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Characterization of ion species mix of the TEXTOR diagnostic hydrogen beam injector with a rf and arc-discharge plasma box

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The ion specie fractions of the diagnostic hydrogen beam of TEXTOR tokamak have been determined by making use of a H_α-light Doppler shift spectroscopy and alternatively by a magnetic mass spectrometer. The measurements were done for the fixed beam energy of 50 keV and beam current variable up to 2.5 A. According to the measurements, the full energy beam component is for a radio frequency plasma box ~50% by the particle density and more than 75% for an arc-discharge plasma box. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1699508]

I. INTRODUCTION

Hydrogen diagnostic beams are now widely exploited in magnetic fusion devices[1–4] providing local parameters of the plasma and magnetic field. In particular, the diagnostic neutral beam injector of TEXTOR is envisaged to measure the ion temperature and impurity profiles via active charge exchange recombination spectroscopy (CHERS).[4] As well as the beam angular divergence and current density, the beam species mix is critically important for this diagnostic. The ion species mix can be deduced from a Doppler shift spectroscopy (see, for example, Refs. 5 and 6). This spectroscopic technique has been first applied to neutral beam injectors for plasma heating,[5,7] and later to diagnostic neutral beams.[8,9] In the measurements we followed the standardized procedure described in Ref. 7 to evaluate the beam species mix of the TEXTOR diagnostic neutral beam. As in Ref. 7, it was adopted that the observed intensities of the light emitted by the beam species are governed by the corona model, i.e., collisional de-excitation rates are small compared to the radiative decay rates, which in this case balances the collisional excitation of a level. This assumption was supported by comparison of the obtained ion species mix with that provided by the measurements with a magnetic mass spectrometer installed on the beam axis. The measurements were done for the diagnostic beam source equipped with different plasma boxes, namely, the radio frequency (rf)-based and arc-discharge ones, to find optimal conditions when the full energy specie is maximal.

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II. ION SOURCE OF THE TEXTOR DIAGNOSTIC NEUTRAL BEAM INJECTOR AND MEASUREMENTS SETUP

In the injector ion source (see Fig. 1), the ion current ~1.8 A is routinely extracted and accelerated by a four-grid ion optical system to 50 keV energy. The grids have 163 holes of 4 mm diameter arranged into a hexagonal array and are made of molybdenum. In order to provide beam focusing the grids are formed to be spherical segments with the radius equal to the desired focal length. Originally, the ion source was designed to operate with the rf plasma box, which has a cylindrical discharge chamber made of alumina ceramic with a 4-mm-thick wall. The rear copper flange and spacer between the ceramic tube and the plasma grid are water cooled. The discharge is exited by a six-turn coil installed at the ceramic chamber. The coil is connected to 4.65 MHz amplifier though an insulating oil transformer. For more details, this ion source is described further in Refs. 3 and 4. As has been already pointed out, an essential parameter of the diagnostic beam is power fractions $H^0(E)$, $H^0(E/2)$, and $H^0(E/3)$ which appeared after the beam passing through a neutralizer and deflection magnet in the beam line. Those fractions are originating from the H^+, H_2^+, and H_3^+ ions of the extracted beam. Their relative densities have first been measured at the test stand at Novosibirsk using a magnetic mass spectrometer located on beam axis 5 m downstream from the source. For the beam current of 1.7 A and hydrogen gas puff rate into plasma box 1 Torr l/s, the ion species mix in the extracted beam was H^+—66.4%, H_2^+—26.9%, H_3^+—5.3%, and water ~1.4% (by current). The beam composition varies either with the absorbed rf power and the gas puff rate. The general tendency was observed that full energy

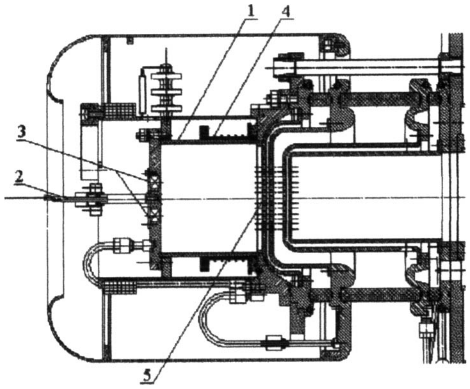

FIG. 1. Ion source with rf plasma box: 1—ceramic discharge chamber; 2—gas inlet; 3—permanent magnets; 4—rf coil; and 5—grids.

