

Plasma behaviour affected by a magnetic filter

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Abstract. Operation of magnetic filters is studied experimentally regarding their use for electron cooling in the sources of the negative hydrogen ion beams. Axial profiles of the plasma parameters – electron temperature and density – are measured by probe diagnostics in the expansion plasma region of an inductively driven tandem type of a plasma source. The obtained drop of the electron temperature down to values of about and below 1 eV required for efficient production of negative hydrogen ions is the result proving the proper operation of the filter. The mechanism of electron cooling is discussed based on thermal conductivity effects.

1. Introduction

It is well-known that the magnetic fields are the most often used means for controlling the plasma behaviour. In the ion beam sources [1-3] developed regarding additional heating of fusion plasmas by neutral beam injection, magnetic fields are in use both for reducing the electron losses at the walls (through the – so-called – cusp magnets) and as magnetic filters for separation of the beam extraction region from the volume of plasma production. In the sources of negative hydrogen ions a magnetic filter is employed also as a device for electron cooling. The latter is needed regarding proper conditions for negative ion yield by volume-based processes in the discharge.

The volume production of negative hydrogen ions is via dissociative attachment of electrons to vibrationally excited molecules. Achieving optimum conditions for this reaction requires space separation in the source of regions with comparatively high and low electron temperature favouring, respectively, the vibrational excitation of the hydrogen molecules and the production – from them – of negative hydrogen ions. Such a space separation of two regions is a general property of the – so-called – tandem plasma sources [4].

The discussions on the operation of the magnetic filters in the sources of negative hydrogen ions have been usually based on results from measurements of the extracted ion-beam current [2, 5-7]. Certainly, the current of the extracted ion beam is the most important characteristic of the efficiency of the source operation. However, it is a measure of the overall performance of the source that depends on many factors, e.g., type of the discharge, gas-discharge conditions, configuration and construction of the source and of its ion-extraction and beam-formation systems. Judgments on the operation of the different devices completing the sources of negative hydrogen ions could be achieved by measurements of the spatial distribution of the plasma parameters in the different regions of the source [8, 9]. However, having access to the different space regions of the big sources by tools of plasma diagnostics is not always possible, thus, justifying necessity of experiments at smaller-size set-ups.

This study aims at providing experimental results on the operation of the magnetic filter for electron cooling in the sources of negative hydrogen ion beams. The measurements are carried out in a tandem rf plasma source with an inductive coupling, which is of the type of the sources at IPP-

Garching [2] developed for use in ITER. In the inductively-driven sources, the scenario of the electron cooling is more complicated than that in the dc discharge sources because the construction of the source itself, with a smaller-volume driver region and a larger-volume expanding-plasma region, leads [10, 11] to electron cooling in the plasma expansion volume. Therefore, in the inductively driven sources of negative hydrogen ions the electron cooling caused by the magnetic filter would be in addition to the cooling due to the plasma expansion.

The study presents results for the spatial distribution of the plasma parameters (electron temperature T_e and density n) obtained via probe-diagnostics measurements in the expansion plasma region of the discharge, with a magnetic filter located therein. In order to have the “pure” effect of the magnetic filter shown, the measurements are carried out without the filter, with the magnet holder only (without the magnets) and with the complete device of the filter (magnets mounted on the holder). The obtained sharp drop of the electron temperature caused by the magnetic field and the values of T_e below 1 eV reached behind the filter demonstrate its efficient operation. The discussion is in terms of thermal conductivity effects.

2. Experimental set-up and data processing procedure

The experimental set-up (figure 1) is a tandem type of a plasma source consisting of a driver and an expanding plasma region. An inductive discharge – with a cylindrical coil – produced in a quartz tube (with an inner radius and a length, respectively, of $R_1 = 2.25$ cm and $L_1 = 30$ cm) is the driver. A stainless steel chamber with an inner radius and a length, respectively, of $R_2 = 11$ cm and $L_2 = 47$ cm provides the volume for plasma expansion. The source operation is in a hydrogen gas. The rf power input is at 27 MHz, from an ICOM IC-718 generator and ACOM 2000A linear amplifier, through a matching box.

