Plasma Heating & Current Drive*
ELECTRON CYCLOTRON WAVES

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ABSTRACT

An introduction is given to plasma heating and current drive with electromagnetic waves in the electron cyclotron range of frequencies, with emphasis on application in tokamak plasmas. Propagation and absorption of these waves is generally well described by linear theory, a short overview of which is given. Electron cyclotron absorption is limited to regions of the plasma where the gyromotion of electrons is in resonance with the wave frequency and can be well localised, even in smaller experiments. Apart from being able to provide global heating and non-inductive current drive, ECRH and ECCD are therefore important tools to study and manipulate locally instabilities in the plasma which are electron temperature gradient or current driven. Important potential control applications in a reactor grade plasma include mode stabilisation to prevent disruptions, transport manipulation (e.g. to maintain burn) and correction of the bootstrap current profile. The use of EC waves in major tokamak experiments has in the past been restricted due to the lack of suitable sources. These sources are, however, now rapidly becoming available.

I. CHARACTERISTICS

Electron Cyclotron Waves only heat a single species (the electrons) directly. Ions are indirectly heated by collisions with the electrons and the ion temperature, T_i remains below (at low density) or equal to (at high density) the electron temperature, T_e. This feature excludes the use of ECRH alone to create a plasma in the hot ion mode, which mode has been successfully exploited in high fusion yield D-T experiments in TFTR and JET. In view of the relatively low density, the hot ion mode is less relevant for a reactor.

Heating is localised to the resonance layer(s) where the wave frequency is resonant with the fundamental or harmonic electron cyclotron frequency, $\omega_{ce}=eB/m_e$. Since the magnetic field in a tokamak varies roughly with 1/R, the resonance layer is a narrow layer in the radial direction, extending in the vertical direction. Relatively narrow wave beams with high power density can be injected (and even focused) and the interaction is localised to the intersection of the wave beam and the resonance layer. Heating and/or current drive can thus be well localised, even in smaller experiments. This makes a variety of detailed physics and plasma control experiments possible (manipulation of transport barriers, MHD mode stabilisation, heat pulse propagation etc.). The localisation can be varied by changing the magnetic field strength or by changing the direction in which the beam is launched. However, if single pass absorption is incomplete, the transmitted power is (mostly) reflected off the wall to be eventually absorbed at less well defined intersections with the resonance layer. In present day experiments complete single pass absorption is generally realised, especially when absorption is in the central regions of the plasma. Preferential heating of thermal or tail electrons is then possible, dependent on the direction of propagation. This is an important characteristic for current drive and for synergy applications with other heating and current drive systems.

The use of EC waves for heating and current drive in a reactor grade plasma is attractive because there is a smooth transition from vacuum propagation to plasma waves. The launching structure can therefore be relatively far from the plasma and there is no inherent introduction of impurities. Also, there is no problem with accessibility to central (or other) regions of the plasma. The power density can be very high (~100 MW/m^2, which can be further increased in vacuum) and the power can be transmitted to the plasma through waveguides or quasi optically. Neutron screening is relatively straightforward using simple mirror bends. On the other hand, to make full use of the specific advantages of EC waves, the development of variable frequency sources or the use of steerable launchers (mirrors) near the plasma is required. Also, ECW power is still relatively expensive. EC waves can provide efficient and reliable pre-ionisation and plasma start-up and a separate ECW system is considered for this purpose in ITER.

The theory of ECW propagation and absorption is well understood and experimentally verified. This can, however, not be said of all effects. There are, for instance, effects on particle and impurity transport which are not always understood but may be extremely useful in a reactor. EC waves can be used to influence the re-cycling at the wall. The use of EC wave systems has in the past been lagging behind other additional heating systems due to the lack of suitable sources. High power (MW), long pulse (many s), high frequency (>100 GHz) sources are only now becoming available and the full potential of ECW applications is still to be assessed.

