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ROTATION OF A NEUTRAL BEAMLINE TO OBTAIN COUNTER-INJECTION ON THE DIII-D TOKAMAK

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ROTATION OF A NEUTRAL BEAMLINE TO OBTAIN COUNTER-INJECTION ON THE DIII-D TOKAMAK

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Until the recent experimental campaign in 2006, all the neutral beam systems on the DIII-D tokamak injected power with the momentum in the same direction as the usual plasma current ("co-injection"). A major modification made during the April 2005 – March 2006 shutdown period rotated one of the two-source beamlines to allow injecting power with the momentum opposite that of the plasma current ("counter-injection"). This modification provides the capability of injecting up to 10 MW of neutral beam power with zero net momentum input to the plasma. Decoupling the injected momentum and power opens a previously inaccessible parameter space for experiments that study the effect of rotation on various plasma instabilities, transport, and operational scenarios.

Rotating the 5 MW neutral beamline presented significant technical challenges. The beamline and several major subsystems required extensive dismantling and rebuilding, and a careful alignment of the ion sources was required to document the new injection paths. We present a summary of the tasks required for the beamline rotation, describe major technical issues addressed, and discuss the advantages of the new configuration.

I. INTRODUCTION

The neutral beam system[1] on the DIII-D tokamak is capable of injecting up to 20 MW of power for auxiliary heating of the plasma up to temperatures near 200 million ˚C. Three of the four beamlines have two ion sources; the 30-deg beamline currently has only one source. For each of the seven ion sources of the system, a 75-80 kV, 61-68 amperes beam of neutral deuterium atoms is injected, providing a large source of momentum as well as energy. Until recently, all beams were injected in the same direction, typically "co-injection", driving momentum in the same direction as the normal plasma current. When the plasma current was reversed, all beams became "counter-injection". In either case, the injected energy and momentum could not be decoupled. Thus, high temperature plasmas achieved using high power injection rotated at high frequency due to the large amount of torque applied by the neutral beams. Intriguing plasma physics regimes requiring high injected power and *low* rotation could not easily be reached.

During the recent long DIII-D maintenance period (April 2005 through March 2006), several major revisions were made to the tokamak.[2] One of the largest modifications was the rotation of the two-source 210-deg beamline to provide the capability for simultaneous co- and counter-injection for the first time on DIII-D. Figure 1 illustrates the relocation achieved by rotating the beamline through an angle of 39 degrees.

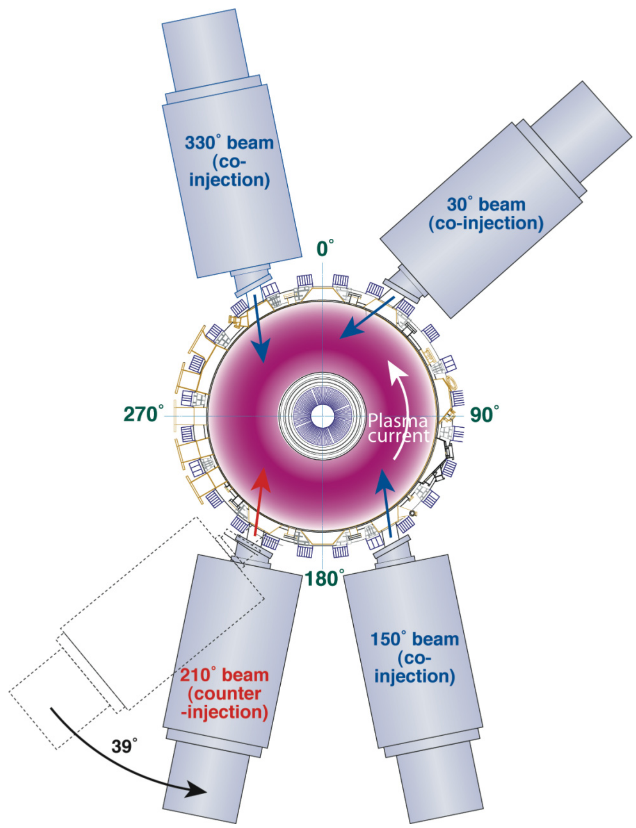

Fig. 1. The 210-deg beamline was rotated to provide the capability for simultaneous co- and counter-injection.

