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PLASMA HEATING AND THE IGNITION PROBLEM

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Abstract. — The paper deals with the various plasma heating methods which can be used to overcome the limitations of Ohmic heating in order to achieve ignition in low-\(\beta\) toroidal systems.

The overall power balance equation of a « neoclassical » plasma is discussed without and with the addition of a given amount of supplementary power. Then attention is directed to a) Adiabatic Compression, b) Neutral Beam Injection, and c) slow HF-plasma interactions, leaving aside those fast processes like Shocks, Turbulence, Intense HF-Fields, Relativistic Electron Beams, Lasers, which are obviously impracticable in large energetic low-\(\beta\) toroidal systems. The most interesting HF Heatings are, in order of increasing frequency: Transit Time Magnetic Pumping, Ion Cyclotron Absorption (in 2 versions) and Heating at the Lower Hybrid Resonance. For each method we briefly explain the basic physical mechanisms involved and point out the important aspects which remain to be clarified.

1. Ohmic heating and the ignition problem. —

A feasibility test of the ignition process in low-\(\beta\) toroidal devices (Tokamaks and Stellarators) requires a substantial improvement of the plasma parameters compared to those of present day facilities. This is shown in the following table, where \(T_i\) is the ion temperature, \(n_e\) the plasma density, and \(\tau_E\) the energy confinement time.

<table>
<thead>
<tr>
<th>Present Devices</th>
<th>Ignition Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>(T_i)</td>
<td>several 100 eV</td>
</tr>
<tr>
<td>(n_e)</td>
<td>(\approx 10^1) cm(^{-3}) s</td>
</tr>
<tr>
<td>(\tau_E)</td>
<td>(\approx 10^{13}) cm(^{-3}) s</td>
</tr>
</tbody>
</table>

Such a progress apparently depends on:

\(a)\) increasing the toroidal current \(I_p\) from a few 100 kA to a few MA (in Tokamaks, \(I_p\) is the plasma current, in Stellarators, \(I_e\) is an equivalent external current);

\(b)\) increasing the plasma volume \(V\) by a factor of about 30 by keeping constant the aspect ratio \(R/a\approx 4-3\) (\(R\) is the major radius, \(a\) the minor radius of the plasma). The toroidal magnetic field necessary to have plasma stability can be \(\approx 50\) kG also in an Ignition Experiment, but it must be \(\approx 100\) kG in a full scale reactor;

\(c)\) applying auxiliary (non-ohmic) heating methods since the power released by classical ohmic heating

\[ P_{\text{OH}} \approx (R/a)^2 I_p^2/\rho_{\text{OH}} T_e^{3/2}, \]  

is limited to a few 100 kW both in present devices and in the much larger ignition experiments.

In order to see 1) whether ohmic heating is by itself sufficient to achieve ignition, and 2) what is the effect of the addition of a given amount of supplementary power, \(P_H\), we consider the overall power balance equation [1]:

\[ P_D + P_s + P_H = P_{br} + P_{ne} + P_{sy}, \]
where \( P_a \) is the thermonuclear power input from alpha-particles
\[
P_a \sim n^2 T_e f(T_e),
\]
\( P_{Br} \) is the Bremsstrahlung loss
\[
P_{Br} \sim n^2 T_e^{1/2},
\]
\( P_{ne} \) is the loss due to ion thermal conduction as given by the «banana» model of the neoclassical theory:
\[
P_{ne} \sim \left( \frac{\alpha}{R} \right)^{5/2} \frac{R}{I_p} \frac{n^2 T_e^{1/2}}{P_{Br}},
\]
\[
(\text{therefore,} \quad P_{Br} > P_{ne} \text{ if } I_p \geq 3 \text{ MA},) \quad \text{and} \quad P_{sy} \text{ is the loss by synchrotron radiation.}
\]
Since
\[
P_{sy} \approx \sqrt{n} T_e^2
\]
synchrotron loss turns out to be relatively unimportant unless \( T_e \gtrsim 10 \text{ keV} \) and \( n \lesssim 2 \times 10^{13} \text{ cm}^{-3} \).

