The Potential of ECE Measurements on Next Step Tokamaks

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ABSTRACT

The likely role of diagnostics on next step tokamaks such as ITER is outlined. The physics effects which will limit the potential of ECE as a useful diagnostic are identified and examples given of the limits that they will set. Key practical problems that will be experienced in the implementation of ECE are identified, and important areas for future research and development are highlighted.

1. INTRODUCTION

The diagnosis of next step tokamak plasmas will be a major challenge. As for existing tokamaks, accurate measurements will be required of all the main plasma parameters for understanding, optimising and documenting the performance of the plasma. In addition, there will be an important new area of application: many of the measurements will be used in plasma control and machine safety systems. This will demand a degree of reliability much higher than that usually achieved in present day applications. There will also be severe practical problems: the access will be very limited, the radiation levels near the tokamak will be extremely high, and all the sensitive measurement equipment will have to be placed remote from the tokamak.

The measurement of ECE has considerable potential to contribute to this task. The level of the emission will be high and, under many circumstances, directly related to the electron temperature. The emission will occur at millimetre and submillimetre wavelengths and so can be transmitted over long distances using quasi-optical or waveguide transmission systems. The measurement instrumentation is already highly developed and reasonable further development should produce the required reliability. However, the measurement will be limited by both physics effects and by practical considerations. In both cases, these are more severe than for present-day tokamaks.

In this paper we make an initial assessment of the potential of measurements of ECE for next step tokamaks. We discuss and make a preliminary estimate of the limits set by the important physics effects. We identify the key practical problems that will be experienced in the implementation of ECE measurements. Important areas for future research and development are identified. Our treatment is based mainly on the anticipated requirements for ITER which arose during the Conceptual Design Activity (CDA). We use ITER (CDA) parameters for the calculations. We are aware that for the present ITER design some of the machine parameters, especially the major radius and magnetic field, are higher. However, we believe that our conclusions will also apply in this case.

2. THE NEXT STEP TOKAMAK AND ROLE OF DIAGNOSTICS

The objective of the next step tokamak will be to establish the physics and technology data base for designing a fusion power plant. In order to achieve this, the device will be physically larger, will operate at higher plasma currents and have considerably longer pulse lengths than existing machines. The plasma will operate with sustained fusion burn and the structure of the device will quickly become highly radioactive. The most advanced design for a next step tokamak device is that of ITER [1]. The principal parameters of ITER at the conclusion of the Conceptual Design Activity, are shown in Table 1.

Table 1
Values of the Principal Parameters of ITER (CDA)

Major Radius	6.0 m
Minor Radius	2.15 m
Elongation	1.98
Toroidal field	4.85 T
Plasma Current	$\lesssim$ 22 MA
Electron density	0.1 - 5 x 10^{20} m^{-3}
Electron temperature	0.5 - 40 keV
Pulse length	Up to 200s (inductive drive) Continuous (current drive)

The priorities in the programme will change during the life of the machine. During the early years, the emphasis will be on the exploration and optimisation of the device, and understanding any new phenomena which arise especially those associated with alpha particle heating. The most important goal will be to establish various operational scenarios for sustained fusion burn. During the latter years, the emphasis will be on technology issues. Materials, systems and instrumentation necessary for designing a demonstration fusion power plant will be tested.

In response to the change in programme priorities, the role of diagnostics will change during the life of the machine [2]. During the initial stages, they will be used in a manner similar to those on existing devices, that is for understanding, optimising and documenting plasma performance. Some diagnostics, for example magnetics, will also be used for machine control and safety. As the programme develops more diagnostics will be required for plasma control and safety functions. It is expected that eventually a large number of plasma parameters will be controlled. Many of these, for example, electron temperature, plasma current profile, confined and escaping alpha particles, helium concentration, impurity concentration, are not controlled on existing devices and so the necessary control systems will have to be developed. This new role for the diagnostics will require a very high reliability in the measurement techniques, interpretation, and in the instrumentation especially for those systems involved with safety. Reliability is a difficult parameter to quantify but improvements of at least one and possibly two orders of magnitude over those currently achieved are likely to be required. Real-time data processing, analysis, and validation will obviously also be necessary along with appropriate feedback loops and control systems.

The access and space available for diagnostics will also change during the life of the tokamak. For ITER (CDA), initially five of the 16 radial ports will be made available but as the programme develops this number reduces. Eventually only three radial ports will be available for diagnostics because the others will be required for the fusion technology programme. Unfortunately, vertical access will also be very limited because of the installation of machine systems above and below the machine. A particularly difficult area appears to be the diagnosis of the divertor area. For safe machine operations this will have to be well diagnosed with control diagnosis on, for example, the divertor plate heat loads and erosion rates, and radiative loss, but access to this region will be very limited. Access to the plasma will, of course, have to be through a highly reliable vacuum interface and many diagnostics will have to be sited several tens of metres remote from the plasma.

