Producing Continuous Electrical Currents in a Fusion Device Using High Power Radio Waves

Electrical currents driven by pushing electrons with radio-frequency waves will help realize a commercially attractive fusion reactor concept.

One of the most promising devices for producing nuclear fusion power is the doughnut shaped magnetic bottle known as a tokamak. This fusion concept relies on electrical currents flowing in the torus to produce magnetic fields that confine an ionized gas or plasma in the doughnut as it is heated to the temperatures needed for atoms to fuse together and release vast quantities of energy. In order for a tokamak fusion reactor to be commercially attractive however, these currents must be produced continuously and the spatial distribution of current must be controlled in a way to produce improved modes of plasma performance.

Continuous electrical currents can be produced efficiently by using radio waves to push electrons preferentially in one direction of the tokamak [1]. A type of antenna called a waveguide is used to launch the radio waves. Recently, a special type of wave known as the “lower hybrid wave” has been used to produce or “drive” electrical currents continuously [2] in the Alcator C-Mod tokamak at the Massachusetts Institute of Technology (MIT). These waves are generated by devices called klystrons at a frequency of 4.6 Giga Hertz (GHz), which is slightly above the frequency of 2.45 GHz that characterizes radio waves used in a kitchen microwave oven. Up to 900,000 watts of microwave power was coupled into Alcator C-Mod to sustain electrical currents of almost 1,000,000 Amperes (1 MA). In these experiments, the lower hybrid waves push electrons to relativistic speeds, close to the speed of light, at which point the electrons emit a type of radiation called “hard x-rays” in a narrow beam or “headlight” pattern aligned in the direction of their motion. The spatial and energy distribution of these hard x-rays is detected using a sophisticated diagnostic called a hard x-ray camera. The information from this diagnostic provides critical data for validating our physics understanding of the lower hybrid current drive process.

The distribution of fast electrons in space and velocity is described by a quantity known as an electron distribution function. This complicated function is computed by first using a technique called ray tracing to calculate the path or trajectory taken by radio waves as they propagate into the tokamak and accelerate electrons in the plasma. The process by which these fast or “nonthermal” electrons slow down via collisions with background or “thermal” ions and electrons is described by what is known as a Fokker Planck code [3]. Shown in Figure 1 are the simulated and measured hard x-ray emissivity profiles for a plasma discharge in Alcator C-Mod in which lower hybrid current drive was present. The simulated hard x-ray profiles were computed using the predicted fast electron distribution function. A physics mystery arises from Figure 1 related to why the simulated hard x-ray profiles are significantly narrower than the measured profiles. This discrepancy can be caused by a number of physical effects not yet included in those simulations. First, the fast electrons can move or “diffuse” spatially in the torus as they slow down in velocity space. Preliminary simulations of this effect have been done on a powerful computing cluster at MIT and show that indeed the fast electron diffusion can result in some spatial broadening of the hard x-ray profile. Two other effects that could potentially be very important are that of wave diffraction and focusing. For example, radio waves can undergo significant spatial broadening in their illumination pattern due to diffraction, in the same way that light is diffracted upon passing through a slit. This effect cannot be easily calculated using ray tracing, but rather must be computed by solving a set of equations known as Maxwell's equations. An example of this type of calculation is shown in Figure 2 for an Alcator C-Mod plasma [4]. The radiation pattern of the microwaves is clearly confined to an annular ring with cusp shaped filaments extending from the edge of the device to a distance of closest approach known as a caustic. This simulation was performed on a powerful computer at the Oak Ridge National Laboratory using 4096 computer processors operating simultaneously or "in parallel" for 1.5 hours of wall clock time. This type of more realistic wave propagation calculation could lead to three dimensional distribution functions that will result in more accurate predictions of the profiles of hard x-ray emissivity from fast electrons. The resulting advanced simulation tool will then provide the predictive capability needed to design the lower hybrid current drive and current profile control systems needed for the first generation of tokamak fusion reactors.

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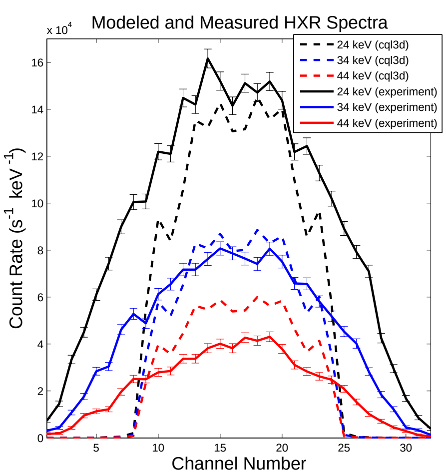

Figure 1: Measured and simulated profiles of hard x-ray emissivity for a discharge in Alcator C-Mod with lower hybrid current drive.

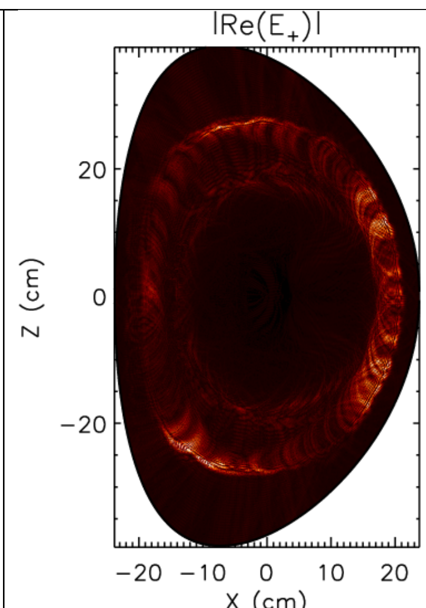

Figure 2: Electromagnetic field simulation of lower hybrid waves in Alcator C-Mod.

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