Experimental results with the new ITER-like 1 MV SINGAP accelerator

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ABSTRACT

A new "ITER-like" accelerator, which is a scaled down version of the ITER SINGAP (SINgle GAP, SINGle Aperture) accelerator, has been built and installed on the Cadarache 1 MV test bed. The objective is to demonstrate reliable D^- beam acceleration as close as possible to 1 MeV with a current density $j^- \approx 200$ A/m^2 with the parameters and beam optics required for ITER aiming at a near parallel 1 MeV beam of 5 mrad divergence.

The accelerator is designed in such a way that changing from on to off-axis beam steering can be done by a simple transverse displacement of the post-acceleration electrode. High Voltage hold off tests have been performed and 940 kV have been held without any breakdowns. The first beams up to 850 keV have been obtained after only 4 weeks of conditioning and the highest current density that has been obtained so far is 85 A/m^2.

1. INTRODUCTION

The European concept for a 1 MeV, 40 A negative ion based accelerator for the neutral beam system on ITER, the SINgle GAP, SINGle Aperture (SINGAP), is an attractive alternative to the ITER reference design, the so-called Multi-Aperture, Multi-Grid (MAMuG) accelerator. A prototype SINGAP accelerator has been used for several years and produced D^- beams with an energy of 910 keV, 60 A/m^2 simultaneously [1]. The measured beam profiles on the target agree well with the ones predicted by beam optics calculations [2]. However with this prototype accelerator it was not possible to produce near parallel beams with a 5 mrad divergence needed for ITER. A new accelerator has therefore been built in order to demonstrate that the beam optics required for ITER can be achieved. Two new ion sources have also been constructed [3].

2. THE SINGAP TESTBED

2.1 General layout

The Cadarache 1 MV negative ion beam facility is capable of producing H^- or D^- ion beams up to 1 MeV, 100 mA. A schematic view of the test bed is shown in figure 1. Two different ion sources, the so called "Drift Source" and the "Alternative Source" can be used. The ion source is installed at ground potential.

The negative ions are first accelerated in the pre-accelerator to energies of 10-50 keV and thereafter up to 1 MeV in the post-accelerator. The beam calorimeter is located at high voltage (HV).

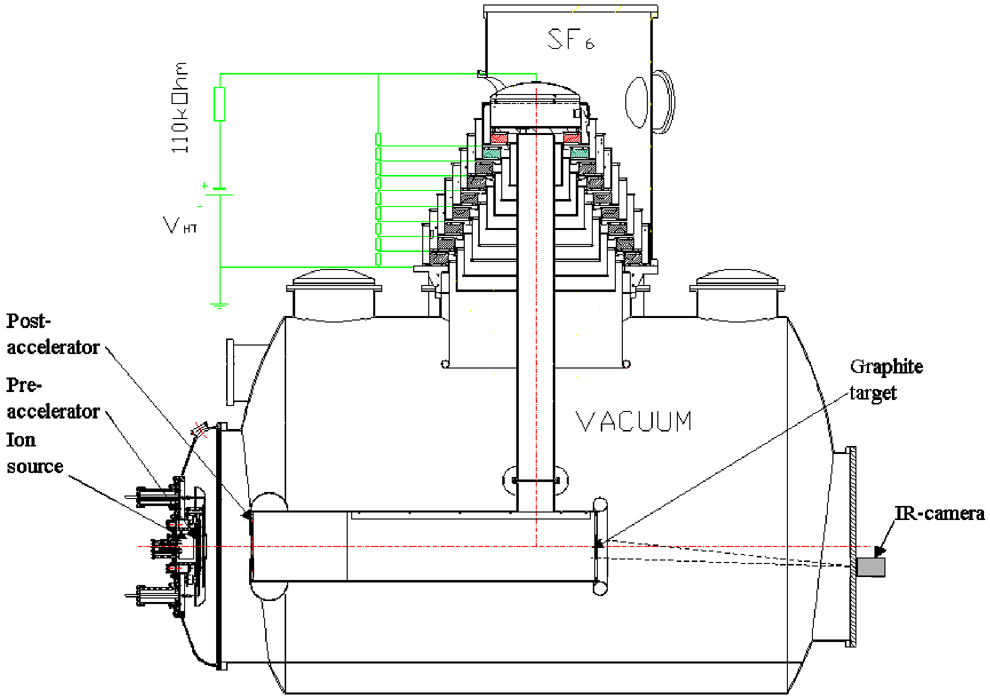


Figure 1. The 1 MV test facility at Cadarache.

