MAGNUM-PSI, a Plasma Generator for Plasma-Surface Interaction Research in ITER-like Conditions

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Abstract. The FOM-Institute for Plasma Physics – together with its TEC partners – is preparing the construction of Magnum-psi, a magnetized (3 T), steady-state, large area (100 cm^2), high-flux (up to 10^{24} H^+ ions $m^{-2}s^{-1}$) plasma generator. The research programme of Magnum-psi will address the questions for the ITER divertor: erosion, redeposition and hydrogen retention with carbon substrates, melting of metal surfaces, erosion and redeposition with mixed materials. In order to explore and develop the techniques to be applied in Magnum-psi, a pilot experiment (Pilot-psi), operating at a magnetic field up to 1.6 Tesla, has been constructed. Pilot-psi produces a hydrogen plasma beam with the required parameters ($T_e \leq 1$eV and flux $\geq 10^{23}$ $m^{-2}s^{-1}$) over an area of 1 cm^2. In this paper the results of extensive diagnostic measurements on Pilot-psi (a.o., Thomson Scattering and high-resolution spectroscopy), combined with numerical studies of the source and the expansion of the plasma will be presented to demonstrate the feasibility of the large Magnum-psi plasma generator.

1. Introduction

A study of plasma-surface interaction in conditions similar to those in the divertor of ITER and fusion reactors beyond ITER requires a plasma generator capable of producing a high flux of magnetized hydrogen plasma [1]. Typical values are 10^{24} H^+ ions $m^{-2}s^{-1}$ over an area of 100 cm^2. The large flux is needed to enter the regime where the net erosion decreases when the flux is increased, while the area is required to ionize species leaving the wall and redeposit them before they are lost from the plasma column. An additional challenge is the temperature range, that has to match the conditions set by detached operation (0.5-7 eV), leading to a recombining plasma at the lower end.

Plasma-surface interaction in this range of temperatures and fluxes is an unexplored area. Even in present-day large Tokamaks the fluxes are too low to enter the regime relevant for ITER and beyond. Furthermore, divertor chambers in Tokamaks are difficult to access with diagnostics, and variations between successive discharges can be substantial, making it very hard to investigate plasma-surface interaction under well defined conditions. Present-day linear machines are unable to produce the high flux at low temperatures. As mentioned above, for relevant research in a linear machine the area in contact with the plasma should in addition be large enough to capture material released from the surface in the active plasma. We call this the “strongly coupled regime.” Present-day devices operate in the “weakly coupled regime” where reaction products are essentially pumped away.

We expect to reach the relevant parameter in Magnum-psi, a magnetized (3T), steady state, large area (100cm^2) high-flux (up to 10^{24} m^{-2}s^{-1}) plasma generator. Magnum-psi will be embedded in an integrated plasma-surface laboratory including in situ and ex situ, in vacuo surface analysis.

In order to explore and develop the techniques to be applied in Magnum-psi, a pilot experiment (Pilot-psi), operating at a magnetic field up to 1.6 Tesla, has been constructed. In this paper the results of extensive diagnostic measurements on Pilot-psi (a.o., Thomson Scattering and high-resolution spectroscopy), combined with numerical studies of the source and the expansion of the plasma will be presented to demonstrate the feasibility of the large Magnum-psi plasma generator.

2. The Pilot-psi device

In Pilot-psi plasma jets are produced with a wall stabilized DC cascaded arc [2] that expands in a 1 m long 0.4 m diameter vessel kept at a pressure of 2-200 Pa. A strong magnetic field (0.4 Tesla continuous field; up to 1.6 Tesla in 10s pulses) is applied to confine the beam and to transport the plasma with minimal losses over a distance of ~1 m to the target that is inserted from the other end of the vessel. Additional Ohmic plasma heating can be employed along the distance between plasma source and target by drawing an additional current. For this, an auxiliary ring-shaped electrode is installed coaxially with the plasma beam.

