Compact 14.5 GHz all-permanent magnet ECRIS for experiments with slow multicharged ions

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Abstract. A compact 14.5 GHz electron cyclotron resonance ion source (ECRIS) for production of multiply charged ions (MCI) with a plasma-confining magnetic field generated by permanent magnets has been constructed. Microwave power with frequency between 12.75 and 14.5 GHz is transmitted from ground potential via an insulating window into the water-cooled plasma chamber fitted with an aluminium liner. The HF coupling system serves as biased electrode. Operation in the gas-mixing mode is achieved with two remotely controlled gas inlet valves. The triode ion extraction system has been optimized for low acceleration voltages between 1 and 10 kV. The ECRIS is fully computer-controlled and can be remotely operated via Ethernet. Finally, we refer to recent experimental work on collisions of slow MCI generated by the new ECRIS with neutral gas particles and surfaces.

1. Introduction
Impact of slow multiply charged ions (MCI, velocity below 1 a.u./25 keV/amu) on atoms and molecules in the gas phase and on solid surfaces is of interest for various research fields as, e.g., thermonuclear fusion [1], astrophysical and ionospheric plasmas, and surface chemistry and analytics. MCI sources based on electron cyclotron resonance (ECR) plasma heating have been developed by R. Geller and coworkers [2] and are today very common for MCI beam production [3,4]. High ECR frequency is favourable for efficient MCI production [5] and requires sufficiently strong magnetic fields for plasma confinement. Producing them by normal or superconducting electromagnets is energy-consuming and costly in operation. Currently available permanent magnets limit the ECR frequency to about 14 GHz [6]. We have constructed a compact 14.5 GHz all-permanent magnet ECRIS with an extraction geometry optimized to low acceleration voltages for experiments with low-energy MCI beams. The total electrical power consumption of the new ECRIS is quite small and its system costs of less than 100 k$ make it affordable even for small laboratories.

2. Description and performance of the new ECRIS
Schematic drawing and a photograph of the ECRIS are shown in figure 1. The min-B magnetic field for plasma confinement is generated by four permanent magnet rings and a Halbach-type hexapole [7] with 80 mm outer diam. The permanent magnet components were manufactured from high remanence NdFeB alloy (‘VACODYM 7 655 HR’ by Vacuumschmelze Hanau, Germany). Two axially and two radially magnetized rings provide the axial mirror field with a maximum of about 0.9 T and mirror ratios of 2.1 at the microwave entrance side and 1.9 at the ion extraction side, respectively.
For low construction costs the permanent magnet components have been made as small as reasonably possible. The whole magnet system can be shifted along the plasma chamber in order to optimize the currents for different ion charge states.

Figure 1. Schematic drawing (top view; arrows show direction of magnetization) and photograph (side view) of 14.5 GHz all permanent magnet ECRIS (overall length ca. 40 cm).

The 200 W microwave power supply consists of a Ku-band compact travelling wave tube (TWT) amplifier (VZU-6992EC by CPI - Communication and Power Industries) fed by a thin film oscillator (OMNIYIG 1518 YIG). It permits continuous operation between 12.75 GHz and 14.5 GHz. A circulator protects the amplifier from reflected power. Transmission into the discharge chamber with electrical and vacuum insulation is achieved by a 2 mm thick PTFE window separating an outer standard WR-75 rectangular waveguide from the internal 13 mm ID cylindrical microwave launcher. The latter can be biased by up to 2 kV with respect to the plasma chamber potential for serving as biased electrode (see figure 1), which together with an aluminum sheet liner for the 25 mm inner diameter plasma chamber favours MCI production [8]. Two remotely-controlled gas inlet valves connected via insulating breaks permit plasma operation in the gas-mixing mode [8]. The PTFE window has no direct sight contact with the plasma to avoid undesired sputtered metal coverage. Plasma operation with non-gaseous feeding materials can be achieved with a suitable oven inside the plasma chamber. In principle the ECRIS plasma chamber may only be evacuated via the extraction orifice, but for efficient highly charged ion production we apply an additional turbomolecular pump via an insulating break. Without gas inlet the base pressure in the plasma chamber is about $10^{-7}$ mbar.

