UPGRADING OF A SMALL H⁻ CUSP SOURCE FOR THE C-30 CYCLOTRON AT ŚWIERK

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A very small, low power rated H^- multicusp source for the 30 MeV compact cyclotron at Świerk was optimized. H^- yield in the beam injection line to the cyclotron was measured at different arc powers and plasma electrode potentials. The ion current exceeded 0.5 mA at a steady-state operation. Plasma electron density ,temperature and plasma potential in the discharge chamber of the source were measured using a Langmuir probe. The effect of H^- current saturation at low arc voltage was interpreted on the basis of the plasma diagnostic results.

1 Introduction

The C-30 cyclotron is currently run with a small internal H^- source. To avoid problems connected with excessive hydrogen leak into the cyclotron vacuum system a low power rated, external multicusp source is tested and optimized together with a beam injection system. Due to serious budget problems, limitations were imposed on the source operation in the arc power (the arc current did not exceed 11 A) and in the pumping speed. To facilitate the manufacturing problems and reach a relatively high plasma density in the source its size was strongly reduced. Works on magnetic field distribution in the source chamber and the optimal axial position of the emission hole of the source are reported in [1]. In order to reveal the source performance limitation factors a series of plasma diagnostic tests were started. Electron temperature and density as well as plasma potential in different parts of arc chamber were studied at different arc powers, gas pressures and plasma electrode potentials. Some of the results of these studies are reported in this paper.

2 Ion source set-up

A schematic view of the H^- source is shown in Fig. 1. A more detailed description of the device is given in [1]. The arc chamber is a copper cylinder 6 cm long and 3.3 cm in diameter. To assure fast electrons and plasma confinement it is surrounded by 12 rows of SmCo magnets in a line-cusp arrangement. A single permanent magnet is placed on the rear wall of the source. The maximum magnetic field generated on the inner surface of the chamber exceeds 0.1T. A single cathode (tungsten filament) is located in the magnetic field-free volume in the centre of the chamber.

In multicusp sources a "magnetic filter" divides the arc chamber into a discharge and extraction region (Fig.1). In the discharge region excitation and ionization of hydrogen molecules by fast electrons are taking place. The filter is used to reduce fast electron density in the region close to emission aperture and lower plasma electron temperature down to about 0.5-2 eV. H^- are produced by dissociative attachment of low-energy electrons to rovibrationally excited H_2 molecules. In our source a virtual magnetic filter is generated by SmCo magnets situated outside the arc chamber, near its front wall. The source operation was tested with several filter field distributions [1]. The filter composed of two pairs of magnets, separated by a distance of 4 cm, ensured the highest H^- beam intensity at a relatively low extracted electron current. After a series of beam extraction tests it appeared, that a distance of 4 mm between the emission hole and the filter plane ensured the highest H^- yield. It indicates that most of negative ions are formed in the filter region. The filter thickness corresponding to this configuration was 0.032 T.cm.

The front end of the arc chamber is terminated by a plasma electrode which is electrically insulated from the chamber . I has a circular emission aperture, 6 mm in diam., in the centre. Plasma electrons are extracted together with H^- ions. The extracted electron current must be minimized to lower the electron space charge in the acceleration gap. It is normally done by biasing the plasma electrode at a potential slightly higher than that of the arc chamber.

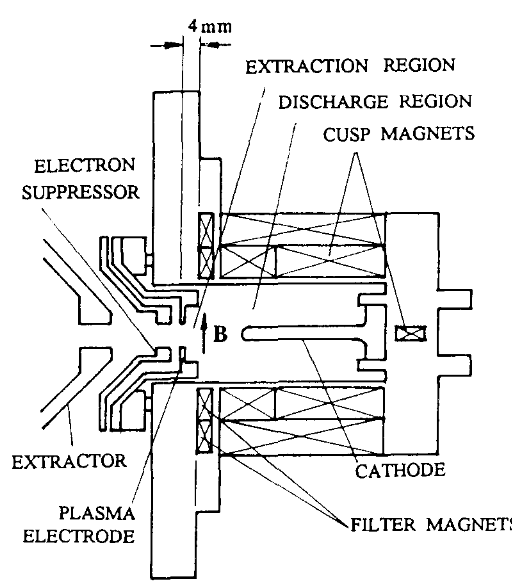

Fig. 1. Schematic view of the H^- source.

At a certain bias voltage H^- contents near aperture is increased significantly [2,3] while the electrons, confined by the transverse magnetic field of the filter, are collected by a copper cylinder inserted into the plasma electrode (Fig.1). The dimensions of the cylinder (18 mm in diam. and 5 mm long) were adjusted experimentally to obtain the maximum H^- yield.

