NSTX UPGRADE

Neutral Beam Injection System
System Design Description

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1. Overview of the NSTX Neutral Beam Injection System

Upon successful completion of the NBI Upgrade, a second Neutral Beam Injector (NBI) will be added to NSTX. The NSTX NBIS configuration will consist of two beamlines (BL) in a co-injecting arrangement in the NSTX Test Cell (NTC). Each beamline has three positive ion sources and associated components to form a neutral beam and to inject the neutral beam into NSTX plasmas in support of the experimental program. Each source can fire separately or in concert. The two BLs can be operated together or each separately. The NSTX BLs will be supported by the NB water, gas, and cryogenic subsystems, high and low voltage power supplies, and the locally operated control and monitoring system. An NBI roughing and backing vacuum system will be connected to the NTC vacuum exhaust stack. The NBIS will be capable of over 15 MW injected neutral power in support of NSTX experiments.

At present, the NSTX device uses one Neutral Beam Injection (NBI) beamline (BL) with three sources for NBI experiments injecting power up to 7.4 MW at 100 keV as requested into NSTX plasmas. Additional power has been available but so far has not been requested to support experiments. This beam injection has provided numerous benefits in heating, fuelling, and added rotation to NSTX plasmas, and has provided diagnostic information intrinsic to the operation of CHERS and MSE. The addition of a second NBI beamline will provide double the power, and additional fuelling, rotation, diagnostics data, and wider tangency radii aiming options.

The NBI system design is a TFTR era NB system chronicalled in IEEE SOFE journals and PPPL reports. The original NBI upgrade on NSTX is discussed in PPPL Report PPPL-3651 and bibliography. The system is capable of operation up to 120 keV for approximately 1 second and 80 keV for 5 seconds. This system operating level is represented by a curve which is primarily dictated by the full energy ion dump low cycle fatigue temperature limits. Additional pulse length would be available for a limited number of shots with appropriate review. At the service ceiling of 110 keV used to optimize power and full energy component of the beam, each source is capable of 3 MW of neutral injected power in deuterium. At 80 keV, each source is capable of about 1.75 MW but for longer durations.

The Long Pulse Ion Source used on NSTX is a legacy device from TFTR. The source consists of an arc chamber and an electrostatic accelerator mounted to a gimbaled exit flange. The source is enclosed in a pressurized SF6 enclosure. The source fires ions through the BL where about half the ions are neutralized and the other half are deflected by a bending magnet into the ion dump. The sources were once used for TFTR DT and as so have some residual contamination but each source is decontaminated as much as practicable and refurbished before use on NSTX. Thus, the contamination levels in the source and beamline while measureable have been very, very low. The NBIS will continue to reuse TFTR era Long Pulse Ion Sources and will be capable of operating a total six sources for NSTX.

In the source, heated tungsten filaments and an arc voltage create positive ions in a low energy plasma discharge formed in an arc chamber. Samarium-Cobalt magnets increase confinement. Langmuir probes and a mask defining the extraction aperture complete the arc chamber. The ions are accelerated from high voltage to ground through a four grid electrostatic accelerator assembly made of many planar, slotted grid apertures. The grids are made of Molybdenum thin wall water cooled tubes. The Accelerator uses an epoxy insulator structure. The source mounts to a gimbaled exit flange which also includes source scrapers for stray ion trajectories due to large divergences. The exit flange forms the seal for the source enclosure which houses an SF6 insulating gas environment for high voltage standoff during operation.

Accel & Gradient grids are used to focus the beam and a negative voltage suppressor (Decel) grid prevents electrons from backstreaming into the source arc chamber. This backstreaming effect can be large and can risk melting the source electron dump at the rear of the arc chamber so Decel must be maintained at 2-2.5% of the Accel operating voltage.

Gas for the beam is injected at the exit of the source (at the OMA box) where part flows back into the arc chamber to serve as the beam feedstock gas while the remainder flows forward to provide the neutralization charge exchange function in the neutralizer. Feedstock gas is then pumped away rapidly by the 8 cryogenic panels that line the walls of the BL.

The BL is a high vacuum enclosure containing individual neutralizers, magnets, and a calorimeter for each of the sources, and common full, half, and third energy dumps for unneutralized ions of the three sources. Water-cooled copper scrapers protect areas around the neutralizer, magnets, calorimeter, and ducts from excessive beam divergence. A separate system provides low conductivity cooling water for the bending magnets and the source arc chambers, grids, and exit scrapers. A single drift duct and isolation valve for each BL provides a vacuum interface with the torus. Vacuum valves also isolate each of the sources from the beamline, allowing individual service and repair.

In the BL, the unused source gas is pumped away by turbomolecular vacuum pumps and, at a higher rate during pulsing, by cryogenically cooled sets of panels lining the inside of the enclosure. The panels consist of a LN panel, a LHe panel, and interior LN chevrons through which deuterium passes. The LHe panels are held to near absolute zero so that source gas freezes and is bound to the panels. The liquid helium boils off and is returned to a compressor and a cold box to be made into a liquid again in a closed refrigeration cycle. Periodically, the helium panels are warmed up and regenerated to release the accumulation of frozen source gas.

The LN panels outboard of the helium panels are cooled by liquid nitrogen to absorb the thermal radiation load coming from the external walls of the beam box. The liquid nitrogen is purchased and stored in a large dewar at D-Site and the boil-off from the panels is released to the atmosphere.

Power supplies for the beamline and sources are located in the Neutral Beam Power Conversion Building (NBPC Bldg) adjacent to the NTC and TFTR Test Cell. Regulation and switching of the voltage for the source accelerator grid is controlled by a modulator/regulator (M/R). The M/R uses a High Voltage Switch Tube which is a power tetrode. The HVST also feeds the Gradient Grid Resistive Divider which supplies the Gradient Grid of the ion source.

The input for each modulator/regulator starts at the 13.8 KV 3 phase Power distribution level in the NB Switchyard. There a Disconnect switch and Fast Vacum Interruptor feed and protect an Autotransformer and a Transformer/Rectifier supplying up to 160 KV DC to the Surge Room.

The Accel DC power then passes through the surge room containing a cap bank and a high voltage crowbar that diverts stored energy in the power line away from the source during a fault. The Surge Room provides the anode voltage for the HVSTX. The anode voltage accelerates the electrons from the HVST electrons guns to switch and regulate Accel voltage. The M/R HVST cathode floats and is held at the desired voltage based on operator input.

The M/R contains the HVST and associated power and controls on the Accel deck, the isolation transformer for high voltage standoff from the Accel deck, an SF6 pump system for the HVST helmet and isolation transformer, and the Gradient Grid Voltage Resistive Divider. The Accel and Grad Grid voltages are connected to an output bushing and triax cable which carries Accel, GG, and Return to the HVE in the NTC.

The negative suppressor grid voltage is controlled by a Decel supply. This Decel supply uses a smaller power tetrode to switch and regulate up to 3 kV and 20 Amps for the suppressor grid in the source.

The beam bending magnets are powered from individual supplies in which the magnet currents are made to track source accelerator grid voltages so that the beams stay aimed at the dumps for all operating levels. The bending magnet power supplies are controlled at the LCC. The Bending Magnet Power Supply is rated for 1000 Amperes at 30 Volts.

The Filament and Arc Power Supplies have two distinct parts. The low voltage sections are at the NBPC 138’ level and are variable transfomres, contactors, and SCRs. The high voltage sections are enclosed in the High Voltage Enclosure HVE in the NSTX Test Cell. The HVE contains an isolation transformer and diode rectifiers as well as ion source protection equipment. It is within the HVE that the Fil and Arc power supplies on the secondary side of the isolation transformers are allowed to float with the accel potential. This tie point is the key to accelerating a positive ion toward a ground potential to initiate the ion beam. Though rated higher, the filament supply typically provides about 4 kA at 10 Volts. The Arc supply typically provides up to 1000 Amperes at 100 volts.

Control systems for the NB power system, water system, vacuum system, cryogenics system, gas system, beamline, interlocks, vacuum pumps, and helium refrigerator are carried forward and updated to current technology from the TFTR era and ten years operation on NSTX. The NB controls combine a Local Control Center, LabView, an Allen-Bradley based PLC system, and Hardwired Interlock System and computing to operate the NBIS for experiments. Typically, a Neutral Beam Operations Supervisor and two Operators as well as two Cryogenics Operators staff one shift. The controls will fold in the second BL such that the existing operating staff will be able to operate two beamlines.

The NBIS control and monitoring functions are implemented in a dedicated fiber optic linked Programmable Logic Controller (PLC) located at D-Site. The PLC also provides the critical interlocks between the beamlines and the power system. The NBIS also uses optical high-speed data links for visual display of waveforms and high-speed fault detection at D-Site.

2. Overview of the NSTXU NBI Upgrade

The NSTX NBI BL2 project has been divided into sections covering general requirements, NSTX Test Cell general arrangement and equipment relocations, the decontamination effort status and progress to reuse a TFTR BL, and the technical design work necessary to add the second beamline in the NTC, connect services, connect power and control, and provide an interconnecting duct and armor in the vacuum vessel.

