Power transmission from the ITER model negative ion source

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Abstract

In Cadarache development on negative ion sources is being carried out on the KAMABOKO III ion source on the MANTIS test bed. This is a model of the ion source designed for the neutral beam injectors of the International Thermonuclear Experimental Reactor (ITER). Its target performance is to accelerate a D^- beam, with a current density of 200 A/m^2 and <1 electron extracted per accelerated D^- ion, at a source pressure of 0.3 Pa. For ITER a continuous ion beam must be assured for pulse lengths of 1000 s, but beams of up to 3,600 s are also envisaged.[1]

During previous campaigns, continuous beam pulses of duration up to 1000 s have been demonstrated both in hydrogen and in deuterium, however the current density of both beams were found to be low in comparison to the specifications of 200 A/m^2. The D^- accelerated beam is collected on a calorimeter, made of water-cooled copper, which is located 1.6 m downstream of the accelerator. A large discrepancy exists between measured accelerated currents and that which is transmitted to the calorimeter. The discrepancy in these values and the possibility that the accelerated current included electrons, either from extraction or stripping was investigated.

A comprehensive study of the accelerator optics and beam transmission has been carried out. A new drift duct for MANTIS has been fabricated and installed. This drift duct is well instrumented to allow measurements of the power deposition between the accelerator and the calorimeter to be carried out. Beam profiles are measured with an IR camera looking at the beam deposited on a newly installed inertial calorimeter.

Studies into the effect of pulse length on the power transmission have also indicated problems with bad beam optics as a result of power loading in the accelerator.

The results of these power transmission studies are described herein.

The Experimental Set-Up

The source used at the MANTIS test stand is a small-scale version of the source designed for the ITER neutral beam injection system called the Kamaboko III ion source. It has been well described in the past [2]. It is a 30 litre quasi-cylindrical chamber of machined oxygen free copper, which forms the anode; with 12 filaments mounted on water cooled co-axial mounts (see Fig. 1). The plasma confinement is achieved by 16 magnetic line cusps generated by SmCo permanent magnets (width x height = 10 x 20 mm^2) arranged in longitudinally machined 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. This source is normally operated with Cs seeding which is achieved with a Cs oven, filled with Cs and heated and controlled with a feedback controlled circuit to allow constant temperatures and therefore constant fluxes of Cs to the plasma.

Fig 1 Cross sectional view of the high confinement KAMABOKO ion source

The source is directly attached to, but electrically insulated from, the accelerator. Columns of large (30 x 30 x 20 mm^3 or 50 x 30 x 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 strength of 1200 Gauss.cm. The plasma grid is “frame cooled” by water tubes attached to the framed support of the plasma grid. It is electrically biased with respect to the source.

The electrical connections for the source and the accelerator and their power supplies are shown in Fig. 2. The maximum acceleration energy is 30 keV.

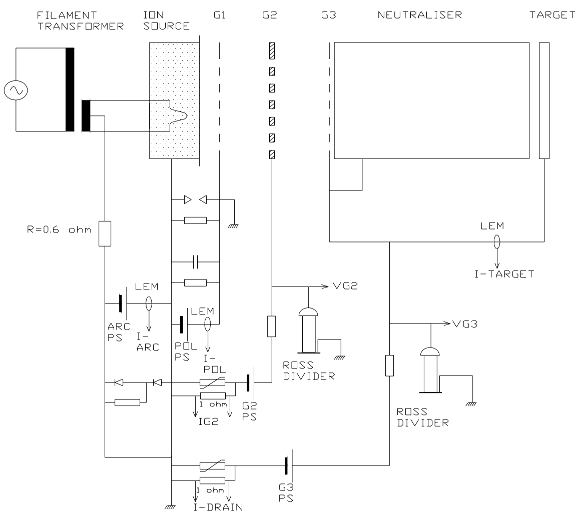


Fig 2 Electrical Schematic of MANTIS

Up until recently the beam has been measured on a water-cooled copper target, located 1.6 m downstream of the accelerator. However, this calorimeter has recently been replaced with an inertial copper target capable of measuring both long and short pulses; this target is placed 1.2 m from the accelerator. The drift duct between the accelerator and the target has also been modified, this is explained in detail below.

