Electron-beam extraction system for the Frankfurt 14 GHz electron cyclotron resonance ion source

S. Runkel and O. Hohn
Institut für Kernphysik and Institut für Angewandte Physik, Johann Wolfgang Goethe-Universität, D-60054 Frankfurt am Main, Germany

L. Schmidt, K. E. Stiebing,[a] and H. Schmidt-Böcking
Institut für Kernphysik, Johann Wolfgang Goethe-Universität, D-60486 Frankfurt am Main, Germany

A. Schempp and R. Becker
Institut für Angewandte Physik, Johann Wolfgang Goethe-Universität, D-60054 Frankfurt am Main, Germany

(Presented on 10 September 1997)

A new concept to assist in the extraction of ion beams from an electron cyclotron resonance ion source (ECRIS) by the injection of an electron beam from the extraction side into the ion-source plasma is proposed. In this article, the construction of a test setup is described and first results of experiments with this setup at the 14 GHz ECRIS of the Frankfurt ECRIS-(ve)RFQ facility are reported. © *1998 American Institute of Physics.* [S0034-6748(98)54502-9]

I. INTRODUCTION

It is generally accepted that the plasma potential of an electron cyclotron resonance ion source (ECRIS) captures the highest charge states in the middle of the plasma region and thus suppresses their extraction in continuous mode, a feature assumed responsible for the ''afterglow effect.''[1] One possible way to overcome this limitation is the injection of an electron beam from the extraction side into the source plasma to provide an ''exit channel'' for the highly charged ions. Here the intensity of the electron beam can be used to control this manipulation. In addition the e^--beam will also have an influence on the beam formation itself. Two main effects can be expected to work together to improve emittance and intensity of the extracted ion beams. First, the positive ions will experience an attractive potential towards the axis, which effectively will confine the beam closer to the axis. Hence the problematic influence of fringing fields of the magnetic trap inside the extraction region, which usually limits the emittance of an ECRIS, may strongly be reduced. Second, an electron beam will lead to a compensation of the space charge of the ion beam at the extraction hole which is the general limit for the extraction of the highest beam currents from the source.[2] Injection of an e^--beam therefore will allow one to overcome this limitation and to enhance the overall current extracted from the source.[3,4]

Injection from the extraction side has the advantage of leaving the constructive details of the ECRIS itself more or less unchanged. On the other hand, it means to extract the ion beam through a hole in the cathode of the electron gun and to generate energetic electrons that either they have to be dumped on a collector at the position of the disk of the ECRIS or have to be reflected at the disk/collector. The e^--beam energy depends on the position of the e^--gun in the extraction area and on the source potential. In the tests described here the e^--gun was on ground potential and the extraction voltage was 10–15 kV leading to an electron energy of 10–15 keV at the source extraction hole.

This energetic e^--beam can advantageously be used to evaporate solid materials by heating a sample positioned at the disk/collector or to precharge injected neutrals so they are better captured in the plasma. Finally it may be used to enhance the plasma density (e.g., by generating an oscillating beam inside the plasma chamber by reflecting the beam at the disk/collector). It is worth noting that this way of enhancing the plasma density is quite different from the use of a low voltage electron gun on the terminal side of the source to enhance the plasma density by injection of cold electrons.[5] A dense reflected electron beam not only enhances the plasma density close to the source axis but it will also provide enrichment of the plasma with electrons with energies appropriate for ionizing strongly bound electrons and therefore better represents a combination of an ECRIS with an electron beam ion source (EBIS). It has to be proven, however, that this beam will not lead to the complete destruction of the potential well that is responsible and necessary for the breeding of high charge states inside the source.

II. EXPERIMENTAL SETUP

For the tests at the Frankfurt ECRIS[6–8] a well proven electron-gun geometry was chosen.[9] It consists of a high-current cathode (tungsten impregnated) positioned inside an iron cylinder to reduce the influence of the magnetic fringing fields of the solenoidal trap of the ECRIS to allow partially immersed flow focusing of the e^- beam.[10] A delineation of the electron-gun assembly at the extraction area of the ECRIS is given in Fig. 1. An IGUN[11] simulation of the beam formation setup is shown in Fig. 2. The operational param-

