NCSX

TO: **M. ZARNSTORFF**
FROM: **H. W. KUGEL**

SUBJECT: **NCSX PORT ACCESS REQUIREMENTS FOR NEUTRAL BEAM INJECTION SYSTEM, TORUS VACUUM PUMPING SYSTEM, FUELLING, GLOW DISCHARGE CLEANING, WALL CONDITIONING, AND CERTAIN MACHINE PHYSICS REQUIREMENTS.**

01-MAR-00-HK-01

Outline

1. Introduction

2. NBI System General Port Access Requirements

- **2.1 Optimum Aiming Angle (RTAN)**
- **2.2 Maximize Absorbed Power**
- **2.3 Maximize the Desired Injected Species**
- **2.4 Allow Far-Wall Armor to Absorb Beam Shine-thru**
- **2.5 Minimize Need for Beam Duct Conditioning**
- **2.6 Provide for NBI and Physics Diagnostics Requirements**
- **2.7 In-Vessel Constraints**
- **2.8 Ex-Vessel Constraints**

3. Overview of the Neutral Beam Injection System

4. ORNL Ion Source Qualification and Conditioning

5. Ion Source Focal Length, Focusing, and Power Density profiles

6. Maximizing Absorbed Power

7. Maximizing Desired Neutral Beam Species

8. Power transmission to the Far-Wall

9. Minimizing Duct Wall Conditioning

10. NBI Duct Design Optimization and Port Access Requirements

11. Torus Vacuum Pumping System Port Access Options

12. Port Access Requirements for Fuelling

12.1 Gas Puffing

12.2 Cryogenic Pellet Injection

12.3 Compact Toroid Injection

13. Port Access Requirements for HeGDC

14. Port Access Requirements for Wall Conditioning

14.1 Gaseous Boronization via HeGDC or Fuel Gas

14.2 Solid target Boronization

14.3 Lithiumization

15. Port Access for Other Machine Physics Requirements

15.1 Fast Neutral Pressure Gauges

15.2 Vessel and Internal Hardware Thermocouples

15.3 Plasma TV Views for Operators

15.4 IR Camera Views

16. Summary and Conclusions

16.1 Conclusions on Neutral Beam Injection System and Torus Vacuum Pumping System Port Access Requirements

16.2 Conclusions on Machine Physics Requirements

16.3 NBI Port Access Interferences

1. Introduction

The port access requirements for the Neutral Beam Injection Systems and Torus Vacuum Pumping Systems are usually approached as separate and independent design problems. The Neutral Beam Injection System port access requirements for NSCX are determined by Neutral Beam physics and engineering constraints. The Torus Vacuum Pumping System (TVPS) port access requirements are determined by the vacuum science and engineering constraints. This Report discusses synergies that accrue from combining the respective duct requirements of these systems. In addition, the port access requirements for Fuelling, Glow Discharge Cleaning, and Wall Conditioning and certain Machine Physics systems are discussed.

2. NBI System General Port Access Requirements

The Neutral Beam Injection System port access requirements for NSCX are determined by the following Neutral Beam physics and engineering constraints.

2.1 Optimum Aiming Angle (RTAN)

A suitable NBI port should allow a Neutral Beamline to be positioned at the optimum aiming angle. The aiming angle is specified by "RTAN", the radius of the circle (cm) centered at the origin of the Major (R = 0) and tangent to the beam axis. The optimum aiming angle is determined from complex simulation studies of power deposition, heating, profile control, beta, neutron yield, ion orbit effects, instabilities, and other issues of interest to the Experimental Program.

2.2 Maximize Absorbed Power

A suitable NBI port should allow maximizing the absorption of injected beam power over the desired plasma region. The absorbed power is determined by the beam focusing (perveance), the distance of the ion source from the deposition region, the aiming angle, and target plasma parameters.

