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ENGINEERING PROBLEMS OF FUTURE NEUTRAL-BEAM INJECTORS*

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ABSTRACT

Because there is no limit to the energy or power that can be delivered by a neutral-beam injector, its use will be restricted by either its cost, size, or reliability. Studies show that these factors can be improved by the injector design, and several examples, taken from mirror reactor studies, are given.

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[†] On loan from Westinghouse Electric Corporation

INTRODUCTION

Neutral beams have been so successful in plasma heating experiments that their role in future experimental fusion reactors is almost assured. However, major advances in the technology will be needed before neutral beams can be used in a power-producing fusion reactor.

Although there is no fundamental limit to the power or energy that can be delivered by a neutral-beam injector, several constraints must be met; that is, the specified current of neutrals must be delivered at the desired energy via an injector of reasonable cost, acceptable size, and adequate reliability.

High-power, high-energy injectors will be very costly and very large. The injector cost is estimated to be $320 divided by the injector power efficiency per kW of neutral beam. As a consequence, to meet the cost objectives of a fusion reactor [$1000 to $2000/kW(e)], the efficiency of the injector must be better than 70%.

To form an operating ensemble, the injector must be reasonably compact and physically compatible with the reactor layout. For instance, the aperture through which the beam leaves the injector and enters the reactor must not be too large. Furthermore, the presence of the injector must not interfere with other reactor components.

Finally, the injector must be sufficiently reliable to sustain at least 6 months of continuous operation. More frequent interruptions would be intolerable. To achieve this reliability, only the most conservative designs can be considered and only the most ideal materials used.

CONCEPTUAL STUDIES

During the past few years, we have studied several conceptual designs of different mirror reactors. The associated neutral-beam injector designs represent our attempts to resolve some of the problems previously mentioned.

The injectors for the Fusion-Fission Mirror Hybrid[1] uses positive ions as a source of neutrals, a liquid nitrogen-cooled neutralizer cell, and energy-

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recovery electrodes to enhance the injector efficiency. The injector for the Reference Mirror Reactor[2] employs a negative-ion beam formed by double charge exchange in cesium vapor and a photodetachment cell. Finally, the injector for the Tandem Mirror Reactor[3] runs on negative ions with a plasma-stripping cell. A thermal beam dump is used to recover the energy remaining with the unstripped negative ions.

These studies of neutral-beam injector designs have proven useful not only in the reactor studies but also as a guide to establish neutral-beam development objectives. In the following, some features of these designs are described.

GENERAL DISCUSSION

A neutral beam (Fig. 1) is formed from either positive or negative ions that have been extracted from a source, then accelerated, and finally focused at or near the reactor plasma. While traveling from the ion source to the reactor, the beam passes through a neutralizer cell in which positive ions become neutralized by picking up an additional electron or negative ions are neutralized by being stripped of their extra electrons. Subsequently, the beam passes through an energy-recovery unit in which some fraction of the energy remaining with the un-neutralized portion of the beam is recovered.

Conservative source design entails a low-extraction current density, possibly 100 mA/cm^2. This assures a long operating life by limiting sputtering and holding down the grid dissipation. As a result, the emitting source-area of a high-current injector will be quite large. However, the aperture through which the beam enters the reactor blanket can still be small if the entire beam is aimed at a common focus in the plane of the aperture. Thus, as shown in Fig. 2, an injector will assume the approximate shape of a pyramid, with the ion sources at the base and the beam aperture at the apex.

INJECTOR DESIGNS

Several source details are shown in Fig. 3. Using the Lawrence Berkeley Laboratory/Lawrence Livermore Laboratory (LBL/LLL) source as a reference, the preferred ion source design is found to be long and relatively narrow. This configuration makes it easier to pump the gas that escapes from the source out of the beam line. It also makes it easier to cool the grids, forms a favorable configuration for neutralizing the beam, and makes the design of the energy-recovery electrodes less critical. In general, smaller sources are advantageous because they are easier to make, easier to align, and less difficult to install. Furthermore, they require less expensive equipment for testing. Also, sources with smaller grids store less electrical energy and are not as vulnerable to damage from arcing.