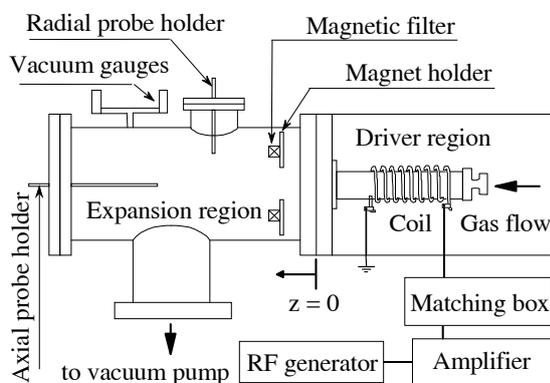


Figure 1. Schematical presentation of the experimental set-up of the inductively-driven tandem source, with the magnetic filter located in the expanding plasma region.

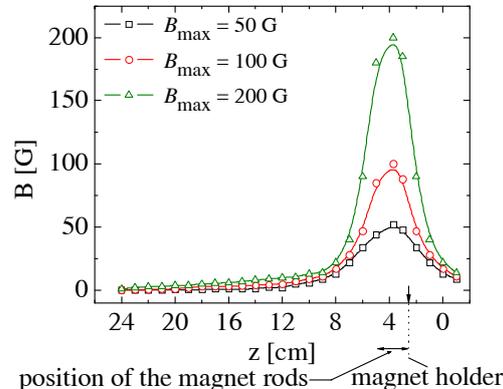


Figure 2. Axial profiles of the magnetic field of the filter. The position of the magnet holder in the expanding plasma volume of the source as well as the extension of the magnet rods is marked on the figure. The orientation of the z -axis is according to the ($z = 0$)-position indicated in figure 1.

The plasma source is the same as described before [10, 11]. Insertion of a magnetic filter in the expanding plasma chamber is the modification of the source stressed here. The filter is made from permanent magnets arranged in two rods (with width of 2 cm) mounted (figure 1) on a holder. The latter is a stainless steel sheet (19 cm in a diameter) with a hole in its center. The diameter (of 6 cm) of the hole exceeds slightly the diameter of the quartz tube of the driver. The magnetic field is perpendicular to the plasma flow coming out from the driver region. The distance between the magnet

rods as well as the distance between the magnet holder and the end of the quartz tube can be changed and controlled outside the vessel, providing possibilities for variation of the strength of the magnetic field and its location in the vessel. In the measurements presented here, the magnet holder is located at a distance of 2.5 cm away from the quartz tube. The results for the plasma parameters in the next section are obtained for three values $B_{\max} = 50, 100$ and 200 G of the magnetic field at the center of the filter, determined by changing the distance between the magnets. The axial variation of the magnetic field for these three values, measured by a Hall-probe, is shown in figure 2. The center of the filter is at $z = 3.7$ cm. In the discussion of the results, the regions $z \delta 2$ cm and $z \tau 6$ cm are marked as regions before and behind the filter.

The influence of the magnetic filter on the plasma behaviour is studied by Langmuir probe diagnostics of the discharge. The distribution of the plasma parameters is obtained by using a probe, movable in the axial direction and positioned at the axis of the metallic chamber. The probe tip is a straight tungsten wire orientated perpendicular to the magnetic field in the filter region. The radius and the length of the probe tip are, respectively, $R_p = 0.25$ mm and $L_p = 6.3$ mm. A passive compensation [10-13] is applied against distortions of the probe characteristics due to the influence of the plasma potential fluctuations caused by the rf field in the driver.

