

# ECE: THE STORY SO FAR

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In this paper we trace the development of measurements of ECE on fusion machines from the early days, when the main interest in this emission was its contribution to the power loss, to the present, where such measurements are employed as a powerful diagnostic of the plasmas produced in most contemporary tokamak and stellarator machines. The development path has not always been smooth but it has always been rich in creativity, surprises, debate and ultimately success. The significant developments in the field are identified and illustrated with examples.

## 1. Introduction

Measurement of ECE is nowadays a highly productive and ubiquitous diagnostic. Most tokamaks and stellarators have extensive ECE measurement systems and these routinely provide measurements of the spatial profile of the electron temperature; the location, type, and size of MHD modes; and information on suprathermal populations. More sophisticated dedicated applications can provide the amplitude and location of broadband temperature fluctuations, the length of the spatial correlations of the underlying fluctuations, and 2D images of MHD modes. The spatial and temporal resolutions are impressive even by modern standards — full profiles being measured in microseconds with spatial resolutions of millimeters. Altogether ECE is generally regarded as a ‘good thing’. But it was not always the case.

The initial theoretical investigations of ECE indicated that the power loss due to ECE could be significant, possibly even a potential threat to fusion. Similarly, the initial attempts to use measurements of ECE as a diagnostic brought forward unexpected characteristics of the emission that puzzled experimenters at the time and led to great debates and investigations. Different techniques to measure the emission were developed and it was some time before the relative merits of these techniques were established and agreed. The calibration of the measurement systems was a very difficult task and taxed the experimenters for almost a decade. Through its long and ultimately successful career ECE has been a topic of deep investigation and debate that has challenged those who undertook to work on it but ultimately has delivered outstanding success.

In this paper we trace the path of the development of ECE from the early days to the present. We tell the story by identifying and illustrating the key steps in the field. It is not a comprehensive review. For such a treatment the reader is

referred to the excellent early review by Bornatici *et al* [1] and the reviews published recently by Taylor [2] and Luhmann *et al* [3], and the articles cited therein. The contribution of measurements of ECE to the development of fusion has been quite remarkable. It is as rich now as it has ever been in terms of debate and opportunity. We conclude with a brief look forward.

## 2. The Early Days

ECE first came to the attention of fusion researchers in 1958 when, in a series of papers by Trubnikov and others, it was realised that the power loss due to ECE (or “magnetic bremsstrahlung” as it was then known) would be significant in a fusion reactor [4,5]. These researchers calculated the emission and absorption from high temperature plasmas of the type then envisaged for successful fusion, particularly D-D plasmas. They identified the main characteristics of the emission — a harmonic spectrum with the lines broadened by the relativistic effect and with optically thick and thin region (Fig. 1). They pointed out that whereas the rate of power production depends on the plasma volume, the power loss depends on a combination of volume (for the optically thin region) and surface area (for the optically thick region), and hence there will be a critical size for net power production. They predicted that for the plasmas considered sizes of several 10 s of meters would be required which would be difficult to achieve. In Trubnikov’s words “...the radiation is trapped to the extent necessary for a self-sustaining thermonuclear D-D reaction only when the dimensions of the layer are considerable, lying at the limit of achievability” [5].

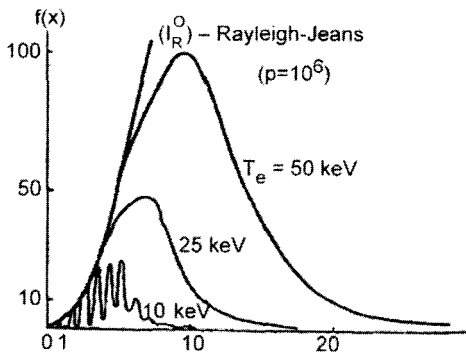


Figure 1. ECE (“magnetic bremsstrahlung”) from hot plasmas ( $T_e = 10, 25$  and  $50$  keV) with a Maxwellian velocity distribution and confined by a magnetic field [after [4], (1958)].

This statement produced some concern in the fusion world at the time. Trubnikov *et al* went on to show that the power loss could be manageable for D-T fusion plasmas that will operate at lower temperatures and that by surrounding the plasma by reflectors the power loss could be further reduced by

enhancing the optically thick region of the spectrum. The immediate concern abated but ECE was firmly established as a constituent of fusion science.

Shortly after this theoretical work, laboratory experimental work began. Probably the first measurements were those made by Lichtenberg *et al.* of the emission from a “hot electron” plasma at the University of California, Berkeley [6]. In the initial measurements the spectrally integrated emission was measured but later an Echelette grating monochromator was used to measure the emission at the cyclotron frequency and in the harmonics up to the ninth ( $0.2 \text{ mm} < \lambda < 4.0 \text{ mm}$ ) (Fig. 2) [7]. A liquid helium cooled “Putley type” indium antimonide detector was used. The plasma was produced multiple times and the emission was measured at each wavelength sequentially. The measured spectrum showed the expected harmonic nature and was compared with the predictions of the Trubnikov theory. The plasma was not sufficiently optically thick for there to be appreciable self absorption. There were discrepancies with the theoretical predictions: ‘the experimental spectrum indicates some additional structure not accounted for by the theory’ wrote the authors [7]. By this time, that is the late ’60s, there was already all the constituents of a scientific endeavour — theory, experiment, discrepancies and debate — and more researchers were attracted to the topic.

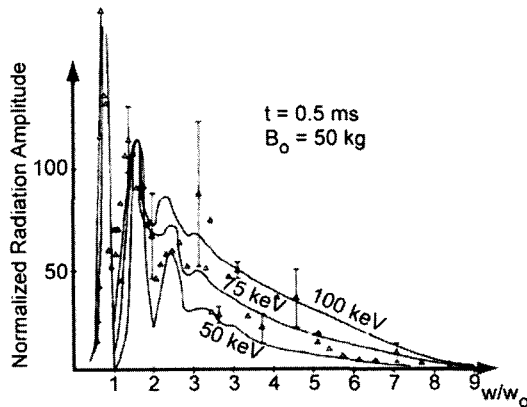


Figure 2. The electron cyclotron (synchrotron) emission spectrum from a “hot-electron” plasma produced in a magnetic mirror device [after [7] (1964)].

