CONFERENCE REPORT

Summary of the EC-17, 17th Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating, 7 – 10 May 2012, Deurne, The Netherlands.

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Abstract. An overview is given of the papers presented at the 17th Joint Workshop on Electron Cyclotron Emission (ECE) and Electron Cyclotron Resonance Heating (ECRH). The meeting covered all aspects of the research field ranging from theory to enabling technologies. From the workshop, advanced control by electron cyclotron heating and current drive is emerging as probably the main application of ECRH in fusion devices. Large progress is reported from various experiments on real-time control applications. At the same time ECE is developing into a multi dimensional plasma diagnostic taking advantage of new technological developments. The resulting multi dimensional ECE data reveal exciting new details of the complicated plasma dynamics in fusion devices.

1. Introduction

The EC-17, 17th Joint Workshop on Electron Cyclotron Emission (ECE) and Electron Cyclotron Resonance Heating (ECRH) was held in Deurne, The Netherlands, on May 7–10, 2012. The workshop was hosted jointly by the Control Systems Technology and Science and Technology of Nuclear Fusion Sections of the Eindhoven University of Technology and the FOM Institute DIFFER, Dutch institute for Fundamental Energy Research (formerly known as FOM-Rijnhuizen). This is already the 17th in a unique series of meetings in which not only the theory and experimental achievements in the field of ECE and ECRH are discussed, but in which also the progress in various enabling technologies are presented. The programme committee consisted of eleven active researchers in the wide range of topics covered by the meeting and at the same time representing the world wide community contributing to the field: Egbert Westerhof (Chair, The Netherlands), Max Austin (USA), Young-Soon Bae (Korea), Gregory Denisov (Russia), Daniela Farina (Italy), Mark Henderson (ITER-IO), Shin Kubo (Japan), Y.R. Lin-Liu (Chinese Taipei), John Lohr (USA), Burkhard Plaum (Germany), and George Vayakis (ITER-IO).

The meeting was organized along four main themes: electron cyclotron wave theory, experiments applying electron cyclotron waves for resonant plasma heating (ECRH) and current drive (ECCD), experiments using the measurement of electron cyclotron emission (ECE) as a diagnostic for plasma properties, and the enabling technologies. Additionally, two sessions were dedicated to the application in ITER of ECRH and ECCD and of ECE, respectively, covering the whole range from modelling of ECRH/ECCD and ECE to the design of ECRH and ECE systems for ITER and the required high power microwave source development. The contributions in each of the main themes (including the relevant contributions from the special ITER sessions) are summarized in this conference report. As this summary shows, both ECE and ECRH are developing into ever more accurate and detailed diagnostic and actuator of fusion plasmas enabled by technological developments resulting in higher dimensional or increasingly more flexible tools. While 3D imaging of the plasma emission is now possible, real-time plasma stability control is emerging as a prominent application of ECRH.

Most authors submitted proceedings papers, which have been published on-line in the open access EPJ Web of Conferences journal [1]. Papers that can be found in these proceeding will not be explicitly referenced in this report. Several of the exciting new results reported at the meeting have already found their way in recent journal publications as indicated by references.

2. Theory

A total of 15 contributions were presented in the Theory and Modelling session. One Theory and Modelling paper was included in the ITER ECRH and ECE sessions each. Three papers were in the area of nonlinear physics discussing parametric processes accompanying ECRH. Eight papers were based on the quasi-linear theory of wave heating and current drive. Three of these addressed the application of ECCD for NTM stabilization. Two papers considered scattering of EC waves by edge density fluctuations and related phenomena. In this summary, we briefly describe the highlights of these contributions. Papers concerning modelling of various aspects of ECE are reported in the ECE session.

2.1. Parametric effects

In a set of two presentations, E.Z. Gusakov and A.Yu. Popov analyzed three possible parametric decay processes for second harmonic X-mode waves in toroidal devices: ($t \rightarrow t' + \ell_{IB}$, $t \rightarrow \ell_{EB} + \ell_{IB}$, and $t \rightarrow \ell_{UH} + \ell'_{UH}$, where IB, EB, and UH, respectively, stand for the ion Bernstein, electron Bernstein, and upper hybrid waves). They found that the instability threshold could be substantially reduced (up to 5 orders of magnitude) if trapping of one or both daughter waves occurs preventing convective losses of the daughter waves. Such trapping is possible in a non-monotonous density profile as, for example in case of a hollow central density or in case of local density peaking inside a magnetic island, or in case of poloidal magnetic field inhomogeneity. The theory is proposed as a plausible cause for anomalous backscattering observed at TEXTOR and for ion acceleration and heating at TJ-II and TCV accompanying ECRH [2]. Confirmation of these theoretical proposals still requires more quantitative comparison with experiments.

The parametric excitation of surface electron cyclotron waves relevant for plasma technology was discussed in a contribution from V.O. Girka.

2.2. Wave heating and current drive

In this category, there were four papers devoted to the modelling of operational scenarios using ECRH and ECCD and one paper discussing an adjoint calculation of the ECCD efficiency.

Within the ITER ECRH session D. Farina presented a thorough analysis of the capabilities of the ITER ECRH equatorial launcher using the GRAY quasi-optical beam tracing code including the state-of-art CD package of Marushchenko [3]. The equatorial launcher is shown to be able to contribute to a wide range of ITER scenarios and fields, in all phases of the discharge. It is suggested that the radial coverage of the system can be extended considerably by changing the poloidal rather than the toroidal steering of the current design.

E. Poli gave a talk on an assessment of ECCD-assisted operation on the DEMO reactor (under design). The major modelling tool in this work is his TORBEAM code which includes now the fully-relativistic absorption routines of the GRAY code and the state-of-art CD package of Marushchenko [3]. He found that under optimum conditions the figure of merit of ECCD can reach a value of $\gamma = R n_{20} I_A / P_{EC} \sim 0.3 - 0.4$ comparable or better than that of neutral beam current drive. This is achieved by using fundamental O-mode waves at a high frequency and large parallel refractive index, yet avoiding parasitic damping at the second harmonic in the high temperature (50 keV) DEMO plasma by moving the point of injection to the high field side using an upper port of the vacuum vessel.

A talk on scenario modelling for the W7-X stellarator (under construction) was given by N.B. Marushchenko. He used his TRAVIS ray-tracing and current drive code coupled with VMEC (stellarator equilibrium code) and stellarator transport codes for performing simulations of various issues involving the operation of W7-X. The most important finding of the work is that the optimum ranges of magnetic field B_0 for start-up (using second harmonic X-mode at low to moderate density) and steady state operation (using second harmonic O-mode at high density and pressure) do not overlap. The adjustment of the magnetic field during high performance operation seems necessary.

The last paper on scenario modelling was the poster presentation of L. Figini on the code benchmarking for ECRH and ECCD scenarios in ITER under the European Integrated Tokamak Modelling Framework. This is a new European version of Ron Prater's code benchmarking [4]. A total of five European codes participated in this benchmark ranging from ray tracing and Fokker-Planck codes to quasi-optical and beam tracing codes. There is general agreement among predictions for the EC power deposition and current profiles. The differences between these predictions are coming from differences in the beam description between beam- and ray-tracing codes and from different treatments of the plasma-vacuum boundary in the codes.

Y.M. Hu gave a poster presentation which developed a relativistic model of ECCD efficiency based on Hirshman's variational principle. The model is similar to that of Marushchenko's [3] with a different set of variational basis functions.

2.3. ECCD for NTM stabilization

Another series of papers addressed the topic of neoclassical tearing mode (NTM) suppression by ECCD. These papers made more realistic modelling than the standard treatment. I. Chatziantonaki, considered the effects of island geometry on the wave propagation, deposition, and current drive. The power deposition and current drive efficiency were shown, as expected, not to be significantly affected due to the small perturbations in magnetic field, plasma density, and electron temperature originated from island formation. Nevertheless, the instantaneous flux surface averaged absorbed power density and driven current density are greatly enhanced by the small flux surface volume of the magnetic islands [5]. The correct account of these effects on the growth or suppression of NTMs, requires proper averaging of these current densities over the different phases of the island as it rotates through the EC power deposition region. An investigation along this line of thought was provided by B. Ayten and E. Westerhof. In their model, the instantaneous power deposition is calculated with account of island geometry and rotation. The driven current density, which is obtained through a simplified time-dependent current drive equation, is then incorporated into the modified Rutherford equation to determine the evolution of the island width. There are three time scales involved in the problem: τ_{coll} (collisional relaxation time), τ_{rot} (island rotation time), and τ_{NTM} (island growth time). The conventional approach averaging the ECCD over a full island rotation period is shown to be valid in the limit $\tau_{rot} << 0.01\ \tau_{NTM}$, while $\tau_{rot} >> \tau_{NTM}$ is identified with the locked mode regime. An increase of the averaged stabilizing effect was shown for $\tau_{rot} \sim 0.1\ \tau_{NTM}$ and larger [6].

J. Pratt and E. Westerhof reported plans to use the nonlinear reduced-MHD simulation code, JOREK [7] to study NTM dynamics more quantitatively in the future.

2.4. Wave propagation in the presence of density fluctuations

Finally, two papers were devoted to the study of the effects of edge density fluctuations on the propagation of EC waves and related phenomena. A. Ram gave an oral talk which emphasized the importance of these effects for ITER operation and discussed general theoretical approaches for dealing with wave propagation in such a random medium. J. Decker presented a poster presentation of their work on this problem. They used an electrostatic turbulence model to describe the density fluctuations and ray-tracing techniques for wave propagation and deposition in successive perturbed equilibrium states. They concluded that the effects of fluctuations could improve the modelling of fully non-inductive ECCD discharges in the TCV tokamak: the wave scattering off edge density fluctuations can explain the current profile broadening and concomitant suppression of nonlinear effects as observed in the experiments. They also discussed implications of their theoretical results on the stabilization of NTMs in ITER.

3. Electron Cyclotron Resonance Heating experiments

The 19 contributions in the ECRH experiments sessions covered a wide range of applications. From these, real-time and feedback control is emerging as the most prominent application of ECRH with a total of 8 papers within this session alone. Four papers addressed the development and status of ECRH systems and subsystems in DIII-D, ASDEX Upgrade, and KSTAR. The remaining papers discussed the detailed applications of ECRH ranging from transport studies, high energy electrons and their effect on plasma stability to electron Bernstein wave heating and ECRH plasma start-up assist.

3.1. Real-time control, feedback control

One of the hot topics of ECRH experiment discussed in this workshop was real-time control or feedback control fully utilizing the local controllability and fast time response of the ECRH system. The real-time system for MHD activity control in the FTU tokamak was presented by C. Sozzi. The several hardware components and control algorithms implemented on FTU for the feedback control of MHD activities (sawtooth, NTM) were discussed. Initial tests were shown to be successfully executed. A related series of papers on FTU was presented by E. Alessi on the real-time data interpretation required for the feedback control, C. Galperti (in the technology session) on the technical specifications of the real-time controller and A. Moro on the real-time ECRH launcher control.

ELM control or pacing as well as the suppression of MHD instabilities are also a hot topic of ECRH experiments. Outstanding experimental results in TCV were presented in two papers by F. Felici and M. Lauret. Utilizing newly installed real-time antenna control system with flexible digital real-time control system, sawtooth pacing, ELM pacing, and NTM suppression were demonstrated [8,9].

J. Lohr reported the development of and execution of real-time control schemes in DIII-D. Both the plasma control system (PCS) and field programmable gate arrays (FPGA) connected to ECRH system were shown to allow fast control of the injection angle and gyrotron output power. These capabilities are utilized to control plasma instabilities and secure operation of the gyrotrons as well.

A new fast steerable launcher and ”NTM feedback suite” (equilibrium, density profile, ray tracing, correlation analysis, mirror control) are implemented in ASDEX Upgrade were presented in a talk by J. Stober. Successful feed-forward tests of the system were shown. In the mean time also the feedback control has been demonstrated [10].

ECH and ECCD effects on NTMs stabilization by ECRH is also investigated for JT-60SA tokamak and presented by C. Sozzi.

3.2. ECRH system upgrades and demonstration of its potential

In his presentation of the applications of ECRH on the DIII-D tokamak, R. Prater thoroughly reviewed the potential of ECRH in the investigation of the tokamak operation. Topics included are the effects of electron heating on plasma rotation and H-mode threshold power, modifying the temperature gradient for studying the trapped electron mode, and QH-mode. In ITER demonstration discharges, the many different roles of ECCD were demonstrated: radially distributed current drive in support of fully non-inductive operation at high beta; control of neoclassical tearing modes. In addition ECCD was shown to be crucial in experiments on resistive wall modes in low rotation, high beta discharges, studies of the validation of resistive MHD models, and development of model-based current profile control. In accordance to the increasingly important role of ECRH, the DIII-D ECRH system is proposed to be upgrade to a total injection power of up to 12 MW.

J. Stober reported on the ongoing upgrade of the ASDEX Upgrade multi frequency ECRH system (140/105 GHz): the injected power reached 3.9 MW at 140 GHz and 2.1 MW at 105 GHz. The enhanced ECRH power was used for several physics studies such as H-mode optimization. In relation to the system upgrade, monitoring the stray radiation in the vacuum vessel becomes more important. In this context, M. Schubert discussed the use of sniffer probes and large area bolometer detectors.

J.H. Jeong reported the successful commissioning of the 170 GHz, 1MW ECH&CD system on KSTAR. High power long pulse injection experiments are expected to start soon.

3.3. Detailed Physics Study

3.3.1. Confinement

M. van Berkel discussed the determination of localized heat transport in fusion plasmas using ECRH and ECE. He developed a new identification method to estimate the different components of the one dimensional radial heat transport as function of the radius. The method was tested using finite difference simulations in the presence of additive noise and it was shown that it is possible to estimate the local diffusion coefficient, damping term and convection velocity in slab geometry as well as the associated uncertainties.

3.3.2. High energy electrons

X. Ding gave an invited talk on energetic particle physics with high power ECRH on HL-2A. The high power ECRH is used to study high energetic particle physics which becomes important in plasmas with high heating power or in burning fusion plasma. The electron beta induced Alfven (e-BAE) mode is excited in HL-2A under 600 kW, 68 GHz ECRH [11,12]. S. Kubo discussed the production of the high energy electrons and its effect on the ECRH in LHD. With much production of the high energy electrons, relativistically down shifted higher harmonic resonance appears in case of low field side injection and the power absorption there can alter the ECRH power deposition.

3.3.3. Electron Bernstein Wave (EBW) Heating

Two papers related to heating of over-dense plasma by electron Bernstein waves were presented from LHD and NSTX-U. H. Igami reported the EBW heating results employing the O-X-B mode conversion scenario in LHD: an apparent but small heating effect is demonstrated in over-dense plasma using 1 MW, 77 GHz power. Also ECCD in LHD is investigated using the change in the rotational transform and its effects on transport. G. Taylor presented a conceptual design of the ECRH system on NSTX-U. Due to the enhancement of the toroidal field coil, a 28 GHz, 1 MW system is under consideration. The system is expected to contribute to an efficient breakdown, fundamental EBW heating and current drive in NSTX-U plasma. It should be noted that several EBW-Emission measurement systems are presented in the ECE session.

3.3.4. Plasma production/start-up

To support the development of the ITER start-up scenario, breakdown and current start-up experiments have been done in several machines. New reports from T-10, KSTAR and FTU were presented in this meeting. A. Borshchegovskiy reported Optimization of ECR-breakdown and plasma discharge formation on T-10 using X-mode second harmonic of ECRH. With the injection of a 1MW focused wave beam, optimal plasma parameters with electron temperature T_e = 100-150 eV and density $n_e = 5x10^{18}$ m^{-3} were achieved in the presence of a plasma current of 3 kA. M. Joung reported the second harmonic 110 GHz ECH-assisted start-up in KSTAR. ECRH injection during the toroidal current ramp-up phase is effective but needs poloidal field control to keep the plasma equilibrium stable. G. Granucci reported the studies on absorption of EC waves in assisted start-up experiment on FTU. It is shown that 20^o oblique injection of O-mode results in a dominant X-mode wave after reflection on the inner wall with the result of efficient plasma buildup.

4. Electron Cyclotron Emission experiments

There were 16 presentations in the topic of diagnosing plasmas by measuring radiative emissions, mainly by ECE with one talk on EBW imaging. The number of ECE imaging systems on plasma devices has increased and new discoveries are being made from the expanded data set they provide. Technology continues to improve with some significant advances in receiver capabilities and clever designs for coupling to the plasma. A wide variety of ECE systems on many machines are providing crucial information on electron temperature and other plasma parameters, particularly on fluctuations related to MHD modes, their temporal and spatial structures. The ITER ECE system design is well along with the recent successful completion of the conceptual design review.

4.1. Imaging measurements

The number of imaging measurements of plasma waves continues to grow with new systems planned or coming online on several machines. G. Yun presented results of ECE imaging from KSTAR, showing poloidal rotation of modes, dual flux tubes, and structures propagating near the plasma edge [13,14,15]. First results from MAST were shown from a microwave imaging system that was looking at EBW emission (R. Vann). The 2-D imaging is accomplished with a novel phased array antenna system that is capable of both passive and active operation [16]. A summary of measurements from the ECE imaging diagnostic on ASDEX-Upgrade was presented (A. Bogomolov) focusing on ELM observations. Rotating filaments associated with the type-I ELM precursor are seen and type-II ELMs show a broadband MHD fluctuation [17].

4.2. EC emission and radiation transport

A number of papers addressed the basics of electron cyclotron emission and transport. S. Rathgeber presented analysis of radiation temperature from ECE edge emission on ASDEX-Upgrade. A key result is that the bump in T_{rad} associated with ECE resonances just outside the LCFS in H-mode discharges has been shown to be due to emission from inside the steep gradient region in the plasma. This is extremely important for the ECE imaging diagnostics that are trying to interpret T_e structures associated with the edge. A. White gave a talk on a statistical comparison of Thomson Scattering (TS) and ECE T_e measurements up to 8 keV on C-MOD, looking for the TS/ECE discrepancy seen at high T_e on other tokamaks. No discrepancy was found which motivates a need for modelling to interpret the multi-machine observations [18].

A couple of papers addressed non-thermal emission. A new vertical viewing ECE system has been set up on TCV to study the electron distribution function in this tokamak's high power density ECH discharges (W. Eshetu). On the T-10 tokamak, a number of cases of non-thermal emission have been noted with apparent invariant distribution function shape, implying a persistent turbulent state (V. Poznyak). P.V. Minashin presented a reconstruction of the suprathermal electron distribution in T-10 from the observed ECE spectra at downshifted frequencies. Finally, a paper on the radiative transport of energy via cyclotron resonances was given by F. Albajar, discussing the importance of this effect on ITER for the case of suprathermal electrons.

4.3. ECE with heterodyne receivers

A collection of presentations showed results from new or improved ECE heterodyne radiometer setups. First results from the line-of-sight ECE system incorporated into the ECRH launcher on ASDEX-Upgrade were presented by W. Bongers. This difficult engineering feat is necessary for feedback control of ECRH for NTM suppressing [19], and the early results are promising. L. Porte gave a talk on correlation ECE (CECE) measurements on TCV. Dramatic reductions in the turbulence correlation length were seen as collisionality was increased and surprising changes in fluctuation spectral content were observed for different z-height views. High frequency MHD modes were studied with the upgraded heterodyne radiometer on Tore Supra and differences in simultaneous half-radius low frequency modes were noted (D. Elbeze). The extensive suite of ECE instruments on T-10 was described by V. Poznyak where simultaneous measurements of 1st harmonic O-mode and 2nd harmonic X-mode are regularly made. Finally, R. Pavlichenko showed data from a heterodyne receiver measuring optically thin emission from the Uragnan-3M tokamak, demonstrating once again the broad range of usefulness of ECE measurements from magnetized plasmas.

4.4. ECE on ITER

On the last day of the workshop, the most recent work and progress on the ECE diagnostic system design was presented in the ITER session. An overview of the recently completed conceptual design review was given by M. Austin, showing the design is well along while some issues need to be addressed and decisions need to be made for the transmission line and Michelson interferometer instrument. H. Pandya gave a paper on plans for the back-end instruments and their expected performance. A talk on the application of ECE for control of NTM suppression was given by H. van den Brand, showing that even with relativistic broadening the ECE should have sufficient resolution with appropriate channel layout to assist in the detection of modes [20]. The effects of suprathermal electrons generated by localized ECCD on the ITER ECE spectra were discussed by P.V. Subhash. Finally a presentation of the possibilities of extending the capabilities of ECE on ITER by utilizing other millimetre wave access channels such as the reflectometer port, and collective Thomson scattering and ECH launchers (V. Udintsev).

4.5. Concluding remarks

ECE is still an active area for research and development. Two dimensional imaging systems are the putative state-of-the-art diagnostic for magnetically confined plasmas and are providing intriguing new insights. Measurement of coherent and turbulent T_e fluctuations remains the bailiwick of ECE instruments. The ECE/TS discrepancy is still an open question and is in need of modelling work. An ITER-ECE diagnostic design is at hand but several potential problem areas need to be addressed, and in-the-lab tests will be required to verify the solutions.

5. Technology

The main enabling technology for ECRH is the gyrotron: presently the only commercially available long pulse, high power source in the required range of frequencies. Of the total of 22 papers presented on technology about half was devoted to recent progress in gyrotron development, detailed measurements of gyrotron performance or the modelling of gryrotron interaction. The remaining papers discussed overall systems (2 papers), various transmission line components (8 papers), control systems, power supply, ITER gyrotron test bench, and ITER launcher design.

In a special honorary lecture, a historic overview of gyrotron development was presented by G. Nusinovich, recipient of the 2012 Kenneth J. Button Prize of the International Society of Infrared, Millimeter and Terahertz Waves for “fundamental contributions to the theory and development of gyrotron oscillators and amplifiers with frequencies up to the terahertz range".

5.1. Gyrotrons

The results from the Russian ITER gyrotron development (G. Denisov) [21] show stable 960 kW operation over pulse lengths of 400 s. The reproducibility and the similarity of the parameters of two test tubes where emphasized. Further development focuses on multi-frequency operation, where the vacuum window is identified as the main challenge. Several approaches for broadband windows were presented.

From CPI the status of gyrotron development was presented by K. Felch. The 110 GHz 1.2 MW Gyrotron for General Atomics achieved the design power with an efficiency of 41 % in short pulse operation and is shipped to GA for testing with 10 s pulses. Another development is for a 170 GHz 1 MW gyrotron for ORNL.

The status of the European 2 MW coaxial gyrotron ITER was reported by S. Kern. After experiences with the first CW prototype, improvements were done for the electron gun, the launcher and the beam tunnel. These changes suppressed the parasitic oscillations and improved the Gaussian content of the output beam to 96 %. The refurbished CW prototype was tested successfully for 4 days until an absorber failure permanently damaged the tube and terminated the experiments. If the 2 MW project will be terminated in favour of an 1 MW conventional gyrotron is still to be decided.

In the ITER session, the JAEA activities for developing a dual frequency (170 GHz and 137 GHz) gyrotron where presented by Y. Oda along with test results of the ITER type transmission line. During the tests, a power of 600 kW was obtained for 160 s.

Further gyrotron related topics focused on a better understanding and modelling of the interactions of the electron beam and the microwave. This is important especially for the suppression of parasitic oscillations, which were observed in several MW gyrotrons and which can decrease the performance.

On the modelling side, the EURIDICE code package was presented and benchmarked against other code packages (K.A. Avramides). More specific, the suppression of spurious oscillations by using dielectric ring loaded aperiodic beam tunnels was investigated (J.G. Chelis).

A system for time- and frequency dependent characterization of gyrotron radiation was presented (A. Schlaich). It allows to observe transient phenomena (e.g. the frequency change at the beginning of the operation) as well as parasitic oscillations. It therefore provides a tool for further optimizing the interaction of the electron beam and the microwave.

Another advanced gyrotron topic is the multi-frequency operation. While the Russian activities in the development of multi-frequency gyrotron mode converters (as presented by G. Denisov) sound very promising, the development of multi-frequency diamond windows is still an open issue. Brewster windows require large disk sizes of CVD Diamond, which are not yet available. The principal feasibility was, however, investigated by simulating the brazing and cooling process and doing an FEM stress analysis, and suitable parameters were found (G. Aiello). The 3.6 MW power supply for the 170 GHz ECRH system in KSTAR was presented Eun-yong Shim.

5.2. Diplexers

Several papers reporting about the development of resonant diplexers were submitted. The diplexers are four-port devices with 2 input- and 2 output ports. They can be used for many applications, like fast switching between output channels (by electrically tuning the gyrotron frequency), slow switching (by mechanically tuning the resonator), power splitting, power combination and ECE diagnostics with the ECRH antenna. The overview talk (W. Kasparek) described the principle, the realisation and the results of high power experiments at the ECRH facilities of W7-X and ASDEX-Upgrade [22]. The mirror control for tuning the resonator was presented by N. Doelman. Investigations of the mode filtering capabilities of a diplexer designed and built in Japan were presented by Y. Oda. Measurements on a diplexer for FTU were reported by O. D'Arcangelo.

5.3. Overall systems

The complete 2 MW 140 GHz ECRH system of the HL-2A tokamak was presented (M. Huang), and the current status of the development of the ECRH system for ITER [23] was presented by C. Darbos.

Furthermore, some more general remarks about large scale ECRH systems were given by V. Erckmann. Based on the experiences with the development of the ECRH system for W7-X several issues were discussed. The gyrotrons in the MW class are still designed for each customer separately, preventing a real series production. One possible solution would be slightly relaxed gyrotron requirements (e.g. frequencies slightly different from the ideal) with the goal to have standard gyrotron specifications suitable for a large number of fusion experiments. This would reduce development costs and enable a real international competition of manufacturers. In addition, the importance of diplexers and the advantages of remote steering launchers, especially for DEMO, were outlined.

5.4. Further topics

A method for synthesizing waveguide components was presented by D.I. Sobolev [24]. The algorithm does two propagations, one from the input (with the starting field pattern) in forward direction. The second propagation starts with the desired field pattern at the output and goes in backward direction. For an ideal device, the two field amplitudes for both propagations are identical. By comparing the amplitudes at different locations, a geometrical perturbation is introduced and the propagation is repeated. The algorithm converges very fast with good results.

The characterization of spurious modes in HE_{11} transmission lines with a 5-port coupler was presented by B. Plaum. By integrating leaky wave antennas into a mitre-bend, one can sample the field at 5 positions, which allows the detection of the powers of 5 modes. A formalism for obtaining the mode amplitudes from the coupler channels was developed and experimental results confirm the behaviour of the device [25].

For the ITER ECRH system, D. Strauss gave an overview of the current status of the upper launcher [26]. R.A. Olstad presented the development of transmission line components at General Atomics. These include miter bends for power monitoring, colorimetry and polarization control, a 2 MW DC break, double Helicoflex seals for Tritium containment. Finally, A.P. Khvostenko presented the CW test bench for the ITER gyrotrons at the Kurchatov Institute. The high-voltage power supply, evacuated transmission line, cooling systems, data acquisition, gyrotron protection systems, and calorimetric measurements were presented.

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