EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN - PS DIVISION

CERN/PS 99-52 (HP)

Experiments on the Pulsed Afterglow Operation of an ECR Ion Source

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No proof for higher intensities was seen for any of the tested modifications. On the contrary, several of the modifications resulted in lower source performance, and less stability. Although the source has previously proved to have very stable modes of operation, during the last physics run, after the above tests, the stability decreased and the source settings were very different from the normal operation values.

Paper presented at the 14th International ECRIS Workshop, ECRIS99
CERN, Geneva, May 3-6, 1999

Geneva,
29 October 1999

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Various experiments have been performed on the 14.5 GHz ECR4 in order to improve the beam yield. The source operates in pulsed “afterglow” mode, and provides currents >120 eμA of Pb^{27+} to the Heavy Ion Facility on an operational basis. In the search for higher beam intensities, the effects of a pulsed biased disk on axis at the injection side were investigated with different pulse timing and voltage settings. Different plasma electrode geometries were also tested, including running the source without a plasma electrode. The use of CF_4 as mixing gas was investigated, and high secondary electron emission materials, such as LaB_6 and Al_2O_3, were inserted inside the plasma chamber in an attempt to increase the cold electron density.

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Introduction

The CERN Heavy Ion Accelerating Facility [1] has now completed five periods of operation, and has become a reliable system for the first stage acceleration of lead ions used for the heavy ion physics experiments. Each year, the ion intensity and the integrated number of ions delivered to the physics targets have increased (Fig. 1). The increase is partly due to a performance enhancement of the Electron Cyclotron Resonance Ion Source (ECRIS, Fig. 2), which utilises the afterglow phenomenon [2] to produce short pulses (500-1500 μs suitable for synchrotron operation) of high charge state ions (Pb^{27+}) that are injected into the heavy ion linac (Linac3). Even though the linac runs at 1 Hz, the source is pulsed with 10 Hz to obtain a higher pulse to pulse stability. So far, the maximum intensity obtained from the source in an exceptionally stable afterglow mode of operation is more than 120 eμA of Pb^{27+}, extracted at an energy of 2.5 keV/u

Nevertheless, the search for higher beam intensities continues. Present physics experiments have a constant call for more particles, and when the LHC project goes into operation with heavy ions, the lead ion production has to be increased almost an order of magnitude compared to present values to fulfil the specifications set by the experiments. For this reason, several months of 1998 were dedicated to a continuation of the yield improvement experiments on the ECR ion source. Two different approaches were tried: either to increase the total number of ions inside the plasma, or to extract the available ions within a shorter period of time (presently the extracted pulse length from the ECR exceeds the typical 400 μs accepted by the synchrotron). The requirements of a high pulse to pulse stability and a flat pulse top were not relinquished.

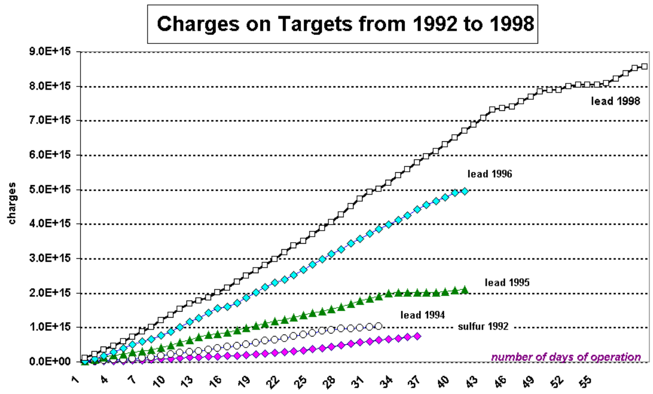

Figure 1. Integrated charges delivered to physics target.