2.3 Maximize the Desired Injected Species

A suitable NBI port should be located so as not to effect the injected beam particle species. Neutral Beam Ion Sources produce three ionic species [$H^+(E)$, $H^+(E/2)$, $H^+(E/3)$, or $D^+(E)$, $D^+(E/2)$, $D^+(E/3)$]. The Ion Source and Neutralizer, which are operated so as to maximize the full energy operation, determine the net neutral species fractions entering the Transition Duct [$H^0(E)$, $H^0(E/2)$, $H^0(E/3)$, or $D^0(E)$, $D^0(E/2)$, $D^0(E/3)$]. A port that requires a long, narrow, low conductance Transition Duct will cause changes in these fractions and beam broadening. These effects increase uncertainties in the simulation of beam power deposition in the target plasma region.

2.4 Allow Far-Wall Armor to Absorb Beam Shine-thru

A suitable NBI port is located so as to minimize beam power deposition on ports on the opposite wall. The port location should allow the mounting of Far-Wall Armor to absorb shine-through power and allow full-power, short-pulse beam injections in the absence of plasma for calibrations. Hence, Far-Wall Armor provides wall protection and functions as an instrumented NBI diagnostic (IR Camera viewable, thermocouples, and/or water calorimetry).

2.5 Minimize Need for Beam Duct Conditioning

A suitable NBI port location should allow the Transition Duct to be located far from the beam. A tight, low conductance Duct increases reionization of neutral particles by charge exchange interactions with background cold gas from the Ion Source and Neutralizer. The fringe magnetic field in the Duct region causes these reionized particles to impinge on the Duct walls and eject surface gas, which in turn causes more reionized power loss. Typically the first 3-5 daily NBI injections are short pulse for Duct conditioning. This was not done for initial DIII-D NBI operations, and it resulted in an injection with an estimated %90 reionized power loss some of which destroyed a nearby vessel window and vented the vessel. A suitable port location should allow for a spacious Duct design to minimize reionization losses, and also, a design that

allows the use of appropriate materials and techniques for minimizing Duct conditioning requirements.

2. 6 Provide for NBI and Physics Diagnostics Requirements

A suitable NBI port location should allow views of the Neutral Beam in the Duct region and as it enters the vessel. The Neutral Beam needs to be viewed in the Duct region for Reionization and wall condition monitoring, possible neutral species measurements, and Beam Emission Spectroscopy (BES) calibrations. The Neutral Beam needs to be viewed as it enters the vessel and transits the plasma edge for Charge Exchange Recombination Spectroscopy (CHERS) and other measurements.

2.7 In-Vessel Constraints

A suitable NBI port location should allow for RF Antenna positioning requirements and special Diagnostic location requirements. The requirements pertaining to the deposition of absorbed Beam power are addressed above. Usually this involves not aiming at a port but if this is not possible, it can also involve the width of the required Neutrals Beam Armor. Other constraints may pertain to toroidal location (e.g., plasma shape, Beam orbit loss deposition), and Diagnostic relationships (*e.g*., optical and IR views, the proximity to RF Antennas of Magnetic Diagnostics for control and MHD measurements, *etc*.).

2.8 Ex-Vessel Constraints

A suitable NBI port location should avoid interference issues with nearby Test Cell walls and platform diagnostic equipment.

3. Overview of the Neutral Beam Injection System

The requirements and constraints discussed above (Sec. 2) are both generic to NBI systems and derive from the particular design of the Neutral Beam Injection (NBI) system. The candidate NBI system for NCSX is the present PBX-M NBI system, consisting of 4 beamlines

and 1 spare Ion Source. PBX-M is the third embodiment of a Tokamak on which this heating system was used (PDX; 1979-1984, PBX; 1985-1986, PBX-M; 1987-1993). This NBI system was developed by the Joint PPPL/ORNL PDX 8 MW Neutral Beam Project (1978-1980). Each Ion Source was fabricated and tested by ORNL. Most of the beamline mechanical engineering design was performed at ORNL. The fabrication of beamline components was done at ORNL and by outside vendors. The beamlines were assembled and field engineered by PPPL. After installation, PPPL developed full computerization for the NBI system, including control of Filament, Arc, and Accel Conditioning, and Fault Response. One Operator monitors all four systems in a "hands-off" manner. The computer control has provided unforeseen benefits in reliability, reproducibility, and safety. This NBI system has injected 8.3 MW in the absence of fringe magnetic fields. In practice, the presence of fringe magnetic fields results in Neutral Beam power reionization losses which reduce the injected power by amounts related to the system geometry.

