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CONSIDERATIONS INVOLVED IN THE DESIGN OF NEGATIVE-ION-BASED NEUTRAL BEAM SYSTEMS

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ABSTRACT

We consider the requirements and constraints for negative-ion-based neutral beam injection systems, and show how these are reflected in design considerations. We will attempt to develop a set of guidelines for users and developers to use to see how well (in a qualitative sense, at least) a particular neutral beam system fits a particular proposed need.

INTRODUCTION

A neutral beam injection system, whether based on negative ions or on positive ions, is a complex entity. It is composed of interacting and interlocking components, which cannot be designed separately in isolation and simply fitted together. Similarly, a neutral beam injection system is not simply an "add-on" to a reactor; each must take into account the constraints and limitations imposed by the other. I will try in the following discussion to outline, at least in a qualitative sense, how these constraints affect the design of a negative-ion-based neutral beam system.

APPLICATIONS

Neutral beams can perform several necessary functions for fusion reactors. The most obvious application is to heat the confined plasma. Heating of confined plasmas by beams of neutral atoms has been adequately demonstrated, both for mirror and for tokamak experiments; the highest temperatures reached to date in both cases have been achieved by neutral beam heating.

Another proposed application is to utilize the momentum transferred from the injection of neutral beams tangentially into a tokamak to drive a circulating current to aid in plasma confinement. This application for "current drive" has not yet been convincingly demonstrated.

Tandem mirror reactors will require the injection of neutral beams into the end plugs of the reactor to create a "sloshing ion" population to aid in the electrostatic confinement of ions in the axial direction. It is likely that this application will be the first test of negative-ion-based neutral beam systems on a reactor. We will consider the implications of this choice in subsequent discussions.

In the following discussion, we will examine the various system requirements and constraints, and consider the implications on the design of the neutral beam system. The information is also summarized in short form in Table I.

SYSTEM REQUIREMENTS, CONSTRAINTS, AND DESIGN IMPLICATIONS

A. FUNCTIONAL CONSTRAINTS

Beam Power: Next generation tokamaks, if they use neutral beams for heating or current drive, will require the injection of 20-50 MW of neutral beam power.[1] A more likely first application would be the injection of about 2 MW (1 MW into each end of the machine) into an upgrade of MFTF-B, the so-called MFTF-α+T version,[2] to create a sloshing ion population in the end plugs. This mirror need could be satisfied by neutral injector modules handling 1 or 2 MW per module; the tokamak requirements would require 5 to 10 MW per module. In any case, the neutral beam injection system will have to handle quite a few MW of power per injector, which means that the systems will have to be carefully protected from self-destruction.

Beam energy: Beam energy requirements range from 200 keV for the mirror application just discussed to 400 to 800keV for heating or current drive of next-generation tokamaks. The implication of this requirement is that we must devise accelerators capable of accelerating deuterium ions to these energies without excessively frequent sparking. Since current-carrying capability is directly related to the electric field in the accelerator, a conservative design that leads to infrequent sparking will also result in a design with a low current-carrying capability compared to a less conservative design. A clear understanding of the requirements is necessary, as well as a compromise in one area or the other.

Angular Divergence: Access for neutral beams to a reactor is usually limited, in the case of tokamaks, by the size of apertures between magnetic field coils, and in the case of mirror machines, by this plus the small size of the plasma. In all cases, from a neutronics point of view, it is desirable to minimize the area of penetrations through the shielding of the reactor. Typical angular acceptances for tokamaks are $\pm 0.5°$ by $\pm 1°$. The plasma target in MFTF-α+T presents a smaller target: the target is 10 cm wide, at a distance of 9 meters. This target subtends a half-angle of only 0.32°. This small acceptance angle places stringent restrictions on the maximum transverse energy that the negative ions can have, and on the quality of the accelerating and transport systems. For the 200 keV MFTF- -T application, the maximum transverse energy acceptable, assuming perfect acceleration and transport, is 200 $\tan^2$ (0.32) keV, or 6.2 eV. This assumes no compression of the beam during transport and acceleration. With slot accelerators, the beam is typically compressed a factor of 3, which reduces the maximum tolerable ion transverse energy by a factor of 3^2, to 0.7 eV. These numbers may be used as an initial check to see if a particular concept for a negative ion source might be suitable for this application. Surface-conversion sources, with transverse energies of about 5 eV, barely pass this test and then only if the source and accelerator can be oriented in the "good" direction. Volume-production sources, with transverse energies of about 0.5 eV,[4] will certainly be acceptable from this standpoint after they have been developed to the point of producing interesting quantities of negative ions. Sources producing negative ions with larger transverse energies are not necessarily excluded from consideration; if the currents produced are large enough, the fraction of ions with excessive transverse energy can always be thrown away, leaving only those ions with acceptable transverse energies.