If we assume \( T_e = T_i = T \), and define the self-sustaining temperature \( T_o \) by the equation
\[
P_a = P_{Br} + P_{ne},
\]
we find that \( T_e \) depends on \( I_p \) only and \( T_e \lesssim 10 \text{ keV} \) if \( I_p \gtrsim 2 \text{ MA} \). Then, if we define the temperature \( T_0 \) which can be reached by ohmic heating
\[
P_\Omega = P_{Br} + P_{ne}
\]
we find
\[
T_0 \sim \frac{I_p}{n} (1 + P_{ne}/P_{Br})^{-1/2}.
\]
Considering the \( T-n \) plane (keeping \( I_p \) constant) one could prove that:

a) by straining every assumption to its most optimistic limit (e.g., absence of any impurities) the \( T_0 \)-curve is connected with the \( T_e \)-curve, i.e., ignition by ohmic heating alone is possible, but only at a density value of \( \sim 3 \times 10^{13} \text{ cm}^{-3} \), which is one order of magnitude smaller than the operating density of a reactor. Then, alpha-particles heating could be used to bring freshly injected gas up to the ignition temperature as the plasma density is slowly raised;

b) under reasonable assumptions, even modest amounts of added heat (several 100 kW) can introduce impressive changes in Tokamaks and Stellarators of high performance, and can greatly simplify the ignition of a reactor plasma at low density;

c) larger amounts of added heat (10-100 MW) are necessary to make ignition possible at full operating density.

Concerning point a) we should keep in mind, however, that at a density of \( \lesssim 3 \times 10^{13} \text{ cm}^{-3} \) and a temperature \( \approx 10 \text{ keV} \), the energy confinement time is as large as 10 s or \( \gtrsim 10^4 \tau_B \), where \( \tau_B \) is the Bohm diffusion time. This seems to imply extremely small plasma fluctuation levels and/or magnetic field asymmetries. It is worthwhile to mention that in all present devices \( \tau_E \lesssim 300 \tau_B \). Measurements made in Princeton on the FM-1 hard-core device show [2] that \( \tau_E \sim T_e^{1/2} \) according to neo-classical law only below some critical temperature and that
\[
\tau_E \sim 1/T_e \simeq (150-300) \tau_B
\]
above this temperature!

Finally, we notice that there seems to be little hope to enhance the plasma resistivity in a substantial fraction of the plasma volume over the purely collisional value used in eq. (1), for example as a result of current driven micro-instabilities. As a matter of fact, the ratio between the mean drift velocity of the current carrying electrons and the sound speed is proportional to \( (a \sqrt{n})^{-1} \) and will be well below 1 for plausible ignition parameters.

The fundamental weakness of ohmic heating in bringing Tokamaks to ignition serves to keep attention directed to:

a) adiabatic compression,

b) neutral beam injection,

c) slow HF-interactions,

as alternative heating mechanisms.

Fast heating processes like shocks, turbulence, intense HF-fields, which are at present probably the cheapest and most flexible ways to produce kilojoules of plasma energy, imply, when approaching reactor parameters, exceedingly expensive energy storage and enormous technical difficulties. On the other hand, Relativistic Electron Beams (which can deliver as much as \( 10^5 \text{ J} \) to a target) cannot be introduced in large toroidal traps for they are just designed to be successfull in preventing charged particle motion across the magnetic surfaces.

2. Adiabatic Toroidal Compression (ATC). — Three magnetic field components are needed to maintain equilibrium and stability of a Tokamak: the toroidal component \( B_t \), the poloidal component \( B_p \), and the vertical field \( B_v \). It has been shown [3] that the best way to compress a torus is to reduce \( R \) by varying \( B_e \) only. This must be made slowly compared with the collision time \( \tau_{coll} \), but fast compared with \( \tau_E \):
\[
\tau_E > \tau_{ATC} > \tau_{coll}.
\]
An ATC is a reversible transformation whose scaling laws follow immediately from the assumption that the plasma is an ideal gas
\[
T/n^{2/3} = Cte,
\]
with infinite electric conductivity, which implies magnetic flux conservation
\[
\pi \alpha^2 B_i = Cte, \quad 2 \pi RaB_p = Cte.
\]
Then, 
\[ a^2 \to R; \quad n \to R^{-2}; \quad T \to R^{-4/3}; \]
\[ I_p \to R^{-1}, \quad \text{etc...} \quad (11) \]

