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Mechanical Design of the Positioning System for an Off-axis Neutral Beam*

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***Abstract*—The DIII-D tokamak has 4 neutral beams (NB) for plasma heating, rotation control and current drive. These NBs are all horizontal injection at 19° offset from radial. Three NBs inject in the co-current direction and one NB injects in the counter current direction. The physics program requires two of the co-current NBs to be converted to allow injection at angles between 0° and 16.5° from horizontal by 2013 in order to investigate enhanced off-axis current drive. Each NB will be fully disassembled and it is planned during this task to upgrade thermal performance of internal components to allow for increased pulse length.**

The positioning system will incorporate 3 hydraulic cylinders to elevate the front and rear of the 35 ton NB. Hydraulic cylinder displacements will be supplied by hydraulic spool valves controlled by a programmable logic controller (PLC). The paper will present the following information for this mechanical positioning system:

- **Design requirements**
- **Linkage arrangement**
- **Loads evaluation including vacuum and seismic loads**
- **Hydraulic circuit including instrumentation**

Keywords: Neutral beam, current drive, off axis

I. Introduction

The DIII-D tokamak has four beam lines for plasma heating, current drive, and plasma rotation control. Each beam line currently injects horizontally from two ion sources: one aiming more tangentially with tangency radius of 1.17 m and the other less tangentially with the radius of 0.74 m.

Three beam lines inject in the direction of the plasma current (co-current) and one beam line injects in the counter current direction. The physics research program requires two of the co-current beam lines to be converted to allow variable injection angles between 0° and 16.5° from horizontal by 2013 to investigate enhanced off-axis current drive. However, experiments on ASDEX-U [1] reported lack of localization of off-axis neutral beam current drive (NBCD) at high power. New calculations [2] for DIII-D indicate very good current drive (CD) and localization if the toroidal field and plasma current are in the same direction (for a beam steered downward) due to the improved alignment of the neutral beam injection relative to the magnetic field line pitch. This prediction/model has been tested successfully by the recent off-axis NBCD experiments utilizing small cross-section plasmas that are vertically shifted [3]. The first beam line will be modified in 2010/2011 and it is planned at this time to upgrade the thermal performance of internal components to allow for longer pulse operation.

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II. Beam Line Selection

The DIII-D tokamak has an anti-torque structure to react the overturning moment on the machine using six diagonal members to connect three points below the TF coils to three points above the TF coils as shown in Fig. 1.

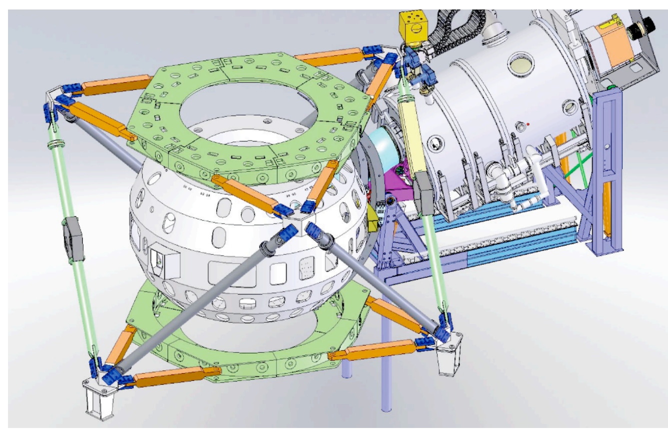

Figure 1. Spaceframe structure supporting tokamak vessel.

Neutral beams connect to the vessel through 4 of the 6 nearly vertical triangles formed by the anti-torque structure. The beam line locations with high connection points (30° and 150°) are better suited for tilting the beam line upward due to clearances for the beam line and more useful space allocation in front of the beam line. The 150° beam line will be the first to be modified for off-axis injection because of minimal impact on existing diagnostic systems.

III. System Requirements

The following are major requirements for the off axis beam line modification:

1. The beam line should be fully operational at inclination angles of 0° and 5° with infinite adjustment from 5° to 16.5° from horizontal.