Pulse lengths: Pulse lengths range from a proposed 100 hours for MFTF-α+T to weeks or months for a bona-fide reactor. Anything over a few seconds should be considered steady-state, which means that all portions of the beamline that beam particles could possibly hit should be water-cooled. Another implication of these long pulse lengths is that pumps used in the vacuum system must be capable of being recycled on-line. Reactors will use only a relatively few number of beamlines, sometimes only one per critical application (as in the case of the sloshing ion beams for MFTF-α+T), and so the possibility of simply shutting down the beamline for routine recycling of cryopumps does not exist. The time until recycling is required, in the case of cryopumps or other pumps that store deuterium, may be set either by the inventory of deuterium necessary to make an explosive mixture in the event of an up-to-air accident, or by the allowable tritium inventory in the beamline.

Reliability: This is a very critical area, to which, unfortunately, very little development effort has been devoted. As discussed above, since so few sources may be involved, each one must operate very reliably. Even the positive sloshing ion beams for MFTF-B require 99% reliability; the requirement will be even higher for a reactor. The way to achieve reliability is first by conservative design, which unfortunately runs counter to the simultaneous requirement of high performance, and second, by building as many units as is practical (or affordable), and running them to obtain reliable statistical data on failure modes. This is also not a palatable approach for first-of-a-kind reactor designers, and so I believe that this is going to remain a serious problem. We should continuously strive for simpler systems, for passive rather than active controls, and for systems that do not have important variables that are difficult to control. Cesium control in surface-conversion sources is one example of the latter problem, as is the problem of the simultaneous control of the primary beam, a metal vapor jet, and a second, high energy, accelerator in the case of systems utilizing double electron capture. One of the strongest arguments against neutral beam systems is their complexity, with the attendant problems of reliability.

Beam Purity: Negative ion beams typically contain a percent or so of atoms or molecules other than the desired D^- ion. Typical impurities are O^-, O_2^-, OH^-, and CH^-. The operation of mirror machines is very sensitive to these impurities; the operation of tokamaks is not. In the worst case, mirror machines can only stand 10^{-6} of O in the D beam for 30-sec pulses (MFTF-B). Worse yet, the ions accumulate, which means the beam purity becomes even more critical for longer pulse lengths. Clearly some means must be found to remove the offending ions from the machine. Forms of resonant pumping have been proposed, but not yet tried. Although a suitable first step is to improve the beam purity by momentum selection or by some other means (such as choice of a wavelength in a photoneutralizer to selectively discriminate against conversion of impurity negative ions to neutrals), in the long run some other solution must be found. It is likely, therefore, that this constraint will be relaxed for neutral beam systems on functioning reactors.

B. ENVIRONMENTAL CONSTRAINTS

The requirements on performance of negative-ion-based neutral beam systems that we have discussed so far fall into the category of functional, first-order requirements on the injection systems. That is, the experiment or reactor will not function if these requirements are not met. Other classes of requirements and constraints fall into different categories, such as environmental (we are speaking of the problems associated with the environment of the beamline) or economical; we turn to each of these now in turn.

