Single-stage 5 GHz ECR-multicharged ion source with high magnetic mirror ratio and biased disk

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A low-cost, single-stage 5 GHz electron cyclotron resonance (ECR) multicharged ion source (MCIS) has been constructed for various atomic collision experiments. It features an axial magnetic field with a mirror ratio of up to five, and a magnetic hexapole field produced by a simple Nd–Fe–B permanent-magnet assembly. A disk probe axially mounted near the ECR resonance zone opposite to the ion extraction, and negatively biased with respect to the ECR plasma potential, permits reduction of the appropriate neutral feeding gas pressure by an order of magnitude, resulting in greatly improved ion charge state distributions, as normally offered by two-stage ECR–MCIS only. We present performance data for multicharged ion production from Ar and N_2, including measured ion current emittances.

I. INTRODUCTION

Electron cyclotron resonance (ECR) plasma heating in magnetic mirror fields permits efficient production of multicharged ions (MCI), as first pointed out[1,2] and practically demonstrated[3,4] some twenty years ago. Improved ion confinement within the magnetic mirrors by superimposed magnetic multipole fields[5] and creation of the latter by permanent magnets[6] constituted further important steps toward the nowadays available, highly efficient ECR–MCIS.[7,8] Empirical scaling laws[9] predict enhancement of both the attainable charge states and the currents of the extracted MCI with the ECR frequency $\omega_{\mathrm{ecr}}=(e/m_e)B_{\mathrm{ecr}}$, which also necessitates a corresponding increase of the magnetic field strength B_{ecr} at the ECR heating zone. With present-day performance of permanent magnet materials this has already led to an increase of $\omega_{\mathrm{ecr}}/2\pi$ beyond 30 GHz. However, apart from shooting at still higher performance, there is a considerable interest for technical improvements at somewhat less ambitious conditions for, e.g., many interesting experimental studies on MCI-related atomic collisions both in the gas phase and at solid surfaces. In this article we describe a home-made single-stage ECR–MCIS based on a similar device built by E. Salzborn and co-workers at the University of Giessen/Germany.[10] It involves an ECR frequency of 5 GHz, an axial magnetic field configuration with high mirror ratio (up to five), and a magnetic hexapole field produced by a simple Nd–Fe–B permanent magnet assembly. In the following we shortly describe the construction of this MCIS and its performance for MCI production from Ar and N_2 feeding gases, including some preliminary information on measured ion current emittance.

II. CONSTRUCTION OF THE MULTICHARGED ION SOURCE

A. General layout of electron cyclotron resonance ion source

A schematic view of the (ECRIS) setup is shown in Fig. 1. The general design is based on the Giessen 5 GHz ECR ion source,[10] which involves one plasma stage only. A biased copper disk serves as electron emitter, which gives rise to greatly improved ion charge state distributions, otherwise only obtained from double-stage ECR ion sources (see below). This greatly simplifies the ion source construction and also reduces its costs. As compared to the Giessen ECR–MCIS, both the magnet structures and the geometry of the extraction region have been considerably modified.

B. Microwave system

5 GHz operating frequency has been chosen because for this range rather cheap microwave components are widely available. A klystron (Thomson-CSF; gain 38 dB) delivering microwave power of up to 1 kW is coupled by a rectangular-to-cylindrical waveguide transition to the rear of the plasma vessel with an inner diameter of 66 mm, for which reason only the transverse-electric (TE)11 microwave mode can be transmitted. The waveguide transition is also connected to two conflat flanges brazed to ceramic insulators for the feeding gas inlet and a 60 ℓ/s turbomolecular pump, respectively. The residual gas pressure in the plasma vessel is about 10^{-7} mbar.

C. Magnet system

Enhanced longitudinal magnetic confinement of the ions is achieved by an axial mirror ratio of up to five. Two solenoids, each made of four water-cooled copper pancakes (8×8 mm^2 conductor cross section with a 5-mm-diam bore for water cooling), produce the magnetic mirror field. The magnetic mirror ratio is enhanced by encasing the solenoids with soft iron (see Fig. 1). The magnetic field maximum on axis amounts up to 0.5 T at a power consumption of 30 kW (20 V/750 A per solenoid).