II. THEORY

II.A. Modes

EC waves injected into the plasma will couple to the Ordinary mode and/or the eXtraordinary mode which have different polarisation[1]. For perpendicular (to the magnetic field direction) propagation the O-mode is linearly polarised with the wave electric field along B while the X-mode is elliptically polarised with $E_w \perp B$ (reducing to linear for $n_e \rightarrow 0$). For general oblique propagation both modes are elliptically polarised. The dispersion, accessibility and absorption characteristics are different for the two modes. Radiation injected into plasma will separate into O-mode and X-mode components which propagate and refract independently. During propagation the polarisation will change to conserve mode. It is generally important to offer a polarisation to the plasma which maximises coupling to one (and minimises coupling to the other) mode. The optimum polarisation for this varies with the angle of injection

II.B. Dispersion and propagation

Dispersion and propagation of EC waves is generally adequately described by the Appleton-Hartree cold plasma ($v_t/c << 1$) dispersion relation for the refractive index:

$$N_{O/X}^2 = 1 - \frac{\omega_{pe}^2}{\omega^2} \frac{2(\omega^2 - \omega_{pe}^2)}{2(\omega^2 - \omega_{pe}^2) - \omega_{ce}^2 (\sin^2\theta -/+ \rho)}$$

where $\rho^2 = \sin^4\theta + 4\left(\frac{\omega^2 - \omega_{pe}^2}{\omega\omega_{ce}}\right)\cos^2\theta$,

ω is the wave frequency (or rather $2\pi\nu$), ω_{pe} is the electron plasma frequency $\omega_{pe}^2 = {n_e e^2}/{\varepsilon_0 m_e}$, $\omega_{ce} = eB/m_e$ the fundamental electron cyclotron frequency (ν_{ce}=28 B(T) GHz) and θ the angle between the wave vector and the magnetic field. It is seen that as $n_e \rightarrow 0$, $N \rightarrow 1$ for both modes and there is a smooth transition to vacuum propagation. In plasmas with high T_e (~10 keV), a fully relativistic treatment shows some deviations, especially near X-mode cut-off, but for most ECRH/ECCD applications these deviations are not very important.

Analysis of the dispersion relation shows 2 branches for the X-mode (slow X-mode and fast X-mode) and a single one for the O-mode. For the O-mode there is a single cut-off (N=0) at $\omega=\omega_{pe}$, which constitutes a density limit. Note that the maximum density scales with ω^2. In early experiments at 28 GHz this density limit was very severe but at 140 GHz, a frequency which is now available, it is 2.4 10^{20} m^{-3}, a value which does generally not restrict operation. For the X-mode there are 2 cut-offs which vary with density as well as with magnetic field. For propagation perpendicular to the magnetic field:

$$\omega^{+/-} = +/- \omega_{ce}/2 + (\omega_{pe}^2+\omega_{ce}^2/4)^{1/2}$$

where ω^+ is known as the low density cut-off and ω^- as the high density cut-off. For oblique propagation these cut-offs are displaced. The expression is generally given for constant $N_{//}$:

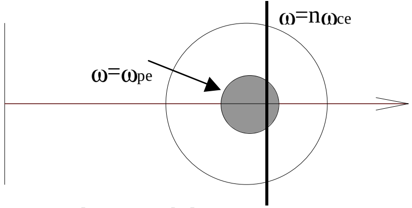
$$\omega^{+/-} = +/- \omega_{ce}/2 + (\omega_{pe}^2/(1-N_{//}^2) + \omega_{ce}^2/4)^{1/2}$$

For the X-mode there is also a resonance ($N = \infty$) at the upper hybrid frequency $\omega^2_{UH}= \omega_{pe}^2+ \omega_{ce}^2$

There are also fundamental and harmonic cyclotron resonances but these are not described by cold plasma theory since they are a kinetic effect.