The new capability for simultaneous co- and counter-injection enabled by the beamline rotation allows the injection of up to 10 MW of power with zero net momentum input. Also, by varying the mix of co- and counter-injection beams, the plasma rotation velocity can now be controlled throughout the discharge. The capability for simultaneous feedback control of the plasma stored energy and the rotation velocity[3] has recently been used in a variety of experiments designed to study the effect of low rotation in high-energy plasmas. Experiments that study the resistive wall mode (RWM), for example, can now separate the stabilizing effects of plasma rotation from that of feedback control coils.[4]

II. BEAMLINE ROTATION TASKS

Rotation of the 210-deg beamline was a complex task, the effort effectively requiring the complete disassembly and rebuilding of one entire quadrant of the machine hall. Planning for the task began more than a year prior to the start of disassembly. A considerable amount of time was spent planning the entire project before the tokamak was ever shut down. A large number of subsystems were affected, as well as many systems not associated with the beamline, but impacted by the relocation. Extreme care was taken to reassemble the beamline at the precise desired new location and orientation. Some of the major efforts involved in the beamline rotation are described in this section.

II.A. Planning and Task Management

The development of a detailed plan for beamline disassembly and relocation was critical in order to accomplish the task in the relatively short period of time allotted. Initial planning for all the long torus opening activities (LTOA), one of the largest being the beamline rotation, was started as early as January 2004. Engineering designs were commenced in April 2004, one full year ahead of the actual disassembly tasks that started April 19, 2005. Figure 2 shows some of the major events along the timeline of the 210-deg beamline rotation task.

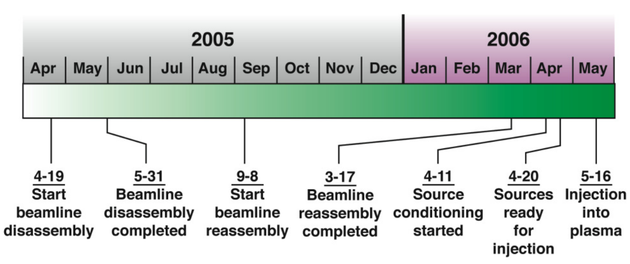

Fig. 2. Timeline showing milestones of the beamline rotation task.

The entire LTOA, including beamline rotation, was managed using Microsoft Project software. The final schedule for all tasks contained more than 3000 lines of subtask activities. Each major task was managed independently by a "traveler" document that contained the detailed procedures for the task, including inspection and quality control, and was signed off line-by-line as the task was completed. Seventy-five travelers covering disassembly, re-assembly, and testing were completed as part of the 210-deg beamline rotation task.

II.B. Auxiliary System Modifications

The first step in the disassembly of the beamline was the disconnection of all the auxiliary systems. In most cases, the auxiliary systems for both the 150 and 210-deg beamlines required rebuilding, since they occupy a common end of the machine hall. A summary of the major modifications made to the various auxiliary systems is listed in Table I.

TABLE I. Beamline Auxiliary System Modifications

Auxiliary System	Modifications Required
Cryogenics delivery system	Reroute piping, rebuild cold boxes on two beamlines
Vacuum system	Reroute vacuum lines, pumps, and controls for two beamlines
Gas system	Reroute tubes, rebuild gas manifold
Water cooling system	Reroute piping, relocate four manifolds
Power transmission system	Reroute ion source and bending magnet cables through new shield wall penetration
Instrumentation and control system	Reroute cables, relocate two interface stations
Beam diagnostics	Rebuild beam strike point pyrometer support system

In addition to the beamline auxiliary systems, another major tokamak modification necessitated by the beamline rotation was the complete rebuild of the toroidal field coil feed buswork located at 195 degrees. A new geometry was required to avoid beamline interferences and the new design provided the opportunity to reduce the magnetic error field as well.[2] The original feed had produced a dipole magnetic error field in the plasma near 195 degrees, whereas the new design eliminates that dipole field and improves plasma stability.

II.C. Beamline Disassembly/Reassembly

After the disconnection of all auxiliary systems and the removal of work platforms and floors, the beamline itself was disassembled. The beamline was separated into five major pieces, including three beamline spools, the ion source housing, and the front plate with torus isolation valve and vessel connection duct. Each of the five pieces was carried out of the machine hall using the overhead 20-ton crane, maintained, and stored until time for reassembly. In addition, the stand on which the three spools of the beamline rest was unbolted and removed, as was the source housing stand. The entire disassembly process took less than six weeks.

Once the 210-deg beamline was removed and that quadrant of the machine hall cleared, the open floor was accessible. Survey transits were then brought into the machine hall to carefully measure and mark the new position and alignment of the rotated beamline and source housing stands. After the floor was marked, the stands (modified for the new orientation) were brought back into the machine hall and very carefully installed and leveled along the new orientation. The three spools of the beamline were then remounted on the beamline stand and reconnected to each other. Since the spool pieces each have rollers that sit on rails on top of the stand in a fixed alignment, the orientation of the beamline is determined by the position of the carefully-located stand.

