Summary of ECE Techniques and Experimental Sessions

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Measurements of ECE from fusion plasmas have been made for more than twenty years and yet the subject is still expanding and developing. Fruitful areas for improvement and new applications are being found and explored by a steadily growing community of specialists. The subject now encompasses measurements of ECE, electron cyclotron absorption (ECA), combined ECE/ECRH for determination of transport coefficients, and correlation radiometry for fluctuation studies. Papers in all these areas were presented at EC8 and the discussions were lively and informative.

Several comprehensive measurement systems for measuring ECE were described. M Talvard et al (CEN, Cadarache) described the system on TORE SUPRA which comprises three Michelson interferometers and 12 Fabry Perot interferometers and has 15 different sight-lines, mostly in the poloidal cross-section but including two oblique viewing sight-lines in the equatorial mid-plane. J Fuchs et al (IPP, Garching) described the system on ASDEX-Upgrade which comprises a scanning Michelson interferometer, an eight channel grating polychromator, and a 16 channel heterodyne radiometer which is under construction. Currently, instrument development is concentrated mainly on heterodyne radiometers and advanced systems were described by D Bartlett et al (JET Joint Undertaking, Abingdon) and D Pinsonneault et al (Centre Canadien de Fusion Magnétique, Varennes). Both systems enable measurements to be made over a wide frequency range. In the case of the system described by Bartlett this is achieved by having 44 measurement channels distributed over the range 73 - 127 GHz, whereas in the system described by Pinsonneault three swept frequency receivers cover the ranges 65 - 69 GHz, 70 - 75 GHz and 75 - 110 GHz.

Most early systems employed oversized waveguides to transmit the radiation but quasi-optical systems have some advantages especially at high frequencies where the losses in waveguide can be high. T Hsu et al (MIT, Cambridge) described an advanced system being prepared for ALCATOR C-MOD. The system uses only reflective optics and is expected to have a high performance. It will operate over a broad frequency range, 100 - 1000 GHz, with low loss and enable an image of the plasma to be obtained with centimetre spatial resolution. The combination of such a system with efficient spectrometers and sensitive detectors offers exciting measurement possibilities especially in studies of small-scale temperature perturbations associated with MHD phenomena. The calibration of the measurement systems continues to be an important area with uncertainties in the calibration frequently limiting the information that can be obtained from the measurements. Two papers deal with developments in this area. Pinsonneault et al also described a recently developed black body cavity which operates at temperatures up to 600°C and has a measured emissivity close to unity. Talvard et al described a method for calibrating Fabry-Perot interferometers. These instruments are particularly difficult to calibrate and so the development of this method represents a significant advance. The method, which involves the coherent addition of a sinusoidally modulated signal and Fourier transformation of the resulting waveform, appears to have a significant practical advantage over conventional synchronous detection and permits a calibration of the full system in an acceptable time.

Analysis and processing of the measurements is clearly important and several papers concentrated in this area. P Buratti and M Zerbini et al (ENEA, Frascati) described an attempt to derive the electron density profile from measurements of the emission in the optically thin third harmonic on FTU. Previous attempts on other tokamaks at such a derivation have found that while the peak density can be obtained profile information is limited principally because of harmonic overlap. This latest work came to the same conclusion. H Idei et al (Nagoya University, Nagoya) described a determination of the electron temperature profile from measurements in the optically thin plasma in the Compact Helical System. By taking into account wall reflections and the plasma density known from other measurements it was possible to derive a temperature profile which agreed closely to that measured by Thomson scattering. In discussion it was generally agreed that the best use of measurements of the emission in the third harmonic is for obtaining information on the electron temperature rather than on the electron density.

