Direct Energy Conversion Beam Dump for a 1.6 MeV Neutral Beam for the International Thermonuclear Experimental Reactor (ITER)

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Abstract

A beam direct converter of the Kyoto type that uses magnetic separation of the D^+ and D^- leaving the neutralizer, is adapted to a Lawrence Berkeley Laboratory concept of a neutral-beam injector for the International Thermonuclear Experimental Reactor, which used electrostatic separation of the D^+ and D^-. Among the advantages of a direct converter over an ordinary beam dump for the residual D^+ and D^- beam leaving the neutralizer is that the power density on the beam dump is reduced by a large factor, making heat removal easier. Further, "soft landing" virtually eliminates deuterium-deuterium neutron production on the dump electrodes, a particular advantage in the development stage. In addition, the total power consumed is less. This paper addresses the technological obstacle to feasibility, which is holding the large voltage (+1.6 and -1.6 MV for a 1.6-MeV neutral beam). The electrode system in the present design uses 15 grading electrodes around each 1.6 MV collector with 100 kV between them. Each grading electrode is subdivided into two. The total stored energy is 260 J (4 J per electrode) and an average of 10 kV/cm on the insulators. The calculated efficiency is 92%.

Introduction

The Lawrence Berkeley Laboratory (LBL) negative ion neutral-beam injector for the International Thermonuclear Experimental Reactor (ITER) at 1.6 MeV is shown in Figure 1.[1] The region containing the electrostatic deflector plates and beam dump (circled in the figure) could be replaced with electrostatic plates plus high-voltage collector plates, as shown in Figure 2. These high-voltage collector plates turn this beam dump into a direct energy converter of the in-line type without the use of grids that intercept beam particles and limit beam power.[2,3] Fumelli's early work[4] used the inline concept but with grids. Later he adopted the in-line concept without grids[2,3] on his beams for Tore Supra.[5] The state of the art has considerably advanced with direct conversion systems handling beams of up to 3 MW of power.[6]

In this work, we assume the power carried by the neutral beam is 4 MW; the charged component is also assumed to be 4 MW, split evenly, although not necessarily evenly between D^+ and D^-. By varying the neutralizer density, the D^+/D^- ratio can be changed. Hopman proposes using an under-dense neutralizer, resulting in a larger fraction of the beam in the D^- state.[7] While the efficiency of that system is slightly lower, the negative-voltage recovered power is more useful, and less gas pumping is necessary than with an even split. Because the beam is very narrow, over 90070 of the beam power is within ± 7 cm. The beam length is 2.4 m.[8] The D^+ beam current is 1.25 A (2 MW/ 1.6 MeV) over the 2.4-m length, or 0.52 Aim. The D beam current is equal to this value.

Rather than deflect the ions with a magnetic field, as in the Kyoto-type[9] direct converter, we employ electrostatic deflection, as in the LBL design (Figure 1). The use of electrostatic deflection avoids the problem of electrons being trapped and forming a Penning discharge and avoids a large heavy magnet. This design, while independently carried out mostly in 1988, uses the same configuration as that now published by Pamela and Laffitel[10] at Cadarache. Pamela and Laffite's paper goes into more detailed analysis of loss mechanisms, and they have proposed ways of greatly reducing secondary emission losses from the negative electrode. This paper emphasizes a way to handle the extremely large voltage on electrodes and to prevent catastrophic sparking damage.

A version of this design is shown in Figure 3. Figure 4 shows the insulators that bring in the + 1.6 and -1.6 MV.

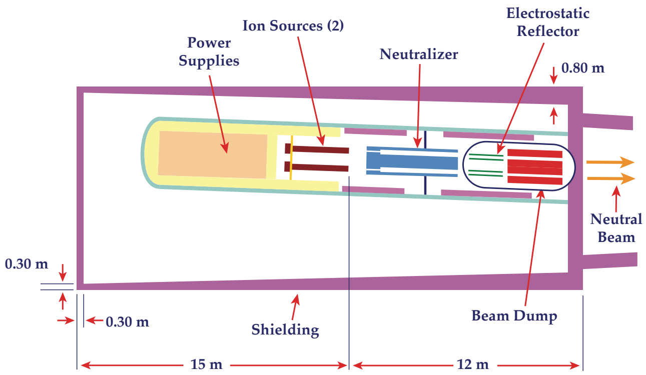

Figure 1 — The LBL negative-ion-produced neutral-beam design for ITER. The un-neutralized ions are bent into a beam dump. Later versions of the design employ magnetic deflection. Encircled area is shown in greater detail in Figure 2.

