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A SIMPLE LOW-LOSS COUPLING METHOD FOR RF HEATING OF PLASMA IONS BY ELECTROSTATIC ION-CYCLOTRON WAVES+)

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A Simple Low-Loss Coupling Method for RF Heating of Plasma Ions by Electrostatic Ion-Cyclotron Waves

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Due to the possibility of neutron damage in a fusion reactor, it is desirable that no coupling structures like coils be present in the vicinity of the plasma. In the absence of such structures any rf heating scheme is reduced to the study of propagation and absorption of waves in a plasma-filled waveguide. The conversion of electromagnetic waves in the vacuum region to slow electrostatic waves and their eventual absorption via collisionless Landau and cyclotron damping has been proposed by Stix [1)]. To obtain large $k_{\parallel}$ in order to create the necessary conditions for collisionless damping, Derfler [2)] has proposed the construction of a slow-wave structure along the waveguide wall. This structure could, in principle, be made of the wall material itself.

The prinicpal contribution of this paper consists in the recognition that for the ion-Bernstein modes, the time of energy propagation readily exceeds the energy equipartition time τ_{ii} due to ion-ion collisions. Since a large part of the wave energy resides in the ion motion perpendicular to the magnetic field direction, plus the fact that the energy density in the wave is small compared to the thermal energy density in the plasma, the wave is absorbed through ion-ion collisions in a manner remniscent of gyro-relaxation magnetic pumping. The earliest references to the importance of such a damping process are to be found in the works of Farley and Dougherty [3)] who explain the absence of ion-cyclotron harmonic signals in the ionospheric backscatter experiments.

In a rigorous derivation of the damping rate, the viscosity should be included at the outset in the Vlasov description. However, in this work we assume that the ion energy is indeed randomized in a time of the order of τ_{ii}.

Since we no longer need $k_{\parallel}$ to be large, structures within the vacuum vessel may be immediately dispensed with. Rf energy is very simply fed in with a loop as shown in Fig. 1.

Because a plasma readily supports a current along the magnetic field direction, quasi TM waveguide modes with an azimuthal magnetic field at the plasma boundary are readily excited. The lowest order TM mode in a coaxial waveguide has only transverse field components and is sometimes referred to as the TEM mode.

For the TM modes with azimuthal variation m = o or 1, the problem may be conveniently studied in a parallel plate geometry with a slab plasma model.

Before treating the hot-plasma case, it is instructive to study the TEM wave on a cold-plasma column. The plasma profile is assumed to be stepwise linear with a flat top. There are twenty steps on either side of the column with a large concentration in the neighborhood of the lower hybrid frequency. The gas used is deuterium, the column width is loo cm and the perfectly conducting walls are 2oo cm apart. The central plasma density is 5×10^{14} cm^{3}. The axial magnetic field strength is loo kG and the operating frequency is selected to be near the loth ion-cyclotron harmonic.We assume a $\exp j(k_{\parallel}z - \omega t)$ field dependence in the axial direction and field uniformity in the y-direction.

The waveguide problem (filled partially with plasma) so formulated can be solved exactly using the complete cold-plasma dielectric tensor. Quite predictably, we find the extraordinary wave propagating almost at right-angles to the magnetic field. This wave has low phase and group velocities, both of the order of 2×10^{7} cm/sec. The amplitude of this wave is roughly 6o % of the vacuum field just outside the plasma.

The fast-Bernstein mode is the continuation of the extraordinary mode when the plasma is no longer cold [4]. In fact, the dispersion relation is not substanially affected if one stays away from the cyclotron harmonic as well as from the lower-hybrid frequency (see Fig.2). Therefore, as a crude approximation we assume that in a hot plasma the fast ion-Bernstein mode has the energy density, group velocity, and wavelength comparable to the extraordinary mode in the cold plasma, provided we stay away from the resonances.

Keeping in mind the assumptions and qualifications listed already, we proceed to estimate the extent of ion heating using the proposed scheme. Given the group velocity of 2×10^7 cm/sec, an energy pulse will require 5 μsec to traverse the plasma column of 100 cm width. Since τ_{ii} must be less than 5 μsec in order to dissipate the energy carried by this pulse, the plasma temperature calculated from the Spitzer [5] formula must be below 100 eV. The thermal energy density of the plasma is 20 mJ/cm^3. Assuming a vacuum field of 10,000 V/cm just outside the plasma boundary, the wave energy density given by

$$W_{wave} = \frac{1}{16\pi} E \cdot \frac{\partial}{\partial\omega} (\omega \bar{\bar{K}}) \cdot E$$

is 24 μJ/cm^3. Observe that even for extremely large electric fields the wave energy density is small compared to the thermal energy density of the plasma. The energy flux given by

$$\varepsilon = W_{wave} \; v_{group}$$

is 480 watt/cm^2 for this case. This is substantial for producing thermonuclear ignition.

For thermonuclear temperature the energy equipartion time is of the order of a millisecond. The problem of obtaining lower group velocities, however, is easily resolved by using frequencies closer to a cyclotron-harmonic frequency. This is expecially true for the slow-Bernstein mode which will exist in a hot plasma, in addition to the fast mode considered here.

Assuming that the slow-Bernstein mode is excited just as strongly as the fast-Bernstein mode, we shall indulge in some heating-effeciency calculations. The losses at the Niobium wall and the collisional dissipation at the plasma boundary due to the surface current carried by the electrons were calculated as perturbations. The heating effeciency ignoring all other losses, typically exceeds 7o %. Finally, we note that although the viscous effects cause a large dissipation of the wave, the fractional energy absorbed per wavelength or per cycle is less than one part in a thousand.