specie increases with both higher rf power and gas puffing, that, for the studied parameters range, corresponds to higher beam currents. Accordingly, the maximal full energy specie current of ~70% was achieved for the beam current of 2–2.3 A. As mentioned earlier, an increase of the full energy component current is of prime concern for the TEXTOR diagnostic beam for accurate measurements of the CHERS signals. It was therefore decided to test an arc-discharge version of the plasma box for the diagnostic beam that is potentially capable of providing a higher proton fraction in the beam because of higher power density in the discharge. A general view of the arc-discharge plasma box is shown in Fig. 2. This version of the plasma box is fully compatible with the ion optical system. The plasma stream, which is produced by the arc-discharge plasma source, expands into a region with peripheral magnetic field produced by a picket fence magnet (Fig. 2). As a result of ion reflection by the magnetic field, a density profile with the required uniformity was formed at the plane of the plasma grid. The magnetic field in the expander periphery was produced by an array of 16 Nd–Fe–B permanent magnets 8 cm in length and 1 cm in width each. The magnetic field strength at the inner wall of the expander is 0.2 T and falls down radially to less than 0.01 T at 2 cm distance from the inner wall.

The plasma source has an augmented cooling of the electrodes and washers to ensure multiple second operation. The copper cathode of the source has a spherical cavity 1 cm in radius. The cathode is cooled by the water supplied thought a ring-shaped channel in the cathode body with wall thickness of 2–3 mm. The anode copper insert has an inner water cooling loop. The washers are also cooled from their edges by water flow. The gas is supplied through a hole an a special triggering electrode located at the center of the cathode.

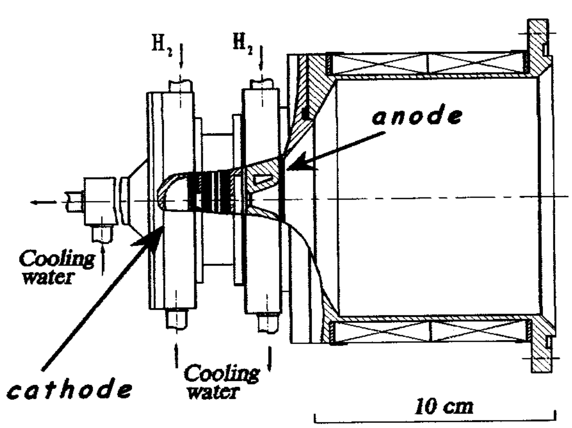

FIG. 2. Schematic view of the arc-discharge plasma box.

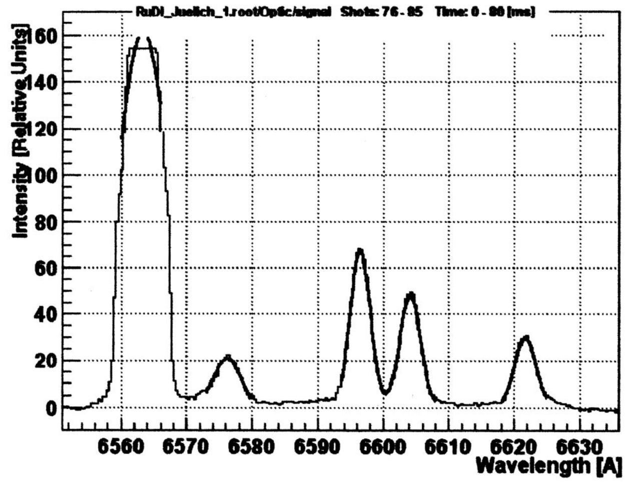

FIG. 3. H_α—light spectrum of 50 keV, 1.75 A hydrogen beam ("old" rf plasma box), which corresponds to about 40% of the full energy component.

The arc plasma source was operated in up to 2 s duration pulses providing ion current density of the emitter in the range of ~130 mA/cm^2 (for the discharge current of 300 A).

In the experiments, we use for beam formation, with the arc-discharge and rf-plasma plasma emitters, a grid system which is identical to that of the original TEXTOR diagnostic beam. The beam profile is monitored by an array of secondary emission detectors and miniature calorimeters. Typically, the beam was extracted during 100–200 ms, whereas the spectroscopic data were collected during 80 ms.

The existing test stand was additionally equipped with a grating spectrometer based on standard MDR-23 monochromator to measure the ion species mix. The beam is viewed under an angle of 30° by an optical system consisting of a lens, prism, and mirror which focus the light on the entrance slit of a grating monochromator. The spectrum reflected from the grating is focused on the entrance of the dissector after passing through the 50 mm focal length objective. Then the image is scanned over the 0.1 mm slit of the dissector and transmitted to an analog-to-digital converter together with the base generator signal. With a 1200 line/mm grating, a focal length of 600 mm, and 0.2 mm width of the entrance slit of the monochromator the spectral resolution of the system is about 3 Å. Taking into account 1/2 scale reduction of the image by the optical system one can estimate the dimensions of the volume the light is collected from as 0.4 mm along the beam and 36 mm in the transverse direction.