### 3. The Birth of ECE as a Diagnostic of Tokamak and Stellarator Plasmas

Around 1970 tokamak plasmas were beginning to approach the keV temperature range. In a pivotal paper Rosenbluth pointed that there are several reasons why the situation regarding ECE from such plasmas would be different from that examined previously: these plasmas have a relatively low density, strong

inhomogeneity in the magnetic field that will provide the dominant line broadening, relative small sizes as compared to reactors, and are difficult to surround by effective reflectors in an experimental device [8]. He went on to calculate the contribution to the power balance and, as Trubnikov had found earlier for the high temperature plasmas, concluded that it would be significant.

Building on this work, Engelmann and Curatola performed a comprehensive treatment of the effects of cyclotron radiation [9]. They examined the volume power loss and the contribution of cyclotron radiation to the electron heat conductivity. They derived simple, analytical expressions for the emission taking into account self-absorption. In a step of far reaching consequences, they pointed out that the spatially dependant magnetic field gives rise to the possibility of obtaining localized diagnostic information by measuring the emission perpendicular to the magnetic field with spectral resolution, and they showed how it should be possible to determine the spatial profile of the electron temperature and electron density from measurements of the emission in optically thick and thin harmonics respectively. Under certain conditions it may also be possible to determine the poloidal magnetic field. Their paper lays the foundations of measurements of ECE as a diagnostic technique.

In a parallel development, experimenters were attempting to measure the emission from tokamak plasmas. Costley *et al* measured the emission from the CLEO tokamak using a specially developed rapid-scan Michelson interferometer and the technique of Fourier transform spectrometry (Fig. 3) [10]. Because of

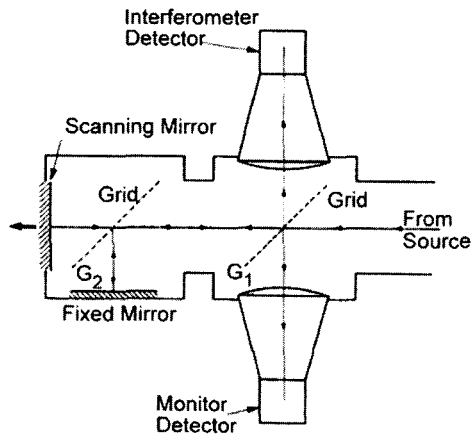


Figure 3. Rapid-scanning Fourier transform spectrometer for time resolved ECE measurements on the CLEO tokamak plasmas [after [10] (1973)].

the high étendue and simultaneous observation of a wide frequency range (multiplex advantage) this technique gives very high signal/noise values (typically  $10^3$  times higher than grating spectrometers). The measuring system

was calibrated with a mercury arc lamp. The relative calibration was good ( $\pm 10\%$ ) but the absolute calibration was subject to large uncertainty ( $\sim$  factor of three). Boyd *et al* measured the emission from the ATC tokamak using band pass filters in the range 35–450 GHz, with low frequency resolution,  $f/\Delta f \approx 2$ , but with high time resolution,  $\Delta t < 10$  ms [11]. Sometimes in these experiments some of the characteristics of the emission were as expected — a line spectrum with lines at  $n\omega_{ce}$ , but on other occasions the spectrum was almost featureless (Fig. 4) [12]. Unexpectedly the emission was found to be unpolarised and the same in the radial and vertical directions (Fig. 5) [13]. Reflections of the radiation in the vacuum vessel were advanced as an explanation for the lack of polarisation and the apparent isotropy of the emission and a model of the plasma/vacuum chamber system was developed to explain the results [10]. By the mid 1970s measurements of ECE were a recognized part of fusion science but were far from being a useful plasma diagnostic technique.

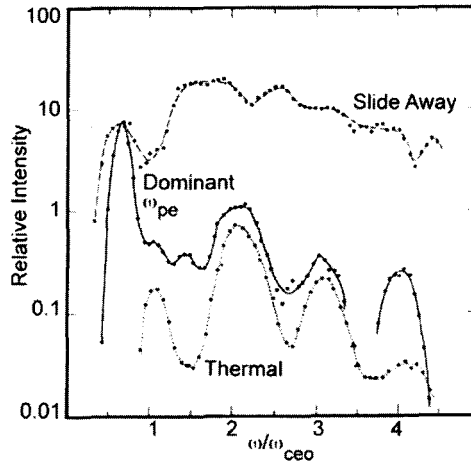


Figure 4. ECE spectra for different tokamak operating conditions. At low densities (typically  $n_{e0} < 1 \times 10^{19} \text{ m}^{-3}$ , slideaway regime) the emission is intense and relatively broadband but as the density increases the spectra rapidly approach the thermal level. In an intermediate region the emission spectrum is dominated by a feature near  $\omega \sim \omega_{pe}$ , the plasma frequency [after [12], (1977)].

