Development of the Long Pulse Negative Ion Source for ITER

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Abstract

A model of the ion source designed for the neutral beam injectors of the International Thermonuclear Experimental Reactor (ITER), the KAMABOKO III ion source, is being tested on the MANTIS test stand at the DRFC Cadarache in collaboration with JAERI, Japan, who designed and supplied the ion source. The ion source is attached to a 3 grid 30 keV accelerator (also supplied by JAERI) and the accelerated negative ion current is determined from the energy deposited on a calorimeter located 1.6 m from the source.

During experiments on MANTIS three adverse effects of long pulse operation were found:

- The negative ion current to the calorimeter is ≈50% of that obtained from short pulse operation
- Increasing the plasma grid (PG) temperature results in ≤40% enhancement in negative ion yield, substantially below that reported for short pulse operation, ≥100%.
- The caesium “consumption” is up to 1500 times that expected.

Results presented here indicate that each of these is, at least partially, explained by thermal effects. Additionally presented are the results of a detailed characterisation of the source, which enable the most efficient mode of operation to be identified.

Background

Each of the neutral beam injectors of ITER is designed to deliver 17 MW of 1 MeV D^0 to the ITER plasma throughout the ITER pulse, i.e. for up to 3600 s [1]. The design of the injectors is based on the acceleration and neutralisation of D^-, assuming an accelerated D^- current density of 200 A/m^2 with <1 electron extracted per accelerated D^- ion. The reference design of the negative ion source is a caesiated, filamented, multi-pole, arc discharge source requiring an arc power of about 1.5 kW per litre of source volume, at a source pressure of 0.3 Pa. The KAMABOKO III source has operated at these parameters for 5 s pulses [2], and the aim of the ongoing experiments is to achieve them during long pulse operation, when the system reaches thermal equilibrium.

1 Experimental Apparatus

The source has been described in the past [3] and only some features are briefly summarised here. The source is a 30 *l* quasi-cylindrical chamber of machined oxygen free copper, which forms the anode; with 12 filaments mounted on water cooled co-axial feedthroughs. The primary electron confinement (and some plasma confinement) is achieved by 16 magnetic line cusps generated by SmCo permanent magnets (width x height = 10 x 20 mm^2) arranged in machined vertical channels on the outside of the chamber. The cooling of the source is achieved by water lines brazed into channels on the outside of the source next to the columns of magnets.

The source is directly attached to, but electrically insulated from, the accelerator. The end wall of the ion source is the "plasma grid" (PG), the first grid of the accelerator, which is biased with respect to the source walls (the anode) to +5V. Columns of large ($30 \times 30 \times 20$ mm^3 or $50 \times 30 \times 20$ mm^3, length by width by height) permanent magnets mounted inside the source flange produce a horizontal magnetic field across the front of the plasma grid. This field forms the "standard" magnetic filter with a strength of ≈900 G cm, defined as $S = \int_0^{\ell_{fil}} B.d\ell$ where B is the local field strength, ℓ is the distance from the PG along a line between the PG and the filaments, and ℓ_{fil}.is the position of the filaments. Electrons and negative ions arriving at the apertures in the PG are extracted and accelerated to ≤30 keV. As they have the same charge it is not possible to distinguish between electron and negative ion extraction and acceleration electrically. Therefore the accelerated negative ion current is usually determined from the energy deposited by the ions on a calorimeter located 1.6 m downstream of the accelerator which electrons are unable to reach as they are deflected out of the beam path by a small transverse magnetic field.

2 Beam Transmission

Fig. 1 shows the accelerated current and the current to the calorimeter as a function of the arc power.

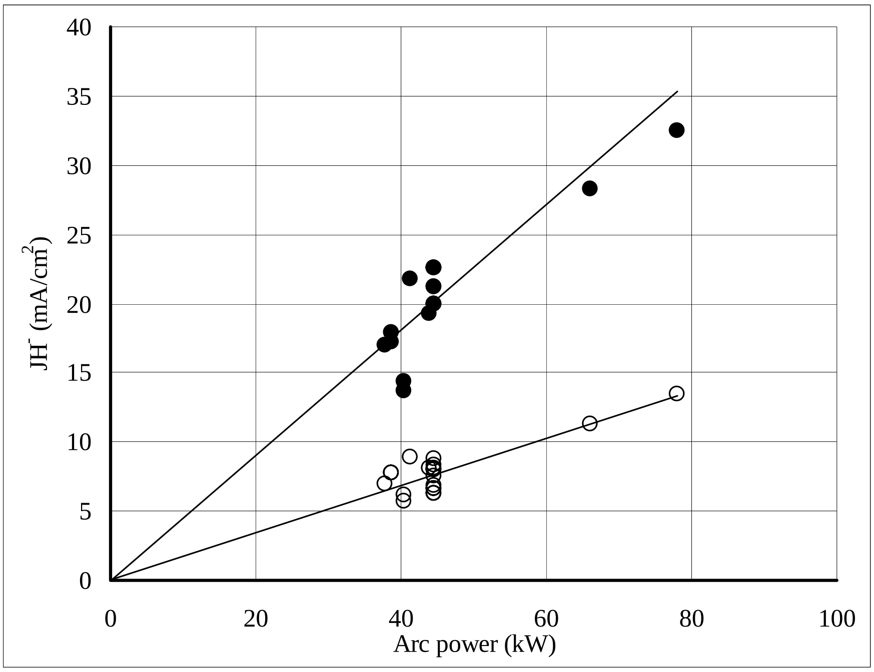

Fig. 1 Accelerated current and the current to the calorimeter as a function of the arc power. The filled circles are the H^- current density calculated by assuming the drain current from the high voltage power supply is entirely accelerated H^-. The open circles are the H^- current density derived from the energy falling on the calorimeter. As can be seen from Fig. 1, only about 50% of the accelerated current reaches the calorimeter.

