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UPGRADES COMPLETED AT THE DIII-D FACILITY DURING THE LONG TORUS OPENING IN FY05-FY06

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J.F. TOOKER for the DIII-D TEAM

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GENERAL ATOMICS

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ABSTRACT

DIII-D has returned to operation with a substantially enhanced capability to increase the understanding of advanced fusion plasmas and to support the U.S. contribution to ITER. Several upgrades to the DIII-D facility, driven by physics needs, were completed during the long torus opening activities period spanning April 2005 through March 2006. To make this 12-month period available without sacrificing operating time, two of the normal periods for construction, refurbishment and maintenance were performed back-to-back. These upgrades included installation of a new divertor for improved pumping of high triangularity plasmas, rotation of one of the four neutral beamlines from co-injection to counter-injection, and replacing the short-pulse gyrotrons in the electron cyclotron system with 1 MW long-pulse gyrotrons. In addition to these high priority tasks, the upgrade of the toroidal coil return bus for long-pulse operation was started. During this period the heat rejection of the cooling water systems was improved, part of which involved replacing two cooling towers with higher capacity units. In addition, the exceptional suite of plasma diagnostics at DIII-D was improved in nearly all areas.

1. INTRODUCTION

The fundamental goals of the DIII-D program, i.e., advancing the physics of Advanced Tokamaks, exploring basic fusion physics, and addressing critical issues for ITER, set into motion several upgrades to the DIII-D machine. These upgrades required that machine operations be temporarily suspended and the machine be opened for an extended period of time, up to one year. This time was much longer than that which is normally available during a typical year of operations. However, if two maintenance and vent periods were scheduled back-to-back, then a sufficiently long period of time would be made available to perform these upgrades. In doing this, DIII-D operated 34 straight weeks for physics in FY04 and FY05, the longest recorded continuous period of operation for the facility. The upgrades were carried out in FY05 and FY06 and followed by over 12 weeks of operation in FY06.

The selected activities to be accomplished were: the replacement of the three short-pulse Russian gyrotrons with three additional long-pulse gyrotrons from Communications and Power Industries (CPI), installation of a new lower divertor, rotation of one of the four neutral beamlines from co-injection to counter-injection, upgrades to the water-cooling systems, and the initiation of some of the upgrades needed for long-pulse operation of DIII-D.

The planning for the long torus opening activities (LTOA) began during FY04. The FY05 physics campaign occurred in the first half of the fiscal year. The LTOA started on April 19, 2005 and ended on March 29, 2006 when the torus was closed and pumped back down. The DIII-D machine went through its startup and the FY06 physics campaign began on June 7, 2006.

The engineering efforts, during which the designs for the upgrades were prepared and parts were fabricated, began a year before the opening period. During this time, the personnel simultaneously supported the engineering efforts and the operation of the DIII-D tokamak. Some of the engineering effort extended into the LTOA. During the LTOA, the DIII-D operational staff was redirected to accomplish the activities.

2. LONG TORUS OPENING ACTIVITIES

The following sections describe the upgrades installed by the activities accomplished during the LTOA.

2.A. Replacement Gyrotrons

The electron cyclotron (EC) system at DIII-D has become a valuable tool for plasma heating, current drive, stabilization or avoidance of instabilities, and control of plasma current profiles. The EC system had been supporting the physics experiments with three short-pulse (2 s), 0.75 MW Russian gyrotrons and three long-pulse (10 s) 1 MW gyrotrons from CPI. The Russian gyrotrons are being replaced with three additional gyrotrons from CPI in order to increase the power and pulse length capability of the EC system for physics. Two of the Russian gyrotron "sockets," comprising the various gyrotron subsystems such as support stands, water manifold, rf transmission system, and instrumentation and controls, were refurbished to accept a CPI gyrotron. The third Russian socket was left intact for now.

A new sixth gyrotron socket was installed during the LTOA that has the additional modifications necessary to support the operation of a depressed collector gyrotron. The U.S. gyrotron community has been developing a depressed collector gyrotron. This gyrotron was tested at CPI, generating up to 1.2 MW for short pulse lengths, and has now been installed into the new gyrotron socket for conditioning to full parameters. If this gyrotron conditions up well, it would be used for physics. If not, this gyrotron socket would be reconfigured for one of the 1 MW CPI gyrotrons.

