Progress in the development of a RF Driven D^- Ion Source for ITER NBI

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1. Introduction

Research and development has been going on for the past two years under a contract with EFDA to develop a RF driven ion source as an alternative to the current ITER reference design arc source based on the KAMABOKO sources developed at JAERI. This paper will detail the developments that have taken place on the BATMAN test facility since the start of 2005. During this time period the Type VI-1 RF ion source[1] has routinely reached or exceeded the ITER design requirements that are not precluded by technical limitations of the test facility.

The test facility has a 150 kW RF generator capable of 10 second operation. The high voltage is provided by the central power-supply group of IPP. The voltage and current is limited due to the 750 ohm voltage divider to 30 kV, 40 A for 4 seconds. The voltage divider is used to provide both extraction and acceleration voltage, but has the limitation of not allowing independent variation of their values. The main vacuum tank is pumped by Ti pumps and in which is mounted the calorimeter. The calorimeter is a water-cooled copper panel which has specially designed thermally isolated areas which are read by thermocouple. Software allows for an evaluation of the power on the calorimeter both from the change in water temperature and from a fit to the thermocouple profiles. Recently added is an array of optic fibres, which allow for Hα spectroscopy of the negative ion beam. The ion source has a number of diagnostics mounted on it either specifically for an experimental campaign or routinely in operation [2]. In addition the walls of the expansion body are designed to accept external magnet holders so that the effect of magnetic confinement can be studied easily. Control of the test facility is via a computer controlled Simatic S7 system and the data is collected via a CAMAC based DAQ and analysed and displayed via in house developed software.

This paper will cover four topics: the current status of results from BATMAN as compared to the ITER requirements, the results of our investigations in to the effects of magnetic confinement on extracted ion current, a discussion on our empirically derived process to maximise negative ion current, and finally the new Hα beam spectroscopy.

2. Recent Results with BATMAN

Good progress has been made since the beginning of 2005 in achieving the ITER requirements that can be met within the technical limitations of the BATMAN test stand. In both hydrogen and deuterium operation current density, source pressure, and electron to ion ratio targets have been achieved on multiple days. The results achieved as compared to the ITER requirements are presented in Table 1.

Table 1: Shown below is the ITER requirements and the results obtained in specific shots in both Hydrogen and Deuterium on BATMAN with the Type VI source. The final two values in the table are added to give further information although they are not part of the ITER requirements.

Parameter	***ITER Requirement***	***Status BATMAN H***	***Status BATMAN D***
Current Density H ($mAcm^{-2}$)	28	33	--
Current Density D ($mAcm^{-2}$)	20	--	23
Electron-Ion Ratio	<1	0.36	0.9
Source Pressure (Pa)	0.3	<0.3	<0.3
Pulse Length (s)	3600	4	4
Extraction Voltage (kV)	9	9.6	9.9
RF Power (kW)	--	144	125
Plasma Grid Temperature (C)	--	197	222

Presented in Fig. 1 are the results for deuterium showing the calorimetric current density and the electron to ion ratio. This is the complete deuterium data set collected since January 2005. What is clear is that a great many shots exceeded the ITER requirement for current density, which is of critical importance to the long-term operation of ITER as it means the source has a reserve capacity and must not be operated at its limit. This should mean a far more reliable ITER NBI system. It is also clear when comparing the results for deuterium to those for hydrogen shown in table 1 that suppression of the co-extracted electron current was not achieved as well in deuterium as in hydrogen with the current filter magnet configuration, though for the best current density is also achieved the lowest co-extracted electron current.

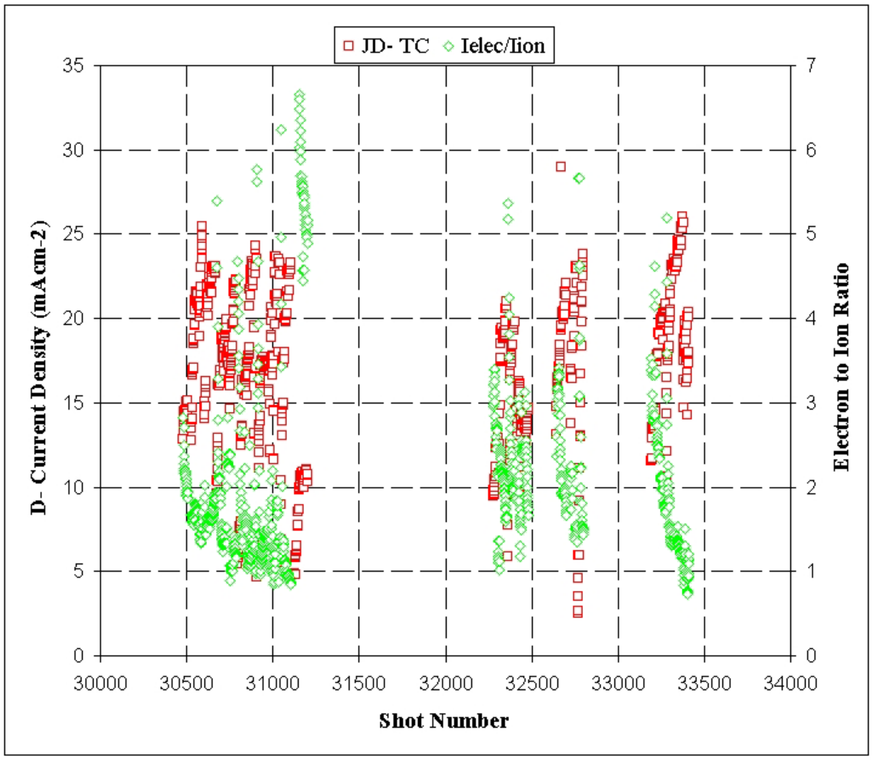

Figure 1: The current density and ion to electron ratio are shown above for the total data set for all deuterium shots made on BATMAN since January 2005.