Since the extracted electron current control by varying the plasma electrode bias was not sufficient, an electron suppressor electrode was placed 3 mm downstream of the plasma electrode. It was typically biased at a potential 900V higher than that of the arc chamber. The electrons extracted from the emission aperture were deflected in the stray magnetic field of the filter and intercepted by the suppressor while the ions passed through a 6 mm diam. extraction hole in its centre.

3 Experimental results and discussion

3.1 Effect of plasma electrode bias on H^- and electron currents

The joint effect of the magnetic filter field and plasma electrode bias on H^- and electron densities as well as plasma potential in front of the plasma electrode has been studied extensively by other authors [2-4]. Maximum H^- density near the emission hole is normally reached at a value of bias voltage close to the plasma potential in the discharge region. The dependence upon the plasma electrode potential of H^- and electron currents extracted form the emission aperture of our source was investigated. The arc current was I_{arc} = 10 A and the applied arc voltages V_{arc} =75V and 135 V. The negative ion current was measured in the beam line using a Faraday cup. Well observed maxima of H^- beam current as a function of bias voltage were obtained. Increasing the arc voltage from 75V to 135 V or the gas pressure in the plasma chamber from 0.15 Pa to 0.42 Pa, shifted the optimum bias voltage towards higher potentials by several tenths of V. The biggest H^- yield was obtained at a hydrogen pressure of 0.26 Pa. The optimum bias voltages were +2.5 V and +3 V for V_{arc} = 75 V and 135 V, respectively (Fig.2).

The electron current from the source was deduced from the current collected by the suppressor electrode. The dependence of the extracted electron current on the plasma electrode bias is given in [1]. At a lower range of bias potentials the current does not change. The length of this plateau, indicating the plasma potential value in the extraction region , changes with arc voltage and the gas pressure in the source. Further increasing the bias voltage up to +4 V makes the extracted electron current drop by roughly one order of magnitude.

3.2 Plasma diagnostic measurements

Plasma parameters dependence on arc current was measured. Due to space restrictions a small cylindrical Langmuir probe was used. It was inserted through the emission hole (40% of the hole area was left for pumping) and located on the axis of the source. In order to study plasma potential, electron density and temperature in the discharge region the probe was placed 2.5 cm upstream of the filter plane, where magnetic field did not exceed 0.003 T. Plasma parameters were also determined in the vicinity of the emission aperture, in a copper cylinder inserted into the plasma electrode. Transverse magnetic field in this position was close to 0.016 T. The source was operated at arc currents of 3 A, 6 A and 9 A and arc voltages of 75 V and 135 V. When the probe was situated in the discharge region (upstream of the filter), the arc current was limited to 6 A at an arc voltage of 135 V to avoid destruction of the probe. The hydrogen flow for all experiments was the previously determined optimum, which corresponded to gas pressure in the source equal 0.26 Pa. Plasma electrode potentials were +2.5 and +3 V for V_{arc} = 75 V and 135 V, respectively.

The obtained voltage-current characteristics of the probe in the discharge volume show, in most cases, electron energy distributions which consist of two quasi-maxwellian components. Typically above 80% of electrons are thermalized at temperatures of 1.3 - 5 eV, depending on arc power and gas flow rate. These will be further referred to as cold electrons. Energy distribution of the rest of electrons may be approximated by a maxwellian distribution truncated at the high energy end, due to a finite value of discharge voltage. The corresponding "electron temperatures", determined from the slopes of the probe characteristics, varied roughly from 20 to 70 eV. Electrons of this energy range are called fast electrons.

The measured cold electron densities as functions of arc current in both discharge and extraction region are given in Fig. 3. In the discharge region electron concentration N_e reaches 10^{12}cm^{-3} and saturates above an arc current of I_{arc}=6A, at an arc voltage V_{arc}=75V (Fig. 3 a)). This effect is much less pronounced in the extraction region (Fig. 3 b)), since the electron transmission through the filter is doubled when rising the arc current from 3 to 9 A. It is because the coefficient of electron diffusion through a magnetic filter raises linearly with plasma density in the discharge region [5]. There is no N_e saturation in the extraction region at V_{arc}= 135 A.

