CADARACHE 1MeV NEGATIVE ION ACCELERATOR DEVELOPMENT FOR APPLICATION IN THERMONUCLEAR FUSION RESEARCH

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Abstract

Additional plasma heating in the new generation of large magnetic fusion devices like ITER requires deuterium atom beams of about 1MeV at a total neutral power of >50MW based on negative ions. At Cadarache, ITER relevant research is performed regarding the development of a 1MeV high beam current density (10-20mA/cm^2) electrostatic accelerator (SINGAP). The SINGAP experiment consists of the acceleration to 1MeV of a substantial D^- current (100mA) in a simplified accelerating electrode structure. This is composed of only two acceleration stages: a pre-acceleration to 60keV in a multi-aperture structure for ion extraction and electron suppression, and a post-acceleration stage 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. Subjects of the study are the voltage holding at 1MV with large electrode areas (about 60m^2) and insulators in vacuum in the presence of an intense ion beam and radiation. The first experimental results of SINGAP are very encouraging. Up to now, H^- beams of 40mA have been accelerated to 915keV.

I INTRODUCTION

The objective of Fusion research is to produce plasma conditions under which thermonuclear power is produced. In magnetic confinement systems such as the Tokamak, this requires the plasma to be heated to an ion temperature of the order of >10keV. One method currently used for plasma heating is the injection of beam of energetic atoms, which transfer their energy by collisions to the plasma particles. The new generation of large magnetic fusion devices requires deuterium atom beams with energies in the range 0.5-1MeV and power of tens of MW; ITER for instance requires steady state 50MW D^0 beams at 1MeV energy [1]. These high energy neutral beams are created by charge exchange of 1MeV negative ions with deuterium molecules in a gas cell (called the neutralizer). High quality beam optics with low divergence (< 5mrad) are required, because the accelerator has to be installed about 25m from the Tokamak.

The research in the field of Neutral Beam Injection (NBI) focuses on the development of large area high current density negative ion sources, and the development of DC electrostatic high power high energy accelerators.

In this paper, we present a 1MeV 100kW electrostatic accelerator (SINGAP) which has been in operation since September 1995. The objective of the SINGAP accelerator is to demonstrate for the ITER NBI system design the acceleration of a substantial D^- current (100mA) in a simplified scaleable accelerator concept. The SINGAP is a long pulse (several seconds) electrostatic accelerator composed of two acceleration stages: a pre-acceleration stage up to 60keV in multi-hole structure for ion extraction and electron suppression, and a post-acceleration stage to 1MeV. The particular feature of the SINGAP accelerator, is that the post-accelerator merges by means of an electrostatic lens the 60keV beamlets in a single beam, thus accelerating the whole beam to 1MeV in a single gap. After a brief description of a standard NBI system, we present in the second part of this paper the SINGAP concept and the very encouraging experimental results obtained up to now.

II NEUTRAL BEAM INJECTOR BASED ON NEGATIVE IONS

Electrostatic acceleration has up to now demonstrated its reliability and efficiency in the 20-160keV DC NBI systems based on positive ions (at JET for instance: 14keV, and 25MW of D^0 [2]).

But for higher energy, their neutralization efficiency in a gas target drastically decreases, in constrast to Negative Ions (about 60% at 1MeV).

NI are formed in a cesiated cold plasma (a few eV), which is confined in a multi-cusp ion source. The ions are then extracted from the plasma and accelerated in independent channels (several tens or hundreds), to form so called beamlets. The geometry of one beamlet, shaping and gap distances, is designed by 2D and 3D space charge simulation codes [3]. The accelerator is composed of copper plates (grids) in which matrices of cylindrical apertures are drilled. The first grid separates the source plasma from the accelerating column, and is at source potential. The second grid (extraction grid) has two functions: 1) to extract negative ions following the Child-Langmuir law [4] : $I_{D-} \propto V^{3/2}$ in the range 5-10keV; 2) to stop the plasma electrons extracted simultaneously with the negative ions (typically from 1 to 5 electrons per ion), in order to prevent them from being further accelerated.

The electron suppression efficiency must be as high as possible (near 100%) [4]; this is realized by deflecting the electrons out of the beamlet by permanent magnets inserted in the grid. The extraction grid design is determined by a 3D electron trajectory code which takes into account the secondary emission and backscattered electrons. The third and following grids are the accelerating grids which give the relevant energy to the ions. After acceleration, the beam passes through the neutralizer gas cell. After the neutralization, a last device (Residual Ion Dump: RID) is necessary to deflect out from the neutral beam the residual positive and negative particles (for ITER: about 20% for each species). The total NBI system efficiency is in the order of 25% at JET (140keV and positive ions), and estimated at about 35% at 1MeV.

