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MAGNETIC-FUSION REACTORS

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NEUTRAL-BEAM SYSTEMS*
FOR MAGNETIC-FUSION REACTORS

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ABSTRACT

Neutral beams for magnetic fusion reactors are at an early stage of development, and require considerable effort to make them into the large, reliable, and efficient systems needed for future power plants. To optimize their performance and establish specific goals for component development, systematic analysis of the beamlines is essential. Three ion source characteristics are discussed: arc-cathode life, gas efficiency, and beam divergence, and their significance in a high-energy neutral-beam system is evaluated.

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I. INTRODUCTION

To meet the energy needs of the future, magnetic fusion reactor power plants will probably be large, each capable of delivering at least 2 GW of electrical power. Assuming they operate with reasonable efficiency, the power required to sustain the reactors must be of the order of several hundreds of MW. Although we cannot be certain what fraction of this sustaining power will be provided by neutral beams, we know that the neutral-beam system will be huge by today's standards.

Estimates of today's neutral-beam injector installations indicate that their costs are one to two times that of their high-voltage power supplies. Because the power required is inversely proportional to the efficiency η of the neutral-beam system, tomorrow's injector (including several beamlines, housing, shielding, remote maintenance, etc.) will cost about η^{-1} dollars per output watt of neutral beam. This high cost is important because it provides an impetus for improving system efficiency concurrently with the development of advanced neutral-beam systems.

To date, the urgency to develop reactor scenarios and demonstrate fusion feasibility has been great, whereas the costs of experimental devices have been relatively small. Hence the need to optimize performance has not been important. However, in the next generation of experimental reactors, the cost of the neutral-beam injector will be significant.

In the following, I discuss applications of neutral beams in the two leading concepts for magnetic fusion reactors, i.e., in the tokamak and the tandem mirror reactor. Then I describe today's neutral-beam systems, which are based upon positive ions, and contrast them with the negative-ion-based systems under development. Finally, I point out the need for a systematic approach to optimizing the performance of large neutral beamlines. The

objectives are not only to reduce costs, optimize efficiency, and improve the reliability of the injector, but also to provide specific goals for the development of beamline components. In particular, I discuss arc-cathode life, gas efficiency, and beam divergence in high-energy beamlines.

II. NEUTRAL-BEAM APPLICATIONS

Neutral beams were first proposed for increasing the density and temperature of the plasma in magnetic fusion reactors in the 1950's.¹ It was recognized that high-energy neutrals could pass unperturbed through a confining magnetic field, to be ionized upon impact with the trapped plasma. The newly formed, high-energy ions and electrons would also be trapped, causing the plasma density and temperature to rise.

Experiments conducted in the 1960's and early 1970's led to a better understanding of this process and, in 1976, to a successful demonstration of plasma buildup and heating in the 2XI1B mirror experiments² at the Lawrence Livermore National Laboratory (LLNL). Extrapolation of these results, and those of subsequent experiments, provide the present bases for neutral-beam applications in magnetic fusion reactors.

An experimental version of one of the fusion reactor concepts, called the Tokamak Fusion Test Reactor³ (TFTR), is being built at the Princeton Plasma Physics Laboratory (PPPL). As shown in Fig. 1, the reactor plasma is confined within the vacuum vessel by a magnetic field established by the toroidal field coil. The ohmic heating coils induce a circulating current in the plasma, while the four neutral-beam injectors, similar to the one shown in the figure, provide additional heat to the plasma.

Each of the TFTR injectors was originally designed to deliver approximately 4.7 MW of 120-keV deuterium atoms in 0.5-s pulses via three

beamlines.⁴ However, the injectors are now being updated to deliver 1.5-s pulses, using four beamlines each.

In an actual tokamak power plant, it is anticipated that continuously operated deuterium beams at something like 400 keV will maintain the plasma at fusion temperatures. The poloidal, ohmic heating coils, which are pulsed in the TFTR, might be replaced by a continuously circulating plasma current, driven by rf or else by very high energy neutral beams.⁵ Theoretical analysis suggests that the energy of the driving beams must be of the order of 1 MeV, but this is highly speculative without experimental verification.

