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HEATING OF TOROIDAL PLASMAS

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Résumé. — Différentes méthodes de chauffage peuvent être utilisées afin de surmonter les limitations du chauffage ohmique dans la réalisation des conditions d'ignition d'un plasma toroïdal à bêta faible. Les méthodes envisagées sont :

a) l'injection de faisceaux d'atomes neutres rapides (éventuellement combinée avec une compression adiabatique ou autres expédients) et

b) les chauffages HF, dont les plus intéressants sont ceux qui exploitent une des résonances du plasma.

On donne une explication simple des mécanismes physiques qui sont à la base de chacune des méthodes et on signale les résultats les plus significatifs qui ont été obtenus.

On décrit enfin une nouvelle proposition de chauffage qui utilise une fréquence extérieure de quelques kHz, ce qui permet de placer les bobines excitatrices à l'extérieur de la chambre à vide (certaines de ces bobines peuvent être celles qui produisent le champ magnétique vertical nécessaire à l'équilibre du plasma).

Abstract. — Various heating methods can be used in order to overcome the limitations of ohmic heating in low-β toroidal systems. Attention is directed to fast neutral beam injection (possibly supplemented by adiabatic compression, etc.) and to RF-heating methods based on the existence of resonances. The basic physical mechanisms involved and the most significant results obtained are briefly explained. Finally, a new heating scheme is proposed which uses kHz-frequencies and rf-coils located outside the liner.

Extended synopsis. — Because of the Kruskal-Shafranov current limitation ohmic heating alone cannot bring a Tokamak plasma to thermonuclear ignition. Moreover, in a Tokamak with circular cross-section, the ohmic heating time τ_Ω is related to the skin time τ_s (characterizing the **B**-field diffusion through the plasma) by the simple relation $\tau_\Omega \simeq \tau_s \beta_p$ (β_p is the usual poloidal β), which indicates that ohmic heating alone cannot increase β_p substantially above unity. As the product $n\tau_E$ (plasma density x energy confinement time) has been shown to scale as $(na)^2 \propto \beta^2 \propto \beta_p^2$ (a is the plasma minor radius), it is obviously important to appeal to non-ohmic processes.

The presently estimated requirements for non-ohmic power exceed by orders of magnitude the ohmic level (but non-ohmic heating is still euphemistically called *auxiliary* !).

Cross-field penetration of non-ohmic energy is possible only in two ways : 1) with fast neutral atoms, and 2) with EM-fields.

1) *Neutral injection* (NI) with $E_0 \simeq$ a few 10 keV (H^0) has been successfully used at the MW level. However, since $n\tau_E \propto (na)^2 \propto E_0^2$, a large aperture high density future device would require

$$E_0(H^0) > 100 \text{ keV},$$

unless NI is combined with some expedients like the expanding limiter, deliberate ripple trapping and adiabatic magnetic compression. Major long-term concerns are : wall sputtering, straight-line accesses open to neutron flux escape, energy recovery, etc...

2) The required power and energy is available for RF-*heating* with high efficiency up to $f \simeq$ a few GHz. Three main heating processes exist : collisional, collisionless-linear, and non-linear.

Purely collisional heating (gyrorelaxation) is inefficient.

Heating based on a selective interaction between a RF-wave (ω, **K**) and particles whose velocity and gyrofrequency ω_c satisfy the resonance condition

$$\mathbf{K}.\mathbf{v} + n\omega_c = \omega \gg \nu_{coll} \qquad (n = 0 ; \pm 1 ; \pm 2 ; ...),$$

can be very efficient because small-angle Coulomb collisions allow both a long resonance duration and rapid remaxwellisation of $f(\mathbf{v})$.

$n \neq 0$ single-particle resonances are also resonances of collective oscillations of the plasma ($\mathbf{K} \to \infty$). At least three more collective resonances occur in the plasma : *a*) the non-WKB Alfven wave resonance

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$\omega = K_{\parallel} v_A$; *b*) the lower hybrid resonance (LHR) $\omega \simeq \omega_{pi}$ (ω_{pi} is the ion plasma frequency) and the upper hybrid resonance (corresponding to several tens of GHz). Since, quite generally, the energy flux $\mathbf{S}$ is equal to $\mathbf{v}_g W$, where $\mathbf{v}_g$ is the group velocity and W the field energy density, at a collective resonance we have $\mathbf{v}_g \to 0$, $W \to \infty$. Because of the variety of waves which can penetrate a hot plasma, condition $\mathbf{v}_g \to 0$ implies mode conversion. When $W \to \infty$ non-linearities become important and may completely dominate wave propagation.

The two most important classes of non linearities are parametric mode coupling and stochastic particle acceleration.

Two global necessary conditions for the appearance of parametric instabilities are given : the power input by the pump wave must exceed power dissipation by the plasma, and at least one of the side-band modes has to be a plasma eigenmode. Parametric instabilities can occur also far from a field resonance, as is strongly suggested by experiments on TTMP in two small Stellarators.

Stochastic acceleration is illustrated most simply by means of the Fermi model of a particle bouncing between two vibrating walls. « Heating » occurs when the transit-frequency modulation due to the wall vibration is larger than the spacing in the frequency spectrum of the forces perturbing particle motion.

In a plasma stochasticity is favoured by both large W-values and short wave lengths ($v_g \to 0$), and results in energetic tail formation.

The most significant RF-heating experiments are briefly reviewed. Up to now TTMP experiments have been dominated by pumpout, most probably due to parametric effects induced near the plasma periphery.

Various ICRH experiments on hydrogen contaminated deuterium plasmas showed that linear cyclotron damping is not the dominant absorption and heating mechanism : at least mode-conversion and stochastic acceleration have to be taken into account to interpret the results. Energy deposition is eventually limited by MHD disruptions.

Some LHR heating of the bulk of the ions has been produced together with a hot maxwellian tail (of stochastic origin ?). How much is surface heating remains to be measured. Wave-guide rf-power launching has been produced very successfully : wave-guide launching is indeed a distinctive advantage of this method compared with the others which need coils in face of the plasma within the vacuum chamber.

Finally, a new heating scheme is proposed which uses a number of rf-current carrying azimuthal coils placed at various distances z from the equatorial plane of a toroidal device (some of these coils can be those producing the equilibrium vertical **B**-field). By proper choice of both frequency and dephasing along z, a plasma major-radius perturbation $\xi(R, z, t)$ may be induced which *travels along z* with phase velocity of the order of the toroidal drift velocity of the thermal ions. It is shown that in a well confined plasma, subtantial ion heating by perpendicular Landau-like damping may occur by producing a small radial oscillation rate $\xi/R \simeq 10^{-2}$ at low frequency $\omega/2\pi \simeq$ 1-5 kHz, thus allowing the rf-coils be located outside the liner. A distinctive feature of the new heating scheme is that only the third adiabatic invariant of particle motion is destroyed by the rf-field. A test of this scheme is possible on devices having a sufficient number of vertical field coils.