The ion source shown in cross section in Fig. 3 has a hollow cathode that is proposed as a substitute for the tungsten hairpin filaments now in use. Studies[4] indicate that this type of cathode should be capable of thousands of hours of continuous operation.

The anode mounting detail in Fig. 4 shows how small alumina buttons can be used for low-voltage insulation between adjacent components of the ion source. This mounting can be effective in regions of intense neutron bombardment: a small percentage change in the insulator dimensions will not seriously alter the spacing between the electrodes and, because of the low voltage and the small contact area, degradation of the insulation will not cause a significant increase in leakage current. More massive, high-voltage insulators must be shielded from the neutron radiation and gamma flux originating in the reactor.

Figure 5 shows a version of the LBL/LLL ion source[5] that was designed for the Mirror Fusion Test Facility. The arc source is supported by two triaxial feedthroughs, each of which is housed within its own cylindrical insulator column. All of the services (i.e., power, gas, and water) are brought through the back of the source. The high voltage (80 kV) is sustained over the outer surfaces of the insulator and across the low-pressure gaps between the arc chamber, the 60-kV corona shield, and the grounded frame. The structure is compact, making it possible to house the source within the grounded vacuum wall (Fig. 6). In this way, many individual sources can be stacked, one upon the other, to form a relatively small injector assembly.

Figure 7 shows an injector made of many individual beam lines. The sources, at high voltage, are mounted within grounded electrostatic shields. This makes it possible for each source to be turned on or off without disturbing its neighbor. As a result an assembly of many beam lines (Fig. 8) can provide reliability through redundancy. In the event of an arc in any beam line, vacuum switches open the circuit, crowbars short out the residual voltage, and special arc snubbers dissipate the residual stored energy. Thus, the injector continues to operate with one beam line turned off, while the faulted beam line remains unharmed, ready to be re-activated in a few seconds.

It is well known that the fraction of neutrals available from a positive-ion beam passing through a neutralizer of optimum design falls off with increasing beam energy.[6] Therefore, it is necessary to use negative ions (Fig. 9) to obtain efficient neutral beams at energies greater than 150 keV. Negative-ion stripping in a gas cell is 62% effective. In a plasma, the stripping efficiency is 82% while in a photodetachment cell it reaches 95%. Thus, negative ions are a desirable source of high-energy neutrals.

Unfortunately, negative-ion sources are still in development. Figure 10 shows a conceptual design of a negative-ion beam line that uses an LBL/LLL positive-ion source, operating at about 2 kV to form negative ions via double charge exchange in a cesium vapor cell.

The cesium vapor also acts as a pressure barrier. This allows the neutral gas, escaping from the positive-ion source, to be pumped away at roughly 2×10^{-3} Torr, whereas the pressure on the other side of the vapor cell is maintained at 10^{-4} Torr by many cryopanel pumps.

The 20% of the incident beam that becomes negative in the cesium cell is accelerated to high voltage. Meanwhile, the balance of the positive-ion beam becomes neutral and is collected at the low-energy neutral target.

Photodetachment can be used to form a very efficient injector of high-current beams. Many negative-ion beam lines can be operated in parallel so that they pass through a large common, stripping cell (as shown in Fig. 11). The high-voltage insulators, not shown in Fig. 11, are mounted in a shielded region above and below the beam line. To enhance the efficiency, energy-recovery electrodes are also included in the system.

A 1.2-MeV injector has also been considered (Fig. 12). As before, a double-charge-exchange source of negative ions is used. The source is mounted in a pump duct that is supported at high voltage by insulators above and below the beam line (Fig. 13). To minimize the high-voltage insulating problems, the source is maintained at -600 kV and the stripping cell at +600 kV. Perforated electrostatic shields at -400 and -200 kV help maintain the high-voltage standoff between the ion source and the grounded injector walls. Similar shields at +200 and +400 kV surround the stripping cell.