Connection of the beamline to the vessel is made when the front plate assembly (with isolation valve, bellows, and drift duct) is remounted to the front spool and rolled on the rails of the stand up to the tokamak vessel for welding. Only a very minor adjustment of the large bellows between the beamline and the tokamak was necessary to align the new front plate assembly to the tokamak vacuum vessel. The bellows adjustment is made by slightly stretching or compressing the bellows around its perimeter using adjusting rods. Figure 3 illustrates the position of the 210-deg beamline in the machine hall before and after the rotation, showing photographs looking down on the beamline from above the tokamak.

III. SOURCE HOUSING IMPROVEMENTS

Since the neutral beamlines extend radially from the DIII-D vessel to the walls of the machine hall, personnel access bridges are required across the ion source housings to get around the perimeter of the machine hall. In the past, accessing the sources required the removal of the personnel bridge and the source housing walls, requiring considerable time and effort. This situation was improved significantly during the LTOA by a modification of the bridge and source housing during the rebuild of the machine hall.

As shown in Fig. 4, access to the ion sources was made far easier by the addition of some well-placed hinges. The sides of the ion source housing were removed, cut in half, hinged, and reattached. A special cutting process using a high-pressure water jet was employed to preserve the magnetic shielding properties of the side doors. Hinges were also installed in the bridge modifications, transforming the one-piece bridge into three separate pieces, two "drawbridge" stairs and a walkway attached to the source-housing ceiling. The modifications allow easy access to the ion sources for inspections or simple repairs using the side doors. To extract a source, only the walkway and attached ceiling need be removed after opening the drawbridge stairs. During normal operations, the source housing doors are closed, drawbridge stairs are down and the ceiling and walkway are installed, allowing easy access to every part of the machine hall.

IV. SOURCE ALIGNMENT

After reassembly of the entire beamline, including the ion source housing but not the ion sources, a careful alignment procedure was followed to adjust the bases on which the ion sources are mounted. Critical alignment of the ion source injection path is required for several reasons. First, the beam must travel through the center of all apertures on its way into the tokamak to minimize

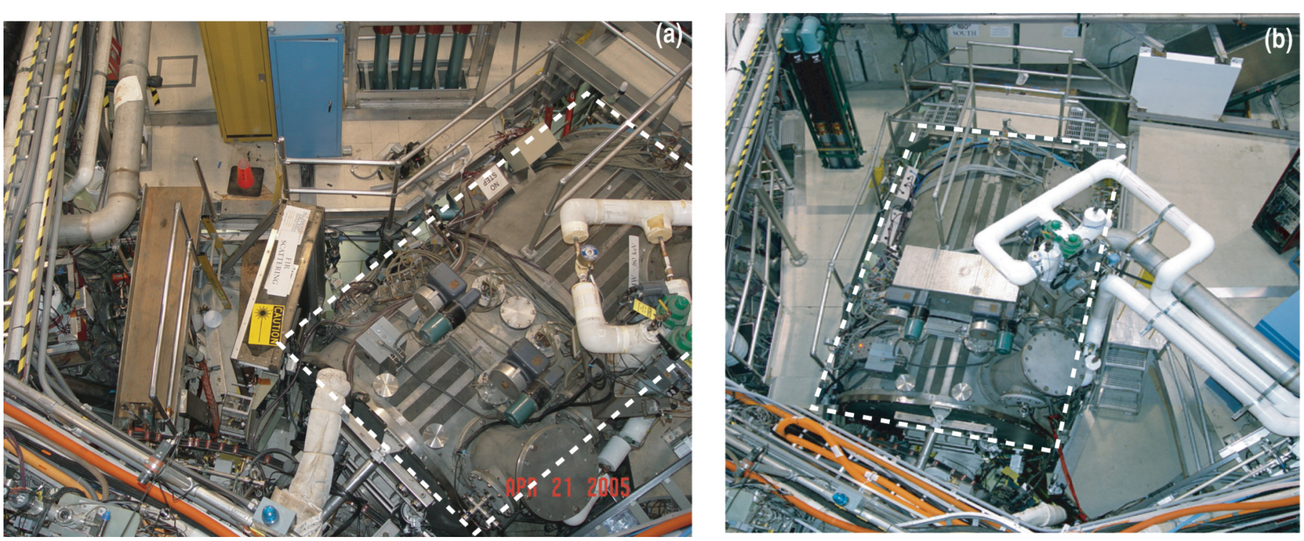

Fig. 3. Location of 210-deg beamline (marked by white dashed line) (a) before rotation and (b) after rotation.