Radiation Environment: Fusion reactors produce neutrons. These neutrons will come out through the shielding penetrations that permit the neutral beams to enter the reactor; consideration must therefore be given to problems associated with activation of parts of the neutral beam injection system. One solution would be to make the neutral beam system remotely maintainable. To anyone who has seen a large negative ion source, with its multitude of electrical cables and water feed lines, or an installed and functioning beamline, this seems a difficult route to pursue. A much more attractive solution is to design the beamline, by suitable choice of materials, and by utilizing recent improvements in beam transport systems that can permit transporting the negative ion beam through a maze in the neutron shielding, so that the high-technology components are outside the shielding,[5] and so that the fraction of the beamline that has to be maintained remotely is minimized. Recent neutronics calculations indicate that hands-on maintenance of sources and accelerators so protected is probably feasible within two days of reactor shut-down.[6]

The neutral beam injector must be designed to be compatible with tritium operation. In extreme cases, the injector may have to produce tritium beams. Even if this is not the case, tritium from the reactor will leak into the neutral beam system and contaminate it. It is likely that the entire beamline will have to be bakable to 150 degrees C to purge the tritium from the beamline before opening it to the atmosphere; it is also possible that the entire beamline will have to be constructed with remote maintenance capability, in case the entire reactor hall is contaminated by a tritium spill.

Neutral beam systems have been criticised severely in comparison with competing RF systems on the grounds of difficulty of remote maintenance of complex components; this real or perceived disadvantage is important enough that designers of neutral beam systems should try very hard to find ways to alleviate the problem areas.

An important distinction is that the radiation environments for neutral beam systems are very different for tokamaks and mirrors. Since the neutral beam system (for sloshing ions, at least) on a mirror machine "sees" a region of the plasma that is not the primary neutron producer, the neutron flux into the beamline is lower than in the case of a tokamak, by a factor of a thousand or more. This means that it is easier to reduce the flux at the source to an acceptable level in the case of mirrors than in the case of tokamaks, and also that the development lines for the two systems are likely to diverge.

Magnetic fields: Neutral beam systems must operate in the fringe fields of the magnets used to confine the plasma. These fields can be up to 0.1 Tesla at the front end of the beamline. Sources typically can tolerate fields of only 10^{-3} of this field (1 Gauss), and ion trajectories also are influenced by stray fields, so magnetic shielding must be provided for most of the beamline. Eddy current effects can be used for short pulse systems, but not for 30 sec or longer pulse lengths. Shielding may be active (opposing fields generated by coils) or passive (magnetic materials or cryogenic superconducting materials), but it must be provided.

C. ECONOMIC CONSTRAINTS

We now turn to a number of economic constraints. These are constraints which if not satisfied, mean that the neutral beam system is too expensive to construct or operate, either because the entire reactor cannot compete against alternative power sources, or because the neutral beam system cannot compete against alternatives, such as RF systems.

Space: Free space around a reactor is at a premium. In some cases, the neutral beam system must fit into a vault already constructed. In others, building costs may increase because of excessive room needed by neutral beam systems surrounding the reactor. The reactor must be able to be taken apart, however, and so some space must be left around it to set down large components during assembly and disassembly. This requirement varies from design to design, but as a rule of thumb, the beam designer should aim to occupy no more space with his injectors than is required for disassembly of the reactor. The argument here is that the neutral beam injectors would first be removed from the reactor hall to provide space for reactor components. This is actually an argument for high current-density negative ion sources. Although it appears that negative-ion neutral beam systems based on present and near-future technologies are at least commensurate with the size of projected large tokamaks,[5] the systems would certainly be improved if one could produce more current per injector.

Efficiency: A number of constraints fall into this category, although their inclusion may appear surprising at first. RF accelerators suffer in comparison with DC accelerators because of their poor power efficiency. The reason is that the RF systems do not actually spend a large fraction of the available time accelerating ions. Overall accelerator efficiencies may be only 1/2 to 1/3 of DC systems, and that is a very severe penalty to pay. The goal, therefore, is to push DC accelerator technology to its farthest limits.

