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RESONANT MAGNETIC PUMPING AT VERY LOW FREQUENCY

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ABSTRACT : We propose to exploit for plasma heating purposes the very low frequency limit of the Alfvèn wave resonance condition, which reduces essentially to safety factor q = m/n, a rational number. It is shown that a substantial fraction of the total RF-energy can be absorbed by the plasma. The lowest possible frequency value is determined by the maximum tolerable width of the RF-magnetic islands which develop near the singular surface. The obvious interest of the proposed scheme is the low frequency value ($f \leq 10$ KHz) which allows the RF-coils to be protected by stainless steel or even to be put outside the liner.

The spectrum of possible auxiliary plasma heating methods reduces drastically if one consider a truly thermonuclear environment. The potentially most interesting remaining approaches are :

1 - High frequency (≥ 1 GHz) heating methods using wave guide systems which are compatible with reasonably small wall apertures (e.g. those foreseen for neutral injection). Being extensively studied by many authors, they will not be considered in this paper.

2 - Low frequency heating schemes using RF-coils which can be completely protected by stainless-steel (or titanium) or can even be put outside a metallic first wall. Indeed, insulating free surfaces (e.g. ceramics) should be avoided as far as possible within the first wall, if only for the degradation they would suffer from the thermonuclear neutron flux. The useful frequencies, therefore, are those which correspond to skin depths (in stainless-steel and titanium) around and above 1 cm, that is to say $f \leq 10$ KHz.

Besides their interest for RF-power deposition, the very low frequency schemes are attractive for dynamic stabilisation of the MHD modes which control the value of the toroidal current of a Tokamak, and hence the ohmic heating level.

The use of horizontal coils carrying properly dephased axisymmetric RF-currents in the KHz range, has been proposed recently /1/. RF-power is dissipated into a toroidal plasma by perpendicular Landau damping of an essentially MHD pump wave. The vertical phase velocity of the pump matches the value of the toroidal drift velocity of a suprathermal ion population. The heating efficiency turns out to be strongly dependent on the plasma parameters.

A systematically much higher heating efficiency can in principle be achieved /2/ at equally-low frequencies if one gives up axisymmetry and exploits the very low frequency limit of the shear Alfvèn-wave resonance condition :

$$\omega^2 = |\vec{k} \cdot \vec{v}_A|^2 \equiv |\frac{m}{r} B_\theta - \frac{n}{R} B_\phi|^2 / 4\pi\rho \qquad (1)$$

where m/r is the poloidal-and n/R the toroidal wave number, and ρ is the plasma mass density. This limit reduces essentially to

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$$q = m/n \tag{2}$$

where $q = r\,B_\phi/RB_\theta$ is the usual safety factor. We will consider, in particular, the case of frequencies $\omega < \nu_e$, where ν_e is the electron collision frequency. If the singular surface $q(r) = 1$ is present - at least marginally - in the flat central region of the plasma, than the most appropriate poloidal and toroidal mode combination is m = n (but not necessarily m = n = 1). In the absence of the q = 1 surface, other singular surfaces can obviously be considered. What should in any case be avoided is the presence of mode numbers matching condition (2) on the very edge of the plasma, because of the abverse effects they would have on thermal insulation and plasma confinement. The appropriate wave numbers are produced either by helical RF-coils (all the harmonics they can create have essentially the same helicity) or by the two annular plates located above and below the plasma ring as proposed for torsional TTMP heating /3/. The latter solution is most probably the best way of producing shear modes with the required helicity, because it does not imply putting RF-coils in the high-B_ϕ inner region of the toroidal device.

Wave propagation and power deposition can be studied in the usual collisional tearing mode stability scheme /4/, that is to say by assuming that each singular surface is embedded in a thin resistive layer which separates two perfectly conducting plasma regions. Another important approximation is the use of the Tokamak ordering $B_\phi \gg B_\theta$ to expand the magneto-hydrodynamic equations to lowest order in the inverse aspect ratio. Thus we replace the torus with a cylinder of length $L = 2\pi R$. Power deposition can conveniently be derived by means of a heuristic procedure (as in the tearing mode case /4/) which gives the correct parametric dependence of the relevant quantities while producing the numerical factors with sufficient accuracy in view of the various uncertainties inherent to the model. In this model RF-power can only be deposited in the resistive layer. Assuming that within this layer (whose radius is r_s and thickness Δ) both the electrical resistivity and the RF-current density j are essentially uniform, we write for the total RF-power absorbed :

$$P_{RF} \simeq 4\pi^2 R r_s\, \Delta \cdot \eta j^2 \tag{3}$$

Notice, incidentally, that in order to have $P_{RF} > P_{Ohmic}$ the RF-current amplitude in the resistive layer must exceed the ohmic dc-current. Introducing the surface current $j^* \simeq \Delta . j$ which is determined by the jump of the tangent components of the RF $\vec{B}$- field across the layer, $< \vec{B}_t >$, the mean power density, absorbed is

$$\bar{P} \simeq \frac{r_s}{2\pi a^2} \left|< \vec{B}_t >\right|^2 \cdot \frac{\eta c^2}{4\pi\Delta} \tag{4}$$

where a is the minor radius of the plasma. Within the resistive layer the radial components of Faraday's law and of momentum balance law are found to involve only B_r and v_r, the radial components of the $\vec{B}$ and $\vec{v}$ disturbances :

$$\partial B_r/\partial t = \vec{B}_o \cdot \text{grad } v_r + \frac{c^2\eta}{4\pi} \cdot \nabla^2 B_r \tag{5}$$

$$4\pi\rho\, \partial v_r/\partial t \simeq \vec{B}_o \cdot \text{grad } B_r \tag{6}$$