References

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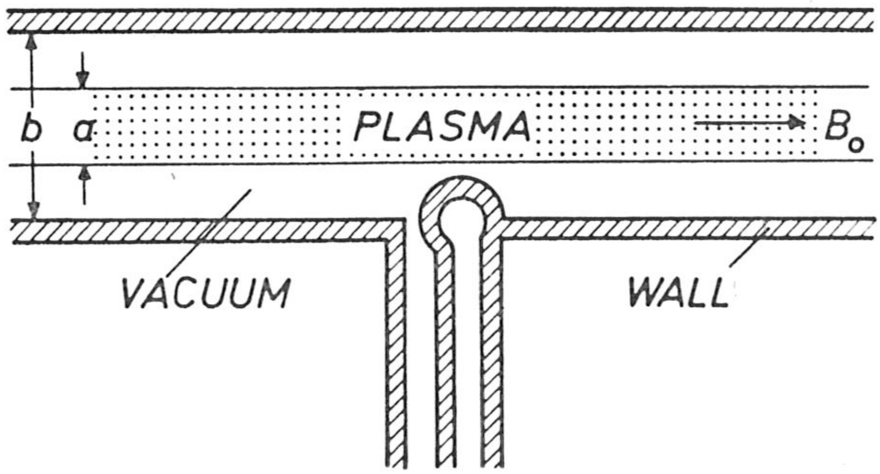

Fig.1 The coupling geometry

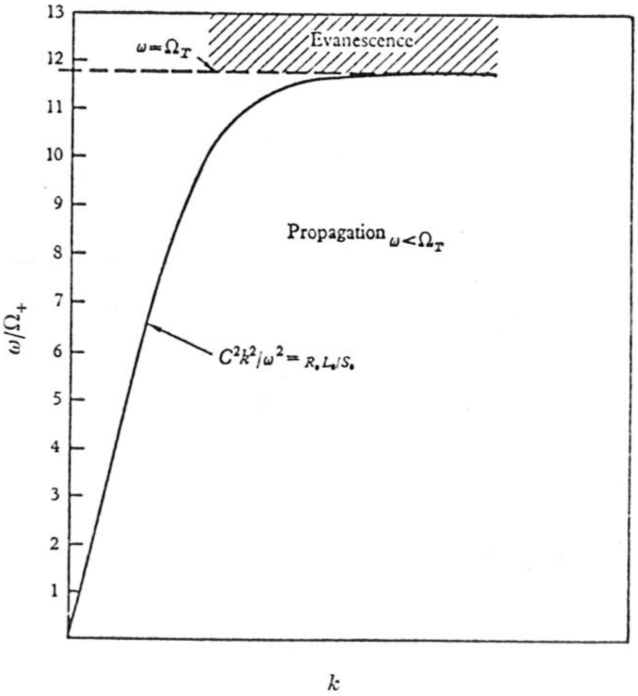

Fig.2a Schematic of the dispersion curve for waves propagating perpendicular to the magnetic field (k/B_o) in a zero-temperature plasma of two oppositely charged species, for frequencies below the lower hybrid frequency. (From Fredricks)

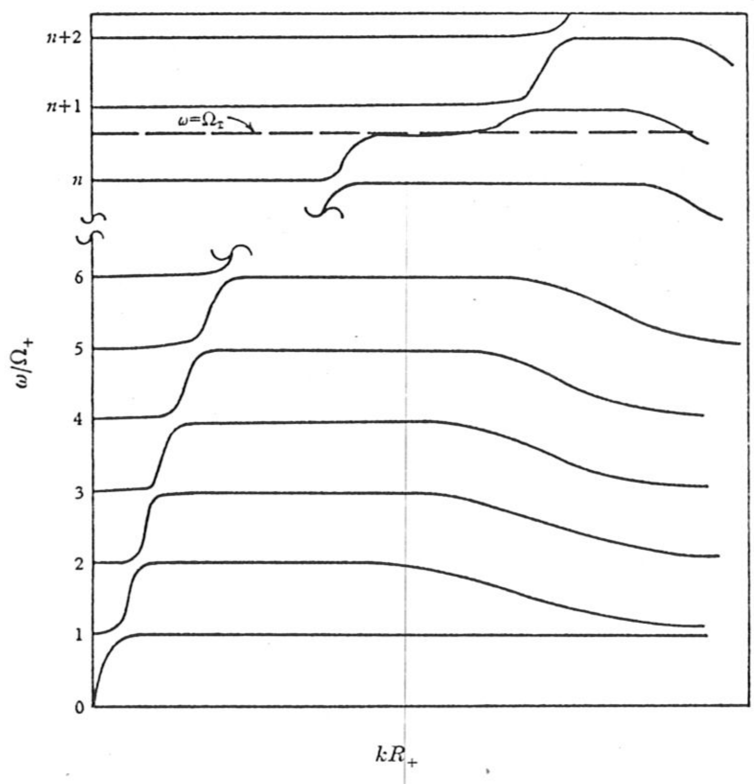

Fig.2b Schematic of the multi-branched dispersion curve for waves with k B_o in a warm, low beta plasma of two oppositely charged species. The envelope of the steeply sloped regions in each branch is approximately the cold plasma curve of Fig.2a. However, the resonances and cut-offs near the frequencies $\omega = n\Omega_+$ are due to thermal effects. Note the appearance of propagating solutions in branches above that containing the lower hybrid frequency. (From Fredricks)