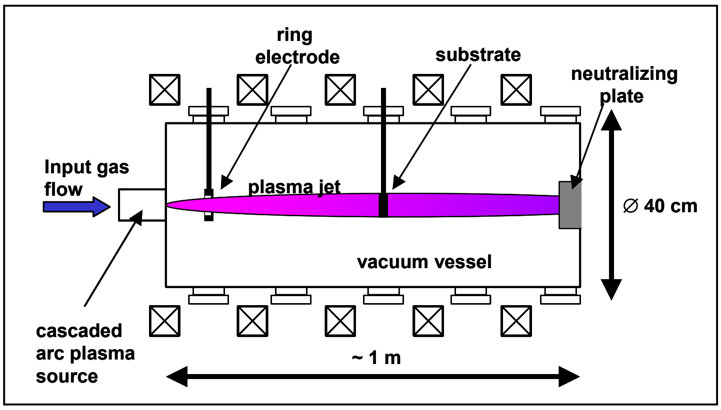

FIG. 1. Scheme of the Pilot-psi device

The plasma source (Fig. 2) consists of a cathode chamber with three tungsten cathodes, a series of 5 mm thick copper cascaded plates and an anode plate with a nozzle. The discharge channel diameter was 4 mm. All components are water-cooled. The arc plates are electrically insulated with 1 mm thick boron-nitride plates to operate at the floating potential. The working gas (Ar, H_2) continuously flows into the plasma source with a flow rate of 1-3.6 slm at a pressure of 1-2x10^4 Pa and is ionised there. The arc is operated at currents in the range of 10-100 A. The arc voltage ranges from 50 V for pure argon plasma to 250 V for pure hydrogen plasma at a current of 60 A.

3. The cascaded arc plasma source

The desired particle flux and covered area in Magnum-psi require a source capable of delivering 10^{22} ions per second. A single cascaded arc as used for plasma-chemical processing typically yields an ionisation degree of 5-10% in Argon and Hydrogen at a flow of 3 slm (10^{21} at.s^{-1}), a discharge current of 70 A and a voltage of 100V. This makes an array of arcs a good candidate to produce the required ion fluence. In Pilot-psi we have investigated several approaches to enhance the efficiency of the arc. Enhancing the bore of the arc channel, while simultaneously increasing the current and the gas flow proportional to the area of the channel, reduces the amount of heat lost to the channel wall. Further, constricting the channel close to the cathode improves the efficiency of the source. Also the shape of the nozzle strongly influences the efficiency. Further, we used tungsten as wall material, with the aim to reduce association of atomic hydrogen and promote dissociation. The ion production could be enhanced by more than a factor of two by combining these methods. The possibility to use an array of arcs has been tested in two and three channel arcs, the design of which was patented. Stable operation with multiple channels was obtained in argon. With hydrogen the current tended to concentrate in a single channel. This was attributed to the observed negative I-V characteristic of the arc in the explored parameter range. It is expected that increasing the arc current will stabilise the multiple channel operation in hydrogen.

