

Status of the European Concept of the 1 MV Negative Ion Accelerator for the ITER Neutral Beam Injectors

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The European concept, the SINgle GAP, SINgle APerture (SINGAP) accelerator is an attractive alternative to the reference design, the so called Multi-Aperture, Multi-Grid (MAMuG) accelerator, which is being developed in Japan. Although SINGAP has many potential advantages, the MAMuG concept is the more straightforward extrapolation from the “conventional” accelerators developed for positive ion acceleration. Before SINGAP can be confidently chosen for the ITER injectors it is necessary to demonstrate the ability to withstand the required voltage, 1 MV, over the single main acceleration gap and that the model of the beam accelerator used to design the beam optics for the ITER injectors can correctly predict the actual performance. Work with a prototype accelerator has demonstrated voltage holding of >940 kV and good agreement between the measured beam profiles and those predicted by calculation for low current density beams. Some discrepancies have been found between the predicted and measured profiles with high perveance beams but these are thought to arise from space charge neutralisation inside the prototype accelerator that is not included in the modelling. This paper describes the status of the SINGAP experiments and comparisons with modelling as well as the design of an “ITER-like” prototype accelerator in which space charge neutralisation is avoided (like the ITER SINGAP accelerator).

1 Introduction

It is recognised that the SINGAP accelerator concept offers substantial advantages over the MAMuG reference design[1] (see Table I). As a first step to demonstrating the viability of the concept a prototype SINGAP accelerator has been built and operated at the DRFC, Cadarache. Subsequently a complete design has been produced of a SINGAP accelerator for ITER[2]. The prototype differs in some significant aspects from the ITER design; see Fig. 1, and a new “ITER-like” SINGAP accelerator is being designed for testing on the 1 MV test bed. The objectives of the ongoing experiments are to demonstrate SINGAP voltage holding and beam quality at parameters as relevant as possible to those foreseen for ITER. The ITER-like prototype will aim at validating the design of the ITER SINGAP accelerator.

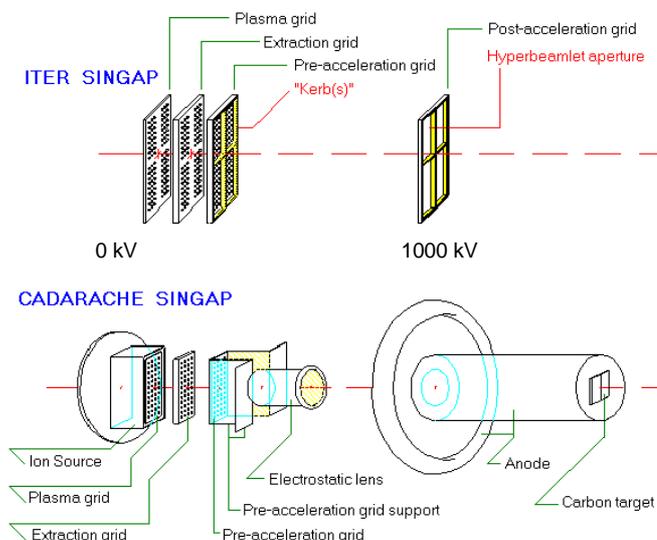


Fig. 1 Schematic of the ITER and Cadarache prototype SINGAP accelerators.

TABLE 1 COMPARISON OF SINGAP AND MAMuG ACCELERATION CONCEPT

	MAMuG	SINGAP
Stripping losses	25% of extracted current	<20% of extracted current
Electron acceleration	Most electrons accelerated to <200 keV	Electrons created in the acceleration gap are accelerated up to ≤ 950 keV.
Beam steering	Aperture offset and inclined sections needed to obtain the necessary steering. Each stage has different grids.	Offsetting the SINGAP apertures can achieve the required steering. Grid sections do not need to be inclined.
Accelerator	5 main acceleration stages => complex grid supports, connections, electrostatic screens etc.	All connections within 1 MV envelope.
Global beam aiming	Tilting of whole beam source and beam source vessel needed	Movement of the grounded grid is sufficient
1 MV power supply	Voltages of 200, 400, 600, 800 and 1000 kV needed.	Only 950 kV (pre-acceleration voltage) and 1000 kV needed.
Transmission line	Multi-way transmission line with 200, 400, 600, 800 and 1000 kV lines	Simple co-axial line (central conductor at 1000 kV)
1 MV Bushing (transmission line at high pressure to vacuum)	Must act as multi-way feedthrough for all grid voltages and cooling water for each grid.	All feedthroughs at 1000 kV