II.C. Accessibility

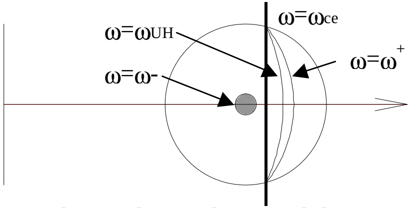
The dispersion characteristics can give some restrictions with regard to accessibility of the EC fundamental or harmonic resonance layer for waves injected from the outside. For the O-mode there are no problems of accessibility as long as the density is below the cut-off density. If the 2nd or higher harmonic frequency is used (at the same field) the cut-off density is much higher. However, absorption is rather poor and at higher harmonics than the 2nd harmonic resonance, other harmonic resonances can get in the way. If the density is sufficiently high for the waves to encounter a cut-off they are reflected off this.



O-mode accessibility

Accessibility is more complicated for the X-mode near the fundamental cyclotron frequency. The X-mode injected from the low field side first encounters the low density cut-off from which it is reflected. Fundamental X-mode heating therefore requires a high field side launch and the waves can then reach the cyclotron resonance as long as the high density cut-off does not interfere ($\omega_{pe}^2 < 2\omega_{ce}^2$ for perpendicular injection, i.e. twice the density limit of the fundamental O-mode). The 2nd harmonic X-mode can reach the resonance also from the low field side as long as the density is below the low density cut-off ($\omega_{pe}^2 < 2\omega_{ce}^2$ ~

$\omega^2/2$ i.e. the same density limit as the fundamental X-mode from the high field side at the same field). Since high field side launch is technically difficult (especially beam steering) many experiments are now done using the 2X mode after high frequency sources became available.



Fundamental X-mode accessibility

II.D. Absorption

The most widely used scheme is absorption at the electron cyclotron resonances (although in some instances conversion of the X-mode to Bernstein modes at the UH resonance has been used to overcome the density limit - this conversion is also thought to be important in plasma start-up). Cyclotron resonant absorption is a kinetic effect. The strongest effect is acceleration of the electrons by the electric field of the wave when particle and field rotate in phase and in the same direction. The perpendicularly injected fundamental X-mode is almost fully left-handed polarised and thus counter-rotates to the electrons. However, efficient absorption occurs for oblique injection as long as the density is not too high. Another accelerating effect arises from the Lorentz force associated with the wave magnetic field and the parallel electron velocity (for perpendicular propagation this is the main mechanism for O-mode absorption). In all cases the absorption mainly increases the perpendicular energy of the electrons.

Absorption by individual electrons requires the resonance condition to be fulfilled:

$$\omega - k_{//}v_{//} - n\omega_{ce} / \gamma = 0 \cdot$$

Here γ is the relativistic mass factor, n the harmonic number and $k_{//}v_{//}$ is the usual Doppler shift. An important consequence is that waves injected perpendicularly from the low magnetic field side first encounter resonant electrons with low energy (γ =1), while from the high field side high energy electrons are first in resonance. For oblique propagation the Doppler shift becomes important. Waves injected from the low field side first encounter resonant electrons with positive $k_{//}v_{//}$ and after they pass the resonance (if not yet fully absorbed) electrons with negative $k_{//}v_{//}$ become resonant. This is important for current drive. The relativistic and Doppler shifts widen the resonance layer. When a significant Doppler shift is used, a higher frequency is required for low field side launch (up-shifted absorption) than for high field side launch (down-shifted absorption) to deposit at the same radial location.

