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OPTIMUM LAUNCHING OF ELECTRON-CYCLOTRON
POWER FOR LOCALIZED CURRENT DRIVE
IN A HOT TOKAMAK

Gary R. Smith

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Livermore
National
Laboratory

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Gary R. Smith
Lawrence Livermore National Laboratory
University of California
Livermore, CA 94550

ABSTRACT

Optimum launch parameters are determined for localized electron-cyclotron current drive near the magnetic axis and the $q = 2$ surface by solving several minimization problems. For central current drive, equatorial and bottom launch are compared. Localized current drive near $q = 2$ is studied for equatorial launch and for an alternative outside launch geometry that may be better for suppressing tearing modes and controlling disruptions.

INTRODUCTION

One of the best uses of electron-cyclotron power in a tokamak is for localized current drive, because superior localizability tends to compensate for lower efficiency compared to other *current-drive schemes. Localization near the magnetic axis and the $q = 1$ and $q = 2$ surfaces* is of interest. To determine launch scenarios that yield an optimum combination of efficiency and localizability, one must search through a parameter space that includes the poloidal launch location, the launch direction, and the ratio Ω_{axis}/ω of on-axis cyclotron frequency to wave frequency. This paper determines optimum launch parameters automatically by solving several *minimization* problems. Application is made to the ITER tokamak.

PLASMA MODEL

We use flux surfaces computed at Livermore for the ITER Basic Engineering Device during the technology phase. The specific case "j023" corresponds to the start of burn. At the nominal major radius of $R_0 = 5.6$ m, the magnetic field is $B_0 = 5.3$ T. The magnetic axis is at $R_{axis} = 5.76$ m, where the field is $B_{axis} = 5.08$ T. The safety factor q increases monotonically from $q_{axis} = 1.14$ at the magnetic axis to $q_{95} = 3.64$ at $\psi = 0.95$. The poloidal flux ψ is normalized so that $\psi = 0$ at the axis and $\psi = 1$ at the separatrix. The $q = 2$ surface is located at $\psi = \psi_2 = 0.725$.

The density and temperature profiles are not consistent with the pressure in the flux-surface calculation but have the widely used forms $n(\psi) = \hat{n}(1 - \psi)^{\alpha_n}$ and $T_e(\psi) = \hat{T}_e(1 - \psi)^{\alpha_T}$ with $T_i = T_e$ and $\alpha_n = 0.5$ and $\alpha_T = 1$. The peak (on-axis) density and temperature are $\hat{n} = 10^{20} \ m^{-3}$ and $\hat{T}_e = 35$ keV.

Ray tracing and absorption is based on the weakly relativistic dielectric tensor of *Shkarofsky*.[1] Current-drive efficiency is calculated with the inclusion of trapped-particle effects[2] but with the omission of momentum transfer from hot to bulk electrons.[3] The latter effect enhances current-drive efficiency by roughly 50% near the magnetic axis but much less on outer flux surfaces. Current-drive efficiency is reduced from that found in a pure plasma by our choice of $Z_{eff} = 2.2$. In studying all physical situations, we employ single-ray calculations *to understand the absorption and current-drive physics, then we complete the study with multi-ray calculations* to learn about the sensitivities to finite size and divergence of realistic microwave beams.

FORMULATION OF OPTIMIZATION CALCULATIONS

Optimization calculations are performed with the aid of IMSL routine N0ONF, which is based on work by Schittkowski.[4] *This routine attempts to minimize an objective function $F(x)$,*

subject to constraints and lower and upper bounds on the variables x. In this work we use no constraints but specify bounds to limit the parameter space searched by the solver. Depending on the current-drive problem of interest we make various choices of F and x.

