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The production of highly unidirectional lower-hybrid waves

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The coupling of increasing spatial intermittency with increasing attractor size, which occurs for $D > 4$, is perhaps counter-intuitive. It arises because the relation (4) between k_d and k_s is independent of D, while the rate of growth with k_d of the total number of excited modes, at fixed δ, increases with D. There seems nothing internally inconsistent about the behavior for $D > 4$, at least at the primitive level of analysis employed above. Thus $D = 4$ may be a transition dimensionality for inertial-range behavior. Of course it could turn out that K41 is asymptotically exact for $D > 4$. Whatever intermittency there actually is in the inertial range involves competition between cascade in scale size, which tends to increase intermittency, and mixing of spatial regions, which tends to obliterate intermittency.[6] Neither scaling analysis nor calculations based on low-order perturbation theory can settle this question.[11]

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The development of a highly unidirectional lower-hybrid wave source would improve the electron current drive efficiency in tokamaks. Lower-hybrid waves launched from a phased wave array are shown to be reflected from a grid placed in a cold, low-density plasma. The antenna–grid combination results in highly unidirectional lower-hybrid waves.

Lower-hybrid current drive is now capable of producing greater than 100-kA discharges in tokamaks.[1] With the power levels required for sustaining such a discharge, it is desirable to achieve the best A/W (of wave power) figure. Wave phasing is thus chosen to couple as efficiently as possible to the electrons which drive the current. Present day antennas launch waves in both directions around the torus while it is desired to have waves traveling in only one direction, the direction in which the electrons are to be driven. Proper phasing of the antennas reduces the unwanted wave component somewhat. There is, however, commonly a trade-off between better unidirectionality and wave spectrum choice. Here we report a method of producing a highly unidirectional lower-hybrid wave and, at the same time, improving control of the wave spectrum.

A typical antenna–plasma configuration will have the main magnetic field along the z axis with the antenna specifying the k_z spectrum of the launched waves. Commonly, the current is to be driven in the $-z$ direction, that is, it is desired to use the waves to drive the electrons in the $+z$ direction. Because of the finite spatial extent of any antenna, there will be $-k_z$ components regardless of phasing on the antenna. These $-k_z$ components are deleterious for two reasons: First, they reduce the wave power available to drive electrons in the $+z$ direction. Second, they may drive electrons in the $-z$ direction, further reducing the overall current drive efficiency. We desired, then, to change the sign of the $-k_z$ portion of the spectrum so that all wave power has only $+k_z$. The experiments reported here show it is possible to create a highly unidirectional wave spectrum by placing a grid on the negative z side of the antenna. This grid reflects the $-k_z$ portion of the spectrum so that nearly all wave

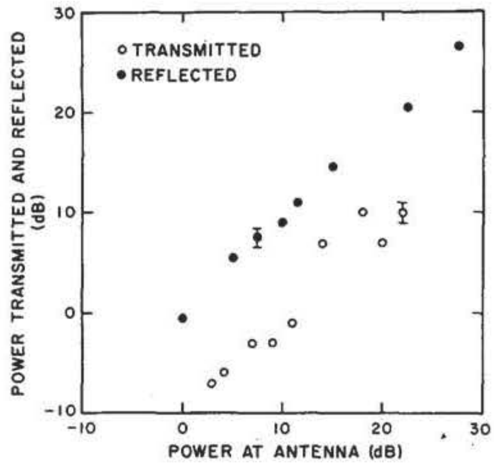

FIG 1. Lower-hybrid wave power reflected by or transmitted through the grid as a function of wave power approaching the grid. Wave frequency, 30 MHz. Here 0 dB corresponds to 29 mW delivered to wave launching antenna.

power is directed in the $+z$ direction.