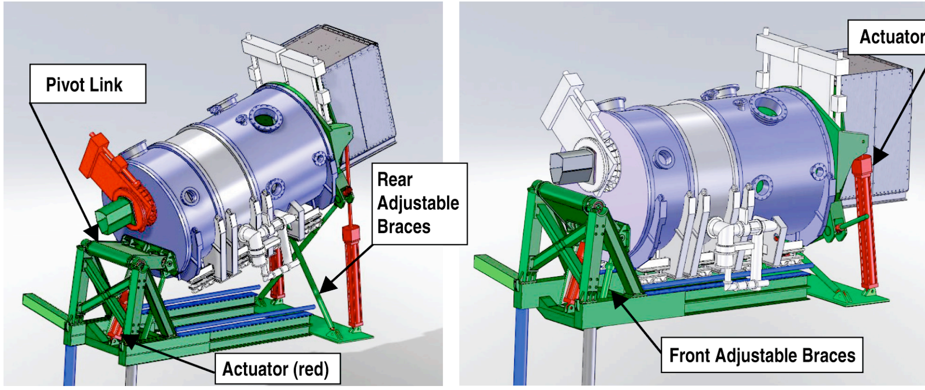

Figure 2. Neutral beam tilt mechanism (15 and 0 deg positions).

2. Adjustment of beam-line positions should be done in less than 16 h without venting of either the beam line or the vacuum vessel, or warming of the beam line cryogenic system.
3. The structural support for the beam line must meet the seismic requirements for equipment for the DIII-D facility in San Diego, California. The requirement is 1.1 g lateral acceleration applied statically to the beam line. The allowable stress for structural elements during an earthquake is 75% of yield. Deflection of the beam line must not exceed clearances of critical components.
4. The positioning system must fail in place safely on loss of electrical power or hydraulic pressure.
5. The system should use existing equipment where possible, require minimal additional space and fit within the existing facility.

IV. Positioning System Concept

Seven proposed concepts for positioning a beam line were ranked using a weighted scoring system that evaluated the various design considerations and criteria. The pivot-link design was selected and requires the beam line to be modified for positioning using three nearly vertical hydraulic cylinders. These cylinders are arranged one in front and two longer stroke cylinders located in back, outboard of the center of gravity of the beam line. The arrangement is shown in Fig. 2. When operated together, these actuators will maintain the beam line injecting through the virtual pivot point as shown in Fig. 3.

The pivot-link design controls the lift and radial position of the front of the beam line using a hydraulic cylinder to precisely lift the front which is also constrained by a link. This shaft/link combination forms a horizontal hinge that prevents roll of the beam line thereby preventing torsional deflection and loading of the bellows connecting the beam line and the DIII-D vessel. This front end system is designed to react the 10,000 pound vacuum load developed by the beam-line bellows anytime the DIII-D vacuum vessel is under vacuum. The system also reacts some of the horizontal and vertical components of seismic loads. The remainder of the weight of the beam line will be lifted using two hydraulic cylinders near the rear of the beam line. Displacements of the front and rear cylinders are coordinated using position feedback to a Programmable Logic Controller (PLC), which ensures that the neutral beam is properly aimed through the drift duct. Once the aiming position is achieved, adjustable braces securely lock the entire beam line in place in case of a seismic event. Fig. 4 shows the structures used to constrain the rear end of the beamline.

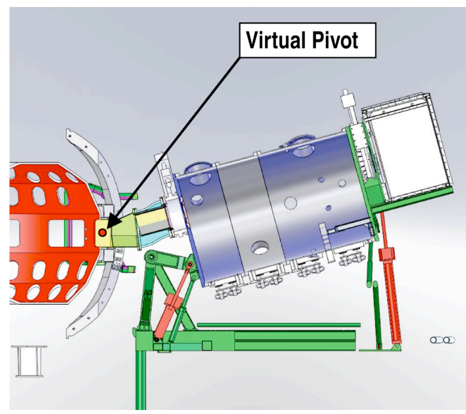

Figure 3. Front-end mechanism pivots about a virtual pivot point.

