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NEGATIVE-ION-BASED NEUTRAL BEAMS FOR FUSION

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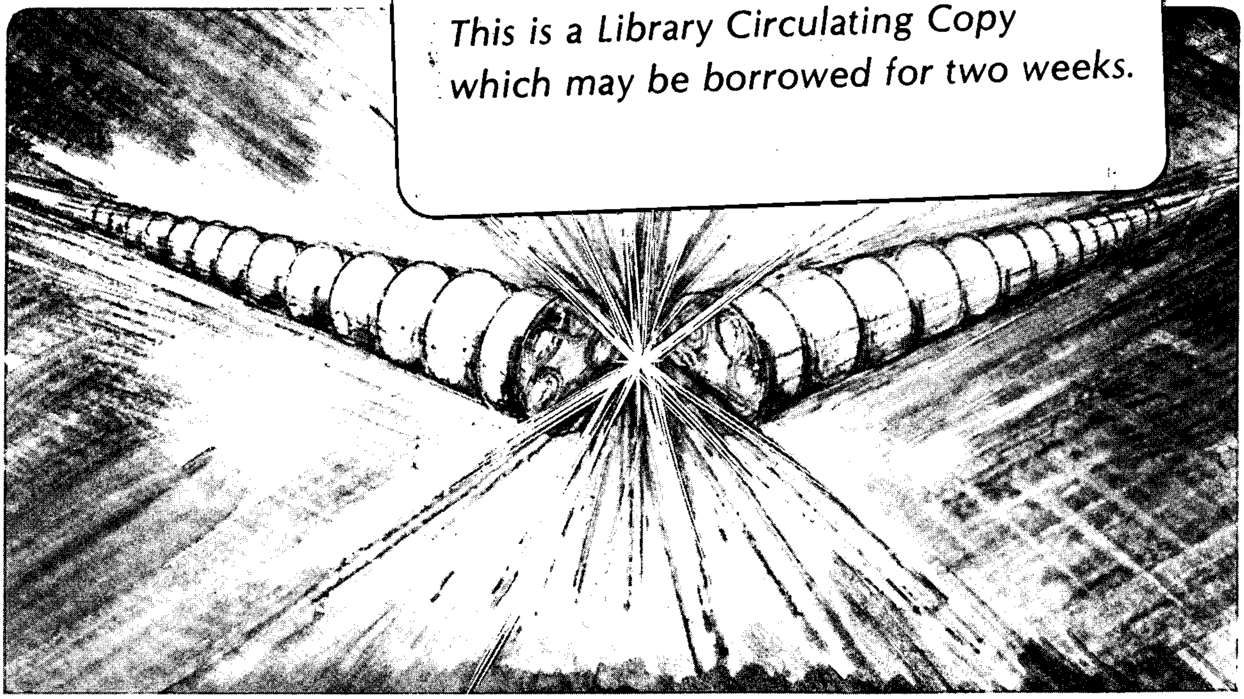

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Abstract

To maximize the usefulness of an engineering test reactor (e.g., ITER, TIBER), it is highly desirable that it operate under steady-state conditions. The most attractive option for maintaining the circulating current needed in the center of the plasma is the injection of powerful beams of neutral deuterium atoms. The beam simultaneously heats the plasma. At the energies required, in excess of 500 keV, such beams can be made by accelerating D^- ions and then removing the electron. Sources are being developed that generate the D^- ions in the volume of a specially constructed plasma discharge, without the addition of cesium. These sources must operate with minimum gas flow, to avoid stripping the D^- beam, and with minimum electron output. We are designing at LBL highly efficient electrostatic accelerators that combine electric strong-focusing with dc acceleration and offer the possibility of varying the beam energy at constant current while minimizing breakdown. Some form of rf acceleration may also be required. To minimize irradiation of the ion sources and accelerators, the D^- beam can be transported through a maze in the neutron shielding. The D^- ions can be converted to neutrals in a gas or plasma target, but advances in laser and mirror technology may make possible very efficient photodetachment systems by the time an ETR becomes operational.

