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# Overview of DIII-D Off-Axis Neutral Beam Project\*

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**Abstract**—DIII-D has four neutral beamlines (NB). Each of these beamlines has two ion sources, each of which injects up to 2.5 MW for 3 s. These beamlines intersect the vacuum vessel at an angle of 19.5 deg off from radial, enabling current drive in the same direction as the plasma current (co-injection). In 2004, one of these beamlines (210 deg) was rotated to provide counter-injection (opposite of plasma current). A different beamline (150 deg) has been modified to have the capability to provide off-axis neutral beam current drive. The goal of the off-axis injection is to have the center of the ion sources aimed at a position 40 cm below the geometric center of the plasma. To achieve this off-axis injection, the beamline requires a mechanical lifting system that can elevate the beamline up to 16.5 deg from horizontal. The beamline also requires more strongly vertically focused ion sources (in order to pass the beam through a reduced effective aperture) as well as modified internal components. Additionally, the design of the new internal components incorporated modifications to allow for the doubling of ion source pulse lengths without the need for active cooling.

This paper discusses the various beamline system design requirements for off-axis injection, as well as the results from the actual commissioning of the beamline. Overviews of the design and performance of mechanical lifting system (hydraulics and controls), focused ion sources, flexible beamline support systems (vacuum, cryogenic, power and water cooling), and internal beamline collimators are included. Additionally, the in-vessel monitoring and shine-through protection requirements are discussed. The actual data obtained during beamline commissioning and during normal physics operations is also presented.

## I. SUMMARY OF DIII-D NEUTRAL BEAM SYSTEM

The DIII-D fusion research tokamak utilizes eight neutral beam ion sources on four beamlines for plasma heating and current drive. Three beamlines are co-injection and the fourth is a counter-injection beamline. These ion sources and the neutral beam system have performed with high availability and reliability since 1987, and have achieved injecting a total of 20 MW of deuterium neutrals into the plasmas. A more detailed description of the DIII-D Neutral beam system is presented in [1].

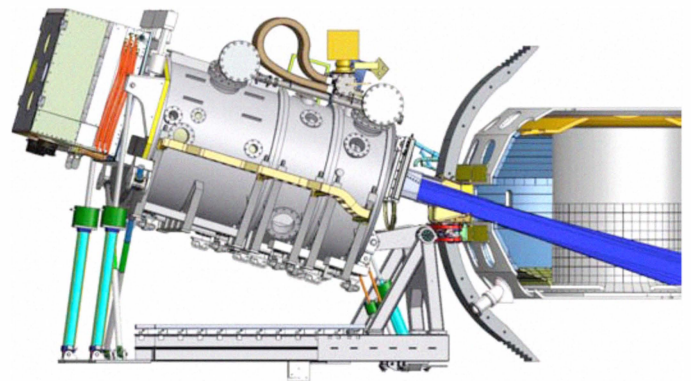


Figure 1. OANB injection into DIII-D.

## II. DIII-D OFF-AXIS NEUTRAL BEAM (OANB)

The objective of the OANB project was to modify one of the existing DIII-D neutral beamlines to enable off-axis injection while also allowing for that beamline to be operated in a standard on-axis injection position upon request. The 150 deg beamline was chosen to be modified into the OANB (Fig. 1). The OANB targeting design requirements were: off-axis injection from the right and left ion sources aimed at a position as close as possible to 40 cm below the geometric center of the plasma (this will be referred to as the off-axis target), the capability to inject at positions between the off-axis target and the on-axis position, and changing of the OANB position to take less than one day.

Injection of the beams at the off-axis target required a combination of both beamline tilt and ion source tilt. Tilting of the ONAB was limited to a maximum of 16.5 deg due to major mechanical interferences around the DIII-D vacuum vessel and in the machine pit area. This 16.5 deg beamline tilt alone did not aim the beams low enough to reach the off-axis target. Tilting of the ion sources with respect to the beamline itself was necessary to achieve the desired off-axis target. An ion source tilt of 0.58 deg was required. The ion source tilting mechanism which is used by the OANB is a capability that exists on all of the DIII-D neutral beamlines.

