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The Upgrade of the DIII–D 110 GHz ECH System to 6 MW*

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Abstract

ECH power has proven capabilities to both heat and drive current in energetic plasmas. Recent developments in high power sources have made the use of these capabilities in energetic plasmas feasible. For the second phase of ECH power on DIII–D, there will be three 1 MW sources added to the existing 3 MW for a total generated power of 6 MW. The upgrade is based on the use of single disc CVD (chemical vapor deposition) diamond windows on 1 MW gyrotrons developed by CPI. All gyrotrons are connected to the tokamak by low-loss-windowless evacuated transmission lines using circular corrugated waveguide for propagation in the HE_{11} mode. Each waveguide system incorporates a two-mirror launcher which can steer the rf beam poloidally from the center to the outer edge of the plasma and toroidally for either co- or counter-current drive. The total system overview and integration with existing systems will be discussed along with the new aspects of the upgrade from building modifications to the new launchers. Much of the upgrade is comprised of existing designs, which will need only slight modifications, while some components have required new designs because of longer pulse lengths.

I. INTRODUCTION

Over the past ten years gyrotron technology has progressed in both output power and pulse length capability. In 1986 DIII–D came on-line with ten, 60 GHz 200 kW gyrotrons giving a total capability of approximately 1.5 MW of delivered power for relatively short (<1 s) pulses. The next step in gyrotron development took place in 1990–1991 with the development of 500 kW 110 GHz gyrotrons [1]. Initial plans called for the installation of four of these gyrotrons on DIII–D, but, due to gyrotron developmental problems, this program was redirected to focus on the megawatt-class gyrotron. Currently there are three gyrotrons installed on DIII–D [2,3]. Two of these gyrotrons are of Communications and Power Industries (CPI) design using the triode gun configuration and one is of Gycom design using a diode gun configuration.

In support of the Advanced Tokamak (AT) experimental program on DIII–D, methods are being developed to control the current and pressure profiles of plasma discharges, with particular interest in generating large amounts of off-axis current. It was predicted and demonstrated that an attractive method of generating these currents is with electron cyclotron current drive systems. The first step was to install 3 MW of electron cyclotron heating power at 110 GHz. This step was completed in 1999. Step two calls for increasing this power to a total of 6 MW of installed power. This additional power capability will also be enhanced by the ability of extending the pulse length from the current 2 s out to 10 s for the new gyrotrons. This paper describes the hardware and expected operating parameters of the upgrade gyrotron systems.

II. PHYSICAL INFRASTRUCTURE OVERVIEW

In order to accommodate the addition of three new gyrotron systems and associated high voltage power supplies, water-cooling, and controls, it was necessary to add additional floor space to the existing DIII–D facility. This was accommodated with the addition of approximately 3000 sq ft of dedicated floor space in addition to the same amount of space for non-related activities. Figure 1 shows the location of the various major components associated with the upgrade. This is the first time in over ten years where we were able to have a clean slate in regards to appropriate space. In the past we were given an area to install the systems and had to adjust to fit that space while here we dictated the space requirements. Every effort was made early in the design and building layout phase to factor in future growth along with serviceability. The addition of gyrotron systems required not only space for the gyrotrons themselves but also required adequate room for the instrumentation and data acquisition equipment, high voltage modulator regulators, and the main gyrotron control room.

Due to the expected floor loading and the requirement to withstand seismic events associated with being located in southern California, the physical building required substantial strength. Rather than use standard I beam construction practices, which would tend to concentrate magnetic flux lines and therefore interfere with the gyrotron magnetic optics, it was decided to disperse the steel as evenly as possible. Building in such a fashion required the use of 35 tons of steel rebar and almost 400 cubic yards of concrete. The end result, magnetically, should be the equivalent of placing the gyrotrons on an infinitely large steel plate. To further mitigate any magnetic anomalies, the gyrotron gun region is raised off of the floor by almost a meter.