Possible reasons for this poor transmission are:

a) *The "lost" beam is electrons, arising from either accelerated extracted electrons or electrons created by stripping in the accelerator.*

Extracted electrons: Extracted electrons are deflected onto the surface of the extraction grid by the magnetic field from the filter in the ion source and the field from permanent magnets buried in the extraction grid, but some electrons escape to the acceleration region. The fraction of the extracted electrons that are accelerated has been measured by operating the source in pure argon. In this situation no negative ions are produced in the discharge, but a high electron current (assumed equal to the current to the extraction grid) of 2.8 A was extracted. No power was recorded on the calorimeter, and the accelerated current, was 50 mA, i.e.<2% of the extracted current. Furthermore the current to the acceleration grid was equal (within the measurement error) to the current drain from the high voltage power supply, which means that most of the accelerated electrons were collected on that grid. As the extracted electron current during H_2 operation is typically <20% of the accelerated current, and approximately equal to the accelerated current in D_2 operation, extracted electrons cannot explain an accelerated electron current that is 50% of the total accelerated current

Electrons from stripping. To a first approximation the fraction of electrons stripped during the passage of the H^- or D^- through the accelerator is proportional to the source pressure. Thus if stripping were the cause of the "lost" beam, the transmission should vary strongly with the source filling pressure. Fig. 2 shows the transmission as a function of the source pressure. Within the experimental errors there is no variation with pressure from 0.18 to 0.7 Pa. (Note that the calculated stripping fraction in the acceleration gap at a source filling pressure of 0.3 Pa is ≈3%.)

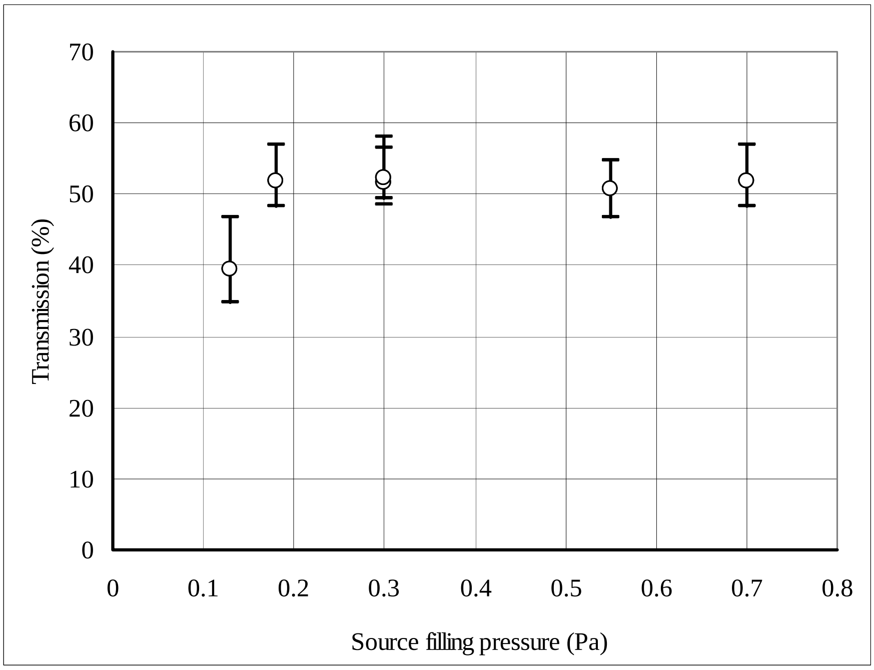

Fig. 2 Beam transmission as a function of the source filling pressure.

b) The beam optics is extremely bad.

Careful simulations of the beam optics have been carried out with assumed possible variations and errors in extraction and acceleration gaps, grid misalignment and negative ion current density and magnetic field effects. All the simulations predict beams with adequate optics to achieve transmissions of >90%. However it has recently been realised that the acceleration grid could be bowing under the heat load received from intercepted ions and electrons. The circular grid plate is cooled by water flowing in small (1.5 mm ID) tubes brazed between the rows of apertures onto the downstream surface of the grid. The power to the acceleration grid is small, ≈1.5 kW under typical conditions, and the equilibrium temperature is ≈70 °C. Because it is heated, the grid will try to expand, and, if it is fixed at its circumference, it will bow, or buckle, in order to have the correct, increased, size. If the grid bows the convex surface will have been stretched and concave one compressed. If the forces needed to compress and stretch the material are less than the force due to thermal expansion, the grid will resist bowing. In the case of a temperature increase of 50 °C, grid bowing would lead to a change in the 10 mm acceleration gap of about 3 mm. Now the copper acceleration grid is 3 mm thick over the rectangular aperture array; the thickness increases to 10.5 mm outside the array, and the circular rim is 6.5 mm thick. A photograph of the grid is shown as Fig. 3.

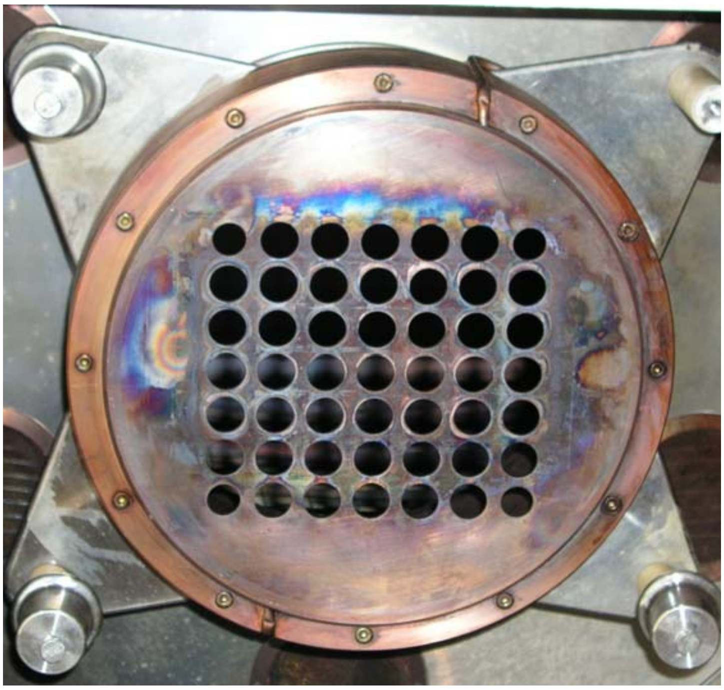

Fig. 3 Photograph of the acceleration grid

The 3mm thick section will heat first, and it is likely that it will distort as its expansion is resisted by the cooler thicker outer section, then the outer sections will heat by conduction and expand until the expansion is resisted by the contact of the fixing screws with the edges of the holes in the rim. To test this hypothesis the beam transmission was measured as a function of the pulse length, see Fig. 4. The measured data give the average transmission for each pulse, and the instantaneous transmission was derived from a “by eye” fit to those data.

