A REVIEW OF RF HEATING

by

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ABSTRACT

The funadmental aspects of RF heating theory is reviewed and a summary of recent experimental results are given. All frequency regimes are covered, from very low frequency magnetic pumping to electron cyclotron resonance heating.

A Review of RF Heating

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We review briefly the present status of the theory and the experimental results of heating toroidal plasmas (mainly tokamaks) by radiofrequency (rf) power. We shall discuss a number of different frequency regimes beginning with the electron cyclotron frequency (i.e., $f \simeq 100$ GHz) and ending with very-low frequencies (i.e. $f \simeq 1\text{-}10$ KHz). Before we discuss the details of rf heating, let us briefly point out the importance of supplementary heating of fusion plasmas in order to reach ignition temperatures. In tokamaks initially ohmic heating will provide a relatively hot ($T_e \simeq T_i \simeq$ 2 keV) target plasma. However, as the temperature rises, the resistivity decreases as $T^{-3/2}$. In addition, losses due to radiation increase as $z^3 n^2 T^{\frac{1}{2}}$. Hence, at some point radiative losses overcome ohmic heating, and the attainment of ignition conditions by ohmic heating alone is doubtful. Furthermore, the ohmic current cannot be increased by arbitrary amounts or MHD stability will be violated. A simple relation between typical losses and power input is given by the following relationship:

$$P_\eta + P_\alpha + \Delta P_s = P_{loss} \qquad (1)$$

where P_η represents ohmic heating, P_α represents α-particle heating, ΔP_s represents supplementary heating, and P_{loss} is due to synchrotron radiation, bremsstrahlung, and heat transport to the walls and the limiter. We note that in order to contain α-particles, we need approximately 3.5 Mamperes of ohmic-heating current. Assuming that this is provided, in most devices with $Z_{eff} \simeq 1$ some form of supplementary heating will be necessary to achieve ignition conditions. While at present the forerunner is neutral beam heating, in reactor-size plasmas beam energies of the range $\varepsilon \simeq 300\text{-}500$ keV will be necessary. At present such beams do not exists, and the low efficiency of neutralization above 150 keV dictates the use (and development) of negative ion beams. An alternative approach would be to learn how to use the large amounts of RF power available to heat plasmas to high temperatures. This is especially true due to the following additional reasons: (1) With the exception of a few clean tokamaks, in most devices $Z_{eff} > 1$. However, since radiative losses are especially sensitive to Z_{eff}, impurities will have to be greatly reduced in reactor grade plasmas so that $Z_{eff} < 2$, (and $Z_{eff} \simeq 1$ is highly desirable) [1]. However, the effectiveness of ohmic heating in "clean" plasmas above $T \approx 2$ keV is greatly reduced. The effectiveness of supplementary heating can be demonstrated by the simple formula (valid for $\Delta t > \tau_E$)

$$\Delta P = \frac{3}{2} V \frac{\Delta(nT)}{\tau_E} \qquad (2)$$

where τ_E is the energy confinement time, ΔP is the supplementary heating power, V is the plasma volume, and $\Delta(nT)$ is the additional rise in plasma energy. If we take $\tau = C_o na^2$, where c_o is a constant (as is observed in present day experiments) then

$$\Delta P \propto (\Delta T) R\, C_1, \qquad (3)$$

where $C_1 = 3\pi^2/C_o$, and R is the machine major radius. Thus, we see that the smaller the major radius, the less supplementary power one needs to attain ignition temperatures. Implicit in these considerations is that C_o is independent of T. Although at present this appears to be consistent with experimental observations, in future, hotter plasmas where trapped particles will be dominant this may no longer be so, and a deterioration of τ_E may be expected.

Let us now examine in a few cases of interest how effective supplementary heating is. In particular, we shall consider three different sized machines and in each case we shall assume that the energy confinement time scales as $\tau_E \propto na^2$, with the constant C_o obtained from the best present date results, namely Alcator A [2]. Table 1 summarizes the expected confinement times for a "conventional" large (low-density) device, an intermediate device, and a high density, compact device ("ignitor"). The expected magnetic fields and machine parameters are also shown, including the necessary temperature changes which the "supplementary" heating system must provide in order to reach ignition temperatures. Here we assumed that eventually the contribution of ohmic heating becomes negligible as compared with the supplementary heating power (with the exception of the last case which is called "ignitor" [3]). While an intermediate to large system will require 55-125 MW of net additional heating power, a small system can "ignite" with only a few MW of supplementary power. Of course, in a smaller device materials damage due to neutron bombardment may be unacceptably high for reactor purposes. Nevertheless, "ignitors" should be considered as relatively "cheap" research devices where α-particle heating (for example) and reactor-grade plasmas could be studied. It should be remembered that these powers are the power absorbed by the plasma, and thus the source power will likely be twice as much as that shown in Table 1. Since the total heating pulse length is a few seconds, for all practical purposes we must consider CW power.

