# Compact, low-cost, 14.5 GHz all-permanent magnet field ECR multiply charged ion source

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## Abstract

A compact 14.5 GHz electron cyclotron resonance (ECR) ion source has been constructed with its plasma-confining magnetic field produced exclusively by permanent magnets. Microwave power in the frequency range from 12.75 to 14.5 GHz is transmitted from ground potential via a PTFE window into the water-cooled plasma chamber which can be equipped with an aluminum liner. The waveguide coupling system serves as biased electrode, and two remotely-controlled gas inlet valves connected via an insulating break permit plasma operation in the gas-mixing mode. A triode extraction system sustains ion acceleration voltages between 1 kV and 10 kV. The ECRIS is fully computer-controlled and can be remotely operated from any desired location via Ethernet.

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# 1. INTRODUCTION

Impact of slow multiply charged ions (MCI velocity below 1 a.u. or 25 keV/amu) on atoms and molecules in the gas phase and on solid surfaces is relevant in various fields of research as, e.g., thermonuclear fusion, astrophysical and ionosperic plasmas, and surface chemistry and analytics. Demand for slow MCI beams has thus strongly increased during the last two decades. MCI sources involving electron cyclotron resonance (ECR) plasma heating have been introduced some forty years ago by R. Geller and coworkers[1]. ECRIS have become the working horse for slow MCI beam production[2,3]. ECR plasma heating at enhanced frequency is favourable for MCI production[4], but respectively strong magnetic fields are needed for satisfactory plasma confinement. Producing such magnetic fields by normal conducting or superconducting electromagnet coils is energy-consuming and therefore rather costly in operation. This is avoided by permanent magnet fields, but with nowadays available permanent magnet technology ECR frequencies of about 14 GHz are at the upper limit[5].

We have built a compact 14.5 GHz all-permanent magnet ECRIS, to replace an earlier constructed 5 GHz ECRIS with normal-conducting mirror coils (total power consumption about 30 kW) and a permanent-magnet hexapole field[6]. With the new ECRIS higher ion charge states are obtained, the extraction efficiency at low acceleration voltage could be improved, and the total electrical power consumption of the ion source setup is practically negligible. Last but not least, with total system costs of not more than 100 k$ this ECRIS should be affordable also for smaller laboratories.

# 2. DESCRIPTION OF THE NEW ECRIS

## 2.1 Overview

A schematic drawing of the new ECRIS is shown in Fig. 1a, with its photograph in Fig. 1b. Magnetic field for plasma confinement is generated by four permanent magnet rings and a Halbach-type hexapole.[7] To minimize its construction costs, this magnet system has been kept as small as reasonably possible, and standardized vacuum components were used wherever possible. Production of multiply charged ions can be enhanced[8] by operating the waveguide coupling system as a biased electrode, and by inserting an aluminum sheet liner into the 25 mm inner diameter plasma chamber. Two remotely-controlled gas inlet valves connected via insulating breaks permit plasma operation in the gas-mixing mode[8]. For production of higher ion charge states the water-cooled plasma chamber is evacuated during operation by a small turbomolecular pump at ground potential connected via an insulating break. The whole permanent magnet setup can be shifted along the plasma chamber axis in order to optimize extraction of differently charged ions.

A triode "accel-decel" extraction system sustains ion acceleration voltages from typically 1 up to 10 kV. All operating parameters of the ion source can be remotely controlled by the LabVIEW[9] based programme CODIAN[10] and a VNC[11] client/server software. Simple hardwired interlock systems permit unattended continuous operation of the ECRIS at reduced microwave power, which assures long-term stability of ion currents especially at low extraction voltage.

### 2.2 Permanent magnet system

The permanent magnet system has been manufactured by Vacuumschmelze Hanau, Germany, using the high remanence NdFeB alloy "VACODYM 7 655 HR". Design of the system is based on longstanding experience with permanent magnet ECRIS developed in Gießen, with magnetic field configurations being optimized by computer simulations[12]. The "minimum-B" magnetic field structure needed for plasma confinement is produced inside the plasma chamber by superposition of an axial magnetic mirror field and a radial hexapole field, as shown in Fig. 2. Two axially and two radially magnetized rings provide an axial mirror field with mirror ratios of 2.1 on the microwave entrance side and of 1.9 on the ion extraction side, respectively, with a maximum field strength of about 0.9 Tesla. To keep the resonance zone as far away from the plasma chamber wall as possible, a comparably strong Halbach type hexapole[7] with 80 mm outer diameter has been chosen.

