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**DIII-D ELECTRON CYCLOTRON HEATING 2 MW
UPGRADE PROJECT FINAL REPORT FOR THE
PERIOD FY89 THROUGH FY97**

R.W. CALLIS

Prepared under
Contract No. DE-AC03-89ER51114
for the Oakland Operations Office
U.S. Department of Energy

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AUGUST 1997

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**GA PROJECT 3466
AUGUST 1997**

CONTENTS

1. EXECUTIVE SUMMARY	1
2. PROJECT SCOPE AND OBJECTIVES	3
2.1. Overall Program Mangement.....	3
2.2. Technical Description	4
2.2.1. WBS Element 1 — RF Sources	4
2.2.2. WBS Element 2 — Gyrotron Support Systems	5
2.2.3. WBS Element 3 — Cooling Systems	6
2.2.3.1. Low Conductivity Water	6
2.2.3.2. Cryogenics	7
2.2.3.3. FC-75 Cooling	7
2.2.4. WBS Element 4 — RF Transmission	7
2.2.4.1. RF Transmission Line	7
2.2.4.2. Facility Location	9
2.3. Cost Baseline	10
2.4. Schedule Baseline	11
3. LESSONS LEARNED	13
APPENDIX A	17

FIGURES

1. 1 MW 110 GHz ECH system schematic	4
2. Photos of the 1 MW 110 GHz internal mode converter gyrotrons installed at DIII-D. (a) GYCOM gyrotron and (b) CPI gyrotron	5
3. Diagram of the mirror optical unit for interfacing the gyrotron to the 1.25 in. diameter corrugated waveguide	8
4. Layout of the 2 MW ECH upgrade system	9

TABLES

1. DIII-D 110 GHz ECH upgrade cost baseline	10
2. DIII-D 110 GHz ECH upgrade construction milestones	11

1. EXECUTIVE SUMMARY

The 2 MW, 110 GHz ECH system was based on the General Atomics Proposal to the Department of Energy: DIII-D Fusion Research Program Vol. I Technical, and Vol. II Cost (GACP-72-166, July 1987 and revised). This proposal was reviewed in August 1987 by a senior technical review committee, who recommended to vigorously pursue increasing the ECH power to 6 MW. The realization of the higher frequency and power ECH on DIII-D was recognized by the committee to be important, not only for the DIII-D program, but also for future devices and the whole ECH area. Subsequently, an engineering cost and schedule review was conducted by DOE-OAK which confirmed the GA costs and schedules and recommended proceeding directly to 10 MW. However, because of budgetary constraints, in the April 1988 Field Task Proposal submission, GA proposed a phased ECH approach, Phase I being 2 MW and Phase II increasing the power to 10 MW. After review, DOE instructed GA to initiate the prototype 2 MW, 110 GHz program.

The contract to procure four 500 kW, 110 GHz, 10 s gyrotrons from Varian Associates was initiated in April 1989 with final delivery by November 1990. Because of difficulties in spreading the energy of the electron beam over the collector area, the testing of the first gyrotron delayed its delivery until February 1991. The second gyrotron was able to operate for 1 s at 500 kW and 2 s at 300 kW, but failed when the cavity suffered thermal damage.

On November 4, 1991, Varian was directed by GA to stop all work except for supporting the conditioning of S/N#1 gyrotron required for system testing at GA. Program responsibility and funding for further development of the 0.5 MW, 110 GHz gyrotron was transferred to the OFE/I&T gyrotron development program since it was clear the design was not sufficiently developed to complete the production program. During FY92 most of the hardware required for the remainder of the four-gyrotron system was completed and installed at DIII-D. A successful short pulse, high power test of the first system was completed in March 1992; full power pulses of 5 ms duration followed by a 10 ms idle time were repeated for a total duration of 100 ms. The mode mixture of the output power of S/N#1 was found to be 70%–80% (substantially worse than the 95% specification), so for a 500 kW output into the dummy load only 350 kW was converted to the desired HE_{11} mode. Subsequent measurements confirmed the presence of power in unwanted modes. Using the available 350 kW, the transmission lines transmitted the HE_{11} power with no breakdown and with an efficiency of 81%, which exceeds the 75% target value.

The project was placed on hold in FY93 pending successful resolution of the gyrotron development. The work on hold included all work on long pulse mode converters, as well as completion of items like the pumping stations on lines 3 and 4. Unfortunately, the modified 0.5 MW, 110 GHz gyrotron prototype produced under the I&T program had an unexpected window failure at a pulse length of 1.5 s in December 1992; this failure was similar to one encountered by Varian on a 140 GHz gyrotron for JET, so it appears to be a generic failure. Hence, a decision was made to replace the window on the modified DIII-D gyrotron S/N#2 and restrict operation to 1 s for testing purposes. This gyrotron was conditioned at DIII-D; it was not conditioned at Varian after the repair in order to save money. However, the mode purity continued to be a problem.

