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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
\( k_{2} \) and \( k_{4} \) is independent of \( D \), while the rate of growth with
\( k_{4} \) of the total number of excited modes, at fixed \( \delta \), 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 \( K_{41} \) 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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Alamos National Laboratory, Los Alamos, NM.

\(^{5}\) See P. Constantin, C. Foias, O. P. Manley, and R. Teman, J. Fluid Mech.
(to be published) for an overview and full references.

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No. 3, pp. 408-413 (1964).


The production of highly unidirectional lower-hybrid waves

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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 produc-
ging 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 direc-
tion, 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 spec-
trum 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 elec-
trons in the \(-z\) direction, further reducing the overall cur-
rent 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

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The experiments were performed in a single-ended Q machine which provided a low-density \( (5 \times 10^9 < n_e < 2 \times 10^{10} \text{ cm}^{-3}) \), a low-temperature \( (T_e \approx T_i \approx 0.2 \text{ eV}) \), a 1.0-m long and 5 cm in diameter. The experiments reported here were done by Olson and Motley 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 \( + k_z \) waves. 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 to verify this equation. 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 that 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 three decades of wave power launched. An example, an antenna configuration launching wave power 80% in the \(+ z \) direction and 20% in the \(- z \) direction might achieve about 98% 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% directivity, the grid temperature would increase about 220 °C (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

\[ \lambda_{\text{ref}} = \lambda_{\text{inc}} \frac{\cos(\theta - \psi)}{\cos(\theta + \psi)}, \]
Anomalous losses from relativistic electron rings in decreasing toroidal fields

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Anomally 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 \( B_\phi \); however, it depends on the axial length of the rings, and there may be a threshold in \( dB_\phi /dt \). 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 \( B_\phi \) that is comparable or even somewhat larger than the applied axial field \( B_z \). While stable field-reversing electron rings without \( B_\phi \) have been observed in the smaller RECE-Berta \(^3\) device, the use of \( B_\phi \) 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 \( B_\phi \) 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 \( B_\phi \) values by letting the initially applied \( B_\phi \) 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 \( B_{\phi 0} = 400 - 500\) Gauss, a toroidal magnetic field \( B_\phi \) generated by an axial current \( I_x = 40 - 70\) kA, and various pulsed fields. Here \( I_x \) normally is crowbarred after a quarter-cycle time of \(260 - 500\) \(\mu\)sec, 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 \( B_\phi \) banks and resistors in the crowbar circuit were used to vary the decay of \( B_\phi \). 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);