Results

During previous campaigns, continuous beam pulses of duration up to 1000 s have been demonstrated both in hydrogen and in deuterium, however the current density with each isotope was found, at the expected arc power and filling pressure, to be low in comparison to the anticipated ≥200 A/m^2.

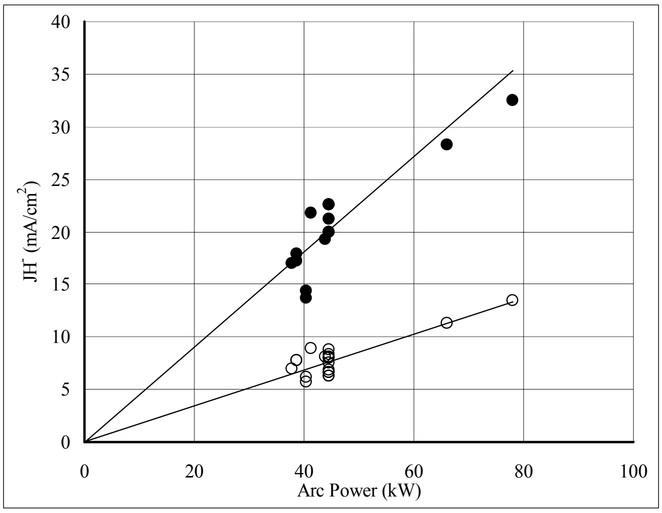


Fig 3 Accelerated current and the current to the calorimeter as a function of the arc power. The filled circles are the H^- current density calculated by assuming the drain current from the high voltage power supply is entirely accelerated H^-. The open circles are the H^- current density derived from the energy falling on the calorimeter. As can be seen only about 50% of the accelerated current reaches the calorimeter

Although ion densities of 280 A/m^2 for H^- and 200 A/m^2 for D^- have been achieved on the calorimeter for shorter pulse lengths,[3], during long pulse operation the objective, to accelerate >200 A/m^2 of D^- has <u>not</u> yet been achieved at the anticipated operating parameters (0.3 Pa source filling pressure and an arc discharge power of ≈45 kW). Also, during long pulse operation, very bad beam transmission (="thermal current to the calorimeter" / "electrical drain current from the power supply") has been observed.

Fig. 3 shows the accelerated current and the current to the calorimeter as a function of the arc power. As can be seen from Fig. 3, 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.

<u>Extracted electrons</u>: Extracted electrons are deflected onto the surface of the extraction grid by the magnetic field from the filter in the ion source and permanent magnets buried in the extraction grid, but some electrons escape from the extraction region and get accelerated. The fraction of the accelerated electrons 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 3 A was extracted.

No power was recorded on the calorimeter, and the accelerated current, was 30 mA, i.e. <1% 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. Within the experimental errors there is no variation with pressure. This is clearly seen in Fig 4 where the source filling pressure was increased from 0.1 to 0.7 Pa and no change in transmission is observed. (Note that the calculated stripping fraction in the acceleration gap at a source filling pressure of 0.3 Pa is ≈3 %.)

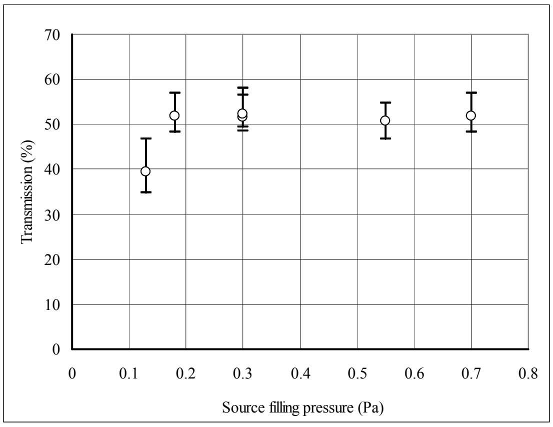


Fig 4 Beam transmission as a function of the source pressure

b) The beam optics are 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 electrons. To test this hypothesis the beam transmission was measured as a function of the pulse length, see Fig. 5. Fig. 5 shows that for very short pulses, <4 s the transmission is >70%. The transmission degrades to its long pulse value of ≈55%. This experiment was recently repeated; the new data are shown to correlate well as seen by the black data points in Fig 5.