III 1MeV ACCELERATOR FOR ITER

Two different designs are proposed for ITER:

1. Multi-grids concept:

A Multi-Aperture MUlti-Grid (MAMUG) system is proposed by JAERI (Japan) [5]; it is composed of 5 large post accelerating grids (area about $1m^2$, and 200kV per grid) where 1300 beamlets (30mA of D^- per beamlet) are accelerated independently to 1MeV.

2. SINGAP concept:

In this case, 1300 negative ions beamlets are in a first step pre-accelerated at 60keV with a multi-aperture grid system, and then merged by means of positive electrostatic lenses into 25 beams and accelerated up to 1MeV in a single gap [6]. This concept allows a consistent simplification of the system, it provides also a high neutral gas pumping speed necessary to reduce beam losses (stripping), with subsequent reduction of the costs.

IV THE SINGAP EXPERIMENT

The experiment has several purposes: firstly, to study the high voltage problems: HV holding under vacuum in the presence of an intense ion beam and radiation plus the development of critical 1MV devices (large insulators, bushing, etc.); secondly, to demonstrate the feasibility of the SINGAP concept for high current beams (up to 40A of D^- with high current densities about 20-30mA/cm^2) in the 1MeV range.

Figure 1 shows a schematic of the experiment: the pre-acceleration stage with the ion source on the left, where negative ions are produced and pre-accelerated in 12 beamlets up to 60keV. Then, an electrostatic lens merges these beamlets into a single beam which is accelerated in a single gap (see figure 2) toward the high voltage electrode (anode). This electrode is suspended in vacuum by a 1MV feed-through insulator (bushing). The ion beam is finally dumped onto an inertial monodirectional graphite (CFC) target closing the exit of the anode. An infrared camera located outside the tank monitors the rear face of this target, and records in real time the temperature profile from which the beam power density can be derived.

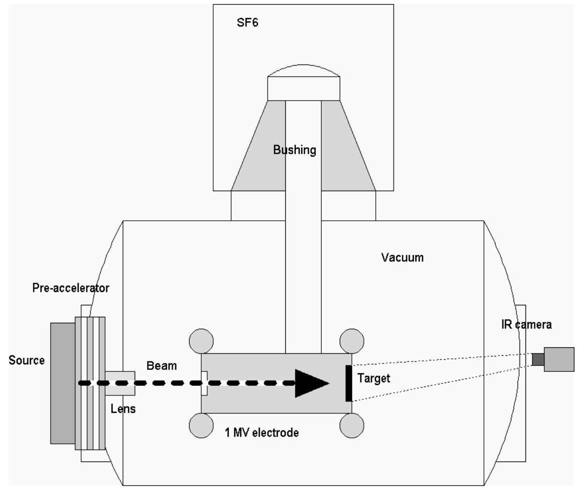

Figure 1. The Cadarache "SINGAP" experiment

The bushing is an important device; it has to sustain 4 bars of SF_6 externally (transmission line from the power supply) and the internal vacuum; it is located about 3m away from the accelerator and beam, minimizes the radiation and particle bombardment rates.

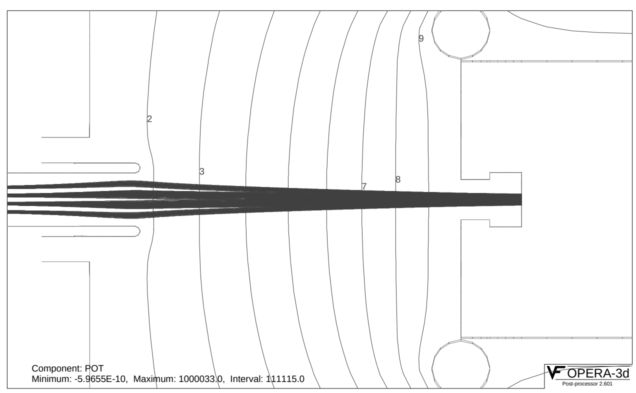

Figure 2: A 3d simulation of SINGAP post-acceleration (electrostatic lens on the left, anode on the right)

V MAIN EXPERIMENTAL RESULTS OF SINGAP

A. High Voltage conditioning:

<u>Dark current</u>: One characteristic of this experiment is the large electrode dimensions (about $60m^2$ cathode, and $5m^2$ anode); these dimensions are comparable to those required for ITER injectors. The application of voltage on the anode gives rise to a "field emission-like" electron current (dark current), associated with outgassing and intense luminescence at the most stressed electrode surfaces [7]. For a given state of conditioning, the dependence of the dark current on the applied voltage has the same functional behavior as the Fowler-Nordheim field emission law but the emission level is larger by orders of

magnitude; the average applied electric field being 2MV/m.

