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Citation: *Rev. Sci. Instrum.* **61**, 389 (1990); doi: 10.1063/1.1141301

View online: <http://dx.doi.org/10.1063/1.1141301>

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Development of H^- and D^- ion sources for plasma heating

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(Presented on 12 July 1989)

The large size of future, and possibly present day, tokamaks requires high neutral atom beam energies for current drive and heating. These injectors must also have a high electrical efficiency and this can be achieved using negative ion sources to create the beam. These large tokamaks, such as ITER or NET require a neutral beam power of around 50–100 MW at beam energy of 1 MeV of D^0 . This power is achieved by operating several sources in parallel, each one of which would extract a 28-A beam of D^- ions of which 57% are converted to D^0 in a gas cell neutralizer and can be transmitted to the torus. The injector for one port consists of four units, each of which is a fully independent unit. This article describes the details of the injector unit which is based on volume plasma sources of D^- ions.

INTRODUCTION

The basic design philosophy is one of modularity and conservative engineering. The injector is subdivided into smaller modules to minimize the unit size and the very long pulse length (several hours to two weeks) demands high reliability which can only be achieved if all components are not highly stressed. An additional feature of the proposed design is to make maximum use of the existing experimental database and technology.

In keeping with this philosophy we have chosen a design where the entire injector is at the end of a long narrow beam-line as shown in Fig. 1. The injector is formed from four modules, each giving a 13 MW beam of D^0 atoms at 1 MeV. Such a design keeps all elements of the injector as far as possible from the torus (55 m in this design) which reduces the neutron flux but demands that the beam divergence is low, ~ 1 mrad. This value is close to that already achieved in experiments with H^- beams at 100 keV (2.5 mrad) at Culham. The modules are independent and can be isolated and removed for repair. The duct contains no beamline elements.

I. THE INJECTOR MODULE

In Fig. 2 is shown a close-up view of a single module. The need for a high-voltage external insulator is eliminated by choosing a grounded source design. This also has the further advantages of simplifying the arc power supplies and control system and eliminating the need for a high-voltage platform and transformer, both of which would be very large at a potential of 1 MV and have a large stored energy. However, the neutralizer is hence at +1 MV relative to earth and has to be surrounded by a series of closed shields only perforated in the beam channel which prevents long path breakdown. These shields are only linked resistively to the accelerator to dissipate their stored energy of ~ 30 J/shield and each shield corresponds to the potential of an accelerating electrode. The cooling and services are brought in the core of a pent-axial line, the inner core of which is surrounded by a 20-m-long by 50-cm-diam toroidal snubber which limits the peak fault current to ~ 275 A at 1 MV for about $8 \mu\text{s}$. The

outer shields of this line are insulated with SF_6 and correspond in potential with the shields around the neutralizer.

The neutron flux has been calculated by a Monte-Carlo code and has a value of 6×10^{13} n/s at the source arising mainly from back-streaming from the torus but having

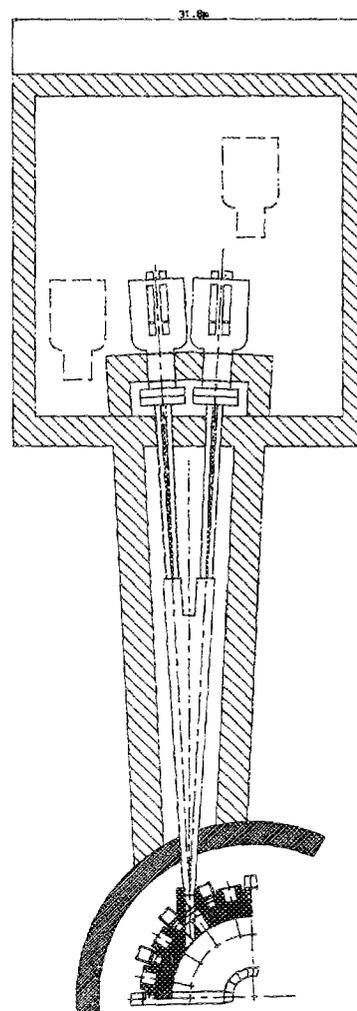


FIG. 1. Plan view of the beamline showing the injector modules and beam ducts to the NET torus.