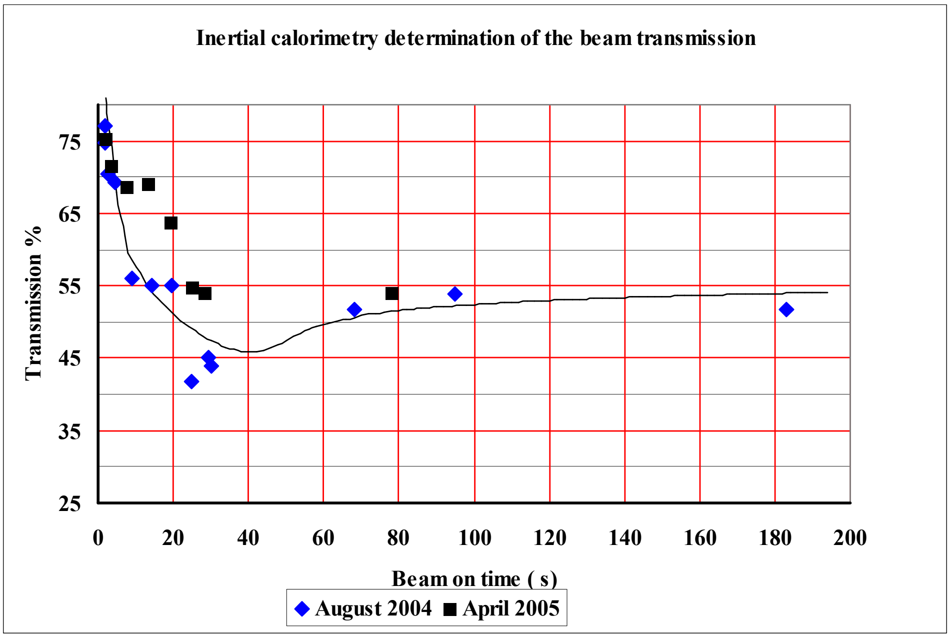


Fig 5 The effect of pulse length on the beam transmission.

The drift duct

Fig 6(a) original drift duct (left) and Fig 6(b) “new” drift duct (right)

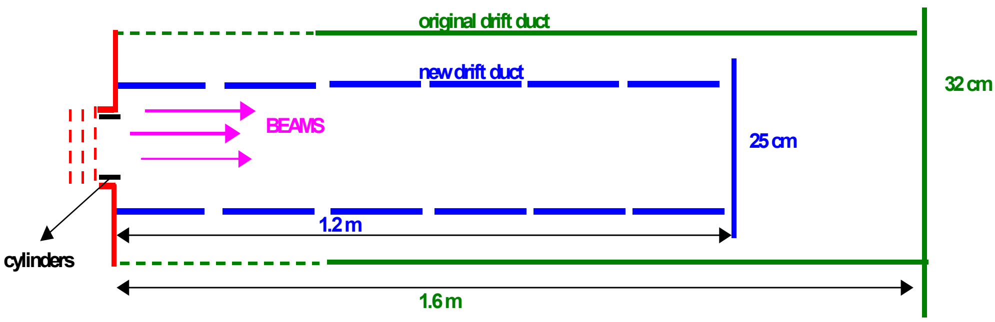


Fig 6(c) Schematic of both ducts imposed on one another

The accelerated beam propagates inside the walls of the drift duct, which fills the space between the accelerator and the calorimeter.
Estimation of the beam profiles on MANTIS up until now is that the beam is always wide, about 3 degrees. Around 50 % of the electrically measured accelerated current disappears between the accelerator and the calorimeter which would imply 15 degree wide halos. A general characteristic of beam halo is the increased population of the outer portion of the beam which is lost from the beam core and therefore is not intercepted on the target.

In order to investigate this “lost” power a new drift duct has been fabricated and installed. This duct is well instrumented to allow the distribution of power deposited between the accelerator and the calorimeter to be determined. If a halo exists it can be measured.

A photo of this drift duct can be seen in Fig 6 (b); beside it a photo of the original drift duct Fig 6 (a) is also shown. A schematic of the layout of both ducts superimposed on each other is seen in Fig 6 (c). Both drift ducts are described here, and the inherent difference between the two discussed.