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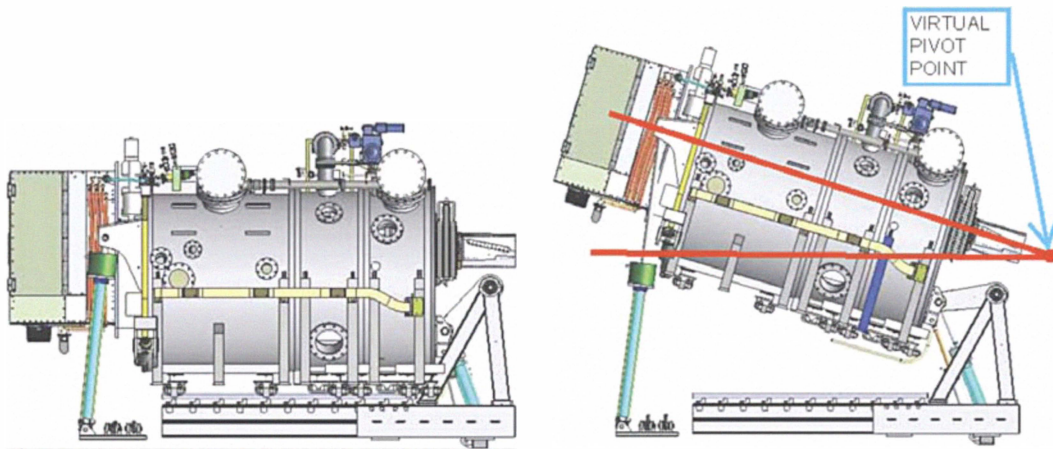


Figure 2. OANB lifting system showing beamline at on-axis and 16.5 deg off-axis positions.

### III. MECHANICAL LIFTING SYSTEM

Many concepts were examined for a mechanical lifting system for the OANB. A discussion of the selection process for the chosen concept, as well as details of the design are presented in [2] and [3]. The OANB was positioned approximately 0.43 m further away from the vacuum vessel as compared to its original location to allow for the installation of a 0.64 m long bellows (0.81 m diameter) which was required for the OANB's 16.5 deg of movement. The bellows is very susceptible to damage from any twisting motion. A design which incorporates a large, stiff front pivot member was chosen to minimize possible twisting of the bellows.

The mechanical lifting system utilizes a single front hydraulic cylinder and two rear hydraulic cylinders. The hydraulic cylinders raise the OANB about a virtual pivot point (Fig. 2). Cylinder shaft clamps are used to hold the hydraulic cylinders in place when the OANB is not being moved. These shaft clamps require hydraulic pressure to open and fail in the

clamped position as a safety measure. The cylinder shaft clamps close within 0.1 s after hydraulic pressure is removed. Blocking valves installed on the hydraulic cylinders also add a measure of safety by trapping fluid in the cylinders when not actively commanded to change cylinder length. The stroke of the hydraulic cylinders is determined by a look-up table which allows for positioning the OANB from 0 to 16.5 deg in 0.1 deg increments. The two rear cylinders are controlled by a single proportional valve for simplicity. Operational results have been excellent as the left and right rear cylinder positions are within 1.0 mm of each other. A single hydraulic pump raises system pressure to approximately 15.5 MPa (2250 psi). A single accumulator is used in order to maintain system pressure during transients such as shaft clamp unlocking. A schematic diagram of the hydraulic system is shown in Fig. 3. Repositioning of the OANB takes approximately 1 h. Seismic concerns were addressed through the incorporation of front and rear seismic support braces (Fig 1).