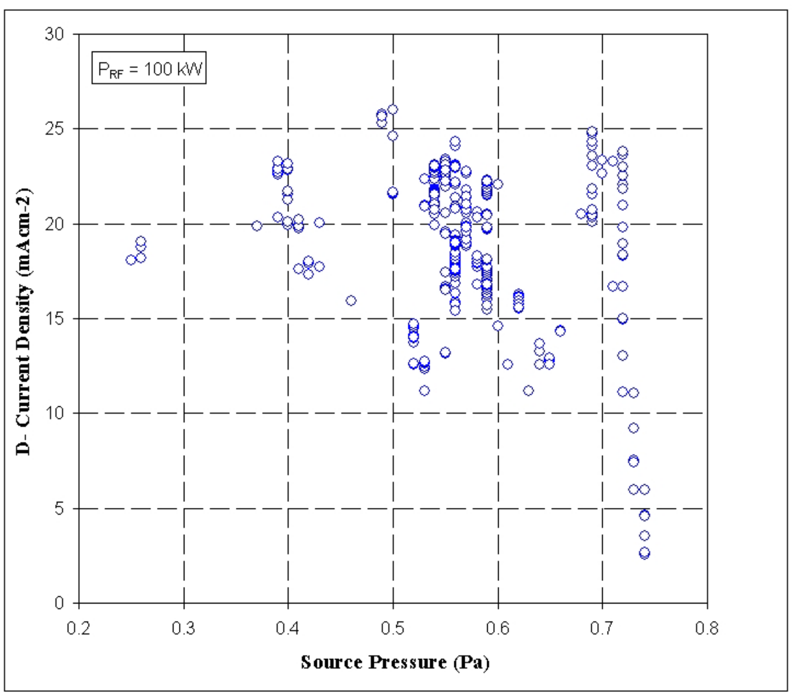

Figure 2: The effect source filling pressure for 100 kW RF power is shown for the total data set of all deuterium shots made on BATMAN since January 2005.

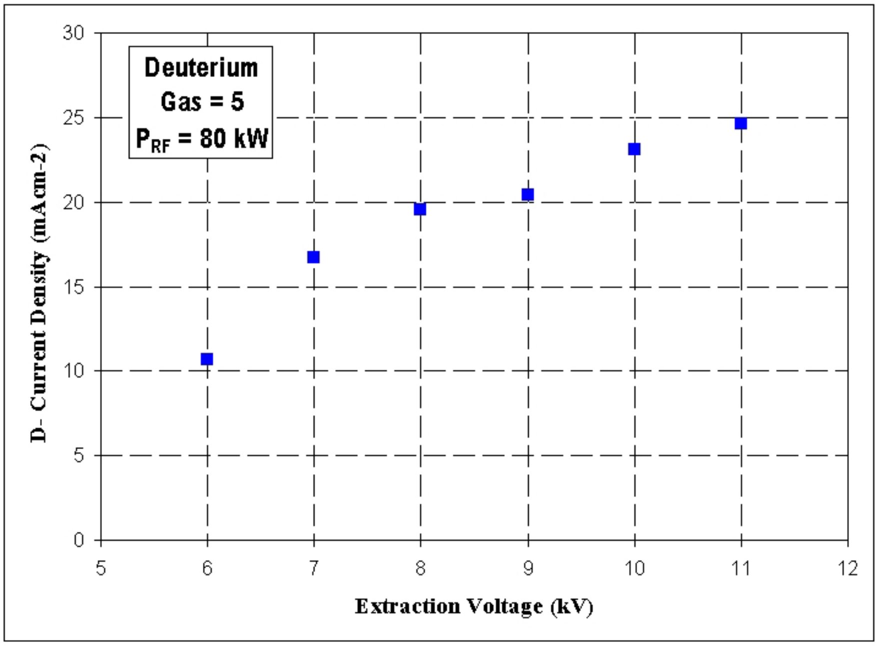

Figure 3: For deuterium shots at gas setting 5, and RF power 80 kW shown above is the effect on calormetricaly measured ion current of variations in the extraction voltage.