Absorption is analytically calculated (from the kinetic equations) assuming the electron population has a Maxwellian distribution. This is not always realistic (e.g. a high power ECW density can affect the distribution) and sophisticated numerical codes (Fokker-Planck codes) now exist to take this and other effects into account. Assuming a Maxwellian distribution, the width of the absorption layer can be analytically calculated. Defining

$$\Delta\omega_n = \int_0^\infty \alpha_n d\,\omega \big/ \alpha_{n,\max} \,,$$

where α is the absorption coefficient, the width in terms of frequency and radius (assuming the magnetic field varies with 1/R) is found to be for perpendicular propagation:

$\dfrac{\Delta\omega_n}{n\omega_{ce}} = 2\sqrt{n}\left(\dfrac{v_t}{c}\right)^2$, where v_t is the thermal e^- velocity and

$$\Delta = 4\frac{kT_e}{mc^2} R\sqrt{n}$$

If the Doppler shift is dominant the frequency width is:

$$\frac{\Delta\omega_n}{n\omega_{ce}} = \sqrt{2\pi}\left(\frac{v_t}{c}\right) N\cos\theta \;\; ,$$

where θ = $\pi/2$ for perpendicular injection. Although the resonance layer becomes wider for increased temperature, at high T_e the absorption is more efficient and a fraction of the resonance width can be sufficient to absorb all power.

The optical depth is defined as $\tau=\int\alpha ds$ integrated along the wave path (the transmitted power is therefore $P_0e^{-\tau}$). Approximate expressions for the optical depth are (formulas for perpendicular propagation are given except for the fundamental X-mode where oblique propagation is necessary for efficient absorption):

$$\tau_n^O(\perp) = \frac{\pi^2 n^{2(n-1)}}{2^{n-1}(n-1)!} N_O^{2n-1} \frac{\omega_{pe}^2}{\omega_{ce}^2}\left(\frac{v_t}{c}\right)^{2n} \frac{R}{\lambda}$$

$$\tau_{n=1}^X(\angle) = \pi^2 N_X^5 \left(1+\frac{\omega_{pe}^2}{\omega_{ce}^2}\right)\frac{\omega_{ce}^2}{\omega_{pe}^2}\left(\frac{v_t}{c}\right)^2 \cos^2\theta\,\frac{R}{\lambda}$$

$$\tau_{n\geq 2}^X(\perp) = \frac{\pi^2 n^{2(n-1)}}{2^{n-1}(n-1)!}\frac{\omega_{pe}^2}{\omega_{ce}^2}\left(\frac{v_t}{c}\right)^{2(n-1)}\frac{R}{\lambda} N_X^{2n-3}\left(1+\frac{\omega_{pe}^2/\omega_{ce}^2}{n\left(n^2-1-\omega_{pe}^2/\omega_{ce}^2\right)}\right)^2$$

The scaling with the (small) parameter v_t/c means that absorption is generally incomplete except for the fundamental O-mode and the fundamental (for oblique propagation) and 2nd harmonic X-mode.

II.E. Current Drive

Contrary to other non-inductive current drive systems (e.g. LH, NBI), EC waves transfer little parallel momentum: Absorption increases the perpendicular energy of the electrons. However, electrons that already have a parallel velocity in the required direction can be heated preferentially. These now slow down with a reduced collision frequency ($\sim v_t^{-3}$) and therefore contribute to the current longer than before (a correction has to be made for trapped electrons since these cannot carry current). This leads to a local current generation. If the optical depth is low, a counter current will be generated on the other side of the cold resonance. Efficient current drive requires a high optical depth (the higher the better, but certainly $\tau>3$).

For efficient current drive power should be deposited as much as possible on the fastest electrons that are available and appreciable Doppler shift is required. Obviously it therefore should help if a population of electrons with high parallel momentum is created by other means (e.g. by LH current drive) and ECCD efficiency can be increased by synergy with such a system. On the other hand the current generated by the other CD system can be locally enhanced by synergy with ECCD. In view of the importance of the collision frequency, low n_e and high T_e also help to increase the efficiency. For small tokamaks and/or low density use of the fundamental X-mode (from the high field side) is advantageous (the optical depth of this mode increases with decreasing density). For larger tokamaks and at higher density the 2nd harmonic X-mode should give the highest efficiency. A simple estimate of the current drive efficiency can be obtained by assuming that the deviation from a Maxwellian velocity distribution, although essential, is small. However, the electron velocity distribution can become significantly non-Maxwellian by heating e^- that are already fast (as in the experiment can be seen from hard X-ray emission). A numerical Fokker-Planck calculation is then necessary to give accurate predictions.

