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A Diagnostic for Electron
Dynamics in Tokamaks

Final Report
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Progress Report: The diagnostic was installed on TdeV and brought into operation. It was optimized to the extent that time and money permitted. A considerable quantity of data was accumulated and analysed. Experiments ended in August 1995. The apparatus has been removed from TdeV and returned to the University of Maryland. Each of these activities is detailed below.

1) Installation and Decommissioning. Shipping and installation of the two chord, four channel electron cyclotron absorption (ECA) measurement system were completed in the spring of 1994. Computer controlled signal generator ramping, and signal acquisition were implemented in the same period. Experiments ceased in August 1995. The apparatus was removed in September 1995 and returned to the University of Maryland in mid 1996.

2) Transmission System. The installed system showed very good performance in vacuum, with only 3db loss between the transmitter and receiver horns. Eliminating the effects of waveguide dispersion on the time-domain data was achieved by using a nonlinear ramp for the control of the frequency generators. It was found that the dynamic range of the measurements was limited by the return losses from the vacuum feedthroughs and horn transitions. By increasing the asymmetry between the microwave time-of flight from the generator to the top and bottom horns, respectively, the interference due to return losses was significantly reduced. The final system dynamic range depends on frequency, but is close to 40 db. The signal analysis was found to be very sensitive to noise on the ramp generator input. A technique was found to suppress this interference.

3) Diagnostic verification. The diagnostic was ready for participation in tokamak experiments in June of 1994. Distribution functions measured in the first run were analyzed, discussed, and first presented at the IAEA conference in Seville. Some unexpected features were evident which caused some concern about the data. Repeated measurements, performed through participation in the TdeV LHCD experiments, and improvement in the dynamic range have established the existence of new phenomena. Run time of the diagnostic was limited some by a change in the plans of the TdeV operations which resulted in operation of the tokamak at higher magnetic field a significant portion of the time, starting in late summer 1994.

4) Participation in TdeV experiments. Participation in TdeV lower-hybrid experiments showed that the ECA apparatus produced the best measurements of suprathermal electron distributions that had been achieved to date. In addition to the features of these measurements which were expected, there were three features, in particular, which were not expected and which call for further study. These are the level of fluctuations in the distributions, the existence of electrons at energies above the resonant energy associated with the launched LHCD spectrum, and the magnitude and character of refractive losses.

5) Results

a) Fluctuations

The amplitude of the measured suprathermal electron distributions are observed to fluctuate in time on millisecond, or even sub-millisecond time scales at a level of 20-30% RMS. We established that the uncertainty in the measurements themselves is much less than 20%. We conclude, therefore, that the fluctuations are real. The fluctuations are not correlated with fluctuations in refractive losses, and only rarely are correlated with the fluctuations which occur at other electron energies. The fluctuations are not correlated between the two vertical chords; therefore are not correlate in the two spatial averages of the chords. One problem we have faced is

that such fluctuations were not predicted to exist, and partially lie outside the time resolution of our current instrument. We are not aware of any theory for these fluctuations.

b) High Energy Electrons

The NII spectrum for the launched lower hybrid waves is very highly peaked. Under such conditions, it is the theoretical expectation that the energy spectrum of the suprathermal current driven electrons will be flat below the resonance energy $E_r(\text{NII})$, and fall off very rapidly above this energy. This is approximately what is observed on the central chord, although the distribution does not fall off as rapidly as expected above $E_r(\text{NII})$ and is not fully flat below $E_r(\text{NII})$ either. The off-axis chord indicates a almost flat distribution which at times extends to energies of, at least, three times $E_r(\text{NII})$.

c) Spatially Hollow Distributions

Since the off-axis chord measurements showed electron distributions extending well beyond $E_r(\text{NII})$ and the on-axis chord did not, the spatial distribution of current driven electrons is hollow at energies above $E_r(\text{NII})$. This occurs independently of the properties of the launched lower hybrid wave spectrum.

d) Refraction effects

We have observed that there are circumstances where the refraction losses are much greater than is predicted by ray tracing which does not include relativistic effects on the ray trajectories. This occurs even with plasma temperatures of 1 keV. Because we can isolate the effects of refraction and absorption, our data are well suited to address this issue. Unfortunately, this new effect can make it difficult to measure absorption losses at low electron energies with the present system because the refraction losses can exceed the instrument dynamic range.

e) Conclusions

The diagnostic worked very well. Although the distribution functions behaved in ways that were not anticipated and the refractive losses were sometimes higher than projected, we were able to adapt to the unexpected. In our estimation, all of the effects listed above are significant, and warrant further study. The diagnostic is ready for use as a tool to study the physics of current drive and current profile modification. A mechanism for steering the launched beams is desirable to cope with the strong variations in refraction which are seen. Phased array launchers seem attractive for this purpose. Tuning of the length of the waveguide run is important to avoid troublesome reflections (return losses). It may be best to build in this capability in a future system. The perpendicular dynamics of the current driven electrons are invisible to us with the present form of the diagnostic. Simultaneous measurements at fundamental and harmonic frequencies would make perpendicular distribution function measurements possible.

Papers Contributed at Scientific Conferences

A) The first presentations of distribution functions obtained with the new diagnostic were presented at the Fifteenth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Seville, Spain, 26 September- 1 October 1994 in a paper presented by R. Decoste.

Biased Divertor Performance Under LH Current Drive and Heating Conditions on the TdeV Tokamak. R Decoste, Y. Demers, J.-L. Lachambre, B. Stansfield, G. Abel, S. Aceto, J. Beckstead, C. Boucher, D. Bourgoïn, D. A. Boyd, P. Brooker, A. C8te, C. Cote, T. Fall, V. Fuchs, J.-L. Gavreau, L. Gauthier, V. Glaude, B. Gregory, S. Gulick J. Gunn, E. Haddad. P. Jacquet, J. Kalnavarns, G. Le Clair, H. H. Mai, J. Mailloux, R. Marchand, F. Martin, F. Meo, D. Michaud, R. Neufeld, D. Pinsonneault, B. Quirion, R Raman, N. Richard, G. Ross, A. Sarkissian, I. P. Shkarofsky, M. M. Shoucri, F. Skiff, M. St-Onge, B. Terreault, W. Zhang, W. Zuzak, Proceedings. IAEA- CN-601A-4-II-5.

B) 36th APS-DPP meeting. Minneapolis MN, November 7-11 1994

Measurement of suprathreshold electron distribution function by extraordinary wave absorption in TdeV. S. Gulick, D. Boyd, F. Skiff, R. Neufeld, D. Pinsonneault. Bull. Am. Phys. Soc. 39 pl534 (1994) Paper Is7.

Spatial Resolution of LHCD Electron Distribution Functions in the Tokamak de Varennes. D. Boyd, F. Skiff, and S. Gulick, Bull. Am. Phys. Soc. 39 pl534 (1994) Paper IsX.

Sensitivity and Resolution of Electron Cyclotron Transmission Diagnostics. F. Skiff, D. A. Boyd, and S. Gulick, Bull. Am. Phys. Soc. 39 pl534 (1994) Paper Is9.

C) The Ninth Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating (EC-9), Borrego Springs, California, January 22-26, 1995.

Invited Paper Vertical View ECA. Principles and Practice. F. Skiff, D. A. Boyd, and S. Gulick.

Contributed Paper ECA Dia-nosis of LHCD Distributions in the Tokamak de Varennes. D. Boyd, F. Skiff, and S. Gulick.

D) Twenty Second European Physical Society Conference on Controlled Fusion and Plasma Physics, Bournemouth, UK 2-7 July, 1995.

Lower Hybrid Current Drive Experiments in the TdeV Tokamak. A. Cote, Y. Demers, C. Cote, R. Decoste, P. Jacquet, G. Abel, C. Boucher, D. A. Boyd, P. Brooker, V. Fuchs, J.-L. Lachambre, D. Michaud, I. P. Shkarofsky, M. M. Shoucri, F. Skiff, M. St-Onge

E) A seminar sponsored by Fusion Power Associates and the Canadian Nuclear Society. "Status and Prospects for Fusion Power Development", Montreal, Quebec, Canada. September 7-8, 1995

Title of talk: A US-Canada Collaboration. D. Boyd and F. Skiff.

F) 37th APS-DPP meeting. Louisville KY, November 6-10 1995.

Suprathermal Electron Distribution Function Measurements during LHCD Experiments on the TdeV Tokamak. D. Boyd, F. Skiff, S. Gulick, D. Pinsonneault, A. Cote, and C. Cote

Generation and Diffusion of Suprathermal Electrons during LHCD Experiments on TdeV. C. Cote, Y. Demers, V. Fuchs, R.A. Cairns, M. Shoucri, I. Shkarofsky, P. Brooker, Y. Peysson, J. Mailloux, D.A. Boyd, F. Skiff, A. Cote

Effect of Refraction in Ray Tracing for the Cyclotron Transmission Diagnostic in TdeV. I. Shkarofsky, D. Boyd, F. Skiff, A. Kritz, G. Smith

I) Seminar: University of Maryland, College Park, MD. February 7 1996

Title of talk: Suprathermal Electron Distribution Function Measurements during LHCD Experiments on the TdeV Tokamak.

H) 11th Topical Conference on High-Temperature Plasma Diagnostics. Monterey CA., May 12-16 1996.

A System to Measure Suprathermal Electron Distribution Functions in Toroidal Plasmas by Electron Cyclotron Wave Absorption. D. A. Boyd, F. skiff and S. Gulick. [To be Published in Review of Scientific Instruments]

I) Seminar at ENEA C. E. Frascati, Italy. June 21 1996

Title of talk: Suprathermal Electron Distribution Function Measurements during LHCD Experiments on the TdeV Tokamak.

J) Invited talk. 23rd European Physical society Conference on Controlled Fusion and plasma Physics. Kiev, Ukraine, June 24-28 1996.

Title of talk: Suprathermal Electrons in Versator, Tore Supra and TdeV as seen by Electron Cyclotron Absorption Diagnostics. [To be published in Plasma Physics and Controlled Fusion]

K) 38th APS-DPP meeting. Denver CO, November 11-15 1996

Study of LHCD physics through suprathermal electron diagnostics on TdeV. C Cote, D. Boyd, P. Brooker, M. Shoucri, V. Fuchs, I. Shkarovsky, R. A. Cairns, A. Cote, Y. Demers.

Properties of LHCD Suprathermal Electron Distributions in TdeV. D. Boyd, F. Skiff, A. Cote, C. Cote, P. Brooker.