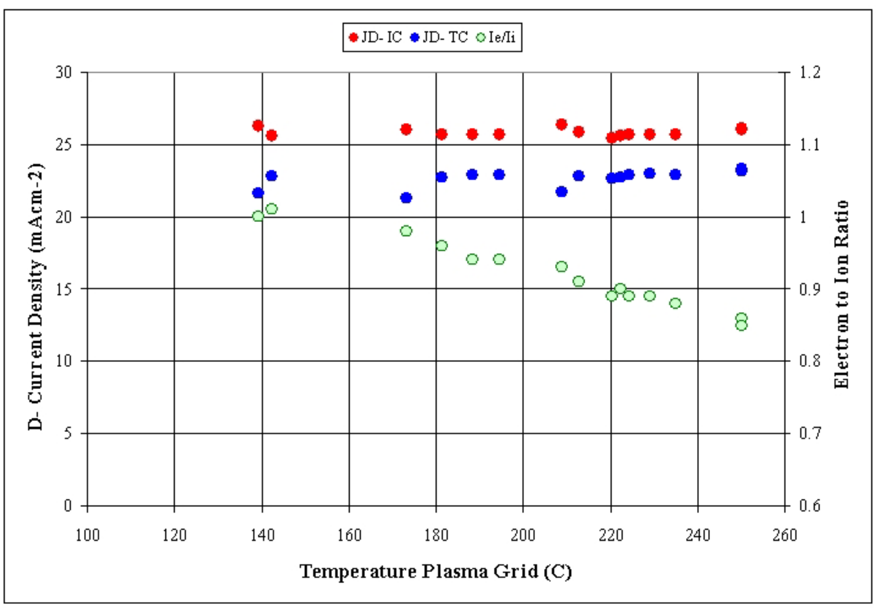

Figure 4: Shown in this figure is the variation of calorimetric (blue) and electrical (red) ion current density plus the electron to ion ratio (green) with plasma grid temperature.

In Fig. 2 is shown the effect different values of gas flow settings or source filling pressures without discharge have on deuterium current density. What is significant here is that the source operates essentially independent of filling pressure, as current densities >15 $mAcm^{-2}$ can be achieved at the same RF power for different values. Though not shown it is possible for the same filling pressure to achieve current densities greater than the ITER requirement over a wide variation in RF power. For the Type VI source a minimum pressure must be present in the driver volume to allow for efficient generation of plasma.

Shown in Fig. 3 are the results of studies on the effect of extraction voltage. The current extracted from the source increases with increasing extraction voltage. A possible explanation for this is that as the extraction field is increased there is greater penetration into the source and an increase in the volume of plasma from which negative ions are extracted. Another possibility is that the increased current has to do with improvements to the beam optic resulting in increased transmission through the grid. To achieve a better understanding of the physics of negative ion extraction a more rigorous investigation of this and other extraction effects by computer simulation is currently underway at the university of Lublin [3]. In Fig. 4 is show the results for a plasma grid temperature scan, no significant temperature dependence is observed, which indicated it may be possible to operate the source with a gas cooled plasma grid.

A new effect has been observed when the plasma grid bias is studied closely. There seems to be a reduced need for bias when the source is operating in a well-conditioned mode. In this case it is possible to reduce the bias voltage to a value that produces a small positive bias current (<1 A) and achieve the best results. Investigations indicate that further decreasing the bias voltage to the point where the current becomes negative results in an increase in co-extracted electrons and an increased bias voltage results in a decreased H^-/D^- current density. It has been suggested that this is resulting from the plasma in front of plasma grid being composed of mostly negative and positive ions with only a small amount of electrons and will be discussed in more detail in another publication at this conference [5].

There have been two primary changes made to the source that are believed to be responsible for the better results reported here. The first is that the central row of holes in the LAG were masked off as they are very close to the heating structure and this structure will have the effect of destroying the plasma near bye it (see Fig. 5). This plasma loss will result in reduced negative ion density due to the requirements the plasma be quasi-neutral. This change does not increase the actual amount of negative ions produced by the source but improves our method of measurement by removing an artificial area of reduced production.

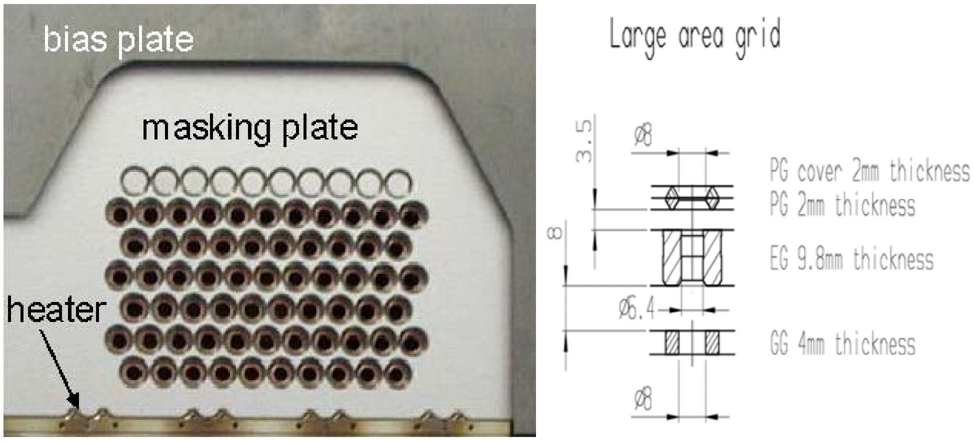

Figure 5: Shown is a picture of the new LAG configuration with the row of holes near the heating element blocked off and the chamfered plate attached. Next to this is a drawing giving details of the extraction geometry.

