PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

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Phil. Trans. R. Soc. Lond. A 1981 **300**, 589-598
doi: 10.1098/rsta.1981.0087

Phil. Trans. R. Soc. Lond. A **300**, 589–598 (1981) [589]
Printed in Great Britain

Heating and plasma interactions with beams of energetic neutral atoms

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The use of fast neutral atom beams to heat toroidally confined plasmas is discussed. The conditions governing the beam power and energy requirements are given, and the limitations on the beams used to achieve these are discussed. The interaction of these beams with the plasma involves several classical collision processes which are described by a Fokker–Planck equation, all the terms of which have now been checked experimentally. The transfer of momentum to the plasma is described, one particular aspect of which is the creation of a beam-driven current. The existence of this current has now been established both experimentally and theoretically and may allow the construction of a continuously operated tokamak reactor.

Introduction

Toroidal confinement systems have traditionally been heated by using the internal transformer-induced current. The power input per unit volume by this means is proportional to ηj^2, where j is the current density and η is the plasma resistivity. For hot plasmas the resistivity falls off as the electron temperature is raised (as $T_e^{-\frac{3}{2}}$) until, for temperatures of more than about 1 keV, the power input becomes small compared with the typical power losses. It is therefore important to have some other heating method if temperatures sufficient to reach ignition (*ca.* 10 keV) are to be achieved.

This paper deals with the use of fast neutral atom beams for this purpose. The other practical alternative, radio-frequency heating, is less well developed and less well understood but may have some practical advantages. It is not yet clear which of the methods will be the more efficient in the long term.

Historically, neutral beam sources of modest intensity were used to heat mirror experiments during the period 1960–70 but it was not until the development of intense multi-beamlet sources in about 1970 that it became possible to heat the larger-volume toroidal systems. Sources have now been developed in several parts of the world with currents in the range 10–100 A and potentials of 20–120 kV, and neutral beam heating is regarded as an essential feature of new tokamak experiments.

The broad achievements during the past decade have been: (*a*) the rapid development of intense neutral atom sources; (*b*) the development of the theoretical and experimental understanding of the physics of beam trapping, energy input to the plasma, scattering and the momentum transfer; (*c*) the use of beams to heat tokamaks to very high temperatures: the record in this respect being held by the Princeton P.L.T. Group (Eubank *et al.* 1979). In this paper it is proposed to discuss areas (*a*) and (*b*) which deal with the input of heat to the plasma. The consideration of the actual temperatures achieved in experiments involves a discussion of the heat losses, which is not the concern of this paper. It is proposed also to discuss the recent experimental establishment of the beam-driven current which may enable the development of a continuously operated tokamak.

Beam power and energy requirements

The beam power required to reach a given temperature depends of course on the losses from the plasma. In future experiments in which it is intended to reach ignition there will also be help from the heating produced by the thermonuclear reaction products. The power required to reach ignition is only a few megawatts if only neoclassical losses are taken into account (Sweetman 1973) but the more recent empirical scaling laws, which show losses increasing as the density is lowered, give a minimum density for ignition of order $n_e \approx 10^{20}\ \mathrm{m^{-3}}$ and hence a minimum power level for ignition that is some tens of megawatts. The power requirements for current experiments range up to 4 MW; future major experiments (of the scale of JET) will require up to 40 MW, and reactors will require power levels of the order of 75–100 MW. Module sizes much smaller than this are of course acceptable and units in the 1–2 MW range are currently being developed.

The optimum neutral atom energy is decided by the need for the neutral atoms to penetrate the plasma before becoming ionized by ion and electron collisions. The principal ionization processes are charge exchange on the plasma ions, ionization by the plasma ions and ionization by the plasma electrons. The cross sections for these processes have been given by Sweetman (1973). Ionization by impurity ions can also play a significant role in laboratory plasmas, and recent work by Olson *et al.* (1978) has shown that the cross sections for these can be expressed as a simple universal relation between σ/q and E/q, where q is the impurity charge state, and σ and E are the cross section and energy/atomic mass respectively. This relation is given as

$$\sigma = 4.6q \times 10^{-16}\{32(q/E)\ [1-\exp\,(-E/32q)]\}\ \mathrm{cm}^2,$$

where E is in keV/atomic mass. The range of validity is quoted as $1 \leqslant q \leqslant 50$ and $50 \leqslant E \leqslant 5000$. For relatively small impurity levels the effect of impurities on the beam penetration is not serious, but the resulting radiation loss following charge-exchange reactions can be important in the energy balance (Abramov 1979).

The total cross section for ionization σ_{T} (with or without impurity present) tends to be a falling function of the atom energy. For convenience a mean free path λ may be defined as follows

$$\lambda = 1/n\sigma_{\mathrm{T}}.$$

The number of ions deposited on a magnetic surface, that is the source rate S, can then be calculated as a function of the mean free path λ and the radius of the minor cross section a. For a pencil beam of current I_0 at an angle θ to the magnetic axis and passing through the centre of the machine the source rate is

$$S = \frac{I_0}{e4\pi^2 rR\lambda \sin\theta}\left[\exp\left(-\frac{1}{\sin\theta}\int_r^a \frac{\mathrm{d}r}{\lambda}\right) + \exp\left(-\frac{1}{\sin\theta}\int_{-r}^a \frac{\mathrm{d}r}{\lambda}\right)\right].$$

A set of these pencil beams may then be summed numerically to form the actual beam deposition profile (Rome *et al.* 1974). An example of the use of this technique for the injection system on DITE is given in figure 1, where $H(r) = 2\pi^2 a^2 ReS/I_0$.

From figure 1 it is clear that there is an optimum energy to deposit as much power as possible in the centre of the plasma: too low an energy deposits the power near the edge; too high an energy results in most of the power escaping from the far side. For current experiments this optimum energy is in the range 20–40 keV/nucleon; for future major experiments (e.g. JET) the optimum is at 80 keV/nucleon or higher; for reactors the optimum energy at full operating density may be as high as 1 MeV/nucleon. However, various heating approaches have been suggested that may reduce the reactor requirements to 80 keV/nucleon (160 keV deuterium) essentially by reducing the density during the early phases of ignition.

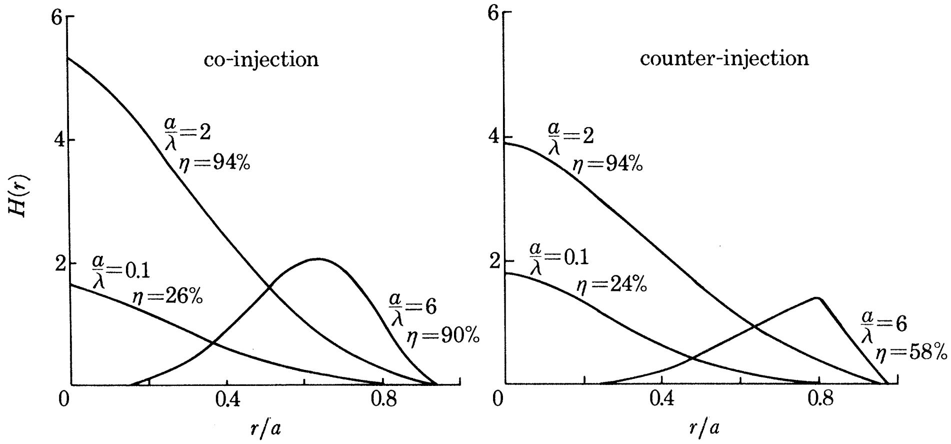

FIGURE 1. Radial profiles of particle deposition for a typical range of ratio of plasma radius, a, to mean free path (λ), and injection conditions characteristic of the DITE tokamak. The fraction of beam trapped is given by η for the various values of a/λ illustrated. $H(r)$ is defined in the text.

NEUTRAL BEAM PRODUCTION

Ion beam power limitations

In the early experiments single ion beams were used and were focused by means of separate electrostatic or magnetic lenses. The power in the ion beam achievable in this way is limited essentially by the Langmuir–Blodgett law which demands that the current density (j) is given by $j = cV^{\frac{3}{2}}/d^2$, where V is the voltage across the gap of width d, and c is a constant which depends on the ion mass and the curvature of the emitting surface. Since the ratio of the radius of the aperture to the gap width is fixed by ion optical requirements, the total current extractable from a single aperture is proportional to $V^{\frac{3}{2}}$ and is independent of the aperture size. For voltages much less than 1 MV this represents a severe limitation on the ion beam power extractable from a single aperture, a power of about 50 kW at 100 kV being typical. The advent of multi-aperture extraction systems (Hamilton *et al.* 1968) has enabled the production of much higher current beams. In these systems the shape of the apertures is carefully arranged to produce beamlets of low divergence (since no focusing can be done subsequently) so that arrays of several hundred beamlets can be combined. Development in the ion optics of such beamlets has been rapid and has now reached the point where the divergence is limited only by the transverse temperature of the ions emerging from the source (Holmes & Inman 1979). The only known limit to the area of such arrays is the energy stored capacitatively in the extraction system which, when it exceeds several joules, can cause excessive damage during voltage breakdown. This typically sets a limit to the total ion power per unit of the order of 10–20 MW.

The practical implementation in recent years has been very rapid and ion beam powers of several megawatts have been achieved in a number of laboratories.

Neutral beam power

Neutralization is done by charge-exchange collisions with a neutral gas, usually hydrogen. A relatively 'thick' gas target is used, the equilibrium fraction of neutral atoms in the emerging beam being decided by a balance between charge-exchange and re-ionization collisions. The cross section for charge exchange falls rapidly with energy above about 40 keV/nucleon and this results in a very low efficiency at high energies. In practice other losses in beam transmission and in efficiency of ion production further reduce the overall efficiency of the complete injector system. Figure 2 shows the overall power efficiency as a function of energy, a realistic neutralizer gas target thickness and range of beam line transmissions being assumed. From these curves it is seen that injectors based on positive ions become unacceptably inefficient above an energy of about 80 keV/nucleon (160 keV deuteron energy).

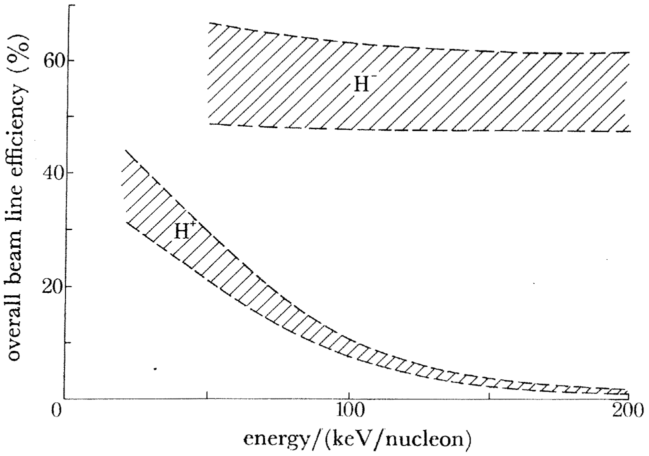

FIGURE 2. Overall efficiency of injector defined as beam power injected into torus in highest energy component divided by high voltage power at ion source. For positive-ion-based systems a range of assumed beam line transmission factors is shown (50–70 %) which covers existing and proposed beam lines. For negative-ion-based systems a range of neutralization efficiencies corresponding to a gas target (lower value) and a full plasma target (higher value) is shown. The beam line transmission is assumed to be 70 %.

A consequence of the rapid fall of the neutralization efficiency with energy is the need to have a very high content of H^+ ions, as opposed to H_2^+ and H_3^+ ions in the primary beam. The molecular ions break up into one-half and one-third energy components which are neutralized much more effectively. The best current ion sources have a yield of 80–85 % H^+ ions (Hemsworth *et al.* 1979; Goede & Green 1979). Even this high yield, when translated into neutral beams, can result in a full energy H^0-component of less than 60 % when operating at 80 keV.

For higher-energy neutral beam production it is necessary to develop systems in which the energy resident in the un-neutralized ions is recovered electrostatically or to develop injectors based on negative ions. Several recovery schemes have been proposed and tested at limited current levels (Fumelli *et al.* 1978; Moir 1978; Stirling *et al.* 1979). Difficulties include coping with the space-charge expansion once the electrons have been removed from the beam, and preventing secondary electrons and ions produced on impact with gas and with surfaces from being accelerated through the full decelerating potential necessary for the recovery. These problems degrade the performance of realistic recovery systems and it seems that in practice it will be difficult to more than double the efficiencies quoted in figure 2. This would extend the acceptable energy from 80 keV/nucleon to 110–130 keV/nucleon depending on which gas is used for neutralization. This may be useful for the next generation of experiments.

For the much higher energies (about 1 MeV/nucleon) required for reactor ignition at full density, injectors based on negative ions must be developed. As figure 2 indicates, since the electron is so easily detached from the negative ion by collision with a relatively low density gas, or preferably plasma, target the neutralization efficiency of such systems is high and essentially independent of energy. There are two main routes to the production of ampere currents of negative ions presently under investigation: (*a*) double-charge capture by low energy positive ions in alkali vapours; (*b*) direct extraction from plasma sources. The feasibility of the use of double-charge capture rests on the high values of the thick target yields of H^- and D^- in transmission through caesium and sodium vapour. The higher value for caesium (0.28) is offset by the fact that it peaks at low energies (less than about 1 keV for D^+) where it is difficult to produce high-brightness positive ion beams (Hooper 1978). One solution to this problem is to accelerate and transport the ion beam in the presence of an axial magnetic field; this technique has been developed by Geller *et al.* (1980) for the production of 1 keV D^+ at a current density of 120 mA/cm² with a divergence of ± 3°.

For sodium, the peak value, although lower, is obtained at a higher energy (20 keV for D^+) at which more intense lower-divergence beams are available. This technique is being pursued by Semashko *et al.* (1977). The problems of the large-volume vapour cells, the transport of low energy negative ion beams and their subsequent acceleration are being actively studied in the U.S.A., the U.S.S.R. and France.

Direct extraction of intense H^- beams from a magnetron-type ion source was developed by Belchenko *et al.* (1977) for use in accelerator injectors. These sources depend on positive-ion bombardment of a caesiated cathode to produce the negative ions which are accelerated through the cathode sheath and across the narrow magnetron discharge plasma. The high current densities (about 3 A/cm²) and short pulse widths (1–10 ms) are matched to the acceleration requirement. Further development by Prelec (1977) is directed towards longer pulses and lower current densities.

Recently Ehlers & Leung (1980) have used a magnetic multipole source with an immersed caesiated surface to produce negative ions by similar surface interactions of incident positive ions from the discharge plasma. The lower plasma density and magnetic fields, compared with those of the magnetron-type source, allow extraction at a lower current density over a large area under steady-state conditions. Up to 600 mA of H^- ions has been produced so far, and the system appears to be extrapolable to much larger currents.

Negative ion production within the volume of magnetic multipole sources has also been reported by Bacal & Hamilton (1979). The measurements of the H^- population in the discharge made by photo-detachment indicates higher densities than those predicted by the reaction normally assumed to be responsible for H^- production. Instead it is proposed that reactions of the form

$$e + H_2(v^x) \rightarrow H^- + H$$

are responsible. To date only modest negative ion currents have been extracted from this source, though its potential for further development is being investigated.

INTERACTION OF BEAMS WITH PLASMA

After ionization the fast ions circulating in the torus lose their energy and are scattered by Coulomb collisions with the thermal ions and electrons. These processes may be described by a bounce-averaged Fokker–Planck equation for the fast ions which may be written in terms of the constants of particle motion v and $\zeta = (1-2\mu B_0/mv^2)^{\frac{1}{2}}$:

$$\tau_s \frac{\partial f}{\partial t} = v^{-2}\,\frac{\partial[(\underset{\substack{\text{ion}\\ \text{drag}}}{v_c^3} + \underset{\substack{\text{electron}\\ \text{drag}}}{v^3})f]}{\partial v} + \frac{\beta v_c^3}{\zeta\langle v/v_\parallel\rangle\, v^3}\,\underset{\text{scattering}}{\frac{\partial}{\partial\zeta}\left\{\frac{(1-\zeta^2)\,\langle v_\parallel/v\rangle}{\zeta}\,\frac{\partial f}{\partial\zeta}\right\}}$$

$$\underset{\text{charge exchange}}{-\tau_s n_0 \sigma_{cx} v f} + \underset{\text{electric field}}{\frac{ez_f}{m_f}\,\boldsymbol{E}\cdot\frac{\partial f}{\partial \boldsymbol{v}}} + \frac{T_e}{m_f}\,v^{-2}\,\underset{\text{energy diffusion}}{\frac{\partial}{\partial v}\left\{\left(v^2+\frac{\gamma v_i^2 v_e}{v}\right)\frac{\partial f}{\partial v}\right\}} + \underset{\text{source}}{SK(\zeta)\;\tau_s\,\delta(v-v_0)},$$

where

$$\begin{aligned}\tau_s &= 3m_e v_e^3 m_f/16\pi^{\frac{1}{2}} e^4 z_f^2 \ln \Lambda n_e\\ &\sim 10^{12} A_f\, T_e^{\frac{3}{2}}/nZ_f^2,\\ \epsilon_c &= \tfrac{1}{2}m_f v_c^2 = 14.8\, T_e A_f/A_i^{\frac{2}{3}},\\ \beta &= Z_{eff} A_i/2A_f,\\ \langle v_\parallel/v\rangle &= (2\pi B_0^{\frac{1}{2}})^{-1}\int [\zeta^2 B-(B-B_0)]^{\frac{1}{2}}\,d\theta,\end{aligned}$$

$\langle v/v_\parallel\rangle$ being given by a similar expression, $\gamma = 0.75\pi^{\frac{1}{2}}$, S is the source strength and $K(\zeta)$ its angular distribution.

This equation has been solved analytically and numerically by Cordey & Core (1974) and Callen *et al.* (1975). Monte-Carlo methods have also been used to obtain a solution (Lister *et al.* 1976).

All the terms in the above equation have been checked experimentally. The ion and electron drag terms which are responsible for the loss of energy of the fast ions were established by comparing the energy distribution of the fast ions in some of the earliest CLEO tokamak heating experiments with the theoretical distribution (Cordey *et al.* 1974). More recent data from Princeton (Eubank *et al.* 1979) and from the DITE tokamak at Culham (Paul *et al.* 1976) confirm the accuracy of the first two terms to within about 10%.

The angular scattering term is the result of collisions with plasma ions. The energy diffusion term arises because of the random nature of the collisions with the ions and electrons, which can give rise, in particular, to a Maxwellian tail on the hot ion distribution *above* the injection energy. Both the angular scattering and the diffusion term have been checked experimentally (Eubank *et al.* 1979). Due allowance must be made in these comparisons for the steady electric field in the tokamak which can accelerate or decelerate ions according to the direction of injection.

The most difficult term to estimate accurately is the loss by charge exchange, which requires a knowledge of the neutral atom density in the plasma. This term may be important in small machines but is relatively unimportant in next generation machines where the neutral density in the centre of the plasma is severely attenuated. In general, however, provided the profiles of plasma density and temperature and neutral atom density are sufficiently well known it is possible to calculate the power input profile with some accuracy. Fairly sophisticated computer programs are required, however, to allow for the complicated geometrical effects, especially when trapped orbits are taken into account.

MOMENTUM TRANSFER

A significant momentum is injected with the beam. This gives rise to a radial electric field (Sweetman 1972) which can, in principle, cause the plasma to rotate in the poloidal and toroidal directions. The poloidal rotation is heavily damped by friction with trapped particles (Stix 1973) but because of the symmetry about the major axis this loss process is less effective for the toroidal momentum. Charge-exchange loss, convective loss, and loss by interaction with particles trapped in ripples in the toroidal field can all play a role but are comparatively small in magnitude and so, if the injection is not symmetrical, large plasma rotation velocities can build up. This has been observed in several experiments (Berry *et al.* 1975; Smith 1976), and in the most careful experiments to date (Suckewer *et al.* 1979) velocities as high as 10^5 cm s^{-1} are observed. Even though such high velocities are seen there is some difficulty in accounting for the momentum loss in these experiments with the known loss mechanisms.