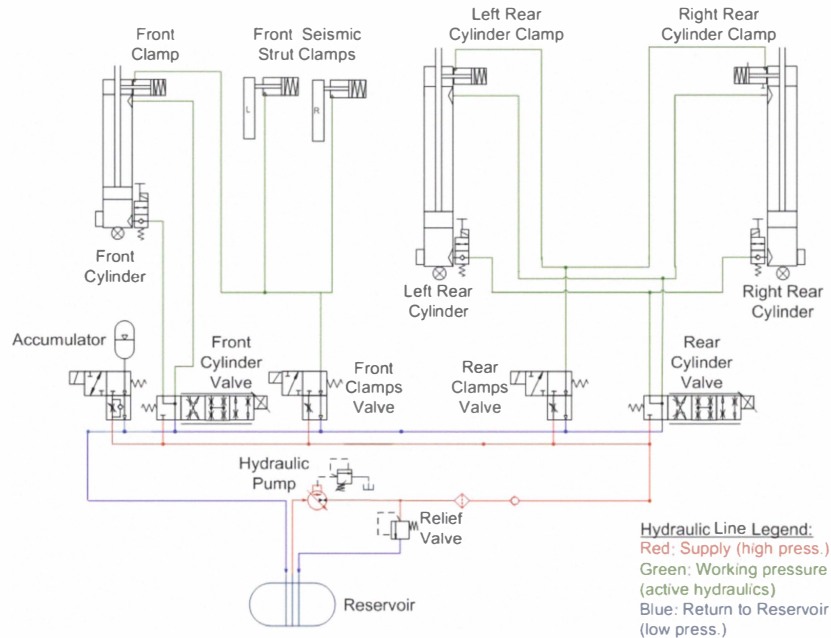


Figure 3. Schematic of OANB hydraulic system.

Lifting system operation starts when the hydraulic pump is started and its output pressure is brought up to nominal operating level. With the cylinder shaft clamps locked and cylinder blocking valves closed, net lifting forces in the front and rear cylinders are ramped up to 90% of the stored force values (which had been measured when the beamline was last supported by hydraulic pressure). The rear shaft clamps are then opened, followed shortly by the front shaft clamps, and the beamline is supported by trapped fluid in the hydraulic cylinders above the blocking valves. Rear cylinder lifting force is then slowly ramped up until upward rear piston movement is detected, at which time the lifting force is held constant, the rear blocking valves are opened, and control of the rear cylinders is changed from force-feedback to position-feedback. The positions of the rear pistons are then adjusted to ensure they are appropriate for the current beamline tilt angle. This process is repeated for the front cylinder. When front and rear cylinders are in position-feedback control and at angle-appropriate positions, the operator initiates beamline movement, during which the commanded beamline angle ramps from its present value to the requested final value. As the commanded angle changes, the positions of the front and rear pistons are commanded to change such that the actual beamline angle tracks the commanded angle. Once the requested final beamline angle is reached, motion is stopped, net lifting force values are stored in memory, all clamps are locked and blocking valves closed, and cylinder control is changed back from position-feedback to force-feedback. Cylinder forces are then ramped back to zero, pump pressure is reduced to minimum and the pump is shut down.

#### IV. FLEXIBLE BEAMLINE SUPPORT SYSTEMS

##### A. Cryogenic System

A movable beamline requires flexible cryogenic lines to deliver the liquid nitrogen and helium for the cryo panels inside the beamline. The five flexible cryo lines include the liquid nitrogen supply line, the nitrogen vent line, the liquid helium supply line, the two-phase helium return line, and the helium cool down subcooler bypass return line. These flexible cryo lines run inside a flexible cable tray.

The liquid nitrogen and liquid helium continue to flow while the beamline is moving, keeping the cryo panels cold. The flow rate of liquid helium is about 4 grams per second. The flow rate of liquid helium is controlled by the differential pressure between the inlet and outlet of the cryo panels. The differential pressure is maintained by a PID loop controlling the helium control valve upstream of the beamline. The rear cryo panel is elevated about 1.20 m above its horizontal position when the beamline is in its maximum raised position. To maintain adequate flow of liquid helium to keep the beamline cryo panel temperature cold and stable while in the raised position, the differential pressure PID loop setpoint was increased from 5.0 kPa psid to 6.2 kPa. The setpoint was determined during beamline operational testing.