II.F. Numerical Tools

Ray tracing

The refractive index for EC waves in the plasma can deviate significantly from unity, especially at the higher densities, and refraction has to be taken into account for calculation of the deposition profile. The commonly used numerical tool for this is ray tracing using the simple geometrical optics approximation. The ECW beam is simply treated as a bundle of individual rays which propagate independently. Ray tracing is done in the WKB approximation (slowly varying plasma parameters compared with λ and ν) and the rays are simply followed, step by step, through the plasma, calculating absorption and refraction along the way using an often sophisticated magnetic equilibrium configuration. Some work has also been done on Gaussian beam tracing, which can lead to somewhat different results when the beam is strongly focussed. A simple estimate of the locally driven current can also be obtained by keeping track of the Doppler shift of the absorbing electrons (assuming a Maxwellian velocity distribution or using a simple correction on the Maxwellian distribution).

Fokker Planck simulation

A numerical Fokker-Planck calculation is required when the electron velocity distribution cannot be considered to be Maxwellian (generally for ECCD experiments). The calculation follows the evolution of the e^- velocity distribution on one or several magnetic surfaces:

$$\frac{\partial f_e}{\partial t} = \left.\frac{\partial f_e}{\partial t}\right|_{collisions} + \left.\frac{\partial f_e}{\partial t}\right|_{ECRH} + \left.\frac{\partial f_e}{\partial t}\right|_{E//} + \left.\frac{\partial f_e}{\partial t}\right|_{(anomalous)transport}$$

Collisions drive the distribution back to Maxwellian. ECRH gives rise to diffusion of resonant electrons in $v_\perp$ (taking multiple pass into account - depending on the phase they can win or loose energy during a pass through the beam). If there is (still) a parallel electric field this leads to a convection in $v_{//}$. A model for radial diffusion has to be included for the calculation to reach stationary conditions. This last term gives the major uncertainty for the calculation, since radial diffusion in tokamaks is anomalous. Fokker-Planck calculations are generally 2-D in velocity. The third (poloidal) dimension is taken into account by bounce averaging which includes trapped electron effects.

III. TECHNICAL ASPECTS

III.A. Sources

The commonly used source for ECW experiments is the gyrotron. In such a device energy is transferred from an electron beam, propagating through a cavity in a magnetic field, to radiation. A bunching of electrons to create electron density variations of a size comparable to the wave length is necessary for efficient energy transfer to radiation. A mechanism for bunching is the relativistic mass dependence of the gyrofrequency: If the electron gives up energy, the gyrofrequency is raised while if it gains energy from the radiation the frequency decreases. As a result the electrons will bunch together in gyration phase, the phase determined by the phase of the radiation. Gyrotrons use weakly relativistic beams (~80 kV) and a magnetic field, B, slightly in excess of ν(GHz)/28 T is required (very stable, generally generated by superconducting coils) for the most efficient fundamental interaction.

The (waveguide) radiation mode that is generated is mainly determined by B, the position of the (hollow) beam in the cavity and the size of the cavity. Modern gyrotrons use a high order volume mode (e.g. $TE_{22,6}$) to limit ohmic dissipation in the cavity wall and an internal quasi optical mode converter to convert the radiation to a Gaussian beam. The most critical components with respect to dissipation are, besides the cavity (ohmic dissipation), the collector (on which the spent beam is dumped) and the window (through which the radiation is transmitted). In the new generation of gyrotrons that is under development, the collector dissipation is limited by using a depressed collector and sweeping the beam over the surface using a special coil. With regard to the window, a breakthrough has been realised by the development of C(hemical) V(apour) D(eposition) diamond windows. CW, 1 MW gyrotrons in the frequency range 100 - 170 GHz are now being developed. Gyrotrons are single frequency devices, but a stepped tunability gyrotron (i.e. tube suitable to operate in different waveguide modes at different B fields and different frequency) is in development.