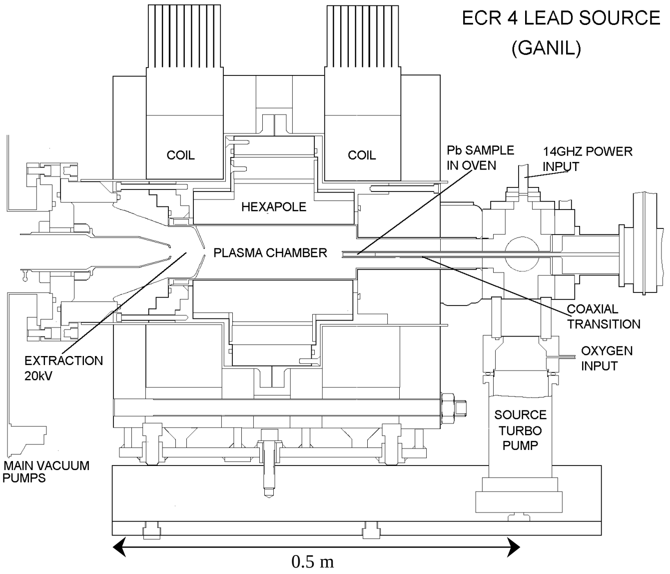

Fig. 2. Cross-section of the ECR4 ion source used at the heavy ion linac at CERN.

Experimental tests

The general test procedure was to first optimise the source before introducing the modification, and thereby obtain an yield reference value. Thereafter the change was carried out, and the source was once again re-tuned to an optimal performance, which was compared with the reference value and the record notation of 120 eμA.

Biased axial electrode

It is usually claimed that a negatively biased electrode, positioned on axis near the plasma at the injection side, may reduce the electron losses out of the magnetic bottle and/or influence the electron density positively due to the injection of cold (secondary) electrons created by bombardment of the electrode with loss electrons and ions. Recent investigations, on the other hand, suggest that the yield increase is solely due to improved extraction conditions [3] or a plasma potential optimisation [4].

It has previously been shown in an ECRIS for sulphur ions that the presence of a biased electrode in the vicinity of the plasma improves the performance and stabilises the afterglow [5]. On the CERN ECR4, biasing tests of the inner conductor of the co-axial transition, which contains the sample oven and which penetrates 8 mm inside the maximum field peak from the injection solenoid in the plasma chamber (see Fig. 3), were performed without any gain in current [6]. A more advanced biasing with a pulsed voltage has now been tested, using a Behlke HTS31 switch. The intensity of Pb^{27+} was measured at Faraday cup positioned after the mass selection and the following acceleration in the RFQ. During normal non-biasing operation the electrode and the plasma chamber are at the same potential.

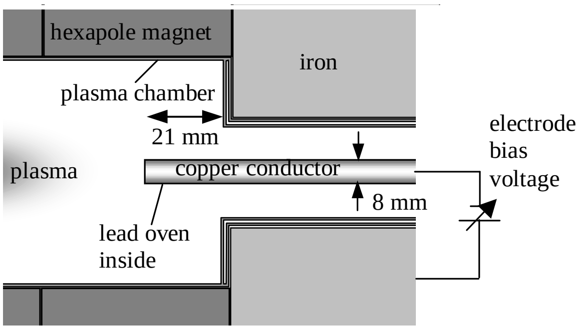

Fig. 3. Schematic drawing of the lead oven arrangement acting as a biased electrode.

With a negative static voltage applied on the electrode, a yield optimum (4% increase) was found for –20 V. Voltages more negative than –50 V quenched the current, and at a maximum voltage of –300 V sparking occurred. After removing the bias the current recovered. The 4% current gain could later be regained solely with tuning efforts and without any bias. A positive static voltage degraded the ion current severely.

Pulsing of the biased electrode was tried, with the opportunity to vary both the voltage, the pulse length and the timing of the pulse relative to the end of the RF pulse. A wide variety of time and voltage settings were investigated. For example, to prevent the electrons from escaping the magnetic bottle a negative bias was applied to the electrode during the breeding phase. With a pulsed bias of -75 V, 1.2 ms long extending 300 μs after RF off flank, a 2% percent current increase was obtained. A negative pulse, active only during the extraction of the beam gave a 3% current increase for a bias voltage of –35 V, while a more negative voltage quenched the beam. The yield increase must have been due to improved extraction conditions, and not due to an increased electron density.