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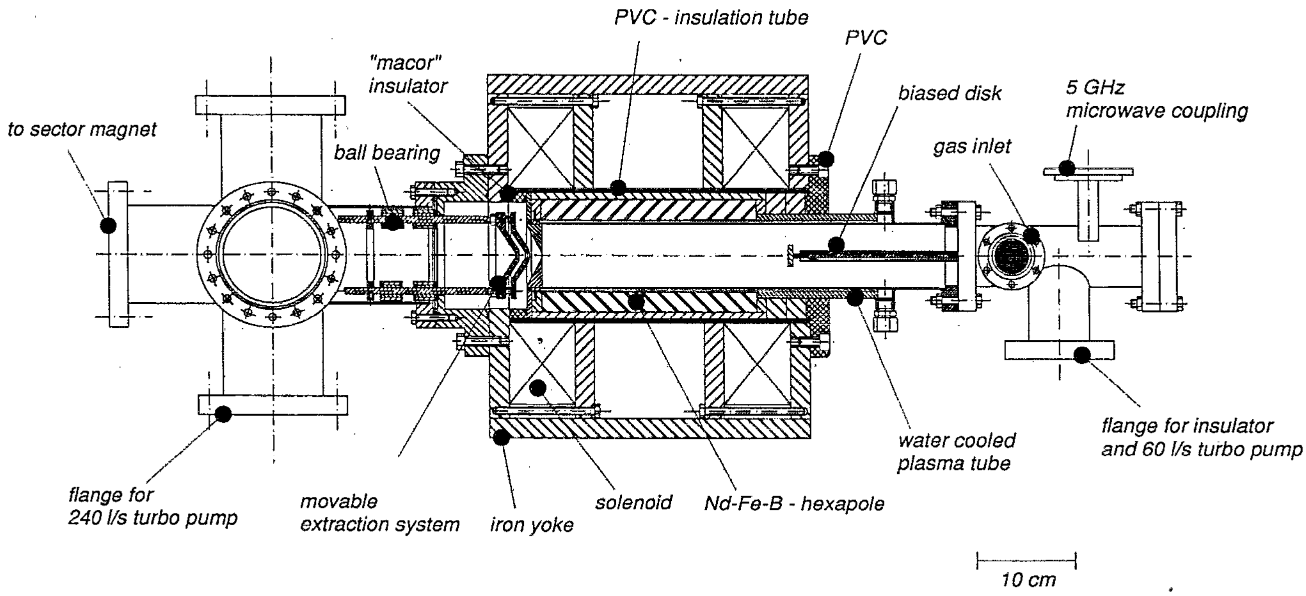

FIG. 1. Schematic drawing of the TU-Wien 5 GHz ECR ion source.

A correspondingly strong Nd–Fe–B permanent magnet hexapole field permits—apart from the 5 GHz ECR zone—formation of a second, closed 10 GHz surface inside the plasma vessel. The radial thickness of the permanent magnet pieces has been minimized to provide room for the largest possible plasma vessel diameter. To obtain a maximum field strength of 0.5 T inside the latter, a fully closed hexapole construction has been designed, with the permanent magnet pieces almost uniformly changing their direction of magnetization ($M=1.2$ T). The advantages of this rather strong hexapole are its relatively simple assembling and the need for only three different kinds of magnet pieces, which also keeps costs down. The plasma tube is equipped with a water-cooled double-walled jacket to limit the temperature of the permanent magnet pieces to about 50 °C.

D. Extraction system

The three-electrode ion extraction is of the accel–decel type with an extraction hole diameter of 6 mm. It can be moved during operation on linear ball bearings along the MCIS axis over a distance of 50 mm. The ion source insulation allows extraction voltages of up to 15 kV with an accel-lens voltage of -6 kV. The extraction region is pumped by a 240 ℓ/s turbomolecular pump. Formation and mass-separation analysis of the extracted ion beam for the planned applications in ion-atom and ion-surface collision experiments are achieved by a magnetic-quadrupole doublet and a 60° sector magnet. The MCI currents presented below have been measured behind this ion-optical system in a 3-mm-diam Faraday cup.