Because of the heavy damping of the rotation velocity in the poloidal direction the radial electric field (E_r) is given essentially by the condition to cancel the poloidal component of the mean fast ion velocity along the field lines ($\bar{v}_{\parallel}$)

$$E_r = \bar{v}_{\parallel} B_\theta,$$

where B_θ is the poloidal magnetic field.

THE BEAM-DRIVEN CURRENT

It was first pointed out by Ohkawa (1970) that substantial currents can be generated in a toroidal confinement system by neutral atom injection. Provided the injected atoms have a net component of momentum around the torus the trapped ion current circulating around the torus gives rise to a total ion current (I_f) which is enhanced over the injected current by the 'stacking factor' ($\tau_f v_f/2\pi R$). This factor is of the order of 10^3 in current experiments but may be as high as 10^5 at reactor temperatures. Thus ion currents can be created that are comparable with, or indeed may replace, the transformer-induced current.

The situation is complicated when the momentum exchange with electrons is taken into account. The fast ions transfer momentum to the electrons which, in turn, transfer it to the plasma ions. This gives rise to a net electron drift velocity in the direction of the ions which therefore tends to cancel the ion current. When the additional effect of trapped electrons is taken into account the net current (I_{net}) can be shown to be of the following form (Start *et al.* 1980):

$$I_{\text{net}} = I_f \left\{ 1 - \frac{Z_f}{Z_{\text{eff}}} \left[f \left(\frac{v_e}{v_b} \right)^2 - A(Z_{\text{eff}})\, \epsilon^{\frac{1}{2}} \right] \right\},$$

where Z_f is the fast ion charge, Z_{eff} is the effective plasma ion charge, v_e is the electron thermal velocity, v_b is the beam velocity and ϵ is the inverse aspect ratio of the torus. The second term on the right-hand side is the effect of the back electron current, and the third term is the correction to this due to the trapping of electrons (Connor & Cordey 1974). This latter correction is only appropriate if the plasma is sufficiently collision free.

If the electron temperature is sufficiently high ($(v_e/v_b)^2 \gg 1$), as is the case in most tokamak experiments, then $f(v_e/v_b)^2 \rightarrow 1$, and for equal beam and plasma atomic number the back electron current can completely cancel the ion current. The net current then depends on the electron trapping term.

The beam-driven current was first observed experimentally in the Culham Levitron (Start *et al.* 1978) in the régime when $(v_e/v_b)^2 \lesssim 1$. The experimental data is shown in figure 3 as the ratio of the observed net current to the calculated ion current. At the time of the original experiments the data were compared with the simplest theory, in which the electron gas is assumed to remain Maxwellian but is displaced by the momentum transfer. This gave a theoretical curve which approached zero monotonically and more slowly than the experimental data indicated (dot–dash line) at large $(v_e/v_b)^2$. Subsequently the Fokker–Planck equation for the electron distribution was solved. This can be solved analytically in the case where

