THEORY OF ION BERNSTEIN WAVE LAUNCHING

M. Brambilla

Max-Planck Institute für Plasmaphysik, Garching bei München, W. Germany

Plasma heating with ion Bernstein Waves has been proposed as a viable alternative to Fast Wave heating in the ion cyclotron frequency domain [1], and moderate power experiments have shown promising efficiency [2]. Here we present results from a three dimensional code for the simulation of BW launching with loop antennas. The two-dimensional limit was treated by Sy et al. [3].

The real configuration is approximated by a slab model: Cartesian coordinates (x, y, z) simulate the radial, poloidal and toroidal directions, respectively, of a tokamak; the plasma parameters vary only in the x direction, curvature and shear are neglected. The wave field is decomposed in a double Fourier sum over toroidal and poloidal wavenumbers n_z and n_y , discretised as appropriate in the equivalent toroidal problem. The solution in vacuum is obtained analytically; the field at the plasma boundary and the antenna radiation resistance are expressed in terms of the antenna current, and of the surface plasma impedance tensor $Z_{ij}(n_y, n_z)$. To evaluate the latter, we solve the finite Larmor radius equations $(c/\omega = 1)$ [4,5]:

$$-(\frac{d}{dx} + n_y)\left[\sigma(\frac{d}{dx} - n_y)(E_x + iE_y)\right] + (n_y^2 + n_z^2 - S)E_x + in_y\frac{dE_y}{dx} + iDE_y - in_z\frac{dE_z}{dx} = 0$$

$$i(\frac{d}{dx} + n_y)\left[\sigma(\frac{d}{dx} - n_y)(E_x + iE_y)\right] + in_y\frac{dE_x}{dx} - iDE_x - \frac{d^2E_y}{d^2x} + (n_z^2 - S)E_y - n_y n_z E_z = 0$$

$$in_z\frac{dE_x}{dx} - n_y n_z E_y - \frac{d^2E_z}{d^2x} + (n_y^2 - P)E_z = 0$$

$$L = 1 + \frac{\omega_{pe}^2}{\Omega_{ce}^2}\left(1 - \frac{\Omega_{ce}}{\omega}\left(1 - i\frac{\nu_e}{\omega}\right)\right) - \sum_i \frac{\omega_{pi}^2}{\Omega_{ci}^2} x_{oi} Z(x_{1i})$$

$$R = 1 + \frac{\omega_{pe}^2}{\Omega_{ce}^2}\left(1 + \frac{\Omega_{ce}}{\omega}\left(1 - i\frac{\nu_e}{\omega}\right)\right) - \sum_i \frac{\omega_{pi}^2}{\Omega_{ci}^2}\frac{\omega}{\omega + \Omega_{ci}}$$

$$P = 1 - \frac{\omega_{pe}^2}{\omega^2}\left(1 - 2i\frac{\nu_e}{\omega}\right) x_{oe}^2 Z'(x_{oe})$$

$$S = \frac{R+L}{2} \qquad D = \frac{R-L}{2}$$

$$\sigma = \frac{1}{4}\sum_i \frac{\omega_{pi}^2}{\Omega_{ci}^2}\frac{v_{thi}^2}{c^2}\left(-x_{oi}Z(x_{2i})\right)$$

Here $Z(x)$ is the Plasma Dispersion Function, with $x_{n,i} = \frac{\omega - n\Omega_{ci}}{k_z v_{thi}}$, and ν_e the electron-ion collision frequency. A finite element discretisation with cubic Hermite interpolation functions is used. The solution is made unique by imposing the outward radiation conditions at sufficiently high density. At the plasma-vacuum boundary, in addition to the continuity of E_y, E_z, B_y, B_z, the condition

$$\sigma(0)\left\{\left(\frac{dE_x(0)}{dx} + i\frac{dE_y(0)}{dx}\right) - n_y\left(E_x(0) + iE_y(0)\right)\right\} = 0$$

must be imposed: it ensures that the kinetic part of the power flux vanish and the total flux is continuous at the plasma edge.