#### 4. Developing the Base

Stimulated by the promise of a new and powerful diagnostic technique, intrigued by the unexpected results that had been obtained thus far, and challenged by the measurement problem, many researchers entered the field bringing with them new ideas, different experiences and different approaches. A variety of different methods were developed to measure the emission: for example, Efthimion *et al* developed a scanning heterodyne system [14]; Walker *et al* developed a scanning Fabry Perot filter [15]; Eberhagen *et al* developed a

scanning grating polychromator [16]; and Tait *et al* developed a multi-channel grating instrument [17]. A scanning detector based on the Josephson junction was also attempted [18]. The challenge of achieving a fast scan for the Michelson interferometer brought forth several novel approaches: for example, Pieroni and separately Akulina developed a rotating spiral mirror [19,20], Campbell used rotating plane mirrors [21]. But perhaps the most novel approach was that developed by Bartlett [22]. In this device a pulsed plasma of varying density is used to achieve a very rapid scan of the path length in the Michelson. There is something especially appealing about this device in which a plasma is used to diagnose a plasma. All the devices cited were used to make plasma measurements on tokamak and in some cases stellarator plasmas. By the early 1980s measurements were being made routinely on at least 15 different toroidal devices worldwide by a variety of measurement techniques.

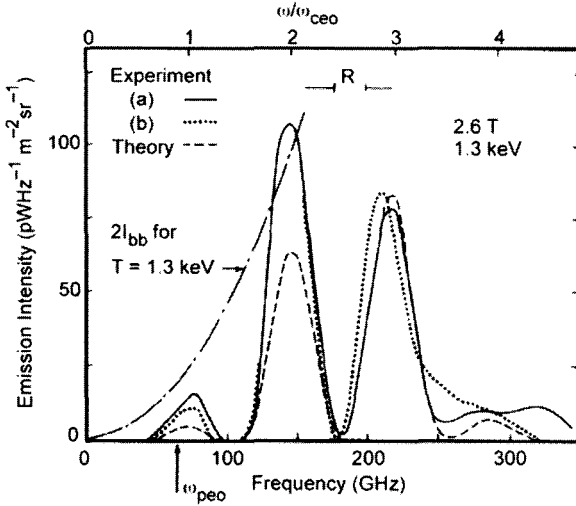


Figure 5. ECE spectra measured on the TFR tokamak for observation in the radial direction [curve (a)] and the vertical direction [curve (b)]. Note curve (b) is normalised to curve (a) at  $\omega \sim 2\omega_{ce0}$ . Predictions for radial emission assuming plane parallel reflection model including polarization scrambling (after [13], (1977)).

The different measurement techniques have different characteristics in terms of spectral range, spectral and time resolutions, sensitivity etc. Great debates occurred especially at the EC workshops through the '80s and into the early '90s about the relative merits of these different approaches. Slowly a consensus emerged that the most effective approach is to use a measurement technique with attributes that match the specific requirements of the measurement: for example, if the full spectrum is required at moderate time resolution then the intrinsic broad band nature of the Michelson makes that the best instrument to

use. On the other hand, if the emission in a narrow range of frequencies is required at high sensitivity then the heterodyne or, at higher frequencies, grating instruments are best.

Possibly the most significant development in the measurement capability was that of reliable calibration hardware and techniques. A large area ( $400\text{ mm}^2$ ,  $400^\circ\text{C}$ ) hot source was developed at the National Physical Laboratory in the UK and fully characterized [23]. It enabled Michelson interferometers and heterodyne instruments to be absolutely calibrated. Other instruments, for example grating spectrometers or Fabry Perot interferometers were cross calibrated using the plasma emission. Alternative techniques for carrying out the calibration were also developed. In one case, an untuned cavity fitted with a calibrated power meter was used to excite all the relevant modes in the measurement system. In another, the antenna pattern was measured absolutely by moving a microwave source of known power in the far field of the measurement instrumentation. Tubbing and Kissel applied all three techniques to the same ECE measuring system at JET and achieved good agreement thereby demonstrating that the ECE measurement system is reliably calibrated [24]. A sophisticated technique in which the toroidal field is ramped during the plasma shot and the ECE is measured was developed to improve the relative calibration by Bindslev and Bartlett [25]. Clark carried out a careful study of the likely sources of systematic errors in measurements of ECE using Michelson interferometers [26].

Armed with this array of measuring instrumentation the experimenters set about addressing the anomalies observed in the early experiments. It was soon realized that the intense broad-band emission was due to suprathermal populations of electrons. When the plasma production was well controlled these populations did not occur and the emission was much closer to that expected from a thermal plasma both in terms of level and spectral variation. Attempts were made to control or avoid reflections in the vacuum vessel. It was not possible to eliminate them completely but sufficiently to support the hypothesis that the apparent lack of polarization and apparent isotropy are indeed due reflections (Hutchinson and Komm [27]). Serious efforts were made to measure the state of polarization of the emission using specially constructed measurement hardware through the determination of the Stokes parameters with success [28,29]. Clear evidence of polarization in line with expectations was observed.

The problems of reflections were completely avoided in some experiments by measuring directly the absorption of a transmitted beam (i.e., [30,31]). A novel approach was applied recently by Austin *et al* [32]. In this case emission measurements were made under plasma conditions where the emission from the optically thick second harmonic was observed through the optically gray third harmonic. The optical depth of the third harmonic layer, and hence the absorption coefficient, were determined. The electron temperature and density of the plasma were known from independent measurements and so the measured value of the optical depth could be compared directly with the calculated value.

The accuracy was such that it was possible to distinguish between different theoretical expressions for the optical depth. In general, theory and experiment were in good agreement. The direct measurement of the absorption coefficient was a major step because it gave an unequivocal confirmation of the underlying theory of ECE at least for the conditions of the experiments undertaken.

Attempts were also made to measure the electron density by measuring the emission in optical gray/thin harmonics (i.e., [26]). These measurements are complicated by reflections of the radiation in the plasma containing chambers. It has never been possible to achieve a completely effective radiation dump. Nevertheless, by modeling the wall reflections, estimates of the electron density have been obtained and these have compared well with those made by other means.