The other major magnetic fusion concept is the tandem mirror reactor.⁶ It will be evaluated as part of the Tandem Mirror Fusion Test Facility (MFTF-B) to be built at LLNL. As shown in Fig. 2, the reactor consists of a long central cell terminated at each end by a large-diameter end-plug housing. Neutral beams are used to heat the central cell and to replace the plasma losses in the yin-yang cells. Microwave sources heat the electrons and raise the plasma potential in the end cells. This potential establishes axial electric fields which supplement the magnetic confinement of the central-cell plasma, as provided by the yin-yang coils.

In the regions between the yin-yang coils and the end cells, other neutral beams are introduced to create thermal barriers for the high-temperature end-cell electrons. The thermal barriers are formed by the removal of low-temperature ions which would normally keep the plasma at a higher-than-desired potential. These ions are neutralized by charge exchange with the injected neutral beams. Moving with the neutral beam, the newly formed ions (formed by charge exchange) are suitably aimed and have sufficient energy to escape the barriers and pass into the central cell. As a result, the density and potential of the barriers are kept low,

thermally insulating the central cell from the hot electrons in the end cells. It should be noted that, although the theory of the tandem mirror is well understood, the formation of a thermal barrier has yet to be experimentally demonstrated.

The Tandem Mirror Next Step⁷ (TMNS) is a small, fusion demonstration reactor. It requires several neutral-beam injectors with a variety of energies. These include 150-keV beams for the yin-yang cells and 200-keV beams for controlling high-frequency instabilities, as well as 2-keV, 66-keV, and 150-keV beams to establish the thermal barrier.

III. TODAY'S NEUTRAL BEAMLINE DESIGNS

Most neutral beamlines designed today are similar to that shown⁸ in Fig. 3 (see Fig. 1 for comparison). Positive ions are drawn out of the source, accelerated to the desired energy, and focused in the vicinity of the beam exit aperture.

Some fraction of the ions is neutralized to form the neutral beam by charge exchange with the gas in the neutralizer. The rest are deflected out of the neutral-beam path by the field of the ion-bending magnet, to be collected at the ion dump. Cryopumps remove the gas flowing out the ion source through the neutralizer and control the density of the background gas in the drift chamber between the neutralizer and the beam exit aperture. Meanwhile, any portion of the neutral beam that is not well focused is intercepted by the beam-defining plates.

During beam startup, the calorimeter measures the injected power; however, during operation it is lifted out of the beam path.

The beamline shown in Fig. 3 was designed and built at the Oak Ridge National Laboratory (ORNL) for a poloidal diverter experiment (PDX-B) that

will be conducted at PPPL. In trial runs, this beamline has delivered 1.5 MW of 50-keV hydrogen in 0.5-s pulses.

Today's injector designs using neutrals formed from positive-ion beams have three inherent disadvantages. For one, the reduction in charge-exchange cross section makes the fraction of neutrals obtainable from a positive-ion beam passing through a gas neutralizer of optimum design decrease with increasing ion velocity. This is shown as a function of beam energy per deuteron in Fig. 4. As a direct consequence, the operating efficiency of positive-ion-based injectors also decreases with increasing beam energy.

Although the efficiency can be improved by electrical conversion of the energy carried by the un-neutralized ions, the neutral current obtained from an ion source cannot be increased. Hence, either more or larger sources must be provided to deliver the same neutral current at higher beam energies.

In Fig. 5, we show the calculated efficiencies of neutral-beam injectors using positive-ion-based beamlines.⁹ We assume that 70% of the energy carried by the un-neutralized ions is recovered. Note how the efficiency of the positive-ion beamline drops sharply with increasing beam energy--regardless of the use of species-separating magnets or direct conversion.

The second disadvantage of positive-ion systems results from the molecular ions D_2^+ and D_3^+ , which are usually present in an extracted positive-ion beam. Moving slower than the monatomic D^+ ions, they are more readily neutralized; upon neutralization, they break up into two neutral atoms of one-half and three neutral atoms of one-third full beam energy. The additional components make the injected current of fractional-energy

neutrals disproportionately large with respect to the molecular composition of the extracted beam.