The U.S. I&T gyrotron development program at Varian was redirected to develop a 1 MW, cw gyrotron with an internal converter similar to a successful Russian design. A prototype 1 MW tube achieved 530 kW for 2 s and 350 kW for 10 s, the first limited by the window and the latter by outgassing of the tube. This gyrotron was delivered to GA in January 1997. In parallel with the Varian development, the DIII-D program ordered a 110 GHz Russian gyrotron from Gycom with a specification of 0.75 MW, 2 s; this gyrotron is claimed to be MW cw capable except for the window. This gyrotron has successfully pulsed 960 kW for 2 s and was delivered to GA in July 1995.

In March of 1997 beam trajectory and profile measurements were made and the CPI tube was operated in conjunction with the GYCOM gyrotron. All testing was done at atmospheric pressure, therefore short pulses 500 μ s or less were used to prevent breakdown. The beam profile measurements were in accord with the launcher optics design. The rf trajectory measurements were consistent with the laser alignment done in the lab. The in-vessel testing of the GYCOM and CPI #1 gyrotrons satisfied the last project milestone (#14) thus bringing the project to closure.

2. PROJECT SCOPE AND OBJECTIVES

The original objective was to design, fabricate, and install a prototype 2 MW ECH heating power system for DIII-D at an operating frequency of 110 GHz. The power is to be contained within 10 s long-pulses with an interpulse period of 300 s minimum. The full 2 MW was scheduled to be ready for service on DIII-D in June 1991 at a cost not to exceed \$7.9 M. These objectives were considered the Level-1 objectives. It was anticipated that this prototype project was to be the first phase of a 10 MW, 110 GHz ECH program. Thus most of the equipment fabricated for the prototype project was designed to be suitable for the 10 MW system unless significant increases in schedule or cost were incurred.

The work breakdown structure was defined in the DIII-D Prototype 110 GHz ECH Upgrade Project Management Plan, which defined the technical, cost, and schedule requirements necessary to achieve the program objectives. GA established within its own project organization, a system for controlling and accomplishing the work assignments.

A prototype system was demonstrated at short pulse, full 0.5 MW source power with 0.35 kW into DIII-D at the end of March 1992. However, difficulties in extending the pulse length of the gyrotrons and the lower than desired mode conversion efficiency, lead to the decision to stop production of the 500 kW gyrotrons and to change to two 1 MW gyrotrons with internal mode converters. To integrate the 1 MW gyrotrons into the system involved adding new superconducting magnets as well as a two gyrotron interface unit that couples the output of the gyrotron into the corrugated waveguide transmission lines. As a result of these necessary changes, the project was completed on March 1997 at a cost of \$13.75 M.

2.1. OVERALL PROGRAM MANAGEMENT

The technical, cost, and schedule baselines were the basis for control of the Prototype 110 GHz ECH Upgrade Project. GA utilized a system of reducing the baselines down to identifiable subtasks and developing an Approved Task Authorization for each subtask, with an appointed subtask manager held responsible for cost and schedule control. A monthly assessment of the progress of each subtask was held and a project cost-to-complete re-estimate was performed every six months.

2.2. TECHNICAL DESCRIPTION

An overall schematic of a prototype 1 MW 110 GHz ECH systems is shown in Fig. 1.

Fig. 1. 1MW 110 GHz ECH System Schematic.

2.2.1. WBS Element 1 — RF SOURCES

The initial rf source chosen for the 110 GHz prototype system was a 500 kW, 10 s gyrotron produced by Varian. However, problems with the development of these 500 kW gyrotrons and promising results with 1 MW gyrotrons led to a decision to use the MW unit with an internal converter.

As indicated in the executive summary, the revised plan to complete this program is to capitalize on the success in gyrotron development and obtain two 1 MW-level gyrotrons, one from Communications and Power Industries, CPI, (formerly Varian), and one from GYCOM, a Russian Company. Because these gyrotrons have a different internal construction new superconducting magnets had to be procured for each gyrotron. Also, a new water cooling system with additional calorimetric instrumentation for the

CPI gyrotron was required.

The GYCOM gyrotron was successfully tested in Moscow to power levels as high as 960 kW and a pulse length of 2 s. The gyrotron was received at GA in July 1995 and was operated into a DIII-D plasma in December 1995. A photo of this gyrotron is shown in Fig. 2(a). The total cost for this WBS was \$5,677 K out of the \$5,876 K budgeted. The reduced expenditures was the result of being able to use the cyromagnet power supplies previously purchased for the 500 kW gyrotrons, and the situation that a distributed window was not built for the CPI gyrotron.

Fig. 2. Photos of the 1 MW 110 GHz internal mode converter gyrotrons installed at DIII-D. (a) GYCOM gyrotron and (b) CPI gyrotron.