4. ORNL Ion Source Qualification and Conditioning

Each of present 4 operating Ion Sources was tested and conditioned with hydrogen to injected Neutral Beam powers of 1.5 MW using a fifth PDX beamline installed at ORNL ("ORNL Medium Energy Stand" now on loan to Madrid). One of these Ion Sources (# 3) was conditioned to 2 MW D^0 at ORNL. The fifth spare Ion Source has never been operated. ORNL Ion Source testing and conditioning work was described in ORNL Ion Source Conditioning and Operation Manuals, ORNL Reports and archival journal articles.

The ORNL Medium Energy Test Stand was configured with a PDX transition duct. The output of the transition duct was 440 cm from the ion grids (the focal length of the grids), and held a "torus target" consisting of a scanning calorimeter for absolute beam power density measurements in the horizontal plane at the entrance to the torus. A Swirl Tube calorimeter was positioned across the beamline ion dump for ion species measurements. At beam scrape surfaces were instrumented with calorimetery to provide full power accountability.

5. Ion Source Focal Length, Focusing, and Power Density Profiles

The Ion Source consists of 3 circular grids, 30 cm in diameter containing about 2000 circular holes for producing 2000 circular beamlets. The grids are shaped spherically concave to provide geometric focusing (aiming) with a focal length of 440 cm, the distance to the PDX torus port (Fig.1).

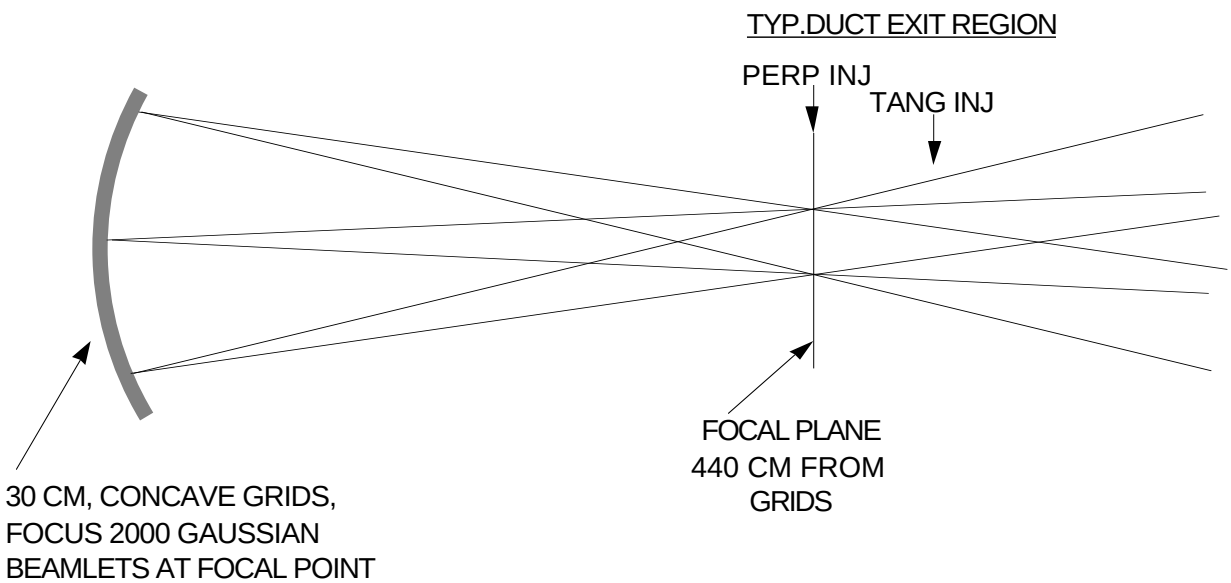

Fig.1. Schematic diagram of PBX-M Ion Source grid optics. The Ion Source grids are curved so as to focus 2000 gaussiam beamlets at Focal Point 440 cm from the grids. Ion Source Optics Determine Duct Size and Achievable Aiming Angles.