The original drift duct and target

Up until recently a water-cooled drift duct was used on MANTIS, however water cooling was implemented on the sides only of the duct and not on the top or bottom. Calorimetric measurements were not possible with this system due to a small heat load over a large area. This duct was 1.6 m long and a water cooled calorimeter was placed at the end to intercept the beam arriving there. To facilitate pumping, this duct had a wire mesh at the accelerator end that allowed for pumping. This mesh was 400 mm in length and could cause breaking of the space charge compensation. Positive ions are produced by ionising collisions between the beam and the background gas, these positive charges stick with the beam and prevent space charge blow up of the beam due to its own space charge. If they are partially absent, beams can significantly blow up. Calculations show that even for a 2 mA/cm^2 beam with uncompensated space charge the beam could be blown up to 100 mrad at the target, giving rise to significant interception on the drift duct. Downstream of the duct a water-cooled target was positioned and water calorimetry utilized to determine the total current density intercepted. Operation with this target was very limiting as only the temperature rise in long pulse operation could be readily observed, whereas short pulse operation did not lead to a measurable temperature rise.

The new drift duct and target

The new drift duct is made of 6 copper boxes; each box is made up of 4 copper plates, each panel is 25 cm high, and 20 cm long, with a thickness of 5 mm. These dimensions were chosen as they gave a good compromise between exposure time and anticipated temperature rise, which has to be measurable. These panels are electrically connected but thermally insulated from each other by means of a stainless steel support structure between them. Each plate is instrumented with 2 thermocouples, one in the centre of each panel and one in the corner, which allow a good measurement of the power received on each panel of the duct; giving a good spatial distribution of the “lost” accelerated power.

It is worth noting that this drift duct has been designed to allow removal of the final panels so as to allow a total distance between the accelerator and the target to be adjusted to 1 m in distance.
The new drift duct has the panels mounted with 5mm spacing between each to allow evacuation of the gas. If bad space charge compensation were the cause of the bad beam optics, this new drift duct would remedy the problem by removing the electric fields and increasing the pressure. If that is the case then no halo will be measured and the previously lost power will be transmitted to the target. The pressure inside the drift duct is expected to be 3-4 10^{-4} mbar. This gives rise to about 10 % stripping losses inside the accelerator, including the extraction region [4].

A new target has been installed at the end of the drift duct. It is an inertial copper plate of dimensions 380mm x 540mm and for all data presented here was placed a total of 1.2 m from the accelerator. This is an inertial target which has 3 thermocouples imbedded in the copper to allow accurate temperature differences to be measured for various pulse lengths.

On the rear of the target an IR camera is focused on the rear of the target , which allows images of beam profiles to be measured.

Acceleration Grid support.
In addition to this new drift duct and beam target, a power loading measurement on the acceleration grid (G3) support has also been installed. This consists of a copper cylinder made of 2 halves, that is inserted into the G3 support structure and protrudes to the mouth of the drift duct. This cylinder is instrumented with 6 thermocouples, 3 on each half, in order to measure any intercepted power to this structure. It has been calculated that any accelerated electrons will be deflected onto this cylinder by the magnetic field.

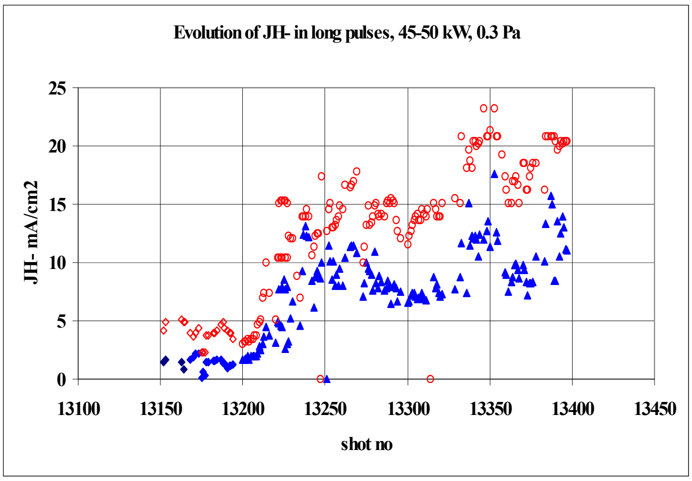
Fig 7 The cylinder to collect any power loading to the grid 3 support is shown. Mask installed down stream of the beam source on the acceleration grid is also shown here.