Since the gyrotron and instrumentation areas have raised flooring, it has enabled us to locate the majority of the service, control, and instrumentation cabling in conduits and trays beneath the floor. This presents not only a neater appearance but also adds a level of protection to these items. We also decided to run the transmission lines beneath the raised floor, thereby preserving overhead crane access for the larger components such as magnets and gyrotrons. To facilitate the installation process, the under floor area was stratified into three zones: ac power and fire protection at the bottom,

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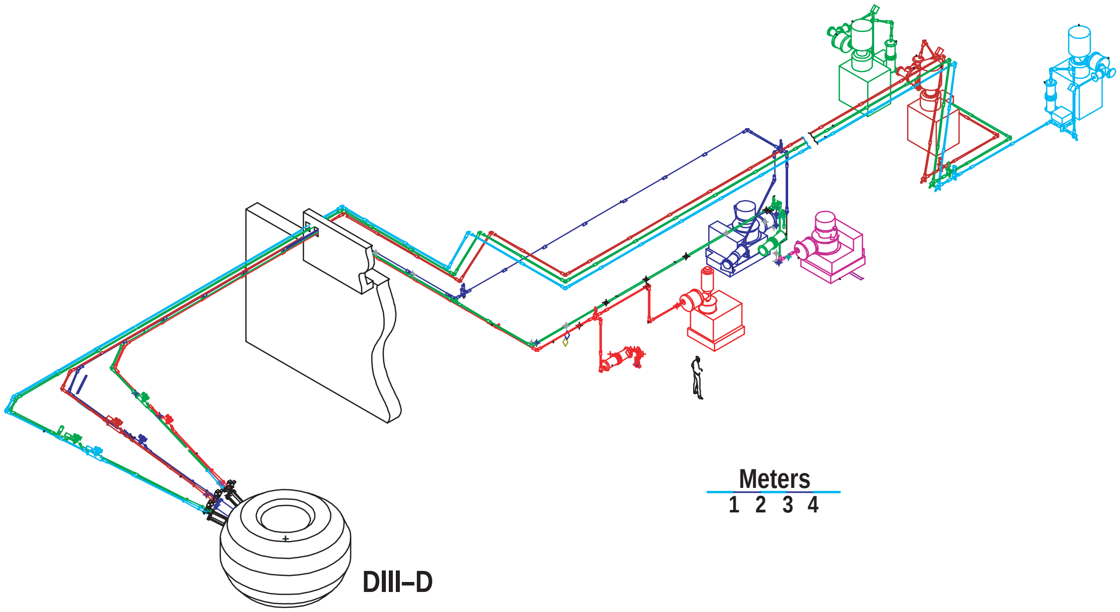

Fig. 1. DIII–D gyrotron installation.

control and signal cable-ways next, and waveguides located in the upper region. Figure 2 shows a cross-section of the under floor.

III. Gyrotron and Transmission System

The upgrade project is based on the use of three CPI 1 MW-class gyrotrons with CVD diamond output windows and diode guns. The departure from the typical CPI triode gun was based on operational experience of existing CPI and Gycom tubes. It was felt that the ease of operation for a diode gun gyrotron far outweighs any loss in modulation flexibility. The use of a long-hold-time superconducting magnet was chosen in lieu of a conventional superconducting magnet. This magnet will only need to be filled with liquid helium about once per month as opposed to about once every two or three days. The savings in labor will more than offset the additional cost over the projected lifetime of the equipment. The transmission line system is comprised of miter bends, polarizer miter bends, power monitor miter bends, straight sections, dummy loads, mirror interface units, and the associated structural support and vacuum components. The transmission line chosen is GA's standard 31.75 mm corrugated waveguide. This transmission line design has been used for several years on existing high power systems on DIII–D without any signs of breakdown when under vacuum. The use of a diamond gyrotron output window enables the direct injection of a Gaussian mode (HE_{11}) into the waveguide. This, along with our small diameter waveguide, has eliminated the need for any phase correction mirrors in the system and their associated costs. Early identification of both the gyrotron orientation and the transmission line routing was essential to the success of this project. There were several iterations made prior to the selection of the final layout shown in Fig. 3. Future expansion and accessibility were major factors in determining the final room layout.

As part of the overall DIII–D ECH program, PPPL has designed and fabricated a new steerable launcher. This launcher has two gyrotrons connected to it and incorporates independent toroidal and poloidal positioning control. This will allow for aiming of the rf into almost any region of the plasma. After validation of the first launcher, which will begin in February 2000, PPPL will fabricate two additional launchers to be installed late FY00 or early FY01. The additional launchers are planned to have active cooling of the mirrors to enable us to use the full pulse length capability of the new generation gyrotrons.