Electron temperature T_e and density n are the plasma parameters measured. With a magnetic filter located in the discharge, obtaining axial profiles of the plasma parameters combines measurements in regions without and with external magnetic field present. According to the probe theory requirements [14, 15], the magnetic field in our case is low enough ($R_p, \lambda_D < r_{Le}; R_p, \lambda_D \ll r_{Li}$) and, thus, the total axial profiles of n and T_e are obtained by applying methods of probe diagnostics of unmagnetized plasmas; here λ_D is the Debye length and $r_{Le, i}$ are the electron- and ion- gyro-radii. The electron temperature is obtained from the transition region [16] of the probe characteristics according to

$$T_e = \frac{e}{\kappa} \left(\frac{\Delta \ln I_e}{\Delta U} \right)^{-1}, \quad (1)$$

where e is the electron charge, κ is the Boltzmann constant and I_e and U are the electron current of the probe characteristics and the bias voltage, respectively. For the probe characteristics measured in the filter region, the beginning [14] of the transition region of the characteristics (i.e., that part of the transition region which is close to the floating potential) has been used. For the ions, the requirements for applicability of methods of probe diagnostics of unmagnetized plasmas are well fulfilled in the filter region and the plasma density n over the total length of the discharge is determined from the ion saturation current of the probe characteristics according to the ABR theory [17, 18] for collisionless sheath and cold ions. The method involves numerical solutions of the normalized Poisson equation in cylindrical co-ordinates [10, 19]

$$\xi \frac{d^2 \eta}{d\xi^2} + \frac{d\eta}{d\xi} - J\eta^{-1/2} + \xi e^{-\eta} = 0, \quad (2)$$

where $\eta = -eU/\kappa T_e$ and $\xi = r/\lambda_D$; $J = I_i (\kappa T_e L_p 2\pi)^{-1} \sqrt{m_i/2\epsilon_0 n}$ is the normalized current to the probe (the saturation current of the ion part of the probe characteristics) with ϵ_0 being the vacuum permittivity. Since the density of the expanding plasmas is comparatively low [10, 11], as the results in the next section also show, the H_3^+ -ions should have the highest concentration [20], among the positive ions (H^+ , H_2^+ and H_3^+). This justifies taking their mass as a value for the mass m_i of the positive ions in the expression for J . The value n of the concentration of the positive ions obtained by adjustment of a theoretical (obtained from equation (2)) probe characteristics to the experimental

one is considered as an electron density. The concentration of the negative ions is too low (of few percentages), for influencing the accuracy of the results.

3. Results and discussions

The axial profiles of the plasma parameters – electron temperature and density – presented here are obtained at gas pressure $p = 10$ mTorr and applied rf power $P = 400$ W. In order to see the “pure” effect of the magnetic filter, the measurements have been carried out in the following three cases: (i) without the filter, (ii) with the magnet holder, however, without the magnets, and finally, (iii) with the complete device of the filter: magnets mounted on the holder. The latter case is presented by results for the three values of the magnetic field $B_{\max} = 50, 100$ and 200 G already mentioned.

Figure 3 shows comparison of the axial profiles of the electron temperature T_e and density n obtained without the filter, with the magnet holder only and with the filter, for $B_{\max} = 50$ G at its center.

In general, a charged particle flux and an electron energy flux (i.e. thermal conductivity flux) from the driver [10, 11] ensure the plasma existence in the plasma expansion region of the discharge vessel. The extension of plasmas from the driver into the bigger volume of the expanding plasma region leads to electron cooling accompanied by an axial decrease of the plasma density (the case marked by “without holder and magnets” in figure 3). The axial profiles of T_e and n have the same behaviour shown before [10, 11] both in argon and hydrogen discharges: a fast drop of both electron temperature and density in the beginning of the expansion region, i.e. close to the driver, which merges in a very slow variation of the plasma parameters in the region away from the driver. Although the plasma expansion causes a decrease of the electron temperature, the obtained values of about 3 eV are still quite above that (about 1 eV) needed for efficient production of negative hydrogen ions.