III. MEASURED ION SPECIES MIX

Figure 3 shows well-separated several light peaks for the 50 keV hydrogen beam extracted with the rf version of the plasma box. The observed shifts of the peaks from the unshifted H_α light emitted by the quiescent background gas are

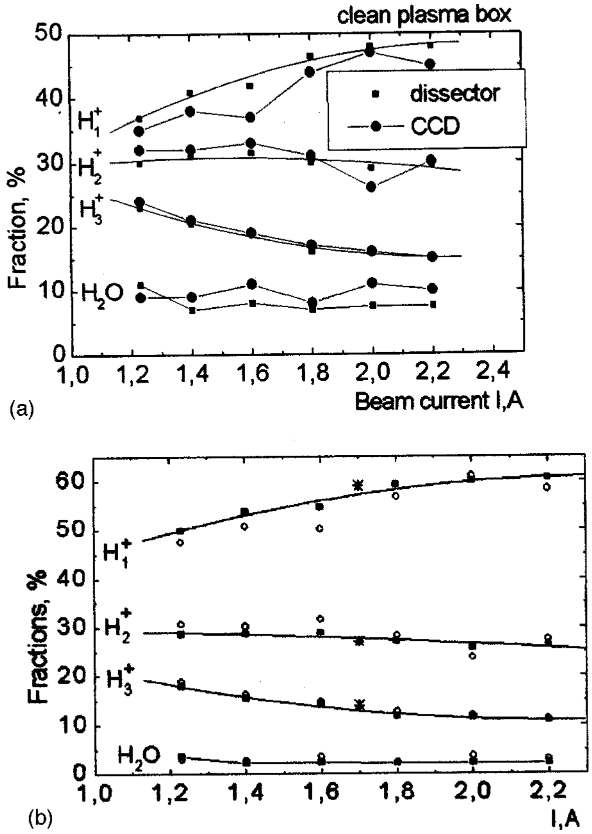

FIG. 4. (a) Beam specie densities vs extracted beam current. Gas puffing in the source is 2 Torr l/s. (b) The same data as in (a), but recalculated for the species current. Circles stand for the CCD data, stars stand for the mass spectrometer data.

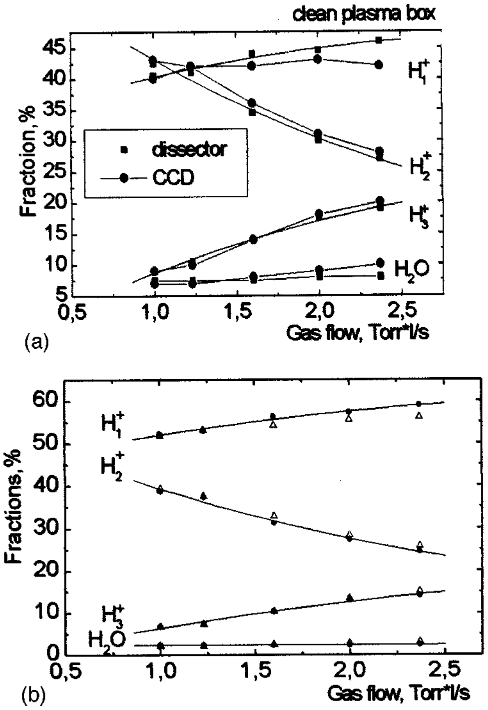

FIG. 5. (a) Beam species density vs gas flow rate for beam current of 1.8 A. (b) Beam species current vs gas flow rate for beam current of 1.8 A. Triangles stand for CCD data.

in good agreement with the calculated values for given beam energy and observation angle. In this series of shot the rf-plasma box was employed which has been operated at TEXTOR for ~2 years, so that integrated beam-on time amounts to approximately 2×10^4 s.

In the course of ion source operation it was observed that the beam species mix slowly degrades, so that full energy component substantially decreases. Initially it was measured to be ~50%, instead of ~40% obtained after long operation of the source. This observation was once again checked by installing the rf plasma box with new ceramic cylinder. In this case, full energy fraction increased up to 52%, which can be explained by the fact that for clear ceramic the recombination at the surface is very small.[10] After long operation of the source, it was noticed that the ceramic surface is covered with gray fur and the surface layer became conductive. It indicates the appearance of metallic aluminum on the surface, that results in an increased recombination and reduction of the proton fraction in the discharge.

Variation of the ion species mix with the extracted beam current and gas puffing rate was studied by using the earlier described optical system with the dissector and, alternatively, by a system with a spectrometer equipped with a charge coupled device (CCD) camera. Both systems provided reasonably close results (see Figs. 4 and 5). For comparison, in Figs. 5(b) and 6 the same data are presented, but recalculated for the ion species current.

In this series of experiments the source was operated with 200 ms pulse duration and with a preshort plasma discharge in the plasma box which lasts during 50 ms for the source conditioning. To collect enough light to the observation system the data were taken during 80 ms.