A top (end) mounting would use space more efficiently than side mounting. The large insulator and electrodes are mounted on a removable top flange plate (not shown). The preferred insulator design, with all parts identical (shown in Figure 5), is based on an average of 10 kV/cm along insulators and 50 kV/cm in vacuum. Figure 6 shows a tapered insulator design. Air pressure of 1 atmosphere puts the ceramic in tension. The central electrode could be pre-tensioned to put all the insulators in compression, and then the insulator configuration could be inverted so that atmospheric pressure would put the insulators in compression.[11]

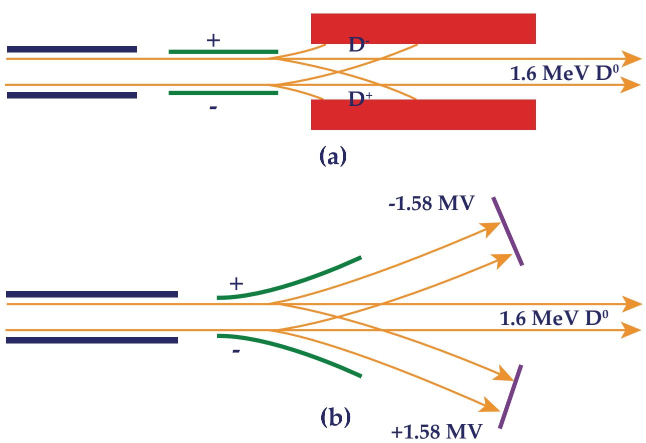

Figure 2 — (a) The electrostatic deflector beam dump is replaced by (b) a curved electrostatic deflector with collector plates at voltages just below the beam energies.

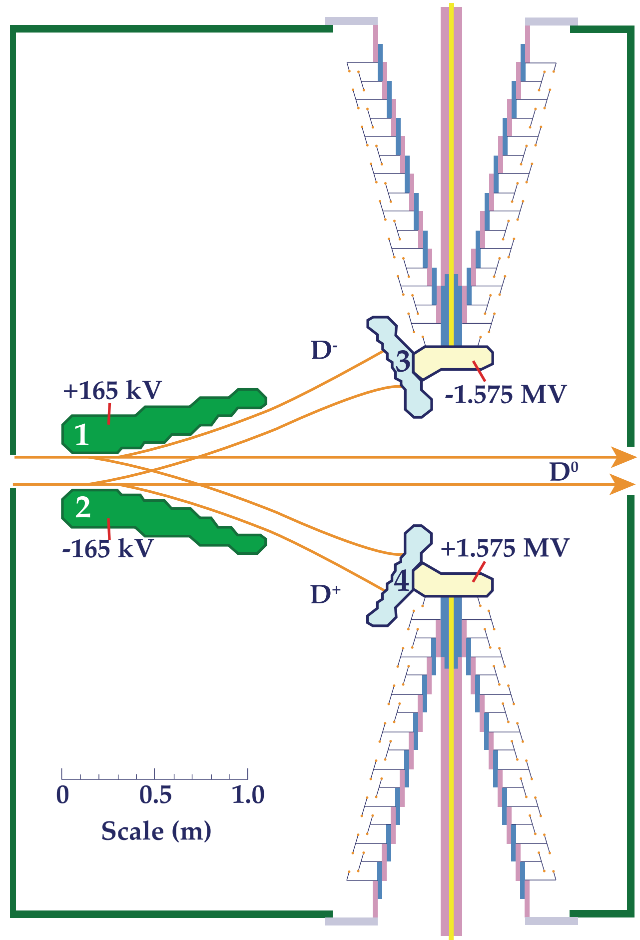

Figure 3 — The electrode design shown in a form useful for DART code calculation.