In a similar way positive bias pulsing was investigated. A positive pulse, with a voltage varying between 0 and 100 V, was applied after the RF off flank and different time settings were tried. The purpose was to facilitate the extraction of the electrons from the plasma, and to repel the positive plasma towards the extraction side, but no significant enhancement of the ion current was detected. In addition, a positive pulse before the RF off flank was applied, but this resulted only in a yield reduction.

The O^{2+} peak (from the O_2 mixing gas) was measured in a Faraday cup before the RFQ for a 1.2 ms long pulse extending 300 μs after RF off flank. When increasing the negative voltage from 0 to about –30 V, the O^{2+} afterglow peak was extinguished completely, while the current intensity in the end of the main pulse increased with 30%. This could be interpreted as a sign of increased cold electron density.

To conclude, no major current increase was noticed for the different arrangements of a biased electrode. A slight enhancement may have been detected for a voltage of about -30 V, which corresponds to the potential that a floating electrode near the plasma would acquire. The electrode size might have been too small to have an effect for certain of the above-described experiments.

Alternative mixing gas

Under normal operation oxygen is used as mixing gas for the ECR4 source at CERN. Other gas combinations have been tried out in the past, without any major improvement [6]. The yield increasing effect by a mixing gas, dominant with respect to the main element and always lighter, has various interpretations: the gas increases the electron density and/or performs cooling of the lead ions by ion-ion collisions.

As an alternative to oxygen, CF_4 was tried as mixing gas (without any pre-calculations and a bit hesitatingly due to the poor reputation of fluorine inside other ion sources), mainly for two reasons:

- F has similar properties as O (mass, electro-negativity).
- The CF_4 molecules (if not immediately dissociated) has several metastable states in the region of 10 to 20 eV that could be excited by lead collisions and act as cooling on the lead.

During the experiment both O_2 and CF_4 were connected as mixing gases. The source was first optimised using exclusively oxygen, and thereafter CF_4 was introduced into the source in varying quantities. For each level of CF_4 gas flow, the oxygen in-flow was varied. A clear correlation between the injected amount of CF_4 gas and the extracted Pb^{27+} current was found: the more injected gas, the less extracted current. The Pb^{27+} current decreased to about a tenth of its nominal value for a

CF_4 gas pressure in the same region as an optimal oxygen pressure. At a higher CF_4 pressure, the source was almost entirely quenched. When going back to the original source settings, i.e. using oxygen as mixing gas again and with no CF_4 gas present, it was very difficult to make the source performing well. In the end, the lead oven had to be turned off, and the source was run only with oxygen for one day until it finally could be re-tuned to reach its pre-test current.

The experiment showed a much poorer yield than expected, and the reasons for this are not fully clear. In the case of non-dissociated CF_4 molecules, large charge-exchange cross-section between the molecule and the multiply charged lead ions may have impeded the production of highly charged ions. An inhibiting compound at the oven could also have been created. It is interesting to note the strong yield quenching effect by the addition of the CF_4. Even after the gas was disconnected, and a good source vacuum had been obtained, it was still almost impossible to keep the plasma ignited. It is suspected that a surface coating on the plasma chamber wall had been created, which produced this “memory effect”. Since the yield was quenched only after a combination of CF_4 and RF had been applied[1], it is believed that the memory effect was due to the fluoride and not the CF_4 since the latter should dissociate when the plasma is ignited.