[a]Electronic mail: stiebing@alpha.ikf.physik.uni-frankfurt.de

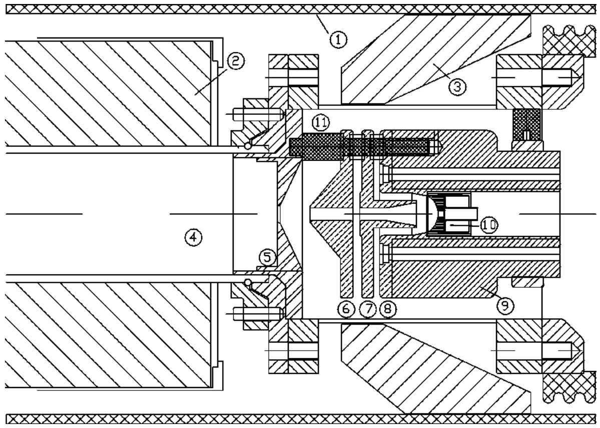

FIG. 1. Cross section through the electron-gun assembly in the extraction area of the Frankfurt ECRIS. (1) Main insulation pipe; (2) hexapole; (3) magnetic-field shaping plug (iron); (4) plasma chamber; (5) moveable plasma chamber electrode; (6) puller electrode; (7) anode; (8) Wehnelt cylinder (water cooled); (9) iron cylinder; (10) cathode with 3 mm hole; (11) insulators.

eters of the e$^-$-gun are given in Table I. Its present range of operation in the ECRIS is limited; however, by the maximum current of the high voltage (HV) power supply and the power that can be dumped onto the ECRIS's disk. Typical e$^-$ currents during the first period of the experiments presented here were in the range of $I_{e^-} \leqslant 30$ mA. Another drawback of the present assembly is a limit of 15 kV on the source voltage. Since all earlier tests with the conventional ECRIS setup have been performed at source voltages around 30 kV, a comparison of the new results to the best results with the conventional setup is difficult.

III. RESULTS

A first test series of measurements was carried out with the cathode's original inner diameter of only 1 mm. Here, of course, the ion beam from the ECRIS is cut down tremendously compared to normal operation with a 14 mm hole in the extraction electrode. Therefore the ion beam currents measured during this first series of experiments are strongly reduced compared to charge state spectra already published.[8] As a result of this first series of experiments, three argon charge-state distributions measured in a Faraday cup placed after the analyzing magnet[8] are shown in Fig. 3. The beam transport has been optimized to the Ar^{8+} charge state. The spectra are representative of a series of spectra taken with two different e$^-$-beam intensities (15/28 mA) and without

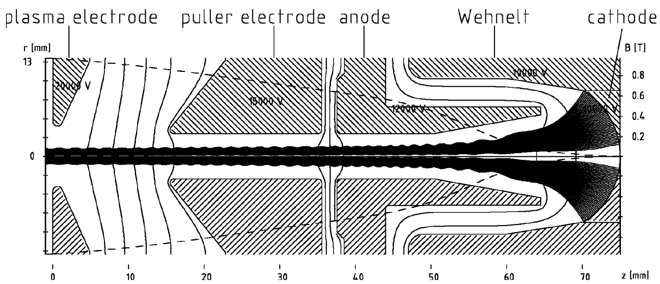

FIG. 2. IGUN simulation of the formation of the electron beam.

TABLE I. Operational parameters of the electron gun.

Electron current	10–3000 mA
Electron energy	5–25 kV
Perveance	2.1 μA/V$^{3/2}$
Cathode heating power	80 W
Current density (200 mA)	5 A/cm^2
Cathode hole diameter	1.0–5.0 mm

the e$^-$-beam (later denoted as ''normal'' mode). Despite the expected poor overall intensities, one promising result is the unproportionally strong enhancement of the intensity of high charge states compared to lower ones when the electron beam is introduced into the plasma chamber.

$$[(I_{(28\ \mathrm{mA})}/I_{(\mathrm{normal})})^{6^+}=6.0,$$

$$(I_{(28\ \mathrm{mA})}/I_{(\mathrm{normal})})^{11^+}=14.1].$$

This increase also depends on the intensity of the electron beam as can readily be seen from Fig. 3 and has been proven in a series of experiments with the above setup. As the total intensity of the charge state spectra is far below what is measured during normal operation of the ECRIS,[3] no preference can be given as to which of the influences discussed above causes this enhancement.