In parallel with the instrumental and experimental work there was continual theoretical development. There are many effects that have to be taken into account for a full treatment of ECE. Finite density effects can give rise to resonances and cut-offs that can affect propagation, and at high densities they affect the basic emission through dielectric effects. They can also couple the polarisation to the direction of the magnetic field. Unfortunately this has the effect of destroying the possibility of measuring the poloidal field from a measurement of the direction of polarization of the radiation except at the plasma edge but there the magnetic field is already well known. For temperatures  $>5$  keV the simplified expressions for the absorption coefficient become inaccurate and more complicated formulae are needed. Electron cyclotron emission and absorption are resonant phenomena, both in frequency and space, and under some conditions the WKB approximate can break down requiring a full wave treatment. There can be coupling of the electromagnetic waves of ECE to electrostatic Bernstein-like modes and this can lead to additional diagnostic possibilities (Sec. 5). Possible nonlinear effects, for example diffusion of the electron distribution in velocity space induced by the presence of waves have to be considered. Since it was known from the experiments that non-thermal, i.e. non-Maxwellian electron velocity distributions can occur, the presence of such populations has to be considered. It is not possible to uniquely determine the electron distribution function from a measurement of the ECE, but a fit forward approach is in principle possible and requires the development of codes that can handle non-Maxwellian distributions. In general, reflections of the radiation cannot be eliminated in the experiments and so models of the combination of the plasma inside a reflecting chamber are needed. Codes that take all these effects into account are obviously substantial undertakings requiring significant computing power to run. Fortunately, giants of theory such as Bornatici, Englemann, Fisch, Giruzzi, Harvey, Tamor, Westerhof and others were attracted by the challenges and worked steadily to improve the theoretical basis. A comprehensive review of the early theoretical developments was published by Bornatici *et al* [1]. For later treatments the reader is referred to the many excellent papers presented at the EC workshops and the papers cited therein.

The combination of the instrumental and technique development, and the development in the underlying theory, meant that by the mid 1980s there was a high level of confidence in measurements of ECE to provide reliable information and especially the electron temperature with space and time resolution. Many comparisons of profiles measured by ECE were made with profiles measured by Thomson scattering and in general good agreement was obtained (Figs. 6 and 7) [33,34].

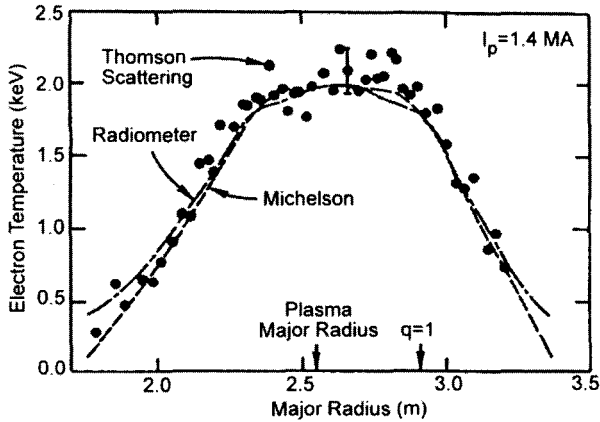


Figure 6. Comparison of independent measurements of the profile of the electron temperature measured by ECE (radiometer (O-mode fundamental) and Michelson interferometer (second harmonic e-mode)) and Thomson scattering [after [33], (1985)].

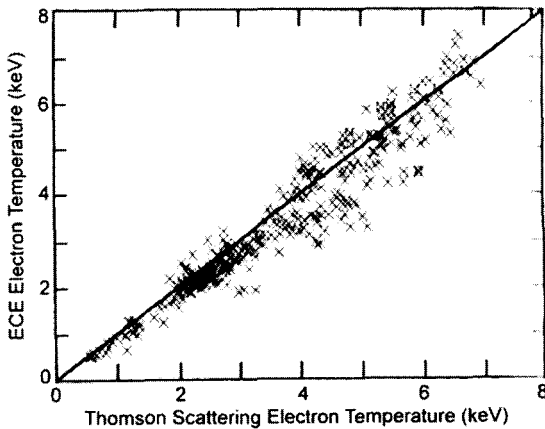


Figure 7. Comparison of measurements of central electron temperature measured by ECE and Thomson scattering on TFTR for pulses which had only ohmic heating during the period 1992–94 (after [34]).

## 5. Applications

The emergence of a measurement technique that can provide the electron temperature ( $T_e$ ) with good spatial and good temporal resolutions (few cms and down to microseconds respectively) over most of the plasma cross-section, for the entire duration of the plasma pulse and with high signal/noise represented a major advance in plasma diagnostics. Immediately many phenomena occurring in the plasma became amenable to study, in some cases for the first time. Not surprisingly the technique received rapid and widespread application.

At that time, the large machines such as TFTR and JET were beginning to achieve high performance and studies of energy confinement, which require good measurements of  $T_e(r)$ , were of central interest. A key topic was 'profile consistency' and measurements of ECE were well placed to contribute to these studies.

"Sawtooth" temporal oscillations were seen in the central values of many plasma parameters including  $T_e$ . The sensitivity of ECE made possible very detailed measurements and enabled the theories of this phenomenon to be challenged. Before the collapse phase the core of the plasma frequently rotated and by assuming this rotation was rigid-body it was possible to determine the internal structure of the plasma from measurements of ECE (Fig. 8) [35]. Good agreement was obtained with independent measurements made by X-ray tomography. Following the sawtooth collapse the heat pulse propagates outwards. Assuming this a diffusive process, it is possible to determine the electron thermal conductivity from the measurements, an important parameter in understanding the energy balance in the plasma. Frequently the plasmas suffer minor disruptions during the pulse when a relatively small region becomes significantly disturbed. Sometimes the disruptions are major and the pulse is lost. Measurements of ECE enable the internal changes of the plasma to be studied during these events (Fig. 9) [36].