(1) $I = AV^2 \exp(-B/V)$

It was also observed that the coefficients A and B in (1) are strongly dependent on the pressure in the tank, and on the total voltage on-time whose effects are to reduce the dark current level. The 1MV was consequently achieved at a helium pressure of 10^{-4} mbar in the tank. After about 2000s of voltage on-time, the 700kV is reached with a pressure of 10^{-8} mbar, and a dark current level of 100mA (maximum current of power supply). We notice that during high voltage conditioning, very few breakdowns occur.

Electrostatic stored energy: Due to the large electrode dimensions, the stored electrostatic energy is about 300 Joules. This energy released during breakdowns has not induced apparent damage on the electrode metallic surfaces. However, in a series of experiment, a degradation in the high voltage holding occurred at 900kV. Important damage (perforations) was observed on the two upper insulator rings (glass epoxy). This seems to have two reasons: 1) a non-uniform distribution of the potential between the different stages of the bushing insulators (despite a resistor divider of 100MΩ per ring) due to intermediate screens (now removed) which intercepted an important fraction of the dark current; 2) a faulty construction of the rings (voids in the epoxy insulator).

B. Beam Acceleration:

Figure 3 shows the beam profile (recorded by the infrared camera on the rear face of a CFC target) for four beam energies (from 400keV to 700keV), and profiles obtained in the same conditions by simulation. At low energy (400keV) the energy is matched to the current density ($4mA/cm^2$): the 12 beamlets are well focused by the lens (beam divergence less than 5mrad). At 700keV, the beam is "over-focused", and the beam is split into 12 discrete beamlets. We can find a good agreement between experimental profiles and simulation. Up to now, H^- beams of 915keV 40mA have been achieved.

C. Neutral beam analysis:

A partial neutralization (5-10%) of the D^- beam occurs in the anode due to the residual gas. A preliminary measurement of the divergence of these neutrals emerging through a slot in the target has been made by an array of secondary emission probes located 3m downstream from the anode. Divergences of the order of 0.34° (6 mrad) have been measured from beams of low energy: 500keV-45mA D^- in accordance with the predictions.

D. Next step:

Having replaced the damaged insulators, we are now trying to achieve a D^- beam of 1MeV 100mA. Neutralization of 1MeV beam and study of the neutral optics will also be undertaken to demonstrate that SINGAP is scaleable for higher current (several tens of amperes) for ITER. This experiment should take place before the end of this year.

VI CONCLUSION

Up to now, despite some problems due to DC high voltage (dark current, damages of insulators), which should be resolved soon, this first step of experiment is very encouraging. Negative ion beams (40mA H^-) have been accelerated up to 915keV This experiment has up to now demonstrated that the SINGAP concept is a good candidate to meet the objectives for ITER NBI.

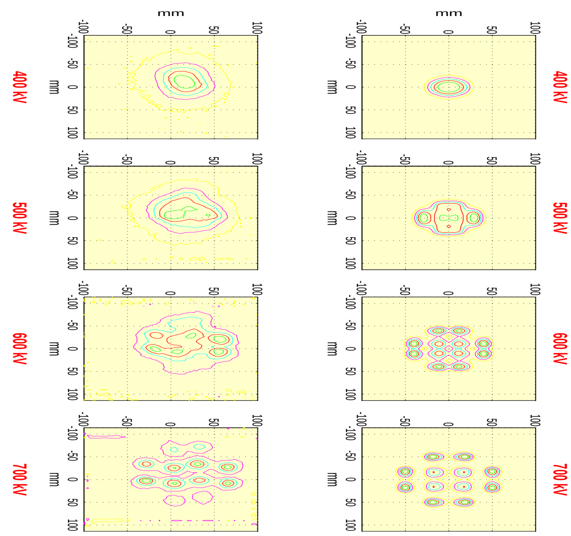

Figure 3: Beam profile (experiment and simulation) for different energies at the same D- current.

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