To maximize the current driven near the magnetic axis, we choose $F(x) = -I_d(\psi_c)$ with $\psi_c = 0.1$, where $I_d(\psi)$ is the current driven on all flux surfaces between the axis ($\psi = 0$) and ψ. We model power launched along the equatorial plane ($Z = 0$) by a single ray, and we choose x to consist of the microwave frequency f and the angle ϕ_ℓ between the launch direction and a line joining the launch point ($X = 750$ cm, $Y = Z = 0$) with the machine center ($X = Y = Z = 0$); symbolically, $x = \{f, \phi_\ell\}$. For power launched below the plasma ("bottom launch"), more variables are required to specify the launch location and direction. Using a cylindrical coordinate system (R, Φ, Z), we fix the radial and azimuthal components of the launch location at $R_\ell = 830$ cm and $\Phi_\ell = 9.25°$ and vary the vertical component of the launch location Z_ℓ and all components (R_t, Φ_t, Z_t) of a target location that determines the launch direction. Thus, we use $x = \{f, Z_\ell, R_t, \Phi_t, Z_t\}$.

Current drive just inside of the $q = 2$ surface is capable, at least theoretically, of suppressing tearing modes, which may help to reduce the number or severity of disruptions. The current required drops dramatically as localization improves,[5] so we choose to maximize $dI_d/d\psi$ just inside $\psi = \psi_2$. For power launched along the equatorial plane, we use $x = \{f, \phi_\ell\}$ as before. An alternative launch geometry fixes the launch location below the equatorial plane at $(X = 750$ cm, $Y = 0$, $Z = -100$ cm) and varies two launch angles θ_ℓ and ϕ_ℓ, which are related to the wavevector components at the launch location by $\tan\theta_\ell = -k_Z/(k_X^2 + k_Y^2)^{1/2}$ and $\tan\phi_\ell = k_Y/k_X$. Thus, we use $x = \{f, \theta_\ell, \phi_\ell\}$.

OPTIMUM LAUNCH PARAMETERS FOR ITER

Power launched along the equatorial plane drives maximum current near the magnetic axis for $f = 198$ GHz and $\phi_\ell = 39°$. In terms of dimensionless parameters that play important roles in the absorption and current-drive physics, this result can be expressed as $\Omega_{axis}/\omega = 0.72$ and, at the absorption peak, $N_\| = 0.82$. These optimum parameters are similar to those found in Ref. 6. However, that work found a substantially higher current-drive efficiency than we do at the optimum launch parameters, for reasons that are not presently understood. Taking momentum transfer into account (which Ref. 6 did not), we find a total driven current per incident watt of $I_d/P_i = 0.05$ A/W, or $\eta \equiv \langle n \rangle I_d R_{axis}/P_i \simeq 0.20 \times 10^{20}$ A/Wm^2.

Bottom launch is optimum for central current drive at $f = 204$ GHz and with launch parameters $Z_\ell = -324$ cm, $R_t = 557$ cm, $\Phi_t = -48°$, and $Z_t = 100$ cm. A projection of the ray trajectory into the poloidal plane is shown in Fig. 1. There is little refraction for this ray. The apparent curvature seen in Fig. 1 is mostly an effect of projection onto the non-Cartesian RZ plane. The wave frequency corresponds to $\Omega_{axis}/\omega = 0.7$ and, at the absorption peak, $N_\| = 0.82$. Although the bottom-launch geometry deposits power on electrons with higher mean energy than does launch in the equatorial plane, current-drive efficiency is only slightly better: $\eta = 0.21 \times 10^{20}$ A/Wm^2. The single-ray bottom-launch calculation shows that over 90% of the driven current is concentrated within the flux surface $\psi = 0.05$, which compares with $\psi = 0.03$ for equatorial launch.

Power launched along the equatorial plane with the optimal $f = 137$ GHz and $\phi_\ell = 25°$ drives a localized current with peak $dI_d/d\psi$ at $\psi = 0.675$. The total driven current, ignoring the small momentum-transfer effect on this outer flux surface, is 0.022 A/W, which corresponds to $\eta = 0.09 \times 10^{20}$ A/Wm^2. To characterize the localization of the driven current, we quote the width $\Delta\psi = 0.15$ that contains the middle 80% of the current.

