Best C^{4+} and C^{5+} Beams of the Kei2 ECR Ion Source

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Abstract With the prototype ECR ion source for the next carbon therapy facility in Japan a new series of measurements has been performed in order (a) to find the highest beam currents of C^{4+} ions, and (b) to study the effect of "special" gas- mixing by using a chemical compound as a feed gas. An isotopic effect has been found in a previous experiment: with deuterated methane (CD_4 gas) the C^{5+} beam currents are about 10 % higher than with regular methane (CH_4 gas). For butane gases (C_4D_{10} and C_4H_{10} respectively) the isotopic effect for C^{5+} production is even stronger (>15%). For production of C^{4+} ions the isotopic effect appears to be absent. It turns out that the relative amount of carbon is much more important: acetylene gives 15% higher C^{4+} current than butane, which in turn gives about 10% higher C^{4+} ion currents than methane.

Key words carbon ions, ECR ion source, isotopic effect, gas-mixing

1 Introduction

A new carbon therapy facility, presently being constructed at NIRS, needs an ion source to produce carbon ions in charge state 4^+ or higher. More specific the ions should have an energy of 10keV/u with a minimum intensity of 50 particle μA. With a prototype all permanent magnet ECRIS (called Kei source) it was shown[1] that a C^{4+} beam of 200eμA at extraction voltage of 30kV could easily be produced.

The improved version[2] of this source, called Kei2, has become available at the beginning of 2004. In the design a magnetic profile was created close to that of the "classic" 10GHz ECR ion source at NIRS, which has proven to operate extremely reliably for long periods during last 10 years. An initial test gave 530eμA for C^{4+} ions at 40kV.

In order to further test the Kei2 - source (with modified extractor system for better stability) a series of experiments[3] was continued. The goal is twofold: (a) to reach best conditions for the medical application, (b) to investigate whether the special technique[4] of gas-mixing can be applied to increase the highly charged ion (HCI) output, thus to increase the production of C^{5+} beams.

2 Scope of the experiment

With different ECR ion sources attempts have been made earlier to find the best feed gas for production of C^{4+} ions (see A. Kitagawa et al[5]), e.g. with CH_4 (methane), with CH_4 + He as a mixing gas, with CO, with CO_2, with fullerenes[6] (thus with pure carbon), with fullerenes + additional mixing gases, and with C_3H_8 (propane). From these gases methane turned out to be the best (without any mixing gas); propane is differing not too much from methane.

In order to obtain results comparably to regular gas – mixing studies, the ratio deuterium (respectively hydrogen) to carbon D/C (respectively H/C) has to be varied. For that we have chosen this series of feed gases:

methanes CD_4 and CH_4 with D/C=H/C=4)

butanes C_4D_{10} and $C_4H_{10}$with D/C=H/C=2.5,

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and acetylene gases C_2D_2 and C_2H_2 with D/C= H/C=1.

In these cases the C^{5+} peaks are clean, but at the position of C^{4+} in the spectrum there might be molecular peaks $(HD)^+$ immediately following a gas change. We always carefully checked the presence of these and other CH_x^+ molecular ions as well as the H^+ peak; we made sure that a possible contamination was not more than 20μA in the measured C^{4+} beam.

3 Measurements with methanes, butanes and acetylenes

Carbon spectra were obtained in a standard set up, and measurements were recorded at extraction voltage from 20 to 45kV in steps of 5kV. First, the source was optimized for maximum C^{5+} current, and after that for maximum C^{4+} current. Optimization parameters include the gas flow, RF frequency (in a small range around 10GHz), biased disk voltage and –position, puller position; the RF power is always set to maximum (= 300W). However, unfortunately it appeared that the tuning was not sensitive to changes of the biased disk position; after the experiment it appeared that the disk part was broken off the rod.

One drawback of this "special gas-mixing experiment" is that only one gasflow regulator is available! (In a standard ECRIS tuning experiment, one is using two regulators to adjust the "beam-gas" and the "mixing-gas" independently, together the most important parameters in an optimization process).

The obtained highest currents are shown in Table 1. It is clear that for production of C^{4+} acetylene is the best gas, or otherwise stated: the gas with the relatively largest amount of carbon is the best. The various measurements could not be performed at perfect source conditions: as remarked above, the biased disk was not correctly functioning. Moreover in case of the methanes there was too much oxygen present. Therefore it is likely that in a new test with well functioning disk the rsults will be higher.

Typical gas-mixing phenomena were demonstrated[3] earlier in the case of producing carbon ions with a chemical compound, in particular the occurrence of Isotopic effects when the regular feed gas CH_4 was replaced by CD_4 (so-called deuterated methane). Chemically, nothing will change, but due to the mass-doubling of the "mixing gas" there might be (in the framework of the "ion – cooling model") an increase in high charge state current. As C^{5+} ions have a much higher ionization potential (390eV) than C^{4+} (64eV) one could call them highly charged ions.

Table 1. Best C^{4+} and C^{5+} currents (eμA) @30kV (NB with not well operating biased disk).

feed gas	C^{4+}	C^{5+}
CH_4	416	66
CD_4	452	80
C_4D_{10}	480	80
C_2D_2	544	83
C_2H_2	600	87

The results of the earlier study are given in Table 2. The isotopic effect is clearly present and appears to be largest for the butanes. Although it is not surprising to see the isotopic effect in the measurement of C^{5+} ions, one now can state firmly that source operation with a chemical compound is similar to operation with separate feeds into the source of the compound's constituing elements. For the same reason as given earlier, absolute comparison of the earlier measurements in Table 2 and the present data in Table 1 can not be made.

A simple test on C^{4+} current optimization was made as follows: as in a regular gas – mixing experiment we connected the C_2H_2 – gas bottle to gas regulator #1 and a H_2- gas bottle to regulator #2. In that way we can obtain in essence all ratios H/C larger or equal to 1. It turned out that highest currents were obtained with the hydrogen bottle closed. So from this simple experiment it can be concluded too that for C^{4+} production the ratio H/C should be lowest.

Table 2. Best currents (eμA) obtained @30kV (June 2005), showing the isotopic effect for C^{5+}.

feed gas	C^{4+}	C^{5+}
C_4D_{10}	607	113
C_4H_{10}	600	97
CD_4	555	110
CH_4	545	95

4 Conclusion

The production of C^{4+} ions clearly is not dominated by mixing gas phenomena. These ions have a low ionization energy and therefore do not need too long confinement in the plasma. Isotopic effects are not present, or just very small. The relative amount of carbon in the molecule is important here: acetylene is significantly better than butane, which in turn is significantly better than methane. From the point of view of source improvement the usage of C_2H_2 is attractive, with C^{4+} currents (at 30kV) of (likely more than) 600eμA. The best C^{5+} current is unfortunately not enough for a change from C^{4+} to C^{5+} in the injected beam to the medical accelerator.

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