A typical rf heating system is represented schematically in Fig. 1. It consists of an rf source, a transmission line, a vacuum (and dc) break, and some sort of antenna structure either inside or flush mounted in a port. Finally, the radiated power must be transported toward the plasma interior by means of electromagnetic or electrostatic waves, and finally this power must be dissipated in the form of thermal energy. Of course, if too much power is dissipated near the plasma periphery, it will quickly be lost and the efficiency of bulk heating will be low. Thus, assuming that the total efficiency of absorption is at best 70% and that at least 20% of the power is lost in the transmission line at the source we would need at least double the power shown in Table 1. It should also be realized that we cannot expect more than 35-40% electric efficiency for the total rf source, and hence the required "plug" power may be four or five times that shown in Table 1.

One important aspect of plasma rf interaction, which is often not mentioned, is that in addition to actual bulk heating, rf power may be used for controlling the plasma properties. Some of these roles are listed in Table 2, and since most are self-explanatory (and some are speculative), we shall not discuss them here any further. Clearly, considerably more research work is needed to determine which of these techniques have potential for practical applications.

2) Regimes of Interest in RF Heating

Let us now list various frequencies of interest, and also make some comments regarding their main features. This is given in Table 3, in order of decreasing frequencies, all the way from electron-cyclotron resonance heating to very low frequency magnetic pumping. We should note that while ECRH is the most recent experimental entry into tokamak rf-heating (at $B \approx 20$ kG) there are some new ideas for very low-frequency heating [4]. Let us now discuss the main theoretical aspects and the status of the experiments in each of these frequency regimes. We note that in the theoretical discussions we shall present only linear mechanisms. In many cases nonlinear effects may become important at high pump powers, and nonlinear effects such as trapping, stochasticity, and parametric instabilities may have to be taken into account. A recent review of parametric phenomena has been given by the present author elsewhere and we shall not discuss them here [5].

3) Electron Cyclotron Resonance Heating

A. Theoretical Considerations

The linear theory of electron-cyclotron resonance heating applicable to tokamaks has been examined recently by a number of authors [6-8]. The renewed interest in this high frequency regime stems from new developments in the field of high-frequency technology, namely the development of gyrotrons [9,10]. Thus, it appears that cw sources with power levels of the order of $P \approx 0.1$-0.2 MW, $f = 28$

GHz, and pulsed sources with $P \simeq 70$ kW, $f \simeq 65$ GHz are available now [11] and cw sources with frequencies of $f \simeq 100$ GHz and $P \simeq 100$-200 kW expected to be available within three years [12].

The linear absorption mechanisms in this frequency regime are due to either finite values of $k_\parallel$ and cyclotron damping, or due to the inhomogeneous magnetic field. Let us now summarize the main results of the theoretical predictions obtained by Antonsen and Manheimer [6]. Defining

$$T = \exp[-2\pi\eta] \qquad (3)$$

as the transmission coefficient, $A = (1-T)$ is the absorption coefficient. Furthermore, the magnetic field gradient scale length is defined as

$$\nabla_R B = B/R_B \qquad (4)$$

where the spatial derivative is taken along the major radius, R_B. These relationships predict efficient absorption of the microwave beam in one passage when

$$2\pi\eta > 1. \qquad (5)$$

The results of the theoretical predictions are as follows:

a. Ordinary mode of propagation

In this case $E_o \| B$, $k_o \perp B$, where B is the external magnetic field. Accessibility requires that $\omega_o > \omega_{pe}$, and hence this mode of propagation is useful only when $\omega_{pe} < \omega_{ce}$. The absorption coefficient at $\omega = \omega_{ce}$ is given by (using $v_t^2 = T/m$)

$$\eta = \frac{R_B}{4} \frac{\omega_p^2}{\omega^2} \left(1 - \frac{\omega_p^2}{\omega^2}\right)^{\frac{1}{2}} \frac{\omega}{c} \frac{v_{te}^2}{c^2} \quad . \qquad (6)$$

For example, for $f_o = f_{ce} = 100$ GHz one finds that $2\pi\eta > 1$ if $T_e > 0.4$ keV. Thus, absorption is efficient only in hot plasmas. It is also found that at $\omega = 2\omega_{ce}$ this mode of propagation is not effective in heating the plasma.

b. Extra-Ordinary Mode of Propagation

In this case $E_o \perp B$, $k_o \perp B$, and we are interested in absorption near $\omega = \omega_{ce}$, $2\omega_{ce}$, ω_{UH} (where $\omega_{UH}^2 = \omega_{pe}^2 + \omega_{ce}^2$ is the upper-hybrid frequency). Direct accessibility is prevented by a cut-off layer in front of the upper-hybrid layer when the wave propagates from the low magnetic field side. The cut-off layer is given by

$$\omega_+ = \frac{\omega_{ce}}{2}\left[1 + \left(1 + \frac{4\omega_{pe}^2}{\omega_{ce}^2}\right)^{\frac{1}{2}}\right] \qquad (7)$$

