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Gyrotron and power supply development for upgrading the electron cyclotron heating system on DIII-D

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HIGHLIGHTS

- Vendor completed design of 1.5 MW, 117.5 GHz gyrotron for DIII-D.
- Fabrication of gyrotron by vendor underway.
- Finalizing design of solid-state high voltage modulator for cathode power supply.
- Fabrication of solid-state high voltage modulator has begun.
- Finalizing design of high voltage linear amplifier for gyrotron body power supply.

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ABSTRACT

An upgrade of the electron cyclotron heating system on DIII-D to almost 15 MW is being planned which will expand it from a system with six 1 MW 110 GHz gyrotrons to one with ten gyrotrons. A depressed collector 1.2 MW 110 GHz gyrotron is being commissioned as the seventh gyrotron. A new 117.5 GHz 1.5 MW depressed collector gyrotron has been designed, and the first article will be the eighth gyrotron. Two more are planned, increasing the system to ten total gyrotrons, and the existing 1 MW gyrotrons will subsequently be replaced with 1.5 MW gyrotrons.

Communications and Power Industries completed the design of the 117.5 GHz gyrotron, and are now fabricating the first article. The design was optimized for a nominal 1.5 MW at a beam voltage of 105 kV, collector potential depression of 30 kV, and beam current of 50 A, but can achieve 1.8 MW at 60 A. The design of the collector permits modulation above 100 Hz by either the body or the cathode power supply, or both, while modulation below 100 Hz must use only the cathode power supply.

General Atomics is developing solid-state power supplies for this upgrade: a solid-state modulator for the cathode power supply and a linear high voltage amplifier for the body power supply. The solid-state modulator has series-connected insulated-gate bipolar transistors that are switched at a fixed frequency by a pulse-width modulation regulator to control the output voltage. The design of the linear high voltage amplifier has series-connected transistors to control the output voltage, which was successfully demonstrated in a proof-of-principle test at 2 kV. The designs of complete power supplies are progressing.

The design features of the 117.5 GHz 1.5 MW gyrotron and the solid-state cathode and body power supplies will be described and the current status and plans are presented.

1. Introduction

The electron cyclotron heating (ECH) system on DIII-D has six gyrotrons supporting plasma physics experiments [1]. Each of these non-depressed collector gyrotrons has an 80 kV, 40 A electron beam. The gyrotrons are connected to three ECH power supplies (ECHPSs) that have tetrode-based modulators to control the cathode voltage applied to the gyrotrons. A seventh gyrotron, a depressed collector 1.2 MW 110 GHz gyrotron was recently delivered to DIII-D and is being commissioned. This gyrotron has a nominal 95 kV, 40 A electron beam, with a cathode voltage of −70 kV and body voltage of 25 kV. A 4th ECHPS, which can operate two depressed collector gyrotrons, has been installed and tested. It has two tetrode-based modulators to independently control the cathode voltages applied to the two gyrotrons and commercially available high voltage amplifiers to separately control the body voltages.

A new gyrotron was proposed for the upgrade of the DIII-D ECH system that would produce higher power but still stay within the voltage and current capability of the existing power supplies to

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reduce the cost of the upgrade. This resulted in a design target of 1.5 MW. A frequency of 117.5 GHz was selected for this gyrotron to better match the needs of future planned experiments on DIII-D. Communications and Power Industries (CPI) completed the design of this gyrotron and the fabrication of the first article was initiated.

General Atomics (GA) started the development of a solid-state modulator for other projects [2], and is continuing its development for the cathode power supply of future gyrotron power supplies to overcome the shortcomings of the tetrode-based modulators, one of which is the dissipation at low frequencies of modulation. The design utilizes series-connected IGBTs that feed an inductor-capacitor filter network and that are switched at a fixed frequency by a pulse width modulation (PWM) regulator to control the output voltage. A modulator will be fabricated and tested to validate its operation at 50 kV, 50 A for 30 s into a dummy load and to demonstrate modulation at frequencies approaching 1 kHz.

GA also initiated the development of a linear high voltage amplifier for the body power supply that has higher voltage and current capability as well as a smaller package than other available units. The design has series-connected transistors to control the output voltage, and proof-of-principal tests successfully demonstrated control of voltages up to 2 kV dc and with modulation greater than 5 kHz. The design of a complete 45 kV, 250 mA power supply is underway.

The design features and status of the 117.5 GHz 1.5 MW gyrotron and the solid-state cathode and body power supplies are described below.

