JOINT EUROPEAN TORUS

JET–P(93)59

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Preprint of a paper to be submitted for publication in
Nuclear Fusion (meeting reports)
July 1993

The Eighth Joint Workshop on Electron Cyclotron Emission (ECE) and Electron Cyclotron Resonance Heating (ECRH) was held at Gut Ising, Germany, from 19-21 October 1992. The workshop was organised by the Max-Planck-Institut für Plasmaphysik, Garching. Fifty-six delegates attended and forty-seven papers were presented including five invited papers. The main subjects of the meeting were the theory of electron cyclotron resonance phenomena and the exploitation of these phenomena in plasma diagnostics (ECE and electron cyclotron absorption (ECA)), plasma heating (ECRH) and plasma current drive (ECCD). Significant results were presented in every topic and examined in depth in an open and informal atmosphere.

THEORY AND CALCULATIONS

The theory of electron cyclotron resonance phenomena is highly developed and well documented. The main theoretical tools are well established, generally accepted and able to give a satisfactory description of the main results obtained in electron cyclotron emission, absorption and current drive experiments. In this workshop some advanced theoretical and numerical tools were presented (for example, 3-D Fokker-Planck codes, treatment of the RF beam as a whole, description of non-linear and finite-beam effects) together with proposals for new scenarios for ECE and ECA measurements (for example, for diagnosing suprathermal populations and their radial transport).

Two main topics were analyzed by U Gasparino (IPP, Garching). An extensive and instructive review was given of the application of ECE and ECA measurements to the analysis of suprathermal electron populations. The intrinsic limits of the diagnostics and the possible ambiguities in the interpretation of the measurements were pointed out. In addition, the effects of RF heating on neoclassical transport were treated theoretically, and the RF driven current and particle fluxes both in tokamak and stellarator geometries were discussed. M Bornatici (University of Ferrara and University of Pavia) described the basics of absorption and emission. Expressing the effects of spontaneous emission in terms of a drag force and treating the absorption as a diffusion process in momentum space, the electron heat balance equation was written in a form clearly compatible with the relativistic Fokker-Planck equation for cyclotron radiation. As an application, the relativistic Maxwellian distribution function was shown to be the solution of this equation, in the specific case of the black-body radiation in the Rayleigh limit. E Borie et al (KFK, Karlsruhe) presented the numerical solution of the full dispersion relation for a Maxwellian distribution (including a parallel drift or a temperature anisotropy) and for a loss-cone distribution function. As a specific application, the sensitivity of the cut-off frequency to the velocity space anisotropy of the distribution function was discussed.

At extremely high power densities (as expected for free electron lasers) non-linear mechanisms play a dominant role in the absorption process. R Pozzoli and D Farina (University of Milan and CNR, Milan) analyzed the non-linear interaction of a single electron and an intense spatially localized electromagnetic wave. The trapping time was assumed to be shorter than the time scale of variation of the field amplitude (adiabatic regime, in contrast to the stochastic regime). For the case of perpendicular propagation the results were compared to those of linear theory. In the discussion, R Pozzoli indicated that the condition for entering the weakly non-linear regime $\omega_T \tau_F \geq 1$ (where $\tau_F = L/v_{||}$ is the electron time of flight through the beam, and ω_T is the non-linear trapping frequency in the wave field) could already be fulfilled in heating experiments with gyrotrons (for ordinary-mode first-harmonic the condition reduces to $3x10^{-4}$ P (MW) $(L\omega_{ce}/c)^2>1$).