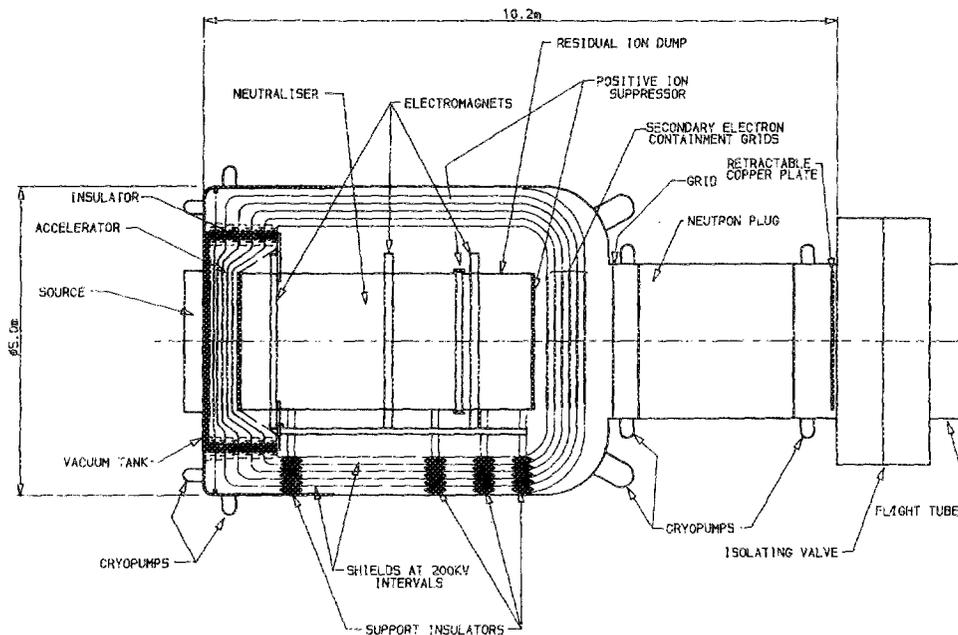


FIG. 2. Cross-section view of the injector module which produces 13 MW of D^0 atoms at an energy of 1 MeV.

~30% generated by $d-d$ reactions in the neutralizer tube walls. The flux has been attenuated by the long beam path and by the neutron plug shown in Fig. 2 which has small perforations to permit passage of the beam. The dominant activation channels are via the $Co^{59}(n,\gamma)$ reaction in the permanent magnets in the source and accelerator and by the $Cu^{63}(n,\alpha)$ reaction which also forms Co^{60} .

Gas handling is via two sets of cryo-sorption pumps which interchange every hour to give continuous operation. The pumps are divided into 10 units of 10^5 l/s each and the first two units pump the first acceleration stage (to 60 keV), two more pump the rest of the accelerator, a further four units pump the neutralizer gas at the far end and the remaining two reduce the duct pressure to $\sim 2 \times 10^{-6}$ to minimize reionization. The neutron plug and these pumps virtually prevent migration of tritium into injector; only 85 mg being pumped in a two-week pulse by the pump upstream of the neutron plug.

II. THE PLASMA SOURCE

The chosen plasma source for this injector design is the so-called "volume" source where the D^- ions are made by dissociative attachment in the plasma volume. This type of source is almost identical (except being larger) to the multipole positive ion sources such as those on the JET or TFTR injectors. The only significant differences are the inclusion of a magnetic "filter" which separates the electron emitting filaments at the back of the source from the extraction plane at the front.

Experimental work on large sources of this type (i.e., $55 \times 31 \times 21$ cm³) has shown that significant current densities of D^- ions can be extracted (Lea *et al.*, the proceedings) at an optimum operating pressure of 10 mT when stripping losses in the accelerator are included. If this performance is extrapolated to the size required for an injector module then two sources of dimensions $2.3 \times 0.55 \times 0.21$ m³ are needed of which each has a 2200-A discharge at 100 V. This would

provide 17 mA/cm² of D^- ion current density which is attenuated to 11 mA/cm² (see next section) after stripping. The total extraction area of the two sources provides a total accelerated beam current at the accelerator exit of 28 A.

The electrons are suppressed by a thin sheet of magnetic field sandwiched between two layers of current-carrying rods and experiments by Lea *et al.* have shown that the extracted electron current is proportional to $1/B^2$ and is five-fold the D^- current when $B = 200$ G.

III. THE ACCELERATOR

An illustration of the accelerator is shown in Fig. 3. It consists of a set of flat accelerator electrodes which both accelerate and collimate the beam via the circular lenses created by changes in the axial electric field. The total aperture array is 1120 circular holes of 12 mm diam arranged in groups of 4 in a total pattern of 7×40 groups for each of the two sources.

The electron current is reduced by the suppressor field described above and the remaining electrons are extracted across the first gap where they are deflected by an additional magnetic field at the upstream edge of the second electrode. They are dumped on highly cooled strips within the second electrode as shown in Fig. 3. The total electron power is determined by the ratio of aperture radius to extraction gap which has to be less than 0.5 if aberrations are to be avoided and also the beam perveance density which controls space charge expansion. This results in a first gap extraction voltage of 9 kV, resulting in an electron power density of ~ 600 W/cm² on the dump. The beam is mainly collimated by the combination of potentials on the second and third electrodes and results from the AXCEL code predict a 55-kV potential for the latter. Thereafter there is an essentially uniform electric field with electrodes at 200, 400, 600, 800, and 1000 kV. The final divergence angle is predicted to be 1 mrad and is mainly controlled by the beam emittance.