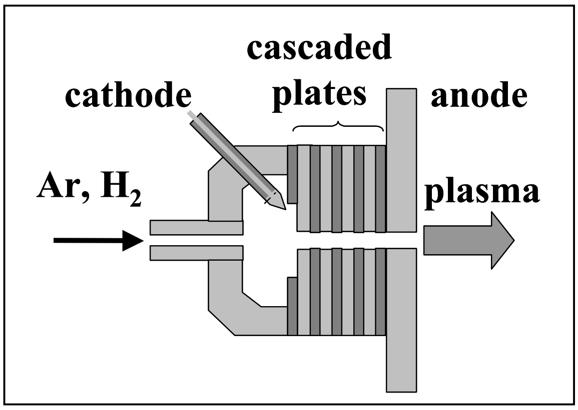

FIG.2: The cascaded arc plasma source

In order to assess the efficiency of hydrogen plasma production with the cascaded arc as a function of the magnetic field, we determined the power lost to the cooling water and compared this with the total power consumed by the arc (i.e., the voltage over the arc times the total arc current). Measurements of the temperature rise as well as the flow of the cooling water through each individual arc component demonstrated that the total power lost to the cooling water increases with the magnetic field, as can be seen in Figure 3. This increase can be attributed totally to the losses at the anode, the power lost to the plates and the cathodes is unaffected. For magnetic fields in excess of 0.4 T, the power loss to the anode and plates cannot be determined, as the rise time of the temperature is longer than the 3 seconds of the magnetic field pulse. The slope of the temperature rise at higher fields suggests, however, that the power lost to the anode increases linearly with the magnetic field. To assess the efficiency of the source, we determined the electron density at the source exit by means of high-resolution optical emission spectroscopy.

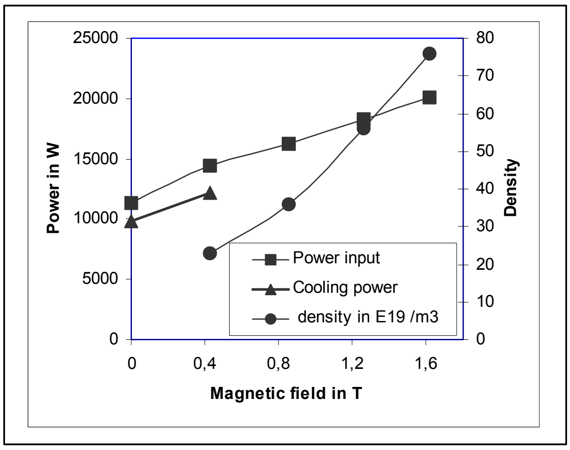

FIG.3. Power balance of the cascaded arc for different magnetic field strengths

4. Thomson scattering on Pilot-psi

Figure 4 shows the Thomson Scattering set-up. The laser is passed vertically through the vessel and focused in the centre of the plasma jet with an f=2500 mm lens. Stray light is minimised by the long entrance and exit tubes with baffles. The scattered light is imaged on a fibre head with an f=80 mm viewing lens. The fibre head contains an array of 50 individual fibres and relays the image of the complete radial plasma jet profile to an in-house constructed spectrometer in Littrov configuration (f=1000 mm, 1200 lines/mm grating), for spatially resolved analysis. Figure 5 shows the central part of the spatially and spectrally resolved scattered light collected at 3.5 cm from the nozzle of the arc. It clearly reveals the

Doppler broadened scatter signal from the individual fibres along the vertical (spectral) axis and the plasma jet profile along the horizontal (spatial) axis. The Thomson signal is calibrated by Rayleigh scattering on N_2.