The diagnostic programme will therefore be qualitatively different to that on existing tokamaks. Initially the diagnostics will be used primarily for physics studies and plasma optimisation while as the programme develops they will increasingly become integrated into the machine operations. After the initial stages or so of tokamak operation the diagnostic systems should really be regarded as machine subsystems rather than diagnostics in the conventional sense. Because of the decreasing space for diagnostics, the number of diagnostics will have to reduce during the life of the machine rather than increase which has been the pattern on devices constructed to date. For ITER, the proposal of the CDA phase was that all necessary diagnostics would be installed and available at the beginning of the machine operations and then systems would be removed as the programme develops. The operational phase is likely to last at least 15 years and during this time diagnostic techniques and relevant technologies are likely to develop substantially. A major challenge, therefore, will be to balance the needs of the tokamak operations, especially for reliable measurements and systems, and the requirement to keep the diagnostics up to date and performing at the best possible level. Much of what has been learnt on existing devices will be relevant but clearly there will also be major new challenges.

3. THE POTENTIAL OF ECE MEASUREMENTS: LIMITS SET BY THE PHYSICS

Measurement of ECE has considerable potential to contribute to the diagnosis of the next-step tokamak. Based on our experience to date, we would expect it to have potential to provide measurements of the electron temperature (T_e), estimates of the energy and density of suprathermal electron populations which may be present during non-inductive current drive, and an estimate of the total power radiated due to ECE which, for ITER parameters, could become significant in the plasma power balance.

3.1 The Emission Spectrum

The level and spectral shape of the emission, however, will be substantially different to that on existing devices because of the values of key plasma parameters. These are the aspect ratio (R/a), the magnetic field (B_T), the ratio of the plasma frequency to the cyclotron frequency (ω_{pe}/ω_{ce}), the electron temperature (T_e), and the plasma volume (V). The values of these parameters and the corresponding change in the emission compared to that from JET, are summarised in Table 2. Of particular note are the values of the electron temperature and the plasma volume. The higher electron temperature means that the emission at higher harmonics is increased and that the relativistic and Doppler effects will be considerably enhanced. This will have significant implications for the diagnostic potential and these are dealt with in more detail below. The larger volume will also mean that the emission in the higher harmonics is substantially increased.

Table 2

Values of the Key Plasma Parameters which Determine the Characteristics of the ECE for JET and ITER

Parameter	JET	ITER	Comments
R/a	2.6 - 3.1	2.8	Similar geometric harmonic overlap
B_T(T)	3.4	4.85	ECE at higher frequencies
ω_{pe}/ω_{ce}	0.3 - 0.7	0.7 - 1.5	First harmonic O-mode cut-off at high densities
Te(keV)	10	20	Enhanced emission at higher harmonics. Increased relativistic and Doppler effects.
V(m^3)	150	1150	Enhanced emission in optically thin region

An indication of the level and shape of the spectrum can be obtained from a simple calculation. We assume that the plasma is thermal and that it is viewed precisely along a major radius (no Doppler broadening). We use the relativistic, 'mid-temperature', absorption coefficient including finite density effects [3] and a simple plane-parallel model for wall reflections. The shape of the plasma is assumed to be the same as that of JET and the profiles of electron density and temperature are assumed to vary as $(1 - \psi^{\alpha})^{\beta}$ where ψ is the magnetic flux. In figure 1 we show a calculated spectrum for the extraordinary mode with central electron temperature $T_{eo} = 20$ keV, central electron density $n_{eo} = 5 \times 10^{19}$ m^{-3}, and wall reflectivity r = 0.6. We take $\alpha = 2$ and $\beta = 1.5$ for $T_e(\psi)$, and $\alpha = 2$ and $\beta = 0.6$ for $n_e(\psi)$. A spectrum mesured on JET is shown for comparison.

The most striking difference between the two spectra is the high level emission at the high harmonics of ITER compared to the level of emission on JET. This is due to the combined effects of the higher temperatures and much larger plasma volume. It should also be noted that on ITER harmonics up to the fifth or sixth will be optically thick, whereas on JET it is usually only the second or third. However, it is only the fundamental O-mode (n = 1) and second harmonic E-mode (n = 2), that are likely to be useful for measurements of the electron temperature.