The application of ECE was not limited to tokamak plasmas. Stellarator plasmas also have a spatially dependant toroidal magnetic field which, although more complicated, has characteristics which make possible application of ECE. Measurements of ECE have also been used to diagnose mirror plasmas (for example [37]). Some devices, for example spherical tori and reverse field pinches, are over dense (plasma frequency  $>$  electron cyclotron frequency) and for these the ECE at the low harmonics cannot propagate outwards. However, plasmas can support electrostatic electron Bernstein waves (EBWs) and these are strongly absorbed and emitted at electron cyclotron resonances. EBWs can convert to the electromagnetic (ECE) waves near the upper hybrid resonance and thereby allow the inner region of the plasma to be probed by measuring the ECE. Two different mode conversion schemes have been employed [38,39].

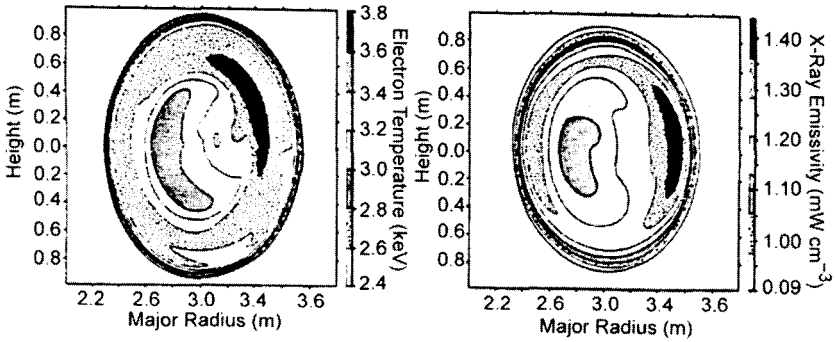


Figure 8. Comparison of 2D temperature contours reconstructed using the ECE tomography technique (left) with X-ray tomography reconstruction (right) just after a sawtooth crash [after [35], (1989)].

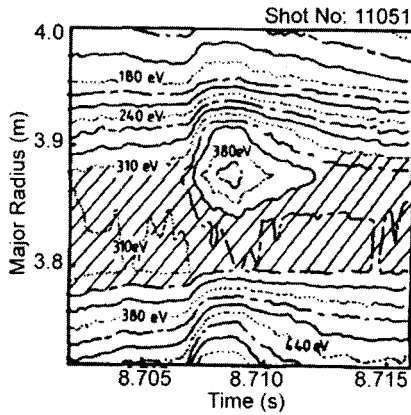


Figure 9. Temperature contours around the  $q = 2$  surface during a minor disruption in which there is a large change in the central temperature [after [36], (1987)].

Utilising the special attributes of ECE and applying correlation techniques developed in astronomy, Sattler and Hartfuss, and separately Cima, successfully measured the fine scale broad band temperature fluctuations [40,41]. By viewing the plasma from two different directions but at the same frequency correlations in the measured signals can be related to fluctuations in the temperature of the plasma in the sampled volume. In an alternative approach, the emission is measured along the same line of sight but with two radiometers operating at slightly different frequencies. Fluctuations due to noise in the detectors are random and therefore cancel: correlated signals are due to fluctuations in the temperature. Using these techniques the authors measured temperature fluctuations at the level  $\sim 1\%$ . Such measurements are important in

studies of the mechanisms underlying energy transport in fusion plasmas. They have recently been reviewed by Watts [42].

## 6. $T_e$ (ECE) vs $T_e$ (TS) Discrepancy: A Problem or an Opportunity?

During the course of the applications of measurements of ECE systematic comparisons of  $T_e$  measured by ECE and those measured by Thomson scattering were carried out. As mentioned above, in general these gave good agreement. However, at high temperatures ( $>7$  keV) Taylor *et al* began to observe on TFTR a discrepancy that was apparently temperature dependant (Fig. 10) [43]. Because Thomson scattering measurements are subject to statistical noise which leads to scatter in the measurement points, it was not at first clear that this was indeed a real effect and since it was contrary to expectations, and potentially very important, very careful experimental work was needed. Systematic errors can occur in both ECE and Thomson scattering measurements and could lead to such an effect. No such errors were found. The observation of a similar effect on JET, where the instrumentation was not only different but in the case of Thomson scattering a different approach was adopted (LIDAR rather than conventional), confirmed the existence of the effect. The most recent results on JET show a most intriguing effect. The discrepancy usually occurs at high temperatures and at these temperatures both the second and third harmonics are optically thick and  $T_e$  can be deduced from each one. When the discrepancy with the Thomson temperature is present there is a difference between the  $T_e$  deduced for the two ECE harmonics with that deduced from the third harmonic being closer to that obtained from the Thomson measurement (de la Luna *et al* [44]).

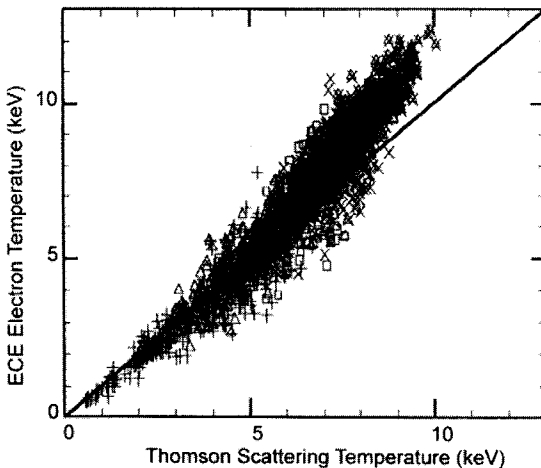


Figure 10. Comparison of measurements of central electron temperature measured by ECE and Thomson scattering on TFTR, including pulses heated with neutral beams, ICRH and ohmic heating during the period 1992-94 (after [43]).