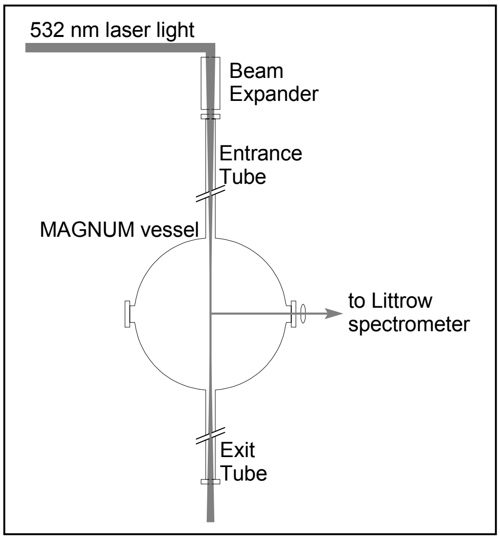

FIG. 4: The Thomson Scattering set-up

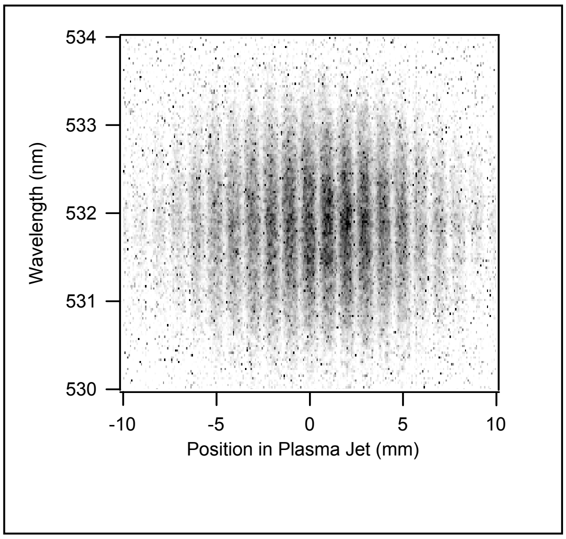

FIG. 5: Recorded TS spectra

Deduced radial profiles of the electron temperature and density are shown in figure 6 for an applied magnetic field of 0.4 and 0.8 Tesla, in Argon and in Hydrogen. It demonstrates that the plasma density increases strongly with increasing magnetic field and reaches ITER relevant values. The electron temperature is constant within the experimental error, with respect to both the radial coordinate and the magnetic field strength.

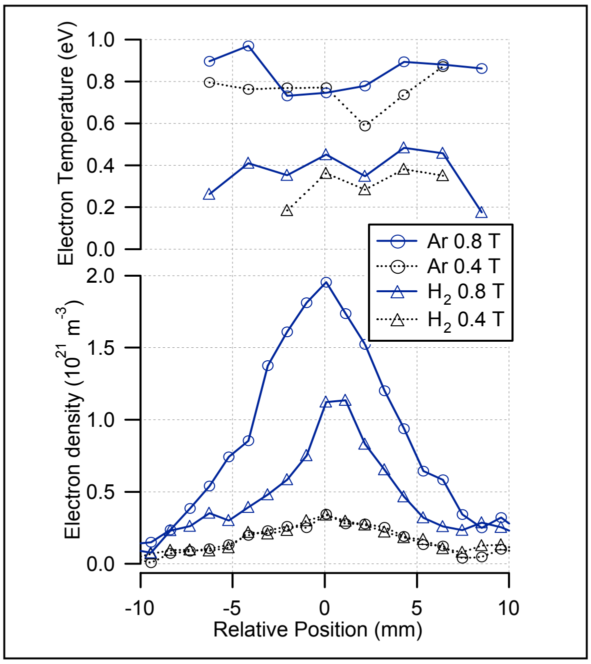

FIG. 6: Electron temperature and density profiles in Argon and Hydrogen, for B=0.4 and 0.8 T.

5. High-resolution spectroscopy

Since Thomson scattering can only be applied at one position, we have to rely on other techniques to obtain data on the electron density and temperature along the axis of the plasma jet. High-resolution spectroscopy is a flexible diagnostic that can be used to analyse spectral line profiles broadened by the Doppler and Stark effect. Comparison with Thomson data offers a good calibration.

In our high-resolution set-up the optical emission of the plasma is again recorded with the array of fibres to obtain a radial profile and analysed in second order with a 2.5 m Littrov spectrometer equipped with a grating of 1200 lines/mm. The Stark broadening of the H_β line has been used to measure the electron density along the axis of the plasma beam. In order to obtain the density, the measured line profile is fitted with a Voigt profile to separate the Lorentzian contribution (Stark effect) from the Gaussian contribution (Doppler broadening).