2 Dark Current

It is observed that a “dark current” flows when high voltage is applied to the prototype SINGAP accelerator without source operation, with a base pressure of $<10^{-5}$ Pa. The dark current is initially very high at modest applied voltages (300 – 400 kV), but falls with voltage on time. Investigations have begun into its cause using a “dark current probe” consisting of an isolated section of the tank wall in the form of a disk 200 mm in diameter[3]. An isolated back plate of the same dimensions is located behind the probe. Different materials have been used for the probe and the back plate, stainless steel, copper, lead, and aluminium, as well as stainless steel mesh. Of the materials tested, stainless steel (the present wall material) gives the lowest current. The current appears to be proportional to the both the cathode and anode surface areas.

Once the accelerator is conditioned to 500 – 600 kV, no further improvement with beam on time is observed, but it is found that the dark current is a strong function of the gas pressure. The pressure required to suppress the dark current increases with voltage, and at >900 kV a pressure of H_2 , D_2 or He of $\approx 2 \times 10^{-2}$ Pa (the pressure expected around the accelerator of the ITER injectors) suffices to reduce the dark current to near zero.

3 Results from the Prototype SINGAP Accelerator

3.1 Conditioning and Voltage Holding

Initially the prototype accelerator was set up with a long, 627 mm main acceleration gap, and conditioning was found to be rather rapid, requiring <130 min of voltage on-time to reach >1 MV. Subsequently the accelerator has been modified to have the same acceleration gap as the SINGAP accelerator for ITER, 350 mm. Conditioning was again straightforward and 940 kV, the present limit of the power supply, was reached in <160 min, see Fig. 2.

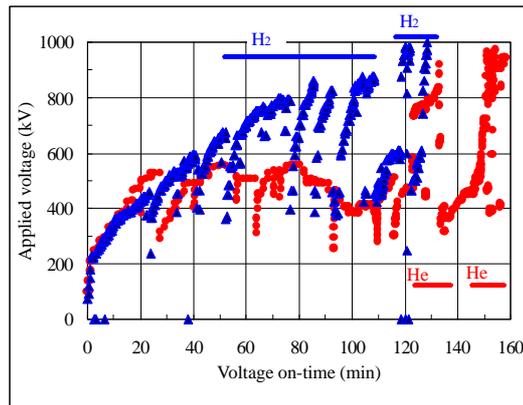


Fig 2 Conditioning curve for the prototype SINGAP accelerator with the 627 mm (triangles) and 350 mm (circles) main acceleration gaps.

3.2 D⁻ Beam Acceleration - Comparison with Predictions

3.2.1 627 mm Main Acceleration Gap

The prototype SINGAP accelerator has accelerated 33 mA of D⁻ to a world record of >900 keV, with a main acceleration gap of 627 mm, and the variation of the beam optics has been measured for a wide range of parameters such as gas type (H⁻ and D⁻), beam energy, current density and the pre-acceleration energy. The initial analysis shows a close agreement between the measured profiles and the predictions for low perveance beams see, for example, Fig. 3. However some discrepancy is found when the beam perveance is increased, see Fig. 4. It is hypothesised that the observed disagreement between predictions and measurements at high perveance is due to complete or partial space charge neutralisation in the low electric field region that exists between the exit of the pre-accelerator grid and the main acceleration gap. To confirm this hypothesis, and to verify further the ITER design, a new “ITER-like” pre-accelerator is to be built and tested at Cadarache. (Note that no such low electric field region exists in the ITER SINGAP design.)