The initial thoughts were that a population of relatively high energy electrons existed in the plasma and they had the effect of raising the average electron energy. ECE and Thomson scattering measurements sample the velocity distribution in different ways and so this could perhaps lead to the discrepancy. However, it was soon realized that because ECE measurements probe the plasma from the low field side, and therefore only sample the low energy electrons in the velocity distribution, they should be relatively immune from such populations. A more likely explanation was advanced by Taylor *et al* at EC-9 and that is that the discrepancy may result from the strong coupling from the energetic ion beams used to heat the plasma with the electrons in the low energy range [43]. As a consequence the electron velocity distribution is distorted in this region and the ECE is enhanced. This could also explain the difference between the radiation temperatures of the second and third harmonics. The optical depth is not so high in the third harmonic and so more of the velocity distribution is sampled. On the other hand, given that electron-electron collisions are very effective at restoring a Maxwellian velocity distribution it is not at all clear how such a distortion can exist quasi-statically.

Thus far very little theoretical work has been undertaken on this topic. An investigation of the effect on ECE and Thomson measurements on a plasma heated with high power ECRH was undertaken by Krivenski [45]. This showed that indeed distortions in the velocity distribution can occur and that both diagnostics are affected but in different ways. He predicts an apparent discrepancy in the measured temperatures and that this would be temperature dependant. These calculations need to be repeated for the beam heated and ion cyclotron heated plasmas of JET and TFTR.

There has been a tendency to regard this discrepancy as a problem and as probably being caused by a systematic error in one of the diagnostics. A common question from those not familiar with ECE or Thomson scattering measurements is "so which diagnostic is right and what is the temperature?" Of course, such a question is ill-posed. If the velocity distribution is non-Maxwellian then the concept of temperature is inappropriate. But even more important, the measurements are apparently telling us that the velocity distribution is distorted and that distortion is probably being maintained by the energy input of the additional heating systems. Since this is contrary to expectations then our understanding of the basic physics of the heating systems has to be questioned and thus there is an opportunity to learn. The experiments currently planned on JET in which the emission will be measured at three different oblique angles are on a good path and should give important additional experimental information. But what this topic really needs is additional theoretical effort.

## 7. Now and in the Future

The many years of successful development and application have resulted in measurements of ECE being used routinely on almost every toroidal device exploited in magnetic fusion research: these measurements are now considered to be part of the basic diagnostic set for such plasmas. But neither the technique nor the applications are standing still.

A recent instrumental development that shows great promise is that of ECE imaging (ECEI). This technique utilises large area heterodyne detector arrays that have been developed recently in the microwave/millimeter wave field. The plasma is viewed with large aperture optics and an image of the plasma is formed on the detector array using ECE (Fig. 11) [46]. By sweeping the LO the viewing chord is swept through the plasma and thereby a 2D image of the plasma in the poloidal plane is formed. By making such measurements on optically thick harmonics and employing the usual frequency to space mapping the spatial profile of  $T_e$  is obtained in 2D. It is possible to carefully control the optics and thereby obtain very good spatial resolution (typically 10 mm), and because of the high sensitivity of the heterodyne receivers, fast sweeping of the LO is possible giving a high time resolution (down to 5  $\mu$ s). Because of the large number of receivers involved, it has been difficult to perform independent calibrations and in the first applications cross calibrations to Thomson scattering measurements have been used. More recently independent calibrations using large area sources have been performed.

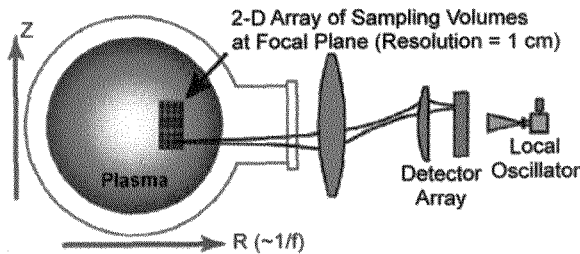


Figure 11. Schematic of the principle of ECE imaging [after [46], (2004)].

This technique is ideally suited to the study of internal structure of the plasma. Recently, some very impressive measurements have been made of the sawtooth oscillations (Fig. 12) [47,48]. The quality of the measurements was such that it has been possible to completely rule out one of the candidate theories of this oscillation. The measurements are not completely explained by any of the theories thereby showing that we still do not have a complete understanding of this phenomenon. It is clear that the development of ECEI represents a major advance in our measurement capability and we can expect many successful applications in the future.

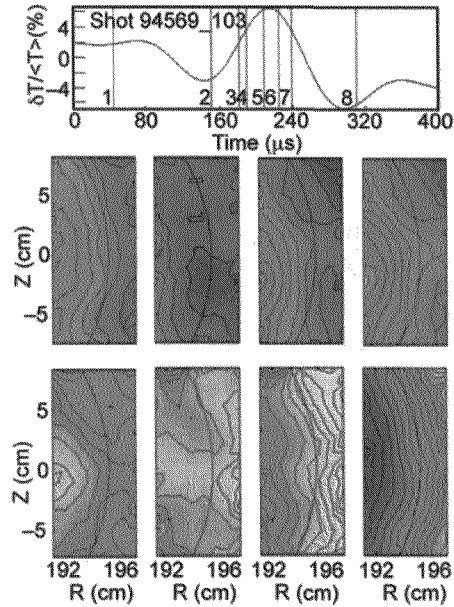


Figure 12. 2D images of the sawtooth crash indicated in the  $T_e$  time trace at  $z = 0$ ,  $R = 191$  cm [after [47], (2006)].

One sign that a diagnostic has reached maturity is when the measurements that it generates are used to control the plasma. In such cases the performance of the plasma is effectively being entrusted to the diagnostic. Measurements of ECE give  $T_e(r,t)$  in real time and so are well suited to be used in feedback loops and there have been several such applications recently. For example, Zerbini *et al* have used ECE measurements of the gradient of the electron temperature to control the amount of additional heating power injected in the plasma (neutral beams or ion cyclotron heating) and thereby control the formation of an internal transport barrier (ITB) [49]. The performance of the plasma is significantly changed by the existence of an ITB and so by this method the performance of the plasma comes under real time control. In another example, internal MHD modes are suppressed by localized heating and current drive from a high power gyrotron [50]. The ECE measurements are used to ensure that the ECRH power is deposited exactly on the spatial profile of the mode.