On all of these areas, the duct, the target and the cylinders, many thermocouples have been installed, and a data acquisition system commissioned to monitor all 33 thermocouples during each shot. (24 thermocouples on the 24 panels of drift duct and 3 thermocouples on the target and 6 thermocouples on the accelerator grid support.)

Effectively the area from the accelerator to the target is now a "closed" box, which is well instrumented to carry out extensive beam calorimetrical measurements and determine the loss of the accelerated power between the accelerator and target.

Results and Power accountability

A Cs campaign was run over a period of 2 weeks with this new setup. Fig 8(a) below shows the evolution of the JH- accelerated and the JH- collected on the target as a function of shot number and in Fig 8(b) as a function of the evaporated Cs in mg.



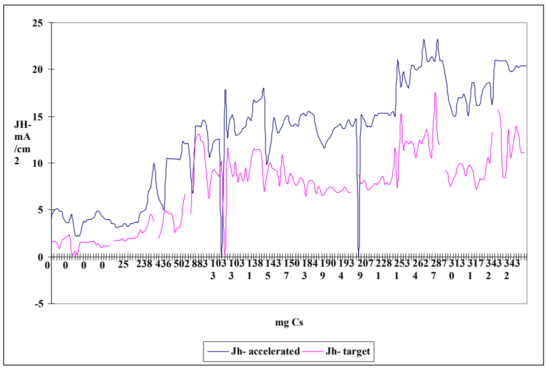


Fig 8(a) and Fig 8(b) evolution of the JH^- with time and with amount of evaporated Cs.

In the data shown above, Figs 8, shots no. 13150 – 13200 were volume shots. Following this Cs was evaporated into the source and the expected increase in the production of negative ions is observed. From Fig 8 (a), its is clearly observable that there still exists a discrepancy between the accelerated and intercepted power on the target. Typical transmissions are of the order of 60-70 % for the majority of shots analysed during this campaign.

Target Interception

All the data were collected with an arc power of between 45-50 kW and 0.3 Pa source filling pressure. A typical current density was found to be 13 mA/cm^2 intercepted on the target, with typically 21 mA/cm^2 accelerated (measured electrically). On close inspection of a shot at this typical condition, for example shot no. 13349, 21 mA/cm^2

was accelerated, indicated from Idrain, and 13.5 mA/cm^2 was intercepted on the target. This would imply 64 % transmission.

The current intercepted on the target is measured from the thermal data collected by the 3 thermocouples imbedded in the copper plate. This thermal data is shown in Fig 9.

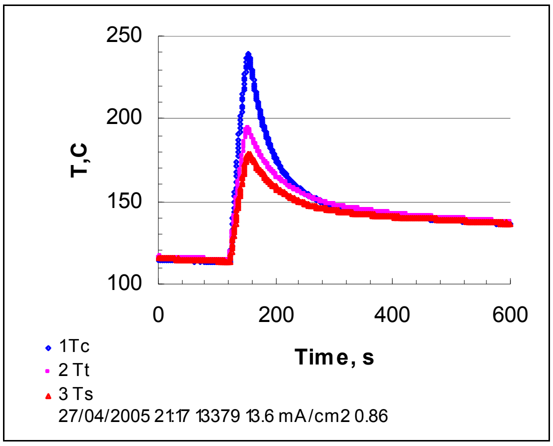


Fig 9 Thermal measurements on the copper target

The IR image collected by the IR camera located 3 m from the rear of the graphite painted copper target is shown below, the resulting Gaussian profiles in the horizontal and vertical are also shown. Fig 10. The core beam divergence is calculated as being 70 mrads.
Images collected with the IR camera are also shown below. The image seen by the IR camera is always low on the target, interception of the beam on the horizontal panels is seen to be similar and the bottom panel shows a higher interception. This deflection of the beam downwards is due to the magnetic filter field deflection

Fig 10 the IR image of the beam intercepted on the target, and the Gaussian profiles that are fitted to the data.