Notice that \( P_{A} \to \text{Cte.} \)

The Princeton ATC-device [4] has proved the efficiency of this method by compressing a plasma with 
\[ R_i = 90 \text{ cm}; \quad a_i = 17 \text{ cm}; \]
\[ B_i = 20 \text{ kG}; \quad I_p \gtrsim 60 \text{ kA} \]
to a final position \( R_2 \approx 38 \text{ cm}, a_2 = 11 \text{ cm}. \) The results are
\[ (nT)_2 \approx 16(nT)_1; \quad T_{i2} \gtrsim 600 \text{ eV}; \]
\[ n_2 \gtrsim 10^{14} \text{ cm}^{-3}; \quad I_{p2} \approx 2.4 I_{p1}, \]
which agree with the ATC laws (11), while the electron temperature is only \( T_{e2} \sim 2.5 \text{ keV} \) since \( \tau_{\text{ATC}} > \tau_{\text{Be}}! \)

From laws (11) and eq. (1), (4) and (5) one can show that a fourfold improvement of \( nT \) by ATC as compared to the \( nT \) attainable by simple ohmic heating directly at the same \( R_2 \) position, can only be obtained if \( P_{Br} > P_{Ne}. \) Otherwise an adiabatic compression is of minor advantage.

An ATC ignition experiment would require \( R_1 \sim 5.5 \text{ m}, R_1/R_2 = 3, B_{i1} \approx 30 \text{ kG}. \) It would be say 3 times more expensive than a conventional device!

Finally we must keep in mind that the compressed stage of an ATC, could never correspond to the running parameters of a reactor since the average beta value inside the blanket would be too small. However, this process could compress up to ignition a small volume of plasma; then again alpha-particles heating could be used to bring freshly injected gas to ignition as the full volume which is available for the plasma is slowly filled.

3. Neutral Beam Injection (NBI). — Fast neutral atoms penetrate across magnetic surfaces, can ionize well inside a dense plasma, and then heat the plasma quite uniformly by ion-ion and ion-electron collisions. Small currents of fast neutrals produce at high temperatures more collisional heating than large currents of thermal electrons (responsible for the ohmic heating). Thus the equilibrium of the plasma is much less perturbed by NBI than by ohmic heating.

If the kinetic energy of the atoms
\[ E_0 = \frac{1}{2} m V_0^2 \gtrsim 30 \text{ keV}, \]
ionization takes place mainly on the plasma ions, and the ionization rate \( v_i \approx 6 \times 10^{-8} \text{ n (cm}^{-3}) \), is almost independent of \( E_0 \) and \( T. \) By imposing that the penetration length \( V_0/v_i \approx a, \) we find \( \frac{1}{2} m V_0^2 \sim (na) \) and
\[ E_0 \approx 25-50 \text{ keV for present day devices}, \]
\[ \approx 50-150 \text{ keV for an Ignition experiment}, \]
\[ \approx 1-5 \text{ MeV for a full density reactor}. \]

Since in all cases \( E_0 \gg T, \) NBI is really an heating process rather than a density source.

By comparing the ion slowing down forces due to the ions and the electrons of the plasma, one can prove that ions are heated primarily if \( E_0 \ll 40 \text{ T}, \) which is the case in present day devices but not in reactor plasmas. There the plasma ions are heated by electron-ion collisions in an equipartition time.

The equivalent neutral beam current \( I_{NB} \) required to double \( T_i \) in present generation devices turns out to be roughly the same as that required to ignite a reactor: for instance 500 kW at 50 keV gives \( I_{NB} = 10 \text{ A}, \) just as 30 MW at 3 MeV.