2.2.2. WBS Element 2 — GYROTRON SUPPORT SYSTEMS

The gyrotron is supported on an oil tank which contains the insulating and coolant oil for the cathode assembly and the components and circuits associated with the filament, cathode and modulating anode. Four gyrotron tanks were fabricated for the 500 kW gyrotrons. One of these tanks is used for the CPI gyrotron. Because the GYCOM

gyrotron has a longer cathode-to-cavity separation, a new tank has been installed. Efforts have been made to minimize magnetic field perturbations. All communication with the gyrotron and its auxiliaries and diagnostics is from the control room via fiber optics. All important signals and wave forms are digitized and stored for recall and analysis on a shot-by-shot basis. In addition, control and interlock functions are hardwired in order that the system can be operated and protected independent of the status of the computer, which will operate as a backup to the primary control system. The important signals and waveshapes have analog displays on the control console and are interfaced with the DIII-D control room.

The total cost for this WBS element was \$2,574 K with a budget of \$2,425 K with the increase stemming primarily from the additional work to install and integrate the gyrotron into the ECH vault area.

2.2.3. WBS Element 3 — COOLING SYSTEMS

The total cost for this WBS element was \$479 K out of a budget of \$475 K.

2.2.3.1. Low Conductivity Water

The four 500 kW gyrotrons each require approximately 450 gpm of deionized cooling water at 200 psig. There was insufficient reserve capacity of cooling water at this pressure at the DIII-D site to satisfy this requirement as well as to operate the entire neutral beam system, so an additional 1000 gpm water pump was added to our existing pump pad with the necessary heat exchanger plates to increase the cooling tower capacity. An additional 12 in., 200 psig water line was installed to accommodate the additional pumping capacity. This added approximately 1000 gpm to the existing capability. Non-ECH loads were removed from the 200 psi system and transferred to a new low pressure (100 psi) water-cooling system. The cost of the low pressure system was not part of the original 2 MW ECH project.

Although the new 1 MW gyrotrons require approximately the same water flow, some of the cooling circuits operate at lower pressure, and in order to protect the gyrotrons, a pressure reducing station has been installed to regulate the pressure at the lower value for those circuits. The water manifold for the CPI gyrotron had to be redesigned to accommodate the increased number of cooling and instrumentation circuits required to cool and monitor the gyrotron.

2.2.3.2. Cryogenics

The cryogenic magnets for the 110 GHz gyrotrons are filled with liquid helium using a manual system, which consists of a traveling cryogenic line that mates with the vertical fill pipes on the focus magnets. The liquid nitrogen jacket is connected to a large LN₂ dewar and uses a auto fill system to keep the levels within the operating ranges.

2.2.3.3. FC-75 Cooling

This coolant is required for the CPI gyrotron windows. The existing FC-75 cooling system was adequate for the additional gyrotrons and it was necessary only to make the additional connections to the system.

2.2.4. WBS Element 4 — RF TRANSMISSION

2.2.4.1. RF Transmission Line

Each component in the rf transmission system was a new design as the propagating mode is different from that previously used and the power level and frequency are greater. Because the new MW 110 GHz gyrotrons have an internal mode converter, no external converter is required; however, an interfacing unit between the gyrotron and the transmission line is required to take the 4 in. diameter flattened Gaussian output of the gyrotron and focus it into the 1.25 in. diameter transmission line. This focusing is performed with a pair of mirrors, which are simple and straightforward to manufacture, but must be housed in a vacuum tank. The tank must also be fitted with an rf absorber since about 15% of the gyrotron output power is expected to be in a mode not suitable for waveguide transmission and must be absorbed. Figure 3 shows a diagram of the Mirror Interface Unit.

The transmission line is a windowless low loss 1.25 in. diameter aluminum evacuated corrugated waveguide carrying the HE₁₁ mode. The only window in the system is that on the gyrotron, boron nitride, BN, for GYCOM and a double disk sapphire for CPI. Presently the thermal stress limits of these windows is what limits the system pulse length at full power to 2 s and 0.8 s respectively. The waveguide diameter represents a compromise between power handling capability and the desirability that the transmission line be insensitive to misalignment, thermal growth, and motion.

Fig. 3. Diagram of the Mirror Optical Unit for interfacing the gyrotron to the 1.25 in. diameter corrugated waveguide.

The entire transmission line system contains six mitre bends and is ≈ 40 m long with estimated 2% loss in the waveguide and 0.6% loss per mitre bend. The mitre bend losses are from mode conversion 0.5% and ohmic losses 0.1%. The waveguide is evacuated to a pressure of $\approx 1 \times 10^{-5}$ Torr by a turbomolecular pump at the MOU and a similar pump on a special section of waveguide near the tokamak, where the waveguide has been slotted to allow pumping between the corrugations. This waveguide pumping section is placed as close to the DIII-D vacuum vessel as practical so that any impurities evolved from the waveguide upstream of the tokamak can be pumped out before they reach the plasma and possibly contaminate it. However in the case of a catastrophic vacuum failure, there is a fast shutter located just upstream of the pumping section, this shutter can close faster than the pressure wave can travel down the waveguide and in conjunction with the pumping section, maintains the vacuum pressure at the tokamak entrance waveguide long enough for the torus isolation valve to close ≈ 0.8 – 1.0 s.