The wave may propagate to the upper-hybrid layer by tunneling from the low magnetic field side if $\omega_{pe}^2 \ll \omega_{ce}^2$. Since in tokamaks $\omega_{ce} \simeq \omega_{pe}$, accessibility exists when the wave propagates from the high magnetic field side [13] or when $\omega \simeq 2\omega_{ce}$. Thus, we see that even if the wave is launched from the outside in the equitorial plane, accessibility may be achieved by scattering around the torus (between the chamber wall and the plasma column) and penetrating from the high magnetic field side.

i. $\underline{\omega = \omega_{ce}}$

One finds then that if $k_\parallel \neq 0$, strong absorption by cyclotron damping takes place if $\omega = \omega_{ce}$. On the other hand, if $k_\parallel = 0$ efficient absorption at $\omega = \omega_{ce}$ does not take place since $|E_o| \to 0$.

ii. $\underline{\omega = 2\omega_{ce}}$

Absorption can be efficient even if $k_\parallel = 0$ and $2\pi\eta > 1$ where

$$\eta = R_B \frac{\omega}{c} \frac{v_{te}^2}{c^2} \tag{8}$$

Again, this absorption mechanism is efficient if the plasma is relatively hot (i.e., $T \gtrsim 0.5$ keV).

iii. $\underline{\omega = \omega_{uh}}$

In this case heating occurs by absorption of the Bernstein wave which is a consequence of linear mode-conversion of the extraordinary mode at $\omega = \omega_{uh}$ [14]. Alternatively, Bernstein waves may be generated by parametric decay processes also [15]. Accessibility is best by propagation from the high magnetic field side, or by tunneling if $\omega_{pe}^2 \ll \omega_{ce}^2$, or by the so-called z-hole effect [16].

From these considerations one may conclude that the best strategy is to use the 0-mode in tokamaks with $\omega_{pe} < \omega_{ce}$, and when $\omega_{pe} \gtrsim \omega_{ce}$ use $\omega \approx 2\omega_{ce}$. In addition, one may want to beam the microwaves at some critical angle to optimize the $k_\parallel$ spectrum for the 0-mode of propagation (although a spread in the $k_\parallel$ spectrum will automatically be introduced due to the finite launching horn-size).

B. Experimental Results

The only experimental results to date on ECRH heating of tokamaks have been obtained in the TM-3 tokamak [11]. In these experiments, the frequencies used were in the range $f \approx 35\text{-}65$ GHz, and the power was injected by open ended waveguides. At low densities ($n < 10^{13}$ cm^{-3}) most of the energy ended up in a high energy tail. At high densities ($n \gtrsim 10^{13}$ cm^{-3}) efficient bulk electron heating was observed at both $\omega = \omega_{ce}$ and $\omega = 2\omega_{ce}$. To date heating at $\omega = \omega_{UH}$ has not been observed. Typical pulse lengths were $\Delta t \approx 1$ msec and maximum power levels at 70 GHz were $P \approx 60$ kW, which raised the peak electron temperature in the center of the discharge by as much as $\Delta T_e \approx 150$ eV. The maximum absorption efficiency for bulk electron heating in these experiments was estimated to be 30%. There has been experimental evidence that the electron energy confinement increased with electron temperature, at least in the range $T_e = 100$ to 500 eV. Whether these trends would remain at temperatures above a few keV, remains to be seen. In summary, while the mechanism of absorption was not determined, the initial ECRH results are encouraging, and we expect to see a big increase in the research activities in this regime. Whether enough CW power can be developed to heat large tokamaks to ignition by the use of ECRH alone remains to be seen. Nevertheless, one can consider ECRH heating to provide power for radial profile modification in order to improve MHD stability.

4. Lower-Hybrid Range of Frequencies

A. Theory

In the lower-hybrid range of frequencies we may consider heating at the lower-hybrid resonance frequency (or slightly above if temperature effects are included),

$$\omega_{\ell h} \simeq \omega_{pi}(1 + \omega_{pe}^2/\omega_{ce}^2)^{-1} \qquad (9)$$

by the process of mode-conversion into ion plasma (Bernstein) waves [13,17] or we may consider heating by electron Landau damping if $\omega > \omega_{\ell h}$ [18,19,20]. In both cases one assumes that the so-called slow-wave

$$\omega = \omega_{\ell h} \left(1 + \frac{k_\parallel^2}{k^2}\frac{m_i}{m_e}\right)^{1/2} \qquad (10)$$

is excited at the surface by a slow-wave structure, and the wave propagates inward along "resonance cones" (which are trajectories of the group velocity in the $\hat{z}$, $\hat{r}$ plane) [21-23]. Since the $k_\parallel$ spectrum is fixed by the slow-wave structure, $k_\perp \simeq k_r$ increases as the wave propagates radially inward until at r = 0, $\omega = \omega_{\ell h}(0)$ and $k_\perp \to \infty$. If hot plasma effects are included, the slow-wave converts into an ion plasma wave before the resonance layer, i.e. where

