Final Report

ECH Technology Development

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Abstract

Electron Cyclotron Heating (ECH) is needed for plasma heating, current drive, plasma stability control, and other applications in fusion energy sciences research. The program of fusion energy sciences supported by U. S. DOE, Office of Science, Fusion Energy Sciences relies on the development of ECH technology to meet the needs of several plasma devices working at the frontier of fusion energy sciences research. The largest operating ECH system in the world is at DIII-D, consisting of six 1 MW, 110 GHz gyrotrons capable of ten second pulsed operation, plus two newer gyrotrons. The ECH Technology Development research program investigated the options for upgrading the DIII-D 110 GHz ECH system. Options included extending present-day 1 MW technology to 1.3 – 1.5 MW power levels or developing an entirely new approach to achieve up to 2 MW of power per gyrotron. The research consisted of theoretical research and designs conducted by Communication and Power Industries of Palo Alto, CA working with MIT. Results of the study would be validated in a later phase by research on short pulse length gyrotrons at MIT and long pulse / cw gyrotrons in industry. This research follows a highly successful program of development that has led to the highly reliable, six megawatt ECH system at the DIII-D tokamak. Eventually, gyrotrons at the 1.5 megawatt to multi-megawatt power level will be needed for heating and current drive in large scale plasmas including ITER and DEMO.

Report

1. Introduction

We have investigated multi-megawatt, 110 GHz depressed collector gyrotrons for the DIII-D ECH system upgrade. The existing ECH system of DIII-D, which is the highest power ECH system in the world, is schematically presented in Fig. 1 [Gorelov, 2009]. It includes six 1 MW 110 GHz gyrotrons built by CPI [Felch, 2008]. These gyrotrons are based on an older design and they do not have depressed collectors.

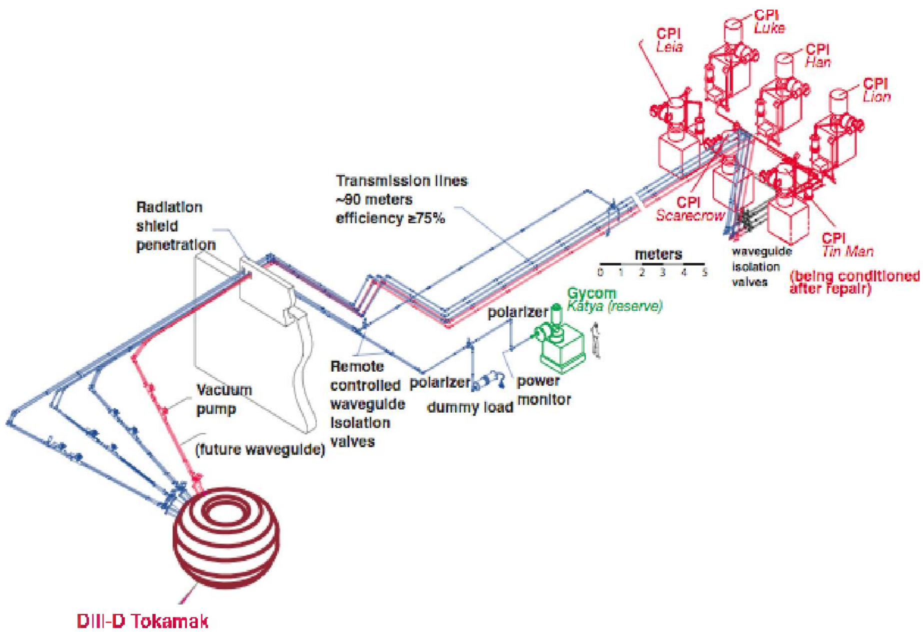

FIGURE 1. Schematic of ECH system at DIII-D.