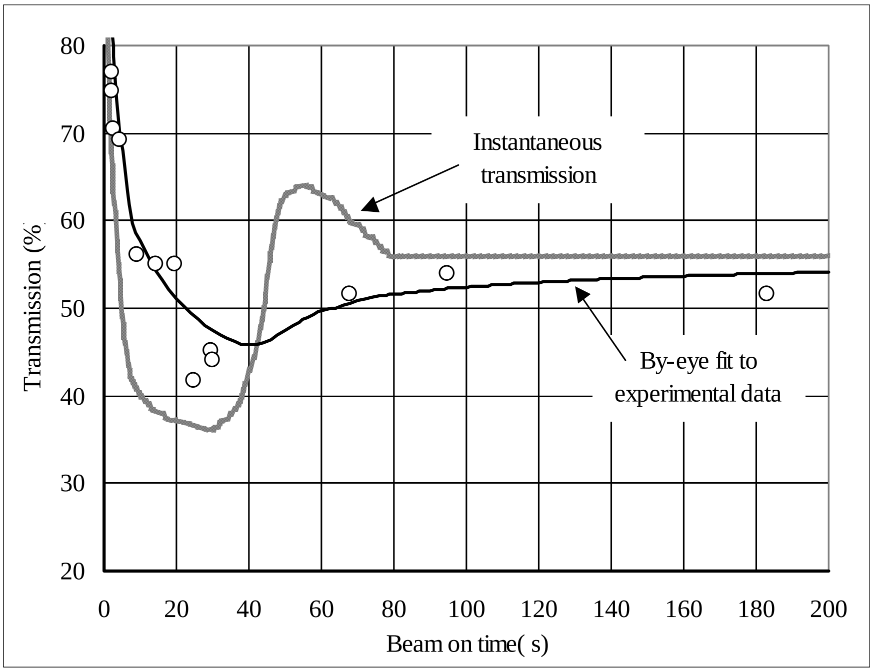

Fig. 4 Beam transmission as a function of the pulse length. The open circles are the measured values. The instantaneous transmission is derived from the "by-eye" fit through the experimental data.

Fig. 4 shows that for very short pulses, <4 s, the transmission is >70%. The transmission degrades to a minimum at about 25 s, then improves to its long pulse value of ≈55%. This is qualitatively in line with expectations as the inertial time constant for the thin part of the grid is 4.5 s, and that of the rim is 22 s.

3 Effect of the plasma grid temperature with caesium seeding

A caesiated source is thought to operate on the principle of the production of negative ions (H^- or D^-) by surface scattering of neutral atoms and positive ions from the PG surface. An essential feature of this hypothesis is the reduction in the work function of the grid surface, due to caesium (Cs) coverage of the surface. In short pulse operation an optimum in the negative ion yield has been found when the PG temperature is increased to between 200 and 300°C [4]. It is reasonable to assume that the Cs coverage on the PG surface is a dynamic balance between evaporation from the grid and the arrival of Cs from the source volume [5]. Heating the PG changes the rate of evaporation loss from the grid but has little effect on the flux to the grid, thus the surface coverage should change. It is assumed that the observed increase of the negative ion yield with the PG temperature occurs because the increased evaporation loss changes the surface coverage towards the optimum value. The increase in negative ion yield with the PG temperature is referred to as the "PG temperature effect".

Two types of long pulse PG's have been designed and fabricated (by JAERI) that have an equilibrium temperature in the desired range, whilst using conventional cooling (water at <10 bar). These are the so-called "frame cooled grid" (FCG, made of Cu/Cr/Zr alloy) and the "actively cooled grid" (ACG, made of molybdenum). Both grids are designed to be heated by the power from the arc discharge arriving at the PG surface, mainly by radiation, and both are designed to have an equilibrium temperature of ≈300 °C with an arc power of ≈45 kW. Both grids perform correctly in that they reach, approximately, the design temperature at the design power flux to them.

No difference in source efficiency (with or without Cs seeding of the ion source) was observed with the two different grids, i.e. with different materials.

The PG temperature effect measured with the two grids is similar, ≤40%. The effect of the temperature of the FCG on the negative ion yield from the KAMABOKO III ion source can be seen in Fig. 5. This variation in the negative ion yield is typical for the KAMABOKO III ion source on MANTIS when operating in long pulses. The arc power was 40 kW, and the filling pressure was 0.3 Pa of H_2. The negative ion yield is assumed to be proportional to the accelerated current (I_{drain}) which increases from 0.59 A to 0.73 A, an increase of 24%, with the increase of the temperature of the PG. JAERI have reported PG temperature effects resulting in increases in the negative ion yield of >100 % during short pulse operation, 0.1 s [6], and it had been anticipated that a similar increase would occur during long pulses.