3.2.2 350 mm Main Acceleration Gap

The main acceleration gap of the prototype accelerator has now been shortened to 350 mm, the same as that of the ITER SINGAP design. This has allowed the voltage holding of this gap to be demonstrated (see section 3.1) and beam acceleration experiments have begun. The initial results are very encouraging, with D⁻ beams of >575 keV being rapidly produced. Good agreement is again found for the low perveance beams so far produced, see Fig. 5. With the shorter gap the beamlets are more separated because the shorter gap increases the strength of the electrostatic lens at the exit of the pre-accelerator. In fact it can be seen on Fig. 5 that the edge beamlets are starting to miss the target. To ensure that the beamlets remain on the target as the beam energy is increased, the accelerator has been modified so that only the central 4 beamlets are produced. This will also allow higher current densities to be accelerated whilst remaining within the 100 mA current limit of the 1 MV power supply. After 1 day of experiments with the modified accelerator, the beam energy was increased to ≈760 keV, although at low current density, 8 A/m². Unfortunately the system had then to be let up to air to change the filaments as one had failed. Operations have now successfully recommenced and beams of 849 keV have been produced at a current density of ≈20 A/m².

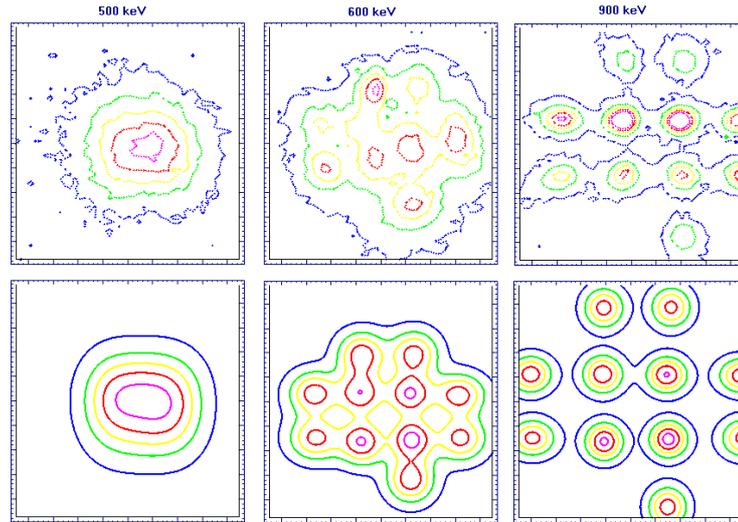


Fig 3 Measured (upper row) and simulated (lower row) beam profiles measured 2.00 m from the accelerator with the 627 mm gap, D . Beam parameters: left 500 keV, 37 A/m^2 , middle 595 keV, 9 A/m^2 , right 914 keV, 20 A/m^2

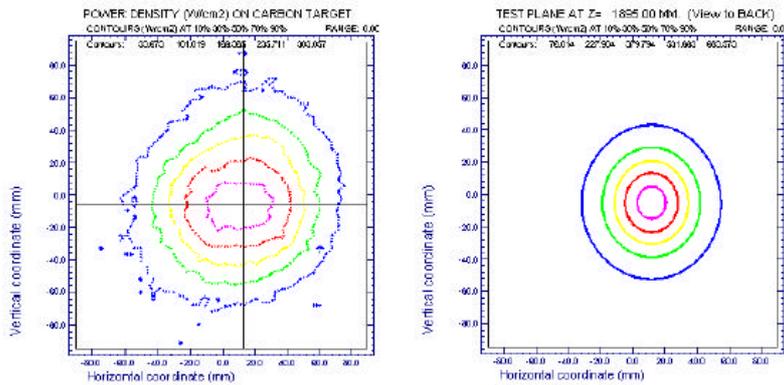


Fig. 4 Measured and predicted beam profiles 2.00 m from the accelerator with "high" perveance, D . Beam parameters: 50 A/m^2 , 400 keV. The measured profile is quite broad and inconsistent with the calculation, which predicts a rather peaked profile.