The experiments were performed in a single-ended Q machine[2] which provided a low-density ($5\times10^{9}<n_e<2\times10^{10}\,\mathrm{cm}^{-3}$), low-temperature ($T_e \approx T_i \approx 0.2$ eV), almost completely ionized potassium plasma 1.0-m long and 5 cm in diameter. The confining magnetic field $\mathbf{B}_0$ was 3.5 kG. The lower-hybrid waves were launched from a slow-wave antenna consisting of eight coaxial loops[3] with the 25–110-MHz pump signal applied to the loops so that lower-hybrid waves of principal wavelength 12 cm were launched. Plasma density was estimated both from the angle of propagation θ of the lower-hybrid wave with respect to $\mathbf{B}_0(\theta \approx \omega/\omega_{pe})$ and from a Langmuir probe. Electron temperature was estimated with a Langmuir probe. Ion temperature was measured with laser-induced fluorescence.[4] The radial wavelength, resonance cone width, and angle of wave propagation were measured and found to be consistent with theory.[3]

A copper grid was placed downstream in the plasma on the negative z side of the antenna. The grid had 110 lines per inch with an optical transmission coefficient of 55%. The grid was placed with the vector normal of the grid at an angle of Ψ with respect to $\mathbf{B}_0$. It is of interest to note that the waves approach and reflect from the grid at an angle of $\theta \approx \omega/\omega_{pe}$ with respect to the confining magnetic field instead of following the usual rule for reflection of waves at a boundary. Because of this oddity, the experimenter has some control over reflected wave spectrum through choice of the angle of grid orientation. This may be seen by calculating the reflected wavelength in terms of the incident wavelength:

$$\lambda_{\perp,\mathrm{ref}} = \lambda_{\perp,\mathrm{inc}}\,[\cos(\theta-\Psi)/\cos(\theta+\Psi)], \qquad (1)$$

where $\lambda_\perp$ refers to the wavelength perpendicular to $\mathbf{B}_0$. Some experiments have been done by Olson and Motley[5] to verify this equation. The experiments reported here used $\Psi = 0$. A very handy point about the way these waves reflect is that the reflected waves will not interfere directly with the originally launched $+k_z$ portion of the spectrum since the reflected waves are spatially separated from the initial $+k_z$ waves because of the constant angle of reflection.

The rf detection probes were designed to ensure that the incident, reflected, and transmitted waves were measured with identical efficiency. An insulated, coaxial, radially moveable probe was constructed which had the probe tip parallel to the confining magnetic field. This probe could be rotated 180° in order to measure waves approaching or departing from the grid and thus measure the incident and reflected waves with the same probe. Care was taken in probe placement to avoid signal attenuation by probe body shadowing of the waves and plasma. An identical probe was placed on the other side of the grid for transmission measurements. The grid could be removed from the plasma so that the incident wave amplitude could be detected with either probe. The grid was then placed into the plasma, observing by probe that the incident wave remained unchanged, and the reflection and transmission measurements were taken.

In Fig. 1 the effect of the grid on the $-k_z$ spectrum is shown. For 30-MHz, lower-hybrid waves, only 10% of the $-k_z$ spectrum succeeds in passing through the grid on average. A full 89.4% of the $-k_z$ spectrum is converted to $+k_z$ waves at the grid. This suggests that less than 1% of the wave power went into resistive heating of the grid. These statements were found to hold true over approximately three decades of wave power launched. As an example, an antenna configuration launching wave power 80% in the $+z$ direction and 20% in the $-z$ direction might achieve about 98% $+z$ unidirectionality of the wave power if a grid were to be used.

Consideration should be given to the practicality of placing a screen near the waveguide grill in a hot tokamak plasma. A copper grid with 50% optical transmission constructed of 8-mil wire might be 2 cm wide $\times$ 20 cm tall. For a 1 MW pulse of 1 sec with the grill having 80% directionality, the grid temperature would increase about 220° (ignoring radiation cooling and conduction) if 1% of the energy incident on the grid were to be absorbed. In an environment where melting of the grid was a concern, placement of the waveguide near a suitably reflective plasma limiter might yield the same highly unidirectional waves.

Figure 2 shows the power transmitted through the grid as a function of wave frequency. Over the range of 30–110 MHz, the average fraction of wave power to pass through

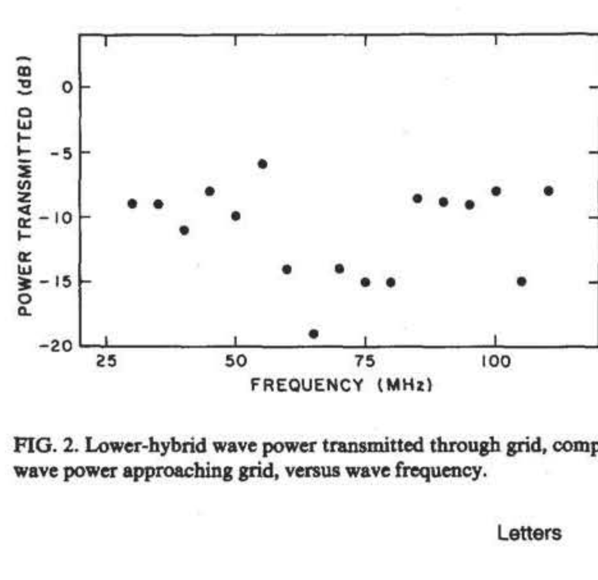

FIG. 2. Lower-hybrid wave power transmitted through grid, compared to wave power approaching grid, versus wave frequency.