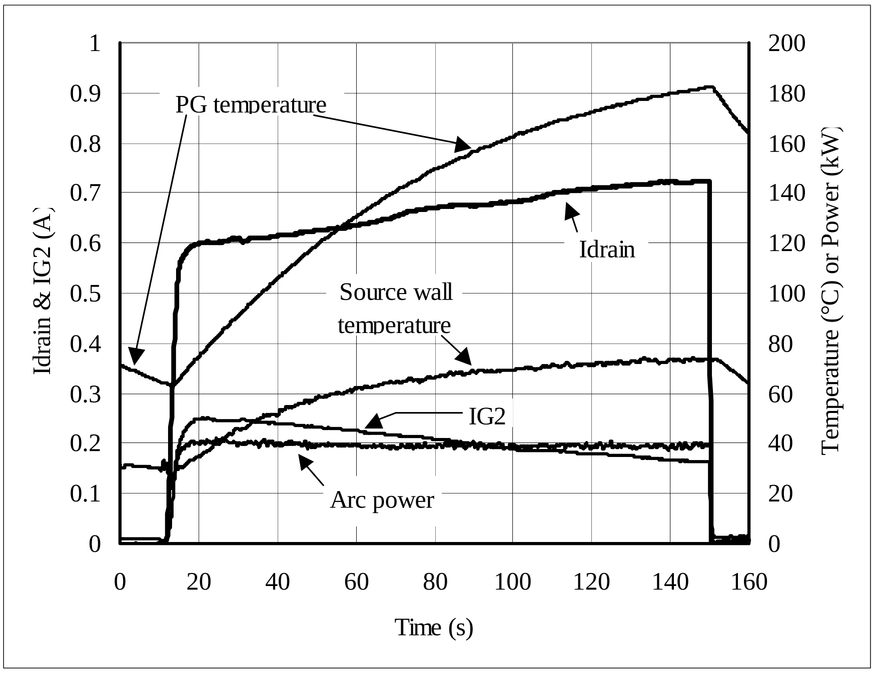

Fig 5 The effect of the temperature of the plasma grid (the frame cooled grid) on the negative ion yield from the KAMABOKO III ion source. Note that at the start of this shot the PG and the source walls were still cooling from the previous shot and their temperatures at the start of the shot were 64 °C and 30 °C respectively.

During the long pulse experiments it is found that the equilibrium temperature of the ion source walls is significantly above that of the cooling water (see Fig. 5). This led to the speculation that the reason for the low PG temperature effect in long pulse operation is due to the increased temperature of the walls. As mentioned above, the Cs coverage of the PG surface is a dynamic balance between the arrival of Cs from the source volume and evaporation from the grid surface. Thus if the flux of Cs to the PG were increased by increased evaporation of Cs from the source walls, and then to the PG, the Cs thickness on the PG would be above the optimum with the PG at the design temperature. If this is correct, increasing the PG temperature or decreasing the source wall temperature would give a higher PG temperature effect. As both the source walls and the PG are heated by the discharge, their temperatures are coupled. To de-couple the temperatures the cooling water was removed from the PG and a sequence of ≈30 s arc discharge pulses used to increase the PG temperature. The source wall temperature does not increase significantly in this situation as it cools in between each pulse. The result was that the accelerated negative ion current increased almost linearly with the PG temperature, with a maximum of ≈60% increase in negative ion yield being obtained at the highest PG temperatures reached, see Fig. 6.

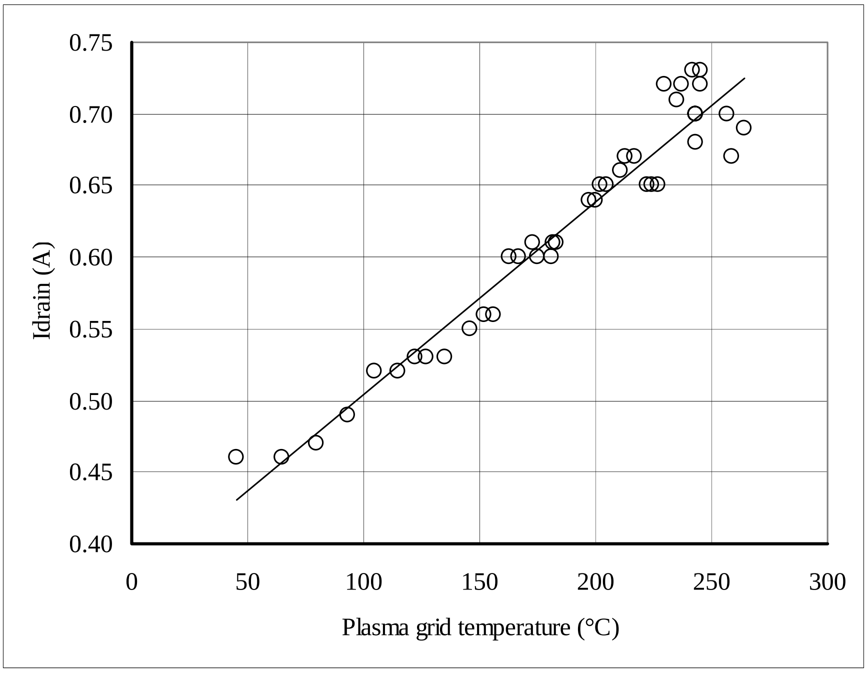

Fig. 6 Accelerated negative ion current as a function of the plasma grid temperature with "cold" source walls.

4 Source characteristics

In an attempt to further understand the physics of negative ion formation in the KAMABOKO III ion source the following experiments described below have been carried out. Here the negative ion yield is assumed tp be proportional to the accelerated current (I_{drain}).

I. The negative ion (H^-) yield has been measured as a function of the source gas filling pressure, the arc current and of the anode to cathode voltage, in each case keeping all other parameters constant. All were measured with caesium seeding of the ion source. Unless otherwise stated all are with H_2 at a source filling pressure of 0.3 Pa..

- No variation of the H^- yield was found with source pressure for source filling pressures of 0.2 to 0.8 Pa, see Fig. 7.
- The variation of the H^- yield with arc current is found to be linear see Fig. 8.
- The variation of the H^- yield with the anode to cathode voltage is offset linear, see Fig. 9. Here it is to be noted that operation at different anode to cathode voltages has only recently become possible on MANTIS, due to the introduction of a feedback between the filament heating current and the arc current. This feedback system allows the arc current and anode to cathode voltage to be selected independently. In most previous experiments the anode to cathode voltage was 45 to 50 V. The data shown here demonstrate that operating with an anode to cathode voltage of >80 V results in an efficiency increase compared with 45 V of >50%, see also Fig. 10.

