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EXPERIMENTAL INVESTIGATION OF THE AFTERGLOW OF THE PULSED ECR DISCHARGE

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During the afterglow of the pulsed ECR discharge, currents can be extracted, which are substantially higher than the ion current during the heating phase of the plasma. This is especially the case for the high charge states of heavy ions. An investigation of the shape and duration of the afterglow for the different charge states of lead compared to the afterglow of the carrier gas is presented. An operating regime was found, which gave an extremely stable and reproducible afterglow. The variation from pulse to pulse is hardly visible and the long term stability is also very good. This mode, which made the setting-up and operation of the accelerators much easier than is normally the case, can also give an insight into the processes responsible for the afterglow, which are not yet fully understood.

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Experimental Investigation of the Afterglow of the Pulsed ECR Discharge

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During the afterglow of the pulsed ECR discharge, currents can be extracted, which are substantially higher than the ion current during the heating phase of the plasma. This is especially the case for the high charge states of heavy ions. An investigation of the shape and duration of the afterglow for the different charge states of lead compared to the afterglow pulse of the carrier gas is presented. An operating regime was found, which gave an extremely stable and reproducible afterglow. The variation from pulse to pulse is hardly visible and the long term stability is also very good. This mode, which made the setting-up and operation of the accelerators much easier than is normally the case, can also give an insight into the processes responsible for the afterglow, which are not yet fully understood.

Introduction

If the energy source of a plasma is abruptly turned off, the plasma decays within a certain time, depending on the confinement conditions and the recombination rate of the ions. This *afterglow* of the plasma is well pronounced in ECR ion sources and can last up to 100 ms, as the confinement conditions are very good and the background gas pressure is low.

For a certain choice of parameters one observes, that the ion current leaving the source at the instance, at which the microwave power is turned off, can be 2-3 times larger than the current during the heating period. If one looks only at a single high ionization state the relative increase in ion current can be considerably higher. For instance in the case of lead ion production - under certain conditions - one hardly measures a current of highly charged ions during the heating phase, while the current during the afterglow can be larger than 100 μA for a single species.

The afterglow as an enhancement for the extraction current was first discussed in [1,2,3] and has been studied thoroughly at GANIL [4,5]. In 1992 it was for the first time applied for acceleration purposes, which resulted in a substantial increase of the ion intensities in CERN's accelerator complex [6,7].

Although various explanations have been suggested [8,9,10,11,12], the afterglow phenomenon is still not fully understood and further investigations can lead to even better performances.

One of the main problems encountered, when applying the afterglow are instabilities - in fact, one could call the afterglow itself an instability. One can observe instabilities in intensity, in the position, in the shape and the duration of the afterglow. In the experiments with the MINIMAFIOS those instabilities were partly overcome using a biased electrode in the first stage of the source and by the introduction of a second short microwave pulse with a small delay to the end of the main pulse [7].

With GANIL's ECR4 source [13] the afterglow is more stable, especially for highly charge lead ions and hence it could be utilized for the new heavy ion injector at CERN [14,15,16].

Terminology

To avoid confusion, care must be taken, when comparing the performance in normal operation to the performance in afterglow mode: The ratio of the current during the afterglow to the current during the main pulse can be very high, i.e. >100, if one calculates it for a single species after a spectrometer.

If, on the other hand, one compares the best performance in afterglow mode with the best performance obtainable during the heating phase of a pulsed discharge, the enhancement factor is usually in the order of 2-3. E.g. with the ECR4 source at CERN one can obtain about 30 μA of Pb^{27+} if the current during the

main pulse is optimized and 100 μA, if parameters are adjusted for the afterglow.

It should also be noted, that the afterglow currents of different elements in the source (e.g. oxygen and lead) differ greatly. Furthermore the shape of the afterglow of the total ion current at the source exit, does not necessarily resemble the shape of the afterglow of the required ion species. The total current does, however, have a strong influence on all ion species in the beam, as it determines the temporal behavior of the extraction conditions.

Experimental setup

As mentioned above, the ion source used at CERN is of the ECR4 type developed at GANIL. It operates at a frequency of 14.5 GHz and the usual pulse length is 50 ms. For a good long term stability, a repetition rate of 10 Hz is used, although slightly higher currents can be obtained at lower pulse rates. The maximum power available is 2 kW - operational values range from 1-1.6 kW. The discharge is maintained with oxygen as a carrier gas and isotopically pure lead 208 is evaporated into the discharge chamber using a micro oven. This oven is situated inside the coaxial feed line of the source.

The tuning to the resonant coaxial line is of great importance for the stability and intensity of the afterglow: The best performance is not found at minimum reflected power, but rather at a point where the voltage distribution on the inner conductor leads to the most favorable energy distribution of the emitted secondary electrons.