Some results of trajectory calculations using the DART code[12] are shown in Figure 7. Minimizing loss on the deflector plates requires a large gap between the plates so that no incoming beam will be intercepted, while minimizing deflector voltage requires a small gap (20 cm, ± 165 kV). The gap shown has no intercepted current. Some electrons might be mixed with the entering beams of charged and neutral particles. These electrons can be prevented from entering the deflector region by designing the potential to drop somewhat after the neutralizer and before the deflector.

The trajectories of the secondary electrons produced on the negative electrode are calculated and shown in Figure 8. The equipotential contours are shown in Figure 9. The shape of the negative electrode (No. 3) and electric fields are such that the secondary electrons do not go to either of the positive electrodes (Nos. 1 and 4). The calculated efficiency of turning kinetic energy of the positive and negative beams into electrical energy is 76%. The charged beam power is 4 MW, of which 3.06 MW is recovered electrically. Fumelli, Jequier, and Pamela[13] have developed an electron emission suppression method using segmented electrodes that capture about 70% of the secondary electrons. Such a method used on the negative electrode (No. 3) is calculated to increase the efficiency from 76 to 92%.

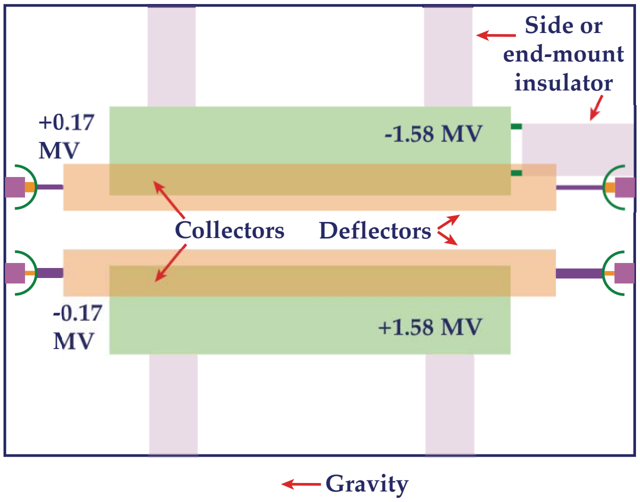

Figure 4 — The insulator support system. Either a side mount or end mount (hanging) configuration would be used. The end mount (Figure 5) seems more practical.

Efficiency Calculations

For illustrative purposes the efficiency calculations are given below:

$$\eta = \frac{1575\ keV\ x\ 0.52\ A/m + 1575\ keV\ x\ 0.2709\ A/m + 165\ keV\ x\ 0.1617\ A/m}{2\ x\ 1600\ keV\ x\ 0.52\ A/m} = 0.76$$

(1)

The secondary emission current from electrode No. 3 is (0.52 - 0.2709) 0.249 A/m, of which 65% strikes electrode No. 2. If the secondary emission current can be suppressed to 0.3 of its value, then the current to electrode No. 3 becomes 0.075 A/m and that to electrode No. 2 becomes 0.05 A/m. The efficiency then becomes

$$\eta = \frac{1575\ keV\ x\ 0.52\ A/m + 1575\ keV\ x\ (0.52\text{-}0.075)\ A/m + 165\ keV\ x\ 0.05\ A/m}{2\ x\ 1600\ keV\ x\ 0.52\ A/m} = 0.92$$

(2)

The loss due to secondary electrons from electrode No. 2 to electrode No. 1, shown in Figure 8, has been neglected. In this case, the 3.7 MW of the 4 MW of charged beam is recovered.

