BOOK REVIEW

Selection of books for review is based on the editor's opinions regarding possible reader interest and on the availability of the book to the editor. Occasional selections may include books on topics somewhat peripheral to the subject matter ordinarily considered acceptable.

American Institute of Physics Conference Proceedings: Sixth Topical Conference on Radiofrequency Plasma Heating, Calloway Gardens, Georgia, May 1985

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This text is a collection of papers presented at the Sixth Topical Conference on Radiofrequency Plasma Heating at Calloway Gardens, Georgia in May 1985. The book contains 55 papers that were presented at the conference and is organized according to the frequency regime addressed in each paper in ascending order of frequency. It starts with Alfvén wave heating and continues up to heating schemes at the electron cyclotron frequency and harmonics. There is no editorial selection or editorial clarification evident in this text. Some of the figures are not strictly of reproducible quality, and some obvious mathematical errors remain.

The Alfvén wave heating papers start with an invited paper by Valanju et al. of the PRETEXT group at Austin, Texas. The paper emphasizes the fitting of the observed frequency-modal structure diagnostic output to a simple model for the plasma's radio-frequency (rf) properties and shows the accessibility of the $m/n = 2/1$ resonance particularly well. Another paper on PRETEXT by Booth et al. gives more details of the resonant character of the plasma's rf impedance. A paper by Chambrier et al. of Lausanne also shows resonant Alfvén eigenmodes on the TCA experiment and has an interesting discussion of the rise of the impurity radiation level with rf power, as seen from a silicon line. An accompanying paper by Collins et al. of Lausanne emphasizes the importance of toroidicity and hall effects in a proper calculation of the resonant modes. A paper by Kortbawi et al. from Wisconsin shows the Alfvén wave heating in the nonaxisymmetric TOKAPOLE tokamak and contains some interesting detail on antenna design. A paper by Cummins et al. of Lawrence Livermore National Laboratory (LLNL) gives details of the 2.67-MHz Alfvén heating system on TMX-U, although this paper is erroneously placed in the section on electron cyclotron heating.

In the section on ion cyclotron heating (ICH), an invited paper by DiMonte et al. (LLNL) describes the central-cell heating on the TMX-U tandem mirror using $\omega < \omega_{ci}$. The most interesting aspect of this work is the asymmetry induced in the end loss from the machine induced by the rf heating. In another invited paper by Wilson et al. of the Princeton Large Torus (PLT) group [Princeton Plasma Physics Laboratory (PPPL)], minority ion heating using helium-3 resonance is described. Second harmonic D+ heating in very pure discharges was found to produce a long-tailed ion distribution ($Ttail = 18.5$ keV), and positive departure from the pessimistic Kaye-Goldston confinement scaling was seen for the highest power inputs (> 4 MW). The Oak Ridge National Laboratory (ORNL) Advanced Toroidal Facility effort was shown in a paper by Baity et al., which shows a novel design for a resonant double loop antenna. In a paper by Barter et al. (LLNL), use of an ICH barrier for drift pumping of the thermal barrier is shown, and a particularly high-quality data characterization of the plasma rf admittance versus density is given.

Results of the 1.0-MW ICH heating experiments on the Tokamak Experiment for Technology Oriented Research are presented by Wynants et al. of the Euratom group. The *L*-mode Kaye-Goldston scaling is reported, but significant drops in the toroidal loop voltage accompany the rf heating. In another PLT paper by Cavallo et al., second harmonic emission from the electrons is used to quantify the rise in electron temperature during the ICH. Sawtooth activity is found to increase dramatically during the ICH. A plan for fast-wave current drive (FWCD) [$\omega_{ci} < \omega < (\omega_{ce}\omega_{ci})^{1/2}$] for PLT is outlined by Colestock et al. from PPPL. A ray-tracing calculation for FWCD is shown by Ehst et al. of Argonne National Laboratory. A paper by Gahl et al. (Texas Tech University) describes FWCD efforts on a small tokamak. In a paper by Fortgang et al. (MDAC), some aspects of ion cyclotron resonance frequency technology are described, accompanied by an unfortunately obscure photograph of their ridged waveguide. Goree et al. (PPPL) give the results of FWCD on the Advanced Concepts Torus I

(ACT-I) research torus and report current drive efficiencies to be on the order of those for lower hybrid. Talmadge et al. (TRW) show data from an ion charge-exchange analyzer indicative of long ion tails observed during ICH of a symmetric mirror machine. Taylor et al. of the University of California, Los Angeles demonstrate quite clearly the presence of nonlinearities during ICH by mixing two rf sources closely spaced in frequency and observing a low-frequency beat component.

There are numerous theoretical and computational studies in this text addressing ICH. Hammet et al. (PPPL) show quasi-linear modeling of second harmonic ICH on PLT, with emphasis on banana effects from the energetic ion tails associated with ICH. Kashuba et al. (MDAC) calculate the ohmic losses in ICH antenna Faraday shields. Kerbel and McCoy (LLNL) use a quasi-linear treatment of the Fokker-Planck equation for non-Maxwellian systems, and Molvik et al. (LLNL) describe the theory of ICH on passing ions in the central cell of a tandem mirror machine. Ono et al. (PPPL) describe a one-dimensional 1-V simulation code known as MICADO, useful in ICH and in the ion Bernstein wave (IBW) heating regimes. A finite element method for calculation of ICH fields in symmetric systems was presented by Philips (Grumman Aerospace Corporation). Skiff et al. (Princeton University) present a study of IBW heating on the ACT-I device, including a discussion of parametric effects caused by the excitation of ion quasimodes. Philips et al. (PPPL) present a study of radial wave propagation in toroidal devices in the fast magnetosonic regime using a superset of the geometrical theory of diffraction (GTD), including lowest order toroidal effects.

A problem generic to ICH is the need for high-current, high-voltage feedthroughs for transfer of rf power into the vacuum chamber. A novel design for such a device is shown in the paper by Owens et al. (ORNL). Their design is remarkable in that it uses a simple cylindrical alumina insulator part with tapered conductors. This level of design ingenuity will become essential if rf heating is to become part of a reactor in the future, when ease of fabrication for high failure-rate components may become critical.

The section on lower hybrid (LH) heating (LHH) and LH current drive (LHCD) starts with an invited paper by Gormezano et al. of the Euratom group. The paper contains a good review of the literature and discusses the experimental results on the PETULA-B tokamak. Ion temperature increases of 500 eV are reported during LHH, and loop voltage was driven to near zero. Metallic impurity line radiation was found to increase by a factor of as much as 3 during the LHH. In a paper by Knowlton et al. of the Massachusetts Institute of Technology (MIT), the LHCD experiments on Alcator were reported. The 4.6-GHz, 1-MW LH system is described. An interesting finding on Alcator was that the electron temperature did not increase over its value in purely ohmic discharges with the LHH on. A paper by Texter et al. (MIT) also presents details of the X-ray emission from Alcator during LHCD, showing evidence of suprathermal electrons during the LHH. In addition to just replacing ohmic transformer flux for toroidal current drive, some LH experiments have been done to ramp up currents in tokamaks using LHCD. A paper by Takase et al. (MIT) describes such experiments on Alcator. In a paper by Chu et al. (PPPL), the LHH experiments on PLT were found to increase the electron temperature and to suppress the 1/1 mode. In a companion paper by Bernabei et al. (PPPL), the relative merits of top launch versus side launch of the LH waves is discussed; the side launch was found to be more efficient, in part due to a tighter spectrum of parallel wavenumber at the antenna. A paper by the FT group at Frascati shows increased sawtooth activity during LHH and reports electron temperatures up to 3 keV during LHH. On another MIT tokamak (Versator II), Mayberry et al. explored the so-called "density limit" associated with LHCD, using a 2.45-GHz source. A description of an interferometer system for detection of LH waves in this same device is given by Rohatgi et al.

The LH theory papers concentrate on the breakdown of geometrical optics, spectral antenna methods, and parametric effects. Bonoli et al. (MIT) couple toroidal ray tracing with a one-dimensional transport code to obtain heating profiles. Cannobio and Croci (Max-Planck Institute) use harmonic expansions of a nonlinear PDE to find LH electric field amplitudes. Bravo-Ortega and Glasser (Auburn University) use a generalized GTD method to calculate rf propagation with harmonic generation. A two-dimensional Fokker-Planck treatment of LHCD with a quasi-linear model is used by Englade and Bonoli (MIT) to look at current ramp-up in tokamaks. A paper by Liu et al. (GA Technologies) uses a simple inductance model with runaway electrons to determine current drive efficiencies. A paper by Luckhart (MIT) gives matching conditions for parametric conversion of the LH wave to an electrostatic Doppler-shifted Langmuir wave. A paper by Stevens et al. (PPPL) uses Karney-Fisch theory in a model to find the current ramp-up on Alcator and to find the balance between the energy into magnetic fields, the bulk plasma, and an energetic electron tail. Swanson and Cho (Auburn University) present their calculation of mode conversion of the LH wave into high ion cyclotron harmonics. Wersinger and Park (Auburn University) combine a GTD model for propagation with a model for parametric decay to obtain LH heating and current drive profiles.

An interesting technology paper by Motley and Greene (PPPL) shows their efforts at raising the power levels before arc-over in LH waveguide launching arrays. They find that a choke groove at the end of the array significantly reduces the peak electric field at the mouth of the waveguides.

As electron cyclotron heating (ECH) is still in its infancy, the ECH section of this text is understandably short. In fact, only two experimental papers on ECH were included. An invited paper by Erckmann et al. (Stuttgart) gives the details of ECH heating using a 200-kW, 28-GHz source on the Wendelstein stellarator. Electron temperatures as high as 2.3 keV were measured, and efficiency was found to be much higher with an HE-11 mode launch rather than the TE-02 mode straight out of the gyrotron. A paper by Booske et al. (University of Michigan) shows efforts at startup of a small mirror machine with a 7.43-GHz ECH source.

The theory papers on ECH are more numerous. A paper by Hayes et al. (Dartmouth) gives a theoretical model for ECH current drive using the variation of the electron magnetic moment during the ECH. Matsuda et al. (GA Technologies) give the linear dispersion curves and warm-plasma damping rates for second harmonic cyclotron heating. A paper by Mazzucato et al. (PPPL) gives ray-tracing results for ECH heating at downshifted frequencies for PLT and the Tokamak Fusion Test Reactor. Such frequencies can be absorbed by the plasma due to Doppler-shifted resonance and may allow the use of more readily available, lower frequency sources. A Monte Carlo Fokker-Planck computer model is presented by Rognlien et al. (LLNL), showing the use of ECH in potential formation in tandem mirrors. These studies show the formation of very hot tails (> 250 keV) with ECH and also emphasize the importance of keeping high-harmonic terms (up to fourth harmonic in some calculations). Another LLNL paper by Smith et al. describes the global modeling code MERTH, which includes a McVey antenna package and uses a bounce-averaged Fokker-Planck model. A paper by Kritz et al. (PPPL) describes the marriage of the BALDUR transport code to a standard ray-tracing code package TORAY.

I found that reading these papers was educational and formed a good backdrop for understanding the latest developments in rf heating work in magnetically confined fusion experiments. This field is changing faster than almost any other in fusion. Even though rf heating took a backseat to neutral beam injection following the famous experiments of July 1986 at Princeton University, we can expect to find rf heating playing a crucial role in the heating and current drive of ignition fusion devices in the future because of its simplicity and its mature technological base. This text represents the state of the art and is most certainly recommended reading.

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