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by

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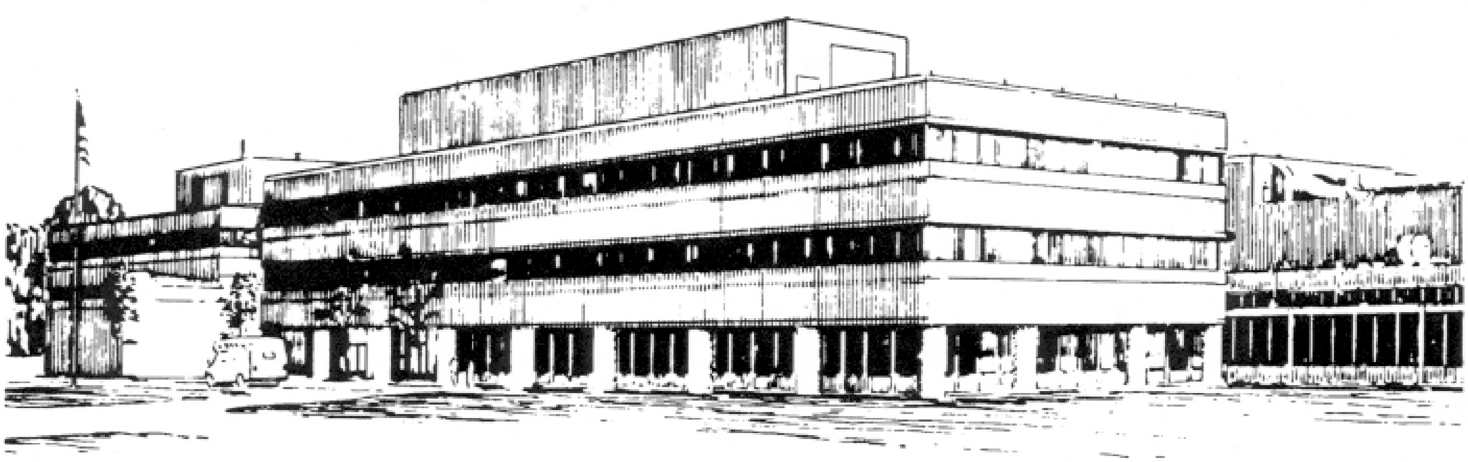

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A Neutral Beam Injector Upgrade for NSTX

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Abstract-- The National Spherical Torus Experiment capability with a Neutral Beam Injector (NBI) capable of 80 kiloelectronvolt (keV), 5 Megawatt (MW), 5 second operation. This 5.95 million dollar upgrade reused a previous generation injector and equipment for technical, cost, and schedule reasons to obtain these specifications while retaining a legacy capability of 120 keV neutral particle beam delivery for shorter pulse lengths for possible future NSTX experiments[1]. Concerns with NBI injection included power deposition in the plasma, aiming angles from the fixed NBI fan array, density profiles and beam shinethrough, orbit losses of beam particles, and protection of the vacuum vessel wall against beam impingement. The upgrade made use of the beamline and cryo panels from the Neutral Beam Test Stand facility, existing power supplies and controls, beamline components and equipment not contaminated by tritium during DT experiments, and a liquid Helium refrigerator plant to power and cryogenically pump a beamline and three ion sources. All of the TFTR ion sources had been contaminated with tritium, so a refurbishment effort was undertaken on selected TFTR sources to rid the three sources destined for the NSTX NBI of as much tritium as possible. An interconnecting duct was fabricated using some spare and some new components to attach the beamline to the NSTX vacuum vessel. Internal vacuum vessel armor using carbon tiles was added to protect the stainless steel vacuum vessel from beam impingement in the absence of plasma and interlock failure. To date, the NBI has operated to 80 keV and 5 MW and has injected requested power levels into NSTX plasmas with (NSTX) has upgraded its auxiliary plasma heating good initial results, including high beta and strong heating characteristics at full rated plasma current[2].