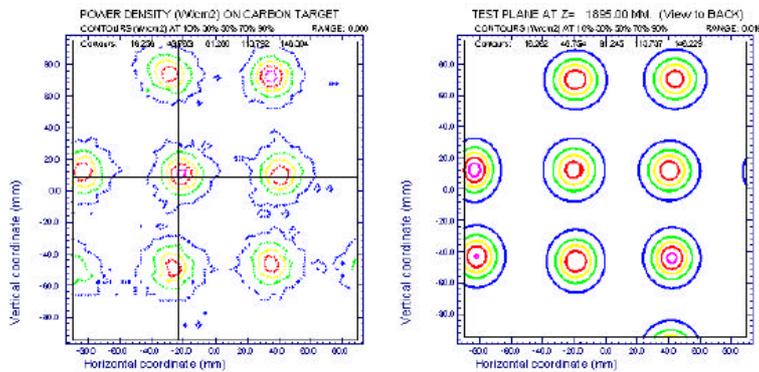


Fig. 5 Measured and predicted beam profile with 350 mm gap, 2.28 m from the accelerator, D , 575 keV, 9 A/m^2 .

4 The “ITER-like” SINGAP accelerator at Cadarache

As mentioned in section 3.2.1, an “ITER-like” prototype SINGAP accelerator is to be built and tested at Cadarache, which has the following main features:

- 5x5 aperture array with geometry identical to that of the ITER SINGAP accelerator.
- “Kerbs” fixed to the downstream side of the pre-acceleration grid as per the ITER SINGAP. These are demountable to allow various geometries to be tested.
- The final “SINGAP” electrode is moveable across the beam axis to allow global beam steering by aperture displacement to be demonstrated.

The apertures on the plasma grid are 14 mm in diameter, so each will produce >30 mA if the accelerated current density is 200 A/m^2 (the ITER design value). Therefore, to remain within the current limit of the Cadarache 1 MV power supply, 100 mA, only 3 of the possible 25 apertures will be used for high current density studies. Simulations have shown that several arrangements with 5 apertures should be used to demonstrate various aspects of the beam and beamlet optics. A new negative ion source will be built to be used with the ITER-like accelerator in order to allow repetitive high power operation, which is not possible with the existing ion source.

5 Summary

- Voltage holding of >940 kV has been demonstrated across the single 350 mm main acceleration gap with gas pressures relevant to those anticipated for ITER.
- A relatively high dark current is observed on the Cadarache 1 MV test bed that impedes accelerator conditioning. However this current is suppressed when the pressure in the accelerator is raised to the level expected for the ITER accelerator after initial conditioning under vacuum up to $\geq 500 \text{ kV}$.
- With a main acceleration gap of 627 mm D^- beams of >900 keV, 30 A/m^2 and 600 keV, 74 A/m^2 (both world records) have been obtained.
- With the ITER gap of 350 mm D^- beams of $\approx 760 \text{ keV}$, 8 A/m^2 and 849 keV, $\approx 20 \text{ A/m}^2$ have been obtained. Ongoing experiments aim at increasing the beam energy and the accelerated current density to near the ITER parameters, 1 MeV and 200 A/m^2 .
- For low current density D^- beams, good agreement is found between predicted and measured beam profiles at the calorimeter, $\geq 2 \text{ m}$ from the accelerator for both acceleration gaps tested, 627 and 350 mm.
- Some discrepancies between prediction and measurement have been identified with “high” perveance beams. This is believed to arise from partial space charge neutralisation in the prototype accelerator.
- An ITER-like SINGAP prototype accelerator is to be built to verify the ITER SINGAP accelerator design and the aforementioned hypothesis.

6 References

- [1] Inoue, T. et al., “Design of neutral beam system for ITER-FEAT”, Fusion Engineering and Design, 56-57 A (2001) 517.
- [2] De Esch, H. P. L. et al., “SINGAP: the European Concept for Negative Ion Acceleration in the ITER Neutral Beam Injector”, Rev. Sci. Inst. 73 (2002) 1045.
- [3] Massmann, P. et al., “Voltage Holding and Dark Currents in the Cadarache 1 MV Ion Beam Facility”, XXth ISDEIV, Tours, France, (2002).