This current of fractional-energy neutrals presents a serious problem in some applications. Less than 5% fractional-energy neutrals in a beam is deleterious to plasma heating in a tokamak and disruptive to ion pumping in the tandem mirror. Recent advances in ion-source technology make it possible to extract very large currents of positive ions with an atomic fraction approaching 90%. Although a magnet located between the ion source and the neutralizer can remove the remaining molecular ions by separating the ion species, a severe loss of atomic ions can occur by charge exchange with the background gas along the now extended ion path. This explains the lower efficiency found for an injector which uses a species-separating magnet. For the calculation in Fig. 5, the extracted ion beams were assumed to be 90% monatomic and the path through the magnet was 1-m long.

Finally, the third disadvantage of positive-ion systems results from three factors: the use of the gas coming from the source to feed the neutralizer; the large emitting area of the ion sources; and the broad, open cross section of the gas neutralizer. These make it impossible either to control the background gas density along the accelerator or to maintain it at an acceptable minimum near the ion-bending magnet.

In the vicinity of the ion accelerator, the gas density should be no more than sufficient to provide a background plasma that will support space-charge neutralization of the ion beam. A higher density will cause an unnecessary ion-beam loss from charge exchange. Around the bending magnet, the beam is already neutral, so that space-charge neutralization is no longer a factor. Hence, the background density must be as low as practical to minimize the neutral-beam losses resulting from impact ionization.

IV. NEUTRAL BEAMS MADE FROM NEGATIVE IONS

The three disadvantages of today's neutral beamlines can be overcome by using beams made from negative ions. First of all, a larger fraction of neutrals is obtained from negative-ion beams at higher energies than can be obtained from positive-ion beams. The optimum neutralization fraction of D^- in a gas cell used for stripping electrons is relatively constant. As shown in Fig. 4, it is about 62% for high-energy D^- beams. However, almost 100% stripping can be achieved at any beam energy by means of photodetachment. Calculated efficiencies, as a function of beam energy, are shown in Fig. 5 for both types of stripping cells. At high energies, negative-ion beams are more efficient than positive-ion-based beams.

The second disadvantage of positive-ion-based neutral beams, the presence of D_2^+ and D_3^+ , does not exist. For all practical purposes, negative ions are monatomic.

Finally, when using an ion source of reasonable gas efficiency, a photodetachment cell, and suitable cryopump panels, the background gas density in the vicinity of a negative-ion-beam accelerator should be well controlled. Negative ions present a problem in that they are subject to a beam loss which is greater than that of positive ions of the same energy passing through a background gas of the same density. This is because the negative-ion stripping cross section σ_{-10} is larger than the charge-exchange cross section σ_{10} of the positive ions.

To minimize this loss, it is conceivable to reduce the neutral background density--but only so far. As stated earlier, high-energy, positive-ion beams depend upon electrons, generated by impact ionization of the background gas, to provide space-charge neutralization and prevent beam blowup. Similarly, negative-ion beams depend upon positive ions, generated

by impact ionization, to provide space-charge neutralization. Because electrons are so much more mobile than ions, the background gas density needed to space-charge neutralize a positive-ion beam is almost an order of magnitude greater than that required for a negative-ion beam.

But the ratio of the stripping to charge-exchange cross sections σ_{-10}/σ_{10} , as shown in Fig. 6, is not very great at low beam energies. It approaches 10 at 160 keV. As a consequence, negative-ion beams with energies less than 160 keV can be made to operate with lower losses than positive-ion beams of the same energy. At 160 keV or more, the positive-ion charge-exchange and the stripping cross sections are small. Thus, the beam loss along a reasonable path length through an appropriate, low background-gas density need not be excessive.

At present, neutral beamlines based upon negative ions are at a very early stage of development. Continuously operated negative-ion sources are being developed at three laboratories in the United States: Brookhaven National Laboratory (BNL), Lawrence Berkeley Laboratory (LBL), and Oak Ridge National Laboratory (ORNL). The Department of Energy (DOE) development schedule calls for a demonstration of a 10-A, 10-40-keV, continuously operated, D^- source by 1984.

Several alternate concepts for negative-ion sources have been proposed, but most of the sources under consideration at the various American laboratories use a cesiated molybdenum electrode to form the negative ions. The electrode is mounted in a discharge plasma and biased so that positive ions are accelerated towards the electrode through a surrounding plasma sheath. Newly formed negative ions leaving the electrode are accelerated away from it. By shaping the electrode and aligning it with an exit

aperture, the negative ions escape from the ion source with an energy equal to the potential of the plasma sheath.