$$\omega \simeq 3k_\perp v_{ti}, \qquad (11)$$

and this ion wave then propagates outward. The ion wave is either absorbed by "ion-landau" damping in the inhomogeneous magnetic field [24,25] or is soon converted once more into an ion-Bernstein wave which then propagates back toward the center and is absorbed by harmonic-ion-cyclotron damping at the next exact cyclotron harmonic layer [13]. The accessibility conditions is roughly [17]

$$n_\parallel^2 > 1 + \omega_{pe}^2/\omega_{ce}^2\Big|_{Res} \qquad (12)$$

where $n_\parallel = ck_\parallel/\omega$ is the index of refraction, and the right-hand-side is to be evaluated near the resonant layer. When such a layer is not present in the plasma, a more exact accessibility condition must be satisfied, namely

$$\omega_{pi}/\omega = n_\parallel y \pm \sqrt{1 + n_\parallel^2(y^2 - 1)} \qquad (13)$$

where $y^2 = \omega^2/\omega_{ce}\omega_{ci}$. Equation (13) is especially important when one considers an inhomogeneous plasma, or when one desires to heat by electron Landau damping. In the latter case, one relies on the fact that if the $k_\parallel$ spectrum is "tailored" so that in the outer layers of the plasma

$$c/v_{te} \gg 3n_{\parallel} \,, \qquad (14a)$$

and near the center

$$c/v_{te} \approx 4n_{\parallel} \qquad (14b)$$

then absorption occurs near the center (where $v_{te}^2 = (T_e/m_e)$). In fact, in a hot plasma (i.e. $T_e \gtrsim 10$ keV) it may be difficult to satisfy Eqs. 13 and 14a simultaneously, and at these temperatures we may have to abandon the slow wave as a useful means to deliver the rf energy to the core of the plasma column. However, one could then use the whistler mode (fast wave) and rely on electron Landau damping for absorption [25]. Alternatively, sufficiently strong rf fields could flatten the distribution function and allow penetration [19,20].

Because the path of wave-penetration is long, (typically $L_z \approx (m_i/m_e)^{1/2}\, a$, where a is the plasma radius and L_z is the path length along the magnetic field) nonlinear effects in the outer plasma layers are particularly dangerous, especially parametric instabilities, solition formation, and scattering by drift wave fluctuations [27,28]. Again, some of these phenomena were discussed in our recent review paper and we shall not discuss them here. We note, however, that in addition to parametric effects [27,28] stochastic rf fields could also play an important role in nonlinear ion heating [29].

B. Summary of Lower-Hybrid Experimental Results

In recent years there have been several large-scale lower hybrid experiments performed in tokamaks, and some of these investigations are still going on at the multi - 100 KW level [30-32]. The great interest in this regime arises from the particularly advantageous technological aspects of LHRF heating, namely that one can use phased-arrays of waveguides mounted in ports as sources of the microwave power [33,34]. It has been shown recently that such a "grill" structure behaves as a slow-wave structure [35], and the theoretical work of Brambilla [34] allows one to design grills for different machine parameters (the "Brambilla code"). In addition, ample power sources are available, or can be built upon demand, with frequencies up to 10 GHz. In most cases one would use f ≈ 1-5 GHz for the frequency. The most recent experiments at the lower hybrid frequency were carried out on the Princeton ATC tokamak at f = 800 MHz where 2 waveguides phased $0,\pi$, were used as a phase-array system [30,31]. At Grenoble in the Wega experiment loops phased appropriately are being used to inject the rf power at 500 MHz [32]. In preparation at present is the general Atomic Doublet II experiment where a slotted slow wave structure will be used to launch waves at $\omega > \omega_{\ell h}$, and heating by Landau damping will be attempted. At MIT, preparations are under way for a 100 kW split waveguide experiment on Alcator A.

From the past experiments the following conclusions may be drawn:

a. The phased array grill works as predicted by the Brambilla theory; namely, while in a single waveguide most of the power is reflected, in at least 2 waveguides driven out of phase $(0,180^o)$ the reflection was reduced to about ten percent, as predicted by theory. In particular, no tuning elements were needed, which is an important technological advantage of this type of coupling system. In the future four (or more) waveguide grills will be used.

b. Perpendicular charge-exchange results are similar in both Wega and ATC; namely, upon application of $P \simeq 100$ kW, typically $\Delta T_i \simeq 100$-150 eV increase was observed.

c. While in ATC parallel charge-exchange measurements were inconclusive, in Wega good agreement with the perpendicular measurements were obtained.

d. Doppler-broadening measurements of OVII, CV and CIV impurities showed similar results in both ATC and Wega. In particular, while the CIV measurements (which represent T_i near the edge) showed little or no heating, the OVII on CV lines showed good heating, although typically less than the perpendicular charge-exchange measurements indicated (i.e. $\Delta T \simeq 50$-100 eV).

e. While in ATC the density increase did not exceed 10%, in Wega in some cases a density increase of 50% (or more) was observed.

f. The total energy absorbed by the bulk of ions was difficult to estimate; however under reasonable assumptions 15-20% could be accounted for by bulk-ion heating.

g. In ATC a definite threshold power and density for heating was observed [31]. In particular, as the density was decreased, the threshold power increased from $P \simeq 10$ kW to $P > 100$ kW, until neither parametric decay (monitored by a probe at the plasma edge) nor plasma heating were observed. From a theoretical analysis it was concluded that in ATC the heating took place at $(r/a) \simeq 0.3$-0.5 when $1 \lesssim \omega_o/\omega_{\ell h} < 2$. In Wega heating was studied only when $1 \lesssim \omega_o/\omega_{\ell h} \lesssim 1.3$.

h. More recently, in Wega heating of electrons was also observed [36]. It is not clear, however, whether such an electron heating was due to impurities or direct heating by the pump wave, or by the parametric decay waves.

We also note that in addition to bulk ion heating an energetic perpendicular ion tail was also observed, with a life-time of 50-100 μsec. It was concluded that this ion tail was produced on the surface of the plasma. Similarly, an increase in soft and hard x-rays were also observed.

In summary, while the initial results are encouraging a clear understanding of the physics of LHRH is not yet available. In particular, the fate of the rf power-flow is not understood, and clearly more experimental work is required.

5. Ion Cyclotron Range of Frequencies (ICRF)

A. Theory

Heating near the ion-cyclotron frequency may be done via the slow wave near $\omega \approx \omega_{ci}$ or the fast wave near $\omega \approx \omega_{ci}$ [37-40]. In tokamaks the most important regime is $\omega \approx 2\omega_{ci}$ and heating is achieved by the small left-hand component of the fast wave (magneto-acoustic wave). The slow-wave is expected to mode-convert near the tokamak surface, and it may be used mainly in heating stellarators. The dispersion relation for fast waves is given by the following expression [40,41]:

$$\frac{\omega^2}{V_A^2} = \left(\frac{\pi\nu}{a}\right)^2 + \left(\frac{\omega+\omega_{ci}}{\omega_{ci}}\right)\left(\frac{N}{R}\right)^2 \qquad (15)$$

where

$$V_A = B/[4\pi n(m_e+m_i)]^{\frac{1}{2}} = (\omega_{ci}/\omega_{pi})c$$

is the Alfven speed, R is the major radius, a is the minor radius, and

$$\nu = \mu + |M/2|$$

and where μ, M, and N are integers. In particular, ν is the "perpendicular" wave number consisting of the radial mode number μ and the poloidal mode-number M, and $N/R \approx k_\parallel$ is the toroidal mode number. The important prediction of Eq. 15 is that fast-wave propagation is possible only if the density and radius is such that $\nu \gtrsim 1$, $N > 0$, and Eq. 15 becomes

$$na^2 > \left(\frac{\pi^2 B^2}{4\pi m_i\ \omega^2}\right) \approx 5\text{x}10^{15}\left(\frac{m_i}{m_{iH}}\right)\left(\frac{\omega_{ci}^2}{\omega^2}\right)\text{cm}^{-1} \qquad (16)$$

Thus, fast wave propagation demands sufficiently large and dense devices, especially if $\omega < \omega_{ci}$ is desirable. The heating rates are given by the following expressions [42]:

a. $\underline{\omega \approx \omega_{ci}}$

$$P = \frac{1}{4\pi\omega_o}\ \frac{\omega_{pi}^2}{c^2}\ \frac{R}{a}\ |E^+|^2 \qquad (17a)$$

We notice that since in a single ion-species plasma $E^+ \to 0$ at $\omega = \omega_{ci}$, the power absorbed, $P \approx 0$. However, in a two-ion species plasma this is no longer so.

b. $\omega \approx 2\omega_{ci}$

$$P = \frac{\beta_i c^2}{16\pi\omega} \frac{R_o}{r} |E^{+'}|^2 \qquad (17b)$$

where $E^{+'} = \nabla_{r,\theta} E^{+}$ is the gradient of E^{+}, and $\beta_i = 8\pi n T_i / B_\phi^2$ is the ion "beta". We note that while Eq. 17b predicts weak absorption in present tokamaks, in future high density, hot tokamaks the absorption is expected to be efficient.

c. Heating by Electron-Landau Damping

This has been calculated by Stix [40,41], and again, in hot tokamaks it is expected to be an efficient absorption process, while in machines with $T_e \lesssim 1$ keV it is a rather weak process. An advantage of this process is that it allows operation at $\omega < \omega_{ci}$, where it can be considered a type of "Alfven wave heating" (rather than ICRF).