The second change is one that is believed to responsible for both an increased negative ion production on the plasma grid and an increased probability to extract such ions. The change was to add to the plasma side of the plasma grid a copy of the plasma grid itself resulting in each extraction aperture being surrounded by a chamfered surface (see Fig. 5). The principle is based on the computer simulations of M. Bandyopadhyay [3]. The effect of the chamfered surface is to both increase the area near the hole available for surface conversion to take place and increase the probability that any such negative ion will be extracted by giving it a higher chance to be emitted in a direction where its trajectory takes into the region of the extraction electric field. Simple geometric arguments indicate that this change results in an increase, of nearly a factor of 2, in the emission angles for which an ion leaving the surface is likely to end up in a trajectory which enters the region where the negative ion will be extracted.

3. Effect of the Magnetic Filter Field and Wall Confinement Field on Negative Ion Production

Based on several experimental campaigns in deuterium the need for a stronger filter field to control the co-extracted electron current compared to that required for hydrogen is well established. In Fig. 6 is shown a schematic of the Type VI source showing where the additional magnets used in the study were added. Additional rods of SmCo magnets could be added to strengthen or weaken the filter field and either SmCo or FeNd wall confinement magnets could be added to see their effect on source performance.

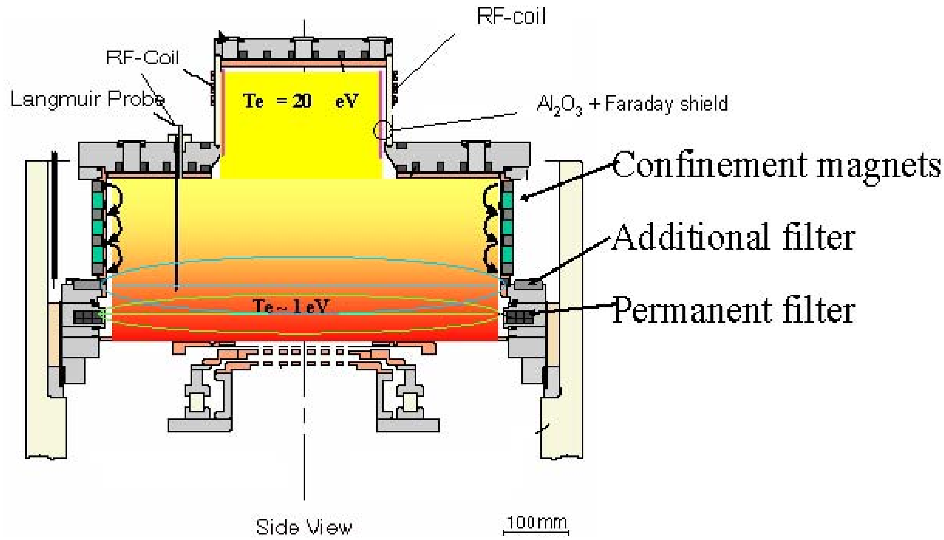

Figure 6: Shown here is the additional magnet bars and wall confinement magnets added to the normal source configuration to test the effect of different magnetic configurations on source performance.

The source efficiency is defined as the ratio of either electrically determined ion current density or co-extracted electron current density to measured RF power. Shown in Fig. 7 are the deuterium and electron efficiencies as a function of different filter strengths and the presence of absence of wall confinement. It has been found that the source has the same efficiency in both hydrogen and deuterium (see Fig. 8). However, this requires a higher extraction voltage in deuterium and results in a higher co-extracted electron current. This higher co-extracted electron current limits operation in deuterium due to the potential for the power load to cause damage to the extraction grid. Under the assumption the electron to ion ratio can be brought in line with that achieved with hydrogen it should be possible to achieve the same levels of extracted negative ion current density in both deuterium and hydrogen.

With no wall confinement the co-extracted electron current is higher and ion current is lower, strengthening the filter in this case by the addition of external rods results in a strong decrease in co-extracted electron current and an increase in ion current. The FeNd confinement magnets used without additional filter rods have the highest efficiency for ion current but unfortunately also the highest co-extracted electron efficiency. The lowest efficiencies (both ion and electron) are achieved when no confinement is used and the filter is strengthened.

