THE CAPRICE ECR SOURCE OF MULTICHARGED IONS NEW RESULTS AND A NEW PROTOTYPE

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Abstract

An upgrade version, 1.2 Tesla hexapole magnetic field - 14.5 GHz rf frequency, of the compact Caprice ECR source of multicharged ions is presented. The three main ingredients of ECR ion source are optimized : i) the magnetic configuration has high axial and radial magnetic fields, ii) the 14.5 GHz rf frequency is compatible with the high magnetic field, iii) more efficient electron sources allow the plasma electron density to reach higher values. Therefore the source can deliver high extracted ion currents both for gases and metals : 1130 eμA of O^{6+} , 190 eμA of O^{7+} and 100 eμA of Ar^{12+} , as well as 10 eμA of Ca^{14+}, 3 eμA of Fe^{17+} and Ni^{20+} , 1 eμA of U^{37+} . A new prototype, Caprice II, being designed is also presented : the hexapole field is 1.6 Tesla, the source will be able to work at 14 GHz and 18 GHz with boosted performances.

1 INTRODUCTION

The Caprice electron cyclotron resonance (ECR) source of multicharged ions has been described in previous articles [1]. The Caprice source has specific features : it is a compact in size source (16 cm long 6.6 cm diameter plasma chamber), it has a strong iron yoke and a simple mechanical design ; it also has a unique coaxial rf coupling system which is very efficient, and offers an easy access for using a micro-oven in order to vaporize metallic elements along the main axis of the source. The recent version of the Caprice source, 1.2 Tesla hexapole magnetic field -14.5 GHz rf frequency, whose performances are described in this article, is optimized with respect to the three main ingredients of ECR ion sources : magnetic configuration, rf electron heating and electron sources.

1.1 Magnetic configuration

The magnetic field theoretically determines the maximum plasma pressure ($\approx (n_e k T_e)_{max}$) that the source can hold. The $|B|$ surfaces created by the magnetic structure have to be closed and nested in each other with an increasing $|B|$ value when moving outwards. This minimum –B structure is created by the association of an axial mirror field and a radial mutipolar field, usually hexapolar. In such a magnetic configuration the plasma is confined as long as the $|B|$ surfaces do not touch the walls [2] ; therefore the $|B|$ surface touching the walls when moving outwards from the center has to be with a $|B|$ value, $|B|_{last}$, as high as possible. In Caprice $|B|_{last}$ is about 1 Tesla.

1.2 rf electron heating

The interaction of injected rf waves with electrons is optimized, and the muticharged ion production is efficient only if some conditions are satisfied. The resonance surface defined by $|B|_{ecr} = \frac{m_e \omega_{rf}}{e}$ is one of the closed $|B|$ surfaces, and the effective mirror ratio, $R = |B|_{last} / |B|_{ecr}$ has to be as high as possible. In Caprice the effective mirror ratio R is close to 2.

1.3 electron sources

Efficient internal and/or external sources are necessary in order to allow a high electron density n_e to build up in the source thus enhancing the source performance. External sources are more commonly used, first stage or plasma cathode (auxiliary ECR discharges), low voltage biased probes or disks ; internal sources such as wall coatings, Th O_2, Si O_2, and Al_2 O_3, are also very efficient in producing electrons from secondary emission under plasma particle impact within the plasma chamber. In Caprice both the first stage technique (external source) and the Al_2 O_3 coating technique (internal source) are employed as sources of electrons. The efficiency of the Al_2 O_3 coating was previously noticed by others [3] [4].
Table 1 illustrates the importance of the wall coating effect by comparing the extracted currents of the Caprice source with two different plasma chambers in the same operating conditions.

ION	STAINLESS STEEL	ALUMINUM
O^{4+}	620	770
O^{5+}	470	650
O^{6+}	460	760
O^{7+}	43	100
Ar^{9+}	380	270
Ar^{12+}	60	74
Ar^{14+}	9	15
Ar^{16+}	0.5	1

Table 1 - Comparison between a stainless steel chamber and an aluminum chamber (intensities in eμA)

1.4 Importance of the above ingredients

As the step by step ionization of atoms by electron impact is the dominant ionization process in ECR ion sources, the importance of the above ingredients can be easily understood [5] : the electron temperature (Te) control by the rf electron heating can optimize the ionization rate $<\sigma v>_{q-1}^{ioniz}$ from charge state q-1 to charge stateq ; the electron density n_e can help reduce the ionization time $(n_e<\sigma v>_{q-1}^{ioniz})^{-1}$ from charge state q-1 to charge state q therefore allowing the source to reach higher states and to deliver higher intensities.

2 RESULTS WITH GASES

The best data for high charge states are always obtained by using the gas mixing technique, where a carrier gas dominant in density is mixed in the main element to be extracted. The emittances of the Caprice source were measured in argon at 18 kV extraction voltage with different charge states (table 2).