The general requirements document GRD indicates the need for injected neutral power in keeping with the existing specifications and operating parameter space of the TFTR and NSTX Beam system. The aiming angles require tangency radii of 110, 120, and 130 cm for the new beamline. This requirement drove the need to make changes to the vacuum vessel and Bay K. This design accommodates these aiming angles.

The NSTX NBI 2nd Beamline Upgrade will add a second BL to the NSTX machine in a V arrangement. The existing BL, which resides in the Northeast (NE) corner of the NSTX Test Cell (NTC), would remain as presently aimed and situated. The additional BL would reside in the Northwest (NW) corner of the NTC and would be aimed at tangency radii more outboard than the first BL.

This upgrade requires the rearrangement of machine equipment and systems to clear the appropriate floorspace for the additional BL and its paraphernalia in the NW area of the NTC. This upgrade requires relocation of various diagnostics so the 2nd BL can make use of the Bay K port on the midplane of the device. This port has already been sized for NBI. Due to the more outboard aiming angles of the 2nd BL the port will require some in situ modifications.

The equipment relocations have been mapped to new locations as appropriate. The racks have been rearranged accordingly. Additional platforms have been added to improve space utilization. The TVPS control racks, the Gas Injection bottle racks, and the NBI racks will move to the NSTX Gallery North and East hallways.

In large part, the 2nd NBI upgrade scope tracks the original NBI upgrade installed on NSTX in 1999 and 2000. As noted, the original NBI upgrade is described in PPPL Report 3651, January 2002. This scope includes refurbishing three NBI power systems, one for each source, and installing the associated cabling to the NW location in the NTC, refurbishing three ion sources for operations, refurbishing a TFTR era BL, relocating it and supporting it in the NW area of the NTC, and commissioning it for operations. Auxiliary services will be upgraded to provide water, cryogenics, vacuum, pneumatic, and SF6 services.

A new interconnecting drift duct design and fabrication effort will be required to attach the 2^{nd} BL to the torus vacuum vessel. The beam portion of the design is much like the first, including a new bellows to account for bakeout expansion of the vessel; however, the larger tangency radii desired for the second beam will require modifications to the existing design of duct and port to clear outer legs and provide beam free aperture. Also, the Torus Vacuum Pumping System will be connected to the new duct and its TMPs will be underslung to fit into existing floor space. The existing armor design will be moved to center on Bay H. Armor tile modifications will be required in the NSTX vacuum vessel to accommodate the additional beam trajectory overlapping regions.

New scope required for this 2^{nd} BL upgrade also includes the decontamination of the TFTR era BL prior to refurbishment. The original beamline, which had been used as an ion source test stand, was selected for the first beam upgrade because it had not been used with tritium. The next beamline saw active service on TFTR during the TFTR DT campaign. These beams have been on continuous air purge to ameliorate tritium since TFTR was shutdown in 1997. This decon effort has taken place in the Test Cell where the TFTR BLs are stored. Techniques used during the very successful TFTR DT experimental campaign and the TFTR Decontamination and Decommissioning project have been used to remove as much residual tritium contamination as possible prior to use on NSTX. This effort has culminated in a successful Decon Peer Review which concluded that the BL is ready for reuse and will have minimal impact on NSTX operations in the future.

Existing infrastructure (stacks and elephant trunk stations) and existing HP coverage provides coverage for this decon effort and the decon of sources. This project makes full use of the existing staff. Additional stack and elephant trunk stations will be required in the NSTX Test Cell and South High Bay areas to allow work on components with minor residual contamination.

The existing BL has been operated to 7.4 MW at 100 kV but the original TFTR capability of 110 kV and 9 MW was retained in the original NSTX upgrade. This capability would also be retained for the second beamline, raising the total power available to heat plasmas to 18 MW injected which exceeds the GRD requirement of 15 MW.

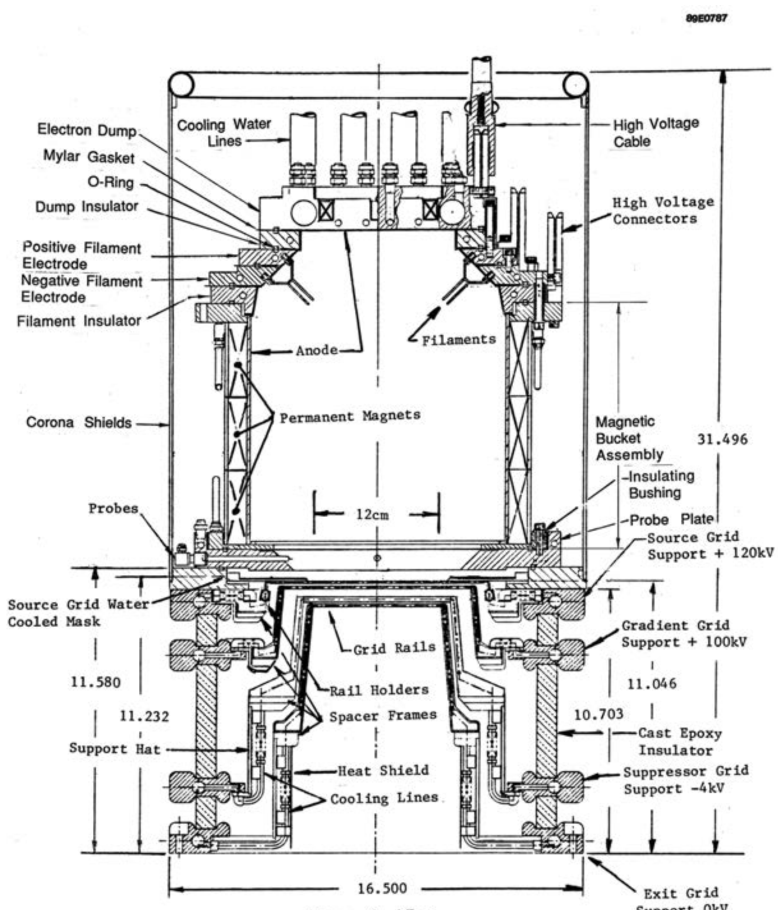
This upgrade reuses an extensive amount of NBI equipment that has been preserved as site credit, including the BL, power systems, legacy spare sources from TFTR, and fixtures and support equipment. The existing and operating cryogenics Helium refrigerator will also supply the second NBI by using fairly short piping runs and by making use of some spare capacity.

Further, the existing ion source refurbishment facility has been in operation for the life of TFTR and NSTX and would continue to provide sources as needed for both beamlines for future operations.

The Neutral Beam Injector Upgrade for NSTX reuses the technology of the Tokamak Fusion Test Reactor (TFTR) Neutral Beam Injector. The NBI Upgrade reuses spares and existing equipment where practicable. This upgrade includes the design, procurement, fabrication, assembly, installation, and construction activities associated with adding another three source neutral beam injector onto the NSTX machine in the NSTX Test Cell (NTC), located at D site, Princeton Plasma Physics Laboratory.

3. NBI Source

The NBI Source is comprised of multiple stages for filament, arc, bucket, mask, probes, and accelerator to form an ion beam. The Long Pulse Ion Source Assembly is shown in the figure below. The source materials are a combination of copper, nickel plated copper, molybdenum, and epoxy insulator structure. The source is water cooled using deionized water. The source sits in a Mu metal magnetic shielding structure inside a steel enclosure.



12CM X 43CM
LONG PULSE SOURCE ASSEMBLY

This source has demonstrated its performance on TFTR and TFTR DT from 1987 to 1997 and on ten years operating experience on NSTX from 2000 to the present. The source is rated for 120 keV, 70 Amps, 2 seconds, with a duty factor of .017. The full energy, half energy, and third energy components arise from the reduction of D2 covalent bonds to ions in the arc plasma.

The Long Pulse Ion Source uses 32 .060 inch filaments in parallel to produce electrons. The source is an emission limited design so reproducible filament temperature is paramount to reliable source operation. The previous generation of sources were space charge limited so the power supplies could be unregulated without much impact on source operation. However, in retrofitting the emission limited sources to these unregulated supplies the mismatch requires constant vigilance on the part of the operator to monitor and control the filament temperature and arc signature. Also, phaseback controls were introduced to allow operators to reduce filament heating at appropriate times during the pulse to compensate for heating done to the filaments by the arc and by the combination of arc ions and backstreaming electrons during beam.