The first replacement long-pulse gyrotron arrived at GA and was installed in one of the refurbished sockets. This gyrotron is shown in Fig. 1. It supported the FY06 physics campaign, along with one of the original 1 MW CPI gyrotrons. The second replacement gyrotron was recently delivered, having been delayed by unexpected problems at CPI. The third is now projected to arrive before the end of 2006.

Two of the original 1 MW gyrotrons had to be sent back to CPI for repair of water-to-vacuum leaks in the collectors. The first gyrotron was repaired and returned and will be reconditioned. The repair of the second gyrotron is projected to be completed in early 2007. It is anticipated that up to six 1 MW CPI gyrotrons will be available for physics in FY07. The developmental depressed collector gyrotron could also be available if it conditions up in power and pulse length satisfactorily.

2.B. Lower Divertor

To enhance the capability of controlling the density of high triangularity, high performance single-null and double-null Advanced Tokamak plasmas, the pumping of the lower cryopump inside the DIII-D vessel needed to be improved. This required a new lower divertor [1] be installed with the pumping aperture extended further inward radially, closer to the divertor strike point.

The fabrication of the new divertor was done in collaboration with ASIPP in China. The eight stainless steel cooling plates were fabricated and assembled into the four panels by ASIPP. The fabrication steps were demonstrated during the manufacture of a prototype panel. The four panels were installed and mounted to the vessel floor in November 2005 and the full installation was completed on March 27, 2006, including plasma facing tiles and diagnostics. The completed installation is shown in Fig. 2.

The designs of the plasma facing tiles for the new divertor were developed to reduce material erosion. Mounting holes in the high heat flux areas were eliminated, the gaps between tiles were reduced to 0.4 mm, and the tiles were leveled to within 0.1 mm. The bottom four rows of tiles on the center post were also replaced with faces contoured to the radius of the center post to reduce toroidal asymmetry from edge heating. The 579 new carbon tiles were designed, fabricated, cleaned, and installed [2]. They were conditioned with plasma during the plasma startup of the DIII-D machine and DIII-D is now routinely running various high performance plasma configurations with the upper and new lower divertors. Figure 3 shows images from an IR camera viewing the old and new lower divertors, clearly showing the reduction in asymmetries of tile heating.

Fig. 1. First replacement gyrotron installed in a refurbished gyrotron "socket."

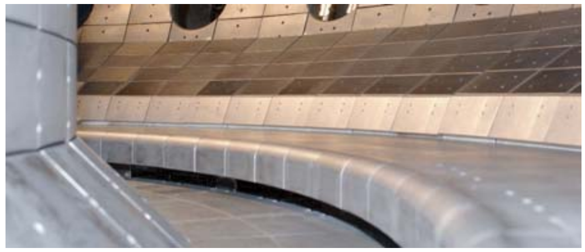

Fig. 2. Completed installation of a new lower divertor in the DIII-D vessel.

There were several plasma diagnostics which had to be modified as a result of the installation of the new divertor. For example, the Thomson scattering alignment mirror and the diagnostic head of the Divertor Material Exposure System, both of which pass through the vessel floor and the divertor, needed to be adapted to the new height of the divertor shelf. Several of the existing Langmuir probes and some of the magnetic probes located on the floor of the vessel were moved onto the divertor shelf. In addition, some new optical diagnostics were incorporated into the new divertor, as well as new toroidally continuous magnetic flux loops on the divertor shelf and current monitors on the support legs of the shelf.

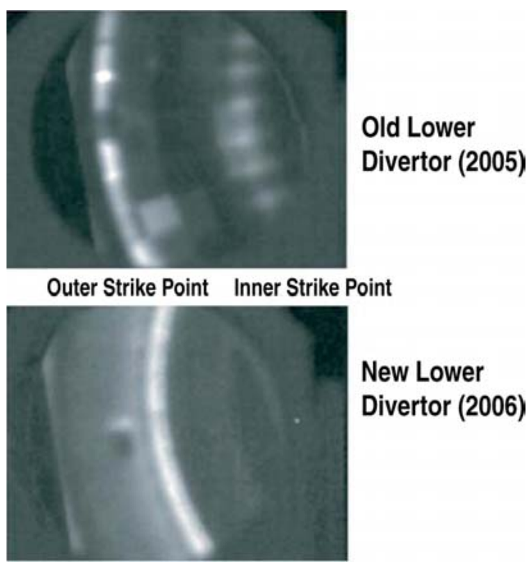

Fig. 3. Comparison of surface temperatures on the old and new divertors from IRTV.