the grid was 0.08, showing the ability to produce a very high degree of unidirectionality over the frequency range tested.

The reflection and transmission coefficients of the grid were also tested as a function of antenna phasing. The results from varying the phase were similar to those already described.

These experiments show that a grid may be placed in a cold plasma near a lower-hybrid wave launching antenna so that a highly unidirectional lower-hybrid wave may be produced, regardless of the phasing applied to the antenna. The experimenter may modify the wave spectrum upon reflection by choice of grid angle. There was no wave interference between the initially $+k_z$ portion of the spectrum and the reflected waves. It is expected that such a grid would improve lower-hybrid current drive efficiency in tokamaks.

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Anomalous losses from relativistic electron rings in decreasing toroidal fields

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Anomalously enhanced fast-electron losses are observed on relativistic E layers in the RECE-Christa device when the applied toroidal magnetic field decreases to zero in times shorter than ring lifetime. These losses consistently occur in a certain region of the field-reversal parameter and the ratio of applied toroidal to axial magnetic fields at the ring position. The critical parameter range is independent of the radial gradient of the applied mirror field, the background gas pressure, and the rate-of-decay of B_θ; however, it depends on the axial length of the rings, and there may be a threshold in dB_θ/dt. The observed parameter dependence as well as the absence of any kink or tilt motions point to new orbital resonances as the cause of these losses.

Most of the earlier electron ring experiments[1] in the RECE-Christa device[2] have been performed using an externally applied toroidal field B_θ that is comparable or even somewhat larger than the applied axial field B_z. While stable field-reversing electron rings without B_θ have been observed in the smaller RECE-Berta[3] device, the use of B_θ so far has proven very helpful for the generation of such rings in RECE-Christa. On the other hand, the central axial conductor required for the generation of such B_θ obviously introduces sizable problems for any fusion reactor application of such rings, in particular in a moving-ring-type design.[4] Correspondingly, a series of experiments has centered on obtaining field-reversing rings at low B_θ values by letting the initially applied B_θ decay during the normal ring lifetime.

In this paper results of two sets of experiments are reported.[5,6] As described below, sizably enhanced dump-like losses of the fast electrons occur under certain circumstances. In view of the observed parameter dependence of the dumps and the ring behavior during their occurrence, these losses appear to be caused by orbital resonances between the poloidal motion of the fast particles and the toroidal ($m = 1$) perturbations of the magnetic field. Similar losses were observed in the RECE-Berta device when additional quadrupole fields were applied.[7] These results appear to constitute another example of severe degradation of particle confinement caused by orbital resonances, as it appears to occur also in the recent tandem mirror experiments.[8] Clearly, similar resonances and corresponding losses also may occur in modified betatron[9] experiments, the magnetic configuration of which is quite similar to that in our experiments.

The RECE-Christa device has been described earlier.[2] In brief, an intense electron beam pulse (typically 2–3 MeV peak, 40 kA peak, 80 nsec duration) is injected tangentially into a magnetic field consisting of a nearly homogeneous steady-state axial mirror field $B_{z0} = 400$–500 Gauss, a toroidal magnetic field B_θ generated by an axial current $I_z = 40$–70 kA, and various pulsed fields. Here I_z normally is crowbarred after a quarter-cycle time of 260–500 μsec, providing a resistive decay time > 5.5 msec. In contrast, the present experiments are performed with the decay of the toroidal field altered by delaying the crowbar up to a quarter-cycle time. In addition, varying sizes of B_θ banks and resistors in the crowbar circuit were used to vary the decay of B_θ. Most of the experiments were performed using a flux-conserving copper liner as in our earlier RECE-Christa experiments[2] (6 mm thick, with holes, flux penetration time about 30 msec);