It is desirable to upgrade the DIII-D ECH system. First, the existing gyrotrons have a very high heat load in the collector of the tube because the gyrotrons do not have depressed collectors. Ultimately, this high heat load may lead to a shortened lifetime of the gyrotrons because of metal fatigue. In that case, the replacement of the gyrotrons would occur out of necessity. Second, the 1 MW gyrotrons are also under consideration for replacement because the available power level of 6 MW total is lower than the desired power level of about 10 to 15 MW. The addition of two more gyrotrons and the replacement of the 1 MW gyrotrons by 1.5 to 2 MW gyrotrons would allow higher power, up to 16 MW depending on power supply availability, to be achieved for plasma heating and current drive. New gyrotrons with depressed collectors would also operate at higher efficiency and would require less water cooling.

2. Research Program

During the past decade, research funded through the DOE Virtual Lab for Technology has resulted in the design, fabrication and testing of 1.5 MW, 110 GHz gyrotrons. CPI built a long pulse 1.5 MW gyrotron (Fig. 2). Results were reported in [Chu, 2004] and [Chu, 2005]. That gyrotron was built over the course of several years using funding from this research program. The funding has been provided by US DOE OFES to MIT and is subcontracted by MIT to CPI for research and development. This research was followed by a subcontract to CPI for further design studies of 1.5 to 2 MW, 110 GHz gyrotrons.

In parallel with the industrial program at CPI, MIT conducted basic research at short pulse lengths, on the microsecond time scale; the MIT system is shown in (Fig. 3). The ECH development effort included collaboration with theoretical gyrotron research at University of Maryland [Vlasov, 2008]; research on mode converters and microwave component testing at University of Wisconsin – Madison [Perkins, 2007]; and research on auxiliary components and mode converter codes at Calabazas Creek Research, Inc. (CCR) [Neilson, 2002]. The CPI tube successfully demonstrated operation at an output power of 1.28 MW in millisecond pulses and 0.5 MW in ten second pulses. The electron gun for the CPI and MIT gyrotrons was designed within this collaboration. The internal mode converter for the CPI tube was developed by Calabazas Creek Research (CCR) and Univ. of Wisconsin.

The MIT tube demonstrated an output power of 1.5 MW in 3-microsecond pulses. The tube parameters are listed in Table 1. The mode competition that affects the gyrotron efficiency was theoretically studied at Univ. Maryland and at MIT. The gyrotron cavity was optimized to reach higher efficiency. The higher efficiency operation without a depressed collector was experimentally demonstrated at MIT using the new cavity. The depressed collector operation of the MIT gyrotron was studied, and an efficiency of 50% was demonstrated. A new effect of an after-cavity interaction that reduces the efficiency of depressed collector gyrotrons was observed at MIT experimentally for the first time. Results were reported in [Anderson, 2002, 2004] and [Choi, 2005, 2006, 2007a, 2007b].

The MIT research group has conducted experimental and theoretical studies of the gyrotron internal mode converter. From the beginning, the MIT tube utilized the old mode converter. From comparison of the output power measured with- and without the internal mode converter, a conversion efficiency of about 90% was estimated. The latest version of the MIT tube includes an improved mode converter. The mode converter includes a launcher, three smooth quasi-optical mirrors and a flat mirror. This is a new approach as compared to the previous version of the mode converter used in all of the 1 MW CPI tubes. The launcher was optimized by CCR and cold tested at the Univ. of Wisconsin. The mode converter including the mirrors was cold tested at MIT using a $TE_{22,6}$ 110 GHz mode generator built by General Atomics. Figure 4 show the MIT cold test lab. The quasi-optical mirrors were re-designed to produce a round Gaussian beam at the mode converter output. The mode converter was then installed in the tube, and the output beam was measured in short pulse operation of the tube (hot test). The cold test and hot test results agreed very well. The gyrotron output radiation was characterized as a 96% Gaussian beam.