Insertion of internal electron donors

The supply of cold electrons to the ECRIS magnetic trap is necessary to have a large electron density and thereby obtain an efficient ionisation. Plasma chamber coatings with high secondary emission have been tested in several CW ECRIS with a positive effect on the ion current. A chamber liner of aluminium has previously been inserted in the CERN ECR4, but no improvement in the Pb^{27+} current was noticed. This time a slab of Al_2O_3 ($40*10*4\ mm^3$) was inserted in the chamber at the pole tip of the hexapole magnet to be bombarded by plasma particles. Unfortunately, the RF power could not be increased to its nominal value due to heavy discharging and source runaways. The Al_2O_3 being melted by the plasma caused this misbehaviour, which started a violent outgassing and vacuum perturbations.

The next step was to place a small sample of LaB_6 ($\sim 50\ mm^2$) just behind the plasma electrode, but the result from this test was not extraordinary. After one day of adjustments we reached 93% of the record intensity for this set-up. Moreover, we had to start up the source fairly slowly in order to avoid discharges and a high load current. Possibly a better result could be obtained with a larger piece of LaB_6 positioned further into the plasma chamber where the plasma particle bombardment rate is higher.

Plasma electrode variations

Different plasma electrode apertures were tested, including the complete removal of the plasma electrode. The ECR4 source was originally designed with a 6 mm diameter extraction hole, but is normally operated with a 16 mm hole because of its higher performance.

After a stable run of >40 days, the 16 mm plasma electrode was exchanged for the smaller with a 6 mm opening. The source showed an extremely poor yield, a factor 1/75 compared to the unmodified set-up, while simulations predicted a current of 1/10. In spite of tuning, the low current persisted, so the experiment was abandoned and the plasma electrode changed back. Nevertheless, the yield still remained low and spontaneous runaways occurred. Possible explanations for this behaviour could be a malfunctioning oven or too high outgassing, and therefore no direct conclusions can be drawn from this test.

Following an idea of Geller in ref. [7], the plasma electrode was completely removed. Without a plasma electrode the plasma should be confined by the magnetic field lines from the hexapole magnet. When tested, Penning discharges occurred in the extraction, and the nominal extraction voltage could not be reached. It is believed that since the differential pumping usually obtained by the small plasma electrode hole did not exist anymore, the gas pressure in the extraction region became too high. The only way to stop the discharges was to go down with the gas pressure.

Conclusions

Similar tests as described in this report have resulted in a current improvement for ECR ion sources operating in pulsed or CW mode. For the CERN ECR4 source operating in afterglow mode, no significant current increase was noticed in connection with these experiments, neither with previously carried out tests [6,8]. Instead, when introducing the changes the source demonstrates a less stable behaviour; only a minor current increase that can often later be regained by fine-tuning the source without the modification; and in most cases a decrease in the desired Pb^{27+} ion current. Consequently, the experience gained from CW sources seems not to be directly applicable on an ECR source running in afterglow mode.

The source performance might already be optimised, i.e. an enhanced production of highly charged ions, or a more rapid extraction of the ions, only result in worse beam extraction conditions. Even though the beam extraction should not be space charge limited for the present intensities, ion extraction simulations suggest that the plasma meniscus becomes distorted and the extraction conditions degrades for higher ion currents.

Future tests

In a near future, experiments with a larger (20 mm diameter) biased electrode will take place. Electrode materials with different secondary electron emission coefficients (Cu, Ta, Al_2O_3 and stainless steel) will be tested to investigate if a possible current gain is due to a higher electron density or a plasma potential optimisation. An axially moveable puller has

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[1] The source performed normally after the CF_4 gas pressure calibration, which was carried out without the RF on.

recently been designed to allow a continuous variation of the plasma electrode to puller distance without opening up the source. A current increase is expected for larger distances than have been tested so far [8]. A recently purchased x-ray diagnostics system will give information about the characteristic x-rays of the ions and bremsstrahlung of the electrons emitted from the ECR plasma. The wide energy-range for the detector (500 eV to ~500 keV) allows determination of the energies for both the cold and hot electrons. Since the measurement will be time-resolved, the plasma build-up and release can be studied, and hopefully contribute to the understanding of the processes in the plasma and the release of electrons and ions.

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