##### B. Water System, Vacuum System & Instrumentation Cabling

The OANB's numerous water-cooled components required flexible connections to allow for beamline repositioning. This

was accomplished through the use of flexible hoses and a large, flexible cable tray, which allow for the water lines to stay connected and strain-free in all of the OANB positions. This cable tray was also used to route the various instrumentation cabling required by the OANB. The OANB vacuum system was designed to be attached to the beamline itself and the main roughing line was connected to the stationary turbo pumps through flexible lines.

##### C. High-Voltage Transmission Lines

The high-voltage transmission lines had to be modified from a fixed position, cylindrical arrangement of bifilar cables to a flat layout of bifilar cables in a flexible cable tray inside of a grounded, collapsible housing. The housing had to move the full height of the beamline (approximately 2.0 m) and nest in itself as the beamline came to the 0 deg position, all the while maintaining a strong ground connection. The system was successfully assembled and was hi-potted to 100 kV.

#### V. STRONGLY FOCUSED ION SOURCES

A more strongly vertically focused ion source for the OANB was required since the effective aperture into the vacuum vessel is reduced as the OANB tilted up to 16.5 deg. The more strongly focused source has four accelerator grid modules (each 0.12 m high) which are angled as shown in Fig. 4.

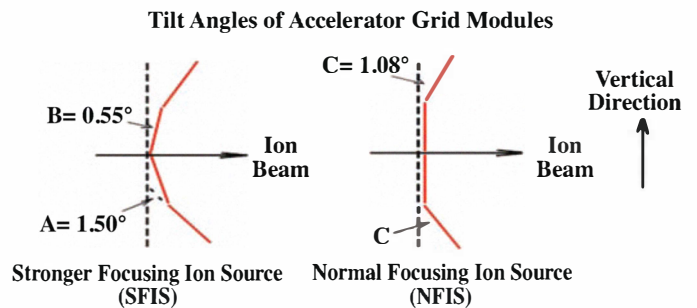


Figure 4. Tilt angles of four ion source grid modules for normally focused and strongly focused ion sources.

The effect of the stronger focusing is shown in Fig. 5. The strongly focused beam is narrowed from 0.48 m to approximately 0.33 m tall at the vessel port box whereas the normally focused beam at that location is 0.42 m tall. The more strongly focused beam is able to enter the vacuum vessel through the reduced effective aperture at the port box when the beamline is at 16.5 deg. This more strongly focused beam also allows for the source to be tilted downward with respect to the beamline by 0.58 deg while the beamline is at 16.5 deg. The combination of 16.5 deg beamline tilt and 0.58 deg strongly focused source tilt achieves desired off-axis injection and has a “zero” gap between the edge of the beam and the closest point of the vessel port box. The proximity of the beam to the port box is much closer than on a standard DIII-D beamline and required the OANB to have enhanced collimation. A detailed description of the more strongly focused source and a comparison of this source to a normally focused DIII-D ion source is presented in [4].



Two strongly focused sources were built and tested and have been successfully operating since DIII-D operations resumed in April 2011.

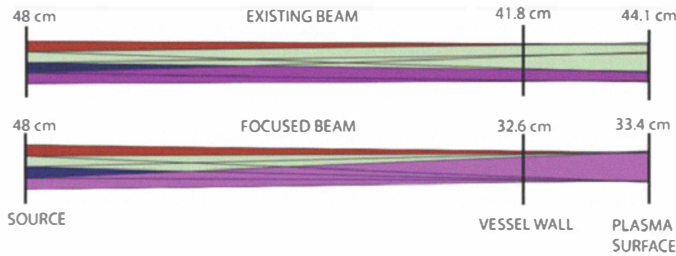


Figure 5. Comparison of beam sizes for the four modules of the normally focused and strongly focused ion sources.

## VI. BEAMLINE INTERNAL COMPONENTS

A standard DIII-D ion source sends its beam through six collimators before entering the port box. Five sets of these collimators are placed separately for each ion source and the last collimator in the beamline has both left and right sources passing through it. These C10100 (OF Copper) collimators have symmetrical apertures around the source centerlines (with the exception of the last collimator which has both beams) and are in place to protect beamline components from stray beam energy. These collimators provide both vertical and horizontal collimation. The collimators are inertially cooled during the beam pulse with water cooling providing cooldown between shots to nominal starting values. Thermocouples in the copper are used to monitor temperature and water flow calorimetry in the cooling circuits is used to measure deposited power.