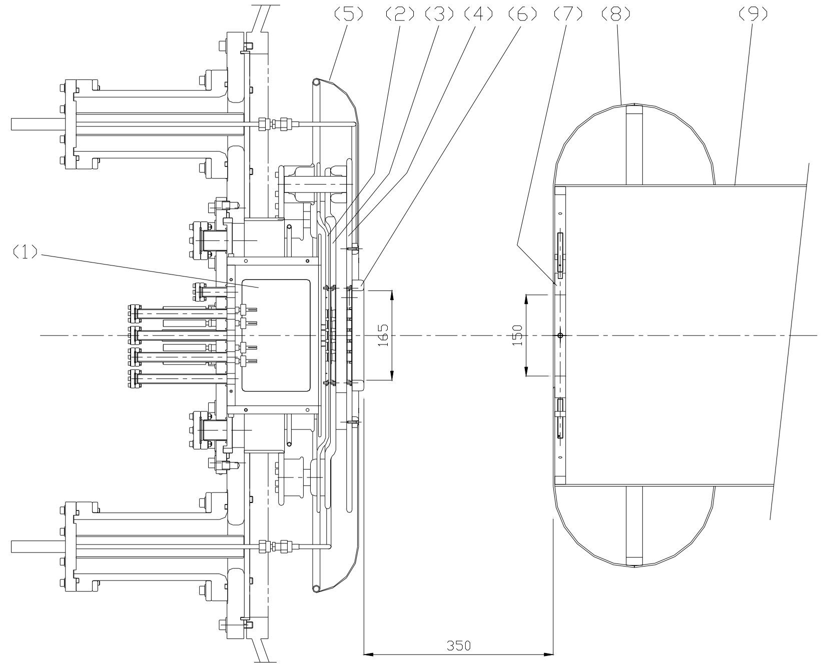
2.2 The ion sources

The “Drift Source” is a revised version of the earlier prototype [4]. The source, which is now properly water cooled, is mounted inside the vacuum. The side plates are made by Cu deposition and contain the CoSm magnets for plasma confinement and the electron suppression filter. The top, bottom and back plates are made of OFHC Cu. They contain no magnets and the cooling water channels are made by deep drilling.

The “Alternative Source” is a new design where simple manufacturing techniques are used to provide a high performing source at a low cost. It can easily be interchanged with the “Drift Source” since it has the same space envelope and is using the same cooling water manifolds. The side walls are made of explosion bonded Cu/SS sheet material. The cooling channels are deep-drilled in the Cu layer and the sheets are thereafter bend into a L-shape perpendicular to the water channels with the copper inside the L. Two such L’s are then assembled to form a rectangular source body. All welds are done with TIG. The grooves for the confinement magnets and the electron suppression filter magnets are machined around the walls leaving 2 mm of copper between the magnets and the inside of the source. More detailed information can be found in [3].

2.3 The accelerator

The pre-accelerator consists of a plasma grid, an extraction grid and a pre-acceleration grid. Each grid and its water tubes are embedded in a circular stainless steel (SS) grid support plate. These plates are mounted with alumina post insulators onto a common SS base plate. The extraction grid and the pre-acceleration grid have aperture patterns of 5 x 5 with a horizontal and vertical pitch of 20 mm. A 20 mm high "kerb" made of stainless steel is fitted at the exit of the pre-accelerator. This kerb is used to "push" the outer beamlets towards the centre in order to merge the 25 beamlets to a near parallel beam while traversing the post-acceleration gap. Four different plasma grids have been made, with number of apertures varying from 3 to 25. The Cadarache 1 MV power supply has a current limit of 100 mA. This limits the numbers of apertures on the plasma grid to only three when 200 A/m^2, 1 MeV beams are to be produced. However, for comparison of experiment and modelling it is more suitable to use rows of 5 apertures and reduce the beam energy. Two plasma grids, each with a row of 5 apertures have been made. One grid with a centre row and the second with the row placed at the bottom. This enables studies of space charge effects and the effects of the "kerbs" at a reasonable high current density. The plasma grid with 25 apertures will be used when the SINGAP accelerator will be tested at the megavolt test stand at JAERI, Naka in Japan in the near future, where a 1 MV – 1 A power supply is available. A cross section of the "ITER-like" accelerator with the ion source can be seen in figure 2.



(1) 'Drift Source'
(2) plasma grid support (~10 V)
(3) extraction grid support (<+10 kV)
(4) pre-acceleration grid support (<+50 kV)
(5) electrostatic screen
(6)electrostatic "kerb" structure
(7) post-accelerator electrode (+1 MV)
(8) electrostatic stress ring
(9)drift tube

Figure 2. Vertical section of the "ITER-like" SINGAP Beam Source.