ION	ε_h	ε_v
Ar^{4+}	94	170
Ar^{6+}	110	166
Ar^{8+}	90	130
Ar^{11+}	47	70

Table 2 - Absolute horizontal and vertical emittances (in π mm.mrad) for 86 % of the total beam intensity

2.1 Argon

The maximum extracted argon ion currents at 20 kV extraction voltage are given in table 3.

Ar^{8+}	Ar^{9+}	Ar^{11+}	Ar^{12+}	Ar^{13+}	Ar^{14+}	Ar^{16+}	Ar^{17+}
685	400	185	100	45	17	1	0.010

Table 3 - Argon ion currents (eμA) obtained with Caprice at 20 kV, ^{16}O as a mixing gas.

The Ar^{17+} ion current has been deduced from the Kα line photon counting from a Ar^{17+} ion beam recombined on a silver target.

2.2 Oxygen

Similarly the maximum extracted oxygen ion currents are given in table 4.

O^{6+}	**O^{7+}**	**O^{8+}**
1130	190	22

Table 4 - Oxygen ion currents (eμA obtained with Caprice) at 20 kV, ^4He as a mixing gas.

The O^{8+} ion current has been measured by using the ^{18}O isotope.

The rf power necessary to obtain the maximum currents presented in tables 3 and 4 is usually no more than 800 W. Note that the extracted ion current does not increase linearly with the rf power [5], thus it is possible to obtain 200 eμA of Ar^{8+} ion current with only 100 W of rf power.

3 RESULTS WITH METALS

The electrical micro-oven technique which allows to separate the metal vapor production from the ionization function within the plasma is now extensively utilized [6] owing to its flexibility. Here we present the results obtained with Caprice by using this method for several metallic elements which require different evaporation temperatures, calcium (700°K), iron (1400°K), nickel (1500°K) and uranium (2100°K). In all cases oxygen is used as a mixing gas.

3.1 Calcium

Because of its low evaporation temperature the calcium evaporation is well controlled by the electrical heating of the oven. The maximum extracted calcium ion currents are given in table 5.

Ca^{8+}	**Ca^{9+}**	**Ca^{11+}**	**Ca^{12+}**	**Ca^{13+}**	**Ca^{14+}**	**Ca^{16+}**
300	320	150	60	25	10	0.6

Table 5 - Calcium ion currents (eμA) obtained with Caprice at 20 kV.

3.2 Iron and nickel

The best results are shown in table 6 for these two metals (electrical heating only of the oven).

Fe^{11+}	**Fe^{12+}**	**Fe^{13+}**	**Fe^{14+}**	**Fe^{15+}**	**Fe^{17+}**	**Fe^{18+}**
105	85	40	30	25	5	1

Ni^{16+}	Ni^{17+}	Ni^{19+}	Ni^{20+}	Ni^{21+}
25	25	10	3	0.6

Table 6 - Iron and nickel ion currents (eμA) obtained with Caprice at 20 kV.

3.3 Uranium

The main difficulty for the production of uranium vapor is its corrosive nature at high temperature ; therefore it is more convenient to operate with uranium oxide UO_2 although this requires a higher temperature (2100°K). Thus the micro-oven technique is here combined with the insertion technique [6] (partial heating of the oven by the plasma electrons) in order to reach the required temperature. This oven is located closer to the resonance

zone within the plasma chamber than for operation with others metals. In such conditions the maximum extracted uranium ion currents are shown in table 7.

U^{25+}	U^{27+}	U^{28+}	U^{29+}	U^{31+}	U^{32+}	U^{33+}
20	19	18	15	8	6	5.2

U^{34+}	U^{35+}	U^{36+}	U^{37+}	U^{38+}	U^{39+}
4	2.4	1.4	0.9	0.6	0.17

Table 7 - Uranium ion currents (eμA) obtained with Caprice at 20 kV.

4 NEW CAPRICE PROTOTYPE

The main objective of this new prototype, Caprice II, is to improve the magnetic configuration, more specifically to increase the radial field of the present Caprice magnetic structure : the new hexapole of Halbach type [7] has 24 permanent magnet elements and a field of 1.6 Tesla on each pole, whereas the hexapole of the present Caprice has only 12 permanent magnet elements and a field of 1.2 Tesla. The axial field of Caprice II has a different profile so that the highest $|B|$ closed surface just touching the walls in Caprice II has $|B|_{last}$ = 1.3 Tesla, which greatly increases the confinement capability of the magnetic trap (higher $(n_e KT_e)_{max}$). In Caprice II two rf frequencies, 14 GHz (effective mirror ration 2.6) and 18 GHz (effective mirror ratio 2) are usable, individually or together according to the multiple frequency concept [8] which enhances the source performance. The larger dimensions of the plasma chamber of Caprice II (28 cm long, 7.0 cm diameter) should also result in increased ion confinement times. Therefore the most abundant charge state should move towards higher charge state, and the extracted ion intensities should also increase accordingly.

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