Beam Requirements for Future Fusion Experiments

Background

Planning of neutral beam development for future experiments is centered on meeting the requirements of an ETR--we have rather carefully considered TIBER requirements, and are now considering beams for ITER. In both cases, the reactors will have to operate with very long pulses (days to weeks), and some non-inductive method of maintaining the plasma current is required. Of the several methods considered so far (lower hybrid slow waves, lower hybrid fast waves, waves at the electron cyclotron frequency, and neutral beams), high energy beams of D^0 atoms are an attractive option, as they have been demonstrated to drive current, are expected to be reasonably efficient, and will penetrate to the axis of a dense plasma. They will also heat the plasma, and will provide some degree of fueling. Substantial development will be required, however, to produce the beams needed for an ETR.

Choice of beam energy

To provide current drive and heating in the center of the plasma, the beams must be energetic enough to penetrate as neutrals into this region; this requirement sets the lower limit for the beam energy. It is about 0.5 MeV for a TIBER size device (R = 3 M) and about 1 MeV for a tokamak the size of ITER (R $\cong$ 4.5 M). These may be considered lower limits, as uncertainties in the atomic physics of beam penetration can raise the required minimum energy, but are very unlikely to reduce it. The upper limit is even less certain--there is a possibility that the beams will excite an Alfven wave instability, but the consequences if this happens are not clear. It is certainly undesireable to have the beam energy so high that a large fraction penetrates the plasma completely without being ionized and trapped ("shine-through")--this would be wasteful of power and could possibly result in damaging the far wall of the reactor. The physics Q (fusion power divided by injected power) is relatively insensitive to beam energy over a rather broad range. Figure 1 shows for the case of TIBER the incident beam power required, the absorbed power, and the incident neutral beam current as functions of beam energy, all for constant fusion power of 320 MW. The difference between the incident power and the absorbed power is the shine-through. The incident power required is 30-40 MW. For ITER, an incident power of 40 to 70 MW is required, and the energy range is approximately 1 to 5 MeV. It is very desirable to be able to vary the energy without substantial reduction in current, in order to deposit the power in the center of a plasma with variable density.

Choice of beam current

Notice that the current required for TIBER as shown in Fig. 1 drops sharply as the energy is raised. We can expect a similar behavior in the case of ITER. We shall see later that one of the principal difficulties in beam development is the production of large currents of D^- ions; this energy dependence indicates that it may be desirable to go to the highest beam energy permitted, in order to reduce the current requirement. In any event, neutral currents in the range of of 10 to 100 A will be required.

Beamline Components

Ion Sources

It is difficult to produce D^- ions and prevent their destruction before acceleration; the binding energy of the D^- ion is only 0.75 eV. The most successful type of dc negative ion source to date is the volume-production source[1]; as the name indicates, the ions are produced in the volume of the plasma, rather than on surfaces. Such a source is shown in Fig. 2. The physical processes by which the ions are produced and transported to the entrance of the accelerator are not well understood.

We can gain some appreciation of the difficulty of producing 10's or 100's of amperes of D^- ions by comparing the performance of existing volume-production sources with a comparable D^+ source such as the Common Long Pulse Source (CLPS).[2] The negative ion current density available from existing sources is lower by about a factor of 10 than is available from a positive ion source (10-20 mA/cm^2 of H^-, versus 200), and the operating pressure at present is about a factor of 10 higher (10-20 mT, rather than 1-5), which causes a loss of 30-50% of the beam by stripping during acceleration.

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It is essential to avoid accelerating too many electrons along with the D^- ions. At best, existing volume-production sources produce one or more electrons per negative ion; the accelerator must be designed with magnetic fields to sweep the electrons out of the beam before they have gained too much energy.