The required grid curvature was modeled by J. Whealton (ORNL) using a Gaussian geometric optics code. Measurements of the respective as-built focal lengths and focusing were performed using a pinhole camera technique and power density profile measurements at the focal plane torus target. The final measured focal lengths were consistent with the design value of 440 cm. Table 1 gives the H^o angular divergences for each neutral beam at the torus target horizontal focal plane (440 cm). The results shown in Table 1 were obtained from measurements of the respective beam power density profiles measured along the horizontal axis in the focal plane at the torus target using a scanning water calorimeter behind pin-hole apertures (Fig.1). The semi-log plots exhibit Gaussian behavior down to about 10% of full power. Below the 10% power level, the profiles

exhibit "wings" that have been characterized by asymmetric Gaussian, or polynomial least-squares fitting.

NBI System [a)]	$q_{HW@HM}$ [b)]	$W_{HW@HM}$ [c)]	$q_{HW@1/e}$ [d)]	$W_{HW@1/e}$ [e)]
S	1.5°	11.58 cm	1.8°	13.9 cm
E	1.13°	8.75 cm	1.36°	10.5 cm
NW	1.2°	9.25 cm	1.44°	11.1 cm
SW	0.94°	7.25 cm	1.13°	8.7 cm

Table 1. Summary of NBI Optics. Ion Source optics effect port location requirements.

Notes

a) NBI System listed in order of Ion Source fabrication and testing at ORNL.

b) Angular Divergence from centerline to edge at one-half of full power.

c) Angular Divergence from centerline to edge at 1/e of full power.

d) Beam Half-width from centerline to edge at one-half of full power.

e) Beam Half-width from centerline to edge at 1/e of Full Power.

NCSX NBI access requirements depend on the desired injected power, which in turn depends on the effective focal length, focusing, and steering of the output neutral beam. These factors are essentially significant considerations in the design of long, tight, transition ducts for tangentially injecting beams. Preliminary NCSX neutral beam configurations and transition duct designs should use the above results. However, the results shown in Table 1 and Fig.2 were measured at ORNL

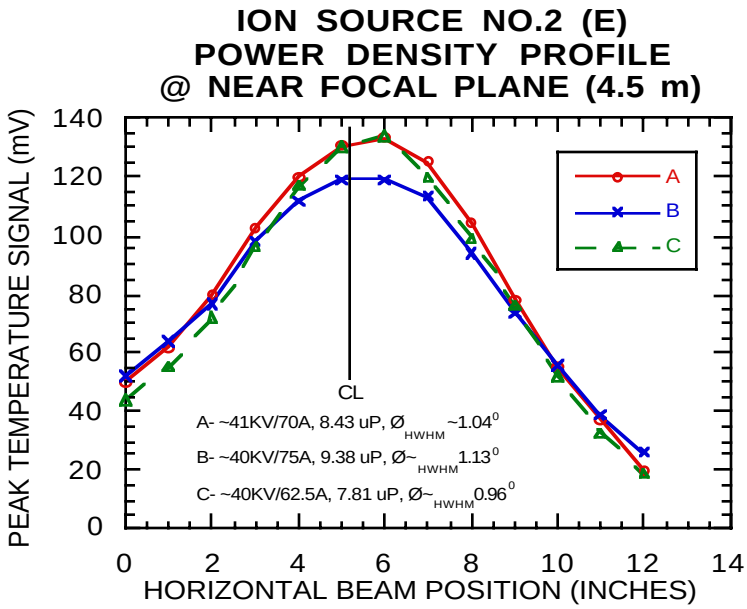

Fig.2. Power Density Profile measured at ORNL for PDX ion Source No.2 (East NBI). Note that the resultant beam trajectory at the Tourus Target attend of the Transition Duct is not entirely determined by simple, *apriori* mechanical alignment of the Ion Source. Measuring the actual bean position in the Duct is important for proper beam alignment.

in 1978-1979 and ought to be the measured. The present beamlines do not have diagnostics for measuring power density profiles. Previous plans to mount an array of thermocouples on the calorimeters, or to install insertable scanning water calorimeters in the transition ducts were never funded. The Ion Source grids were fabricated in 1978-1979 from copper which has probably become fully annealed due to extensive usage. This suggests that NCSX should consider installing instrumentation for measuring beam power density profiles. This would allow determining the extent of possible the grid curvature changes, and therefore focal length, focusing, and possible asymmetric steering since fabrication. Using such measurements, it would be possible to reshape grids, as required, or possibly each grid for improved focusing.