The internal components of the OANB had three requirements that were not called for in other DIII-D beamlines. The OANB internal components are required to shape the beam to avoid port box damage, to protect the bellows and to facilitate longer pulse operation.

The OANB internal components need to collimate the strongly focused beams to allow for a 16.5 beamline tilt with a 0.58 deg ion source tilt without damaging the edge of the port box closest to the plasma. The five sets of OANB collimators that are separate for each source are positioned to gradually reduce the left and right beam apertures and share scraped off power as uniformly as possible between the collimators along each beam path. Since the OANB sources are more strongly vertically focused, the collimator apertures are smaller than for the normally focused sources, so the nominal spacing between the beam edges and the collimators is similar for both types of sources. The left and right OANB magnet entrance collimators are shown in Fig. 6. The OANB has an additional collimator not found in the other beamlines, downstream of what is the last collimator in the other DIII-D beamlines. This collimator was added on the vessel side of the beamline isolation valve to provide additional collimation of the beams as well as a cooled mounting surface for the TZM Moly shield that protects the inside of the bellows.

The OANB internal bellows protection is provided by a TZM Moly shield that protects the bellows from any stray beam energy and provides the last scrape-off point for the

beams before they enter the vacuum vessel port box. This TZM Moly shield was built by PPPL in two pieces to allow for installation and is shown inside the collapsed bellows in Fig. 7.

The OANB internal components were also designed to enable longer beam pulse durations, on the order of 6 s (compared to 3 s for other DIII-D neutral beamlines). The pulse length limiting component for standard DIII-D beamlines is the bending magnet thermal shield. These shields have failed in the past when cracks in the plates caused by thermally induced stresses have propagated to water lines, resulting in water leaks into the beamline vacuum. The bending magnet thermal shields used in the OANB are significantly stronger than those used in other beamlines as the copper plates in the other beamlines have all been annealed when cooling tubes were brazed in place. The cooling tubes for the OANB bending magnet thermal shields were flame sprayed in place and the strength of the copper plates was not reduced during that process. The other collimators in the OANB are made from C18150 (Cu-Cr-Zr) which has a substantially higher fatigue strength than OF Copper. These collimators are also designed with gun-drilled cooling passages to allow for more efficient cooling to support longer beam pulses.

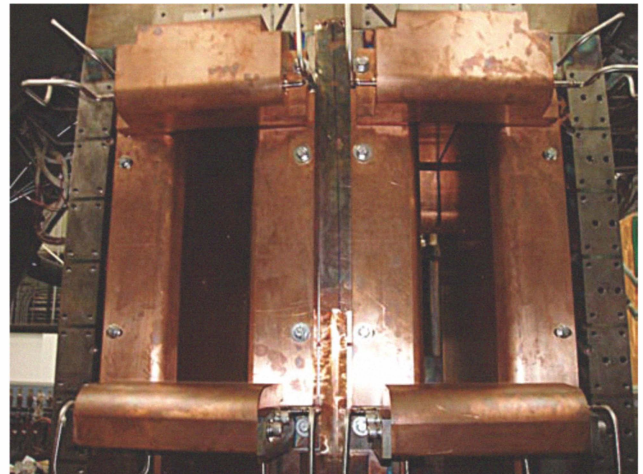


Figure 6. OANB magnet entrance collimators.