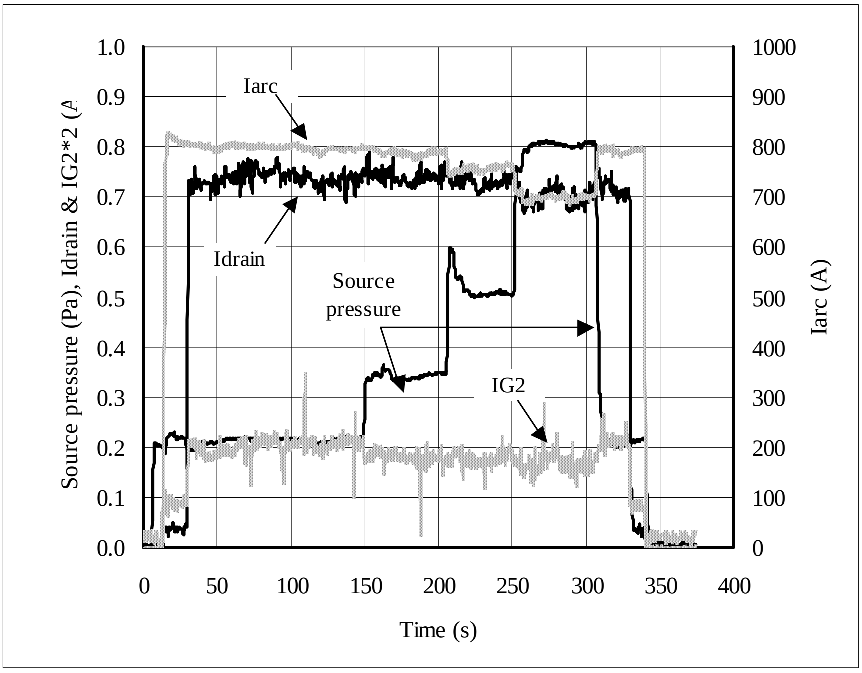

Fig. 7 Shot demonstrating that the accelerated H^- current (I_{drain}) does not vary with the source pressure.

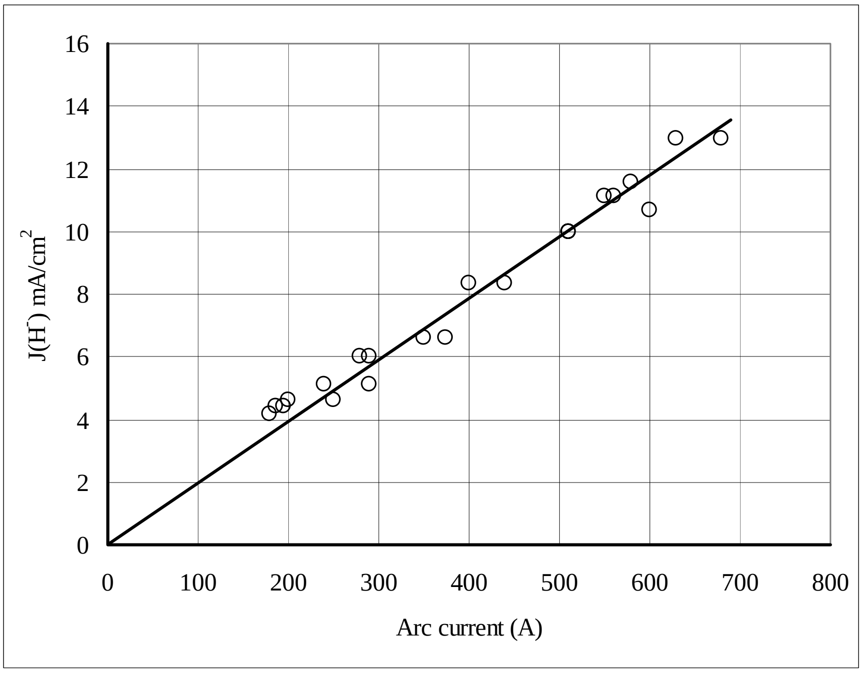

Fig. 8 JH^-, the accelerated negative ion density derived from Idrain, as a function of the arc current at constant anode to cathode voltage (75 V).

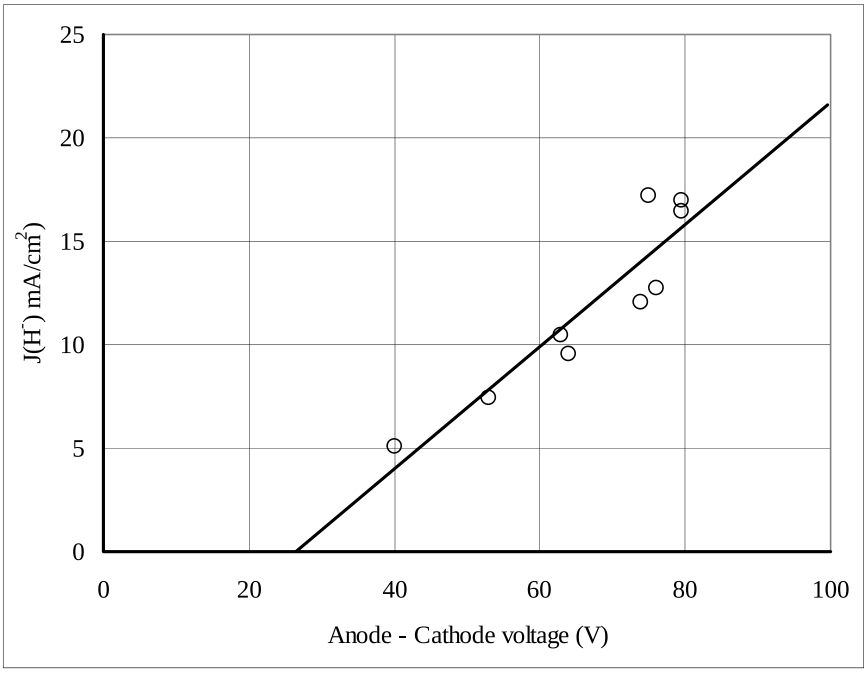

Fig. 9 JH$^-$, the accelerated negative ion density derived from Idrain, as a function of the anode to cathode voltage at constant arc current (600 A).