2.C. Neutral Beamline Rotation for Counter-Injection

The four neutral beamlines on DIII-D were all originally installed for co-injection. Rotating one of the beamlines to counter-injection, as shown in Fig. 4, opened the new areas for physics studies. These include:

- QH-mode ELM-free regime with central co-rotation
- Understanding physics of rotation
- Resistive wall mode stability with low rotation

- Transport barrier control
- Fast ion physics
- Understanding the physics of neutral beam current drive

This was the largest activity accomplished during the LTOA [3]. The 210 deg beamline was removed from the machine pit, including all of it supporting subsystems, as well as other equipment located in the area into which the beamline was to be reinstalled. Much of the removed equipment required modification before reinstallation into their new locations. For example, the drift-duct that connects the beamline to the port on the torus needed to be remade in a mirror-image and the port itself had to be modified to accept it. In another example, the toroidal coil feed located at 210 deg was rerouted to avoid interferences with the rotated beamline. The new design of the feed significantly reduced its contribution to the error fields experienced by the plasma. The removal, modification, and reinstallation of the beamline were successfully completed within the planned time and the beamline was returned to operational readiness at plasma startup.

During the FY06 physics campaign, the new capability provided by counter neutral beam injection was demonstrated. Figure 5 shows the effect on the plasma rotation, where the plasma goes from rapid co-rotation to near zero rotation with introduction of counter beams.

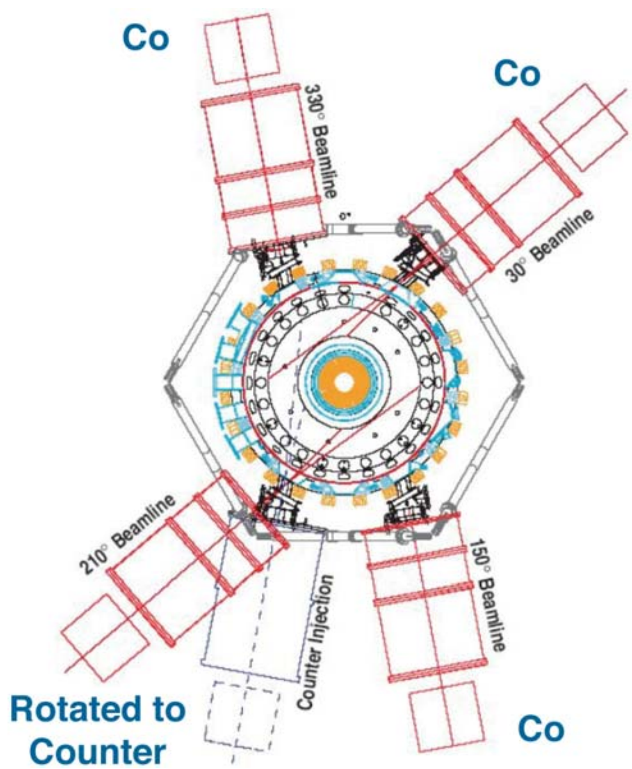

Fig. 4. Rotation of 210 deg beamline from co-injection to counter-injection.

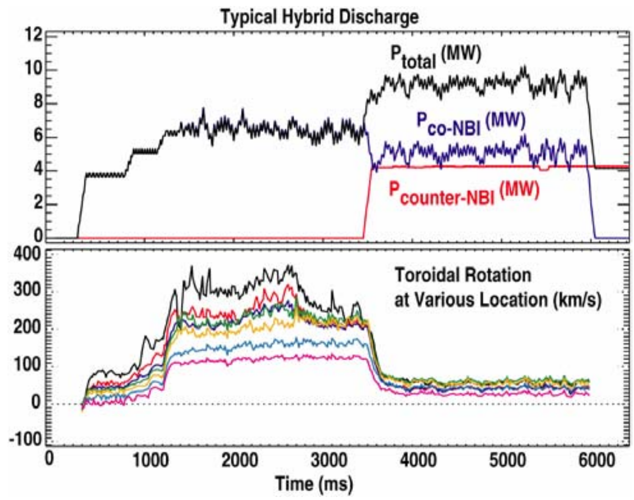

Fig. 5. Modification of plasma rotation by counter-injection of neutral beams.

