Conf-890302--19

UCRL- 99981
PREPRINT

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This paper was prepared for submittal to the
16th European Conference on Controlled Fusion
and Plasma Physics
Venice, Italy
March 13-17, 1989

February 1, 1989

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COMPUTATION OF LOWER HYBRID, NEUTRAL BEAM AND BOOTSTRAP CURRENTS IN CONSISTENT MHD EQUILIBRIA*

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UCRL--99981

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INTRODUCTION

A possible scenario for steady state current drive in large, high-temperature tokamaks includes current driven by lower hybrid (LH) waves in the outer region with high-energy neutral beams (NB) used for current drive in the core. In addition, provided the poloidal beta is sufficiently high, there can be substantial bootstrap (BS) current, as observed in the TFTR and JET experiments. In work reported previously [1]-[2], a computer code, ACCOME, was written to obtain a solution to the MHD equations which is consistent with current driven by neutral beams, electric fields, and neoclassical (bootstrap) effects. For the computation of the solution to the Grad-Shafranov equation, the SELENE code [3] is used. Iteration is necessary between SELENE and the current-drive computations to obtain a consistent solution. In this paper we describe modifications to ACCOME to enable the computation of LH current in addition to the NB, BS, and OH currents. The next section describes the models used and then the final section presents an application to ITER.

DESCRIPTION OF THE MODEL

The LH module, which has been modified to model elongated plasmas, is based on a code developed for circular geometries [4]. The density and temperatures are taken as algebraic functions of the poloidal flux. The numerically computed flux is fit with bicubic splines. The magnetic field and derivatives are obtained from differentiation of the splines. The ray trajectories are computed with a variable-order predictor-corrector algorithm. The accuracy of this method is examined by computing the deviation from zero of the dispersion relation along a ray path. Errors are typically less than 10^{-5}.

The 1-D ($v_{||}$) Fokker-Planck equation for the fast electrons with quasi-linear diffusion from the lower hybrid waves is solved to obtain the

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*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.
+On assignment from TRW, Redondo Beach, CA

power absorption and the driven current on each flux surface. The $v_\perp$ portion of the distribution is assumed to be Maxwellian with temperature typically that of the thermal electrons.

The lower hybrid current is included in these calculations in the same manner as the other components. First, SELENE is used to obtain a reference MHD equilibrium from a model current distribution. Next, the values of the neutral beam, ohmic, bootstrap and lower-hybrid currents on the flux surfaces are computed. These currents are summed to yield the total flux-surface-averaged parallel current $\langle J_{||} B\rangle/B_{to}$, where B_{to} is the vacuum toroidal magnetic field at the geometric major radius, R_0. This quantity, together with the pressure function, $p(\psi)$, and the previous values of the toroidal function, $f = R B_t$, and $\langle B^2\rangle$ from SELENE, allows the computation of new values of the function, $ff' = -\mu_0(f^2p' + f\langle J_{||}B\rangle/\langle B^2\rangle)$ on the flux surfaces. This quantity, along with $p(\psi)$, is used in the next solution of the Grad-Shafranov equation with SELENE. This method is continued for 5-10 iterations until the current profile no longer changes between iterations.

APPLICATION TO ITER

We have carried out calculations for ITER in steady state operation with R_0 = 5.5 m, a = 1.8 m, κ_{95} = 2.0, and B_0 = 5.3 T. Density and temperature profiles are taken to vary as $(1 - \psi)^\alpha$, with α = 0.5 and 1.0 for density and temperature, respectively. Lower hybrid waves are launched from the outer periphery with frequencies of 4.6 or 8.0 GHz. The $n_{||}$ spectrum is typically centered at 1.7 to 1.9. Various half widths of the spectrum, $\Delta n_{||}$, have been tried. Several different neutral beam energies from 1 to 1.5 MeV have been used. The beams are usually aimed at the magnetic axis, which is near R = 5.7 m, but aiming inside of this radius has also been investigated.