III.B. Transmission

For transmission from the source(s) to the plasma, quasi-optical, waveguide or mixed Q.O./waveguide lines are used. Waveguides are now generally corrugated oversized waveguide with HE_{11} transmission (hybrid TE_{11}/TM_{11} mode, close to free space Gaussian beam). This waveguide mode couples well to a Gaussian beam (and vice versa). Alignment is critical for highly oversized waveguides at high frequency (radius of curvature > 3km for 140 GHz, 88.9 mm waveguide) but optical techniques like mitre (mirror) bends including polarisation changing bends (using a grooved mirror) can be used. Transmission is very efficient, losses being mainly determined by the bends (0.25 to 0.5% loss/bend dependent on polarisation). The waveguide diameter can be significantly reduced (e.g. 31.75 mm) if evacuated and alignment becomes much less critical. Quasi optical transmission is equally efficient but requires more space due to the Gaussian beam expansion between mirrors and often needs screening where an open line conflicts with safety requirements. Once the radiation is transmitted to the plasma, it is generally launched into the plasma quasi-optically using a steerable mirror

IV. EXPERIMENTS

IV.A. Experimental Verification

EC absorption and EC emission are related; in case of thermodynamic equilibrium by Kirchhoff's law. Many diagnostic observations of ECE provide a confirmation of the basic linear theory.

Wave transmission measurements have been done in different experiments and generally agree well with ray tracing calculations, as long as refraction (and diffraction) effects are not too severe. Diffraction does not explain some results at higher density. It is likely that density fluctuations in the plasma give rise to time varying refraction effects leading, in average, to beam broadening.

The absorption profile, as determined by the initial plasma response after switch-on of ECRH:

$$p_{ECRH} = \frac{\partial}{\partial t}\left(\frac{3}{2}n_e k T_e\right)\Big|_{t=t+}$$

is generally in agreement with theory but the absolute value sometimes (not in all experiments) deviates (missing power fraction). This can be described by assuming (almost) instantaneous and non-local degradation of transport, associated with additional heating.

IV.B. Start-up

Preionisation and plasma start-up is an important application of EC waves in stellarators (currentless plasma formation) and also considered to be important for tokamaks with superconducting poloidal field coils, where the loop voltage has to be very limited. Successful. start-up experiments have been reported by several groups. Prompt ionisation is observed using limited ECW power when a resonance is present in the plasma. It is sometimes reported that the best results are obtained when the UH resonance is present in the plasma. The injected mode (O/X) is not important for the initial plasma formation: At low density multiple reflections off the wall give rise to mode scrambling. The theory is fairly well understood. Although less efficient, even the 2X resonance can be used, as verified in experiment. EC assisted start-up is considered to be essential for ITER. The required power level depends on error fields and impurity level, but a few MW should be sufficient to obtain break-down at sufficiently low loop voltage.

IV.C. Confinement

Global energy confinement is degraded in much the same way as with other additional heating methods. Some differences in scaling (e.g. with n_e) that are sometimes reported may be attributable to:

- Creation of a suprathermal e^- population with ECRH at lower densities.
- Creation of a suprathermal ion population with some other heating methods.
- Power deposition more localised for ECRH.
- Co-variation of parameters different.

In several experiments very high central T_e (~10 keV) has been achieved with central deposition, sometimes in narrow spikes (or filaments). Some current drive can be beneficial: In TCV it was found that limited counter current drive (leading to reduced or negative shear in centre) is optimal, producing a very peaked T_e profile. This illustrates the effect ECCD can have on local transport properties (formation of transport barriers) of the plasma[2].