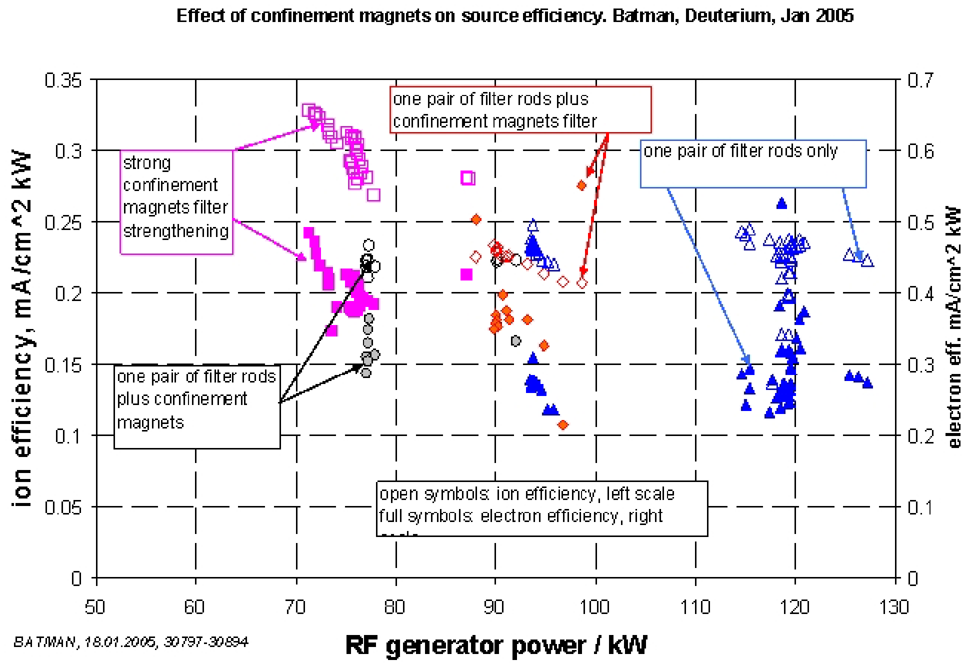

Figure 7: Shown is the effect on source efficiency of different magnetic configurations.

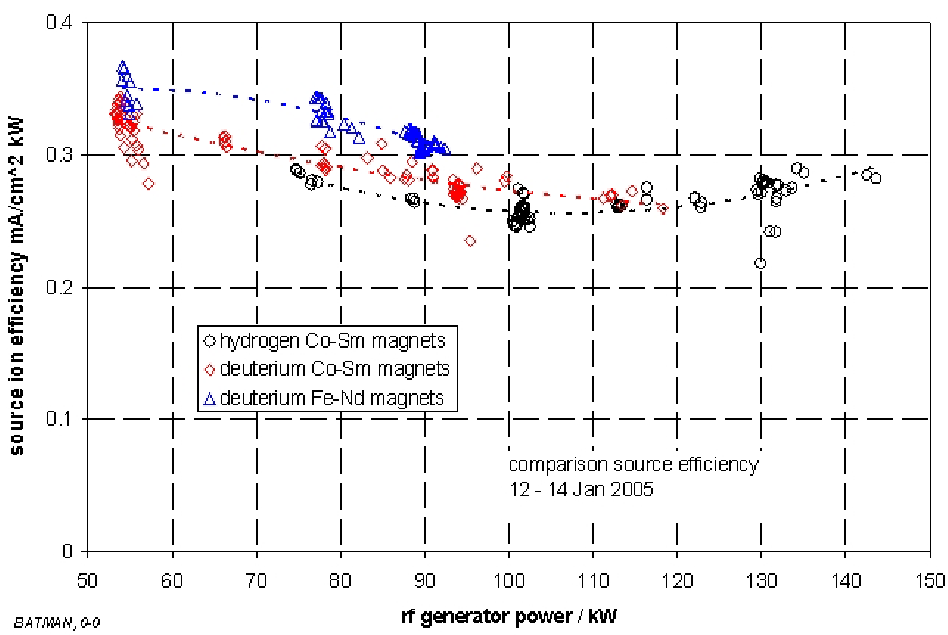

Figure 8: A comparison of source efficiency for hydrogen and deuterium with identical magnetic configuration, plus it also shows the effect of stronger wall confinement magnets for deuterium.

However, changing the filter strength by adding additional magnets to the diagnostic flange has other effects on the plasma as the filters configuration generates a particularly long reaching field that will both impede plasma flow out of the driver region and is present in the extraction system. There is also the fact that the field of the electron suppression magnets in the extraction grid penetrate to the region of the plasma near the plasma grid and have an influence on the initial negative ion trajectories. In addition, changes to the magnetic configuration of the source change the flow of plasma to the inner surfaces. This change will result in a different caesium dynamic in the source, which will result in a different thickness of caesium on the plasma grid leading to a different production rate of negative ions.

While it is proven that strong magnetic confinement on the walls is essential to the proper operation of arc sources, the evidence for its effect on the Type VI source is less clear cut. Wall confinement magnets are most effective at confining high energy or hot electrons, as low energy or cold electrons move across the field lines by collisional diffusion. Thus for an RF source, that is not dependant on energy loss from primary electron collision to sustain the plasma, wall confinement will have different behaviours than has been observed in arc sources. A good example of this is that with the present source body, where it is possible to operate the source with no expansion volume wall confinement, the source can yield good results (J_{D-} (calorimetric) = 18 mAcm^{-2}). The primary effect of wall confinement is on the source RF power efficiency, unsurprisingly the ratio of negative ions to RF power increases with increasing wall confinement. It is clear that further work is required to modify the magnetic configuration to achieve optimal source performance.

4. Reproducibility of Results

A key issue for the ITER neutral beam system will be source reliability and reproducibility. As there are only two sources in the system if one source is performing significantly below requirements there will be a substantial impact on possible injected power. Yet in the past it has proven difficult to get reproducible results from one campaign to another when caesium seeding is used to enhance the negative ion production. Therefore considerable effort has been expended in determining how one can achieve the same level of performance from experimental campaign to experimental campaign plus determining which source parameters can be monitored to provide indicators of the status of the source conditioning.