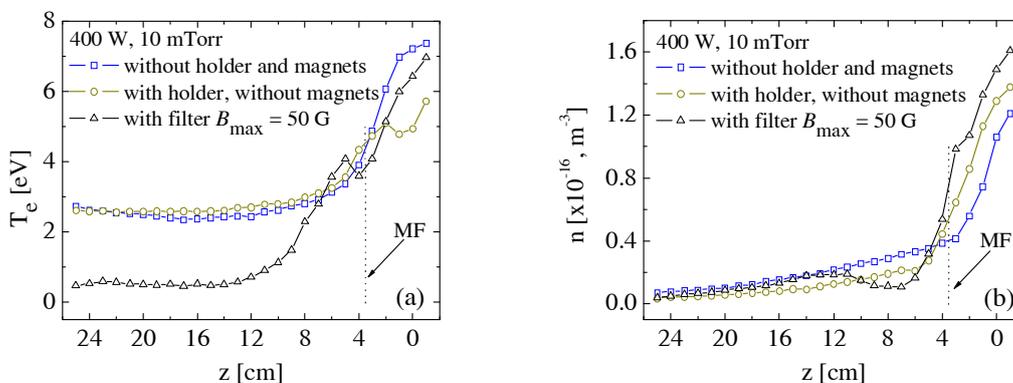


Figure 3. Axial profiles of the electron temperature (a) and concentration (b), in the three cases: without the filter, with the magnet holder only and with the filter ($B_{\max} = 50$ G). The dotted line marks the position of the center of the magnetic filter (MF).

Insertion of the magnet holder changes the configuration of the expanding plasma region of the source leading, as it has been expected, to changes in the axial profiles of the plasma parameters. The obtained results (figure 3, the case marked therein by “with holder, without magnets”) show that the influence of the magnet holder on the plasma parameters is mainly in the region between the driver and the holder: The electron temperature decreases there and the plasma density increases. The decrease of the electron temperature may be related to reduced particle losses in the radial direction. It looks like that the effect of the holder – with a hole in its center which is of the size of the cross section of the quartz tube – is to confine the plasma flux from the driver preserving its transverse size.

Figure 3 shows also the effect of the magnetic filter (the case marked by “with filter” in the figure). The axial profile of the electron temperature (figure 3(a)) is strongly modified. The axial profile of the

plasma density (figure 3(b)) is also influenced by the magnetic field. Comparison with the axial profiles of T_e and n obtained with the holder, without the magnets, shows an increase of the electron temperature and of the plasma density in the region between the driver and the magnetic filter. However, the strong reduction (figure 3(a)) of the electron temperature in the expansion plasma region behind the filter is the main effect of the filter. Moreover, the value of T_e about and below 1 eV reached is exactly what is needed for an efficient production of negative ions in the source. The strong decrease of the electron temperature is accompanied with a strong increase of the axial gradient of the plasma density (figure 3(b)) in the region of the filter.

Recent discussions [10, 11] on the experimental results for the axial distribution of the plasma parameters in the expanding-plasma region of inductive discharges both in argon and hydrogen put charged-particle and electron-energy fluxes from the driver in the basis of the plasma existence in expansion volumes. Such a concept stresses the importance of the nonlocality of the electron heating in the expansion plasma region. Continuing on these lines, it is reasonable to consider the influence of the magnetic field on the charged-particle and electron-energy fluxes as a mechanism of the operation of the filter. The magnetic field of the filter is perpendicular to the direction (z) of the plasma expansion. Therefore, according to the classical plasma description, the diffusion coefficient and the thermal diffusion coefficient of the electrons along the axis (z) of the expanding-plasma chamber are, respectively:

$$D_{ze} = \frac{D_e}{\left[1 + (\Omega_e/v_{e-n})^2\right]}, \quad \chi_{ze} = \frac{\chi_e}{\left[1 + (\Omega_e/v_{e-n})^2\right]} \quad (3)$$