To keep to a minimum the loss of negative ions via charge exchange with the background gas in the beam acceleration region, it is essential that the background gas pressure be low. Thus, the outer walls at the injector are covered with cryopanel pumps.

The ions are stripped using a cesium-plasma cell that is maintained by surface ionization on hot-tungsten plates. To maintain the space-charge neutrality of the cesium plasma, the tungsten plates also emit electrons. If we assume that 82% of the negative ions get stripped, the balance of the beam (consisting predominantly of positive ions) is collected in a beam dump at ground potential.

CONCLUSION

In this paper, we have briefly described some conceptual neutral-beam injectors that were designed in various mirror fusion reactor studies. From these studies and from some of the more detailed analysis that went into their preparation, it is possible to draw some specific conclusions about neutral-beam development.

For instance, we conclude that negative ions are essential to the formation of very high-energy beams. The power efficiency of the source is not critical because it does not have a significant impact upon the overall efficiency of the injector.

Although a compact source of ions would be advantageous, this cannot be achieved. Considerations of long life, grid heating, sputtering, and reliable high-voltage stand-off between the acceleration grids require low ion current densities, albeit large emitting areas for the ion source. Those procedures that might be used to enhance the extracted current density make the source less reliable and unfavorably affect the beam optics.

Even though gas efficiency is often considered an important source parameter, the critical factor is the density of the residual background gas in the region of the extraction grids. Charge exchange between the ions in the beam and the residual gas molecules can cause the loss of a significant fraction of the ion beam and also result in excessive grid loading. The most effective method to reduce the density of the background gas is to minimize the operating pressure of the ion source. Because several different types of negative-ion sources are now under development there is no point in discussing this problem further. However, it is important to note that the removal of excess gas is more economical at higher pressures, near the ion sources, rather than further down the beam line. In all of the conceptual injector designs, the gas coming out of the ion sources has been drawn back into a pump duct behind the ion sources.

In a continously operated system, grid cooling appears to be the most serious problem of ion source design. Solid grid rods can not transfer the heat load; as a result, direct cooling of hollow rods is necessary. To do this, the grid rods must be large in diameter and subject to puncture as a result of arcing or sputtering. To minimize this problem the grid structure must also be large, the grid transparency reduced, and the allowable beam current density limited. All these are undesirable, and the compromises needed to form a workable system must be carefully evaluated.

Another factor of importance in grid design concerns the prospect of metal flaking as a result of bombardment by neutrons and alpha particles. Although the problem appears to be far less severe at the ion source than at the first wall, the prospect of this flaking causing high-voltage arcs is very serious. Fortunately, there is hope that the flaking will not be as bad as it once appeared: there are techniques that can mitigate the effect.

High-voltage insulation in an injector needs considerable study. After 100 years of research, we are still unable to accurately specify the minimum spacing required to hold off high voltage in vacuum. Small spacing at low pressure works, but the factors that assure reliability over large areas (to provide compactness) are not known. To overcome this, we propose a redundant design in which arcing components can be turned off before serious damage occurs. The actual details of such procedures have yet to be worked out.

As for stripping negative ions, a gas stripper can be ruled out. At the price of adding gas to the system the 62% is not that good, particularly when there is a prospect of getting 82% efficiency from a plasma cell. We have considered a cesium plasma cell, recognizing that the cesium containment is a problem. But despite that, plasma stripping is not too desirable either, because at optimum stripping the unneutralized fraction of the beam is composed of almost equal parts of positive and negative ions. It is difficult to obtain energy recovery from such a beam composition in a compact beam line. If the plasma cell were made over-dense, the stripping efficiency would drop to 80%, and the remainder of the beam would become almost 100% positive ions. However, the recovery of the energy of the positive ions in a negative-ion beam line creates undesirable voltage-holding problems. Of course, a thermal beam dump can be used, but its efficiency is not very good. Thus, we turn to photodetachment. It is expected that laser technology can be brought along to meet our needs.