To aide in gyrotron optimization a dummy load is connected to the system via a waveguide switch located near the gyrotron. Polarization control is achieved by a set of grooved polarizing mirrors mounted in two of the mitre bends. By appropriate rotation of these two mirrors, any elliptical polarization desired can be obtained. Inside the tokamak are two mirrors, a focusing mirror and a flat turning mirror, permanently angled at 19° off

normal to provide the appropriate current drive injection. The tilting mirror rotates vertically so the injected beam can be steered poloidally from slightly below the midplane of the plasma, to the outermost top edge of the plasma.

2.2.4.2. Facility Location

Four 0.5 MW 110 GHz systems had been installed in the room located directly northeast of DIII-D that originally housed the ten 60 GHz gyrotrons. Because of the geometry of the 1 MW gyrotrons and the structures to support the tanks containing the focusing mirrors, as well as the space needed for the more extensive water cooling systems, the physical arrangement of the 0.5 MW equipment within this room had to be changed. The indoor equipment for the HV supplies is located adjacent to the gyrotrons area on the same level. This minimizes the length of the high voltage cables, which is important to the gyrotron protection systems. The outdoor HV power supply equipment is north of and adjacent to the existing neutral beam HV power supplies. A layout diagram of the two ECH Systems is shown in Fig. 4.

Fig. 4. Layout of the 2 MW ECH upgrade system.

The total cost for this WBS element was \$4,323 K with a budget of \$4,242 K. The cause of the increase was additional work required on the mirror optical units to make the exit waveguide location adjustable, since the output rf beam of each gyrotron as received from the manufacturer did not exit the gyrotron normal to the gyrotron window. The exit waveguides add to be offset and tilted appropriately.

2.3. COST BASELINE

The original budget established for the 2 MW 110 GHz ECH Project is shown in Table 1 with the final budget expenditures shown by task. The Project was originally started in FY89 with an approved budget of \$7,901 K, in FY91 the total Project budget was raised to \$11,316 K, and finally in FY96 the budget was changed to \$13,741 K. The final expended funds for the 2 MW 110 GHz ECH Upgrade Project was \$13,752 K.

TABLE 1
DIII-D 110 GHZ ECH UPGRADE COST BASELINE

Work Breakdown Structure all costs in \$k	Approved Aug 89	Approved Jan 91	Approved Jan 96	Final Costs March 97
1. RF Sources 1.1 Gyrotrons 1.2 Gyrotron Focus Magnets 1.3 Gyrotron Contract Mgmt	3621	4609	5876	5677
2. RF Support Systems 2.1 Gyrotron Controls 2.2 Gyrotron Tanks 2.3 DIII-D Interface	1089	1882	2424	2562
3. Cooling Systems 3.1 Low Conductivity Water 3.2 Cryogenics 3.3 FC-75 Window Cooling	721	329	475	484
4. RF Transmission 4.1 Component Development 4.2 Fabrication 4.3 Dummy Load	2125	3692	4242	4323
5. Project Management 5.1 Project Organization and Control 5.2 Quality Assurance 5.3 AFI	345	804	724	706
Totals	7901	11316	13741	13752

2.4. SCHEDULE BASELINE

The project schedule was primarily driven by the delivery and checkout of the gyrotrons. A list of the milestones used for the Project is given in Table 2.

TABLE 2
DIII-D 110 GHZ ECH UPGRADE CONSTRUCTION MILESTONES

	Milestone	Original Date August 89	Rev Date	Achieved
1	OFE initiation of project	May-89		May-89
2	Decision on mode converter concept & waveguide fabrication	Aug-89		Feb-90
3	RF Transmission component design completed	Feb-90		Mar-90
4	First Gyrotron tank system completed	April-90		July-90
5	Delivery of first gyrotron to GA	June-90	Jan-91	Feb-91
6	Complete test of first system at GA	July-90	June-91	July-91
7	Four gyrotron system installed at GA	Jan-91	deleted	
8	Procure 1 MW internal converter gyrotron from GYCOM		Aug-93	Aug-93
9	Evaluate Varian 1 MW capability		Apr-95	Apr-95
10	Evaluate 1 MW gyrotron window capability		Mar-96	Oct-96
11	Receive 1 MW gyrotron from GYCOM		July-95	July-95
12	Complete test of GYCOM gyrotron at GA		Mar-96	Mar-96
13	Receive 1 MW gyrotron from Varian		July-96	Jan-97
14	Complete dummy load test of CPI#1 at GA		Dec-96	Mar-97

3. LESSONS LEARNED

There is one underlying theme that covers the entire fabrication cycle of the 2 MW 110 GHz ECH Upgrade Project, it is that the project was started with a too optimistic assessment of the state of the technology for high power, high frequency, long pulse length gyrotrons and associated transmission components. GA's entered into the project based upon information gained from the gyrotron developer group. However, GA was not a member of this group, owing to corporate concerns that Varian had that GA might become a competitor in the microwave generation market, and thus GA has limited knowledge of the technical design of the gyrotrons. The situation was not changed until 1991 when GA and Varian signed a non-competition agreement, and GA was allowed to become a member of the gyrotron developers group, and since then has been an active member helping lead the development towards a reliable long pulse high power gyrotron.