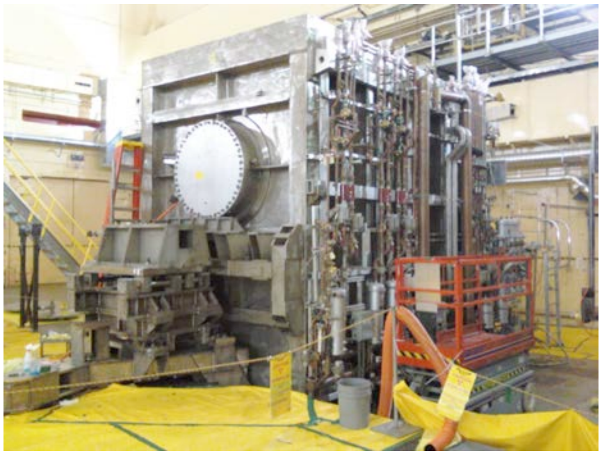
The ion source has an electron dump at the very rear plane of the arc chamber. The electron receives electrons accelerated back through the accelerator toward the positive voltage. The multiple layers of arc chamber plates are electrically insulated by mylar gasket materials and maintain vacuum by the use of compressed o-rings. The grid aperture lit by the arc is defined by a molybdenum mask. The mask defines the initial size of the beam extraction area to 12 x 43 cm oriented in the tall rectangle direction. The arc chamber also has a probe plate section where six Langmuir probes are mounted to detect and monitor arc density.

4. NBI Beamline

The Neutral Beam Injection System Beamline (BL) is a 50 m^3 stainless box capable of withstanding atmospheric loads with a lid weldment that supports cryogenics panels, deWars, manifolds, and the ion dump and calorimeter. At the back of the BL and aiming at the target, the sources mount to a cantilevered and supported source platform on the back of the box. The source connects to an antechamber called the Optical Multichannel Analyzer box. The OMA box was used for a spectrum analyzer on TFTR but this device is no longer active. The OMA box is used for gas injection which is mounted to the OMA box lid. The OMA box connects to the 90 inch flange which provides primary vacuum seal on the beam box proper.

The 90 inch flange has a spool piece and neutralizer for each source arranged in a 4 degree fan array to aim the sources at a focal point downstream of the BL. The sources and associated neutralizers aim through the bending magnet toward the calorimeter or through the NBI duct into the machine. The bending magnet deflects unneutralized ions upward into the ion dump. The ion dump has three parts: the full energy dump which is a 2 inch rounded backstop plate, a half energy dump which is the top plate, and a third energy dump which faces the full energy dump.

NBI Beamline Box, Lid, and components dismantled for decontamination and assessment

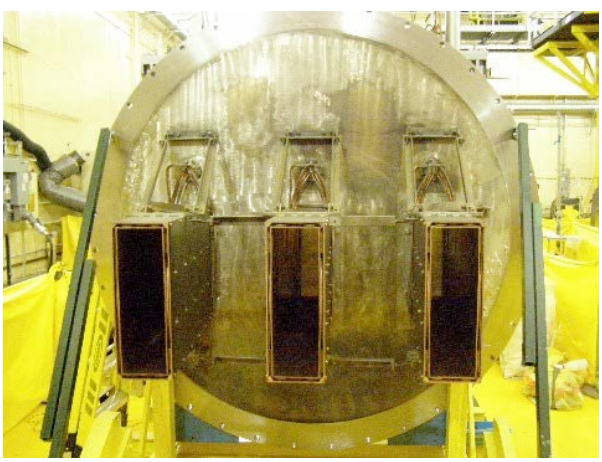


BL BOX

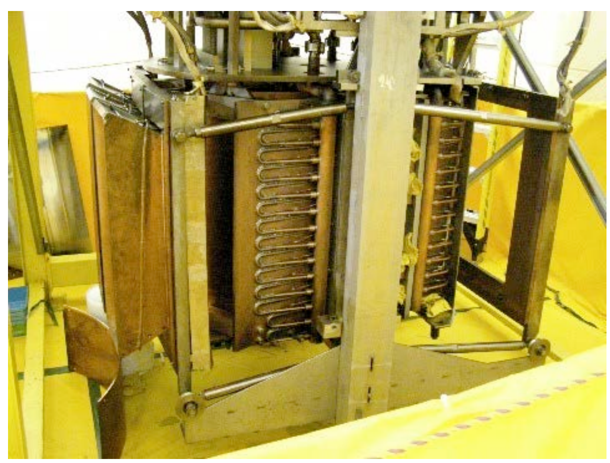
LID & CRYO PANELS

90 INCH FLANGE AND MAGNET

FULL ENERGY ION DUMP



NEUTRALIZERS



CALORIMETER

5. NSTX Neutral Beam BL2 Interface

Neutral Beam 2 Interface Overview:

The larger target tangency radii for the second neutral beam presented some unique challenges in designing a vacuum vessel port and accompanying beam duct to carry the beam into NSTX. The vacuum vessel was originally configured with a second neutral beam-sized rectangular port at identical tangency radii to the first at Bay K. Unfortunately, this port will not accommodate the wider angle required to meet the physics goal of providing neutral beam heating at 110, 120, and 130 centimeters tangency radii. The direct beam path passes through what is currently the edge of the nozzle/vessel joint (for comparison the original beam is centered at 60 centimeters radius). Additionally, in order to free up a diagnostic port on the machine and free floor space for the second neutral beam box the current Torus Vessel Pumping System (TVPS) was moved to a location under the new beam duct. The goals for the interface design were to solve the bay K geometry problem, to redesign TVPS, and to provide accommodations for the system to fit under the new beam duct.

Vacuum Vessel Modifications:

Structural Issues

Even after optimizing the incoming neutral beam angles, part of the beam still clipped the original nozzle opening, which required opening up the bay K port towards the 24" diagnostic port, bay J, adjacent to K. The result was a keyhole-shaped opening with a 1" strip of metal connecting the upper and lower regions of the vacuum vessel. An effort was made to stiffen this area using internal gussets; however, Ansys analysis showed the stress in the vessel metal was still unacceptable. Additionally, the modified ports were approximately 1" from the main beam footprint too close to survive un-shielded.

Vessel "Cap" Design

In order to satisfy both the problem physical proximity of the vessel to the beam and to provide additional structure, the vessel was extended radially outward around the Bay J-K area. This solution gave more physical separation between the J and K port openings, and the added frame around the opening helped to carry load around the area rather than through it (see figure 1). This configuration also moved the edges of the nozzle outside the expected area of significant neutral beam energy. Further analysis has shown that the additional structure provided from the cap, outweighs the loss of material from the cutout needed to install the cap. Before the vessel is cut additional temporary supports will be welded to the vessel base metal to minimize any stress-induced distortion during machining. Bay K diagnostics will need to be removed for the upgrade. Bay J's port cover and diagnostics will be removed and reinstalled in a new port relocated 4.88" further outboard with minimal impact to diagnostics. The Resistive Wall Mode (RWM) coil surrounding J and K will need to be removed and modified and reinstalled once the work on the cap is complete. The cap has been designed to maintain the vertical height and radius of the RWM coil.

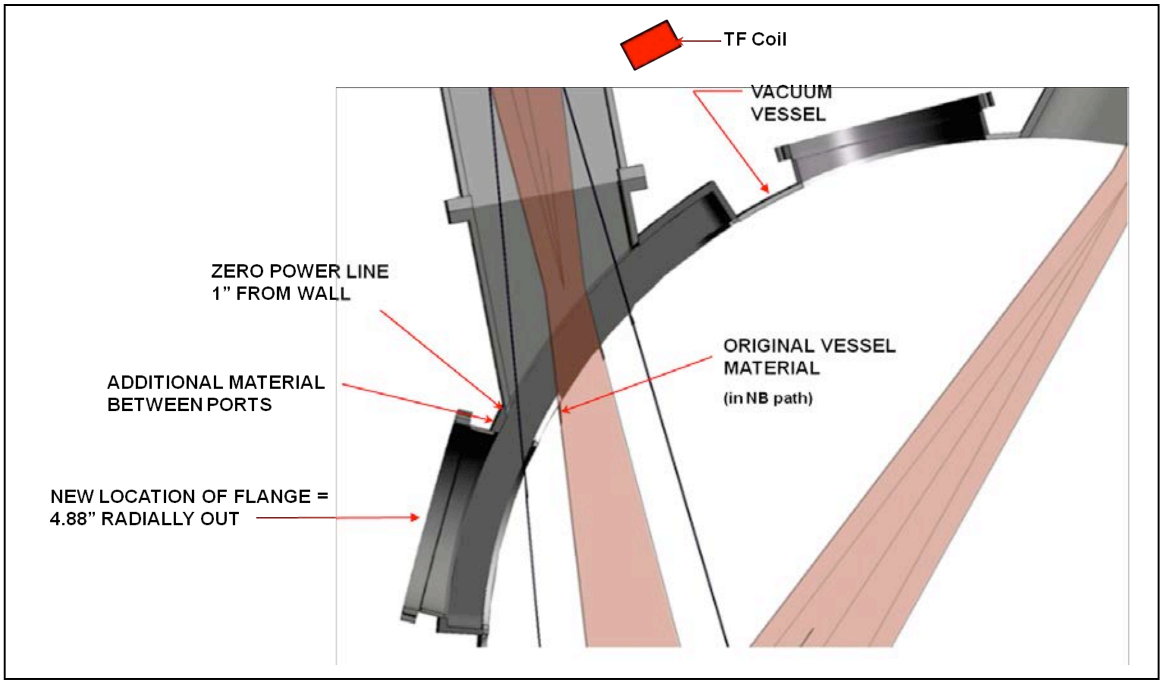


Figure 1: Vessel Cap with Current Vessel

Neutral Beam 2 Transition Duct

The transition duct has three primary functions: 1. Extend the NSTX vacuum vessel to the Neutral beam box, thereby providing a clear path for the neutral beam sources, 2. Provide vacuum, electrical, and mechanical isolation between vacuum vessel and beam line systems, and 3. Create provisions for connecting to a new TVPS system. The duct is split into two portions - a permanently bolted-on port extension for the vessel and a demountable transition duct adapting the 40" diameter neutral beam aperture down to a more conformal rectangular port to get through the Toroidal Field (TF) coils. The transition piece also mates to the TVPS ducts on the bottom of a 40" diameter spool piece.