In this discussion, we have not mentioned either continuous cryopanel pumps or the power supply requirements. Obviously, much effort is also needed in these fields. To make reliable, high-energy, high-power, neutral-beam injectors for operating fusion reactors, much effort, time, and money are required. However, there are no insurmountable obstacles.

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FIGURES CAPTIONS

Fig. 1. Formation of neutral beams.

Fig. 2. *Injector configuration.*

Fig. 3. Positive-ion source. Inset shows design of hollow cathode.

Fig. 4. Anode Mounting Detail.

Fig. 5. A compact, 80-keV neutral-beam module.

Fig. 6. The outer magnetic shield forms the vacuum wall around the arc chamber, extractor, and cylindrical isolation valve. The arc chamber is mounted off the grounded back plate by two triaxial feedthroughs. The extractor is supported by a grounded frame from an annular backplate. The isolation valve is mounted on the neutralizer tube, which is cantilevered from the exit end.

Fig. 7. A 225-MW neutral-beam injector delivering a mixture of 100-keV deuterium atoms and 150-keV tritium atoms.

Fig. 8. 100 keV neutral-beam injector beam line.

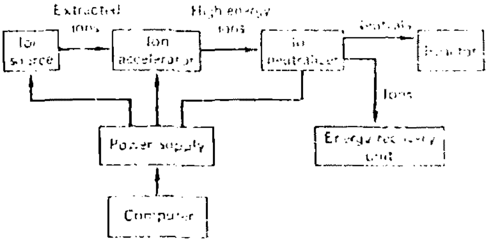
Fig. 9. Optimum neutralization efficiency of a deuterium-gas cell as a function of the energy of an incident deuterium atom.

Fig. 10. Negative-ion injection module delivering 84 A of 150-deV D^- ions.

Fig. 11. Neutral-beam injector delivering 1800 A of 150-keV deuterium and tritium atoms.

Fig. 12. A 1.2 MeV nautral-beam injector.

Fig. 13. Pumping through the high-voltage insulators.



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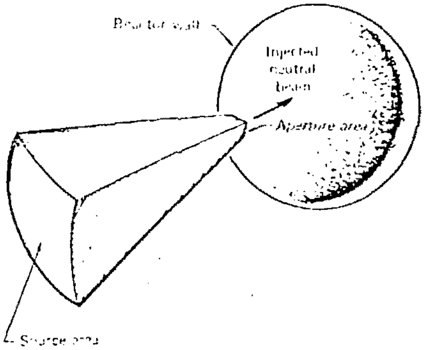
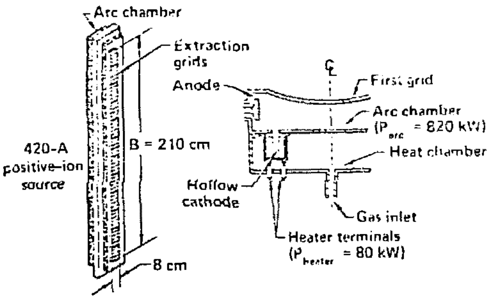


Fig. 2. Injection configuration.



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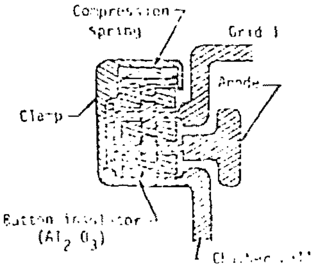