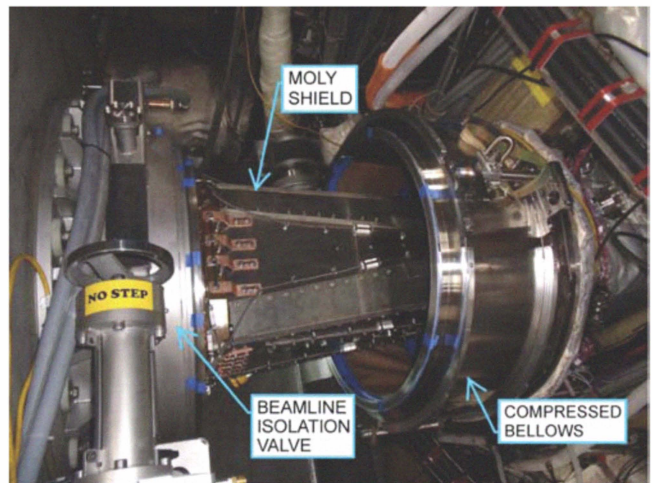


Figure 7. TZM Moly Shield extending into compressed bellows

## VII. SHINE-THRU PROTECTION AND IN-VESSEL MONITORING

The OANB is the first DIII-D beamline to inject power into the vacuum vessel at targets below the vessel midplane region. DIII-D NB systems have always provided real time graphite tile protection through the use of pyrometers that monitor tile surface temperatures and shut off the beam if critical temperatures are reached. The standard fixed pyrometer mounting scheme was not sufficient to provide tile protection at all of the off-axis OANB injection angles. Two fiber-optic pyrometers (one for each OANB ion source) were installed in manually adjustable mounts to allow for the real time tile protection over the full range of the OANB off-axis injection positions.

Thermocouples are installed in DIII-D NB target tiles to allow for beam shine-thru power measurements. Additional thermocouples were placed in tiles along the OANB left and right beam target paths as described below.

The OANB right source is capable of aiming at the vessel centerpost from the midplane, down to a position approximately 0.5 m below the midplane. The graphite tiles on the centerpost are well-cooled tiles which are normally exposed to NB shine-thru. Thermocouples were added to the centerpost tiles below the midplane down to the lowest OANB right source target.

The left source in the OANB now is capable of aiming as far down in the vessel as the lower outer baffle plate (Fig. 8). The graphite tiles on the R0 (midplane) and R-1 surfaces are well-cooled and were instrumented with thermocouples to track beam shine-thru. The baffle plate below the R-1 area is not well cooled. Modeling showed that these tiles would heat up over the course of repeated shots, but would cool radiatively sufficiently to avoid any tile damage. OANB operation has shown the modeling to be accurate. The lower divertor tiles below the lower outer baffle plate are very well cooled and designed for high power operation.

To protect the vacuum vessel port box from any beam power which was not scraped off by the collimators in the beamline, a 4 mm thick molybdenum plate was installed on the floor of the port box (Fig. 9). Molybdenum was chosen as it has approximately double the melting temperature and ten times the thermal conductivity of the port box inconel. The underside of the plate was insulated with alumina to disrupt currents which threatened to rip the plate up off the port box. This plate is instrumented with thermocouples to monitor beam interaction and in the event large amounts of power are deposited on the molybdenum plate, it is replaceable. Modeling of the plate showed that radiative cooling between shots allows the plate to have only minimal temperature ratcheting over the course of a day. Operations have validated this modeling. Maximum observed temperature on the molybdenum plate has been approximately 200°C.