d. Cavity Modes

Once the fast wave propagates, it is possible to set-up standing waves around the major circumference of the torus, the condition being $k_\parallel L_z / 2\pi \approx$ integer. This allows setting up modes with relatively large values of the "quality factor", Q. Since the power absorbed depends on the coil impedance R_M, and is given by in terms of the current I, by

$$P = \frac{1}{2} I^2 R_M \qquad (18)$$

it turns out that relatively large values of Q allow efficient power absorption for acceptable values of the RF voltage (namely, R_M depends on Q, and I_{max} is limited by voltage breakdown). Thus, if cavity modes are excited it is desirable to "lock onto" one mode and "stay with it" during the rf pulse. However, since

$$Q = (\omega_o/\Delta\omega) \propto 2n_o/\Delta n \qquad (19)$$

where $(\Delta n/n_o)$ is the fractional density change, we see that as the density changes in time one jumps from one mode to the next, and a feedback system may be necessary to track the mode. This is a rather difficult technical task if many modes are present in the system. In fact, in a reactor size plasma hundreds of modes may be excited as it will no longer be feasible to track modes [41]. One may have to consider then the effects of the rotational transform also [43].

e. Impurities

Recently a number of authors discussed the effects of even a few percent of impurities present in the plasma upon the fast wave propagation [38,44,45]. For example, a few percent of hydrogen present in a deuterium plasma presents an H^+ fundamental resonance ($\omega = \omega_{ci}(H^+)$) when $\omega = 2\omega_{ci}(D^+)$ which may provide a mechanism of efficient power absorption by the H^+ minority rather than the D^+ majority species. Absorption by H^+ leads to a large and fast H^+ tail which will have to be confined and its energy transmitted to D^+ by slow collisions. Additional problems may be created by setting up an ion-ion hybrid resonance layer near the plasma edge which may lead to mode conversion and large damping near the edge. Additional enhanced absorption near the ion-ion hybrid layer may also be due to large gradients in E^+ between the cyclotron and the hybrid layers [45].

B. Experimental Results

Experimental results on ICRF heating of tokamaks have been obtained in the past in a number of devices, and further experiments are planned on the TFR device in France and the PLT device in Princeton, USA. In particular, the following is a brief summary of the main features of these experiments.

a. On the Princeton ST device the ICRF experiment showed ion heating, but there were also impurity problems present [46]. In particular, the impurity level increased with injected energy. When the total external rf energy exceeded the plasma thermal energy, namely $\Delta t P_{RF} \gtrsim nkT \approx 200$ Joules, disruption occurred [46]. These results were blamed on bad banana orbits and fast particles hitting the wall.

b. On the Soviet TM-1-VCH device efficient heating of an energetic H^+ tail was detected (rather than heating of D^+) when an $\omega \approx 2\omega_{ci}(D^+)$ heating experiment was carried out [47].

c. Coupling experiments carried out at low powers in the French TFR device showed lower-Q values (by one to two orders of magnitude) than predicted by theories which ignored impurity effects [48]. Again, the importance of small amounts of impurities were blamed for the results, especially in D_2 plasmas.

d. The Princeton ATC experiments showed the best ion heating to date using ICRF power near $\omega \approx 2\omega_{ci}(D^+)$ [49]. In this experiment good bulk ion heating was obtained. In addition, a significant ion tail was also produced. However, it was not determined experimentally whether this ion tail consisted of deuterium or hydrogen. The maximum input energy was $P \lesssim 2$ kJ which was comparable to the thermal energy content of the plasma. At higher energies the m = 2 MHD mode was intensified and no experiments were carried out. The maximum heating efficiency was about 40%, and the energy absorbed by ions was comparable to that obtained by neutral-beam heating. The heating mechanisms in these experiments were not determined, and Q-measurements and their comparison with theory have not yet been published. In summary, the ATC ICRF experiments are most encouraging and further improvements can be expected in the forthcoming PLT experiments.

6. Alfven Wave Heating

A. Theory

This is the regime of low frequencies, such that $\omega < \omega_{ci}$, typically 100 KHz - 10 MHz in tokamaks. Two types of modes are of interest, namely the compressional Alfven wave ($\omega \simeq k_\perp v_A$) and the shear Alfven wave ($\omega \simeq k_\parallel v_A$). The compressional Alfven wave with a small component of $k_\parallel$ may be described by Eq. (15), and it may be used to heat electrons by Landau and transit-time damping in reactor size plasmas [41]. The frequency to be used is expected to be $\omega \simeq \omega_{ci}/10$, so that direct acceleration of 0^{8+} impurities may be avoided. The critical density may be set at

$$na^2 \gtrsim 5\times10^{17}\ \mathrm{cm}^{-1}. \qquad (20)$$

For example, a plasma column with $n \gtrsim 5\times10^{13}$, $a \simeq 100$ cm would satisfy this condition (such as the forthcoming TFTR device at PPL). The damping rate and power absorption is given by Stix as follows [40,41]:

$$P = |E_0|^2 \frac{\omega\beta_e}{16\sqrt{\pi}} \left(\frac{k_\perp c}{\omega}\right)^2 \frac{\omega}{k_\parallel v_{te}} \exp\left(-\frac{\omega^2}{k_\parallel^2 \bar{v}_{te}^2}\right) \qquad (21)$$

where $\beta_e = 8\pi n_e T_e/B_\phi^2$ is the total beta of electrons, $\bar{v}_{te}^2 = 2T_e/m_e$ and E_θ is the electric field intensity. (We note that Eq. (21) may be used both at $\omega < \omega_{ci}$ and $\omega_{ci} < \omega < 2\omega_{ci}$.) Since the damping is weak, high Q-values may be established for one or two cavity modes which may then be tracked by a feedback system. In particular, by lowering the frequency the number of modes in reactor-size plasmas can be lowered by orders of magnitude from the ICRF regime.