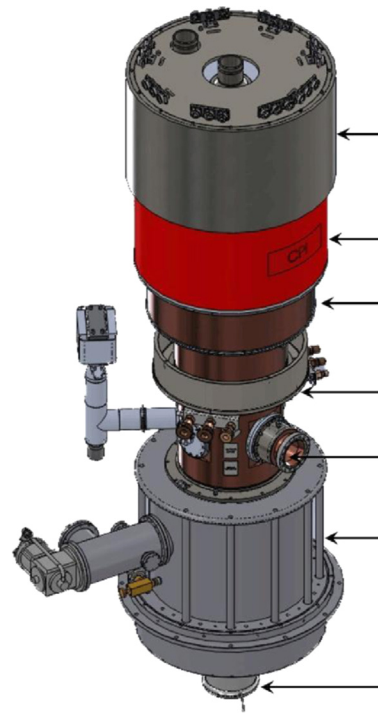

Fig. 1. Solid model of 117.5 GHz gyrotron.

2. 117.5 GHz gyrotron

CPI successfully completed the design of the 117.5 GHz VGT-8117 gyrotron. It has been optimized for a nominal output power of 1.5 MW when operated with a total beam accelerating voltage of 105 kV and a beam current (I_b) of 50 A. The accelerating voltage is achieved by holding the cathode 75 kV below ground and the gyrotron interaction circuit (body) 30 kV above ground. The depleted electron beam is collected at ground potential, so the net dc-to-rf conversion efficiency is 40%. Although the gyrotron is intended for nominal operation at $I_b = 50$ A, all components have been designed to withstand operation with I_b up to 60 A, and output power levels up to 1.8 MW.

A solid model of the gyrotron is shown in Fig. 1. The design employs a diode magnetron injection gun with a thermionic cathode operated in the temperature-limited emission regime, so that beam current and accelerating voltage can be independently controlled. The electron gun produces a thin, annular electron beam which streams along the lines of magnetic flux produced by a superconducting magnet. As the beam propagates to the high-field region in the magnet, where the interaction cavity of the gyrotron is located, adiabatic compression yields a mono-energetic beam with a significant rotational velocity (with $v_\infty/v_\parallel \sim 1.4$), which is resonant with the $TE_{20,9,1}$ mode of the gyrotron cavity. Self-consistent simulations of the beam-wave interaction using the MAGY code [3] predict that for a peak magnetic field of 47.7 kG, a 105 kV, 50 A beam will generate 1.63 MW of RF power at the cavity exit.

The interaction mode is converted to a Gaussian output beam using an internal converter consisting of: (1) a numerically optimized dimpled-wall launcher, which produces a spot-like beam that exits the launcher through a helical cut in the launcher wall, and (2) a set of three mirrors to steer the beam and apply phase corrections to maximize the Gaussian content of the beam before it reaches the output window of the gyrotron. The launcher produces a beam with 96% complex coupling to a Gaussian beam, and subsequent phase correcting mirrors increase the Gaussian coupling to 99% at the window. Theoretical diffraction losses due to stray power missing the mirror surfaces or falling outside the window aperture are estimated to be 2.1% of the power exiting the cavity. The output window is an edge-cooled chemical vapor disposition (CVD) diamond disk with a thickness of 1.5 wavelengths at 117.5 GHz, to minimize reflection. Thermal analyses indicate that peak stresses are about half the tensile strength of the diamond material during operation at 1.8 MW, using conservative estimates of window loss.

The depressed collector, which must dissipate the residual energy in the electron beam, employs a combination of features to ensure significant safety margin in its thermal–mechanical design. The collector itself is constructed from a strengthened copper alloy in a configuration that locates the depression ceramic below the superconducting magnet so that the collector and the output window are both at ground potential. The use of a strengthened copper alloy allows the collector walls to be thinner than would otherwise be practical, and reduces temperature gradients accordingly. In addition, iron shielding and the dc magnetic field from a large collector coil serve to optimize the beam strike position in the collector and spread it over a wider range of magnetic flux lines to reduce instantaneous power densities. Applying a sinusoidal sweep signal to the collector coil varies the beam strike point on the collector surface, to further lower time-averaged power densities. Thermal–mechanical analyses of cyclic fatigue effects have been performed for a variety of operating conditions, including power modulation scenarios employing either the body voltage or the cathode voltage. These simulations predict lifetimes in excess of 10,000 h of operation when operating at 1.5 MW CW, or when modulating power from 0 to 1.5 MW using either the cathode or body power supply, for modulation at rates of 100 Hz or higher. Modulation below 100 Hz must be performed using only the cathode power supply. This offers greater flexibility for modulation and eases some of the requirements on the power supplies.

The first article of the 117.5 GHz, which will be the eighth gyrotron in the DIII-D ECH system, is now being fabricated and delivery is expected in late summer of 2013. Upon successful testing of this gyrotron, the plan for the upgrade of the DIII-D ECH has the procurement of the ninth and tenth gyrotrons, which will be