A major problem in the accelerator design is caused by

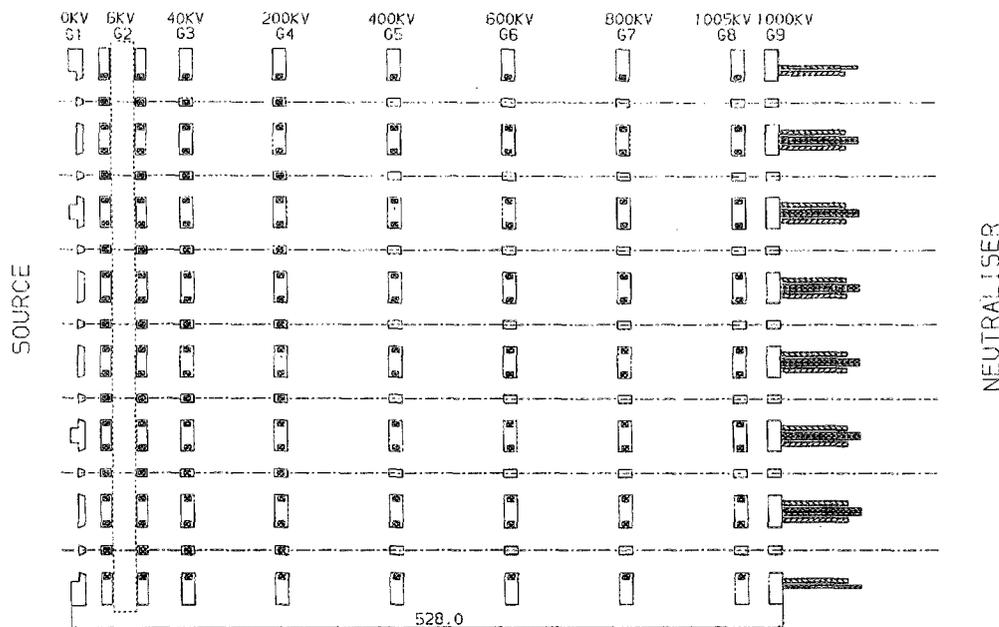


FIG. 3. Illustration of the accelerator geometry showing magnetic suppression of the electrons.

the gas exhaust from the source which induces stripping of the D^{+} beam. A 2D Monte Carlo code has been used to analyze this problem and predicts that the optimum arrangement of pumps and apertures is to arrange the apertures in 7×40 groups of 4 holes and use by-pass pumping. A gas-tight membrane is connected from the third electrode to the tank wall and isolates the gas in the first two gaps from the rest of the accelerator and pumps it by two pumps of 10^5 ℓ/s each. The gas flow into the rest of the accelerator is reduced drastically by this differential pumping technique and hence confines virtually all losses to the first two gaps. This results in a total loss of 36% of all D^{+} particles and 1% of the total energy (as the resulting electrons are mainly collected on the second electrode at 9 kV). The gas exhaust is 123 Torr ℓ/s for a source pressure of 10 mT.

IV. THE NEUTRALIZER

In the present design a gas cell neutralizer has been selected which gives a maximum conversion efficiency of 57% of D^{+} to D^0 at 1 MeV. In order to avoid the complexities of the large scale bending magnet and beam dump such as those

existing in present-day injectors, an integrated neutralizer and dump has been designed as shown in Fig. 2. This consists of an array of center fed gas filled tubes of 42 mm diam and 3 m length to give a target of 1.5×10^{20} mol/cm². Each tube is filled with a group of four beamlets arranged in a square and corresponding to the pattern of holes in the accelerator. The beam dump is a further array of tubes which are cooled by an external water jacket to handle 1 kW/cm² and are coaligned with the neutralizer. The unneutralized ions are deflected by a simple "window-frame" dipole magnet giving an 8° bending angle. A further magnet is located at the upstream edge of the neutralizer as an alignment/steering magnet.

This design has three clear advantages, it is significantly more compact than the single neutralizer duct design, it has a large cooled surface, hence reducing beam power density problems, the gas exhaust is reduced significantly and it provides a measure of neutron shielding.

The overall efficiency of the injector (excluding power supply efficiencies) is 0.45 with a gas cell and this would rise to 0.65 with a plasma cell which is essentially a large plasma source. A major element in the long-term program for the development of these injectors should be the testing of a plasma neutralizer as this can enhance the input D^0 power into the torus by $\sim 50\%$ for a given investment in power supplies.