Halos

The thermal measurements collected for all 6 boxes of the drift duct are shown in Fig 11. The total intercepted power on this duct can be calculated from this data and a 30 % interception is found, indicating quite large beam halos. Note this is the power intercepted on the duct as a function of the total intercepted power, ie the target, the duct and the cylinders. This would suggest a halo of around 200 mrad divergence.

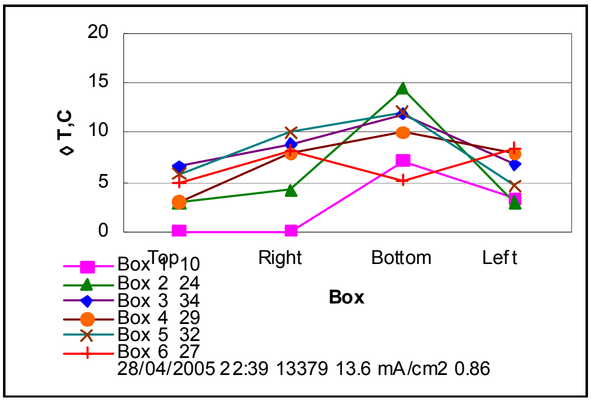


Fig 11 power distribution of the accelerated power to the 6 boxes of the inertial drift duct.

This is a typical halo found for all the data taken during this campaign in Cs seeded discharges. It is an important result as it shows that typically 94 % of the total accelerated power can be accounted for as negative ions, which either hit the target as a core beam or hit the drift duct in the form of a halo.

Previously quoted negative ion densities were grossly under-estimated (approx 40 %) due to the missing power which could not be detected as a halo with the previous system.

It can be said that in shot 13349 (a typical shot) the accelerated JH- was 21 mA/cm2 of which 19 mA/cm2 were negative ions. Therefore operating at ITER specifications of 45-50 kW arc power in the KAMABOKO ion source, with 0.3 Pa filling pressure gives Jh- of typically 19 mA/cm2. While this current density is lower than required, 28 mA/cm2, it still remains an important and promising result for long pulse operation of the ion source. Although the halo is no good at all for ITER beams, the point of the MANTIS experiment is to prove that the *source* can deliver the current density. The acceleration of the negative-ion current produced is a different matter.

So the question remains, where does the resultant power go (that is, the 6% (9%?) still unaccounted for)? To investigate the accelerated electrons that would increase Idrain measurements, the thermal measurements on the grid 3 cylinders were measured. It is found that approx 1 % of the total power accelerated falls on this support structure. It is calculated that the electrons accelerated would be intercepted on this area due to the magnetic field.

What about positive ions?

Current flowing through Idrain could be either negative ion current or positive ion current returning from the drift duct and accelerated to high voltage. In order to reduce some of this current apertures that are masked on the plasma grid are also masked downstream on the acceleration grid. Photos of this mask on the drift duct side of the acceleration grid can be seen in Fig 7. However some of this current cannot be avoided. In order to determine the percentage of back streaming positive ions a small copper piece has been installed on the back side of the source wall, the temperature of this copper piece with and without beam on is monitored to determine the percentage back streaming ions hitting it. During arc operation this copper piece increases in temperature due to plasma radiation. However during beam operation any further increase in temperature would be due to back streaming positive ions hitting the copper.

A number of shots with and without beam extraction were carried out to get a good average for the % of positive ions arriving. Fig 12 shows the temperatures with arc only and with beam on. The blue curve shows the increase in temperature of the copper piece due to radiation from the arc discharge. The red curve shows a further increase in temperature caused by back streaming positive ions. A temperature difference of 9 °C is seen between arc only and beam extraction. It is estimated that 2 % of the accelerated current is due to back streaming positive ions. It is noted that this increase in temperature was only observable for high current density shots with Cs. Measurements carried out in volume shots showed no thermal difference of the copper piece with beam extraction.