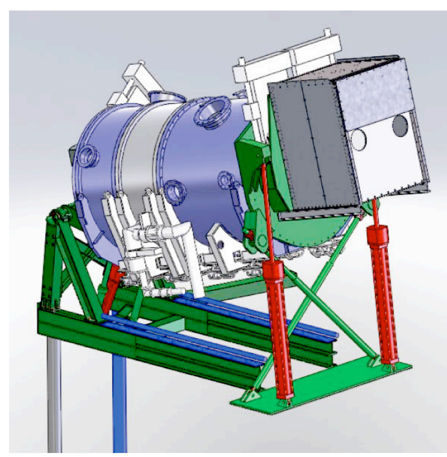

Figure 4. Rear actuators (red) and diagonal adjustable braces (green).

V. Design Features

In order to maximize the height through the port aperature, the beam line is designed to pivot vertically about a point located just outside of the DIII-D vacuum vessel. This point, inside the toroidal field coils, is radially inside of any feasible location for pivot hardware and as such is considered a virtual pivot point. The front and rear cylinder pairs provide 2 deg of freedom allowing the injected beam to always align with the virtual pivot. The pivot-link system has the axis of the beam passing through the virtual pivot point but the beam line moves outward along the axis of the beam about an inch between the minimum and maximum angles. This variation in beam line source to tokamak distance is acceptable.

The bellows between the beam line and the DIII-D vessel was specified based on size and angular displacement requirements. The virtual pivot point is inboard beyond the end of the bellows and this condition applies an offset deflection to the bellows. The bellows is straight at 8.25° and develops an S shape when it approaches either end of the bellows stroke. To create the 16.5° motion, a large circular welded metal bellows approximately 32 in. outside diameter is used to connect the neutral beam to the tokamak vacuum vessel. The inside of this bellows is protected from beam heating by a conductively cooled molybdenum sleeve attached to the beam line.

The beam line will be relocated away from the tokamak 16 in. from its current position. This location is constrained by the facility concrete wall. The move is required to allow for the necessary bellows length and to eliminate most mechanical interferences as the beam line is tilted. The tilted location interferes with an anti-torque frame member. Analysis indicated that the member can be rebuilt without impacting its function.

VI. Neutral Beam Positioning Controls

The three hydraulic positioning cylinders will each include a linear position sensor as well a pressure sensor for each side of the piston. These signals will be monitored and hydraulic flow controlled by a Programmable Logic Controller (PLC). Hydraulic flow will be controlled by servo valves. The two rear cylinders will be connected to common supply and return lines to equalize force output since they are mechanically constrained to move together by the front pivot system. The front cylinder will be controlled independently. The PLC will monitor the linear position of each cylinder: (1) to coordinate movement of the front and rear of the beam line and (2) to assure that each rear cylinder position compares closely to the position of the other rear cylinder to confirm zero roll of the beam line. Digital position indicators on the cylinders have a resolution of better than 0.005” which is adequate for the positioning requirements. A schematic of the hydraulic system is shown in Fig. 5.

The hydraulic system operates by maintaining a pressure supply circuit at 2000psi (shown in red). Fluid flow to the actuators is controlled by proportional valves while flow to the shaft clamps is controlled by simple on-off valves. The pump is fed by a large accumulator that is held at a low static pressure. An accumulator was used instead of a reservoir to prevent fumes from entering the machine hall and to ensure a reliable fluid supply to the pump.

The positioning system is designed to fail in place for loss of electrical power or hydraulic pressure. The flow control valve for each cylinder is opened with electrical power and spring closed during loss of electrical power. The three double acting cylinders have commercial spring-loaded cylinder shaft clamps that require high hydraulic pressure to release the rod and grip the cylinder rod if pressure is lost due to system leakage, power loss, etc. Seismic-rated mechanical locking restraints will be manually adjusted once the NB is positioned by the hydraulic system. The details of these restraints are shown in Figs. 6 and 7.