IV. Control and Instrumentation

The control system uses software distributed among networked computers interfaced to a programmable logic controller (PLC), the timing and pulse system, power supplies, vacuum and waveguide controls, and instrumentation. During DIII–D operation, the system will allow for control and monitoring of each of the operational gyrotrons. The software, written using LabView®, allows for remote control by multiple operators. The LabView® programming language was chosen because of existing in-house expertise (ICH control system) and available help from ORNL. It also makes programming of the various commercial instruments rather simple due to the large base of existing drivers. Any supported computer can become a control station, and multiple tasks can be simultaneously accommodated. Each operator can be given access to the control of all or a subset of the operational gyrotrons. The use of a PLC simplifies the hardware and software design. It reduces interlock and control circuitry while improving reliability and flexibility. The pulse control system is designed around arbitrary function generators, allowing for various modulation schemes to be implemented including real-time modulation control. With the recent boost in performance of the Intel-based personal computers, we

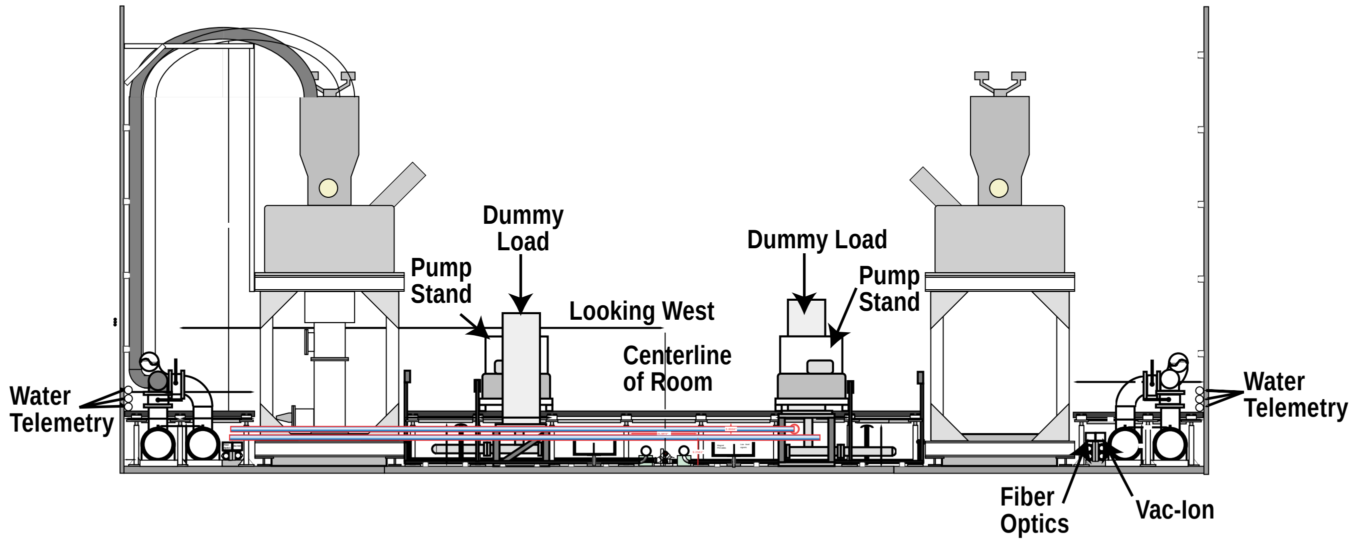

Fig. 2. Under floor cross-section.