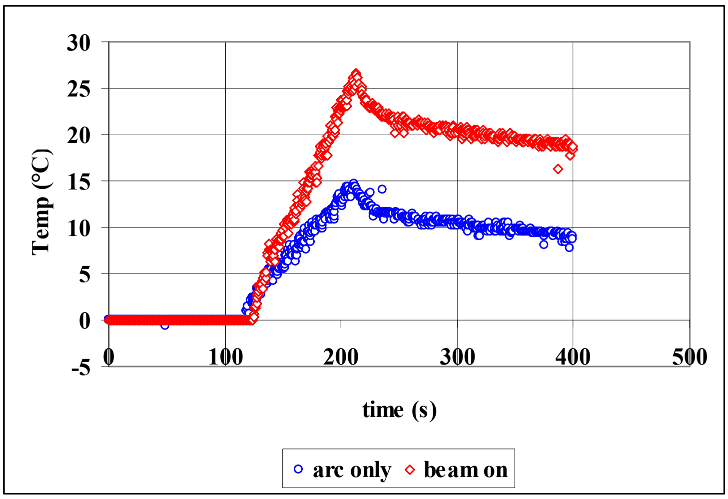


Fig 12 Back streaming positive ion measurement

These measurements can be summarized in the following table:

Shot	JH- I drain (mA/cm2)	JH- target (mA/cm2)	Transmission %	% halo	% cylind	% back streaming ions	total accountability %	JH- from KAMABOKO mA/cm2
13349	20.9	13.5	65	30	1	2	98	**20**
13338	18.8	11.4	61	32	1		94	**17**
13339	18.1	12.3	68	28	1		97	**17**
13340	20.4	12.0	59	30	1		90	**18**
13341	20.4	12.3	60	28	1		89	**18**
13342	20.0	12.0	60	30	1		91	**18**
13343	20.2	10.6	52	32	1		86	**17**
13344	20.4	12.4	61	33	1		95	**19**
13346	23.2	12.0	52	30	2		83	**19**
13348	20.9	12.7	61	34	1		96	**20**
13350	21.3	11.3	53	33	1		87	**18**
13552	20.9	10.7	51	35	1		87	**18**

Table 1 summarizing the power accountability of a number of typical shots from MANTIS

Now that the presence of a halo has been determined the question remains as to why these large halos exist. One hypothesis is presented here as a possible effect of such a large halo on MANTIS.

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, which varies with the caesium (Cs) coverage of the surface.

It has been proposed that the generation of negative ions could also take place in the apertures of the extraction grid. It is hypothesised that the neutral hydrogen atom is responsible for the generation of the negative ions; therefore for the purpose of negative ion generation the extraction grid could be an ideal surface. Neutral Cs escapes the ion source and covers the extraction grid; tungsten pollution would not occur in this region; therefore during the pulse negative ions then could be generated on this surface. If this indeed was the case then it is proposed that ions generated here would add to the halo found on the drift duct. In order to investigate this fully a comparison of the electrical and calorimetrical power falling on Grid 2 is carried out. If the negative ions are generated on G2 and accelerated then they increase the Idrain value of accelerated ions. However because the optics of ions generated on grid 2 is calculated to be extremely bad, these ions will be intercepted for a large part on the drift duct walls and therefore never reach the target.

The fraction of negative ions produced on grid 2 could be assumed to be :

$$I_{G2}^{H^-} = \left(P_{cal}^{G2} - P_{elec}^{G2}\right) \Big/ VG2$$

The accelerated current measured by Idrain is composed of the sum of ions produced on the plasma grid and any ions generated from Grid 2 and secondary electrons as indicated here:

$$I_{drain} = I_{PG}^{H^-} + I_{G2}^{H^-} + e_{\sec ondary}^{-}$$

If it is assumed that the halo fraction arises entirely from the H^- created at G2 as such ions would be expected to have bad optics. Then

$$halo = \left[\frac{PowerDuct}{TotalPower}\right]$$

Then the power to the duct comes only from IH- created on G2:

$$PowerDuct = \left[I_{GRID2}^{H^-} * (VG3 - VG2)\right]$$

and the total power, measured calorimetrically from the duct plus the target will be:

$$TotalPower = \left[\left(I_{pg}^{H^-} * vg3\right) + \left(I_{G2}^{H^-} * (VG3 - VG2)\right)\right]$$

ignoring secondary electrons for this estimate we determine the halo to be

$$halo = \frac{\left[I_{G2}^{H^-} * (VG3 - VG2)\right]}{\left[\left(I_{drain} - I_{G2}^{H^-}(VG3)\right) + \left((VG3 - VG2) * I_{G2}^{H^-}\right)\right]}$$