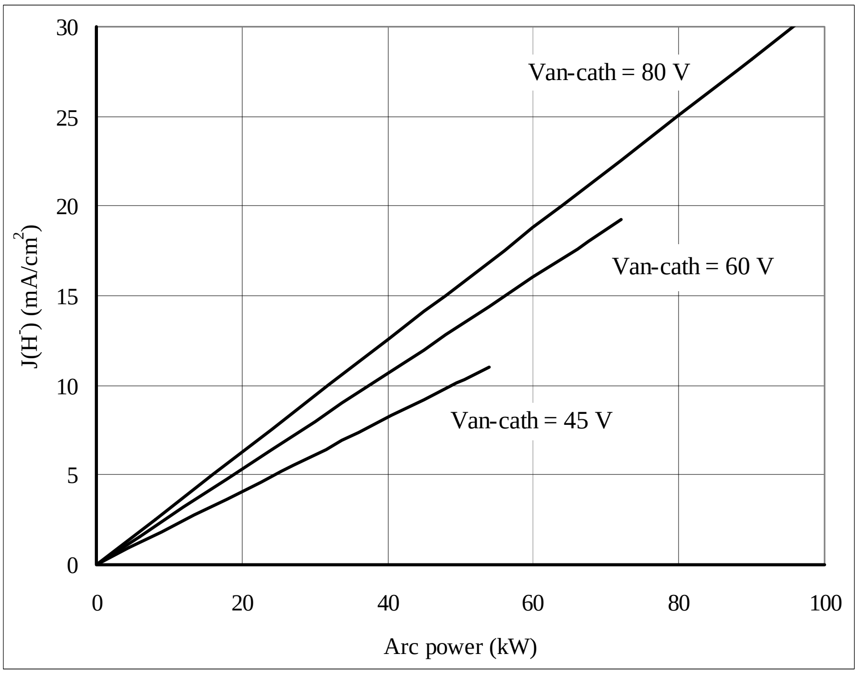

Fig. 10 Calculated accelerated negative ion density as a function of arc power for different anode to cathode voltages, with the maximum arc current limited to 1200 A. It is to be noted that the actual negative ion current depends on the operating conditions such as the amount of Cs in the source and the time of operation since the Cs was introduced into the source. The curves shown here are only valid for the operating conditions pertaining when the data of Figs. 8 and 9 were taken.

II. The plasma density 17 mm in front of the PG has been measured using a small cylindrical Langmuir probe as a function of the arc current and of the anode to cathode voltage, in each case keeping all other parameters constant. For these measurements there was no caesium seeding of the ion source, but it has been previously found that caesium seeding has no effect on the plasma density. Judged from the probe characteristics the electron energy distribution seems to be reasonably well described as a bi-Maxwellian with >99% of the electrons having the lower, “bulk”, temperature.

- The variation of the plasma density with arc current is found to be linear, see Fig. 11.

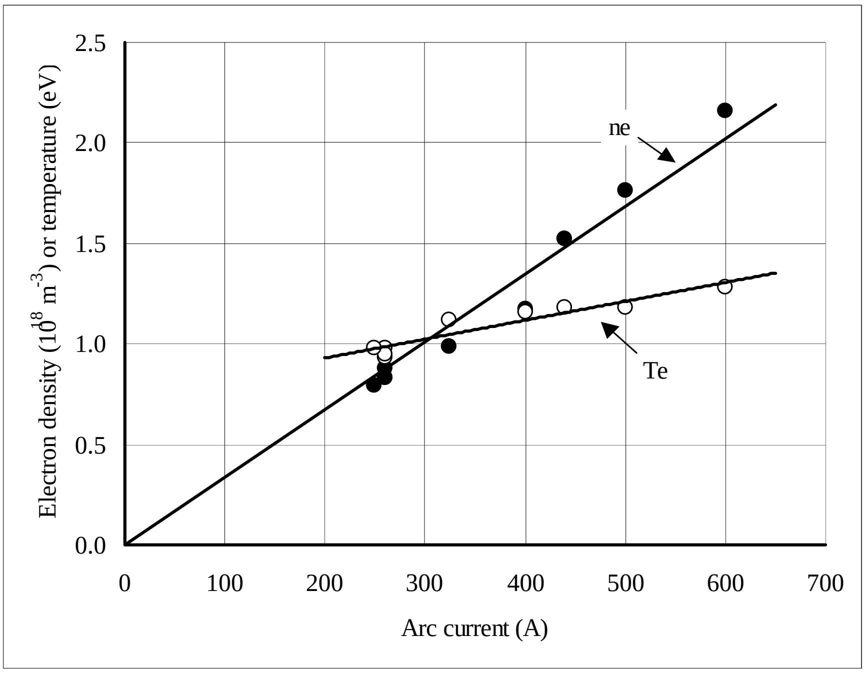

Fig. 11 The plasma density and bulk electron temperature 17 mm in front of the PG as a function of the arc current at constant anode to cathode voltage (70 V). The probe was at x = 20 mm, y = 0 mm where x is horizontal, y vertical and the origin is the centre of the source in the x-y plane.

- The variation of the plasma density with the anode to cathode voltage is approximately offset linear, but tends to saturate above 80 V, see Fig. 12.