### 2.3 Microwave power system

The microwave power supply system 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 in the range from 12.75 GHz to 14.5 GHz. A circulator protects the amplifier from too high reflected microwave power. Transmission into the discharge chamber with electrical insulation from the latter is made through a simple 2 mm thick PTFE window. The microwave guiding system changes from WR-75 rectangular- to 13 mm ID cylindrical waveguides. The part of the microwave guiding system inside vacuum can be biased with respect to the ion source chamber potential by up to 2 kV, in order to serve as biased electrode[8] (see Fig. 3). By avoiding coaxial waveguides the microwave power can be efficiently transmitted into our comparably narrow plasma chamber, allowing the necessary vacuum pumping speed and

biased electrode operation. The PTFE window has no direct sight of the plasma which would result in undesired coverage by sputtered metal films.
Plasma operation with non-gaseous feeding compounds is possible with minor modification of the present microwave coupling system by adding a suitable oven.

### 2.4 Ion beam extraction system

The ion source is equipped with a triode "accel-decel" extraction system, featuring a 5 mm diam. extraction aperture in the discharge chamber. Three cylindrically concentric electrodes are supported, precisely positioned and isolated by ceramic spacers. The accel (suppressor) and decel (extraction) electrodes are fixed on the plasma electrode which fits snugly into the plasma chamber, in order to be easily removed from the latter for maintainance. The extraction system can be operated with a potential difference of up to 10 kV between the decel electrode and the ion source chamber, and of up to 2 kV between accel and decel electrode. It is operated at „perveance-match" conditions, to which purpose extensive ion beam modelling simulations with space charge taken into account have been performed, in order to match ECRIS plasma conditions to the given extraction system geometry and applied electrode potentials. This has been approximated by properly adapting the accel voltage to the final ion beam energy.

## 3. PERFORMANCE OF THE NEW ECR ION SOURCE

Measurements to characterize the overall performance of the ECRIS have been carried out at ion extraction voltage of 5 kV, using a 3 mm aperture shielded Faraday cup[13] behind a 60$^o$ analyzer magnet. Relevant ion source parameters have been adapted to achieve maximum currents for selected ion charge states q, with oxygen as "mixing-gas". The detected currents with corresponding main parameters of the ion source are given in Table 1. Even higher ion charge states then listed could be observed but not quantified in the same way. Figs. 4 and 5 show dependences of the $Ar^{8+}$ ion current on microwave power and bias-voltage of the microwave coupling electrode, respectively. Negative biasing proved to be beneficial for extraction of higher charged ions. For lower ion charge states the listed ion currents reached saturation well below the maximum available microwave power. However, for charge states beyond $Ar^{11+}$ highest ion currents required maximum available microwave power. Typical mass-to-charge spectra are presented in Fig. 6, for which purpose ion source and extraction conditions have been optimized for $Ar^{13+}$ ion currents.

The new ECRIS (with total system costs of about 100.000.- USD) is now routinely used for experiments with low-energy MCI collisions in the gas phase and on surfaces. For improved ion beam stability the source, if not used for experiments, is run continuously at reduced microwave power. It can be operated without maintenance for weeks, with intermissions caused primarily by short-circuits in the extraction system. The operating parameter field of the ECRIS has so far by no means been fully explored, and therefore its performance may well exceed the here described status.

## ACKNOWLEDGEMENTS

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**Table I**

Typical achievable Ar ion currents with corresponding ion source parameters as measured with a 3 mm aperture Faraday cup (see text). Since $Ar^{5+}$ and $Ar^{+10}$ match in mass-to-charge ratio some impurity ions, their currents could not be explored. 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 CAPTIONS

Fig 1. (a) Schematic drawing of the 14.5 GHz all permanent magnet ECR ion source (top view)

(b) Photograph of the MCI source (side view; overall length approximately 40 cm).