In the case of the shear Alfven wave one would use a coil structure such that the resonance

$$\omega \simeq k_\parallel(r)\cdot v_A = \left(\frac{m}{r} B_\theta + k_z B_z\right)/4\pi\rho \qquad (22)$$

would be achieved at some radial position, r. Then a mode conversion into short wavelength electrostatic waves may take place [50] or MHD multi-spectral absorption may take place [51], both leading to absorption of the energy. In particular, in the mode-conversion model [50] the converted wave would have to travel around the torus once or twice (similarly to the lower-hybrid wave) and absorption by collisional, Landau, or parametric effects may take place.

B. Experimental Results

There are to date two experiments where shear-Alfven wave heating have been studied: (a) In proto-cleo at Wisconsin a doubling of T_i and T_e was observed when a power of $P \approx 10$ kW was applied in an initial low density plasma with temperature $T_e \approx 10$ eV [52]. However, after the heating strong "pump-out" was observed in this device. (b) In the Heliotron-D torsatron at Kyoto the following results were obtained [53]: applying a power of $P \approx 400$ kW, T_e changed from 150 eV to 300 eV and T_i changed from 20 eV to 50 eV. A maximum heating efficiency of about 30% was observed. The physical mechanism responsible for the heating remains unclear.

7. Transit Time Magnetic Pumping

A. Theory

This technique has been studied years ago extensively by Canobbio at Grenoble [54]. The electron TTMP is similar to the compressional fast wave heating proposed by Stix more recently, namely toroidal eigen-modes are set up and absorption takes place by modulation of the magnetic field. The power absorption is given by

$$P/\mathrm{vol} \approx \frac{3}{2}\, nT \,\frac{v_{te}}{R} \left(\frac{\tilde{B}}{B_o}\right)^2 \qquad (23)$$

where R is the major radius, and $\tilde{B}$ is the modulated magnetic field intensity. Electrons are preferentially heated since $\omega/k_\parallel \approx v_{te}$ is set up by the coils. Frequencies contemplated are typically $f \approx$ 1-10 MHz. On the other hand, ion TTMP relies on forced (evanescent) rf fields such that $\omega/k_\parallel \approx v_{ti}$, and since $v_{ti} \ll v_A$ the mode is evanescent. Here ions are preferentially heated, and frequencies of the order of $f \gtrsim 100$ KHz are contemplated.

B. Experiment

The only results to date have been obtained by using ion TTMP on the Petula tokamak at Grenoble [55]. This experiment confirms the predictions of theory, namely good bulk ion heating has been obtained $(\Delta T_\perp \sim \Delta T_\parallel \sim T_i/2)$ with $(\Delta\tilde{B}/B) \approx 0.015$ without major disruption or impurity problems. In particular, the results were in agreement with theoretical predictions, and scaling should improve with larger machine size.

8. Very Low Frequency Heating

This case was studied originally by Schlüter in the 1950's and the main absorption mechanism considered was due to ion-ion collisions [56]. The absorption-rate obtained is given by

$$\nu_h \approx \frac{\nu_i}{8} \left(\frac{\Delta\tilde{B}}{B}\right)^2 \frac{\omega^2}{\omega^2+\nu_i^2} \qquad (24)$$

where $(\Delta\tilde{B}/B)$ is the modulation depth. The advantage of this heating technique is due to the possibility of using a few kHz for the frequency so that the rf coils could be placed outside the vacuum chamber. However, since we expect that $\omega \lesssim \nu_i$, we see that in order to obtain absorption rates comparable to the ion collision frequency one needs $\Delta B/B \approx 1$, which is energetically not practical.

More recently Canobbio proposed that the efficiency of this type of magnetic pumping could be improved by coupling to a low-frequency resonance, for example that due to the ∇B drift, and in that case considerable improvement over Eq. 24 could be obtained [4]. This work is still in progress and preliminary indications are that significant heating (i.e. $\Delta T/T \approx 1$) may be obtained by modulation depths of $\Delta B/B \approx 0.1-0.2$.

9. Summary and Comments

It is clear that the physics of rf heating is complicated, and there are still too few experimental results available. However, it appears that in the available experiments efficiencies of 20-40% have been obtained (where by efficiency we mean $\eta = \Delta(nT)/P(\text{incident})$. Furthermore, in many cases improved efficiency is expected with larger machine size and hotter target plasma, and theoretically efficiencies of $\eta \approx 60-70\%$ appear achievable. The efficiency of rf power generation is good, typically 30-70%, and thus technologically speaking rf heating is attractive for the purposes of reactor-grade plasma heating. More experiments are clearly needed in order to learn more about the physics of wave penetration, heating and impurity problems. Finally, more materials research will be necessary to solve the problem of coil shielding at low frequencies. Since at present no clear "winner" is apparent, experiments in all frequency regimes should be vigorously pursued.

