FR7800837

8. European conference on controlled fusion and plasma physics. Prague, Czechoslovakia, 19-23 September 1977

CEA-CONF--4122

RESONANT MHD-PUMPING AT ARBITRARILY LOW FREQUENCY

E. CANOBBIO

ASSOCIATION EURATOM-CEA
Département de Physique du Plasma et de la Fusion Contrôlée
Service IGn - Centre d'Etudes Nucléaires
85 X - 38041 GRENOBLE CEDEX

ABSTRACT : Helical rf-fields with appropriate wave numbers can be used to exploit for heating purposes the existence within the plasma of the MHD-singular surfaces where $\vec{k}\cdot\vec{B}_0 = 0$. In this way the TTMP heating rate can exceed the non-resonant value by a factor of order $1/\beta$ and the working frequency $\omega = (\vec{k}\cdot\vec{B}_0/B_0)v_{ti}$ can in principle be choosen arbitrarily low (but preferentially $\omega \gtrsim \nu_{coll}$).

INTRODUCTION. RF -launching structures designed to produce nonvanishing poloidal wave numbers $K_\theta \equiv m/r$ in addition to toroidal wave numbers $K_\phi \equiv n/R$, have been considered for ICRH /1/, TTMP /2/,/3/, Alfvèn-Wave Heating /4 - 7/, and for Toroidal Drift Magnetic Pumping /8/. In the Proto-Cleo experiment /7/ the inequality

$$|\vec{k}\cdot\vec{v}_A| \equiv |\vec{k}\cdot\vec{B}_0(4\pi\rho)^{-1/2}| \equiv |m\,B_\theta/r + nB_\phi/R|(4\pi\rho)^{-1/2} < \omega_{ci} \qquad (1)$$

($\omega_{ci} = eB_0/m_ic$) was satisfied in spite of the fact that $|m\,v_{A\theta}/r|$ and $|nv_{A\phi}/R|$ were both larger than ω_{ci}.

In the TTMP litterature there is no mention of the analogous possibility of lowering the working frequency by exploiting the existence of the MHD singular surfaces within the plasma. The TTMP frequency is $\omega \simeq nv_{ti}/R$ in the compressional version ($v_{ti}^2 = 2T_i/m_i$), $\omega \simeq v_{ti}/R$ in the torsional version of Ref. /2/ and $\omega \simeq v_{ti}/qR$ ($q \equiv rB_\phi/R\,B_\theta$) in the axisymmetric $|m| = 2$ version /3/ producing surface heating. This oversight is surprising in view of the obvious interest of using frequencies which are so low that the rf-coils can either be put outside the liner (if $\omega/2\pi \lesssim 10$KHz) or be protected by stainless steel if they have to be in face of the plasma ($\omega/2\pi \simeq$ a few 10 KHz).

WORKING FREQUENCY. The correct expression of the optimum TTMP frequency is

$$\omega = (\vec{K}\cdot\vec{B}_0/B_0)\, v_{ti}\, F(T_e/T_i, m, n) \qquad (2)$$

where F is a factor of order unity /2/, /3/, /9/. Power deposition is still substantial at $\omega \pm \Delta\omega$ with $\Delta\omega \leq \omega/2$.

Eq. (2) implies that in the neighbourhoods of the singular surfaces $r = r_s$ where $\vec{K}\cdot\vec{B}_0 = 0$ (or $q = -m/n$) plasma heating may be produced at arbitrarily low ω. Since in most of the performant Tokamaks $q(0)$ is slightly below unity, the singular surfaces $q(r) = 1$ is imbedded in the flat central region of the plasma : therefore $n = - m = \pm 1$ are the most interesting combinations. They are produced either by a pair of helical windings (ideally represented by a sheet current $\vec{J}^{R}.\delta(r-r_c)$ with $j_{\phi}^{R} / j_{\theta}^{R} = - R/r_c$) or, more conveniently, by the pair of horizontal coils proposed in /2/. In the absence of surface $q = 1$, surface $q = 2$ can be considered. The rf-coils should be designed so as to avoid the production of intense higher-(m, n) harmonics which would satisfy condition $\vec{K}.\vec{B}_0 \to 0$ at the plasma edge, with adverse effects on confinement. Notice, incidentally, that in the Stellarators, where $|B_\theta/r|$ increase with r, such peripheric resonances may well have been excited in the TTMP and Alfvén-wave experiments, where pumpout occurred during heating /10/, /7/.

<u>RF-FIELD STRUCTURE</u>. As is well known from stability theory in cylindrical geometry /11/,/12/, the whole set of the linear ideal MHD-Eqs. reduces to a single Euler Eq. $(f\xi')'-g\xi = 0$, where ξ is the <u>radial</u> component of the displacement vector $\vec{\xi} = \vec{\xi}(r).\exp i(m\theta + kz-\omega t)$, and the prime indicates d/dr. Since in a low-β plasma, the TTMP frequencies (2) are very small compared with the MHD frequencies (1), we may limit our attention to the "marginal stability" limit $\omega^2 = 0$. Assuming, moreover, $k^2r^2 << m^2$, which is appropriate to the Tokamak scaling, we have

$$f = (\vec{K}.\vec{B}_0)^2\, r^3/m^2 \quad ; \quad g = f(m^2+ k^2r^2-1)/r^2 + $$
$$+ \ \{8\pi p' + (\vec{K}.\vec{B}_0)(kB_z-mB_\theta/r)2r/m^2\}\, k^2r^2/m^2 . \qquad (3)$$

In the neighbourhoods of a singular surface $r = r_s$, if $x \equiv r - r_s$, we may write $f = \alpha x^2$, $g = \beta + \gamma x + \delta x^2$ and find the solutions to Eq. (3) in terms of hypergeometric functions /11/, which behave like $\xi_1 = x^{\nu_1}$ and $\xi_2 = x^{\nu_2}$ (if $x \to 0$) with

$$2\,\nu_{1,2} = -1 \pm \{1 + 32\pi\, p'/r\, B_z^2\, [(\ln\,(B_\theta/r\,B_z))']^2\}^{1/2} \qquad (4)$$

The sign of the expression under the square root is positive when Suydam's criterion is satisfied : then one of the solutions is infinite at r_s.