The 4 plasma grids have each two thermocoax heater elements embedded in the source side of the grids. This enables heating of the plasma grid to ≈300 °C for efficient negative ion production with Cs seeding of the source [5].

The extraction grid and the pre-acceleration grid are both water cooled through horizontal channels between the aperture rows and incorporate CoSm magnets for electron suppression and/or ion trajectory correction. A schematic of the grids with their water channels and the magnets are shown in figures 3 and 4. Since the grids are rather complex they were manufactured using electrolytic Cu deposition in 3 cycles. A piece of OFHC Cu was first machined on one side for the cooling water channels and on the other for the magnets. The copper was thereafter deposited in two cycles to form the channels. The stainless steel water connections were thereafter fixed to the copper in a third cycle.

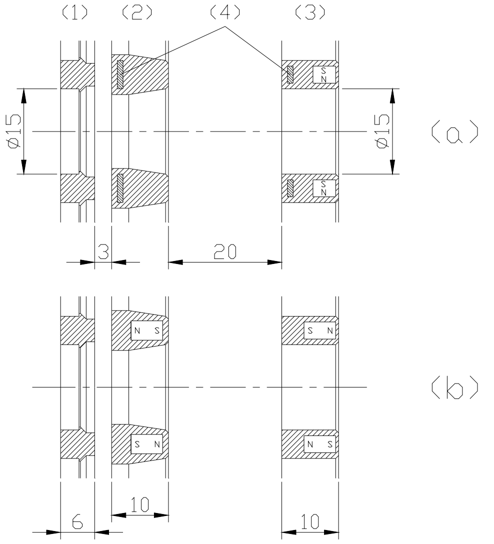


Figure 3. Pre- Accelerator Aperture Geometry
(a) vertical, (b) horizontal cut
(1) plasma grid, (2) extraction grid
(3) pre-acceleration grid, (4) water channels

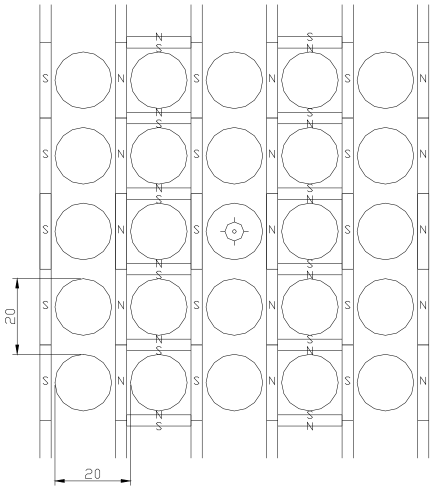


Figure 4. Magnet Configuration in the pre-acceleration grid viewed from downstream

The beamlets formed in the pre-accelerator are thereafter accelerated to an energy of 1 MeV in one step across the main acceleration gap of 350 mm. The post-accelerator electrode has only one large square opening and is made of OFHC Cu. It can be displaced vertically and horizontally, thus providing aperture offset beam steering to simulate the vertical steering (±0.55°) required on ITER or just for correction of misalignment.

Both the pre-accelerator and the post-accelerator have been provided with electro-polished SS screens to reduce the electrostatic stresses and they are arranged to ensure that the beam optics is not influenced by fringe fields.

3. THE FIRST EXPERIMENTAL RESULTS AND COMPARISON WITH SIMULATIONS

3.1 Voltage holding

The HV conditioning time has been drastically reduced from several days of conditioning to a few hours thanks to the new high power resistors installed in series with the 1 MV power supply. The resistor value is now 110 kΩ instead of 1 MΩ with the old prototype accelerator. The pulse length is now only restricted by the existing timing system, which limits the pulse length to 40 s. The anode structure inside the tank is getting warmer than before and some hot spots have been observed. Breakdown free HV pulses up to 940 kV were achieved after only 160 minutes of accumulated voltage on-time. Helium gas with a pressure of about 0.03 Pa was added into the vacuum tank in order to suppress dark currents [6]. This is slightly higher than what has been predicted for ITER (0.02 Pa) [7]. Higher voltages have not been attempted in order to spare the 1 MV power supply. The results of the HV conditioning can be seen in figure 5.