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FIGURE CAPTION

Fig. 1) A schematic representation of an rf heating system.

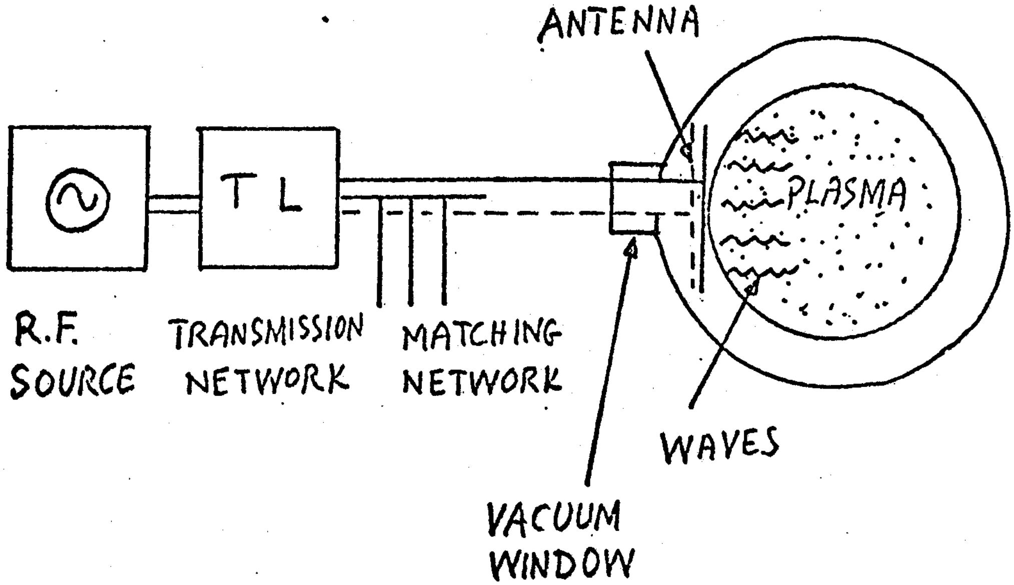
ANTENNA
T L
PLASMA
R.F. SOURCE
TRANSMISSION NETWORK
MATCHING NETWORK
WAVES
VACUUM WINDOW

Fig. 1

B(0) (Tesla)	$\overline{n}$ (cm^{-3})	a (m)	R (m)	τ_E (sec)	ΔT (keV)	V cm^3	ΔP (MW)
4	$1x10^{14}$	2	8	2	10	$6.4x10^8$	125
6	$4x10^{14}$	1	4	2	8	$8x10^7$	54
15	$1x10^{15}$	0.2	0.5	0.2	5	$4x10^5$	4

Table 1

Examples of Hypothetical Tokamak Parameters Near Ignition Conditions

B = Toroidal magnetic field; $\overline{n}$ = average density; a = minor radius; R = major radius; τ_E = energy confinement time; $\Delta T = \Delta T_e = \Delta T_i$ = temperature increase needed to achieve ignition (assuming that the ohmic heating contribution will be negligible); V = plasma volume; ΔP = power absorbed to achieve the ΔT indicated.

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1. Bulk plasma heating
2. Tail-Heating for a 2-component tokamak
3. Radial temperature profile modification
4. Measurement of the transport coefficients by local heating
5. Feedback control
6. De-trapping of trapped particles
7. Enhanced dc resistivity
8. DC currents due to quasi-linear effects
9. RF plugging of mirrors
10. Density build-up
11. RF confinement.

Table 2

Possible Roles for RF Heating

Nature (Type)	Characteristic Frequency	Coupler	Sources	Comments (CW sources)
Electron Cyclotron Resonance (ECRH)	$f_{ce}, 2f_{ce}, f_{uh}$ ~100 GHz	Waveguide or horn	Gyrotron	Presently available: $P \lesssim 200$ kW, $f = 28\text{-}65$ GHz Next 3 years $P \approx 200$ kW, $f \lesssim 100$ GHz
Lower Hybrid Range of Frequencies (LHRF)	$f_{Lh} \gtrsim f_{pi}$ ~1-8 GHz	Waveguide Array (grill)	Klystrons	Presently available, 0.25-0.5 MW/tube, 1 MW possible, CW
Ion-Cyclotron Range of frequencies (ICRF)	$f_{ci}, 2f_{ci}$ 50-100 MHz	Coils (Ridged waveguides may be possible)	Tubes	Presently available, 0.5-1 MW
Alfven wave: shear or compressional	$f < f_{ci}$ 1-10 MHz	Coils	Tubes	MW-S
Transit time magnetic pumping (TTMP) – electron or ion	0.1-1 MHz	Coils	Tubes	MW-S
Very low frequency (VLF)	1-10 kHz	Coils outside chamber	Generator	MW-S

Table 3