The following data are typical for the present effort in NBI in Tokamaks.

3.1 CLEO-TOKAMAK (UK): \( I_p \sim 60-80 \text{ kA}, \)
\[ P_{A} \sim 200 \text{ kW}. \] — 35 kW of 10-30 keV have been introduced during 40 ms into the plasma (and have been thermalized) from a 50 kW injector tangent to the magnetic axis. A 100 kW injector will be available in the next future.

3.2 ORMAK (USA): \( I_p \sim 150 \text{ kA}. \) — Two 125 kW, 30 keV injectors tangent to the magnetic axis are now assembled, one injecting parallel to \( I_p, \) the other antiparallel to \( I_p, \) \( T_i \) is expected to grow from 0.4 keV to 1 keV in 60 ms. Four such sources are planned for the next future.

3.3 TFR (France): \( I_p < 400 \text{ kW}. \) — In order to enhance \( T_i \) from say 2 keV to 5 keV in 200 ms, a number of Oak-Ridge units giving 11 A of 25 kW (300 kW) neutrals should be used. Lack of accessibility for tangent injection imposes injecting almost perpendicular to the magnetic axis.

3.4 An ignition experiment would require injecting 2 MW of neutrals from (7-14) units giving (280-140) kW at 50-100 keV during \( \sim 3 \text{ s!} \) These units will probably be not available in due time. On the other hand, the realization of NBI at the level required for ignition in a full density reactor represents a substantial extension of the existing technology. Areas for future work are: large-surface plasma sources, cooling techniques, larger electrodes, understanding space charge neutralization, higher energies, \( D^- \) beams.

Finally, we mention a number of physical effects associated with the interaction of neutral beams with a toroidal plasma. They are predicted by theory and deserve a detailed experimental study:

- Microinstabilities induced by the anisotropy of the particle velocity distribution function [5];
- Electric fields stemming from charge separation due to the large radial excursions of the injected ions [6];
- Nonambipolar radial flux of the plasma during injection [6]!
- Poloidal and toroidal rotations of the whole plasma torus [6].
Injecting pairs of tangent beams, parallel and anti-parallel to the plasma current \( I_p \), should be the NBI scheme which minimizes the plasma perturbation.

4. **High-frequency heating.** — MW-CW rf-power is already available from single units below say 3 GHz. In this frequency range there is a large variety both of waves which can exist in a magnetized plasma and of methods to excite them for the purpose of plasma heating. The useful frequency and wave length ranges, the corresponding heating process, and the available CW-power from a single unit are given in the following table, where \( v_{ci(e)} \) is the ion (electron) thermal speed, the subscript \( \parallel \) refers to the lines of force, \( v_{pi(e)} \) is the gyrofrequency, \( v_{pe(e)} \) is the Langmuir frequency, and \( v_{Li} \) is the lower hybrid frequency (see below).

<table>
<thead>
<tr>
<th>Frequency ( v )</th>
<th>Wave length ( \lambda )</th>
<th>Heating frequency</th>
<th>CW-rf power</th>
</tr>
</thead>
<tbody>
<tr>
<td>150 kHz</td>
<td>2 km</td>
<td>ion TTMP</td>
<td>( \gtrsim ) 5 MW</td>
</tr>
<tr>
<td>10 MHz</td>
<td>30 m</td>
<td>Electron TTMP</td>
<td>&gt; 1 MW</td>
</tr>
<tr>
<td>50-150 MHz</td>
<td>6-2 m</td>
<td>ICH</td>
<td>1 MW</td>
</tr>
<tr>
<td>1-3 GHz</td>
<td>30-10 cm</td>
<td>LHRH</td>
<td>0.5 MW</td>
</tr>
<tr>
<td>( \gtrsim 100 \text{ GHz} )</td>
<td>( \lesssim 3 \text{ mm} )</td>
<td>Electron heating</td>
<td>( \lesssim 3 \text{ kW} )</td>
</tr>
</tbody>
</table>

Above \( v \sim 30 \text{ GHz} \) the available power decreases as steeply as \( \sim 1/v^9/2 \).