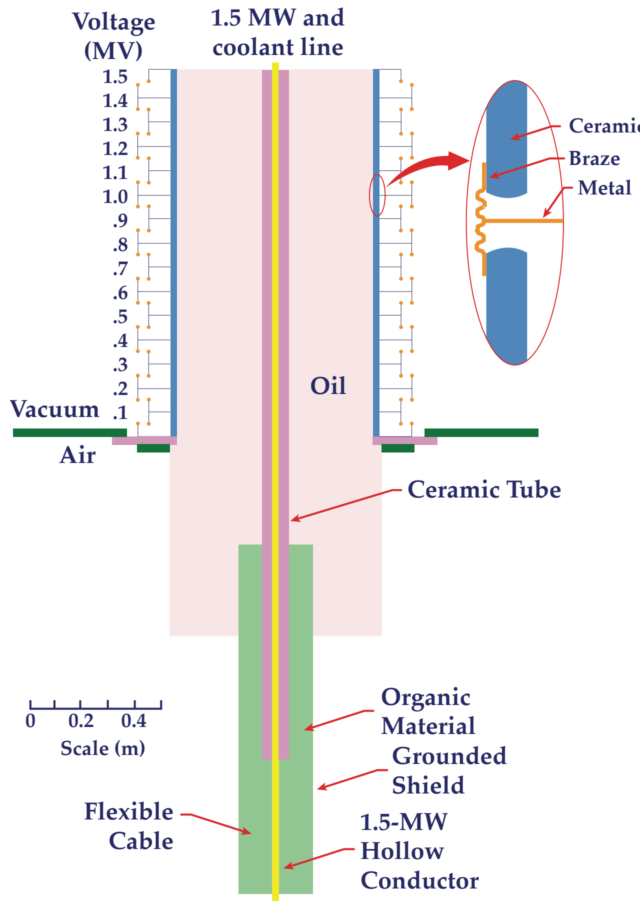

Figure 5 — This insulator design uses many identical parts that would reduce cost.

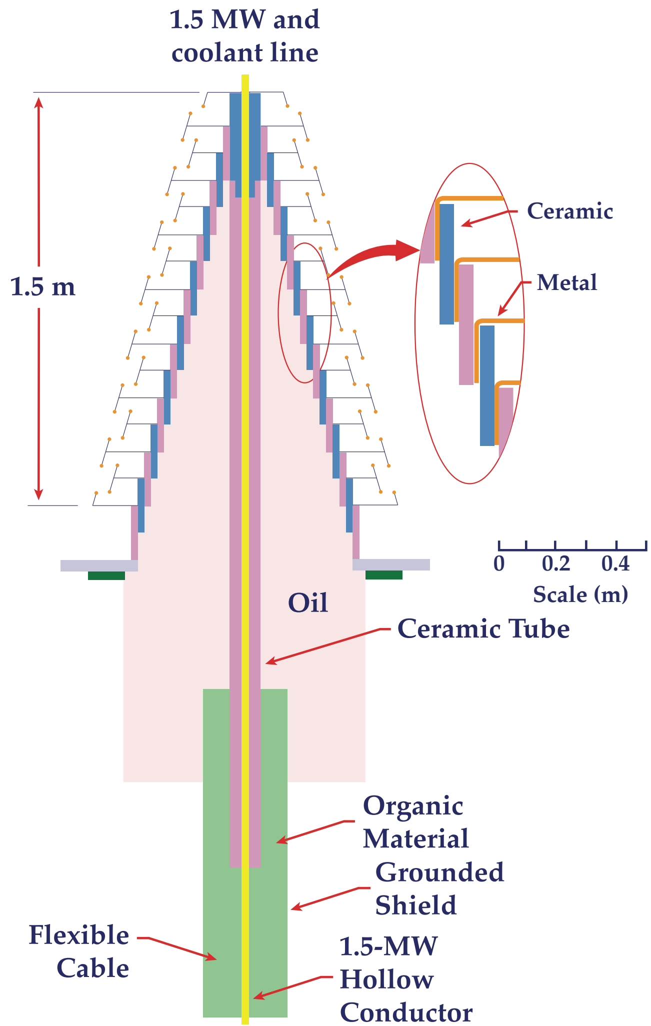

Figure 6 — The tapered insulator is not preferred because each part is different.

