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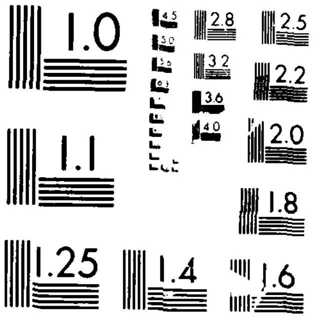

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NEGATIVE ION BEAMS FOR HEATING AND CURRENT-DRIVE IN NET

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ABSTRACT

A study of the capabilities of beam injection into NET as determined by the plasma and beam characteristics has recently been undertaken; this paper summarises its findings. The report divides into two parts namely a study of the restrictions on beam parameters introduced by physics requirements and a review of the technical potential of negative ion based injection systems. Positive ion beam systems are excluded from consideration since their electrical efficiencies are too low to be practicable at the high energies needed to give acceptable beam penetration, optimum current drive efficiency and low divergence (to allow beam transport through narrow ducts in Tokamak blankets).

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PART 1: PHYSICS REQUIREMENTS

The choice of beam energy and geometry is influenced by several distinct physics requirements which are discussed separately below.

Heating

The major physics requirements of a neutral beam heating system are that the energy of the beam is sufficient to give adequately good penetration to the plasma centre at the highest density used while still giving acceptably low transmitted power density on the wall of the machine ("shine-through") at the lowest plasma density used. The former sets a lower limit to the beam energy and the latter a higher limit. Since the beam energy necessary to meet these conflicting requirements depends on plasma parameters it is necessary to define the reference conditions.

The most significant features of a plasma as far as beam heating is concerned are its geometry, density and ionic content; the plasma ion and electron temperatures are not important since the cross-sections in the conditions of interest are only weakly dependent on them. The plasma configuration for this study is NET 3A and the two plasma densities considered approximate those expected at the end of the ohmic heating ($\bar{n}_e = 6.2 \times 10^{19} m^{-3}$) and during the burn phases ($\bar{n}_e = 1.25 \times 10^{20} m^{-3}$) respectively. In both cases the density profile is assumed to be broad ($n_e \approx \Psi^{0.5}$) which is typical of the profile expected in low q ohmically heated plasmas. The use of the same profile shape for the high density case is somewhat pessimistic since beam fuelling will almost certainly lead to more peaked (and therefore more easily penetrated) density profiles. It does have the advantage, however, of being a 'safe' choice in that any combination of beam energy and geometry which gives adequate penetration and acceptable shine-through with a broad density profile will also be acceptable for any density profile which is more peaked. Throughout this study the effect of beam ionisation by impurities has been neglected.

For the conditions outlined above the results from a beam deposition code indicate that the energies necessary to meet the penetration and shine-through requirements for normal and tangential injection are as shown in Table 1.

Table 1

	Normal injection		Tangential injection	
	Low n_e	High n_e	Low n_e	High n_e
"Shine-through" limit (keV/amu)	<100	<200	<300	<600
Penetration limit (keV/amu)	>50	>100	>100	>200

It can be seen that the energy 'window' over which the penetration is adequate at high density ($\bar{n}_e = 1.25 \times 10^{20} m^{-3}$) and the shine-through is acceptable at low density ($\bar{n}_e = 6.2 \times 10^{19} m^{-3}$) is very narrow for normal injection. It appears from these results that variable energy beams are desirable in this case and would become even more important if the density range was greater than the factor of two assumed here. The need for variable energy beams when using tangential injection is less clear but would offer a means of optimising the beam deposition. It should also be recalled that the 'energy window' will be larger for both normal and tangential injection if the density profile is more peaked than the one assumed here.

Particle Re-fuelling

If the beam power is taken to be half the α-particle power then the ratio of beam to α-particle source rates in the machine is

$$\frac{S_b}{S\alpha} = \frac{2\ S_b}{S_D + S_T} = \frac{1.75}{(E_b/\mathrm{MeV})}$$

If the plasma is to be fuelled entirely from the beams (which would obviously require tritium as well as deuteruim beams) then this restricts the beam energy to $E_b < 0.85$ MeV. If the beam energy is lower than this value the excess source of particles must be balanced by a net radially outward flow to achieve steady-state. As well as providing the volume-average source it may be desirable to match approximately the strongly peaked radial profile of α-particle production. This requires a beam energy $\gtrsim$ 0.3 MeV/amu for a high density burn.