Transition Duct

The transition duct begins at the exit of the neutral beam box with a new 40" VAT gate valve serving as the isolation valve separating the beam from the NSTX vacuum as needed. In front of this configuration is a set of 40" diameter welded bellows, collapsible to facilitate assembly and removal (see figure 2.). Next, is a large self-supported spool piece. This portion of the duct has two 14" O.D. down-comers that connect up to the TVPS turbo pumps. The face of the spool piece is capped off with a circular flange containing a ceramic break to electrically isolate the beam line from NSTX proper. This flange also starts the transition to a rectangular cross section for the beam. The final component in the transition duct is a large welded rectangular bellows. This set of bellows absorbs any relative motion of the NSTX and vacuum during bakeout. The design of the bellows is a duplicate of the bellows used successfully for 9 years on the first beam line duct. The final flange on the bellows mates up with its partner on the end of the port extension.

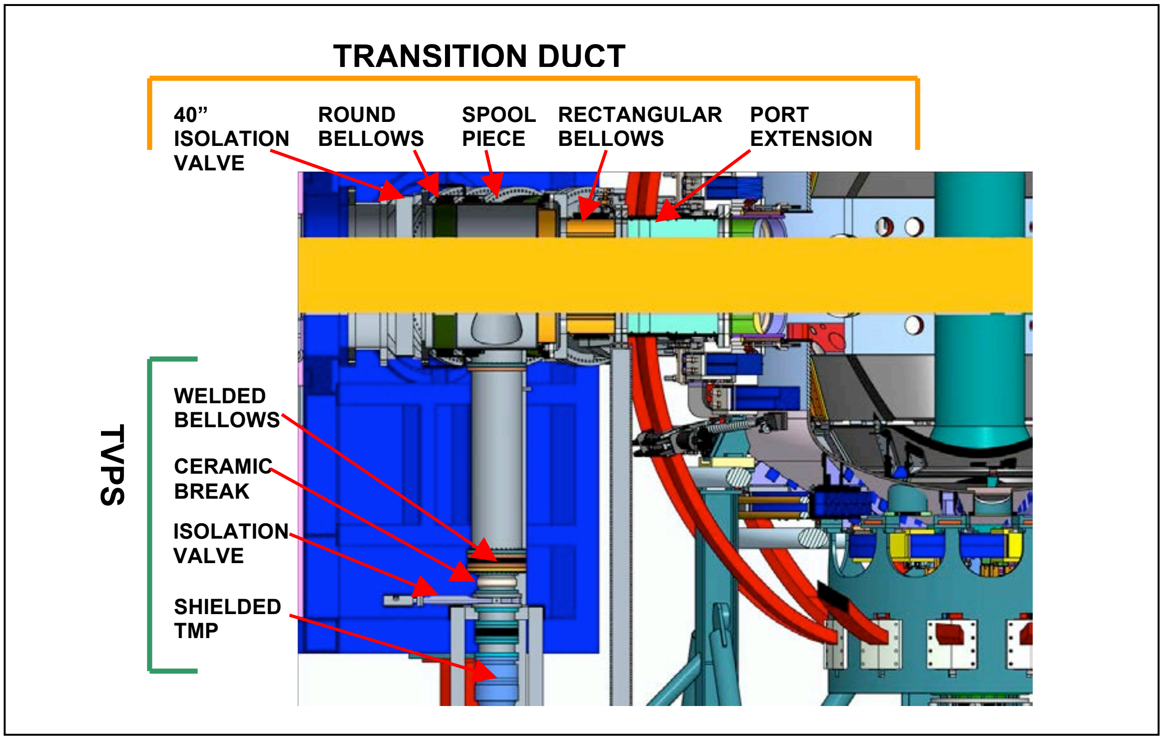


Figure 2: NB2 Transition duct and TVPS pumps below

Port Extension

The bolt up port extension adapts from a TFTR standard neutral beam flange down to a slightly narrower version that mates with the welded on J-K cap (see figure 2). The three neutral beam sources converge in this duct so it is possible to make it narrower than the sections further outboard. The port extension has a paneled, welded duct that conforms to a TF coil that is within 6" of the beam path, making the use of a bellows or flanges impossible in this region. In addition, the extension provides room for tangential diagnostic ports since it will be left in place durring maintenance and operations. Internally the duct will be protected from stray neural beam energy by molybdenum plate shielding were practical.

Torus Vessel Pumping System

The intent of relocating the pumping system was two-fold, to maintain independent torus pumping (without beam line pumping) and to free up mid-plane access for diagnostics. The current TVPS design is located at the end of a 17' long, 24" diameter drift duct that provides magnetic isolation to the turbomolecular pumps (TMP) near the far end. With the inclusion of a second neutral beam box and supporting equipment in the test cell, there was not adequate room to reuse this duct. The present solution has two vertical ducts, one for each turbo pump, under the spool piece of the transition duct. Each vertical duct has a welded bellows, ceramic break, and isolation valve for its associated pump, providing the necessary electric and mechanical isolation from the other beam systems (see figure 2). The current 1500 l/s TMPs will be replaced with larger pumps (about 2600 l/s) and the upgraded design will provide for a significant increase in effective pumping speed. Since the TMPs are being relocated closer to the vacuum vessel, magnetic shielding will be provided for the TMPs to reduce the field to less than 50 Gauss at the pumps.

6. Beam Relocation

The NSTX Upgrade Project requires the relocation of TFTR Neutral Beam 4, now called Neutral Beam 2, into the NSTX Test Cell. The ancillary equipment for this beam must also be moved to new locations. The current plan is to move all components through the door between TFTR Test Cell and the NSTX High Bay area. This will require the removal of the shielding lintels from the doorway and the construction of a steel plate road way. The beam box and lid (in stand) will be moved in separately on roller dollies and individually lifted over the south shielding wall. Clearances for this movement path have been verified and found adequate. Flanges and internal beam components will also be brought in separately and assembled on the beam box. The High Voltage Enclosures will be lifted out of the TFTR basement in sections, follow the same path as NB2, and be reassembled in the NSTX Test Cell.

7. Beam Services

The NSTX Upgrade Project requires additional services to be brought to the NB2 in the NSTX Test Cell. These services are High Voltage Enclosure Cooling Water, Ion Dump Cooling Water, Ion Source Cooling Water, SF6, Liquid Nitrogen, Liquid Helium, Vacuum Backing, and a Gas Injection System.

HVE cooling water will come from 3 existing pumping skids that will be refurbished. Pipe will be run from the skids, through the Pump Room and MER, and through penetrations in the Test Cell floor. (See: Green path in attached layouts.)

Ion Dump and Source cooling water will require new pumps to be purchased. Pipe will be run from the pumps, through the Pump Room and MER, and through penetrations in the Test Cell floor. (See: Red and Blue paths in attached layouts.)

SF6 piping will be teed from its current termination point in the Test Cell, over head to a new tap point centralized to NB2 and new HVEs. Valving will be utilized to maintain existing tap point. (See: Yellow path in attached layout.)