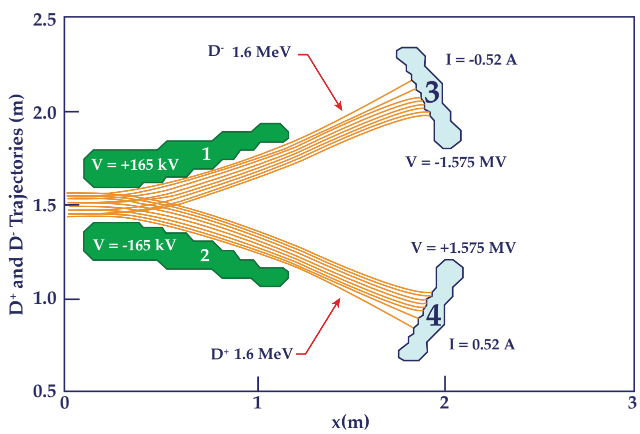

Figure 7 — The trajectories calculated by the DART code. Note that the electrodes would actually be built with a smooth surface. DART assumes straight lines between mesh points and therefore takes the shape shown. The current is in units of ampere per meter.

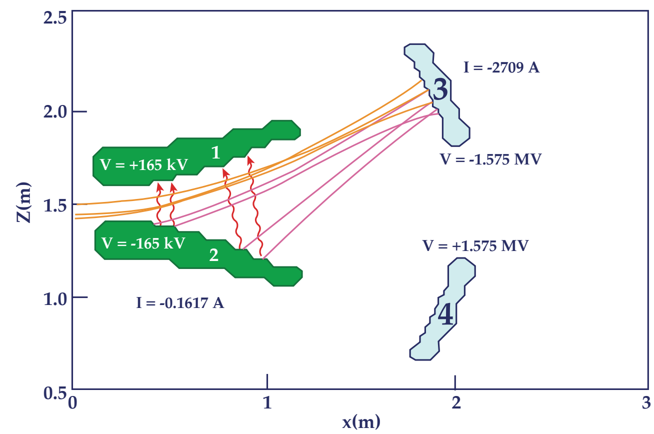

Figure 8 — Secondary electron trajectories caused by ion impact. The electrons themselves make secondary electrons (shown as wavy lines), which are not calculated by DART. The current is in units of ampere per meter.

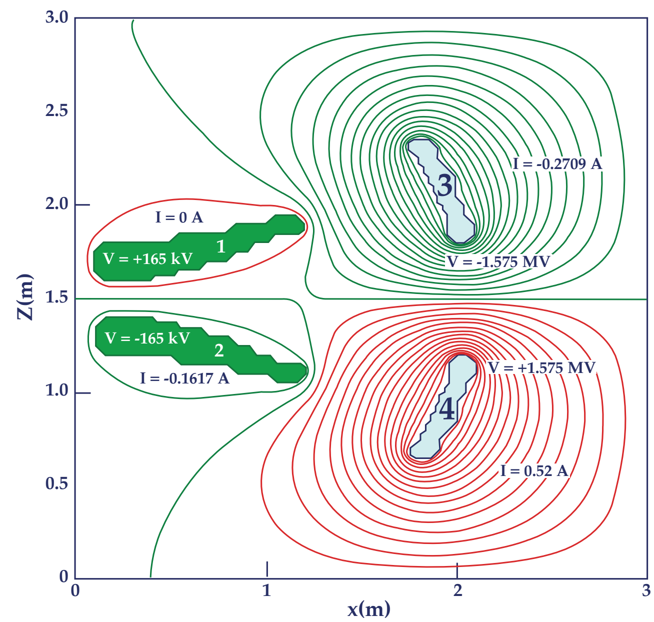

Figure 9 — Equipotential contours, 100 kV/contour. The efficiency is 92% without secondary electrons and 76% with secondary electrons (neglecting secondaries made by electrons, which should be a small correction). Clearly, suppression of secondary electrons from electrode 3 would result in a large improvement in efficiency. The current is in units of ampere per meter.