The H^- current in the beam line (I^-) also exhibits a tendency to saturate at V_{arc}=75V. Higher arc voltages delay the onset of this saturation (Fig. 3 c)). It may be explained taking into account the changes with rising I_{arc} of plasma

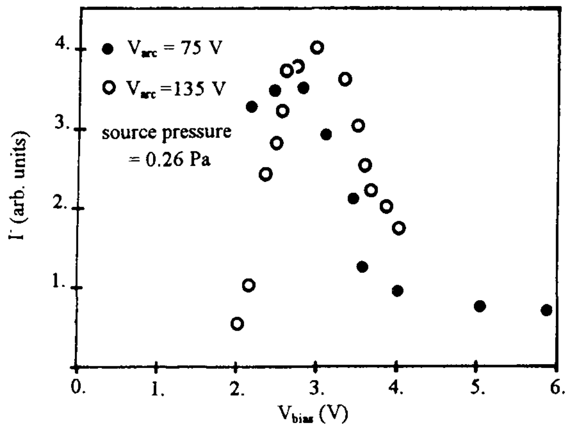

Fig. 2. H^- current as a function of plasma electrode bias.

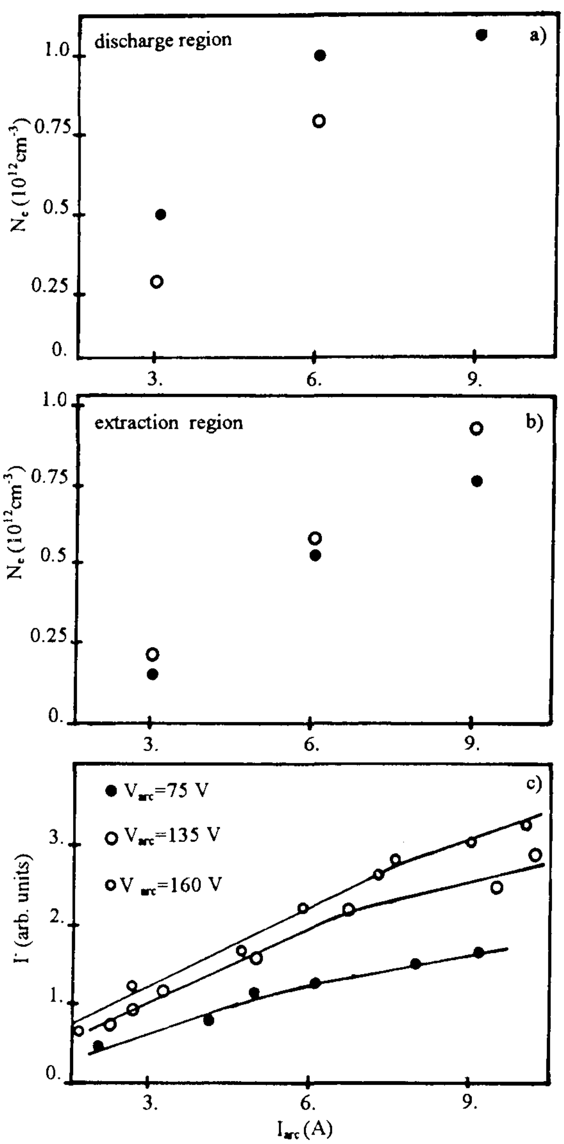

Fig. 3. Cold lectron densities in the discharge region - a), in the extraction region - b) and H^- current - c) as functions of arc current.

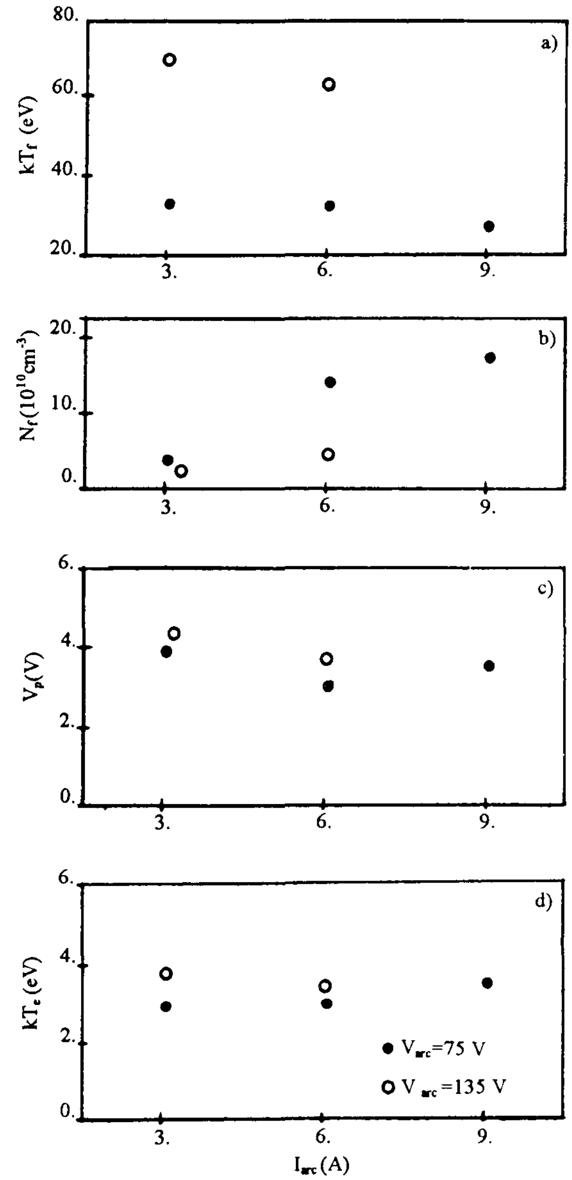

Fig. 4. Fast electron temperature - a) and density - b), plasma potential - c) and cold electron temperature - d) in the discharge region as functions of arc current.