The alternative launch geometry for localized current drive near $q = 2$ has optimum ray trajectories shown in Fig. 2. To account crudely for finite beam divergence, we model a Gaussian beam emerging from a corrugated waveguide with i.d. of 9 cm by means of three rays. All rays have the same ϕ_ℓ, but the outer rays have θ_ℓ that differ by $\pm 1°$ from the central ray. For an optimal $f = 148$ GHz, the maximum $dI_d/d\psi$ at $\psi = 0.7$ occurs if the central ray is launched
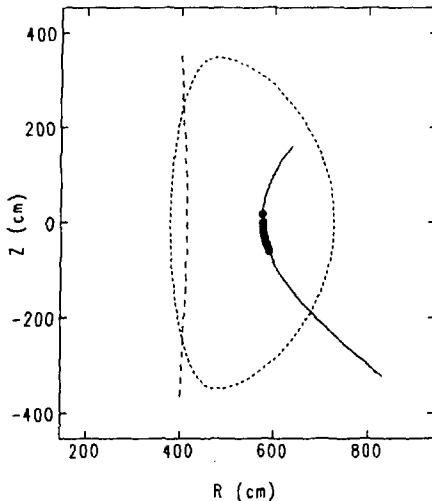
Fig. 1. Poloidal projection of a ray trajectory launched far below the equatorial plane and passing up through the plasma center. The short-dash curve is the $\psi = 0.95$ flux contour of an equilibrium calculated for the ITER tokamak. The long-dash curve is the fundamental cyclotron resonance. The filled circles indicate the location of wave absorption.

with $\phi_\ell = 45.5°$ and $\theta_\ell = 23°$. At the absorption peak, $N_\parallel \approx 0.5$, slightly more than the 0.4 found for equatorial launch. The total driven current is 0.030 A/W, which corresponds to $\eta = 0.12 \times 10^{20}$ A/Wm^2. The middle 80% of the current occurs in a width $\Delta\psi = 0.03$. Thus, the efficiency and especially the localization are significantly better for the alternative launch geometry than for equatorial launch.

CONCLUSIONS

Central current drive, optimized for either equatorial or bottom launch, is found to have an efficiency of $\eta \approx 0.2 \times 10^{20}$ A/Wm^2. Localization is somewhat better with equatorial launch.

Current drive just inside the $q = 2$ surface is more efficient and much more localized if the power is launched so that the power is absorbed while the microwave beam is nearly parallel to the flux surface. A specific launch geometry with these characteristics is found here for ITER. Further studies should address the degradation of efficiency and localization that would occur if T_e were lower at $q = 2$ or if scattering by drift-wave fluctuations caused the beam to broaden significantly.

For all of the current-drive schemes discussed here, we must assess the prospects for tracking moving flux surfaces using the simplest possible technology.
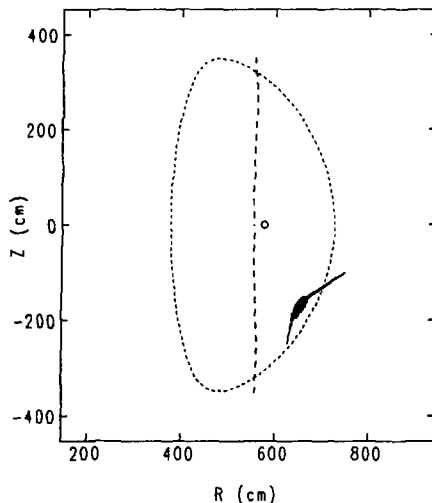
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Fig. 2. Poloidal projection of three ray trajectories launched below the equatorial plane at angles designed to drive current localized just inside the $q = 2$ surface. The open circle is the magnetic axis.

the equilibrium magnetic-field results. A. V. Kluge, A. H. Kritz, and I. P. Shkarofsky made major contributions to the ray-tracing code. R. H. Cohen made his calculations of current-drive efficiency available.

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