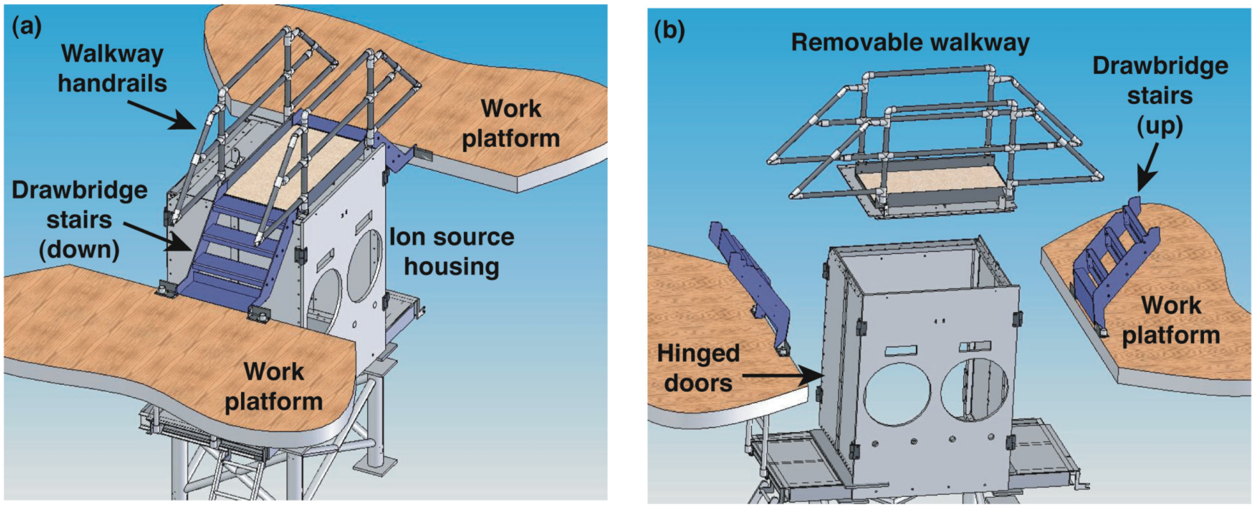

Fig. 4. (a) Modified ion source housing crossover allows access to all areas around perimeter of torus hall. (b) Ion source maintenance or extraction is enabled using removable ceiling (and walkway), drawbridge stairs, and hinged side doors.

potentially destructive interference with walls, ports, and collimators. Second, the beam path through the plasma must be accurately known, for diagnostics such as the charge exchange recombination (CER) system and the motional Stark effect (MSE) system, since these diagnostics must know the point of origin of the photons created by the beam traversing the plasma. Finally, the strike point of the beam on the tokamak wall must be well known to ensure the shine-through beam energy is deposited on the armor tile being monitored by a pyrometer system to prevent excessive heating.

To check and adjust the source injection paths, special fixtures were fabricated to hold low-power He-Ne lasers in the exact center of an ion source beam extraction aperture. Careful alignment procedures were followed to insure the laser path was normal to the plane of the mounting base. One laser apparatus was mounted on each of the two ion source adjustable bases and energized with personnel inside the tokamak vacuum vessel to document the laser paths. The critical measurements necessary to define the beam path are the locations of the two beams as they enter the vessel and the strike points on the vessel walls. The former is measured using a target mounted on a Plexiglas plate centered in the duct between beamline and vessel. Strike point measurements are taken using targets mounted on the vessel wall. An example of these measurements is shown in Fig. 5.

The initial location of the measured 210-deg armor tile strike points varied slightly from the desired nominal locations. Minor adjustments of the strike points were made using the ion source adjustable bases until strike points were located within the desired tolerance, approximately 0.5 degrees from nominal, or 1.5 cm on the outer wall and 1.0 cm on the inner wall.

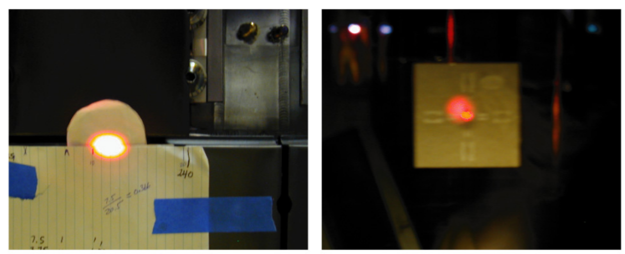

Fig. 5. Laser spots mark beam strike points on targets affixed to vessel wall (left) and to a Plexiglas plate mounted within beam duct near vessel entrance (right).