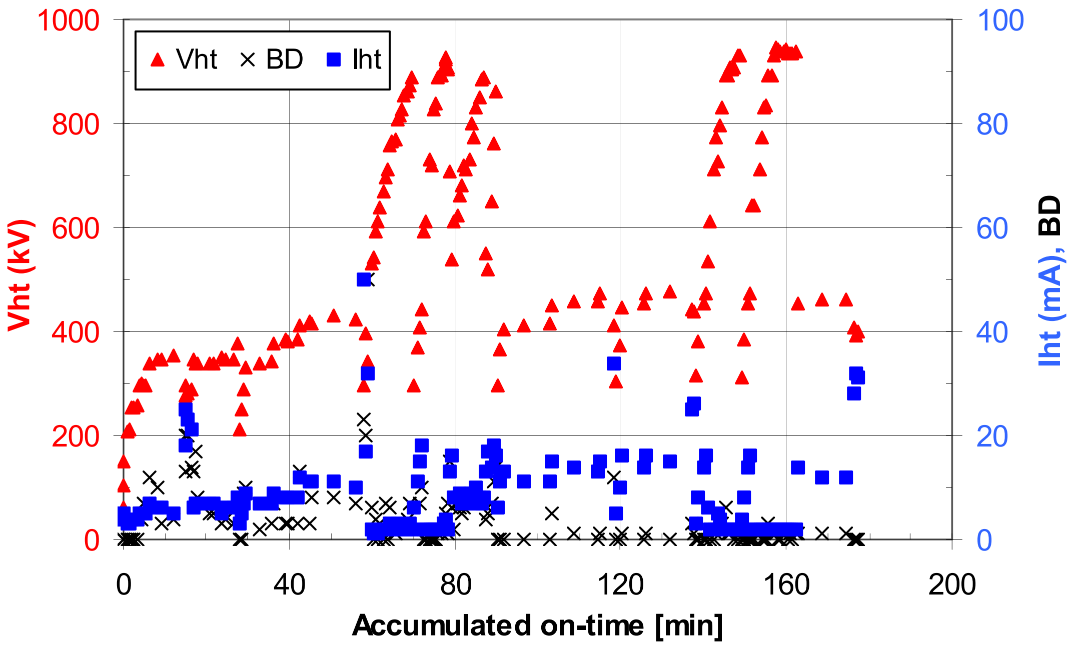


Figure 5. HV conditioning of "ITER-like" accelerator. Vht is the voltage holding in kV, Iht is the total electric current in mA and BD is the number of breakdowns in one pulse. Because no beams were extracted the electric current is equal to the dark current.

3.2 Beam optics simulations

The first comparisons between simulations and experiments have been done for SINGAP in the ITER-like configuration. Shot 7545 was chosen for the simulation because the experimental data shows the three beamlets resolved. Thanks to this, a maximum of details can be compared.

The ITER-like accelerator is being operated with three beamlets. Looking from the target towards the pre-acceleration grid (against the beam direction), the apertures appear as in figure 6.

Shot 7545 had 1.8 s of 28 A/m^2 D$^-$ beams, 13 mA in total. This number is determined calorimetrically from the energy deposited onto the 19 mm thick Mitsubishi MFC 1A graphite target. Taking stripping losses into account, the extracted current density from the source was 36 A/m^2. The extraction voltage was 2.5 kV, the pre-acceleration voltage 18 kV and the post-acceleration voltage 625 kV. The source pressure was 0.4 Pa, the plasma grid was at 225 °C and caesium was introduced.

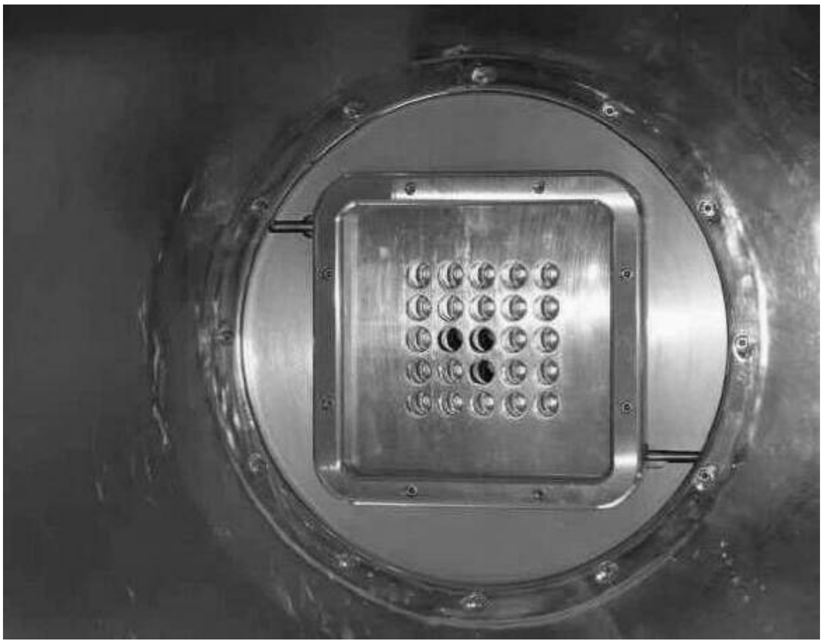


Figure 6. The apertures as seen against the beams (at an angle). The beam line centre goes through the middle aperture.