The fusion community is now preparing for ITER and it is planned that a substantial ECE system will be included in the ITER diagnostic set. In several ways ECE is well suited to diagnosing reactor grade plasmas. It operates in a wavelength range where it will be straightforward to ensure that the plasma facing components (antennas) will be rugged and not damaged by the plasma, and the signal beams can be easily transported to the remotely sited spectrometers and detectors. It produces real time measurements and these

measurements can be made steady state if needed. On the other hand, the relatively high temperatures of the ITER plasma (up to 30 keV) will mean that the spatial resolution will be degraded due to the enhanced relativistic broadening and, for the ITER plasma, the harmonic overlap will restrict the region of the plasma that can be probed (Figs. 13 and 14) [51–53]. A significant technical challenge will be to develop a broadband, large area, radiation hard calibration source that can be mounted in the vacuum vessel at the front end of the system. Work is already in progress on the development of the calibration source, the design of the system and the integration of the front-end components into an ITER radial port.

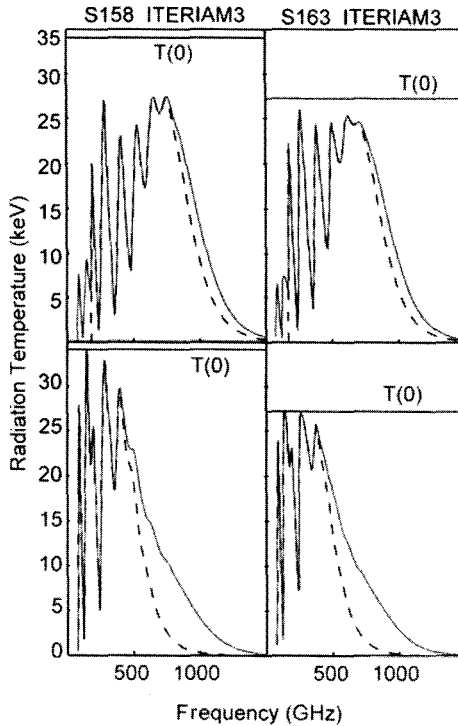


Figure 13. X-mode (top) and O-mode (bottom) emission spectra, with (solid) and without (dashed) reflections, for the ELMy H-mode (left) and Reverse Shear case (right). The reflection coefficients were 0.45 (same polarisation) and 0.15 (cross-polarisation), respectively. ELMy H-mode [after [51] (2001)].

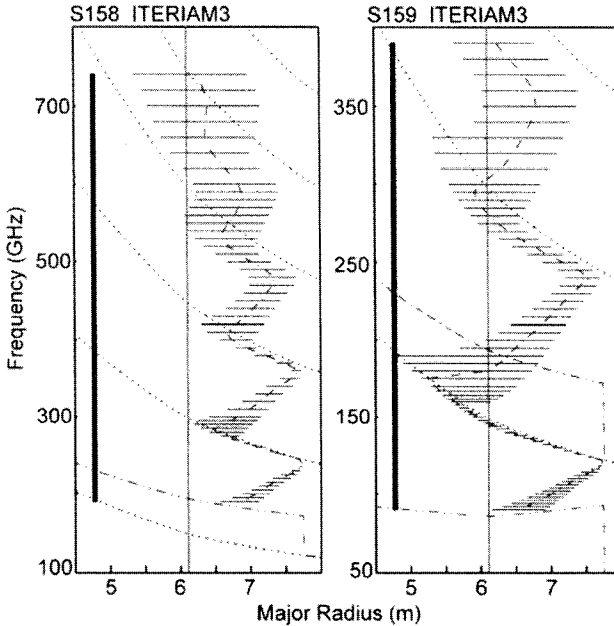


Figure 14. Overview of the X-mode (Left) and O-mode (right) emission characteristics. The horizontal bars represent the width of the emitting layer. The vertical bar indicates the extent of the optically thick region. The vertical line indicates the magnetic axis. ELMy H-mode case [after [51] (2001)].

## 8. Summary and Concluding Remarks

ECE has been at the centre of fusion research since almost the beginning of studies on fusion energy. It entered in a high profile way. Predictions of the power loss due to ECE showed that it could be a threat to economic operation of fusion reactors, especially for the high temperature DD reactors that were originally envisaged. It has kept this high profile ever since but for different reasons. The early measurements gave unexpected results and challenged the theorists and experimenters. 10–15 years of vibrant research followed and eventually led to highly developed measurement instrumentation and a good theoretical basis. This unleashed the diagnostic potential and applications and advances flowed copiously. In some cases, the performance of the plasmas is now entrusted to measurements of the emission through real time plasma control. Almost everything is in good condition except for the unexplained discrepancy between the ECE and the Thomson scattering measurements of  $T_e$  that occurs under high power auxiliary heating conditions. It now seems certain that this is not an instrumental effect or a measurement error: the origin of the discrepancy lies in the plasma. The unraveling of this will be the next major advance in ECE and could have implications for fusion science generally since

it probably goes to the very heart of how the main constituents of the plasma interact. Going forwards, ECE is well placed to play a major role in the diagnosis and possibly the control of the next generation of fusion devices and especially reactor grade plasmas such as ITER. The topic is as rich now as it has ever been in terms of challenge and opportunity. It is remarkable that it could have maintained this position for so long and this, in turn, is a credit to all the many excellent researchers who have used their ingenuity and creative energies on ECE.

### Acknowledgments

I would like to thank John Lohr and the International Programme Committee of EC-15 for the invitation to prepare this paper — a task which I have thoroughly enjoyed.