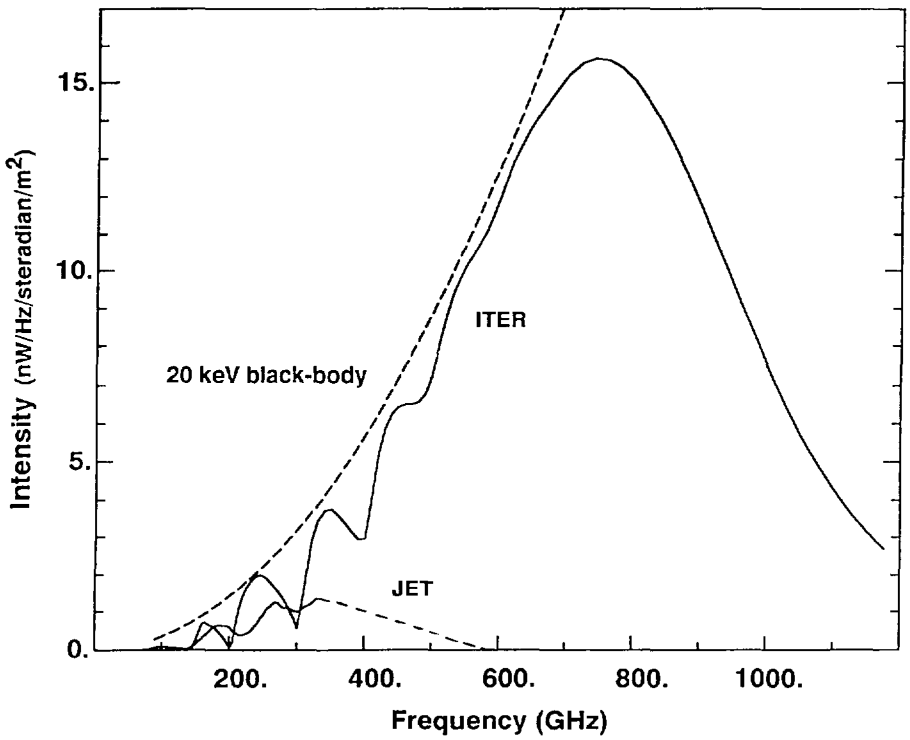

Figure 1: Calculated emission spectrum for ITER and measured JET spectrum for comparison. In the JET case B_{To}*= 3 T,* T_{eo} *= 11 keV and* $n_{eo} = 3 \times 10^{19}$ m^{-3}*. The dotted curve is an extrapolation of the measurements to high frequencies.*

Several effects will limit the diagnostic capability. The principal ones are harmonic overlap and relativistic broadening, Doppler broadening, uncertainties in the determination of the total magnetic field, density cut-offs and refraction. Populations of suprathermal electrons will also limit the temperature measurements and, under some circumstances, can make them impossible. We consider these effects in turn.

3.2 Harmonic Overlap and Relativistic Broadening

As in the case of existing devices, the large variation in the magnetic field across the plasma will limit the range over which localized measurements can be made. The limit depends on the aspect ratio and for ITER (CDA) parameters the range is $4.1 < R < 8.1$ m for fundamental O-mode, and $5.4 < R < 8.1$ m for the second harmonic E-mode. In fact, these are the maximum possible ranges assuming the vacuum magnetic field profile and no broadening of the resonance layers. As in present tokamaks, the plasma generated magnetic fields will tend to flatten the field profile and move the inner radius limit towards the outboard side. More significant will be the effect of line broadening at very high electron temperatures. Both relativistic and Doppler broadening will occur. Initially we consider sightlines along a major radius in the plasma midplane, for which only relativistic broadening is relevant.

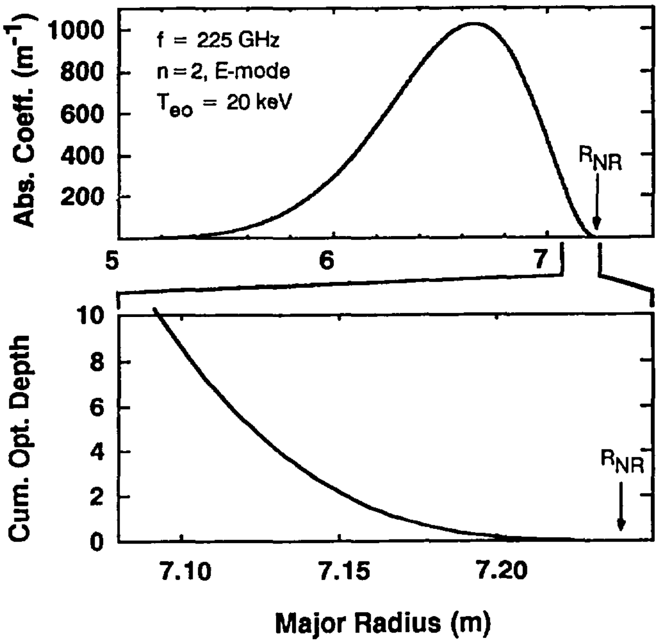

Figure 2: The spatial dependence of the absorption coefficient and the cumulative optical depth calculated for typical conditions expected on ITER. Note the large spatial width of the resonance.