Once the beam has been accelerated, it is important that it not be lost by gas collisions. The cross section for stripping of D^- in D_2 varies from 3×10^{-16} cm^2 at 200 keV to 2×10^{-16} cm^2 at 400 keV. Unfortunately, this is a very large cross-section, and the implication is that to reduce losses to a few percent over path lengths of several meters, background pressures should not be over a few times 10^{-6} Torr. There is an additional complication, since in cryopumped systems, the temperature of the thermally shielded walls and also the temperature of the background gas sink to about 100K,[7] which increases the gas density and the stripping losses. With a source gas efficiency of 10%, about the best so far achieved, to pump the gas coming just from the ion source at such a low pressure would require hundreds of square meters of cryopanels. The corollaries thus are that source gas efficiency should be improved, and that the gas should be pumped at relatively high pressure (10^{-4} Torr, for example). A scheme to transport the pre-accelerated ion beam through a differential pumping section becomes attractive; the beam then can be accelerated to higher energy in a lower pressure section of the beamline.

An additional, geometric, constraint results from this pumping requirement: since negative ion sources produce relatively low current densities of negative ions, to produce the total currents required, a large area beam is necessary. To remove the gas efficiently, the configuration of the beam must be such that the beam is thin in one dimension and long in the other; in addition, differential pumping is probably required.[8] Such a geometry also minimizes the gas flow from a gas neutralizer, and is a good match to a laser photoneutralizer, which will probably be the neutralizer of choice because of the potentially higher over-all system efficiency.[9]

In purely electrostatic accelerators, electrons will be accelerated along with the negative ions. In an efficient system, one would not want to invest more than a few percent of the system power in doing this. Therefore, control and removal of electrons before they reach high energies is important. This is a very important constraint; schemes that fail to remove practically all the electrons from the beam before final acceleration, or that invest too much power in acceleration of electrons, will not be serious contenders for use on reactors.

Cost: To the best of my knowledge, there has been no accurate study of the costs of the negative-ion-based neutral beam systems suitable for reactor application, so this is an open question. An example of the uncertainty is reflected in the choice of neutralizer. Gas targets certainly work, and can be accurately costed, but since the time until the first application of negative-ion-based neutral beam systems is so long, approximately 10 years, gas targets probably will not be the neutralizer of choice. It is more likely that a photodetachment neutralizer will be chosen, perhaps one employing a chemically excited laser. Development of such lasers is proceeding rapidly, and estimates of the cost of this component of the neutral beam system, if they existed, would be changing rapidly. Nevertheless, when such cost estimates are made, neutral beam systems will have a ready-made standard against which they will be judged, namely the cost of competing RF systems. It is therefore important for the designers of neutral beam systems to become and remain cognizant of developments and cost studies for RF systems.

AN EXAMPLE

As an example of the types of considerations necessary in designing a negative-ion-based neutral beam system, I would like to summarize briefly the thoughts that have so far gone into a typical conceptual design, the one utilizing TFF transport and accelerating systems and an LBL surface-conversion source illustrated in Figure 1, also discussed from the point of view of ion optics in another paper at this conference.[10] This design uses a Pierce type pre-accelerator operating at 80 keV; the 80 keV beam is transported through a matching and pumping section, and finally, is accelerated to 400 keV by a TFF accelerator. The choice of the pre-accelerator energy, 80 keV, resulted from a compromise between the conflicting desires of minimizing energy, so that beam loss due to stripping would take place at as low an energy as possible, and of avoiding high perveance pre-accelerator designs, which introduce undesirable aberrations. Once the accelerator was selected, the converter size was fixed -- the converter has to be large enough to illuminate the entrance to the 80 keV pre-accelerator uniformly, without vignetting. Otherwise, intolerable aberrations are introduced into the beam. This sets the size, then, of the ion source.

Design of the matching and pumping section is an iterative process, still going on. The transport electrodes must be as transparent as possible to gas, to facilitate pumping, yet still transport the beam without introducing aberrations. It appears that these requirements can be met in this design; losses up to the final accelerator are estimated at about 7%.