The radial width of the resonance zones is governed by the position of the roots of the quadratic equation $g(\frac{nq(r)}{m}) = 0$ /12/, which in our problem play the role of two cut-offs. If $m^2 = 1$, the resonance zone is quite broad

$$3\,mq(r_{1,2}) = 1 \pm 2\,(1 - 6\pi r p'/B_\theta^2)^{1/2} \qquad (5)$$

If $|m| \geq 2$

$$\Delta q \equiv q(r_2) - q(r_1) = 2\,kr/n = 2|mB_\theta/nB_z| \qquad (6)$$

The largest field components in these zones are $B_{1\parallel} = \vec{B}_1 \cdot \vec{B}_0/B_0 = B_\theta^2\, \xi'/B$, $E_{1r} \simeq -\,\xi'\omega r\, B_z/mc$, and the electrostatic field $\vec{E}_{1es} = (\text{grad}\ n_1)T_e/en_0$ which ensures charge neutrality /2/, /3/, /9/. In contrast with the stability case, these fields are not eigenmodes : they are driven by the external rf-currents.

<u>POWER ABSORPTION</u>. The large rate of change of the kinetic energy of each particle in the resonant zones, $e\vec{v}\cdot\vec{E}_1 + \mu\partial B_1/\partial t$ ($\vec{v}$ is the guiding-center velocity and μ the constant magnetic moment), results in a very important TTMP heating of the plasma ions (primarily along $\vec{B}_0$) if condition $\omega = v_\parallel\, \vec{k}\cdot\vec{B}_0/B_0$ is satisfied by $v_\parallel = O(v_{ti})$ on a substantial fraction of the zones defined by Eqs. (5) and (6). Since $\Delta k_\parallel \equiv \Delta(\vec{k}\cdot\vec{B}_0/B_0) = \Delta q(n/qR)$, in order to have $\omega = \alpha v_{ti}/qR$ with $\alpha \ll 1$, from $\Delta k_\parallel/k_\parallel \simeq \Delta q(n/\alpha)$ we conclude that TTMP occurs on a fraction of order α of the $m^2 = 1$ resonance zone, and on the entire $|m| \geq 2$ - resonance zones it $\alpha \gtrsim 2\,m\,B_\theta/B_z$.

Of course Eq. (4) implies that our ideal model breaks before a singular surface is reached. A reasonable estimate of the average enhancement factor for the rf-energy dersity in zones (5) and (6), is $\simeq (v_A/v_{ti})^2 \simeq 1/\beta$. This implies that a large fraction of the reactive power

$\int_V d^3x(B_\perp^2 + E_\perp^2)/8\pi$ (V is the plasma volume) could be dissipated. However, just as in the case of resonances at higher frequency (Alfvén and hybrid) it is then hard to predict how much heating will be due to Landau processes, to linear mode conversion or to non-linear (e.g. parametric) effects /4/. We also notice that if ω is choosen as low as $v_{ti}^2\ m/rR\omega_{ci}$ - the "transit frequency" in the vertical drift motion - at the singular surfaces the condition $\omega = \vec{k}\cdot\vec{v} + \vec{k}_\perp . \vec{v}_\perp$ can be fulfilled by the vertical drift velocity in the toroidal field /8/.

REFERENCES.

/1/ - OVCHINNIKOV, S.S. et al., Madison IAEA Conference 1971, english transl. : Nuclear Fusion Supplement 1972, p. 307.

/2/ - KOECHLIN, F and SAMAIN, A. Phys. Rev. Lett. 26 (1971) 490.

/3/ - KOECHLIN, F and SAMAIN, A. Plasma Phys. 14 (1972) 349.

/4/ - HASEGAWA, A and CHEN Liu, Phys. Rev. Lett. 32 (1974) 454 ; Phys. Fluids 19 (1976) 1924.

/5/ - TATARONIS, J.A and GROSSMANN W. Nuclear Fusion 16 (1976) 667.

/6/ - IIYOSHI, A., et al., Heating of Toroidal Plasmas, Grenoble 1976, Vol. 2 p. 305.

/7/ - GOLOVATO, S.N., SHOHET, J.L., and TATARONIS, J.A., Phys. Rev. Lett. 37 (1976) 1272.

/8/ - CANOBBIO, E., Berchtesgaden IAEA Conference 1976.

/9/ - CANOBBIO, E., "Plasma Physics and Controlled Nuclear Fusion Research" 1971, Vol. III p. 491.

/10/ - MILLAR, W., Report CLM-R 144 (1975) ; PACHER, H.D. et al., Bull. Am. Phys. Soc. 18 (1973) 1363 ; CANOBBIO, E. Varenna Symposium Sept. 1976.

/11/ - NEWCOMB, W.A., Ann. Phys. (N.Y.) 10 (1960) 232 ; HAIN, K. and LÜST, R., Z. Naturforsch 13a (1958) 936 ; GOEDBLOED, J.P., Phys. Fluids 16 (1973) 1927.

/12/ - SHAFRANOV, V.D., Soviet Phys. Tech. Phys. 15 (1970) 175.

[redacted]