 e$\mu$A)

## Conclusions for SIS operation

For the injection of the analyzed ion beam into the RFQ at the HLI it is most important that the ion beam is within the acceptance of the RF structure. As emittance measurements are not yet available at the EIS simply the dependence of measured ion currents on the width of the analyzing slit was measured to get a rough estimate. Fig. 7 compares the results for both extraction apertures. In the case of 10 mm aperture the ion source was optimized for a moderate level of intensity; for 15 mm aperture the optimization aimed at a high afterglow intensity. While for the small extraction aperture the ion current shows some saturation above a width of 10 mm for the large extraction aperture the increase of ion current continues up to a width of 20 mm. It might be concluded

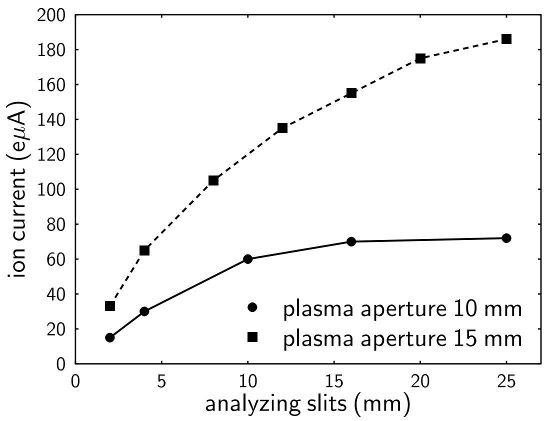

Fig. 7: Measured afterglow intensities for $Pb^{27+}$ versus width of analyzing slits

that the beam envelope increases with larger extraction aperture, but the results also indicate that the beam envelope depends on the ion source setting as well. To get better insight how the beam characteristics is determined by the properties of the respective extraction geometry corresponding simulations of the ion extraction by using a 3–dimensional computer code were performed [6].

Fig. 8 shows a typical spectrum under the conditions of the long time run with the large extraction aperture (see lower part of Fig. 6).

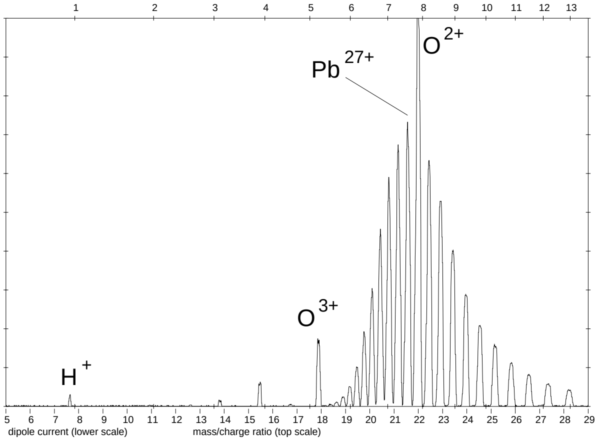

Fig. 8: Afterglow spectrum of Pb (250 e$\mu$A full scale) obtained at 20 kV extraction voltage

## Outlook

It is intended to provide the EIS with further beam diagnostic tools for emittance measurements in order to get better information about beam transport and matching to the beam line at the HLI. This would also allow a direct comparison with computer simulations [6]. For SIS operation it is desirable to provide further heavy ions in afterglow mode. So experiments will be continued with other ion species. For the production of requested elements with low vapor pressure the development of an oven with an extended temperature range is presently performed.

## Acknowledgement

The authors would like to express their gratitude to H. Winter, GSI, for his help in preparing the photomultiplier setup.

## References

[1] P. Briand, R. Geller, G. Melin, Nucl. Instr. and Meth. A 294 (1990) 673

[2] R. Geller, Proc. Conf. on Physics of Highly Charged Ions (Gießen), ed. E. Salzborn, P. H. Mokler and A. Müller; Berlin, Springer (1990) p. 117

[3] M. P. Bourgarel, C. E. Hill, H. Haseroth, K. Langbein, E. Tanke, Proc. of the 12th Int. Workshop on ECR Ion Sources, RIKEN, INS–J–182 (1995) 193;
K. Langbein, ibidem, 198

[4] K. Tinschert, J. Bossler, R. Lang, S. Schennach, H. Schulte, P. Spädtke, Proc. of the 13th Int. Workshop on ECR Ion Sources, College Station, Texas (1997) 172

[5] H. Schulte, K. Tinschert, J. Bossler, B. H. Wolf, J. Klabunde, L. Dahl, T. Schwab, J.-P. Klein, Rev. Sci. Instrum. 63 (1992) 2883

[6] P. Spädtke and K. Tinschert, these proceedings