Fig.3 shows the simulated beam power density profile along the beam axis using the J. Whealton (ORNL) Gaussian geometric optics code and the measurements given in Table 1.

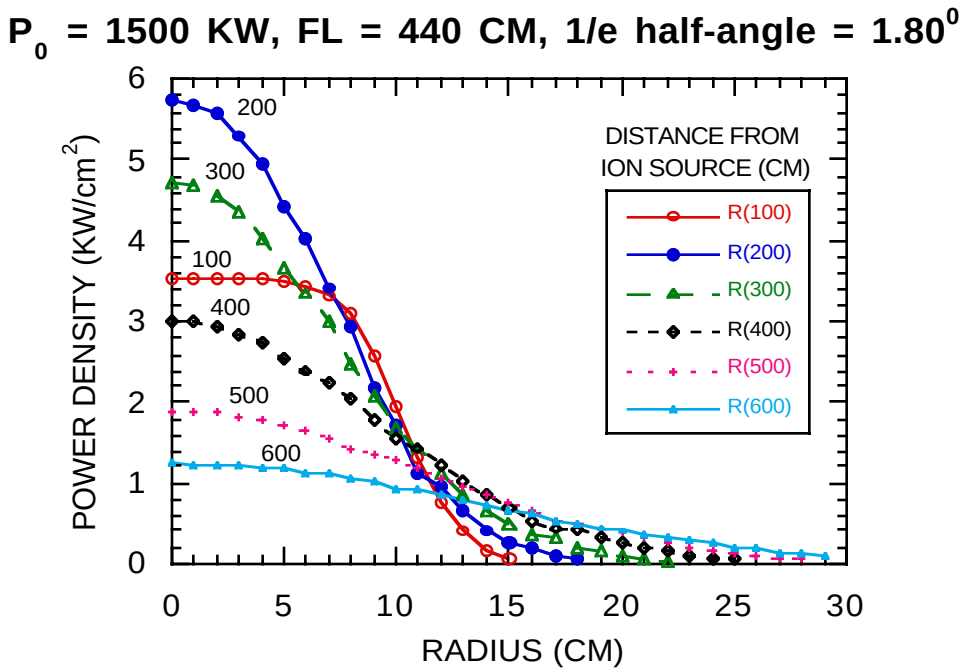

Fig.3. Simulated power density along beam axis. The beam port location should allow adequate Duct width to avoid neutral and reionized power impingement on the Duct walls.

6. Maximizing Absorbed Power

Injected Neutral Beam power is maximized by reducing system gas pressure in the Transition Duct which causes reionization and loss of neutral particles. The deflection of reionized beam particles into the Duct walls by the fringe magnetic field causes additional gas

• **PBX-M Injected Power Capability** • **ORNL Qualification (No Fields)** $H^0 \rightarrow$ = 6 MW (4 x 1.5 MW) $D^0 \rightarrow$ = 8 MW (2 x 2.0 MW) • **PDX Testing (No Fields)** $D^0 \rightarrow$ 8.3 MW (4 NBI @ > 52 KV)
• **Neutral Power Reionization Loss Fractions in PBX-M Due to Duct Neutral Gas (~1-4x10^{-4} T)** • Perpendicular Ducts $\rightarrow$ 0.88 P_0 (12% loss) • Tangential Ducts $\rightarrow$ 0.83P_0 (17% loss)

Table 2. NBI Power Capability and Reionization Losses.

load from out-gassing and an avalanching of reionized power loss. Reduction of Transition Duct neutral gas pressure to the ~10^{-5} T regime significantly increases injected power. This can be accomplished by optimizing the Duct design and installing additional cryopumping in the front box of the beamline.

7. Maximizing Desired Neutral Beam Species

Typically, Neutral Beamlines are operated with the neutralizer cell at ~90-95% equilibrium gas pressure to optimize the yield of the full energy component. The additional gas target through the Transition Duct for different port access geometries can change the fractional ionic yield of the low energy components and produce small differences in the species ratios of injected beam. Small reductions in the percentage of the full energy component have been measured at the edges of beams in a narrow duct.

