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NEUTRAL-BEAM CURRENT DRIVE IN TOKOMAKS

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ABSTRACT

The theory of neutral-beam current drive in tokamaks is reviewed. Experiments are discussed where neutral beams have been used to drive current directly and also indirectly through neoclassical effects. Application of the theory to an experimental test reactor is described. It is shown that neutral beams formed from negative ions accelerated to 500-700 keV are needed for this device.

INTRODUCTION

A method of driving a steady plasma current in tokamaks has been a long-sought goal. Neutral beams, rf waves, and relativistic electrons, among others, have been proposed as possible current drivers. Many successful current-drive experiments have been carried out with slow waves in the lower hybrid (LH) range of frequencies (1-5 GHz). The measured current-drive efficiency, η, which is defined as the plasma current, I, divided by the absorbed power, P, has been found to be within a factor of two of the theoretical efficiency. The discrepancy can be explained and is chiefly due to the generation of back currents from parasitic waves launched in the opposite direction. Unfortunately, lower-hybrid waves of a parallel refractive index suitable for driving electron currents in an Experimental Test Reactor (ETR) cannot penetrate even halfway to the axis. It has been proposed that slow waves be supplemented by fast LH waves which can drive current in the core. However, some predictions show that the fast waves would be damped on fast alpha particles and thus be inefficient in driving current.

Electron cyclotron heating (ECH) has also been shown to generate plasma current in small experiments. The theoretical efficiency is slightly less than that for lower-hybrid waves. Until the recent invention of the free-electron laser there was no reasonably efficient source at a frequency appropriate for ECH drive in the higher magnetic field tokamaks. Experiments are currently underway in large tokamaks such as DIIID at GA Technologies.

A third major candidate for current drive, and the subject of this paper, is neutral beams. Two recent observations, both in the

TFTR tokamak at Princeton[1], serve to make neutral beams the most attractive option at present: the demonstration of current driven by neutral beams in a large tokamak, and the recognition that this driven current was serving as a seed current for the long-sought bootstrap current.[2]. The bootstrap current arises as a result of the radial gradient of pressure and temperature set up by the deposition of beam ions at the magnetic axis and can be larger than the original seed current. In this paper I discuss the theory behind neutral-beam current drive, the experimental results to date, and then the application to a ETR design-TIBER[3].

THEORETICAL PREDICTIONS

A theoretical treatment of neutral-beam current drive starts with the Fokker-Planck equation for the hot ions. In the full, non-simplified form, it includes unlike collisions with the background Maxwellian ions and electrons as well as like-particle collisons among the hot, beam-deposited ions. One approach is to solve this equation directly on several radial flux surfaces in the plasma finding the local deposition rate of hot ions from a simultaneous treatment of the beam absorption. The background plasma density and temperature can either be specified a prioi as a function of radius or the radial transport equations can be solved simultaneously if the transport coefficients are known. These ideas are incorporated into a code called FPT[4] which was recently modified to compute the neutral-beam driven current, j_{nb}.

Because the electrons are much more mobile than the ions, they will speed up by drag on the hot ions and tend to cancel the ion current. If the charge of the beam ions, eZ_b, differs from that of the background ions, eZ_{eff}, the resulting difference in drag allows the electrons to only partially cancel the beam current. Furthermore, because a portion of the electrons are trapped in the toroidal well, the fractional cacellation depends also on the local inverse aspect ratio, $\epsilon = r/R$. The net current can be written as

$$j_{net} = j_{nb} F_{nb}(Z_b, Z_{eff}, \epsilon), \qquad (1)$$

where F_{nb} is of the form[5,6]

$$F_{nb} = 1 - Z_b / Z_{eff} + f(Z_{eff}, \epsilon). \qquad (2)$$

At small ϵ, f is proportional to $\epsilon^{1/2}$ so the trapped-electron correction is small near the the magnetic axis. As a result, although j_{nb} may be peaked on *axis*, j_{net} *may actually show a dip.* An example of this is given in Fig. 1 which shows the current density for injection of 500 keV deuterium into the TIBER ETR[3] as computed with the FPT code.

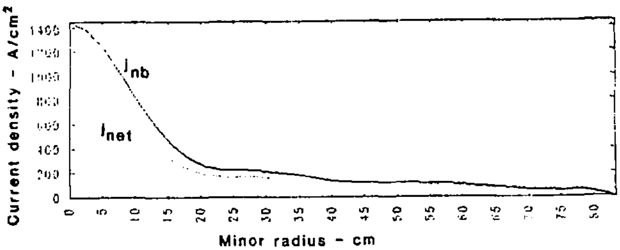

Figure 1. Current profile for TIBER showing the neutral-beam-driven curren, j_{nb}, and the net current after allowance for the induced electron current, j_{net}.