In [6] we have reported simulation of BW coupling in the Alcator C tokamak [7]. Here we will discuss how coupling depends on the edge plasma properties. For convenience, we have kept Alcator C parameters (frequency 183.6 Mhz; on axis $n_e(0) = 10^{14}$ cm^{-3}, $T_e(0) = 1.5$ keV, $T_i(0) = 1$ keV; at the limiter $n_e(a) = 0.6\ 10^{13}$ cm^{-3}, $T_e(a) = T_i(a) =$ 50 eV), and varied the scrape-off plasma characteristics. In the experiment its thickness d_s was 0.5 cm, with decay lengths $\lambda_n = 0.5$ cm for n_e, and $\lambda_T = 1.4$ cm for T_e and T_i. With these parameters (Fig.1 a), the code predicts a radiation resistance R_a close to the measured one when the first harmonic resonance is just behind the antenna; this is also the range in which efficient heating was observed. Outside this range, however, the calculated value is appreciably smaller than the observed one.

BW coupling turns out to be very sensitive to the density, and to a lesser extent to the ion temperature, just in front of the antenna. In Fig. 2 we have kept the magnetic field constant ($B_o = 6.98$ T, $\omega = 1.96\Omega_{ci}$ at the limiter) and varied the plasma density in contact with the Faraday shield by either increasing d_s at constant λ_n (curve a), or decreasing λ_n at constant d_s (curve b).The similarity of the results proves that the important parameter is the density, rather than the density gradient. Fig. 1 b shows the radiation resistance versus ω/Ω_{ci} at the limiter for $d_s = 1$ cm. The dramatic increase of R_a when the edge density is lowered is due to the fact that BW are coupled mainly through E_z, whose amplitude in the plasma is roughly inversely proportional to n_e because of screening by the electrons. The density and temperature in the scrape-off can be strongly influenced by the HF power itself, particularly when $\omega \simeq 2\Omega_{ci}$; moreover nonlinear effects in the near field region cannot be excluded. Nevertheless it is tempting to suggest on the basis of these results that a BW antenna could tolerate the transition from the L to the H regimes better than conventional FW antennas ([8]). Also, an effort to keep the plasma density in contact with the Faraday screen as low as possible, for example using lateral protections, might help improving the antenna loading.

Fig. 3 shows how loading varies with the scrape-off temperature. Matching improves with increasing $T_i(a)$ due to the increase of the BW wavelength (a similar effect explains the peak of R_a near $\omega/\Omega_{ci} = 2$ in Fig. 1).

Since E_z is roughly proportional also to n_z, BW with $n_z = 0$ cannot be directly coupled from outside. This has the same consequences for the antenna design as accessibility at higher frequencies, namely that toroidally antisymmetric antennas are better matched than symmetric ones. Thus the radiation resistance of the Alcator antenna (central feeder and shorts at the ends, quadrupole current distribution, Fig. 1b) is found to be about three time larger than that of an equivalent dipole antenna (feeders at the extremes and central short in push-pull, dipole current distribution, Fig. 1c).

/1/ S. Puri, 3d Top. Conf. on RF Plasma Heating, Pasadena (Calif.) 1978, E1.

/2/ M. Ono, Proc. Course and Workshop on Applications of RF Waves to Tokamak Plasmas, Varenna 1985, p. 197.

/3/ W. N.-C. Sy et al, Nucl. Fusion, **25** (1985) 795.

/4/ D.G. Swanson, Proc. 3d Int. Symp. on Heating in Toroidal Plasmas, 1982, Vol 1, p. 285.

/5/ P.L. Colestock, R.J. Kashuba, Nucl. Fusion, **23** (1983) 763.

/6/ M. Brambilla, 7th top. Conf. on Appl. of RF Power to Plasmas, Kissimmee (Flo.), 1987

/7/ Y. Takase et al, Report PFC/JA-86-60, MIT 1986.