Besides energy loss, the serious problem with secondary electrons is that they are accelerated and hit electrode No. 2 with 1.4 MeV, making a large flux of troublesome X-rays. With the electrode designed with electron suppression, however, the electron current hitting electrode No. 2 drops from 0.16 to 0.07 A/m.

Calculations of stored energy give 130 J (260 J total stored energy) for each of the two supporting 1.575-MV electrodes, about 8.4 J in each 100-kV gap or 4.2 J per electrode (see Figures 5 and 6). As can be seen in Figure 3, there are 31 gaps, but there are two supporting electrodes for each gap, so the stored energy per electrode is 260 J/62 or 4.2 J. A circuit design must prevent anyone spark from discharging more than a few joules of energy to avoid electrode surface damage while the driving voltage is taken away and while each guard electrode at each increment of 100 kV is shorted out or discharged. Subdividing the stored energy is accomplished by grading the voltage as shown in Figure 10. There would be 15 electrode shrouds at 100 kV per gap. Figure 10 shows only six to illustrate the principle while keeping the drawing simplified. To the extent that the electrodes are placed on equipotentials shown from the prior design of Figure 9, the electric fields will be unperturbed and the trajectories will be unaltered. As can be seen in Figure 10, the largest perturbations will be near the axis where the nearest shrouds are at ground potential. Placement of the shrouds around the high voltage electrodes prevents them from "seeing" each other. In a practical sense this means ultraviolet photons, electrons, and ions do not have a chance to travel between the 1.6-MV and the -1.6-MV electrodes. Sparking precursor processes are prevented from occurring and occur with much less energy when they do occur.

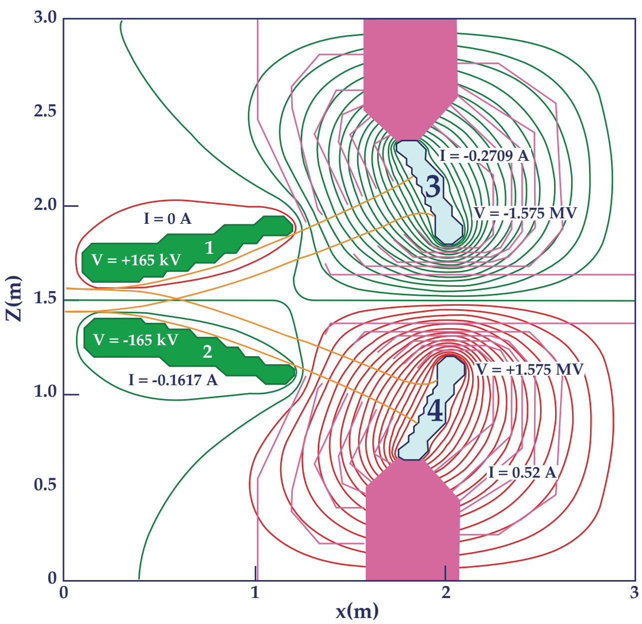

Figure 10 — A series of electrodes grade the voltage and keep the stored energy per electrode down to under the amount that will cause damage during sparking. The drawing only shows six grading electrodes for simplicity to illustrate the point.

A self-consistent design and calculation of trajectories remains to be carried out. It may be possible to design protection systems with 4.2 J stored energy per circuit element. (The voltage divider and protection circuit to each grading 100-kV guard electrode are not shown in Figures 5 and 6.)

This design is very preliminary and would require more work before feasibility could be determined. More work should be carried out on the following topics, some of which have been worked out in Reference 10:

1. A geometry for packing two or more units close together
2. Optimizing of deflector shape and gap distance
3. Means of suppressing secondary electron current drain
4. Calculating of current drain due to ionization of background gas, i.e., determining what vacuum is required
5. A more detailed mechanical design
6. Estimate of power density on electrodes
7. Electrical protection system design.

Item 7 is of special importance, because it is essential to protect against electrode damage resulting from electrical breakdown and to provide for quick recovery to full operation after a spark.

In summary, a concept for a neutral-beam direct energy converter beam dump for a 1.6-MeV beam suitable for ITER is presented with a specific electrode design to handle the high voltage without catastrophic sparking.

Publishing History

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