3.3 Simulation

The simulation procedure has been described in detail in [2] and also at the previous symposium [8]. In addition the temperature profiles are now corrected for the time and temperature dependent 3D heat diffusion occurring during the transit from the exposed front towards the rear face of the carbon target. The temperature and/or power density profiles are calculated using the in-house developed code DIFFUSE. It is the temperature distribution at the rear of the target that is measured with an infrared camera. In brief, our simulation procedure is:

1. The electrostatic extraction and pre-acceleration of one beamlet from the source is modelled with SLACCAD [9]. Space charge and stripping losses are included.
2. The deflection of the beam inside the pre-accelerator due to all the magnetic fields present in the system is calculated by the in-house developed code TRACK [2], which makes use of the potentials imported from SLACCAD. One beamlet at a time is calculated. Because columns of beamlets traverse different magnetic fields, TRACK has to be run twice.
3. The calculated beamlet optics, including the deflection by magnetic fields, is input to the Vector Fields SCALA code [10]. This code handles all three beamlets and their interactions simultaneously in a finite-element model of the post-accelerator. The emittance diagrams of the post-accelerated beams are obtained 106 mm inside the post-acceleration drift tube (anode), where space-charge compensation is assumed to take place.
4. The calculated emittance by SCALA is imported into a transmission code that calculates the drift of the three beamlets. The transmission code then calculates the power density incident on the carbon target.

5. The DIFFUSE code calculates the heating of the target under the incident beam power density profile using the temperature dependent values of the specific heat and conductivity of the MFC 1A material. For the “uni-directional” graphite material used the heat conduction in the beam direction is some 20 times larger in the beam direction than in the perpendicular direction. In this way the beam profile information is almost retained if the beam profiles are not too narrow. However, for the steep temperature gradients produced by the narrow “ITER-like” beam, transverse heat diffusion plays a role and the temperature profile at the back of the target as a function of time is therefore calculated with DIFFUSE.

The parameters for shot 7545 have been put into SLACCAD and the beam optics calculated. The calculated pre-accelerated beamlets are 2.8 mm in radius and convergent by 25 mrad. TRACK calculates almost zero deflection for the beamlets on the right in figure 6 because the deflections by filter and electron suppression fields nearly cancel. The beamlet on the left, however, is deflected 12 mrad downwards and 11 mrad to the right (that is before post-acceleration).

The simulation by SCALA is shown in figure 7 together with a picture of a typical pre-accelerated beam captured from a DVD movie sequence taken by an optical camera through a window above the accelerator. In contrast to our previous (prototype) SINGAP accelerator, the beams do not cross over anymore. This is confirmed by SCALA and all our DVD's.

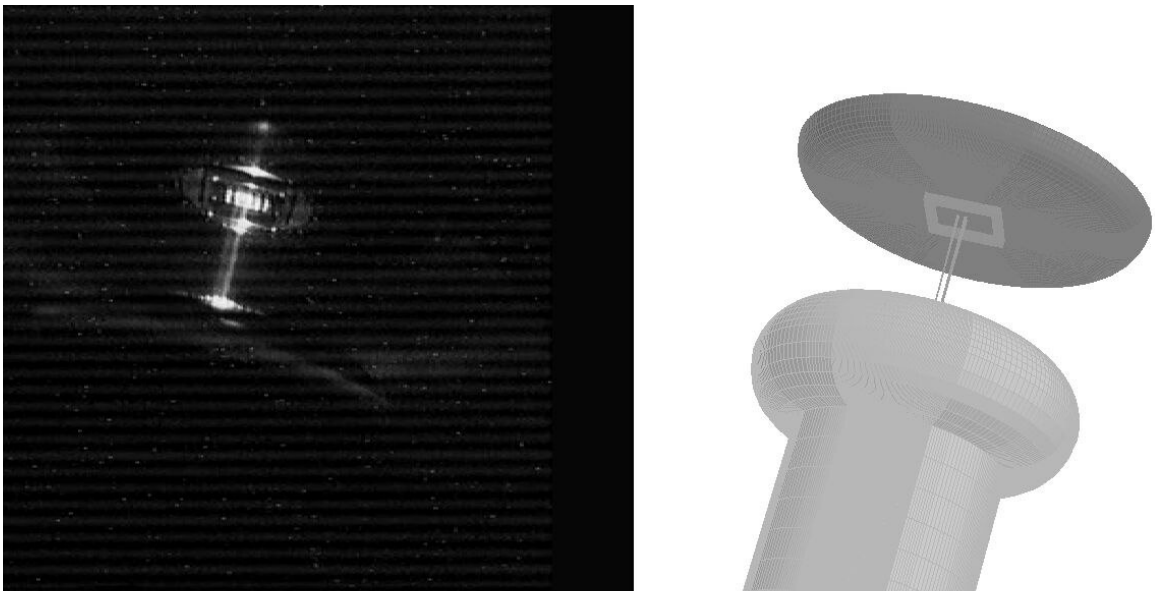


Figure 7. Post-acceleration of three beamlets in ITER-like SINGAP. To the left a photo from the beam taken from above at an oblique angle. To the right a SCALA simulation of shot 7545 viewed from a similar direction. The two beamlets on the right appear as one bright beamlet because the line of sight passes through both of them.

For an ideal beam (realistic beams, see below), neglecting effects of aberration, grid misalignment etc., the beamlet divergence calculated by SCALA is very good, around 2.5 mrad. The horizontal direction angle is around 1 mrad, the vertical direction angles are larger due to the magnetic fields. This is consistent with the ITER design.

The transmission code calculates the power density on the carbon target, 3.1 m further downstream, assuming Gaussian beamlets with the starting position, width, divergence and steering direction calculated by SCALA. Due to the low divergence, the calculated power density is very high, up to 2 kW/cm^2, and contained in a narrow profile.

Figure 8 gives the calculated profiles by DIFFUSE at t = 1.0 s and t=2.8 s. The beam was on from t = 0 to t = 1.8 s. The reason why we take a profile 1 s after the beam is to allow all the heat to diffuse from front to back, thus allowing calorimetric measurements. Due to lateral diffusion, the apparent power density in figure 8 is lower than the calculated input power density.

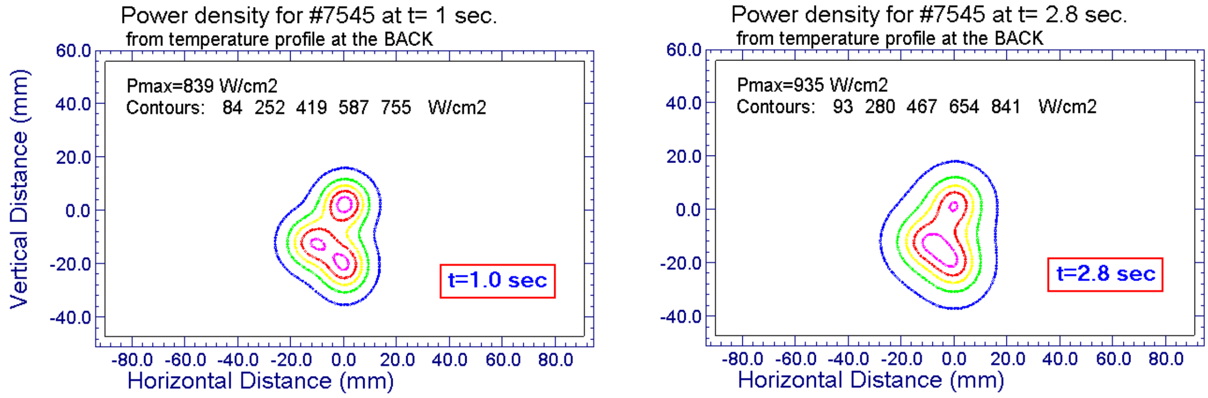


Figure 8. Power density profiles at the back of the carbon target as calculated by DIFFUSE. The beam was on from t = 0 to t = 1.8 s. The power per beamlet is 2.7 kW.

3.4 Experimental data

The measured data are shown in figure 9. The right picture is derived from the standard Agema 782 IR camera system and taken at 2.8 s, which is 1.0 s after the beam was turned off. The left picture is from a modern Flir 550 IR camera system (on temporary loan from UKAEA, Culham, UK) and taken at 1.0 s into the beam.