An additional source of current is the neoclassical current generated by radial gradients of pressure and temperature, the so-called bootstrap current.[2] In the banana regime in a $Z_{eff} = 1$ plasma the current obeys the relation

$$j_{bs} = e \frac{\epsilon^{1/2}}{B_\theta} \left(-2.44 \left[\frac{\partial p_e}{\partial r} + \frac{\partial p_i}{\partial r} - 1.17\, n_e \frac{\partial T_i}{\partial r} \right] + 1.75\, n_e \frac{\partial T_e}{\partial r} \right) \qquad (3)$$

with B_θ the poloidal magnetic field which must be found from the local total current density using Ampere's law. This expression has been incorporated into the FPT code to yield an estimate of the neoclassical current for fixed pressure and temperature profiles. The profiles should come from a solution of the radial transport problem, but, because of the anomolous radial energy transport, there is as yet no accepted form for the transport coefficients. For TIBER, a model pressure profile is used to compute the MHD equilibrium, and , in accord with TFTR results, the density profile is taken as peaked near the center

$$n_e = n_e \, [\, 1 - (r / a)^2 \,]. \qquad (4a)$$

Temperature profiles of both ions and electrons are assumed to have the same shape and from the p and n_e profiles a suitable approximate form is

$$T = T \, [\, 1 - (r / a)^2 \,]^{0.6}. \qquad (4b)$$

These profiles have been used for the case of Fig. 1 to obtain the current profiles shown in Fig. 2. Since no neo-classical current flows on axis, the dip at the origin is slightly more pronounced. However, the finite Larmor radius of the beam ions will probably eliminate this predict dip. It should be noted that a more pronounced dip can be obtained if the ion source is located too far from the tokamak and if it has too much divergence. For example, calculations for a 20 cm-wide source of 5 mrad divergence located at 45 m from the tokamak showed that a current profile with a 30-40 cm-wide dip at the origin would be generated.

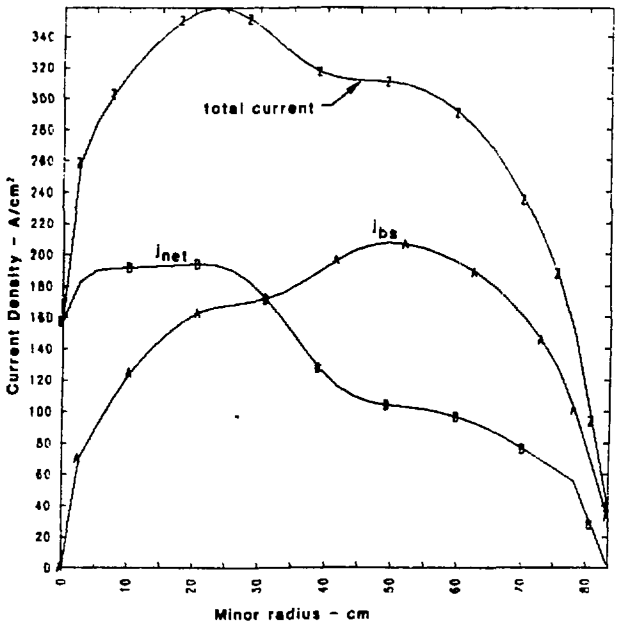

Figure 2. Profile of net beam current, j_{net}, and bootstrap current, j_{bs}, for typical density and temperature profiles in TIBER.

We can form a simple scaling formula for the fraction of current due to bootstrap by estimating the terms in Eq. (3) and noting that $B_\theta \approx I_p / a$ to get

$$\frac{I_{bs}}{I_p} \approx \left(\frac{a}{R}\right)^{1/2} \beta_p,$$

where $\beta_p = 2 \mu_0 p / B_\theta^2$ is the poloidal β. Applying this to TIBER, which has an inverse aspect ratio $a/R = 0.83 / 3.0$ and $\beta_p \approx 1$, we expect the fraction of current carried by bootstrap to be about 50 %. For the case of Fig. 2, the fraction is 3.52 MA / 5.73 MA = 61%. It should be noted that Eq. (3) is only valid for a $Z_{eff} = 1$ plasma; some changes can be expected when an expression including high-Z impurities is used.