An interesting and potentially very important development was described in a paper by D Bartlett and C Bishop (AEA Technology, Harwell). These authors are applying neural network techniques for the conversion of ECE spectra to electron temperature profiles. The network is 'trained' using a large number of temperature profiles measured on JET by LIDAR Thomson scattering. The ultimate aim is to obtain profiles with the low systematic uncertainty of LIDAR measurements, the low random uncertainty of the ECE measurement, but the same temporal resolution as the ECE data. A secondary benefit would be a very fast conversion of the ECE data because once trained only relatively simple calculations are involved. Thus far only preliminary results have been obtained but they are very encouraging.

Small populations of suprathermal electrons can have a dramatic effect on the ECE spectrum and for many years researchers have tried to obtain estimates of the parameters characterising the populations from the measured spectra. D Boyd (University of Maryland, MD) described an experiment on the DIII-D tokamak in which the emission from the plasma along a vertical chord is measured. The plasma is viewed against a radiation dump to minimize the effect of reflections. The novelty in the work concerns the data analysis and two separate approaches were tried. The agreement in the results is encouraging. G Taylor et al (PPPL, Princeton, NJ) described measurements made on the supershot plasmas produced in the TFTR tokamak. These show that for core temperatures less than 6 keV there is good agreement between the temperatures measured by ECE and by Thomson scattering but at high temperatures there is a systematic discrepancy with the ECE values being higher by up to 20%. In addition, a feature appears on the low frequency side of the second harmonic and is believed to be due to an enhanced tail on the electron velocity distribution. The authors interpret the measurements in terms of a bi-Maxwellian distribution. Spectra calculated with a comphrensive code and using such a distribution show good agreement with the measurement. However, this result is contrary to first expectations. At fixed frequency, emission from the suprathermal population occurs at smaller major radius than that from the bulk electrons due to relativistic broadening and, since the optical depth due to the bulk electrons is large, should not propagate to the measurement instrumentation. There does not appear to be a simple explanation for the measurements and so this result, along with the theory underlying this interpretation, stimulated considerable discussion at the meeting.

C Tanzi et al (FOM Instituut, Nieuwegein) reported on the effects of suprathermal populations generated by lower hybrid current drive (LHCD) on ECE spectra measured on JET. Particular attention is paid to the impact on the capability to measure the electron temperature. By comparing ECE derived temperatures with temperatures measured by Thomson scattering it is shown that for LHCD powers $\lesssim 2$ MW the effects are small ($\lesssim 5\%$). However, extrapolation of the results to higher powers shows that when the planned 10MW of LHCD is operational reliable electron temperature measurements will not be possible using ECE. Very similar results obtained on TORE SUPRA were presented by Talvard. He also presented a very intriguing result obtained with the sightlines which view in opposite toroidal directions. The measurements show that even under ohmic conditions a small asymmetry exists and the authors attribute this to a small population of suprathermal electrons associated with the bootstrap current.

Measurements of ECE continue to be used extensively in the study of transient phenomena in which measurements continuous in time with a high time resolution are required. Talvard et al presented measurements during pellet injection and Waidmann et al (KFA-IPP, Jülich) presented measurements on TEXTOR which show that MHD modes and MARFES can be precursors to abrupt current disruptions. Bartlett et al presented measurements on ELMs and MHD modes present in high beta discharges. By correlating the measurements made with different radiometer channels, it was possible to determine the location and spatial extent of the modes.

Measurements of ECA is a potentially powerful technique especially for probing suprathermal populations. The technique enables measurements to be made on optically thin harmonics without the complication of wall reflections. By choosing the sightlines of the measurement, the velocity distribution can be probed in a selected way. J Segui (CEA, Cadarache) described an ECA diagnostic on TORE SUPRA in which the sightline is vertical along a line of constant magnetic field. Preliminary measurements obtained with LHCD were presented. From the measurements, the line-averaged parallel distribution is determined as a function of the parallel momentum. Measurements at oblique incidence enable the contribution to the total current due to the driven suprathermal electron current to be determined. F Skiff and D Boyd (University of Maryland, MD) have studied in detail three important practical aspects of implementing transmission measurements for such an application. They examined the diagnostic resolution and sensitivity, elimination of wall reflections through frequency sweeping and phase-coherent detection, and correcting for the effects of refraction. They propose the use of bi-directional measurements as a means to improve the correction for non-resonant losses such as refraction.