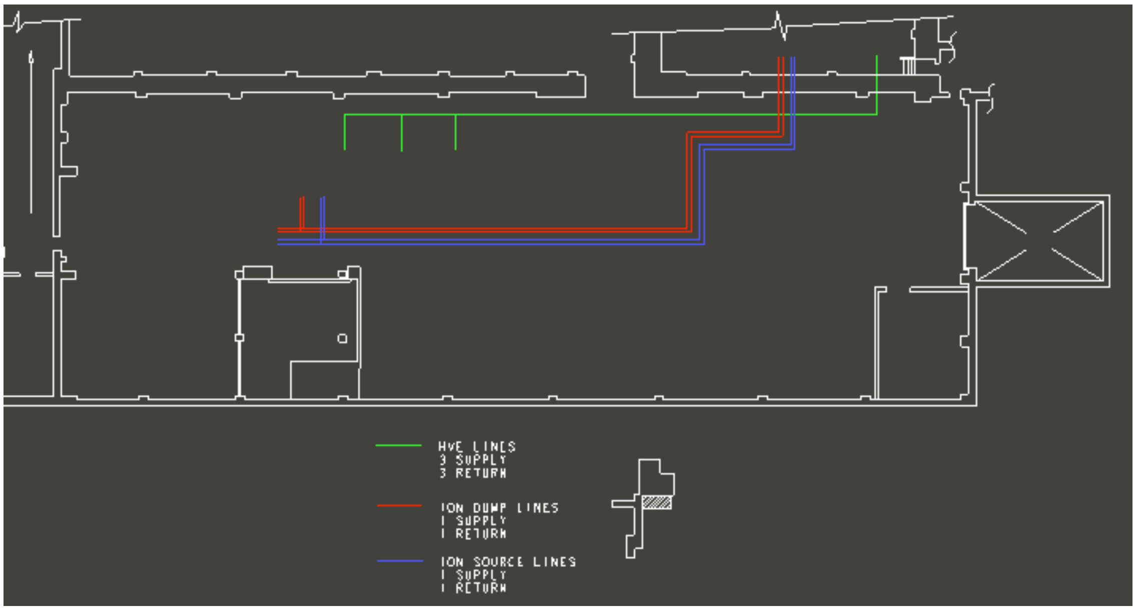
Liquid Nitrogen will be teed from existing piping and run around the north side of the test cell to the top of NB2. (See: Orange path in attached layout.)

Liquid Helium will be run down the Eastern wall of the TFTR Test Cell and penetrate into the NSTX Test Cell. This path was chosen to minimize heat loads on the system. A warm return line will be added to the South wall of the TFTR Test Cell, allowing for the continued use of the existing refrigeration system. One beam will be cooled then held while the other is cooled. (See: Blue, Green and, Pink paths in attached layout.)

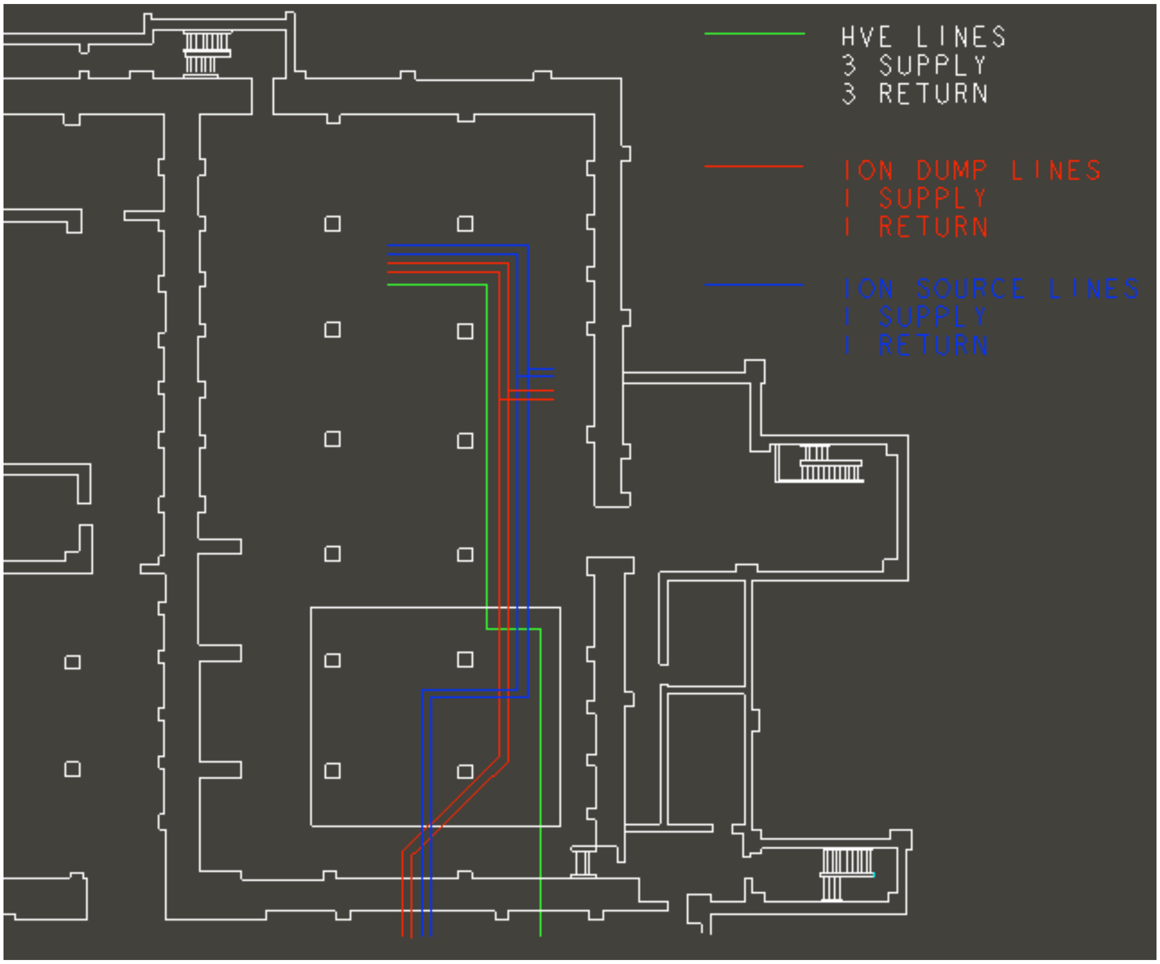
Vacuum Backing lines will be run from the turbo pumps to the existing backing pumps. (See: Purple path in attached layout.)

Gas Injection System will be moved from its current location to outside the North end of the NSTX Test Cell. (See: Dark Green path in attached layout.)

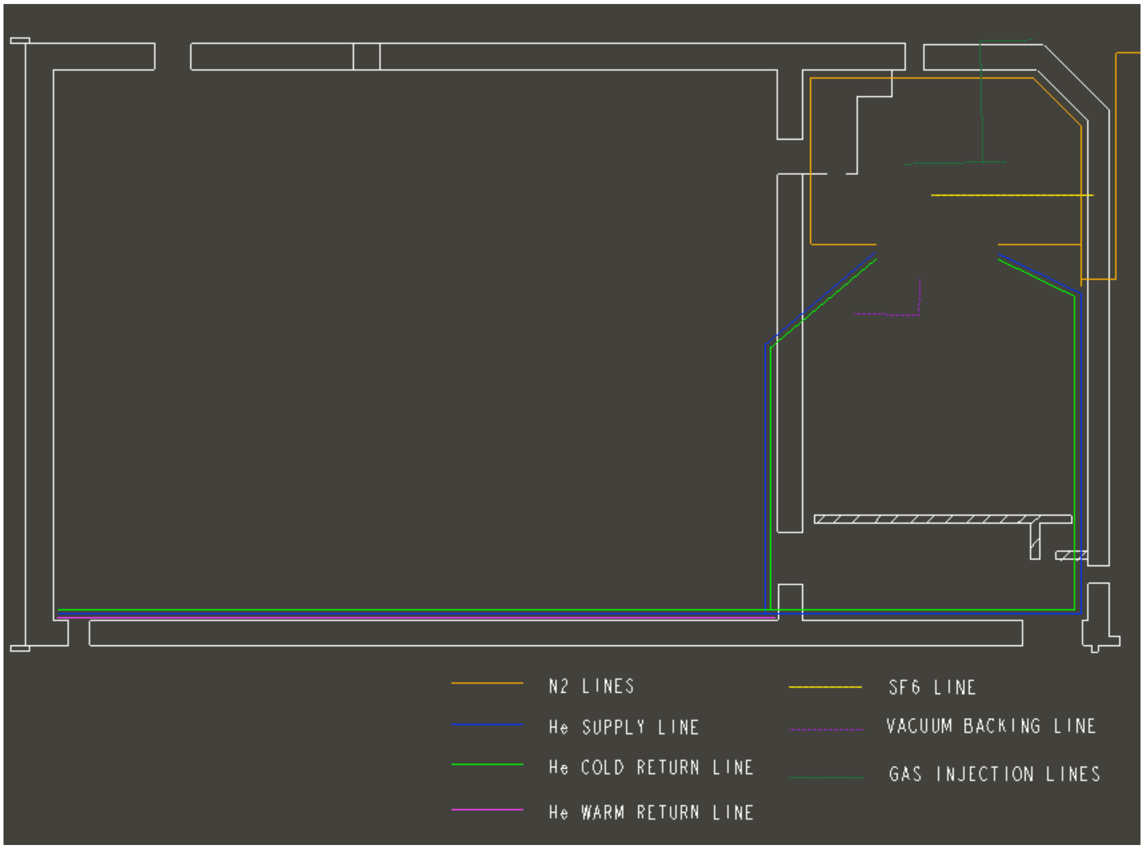
Walk-throughs have been completed for the piping runs of all systems and the routes are mapped. Heat and flow calculations have been performed for water systems and the pipes, pumps, and runs sized accordingly. Cryogenic heat loads have been minimized and found to be acceptable. All planned penetrations have been identified and locations have been approved.



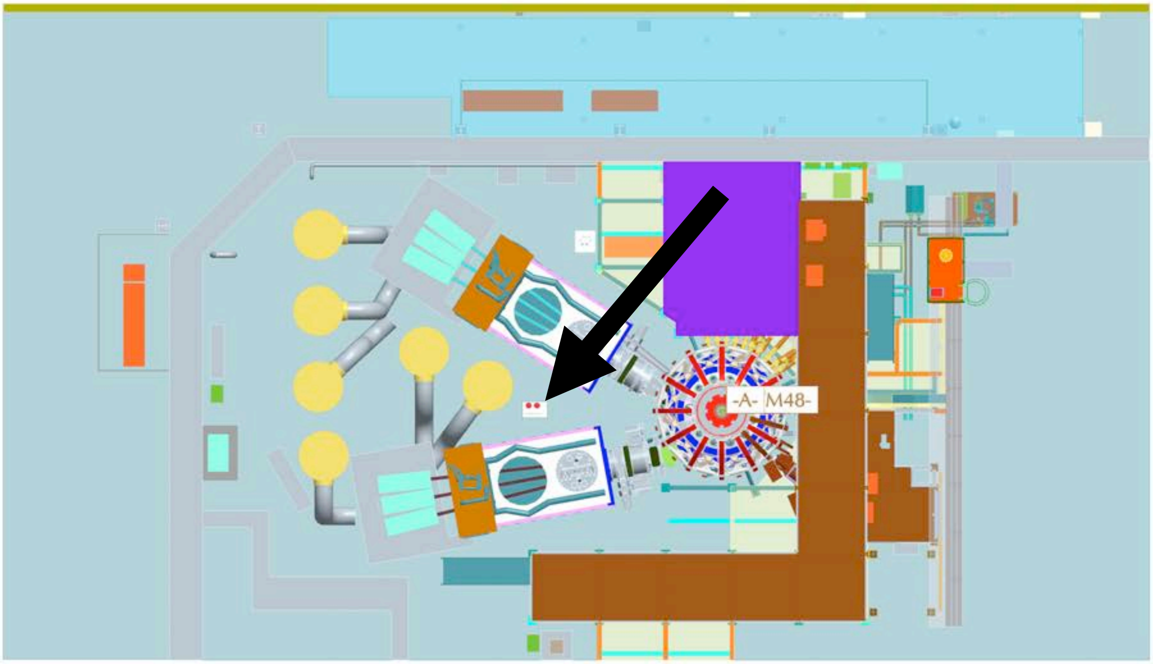
Pump Room



Mechanical Equipment Room



Test Cell



General Arrangement
(penetrations marked)

8. NSTX-U NBI In-Vessel Armor

The current plan for upgrading NSTX's NBI In-Vessel Armor is to reuse the existing armor design relocating it to catch all six sources, updating the materials of the carbon tiles and backing plates, and improving the armor's mounting system for accessibility and the certain increase in mechanical loading.

To establish a basis for comparison, we looked at the present, FDR-defined specifications for the NSTX armor. It was designed for a single beamline, three sources, with a worst case "Fault" condition of 2.8 kW/cm^2 for 0.75 seconds per source. Its thermal tiles are made of isothermal graphite or ATJ. After performing an initial thermal analysis using ALGOR, the consequent temperatures and thermally induced stresses were found to be 1985.07 deg C and 109.5 MPa, respectively. This defines an improbable set of conditions which, upon occurrence, would not destroy the armor, but would warrant physical inspection. With the upgraded armor, we sought to meet these same criteria.

To accommodate the addition of the second neutral beam line, the plan is to move the armor array counterclockwise in order to center all six sources on its surface. By shifting the armor, rather than extending it, more space for diagnostic access was preserved on the midplane. To verify this concept, three different aspects were examined: beam "footprint" fit on armor array, heat flux overlap, and the efficiency of between-shot cooling using the existing cooling system..

The spread of the source profiles or "footprints" is well-behaved, obeying an elliptical edge-divergence of about 0.5 degrees horizontally and 1.5 degrees vertically. This has been empirically confirmed by observation of armor striping on the present array. (Figure 1) This image shows the lack of white lithium deposition due to the high surface temperature of the tiles where they are being struck by neutral beam sources during aiming and MSE calibrations. Taking this dispersion behavior into account, all six sources were laid across the armor to confirm that they did indeed fit. (Figure 2)

Figure 1: NSTX Armor array showing beam striping due to neutral beam sources.

The beam profiles were split into two distinct areas: the core beam which represents the area with the highest power concentration (~80% of total source power), and the divergent beam which represents the area of high beam scatter, (~20% total source power). With the addition of the second beamline, areas of overlap were created on the armor (Figure 2), which creates larger power densities in those zones. Preliminary analyses of these zones or "hotspots" show that the max temperatures and surface stresses make ATJ an insufficient shielding material. We propose replacing the affected tiles with carbon-fiber composite, a material better equipped to handle the temperature and thermal stresses.

Additionally, we will provide a redundant plasma current interlock to further guard against the fault condition via engineering and administrative control. It should be noted that although the current plan is to design the armor to survive such a fault condition, if such an unlikely event would occur, physical inspection of the armor's integrity would still be required.

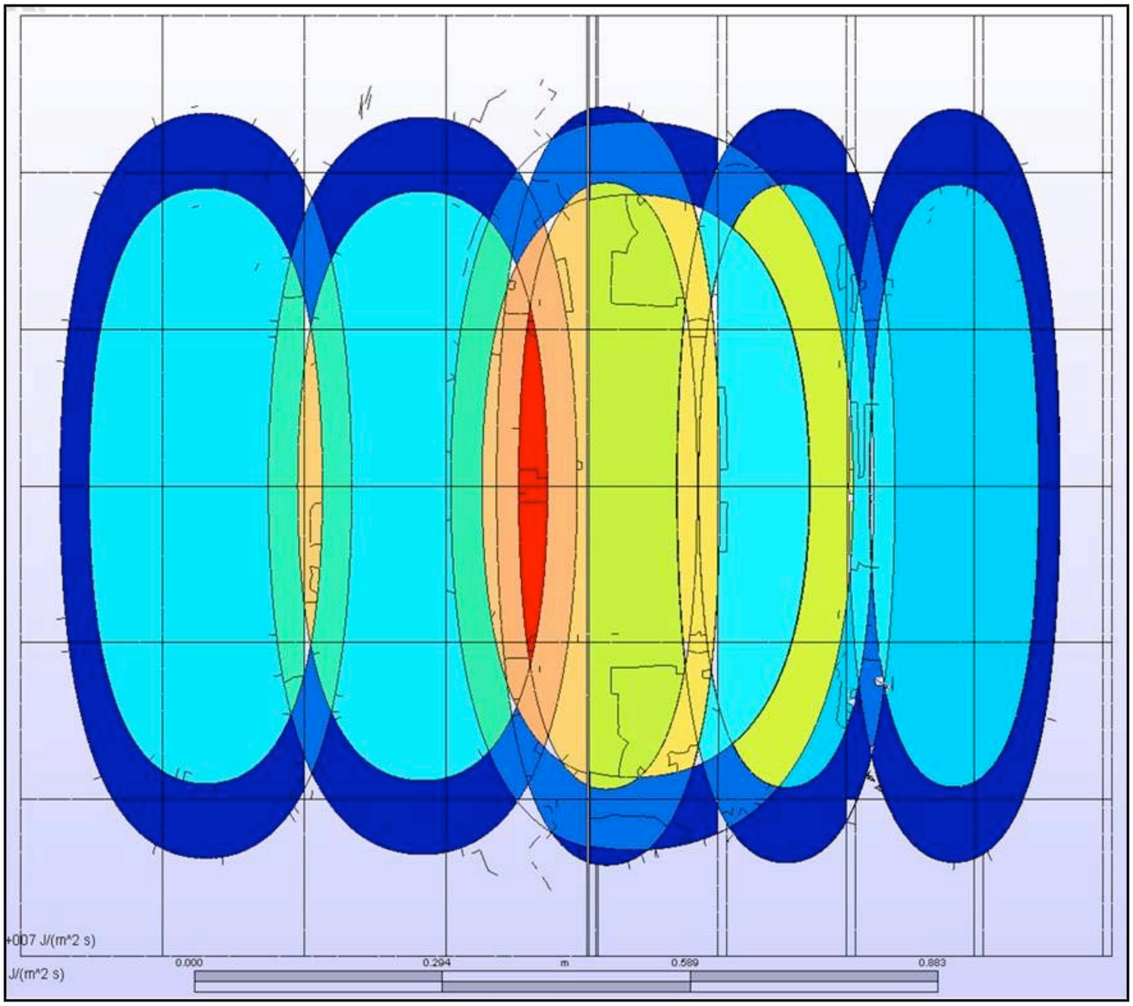


Figure 2: Overlapping beam profiles, showing placement and heat flux.

A preliminary thermal analysis was performed to confirm that the concept to reuse the present in-armor cooling system was viable. A simple, "back of the envelope" analysis with a slice of armor and backing plate, determined the time constant for cooling. Initial results produced a time constant of about 77s, which, since the between shot time for the upgrade was increased from 900s to 1200, suggests that the present cooling system is sufficient.

With the relocation of the armor, we have the opportunity of improving the existing armor design for accessibility as well as the increasing mechanical loads. After the move, the armor will be almost centered on bay H, allowing access to all of the center mounting points. However, as an added improvement, all of the side mounting points on the array can also be accessed via bays G and I. This modification makes installation and repairs much easier to accomplish as well as allowing room for an increase in fasteners, if needed.

In order to give an estimate of the increase in mechanical loads on the armor due to an increase in electromagnetic forces, we looked at the previous FDR specifications, which, for a 16 mount-point array, using a conservative steady-state analysis for disruption loading, produced a force of 13,375 lbs/mount (214,000 lbs total). If we assume that this number will double for the upgrade, we see an estimate of 26,750 lbs/mount, which is an acceptable load. Recent more detailed analysis indicates that the loads will be less than previously calculated.

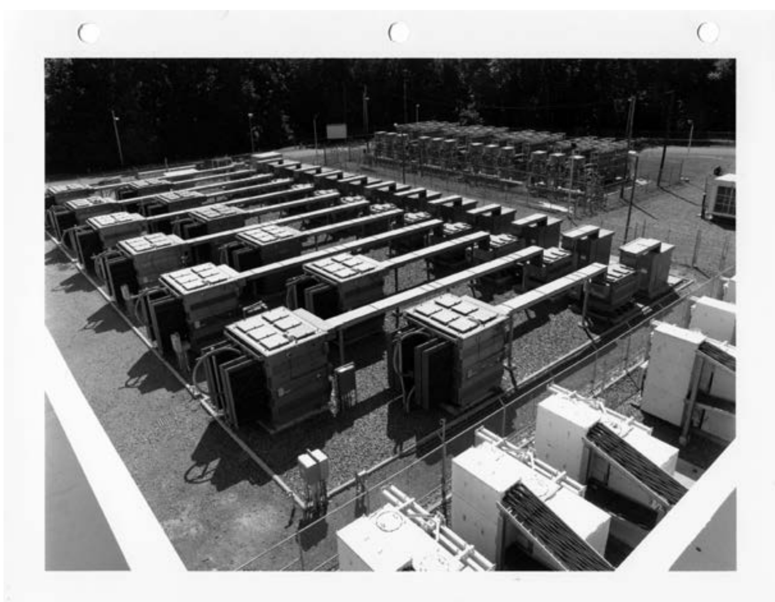
In conclusion, the plan to relocate and reuse the armor array to accommodate the second neutral beam line seems viable. We will make the needed materials improvements, such as changing thermal tile type to carbon-fiber composite and augmenting the backing plates with more material. We will provide increased engineering and administrative control by adding an additional plasma interlock to guard against the fault case. Upon completion of the cooling system analysis, we will verify its re-use for both beamlines and, once the mechanical loads due to electromagnetic fields are confirmed, we will be able to make the appropriate alterations in the mounting scheme.

9. NSTXU NBI BL2 Power and Controls - NBPS

The NBI Power System (NBPS) design for the NSTX upgrade beamline follows the same pattern as with the original existing BL and the TFTR NBPS. The Neutral Beam Ion Source requires power for filament, arc, accel grid, gradient grid, and decel grid, and for the BL bending magnet. The existing TFTR BL4 NBPS for sources AB&C are reusable in their entirety for the upgrade. Thus, three NBPS lineups will be reactivated and updated to the present status as with BL1.

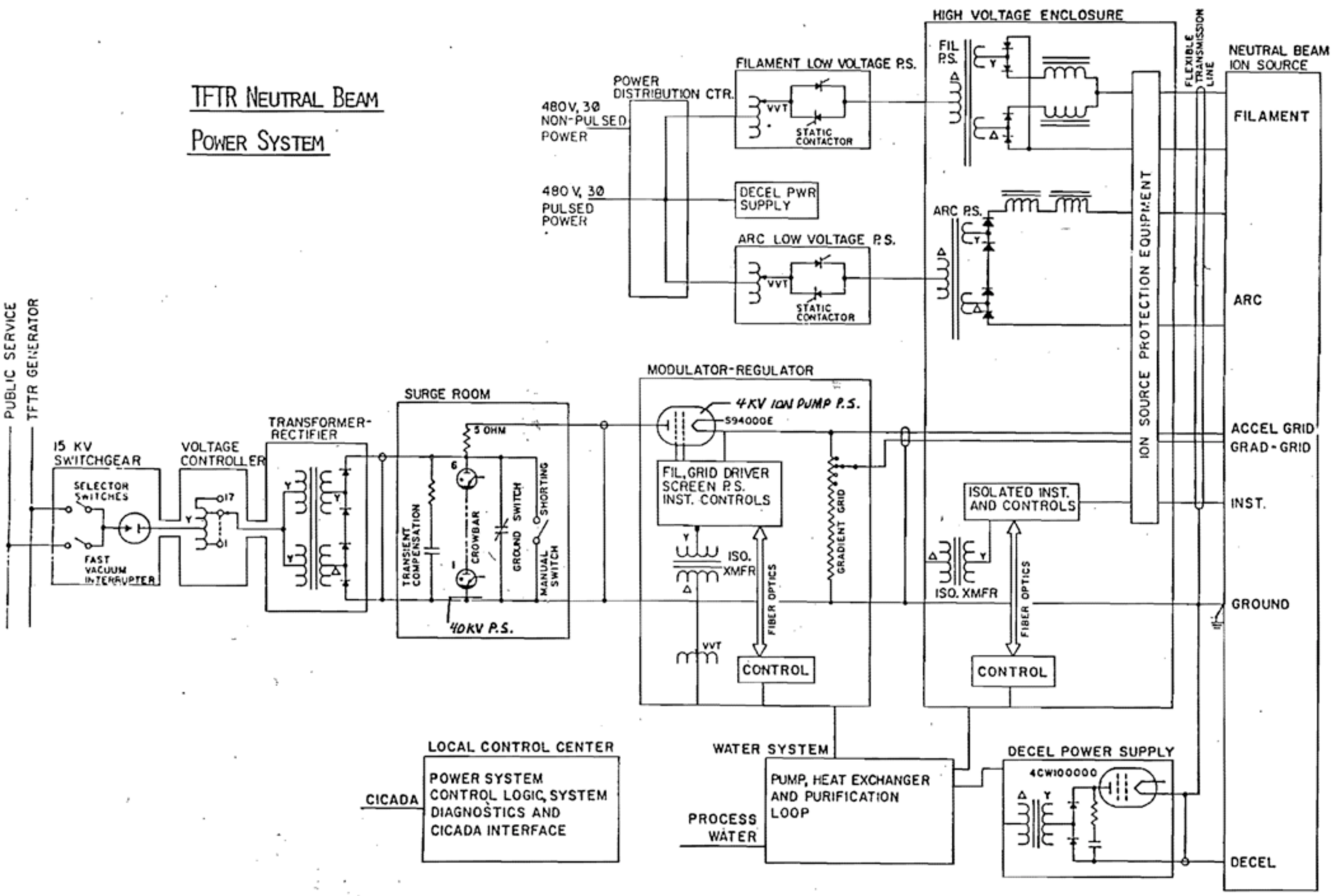
The high voltage Accel and Gradient Grid power require that the N4 ABC switchyard gear be reactivated. These systems are well maintained and available. The surge rooms and modulator/regulators are also available. The mod/reg uses a high voltage switch tube which is a power tetrode originally developed by RCA for TFTR. These tubes provide switching and regulation up to 120 kV and 70 Amperes. The gradient grid dividers will be updated to the present 25 k-ohm air cooled resistive divider design. Some on board electronics will be updated also. These systems feed high voltage to the source on an armored triax cable to the High Voltage Enclosures in the NTC which then communicate that voltage to the ion source via the Transmission Line. The triax cables will be new installations. The HVEs and transmission lines will be reused.

The low voltage arc and filament supplies have useable conductor runs to the TFTR Test Cell Basement. For the upgrade, a junction box will be provided. New conductors will be installed from the junction boxes to the HVEs in the NTC. New Decel and Bending Magnet cables will also be installed to the new BL.



NBPS Switchgear and Transformers

NSTX NBI NBPS One Line Diagram



The HVEs will be moved from Test Cell Basement. New triax cables will be installed from M/R to HVE in the NTC. The single point grounding system used for BL1 will be employed on BL2 also. The large elephant trunk transmission lines have been salvaged from TFTR and will be reused to connect the HVE to the source platform pressure plate connector. The power cabling is otherwise conventional conductors and sizes.

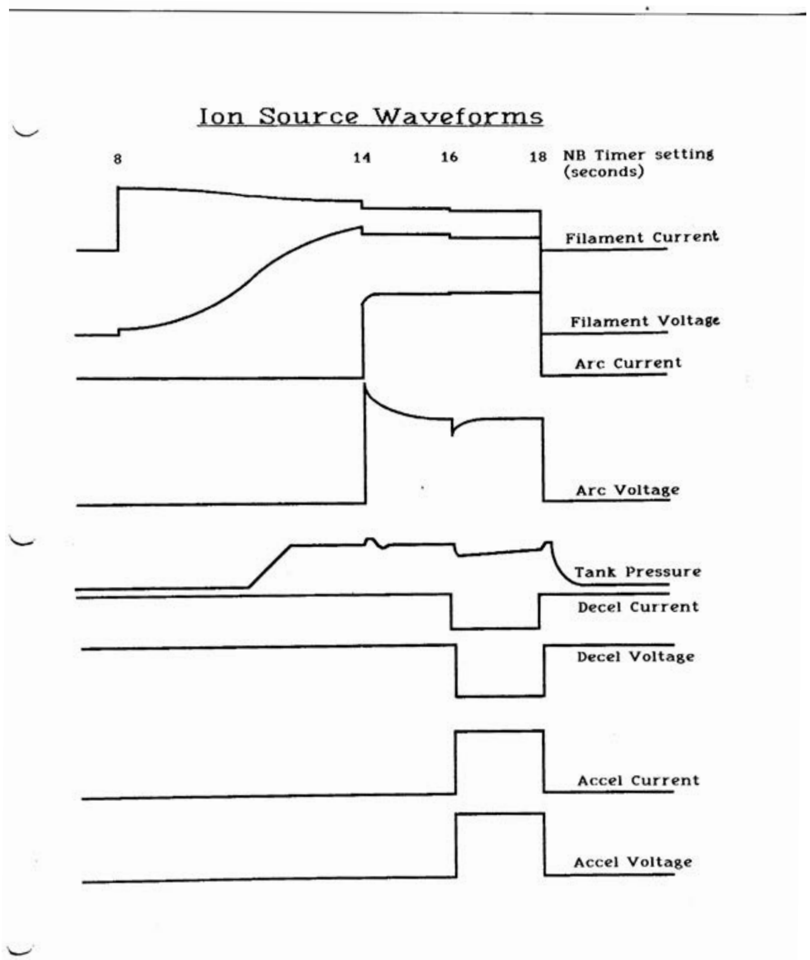
10. NSTXU NBI BL2 Power and Controls – Control System

The control system for the NSTX NBI system is an amalgam of several entities interconnected into a cohesive whole. The beamline, cryogenics plant, and mechanical services are monitored and controlled via an Allen Bradley PLC system and RSView user interface pages. These systems will be expanded using the same technology to include the second beamline. The existing PLC is capable of accommodating two beamlines.

The ion source operator manually controls the ion source at the Local Control Center by adjusting the NBPS settings for best performance and experimental requests. The NBPS is controlled via a local control center, fiber optic telemetry, a fault detector, and a timer. Additional monitoring, timing, interfaces are done through NSTX EPICS. Each of these systems will be mimicked and expanded to include BL2 in like fashion as BL1. Additional racks and fiber optics cables will be installed to connect the controls to the NTC and system. The NTC NBI racks are slated to move into the NTC East gallery. NB data returns to the MDS plus system data tree through CAMAC at present.

The Neutral Beam Operations Supervisor presently uses a LabView based monitoring and control system to supervise the sources and to control injection selection. This system will be expanded so that the existing NBI staff can operate both beamlines without additional operators.

In summary, the NBI power and control required for the second beamline follow the existing design quite closely. The N4 system will be reused to power the NBI BL2. The controls will mimic the existing design and will be expanded to accommodate the second beamline. The operations interface will be expanded so that the existing NBI staff can operate both beamlines without additional operators.



Typical source waveform signatures showing the nesting of filament, gas, arc, decel, and accel for beam formation. Operators monitor and adjust settings manually due to emission limited sources, unregulated filament and arc power supplies, high frequency parasitic oscillations from the HVST, and for adjustments made for experimental requests. Operators assess fault detection, trips, and other anomalies and make corrections between pulses.

List of NBI Controls to be reactivated, added, or expanded for BL2:

NBPS LCC
F/O Telemetry
NBI Fault Detector
BL PLC Control
Cryogenics Control
Gas Injection Control
BL RGA
BL Calorimeter Camera
Thermocouple Scanner System (BL2 and Armor)
NBOS/Operator Control (LabView)
CAMAC
EPICS Timing
EPICS Thermocouples
TVPS PLC Interlocks
Hardwired Interlock System
Plasma Disruption Monitor Ip & Redundant Ip interlocks
PCS Beta Feedback

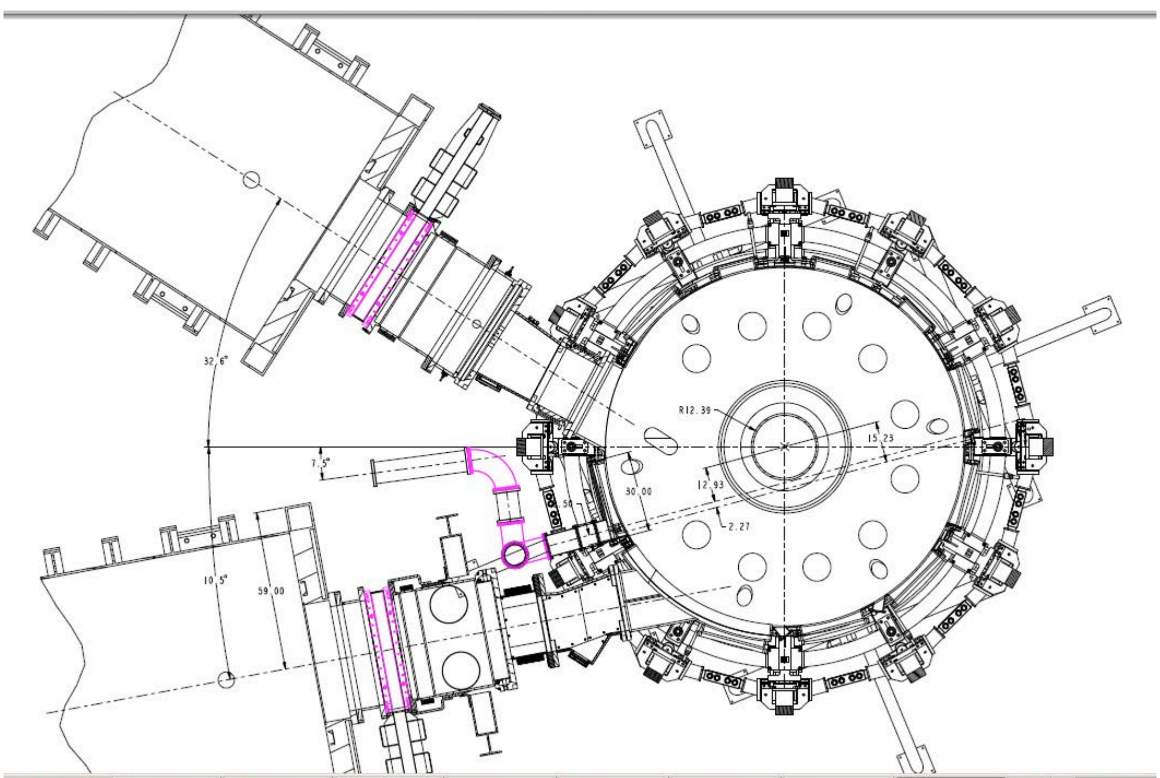
The NBIS is a mature technology with appropriate technical design basis to support the addition of a second BL on NSTX.

11. Equipment Relocations

The NSTX machine and NTC has been in use for 10 years supporting the NSTX experimental program. The area is well filled with experimental apparatus, diagnostics, and associated racks. The addition of BL2 will displace the equipment in the NW quadrant of the NTC. Siting BL2 at Bay K will rearrange diagnostics in place there. Moving the Armor will also shift diagnostics. Finally, due to the size of the BL the Bay L pump duct will be removed. A new pumpduct is planned beneath the NBI duct.

To accommodate the upgrade, a comprehensive list of diagnostics, hardware, and racks affected by the upgrade was prepared and reviewed by NSTX management. Additionally, effort was included to move some hardware and racks to the N and E Gallery outside the NTC. Further, platforms were added at the 118’ level elevation to increase usable floor space. The diagnostics accommodations fully meet program requirements.

Due to the increased Center Stack diameter the Multi-pulse Thomson Scattering system MPTS will require new views. With the loss of the Bay L pumpduct, MPTS also loses the location for its laser dump. A new Bay L port has been envisioned to provide a location for the MPTS view and laser dump. By enlarging the Bay L port, diagnostic space on the mid-plane is also regained. The MPTS plan view is shown below.



MPTS View across machine with new Center Stack diameter and enlarged Bay L port