The most convenient value of the heating time \( \tau_H = T/(dT/dr) \) satisfies the two conditions

\[
\tau_{\text{coll}} < \tau_H < \tau_E
\]

the first of which is necessary in order to preserve thermal equilibrium. In present day devices \( \tau_H \lesssim 10 \text{ ms} \), while with reactor parameters \( \tau_H \lesssim 1 \text{ s} \).

The most appropriate processes which increase the internal energy of the plasma are the linear wave-particle resonant interactions occurring when

\[
v - nv_e = v_{\|}/\lambda_{\|}, \quad n = 0, \pm 1, \pm 2, \ldots
\]

(13)

since they are efficient even at low EM-field amplitudes. In order to have power transfer from the wave to the plasma, there must be more particles with \( v_{\|} < v_{\text{res}} \) then particles with \( v_{\|} > v_{\text{res}} \). Therefore:

\[
\delta f/\delta v_{\|}(v_n = v_{\text{res}}) < 0.
\]

If \( n = 0 \), eq. (13) corresponds to Cerenkov absorption, if \( |n| = 1 \) to cyclotron absorption, and if \( |n| > 1 \) to harmonic cyclotron absorption. In the two last cases eq. (13) cannot be satisfied on the whole volume of the torus, but only within a shell of thickness \( \Delta x \) with

\[
\Delta x = n v_e R \approx v_{\|}/\lambda_{\|}
\]

(15)

around the cylindrical surface which is defined by

\[
v = n v_e (R).
\]

5. **Transit Time Magnetic Pumping (TTMP).** —

When \( n = 0 \), the most appropriate wave frequency for ion heating is

\[
v \simeq v_{ci}/\lambda_{\|} \ll v_{ci}/2 \pi \rho_{Li} = v_{ci}
\]

(17)

where \( \rho_{Li} \) is the ion Larmor radius.

Moreover, \( v_{ci} \ll v_A \ll c \) (\( v_A \) is the Alfvén speed) so that the dispersion relation of the EM-waves reduces to

\[
K_2^2 + K_2^2 = K_2^2.0(v_c^2/v_A^2) \approx 0,
\]

(18)

which corresponds essentially to an evanescent vacuum-wave (mainly magnetic). The radial attenuation is, however, irrelevant if \( |2 \pi \alpha/\lambda_{\|}| \ll 1 \). Since there is no wave propagation along the torus, we must put an array of 2 \( \pi R/\lambda_{\|}/2 \) rf-coils around the torus in order to have the EM-pump everywhere.

One can use 1) conventional meridional coils with \( \mathbf{J}_{\text{RF}} \perp \mathbf{B}_s \) (Fig. 1a) to create a compression \( \mathbf{B}_s \parallel \mathbf{B}_s \), or 2) toroidal coils with \( \mathbf{B}_{\text{RF}} \parallel \mathbf{J} \) (Fig. 1b) to create a vertical \( E_1 \)-field which is linked to a radial \( \mathbf{B}_r \)-field. The latter is the torsional TTMP first discussed in reference [7].

Finally there is within the plasma an electrostatic field \( E_{\|1} \sim T_e \), which ensures charge neutrality in spite of the preferential action of the pumping wave on the ions.

From single particle point of view, power absorption is determined by the energy equation in the drift approximation

\[
\frac{d}{dt} \frac{1}{2} m v^2 = \mu \frac{d B_{\|1}}{dt} + e V_{\|1} + e V_D E_{\text{tv}},
\]

(19)

where \( \mu \) is the magnetic moment and \( V_D \) is the (vertical) toroidal drift velocity. The first term on the
RHS of eq. (19) — the betatron term — gives the compressional TTMP, the second term is the electrostatic (Landau) contribution, the last term is responsible for the Torsional TTMP in toroidal geometry.

From the macroscopic point of view, power absorption is given by the equation for the internal energy [8]:
\[
\frac{d}{dt} \frac{1}{2} n m v^2 \approx - p \nabla \cdot \mathbf{v} \approx n T / \tau_H ,
\] (20)
where \( p \) is the pressure tensor and \( \mathbf{v} \) the fluid velocity.