The application of extraordinary-mode second-harmonic ECE, detected perpendicularly from the low-field-side, to the diagnosis of suprathermal electrons was discussed by A Airoldi and G Ramponi (CNR, Milan) specifically for the case of LHCD. The LH electron distribution function was modelled by superimposing a suitable number of drifting Maxwellians to the Maxwellian bulk. The emission at down-shifted frequencies was shown to be sensitive to the moments of the suprathermal electron distribution function such as the "average" perpendicular energy and density, while its dependence on the "average" parallel energy was shown to be very weak. Airoldi concluded that complementary measurements, for example of the current carried by the suprathermals and the fast electron bremsstrahlung emission, are needed to determine parameters of the fast electrons. To overcome these difficulties, an alternative scenario was proposed by V Tribaldos and V Krivenski (CIEMAT, Madrid). They suggested the use of low-field-side emission detected obliquely at up-shifted frequencies. Under these circumstances at optically thick frequencies the use of a radiation dump can be avoided and the detected emission should originate from regions where the condition $(1-N_{||}^2)^{1/2} < (n\omega_{ce}/\omega) < 1$ is fulfilled. A numerical experiment was performed for LHCD in Tore Supra, using simulated

ECE-spectra for orindary (O)-mode first-harmonic and extraordinary (X)-mode second-harmonic at angles $\Phi=15°$ and $\Phi=20°$ away from perpendicular. Through a numerical analysis of these spectra, the authors reconstructed the electron tail in the resonant portion of velocity space with a good spatial resolution. The class of distribution functions to which this method applies as well as the robustness of the algorithm has still to be addressed.

Two contributions were dedicated to the application of three-dimensional bounce-averaged Fokker-Planck codes describing the time dependent evolution of the electron distribution function under the action of Coulomb collisions, DC electric field, RF heating and radial transport. A G Peeters et al (FOM, Nieuwegein) applied the code to the RTP tokamak. The soft X-ray spectra measured in Ohmic and ECRH-discharges, O-mode first-harmonic from the low-field-side, could be reproduced by the simulations. On the other hand, no plausible explanation could be given to the results of a current drive experiment that used X-mode first-harmonic from the high-field-side. The degradation of the current drive efficiency predicted by the Fokker-Planck calculations to be a consequence of the high power densities and of radial transport is not enough to reconcile the discrepancy between the predictions of linear theory,η_{ECCD}=0.2 A/W, and the upper limit derived from the experiment, η_{ECCD}<0.04 A/W. G Giruzzi (CEA, Cadarache) proposed ECE and ECA as possible tools for gaining an insight into the mechanism for anomalous transport owing to their capability of diagnosing both real space and velocity space. In the case of magnetic turbulence, the $v_{||}$ dependence of the radial diffusion coefficient would tend to pump high energy electrons from the hot central region to the edge. A direct measurement of the induced non-Maxwellian features could be used as an indirect signature for this kind of turbulence. In a numerical experiment, ECE and/or ECA measurements, made vertically on non-central chords (since the non-Maxwellian features are expected to be significant, for, typically, $r > a/2$), as well as in the equatorial plane at large toroidal angle, are shown to be accurate enough to permit these types of measurement in ohmic and LHCD plasmas respectively.

Highly localized ECRH and ECCD as well as diagnostic applications (for example, reflectometry, collective Thomson scattering) have made necessary the development of improved theoretical tools capable of describing the propagation of well focussed radiation beams. As a compromise between the full integration of Maxwell's equation and the usual approach of geometrical optics (i.e. ray tracing), two different approximate solutions have been proposed. A quantitative comparison of the results could give an indication of whether these alternative methods are already robust enough to replace the usual ray-tracing code application. M Lontano and U Tartari (CNR, Milan) presented the quasi-optical approximation, widely used in non-linear optics, for a dispersive anisotropic medium. A geometric optics ray-tracing code can be used to determine the trajectory of the central ray, while the evolution of the beam electric field amplitude and polarization around this trajectory can be described through a diffusion-like differential equation. Alternatively, a closed set of equations for the lowest-order moments of the electromagnetic energy distribution has been derived. Analytical solutions were given for a stationary cold plasma in slab geometry. S. Nowak and A. Orefice (CNR, Milan) treated the problem on the basis of a complex eikonal function, retaining both refractive and diffractive effects. The equation for the complex eikonal allows a quasi-optical treatment, basically preserving the idea of rays (defined as the trajectories orthogonal to the wave-front). Similar to the previous method, ordinary ray tracing can be used to obtain the trajectory of the central ray, and the wave front can be advanced step by step.

