Enhancements for the DIII-D ECH System

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***Abstract*—The expansion and upgrading of the electron cyclotron heating and current drive (ECH/ECCD) gyrotron complex on the DIII-D tokamak are continuing with the addition of the first of a series of depressed collector tubes in the 1 MW class. The ultimate goal is a 10 gyrotron system with rapid steering of the rf beams and full integration into the DIII-D Plasma Control System using the real time EFIT equilibrium calculation to determine the ECH/ECCD deposition locations to guide requirements for both steering and injected power.**

I. INTRODUCTION

THE electron cyclotron heating (ECH) gyrotron system on the DIII-D tokamak has been operating for several years with 6 gyrotrons, all of which generate 110 GHz and nominally 1 MW output power per gyrotron. Although the gyrotron performance has been quite reliable, it has been necessary to operate at lower than maximum demonstrated output power to achieve 85% reliability, which has remained constant for the past 6 years despite many upgrades to the system, including gyrotron exchanges, during this period. The ~100 m long transmission lines leading to the tokamak are evacuated 31.75 mm diam. corrugated circular waveguides which deliver about 75% (-1.25 dB) of the generated power to the tokamak. The pulse lengths are matched to the capabilities of the tokamak and are limited administratively to 5 s. to extend the fatigue lifetime of the gyrotron collectors. The injected power has varied between 3.0 and 3.4 MW during this period, with pre-programmed and reactive modulation up to about 2 kHz.

The long term program plan calls for a system comprising 10 gyrotrons and 5 dual launchers. New gyrotrons, designed to generate 1.5 MW for operational pulse lengths, will feature an rf frequency of 117.5 GHz and operate with collector potential depression (CPD).

II. UPGRADES IN PROGRESS

Gyrotrons using CPD are expected to have improved electrical efficiency compared with the previous generation of undepressed diode tubes; and all future gyrotrons for the DIII-D system will be of this type. The first two of these tubes operate at 110 GHz and are designed for 1.2 MW generated power at 10 s. pulse length. One of these is now in operation at DIII-D and the second should be delivered in mid-2013. The following group is designed to generate 1.5 MW for 10 s. pulse lengths. The first of these 117.5 GHz tubes is being manufactured and should be delivered late in 2013. In addition to the transition to CPD gyrotrons, the previous OFHC copper coaxial collector design is being changed to a CuCrZr alloy with simple cylindrical geometry.

The first of the CPD 110 GHz gyrotrons produced the best quality Gaussian beam of any previous tube installed at DIII-D. The power lost in the Matching Optics Unit (MOU), which indicates the rf beam quality, was ~2%, or about half that of our previous best tube. The infrared power profiles for the beam exiting the gyrotron and then after a length of waveguide, are shown in Fig. 1.

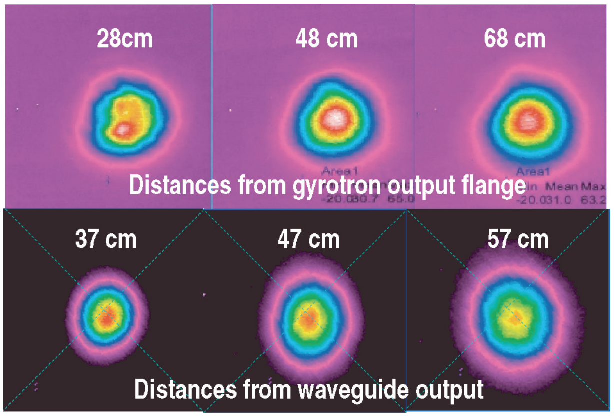

Fig. 1. Free space profiles of the rf beam. The upper row is profiles of the beam propagating from the gyrotron. The lower row is profiles of the beam propagating out from the open end of an 85 cm length of waveguide after the MOU.

This tube, intended to generate 1.2 MW, had a maximum generated power of ~950 kW for 5 s pulses and efficiency of 33%, considerably lower than the 1.2 MW at 41% efficiency achieved during factory testing at short, 2 ms, pulse lengths. Cathode cooling during long pulses, resulting in up to a 10% decrease in electron beam current, is at least partially responsible for the reduced output power. Although filament boosting can mitigate the decrease in electron beam current during a pulse, it has not proved to be possible to develop a boost program that keeps the current constant for this gyrotron at these pulse lengths.

A second difficulty with this gyrotron resulted from the difficulty of brazing the CuCrZr collector material. During pulsing at full parameters, it was noted that the collector cooling water was boiling. Upon investigation, it was found that 9% of the cooling passages in the collector were blocked by braze material. These were located both with a borescope and also by infrared observations of the collector outer surface when the collector was heated to a uniform temperature and then rapidly cooled by opening the water cooling valve.

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During about the first 3 s after opening the valve, the individual cooling channels, both blocked and open, were clearly visible in the infrared. An infrared observation of the channels and a photograph of one blocked channel, visible through the water return port, are shown in Fig. 2. Despite the blockages, the gyrotron is in regular service for experiments with a predicted service life of about 30,000 pulses.