2.D. Cooling-Water System Upgrades

Two of the cooling towers at DIII-D have been in operation since the 1980s. Besides needing an ever increasing amount of maintenance, their heat loads have been increasing and future plans will increase the heat loads even more. These two cooling towers were replaced with higher efficiency, higher capacity stainless steel units, shown in Fig. 6. In addition, portions of the interconnecting carbon steel piping from the towers to the heat exchangers were replaced with PVC pipe.

The EC water-cooling system supplies de-ionized and de-oxygenated water to the gyrotrons and rf transmission line components. The heat rejection capability of this system was upgraded by the installation of a new heat exchanger and pumps. The heat rejection capability of the water system was marginally adequate during previous gyrotron operation. The current upgrade of the EC system to six long-pulse gyrotrons is increasing the heat load, and a future plan to increase the EC system to eight gyrotrons would increase it even more.

Fig. 6. Two new cooling towers installed during the LTOA.

2.E. Long-Pulse Upgrades

A number of upgrades to various systems are needed for DIII-D to routinely run plasma discharges at full toroidal field for 10 s. Two activities were undertaken during the LTOA to begin addressing the upgrades. The return belt bus of the toroidal coil needs additional cooling for the longer pulses at full toroidal field. A new cooling plate was designed and a few were tested during the FY05 physics campaign. These tests showed that the increase in cooling was sufficient. During the LTOA, 24 sets of the 48 required sets of cooling plates were installed. The installation occurred in areas prior to the reinstallation of equipment or in areas where the access was difficult. The remaining areas will be addressed during future maintenance or vent periods.

The second activity involves the ac power for the auxiliary heating equipment which is provided by a 138 kVac-to-12.47 kVac transformer. It has a pulsed rating of 84 MVA for 1 s, having been sized for eight one-half second neutral beam systems when it was installed in 1979. With the increases in the auxiliary heating equipment that has occurred over the years, it is undersized. A new transformer with a pulsed rating of 110 MVA for 10 s is being provided by China. The exchange of the transformers will be scheduled at an appropriate time in the near future, most likely in the summer of 2007.

The ac power needed for the DIII-D facility is nearing the capacity of the substations supplying it. To free up additional power for the facility, the ac power for the motor generator will be transferred to the new 110 MVA transformer. This requires a 12.47 kVac-to-4160 Vac transformer, which is also being supplied by China. The pad for this transformer was built and will be brought on line at the same time as the new 110 MVA transformer.

2.F. Diagnostics

The LTOA provided the opportunity to upgrade the already extensive set of plasma diagnostics on DIII-D. Some diagnostics were upgraded to view the injected beams from the rotated beamline. Many other diagnostics were modified to improve their performance and capabilities. A full discussion of the extensive set of upgrades is included in a separate paper [4].

2.G. Other Activities

A number of other activities were performed during the LTOA to upgrade or enhance the performance of various systems on DIII-D. The following is a partial list of those activities.

- Refurbish fast wave antenna at 285/300 deg
- Upgrade one fast wave transmitter with an Eimac tetrode to increase output power from 1 to 2 MW
- Install new EC launcher with fast steering capability
- Relocate and upgrade audio amplifier system from 6 to 12 amplifiers for energizing the I-coils inside the torus
- Upgrade the hardware and algorithms of the plasma control system

Some major maintenance tasks were performed during the LTOA. One such task was the inspection of the bearings and rebalancing of the motor generator which was performed by the vendor.

3. CONCLUSION

Upgrades to the DIII-D facility were successfully completed during the almost year-long torus opening period of FY05 and FY06. The DIII-D torus was pumped down on March 29, 2006. This was followed by system check-out and plasma startup, during which the upgrades were commissioned, and physics experiments recommenced on June 7, 2006. During the 12-week physics campaign in FY06, the new capabilities provided by these upgrades were used and many exciting new results were obtained. These were highlighted in presentations of the 21st IAEA Fusion Energy Conference and the 48th Annual Meeting of the 2006 APS Division of Plasma Physics.

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