The following is a look at the major subsystems including recommendations.

Gyrotrons

Initially four 500 kW gyrotrons were ordered from Varian based upon a design funded by the DOE I&T division. Later GA ordered a 1 MW 2 s gyrotron from GYCOM.

The problems associated with this section of the Upgrade project were:

- Two Varian gyrotrons were destroyed during testing, one from a melted collector, and one with a damaged cavity.
- The power deposition on the collector could not be spread over the collector surface and was highly asymmetric owing to a large radial magnetic field error. GA developed and demonstrated a fix.
- The mode purity of the whispering gallery mode gyrotrons was way below the design value of greater than 90%, in some cases as low as 75% of the total rf power.
- Converting the output beam of internal mode converter gyrotrons into a HE_{11} mode for the transmission line is less efficient than anticipated.
- Parasitic oscillations of the GYCOM gyrotron at 90 MHz caused most of the fault electronics to activate on noise, requiring a complete redesign of the fault electronics and routing of the interconnecting cables.

Recommendations

- Do not buy gyrotrons that have not been fully developed unless contracts with the manufacturer require payment only after demonstration of performance.
- Gyrotron manufacturers concerns seem to end at the output window; therefore the acceptance tests should demonstrate coupling into a section of waveguide.
- Manufacturers are not forthcoming on production problems, several fact finding trips to the factory should be scheduled.
- All systems should be hardened to EMI radiation, either from sparkdowns or parasitic oscillations of the tube.

Magnets

Initially GA built the first two magnets, then Varian changed the specifications and it was cheaper to order the final two from Oxford Instruments. Later when 1 MW gyrotrons were substituted for the 500 kW units, new magnets had to be purchased.

The problems associated with gyrotron magnets were:

- The first GA magnet sent to Varian was damaged in shipment
- Cryogenic liquid boiloff rate on the Gycom magnet is high

Recommendations

- Insist that the gyrotron be tested with its mated magnet at the final acceptance test.
- Establish the required cryogenic hold times with the magnet manufacturer.
- Procure magnets with external magnet alignment capabilities.

Gyrotron Tanks

Initially four tanks were fabricated for the 500 kW gyrotrons. The length of the gyrotrons required that the tanks be of a low profile in order that the assembly of tank-magnet-gyrotron-converter fit within the building ceiling limit. This low profile puts a considerable constraint on the packaging of the electronics that must reside in the tank floating at the cathode voltage.

The problems associated with gyrotron tanks were:

- The Gycom gyrotron cathode is longer than the Varian gyrotron so a new tank had to be fabricated.

- The steel in the building floor supports created unacceptable perturbations in the gyrotron magnetic field profile. The tanks had to be supported 14 in. from the floor to reduce this perturbation.
- Tight packaging of the electronic packages has lead to several fiber optic failures and has made access for maintenance more difficult.

Recommendations

- The need for maintenance should be factored in during the design phase.
- More protection from voltage transients during sparkdowns should be included in the electronics design.

Transmission Line System

Four transmission lines were fabricated for the four 500 kW gyrotrons, only two lines were used for the 1 MW gyrotrons, leaving two for future systems. Only two Mirror interface units were fabricated. Two launcher assemblies were fabricated and installed, each with dual steerable mirrors. Only one dual mirror launcher was used for the project leaving the second launcher available for future systems.

The problems associated with transmission lines were:

- The phase correction mirrors for both the GYCOM and the CPI gyrotrons did not produce the appropriate beam pattern for entry into the waveguide.
- The copper coating on the launcher mirrors evaporated at the high power impingement location after a relatively short number of pulses.
- Pumping conductance limits prevented the sharing of vacuum pumping stations, thus requiring more pumping stations and vacuum electronics.
- It turned out not to be practical to use only one dummy load and move it among the gyrotrons for testing. Thus each gyrotron has its own dummy load and a waveguide switch to connect it to the gyrotron without breaking vacuum.

Recommendations

- Specify performance specifications into waveguide including measurement techniques.

APPENDIX A
General Atomics Report GA-A22584

See attached paper entitled "The 110 GHz Installation on DIII-D: Status and Initial Experimental Results."

