

Off-axis Electron Cyclotron Current Drive for Current Profile Control in Tokamaks*

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Steady-state operation in a tokamak requires full noninductive support of the plasma current. Known methods of driving noninductive current are too inefficient to support more than a small fraction of the total plasma current. The route to a steady state tokamak lies through the Advanced Tokamak approach, for which improved confinement and stability support the plasma pressure at reduced plasma current. The reduction in current makes the β_p larger and hence the bootstrap current larger, so that the remaining current, which must be driven by external means, can be supported through a more moderate fraction of recirculating power. The improved confinement and stability derive from a radial profile of plasma current which optimizes the magnetic shear. Appropriate control of the current profile requires driving current off-axis, and electron cyclotron current drive (ECCD) is an appropriate way to do this since its location in the plasma may be easily controlled.

The efficiency of off-axis ECCD is an important issue for economic sustainment of the current profile. In the past, experiments on off-axis ECCD in DIII-D have shown that the efficiency decreases dramatically due to trapping of the current-carrying electrons in the magnetic well. However, these experiments were carried out at very low plasma pressure. More recent experiments at higher plasma pressure in DIII-D, made possible by increases in the ECH power to 2.3 MW, have shown a much smaller decay in efficiency. Analysis using the CQL3D Fokker-Planck code of the experiments under a wide range of conditions of β_e , $n_{||}$, and magnetic well depth have shown excellent agreement between theory and experiment. These experiments, when extrapolated to the regime needed by the AT program, show adequate efficiency to sustain the needed profile of plasma current. In addition, the highly localized nature of ECCD has been used in DIII-D to suppress the neoclassical tearing mode and dramatically improve performance.

The increase in normalized efficiency of off-axis ECCD with increased β_e can be understood by examining the rf-driven particle flux in velocity space, as calculated by the Fokker-Planck code. Two effects are important. First, increased electron temperature causes the cyclotron resonance to curve away from the trapped region of velocity space due to relativistic effects. Second, increases in temperature and/or density cause the strength of the absorption to increase, which means that the wave power will be deposited further from the cold resonance as the wave propagates toward it. Both of these effects cause the region of velocity space which is affected by the wave to move away from the trapped-passing boundary. This reduces the trapping effect and increases the efficiency.

In steady-state the total particle flux (rf plus collisional) in velocity space must be divergence free, so convective cells in velocity space are generated. These cells typically extend over much of velocity space, indicating that the interaction with the trapping boundary does not vanish, although it may be strongly reduced. This physical picture can quantitatively explain many of the phenomena observed in experiments.

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