Accelerators

We must develop accelerators that can accelerate 10's of amperes of negative ions to an energy of 1 to 5 MeV, steady-state, with high beam quality and power efficiency, and preferably with variable energy at constant current. All of our positive ion accelerators, such as the 120 keV design used in the CLPS, operate on principles set down by Pierce.[3] In these designs, a suitable longitudinal variation of the potential with position produces a radial component of electric field through Poisson's equation that is just sufficient to balance the radial repulsive forces generated by the beam space charge. This design has a very narrow tuning range; for optimum beam optics at a given voltage, the current is determined by $I = PV^{3/2}$, where P is the perveance. For the application we are facing, we need to separate the problems of accelerating the beam from those of coping with the beam space charge. We can do this by introducing electrostatic strong-focusing elements such as electrostatic quadrupoles (ESQ's) or a series of suitably biased rings (ESR's) to provide radial forces to handle the space charge, and accelerate the beam by biasing these elements with respect to their neighbors. Such an approach has three major advantages over the Pierce column: 1) we can vary the energy over a wide range at constant current with little effect on the beam divergence, 2) we can make the accelerator arbitrarily long, thus reducing the average electric field along insulators and reducing the probability of breakdown, and 3) if the design has transverse fields or potential wells on axis, we can expect a further reduction in tendency to break down. Figure 3 shows a 500 keV design based on these considerations and incorporating rings, or washers, that generate a rippled potential along the axis. The injection energy is 100 keV. This design can either accelerate the beam to 500 keV, as shown, or by changing the potentials, accelerate the beam to any intermediate energy (or even to keep the energy at 100 keV, in which the accelerator serves as a beam transporter).

Can we push dc technology to 1 MeV or more? It is not clear that we can, although dc acceleration will almost certainly offer substantially higher power efficiency than the alternative, rf acceleration. In view of the uncertainly in the limits of dc acceleration, we must consider alternatives.

One approach that has a certain appeal, and one that we are considering, is that of adding an rf "booster" to a dc system. This could be a multiple-aperture high current linac, matching the multiple-aperture dc accelerator, with a current per channel of possibly 0.2 A. Linacs have accelerated such high currents, but not cw; to the best of my knowledge the highest current ever accelerated cw by any type of rf accelerator is 0.1 A.[4] Such a high current multiple-aperture linac would be radically different from existing linacs. For example, if one injected a 400 keV beam and accelerated with less than 25% energy gain per gap, it would only require five acceleration gaps to reach 1 MeV. Preliminary studies indicate that with a sophisticated buncher and pulse shaper (high technology, but low power), which might be incorporated in the preaccelerator design, it should be possible to accelerate the beam to 1 MeV with very little beam loss even though no attempt is made to bunch the beam in such a way that we achieve longitudinal phase stability of the bunch. Each drift space would consist of a series of electrostatic quadrupoles (ESQ's) to prevent beam blowup due to space-charge forces. Variable energy could be achieved by turning off one of more rf accelerating gaps and using the following ESQ drift sections as beam transporters. The phase-space dynamics of such an accelerator are shown in Fig. 4, which shows the energy of each particle as a function of the time that it exits the buncher or an accelerator gap. The buncher generates a sawtooth potential waveform of ± 80 kV to bunch the 400 keV injected beam. This example uses sinusoidal accelerating voltages in five gaps; the final beam energy is 837 keV, with an energy spread of ± 20%, and with little, if any, beam loss due to reflection. Space-charge and transit-time effects are not included in the model. More sophisticated analysis will be required to determine whether the divergence of the accelerated beam is acceptable.

The beam optics analysis is enormously simplified if we can accelerate with an rf square wave, as in that case a dc analysis is sufficient. In that case it might be possible to use efficiently switched dc from existing neutral beam power systems for the rf portion of the system.

Neutralizers

A gas target can be used to convert a beam of D^- ions to neutrals with about 55% conversion efficiency, but for a system that will first operate in the year 2000 we may have more attractive options: we can expect rapid progress in both plasma targets[5] and photon targets[6] as neutralizers. The neutralization efficiencies of these targets are expected to be >80% and >90%, respectively; in either case the beamline power efficiency will be substantially larger than in the case of a beamline using a gas neutralizer.

System Considerations

In positive ion beamlines, the cross section of the beamline is determined by the necessity of providing a large enough area for cryopumps. In negative ion beamlines, the cross sectional area will be determined by the necessity of providing enough ion sources to produce the required current. This is a direct consequence of the low current density produced by negative ion sources. Source development is critical: we need sources that can produce 30 mA/cm^2 of D^-, dc, for months, in order to produce not unreasonably large beamlines. In their present state of development, sources can produce only 10 to 20 mA of H^- over large areas (easier than producing the same current density of D^- because of isotope effects). Every improvement in current density and transparency leads to a reduction in beamline size and cost.