This report was prepared as an account of work by or for the ITER Organization. The Members of the Organization are the People's Republic of China, the European Atomic Energy Community, the Republic of India, Japan, the Republic of Korea, the Russian Federation, and the United States of America. The views and opinions expressed herein do not necessarily reflect those of the Members or any agency thereof. Dissemination of the information in this paper is governed by the applicable terms of the ITER Joint Implementation Agreement.

### References

1. M. Bornatici, *et al*, *Nucl. Fusion* **23**, 1153 (1983).
2. G. Taylor, *Fusion Sci. Technol.* **52**, 119 (2007).
3. N. C. Luhmann *et al*, *Fusion Sci. Technol.* **53**, 335 (2008).
4. B. A. Trubnikov, *Soviet Phys Dokl.* **3**, 136 (1958).
5. B. A. Trubnikov and A. E. Bazhanova, *Plasma Physics and the Problems of Controlled Fusion*, M. A. Leontovich, Ed, **III** 141 (1959).
6. A. J. Lichtenberg *et al*, *Phys. Fluids* **7**, 1549 (1964).
7. A. J. Lichtenberg *et al*, *Phys. Rev. Lett.* **13**, 387 (1964).
8. M. N. Rosenbluth, *Nucl. Fusion* **10**, 340 (1970).
9. F. Englemann and M. Curatolo, *Nucl. Fusion* **13**, 497 (1973).
10. A. E. Costley *et al*, *Phys. Rev. Lett.* **33**, 758 (1974).
11. D. A. Boyd *et al*, *Phys. Rev. Lett.* **37**, 98 (1976).
12. Ph. Brossier *et al*, *Proc. 6<sup>th</sup> Int. Conf. Plasma Physics and Controlled Nuclear Fusion Research, Berchtesgaden*, 1976, IAEA-C35/Vienna, 409 (1977).
13. A. E. Costley and the TFR Group, *Phys. Rev. Lett.* **38**, 1477 (1977).
14. P. C. Efthimion *et al*, *Rev. Sci. Instrum.* **50**, 949 (1979).
15. B. Walker *et al*, *J. Phys. E: Sci. Instrum.* **14**, 832 (1981).
16. A Eberhagen, *Infrared Physics* **19**, 389 (1979).

17. G Tait *et al*, *Phys Fluids* **24**, 719 (1981).
18. B. Ulrich and M. Tutter, EC-2, 203 Oxford, July 1980.
19. L. Pieroni (unpublished) (1977). For a more recent example see P. Buratti and M. Zerbini, *Rev. Sci. Instrum.* **66**, 4208 (1995).
20. D. K. Akulina, *Proc. Course and Workshop Diagnostics for Fusion Reactor Conditions*, EUR 8351-1 EN 1, 167, Varenna, September 1982.
21. D. J. Campbell, PhD Thesis, University of Sydney (1981).
22. D. V. Bartlett, PhD Thesis, University of Sydney (1976).
23. D. G. Moss, P. G. Quincey and J. R. Birch, *IEE Colloquium on Microwave and Millimetre-Wave Radiometry*, p. 3/1-3/3 (1989).
24. B. Tubbing and S. Kissel, EC-6, 317, Oxford, 1987.
25. H. Bindslev and D. V. Bartlett, JET-R(88)04 (1988).
26. W. H. M. Clark, *Plasma Phys. Control. Fusion* **25**, 1501 (1983).
27. I. H. Hutchinson and D. S. Komm, *Nucl. Fusion* **17**, 1077 (1977).
28. I. H. Hutchinson, *Plasma Physics* **21**, 1043, (1979).
29. P. G. Stokes and A. E. Costley, EC-2, Oxford, July 1980.
30. P. C. Efthimion *et al*, *Phys. Rev. Lett.* **44**, 396 (1980).
31. A. Patchman *et al*, *Nucl. Fusion* **27**, 1283 (1987).
32. M. Austin *et al*, *Phys. Plasmas* **3**, 3725 (1996).
33. F. Stauffer *et al*, EC-5, 65, San Diego, 1985.
34. D. V. Bartlett *et al*, *Proc. 15<sup>th</sup> EPS Conf. on Plasma Physics and Controlled Fusion*, Dubrovnik, Vol. 12B, Part III, 1988, p. 1119.
35. D. J. Campbell *et al*, *Proc 16th EPS Conf. on Plasma Physics and Controlled Fusion* **2**, 509, Venice, March, 1989.
36. N. Salmon *et al*, EC-6, Oxford, September, 1987.
37. S. K. Guharay *et al*, EC-6, Oxford, September, 1987.
38. F. Volpe and H. P. Laqua, *Rev. Sci. Instrum.* **74**, 1409 (2003).
39. G. Taylor *et al*, *Phys. Plasmas* **12**, 052511 (2005).
40. S. Sattler and H. J. Hartfuss, *Phys. Rev. Lett.* **72**, 653 (1994).
41. G. Cima *et al*, *Phys. Plasmas* **2**, 720 (1995).
42. C. Watts, *Fusion Sci. Technol.* **52**, 176 (2007).
43. G. Taylor *et al*, EC-9, 485, January, 1995.
44. E. de La Luna *et al*, this workshop.
45. V. Krivenski, *Fusion Eng. Design* **53**, 23 (2001).
46. H. Park *et al*, *Rev. Sci. Instrum.* **75**, 3787 (2004).
47. H. R. Park *et al*, *Phys. Rev. Lett.* **96**, 195001 (2006).
48. H. R. Park *et al*, *Phys. Rev. Lett.* **96**, 195002 (2006).
49. M. Zerbini *et al*, EC-12, 227, May, 2002.
50. J. W. Ooseterbeek *et al*, EC-14, 232, May 2006.
51. G. Vayakis *et al*, *Fusion Eng. Design* **53**, 221 (2001).
52. M. Sato and A. Isayama *et al*, EC-14, 205, May 2006.
53. M. Austin *et al*, this conference.