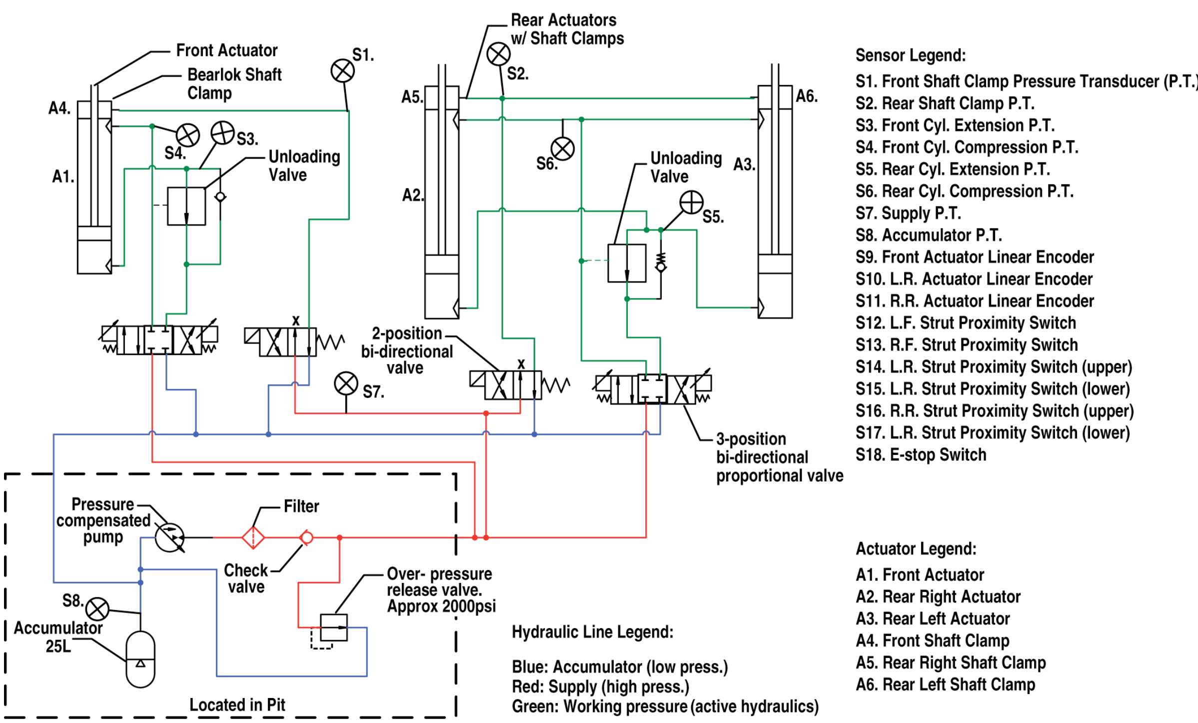

Figure 5. Schematic for hydraulic system.

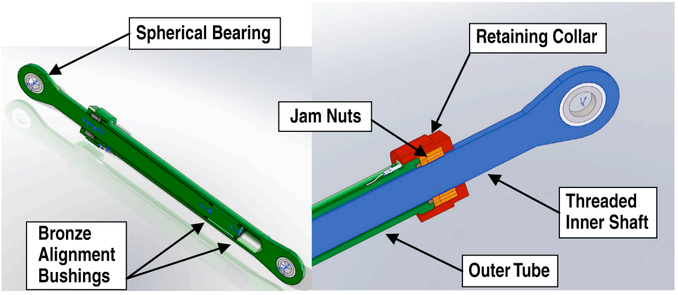

Figure 6. Front adjustable seismic restraint.