At temperatures of several tens of keV the relativistic linewidth is very large, as shown in figure 2 which plots the spatial width of the resonance for a single frequency and a T_{eo} of 20 keV. We also plot the integral of the optical depth from the edge of the plasma, ie the cumulative optical depth. Re-absorption within the line profile limits an observation from the outboard side to sampling only the surface of the resonance layer, which is due to the low energy electrons in the Maxwellian distribution and therefore near the radius calculated using the electron rest mass, ie the "non-relativistic" resonance radius, R_{NR}. However, the high energy electrons in the tail of the distribution have a large relativistic downshift, or equivalently, at a fixed frequency, they will resonate at a smaller major radius where the magnetic field is stronger. There will therefore be frequencies in the second harmonic which will suffer overlap from the third harmonic, even though the non-relativistic resonance radius of the third harmonic is outside the plasma (see figure 3). This is because energetic electrons in the tail of the distribution, located between the second harmonic resonance and the outboard edge, will resonate in the third harmonic at these frequencies. The emission and absorption by these energetic electrons may be sufficient to modify significantly the observed total emission at these frequencies, and hence prevent localized T_e measurements using the second harmonic. The inner major radius limit due to harmonic overlap is therefore modified by an amount which depends on both the electron temperature and density.

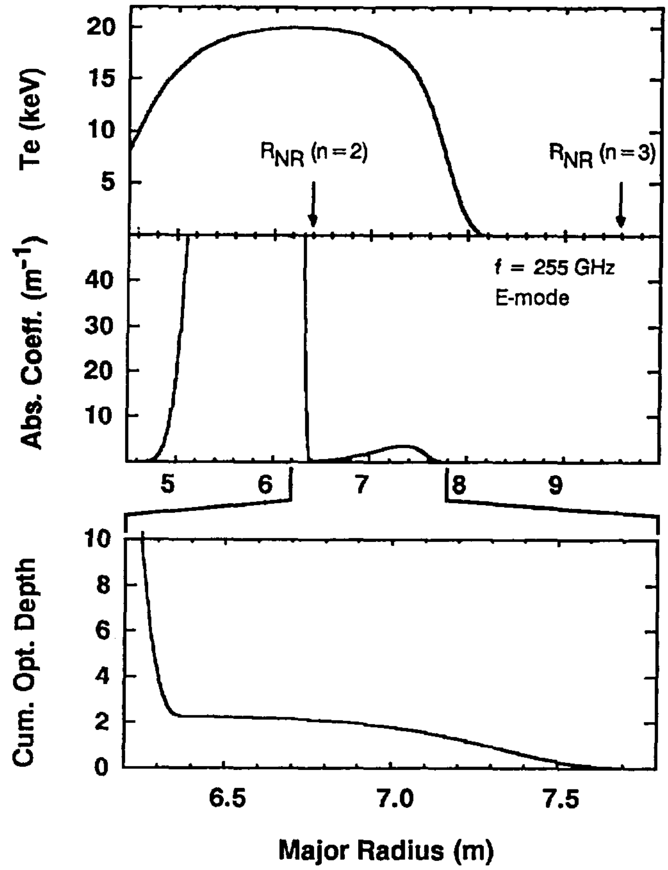

Figure 3: The T_e profile and the spatial dependence of the absorption coefficient and the cumulative optical depth at a frequency of 255 GHz. Even though R_{NR} for the third harmonic is outside the plasma, absorption by electrons in the tail of the distribution is significant and limits measurements in the plasma core using the second harmonic.

The outer major radius limit is also modified by the very large relativistic broadening, especially in plasmas with flat profiles and very steep edge gradients. At frequencies for which the non-relativistic resonance radius is close to the plasma edge, the optical depth due to the low energy end of the distribution function falls to a low value. If T_e rises to a high value a short distance inboard of this non-relativistic resonance location, then electrons in the high energy tail may have sufficient relativistic downshift to resonate at the same frequencies (see figure 4). The emission due to the high energy tail may be much more intense than that due to the low energy electrons at the non-relativistic resonance, and if it is not fully re-absorbed, it will prevent an accurate local measurement of the edge T_e. To avoid this "thermal burn-through" it is necessary to have a large optical depth (about 5) in the low energy part of the distribution function.

An indication of the limits set by these effects can be obtained by calculating the radiation temperature of the emission and comparing it with the model temperature profile. Where these agree, accurate measurements of T_e are possible. The results of such calculations are shown in figure 5 for two different central temperatures (10 and 20 keV) and for both the fundamental O-mode and second harmonic E-mode. We have assumed that the emission is observed from the low field side, precisely along a major radius in the mid-plane. The frequency scale of the calculated emission spectrum has been converted to major radius using the non-relativistic resonance. It can be seen that the reduction in the accessible range of major radius, compared to the values given above, can be substantial in the case of the second harmonic E-mode at high temperatures. The effect is less severe for the first harmonic O-mode, but this will have a lower density cut-off (see section 3.5).