If we plot the heating rate \( \tau_H^{-1} \) versus the collision frequency \( \nu_{\text{coll}} \), keeping constant the modulation rate
\[
b = |B_1| / |\nabla B_1| ,
\] (21)
we find that there are three different regimes (Fig. 2).

Collisions dominate in (A):
\[
\nu_{\text{coll}} > \omega \quad \text{and} \quad \tau_H^{-1} \approx \omega^2 b^2 / \nu_{\text{coll}} .
\] (22)

In range (B):
\[
\omega > \nu_{\text{coll}} > \nu_{\text{cr}} \approx \omega b^{3/2} \quad \text{and} \quad \tau_H^{-1} \approx \omega b^2
\] (23)
collisions are sufficient to prevent local distortions of the distribution function of resonant particles, but are few enough to make the collisionless linear theory to be valid.

In range (C):
\[
0 < \nu_{\text{coll}} < \nu_{\text{cr}} \quad \text{and} \quad \tau_H^{-1} \approx \nu_{\text{coll}} \cdot \sqrt{b}
\] (24)
collisions are insufficient to inhibit the nonlinear distortions of the distribution function but are essential in determining power absorption.

In range (B) a modulation \( b \approx \text{a few } 10^{-2} \) is necessary to double \( T_i \) in present day experiments, while \( b \approx 10^{-3} \) is enough to achieve ignition in large dense devices. In both cases the electric field at the meridian coils (radius \( R_0 \)) turns out to be 100-150 V/cm:
\[
E_{\theta(V/cm)} \approx T_D^{1/4} B_{(K)} (R_{(cm)}) \sqrt{\tau_H (s)}
\] (25)
(\( T_D \) is the deuterium temperature). A similar analysis in the case of electron TTMP would give 10 times larger \( E_{\theta} \) for the same \( \tau_H \) [9].

In moderate scale devices where we want to put into the plasma only 100-200 kW additional power, the power of the TTMP oscillator must nevertheless be as large as \( \sim 10 \text{ MW} \) because of the large rf-dissipation into rf-coils and conducting wall. A much better efficiency can be achieved in large dense plasma devices.

A recent experiment on Proto-Cleo (Culham Laboratory) [10], as well as a theoretical paper [11], indicates that in order to prevent enhanced plasma losses during the heating phase it is necessary to put electrostatic screening around the rf-coils.

To prevent shielding of the electro-magnetic fields, the rf-coils should be put inside the vacuum chamber. However, arcing and surface problems impose to insert between coils and plasma an rf-transparent liner which can be either an insulator or an all-metal structure cut parallel to \( \mathbf{B} \) [12].

The first ad hoc TTMP experiment will be performed in 1974 on the Petula-Tokamak of the Grenoble Laboratory.

6. Ion Cyclotron Heating (ICH). — The ion cyclotron wave (\( \mathbf{B}_1 \perp \mathbf{B}_2 \)) can propagate around a torus if \( \nu < \nu_{\text{cr}} \) and \( m = 1 \), where \( m \) is the poloidal angular wave number. Then, the wave can be excited in a small sector of the torus by using one single rf-coil structure. An excellent coupling to the plasma has been realized in Kharkov, by using the coil represented on figure 3a [13].

A satisfactory result has also been obtained on the ST-Tokamak in Princeton with a single rudimentary half-turn coil figure 3b [14]. In both cases heating of moderately dense \( \gtrsim 10^{13} \text{ cm}^{-3} \) plasmas was achieved.