Under some circumstances, measurements by ECA may be useful on thermal plasmas. R Smith et al (JET Joint Undertaking, Abingdon) are preparing a diagnostic based on ECA for probing the plasma that will be produced in the region of the divertor presently installed on JET. The intention is to measure the frequency dependence of the absorption in the second harmonic extraordinary mode from which the spatial profile of the n_e T_e product i.e. the electron pressure, will be deduced. The measurements will be made using a swept frequency interferometer employing long lengths of oversized waveguide and a coherent radiation source. A major practical problem is to separate the signal due to the single pass transmission through the waveguide from signals due to multiple reflections. This will be done by sweeping the frequency of the source and by filtering: the single pass transmission signal will occur at a specific beat frequency depending on the difference in length between the plasma arm and the reference arm.

The technique in which energy is deposited locally by ECRH and the propagation of the resulting temperature perturbation is measured by ECE is a powerful technique for determining the electron thermal conductivity (χ_e) of the plasma. An extensive series of measurements has been made on the W7-AS stellarator and these were described by H Hartfuss et al (IPP, Garching). The deduced χ_e was found to be the same to within a factor 1.5 as that obtained by global power balance. The value of χ_e was found to be independent of the amplitude and frequency of the power modulation. A similar extensive, systematic, series of measurements is required on tokamak plasmas where the χ_e values deduced from sawtooth induced heat pulses are typically several times higher than the χ_e from global power balance. Such measurements are in preparation at the RTP tokamak at FOM and were briefly described by M Peters et al (FOM, Nieuwegein). Peter's paper concentrated on the many possible sources of error in these measurements which have to be executed and analysed carefully if meaningful results are to be obtained.

For many years, researchers have considered the possibility of using measurements of ECE as a means for determining high frequency, broad-band, temperature fluctuations which are believed to exist in the plasma. Such fluctuations would be relevant to the enhanced cross field energy transport which occurs in tokamak and stellarator plasmas. However, noise due to thermodynamic fluctuations in the radiation and volume averaging have thus far limited the measurements and it has only been possible to determine the upper bound of the fluctuations as less than a few percent. Three papers were presented at the meeting on the novel technique of correlation radiometry which should enable measurements to be made to a lower level. G Cima (University of Texas, Austin) discussed the possible options for the direction of the measurements - radial, poloidal or toroidal. Preliminary measurements using radiometers at two different toroidal locations on TEXT-U were presented by M Kwon (University of Texas, Austin). No evidence of fluctuations above the detection limit of 0.5% was found. S Sattler and H Hartfuss (IPP, Garching) described a sophisticated intensity interferometer which is presently being installed on the W7-AS stellarator. The interferometer consists of two identical four channel heterodyne radiometers with a common local oscillator and Gaussian beam optics viewing the same emitting volume along crossed lines of sight. It is predicted to have a spatial resolution of order one centimeter and a measurement limit for fluctuations of less than one percent.

The value of several of the key parameters which determine the level and shape of the ECE spectrum will be substantially different on next-step devices such as ITER. Moreover, the practical environment will be very different: all components close to the machine will be subject to high levels of radiation for long periods, and the measurements and instrumentation will have to be highly reliable and capable of being maintained remotely. Evaluation of the diagnostic potential of ECE measurements for conditions appropriate to next-step devices is required. A preliminary assessment has been carried out by A Costley and D Bartlett (JET Joint Undertaking, Abingdon). They find that it should be possible to measure the electron temperature with good spatial and temporal resolutions over a wide range of plasma conditions. However, the measurements will be limited by several effects, especially relativistic and Doppler broadening which will be substantial at the high temperatures expected. In general, the limitations are more severe than on present-day devices. In order to implement the technique several difficult practical problems will have to be solved and specific developments carried out, and these are identified in the paper.

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