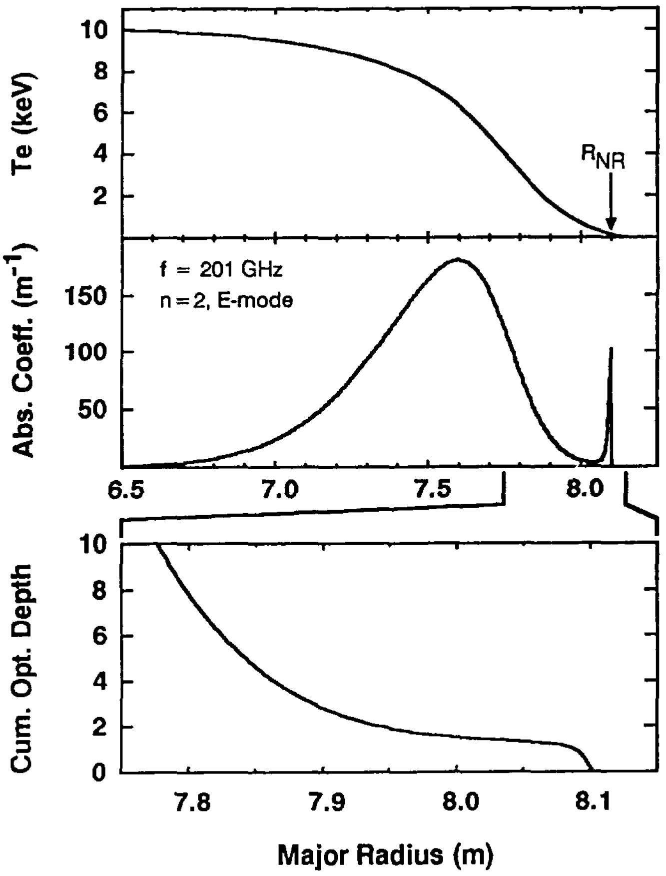

Figure 4: The T_e profile and the spatial dependence of the absorption coefficient and cumulative optical depth at a frequency of 201 GHz. The absorption by the low energy electrons near $R = R_{NR}$ is not sufficient to prevent emission from high energy electrons in the thermal tail escaping from the plasma and limiting the T_e measurement in the edge region.

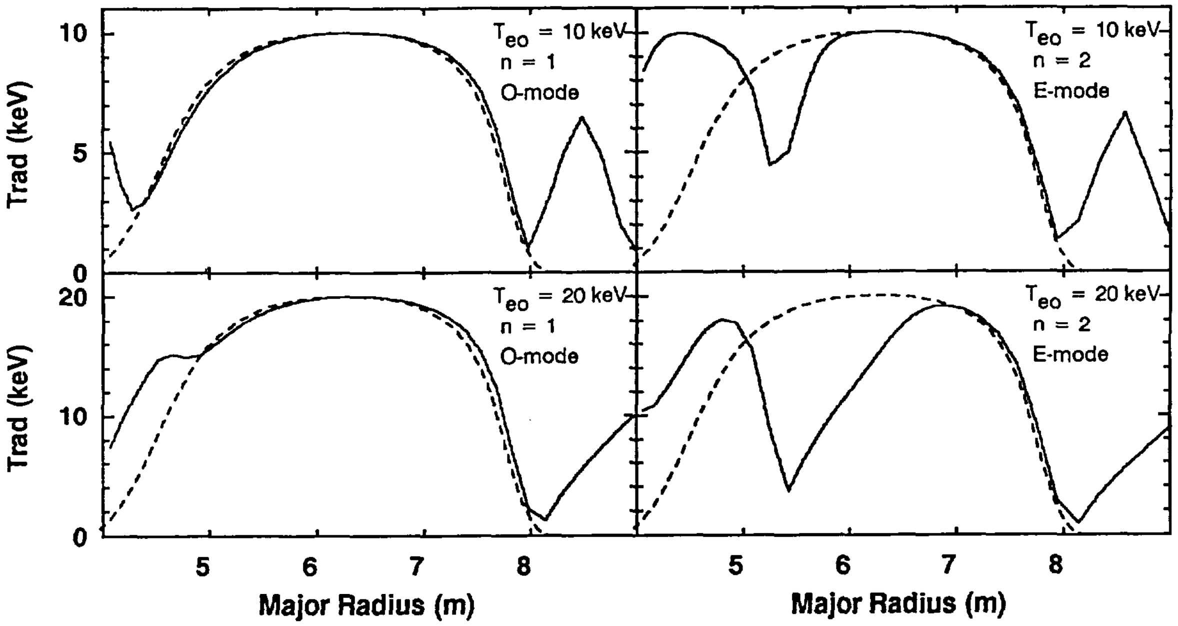

Figure 5: Model T_e profile (dotted line) and calculated radiation temperature (solid line) for two values of the central temperature and two different harmonics taking into account relativistic broadening. Where $T_{Rad} = T_e$ measurements of the temperature profile are possible. Note that as the temperature and the harmonic number increase, the range over which T_e measurements are possible reduces.