V. ROTATION CONTROL EXPERIMENTS

The 2006 experimental campaign concluded in September, with many experiments taking advantage of the new capability for counter-injection using the rotated 210-deg beamline. Some of the topics investigated using rotation control included the effects of error fields, resistive wall mode feedback control, stabilization of neoclassical tearing modes, quiescent H-mode, turbulence, tearing mode island suppression, and low rotation hybrid plasmas, among others. Since the plasma rotation speed enters the physics in a variety of different ways, many future investigations using rotation control are anticipated.[5]

One of the most important tools developed since the rotation of the beamline is closed-loop feedback control of the plasma rotation speed. In fact, since the neutral beam injection system now has two actuators (co-injection and counter-injection), both the stored energy and plasma rotation can be controlled simultaneously for the first time on DIII-D. Stored energy depends on the total beam power injected, while plasma rotation depends on the beam power and on the angle of injection. By tailoring the mix of co- and counter-beams, the applied torque and injected power can be controlled at the same time.[3]

An example of simultaneous closed-loop feedback control of stored energy and plasma rotation is shown in Fig. 6. The top trace plots normalized plasma beta, $\beta_N = \beta/(I/aB_T)$, where I is plasma current, a is minor radius, B_T is toroidal field, and β is a measure of stored energy. The bottom trace plots the plasma rotation speed. The shaded area indicates the feedback phase in each plot, with simultaneous feedback occurring in the time range 2.5-5.0 s. During that period, the rotation speed is programmed down and then a step up and down is programmed in the stored energy. Independent response of the two parameters indicates good orthogonality in the system. This kind of separate, simultaneous control promises to be very useful in future low-rotation plasma experiments and would not have been possible without the rotation of the 210-deg neutral beamline.

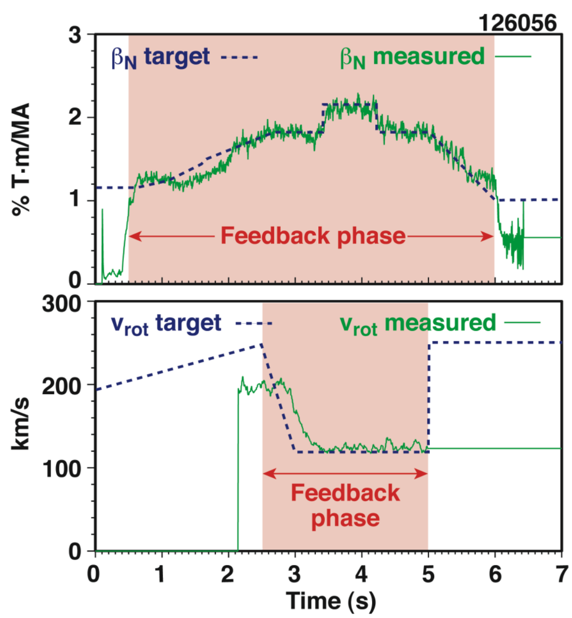

Fig. 6. Simultaneous closed-loop feedback control of stored energy (β_N) and plasma rotation is demonstrated.

VI. SUMMARY

During the LTOA period between April 2005 and March 2006, the 210-deg neutral beamline was completely disassembled and reassembled in a position rotated 39 degrees from the original. The new orientation provides the capability for simultaneous co- and counter-injection for the first time on DIII-D. The task was challenging, necessitating the expenditure of considerable effort before and during the LTOA for planning and scheduling. The task was successfully accomplished on schedule and the 210-deg sources were conditioned and ready for injection exactly one year from the start of disassembly. Very rapid ion source conditioning (only a few days required) was enabled by keeping the ion sources under vacuum during the entire year-long shutdown period.

Auxiliary systems requiring extensive rebuilding included the cryogenic delivery system, vacuum system, water-cooling system, instrumentation and control, and approximately 1/3 of the machine hall flooring and work platforms. During the process, the ion source housings were modified to provide much more efficient access for maintenance and repairs. Before the sources were installed, a careful alignment process was carried out using lasers to insure the correct beam injection paths.

Several experiments have already been performed using the new ability to control the plasma rotation and stored energy simultaneously. Key physics issues that could not be addressed prior to beamline rotation can now be investigated experimentally.

ACKNOWLEDGMENTS

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