The beam is extracted from an aperture of 13 mm diam. with a single extraction electrode at a distance of 43 mm. It is then analyzed in a high resolution spectrometer ($\Delta p/p = 3\times10^{-3}$, see refs. [16] and [17]) and injected into the accelerator chain. Ion currents can measured behind the exit slit of the spectrometer using a Faraday cup with secondary electron suppression.

Measurement Technique for Charge State Distributions

One artifact of afterglow operation is, that all measurements must be performed during a certain time window. Thus a special technique was developed to measure the charge state distribution (CSD): The spectrometer current and proportionally to it, the current of the other magnetic elements of the LEBT are raised in small steps by computer control. At each step the trace of the beam current is recorded using a digital storage oscilloscope. If required, those traces can be averaged for a certain number of pulses.

Finally the current in each trace is integrated or averaged for a given time, e.g., 600 μs, and plotted against the spectrometer current. This method allows a comparison of the CSD at different times during the pulse. Due to the proportional adjustment of all magnetic elements in the LEBT, the beam optics remain constant for all charge to mass ratios, so that the total current for each charge state can be measured directly.

Results

a) The "stable" afterglow

A good afterglow can be obtained for a wide range of source parameters. However great care must be taken to obtain stable conditions from pulse to pulse and - equally important - on a long term basis. To distinguish the different settings a number of operating modes were defined (see ref. [16]).

The most interesting setting for source studies is the so called "stable" mode, which is found at relatively low magnetic fields and at a slightly lower output current than the operational modes. In this case the course of the afterglow pulse is completely smooth, and the decay time for highly charged lead ions is in the order of 10 ms. The advantage of this mode is, that it is possible to study the temporal behavior of the afterglow, without the interruption by the usually encountered unstable cutoff edge. From this one may gain an insight into the processes in the source during the course of the afterglow - the time of flight

through the spectrometer line lies, at the acceleration voltage of 20 kV, between 5 and 7 µs for the different charge states and can therefore be neglected compared to decay the times in the millisecond range.

The following measurements were made at a constant source setting which was optimized for this stable mode. The RF power was 1 kW, the pulse duration was 50 ms at the usual repetition rate of 10 Hz. The current in the source coils was 860 A for the rear and 920 A for the front (extraction).

b) Charge State Distribution

Fig. 1a shows the CSD at this setting, together with the afterglow pulse of Pb^{27+} (fig.1b). The vertical lines on (b) indicate the integration limits for the evaluation. Due to the more

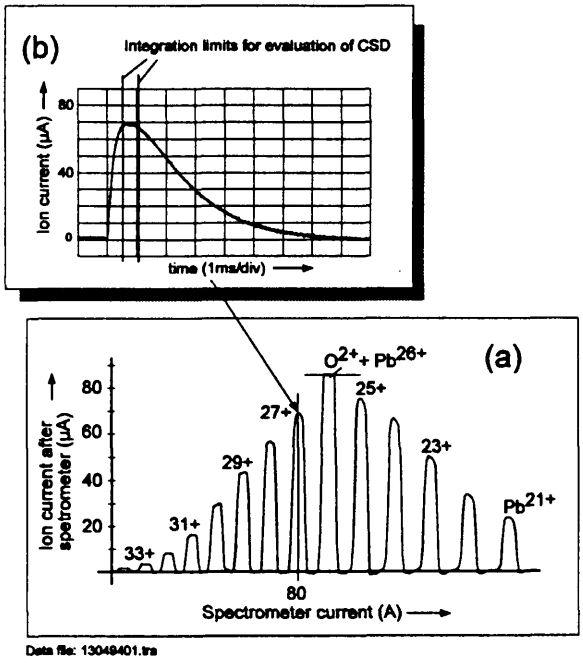

Fig. 1. (a) Charge state distribution during the "stable" afterglow and (b) afterglow pulse of Pb^{27+}.

moderate setting, this distribution has its maximum around Pb^{25+}, opposed to CSD in the mode usually employed for operation, where the maximum lies at Pb^{26+} or Pb^{27+} (see ref. [16], this conference).

If the integration limits are set to a time before the end of the RF pulse one obtains the CSD shown in fig. 2 (note the different current scale). A comparison of the Pb^{27+} ion currents for the two cases (figs.1 and 2) results in an enhancement factor of 35.