The normal duty cycle of the type VI source on BATMAN is one shot per three and half to four minutes depending on RF power used. During the shot beam is extracted for 4 seconds. There is a delay between RF on and beam extraction of 900 ms to allow for plasma stabilization and a further 500 ms period after the high voltage is removed before the RF is terminated for spectroscopic measurement. Caesium is introduced into the source continuously during the experimental day; the temperature of the oven, which is usually around 160 C, controls the rate. The plasma grid is heated by an external power supply that has a feedback circuit to a thermocouple to maintain a user-selected temperature.

Assuming that the source is caesium free at the start of the campaign it has been found that it will take a few days of conditioning to achieve the best results. Conditioning is a process of slow caesium evaporation coupled with normal beam or plasma shots. The key issue seems to be slow but steady introduction of caesium coupled with plasma shots to distribute the caesium in the source. Once the source is conditioned it will take a few hours to achieve those best results again each and every day of operation. Also during a typical campaign as the operating conditions are changed it has proven relatively easy to de-condition the source and while in most cases it has proven possible to re-condition the source there has been cases where the best source performance could not be recovered before the end of the experimental campaign.

By observing various source parameters the degree of conditioning can be monitored. The key signals are the negative ion current and the electron to ion ratio. It is generally irrelevant whether the calorimetric or electric value of negative ion current density is used though often insight in beam quality is gained by monitoring both. The first sign that the caesium amount that has been introduced has reached the point where surface production begins to dominate the extracted negative ion current is an increase in extracted negative ion current in conjunction with a fall in co-extracted electrons. This trend will then continue with continued caesium evaporation until after appropriate adjustments to extraction voltage and RF power the best source performance can be reached. In the Type VI source additional indicators of improving caesium coverage of the plasma grid can be found in the time traces of the extracted ion and electron signals. Early in the evaporation cycle when it can be safely assumed that the caesium coverage of the grid is low the time trace of the extracted ion current will increase during the shot while the time trace of the extracted electron current will decrease. The net effect of low caesium coverage is a lower total extracted current from the source. As the caesium coverage nears optimal values the time traces become flatter eventually becoming essentially constant during the pulse.

The primary requirement to achieve a high level of negative ion production is patience. Though this seems simplistic in the extreme, the lack of any control over the exact rate of deposition of caesium onto the plasma grid stands in the way of a more rigorous procedure. To achieve the optimal caesium coverage of the plasma grid requires both the establishment and maintenance of a dynamic balance between the rate of deposition and removal of caesium onto and away from the grid. Two principle difficulties stand in the way of this balance. The first is that caesium is introduced into the source at a location distant from the grid and follows a poorly understood and largely uncontrollable path from the point of introduction to the grid resulting in poor control over the rate of deposition. The second is as the source has temperature variations the caesium, whether newly introduces or recently removed from the grid, is in danger of being trapped in a location where it will no longer be available to the dynamic balance. Additional studies and extra diagnostic effort will be undertaken to increase our understanding of this critical aspect of the source physics. Further comments will be presented in another paper at this conference [5].

5. Hα Beam Emission Spectroscopy

In an effort to: quantify the stripping losses, determine where the stripping is occurring, to verify our high voltage measurements, and to determine the amount of less than full energy particles in our calorimetric measurement a Hα beam emission spectroscopy experiment has been set up on BATMAN. This experiment also functions as a test for the Hα measurements on the MANITU experiment. Shown in Fig. 9 is a schematic of the experimental set up.

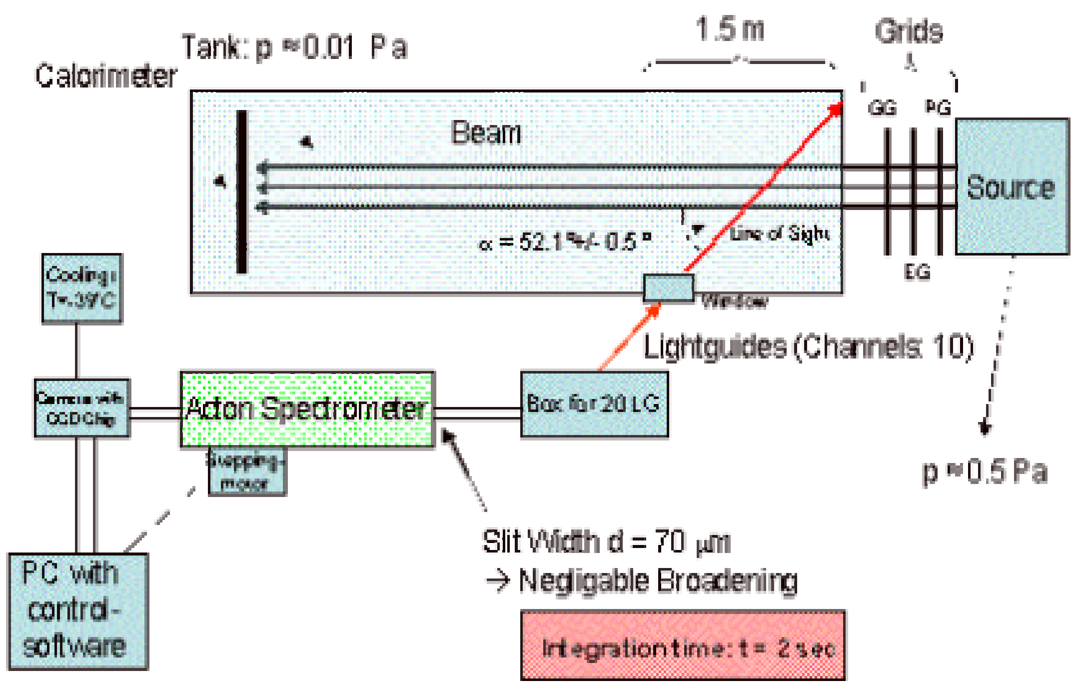

Figure 9: A schematic of the Hα emission spectroscopy experimental arrangement on BATMAN.