III. MULTICHARGED ION SOURCE PERFORMANCE

A. Extractable ion currents

Because of their relatively high operating-gas pressure, single-stage ECR ion sources usually provide considerably lower charge states than double-stage devices. Recent experiments[11,12] have clarified the role of the first stage in a two-stage ECRIS being likely the primary source of cold electrons rather than of low charged ions for the main plasma stage. The latter suffers from a major loss of cold electrons, which diffuse away most rapidly, and an additional electron supply is thus useful for improving the plasma confinement. Any electron emitter as the first plasma stage (see above), an electron gun,[11] or a biased probe[10,12] will serve that purpose. A biased disk in a single stage ECR ion source will thus permit a considerably lower operating gas pressure, since the collisionally induced electrons from this probe provide electrons more efficiently than collisional ionization of the neutral gas atoms within the ECR plasma. This permits them to reach higher electron temperatures and thus also higher ion charge states than without an extra electron supply.

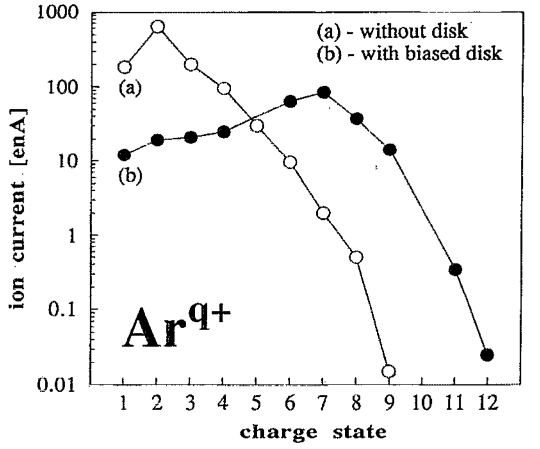

FIG. 2. Argon ion-charge state distributions for the ECR ion source operated without and with biased disk installed. ($P_\mu=60$ W, $U_{ex}=5$ kV, bias voltage -300 V.)

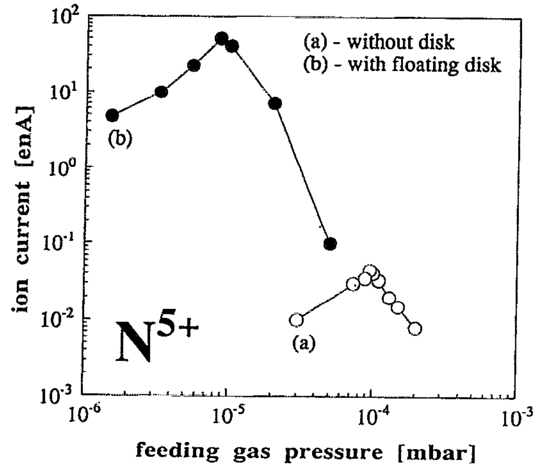

FIG. 3. Extracted N^{5+} ion current vs working gas pressure for the ECR ion source operated without and with biased disk installed. ($P_\mu=60$ W, $U_{ex}=5$ kV.)

Figure 2 shows ion charge state distributions for Ar^{q+}, with and without the biased disk in place. In both cases, with a microwave power of $P_\mu=60$ W only the ion source conditions have been optimized for the respectively highest achievable charge states. With the disk placed near the plasma and biased by up to -300 V, the charge state delivered with the highest electrical current shifted from Ar^{2+} to Ar^{7+}, and the highest detectable charge state from Ar^{9+} to Ar^{12+}, respectively. When increasing the microwave power, the highest achievable charge states and their currents can be further increased.

Figure 3 shows, for optimized production of N^{5+} ions, the respectively attainable source pressure regions for stable plasma conditions, with and without the disk probe in place. The gas pressure can be lowered by more than one order of magnitude with the disk probe in place and just floating. Figure 4 shows the extracted ion currents versus negative bias voltage of the disk probe. Whereas the currents for lower charge states evidently decrease when increasing the bias voltage, the higher ion charge state currents are considerably enhanced.