However, ICH becomes inefficient in larger and denser plasmas since the electric field which rotates in the same sense as the ions is strongly screened by the plasma currents if
\[
K_\parallel^2 c^2 < \omega_{pi}^2 \quad \text{or} \quad \lambda_\parallel \gtrsim 2 \times 10^8 / \sqrt{n} (\text{cm}) .
\] (26)
On the other hand, $\lambda_0$ cannot be made arbitrarily small because $\delta$ (the rf-coil-plasma distance) cannot be made much larger than $\lambda_0/2\pi$, otherwise the rf-power incident on the plasma would be reduced by a factor

$$e^{-4\pi\delta/\lambda_0}.$$  \hspace{1cm} (27)

The efficiency of ICH can be increased substantially in a two-ion species dense plasma if

$$n_{1(\text{Res})} < 10^{-2}(n_1 + n_2),$$  \hspace{1cm} (28)

since then the electric field rotating with the resonant ions would penetrate easily into the plasma. Now the $E_\theta$ value at the coils becomes comparable with the $E_\theta$ value required for TTMP, for the same $v_{\text{th}}$ value. This method has not yet been tested experimentally.

7. Harmonic ion cyclotron heating. — The fast magnetoacoustic wave ($B_1 \parallel B_0$) propagates around the torus if

$$v \gtrsim v_{\text{th}}K_1 c/\omega_{pi}.$$  \hspace{1cm} (29)

The condition to have radial plasma eigenmodes is

$$K_\perp a \approx 2.4N, \hspace{0.5cm} N = 1, 2, ...$$  \hspace{1cm} (30)

Taking account of the ion Larmor motion, the field of an EM-wave as seen by the ion takes the form

$$e^{i(2\pi r-K_\perp x)} \approx e^{i(2\pi r-K_\parallel pl)} \cos 2\pi \nu_{ei}t \approx$$

$$\sim \frac{K_\parallel}{2} e^{i2\pi(r-v_{ei}t) + ...}$$  \hspace{1cm} (31)

Then, if $v = 2v_{ei}$, the ions experience a wave with $v = v_{ei}$ and $K \approx 2\omega_{pe}/c \sim \sqrt{n}$. The wave-particle interaction can be quite strong at high plasma density, and heating comparable with that of a two-ion plasma can be produced.

Incouraging preliminary results at low rf-power level have been obtained on the ST-Tokamak, where a MW-experiment is planned for Spring 1974.

We remark finally, that the ions which are preferentially heated at $v = 2v_{ei}$ have small parallel energy and mainly gain perpendicular energy. Therefore, they tend unfortunately to escape from the configuration via banana orbits.

8. Lower-Hybrid Resonance Heating (LHRH). — If $|n| \gg 1$ Harmonic Cyclotron Heating is inefficient unless the EM-field be strongly amplified within the plasma. Amplification of the radial component of the electric field does occur in a plasma near the surface where $K_\parallel/K_\perp \rightarrow \infty$

$$\frac{1}{v^2} = \frac{1}{v_{\text{LH}}^2} \approx \frac{1}{v_{ei}^2} + \frac{1}{v_{pl}^2 + v_{ei}^2}$$  \hspace{1cm} (32)

$$v_{pl}^2 \ll v_{\text{LH}}^2 < v_{ei}^2.$$  \hspace{1cm}

The EM-power penetrates from the outside up to the resonance surface if the parallel wave number satisfies the condition [15]

$$|K_\parallel| \gtrsim \frac{\omega}{c} \times 1.7.$$  \hspace{1cm} (33)

It is therefore necessary to place around the plasma column (if it is thicker than $\lambda_0/\nu_{ei}$) a slow wave structure at a distance

$$\delta \lesssim \lambda_0/2\pi.$$  \hspace{1cm}

With thermonuclear parameters, $\delta$ should be less than a few cm! From a large number of experiments all over the world, there is now increasing evidence of good coupling efficiency and heating at LHR. Heating in such experiments is probably due to some non-linear effect occurring when the field inside the plasma is amplified above some critical value, rather than to the linear interaction at $v \approx n\nu_{ei}$ (probably a parametric instability develops, wherein the pump wave decays into 2 other waves). A 100 kW-LHR Heating Experiment will be performed (1975) on the WEGA-Stellarator of the Grenoble Laboratory.
PLASMA HEATING AND THE IGNITION PROBLEM

References

A) General References on Plasma Heating and the Ignition Problem:


B) Special Topics: