

BEAM OPTICS OF THE SINGAP 1 MeV 100 mA D⁰ DC ACCELERATOR FOR THERMONUCLEAR FUSION

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Abstract. Injection of intense neutral beams (e.g. ITER up to 50MW of neutral power) based on the neutralisation of negative deuterium ions up to energies of 1 MeV is an important option for plasma heating and non-inductive current drive in future thermonuclear fusion machines. The objective of the SINGAP experiment is to demonstrate the acceleration of 100 mA of D⁰ to 1 MeV in an electrostatic accelerator concept. It is composed of only two acceleration stages : a pre-acceleration to 60keV in a multi-aperture structure, and a post-acceleration to 1MeV. The particular feature of the SINGAP accelerator is that the post-accelerator by means of an electrostatic lens merges the 60keV beamlets into a single beam and accelerates the merged beam to 1MeV in a single gap. The present paper is devoted to the SINGAP optics study (simulation and experiment) for two geometric configurations : cylindrical and rectangular (more ITER relevant). Despite a higher measured divergence (8mrad) than expected (4-5mrad calculated) which is due to the magnetic field of the electron suppression system, this study has proved that the SINGAP concept can meet the optical requirement (divergence <5mrad) for multi-amperes injectors.

1 INTRODUCTION

Magnetic thermonuclear fusion machines have benefited extensively from neutral beam injection for plasma heating, and the physics of the generation of non-inductive current by neutral beam injection, which could be important for the next generation of machines, is well established. In the majority of the present day machines the high energy neutrals are produced by neutralisation of an accelerated positive ion beam in a gas cell. The high density large sized fusion plasmas of the next generation of machines will require neutral beams of even higher energy to reach fusion conditions, e.g. ITER requires 50 MW of 1 MeV D⁰ beams [1]. The very low neutralisation efficiency of positive ions at such high energies means that these beams can reasonably only be produced from an accelerated beam of D⁻ ions [2].

The SINGAP configuration typically consists of a positive electrostatic lens at the exit of the (multi-aperture) pre-accelerator followed by a negative lens formed by the single aperture post-accelerator electrode. The SINGAP principle has been proposed [3] as an

alternative to the multi-aperture, multi-grid [4] beam acceleration system of the ITER injector reference design. The fact that no intermediate post-accelerator potentials have to be transmitted and maintained could result in a substantial cost reduction due to the simpler high voltage power supplies, simpler accelerator grid structure, and transmission lines as well a welcome reduction in size of the high cost 1 MV ceramic insulators.

In this paper, we present the latest experimental results on SINGAP beam optics.

2 APPARATUS [5]

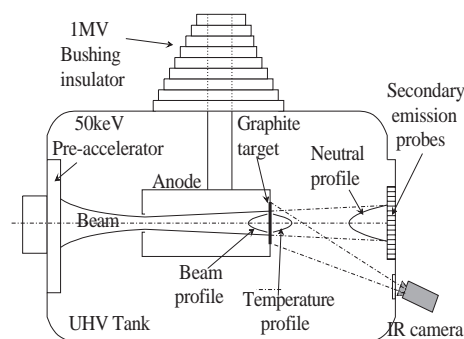


Figure 1 : SINGAP test stand

Multiple beamlets are extracted from an ion source and pre-accelerated up to 50 keV in a multi-aperture 3 grid structure, then post-accelerated to full energy (eventually up to 1 MeV) across a single gap and simultaneously merged into the single aperture (see figures 1 and 2) of the cylindrical post-accelerator electrode which is held at a positive high potential : "the anode". The anode is suspended in vacuum from the 1 MV insulator - bushing. Two diagnostics tools were applied to measure the composite (ion + neutral) or neutral beam profiles. At the end of the anode, the beam is dumped onto an inertial carbon fibre composite (CFC) target. The CFC chosen has a much higher thermal conductivity parallel to the beam than transverse to the beam, this enables the beam power density profile to be deduced from temperature measurements using an infrared camera viewing the rear face of the target. The spatial resolution at the target is $\sim 2 \times 2 \text{ mm}^2$ [6]. Moreover, a

1 mm wide slit in the cfc target allows the D^0 fast particles to leave the anode toward an array of secondary electron emission detectors located 3 m downstream from the anode. About 5% of the D^- is neutralised in passing through the anode. A measure of the current from each probe yields the neutral beam profile. A measure for the "divergence", δ , of the SINGAP beam envelope may be obtained from the profile width at the graphite target and the secondary emission detector.

Two different accelerator arrangements, cylindrical and rectangular, have been studied.

3 Beam optics study [8]

3.1 Quasi Cylindrical accelerator and beam—The first series of experiments was carried out using a configuration in which 12 beamlets were disposed in a quasi-circular array of 65 mm diameter. A near axisymmetric positive lens action on the pre-accelerated beam was achieved adding a cylindrical extension to the exit of the pre-accelerator, see Fig. 2.

Fig. 3 shows a series of experiments in which the accelerated H^- current was kept constant around 30 mA and the beam energy was varied between 400 and 700 keV. At 400 keV the beam profile at 2.63 m is near Gaussian with a footprint of nearly the same size as the initial quasi-circle of 65 mm diameter. If the acceleration voltage is gradually increased the beam profile gets larger, develops discrete structures and finally, at 700 kV, splits up into individual beamlets.