Additional information on confinement can be gained by heat pulse propagation experiments[3]. Detailed information on local e^- confinement was gained by localised ECRH on RTP, where the existence of multiple electron thermal transport barriers was deduced[4]. By means of localised current drive such a barrier can be removed or broadened, but this is often only a transient effect.

H-mode transition is at least as efficient with ECRH as with other heating systems. A puzzling observation is that the efficiency of off-axis heating depends on the experiment. In some experiments (e.g. DIII-D) the efficiency is high and T_e remains peaked, while in many other experiments heating outside the q=1 surface is quite inefficient. Some changes in confinement can also be attributed to the effect on MHD stability.

IV.D. Particle Transport

ECRH often leads to a flattening of the density profile (density pump-out) although there is a bewildering difference between experiments. The density pump-out also depends on the wall conditioning.

ECRH can affect the recycling at the wall by ionisation of the incoming neutrals in the scrape-off layer (either directly or via the creation of suprathermal electrons) and also has an effect on the impurity transport. As yet it is unclear if and under what circumstances this can be used to pump out the impurities preferentially from the plasma. Sophisticated experiments are also necessary to investigate the option of successively destabilising different layers of the plasma to remove ash and other impurities

IV.E. Current Drive

Determination of the current drive efficiency in experiments is often complicated because inductive current drive is still present and the bootstrap current may change. The calculated ECCD then has large error bars. By comparison of the effect of co- and counter ECCD a more reliable picture can be obtained, although the synergy with inductive current drive remains difficult to assess. However, in several experiments (T-10, TCV) full non-inductive current drive has now been realised in limited parameter regimes. A normalised central current drive efficiency $\gamma_{CD20} = \langle n_e(10^{20}m^{-3})\rangle RI_{cd}/P$ of 0.01 to 0.02 A/Wm^2 has been achieved. Off-axis efficiencies are much lower, but increase with β and are sufficient to be able to stabilise tearing modes at reasonable power levels[5].

Comparison with Fokker-Planck calculations, including the effect of trapped particles, shows reasonable to very good agreement. Efficiencies are comparable for down-shifted (X-mode from HFS) and up-shifted (O or 2X mode from LFS) current drive. Synergy with LH current drive has been demonstrated[6].

IV.F. Mode Stabilisation

Many experiments have been done on stabilisation (and de-stabilisation) of MHD modes by local ECRH and/or ECCD. Sawteeth can be changed or stabilised. Central counter ECCD and heating/current drive just outside q=1 are effective for stabilisation. m=2 tearing modes have been stabilised by heating/current drive near q=2. Modulation of ECCD to only drive current inside the (rotating) islands has been tried but does not seem to be much more efficient than continuous current drive (i.e. also in the X-point). This may change for increased plasma size. Various local instabilities can be destabilised (e.g. external sawteeth in RTP).

In several experiments (ASDEX-U, JT-60U, DIII-D) the neo-classical tearing mode could be stabilised. This mode can substantially degrade confinement in high β collisionless tokamak plasmas (reactor) and is associated with the loss of bootstrap current in the island due to pressure profile flattening.

The local stabilisation or de-stabilisation of instabilities is a potentially very important application of EC waves. For many of the experimental results there is agreement with theory, although much work remains to be done on the details. The recent work on e^- transport barriers and NTM's clearly illustrate the potential of ECW to improve and affect some control on plasma properties.

V. CONCLUSION

The EC wave physics is relatively well understood, although not yet verified for reactor parameters. EC wave systems are an invaluable tool to study and manipulate transport in present day tokamaks, providing the benefits of localised heating and current drive even in smaller experiments. ECW are also considered important for a reactor grade plasma in view of potential control and other applications. Suitable sources are now becoming available.

For further information, the interested reader is referred to several reviews[7,8] as well as to the proceedings of recent Plasma Physics and specialised conferences.

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