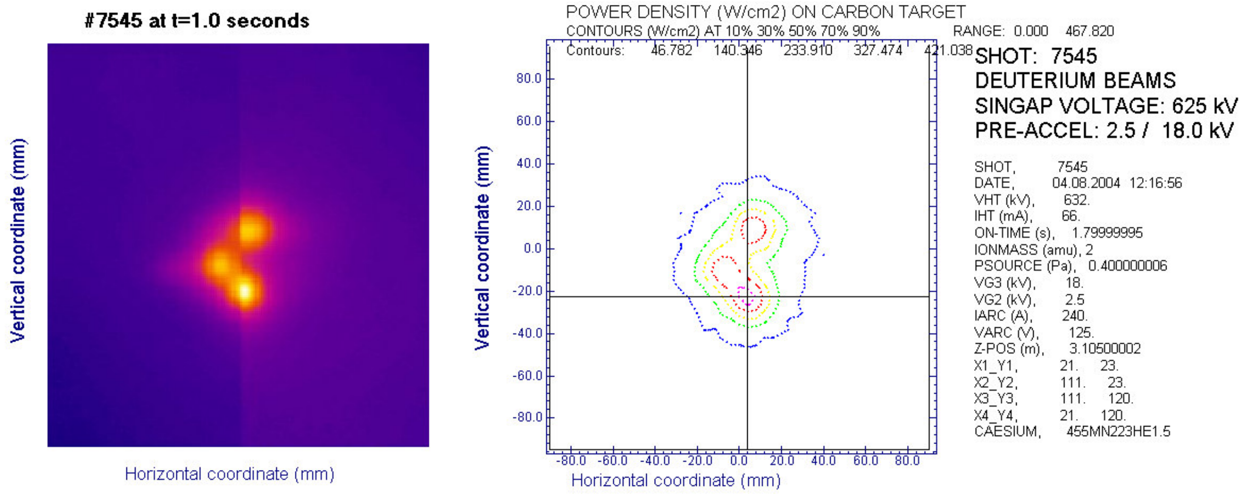


Figure 9. Infrared data from the back of the carbon target for shot 7545 (2.8 mA/cm^2 D$^-$).
LHS: from the new camera, taken during the beams at 1.0 s.
RHS: from the old camera, taken 1.0 s after the 1.8 s beam.

We see from the data in figure 9:

- The two beamlets on the right are vertically 30 mm apart (the calculation gives 23 mm).
- The lower two beamlets are horizontally 11 mm apart (the calculation gives 12 mm).
- The maximum power density is only half the calculated value in figure 8.
- The power density profile is wider than calculated, but the central part not by very much.

The reason why the beamlets are vertically further apart than calculated is not yet clear.

3.5 Realistic beams

The calculations are idealised in the sense that they do not include things like finite ion temperature, mechanical inaccuracies, thermal distortion and expansion of the grids, non-uniformity of D^- flux to the plasma grid, effect of the magnetic fields on the plasma meniscus, etc. To take this into account, we used to arbitrarily degrade the calculated beamlets and call the result "realistic beams" [2], [8].

With the experimental profile information, we have tried to figure out what beams are needed to reproduce the measured profile. From figure 9 the calculated power density is twice the experimentally measured one. Therefore, the simulated beamlet divergence needs to be increased. We assume that the relative starting positions of the beamlets at $z = 478$ mm are correct and adjust the steering angles to match the measured positions on the target. This resulted in calculated profiles that are too narrow at the edge and too wide in the centre (smearing out the individual beamlets). It therefore seems that a narrow beam + halo is required to match the measured profiles.

It turns out that beamlets with a divergence of around 3 mrad fit the central profile well. To match the edge of the profile, a 7 mrad halo had to be introduced. 60% of the power is in the narrow beamlets and 40% of the power is in the halo. Steering angles are within 1 mrad from the calculation, except for the vertical steering of the central beamlet, which appears almost 3 mrad higher than calculated.

Figure 10 shows the calculated and measured power density profiles overlaid. Care was taken that the absolute power density at like coloured contours is the same. It follows that excellent agreement is found.

3.6 Higher current densities experiments

There has been a limited number of shots done so far with the new “ITER-like” accelerator. They are all displayed in figure 11. All shots were done with deuterium. Caesium was gradually introduced to the source from shot number 7280 onward. At the end of the shots shown here we had introduced 1.9 g of Cs. Beam energy of 850 keV was obtained in shot 7143 with a current density of 15 A/m^2. This shot was done without caesium. Breakdown free shots with Caesium gave beams with an energy of 580 keV and a current density of 85 A/m^2.

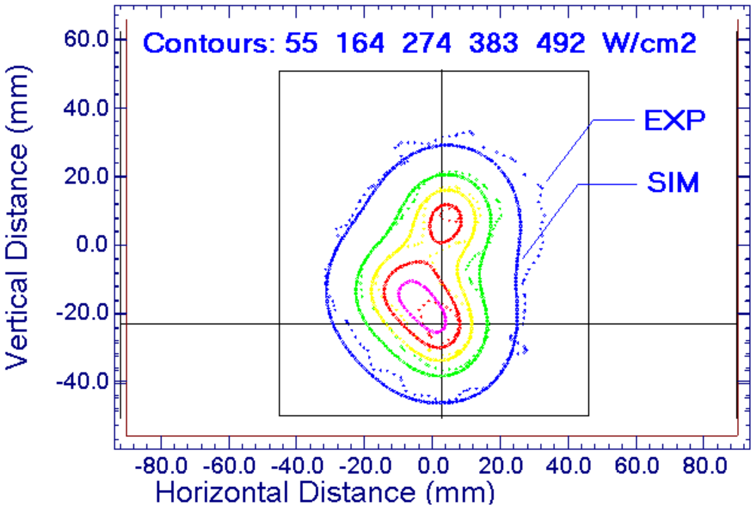


Figure 10. Overlay of a calculated profile (including halo and heat diffusion) and the measured profile of shot 7545, 1 s after the shot. The power density at equally coloured contours is the same.