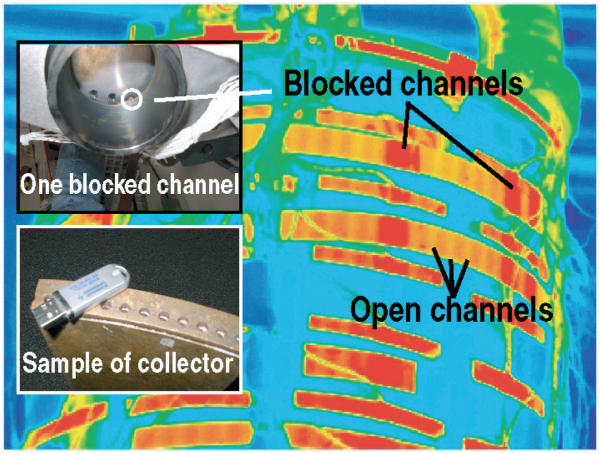
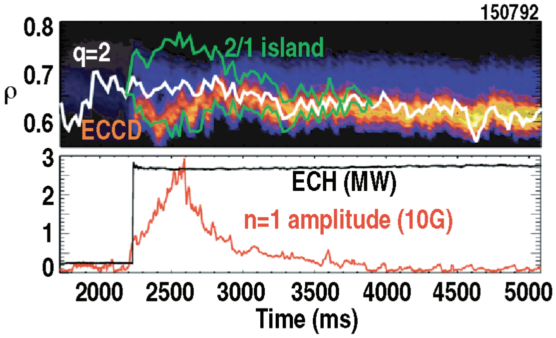


Fig. 2. Infrared view of the collector surface showing cooling channels when the warm collector is suddenly cooled.

The long-term plan for the DIII-D ECH system is for the 1.5 MW 117.5 GHz gyrotrons to be phased in gradually over the next few years. One gyrotron, which had failed due to a water leak, may be repaired and kept as a spare for the tubes currently in operation. The ability to determine the time dependence of the injected power using the Plasma Control System, either with a pre-loaded program or in response to requirements varyingduring the plasma shot is being used regularly and will be enhanced by updating the control algorithms and hardware.

The real time poloidal scan capability of the DIII-D launchers is being exercised for experiments while it is being upgraded. The full 40º poloidal scan can now be covered in 700 ms and this is being upgraded by installation of higher speed motors with three times the present speed. Magnetic encoders are being tested to replace the 14 bit electro-mechanical encoders, which had originally been intended for much slower read-back speeds, and suffered from contact bounce issues at the higher scan speeds now being used. This, in turn, requires improvements to the algorithms which are used to read the encoders which measure the angles of the steering mirrors and control the slowing as the setpoint is reached and enhance the jitter frequency achievable when the rf beams are following a moving target during evolution of the plasma shot.

For example, real time EFIT calculations of the plasma equilibrium, which include direct measurements of the internal magnetic field using the motional Stark effect diagnostic to constrain the equilibrium, are used to calculate the locations of resonant *q* surfaces in the plasma at which the island structures of the neoclassical tearing modes form. The increased scanning speeds will allow the ECH system to be used for some other purpose, for example current density profile control, and then rapidly to be redirected to point at a *q* surface where growth of a neoclassical tearing mode (NTM) has been detected. An example of the coupling of the real time EFITs and the launcher steering to achieve NTM suppression in this way is shown below.



1800 ms: MSE EFITS calculate and track q=2 location
2200 ms: m/n=2/1 island grows
2250 ms: ECH on, 2.6 MW, mirrors steered by Plasma Control System
2600 ms: ECCD location is aligned with q=2 surface
2600 ms: NTM island begins to shrink as aiming is adjusted
3900 ms: NTM is fully suppressed

Fig. 3. Time sequence for NTM suppression with mirror steering and real time equilibrium calculations.

A second reliquifier has been added to the system so that the liquid helium requirements for the remaining gyrotron magnet with a liquid helium reservoir will be greatly reduced. No makeup liquid helium has been required for the first unit to be equipped with a reliquifier except when problems with either the electrical grid or water-cooling system occurred. In these cases, the excess capacity of the reliquifier was used to refill the magnet from bottled helium gas.

The operating system is being upgraded with FPGA-based fault processing and enhanced communications between the DIII-D Plasma Control System and the ECH control system.

To accommodate an experiment unrelated to fusion research, an additional waveguide switch and subsidiary waveguide line have been added to one gyrotron system to provide power for experiments located in a mobile laboratory parked outside the DIII-D building. Microwave power at 110 GHz is being used to study the feasibility of boosting small satellites into earth orbit by expanding gas or ablating material without using fuel that requires an oxidizer. This would allow savings in the net energy required to achieve orbit. Different scenarios include microwave heating following air launch from a conventional high altitude aircraft and ground launch from high elevation points near the equator.

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