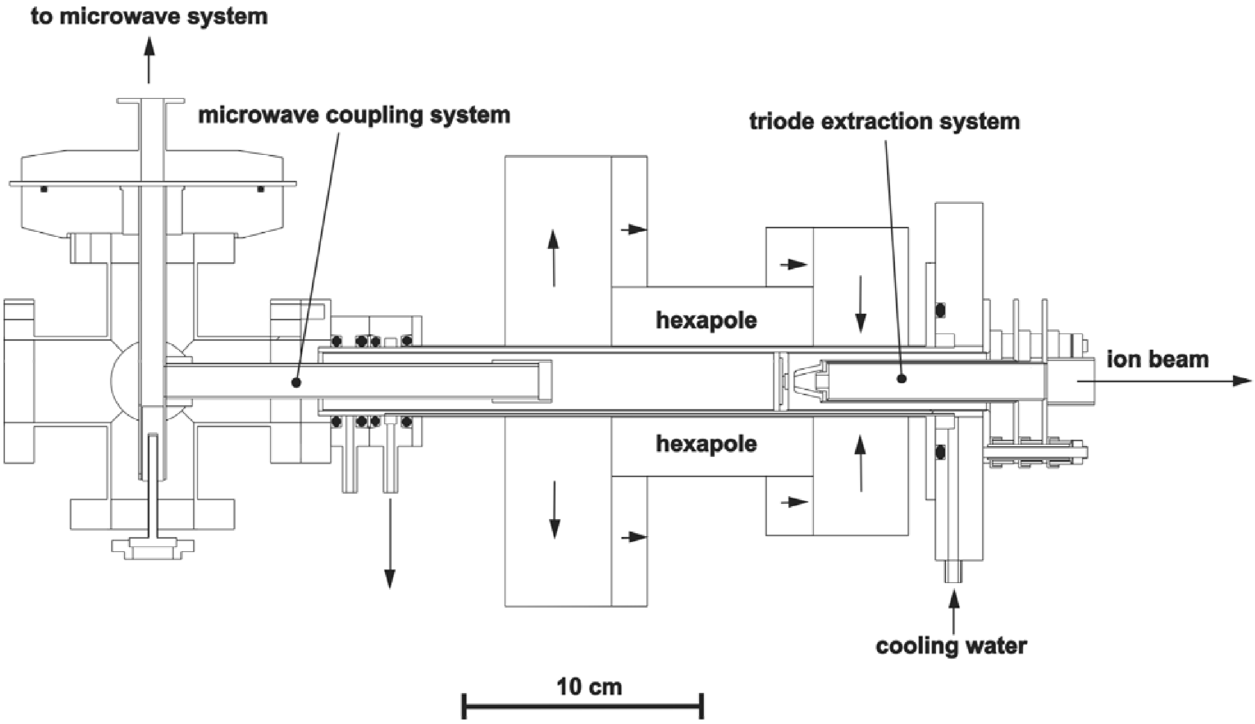
Fig 2. Axial (a) and radial (b) magnetic fields of the permanent magnet system, according to PANDIRA[12] calculations.

Fig 3. Schematic view of the microwave coupling system. The shown waveguide system is insulated from the ion source plasma chamber and can serve as biased electrode.

Fig. 4. $Ar^{8+}$ ion current in dependence of the microwave power. Extraction voltage 5 kV.

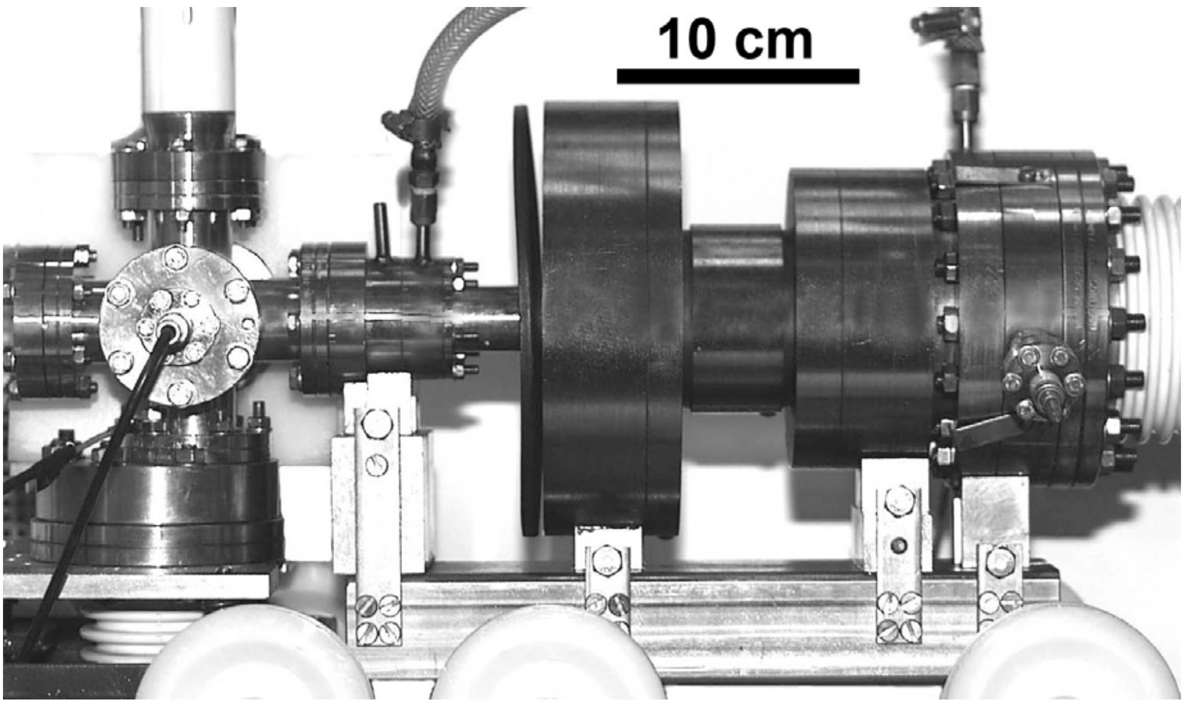
Fig. 5. $Ar^{8+}$ ion current in dependence of negative waveguide bias potential (see Fig. 3). Extraction voltage 5 kV, microwave power 69 W.