In order to verify and to further pursue this result we have redesigned parts of the setup. The bore in the cathode was opened to a diameter of 3.0 mm and the beam transport behind the e$^-$-gun assembly was recalculated and rebuilt. A first preliminary experiment with only low e$^-$-beam intensities, still limited by the HV power supply, yielded charge state spectra with intensities that are enhanced by a factor of 150–200 compared to the experiments with the 1.0 mm cathode diameter. The results differ roughly only by a factor of 4 compared to the best results reached with the conventional ECRIS setup at a 30 kV extraction voltage. A sum of the drain currents of the power supplies indeed indicates that more than 60% of the total available current of positive

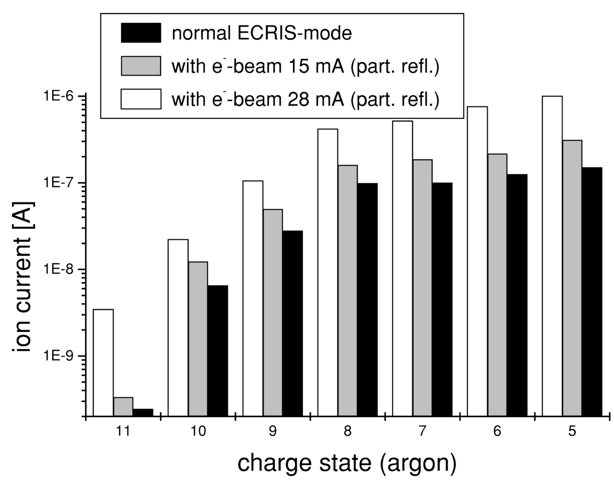

FIG. 3. Charge state spectra measured after use of the analyzing magnet for various conditions as indicated. The source voltage was 15 kV; all charge state spectra are recorded after optimizing the beam optics to transport the Ar^{8+} charge state.

charges has been extracted and transported into the Faraday cup. Also the charge state spectra taken with ''normal mode'' are off the results with the e-gun by only 10%–20%. No unproportionally high enhancement of higher charge states is observed. This indicates that the influence of the e^--beam is too weak now to markably influence the extraction of these stronger beams.

As a next step of improvement the disk will be substituted by a water cooled collector to allow the injection of high-power electron beams and it is planned to further enhance e^--beam intensity by reflecting the beam at the collector and the cathode to form an oscillating beam. In this mode it will also be possible to bring up the source voltage to values better comparable to results of the conventional ECRIS setup.

ACKNOWLEDGMENTS

This work was supported by the Deutsche Forschungsgemeinschaft and by the Ministerium für Wissenschaft und Kunst, Hesse, Germany.

[1] R. Geller, *Electron Cyclotron Resonance Ion Sources and ECR Plasmas* (IOP, Bristol, 1996).

[2] U. Herleb and H. Riege, internal report CERN LHC/96-07 (DLO).

[3] C. D. Child, Phys. Rev. **32**, 492 (1911).

[4] I. Langmuir, Phys. Rev. **11**, 450 (1930).

[5] Z. Q. Xie, C. M. Lyneis, R. S. Lam, and S. A. Lundgreen, in *Proceedings of the 10th International Workshop on ECR Ion Sources*, edited by F. W. Meyer and M. I. Kirkpatrick (Oak Ridge National Laboratory, Oak Ridge, TN, 1990), p. 47.

[6] H. Schmidt-Böcking, A. Schempp, and K. E. Stiebing, in *Materials Research with Ion Beams*, edited by H. Schmidt-Böcking, A. Schempp, and K. E. Stiebing, Research Reports in Physics (Springer, Heidelberg, 1992).

[7] K. E. Stiebing, D. Hofmann, H. Schmidt-Böcking, K. Bethge, H. Streitz, A. Schempp, G. Zschornack, and C. Lyneis, Rev. Sci. Instrum. **63**, 2897 (1992).

[8] K. E. Stiebing, H. Streitz, L. Schmidt, A. Schremmer, K. Bethge, H. Schmidt-Böcking, A. Schempp, U. Bessler, and P. Beller, in *Proceedings of the 12th International Workshop on ECR Ion Sources*, edited by M. Sekiguchi and T. Nakagawa (Riken, Japan, 1995), p. 122.

[9] O. Kester, R. Becker, and M. Kleinod, Rev. Sci. Instrum. **67**, 1165 (1996).

[10] R. Becker, in *Handbook of Ion Sources*, edited by B. Wolf (Chemical Rubber, Boca Raton, FL, 1995), p. 157.

[11] R. Becker and W. B. Herrmannsfeldt, Rev. Sci. Instrum. **63**, 2756 (1992).