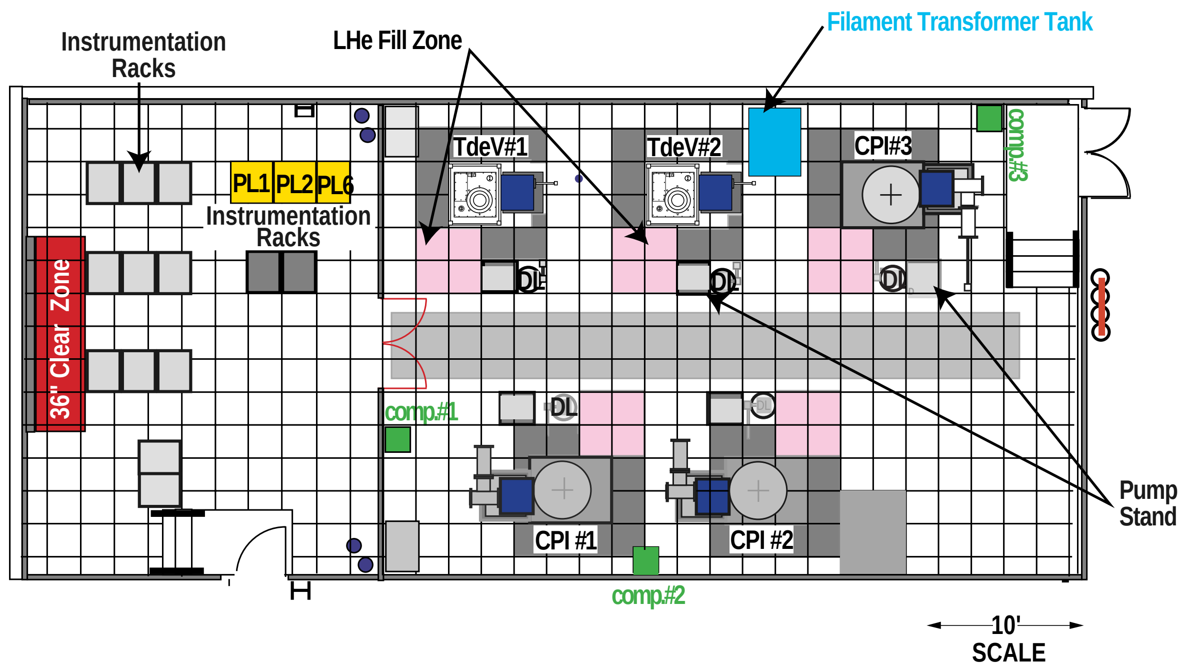

Fig. 3. Layout of CPI and TdeV gyrotrons.

have departed from the use of the more expensive computer platforms. We are now able to distribute various computers throughout subsystems and at the same time reduce the overall cost. The distributed computer technique has also enabled us to have a more robust control system while also realizing an increase in speed.

V. TDEV GYROTRON SYSTEM

When the Canadian government decided to close down the TdeV facility in Quebec, two complete 110 GHz gyrotron systems became available. These systems consisted of two GYCOM gyrotrons and magnets, a separate series high voltage regulator for each of the gyrotrons, and the associated tanks and control systems. Having already had good operational experience with GYCOM (Russian) gyrotrons a.k.a. our Katya gyrotron, it was decided that the procurement of the available systems would be a good way of ensuring at the least spare gyrotrons and at best two complete systems. After evaluating the status of the existing systems there was even more impetus to acquire the TdeV systems and install them as systems rather than as spares. This change in direction required some changes in the layout of the gyrotron and instrumentation rooms. Figure 3 shows the layout for both the CPI and TdeV gyrotrons and instrumentation. In an attempt to minimize the additional cost associated with the installation of the additional systems, every effort was given to using as much of the original cabling and mechanical systems as possible. The physical layout of the TdeV equipment was driven by this requirement. Fortunately the original spacing of the TdeV gyrotron tanks was almost identical to the proposed layout for the GA-CPI systems. This made most of the layout a simple matter of placing the Canadian tanks where we had planned to place the upgrade tanks. There were two areas where some additional work was required. Since the GYCOM gyrotrons require lower cooling water pressure, a pressure reduction station was needed between the newly installed header and the existing TdeV water manifolding. The other area requiring additional work was in the area of control interfacing. Since the existing system used PLCs and a host computer, it was decided to place a dedicated PC as the interface element. This layout provides flexibility and an architecture commonality for both the TdeV and GA systems.

VI. SUMMARY

With the added ECH power, new launcher flexibility, and reduced complexity of both the rf transmission lines and gyrotron control, the DIII–D tokamak will enable critical experiments to be performed to explore advanced tokomak regimes. The careful thought given to the new installation in the early planning stages should make it a relatively easy task to add additional gyrotrons in the future if necessary. The work done on this upgrade should be directly applicable to any future multi-megawatt ECH systems needed anywhere in the world. The use of proven technology and components in nearly all systems provides a high level of assurance that the upgrade project will be successful.

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