where $D_e = \kappa T_e / m_e v_{e-n}$ and $\chi_e = (5/2) [n \kappa T_e / m_e v_{e-n}]$ are the diffusion coefficient and the thermal-conductivity coefficient without magnetic field. Here m_e is the electron mass, v_{e-n} is the electron-neutral elastic collision frequency and $\Omega_e = eB/m_e$ is the electron gyro-frequency. Since $\Omega_e \gg v_{e-n}$, the electrons are strongly magnetized and their transport is strongly affected by the magnetic field. The decrease of the electron diffusion coefficient with the increase of the magnetic field means a reduction of the axial electron flux. This should result in an increase of the plasma density before the filter and its decrease behind the filter resulting in a strong axial gradient of n as the measurements (figure 3(b)) show. With the decrease of the thermal diffusion coefficient caused by the magnetic field, the electron energy flux from the driver, which is the source of the electron heating in the expanding plasma region, is reduced. The low electron temperature behind the filter (figure 3(a)) is the result of this reduction of the electron thermal flux.

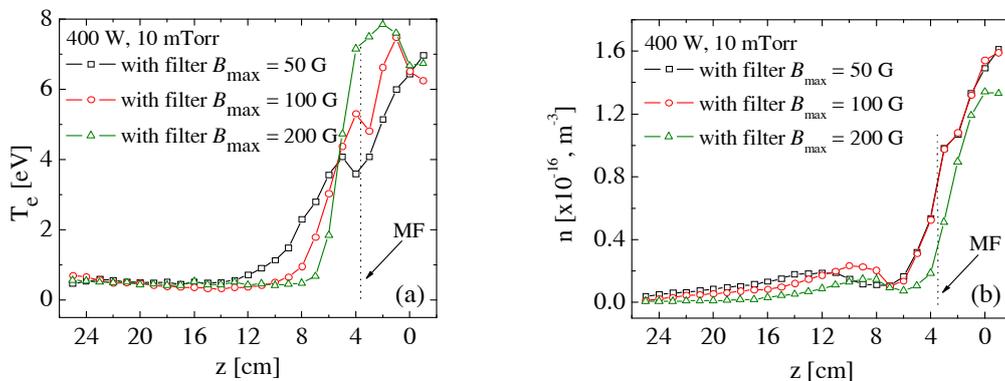


Figure 4. The same as in Figure 3 but for the three values of the magnetic field: $B_{\max} = 50, 100$ and 200 G.

Figure 4 shows the changes of the axial profiles of the electron temperature and concentration with increasing the magnetic field. The results obtained for the three values – $B_{\max} = 50, 100$ and 200 G – of the magnetic field at the center of the filter are compared. The reduction of the thermal flux of the electrons with the increase of the magnetic field leads to a faster drop of the electron temperature and a shift of the region of a low electron-temperature plasma towards the filter. A value of 50 G appears high enough for reaching the saturation value of T_e behind the filter, away from it. The drop of the electron density in the region of the filter is faster when the magnetic field is above 100 G.

4. Conclusions

Electron cooling by magnetic filters is studied by probe diagnostics of hydrogen discharges, regarding the use of the discharges as sources of negative ion beams. The experiments have been carried out in a tandem type of a plasma source with an inductive coupling and a volume for plasma expansion. It is shown that in such type of a plasma source the cooling of the electrons by the magnetic filter is an effect which appears in addition to the electron cooling due to the plasma expansion in a bigger volume. However, the magnetic filter is that ensuring a drop of the electron temperature below 1 eV, necessary for the effective operation of the volume-production based sources of negative hydrogen ions. The reduction of the thermal conductivity caused by the magnetic field is considered as governing the electron cooling by the filter.

Acknowledgements

The work is within the EUROATOM-project FU06-CT-2003-00139 and project no F-1316 of the National Science Fund in Bulgaria.

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