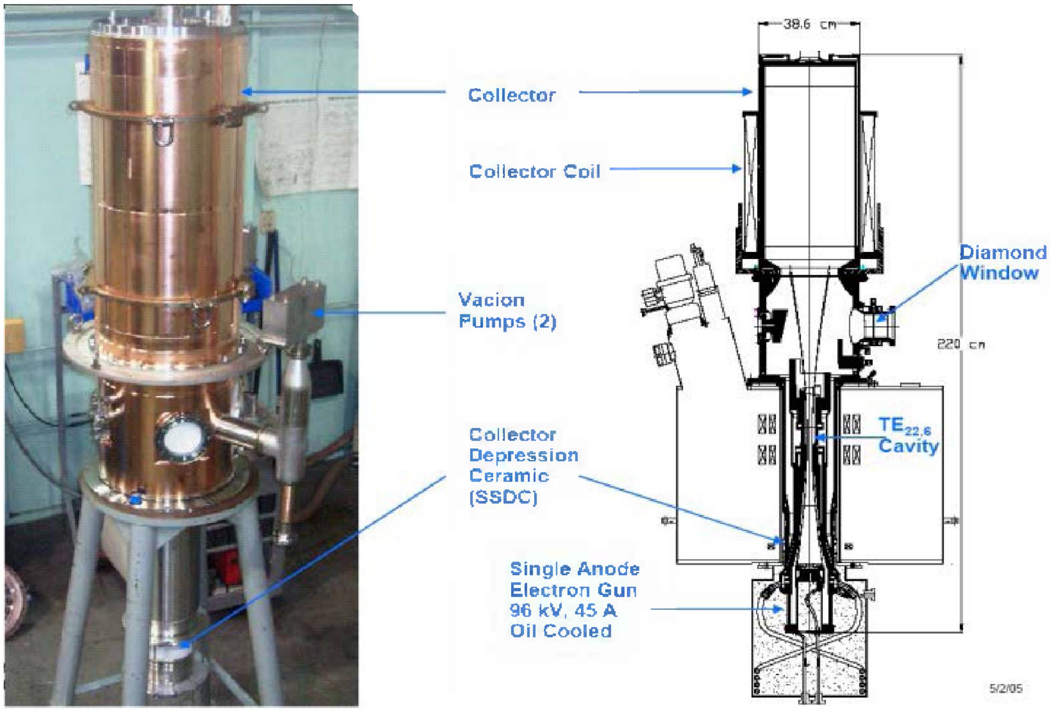

FIGURE 2. CPI 1.5 MW 110 GHz long pulse gyrotron.

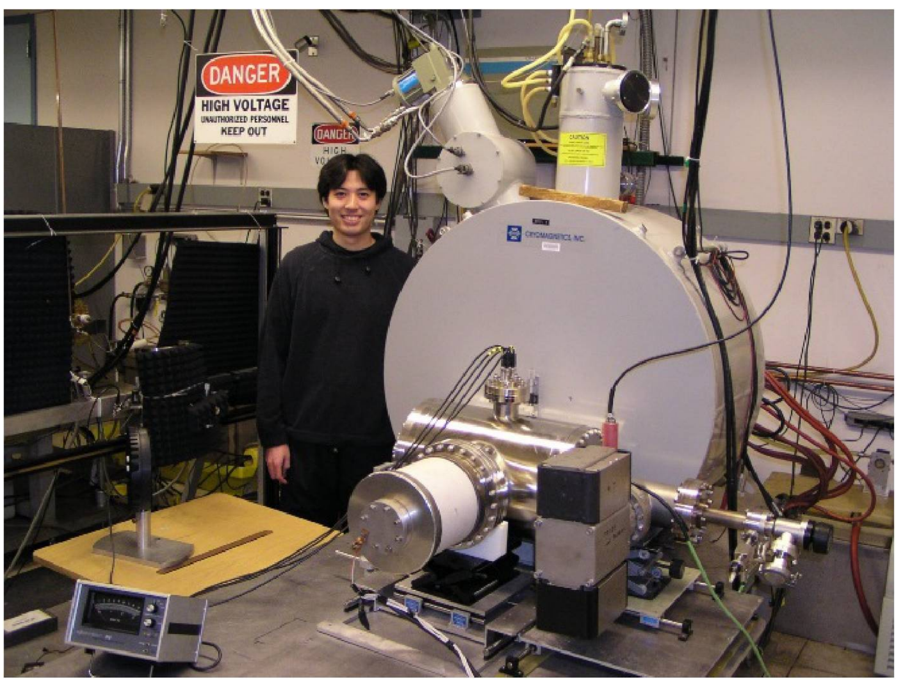

FIGURE 3. MIT 1.5 MW 110 GHz experimental setup for short pulse testing.