In most cases, the hot-ion density is much less than the background density and self collisions can be neglected. Furthermore, the electron thermal speed is usually much greated than the beam speed. Several authors have made use of these simplifications to obtain a series solution for the hot-ion distribution function. A convenient formulation is the one presented by Gaffey.[7] Mikkelson and Singer[8] have integrated this distribution function to obtain an expression for the current-drive efficiency in a circular tokamak

$$\eta = \frac{4.25}{R_0 \ln \Lambda} \int_0^a \frac{T_e \, v_{||} \, H \, J(x,y) \, F_{nb} \, 2r dr}{n_e \, v_b \, a^2} \qquad (5)$$

where R_0 is in m, T_e in keV, and n in 10^{20} m^{-3}. $v_{||}$ is the local component of the beam velocity parallel to the B field, H is the fraction of the total beam power deposited at radius r, a is the

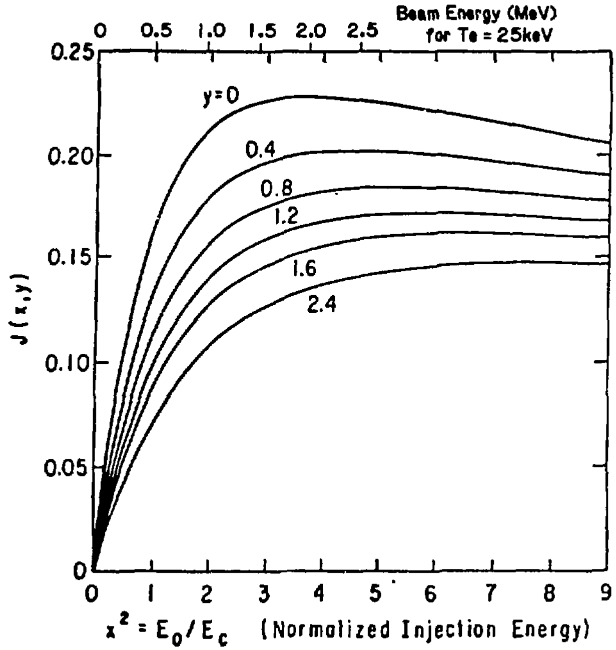

Figure 3. J(x,y) for Eq. (5).

Although we could use Eq. (5) together with a computation of H to determine η, we choose instead to use it as a scaling formula for the FPT code. We replace T_e and n_e in Eq. (5) by their volume-averaged values, take $v_{||} = v_b$ and $\epsilon = 0.1$ for evaluating F_{nb} in TIBER,

$$\eta = \frac{C \langle T_e \rangle J(\langle x \rangle, \langle y \rangle) F_{nb}}{\langle n_e \rangle R_o \ln \Lambda} \qquad (6)$$

For plasmas with profiles like those in Eqs. (4a-b), beam energies from 0.5-2 MeV and average densities of 0.7-1 x 10^{20} m^{-3}, the constant C is about 3.

EXPERIMENTS

Current drive by neutral beams has been demonstrated in four experiments: the Culham superconducting Levitron[9,10], DITE[11,12], JET[13] and TFTR[1]. In the Levitron, a hydrogen neutral beam generated from a positive-ion source with mean energy ≈ 8.5 keV and current ≈ 0.2 A was injected into a $Z_{eff} \approx 1$ plasma which had T_e varying from 1 to 4.7 eV. Under these conditions, the electron thermal speed varies from about ½ to 1 x the beam speed. At the lower value, the electrons are moving too slowly to cancel the ion current and nearly the full ion current was observed. At the other limit, the measured current was found to be opposite to the ion current. In a theoretical paper which treated the electrons <u>without assuming</u> $v_e \gg v_b$, Cordey, et al.[10] were able to predict the entire dependance of the measured current on T_e, including the observed reversal of current direction at $T_e = 4.7$ eV.