3.3 Doppler Broadening

In practice, the plasma will not be viewed precisely along a major radius because of the finite angular width of the antenna pattern. The plasma will be viewed over a range of angles and so Doppler broadening must be considered. The Doppler line shape will be symmetric and centred at $R = R_{NR}$ and so there will be absorption at values of $R < R_{NR}$ and $R > R_{NR}$. At high temperatures, this absorption can be substantial even for small angles of view and give rise to a value of the optical depth $\gtrsim 3$. When viewed from the low field side, therefore, the bulk of the received radiation can originate from locations $R > R_{NR}$. Hence Doppler broadening can lead to an apparent shift in the resonance location.

Doppler broadening will also lead to a lower limit to the spatial resolution that can be achieved. Since the measured radiation will originate from a range of angles, a range of values of major radius will be sampled.

To illustrate these effects we plot the absorption coefficient as a function of major radius assuming the plasma is viewed at an angle of 86° to the magnetic field and for a temperature of 18.5 keV (figure 6). We also plot the relativistic line shape for comparison and the cumulative optical depth in both cases. Because of the absorption at $R > R_{NR}$ the apparent shift in the resonance location is ~0.25m. If the emission is measured with an instrument which has the same sensitivity at all angles over the range 0 to 4° then the lower limit on the spatial resolution would also be 0.25m. In practice, the instrument response will depend on angle and a full treatment must take this into account.

Our treatment of relativisitic and Doppler broadening effects is simple but it demonstrates the consequences of these effects. A full treatment would take into account both effects simultaneously and the actual antenna pattern of the measurement instrument.

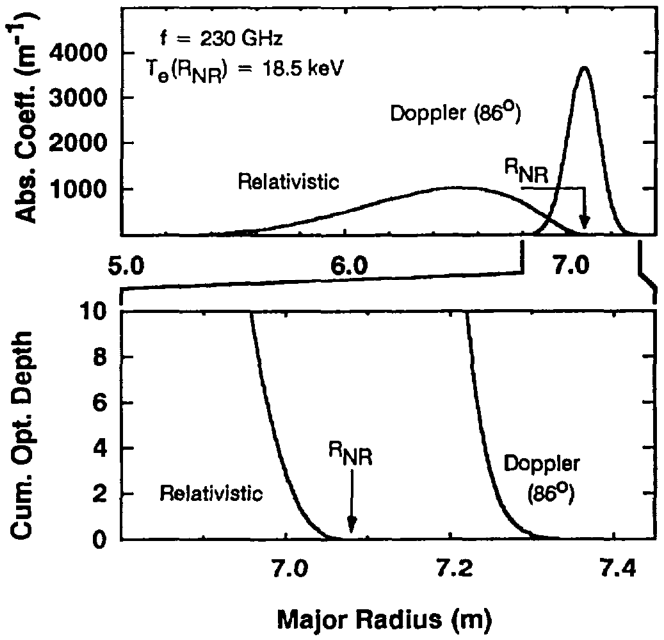

Figure 6: The spatial dependence of the absorption coefficient and cumulative optical depth demonstrating Doppler broadening at an angle of view of 86° and $T_e = 18.5$ keV. The relativistic line-shape is shown for comparison. Note that for an emission measurement the received radiation would originate from $R > R_{NR}$, ie there would be an apparent shift in the resonance location.

3.4 Internal Magnetic Fields

In order to derive the profile of the electron temperature from the measurments of ECE it is necessary to have on accurate determination of the magnitude of the total magnetic field along the line of sight. In present day applications, this is obtained from independent measurements made with the magnetic diagnostics analysed with equilibrium codes. Unavoidably there will be uncertainty in these calculations, especially in the determination of the contribution due to the currents in the plasma, and this will lead to uncertainty in the radial location of the deduced profiles. For present-day applications this can be as large as 5% . It is too early yet to make accurate predictions of the size of this effect for the next-step device but it is unlikely to be smaller than for present devices.

3.5 Cut-offs and Refraction

As in present applications, the dispersion properties of the plasma will limit the density that can be investigated. For propagation in the O - mode the limit will be set by the plasma frequency while for propagation in the E-mode the limit will be set by the right-hand cut-off. For most present day applications it is sufficient to use the cold plasma approximation to the refractive index and for these cut-offs this gives a limit of 2.2 x 10^{20} m^{-3} for the fundamental O-mode and 4.5 x 10^{20} m^{-3} for the second harmonic E-mode assuming perpendicular propagation and a central toroidal field (B_{To}) of 4.85T. At the temperatures expected in ITER, however, relativistic effects will become significant. Recent investigations have shown that these effects cause the cut-offs to occur at higher densities and that the density limits increase with temperature [4]. For propagation in the O-mode the enhancement in the density limit is given approximately by the simple expression

$$\left(\frac{n_{e\,rel}}{n_{e\ cold}}\right)_{O\ cut-off} \approx 1+4.9\ x\ 10^{-3}\ T_e(keV)$$

while for propagation in the E-mode at the second harmonic [5]

$$\left(\frac{n_{e\ rel}}{n_{e\ cold}}\right)_{R\ cut-off} \approx 1+9.8\ x\ 10^{-3}\ T_e(keV)$$

Hence at 20 keV the density limit for the fundamental O-mode is increased by ~9.8% to 2.4 x 10^{20} m^{-3} and for the second harmonic E-mode is increased by ~18.9% to 5.4 x 10^{20} m^{-3} for B_{To} = 4.85T.