/8/ K. Steinmetz et al., 11th IAEA Int. Conf. on Plasma Phys. and Contr. Nucl. Fus. Res. (Kyoto 1986), paper F-I-2.

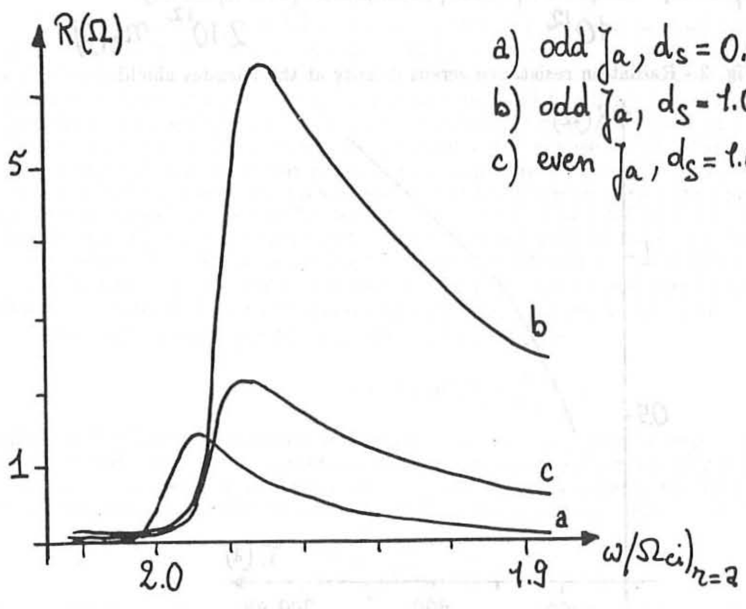

Fig. 1 - Radiation resistance versus ω/Ω_{ci} at the limiter.

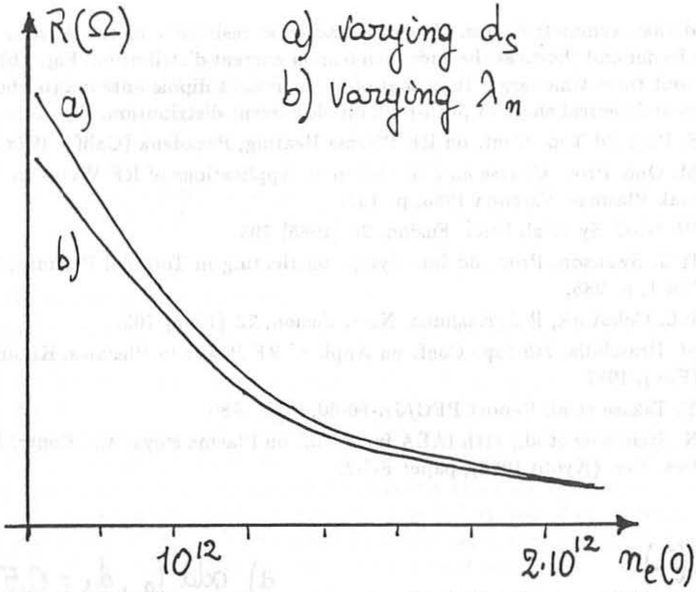

Fig. 2 - Radiation resistance versus density at the Faraday shield.

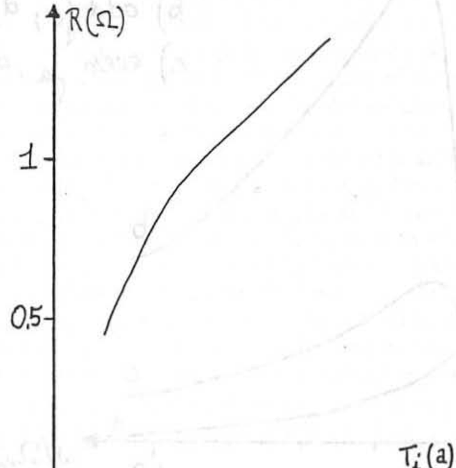

Fig. 3 - Radiation resistance versus edge plasma temperature.