The first application of neutral-beam current drive to a tokamak ocurred in DITE[11,12]. They injected approximately 1 MW of 24 keV neutral beam current into a plasma with peak density from 3.1 to 7.8×10^{19} m^{-3} and peak electron temperature from 0.67 to 1.1 keV. They did not have sufficient power to drive the entire plasma current with neutral beams, so they measured the reduction in loop voltage while the plasma current was held fixed with the ohmic transformer. They verified that co-injection lowered the voltage while counter-injection raised it. Since heating of the electrons by the beam ions could cause a change in the loop voltage, the drop of the loop voltage can not be taken as definitive evidence that beam-injected ions are carrying plasma current. They verified the existance of hot-ion current by computing the theoretical loop voltage from the experimental temperature and density profiles together with a Fokker-Planck computation of the fast-ion current and comparing with the measured loop voltage. The good agreement demonstrated the presense of neutral-beam driven current. The maximum current driven was 38 kA out of a total plasma current of 80 kA. A simple ratio of the current to total injected power for this case yields an apparent current-drive efficiency of 38 / 900 = 0.04. Note, however, that the electric field also accelerates ions so the true efficiency is probably less. The authors report that the effects of electron trapping, neoclassical current and plasma rotation are less than 10 % for this experiment and hence negligible.

Cordey[13] has also recently reported that the neutral beams in JET were probably driving some 0.6 MA of plasma current. For this experiment they find that the neoclassical current is negligible.

The recent TFTR experiments are the main reason for increased optimism that neutral beams can drive steady state currents in eventual reactors. The analysis of these experiments will probably continue over the next several months, but some significant early results are described by Zarnstorff[1]. If the edge density is low enough, as obtained with good outgassing of the walls, <u>and</u>, if the magnetic axis is shifted outward sufficiently (the so-called Shafranov shift), then the neutral beams penetrate to the plasma center and drive substantial plasma current (some 200 kA out of 0.9-1 MA). The experimental signal of these good conditions is the reversal of the surface loop voltage. Like DITE, the plasma current is held fixed by the transformer. The experiment is analyzed by predicting the loop voltage from theoretical expressions together with the measured density and temperature profiles. The measured voltage cannot be duplicated unless both beam-driven and neoclassical currents are included. Thus, the TFTR experiments have confirmed that bootstrap current does exist and can substantially enhance the beam-driven current in a large tokamak.

APPLICATION TO AN ETR-TIBER

The above ideas have been used to predict the performance of a small, superconducting ETR-TIBER[3]. Major parameters for this machine are major (minor) radius = 3 (0.83) m, ellipticity ≈ 2.1, triangularity ≈ 0.5, fusion power = 250-350 MW, average wall neutron load = 1.8-2.2 MW/m^2, plasma current = 8-12 MA, and current drive power = 40-70 MW. Plasma properties have been computed using the CIT physics guidelines[14] with the addition of the neutral-beam current drive as described above. Properties are listed in Table I for cases with and without half of the current supplied by neoclassical effects. We see that the incorporation of

Table I. Comparison of TIBER parameters with current supplied solely by NBI and with ½ of the current supplied by neoclassical effects.

	No Neoc.	*w. Neoc.*
Fusion power-MW	278	345
NBI power-MW @500 keV	72	53
Q	3.9	6.6
Plasma current-MA	8	8
Vol-ave. T_e-keV	20	17
Vol-ave. T_i-keV	28	18
Vol-ave. N_e-10^{20} m^{-3}	0.88	1.2
Z_{eff}	2.0	2.0
shine-through-%	1.6	0.3

neoclassical effects has a very favorable effect on the beam power and Q; but even without these effects, this ETR would still be an attractive machine for physics and engineering testing. The neutral-beam energy was chosen to be 500 keV for these studies because of the report[15] of a design at that energy with a reasonable electrical efficiency of 45 %. The shine-through for this energy is so low (Table I), that it should be possible to raise the energy somewhat and still be able to tolerate the increased shine-through power on the beam dump. Interestingly enough, the plasma parameters, as computed from this point model, do not change appreciably when the beam energy is raised up to 1 MeV, a possible limit for DC accelaration of ions. The cause is not difficult to find: as the beam energy is increased, the power generated by beam-background fusion reactions decreases. There is then less alpha-particle energy to heat the plasma and the temperatures will decrease somewhat. If the decrease in electron temperature is not too great, then the current-drive efficiency can increase because of the increased beam energy, as shown in Fig. 3. But the density will also increase if one operates at the beta limit, and the efficiency could actually decrease with increased beam energy. Both cases, increased or decreased efficiency have been observed. But, there is possibly a more important reason for higher energy:better penetration to the magnetic axis. Figures 1-2 showed results for a plasma with $\langle n_e \rangle \approx 8 \times 10^{10}$ m^{-3}. For higher densities, such as in the second column of Table I, higher beam energies are desirable for peaked current profiles.

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