Fig. 6. Typical Ar ion spectra (extraction voltage 5 kV) with ion source parameters optimized for maximum $Ar^{13+}$ ion current (pressure: 4 mPa, microwave power: 170 W, bias voltage: –2 kV)



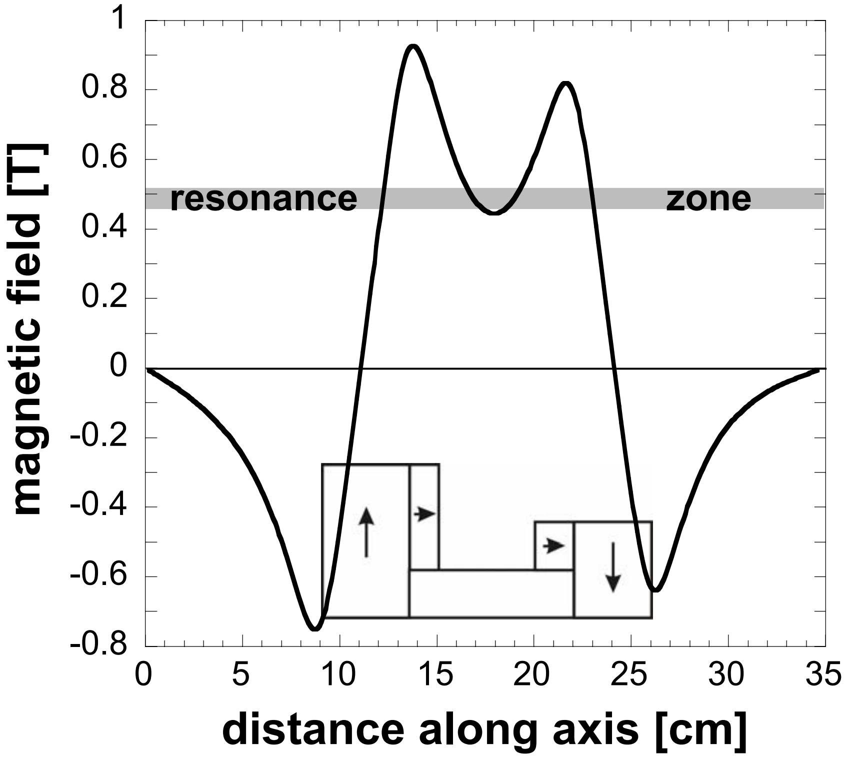
to microwave system
microwave coupling system
triode extraction system
hexapole
hexapole
ion beam
cooling water
10 cm