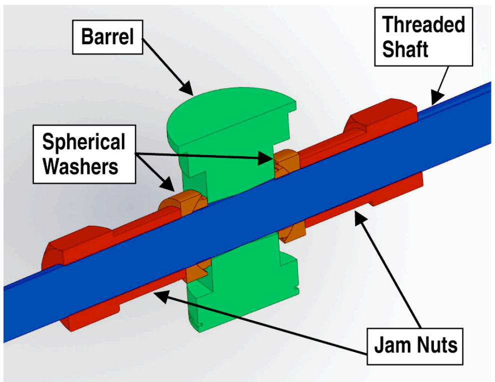

Figure 7. Rear adjustable seismic restraint.

VII. Service Lines

The service lines for cryogenic supply/return and vacuum currently are semi-rigid lines. Sections of these lines will be replaced with flexible lines to allow for beam line motion while evacuated and at cryogenic temperatures. Cooling water lines will also be modified for the necessary travel. There are a total of 30 water circuits for each beam line with operating pressures to 100 psig. Electrical power and I&C also require flexibility modifications but are not described in this paper.

VIII. Seismic Considerations

The DIII-D facility is located in San Diego, California, a relatively active seismic area. The applicable building code requires equipment supports to not exceed 75% of yield stress for a seismic event equal to a static lateral load of 1.1. The mass of the beam line is about 35 tons. Seismic loads along the axis of the beam line are reacted by the linkage system in front of the beam line. The horizontal load acting perpendicular to the axis of the beam line will be reacted partially by the linkage system and by a pair of crossed adjustable mechanical struts that attach to the floor and the opposite side of the beam line on the back plate of the beam-line tank. The struts are designed for both compressive and tensile loads. Extensive finite element analysis has been performed to ensure that both stress and deformation of the structure are kept within acceptable limits. Table I below shows the condensed results of a recent study showing loads in the braces for several configurations and seismic loads. The beam line axis is oriented north-sourth with the vessel at north. The front and rear adjustable links are designed with a safety factor of 3 against buckling. Other structural components are made of stainless steel, steel alloys, or aluminum and experience stresses less than 75% of yield during seismic events.

TABLE I. Worst Case Seismic Loads

Conditions			Results in Kips			
Angle (deg)	Vacuum Load, 10 Kips	Seismic Load	Front Brace, 140° Location	Front Brace, 160° Location	Rear Brace, 140° Location	Rear Brace, 160° Location
16.5	Y	Y	–34.1	–35.3	–10.5	–11.2
16.5	N	Y	1.4	–1.1	–41.2	–41.5
16.5	N	Y	–55.1	24.1	–51.4	–2.4
16.5		N	–14.7	–15.6	–27.4	–27.0
5	Y	Y	–38.3	–39.7	–20.0	–20.8
5	N	Y	10.5	9.5	–54.6	–55.7
5	N	Y	–43.3	17.0	–60.0	–18.3
5		N	–12.4	–13.2	–38.8	–39.7
0	Y	Y	–31.9	–32.1	29.0	29.6
0	N	Y	27.1	27.3	–25.2	–25.6
0	N	Y	–33.4	31.7	–20.5	20.3

IX. Other System Affected

The movable beam line will require neutral beam shine-through armor additions for the extended range of target points on the inner and outer walls of the Tokamak. These armor surfaces will require fast temperature detectors to properly interlock beam injection permits.

X. Beam Line Internal Components Modification

A study of beam profile and transmission along the off-axis beam line tilted vertically 16.5 deg has shown that the beam with existing initial beam size of 12 cm x 48 cm (width x height) would directly heat the vessel port box. The beam height needs to be reduced from 48 cm to about 34 cm by vertical refocusing of the four independent modules comprising a source. Beam collimation locations will be optimized.

The existing DIII-D beam lines can operate for 3 s beam pulses at beam energy of 80 kV, which provides 2.5 MW per source deuterium beam power injected into plasmas and the allowed pulse gets shorter as the injection voltage is increased. The disassembly necessary to modify the beam line for off-axis beam injection presents an opportunity of upgrading the beam line to long pulse operation, further enhancing the capability and scope for supporting physics experiments and study.

XI. Conclusion

This project is in the preliminary design phase and on schedule for installation in April 2010 – March 2011.

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