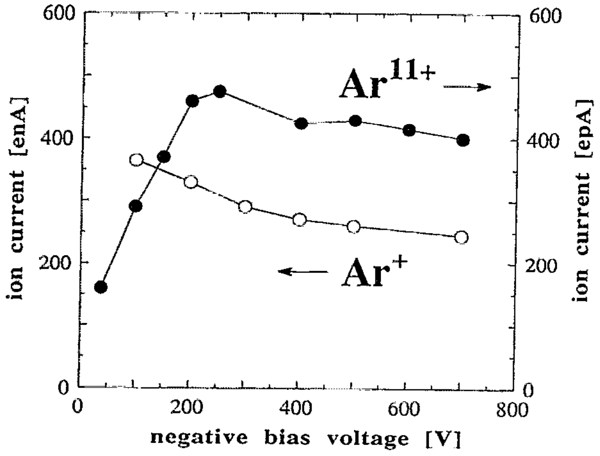

FIG. 4. Extracted Ar^{+} and Ar^{11+} ion current vs negative bias voltage. ($P_\mu=60$ W, $U_{ex}=5$ kV.)

TABLE I. Measured emittances for N^{q+} ion beams ($q=1,2,3,4$).

	N^{+}	N^{2+}	N^{3+}	N^{4+}
90% emittance [π mm mrad]	93	73	71	42

With the available, rather simple ECR–MCIS, long-period stable production of multicharged ion currents in the nA range has been achieved for up to Ar^{12+}, and also up to the H-like MCI of oxygen, nitrogen, and carbon. As to near-future developments, the microwave system will be run up to a power of 1 kW, which should result in accordingly higher extracted ion currents and charge states. In addition, the present source construction is also suited for 10 GHz microwave frequency, without a need to change the existing magnetic structures.

B. Emittance of extracted ions

Emittance measurements have been performed for different charge states with a wire scanner behind a multislit plate mounted in place of the Faraday cup. For N^{+} ions the emittance area corresponding to 90% of the total ion current is 93 π mm mrad. For higher N^{q+} charge states the emittance decreases (cf. Table I). For these measurements the ion source parameters have been optimized for each specific charge state.

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[1] H. Postma, Phys. Lett. A **31**, 196 (1970).
[2] A. van der Woude, IEEE Trans. Nucl. Sci. **NS-19**, 187 (1972).
[3] S. Bliman, R. Geller, W. Hess, B. Jacquot, and C. Jacquot, IEEE Trans. Nucl. Sci. **NS-19**, 200 (1972).
[4] K. Bernhardi, G. Fuchs, M. A. Goldman, H. C. Herbert, W. Walcher, and K. Wiesemann, IEEE Trans. Nucl. Sci. **NS-23**, 999 (1975).
[5] R. Geller, IEEE Trans. Nucl. Sci. **NS-23**, 904 (1975).
[6] R. Geller, IEEE Trans. Nucl. Sci. **NS-26**, 2120 (1979).
[7] Y. Jongen and C. M. Lyneis, in *The Physics and Technology of Ion Sources*, edited by I. G. Brown (Wiley, New York, 1989), Chap. 10.
[8] R. Geller, P. Ludwig, and G. Melin, Rev. Sci. Instrum. **63**, 2795 (1992).
[9] R. Geller *et al.*, Proc. Int. Conf. on ECR ion sources, NSCL Report No. MSUCP-47, 1987, p. 1; R. Geller, J. Phys. Colloq. **50**, C1 887 (1989); R. Geller, Europhys. News **22**, 8 (1991).
[10] M. Liehr, G. Mank, and E. Salzborn, NSCL Report No. MSUCP-47, 1987, p. 292.
[11] C. M. Lyneis, Z. Xie, D. J. Clark, R. S. Lam, and S. A. Lundgren, Report No. ORNL CONF-9011136, 47, 1990; Z. Xie, C. M. Lyneis, D. J. Clark, R. S. Lam, and S. A. Lundgren, Rev. Sci. Instrum. **62**, 775 (1991).
[12] S. Gammino, J. Sijbring, and A. G. Drentje, Rev. Sci. Instrum. **63**,2872 (1992).