The National Spherical Torus experiment (NSTX) physics device has created plasmas of over one megaamperes to study plasma physics and to perform fusion research. To heat such plasmas the device capability originally included High Harmonic Fast Wave auxiliary power to reach higher plasma performance. Additionally, an upgrade to NBI heating was anticipated in the baseline design but this upgrade was scheduled to begin about one year after construction of the machine proper had started.

The NBI upgrade project was based on the reuse of a clean spare beamline from the NB Test Stand facility. The Test Stand spare beamline components had also been saved and could be reused. The TFTR ion sources, which are an integral part of the injector design and prime mover of the particle beams, were all contaminated but previous refurbishment efforts had demonstrated enough success in decontamination that the sources were projected to be cleaned well enough for reuse. The relocation, reuse, and commissioning of this equipment required extensive engineering, fabrication, and installation work. Specific job activities included performing an ion source refurbishment process to build three sources, resurrecting the beamline and it's services, connecting new cabling from the power supplies to the new location, designing a new controls system, a better vacuum interconnecting duct, and new vacuum vessel armor. Thus, the NBI upgrade project established an injector system capable of injecting 80,000 keV deuterons with 5 MW of power for 5 seconds. The project scheduled the upgrade to occur over two years with funding of 5.95 million dollars.

Care was taken to develop the NBI beam deposition, aiming angles, and footprint on the far wall with respect to diagnostic viewing lines. The three ion source beam fan array of 4.039 degrees has many fixed points within the structure of the beamline, which prevented alteration without undue cost. The crossover point for the beam which corresponds to the minimum total beam cross-sectional dimension along the three source trajectories was located just inside the machine NBI port located at Bay A to make the beam port as small as possible. Once chosen, this point then defines the centerline of the beams and the distance from the exit grids of the source to the port. An additional NBI sized port was provided on the vacuum vessel in the event of future upgrade to a second injector.

Concomitantly, the fan array angle spreads the three sources across the far wall. The divergence of the beam vertically and horizontally defines the possible footprint that dictates the extent of the armor. The inner source injected after the crossover point in transit through the machine, which is the "C" source position, was located such that the zero power line was located tangent to the centerstack tiles. The zero power line was estimated by adding half the beam width of 12 cm and the horizontal half angle divergence of 0.5 degrees with a safety factor of 2 onto the centerline for this source. The fixed fan array then defines the middle and outer source trajectories also. These aiming criteria created tangency radii for the A, B, and C sources of 69 cm, 59cm, and 49 cm from centerline of the machine centerstack. Thus, the beam impinges the area corresponding to one and a half midplane ports on the far wall so the machine had to be protected by the NBI armor to that extent.

The rear platform of the beamline supports the three sources used for generating the ion beam. These sources weigh about 3.5 tons each. The rear corner of the beamline location was chosen such that the A source position just fit within the overhead crane envelope of coverage along the East wall of the NSTX Test Cell (NTC).

The NB Test Stand facility had not been operated since 1987 so the beamline required overhaul and leakchecking. It also had to receive the upgrade to the long pulse source requirements. The 90 inch entry flange to the beamline was removed and updated with water-cooled and copper lined spool sections. The flange was then assembled to the beamline and aligned. The calorimeter had already received the upgrade but the alignment was checked.

The beamline requires cryogenics, water, vacuum, and pneumatic services to perform its function of accelerating, neutralizing, and conducting the neutral particles to the machine. The 1070 Watt liquid Helium (LHe) refrigerator was brought back into service, including its tanks, compressors, filters, cold box, and main dewar to service the NSTX NBI. Caretaking measures were successful in preserving the cryogenics plant between shutdown in 1997 and the startup of NSTX NBI in 2000. Approximately 500 feet of new LHe and LN cryogenics piping was required to service the NBI location in the Northeast corner of the NTC. This piping was fabricated at PPPL and installed by the NBI crew.

The neutral beam requires rapid pumping of feedstock gas at the end of the neutralizer to prevent reionization losses so the beamline contains 8 cryogenic panels. The panels consist of a liquid Nitrogen chevron, a liquid Helium panel, and a liquid nitrogen shield in a sandwiched configuration. These panels were repaired and leakchecked. All seals were also refurbished on the beamline.

The beamline must inject at the mid-plane of the NSTX vacuum vessel with some precision for appropriate power deposition in the plasma and superposition of the beam shape on the elongated plasma cross-section. NSTX is one of the tallest fusion devices ever created so the 80 ton NBI box centerline had to be raised to the 13 foot midplane level of the machine. A seismically rated support structure consisting of 5 columns was built and installed so that the NBI box could be located and aligned before the vacuum vessel was installed for better accuracy of NBI aiming. The source platform and deionized water rack on its side were salvaged from TFTR NB #5.

The water services to the NBI include ion source, ion dump, and power system cooling water. These water pumps, motors and valves were resized and reused where possible to accommodate the NSTX NBI. All new piping was run for each system.

A new beamline vacuum system was designed and installed to evacuate the beamline box and sources, to perform regenerations of the cryopanels to remove accumulated deuterium, and to rough down the vacuum of the NSTX vessel when needed. A vacuum roughing pump skid, a turbomolecular pump on the beamline, and a turbo backing pump skid were installed in the NTC on appropriate ports on the beamline. The exhaust of the pumps was attached to the NSTX vacuum exhaust line, which exits the complex via a monitored stack. While some very low level of tritium contamination was introduced into the beamline from the refurbished ion sources, no tritium has been observed on the beamline Residual Gas Analyzers, on the exhaust stack monitors, or in discharges. A recent entry of the vessel showed no contamination within the vessel.

An interconnecting duct was designed using the TFTR duct as its basis. The duct must permit beam transit to the vessel with minimal reionization loss and also must isolate the beamline from the vessel for cryopanel regeneration and venting purposes. A ceramic break provides electrical isolation between the neutral beam injector and the torus, thereby eliminating ground loops. The free aperture of this duct also has importance to minimize reionization of the beam in cold gas where machine fields might deflect and focus beam particles onto unshielded bellows or walls. The beamline exit flange and the one meter torus isolation valve (TIV) flanges have a circular geometry. However, the port for TFTR NB has a rectangular shape just large enough to accommodate the beam footprint and requisite free aperture. This rectangular port geometry was incorporated into the NSTX vacuum vessel in two places in anticipation of an NBI upgrade. Therefore, an interconnecting duct was designed based on the TFTR spool sections and circular and rectangular bellows and mating flanges while reusing a spare one meter TIV. The transition duct piece where the shape changes from circular to rectangular shape was redesigned to allow more free aperture and less fabrication complexity by eliminating a detente that had been required to clear a TFTR torodial field coil case which was no longer a concern for NSTX.

The neutral beam particles injected into the machine enter the plasma and should become reionized and contained by the magnetic fields. However, some beam particles pass through the plasma unaffected and could impact the far vessel wall as shinethrough beam. If a failure of two protective interlocks occurs, a beam pulse could impinge the far vessel wall with deleterious effects. Finally, to minimize cycles on the calorimeter bellows the NBI will occasionally fire a 50 msec tuning pulse through the machine between plasmas. To protect the vessel wall against these insults, neutral beam armor was designed and installed to receive all beam particles so generated. The armor consists of isotropic graphite tiles facing the plasma backed by water-cooled stainless steel plates. For support the plates are pinned to the vessel wall covering Bay H and part of Bay I. The tiles cover the vessel above and below the midplane to the passive plate plasma facing components. Thermocouples were installed on each tile. The NSTX NBI armor is rated for one 80 kV, 5 MW, 5 second shot after which an inspection of armor integrity would be required.

To refurbish ion sources, the upgrade project made use of the Decontamination Facility and Source Clean Room, which had been relocated from the Hot Cell to the Mockup Building to make way for NSTX. The facility consists of a Decontamination Room, a Clean Room for assembly of the sources, an antechamber for donning and shedding anticontamination clothing, a Service Mezzanine, and a Test Mezzanine. A two position Ion Source Test Stand with its vacuum, deionized and deoxgenated water, high voltage tester, and sulfur hexoflouride insulating gas services resides on the Test Mezzanine. The Test Mezzanine also has shop and storage space for source enclosures not in use. So far, the facility has produced 6 refurbished ion sources. Three sources have been in service on the NSTX NBI beamline for about one year and two sources have since been tested and maintained as spares.

The power supplies for TFTR NB#5 had once serviced the NB Test Stand facility prior to the NB#5 installation. Due to proximity, these three power supplies were once again chosen to power the NSTX NBI system. The power supplies required all new cabling to the NTC to power filament, arc, suppressor, accel, gradient grid, and bending magnet functions to operate the ion source. The High Voltage Enclosures that resided in the TFTR Test Cell basement and the transmission lines that connected them to the source were relocated behind the NBI beamline in the NTC thus allowing the reuse of the transmission lines without modification.

The power supplies could be reused without modification with one exception. The gradient grid (GG) voltage is supplied from a resistive divider in the modulator/regulator cabinet. The original GG divider used a chain of resistors in a Freon bath. The Freon dissipated heat and was contained by a bladder in a polyvinyl chloride container. To eliminate the potential for insult to the environment and the cost of purchasing new Freon, the divider was replaced with a newly designed air-cooled divider within the same space envelope of the Mod/Reg cabinet. As the full power capability of the TFTR NB designed was retained throughout the system, this divider was designed for and tested to 120 kV for 1 second and 80 kV for 5 seconds. Testing also defined a potentially catastrophic operating limit of 92 kV for 5 seconds where resistors might begin to fail. The cabinet air cooling was increased by adding additional fans.

The original freon-cooled divider performed its function with a total value of 25 kilohms of resistance. To reduce heat in the cabinet produced during a pulse the new design embodied 50 kilohms of resistance. While the high voltage switch tube turn-on characteristics were affected by less load at the start of a pulse, tuning techniques for the tube and system were successful in making the new valued divider work properly.

The NBI controls were updated in several key ways. The beamline controls retained the Programmable Logic Controller (PLC) with interface software as the approach but a large number of optoelectronic links were eliminated by locating the PLC I/O racks in proximity to the beamline in the NTC. A direct fiber optic connection between input and output racks could then be employed for simplicity and improvement in overall reliability. The PLC software logic was redesigned and updated for the new vacuum system and single beamline. Some upgrades to the LHe refrigerator controls were also possible to include key functions and much more monitoring from the beamline controls station. The ion sources were controlled manually via the remote Local Control Centers and fiber optic telemetry feedback to operators. Workstations were employed to handle injection timing chores, view waveform data for injected voltage, current, and power, and to monitor thermocouple data from armor and duct instrumentation.

The NBI system began preparations to operate in the summer of 2000 with scheduled injection in October 2000. The NBI system first injected during September of 2000, approximately one month ahead of schedule and slightly under budget.

Initial beam injection began with short pulses and reached 80 kV on all three sources in the first run period in 2000. The first experiments were to define orbit losses across the beam injection angles at various fields to ascertain physics performance or machine limitations. At sufficient plasma current and magnetic field strength the orbit losses for all three sources were acceptably low.

The NBI system reached 5 MW of available power in December 2000 during a conditioning run and first injected 5 MW into plasma in June 2001. The system has operated at 80 kilovolts on three sources unless desired otherwise for the full scheduled run period this past year with high reliability. Pulse lengths have varied from a few millisecond beam blips for diagnostics purposes to 400 millisecond heating pulses. Longer pulses have been used for conditioning into calorimeters. Recently, higher voltage pulses were desirable for NSTX diagnostics so the voltage was raised on two sources to 90 kilovolts after appropriate review. Finally, during a conditioning effort at the end of the 2001 run, the A, B, and C sources operated at 95, 100 and 95 kilovolts respectively, reaching a total available power of 7 MW.

The NSTX NBI upgrade has demonstrated its capability with high voltage, high power, and solid reliability. The NSTX NBI has shown extensive promise in heating spherical torus (ST) plasmas. Recent experiments have successfully blended RF heating and neutral beam heating on a ST device. Using NBI heating, NSTX has driven approximately 1.4 million Amperes of plasma current and has achieved a plasma Beta of 24 percent.

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