THE 110 GHz ECH INSTALLATION ON DIII-D: STATUS AND INITIAL EXPERIMENTAL RESULTS

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Two 110 GHz gyrotrons with nominal output power of 1 MW each have been installed on the DIII-D tokamak. The gyrotrons, produced by Gycom and Communications and Power Industries, are connected to the tokamak by windowless evacuated transmission lines using circular corrugated waveguide carrying the HE_{11} mode. Initial experiments with the Gycom gyrotron showed good central heating efficiency at the second harmonic resonance with record central electron temperatures for DIII-D in excess of 10 keV achieved. The beam spot in the DIII-D vacuum vessel was well focused, with a diameter of approximately 8 cm, and it could be steered poloidally by a remotely adjustable mirror. The injection was at 19 deg off-perpendicular for current drive and the beams could be modulated for studies of energy transport and power deposition. The system will be described and the initial physics results will be presented. A third gyrotron, also at 110 GHz, will be installed later this year. Progress with this CPI tube will be discussed and future plans for the ECH installation and physics experiments using it will be presented.

1 Introduction

Two gyrotrons are installed and operating on the DIII-D tokamak. One, a Gycom Centaur tube [1,2] has been in routine service for about a year. The second, a VGT-8011A model [3] from Communications and Power Industries (CPI), has been operating for about a month. Both tubes are nominally 1 MW gyrotrons and produce rf at 110 GHz for full power pulse lengths which are limited by their output windows to 2 sec for the Gycom tube and 0.8 sec for the CPI tube. A second CPI gyrotron was damaged in testing at CPI and will be delivered to

General Atomics (GA) for installation in late 1997. The maximum test parameters for the installed tubes are listed in Table 1. In the case of the Gycom tube, the maximum pulse length achieved at GA has been 0.5 sec, a purely administrative limit. The CPI tube has only operated briefly with an evacuated transmission line and therefore no attempt to increase the pulse length has yet been made.

Table 1: Gyrotron Parameters

	Gycom Centaur	CPI VGT-8011A
Frequency	110.10–109.75 GHz	110.03–109.95 GHz
Output power	0.926 MW	0.905 MW
Max. pulse length, full power	2.0 sec	0.8 sec
Max. pulse power	1.2 MW at 2.0 msec	1.013 MW at 2.0 msec
RF efficiency	38%	32%
Operating current	34 A	35 A
Gun anode voltage	N/A	30 kV
Internal mode	TE _{19,5}	TE _{22,6}
Output mode	HE _{1,1}	HE _{1,1}
Peak cavity Ohmic loss	≤2.0 kW/cm ²	≤2.0 kW/cm ²

2 Transmission Lines

The rf power is delivered from the gyrotrons to the DIII-D tokamak by evacuated windowless transmission lines about 40 m in length. The waveguide lines incorporate forward/reverse power flow monitoring in a miter bend and can generate any arbitrary elliptical polarization by reflection from ribbed mirrors in two of the miter bends. The lines include switches for routing the power to dummy loads capable of absorbing the full gyrotron output power for up to 2 sec, manual and pneumatically operated vacuum valves, vacuum pump connections, and a fast shutter system for protecting the tokamak in case of a vacuum failure in the line. The waveguide lines carry the HE_{1,1} mode, which couples well to the free space Gaussian, permitting a simple launcher to be used in the tokamak. The transmission lines are presented to scale in Fig. 1.

Figure 1. Scale drawing of the DIII-D gyrotron and transmission line layout. The waveguides are 31.75 mm diameter circular corrugated lines and carry the $HE_{1,1}$ mode. A third line is being installed for operation by the end of summer 1997.

In principle, the gyrotrons can operate continuously except for the weak links in the system, the gyrotron output windows. The window in the case of the Gycom gyrotron is an edge cooled disk of boron nitride, which can be operated at temperatures up to 900 K. The CPI gyrotrons both employ double disk sapphire windows cooled by FC-75, a low loss chloro-fluorocarbon fluid. FC-75 boils at about 120°C and this temperature in turn limits the pulse length to 0.8 sec. The designers of both tubes increased the power handling capability of their windows by flattening the Gaussian beam in the internal mirror system and spreading the power more uniformly over the window area. The non-Gaussian modes which are added to the beam in order to achieve this flattened Gaussian are reformed into the main gaussian beam by correction mirrors in the Matching Optics Unit (MOU) an evacuated chamber attached directly to the gyrotron output flange.

The MOUs are pumped by turbomolecular pumps to pressures in the low 10^{-6} torr range and incorporate ZnSe windows so that the gyrotron window temperatures can be monitored by infrared pyrometers. The MOUs also incorporate window arc detection, rf monitor pickoffs, and micrometers for precise alignment of the mirrors. In order to avoid placing mechanical strains on the gyrotrons, the entire MOU assemblies are floating on springs. The MOU mirrors focus the gyrotron output beams onto the input end of the 31.75 mm diameter corrugated waveguide. Transverse alignment to accuracy of about 0.1 mm and coaxiality to about 0.1 deg are required at the waveguide to ensure coupling to the guide with

minimal mode conversion [4,5]. In Fig. 2 the MOU and burn paper patterns are shown for the first short section of waveguide at the output of the MOU on the Gycom system.