parameters in the discharge volume. The variation with arc power of plasma potential , cold and fast electron temperatures (kT_e and kT_f , respectively) and fast electron densities N_f is shown in Fig.4. Fast electron temperature drops with increasing I_{arc}. kT_f decreases from 32 eV to below 27eV with I_{arc} rising from 6 to 9 A at V_{arc} = 75 V (Fig. 4 a)). It reduces the rate coefficient of H_2 ionization by electron impact (the energy threshold =15.4 eV, the maximum cross-section corresponds to 80 eV). At V_{arc}=135 V the ionization rate coefficient is higher. kT_f is above 60 eV (the average electron energy is close to 90 eV) for I_{arc}=6 A and energies of a large part of fast electrons correspond to high ionization cross section. There are no data for kT_f at the highest discharge power (V_{arc}=135 V and I_{arc}= 9 A) but there is a clear tendency to lower the fast electron temperature with rising arc current. Thus the average energy of fast electrons approaches the value corresponding to the maximum ionization cross section. This effect, together with higher electron velocities than at V_{arc}=75 A, compensates for a much lower fast electron density at V_{arc}=135 V (Fig.4 b)). Plasma potential relatively to the chamber wall and cold electron temperature vary slowly with I_{arc} within +3 - +4.3 V and 3 - 4 eV (Fig. 4 c) and d)). It assures a pretty good electrostatic confinement of cold electrons within plasma volume at each arc voltage.

Vibrationally excited hydrogen molecules H_2^* participate in H^- production (H_2^*+e -> H^-+H). Apart from raising cold electron density at I_{arc}=9 A, arc voltage growth increases H^- yield by increasing H_2^* density. H_2^* is generated by high energy electron impact. The corresponding cross sections for all vibrational states of the molecule grow roughly by a factor of 2 when raising incident electron energy from 20 to 50 eV and then decreases slowly with further energy growth` [6]. Thus, kT_f = 60 eV corresponds to high rate of H_2^* production. Plasma diagnostic tests are continued.

3.3 Ion beam formation

The ion beam injection energy to the central part of the cyclotron is 18 keV [7]. The ion source together with a cooling system and power supplies are kept at a potential of 18 kV below the ground. The extraction system, composed of the plasma electrode, electron suppressor and a grounded extractor is shown in Fig.1. The extractor is followed by an einzel lens and a doubly focussing 90° bending magnet to change the beam direction from horizontal to vertical. They were designed to assure waist-to-waist beam transformation.

Electron contamination in H^- was reduced mainly in the transverse fringe magnetic field in the first acceleration gap between the plasma and suppressor electrodes. Negative ion current was measured in the beam line, 70 cm downstream of the source. The beam current exceeded 0.5mA at an arc current of 11 A. Taking into account the beam losses in the transport line the estimated ion beam density in the emission hole is close to 4 mA/cm^2. The ratio of electron to ion current is about 10 in the first acceleration gap. It drops to 2 between the suppressor and the extractor. The electron current that reaches the extractor at full injection energy does not exceed 1mA.

4 Conclusions

H^- ion source operation has been tested to increase the extracted ion current. Optimal working parameters were found for the modified source geometry. The dependence of H^- yield on plasma electrode potential and arc power was studied. At a low arc voltage the ion current in the beam line saturates above a certain value of arc current. Plasma diagnostic measurements revealed a similar saturation of plasma electron density in the discharge volume. The effect became less visible after raising the discharge voltage. It can be explained taking into account the growth of fast electron temperature, which leads to a high rate coefficient of ionization of hydrogen molecules. It is also due to an increase of the concentration of rovibrationally excited H_2 molecules. H^- current of 0.5 mA was reached in the transport line 70 cm downstream of the source. The electron current to the extractor electrode is low enough to ensure stable operation.

The ion current should be further increased to compensate for the beam losses in the injection system to the cyclotron. To this end we propose raising arc voltage with possible cathode modification to avoid plasma breakdown. Increasing the size of emission aperture along with rising the pumping speed in the system is also considered.

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