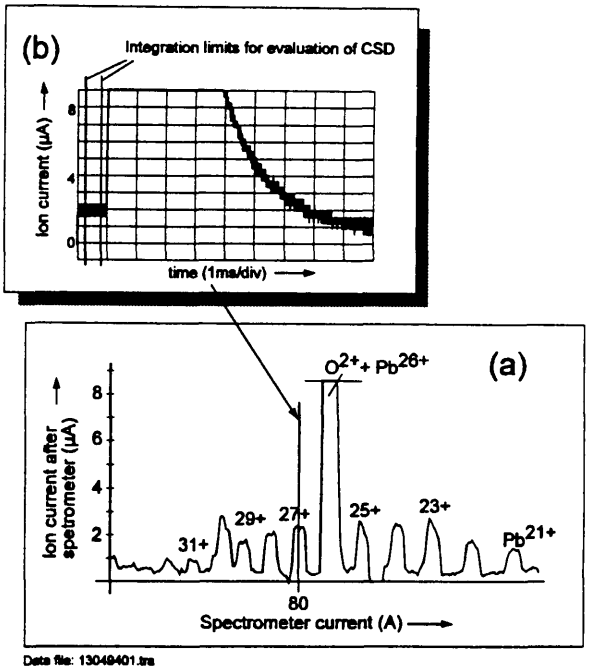

Fig 2. Charge state distribution during the main pulse.

c) Analysis of decay times

Fig. 3 shows the afterglow for the charge states of lead ranging from 21 to 31, normalized to the same height, to allow a comparison of the shape (the maximum currents correspond to the distribution on fig 1a). One sees a shortening of the pulse with an increasing charge state. The pulse shape is very smooth and seems to follow the same mathematical function for all charge states above 24, while

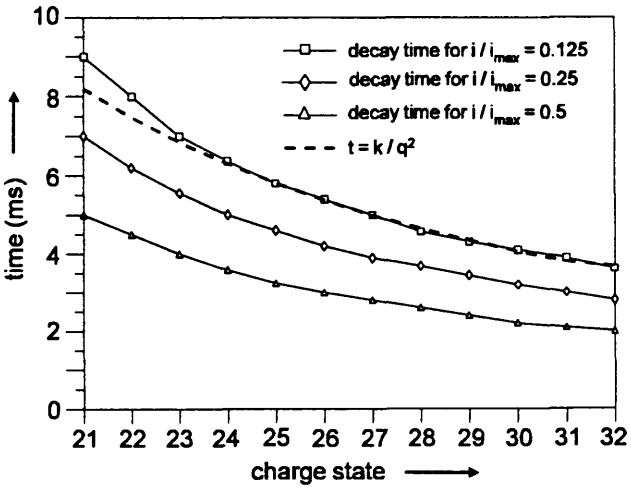

Fig 4. Decay time of the afterglow versus charge state.