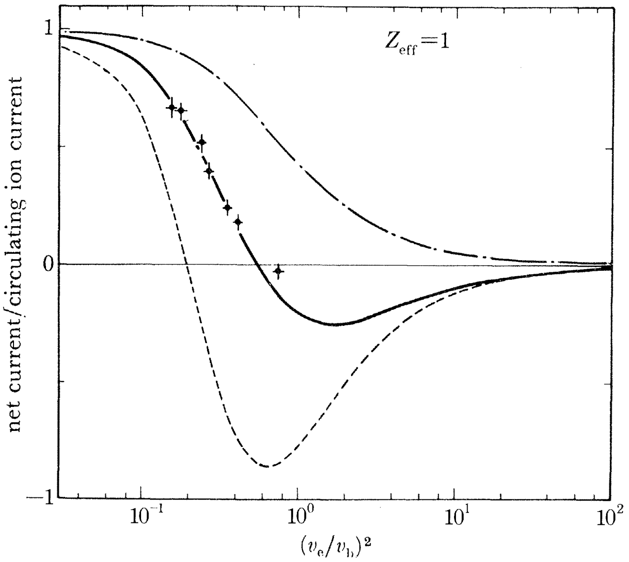

FIGURE 3. Beam driven current predicted by three theoretical models (——, Fokker–Planck; ·–·–, displaced Maxwellian; – – –, Lorentz) compared with the experimental data from the Levitron (Start *et al.* 1978). The experimental data are normalized to the point at $(v_e/v_b)^2 = 0.15$. The implied fast ion current is then 1.15 of the absolute value determined from the known beam parameters on which there is a ± 20 % estimated error.

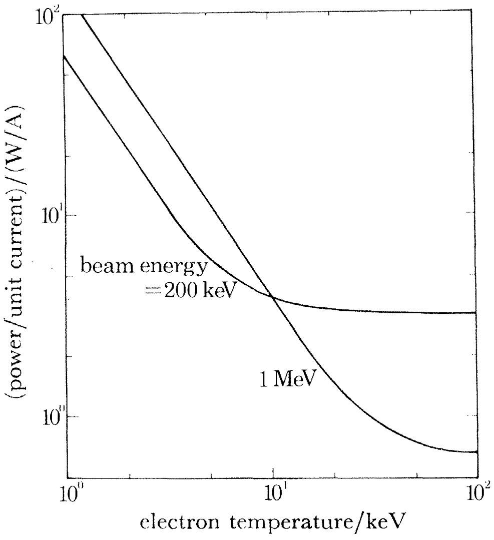

FIGURE 4. Power required to produce a given circulating ion current for two different beam energies by injection of deuterium into tritium. R = 3 m, $n_e = 10^{20}$ m^{-3}, $Z_{\text{eff}} = 1$.

electron–electron collisions are neglected (the Lorentz approximation) and is shown as the dashed line in figure 3. The numerical solution of the full Fokker–Planck equation gave the full line in figure 3 which is in good agreement with the experimental data (Cordey *et al.* 1979). More recent experiments made with the DITE tokamak (Clark *et al.* 1980) have established the existence of this current in the régime where $(v_e/v_b)^2 \approx 100$. Since the total current is held constant by the external circuit, the substitution of transformer-induced current by beam-induced current is observed as a drop in the loop voltage. Careful allowance was made for other changes (e.g. electron temperature rise) that could cause similar behaviour. The magnitude of the net current and the scaling with plasma density are in agreement with predictions. In these experiments the Z_{eff} was in the range 2–5 and the plasma was not collision free; it was not possible, therefore, to check the electron trapping term.

The ability to inject current opens up the possibility of avoiding the pulse operation inevitable with a transformer-induced system. A continuously operated reactor would have obvious technical advantages. Figure 4 shows the neutral beam power required to maintain a given *ion* current as a function of electron temperature. This is relatively high at temperatures characteristic of current experiments but is quite modest for temperatures characteristic of reactors. The power required to maintain a given *net* current is of course higher but is dependent on detailed geometrical and other factors.

CONCLUSIONS

As can be seen from the foregoing discussion, the input of energy and momentum by fast neutral beams is governed by classical collision processes. All the basic energy and momentum exchange processes have now been checked experimentally, for the more important processes to within about 10%. Therefore, provided sufficient sophistication is put into computer codes, and the basic plasma parameters are known, it is possible to calculate with some accuracy the power and momentum input profiles. The power and momentum loss processes are outside the scope of this paper; they involve complex plasma physics and are much less well understood.

The technology for producing intense neutral beams from positive ions has developed rapidly over the past decade and several sources are under construction, working at the megawatt level at 60–80 keV/nucleon. Extension beyond 80 keV/nucleon will necessitate the development of more advanced, possibly negative-ion-based systems.

Finally, the beam-driven current is now well established experimentally and theoretically and may allow the development of a continuously operated tokamak.

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