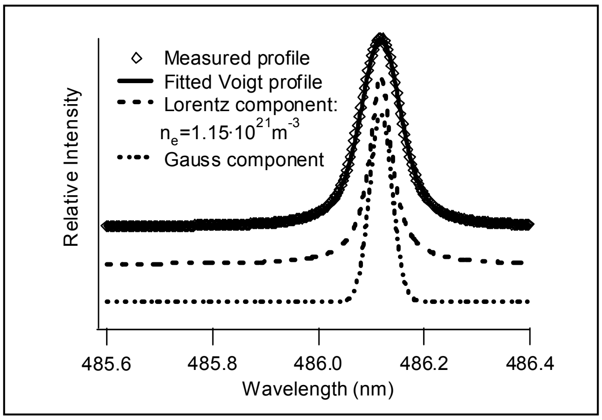

FIG. 7: Fit of the H_β line with a Voigt profile to asses the Stark broadening.

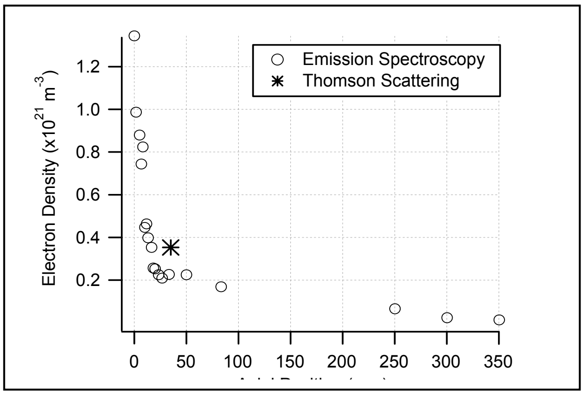

FIG. 8: The electron density along the axis of the plasma jet for a magnetic field of 0.4 T, as obtained from Stark broadening of H_β. The data are compared with Thomson Scattering at 3.5 cm.

Figure 7 shows an example where the measured profile yields an electron density of $1.15*10^{21}$ m^{-3}.

Figure 8 shows the measured electron density along the axis in a magnetic field of 0.4 Tesla. The decay is caused by the expansion of the beam in the region just after the nozzle of the arc, where there are still many collisions and the Hall parameter for the ions is still low. The emission spectroscopy has also been used to determine the electron density at higher magnetic fields. Thomson Scattering in this regime suffered from misalignment of the laser beam due to forces exerted on the vessel. Figure 9 shows the dramatic increase of the Hydrogen plasma density with the magnetic field. The difference between the Thomson scattering results and the spectroscopic data can fully be attributed to the beam expansion over the first few cm, as it roughly corresponds to the inverse of the increase in area of the beam.

Measured intensity ratios of the Balmer series of hydrogen also offer a possibility to obtain the electron density and temperature. Figure 10 shows the observed ratio of the Hβ and Hα and of the Hγ and Hα emission. The large intensity ratios are due to the fact that the plasma is recombining, so the levels are populated by two- and three body recombination process between electrons and atomic ions and by dissociative recombination between electrons and molecular ions. Possibly

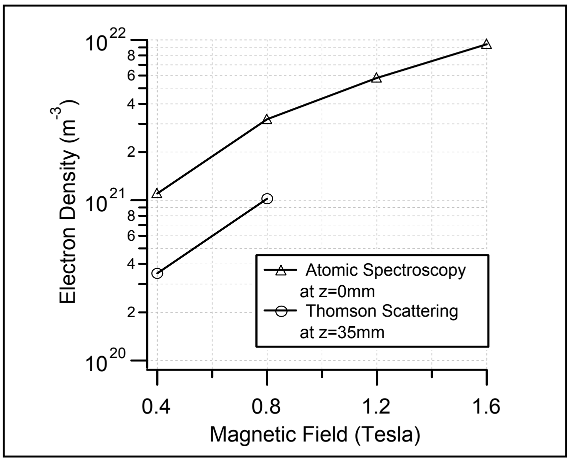

FIG. 9: The strong increase of the plasma density with magnetic field, as probed with Stark broadening at the arc outlet and with Thomson scattering at z=3.5 cm.