The triode “accel-decel” ion extraction system matches the 5 mm diam. orifice of the discharge chamber. Its three cylindrically concentric electrodes are positioned and insulated by ceramic spacers. The accel (suppressor) and decel (extraction) electrodes are fixed on the plasma electrode which for easy maintainance fits snugly into the plasma chamber. The extraction system is operated under perveance-matching conditions with a variable potential difference of 1 to 10 kV between the decel electrode and the ion source chamber, and with up to 2 kV potential difference between the accel and decel electrodes. Extensive ion beam modelling simulations with space charge taken into account have been made for the best possible match of the ECRIS plasma to the extraction system geometry and potentials.

Characterization of overall ECRIS performance has been made at 5 kV extraction voltage by ion detection in a 3 mm aperture shielded Faraday cup [12] behind a 60° analyzer magnet, without subsequent focusing of the different ion charge state beams into the Faraday cup. ECRIS operating parameters have been adapted for maximum current of the selected ion charge states $q$, together with oxygen as mixing gas. The such measured MCI currents with corresponding ECRIS parameters are listed in Table 1. As an example, figure 2 shows the dependence of the measured $\text{Ar}^{8+}$ current on microwave power. Still higher ion charge states than listed in Table 1 could be observed but not quantified by ion current measurements.
Table 1. Typical achievable Ar ion currents with corresponding ion source parameters as measured with a 3 mm aperture Faraday cup (see text). Ar$^{5+}$ and Ar$^{10+}$ ion currents could not be measured because of their match in mass-to-charge ratio with some impurity ions. Extraction voltage 5 kV.

| Argon charge state | FC current [nA] | Microwave power [W] | Microwave frequency [GHz] | Total pressure [mPa] |
|-------------------|-----------------|---------------------|--------------------------|---------------------|
| 1                 | 2500            | 75                  | 13.97                    | 8.0                 |
| 2                 | 1850            | 75                  | 13.95                    | 6.0                 |
| 3                 | 1750            | 74                  | 13.65                    | 7.2                 |
| 4                 | 1480            | 94                  | 13.94                    | 7.0                 |
| 6                 | 1300            | 69                  | 14.03                    | 6.2                 |
| 7                 | 1140            | 69                  | 14.03                    | 6.7                 |
| 8                 | 1100            | 69                  | 14.02                    | 6.7                 |
| 9                 | 380             | 120                 | 13.75                    | 5.8                 |
| 11                | 50              | 169                 | 13.75                    | 5.7                 |
| 12                | 30              | 170                 | 13.56                    | 5.4                 |
| 13                | 2               | 170                 | 13.55                    | 5.1                 |

Figure 2. Ar$^{8+}$ ion current in dependence of negative waveguide bias potential. Extraction voltage 5 kV, microwave power 69 W.

Total system costs for the new ECRIS are about 100 000.- USD. It is now routinely used in our laboratory for experimental studies involving low energy MCI collisions in the gas phase and on surfaces. If no ion beam is needed, especially for subsequent low-energy ion beam production the stability of the ECRIS is maintained by continuous operation at reduced microwave power. The ECRIS can be operated without attendance for weeks, but sometimes short-circuiting of the extraction system occurs due to sputtering. The ECRIS operating parameter field has so far not been fully explored and its performance may thus well exceed the here described status.

3. Selected studies with the new ECRIS

Figure 2 shows the dependence of Ar$^{8+}$ current on microwave power and bias voltage of the microwave launcher, respectively. Negative biasing is favourable for production of higher charged ions. The ion mass-to-charge spectra shown in figure 3 have been obtained with ECRIS parameters and extraction conditions optimized for Ar$^{13+}$ currents. The new ECRIS serves in our laboratory for experimental studies on collisions of MCI in the gas phase as well as with surfaces. E.g., we routinely measure cross sections for collisional processes of relevance for fusion edge plasmas (low energy helium and impurity ion collisions with neutral atoms and molecules [13]), and also study slow MCI induced electron emission from fusion reactor relevant surfaces as CFC graphite [14]. Other research concerns the guiding of slow MCI through nanocapillaries in insulator films [15] and the exploration of nanostructuring for selected insulator surfaces by slow MCI induced potential sputtering [16].
Figure 3. Typical Ar ion spectra (extraction voltage 5 kV) with ion source parameters optimized for maximum Ar$^{13+}$ ion current (Ar pressure 4 mPa, microwave power 170 W, bias voltage –2 kV).

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