Optimisation of a High Flux Hydrogen Plasma Source for Plasma-Surface Interaction Studies

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1. Introduction

We have made a linear plasma generator operational to study plasma-wall interactions under conditions relevant for ITER [1]: Magnum-psi (Magnetised Plasma Generator and Numerical Modelling for Plasma Surface Interaction studies). This device is unique in comparison with other linear devices [1-4] by virtue of a high magnetic field (up to 1.6 T). In order to obtain high ion flux densities ($\sim 10^{22} - 10^{24}$ m$^{-2}$s$^{-1}$) of low temperature ($\sim$ 0.4 - 9 eV) plasma we optimised the plasma source and studied the effect of high magnetic fields on the plasma transport. The results are presented in this contribution.

2. Experimental set-up

A wall stabilized DC cascaded arc is applied to produce a plasma beam which expands in a 0.4 m diameter vessel (Figure 1) that is at a background pressure in the range of 2-200 Pa. A magnetic field of 0.4 T ($< 3$ minutes) or 0.8, 1.2 or 1.6 T ($< 4$ s) can be applied to confine the expanding plasma and to transport the plasma with minimal losses over a distance of $\sim 1$ m to the target at the other end of the vessel. The plasma source (Figure 2) consists of a cathode chamber with three tungsten cathodes, a series of 5 mm thick cascaded copper plates and an anode plate with a nozzle. All components are water-cooled. The plates are electrically insulated from each other and from the cathode part and the anode with boron-nitride plates 1 mm thick. The discharge channel is defined by

![Fig. 1: Schematic drawing of the Magnum-psi linear plasma generator.](image1)

![Fig. 2: Schematic drawing of the cascaded arc plasma source](image2)
typically 4 mm diameter apertures in the centre of the arc plates. The working gas (Ar, H\textsubscript{2}) continuously flows into the plasma source at a pressure of 1-2\times10\textsuperscript{4} Pa and is ionised there. The typical discharge parameters are a gas flow rate of 2 slm and an arc current of 60 A at for an arc voltage of 50 V and 180 V for argon and hydrogen, respectively. Radial profiles of the electron density and temperature are obtained with an electrostatic double Langmuir probe that can be translated perpendicularly to the plasma axis at ~ 30 cm from the nozzle.

3. Plasma transport in a strong magnetic field

The effect of the magnetic field strength on the plasma transport was established by measuring the ion flux densities with the double Langmuir probe for the different preset values of the magnetic field. The results in Figure 3 show that the flux density increases from \(10^{20}\) to \(7\times10^{22}\) m\textsuperscript{-2}s\textsuperscript{-1} for hydrogen plasma and from \(2\times10^{21}\) to \(4\times10^{23}\) m\textsuperscript{-2}s\textsuperscript{-1} for argon plasma. This demonstrates that the magnetic field is a practical tool to control the ion flux. The trend in the data suggests that an additional decade in flux density can be gained by increasing the field strength to 3 T.

4. Plasma source optimisation

4.1. Radial hydrogen inlet

The plasma source was modified for hydrogen operation in order to increase the plasma density as well as to prevent the quick erosion of the cathodes in the original geometry. In this modified arc (Figure 4), pure argon is supplied to the cathode chamber and hydrogen is introduced half way the discharge channel via a radial inlet in an additional cascaded plate. The plasma channel diameter is abruptly increased at this inlet plate from 2 to 4 mm. Langmuir probe measurements (data not shown) demonstrate that this modified source produces plasma with electron densities that are typically a factor of 1.5 times higher compared to the original plasma source. The resonant charge exchange of argon ions with molecular hydrogen (Ar\textsuperscript{+} + H\textsubscript{2} \rightarrow Ar + H\textsubscript{2}\textsuperscript{+}) followed by dissociative recombination of the hydrogen molecular ion (H\textsubscript{2}\textsuperscript{+} + e\textsuperscript{-} \rightarrow H + H\textsuperscript{+}) enhances
the ionisation process as the atomic hydrogen is ionised easier than the molecular hydrogen and is probably the important process underlying the improved plasma yields.

4.2. Diameter of the discharge channel

The efficiency of hydrogen plasma production by the cascaded arc was determined for three diameters of the discharge channel: 3.5, 4, and 4.5 mm. Also smaller and larger diameters were attempted, but these did not allow for stable hydrogen operation. For the efficiency determinations, the heat dissipated by the cooling water flowing through the arc components is measured and it is assumed that the remainder of the power supplied to the arc is converted into plasma. For each channel diameter, the highest efficiencies were observed at the maximum gas flow rate of 3.6 slm and discharge current of 100 A. These efficiencies are plotted in Figure 5. The graph exhibits a similar trend as was observed by de Graaf et al. [7] and indicates that an increase of the channel diameter improves the efficiency. This is also supported by numerical calculations performed with the PLASIMO simulation package [8] (data not shown). It should be mentioned that the present upper limit of 4.5 mm for stable hydrogen operation is imposed by the maximum output power of the power supply. It is envisaged to upgrade this power supply to assess also large channel diameters.

4.3. Multiple plasma channels

We have pioneered the possibility to apply several plasma channels in a single cascaded arc to improve the plasma yield. An arc was constructed with three channels of 4 mm diameter in a 12 mm side length triangular configuration and the original joint cathode chamber. Initial experiments on argon indicated that this arc can be regarded as the superposition of three conventional single-channel arcs. In hydrogen, however, plasma production in the three-channel arc was restricted to only one of the channels. This is explained by the experimentally determined voltage-current characteristic of the arc running on hydrogen (Figure 6). This negative characteristic indicates that the effective resistivity of the plasma channel

![Fig. 5: Effect of the discharge channel diameter on the efficiency of the cascaded arc operating at hydrogen.](image1)

![Fig. 6: The voltage-current characteristic of the cascaded arc operating on hydrogen.](image2)
decreases for increasing current. Consequently, it is favourable to pass all plasma current through a single channel.

4.4. Tungsten inserts in the arc plates
Recombination of hydrogen ions at the wall of the discharge channel are the predominant pathway for energy loss inside the arc. A possible way to decrease this loss is to apply a wall material with minimal recombination efficiency. Tungsten would be an obvious choice. In a preliminary experiment, we inserted a 10 mm diameter tungsten tube (4 mm internal diameter) in the last arc plate. Figure 7 shows the temperature of the cooling water from this plate in two successive experiments: one for the original copper plate and the other for the plate with the tungsten insert. The first part of the graph corresponds to argon operation and the two plates display the same behaviour. At t = 2.7 s the working gas is changed to hydrogen and the temperature rises for both plates. However, it is clearly seen that this temperature rise is significant less for the plate with the tungsten insert, which supports the hypothesis of less recombination losses.

5. Conclusions
- Confinement of the plasma beam with a magnetic field of 1.2 T improves the ion flux density with almost three orders of magnitude.
- The electron density of the plasma produced by the modified cascaded arc with side injection of hydrogen is about 1.5 times higher compared to the original arc.
- The efficiency of the cascaded arc operating on hydrogen improves for increasing gas flow, discharge current and discharge channel diameter. The maximum efficiency is currently ~30%.
- The source with multiple plasma channels operates stable on argon but limits the plasma current to only one channel for hydrogen due to a negative voltage-current characteristic.

References: