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LAWRENCE LIVERMORE NATIONAL LABORATORY DIII-D COOPERATION
1987 ANNUAL REPORT

I. Introduction

This report summarizes the Lawrence Livermore National Laboratory (LLNL) DIII-D cooperation during FY87. DIII-D is a uniquely flexible, large tokamak with many of the features of the Compact Ignition Tokamak (CIT) and International Thermonuclear Experimental Reactor (ITER) designs. It has an elongated cross section with a divertor, high-power neutral beam injection, microwave heating, and extensive diagnostics. These features allow DIII-D to make major contributions to the understanding of beta, confinement, edge physics, microwave heating, and current drive. The LLNL DIII cooperation provides LLNL personnel with an opportunity to become acquainted with and to contribute to tokamak physics and operations. Such cooperation, in turn, provides GA Technologies with additional personnel who are skilled in magnetic fusion physics and technology.

The 16 authors of this report constituted the primary contributors to the LLNL DIII-D cooperation during FY87. The manpower increased during the first quarter as personnel completed their responsibilities on the Tandem Mirror Experiment-Upgrade (TMX-U) experiment. Our manpower effort peaked in the second and third quarters during which we prepared and installed divertor and electron-cyclotron heating (ECH) diagnostics for DIII-D. Several instruments, with support electronics, were borrowed from TMX-U for use on DIII-D prior to their installation on the LLNL Microwave Tokamak Experiment (MTX). During the second and third quarters, 13 LLNL employees resided in San Diego, and three traveled from Livermore. As instruments became operational near the end of the year, the number of employees residing in San Diego decreased to ten.

LLNL personnel were integrated into the DIII-D organization. Five physicists were in the edge physics group, and three were in the rf heating group. The Livermore physics representation in these areas approximately equaled that from GA Technologies. Eight LLNL engineering department employees provided support for the LLNL activities and contributed to the DIII-D engineering, operations, and physics groups.

At GA Technologies, in La Jolla, California, Livermore personnel were provided offices, laboratory work space, and computer access equal to that of

GA Technologies employees. In addition, GA Technologies provided safety training, engineering design assistance and reviews, secretarial help, and library services. We were permitted access to the GA Technologies facilities both at night and on weekends and we fully participated in technical discussions and meetings. In the process of learning about tokamaks from GA Technologies personnel, we appreciate that those individuals went out of their way to make this year's participation highly beneficial for LLNL participants.

The LLNL participation in DIII-D concentrated on three principal areas: (1) ECH and current-drive physics, (2) divertor and edge physics, and (3) tokamak operations. Three areas were selected on the basis of previous LLNL experience, GA Technologies needs, and LLNL long-term interests.

II. Accomplishments during FY87

A. ECH and Current-Drive Physics

During FY87 DIII-D was equipped with eight 200-kW, 60-GHz gyrotrons. The antenna system consisted of eight waveguides located on the outside midplane with x-mode polarization. Five antennas were oriented 17° from perpendicular, aimed clockwise; three were oriented 17° from perpendicular, aimed counterclockwise. DIII-D plasma current is counterclockwise.

Three LLNL physicists, together with a similar number of GA physicists, formed the ECH physics group. Theoretical physicists G. R. Smith (LLNL) and A. H. Kritz (Hunter College) provided theoretical support with the TORAY ray-tracing and current-drive code calculations. LLNL mechanical and electrical technicians provided some assistance during waveguide installation and gyrotron conditioning. Livermore engineering designed and fabricated microwave diagnostic antennas for installation in November 1987.

LLNL personnel participated in and helped lead ECH experiments. Our ECH experiments included basic studies of fundamental and second-harmonic heating, ECH-generated H-mode, ECH suppression of edge-localized modes (ELMs), and preliminary ECH current-drive experiments. An example of data from second-harmonic ECH heating experiments is shown in Fig. 1. In these experiments the toroidal field was varied at constant electron density [Fig. (1a)], and the electron density was varied at constant toroidal field [Fig. (1b)]. The

Figure 1. Measurements of increase of central electron temperature with second-harmonic ECH versus (a) toroidal field and (b) density.

central electron temperature measured by Thomson scattering is shown both with and without ECH. The central heating is seen to be largest when the line-averaged density is below $1.4 \times 10^{19} \text{ m}^{-3}$.

We installed a microwave receiver to monitor edge electron-cyclotron emission (EECE) and central emission during low field operation. This system experienced limited operation due to availability of a receiving antenna and the restricted density range over which the system could operate. The receiver was calibrated with Thomson scattering. An example of signals from the EECE is shown in Fig. 2. This figure shows (a) neutral-beam (dashed) and ECH (solid) power pulses, (b) the EECE signal, and (c) a central chord soft-x-ray signal versus time for second harmonic ECH. The EECE signal shows a temperature rise with neutral-beam injection (NBI) and then later with ECH. Also seen are the effects of sawteeth at the edge.

We initiated a three-way project with GA Technologies and the University of Maryland to install a vertical-viewing electron-cyclotron emission (VECE) diagnostic. The purpose of this diagnostic is to determine the characteristics of high-energy electrons during ECH current-drive experiments in 1988. This project required LLNL to help design and fabricate special sub-millimeter microwave reflectors to collect and refocus the electron-cyclotron emission. Due to the complicated shape, high tolerances, smoothness, and harsh DIII-D environment, no outside vendor could be located to manufacture these metallic reflectors. We used a novel technique on an LLNL three-axis milling machine to successfully manufacture the microwave reflectors, which are shown in Fig. 3.

A major LLNL interest is ECH and neutral-beam current drive. We carried out an exploratory ECH current-drive experiment in which 5 kA of current was driven by unbalanced, bidirectional outside-launch antennas. We expect to carry out current-drive experiments at much higher currents in FY88 with the unidirectional inside-launch system.

We carried out neutral-beam current-drive investigations by examining DIII-D discharge loop voltage characteristics during high-power NBI. Such experiments include those with a combination of NBI and ECH, although generally the effects of ECH are dominated by the much higher NBI power. In addition, we dedicated one day of machine time to neutral-beam current drive. Figure 4 shows an example of an attempt to sustain the plasma current [Fig. 4(a)] with 6 MW of tangential neutral-beam injection [Fig. 4(b)] when

Figure 2. Results from the edge electron-cyclotron emission (EECE) diagnostic.

Figure 3. Photo of the microwave reflectors for the vertical electron-cyclotron emission (VECE) diagnostic.

Figure 4. An example of neutral-beam current drive.

the loop voltage [Fig. 4(c)] is feedback-controlled to zero. These experiments were carried out at low density $\bar{n}_e = 2 \times 10^{19} \text{ m}^{-3}$ and at 1.5 to 2.0 keV of central electron temperature. Analysis of these experiments with the GA ONETWO code and the JAERI code indicates that approximately 0.3 MA of plasma current is driven by the neutral beams.

Livermore personnel helped evaluate possible future experiments with the inside-launch 60-GHz system and with the proposed 120-GHz system. The ideas we evaluated included third-harmonic heating for high-beta experiments and second-harmonic current drive localized near the $q = 2$ surface for current profile control experiments.

B. Divertor and Edge Physics

A critical aspect of the operation of present and future large, high-power tokamaks concerns the removal of heat without melting components or introducing impurities into the plasma. Likewise, special techniques must ultimately be developed to remove alpha ash and to fuel the plasma with hydrogen isotopes. DIII-D is equipped with a divertor configuration prototypical of that envisioned in the larger, next-generation CIT and ITER tokamaks. The LLNL-GA collaboration in divertor/edge physics is directed toward carrying out measurements and theoretical modeling that will develop the understanding of power and particle flow needed to design next-generation experiments and to further improve energy confinement in DIII-D.

The first diagnostic instrument that LLNL installed on DIII-D was an IR camera located above the DIII-D plasma to view the bottom divertor tiles. This instrument provides spatially and temporally resolved measurements of the power density incident on the divertor tiles. Typical measurements shown in Fig. 5 indicate that the shape and position of the heat flux depends on whether the plasma is ohmic, L-mode, or H-mode. The vertical bars indicate the calculated separatrix intercepts. During H-mode, the heat flux shifts toward the separatrix, and the profile becomes even more peaked than during L-mode.

We also added an electronic data-acquisition system to a DIII-D H-alpha TV, which views the divertors from the top, similar to the viewing angle of the IR camera. Figure 6 shows data from this instrument. The horizontal axis shows the major radius; time progresses vertically. The inner and outer

Figure 5. Data from the LLNL divertor IR TV diagnostic measurement of power to the DIII-D divertor showing spatial measurements during (a) ohmic, (b) L-mode, and (c) H-mode operation.

Figure 6. Measurements of spatial and temporal divertor H-alpha profiles.

strike points are evident. The H-alpha spatial distribution shows dramatic changes during the discharge with neutral-beam injection, a transition to an H-mode, and the occurrence of ELMs.

To characterize the plasma striking the divertor, we brought into operation an array of Langmuir probes, which GA Technologies installed in the divertor tiles. The probe voltage is swept every 30 ms to determine the electron density and temperature. Figure 7 shows the currents from four such Langmuir probes when the divertor strike point is swept across the probes during a divertor H-mode shot. The peak signal is a rough measure of the plasma density. We can see that the plasma moves from probe 1807, past 1806, to 1805. We use such measurements from Langmuir probes, together with the measurements of divertor IR TV power flux, in the DEGAS code modeling of neutral-particle transport.

We are adapting and employing the Princeton DEGAS neutral-particle transport code to calculate the spatial distribution of neutral particles. This code uses a spatial coordinate system based on DIII-D EFITD magnetic measurements as shown in Fig. 8(a). Using experimental measurements in the divertor and plasma profile measurements in the core plasma, the DEGAS code calculates the spatial distribution of neutral density as shown in Fig. 8(b). Present efforts are aimed at checking these code calculations against measurements of neutral pressure and H-alpha emission with TMX-U, DIII-D, and ASDEX pressure gauges. In FY88 DEGAS will be used to evaluate possible future DIII-D configurations for the divertor baffle.

We adapted fast, neutral-pressure gauges from TMX-U to DIII-D. These gauges complement DIII-D and ASDEX gauges located at different locations. The gauges not only provide data on spatial measurements of the neutral pressure, but also indicate variations due to changes in operating parameters. Figures 9(a) through 9(c) show variations for a helium plasma, while Figs. 9(d) through 9(f) show variations for a deuterium plasma. Hydrogen beams are used in both cases to initiate an H-mode at approximately 2.5 s. The H-mode is punctuated with large, infrequent ELMs, as seen in the H-alpha traces in Figs. 9(a) and 9(d). Notice the much lower neutral pressure in a helium plasma relative to that for a deuterium plasma.

To provide more detailed spatial resolution of the neutral density distributions, an H-alpha TV camera system has been designed and built at LLNL for installation in November 1987. As shown in Fig. 10(a), this camera will

Figure 7. Langmuir probe measurements of spatial and temporal divertor electron density and temperature.

Figure 8. Results of DEGAS code modeling of deuterium neutral density in DIII-D.

Figure 9. Neutral-pressure-gauge measurements during helium and deuterium plasma operation.

(a) LLNL H-alpha TV camera system

(b) Viewing angle

Figure 10. Divertor x-point tangential H-alpha TV system installed in November 1987.

view the x-point tangentially. The view angle is shown in three dimensions in Fig. 10(b). This system will provide an image of H-alpha emissions every 16 ms.

Impurities can have profound effects on tokamak discharges and on the efficiency of current drive. Because GA Technologies does not have an ultraviolet survey instrument, they were very interested in the instrument we were building for TMX-U and plan to use on MTX. This year, we calibrated our McPherson SPRED instrument at the National Bureau of Standards (NBS) and installed it on DIII-D. This instrument has both a survey grating and a high-resolution grating. Examples of data from a DIII-D divertor discharge with neutral injection is shown in Fig. 11. In Fig. 11(a) spectra between 100 to 1100 Å is shown. In Fig. 11(b) the high-resolution grating is used to examine impurity emissions between 100 to 300 Å.

C. Tokamak Operations

Eight personnel from the LLNL engineering department were located at GA Technologies to bring LLNL diagnostics into operation and to assist with DIII-D operations in certain key areas (7 FTE). This group consisted of a mechanical and electrical engineer, four mechanical technicians, and two electronic technicians. Efforts in tokamak operations provided Livermore personnel an opportunity to become familiar with tokamak engineering and operation.

The two engineers directed the mechanical and electrical design of diagnostic instruments (described previously) that LLNL fielded on DIII-D. They provided the interface between GA engineering design reviews and design and fabrication carried out at Livermore. They also supervised the installation and testing of the instruments. This year, six diagnostic systems were operational on DIII-D, and two were fabricated for installation in November. Electrical engineering support was also provided to review and update documentation of the DIII-D interlock system.

Figure 11. Spectral measurements with the SPRED spectrometer, which was absolutely calibrated at the NBS.

Six technicians located at GA Technologies provided 5 FTE of support to DIII-D tokamak operations. Approximately 1.5 FTE of technician effort at GA Technologies was required to bring the LLNL diagnostic instruments into operation. This support does not include comparable effort carried out at Livermore. A mechanical and an electrical technician helped GA Technologies to successfully bring into operation the long-pulse (2- to 5-s) neutral beams. They assembled source modules, cabled sources to power supplies, modified control electronics, and built cryogenic controls. One mechanical technician was a tokamak operator who assisted with DIII-D operations and discharge cleaning. Two technicians assisted with ECH waveguide assembly and installation as well as gyrotron operations. A mechanical technician worked with the cryogenic plant and in the vacuum shop. Another mechanical technician assisted with GA diagnostics. The diagnostics included the TV Thomson-scattering system and the scanable, multichannel charge exchange analyzer.

III. Publications

Although the primary emphasis of our FY87 work was bringing diagnostic instruments into operation on DIII-D, our work has already generated numerous publications. Several publications resulted from measurements obtained with the IR camera, which was installed in October 1986; others resulted from our work in the ECH area, where LLNL personnel participated with GA personnel in DIII-D ECH experiments. A list of publications to which LLNL personnel contributed is given in the next section.

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