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Status of the Development of the SINGAP Accelerator for ITER

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Abstract. The development of the Single Aperture, Single Gap 1 MV accelerator (SINGAP) is being carried out on the 1 MV test bed at the DRFC, CEA Cadarache, France. This paper reports on the latest performance achieved with the prototype, "ITER-like" accelerator, 730 keV, 120 A/m^2 D$^-$, and of on-going measurements of the beam "halo" fraction, ≈10%. It reviews the status and plans for future studies on D$^-$ production, and the observed "dark current", and presents the basic physics design of a system that should cope with the ≈3 MW of electrons that would be co-accelerated out of the 1 MeV, 40 A, D$^-$ SINGAP accelerator proposed for the ITER neutral beam injectors.

INTRODUCTION

It is planned to install two heating neutral beam (HNB) injectors on ITER for the start-up of the machine, and provision is made to install a third at a later date. Each of these injectors must deliver ≈17 MW of 1 MeV D^0 to the ITER plasma, the D^0 being created by the neutralisation of 1 MeV D$^-$ in a gas target. Taking into account the neutralisation efficiency (≈60%) and various losses in the beamline, to achieve ≈17 MW in the neutral beam means starting with a 40 A, 1 MeV D$^-$ beam.

The Single Aperture, Single Gap accelerator (SINGAP) accelerator concept is an attractive candidate for the ITER neutral beam injectors. Such an accelerator consists of multi-aperture extraction and pre-acceleration stages followed by the acceleration of one or more groups of beamlets in a single step to the full energy. Each group of beamlets exits the accelerator through a single large aperture. With the SINGAP accelerator designed for the ITER neutral beam injectors there are 16 groups of apertures arranged in a regular 4 x 4 matrix. In the extraction and pre-accelerator stages each group consists of a regular rectangular matrix of 5 x 16 (horizontal x vertical) apertures. Thus 1280 beamlets are accelerated to 40 to 60 keV, then 16 groups of 80 beamlets are accelerated to 1 MeV, and out of the acceleration stage through sixteen 135 x 370 mm^2 rectangular apertures [1].

The development of SINGAP is being carried out on the 1 MV test bed at the "Département de Recherches sur la Fusion Contrôlée" (DRFC)of the "Commissariat à l'Energie Atomique" (CEA) at Cadarache, France using the prototype "ITER-like"

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accelerator [2]. That accelerator is designed to accelerate a 5 x 5 array of beamlets up to 60 keV, then to accelerate these as a group up to 1 MeV through a single 150 mm x 150 mm aperture. Because the current from the 1 MV supply is limited to 100 mA, for the experiments reported here it was decided to use only a single aperture in the pre-acceleration stage, which would give a beam current of ≈30 mA at the nominal ITER design accelerated current density of 200 A/m^2 at 1 MeV.

DARK CURRENT AND PRESENT PERFORMANCE LEVEL

On the Cadarache 1 MV test bed a current appears when high voltage is applied, without any ion acceleration, with the ion source not operating [3, 4]. This "dark current" first appears when a voltage of >200 kV is applied for the first time after the system has been pumped down. The onset of dark current is accompanied by a significant increase in outgassing, the principal masses seen on the residual gas analyser being 28, 16, 14 and 12. Continued application of the high voltage results in a decrease in the dark current and the outgassing, i.e. there is some "conditioning". If the applied voltage is increased, the dark current reappears and the process then repeats itself. However with the present configuration of the Cadarache test bed this conditioning stops at ≈450 kV, i.e. the dark current and out gassing remain constant even after many repeated applications of the high voltage. In order to reach higher voltages it is necessary to suppress the dark current significantly below the current limit of the 1 MV power supply at the required voltage. The dark current can be suppressed by increasing the pressure in the system with H_2, D_2 or He [4]. Other gases have not been tried. Unfortunately the pressure required to suppress the dark current increases with the applied voltage – see Fig. 1. The maximum pressure during high voltage application is limited by glow discharges in the vacuum vessel when there is no beam acceleration. At the pressures required to suppress the dark current at ≈750 kV, the pressure around the accelerator and in the acceleration gap are more than a factor 2 above those anticipated in the ITER injector and this leads to excessive stripping losses. This determines the voltage limit during beam acceleration.

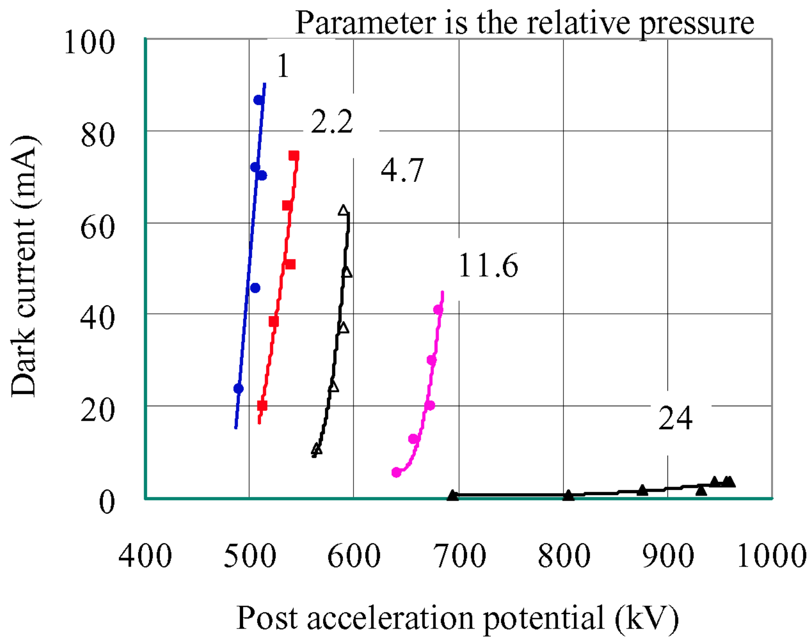

FIGURE 1. Dark current measured on the Cadarache 1 MV test bed. The parameter indicated is the relative pressure of D_2 or He.

Present Performance Level

At the last PNNIB the best performance reached was [5]:

500 keV	85 A/m^2	D^-
850 keV	15 A/m^2	D^-

Since then the performance has improved by further caesiation of the ion source and conditioning in the presence of the higher density D^- available from the fully caesiated ion source. The best performance to date is [6]:

678 keV	170 A/m^2	D^-	
727 keV	120 A/m^2	D^-	(Perveance match)

Influence of the Experimental Configuration on the Dark Current

Two aspects of the present experimental set-up could have a significant influence on the dark current. They are:

a) Cathode and/or anode surface contamination

The system operates with the ion source at ground potential and the D^- ions are accelerated up to high positive potential. The beam is then transported to the target inside the "anode" which is at the high positive potential of the last grid of the accelerator. The beam target is supported on, and electrically attached to, the end of this anode. The walls of the vacuum chamber – the cathode - are lined with 1 mm thick stainless steel to present a "smooth" surface. This surface is not polished, and it has been in the vacuum system for many years. Fig. 2 shows the discolouration of the surface that has occurred over time, indicating that the cathode has become contaminated. The composition of the contamination is not yet determined. It is suspected that this contamination may be a cause or initiator of the dark current, and/or that it enhances the dark current. (In this context it is to be noted that the system is first evacuated with a standard rotary vane fore pump/Roots pump combination, then by a turbo-molecular pump. During ion source operation the main pumping is provided by a cryopump.)

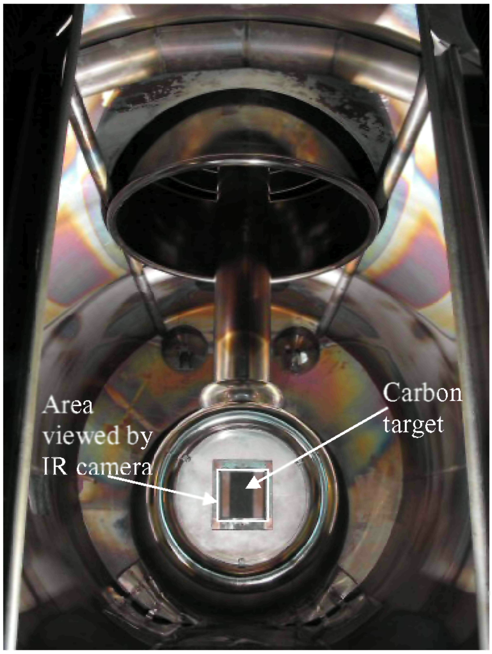

FIGURE 2. Photograph of the interior of the Cadarache 1 MV test bed. The view is from the rear of the system looking towards the ITER-like accelerator. See also Fig. 3.

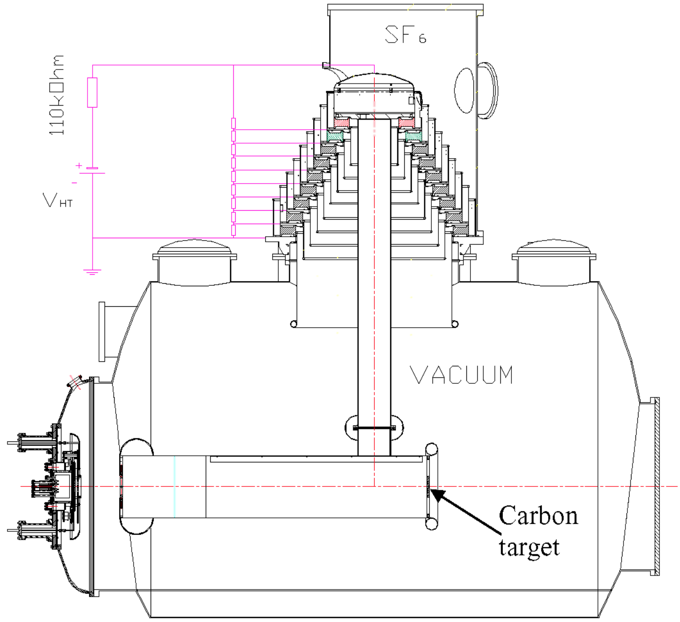

FIGURE 3. Schematic of the present layout of the Cadarache 1 MV test bed.

b) Non uniform electric field

The beam axis is below the axis of the vacuum chamber, see Fig. 3, and the electric field between the anode and the chamber wall is far from uniform. It has been shown in studies of voltage holding that a non-uniform electric field distribution leads to a lower voltage holding limit. As it is likely that voltage holding and dark current are linked, the very non-uniform field in the present set-up could be enhancing the dark current.

New, Heated, Cathode and Anode Assembly for the 1 MV Test Bed

To improve the surface condition of the cathode and the uniformity of the electric field, a new cathode and anode assembly has been designed. The new cathode will be installed inside the existing vacuum vessel, around the new anode structure, as shown schematically in Fig. 4. It can be seen from Fig. 4 that the new cathode is coaxial with the horizontal anode and with the vertical support column, leading to better electric field uniformity in those regions. The peak electric field in the new configuration is slightly below that of the existing configuration. Unfortunately it is not possible to avoid the combination of horizontal and vertical structures, and the field will be quite non-uniform in the transition from one to the other.

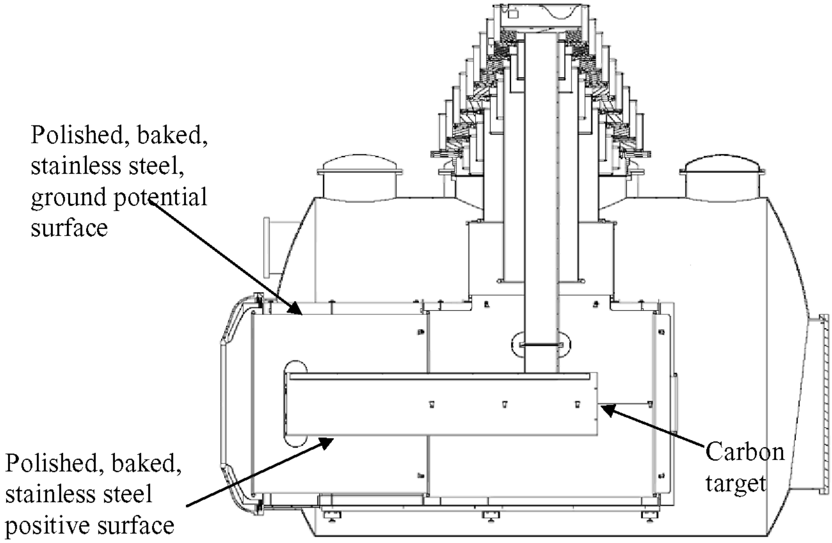

FIGURE 4. Schematic of the new high voltage assembly for the Cadarache 1 MV test bed. (Note that the pre-accelerator is not shown in this schematic.)

It has been found in some experiments that degassing electrodes leads to a better voltage holding. Therefore the cathode and a new anode will:

a) be made of highly polished sheet stainless steel that has been degassed by baking to ≈900 °C;

b) be designed to be baked in–situ, under vacuum to between 200 °C and 300 °C;

c) have a more uniform electric field distribution.

Present planning shows the installation starting and the start of operation with the new assembly in the second half of 2007.

BEAMLET OPTICS – HALO STUDIES

It has been previously reported [7] that a 3 stage multi-aperture, multi-grid negative ion accelerator produces an accelerated H^- beam with large divergence beam "halo" carrying 3 to 4% of the accelerated power when the source was operated at ≈1.7 mA/cm^2 In "pure volume" mode, i.e. with no caesium inside the ion source. The halo fraction increased to 8 to 17% when the ion source was caesiated and operated at higher current density, 5 mA/cm^2 . The latter is in reasonable agreement with the 15% assumed for the design of the ITER neutral beam injectors. Experiments are now underway to measure the halo fraction with D^- acceleration using the ITER-like SINGAP accelerator and to determine the cause of the halo.

Experimental Results

The set-up at Cadarache is well suited to beam profile studies for two reasons: a) the SINGAP accelerator inherently has little vignetting of the beamlets after the pre-acceleration stage due to absence of intermediate acceleration grids and the large opening in the acceleration grid, and b) because the beam profile diagnostic has, in principle, the necessary dynamic range. The accelerated beam impinges on the front of a carbon target, ≈200 mm high x 100 mm wide and ≈20 mm thick located ≈2.7 m from the accelerator. The beam profile is measured with a CEDIP "Jade MWIR" infra-red (IR) camera looking at the rear of this target. This camera can measure temperatures over a very wide range, 1 part in 10^3, in a single image, which is necessary to measure, for example, a halo carrying 10% of the beam power with a divergence 5 times that of the core of the beamlet. (It is to be noted that it has been verified that the magnetic fields in the test bed are sufficient to prevent accelerated electrons from reaching this target and influencing the profile measurement.)

The target is made of a Mitsubishi carbon-fibre composite, which has a thermal conductivity parallel to the beam axis 20 times larger than in the orthogonal directions. This means that the thermal image at the rear of the target seen by the IR camera at the end of a typical shot of ≈1 s duration is almost proportional to the power density arriving on the front surface. Nevertheless the "DIFFUSE" code [8] has been developed, and is used, to correct for the distortion of the measured beamlet footprint by lateral heat conduction.

Unfortunately, an instrumental effect has been discovered that complicates the measurements with the IR camera, and reduces the measurement accuracy. It has been found that when a localised bright spot is present in the field of view of the camera, the apparent temperature of the image outside the bright spot increases. The reason for this phenomenon has not yet been determined, and discussions are underway with the manufacturer of the camera. We presently hypothesise that the effect is due to reflections inside the camera. A series of careful measurements with a black body source and apertures between the black body and the camera, which limit the size of the spot seen by the camera, allows a reasonable estimate of the resulting error to be made

It is found that the profile measured by the IR camera for a beamlet at perveance match is poorly simulated if it is assumed that the beamlet power density profile is a simple Gaussian, but it is reasonably well simulated if it is assumed that the beamlet power density profile is a double Gaussian, see Fig. 5. (Note that the profiles shown in Fig. 5 take account of the lateral heat conduction in the target.) The larger divergence Gaussian is taken as the "halo' fraction. So far it is found that within experimental errors there is no halo when the ion source is operated in "pure volume" mode, i.e. when there is no caesium (Cs) in the ion source. As soon as Cs is introduced into the ion source and the negative ion yield enhancement is observed, a beamlet "halo" is measured, apparently carrying ≈15% of the accelerated power. Typically the above-mentioned instrumental effect causes an apparent halo of ≈5%, so the true halo carries ≈10% of the accelerated power. As adding Cs increases the negative ion yield substantially, it is necessary to establish whether or not the halo is related to caesiated

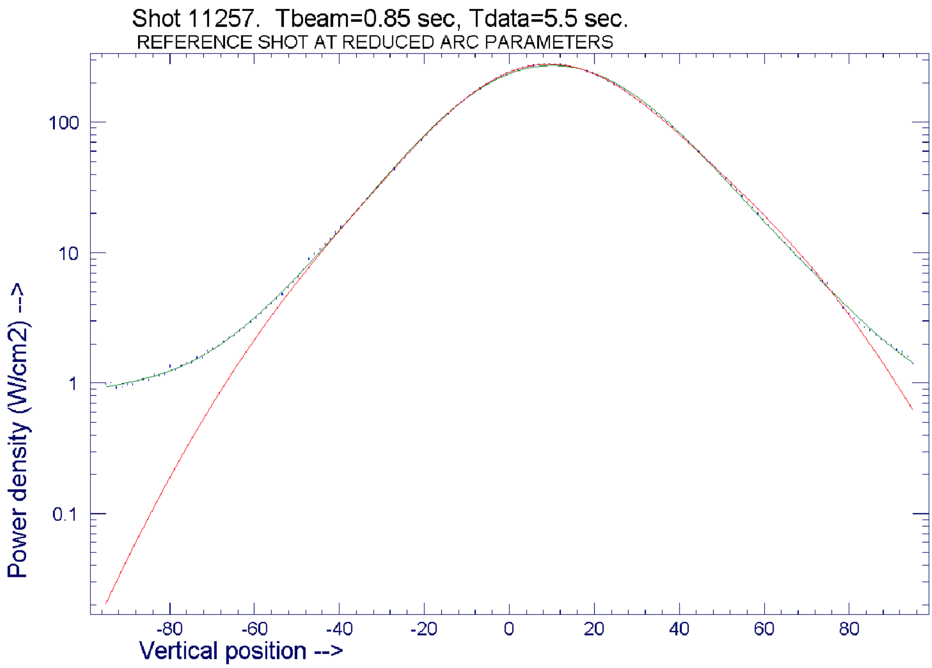

FIGURE 5. Measured (dots) and simulated profiles for a 500 keV, 0.8 s D^- beam. The red curve assumes a beamlet with a simple Gaussian power profile with a divergence (1/e) of 5.5 mrad, the green one assumes that the beamlet has a double Gaussian profile consisting of a "core" carrying 85% of the power with a divergence of 5.5 mrad, and a "halo" carrying 15% of the power with a divergence of ≈40 mrad. Both profiles take account of the lateral heat diffusion in the target. The instrumental effect described in section 3 of this paper accounts for 5% of the halo, so that the real halo carries ≈10% of the power.

operation, or simply operation at high current densities. Therefore the power into the caesiated arc discharge was reduced so as to produce the same accelerated negative ion current density as obtained in the pure volume mode, and the halo fraction measured. Again it was found to be ≈10%, so the halo appears to be connected to operation with the caesiated ion source. To summarise:

Pure "volume" operation	**2 mA/cm^2, D^-**	**halo <2%**
Caesiated operation	**2 mA/cm^2, D^-**	**halo ≈10%**
	10 mA/cm^2, D^-	**halo ≈10%**

Halo Formation - Hypothesis

The experiments at Cadarache strongly suggest that the negative ions extracted from a caesiated arc discharge source are created by the back scattering of H (D) atoms from the surface of the plasma grid as $H^-(D^-)$ [9]. This is consistent with expectations: the measured dissociation fraction (≈25%, i.e. H(D) number density ≈0.66 times the $H_2(D_2)$ number density) and gas temperature measured in similar ion sources [9] combined with the filling pressure (≈0.3 Pa, the pressure measured before arc initiation, i.e. with cold gas) indicate a flux of $\approx 2 \times 10^{18}$ H(D) atoms/s/cm^2 to the plasma grid surface. The H(D) atom temperature in such sources has been measured to be ≈1 eV [10], and the negative ion yield from a flux to a caesiated tungsten surface of 0.7 eV thermal H atoms has been measured to be ≈10% [11], which is assumed to be equal to the yield of 1 eV D atoms. The D- yield would then be ≈35 mA/cm^2. Calculations suggest that ≈30% of the ions created at the plasma grid surface should return to be extracted [12, 13], giving an extracted current density of 10 mA/cm^2, which is remarkably close to that measured.

Cs introduced into the source leaves the source by creep over the plasma grid surface and by Cs vapour flowing out through the apertures in the plasma grid. Therefore Cs will eventually coat the various surfaces of the accelerator. During operation of the ion source, H (D) atoms will flow out of the ion source through the apertures in the plasma grid, and they will impinge on the various surfaces of the accelerator, and, when those surfaces are caesiated, they can be backscattered as negative ions. Ions formed on upstream surfaces will be accelerated, and either impinge on the downstream grid surface, or be accelerated through the apertures in the downstream grid.

Figure 6 shows the calculated trajectories of ions emitted from various surfaces in the SINGAP pre-accelerator. Ions that hit the following grid do not form part of the accelerated beamlet and can be ignored. Ions that are created on the downstream part of the aperture in the extraction grid are accelerated, but highly divergent.

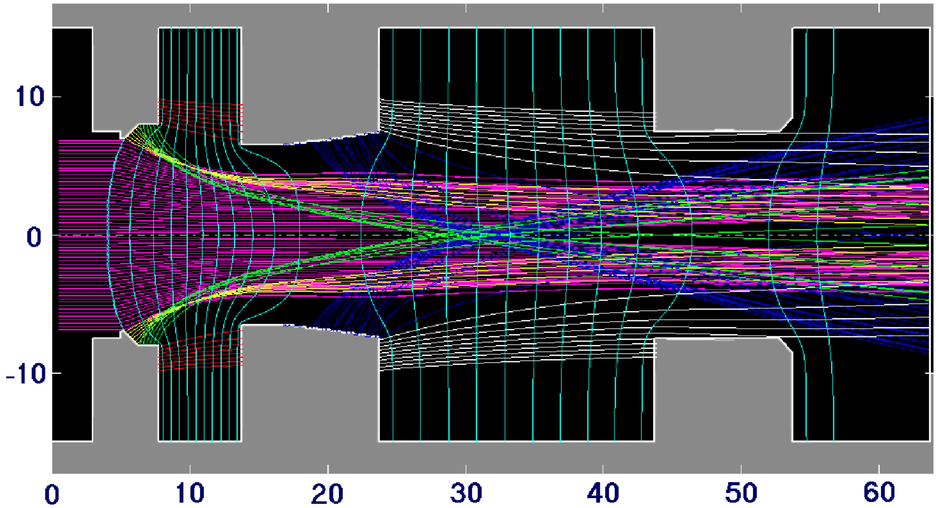

FIGURE 6 Beam ions originating from the beam source (purple) and metallic accelerator surfaces (yellow, green, red, blue, white). The beam source is on the left. The axes are scaled in mm. The voltages on the grids are 0, 8.5 kV and 60 kV. The extraction gap is 6 mm.

The H(D) flux from the ion source is as given above (≈2 x 10^{18} atoms/s/cm^2), but the $H^-(D^-)$ yield from the downstream side of the plasma grid will be reduced compared to that from the front surface as the H(D) flux and the H(D) temperature are reduced due to recombination and thermal accommodation during collisions with the plasma and extraction grids [14]. However, all ions produced would be accelerated from the surface, increasing the effective yield compared to the front surface by 66% as they do not need to turn around before being accelerated. It is concluded that the production of halos carrying >15% of the accelerated power are possible by this mechanism.

If the above described mechanism is the origin of the measured halo, the plasma grid geometry shown if Fig. 7 would result in a much reduced beamlet halo. A grid with this geometry is to be tested in the near future on the Cadarache test bed.

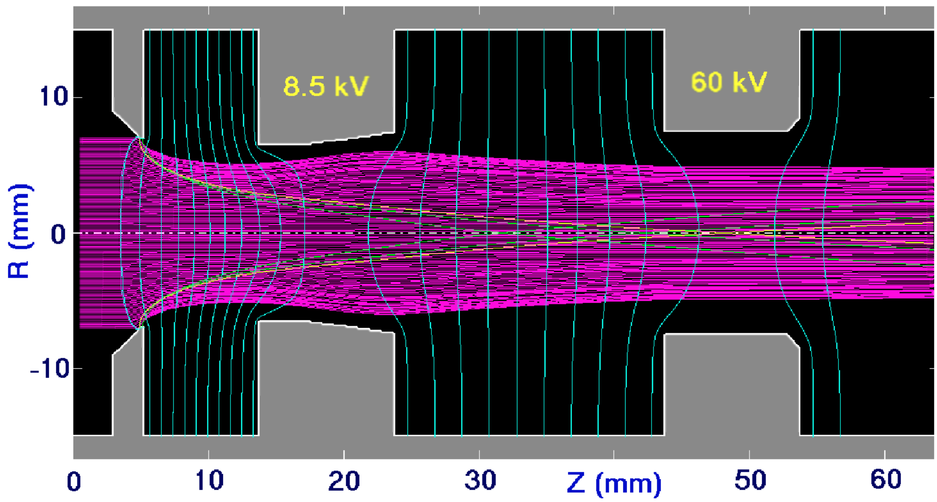

FIGURE 7 Suggested new geometry of the plasma grid. Compared to the design shown in Fig. 5, all the plasma grid metal downstream of the knife edge is removed and the extraction gap is increased to 8.5 mm. With this geometry only ions originating from the knife edge itself are accelerated and produce a halo. Ions produced on surfaces elsewhere in the accelerator are not shown.

STRIPPED ELECTRONS AND THE SINGAP ACCELERATOR

The SINGAP accelerator concept has many advantages compared to the alternative multi-aperture, multi-grid, accelerator being considered for the ITER neutral beam injectors. As regards the stripping of the accelerated negative ions, there are two advantages and one disadvantage. They are:

Pro:

- good lateral pumping
- reduced stripping losses

Con:

- stripped electrons are accelerated from their ‘birth’ position up to the full voltage and they exit the accelerator through the large apertures in the acceleration grid. It is calculated that the ITER SINGAP accelerator will produce 2.7 MW of stripped electrons with an average energy of ≈720 keV [15, 16]

The electrons exiting the accelerator are deflected downwards by the long range field from the magnetic filter in the ion source. As shown in Fig. 8, with the present design of the SINGAP accelerator for ITER, 2.7 MW of electrons hit the neutraliser. If the vertical magnetic field is exactly zero, they will pass between the partitions of the neutraliser, depositing their energy on the floor of the neutraliser., a very small vertical field (≈10^{-4} T), such as could result from the residual stray field from ITER, could

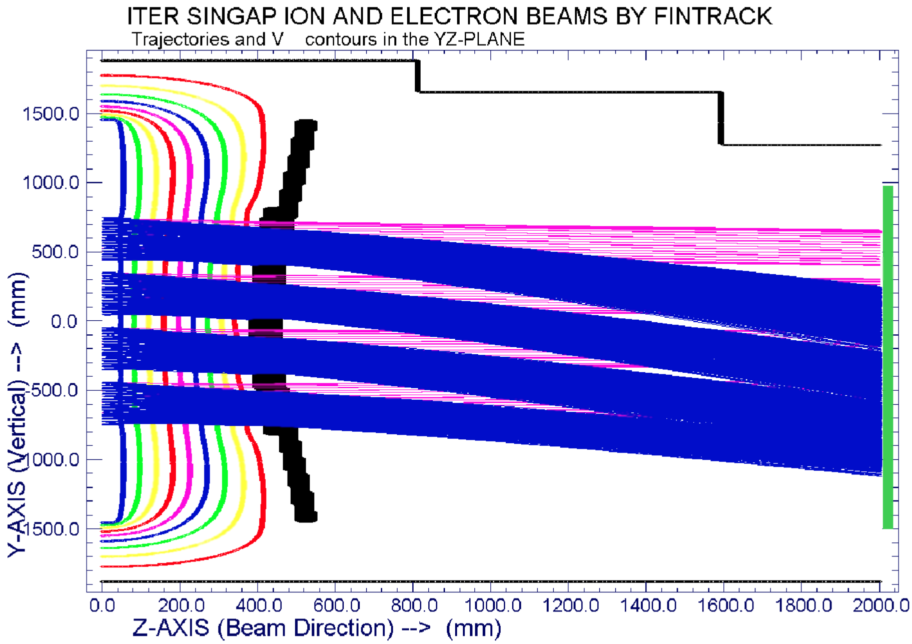

FIGURE 8 Stripped electrons leave the accelerator and are deflected downwards by the magnetic field from the filter of the ion source. Most hit the neutraliser floor or the neutraliser walls, neither of which are shown. Importantly, some can hit the leading edges of the neutraliser entrance (green line), and the local power density on the neutraliser entrance can be ≈3.3 kW/cm^2.

deflect the electrons onto the leading edges of the neutraliser partitions. It has been calculated that in this situation there will be local hot spots with an electron power density of ≈33 MW/m^2 . Although these spots would be small (≈2 mm diameter), cyclic thermal stress would lead to fatigue failure in an unacceptably short time. In addition there would be significant backscattering (≈20 to 30 %) of the intercepted electrons (and backscattering of the backscattered electrons etc.) and copious production of bremsstrahlung. If the cryopump is not protected in any way, these effects would lead to ≈100 kW of additional power reaching the 80 K shields, and ≈600 W to the 4.5 K surfaces. The total heat load budget during pulse operation of the neutral beam injector, calculated without taking these effects into account, was 20 kW for the 80 K shields, and 160 W for the 4.5 K surfaces. Whilst the cryopumps and the associated cryogen supply system can be designed for higher power loads than is presently the case, the power loads indicated above are clearly excessive.

Electron Deflection, Sweeping and Dumping

Many possible ways to handle the power from the accelerated electrons and to reduce the power to the cryopumps have been considered, but here only the currently preferred option of electron deflection and sweeping is considered.

Backscattered electron power arrives at the cryopumps largely from the region upstream of the neutraliser and from the gap between the neutraliser and the residual ion dump. A further deflection downwards of the electrons is advantageous as they then hit the inside of the neutraliser further away from the exit, so that backscattered electrons would, on average, have to undergo several bounces before exiting the neutraliser, reducing the number and energy of the electrons finally hitting the cryopumps. Obviously fewer X-rays would be produced by the reduced flux of electrons from the neutraliser exit, and X-rays produced by electrons hitting the inner surfaces of the neutraliser are attenuated by the neutraliser structure. In this situation more electrons will hit surfaces upstream of the neutraliser entrance, but initial calculations indicate that louvers each side of the beam in that region can sufficiently attenuate the flux of electrons and X-rays to the cryopumps whilst having only a small effect on the gas pressure in that region.

The beam from the ITER accelerator will produce 4 “column beams”, one passing through each channel of the vertically sub-divided neutraliser. It is proposed to deflect the electrons downwards using the magnetic field from columns of permanent magnets placed each side of each column beam, ≈20 cm downstream of the accelerator, the magnets being arranged to produce a horizontal field across the beam. To avoid “end effects” these magnet columns are substantially higher than the accelerated beams, and in addition to the 5 columns each side of the beams an additional column is added to each side of the array, i.e. there are 7 columns of magnets – see Fig. 9.

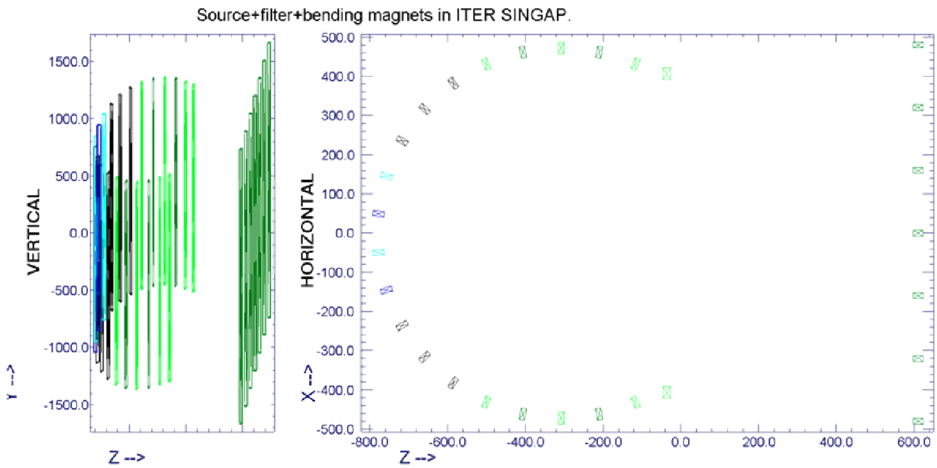

FIGURE 9 Long columns of magnets (2.4 metres high), located downstream of the accelerator, can be used to deflect the electrons downwards. The magnet columns are located 610 mm from the plasma grid. The magnets in the extraction and pre-acceleration grid are not shown.

This results in a uniform, horizontal, magnetic field in the region occupied by the accelerated beams and the electron trajectories are as shown in Fig. 10. To accommodate the power in the deflected electron beams safely it is necessary to install a vertical electron beam dump in front of the neutraliser, below the floor of the neutraliser, as indicated in Fig. 10. The electrons are then collected either on this dump, the entrance to the neutraliser, or inside the neutraliser. The calculated power

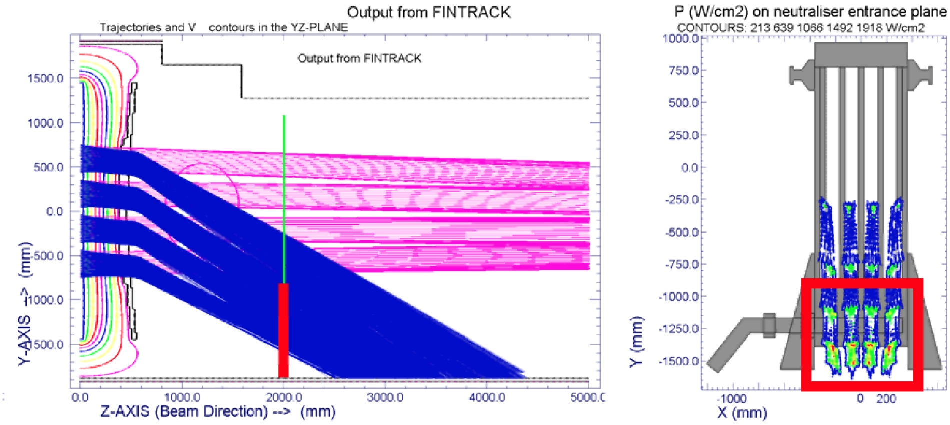

Figure 10 Electron beam trajectories with the proposed deflection system. The peak power density on the neutraliser edges is ≈2.1 kW/cm^2. A vertical electron dump should be installed to intercept all the power that impinges below the neutraliser floor, as indicated by the red line and rectangle.

density on the neutraliser floor is acceptable everywhere (<8 MW/m^2), but there are still hot spots on the vertical electron dump, with a power density of 21 MW/m^2. Such hot spots would still lead to early fatigue failure of the electron dump. Therefore it is proposed to sweep, in an oscillatory fashion, the electron beam on the dump. An essentially fail safe way to achieve this was suggested by M Liniers of CIEMAT, Spain, using the field from the magnetic filter in the ion source. That filter is created in part by passing a current of ≈4 kA vertically through the plasma grid. The necessary sweeping of the electron beam can be realised by simply having a ±10% ripple on the current through the plasma grid, while increasing the mean value of the current by 10%. Since in the ITER beam source only half of the magnetic filter comes from the current in the plasma grid, the variation in the magnetic filter strength is 0% to +10%, which is no expected to affect the extracted electron to negative ion ratio. The resulting oscillation in the long range field from the plasma grid current would sweep the electron beam by ≈±12 cm on the electron dump, greatly reducing the average power density on the dump. Such a system requires no additional elements in the vacuum system and no additional safety interlocks as the plasma grid current interlock already exists.

CONCLUSIONS/SUMMARY

A dark current is observed when high voltage of >200 kV is applied in the Cadarache 1 MV test bed, which is accompanied by significant outgassing in the vacuum vessel.

Some conditioning of the system can be achieved by repeatedly applying high voltage to the system, but this stops at ≈450 kV. In these conditions the dark current reaches the current limit of the high voltage supply and no higher voltage can be achieved.

The dark current can be suppressed by increasing the pressure in the system, but the required pressure increases with voltage. Presently the limit is found to be ≈850 kV, when glow discharges occur in the vacuum vessel.

The pressure required to suppress the dark current at 750 kV is more than double that expected in the accelerator of ITER, producing high stripping losses during beam extraction. The result is that the highest beam energy at the D^- current density required for perveance match is limited to 730 keV. Higher current densities have been achieved with the ITER-like SINGAP accelerator, but at lower energies. The best results to date are those indicated in Present Performance Level Section above.

Voltage holding and the dark current can be influenced by material properties, the cleanliness of the surfaces "seeing" high voltage and the uniformity of the applied electric field. Therefore a new high voltage assembly will be installed in the 1 MV test bed early in 2007. That assembly will produce a more uniform electric field, and it will have clean, polished, baked stainless steel for both the anode and cathode surfaces between which the high voltage will be applied. The assembly can be baked in-situ to be able in order to be able to maintain an optimum cleanliness. First results with this structure are expected in the first half of 2007.

The stripped electrons created in the main acceleration gap of a SINGAP accelerator are accelerated from their birth point up to the final potential. For the SINGAP accelerator designed for ITER it is calculated that this will lead to an accelerated electron beam carrying ≈2.7 MW of power at an average energy of ≈720 keV. These electrons would produce high current densities in local hot spots on the neutraliser entrance, leading to fatigue failure. Backscattered electrons and the bremsstrahlung produced by the electrons would lead to high power loads to the cryopumps. It is proposed to handle these problems by deflecting the electrons onto a special dump in front of the neutraliser and the neutraliser floor, and to sweep the beams backwards and forwards on these components, reducing the peak power density substantially. Backscattered electron and X-ray power to the cryopumps is then reduced by the screening action of the neutraliser and a new louver screen each side of the accelerated beams upstream of the neutraliser.

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