Current-drive

The energy needed to optimise the current-drive efficiency for deuterium injection into a D-T plasma is $E_b \approx 80\ T_e$. Thus energies approaching 1MeV would be needed for standard NET conditions. The current-drive efficiency is still 70% of the optimum value at energies of 25% of the optimum. The usefulness of beam current-drive for driving the whole plasma current for standard NET conditions is questionable, however, since the overall current-drive efficiency is low (~0.03 -0.05 A W^{-1}). Thus beam powers ~200-300 MW would be needed which, as well as causing a significant increase in power loadings in the machine (Pb ~2 -3 Pα), would limit NET to a Q ~ 2-3. Beam C-D would, therefore, only become attractive if either the plasma current could be reduced by a factor ~3 (for example by operation in the second stable regime) or by increasing the current-drive efficiency a similar factor. Since the fusion power is ~ β^2 and the current-drive efficiency is ~ T_e/n_e it would be possible in principle to quadruple the efficiency at the same fusion power output by roughly halving n_e and doubling T_e. The feasibility of both the low current and high temperature options is, however, far from certain at present.

Impurity flow reversal

There have been proposals to control impurity behaviour by altering the neoclassical impurity flows using the momentum input from neutral beams. There is some experimental evidence that appears to demonstrate effects of beams on impurity behaviour similar to the theoretical predictions, namely that directed beam injection in the same sense as the plasma current reduces the impurity influx and vice versa. There are, however, indications from other experiments that this is not always the case. Further experimental and theoretical work is obviously needed to clarify the situation.

The main influence of a desire to exploit impurity flow reversal on the design of a beam system stems from the need to maximise the momentum input parallel to the current. This requires injection as near to parallel as is feasible at as low a beam as possible (since the momentum input per unit beam power is inversely proportioned to the beam velocity) before the penetration of the beam to the plasma centre becomes too poor.

Summary

The optimum strategy for beam heating of NET appears to be tangential injection at energies ~0.2 - 0.4 MeV/amu. This provides good heating of the plasma centre even at high density and is adequately close to the optimum energy for current-drive. The particle source rate at these energies is sufficient to fuel the α-particle production and roughly matches the required radial profile at the higher energies. Tangential injection also maximises the possible effects of beams on impurity transport although lower energies are desirable to maximise the momentum input rate.

If tangential injection is not feasible for engineering reasons then near perpendicular injection at energies of $\lesssim$ 0.1 MeV/amu ($\lesssim$ 0.2MeV/amu) for fixed (variable) energy beams could be used but the current-drive efficiencies and the possible effects on impurity behaviour will then be much smaller.

PART 2: TECHNICAL ISSUES

The issue of the beam power which can be injected through a single duct is discussed in the first section. Two extremes are analysed: one in which the power is determined by the power density on the duct wall and 'shine through'; in the second the beam/duct geometry has also to be considered. The former is essentially the result discussed in the first part of this report. The latter reflects design issues for the beam system and duct setting limits to the beam radius (and hence beam power for given beam current density and energy Fig.1). To inject 20-100MW per duct (taken to be 2m high) without excessively wide ducts (width >70cm) requires beams of less than 35 cm width (full width at 1/e).

An analysis of beam transport based on extrapolation from positive ion beams show that this requirement can be met, in principle, even with the source at 50 metres from the torus at energies greater than 500 keV. The difference in transport of negative ion beams as compared with positive ions is discussed: essentially the difference arises from the fact that space charge compensation is achieved using plasma formed by beam-gas interaction. The plasma potential is effectively repulsive for positive ions but effectively <u>attractive</u> for negative ions.

As a result one expects lower beam divergence for negative ions, consequently the beam width may be reduced or the beam line length increased. However, existing data is for single aperture, we suppose that it can be extrapolated to multi-apertures. The demonstration of low divergence transport of multi-aperture (10-20 A) H beams is a critical issue in development of high power injectors.

Another major advantage of negative ions is the high efficiency at high energies: however this can only be achieved to full effect in plasma or laser neutralisers rather than gas neutralisers. Culham have assessed previously that plasma neutralisers provide a good solution based on technologies readily available. There is a need for a significant development program.

The results obtained in the Culham research programme already provide a data base for design of a 10-20A 100keV source of H^-. Results for D^- so far show reduced current capability, but this is the subject of the next phase of research.

On this basis, it is possible to expect that by 1989 one could have all the data for detailed design of a prototype beam line with a specification of 20A 500kV D^-, capable of injecting 6MW of neutral power into NET. However, several studies and experimental demonstrations are needed in that period, to bring this about.

(1) Study of optimisation of D^- current density.
(2) Demonstration of beam transport, both ions and neutrals, from H^- 20A 80kV source.
(3) Demonstration of operation of a plasma neutraliser.
(4) Design study of high voltage power supply.
(5) Conceptual design of prototype beam line.

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