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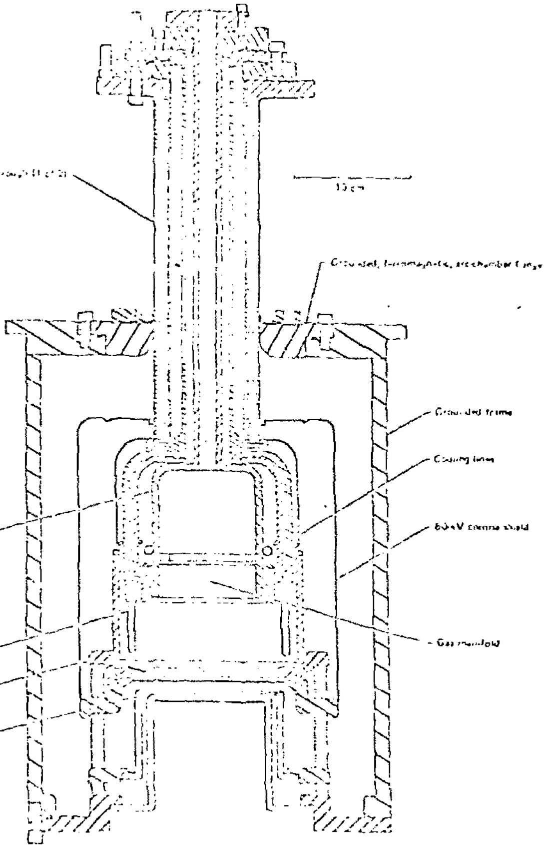

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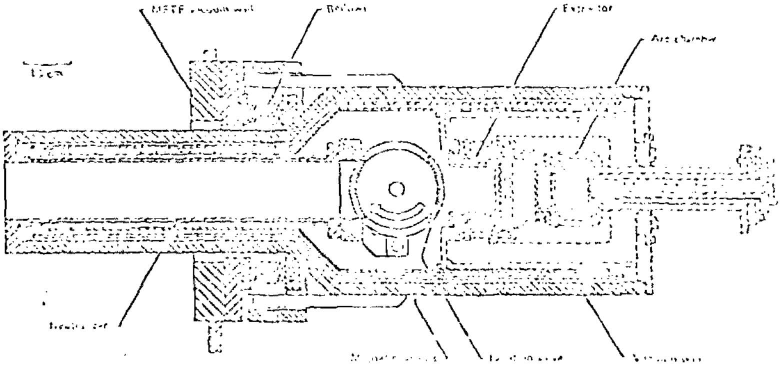

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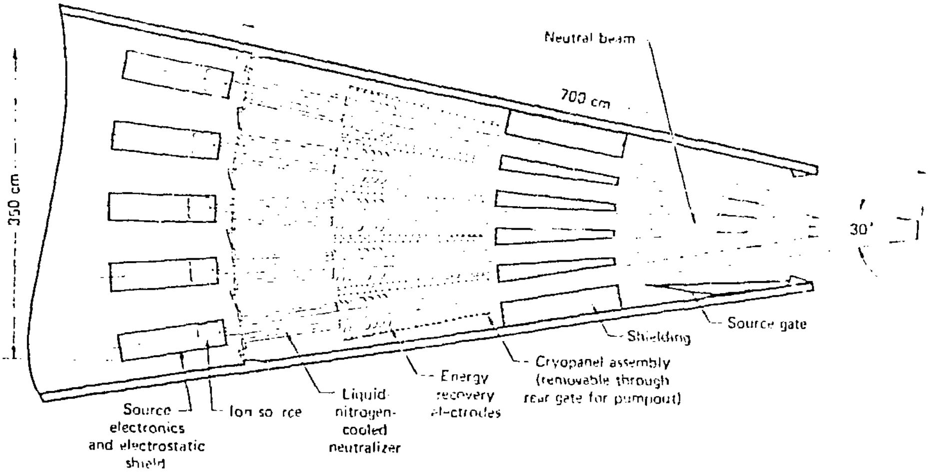

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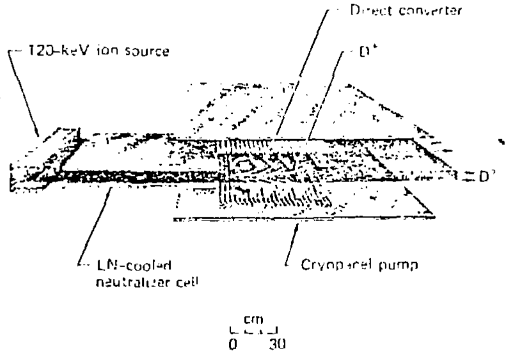
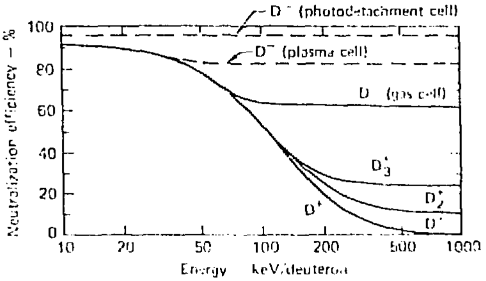


Fig. 8. 100 keV neutral-beam injector beam line.



