GA–A27780

OFF-AXIS CURRENT DRIVE WITH HIGH HARMONIC FAST WAVES FOR DIII-D

by

R.I. PINSKER, R. PRATER, C.P. MOELLER, M. PORKOLAB,
O. MENEGHINI, and V.L. VDOVIN

APRIL 2014

GENERAL ATOMICS

DISCLAIMER

GA–A27780

OFF-AXIS CURRENT DRIVE WITH HIGH HARMONIC FAST WAVES FOR DIII-D

by

R.I. PINSKER, R. PRATER, C.P. MOELLER, M. PORKOLAB,*
O. MENEGHINI,† and V.L. VDOVIN‡

This is a preprint of the synopsis for a paper to be presented at the Twenty-Fifth IAEA Fusion Energy Conf., October 13-18, 2014 in Saint Petersburg, Russia.

*Massachusetts Institute of Technology, Cambridge, Massachusetts.
†Oak Ridge Associated Universities, Oak Ridge, Tennessee.
‡Kurchatov Institute, Sq. Academicia Kurchatov 1, Moscow, Russia.

Work supported in part by
the U.S. Department of Energy
under DE-FC02-04ER54698

GENERAL ATOMICS PROJECT 30200
APRIL 2014

GENERAL ATOMICS

Off-Axis Current Drive with High Harmonic Fast Waves for DIII-D

TH-W

R.I. Pinsker[1], R. Prater[1], C.P. Moeller[1], M. Porkolab[2], O. Meneghini[3], and V.L. Vdovin[4]

[1]General Atomics, PO Box 85608, San Diego, CA 92186-5608, USA
[2]Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
[3]Oak Ridge Institute for Science Education, Oak Ridge, Tennessee 37830, USA
[4]Kurchatov Institute, Sq. Academician Kurchatov 1, Moscow 123182, Russia
e-mail: pinsker@fusion.gat.com

Modeling shows that fast waves at very high ion cyclotron harmonics (also called "whistlers" or "helicons") can drive current efficiently in the mid-radius region of a high beta tokamak plasma, as is required to sustain steady-state high performance discharges in a DEMO-like configuration [1,2]. DIII-D has developed suitable discharges with high electron beta and high electron temperature so that full first-pass damping of such waves is expected to take place off-axis. The calculated current drive efficiency in these discharges is 2 to 4 times higher than that of off-axis neutral beams or electron cyclotron current drive using the present DIII-D systems. Experiments at 0.5 GHz at the 1 MW level in 2016 are planned in DIII-D to validate the physics models used in these calculations and to test the "comb-line" traveling wave antenna for launching the waves.

After previous ray-tracing studies and recent full-wave calculations [2] indicated the promising features of whistler current drive in high-beta regimes, we carried out detailed ray-tracing studies with the GENRAY code [3], with the specific measured equilibrium from DIII-D discharge 122976. The rays are launched with a realistic range of poloidal and toroidal wavenumbers centered at $n_{||}=3.0$, $n_{pol}=0$ from a point at an elevation of 0.34 m above the outboard midplane of the DIII-D vacuum vessel, where the proposed antenna would be located. The radius of the starting point must be chosen so that the wave is propagating, which for these parameters means an electron density exceeding about 2×10^{18} m^{-3}; the chosen starting radius of $\rho=0.98$ satisfies this criterion for the measured density profiles from this discharge. The central ray of the bundle is shown in the figure, with the thickness of the ray being proportional to the power deposited per unit length along the path. The light, nearly vertical contours denote the closely spaced

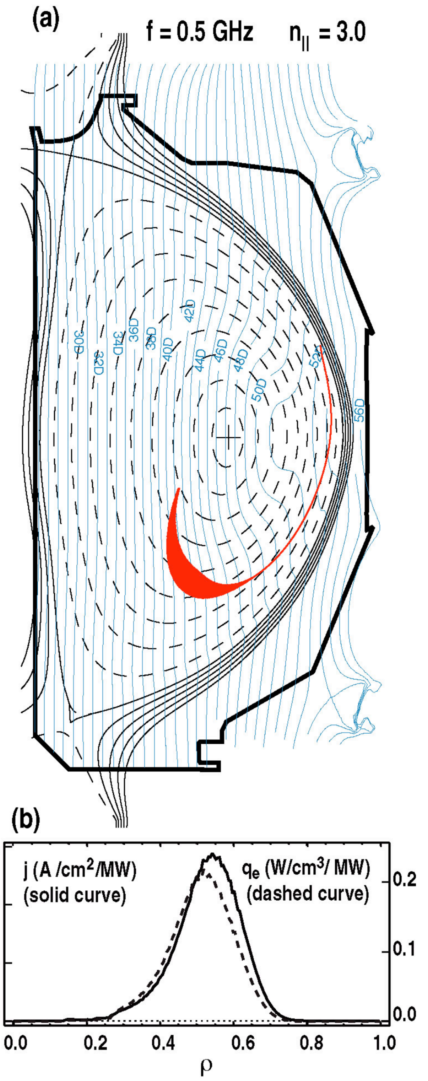

Fig. 1. (a) Ray path of 0.5 GHz whistler in DIII-D equilibrium 122976 with launched $n_{||}=3.0$. Thickness of ray is proportional to -(1/P)(dP/ds), where P is the power remaining in the ray. (b) Driven current density (solid curve) and electron heating density (dashed) as a function of normalized radius.

deuterium ion cyclotron harmonic layers, in the range of about $f/f_{cD} \sim (30–50)$ in the plasma. Also shown are the radial profiles of driven current and electron heat density for this case. The total noninductive current driven is 60 kA/MW, with the deposition peaking at $\rho=0.55$, where the electron density is $\sim 5\times 10^{19}\,\mathrm{m}^{-3}$ and the electron temperature is 3 keV. Essentially all of the rf power is absorbed in that region on the first pass, minimizing parasitic loss processes (mode conversion, far-field sheath formation, etc.) associated with weak single-pass damping. The whistler-like behavior of the ray path, whereby the angle between the group velocity vector (tangent to the ray path) and the static magnetic field cannot exceed about 20 deg., results in the tendency for the ray to primarily follow the field lines with slow radial penetration.

Varying the parameters of the equilibrium has shown that the desired strong, radially localized absorption on electrons can be obtained only for local values of β_e exceeding about 1.8%. At lower values, the waves propagate to smaller minor radius before being absorbed. Interestingly, varying the launched value of $n_{||}$ shows that the driven current hardly changes in either magnitude or in radial location in the range of $2.8<n_{||}<4.2$, for reasons that are understood from examination of the ray data.

The calculations of electron absorption and current drive with the GENRAY ray-tracing code were checked with the completely different model embodied in the CQL3D Fokker-Planck code [4]. These calculations show only a weak dependence of the radial location of the absorption and of the current drive efficiency on rf power level, indicating only small deviation from a Maxwellian electron distribution function, in agreement with previous work. We plan to extend these Fokker-Planck calculations to evaluate the ion cyclotron damping on thermal ions and on fast ions from neutral beams, the latter being a proxy for energetic alphas in a DEMO-scale reactor; previous calculations have indicated that absorption on alphas could be significant [2].

We have identified an appropriate launching structure to excite a well-defined, narrow, and toroidally directional wave spectrum — the traveling wave antenna known as the comb-line [5]. This structure permits the use of a large number of radiating elements in a phased array with feeds only at the ends of the wide, all-metallic antenna, by employing the reactive coupling from element to element to transfer power along the structure. The key parameter determining the necessary width of the array is the radial distance from the antenna surface to the location in the plasma edge where the rays begin to propagate. Since this distance is not well characterized experimentally at the poloidal location of the proposed antenna, DIII-D will test a low-power prototype comb-line at that location to ascertain the needed width of the high-power antenna to ensure successful coupling of the power.

Other aspects of the wave launching process that are under study include the possibility of parametric decay instabilities in the vicinity of the lower hybrid resonance density, which will appear in the pedestal region, and the effect of the non-zero tilt angle of the static magnetic field lines in the antenna near-field region. Suitable resolution of these issues should lead to a 1 MW level test of this concept on DIII-D in 2016.

This work was supported in part by the US Department of Energy under DE-FC02-04ER54698 and DE-AC05-06OR23100.

[1] S.C. Jardin, et al., *Fusion Eng. Design* **38**, 27 (1997).

[2] V.L. Vdovin, Plasma Physics Reports **39**, 95 (2013).

[3] R.W. Harvey, A.P. Smirnov, "*The GENRAY Ray Tracing Code*," CompX Report CompX-2000-01 (2001).

[4] R.W. Harvey and M.G. McCoy, in *Proc. IAEA TCM on Advances in Simulation and Modeling of Thermonuclear Plasmas, Montreal* (1992).

[5] C.P. Moeller, R.W. Gould, D.A. Phelps and R.I. Pinsker, in *Radio Frequency Power in Plasmas (Proc. 10th Top. Conf., Boston, MA, 1993)* (AIP, Melville, NY, 1994) p. 323.