A typical spectrum is shown in Fig. 10 and is the result of two primary processes. The first is stripping in the grid system from the reaction:

(1) $D^{-} + D_2 \rightarrow D^0 + D_2 + e$

The second is Balmer (n=3) excitation in the line of sight:

(2) $D^0_{fast} + D_2 \rightarrow 2D^0_{slow}$ (n=3) + D^0_{fast} (leads to unshifted peak via dissociation)

(3) $D^0_{fast} + D_2 \rightarrow D^0_{fast}$ (n=3) + D_2 (leads to stripping and Doppler shifted peaks)

(4) $D^{-}_{fast} + D_2 \rightarrow D^0_{fast}$ (n=3) + D_2 + e (leads to Doppler shifted peak)

The spectrum, shown in Fig. 10, consists of three main peaks. The left peak is the

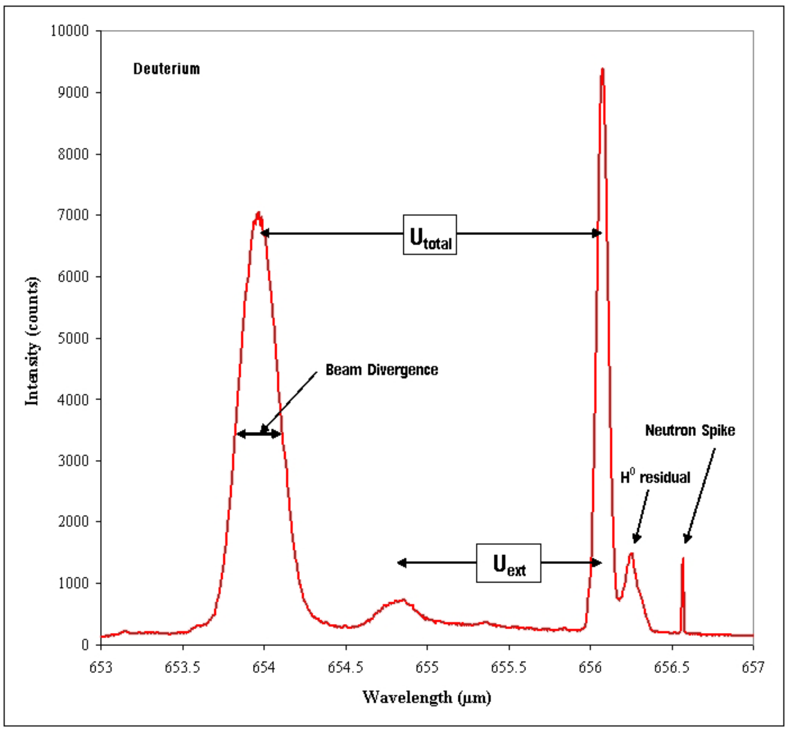

Figure 10: A typical Hα spectrum for deuterium is shown above.

fully Doppler shifted peak, which corresponds to the total acceleration voltage. The shift is given by the formula:

(5) $\Delta\lambda = \lambda_0 * v/c * \cos\alpha$

where: λ_0 is unshifted peak wavelength, v is the particle velocity, and α the angle shown in Fig. 10. The full width at half maximum of this peak is due to the divergence of the beam. A correlation between this width and the measured beam width on the calorimeter has been observed. The underlying reactions are given by equations (3) and (4).

Reaction (2) results in the unshifted peak, which is caused by the dissociation of the D_2 – background – gas by a fast D^0. In the spectrum beside the unshifted peak a smaller peak can be seen, which is caused by residual hydrogen contamination of the source. Furthermore some spikes emerge in the spectrum, which are based on fast neutrons generated by DD fusion processes on the calorimeter.

Between the two main peaks, stripping losses can be observed due to D^0 that have not been fully accelerated. The position of this smaller peak corresponds approximately with the extraction voltage, which indicated that the main stripping losses occur near the extraction grid. The reasons for this are that the magnets for the electron deflection are located in this electrode leading first to a thick grid and therefore to a high pressure in the aperture itself, and second to a bad beam geometry in this area. Both factors that favour stripping processes.

In order to get correlations between stripping processes and relevant source parameters, the stripping losses have been measured at different source pressures. Fig. 11 shows the measured stripping losses (red curve), which has been gained by the ratio of the stripping integral to the full Doppler shifted integral, in each case weighted by the corresponding Balmer (n=3) cross sections. The rate of D^- neutralisation in the line of sight has been calculated from the neutralization cross-sections assuming a constant tank pressure.