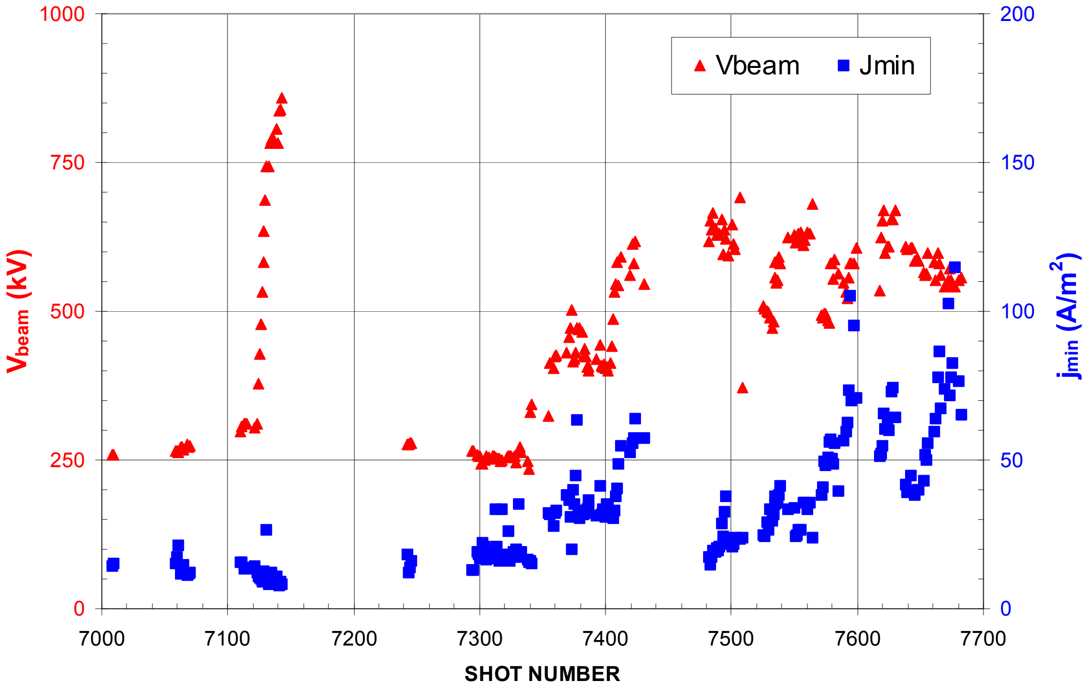


Figure 11. D$^-$ beam energies and current densities for the shots done so far with the “ITER-like” accelerator. The current densities in this graph are slightly over-evaluated due to different software being used.

4. FUTURE WORK

The first experiments have so far confirmed the simulations done for the new ITER-like accelerator. In the near future the current density will be increased as close as possible to 200 A/m^2 and 1 MeV. When that has been achieved further experiments are needed to verify the effects of the “kerbs” and also of aperture offset steering.

A final test of the SINGAP concept will be done at JAERI, Naka in Japan where a 1 MV power supply with a current capability of 1 A is available. Detail designs of how to incorporate the SINGAP system into that test bed are under way.

5. CONCLUSIONS

HV conditioning pulses have demonstrated that the ITER-like accelerator can hold 930 kV without breakdowns. Good agreement has been found between the predicted optics and the measurements done with the ITER-like SINGAP accelerator while using the plasma grid with 3 apertures. From this first simulation we conclude:

- The positions of the beamlets relative to each other are correct (within 1 mrad), except the central beamlet, which is almost 3 mrad too high.
- The widths of the beamlets are close to calculated, around 3 mrad.
- About 40% of the beam power appears to be in a 7 mrad halo.

More simulations will be done to see how well this holds over a large range of parameters.

High current density beams have been produced with caesium added to the ion source and the plasma grid heated to 230 °C. The best results so far are 850 keV D^- beams with a current density of 15 A/m^2 and with Caesium, D^- beams were produced with an energy of 580 keV and $J^- = 85$ A/m^2. The power is measured calorimetrically on the graphite target.

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