ECE TECHNIQUES AND EXPERIMENTS

Measurements of ECE from fusion plasmas have been made for more than twenty years and yet the subject is still expanding and developing. At the workshop, papers were presented on the established areas of the subject, such as instrument and technique development and measurement of transient phenomena, and also on new areas such as the measurement of ECA, correlation radiometry and advanced analysis techniques utilizing neural networks.

Modern ECE systems usually contain more than one type of measuring instrument and several comprehensive measurement systems were described at the meeting. M Talvard et al (CEA, Cadarache) described the system on TORE SUPRA which comprises Michelson interferometers and Fabry Perot interferometers and has multiple sightlines. J Fuchs et al. (IPP, Garching) described the system on ASDEX-Upgrade which comprises a scanning Michelson interferometer, a 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 Canadian de fusion magnetique, Varennes). Both systems enable measurements to be made over a wide frequency range (70 to 120 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. 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.

Analysis and processing of the measurements is clearly important and several papers concentrated in this area. P Buratti and M Zerbini (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. 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. 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 with those measured 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. This is a controversial interpretation and it stimulated a lively debate at the meeting.

C Tanzi et al (FOM Institute, 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 <2MW the effects are small (<5%). However, extrapolation of the results to higher powers shows that when the planned 10 MW of LHCD is operational, reliable electron temperature measurements using ECE will not be possible. Very similar results obtained on TORE SUPRA were presented by M Talvard et al (CEA, Cadarache).

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. M Talvard et al (CEA, Cadarache) presented measurements during pellet injection and G Waidmann et al (KFA-IPP, Jülich) presented measurements on TEXTOR which show that MHD modes and MARFES can be precursors to abrupt current disruptions.

The measurement of ECA is a potentially powerful technique especially for probing suprathermal populations. The technique enables measurements to be made in 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 important practical aspects of implementing transmission measurements for such an application. 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) described a diagnostic technique based on ECA, for probing the plasma that will be in the region of the pumped divertor presently being 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 n_e T_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.

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 (X_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 X_e was found to be the same to within a factor 1.5 as that obtained by global power balance. The value of X_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 X_e values deduced from sawtooth induced heat pulses are typically several times higher than the X_e from global power balance. Such measurements are in preparation at the RTP tokamak and were described by M Peters et al. (FOM, Nieuwegein).

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, system noise 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), R Gandy (Auburn University, AL), and S Sattler and H Hartfuss (IPP, Garching)). Thus far no clear evidence of fluctuations has been obtained, but the new systems in preparation will have an improved sensitivity 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. A preliminary assessment of the diagnostic potential of ECE for conditions appropriate to next-step devices was presented 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, but 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 will be more severe than on present-day devices.

ECRH TECHNIQUES AND EXPERIMENTS

Electron cyclotron heating and current drive is of growing interest both for tokamaks and stellarators. In the last decade, heating powers have been relatively small compared to powers of typical NBI or ICRH systems. Nevertheless, owing to the favourable characteristics of ECRH, it is possible to carry out significant experiments, and the results of several were reported at this meeting. The development of ECRH technology is currently concentrating on high power, high frequency gyrotrons and transmission techniques and several interesting papers on these topics were presented.

There has been considerable progress in the development of gyrotrons since the last meeting three years ago. E Borie et al (KfK, Karlsruhe) described the development of a high power (690 kW), high frequency (140 GHz) gyrotron which operates in a high order cavity mode ($TE_{10,4}$). Thus far, only short pulse (few ms) operation has been achieved, but further development should extend the pulse length to more than 300 ms. The investigations show that more stable operation is obtained by using a built-in quasi-optical mode transducing antenna to convert the rotating $TE_{10,4}$ mode to a Gaussian beam before it propagates through the window. This latter finding is clearly confirmed by the good results of gyrotrons designed at the Institute of Applied Physics, Nizhnij, Novgorod (V. Il'in et al). These gyrotrons emit nearly Gaussian beams with powers up to 1 MW at frequencies up to 166 GHz. The pulse length (0.3 sec at 0.9 MW and >l sec at 0.5 MW) is mainly limited by the window capability. The ECRH experiments, for example at W7-AS, are an impressive demonstration of the performance of these gyrotrons. The results confirm that a 1 MW continuous wave (CW) tube can be built in the near future provided a suitable design can be found for the output window. In this field, the work concentrates on the development of a cryogenically cooled sapphire window as was shown by M Pain et al, (CEA, Cadarache) and E Borie et al, (KfK, Karlsruhe). In spite of possible condensation of many gases on its surface, such a window is seen to be the best candidate for a 1 MW CW vacuum barrier due to the low absorption and the high thermal conductivity of sapphire at low temperatures.

The transmission of millimetre waves in systems which operate at frequencies below 100 GHz at high power (> 200 kW) is effected mainly with smooth-walled waveguides. Usually, the TE_{02} output mode of the gyrotron is transformed to the TE_{01} mode, which is used for transmission, and near to the plasma this mode is converted into an HE_{11} mode by an in-waveguide converter or into a beam with a Vlasov converter. The papers on this subject by T Bigelow et al (Oak Ridge National, Lab, TN), T. Luce et al (GA, San Diego, CA), and W Kasparek (University of Stuttgart) show that this technique is highly developed and that work is mainly aimed at improving the different components or at adapting the antenna systems to requirements given by particular heating experiments.

Several papers dealt with the transmission of millimetre waves with powers in the MW range at frequencies of more than 100 GHz. For this purpose mainly transmission of the HE_{11} mode in corrugated waveguides or the TEM_{00} mode with beam waveguides as well as the combination of both techniques is considered. M Pain et al. (CEA Cadarache) described the 110 GHz/3MW ECRH system planned for Tore Supra. The system uses evacuated corrugated waveguides. This permits a sequence of mode converters with a reduced diameter to be used to transform the TE_{64} output mode to the HE_{11} mode. In addition, it means that a vacuum barrier window is not needed at the tokamak. A similar system is being installed at DIII-D. One channel is already in operation.

A purely quasi-optical ECRH system at 140 GHz is in operation on W7-AS (V Erckmann et al, IPP, Garching. W Kasparek, University of Stuttgart). This transmission line demonstrates a high performance of beam waveguides and the associated quasi-optical components such as polarizers, directional couplers and mode analyzers. Measured transmission efficiencies are in good agreement with theory. Alignment and long-term stability are not critical. Therefore, this system is seen as a basis for the development of multi-beam waveguides, which could be a simple and cost-effective solution for the transmission of high-power millimetre waves. For the planned ECRH system on LHD in Japan, intensive development work for HE_{11} transmission is under way, as was shown by K Ohkubo et al. (NIFS Nagoya). Codes for near-field and far-field calculations have been written and applied to mode purity measurements of the HE_{11} mode, which permits the detection of small amounts of spurious modes. The modelling of gaps in the waveguide yields losses which are approximately 30% higher than calculated by the analytical formula. Results for phase-correcting mitre bend mirrors mainly confirm calculations of other authors.

The determination of the exact mode composition of the HE_{11} mode in corrugated waveguides in terms of eigenmodes of the smooth waveguide has been performed with a scattering matrix code and was presented at the workshop by D Wagner et al (University of Stuttgart). This work is a basis for the optimization of grooved waveguides with respect to the low attenuation of the HE_{11} mode and the high damping of all the other modes as well as for precise calculations of the fields and the propagation constants as a function of the groove parameters. The code is also useful for the design of any axially symmetric mode converter, Bragg-reflector, cavity or waveguide filter.

The exact calculation of wave propagation in strongly oversized (waveguide or quasi-optical) systems with Kirchhoff-Huygens integrals consumes a considerable amount of computer time. Therefore, the technique which divides apertures with complex field distributions into subapertures with known radiation pattern is of great interest. P Winning and M Nakajima (Kyoto University) demonstrated the method. The total pattern, which is the sum of the individual patterns of the subapertures, showed good agreement with exact theory, especially for the main lobe. For typical calculations, the computer time could be reduced by two to three orders of magnitude.

A technique which up to now has not been applied to ECRH systems, but is potentially very important for high-power systems, is power combination of several sources. Schemes for combining beams of coherent radiation, and for combining beams of incoherent radiation, were reviewed by W Kasparek (University of Stuttgart). F Smits (CEA, Cadarache) presented several new types of diplexers that permit a combination of beams from two incoherent sources even when there is a small frequency difference between the sources.

Recent results from the 60 GHz inside launch ECH system on the DIII-D tokamak were presented by T Luce (GA, San Diego). The use of the X-mode shows a clear extension of the accessible density by nearly a factor of two with respect to O-mode heating. Global confinement is approximately described by the Rebut-Lallia scaling law and a nearly linear scaling with the toroidal field. Off-axis heating experiments clearly show an inward transport of electron energy, the mechanism of which is still not clear. In these experiments, soft-X-ray measurements show strongly localized absorption of the waves as predicted by ray tracing calculations and rule out on-axis power absorption as a possible source of errors.

ECRH experiments at 140 GHz on the W7-AS stellarator were reported by V Erckmann et al (IPP, Garching). The high frequency allows heating of plasmas with densities up to $1.1 \times 10^{20} m^{-3}$, where strong collisional coupling between the electrons and ions is detected. For the first time, a transition of the discharge to an H-mode plasma state was observed in a stellarator. This type of discharge could be produced only for separatrix dominated plasmas with densities above $4 \times 10^{20} m^{-3}$ in regions around rotational transform i = 0.5. Essentially all the H-mode related phenomena experienced on tokamaks occurred: Improved particle confinement, drop of D_a line emission signals, reduction of the magnetic turbulence level, edge localized modes, a pronounced steepening of the edge temperature gradient, an enhanced poloidal plasma rotation velocity and an increase in energy confinement.

Under some circumstances, ECRH systems can also be used for diagnostic purposes. At the RTP tokamak the transmitted beam of the ECRH system is detected by a nine channel detector array. F Smits et al (FOM Institute, Nieuwegein) presented measurements of the transmitted beam and comparisons with theoretical predictions which take into account refraction, scattering and absorption. At low densities, refraction measurements and calculations agree whereas at densities near cut-off significant differences are observed which could be due to finite wavelength effects. A result from transmission measurements is the surprisingly high amount of radiation (up to 30%) which can be scattered by electron density fluctuations before reaching the resonance layer. Other experiments show a significant toroidal asymmetry of the absorption of the beam and O- to X-mode conversion. These effects may give information on non-Maxwellian distribution functions.

NOTE ON THE NEXT WORKSHOP

At the end of the workshop, the delegates discussed in an open forum the content and format of the workshop with a view to making recommendations for the next meeting. It was generally agreed that this meeting gave the opportunity for all the electron cyclotron resonance phenomena in fusion plasmas to be covered satisfactorily. It was agreed that the emphasis should be on theoretical and technique developments rather than on applications which are well covered in other meetings. The workshop nature of the meeting was thought to be important and should be maintained. It was generally agreed that the next meeting should be held in about two years time. This meeting will be hosted by General Atomics and held in California, probably in early 1995.

On behalf of all the delegates, the authors of this summary would like to express their gratitude to Dr Hans Hartfuss and Dr Volker Erckmann and the Conference Secretary, Mrs C Stahlberg, for their care and attention in the organisation of the workshop, and to the IPP, Garching, for its support. Every aspect of the organisation was excellent. These meetings have established a very high standard of scientific content and this meeting fully lived up to expectations. They have also established a tradition of open, constructive debate in a friendly and informal atmosphere. This meeting also fully lived up to this tradition and will, we believe, prove to be a landmark in the development of this important field.