The blue curve results from calculations according to a model, which makes the justified assumption of an ideal D_2 - background gas. In order to obtain the stripping losses in a small interval dx from the equation:

$$(6) \qquad dn_{D-} / dt = - n_{D-} * n_{D2} * \sigma_{stripping}(v) * dx ,$$

one has to know the pressure - distribution p_{H2} (x) and the temperature - distribution T_{D2}(x) from the source to the line of sight, in order to determine the gas - density n_{H2} in each interval dx from the ideal gas equation. For the use of the stripping cross section at the right D^- - velocity in each interval dx, the knowledge of the potential function U(x) is necessary.

The pressure distribution is calculated by the conductance of each grid, at which the pressure in the source and in the vacuum tank can be measured. In this calculation only pumping through the grid holes was assumed. The same model was used for the stripping calculations in the ITER reference design. As far as the temperature function is concerned a

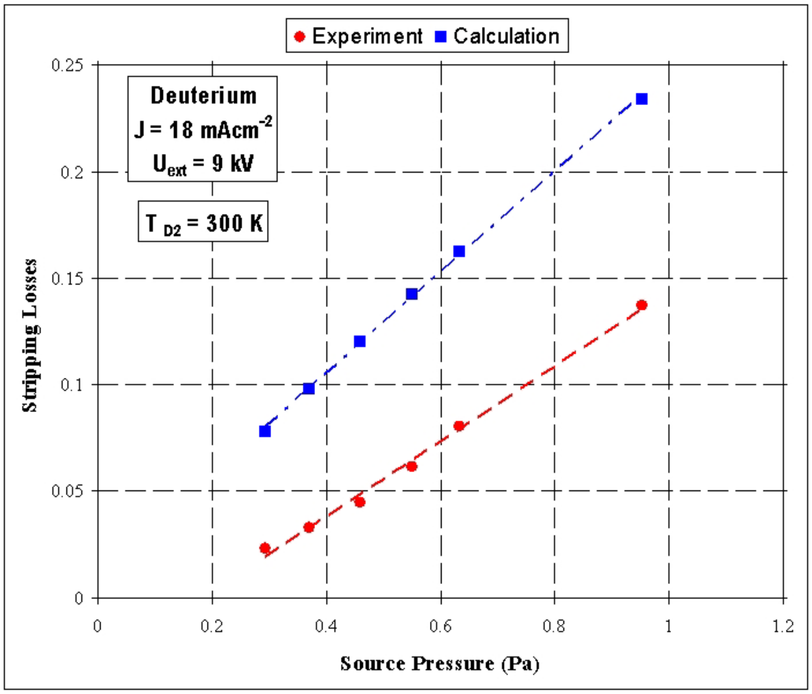

Figure 11: The effect of source pressure on both the measured and theoretical stripping losses for BATMAN are shown. The difference between the theoretical and measured values is due to the assumption of 300 K for the temperature of the gas in

constant temperature of T = 300 K has been assumed. The potential U(x) can be measured at each grid.

Both curves show a linear increase with source pressure. The calculation leads to higher stripping losses than what has been observed due to the low D_2 - temperature of 300 K, which has been used in the calculations. It is very likely that the temperature in the gap between plasma and extraction grid, where most stripping takes place, is higher than 300 K as the gas temperature in the source has been measured to be 1000 K[6] and the plasma grid itself is at 600 K, which leads to a diminished D_2 - density and hence to smaller stripping values. This low value of stripping is the reason our accountability between electrical and calorimetric measurement is so high (on the order of 90%) and also indicates that our calculated calorimetric current well represents the extracted beam current density, as the fraction of ions with less than full energy is low. Based on these results it is likely that the stripping losses in the ITER accelerator are over estimated.

6. Future Plans

The efforts on BATMAN in the future will be changing as MANITU becomes operational and the emphasis changes to showing ITER relevant performance on long time scales. BATMAN will be devoted more and more to physics type studies. But in the near terms four items are planned. The first is a test of the use of a air cooled plasma grid to be accomplished by using the same grid as used on the positive ion sources of ASDEX-UG with the LAG, this should allow for the determination if air cooling has any principle problems. The second is to change the way the magnetic filter field is generated by moving the magnets closer together and possibly adding in iron bars to shape the field. The third is studies of on a long pulse capable RF transformer to be used on MANITU. The fourth is a study on the effect of extraction aperture size to be done by introducing various sized partial masks on the plasma grid.

7. Conclusion

The results obtained on BATMAN with the Type VI ion source have met and exceeded the primary ITER requirement of current density for both hydrogen and deuterium. In the case of deuterium the limitation on our extraction grid of co-extracted electron power limits the source performance so that the deuterium value should not be considered the ultimate possible source performance. These values were obtained consistently and routinely during several days of operation. The experimental results indicate that the source efficiency is the same for both hydrogen and deuterium and that the efficiency is independent of pressure in the driver region or filling pressure when the source is properly conditioned. The co-extracted electron current ratio is within the bounds of the ITER requirements for deuterium operation but it is hoped that further investigations into optimization of the magnetic filter field will allow us to decrease the co-extracted electron to ion ratio to the values achievable for hydrogen operation. The question of pulse duration will be answered by the MANITU facility currently beginning commissioning [7].

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