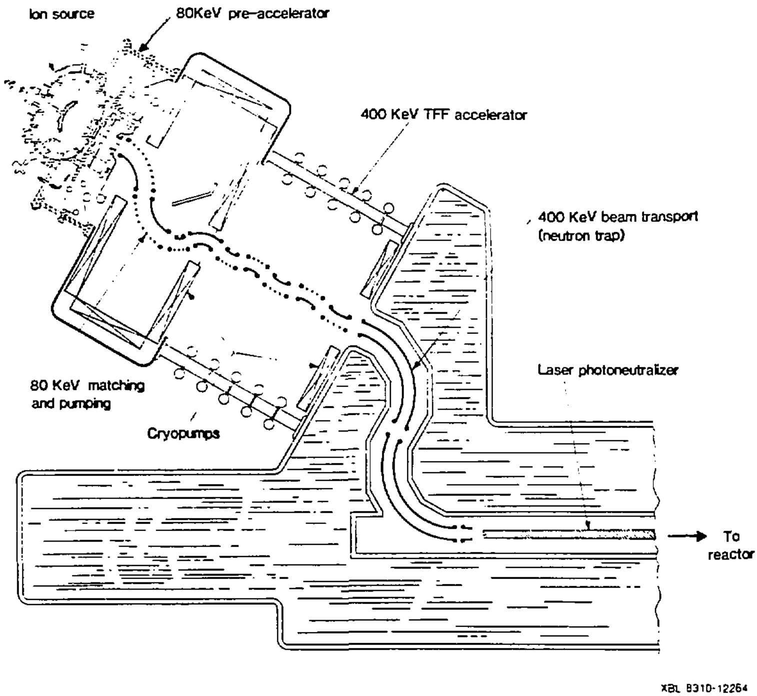

Fig. 1. Plan view of 400 keV TFF-based beam line.

Design of the transport and matching section cannot be fixed without examining ion trajectories all the way through the system. Ion trajectories have in fact been calculated self-consistently from the converter all the way through the final 400 keV transport section.[10] Uncertainties still remain: neutronics studies have not been carried out for this particular design, so we do not know for sure that the two bends shown in Figure 1 will be adequate to reduce the neutron flux at the source to the desired level. Another uncertainty has to do with the particulars of the laser photoneutralizer. To minimize losses, it is

TABLE I
SYSTEM REQUIREMENTS, CONSTRAINTS, AND DESIGN IMPLICATIONS

CLASSIFICATION OF REQUIREMENT	REQUIREMENT	CONSTRAINTS AND DESIGN IMPLICATIONS
Functional	Inject 2-50 MW	Protect system against self-destruction
	Energy 200-800 keV	Balance current density against sparking
	Small target size	Ion transverse energies <1 to 5 eV, or Use high current density ion source
	Pulse length > 100 hours	Actively cool beamline components, Vacuum pumps capable of on-line regeneration
	>99% reliability	Conservative and simple design, Extensive testing of prototypes
	Beam purity	Develop ways to remove impurities from reactor, or from beam
Environmental	Radiation	Transport beam through shielding, Design for remote handling, Source/accelerator bakable, Tokamak and mirror injector designs likely to diverge
	Magnetic fields	Active or passive shielding must be provided
Economic	Space	Neutral beam injectors should occupy no more space than is required to assemble or dismantle reactor
	Efficiency	DC acceleraton rather than RF, Pump gas at high pressure, Sheet-like beams, Probable choice of laser photo-neutralizer, < 5% electrons in beam
	Cost	Should be competitive with RF systems

desirable to minimize the area of mirrors in the laser cavity resonator. If we reduce the final negative ion beam width to permit this, by changes in the design of the final transport section, the beam divergence will increase (Liouville's Theorem). Some balance must therefore be achieved between conflicting requirements of minimizing the laser power and satisfying the beam divergence requirement. Our study has not progressed to this state.

Nor have we completed an analysis of the pumping requirements. Pumping may have to be included in the final transport section or in the laser photoneutralizer section, or both. These pumps take up room -- their space requirement, plus the properties of materials used in their construction, will affect neutron transport and activation.

Finally, magnetic shielding has been ignored completely. We will have to return to this problem at a later date.

SUMMARY

It is not possible to produce a design of a negative-ion-based neutral beam system that will satisfy all requirements. Economic pressures will force each design to be tailored to the requirements of its particular reactor. The neutral beam designer must be aware of all the constraints, and I hope this discussion will provide a first step in this direction, so that the resulting neutral beam system will be at least approximately optimized for the particular application, and so that the designer will be able to avoid designing himself into traps along the way.

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