Prior to high-voltage acceleration, some provision must be made to separate electrons from the negative ions. Subsequently, the negative ions can be brought to high energy by means of the high-voltage accelerator. The electrodes must be designed to shield the high-voltage insulators from radiation and stray particles, and they must be shaped to prevent secondary electrons from being accelerated along with the negative-ion beam.

To obtain maximum efficiency, we expect that the negative-ion beam will be converted into neutrals by photodetachment. This is desirable because the fraction of neutrals which can be obtained from the ion beam can approach 100%, alien negative-ion impurities (such as OD^-) will not be neutralized, and no gas need be introduced to add to the pumping load. The development of continuously operating lasers of high efficiency and of mirrors of high reflectivity is essential.

The small fraction of un-stripped ions leaving the photodetachment cell will be removed from the neutral-beam path by electrostatic deflection and aimed at a direct energy converter. There will be no room for ion-separating magnets in large injectors with many parallel beamlines.

The DOE program¹⁰ calls for a demonstration of a 5-A, continuously operating, 200-keV D^0 beam by 1986.

V. SYSTEM ANALYSIS

Optimizing system performance, that is, finding an acceptable compromise between system output, cost, efficiency, and life, can be difficult: there is usually little room for compromise, and interactions between components and the system are rarely amenable to optimization routines. As a result, optimization entails a study of those factors that

limit the system performance and often leads to a change in the operating mode of the system components.

In the following, I discuss three characteristics of an ion source: arc-cathode life, gas efficiency, and beam divergence, and consider their significance in a high-energy neutral beamline.

The reliability of today's ion sources is limited in part by the life of their arc cathodes. High-temperature filaments with relatively short lines are used as cathodes to provide large arc currents at good efficiency.

While ion sources with such filaments are acceptable in today's experiments, they would be intolerable in a power plant the size of an operating fusion reactor. The costs of unscheduled shutdowns would be prohibitive, and the costs of system reliability, purchased with redundancy or on-line maintenance, would also be excessive. Thus, there is no better method for obtaining system reliability than providing reliable components.

The short life of a high-temperature filament results from its high sublimation rate. A filament at a lower temperature T_2 will operate longer but deliver less current than it would at a higher temperature T_1 . In fact, several filaments operating at T_2 are needed to provide the same current as one filament at T_1 . However, the life of the filaments at T_2 is increased over that of a filament at T_1 by a factor (L_2/L_1) , equal to the inverse of the ratio of the respective filament sublimation rates.

Meanwhile, the ratio (P_2/P_1) , corresponding to the ratio of filament power needed to deliver the same current at both temperatures, increases as the temperature difference between T_2 and T_1 increases.

In Fig. 7, I use published data¹¹ to show how the life of an arc cathode made from tungsten filaments can be increased at the cost of filament power. Over the range of 2300 to 3000 K, (L_2/L_1) as a function

of (P_2/P_1) can be approximated by a single curve. Notice that a 10-fold increase in filament power results in a 110-fold increase in life.

Whereas a state-of-the-art positive-ion source operates at about 2.5 kW/A of emitted ion current, about 30% of that is used to heat the filaments. A 10-fold increase in filament power would then require a new source operating at 10 kW/A. Such a source operating in a 20-keV beamline would be unacceptable because its power requirement is equal to 50% of the power in the extracted ion beam. However, it equals only 5% of the power carried by a beam at 200-keV and 2.5% at 400 keV.

Of course, the increased filament current, area, and power create problems in the design of the source. But the fact is that an inefficient ion source which is impractical at low beam energies can operate with increased reliability at high beam energies.

Although gas efficiency is a useful source parameter, the quantity of gas per ampere of ion beam which must be pumped away is the important feature in a beamline.¹² Obviously, the gas flow out of the sources must match the beamline pumping capability, but in addition, control of the background gas pressure in the vicinity of the accelerator grids is essential.