Special series of experiments were conducted to check whether the corona model is applicable or not. In these experiments we varied the amount of gas puffed into the observation region of the H_α radiation of the beam. The results are shown in Fig. 6 which essentially represents the same data as Fig. 5 does, but includes also the data taken with varying the gas density in the observation region. Namely, points labeled 1–5 were measured for the gas density varied by approximately an order of magnitude. Additionally, in separate experiments the bending magnet of the diagnostic beam injector was energized which caused changes in the beam species mix and in the beam light spectra measured.

At the same time, while the gas target in the neutralizer

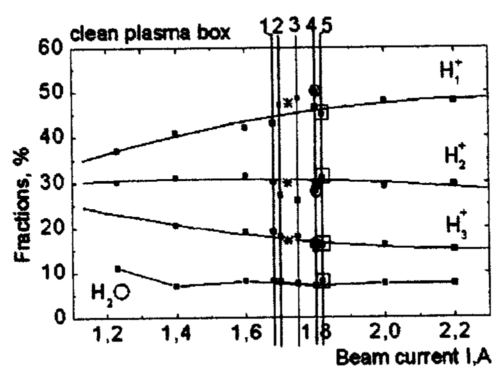

FIG. 6. Beam species relative density. Gas puffing in the source, 2 Torr l/s.

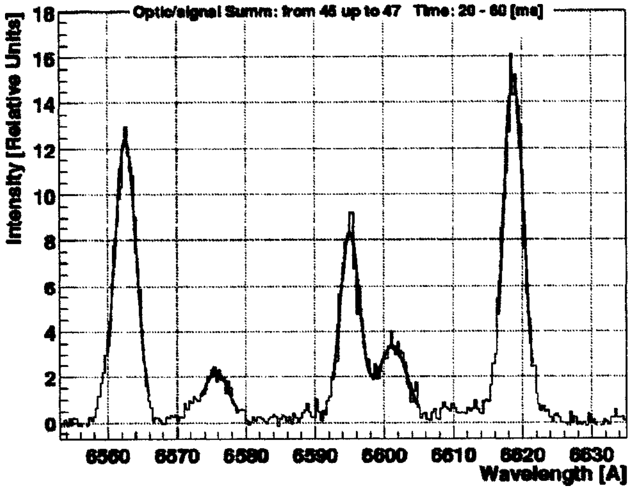

FIG. 7. Ion species mix measured for the ion source with an arc-discharge plasma box. Full energy specie is about 76% in density.

is thick enough providing the charged beam fractions are in equilibrium, one can recalculate these data, so as to obtain the species mix in the extracted beam. These data are represented by points 4 and 5. Note that the gas density in the observation region differed in these points by fivefold. Thus it was proved, that for the gas densities in the tube that were realized in the experiments, the reconstructed beam species did not vary significantly. Therefore, one can conclude that the corona model is applicable in our case. Another argument supporting this conclusion is that the data obtained with the magnetic mass spectrometer are also close to the results of the optical measurements (the stars stand for these data in Fig. 6). A typical Doppler-shifted spectrum of the beam light measured with the arc-discharge plasma box is shown in Fig. 7. It is seen that the full energy fraction is significantly higher compared to the rf plasma box.

It is worthwhile to note that the beam composition measured with the magnetic mass-spectrometer reasonably agrees with the data presented in Fig. 7. Indeed, it provided the following species mix (not including the water, which was 1%–2% in this case): H^+—87%, I_2^+—5%, I_3^+—8% (by current). In terms of the density in different species, it corresponds to H^+—80.6%, I_2^+—6.6%, I_3^+—12.8%.

There was no significant variation of the ion species mix with the beam current. Full energy specie increases just from 79% to 82% for the current increased from 1.6 to 2 A. The contribution of the water specie is not taken into account. According to the spectrometric measurement it amounts in this case to about 5% (in density). Note that the full energy specie appeared to be significantly higher than that measured for the ion source with rf plasma box.

In conclusion, the mixed ion species were measured for the diagnostic hydrogen beam of the TEXTOR tokamak using Doppler-shifted spectroscopy and, alternatively, by the magnetic mass spectrometer. Both methods provided reasonably consistent results. In the experiments, the two versions of the ion source were essentially tested. The first is equipped with the rf plasma box and is being operated at TEXTOR since 1998. The ion source routinely provides the 50 keV, 1.8 A ion beam for 4 s (maximal pulse duration is 10 s). In the second version, the arc-discharge plasma box is employed, which provided the same extracted current for maximally 2 s. It was found that the arc-discharge based version provided higher full energy specie >75% (in density) compared to the rf-based one (~50%).

During operation of the rf version of the source certain degradation of the full energy specie ratio was observed. It could be attributed to modification of the ceramic surface of the plasma box resulting in enhanced recombination of atomic particles at the wall.

ACKNOWLEDGMENT

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