A number of long shots, 90 s beam on time, were carried out to look at the electrical power to Grid 2 and the calorimetrical power. In Fig 13 the halo percentage is plotted as a function of the $\left[\frac{PowerDuct}{TotalPower}\right]$. A definite trend is seen that supports the hypothesis that negative ions produced from Grid 2 could be responsible for some of the halo observed on MANTIS. It must be observed that secondary electrons are ignored in this analysis and that the results are preliminary.

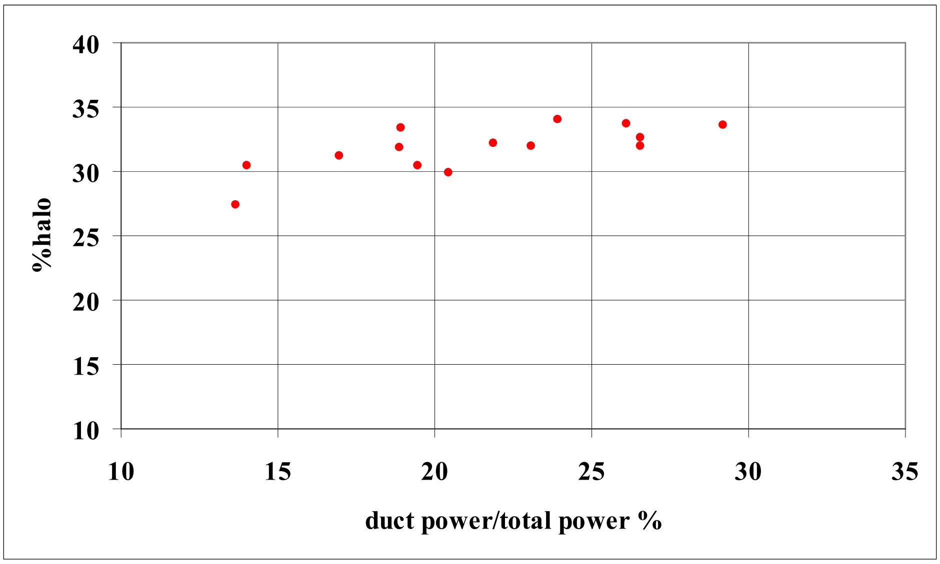


Fig 13

Conclusions

- A new neutraliser has been designed, instrumented and commissioned with the objective of measuring the ~50% of missing power (P_{drain}-P_{cal}) seen on MANTIS during long pulse experiments.
- A core divergence and a very wide halo are necessary to "explain" the measured power density profiles.
- Transmission of the accelerated current to the target is typically 60- 70 %, this is higher than with the previous duct, but probably due to the decreased distance from the accelerator to the target.
- Measurements with this drift duct have shown 30 % halos in Cs operation.
- The speculation that the halo originally was due to impartial space charge compensation is proven not to be the case as the newly designed duct has an increased pressure and large halos still exist
- The accelerated current densities measured on the new inertial target indicate approx 60-70 % beam interception with 27-34 % halos, this means that the accelerated negative ion density is significantly higher than previously estimated.
- It is estimated that a very small percentage of the accelerated power is electrons, as only a small power deposition is measured on the grid 3 support. The magnetic filter will prevent electrons from travelling beyond this point.
- A measurement of the back streaming ions in Cs discharges indicate they account for approx 2 % of the accelerated power.
- Power accountability on MANTIS is now quite high, > 85 % in Cs seeded discharges. Power accountability in volume operation was not successful due to the very small temperature rises from low current densities accelerated.
- Results of Cs seeded operation from this campaign indicate that negative ion densities of 20 mA/cm2 are easily achievable at about 45-50 kW and 0.3 Pa filling pressure, but that the beam optics are very bad, producing a very large halo.
- Core beam divergences are calculated to be of the order of 4 degrees and the halo of 11 degrees. Further investigation into the reason for these extremely wide beams is required.

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