The small diameter waveguide employed represents a compromise between power handling capability and immunity to misalignment and motion of the line. But the requirements for accurately steering the beam into the waveguide, particularly if phase correcting mirrors are installed to form the Gaussian, makes it desirable to mount the MOU so that the beam enters on the optical beam trajectory and therefore hits the first mirror at its center. Free space measurements of the beam trajectory angle and position at the output window were made and then special adapter flanges were manufactured to accomplish this aspect of the alignment. The Gycom beam exited the window with a 0.31 deg up tilt 4.4 mm above the window center and the CPI beam exited perpendicularly to within 0.05 deg but offset 6.4 mm below and 5.5 mm right of the window axis.

3 In-Vessel Testing

Inspection of the DIII-D launcher assembly following operation of the Gycom gyrotron earlier this year revealed signs of arcing on the face of the poloidal steering mirror. This mirror was graphite coated by a 0.15 μm layer of tungsten and overcoated by a 2.0 μm layer of copper to avoid eddy current induced mechanical loading during disruptions. The copper and tungsten had been removed along dendritic tracks at the rf beam strike point. Relaxation of the DIII-D disruption requirements, primarily for the maximum current disruption anticipated, permitted the replacement of the graphite mirrors with solid copper mirrors 3.2 mm thick mounted on a stainless steel support structure. Following installation of the refurbished launcher assembly, new measurements of the beams in the vacuum vessel were made.

Both gyrotron and waveguide systems were tested at atmospheric pressure by propagating short pulses to the DIII-D vacuum vessel during a maintenance vent. A paper target was positioned vertically at the radial geometric center of the vessel with its plane perpendicular to the azimuthal component of the beam trajectory from the launcher. The target was viewed by infrared and visible cameras and the gyrotrons were pulsed for 150–500 μsec pulses at pulse repetition frequencies between 0.5 and 8.0 Hz. A videotape was made which permitted subsequent

Figure 2. Matching optics unit and burn paper patterns for the Gycom installation. The first mirror provides phase correction to form a Gaussian beam and the second mirror focuses the beam onto the waveguide input. The mirrors are micrometer adjustable and the entire assembly is evacuated to pressures in the low 10^{-6} torr range.

analysis of the location and shape of the beam in the chamber for different angular positions of the flat poloidally scanning mirrors.

The scanning mirrors are both angled 19 deg off-perpendicular for current drive and rotate together to scan the beams poloidally. This geometry causes the two beams to encounter the EC resonance at different elevations with respect to the midplane, although it is possible to set the alignment so that the beams are at the same elevation for one poloidal scan angle. In the present case, it was decided to estimate the location of the $q = 1.5$ surface for usual plasmas and to make this be the elevation at which both beams cross the same horizontal plane at the EC resonance. This plane is about 60 cm above the midplane. In Fig. 3 the beams are shown in the infrared striking the paper target at this elevation. At the midplane the two beams are separated by 15 cm vertically, or about twice the full width at half maximum for a single beam as discussed below.

Pulsing the rf at duty cycles differing by a factor of approximately 2.7 permitted the target heating to be related to a Gaussian beam profile. The results of this analysis are shown in Fig. 4, where it is seen that the Gycom system generates an approximately Gaussian beam with full width at half maximum of about 8 cm, which is in agreement with the launcher optical design calculations. The CPI beam has a kidney shape and appears to diverge more rapidly with distance than the Gycom beam. Very little attention has been paid to the alignment of the CPI system and the offset adapter flange was not installed when Fig. 4 was made, therefore the beam shape in the figure should not imply anything about the ultimate beam quality. When a target was placed directly in front of the poloidal steering mirror, both beams were observed with the IR camera to be quite circular and virtually free of sidelobes.

From the operating regimes, the duty cycles used, and the infrared response it was estimated that both tubes were generating about 400 kW and that both transmission lines were working as expected. At atmospheric pressure and relatively high power the pulse lengths were limited by breakdown to about 500 μ sec in length. Testing at full power and pulse length will only be possible when the line is evacuated.

4 Experimental Program

The Gycom gyrotron was used early in 1996 in preliminary physics experiments on DIII-D. In these experiments pulse lengths of 500 msec were used since the tube

Figure 3. Infrared image of the Gycom and CPI rf beams passing through and heating a paper target in the DIII-D vacuum vessel. The target is at an elevation of 60 cm, corresponding to $q \sim 1.5$ in a standard DIII-D plasma.

had not been qualified for longer pulses. About 0.5 MW was injected into the DIII-D plasma. Both continuous and pulse modulated operation were tested.