The results from one set of calculations are included in Figures 1-4. In this case, the LH frequency is 4.6 GHz with the central $n_{||}$ = 1.9 and a Gaussian half-width of 0.05. This width is quite narrow; it was chosen to maximize the penetration of the LH waves into the plasma. The neutral beam energy is 1.0 MeV with tangency radius, R_{tan} = 5.6 m. The beam footprint is elliptic with a half height of 0.92 m and a half width of 0.56 m. Three beams are used, one aimed in the horizontal midplane, and one above and one below it by 1.3 m. Figure 1 shows the trajectory of the central LH ray in the poloidal plane. The outer surface of the plasma is also plotted. The numbers on the ray represent 10% decrements of the power in the ray. As the ray travels through a poloidal angle of 180°, 80% of the power is absorbed. It reflects near the plasma surface, where the frequency equals the local electron plasma frequency, but less than 1 % of the initial power in the ray remains at this point. The variations of $n_{||}$ along the central ray and two other rays are shown in Fig. 2. We see a slight upshift as the rays pass into a higher toroidal field and then a downshift which continues until the central ray passes into the upper half of the plasma where $n_{||}$ again increases. The plasma current distribution is shown in Fig. 3. The neutral beams drive current in the core, as intended, while the lower hybrid is restricted to the outer half (in ψ) of the plasma. In computing these currents, the LH power was fixed at 25 MW and we varied the NB power to obtain the desired total plasma current of 18 MA. The components of the current are: NB: 11.1 MA, LH: 2.9 MA, and BS: 4.0 MA. A respectable 23% of the current comes from bootstrap effects, but this is less than the 30% heretofore assumed in ITER steady state scenarios. The figures of merit, γ ($= \langle n_e \rangle I R_0/P$), for NB and LH are 0.52 and 0.35 x 10^{20} A/W-m^2, respectively. Including the bootstrap current raises the overall figure of merit to 0.61 x 10^{20} A/W-m^2. The absorbed power is used in the figure of merit, but the absorption of both LH and NB power is close to 100% for this case. Figure 4 shows a last quantity of interest, the safety factor. The near flattening of the curve in the vicinity of the LH-driven current is readily apparent. The edge (95% flux) safety factor is only 2.8, somewhat less than the design goal of at least 3.0, but some adjustment of the beam deposition would raise the value to this goal.

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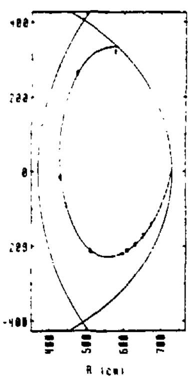

Figure 1. Trajectory of the central LH ray in the poloidal plane. The outer curve is the plasma boundary.

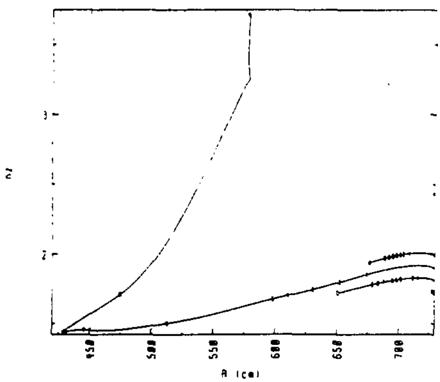

Figure 2. Dependence of $n_{||}$ on the major radius for the central and some adjacent rays. The (barely visible) numbers refer to the percentage absorption of the power in the ray to that point.

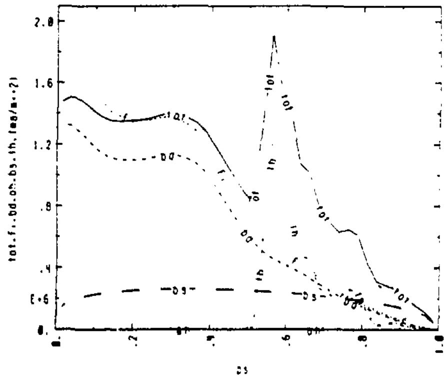

Figure 3. Distribution of current density vs. poloidal flux in the plasma. fi: fast ion current; bd: fast ion current less the partially cancelling electron current; bs: bootstrap current; lh: lower hybrid current; tot: total current.

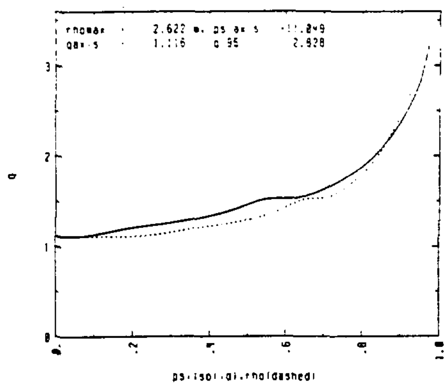

Figure 4. Safety factor vs. poloidal flux (solid line).