In this region, the pressure must be sufficient to provide ion-beam space charge, but not so great as to cause excessive interaction with the beam. Along the accelerator, premature charge exchange of positive ions, or stripping of negative ions, can cause a significant ion-beam loss. These processes introduce less than full-energy neutrals into the beam and create low-energy ions and electrons along the beam path. These low-energy charged particles are pulled out of the beam to bombard the grids, resulting in undesirable power losses.

To minimize the gas flow, ion sources with very good gas efficiencies should be used. However, the pumping load coming out of an ion source can be reduced if the source can be operated at a pressure only a few times greater than that of the background gas. Depending upon the pressure difference, the reverse flow of gas back into the source from the accelerator region can markedly reduce the pumping load.

Because gas efficiency is defined as the percentage of the gas flowing into a source which exits as ions, it is considered to be a measure of the efficiency with which the source converts gas into ions. But this is not the case if the source pressure is of the order of the surrounding pressure. Significant backflow will reduce the gas input and thereby change the apparent gas efficiency.

When designing an ion source for a specific beamline, the source developer must match the gas flow out of the source to the pumping capability of the system. The most favorable source pressure and background pressures must be determined experimentally to provide the optimum beam output.

Traditional analysis of the divergence of a charged-particle beam assumes that the current density distribution in a focal plane is Gaussian. Theoretically, this is the case if the ions in the source have a Maxwell-Boltzmann velocity distribution and the beam optics is free of aberrations. In practice, this assumption is found to be a reasonable approximation at small beam radii. At large radii, the discrepancy can be significant.

It is desirable to make the beam exit aperture as small as possible. However, it must not be so small that it either intercepts an appreciable fraction of the neutral beam current or intercepts the beam at a current density high enough to cause overheating or excessive sputtering.

Because the actual shape of the beam current density distribution in a focal plane is not known, the usual measurements of beam divergence, i.e., the $1/e$ angle, the half-width, half-maximum angle, and the emittance at small beam radii, are not meaningful. At large radii in a focal plane that is located in the vicinity of the beam exit aperture, there is no substitute for current density measurements. An aperture edge bombarded by a 400-keV beam at a current density of only $0.5 \text{ mA} \cdot \text{cm}^{-2}$ will have to continuously dissipate as much as $200 \text{ W} \cdot \text{cm}^{-2}$. To determine suitable aperture dimensions, the current density distribution in the outer extremes of the beam must be known, as well as the precision with which the beamlines are mounted in the neutral-beam injector.

VI. CONCLUSION

Although negative-ion beams are at an early stage of development, it appears certain that neutral-beams based upon negative ions will have a place in future magnetic fusion reactors.

To optimize high-energy neutral beams, the components must be developed to serve the system's need. Because usual interpretations of component performance can be misleading, careful analysis is essential. Examples presented here show that the power efficiency of the ion source, which can limit arc-cathode life, is of little significance at high-beam energies. In addition, gas efficiency, which by itself is meaningful, can be effectively reduced by operating the ion source in an environment whose pressure approaches that of the source. Finally, beam divergence as usually interpreted is not a critical parameter in a large neutral-beam injector. Only a systematic analysis of beamline performance can provide the component developer with guidelines that are consistent with the needs of a large, high-energy, neutral-beam injector.

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FIGURE CAPTIONS.

FIG. 1. The TFTR configuration, showing one neutral-beam injector.

FIG. 2. An elevation view of the MFTF-B installation.

FIG. 3. An exploded view of the PDX beamline, a typical positive-ion-based neutral-beamline.

FIG. 4. Optimum fraction of high-energy deuterium neutrals which can be obtained with a D_2 neutralizer.

FIG. 5. Calculated efficiencies of different positive-ion- and negative-ion-based neutral-beam systems.

FIG. 6. The ratio of negative-ion stripping cross-section σ_{-10} to the positive-ion charge-exchange cross section σ_{10} .

FIG. 7. The relative increase in filament life (L_2/L_1) contrasted to the relative increase in filament power (P_2/P_1) needed to operate several filaments at temperature T_2 , emitting a total current equal to that obtained from one filament at a temperature T_1 where $2800 \text{ K} < T_2 < T_1 < 3000 \text{ K}$.

Fink - Fig. 1

Fink - Fig. 2

Fink - Fig. 3

Fink - Fig. 4

Fink - Fig. 5

Fink - Fig. 6

Fink - Fig. 7

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