For propagation at finite angles to the density gradient, refraction will occur and must be taken into account especially at high densities. The refraction will bend the line of sight and usually lead to an increase in the antenna spot size. To quantify the effect, detailed calculations must be carried out for each specific situation. An approximation can be obtained with the cold plasma model but for accurate work the fully relativistic expressions, or high temperature approximations, will be required [6].

3.6 Emission from Suprathermal Populations

As in the case of present applications, small populations of suprathermal electrons can severely limit the potential of ECE to provide measurements of T_e. The impact on the T_e measurement capability has been studied by several groups with the most recent work presented at this conference [7].

It is possible, however, that measurements of ECE will be able to provide an estimate of the energy and density of the suprathermal populations especially if combined with other measurements particularly measurements of the soft X-ray emission. The technique which is used at present is to adjust the parameters of the suprathermal population for best fit of a calculated spectrum to the measured spectrum. It is unlikely that this will be changed in principle although it should become more developed by the time measurements are possible on the next-step device.

Table 3
Consequences and Limits Set by Physics Effects

EFFECT	CONSEQUENCE	FUNDAMENTAL 0-MODE	SECOND HARMONIC E-MODE
Geometric Harmonic Overlap	Limits range of R for which T_e measurements are possible	$4.1 < R < 8.1$m	$5.4 < R < 8.1$m
Relativistic Harmonic Overlap	Limits range of R for which T_e measurements are possible	$5.0 < R < 8.0$m for $T_{eo} = 20$ keV	$7.0 < R < 8.0$ m for $T_{eo} = 20$ keV
Doppler Broadening	Limits spatial resolution and generates apparent shift		$\Delta R \sim 10$ cm $R_{shift} \sim 25$cm for 86°
Internal Magnetic Fields	Increases systematic uncertainty on T_e profile		
Cut-offs	Upper limit on density	$n_e < 2.4 \times 10^{20}$ m^{-3} for $B_o = 4.85$T and $T_{eo} = 20$ keV	$n_e < 5.4 \times 10^{20}$ m^{-3} for $B_o = 4.85$T and $T_{eo} = 20$ keV
Refraction	Bends line of sight and increases antenna spot size		
Suprathermal Emission (non-inductive current drive)	Severely limits T_e measurements		

The different effects and their consequences to the measurement capability are summarized in Table 3. We have treated these different effects independently to gain insight into the consequences that they will have for the measurement capability. In practice, the they will occur at the same time and so an accurate determination of the measurement limits must treat all relevant effects simultaneously. Such a treatment has not yet been carried out.

4. IMPLEMENTATION

Many factors will have to be considered in designing the optimum ECE system for the next-step tokamak device. These include the role required for the ECE measurements; the limits set by the physics effects; the access restrictions and available viewing directions; integration of the in-vessel components with the machine design; the vacuum window; the transmission of the radiation to the measurement instrumentation; the spectrometers and detection systems; in-situ calibration; real-time data precessing and validation; reliability and duplication; and remote maintainability.

The experience gained on present devices, especially JET and ITER where the measurement systems have been designed for operation during the active phase, will be a useful starting point. This has shown that waveguides or mirrors in the vacuum vessel can be used to view the plasma along sightlines not directly available through radial and vertical ports. Similar arrangements could be used for the next-step device but damage to the in-vessel components due to the high levels of radiation must be considered. At present, crystal quartz windows are used as the vacuum break and a similar arrangement could be used on the next-step. Possible radiation damage is again an important factor. The ECE radiation is currently transmitted to the measurement instrumentation using long lengths of oversized waveguide or quasi-optical beam waveguides and similar systems could be used on the next-step. The existing types of spectrometers and detectors - scanning Michelson interferometers, Fabry Perot interferometers, grating polychromators all fitted with liquid helium cooled detectors, and heterodyne radiometers - have an adequate measurement performance but the reliability and maintainability must be improved. Existing multichannel heterodyne radiometers are limited to operating at frequencies < 150 GHz and an extension to ~250 GHz is desirable. Special calibration hardware and procedures will be necessary because the existing methods require manual intervention in the vacuum vessel or close to the machine. One solution would be to build into each measurement channel and close to the tokamak a remotely controlled calibration source. Satisfactory mathematical algorithms for processing the data exist but procedures and codes for processing and validating the data in real-time need to be developed.

During the CDA phase of ITER, consideration was given to the design of a possible ECE system. The ITER physics programme is expected to require measurements of T_e both in and out of the mid-plane and so an array of viewing directions in the poloidal cross-sections is proposed (figure 7). The in-vessel waveguides and antennas would be installed in slots in the sides of the blanket modules and exit through a radial port. An oversized waveguide or quasi-optical system would transmit the radiation to the measurement instrumentation which would be located several tens of meters remote from the tokamak.