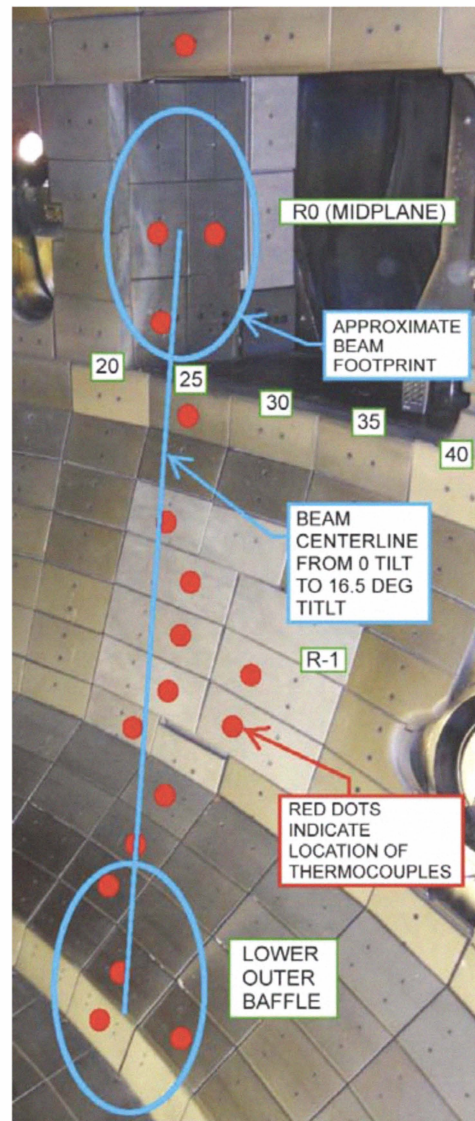


Figure 8. OANB left source vessel outer wall target tiles.



Figure 9. Molybdenum plate in vessel port box.



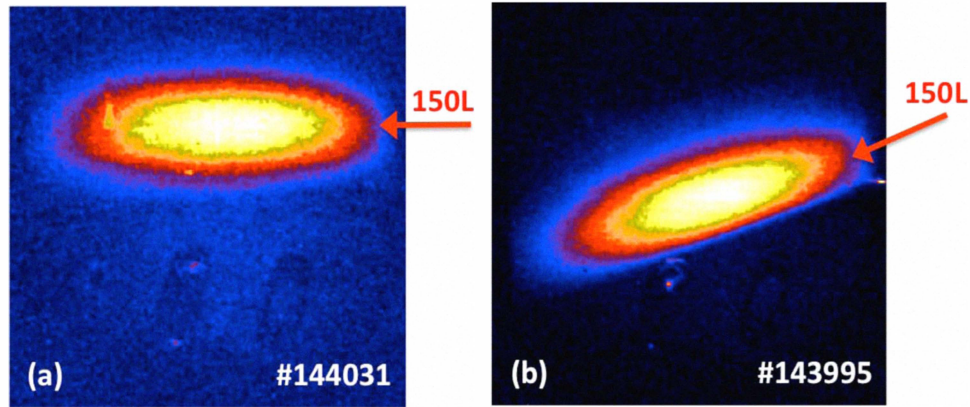


Figure 10. D-alpha images of 150L deuterium beam injection into DIII-D vessel filled uniformly with helium gas. (a) #144031 with un-tilted beam and source. (b) #143995 with beam tilted at 16.5 deg and source tilted at 35 mins. Clipping of lower beam profile is apparent in tilted position. Camera vignetting causes apparent fall-off of beam intensity at left and right edges of images.

### VIII. OFF-AXIS NEUTRAL BEAM COMMISSIONING AND OPERATIONAL RESULTS

The OANB was commissioned in April 2011. Injected power has been conditioned to be approximately 2.25 MW per source (compared to a nominal 2.5 MW from a standard NB source). This power has been injected at the off-axis target and the on-axis position.

Initial experiments to assess the basic beam functionality, geometry, and confinement were carried out.  $D_\alpha$  images of beam into gas and plasma yield beam neutral profiles and are key in assessing beam shape, steering, and clipping (Fig 10). Neutron and fast-ion  $D_\alpha$  (FIDA) diagnostics verify the expected classical behavior of the off-axis beam ions in MHD-quietest conditions. Experiments on off-axis neutral beam current drive (NBCD) have clearly demonstrated off-axis NBCD using the new tilted beamline – the primary goal of the facility enhancement.

OANB beam pulse lengths are currently administratively limited to 3 s when the sources are tilted down to 0.58 deg. When the sources are at a zero tilt, the beam pulse length limit

is 6 s. The pulse length limiting component is the TZM Moly shield. The pulse length limit is not dependent on the beamline tilt, but purely the source tilt with respect to the OANB. Future analysis and experimentation is planned to more fully understand the power flow and resulting pulse length limits in the beamline, TZM Moly shield, port box and vessel for the full range of OANB injection angles and source tilts.

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