(here only the tension of the $\vec{B}$-lines and not the pressure gradient is retained as appropriate to shear disturbances). Since power dissipation requires some relative motion of fluid and $\vec{B}$ -field lines, we see that in the resistive layer ω must exceed the Alfvén frequency $\vec{k}\cdot\vec{v}_A$, which characterizes plasma motions with frozen-in $\vec{B}$-lines. Thus Δ is defined by

$$\omega \simeq |\vec{k}\cdot\vec{v}_A| \simeq \Delta \, |\vec{k}\cdot\vec{v}_A|' \qquad (7)$$

where the prime denotes radial derivative. Notice that in view of the large sheath currents required for powerful heating, the linearization of the problem is questionable. Thus, the $\vec{B}$-field and the derivatives contained in Eq. (7) should rather be interpreted as actual quantities including the RF-perturbations. B_r is assumed continuous across the layer so that B'_r is not especially large. This derivative, however, suffers an apparent discontinuity at r_s as measured by

$$\Delta' \equiv \{ B'_r(r_s + \frac{\Delta}{2}) - B'_r(r_s - \frac{\Delta}{2}) \} / B_r(r_s)$$

Then, within the layer, $\nabla^2 B_r \simeq \frac{i\Delta'}{\Delta} B_r$, and Eq. (5) gives

$$\frac{c^2\eta}{4\pi\Delta} \simeq \frac{-\omega}{\Delta'} \qquad (8)$$

With Eq. (8), Eq. (4) becomes

$$\overline{P} \simeq (\frac{r_s}{a})^2 \cdot \frac{\omega|<\vec{B}_t>|^2}{2\pi r_s |\Delta'|} \qquad (9)$$

The problem is now reduced to calculate $<\vec{B}_t>$ and Δ' from the ideal MHD equations outside the tearing layer. As ω is supposed to be small compared with the natural frequencies of the confined plasma, $\overline{P}$ is accurately given to first order in ω and we only need to consider the zero-frequency MHD solutions. If we assume helical symmetry, all quantities have to be functions of only r and $\tau \equiv m\theta + kz$ (with $k = n/R$). This, together with the Tokamak ordering and the assumption that the axial $\vec{B}$-component is uniform, permits to give $\vec{B}$ in term of only one flux function, ϕ, which can be calculated with a Stokes equation once the functional dependence of $dp/d\phi$ is specified by physical arguments. In the assumed ordering the appropriate equation of state is $\text{div}\,\vec{v} \simeq 0$. The solution to the linearized Stokes equation can then be given in terms of known transcendental functions /5/. A particularly simple case is the force-free situation /6/. The arbitrary coefficients in front of the solutions within the plasma can then be found in terms of the vacuum field by considering a sharp free-boundary plasma and the usual jump conditions across the perturbed boundary (which is a magnetic surface).

It remains to discuss the width of the RF-magnetic islands which develop near the singular surfaces as a result of the applied helical RF-fields. This width is an important quantity, as no pressure gradient can be sustained across a magnetic island, even if only neoclassical diffusion processes operate /7/. The usual estimate /8/ of the full width of the islands, w, gives in our case :

$$w \simeq 4 \{ - B_r / \frac{d}{dr} (\frac{mB_\theta}{r}) \}^{1/2} \simeq 4\,a\,(B_r/B_\theta)^{1/2} \qquad (10)$$

(here B_r is the radial component of the <u>RF</u>-$\vec{B}$ field) which inserted into Eq. (9) gives <u>in order of magnitude</u>

$$\overline{P} \simeq \omega \frac{B_\theta^2}{8\pi} (\frac{w}{4a})^4 \qquad (11)$$

If a given amount of power has to be dissipated into a given plasma, the factor $\omega\,(w/a)^4$ must be kept constant. As a result, the lowest possible frequency value is determined by the maximum tolerable w.

Comparing Eq. (11) with the corresponding estimate for Transit Time Magnetic Pumping with $\tilde{B}/B_o = 3.10^{-3}$ -which should represent the reactor requirement /9/- one finds for $f \gtrsim$ a few kHz, $w \lesssim 0.2$ a. However a more precise derivation of $\overline{P} = \overline{P}(w)$ is required to assess this crucial point. Notice that the island problem is avoided if the proposed scheme is used to heat multiple configurations (Doublets, octupoles, etc.) near the hyperbolic axes : this requires properly dephased axisymmetric horizontal RF-coils, similar to those of Ref./1/.

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