More Efficient Penetration of Fusion Plasmas By Radiofrequency Beams

New insights help account for the fate of radiofrequency power that is launched into magnetically confined plasmas.

One method of heating magnetically confined plasmas to the temperatures needed for a fusion power plant is by injecting power in the form of radio frequency (RF) waves. Properly directed RF waves can also interact with the charged particles to produce beneficial plasma currents to aid in confinement. Designing a wave launcher and determining the plasma characteristics that allow most, if not all, of the RF power to reach and be absorbed in the core plasma has remained a challenging and poorly understood process. The actual inferred core heating efficiency in numerous different devices has ranged from as low as 50% to as high as 95%, at least in some of the operational scenarios that will be utilized in the International Thermonuclear Experimental Reactor (ITER) device. The missing power is presumed to have been lost parasitically either in the edge plasma or in the surrounding vessel and launcher structures, due to such mechanisms as RF sheath formation, parametric decay instabilities, and other dissipative processes. For the long pulse (>180s), high power experiments planned for ITER (~ 20 MW RF), the loss of even 5% of the applied power to the vessel and edge plasma could have a large negative impact on the ultimate success of the ITER program, especially if the lost power is deposited in a localized area not sufficiently cooled to sustain the energy loss. Recent experiments on the National Spherical Torus Experiment (NSTX) device at the U.S. Department of Energy's Princeton Plasma Physics Laboratory (PPPL) have shed some light on some of the mechanisms involved in the parasitic edge losses and have suggested possible methods for avoiding such losses.

The RF system on NSTX operates at 30 MHz, which is considered the high harmonic regime since the frequency is several times the deuterium ion gyrofrequency (~ 3 – 5 MHz) in this magnetic field. It is used to interact with the electrons to assist in bringing the plasma from low current start up to high current operation, and to provide energy to sustain a high pressure plasma. The antenna used to launch the RF waves is a 12-element array, somewhat analogous to phased-array radar systems. By varying the phase relation between the array elements, the parallel wavelength and the direction of the launched wave can be controlled. Once launched, however, the wave propagation and energy flow are strongly influenced by the conditions of the edge plasma, such as the plasma density and the magnetic field strength and direction.

Recent experiments on NSTX have shown that the core heating efficiency is strongly dependent on the launched wave spectrum as well as the other discharge characteristics. The direction of the propagation of the RF waves relative to the magnetic field in the region close to the antenna/wall surface has been established as a contributor to the enhanced surface loss observed at the lower phasing values (longer wavelength). Considerable improvement in coupling efficiency has been obtained by setting conditions to avoid RF wave propagation too close to the antenna and nearby vessel surfaces. Indeed, increasing the magnetic field and lowering the edge density in 2006 resulted in a heating efficiency with -90º between array elements being equal to that with 180º relative phasing [http://meetings.aps.org/Meeting/DPP07/Event/70373].

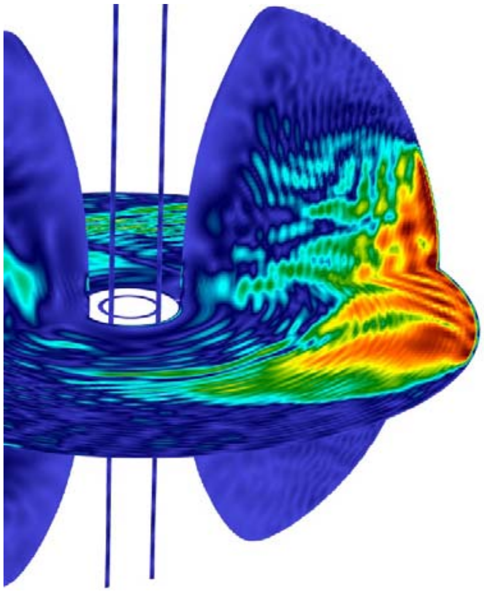

Fig. 1. *3D calculation of the RF wave fields in NSTX from the AORSA code. [http://meetings.aps.org/Meeting/DPP07/Event/70335].*

It turns out that wave propagation at high harmonic frequencies is rather strongly constrained to flow in the general direction of the magnetic field. Right in front of the antenna, the plasma density is typically too low for the launched RF waves to propagate, so the oscillating fields "leak"– or evanesce – for some distance into the plasma until the local density is high enough to support wave propagation. At this location, the direction of the wave path in the high harmonic regime is only about 20º with respect to the direction of the magnetic field and remains so over much of the plasma. This tends to keep the waves confined to the outer region of the plasma, as shown in the 3D wave field reconstruction in Fig. 1, obtained with the AORSA full wave code.

This improved understanding of the connection between wave propagation in the edge regions and the core heating efficiency can be used to optimize the design of the RF heating scenarios for ITER. For the low harmonic waves planned for ITER, the angle of propagation relative to the field continues to increase with density into the plasma, in contrast to the case in NSTX. Therefore one might expect that RF power losses in the edge regions should be less than in NSTX, for most conditions, particularly since the distance between the launcher and the location where the low harmonic RF waves begin to propagate in ITER is very large. However, the possibility of puffing gas in the edge, thereby raising the edge density to allow the fast waves to begin propagating closer to the antenna, is under consideration. The density in the edge in ITER is expected to be nearly constant over a wide region, so, depending on the choice of the edge density, the launched waves may hug the surface of the plasma in ITER over quite some distance, if the propagation starts too close to the antenna. The results on NSTX indicate that this may potentially lead to loss of core heating efficiency and localized hot spot formation on the antenna and adjacent vessel structures. The NSTX experiments have demonstrated that care must be taken to avoid raising the edge density so high that power losses due to surface wave excitation become significant.

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