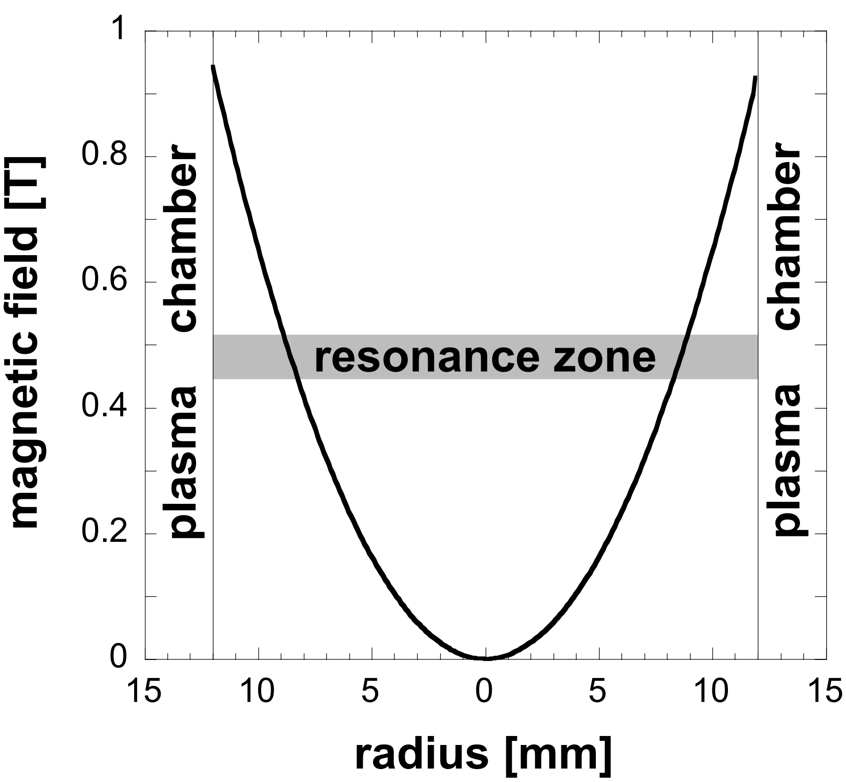

Fig. 1a

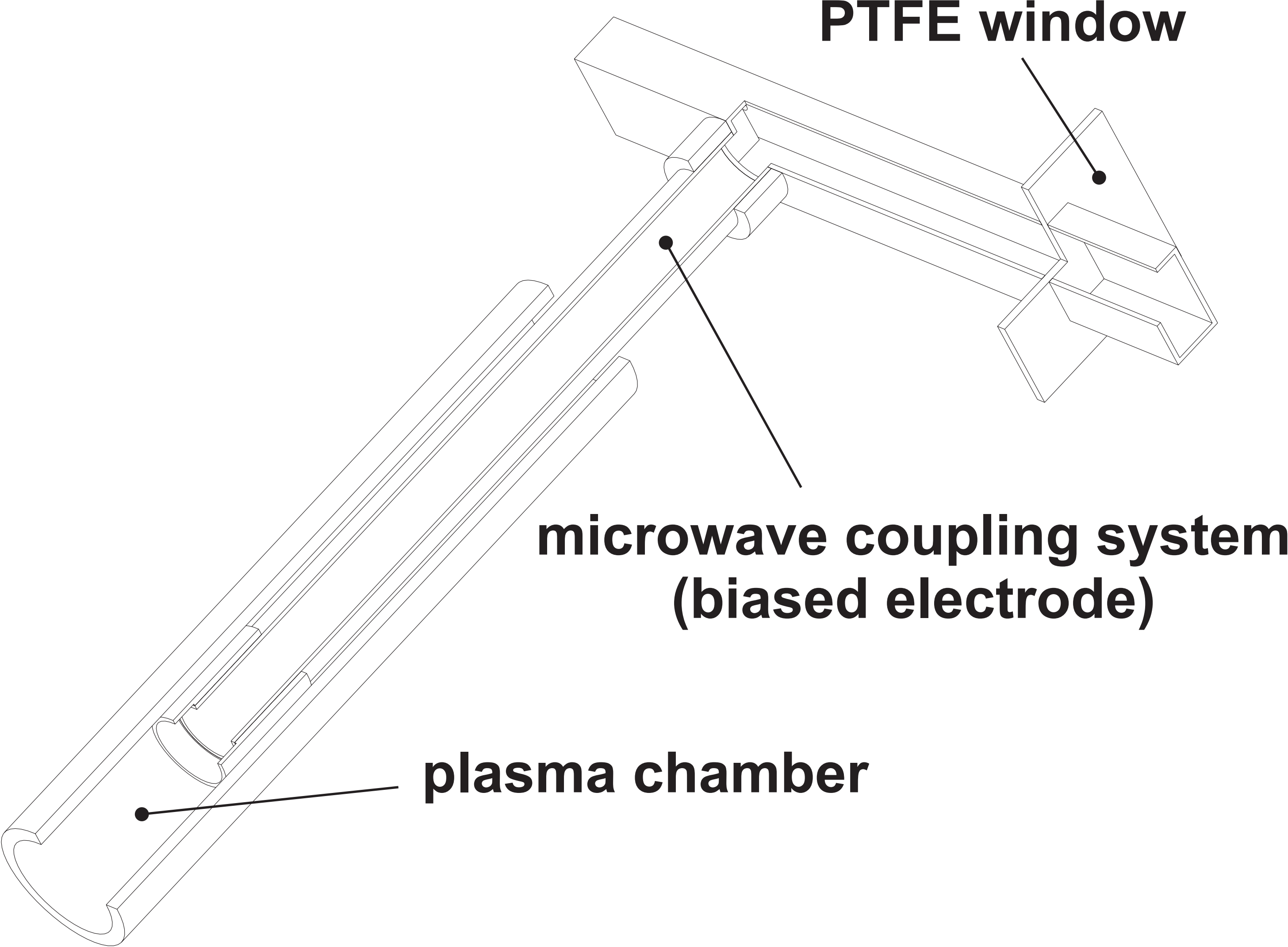


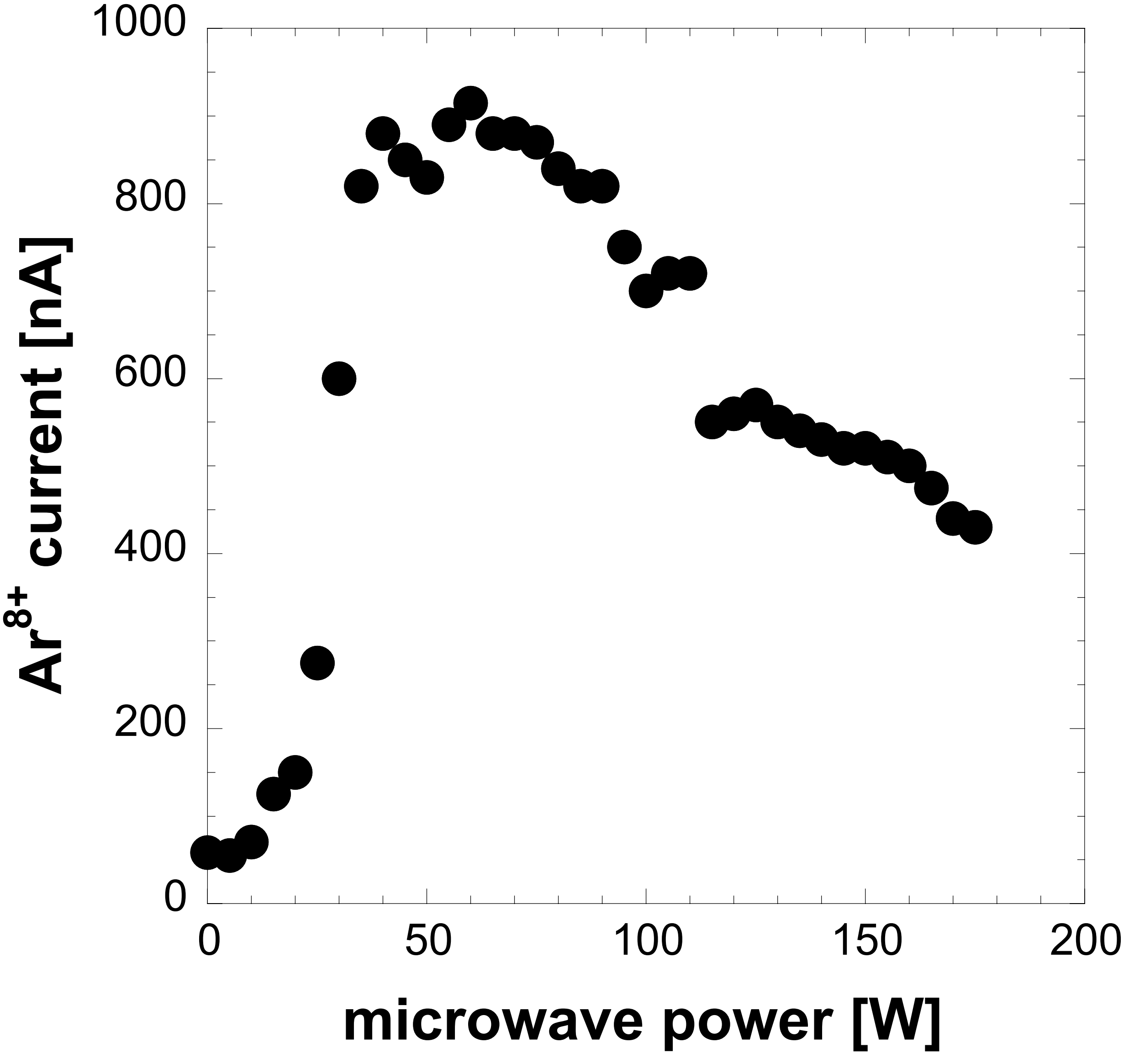
10 cm

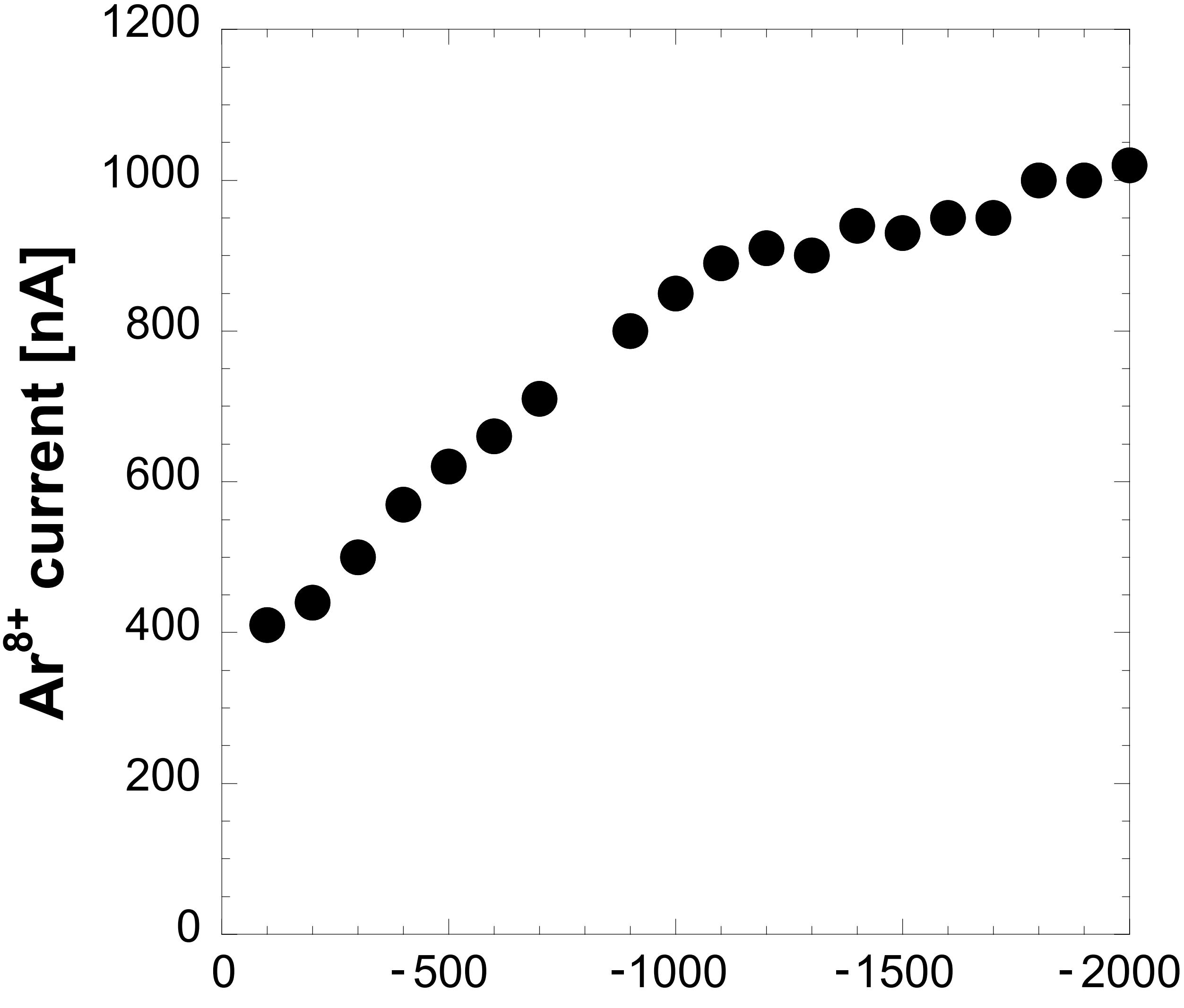

Fig. 1b

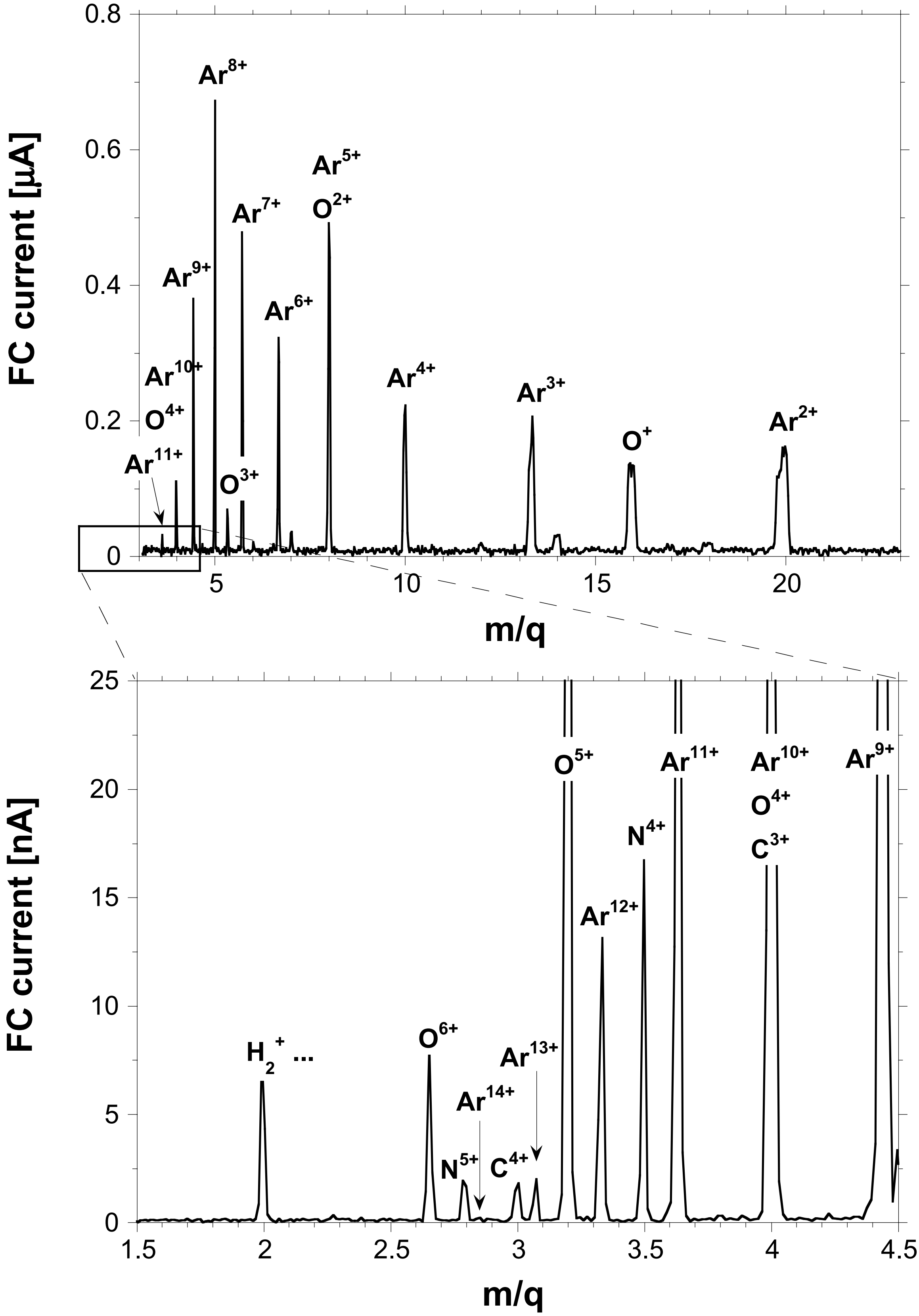

magnetic field [T]
distance along axis [cm]
resonance
zone
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
0
5
10
15
20
25
30
35


magnetic field [T]
radius [mm]
plasma chamber
resonance zone
plasma chamber
1
0.8
0.6
0.4
0.2
0
15
10
5
0
5
10
15


PTFE window
microwave coupling system
(biased electrode)
plasma chamber


1000
800
600
400
200
0
0
50
100
150
200
Ar8+ current [nA]
microwave power [W]


1200
1000
800
600
400
200
0
Ar8+ current [nA]
0
-500
-1000
-1500
-2000
bias voltage [V]



FC current [μA]
0.8
0.6
0.4
0.2
0
Ar8+
Ar5+
O2+
Ar7+
Ar9+
Ar6+
Ar10+
O4+
Ar11+
O3+
Ar4+
Ar3+
O+
Ar2+
5
10
15
20
m/q
FC current [nA]
25
20
15
10
5
0
O5+
Ar11+
Ar10+
O4+
C3+
Ar9+
N4+
Ar12+
H2+ ...
O6+
Ar13+
Ar14+
N5+
C4+
1.5
2
2.5
3
3.5
4
4.5
m/q