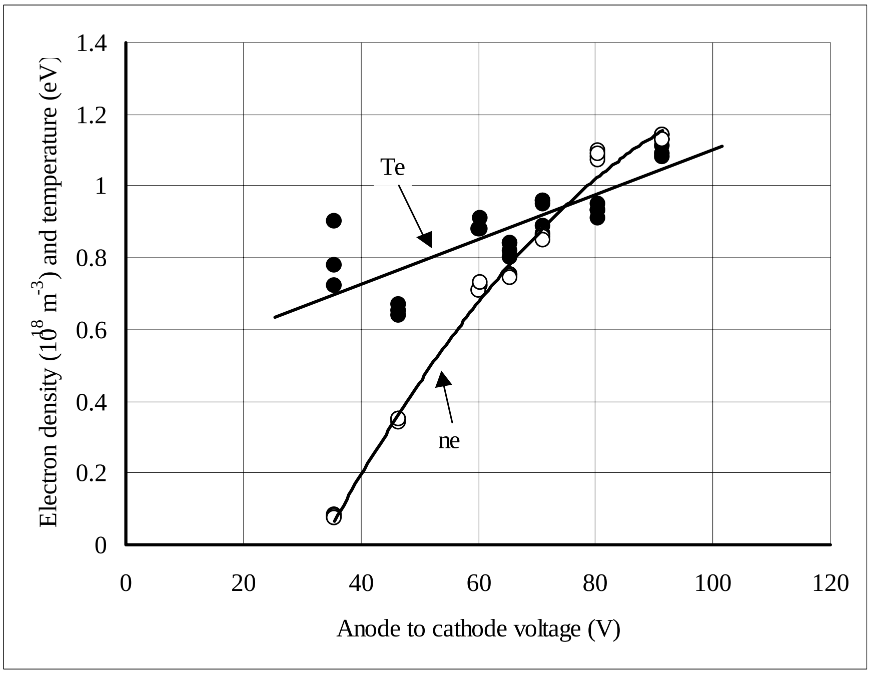

Fig. 12 The plasma density and bulk electron temperature 17 mm in front of the PG as a function of the anode to cathode voltage at constant arc current (260 A). The probe was at the centre of the source in the x-y plane, where x is horizontal and y vertical.

III. The fractional dissociation has been measured as a function of the arc current. It is speculated that in a caesiated ion source most of the accelerated H^- arises from surface scattering of neutral atoms and positive ions from the PG surface. On MANTIS the magnetic filter in front of the PG has been changed from ≈450 G.CM to ≈900 G.cm. The result was that the electron flux to the PG was reduced by a factor 10 without significantly changing the negative ion yield [2]. (Note that in reference 2 the filter strength, S, is defined as $S = \int_{-\infty}^{\infty} B.d\ell$ where B is the local field strength and ℓ is the distance from the PG. This gives a value of S about twice the definition used in section 1 of this papr.) As any reduction in electron flux implies a similar reduction in the positive ion flux, it can be concluded that the main source of the H^- is H atom scattering and not H^+ scattering. As the H^- yield is found to vary linearly with the arc current, if this hypothesis is valid the H atom fraction should increase monotonically with the arc current. The ratio of the Hγ light to that from the d $^3\Pi_u$ to a $^3\Sigma_g^+$ transition (Fulcher spectrum around 600 nm) of H_2 is correlated with the ratio of H atom density to the H_2 molecule density [7]. Using this technique the fractional dissociation (H/H_2) has been measured along a vertical line of sight 17 mm in front of the PG as a function of the arc current, see Fig. 13. The variation is found to be approximately linear with arc current, supporting the aforementioned hypothesis.

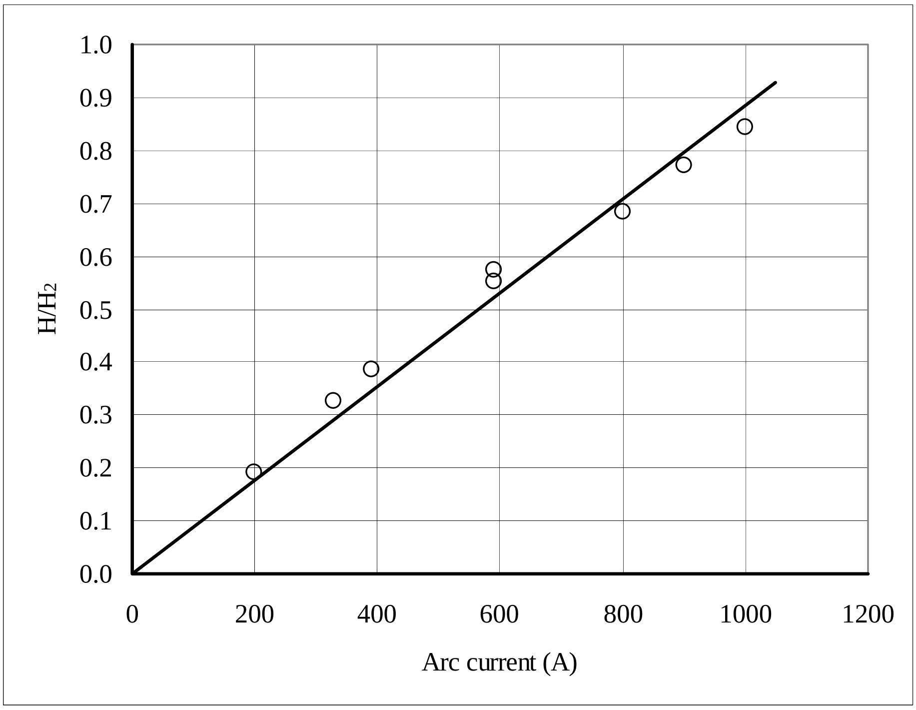

Fig. 13 The variation of the fractional dissociation as a function of the arc current at constant anode to cathode voltage (51 V).

IV. The temperature of the gas in the source has been measured. As the power in the arc discharge is rather high (≤80 kW) it has been speculated that the gas emerging from the ion source might be hot. This would be beneficial as it would result in a lower gas density, hence lower stripping losses, in the accelerator. Adding a small amount of nitrogen to the discharge (10%) the gas temperature can be obtained from the radiation of the N_2^+ molecule (B - X transition, around 391 nm) [7]. The gas temperature is found to be between 2000 and 2500 K at a discharge power of 40 kW and a pressure of 0.3 Pa.

