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SUMMARY OF THE EXPERIMENTAL SESSION EC–10 WORKSHOP

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SUMMARY OF THE EXPERIMENTAL SESSION EC–10 WORKSHOP

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This review summarizes a subset of the EC–10 presentations which had been assigned by the organizing committee identification tags beginning with EX. There were fourteen presentations in this group, seven oral and seven posters. Included among the oral presentations were two invited talks. With the exception of the review of plans for electron cyclotron waves in ITER, these were all reports of physics experiments or operational experience as opposed to accounts of hardware development.

1 EC System on ITER

As the definition of the ITER project takes shape, advocates of the candidate schemes for heating and current drive are considering the not insignificant technical challenges facing implementation of large auxiliary systems on the machine. B. Lloyd (UKAEA, Culham) presented a review of the current thinking regarding electron cyclotron (EC) waves on ITER and discussed the present state of the plans. The conclusion from his presentation was that use of EC waves on ITER will be a key element in the arsenal of heating and current drive schemes, but that in this unfamiliar operating regime careful attention must be paid not only to the technological details but also to the physics details affecting implementation

The presentation highlighted the advantages for the use of EC waves on ITER: current drive on or off axis, no problems with damping on the alpha particles, a relatively simple launcher, and high efficiency for localized power deposition and current drive. The EC waves can be used for breakdown, for heating, for current drive, for burn control, for MHD mitigation and potentially to generate a soft shut down in a disruptive discharge. On the other hand, ITER is a unique device the parameters of which require some adjustment to familiar thinking about EC waves.

The physics regime on ITER, with high beta and concomitant large Shafranov shift, effectively spreads the power deposition profile in flux space even for the relatively localized EC waves. Changing plasma conditions during the evolution of an ITER discharge will require dynamic changes in the frequency and/or injection geometry, both toroidally and in all likelihood poloidally for the EC waves. Achieving good central current drive efficiency will compromise the off-axis efficiency and may require some of the gyrotrons to operate at, say, 150 GHz rather than 170 GHz. The inaccessibility of the installed hardware will require new standards of reliability to be achieved without compromising utility.

In the question period, it was pointed out that the requirement for 50 MW is based mainly on the H–mode threshold and that operation in the so-called AT regimes could require 2–3 MA off axis current drive, which is difficult to achieve by any of the proposed current drive mechanisms. High field launch is not possible in ITER due to complexity and the need to avoid the second harmonic resonance in the transmission line.

2 Transport

A group of presentations highlighted the use of electron cyclotron heating for transport studies. Results of a series of experiments on RTP in which the formation of a thermal transport barrier was studied were presented by M.R. de Baar (FOM, Nieuwegein). In these experiments, edge heating produced a hollow current density profile in which it is probable that the negative central shear configuration was achieved in steady state. There appeared to be a bifurcation in the NCS confinement with the better regime having 30% higher electron temperature than the lower regime. An experiment was performed in which the power deposition profile was changed dynamically during the discharge and this resulted in observation of three relatively stable values of the central T_e. as the power deposition location was scanned. With central heating, the central T_e was highest. Then, over a range of intermediate heating locations, central T_e was nearly constant at about 60% of the central heating value. The central temperature dropped further for extreme edge deposition. The conclusion was that a transport barrier could have been created near the $q = 3$ surface. In a poster, deBaar showed evidence for a transport barrier near the $q = 1$ surface as well from modulated transport measurements performed with the power deposition scanned across the $q = 1$ surface. There was no evidence for heat pinch from Thomson scattering measurements of $T_e(r)$ profiles.

The simplicity principle, which states that generally a simple explanation of a phenomenon is more likely to be correct than a convoluted explanation, was used by U. Gasparino (MPI, Garching) as reported by H. Hartfuss (MPI, Garching) to stimulate analysis which demonstrated that a convective term was not required to explain the electron heat flux measured during modulated transport experiments on W7–AS. In the experiment, power was deposited from gyrotrons at central and off-axis resonant frequencies. Two sets of data were obtained, one with the centrally resonant gyrotron modulated and the off-axis tube constant and the second with the off-axis power modulated and the central power constant. The off-axis modulation results could only be explained by invoking both diffusive and convective transport, which was not consistent with the on axis results. This lack of symmetry in the transport process was resolved by showing that for continuous gyrotron operation the power deposition in the center was itself modulated by the heat pulses propagating inward from the absorption region for modulated off-axis power and no convective term was required.

The flattened temperature profile just after a sawtooth crash cannot drive transport which depends on ∇T_e. This was used by G. Cima (TEXT, Austin) in an experiment where a controlled value of ∇T_e was generated by ECH on top of such a flat profile. Using this gradient free target, he showed that χ_e was no more than 10 times the neoclassical value.

3 Suprathermals

Previous attempts to determine $f_e(v)$ in discharges with suprathermals have used modeling and a view along a line of constant magnetic field, however the problem is poorly determined and technical details such as refraction have made interpretation difficult. J. Van Gelder (FOM, Nieuwegein) analyzed ECH data from RTP in the context of a radiation model using Fokker-Planck calculations to obtain scaling and ECE measurements from both the low and high field sides plus direct measurements of the optical depth to provide additional constraints. The result was an estimate of the non-thermal tail temperature of 5–7 keV with a density of 2%–5% of the bulk density and with the suprathermal population located within 2.5 cm of the discharge center.

The usual signature of a suprathermal population is emission peaking at frequencies corresponding to thermal emission from the edge but originating from high energy electrons located at the discharge center. The usual interpretation of these spectra in all cases was challenged by A.G. Peeters (MPI, Garching), who investigated such spectra in a class of ASDEX-U discharges with large ∇T_e in the scrape-off layer. The emission was affected by ELMs, which would not have been the case for a centrally localized population. The observations can be explained by anomalous transport of a fraction of the high energy electron population from the center to the optically thin edge of the plasma. The main point is that locally non-thermal ECE levels can in fact be generated by high energy electrons which actually are located at the edge.

Non-thermal distribution functions with inverted transverse population density can drive substantial energy losses through excitation of Langmuir oscillations as conjectured by V. Pozniak (Kurchatov Inst., Moscow) from analysis of ECE signals during high power ECH on T–10. Effects such as this may occur due to the extremely large ECH power density on this moderate-sized tokamak when 1.5 MW is injected and may be seen on the next generation of ECH experiments as they come on line at other devices.

Another suprathermal result was presented by V. Rozhdestvensky (Ioffe Inst., St. Petersburg) comparing ECE during the Ohmic and LHCD phases of discharges on FT–2. In the Ohmic case, even at moderate density substantial nonthermal ECE, correlated with HXR emission, was observed, and this increased during LHCD unless the density was increased to values where the LHCD efficiency was low.

4 System Installations

Several installations are beginning to operate the new generation of nominally 1 MW gyrotron systems and there were several reports presenting technical details and the first experiments using these systems. At the EC–7 meeting in China in 1989, experimenters were concerned because of difficulties the gyrotron manufacturers were having with development of high output tubes. The developers have responded and the results are beginning to appear.

Perhaps as a cautionary note, D. Akulina (General Physics Inst., Moscow) presented an analysis of ECH experiments on the L–2M stellarator using two gyrotrons at 75 GHz in which she indicated that, although the absorption should be excellent, only 45%–60% of the input power can be accounted for by standard measurements such as diamagnetism. There are some suprathermals generated, and an experimental program using this system is just beginning.

The 110 GHz system on DIII–D was described by J. Lohr (GA, San Diego). This system currently has two gyrotrons, one from Gycom and one from CPI.

Initial results indicate that the windowless evacuated transmission line works well and that both tubes inject about 0.5 MW into the tokamak. In the first injection into plasma using the Gycom gyrotron, a 10 keV electron temperature was created with a slight suprathermal tail. This was a record value of T_e for DIII–D.

The ambitious installation on the versatile TCV machine is now coming on line and was described by M. Tran (Lausanne). TCV has demonstrated a large number of highly non-circular equilibria, including 1 MA plasma current at elongation of 2.3. The ECH system incorporates 40, 82.7, and 118 GHz gyrotron systems, corresponding to f_{ce}, $2f_{ce}$, and $3f_{ce}$, respectively. The 40 GHz system has been used in breakdown studies and for heating. About 280 kW has been injected and $T_e = 3.5$ keV was achieved. The 82.7 GHz system is a 3 MW system and the 118 GHz system will be 1.5 MW with vertical launch. The goal is auxiliary heating at four times the Ohmic heating power for 2 sec pulse lengths and this is consistent with demonstrated capabilities of all elements in the heating systems.

The RTP tokamak now combines two Varian gyrotrons at 60 GHz producing 200 kW for 100 msec with a Gycom 110 GHz gyrotron at 110 GHz producing 500 kW for 200 msec pulses. The 60 GHz injection is both from the low and high field sides and the 110 GHz at the second harmonic injects from the low field side. R. Polman (FOM, Nieuwegein) described that a main thrust of the experiments has been studies of co- and counter-current drive. Although a direct $j(r)$ measurement is not available, the sawtooth behavior is consistent with substantial ECCD and this is supported by scans of B_T. Analysis is continuing to resolve some discrepancies between theory and the experimental results particularly regarding the magnitude of the driven current.

5 The Oscar

The venue for detailed physics studies of wave propagation and mode conversion tends to be small dedicated experiments in university laboratories rather than major fusion devices at national laboratories. Notwithstanding this tendency, from time to time a team will actually attempt such a study at one of the major installations.

H. Laqua (MPI, Garching) won the experimental session Oscar for most complete physics experiment with a report of demonstration of the mode conversion cascade from O to X–mode with subsequent excitation of Bernstein waves on W7–AS. Above the O–mode cutoff, for small oblique angle, an O–mode wave can be refracted so that it travels parallel the magnetic field. If this occurs at the upper hybrid resonance, conversion to X–mode and thence to a Bernstein mode can occur. The Bernstein wave is resonant at harmonics of the electron cyclotron frequency and for the first time the W7–AS group demonstrated propagation and resonant absorption of the electron Bernstein wave at high density. The experiments also showed the nonlinear response, the opening of the angular window for the process with density fluctuations or a steep density gradient, and the characteristic parametric spectrum. A record T_e of 4 keV on W7–AS and ion thermal conductivity at the neoclassical value were also reported.

6 Conclusion

The presentations reported in the experimental session suggested that ECH and ECCD must now be considered to be mature technologies for fusion applications. Both ECH and ECCD have been demonstrated with relatively good, and in some cases spectacular, agreement with the theory. The required high power sources are now available more or less off the shelf in a range of frequencies and several research programs are putting into service ambitious electron cyclotron installations which make use of advanced high power transmission lines. All this is occurring just in time for the work to have a positive impact on ITER planning.

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