In the first tests, at low target density and about 0.5 MW injected, DIII-D record electron temperatures of over 10 keV were achieved. An electron temperature profile generated from both Thomson scattering and ECE data using the Michelson interferometer is presented in Fig. 5 along with the time dependence of

Figure 4. Infrared images of the beam were obtained for duty cycles differing by factors of e , 2.7. These data permit the profiles to be fitted by a Gaussian beam model and indicate that the Gaussian beam diameter is about 8 cm, consistent with the optics calculations for the launcher system. The beam waist is actually close to the launcher and weak focusing is used to give a slightly diverging beam.

several relevant plasma parameters. The experiment attempted to investigate the synergistic increase in fast wave current drive at high electron temperatures. Despite the extremely high target temperatures, themselves representing a successful result, the synergism with fast wave current drive was not observed, since it proved to be impossible to maintain the required low densities during the fast wave injection, as seen on the time traces. There is approximately a linear tradeoff between T_e and n_e in ECH experiments, so it is anticipated that combining the powers from two, and later this year, three gyrotrons will enable the high target temperature to be maintained in spite of this density increase and the fast wave current drive will increase proportionately.

Initial testing of the Gycom ECH system included measurements of the power deposition profile in the plasma. This was done in two ways, both of which made use of the 32-channel heterodyne ECE system. In the first analysis, the slopes of the ECE signals in the first few msec following turn-off of the rf power were used to infer the deposition profile. At each location in the plasma the temperature,

Figure 5. (a) T_e profile for low density target plasma with about 500 kW injected and central resonance. The ECE data indicate a superthermal tail was present at this low density. The central T_e value is a record for DIII-D. (b) Time dependence of relevant parameters for fast wave synergy experiment. The profile in (a) was obtained at the time indicated by the vertical lines.

hence the ECE signal, is determined by the balance between local power absorption and diffusive power flow. Because the power deposition can be stopped quickly compared with diffusion, the ECE response just after removal of the heating power is indicative of the power which was being deposited.

This analysis indicated that the power deposition profile was somewhat broader than expected from the profile of Fig. 4. In Fig. 6 the profile from this analysis is plotted. The full width at half maximum for the inferred power deposition profile is about 14 cm, compared with the value of about 8 cm measured with the IR camera analysis. The ECE data also have somewhat broader wings than expected from the IR data.

The second analysis was performed for modulated ECH power and used a Fourier transform analysis to obtain the amplitude and phase of the heat pulses propagating away from the point of deposition. The broader profile in Fig. 6 shows the result of the harmonic analysis. For this analysis the modulation frequency was 50 Hz, at a modulation depth of 60%, obtained by a 13% modulation of the gyrotron beam voltage.

The relatively low modulation frequency 50 Hz used in the Fourier analysis makes it difficult to separate transport effects from the effects of the power deposition profile. Sawteeth at or near the modulation frequency can also complicate

Figure 6 Power deposition profile from ECE signals, for modulated and unmodulated ECH. The power deposition profiles from these analyses are also broader than indicated by the IR camera measurements of heating of the paper target.

the analysis. For the next series of experiments, modulation at frequencies up to about 1 kHz will be used.

One explanation for the discrepancy between the power deposition profiles measured with the paper target and in plasma could be that the proper elliptical polarization for the 19 deg injection angle is not being obtained in the launched beam. The gyrotron output polarization was measured to be horizontal and linear as expected, but polarimeter measurements made using a pickoff hole in the last miter mirror before the tokamak were inconclusive. Injection of a fraction of the power in the O-mode, for which the single pass absorption is poor, could result in a broad deposition profile. Since the IR measurements did not indicate sidelobes in the launched beam or a broader than expected profile, a new polarimeter is being prepared to measure the polarization of the launched beam.

The 1997 DIII-D experimental schedule has been announced and nearly half of the planned experiments will make use of the ECH installation. Initial work will verify the basic physics of ECH and ECCD, for which efficiencies will be determined as a function of position, or normalized flux, in the plasma. As part of

this initial work, modulated ECH will be used to continue work on the heat pinch effect seen earlier in off-axis heating experiments. As discussed above, the ECH/fast wave synergy experiment, made possible by the increase in available ECH power above 1 MW, will also be done.

In the transport arena, a series of experiments is planned to investigate transport theories. These experiments will make use of the rapid heating of electrons only by ECH, since the theories have different predictions for plasma response to rapid transients. The fact that ECH injects neither particles nor momentum makes it ideal for tests of theories of transport barrier formation, which differ in their treatment of momentum and rotation. It is known from earlier work that an L-H transition can be induced by ECH with about the same threshold power requirements as for neutral beams, but the relative precision with which ECH power can be applied spatially may reveal changes in the threshold power for H-mode depending upon power deposition location.

Stability and control of MHD modes should be able to be addressed using ECH to stabilize neoclassical tearing modes and the effect of edge resonant ECH on ELMs, seen earlier in poorly controlled experiments can now be done under much improved experimental conditions. Finally, non-inductive startup, current transport during MHD activity and a variety of scaling experiments are planned.

5 Conclusion

The DIII-D ECH installation now consists of two operating gyrotrons with a third expected to be installed by the end of 1997. The transmission lines and ancillary equipment are working well with good efficiency and the launcher is performing as expected. An ambitious series of experiments is planned for the 1997 campaign.

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