5 Cs Consumption

Very high Cs consumption rates have been found during long pulse operation: the amount of Cs “consumed” per aperture in the PG is up to 1500 times that assumed for the ITER source, which is based on extrapolation from short pulse operation. A possible, partial, explanation is that during the operation of long pulses (>100 s), the source walls reach thermal equilibrium at a temperature (typically 60 °C at an arc power of 45 KW) substantially higher than during short pulses (≈20 °C). The increase in the vapour pressure of Cs on the source walls would result in an increase in the Cs flow from the walls into the discharge by up to a factor of 60, see Fig. 14.

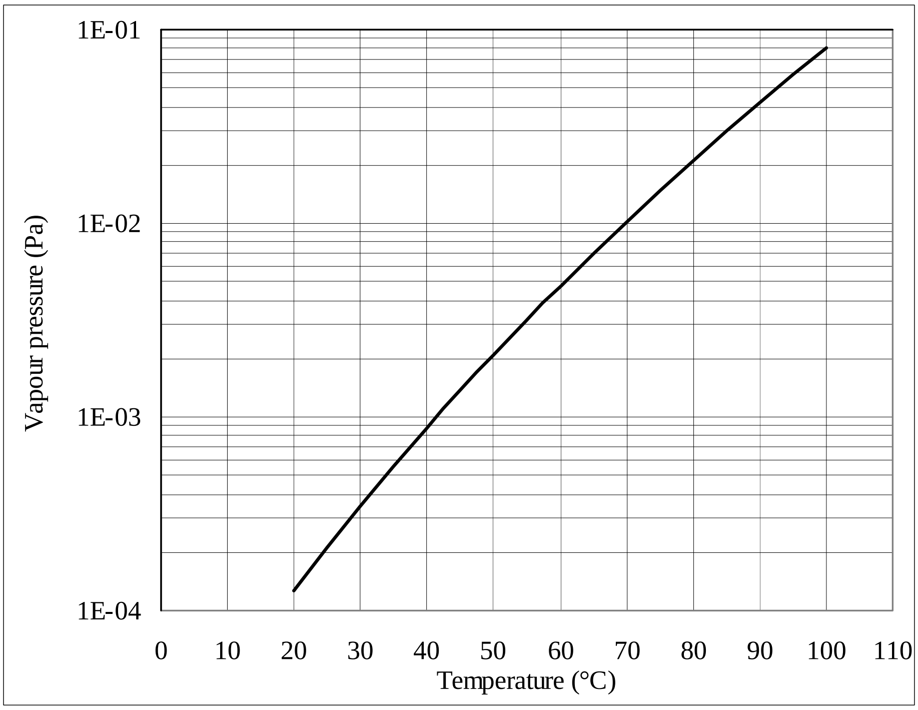

Fig. 13 The vapour pressure of Cs as a function of temperature.

In order to understand better what happens to Cs injected into the ion source, when the ion source was opened after an experimental campaign it was examined carefully. The source itself was covered with what looked like a moist tungsten layer. In order to determine the percentage of Cs left in the source, it was cleaned with water, and the water kept for analysis. Initially the cleaning water was opaque, dark grey, but overnight it became clear with a grey precipitate at the bottom. Chemical analysis of the clear water showed that approx. 4.5 ±0.9 g of Cs was inside the source when it was cleaned. The grey precipitate is presumed to be tungsten. As ≈5 g had been injected into the source since it was last cleaned, this shows that essentially all the Cs was still present within the source. This was unexpected as the Cs effect has started to disappear and evaporation and loss through the accelerator apertures alone should have significantly reduced the quantity of Cs in the source. It is speculated that the Cs on the walls of the source was either covered by a layer of evaporated W or trapped in a matrix of W on the wall.

If the Cs is “buried”, or "blocked", on the wall by W evaporated from the filaments, control of the evaporation of W could prove a key part in the operation of this source for high current density. The W filaments are operated between 2800 and 3000 K in order to obtain the required electron emission current density. At this temperature the evaporation of W from the filaments is significant: it is calculated that the W flux is sufficient to cover all the inner surface of the ion source with a monolayer of W in 125 s of operation. It is proposed to reduce the operating temperature of the W filaments, reducing the evaporated W into the source. This could be achieved by operating at higher anode-cathode voltages and lower emission current, therefore reducing the filament temperature, or by operating with thoriated tungsten filaments, which would allow for operation at 2100 K with the required electron emission density [8].

6 Conclusions and Discussion

The experiments reported here show that:

- The low H^- or D^- current density measured at the calorimeter on the MANTIS test bed during long pulse operation cannot be explained by lost accelerated electrons arising from either extraction from the ion source or creation by stripping in the accelerator.
- The low H^- or D^- current density measured at the calorimeter can be explained, at least partly, by poor beam transmission, which may be due to thermal expansion resulting in distortion of the acceleration grid.
- The negative ion yield has been measured as a function of the arc current and anode to cathode voltage. This has demonstrated that the negative ion yield at a given arc power can be increased by operating at anode to cathode voltages of >80 V.
- The reduced PG temperature effect measured during long pulse operation could be partly explained by enhanced evaporation of Cs from the source walls at the equilibrium temperature reached during long pulse operation perturbing the dynamic balance between the arrival of Cs from the source walls and the evaporation from the plasma grid.
- The H atom density in front of the PG is measured to vary approximately linearly with the arc current, which supports the hypothesis that the extracted and accelerated H^- is created mainly by surface scattering of H as H^- from the PG surface.
- The consumption of Cs is many times larger than expected, which may be partly explained by the increased evaporation from the “hot” source walls. However it is found that most of the Cs remains in the source even after it was expected to have been lost from the source. It is speculated that the Cs could be “blocked” on the walls either by burial under layers of tungsten evaporated from the filaments or by being trapped in a loose matrix of tungsten on the source walls.
- The temperature of the gas emerging from the Kamaboko III source is found to be between 2000 and 2500 °C for an arc discharge power of 40 kW and a source filling pressure of 0.3 Pa.

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