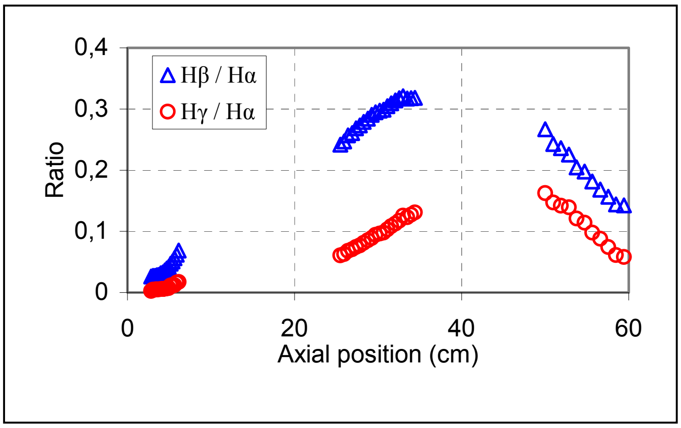

FIG. 10: Measured ratio of Balmer line intensities along the axis of the plasma jet in the first three viewing windows.

also recombination between negative and positive atomic ions plays a role. An analysis with a collisional radiative model [3] confirmed that even in the second viewing window the electron density is still of the order of 10^{19} m^{-3} (cf. figure 8 at z=300 mm)

6. Auxiliary heating

In order to to heat the plasma jet, an additional DC current was drawn between a ring electrode installed at the first window (z=3.5cm) and an auxiliary target at the third window (z=55cm) the plasma jet can be heated by applying a DC voltage. Figure 11 shows a spectrum of a discharge in Argon, recorded at z=30cm, for zero and 70A DC current additional current. The heating turns the plasma into an ionizing mode and enhances the temperature well above 3 eV, as can be deduced from the appearance of spectral lines of the Ar^+ ion around 480 nm.

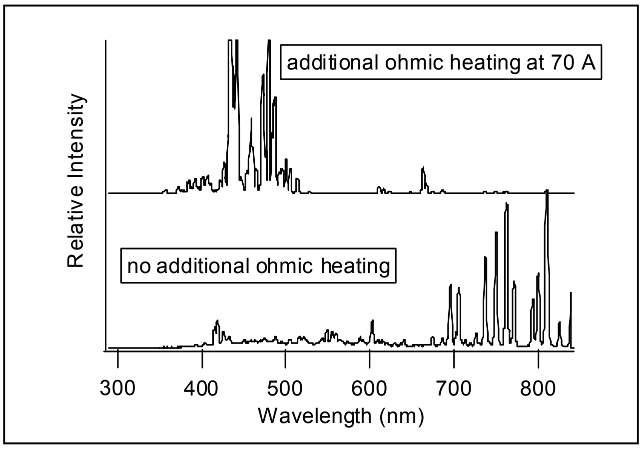

Fig. 11: Spectra in the argon plasma jet recorded at z=30 cm, with and without an additional current drawn. The heating of the jet results in the appearance of argon ion lines around 480 nm

7. Conclusions

Measurements of the electron density and temperature in Pilot-psi show that an expanding cascaded arc plasma source operated in Hydrogen is able to produce plasma fluxes that are relevant for the study of the plasma-surface interaction in detached ITER divertor plasmas. A single cascaded arc has been shown to yield a plasma in the (sub-)eV range covering an area of 1 cm^2 at a particle flux in excess of 10^{23} $m^{-2}s^{-1}$. In order to upgrade the present source to the large area source envisaged for Magnum-psi, an array of arcs will be constructed and the bore of the arc channel will be enlarged to reduce the power loss to the wall.

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Acknowledgement

This work, supported by the European Communities under the contract of Association between EURATOM/FOM, was carried out within the framework of the European Fusion Programme. The views and opinions expressed herein do not necessarily reflect those of the European Commission."