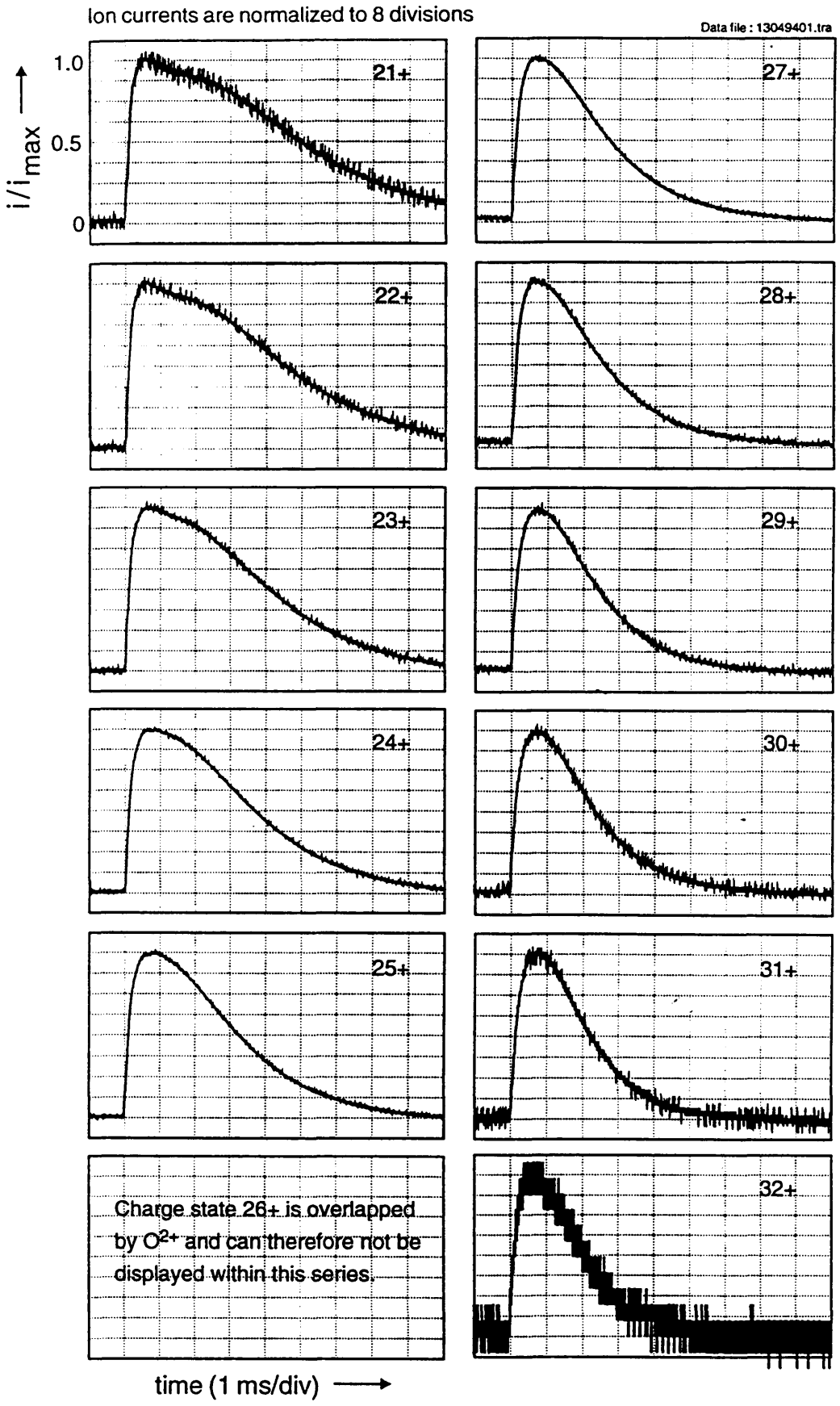

Fig. 3. Shape of the afterglow for different charge states of lead

the shape for the lower charge states is less regular at the beginning.

Fig. 4 shows a plot of the decay times for the different charge states, measured from the end of the RF pulse. As indicated by the dashed line on this figure, one obtains a $1/q^2$ dependence of the decay time, from which only the lower charges deviate slightly.

d) Influence of the extraction system

As mentioned above, the temporal behavior of the total current leaving the source influences the pulse shapes measured in the LEBT because it determines the extraction optics.

Fig. 5 gives a comparison of the afterglow pulse shapes of three different currents, all measured in the "operational" mode (see ref. [16]): The current measured on the extraction electrode (a) grows with a rise time of 1.5 ms until it is abruptly cut off. The spike at the cutoff edge can be interpreted as a breakdown in the extraction gap. The O^{2+} current (b) is already >120 µA before the RF is turned off and then grows with a shallow ramp until it stops at the same instant as trace (a). The Pb^{27+} current (c) has the shortest rise time and reaches its maximum after about 0.7 ms. It is also cut off at the time of the assumed breakdown.

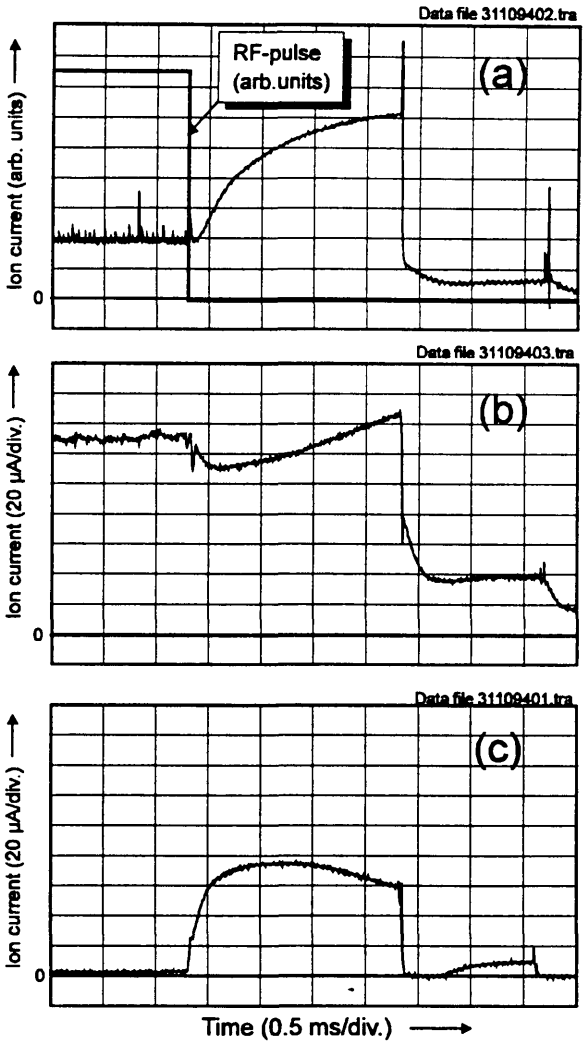

Fig. 5. Comparison of afterglow currents:
(a) Current on extraction electrode,
(b) O^{2+} ion current after spectrometer,
(c) Pb^{27+} ion current after spectrometer.

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