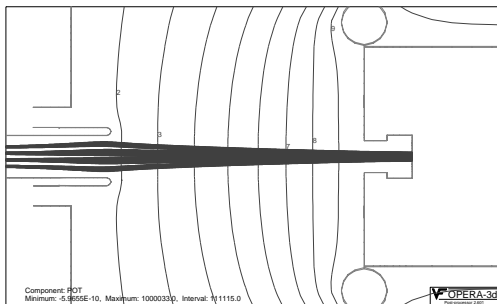
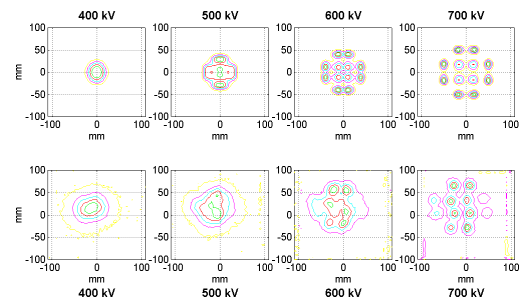


Figure 2 : Post acceleration stage ; a : cathode at ground potential ; b : pre-accelerator exit (50 keV) ; c : anode (up to 1 MeV)

Such a behaviour was predicted by 3D trajectory [7] calculations (Fig. 3 top row). It is worth noting that over the whole range of voltages applied the beam power intercepted by the graphite target is well above 90%. The horizontal displacement of alternate rows with respect to each other found in the measurement (see Fig. 3 bottom row) is due to the alternating sign of the field from the magnets in the extraction electrode of the pre-accelerator, which was not included in the calculations. Changing the electron suppression magnet configuration is envisaged to cancel this perturbation.



Figur e3 : Comparison between calculated (up) and measured (down) 30 mA H^- beam profiles

Fig. 4 shows the variation of the envelope "divergence", measured in the vertical direction with the circular configuration as a function of energy for a 25 mA D^- beam. Within the errors of the measurement a minimum envelope divergence of about 8 mrad is obtained at 260 keV. To get agreement between the measurement and the 3D trajectory simulation a beamlet divergence of 30 mrad at the exit of the pre-accelerator had to be assumed in the calculations. This rather high value is thought to arise principally from the non uniform illumination of the extraction array (see fig 3).

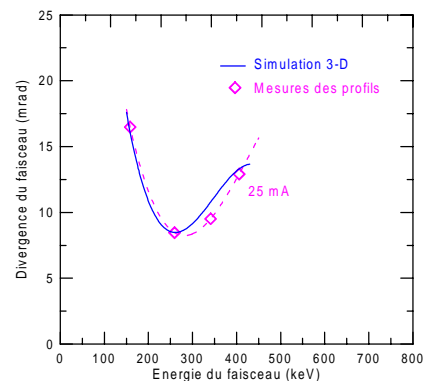


Fig. 4 : Beam divergence as function of beam energy

3.2) Rectangular accelerator and beam :

The ITER accelerator will have rectangular arrays of apertures, therefore a beam formed by 20 beamlets from two columns of ten apertures was studied. In this configuration, an asymmetric rectangular positive lens is formed by a rectangular aperture at the exit of the pre-accelerator. The anode aperture was changed to a rectangular shape, 86 mm x 300 mm (width x height), with rounded corners. (The electrode geometry was designed using a 3D trajectory code [7].) Figure 5 shows an example of a vertical profile of a ribbon shaped deuterium beam—of 430 keV, 100 mA. The cleavage in the neutral profile arises because the beam is composed of two columns. A

double Gaussian fit to the measured profile is indicated by dashed lines.

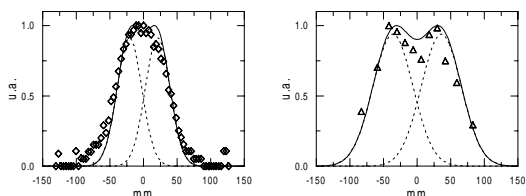


Fig. 5 :430 keV 100 mA D⁻ beam profile ; left : profile on the carbon target ; right : neutral profile on the secondary electron probes

EMBEDPerveance curves for D⁻ beams of 65 and 100 mA in the rectangular configuration are shown in Fig. 6, the "divergence" being measured in the horizontal direction. The minimum divergence (11 mrad) appears to be about 40% higher than for the circular configuration. This is thought to be due to the influence of the field from the magnets in the extractor on the ion trajectories, which acts in the horizontal direction, influencing strongly the horizontal profiles. A comparison of the experimental divergence with simulations show that whilst the measured divergence is higher than expected, the best optics occurs at the predicted energy. (The calculated divergence < 5 mrad.)

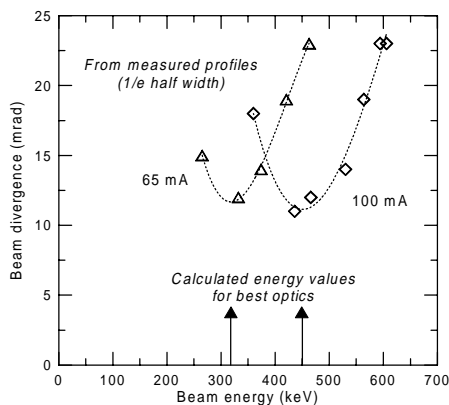


Fig. 6 : Beam divergence as function of energy for 65 mA and 100 mA D⁻ beams.

4 SINGAP perspectives

A new extraction system with a lower perturbation of the D⁻ beam is under development. The ion source has also been changed for a DRIFT source [9] to obtain a uniform negative ion flux over the whole extraction surface. Moreover, 2 epoxy ring insulators of the bushing which had been degraded [6] by high voltage breakdowns have been changed. D⁻ beam experiments at high energy (up to 1 MeV) should start again next autumn.

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