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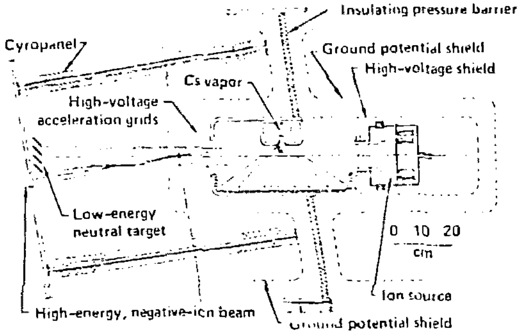

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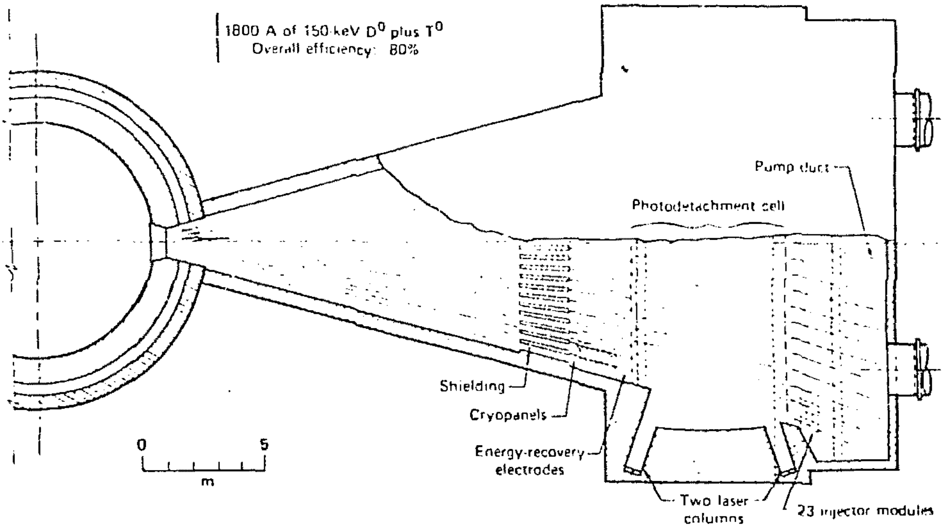

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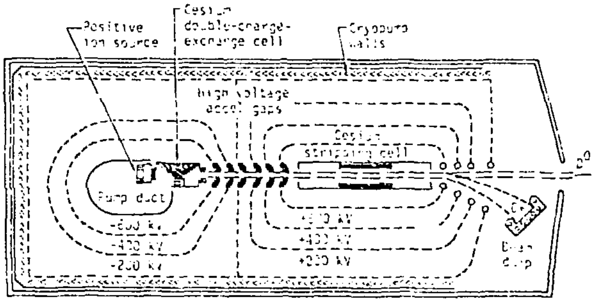

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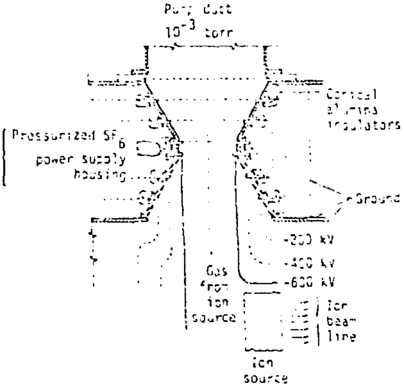

Fig. 13. Pumping through the high-voltage insulators.