As has been pointed out in the JAERI 500 keV beamline study,[7] we can use the anticipated small divergence of these high energy beams to advantage by moving the beamline as far as possible from the reactor in order to minimize magnetic shielding and activation problems. Most likely the entire system will have to be maintained remotely, but the reduction in neutron flux will enhance the lifetime of components. Experiments have shown that if necessary, the D^- beam can be transported through a sinuous channel in the neutron shielding to further reduce the neutron flux into the beamline.[8,9]

Conclusions

Progress has been steady in the development of all beamline components. The most critical requirements now are 1) to develop an ion source capable of producing at least 30 mA/cm^2 of D$^-$, dc, with tolerable gas and electron output, 2) to determine the beam energy required, and 3) to develop the accelerator technology required to produce such high energy, high current beams. The latter problem may be approached by developing dc technology to its near-term limit, then adding rf booster accelerator sections to increase the beam energy to the desired value. On the other hand, once it has been deemed necessary to use rf acceleration, it may be advantageous to do the bulk of the acceleration with an rf system, preferably with one that could be driven from existing NB high voltage supplies, thus avoiding the purchasing of new supplies, and to go to the highest beam energy tolerable to the reactor, in order to minimize the current required. Future optimization studies will determine the best approach.

Acknowledgments

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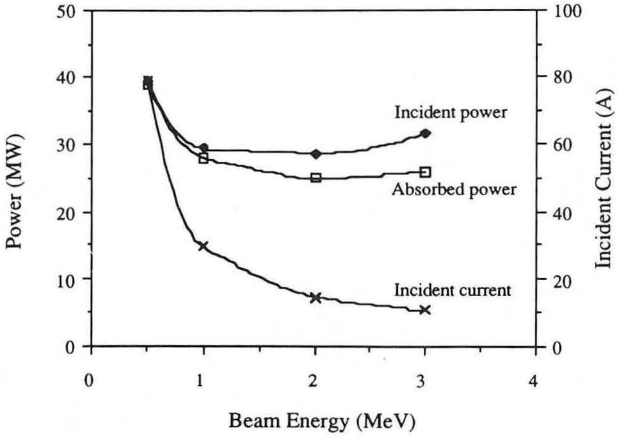

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Fig. 1 Incident power, absorbed power, and incident current for a TIBER neutral beam system as a function of beam energy. The fusion power is constant at 320 MW.

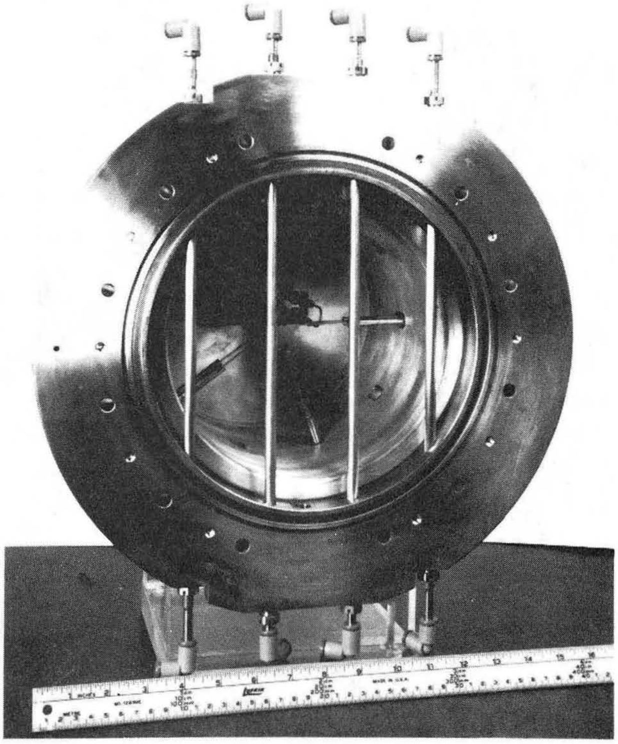

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Fig. 2 A volume-production negative ion source, showing the magnetic filter rods.

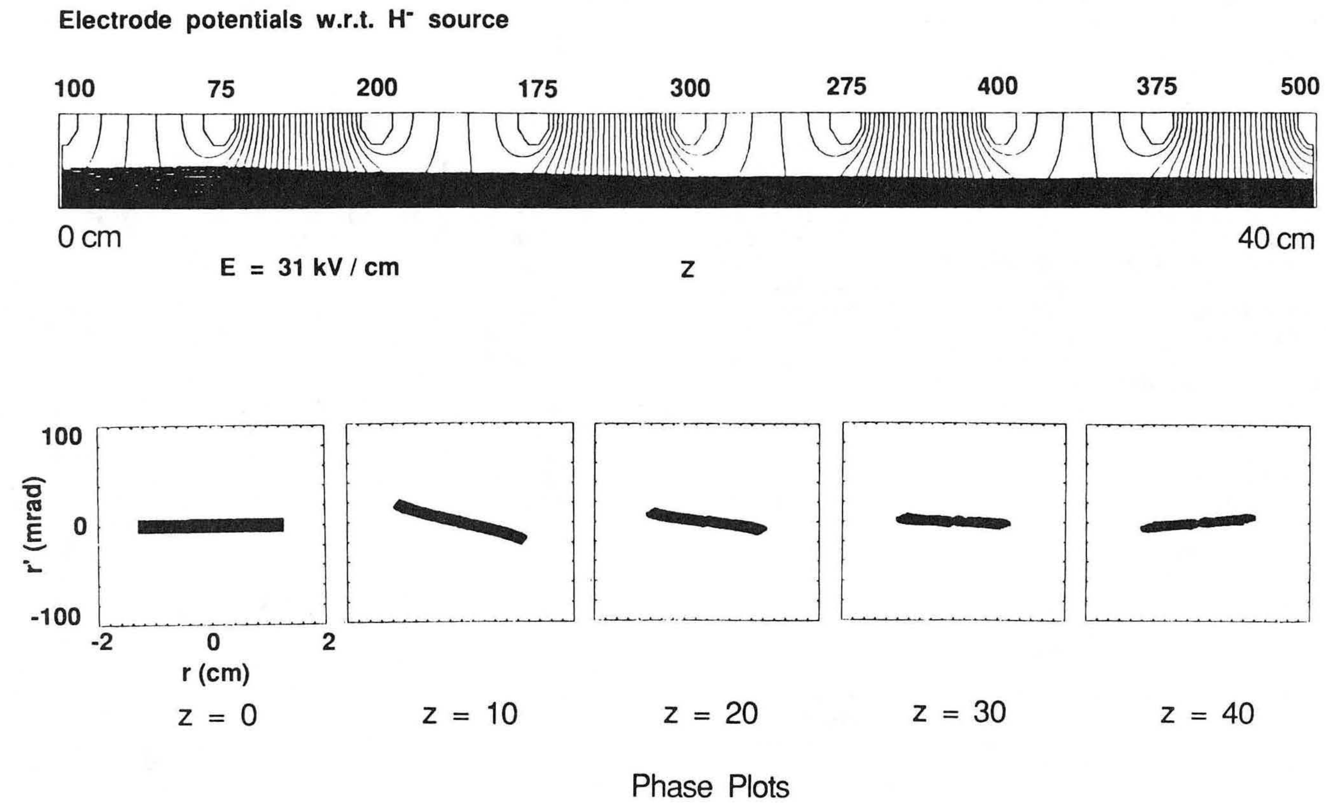

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Fig. 3 Ion trajectories and phase plots for a 500 keV strong-focusing electrostatic accelerator with the capability of varying the beam energy at constant current.

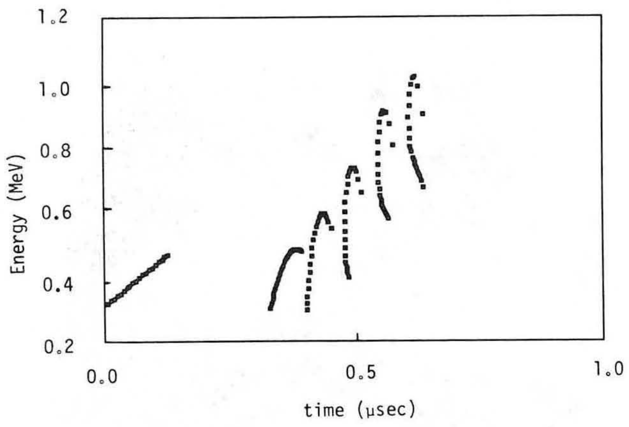

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Fig. 4 The particle energy versus time as particles exit the accelerating gaps of a five gap rf linac with a sawtooth buncher.

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