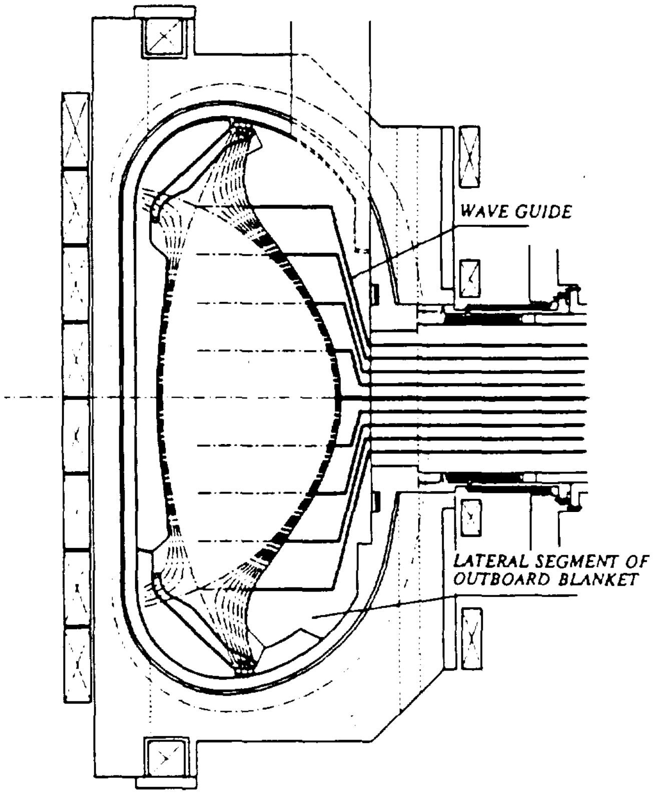

Figure 7: Schematic of proposed measurement channels on ITER.

5. KEY R AND D AREAS

This initial study has shown that there are several areas where R and D is necessary before an ECE system can be prepared for the next-step tokamak. These are as follows:

- the limits of the measurement capability need to be determined by taking into account simultaneously all relevant physics effects.

- the radiation damage to components in the measurement system, especially those that will be installed in the vacuum vessel and close to the machine, needs to be determined and where possible minimized. The effect of this damage on the microwave transmission properties needs to be determined.

- the effect of the high levels of radiation on possible vacuum window materials needs to be determined and a suitable window arrangement designed.

- the design of the existing spectrometers and detectors needs to be improved especially with respect to reliability and maintainability.

- real-time data processing and automatic data validation techniques need to be developed.

- methods for interpretating measurements of ECE when small populations of suprathermal electrons are present need to be further improved.

Some of these developments, for example the further development of methods for analysing non-thermal ECE, will be carried out as part of the experimental programmes on existing devices. Others are also relevant to several diagnostics, for example the development of windows that can withstand the high levels of radiation, and so can be included in wider development programmes. Some, however, are specific to ECE measurements and will require dedicated development programmes. The determination of the limits of the measurement capability and the improvement of the spectrometers and detectors are examples of this type.

6. CONCLUSIONS

Diagnostics will play an important role on the next step tokamak device. In addition to their conventional role in aiding the understanding, optimising and documenting of the plasma performance, they will be required for control and machine safety systems. This will demand a degree of reliability much higher than that usually achieved in present-day applications. Measurement of ECE has considerable potential to contribute to this task especially for the measurement of electron temperature. It should be possible to measure electron temperature with good spatial and temporal resolutions over a wide range of plasma conditions. The measurements will be limited by several effects principally harmonic overlap, relativistic and Doppler broadening, uncertainties in the determination of internal magnetic fields, cut-offs and refraction, and emission from suprathermal electrons. Because of the high temperatures expected, relativistic and Doppler broadening will be substantial and lead to limitations in the measurements which are more severe than on present devices. The implementation of the measurements will require detailed consideration of many practical issues and the solution of some difficult practical problems. Particularly important points are the integration of the in-vessel components with the machine design, radiation damage to antennas, waveguides and other components in and close to the vacuum vessel, the vacuum window break, and calibration techniques. Application of the measurements will require the development of real-time data processing and automatic data validation techniques. These matters will have to be addressed in a R and D programme which will have to be carried out in parallel, but closely linked, to the detailed design of the tokamak.

In this paper we have concentrated on the potential of ECE measurements as a means of determining the electron temperature. Measurements of ECE, however, can be important for other reasons. For the plasma conditions of the next-step, the total radiated power due to ECE could be significant in the power balance. Similarly, the contribution to the heat transport due to emission and re-absorption of ECE radiation could be significant. There is also the possibility of using measurements of electron cyclotron absorption as a diagnostic especially for the divertor region [8]. These areas are also worthy of detailed study and may require specific developments which would have to be carried out in the R and D programme.

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