Table 1. Short pulse MIT gyrotron parameters.

Frequency	110 GHz
Power	1.5 MW
Voltage	96 kV
Current	40 A
Depression Voltage	25 kV
Operating Mode	TE22,6
Pulse Length	3 μs
Magnetic Field	4.3 T
Efficiency (w/o Depressed Collector) (with Depressed Collector)	 40 % > 50 %

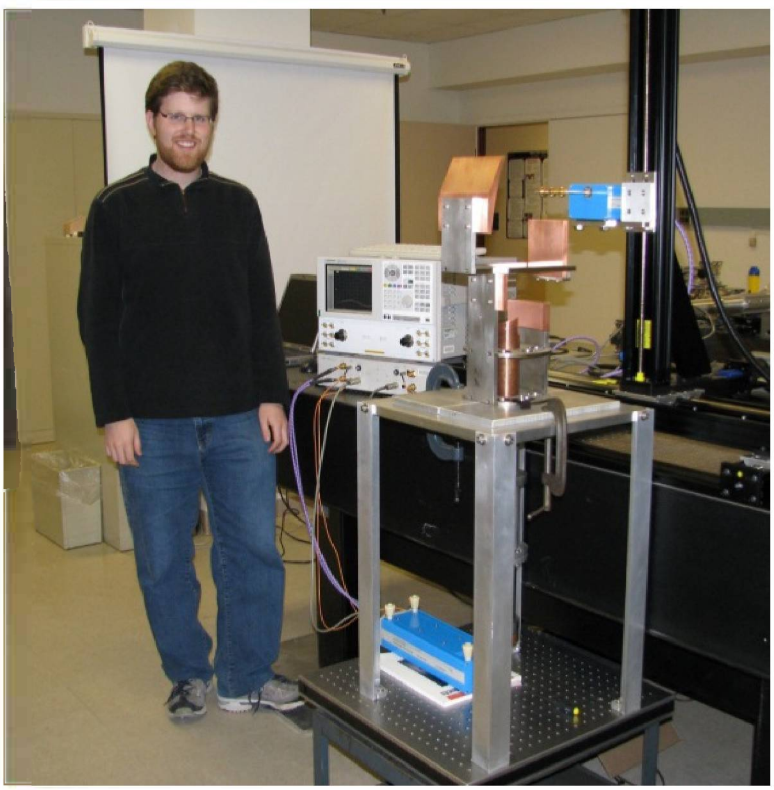

FIGURE 4. Cold test stand for the gyrotron mode converter.

3. Additional Research Results

The research effort consisted of a coordinated research project at CPI and at MIT to identify the most promising approach to a 1.5 to 2 MW, 110 GHz gyrotron for the DIII-D upgrade project. CPI conducted studies of the gyrotron components needed for higher power gyrotron development. The design included selection of cavity modes, basic design of the electron gun, choice of conventional vs. coaxial cavity, selection of voltage and current, and estimated gyrotron efficiency. The CPI research benefited from the research being conducted at CPI on a 2 MW, 95 GHz under funding from the Dept. of Defense. Under that program, a novel gyrotron collector using dispersion hardened copper has been developed [Felch, 2009]. The conclusion of the design study was to develop higher power gyrotrons in two stages. In the first stage, a power level of 1.2 to 1.5 MW would be achieved and in the second stage a power level of 1.8 to 2.0 MW would be achieved.

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