- **Species Measurements**

  H^0 @40 keV

  (ORNL, using ion dump yields)

  - $H^0(E):H^0(E/2):H^0(E/3) = 63:20:17$
  - $P^0(E):P^0(E/2):P^0(E/3) = 80:13:7$

  D^0 @ 47 keV,100 ms, 1.6 MW

  (PDX using RBS on injected neutrals)

  - $D^0(E):D^0(E/2):D^0(E/3) = 53:32:15$
  - $P^0(E):P^0(E/2):P^0(E/3) = 72:21:7$

Table 3. Species Measurements for H^0 and D^0 Using Different Methods.

High Duct pressure may change the species ratios measured upstream in the beamline and broadens the beam power profile. Direct species measurements of the output Neutral Beam reduce uncertainties in the analysis of experiments.

8. Power Transmission to the Far-Wall

Neutral Beam power transmission to the far-wall of the vessel ("shine-through") often requires at minimum sufficient armor to absorb a short full power pulse. This armor is usually designed to absorb at least a short full power pulse so as allow power and position calibration injections in the absence of plasma. Sometimes this armor is used to absorb short NBI conditioning pulses between discharges if the beamline calorimeter is not used. If far-wall armor cannot be installed, then suitable interlocks must be capable of stopping beam injection if sufficient plasma is not present. A useful formula for calculating the approximate fraction of beam that will "shine-through" a PDX plasma (R. Goldston) is:

H^0: 50 keV/nucleon $\sigma_{tot} \sim 3.4 \times 10^{-16}\ cm^{-2}$

$$\text{Shine-thru} = \exp(-n_e \bullet 90 \bullet 3.4 \times 10^{-16})$$

$$= \exp(-n_e / 10^{13} \bullet 0.31)$$

D^0: 25 keV/nucleon $\sigma_{tot} \sim 7.4 \times 10^{-16}\ cm^{-2}$

$$\text{Shine-thru} = \exp(-n_e / 10^{13} \bullet 0.67)$$

Fig.4 shows a plot of transmission through PDX plasmas *versus* density for H^0 and D^0 at 40 and 50 keV.

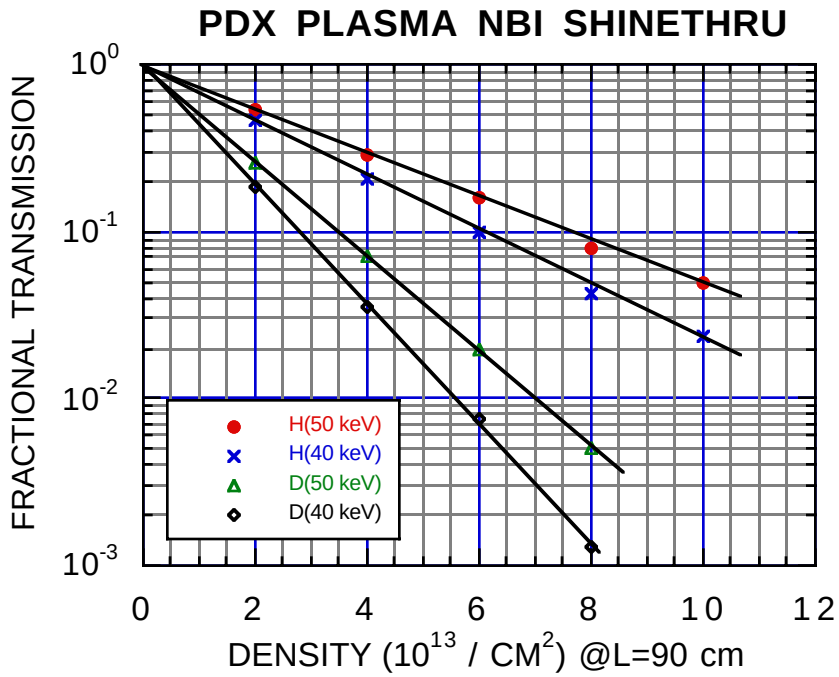

Fig.4. Plot of Neutral Beam power fractional transmission through a 90 cm thick PDX plasma *versus* density. This corresponds to the case of near-perpendicular injection (RTAN = 35 cm).

9. Minimizing Duct Wall Conditioning

Gas absorbed on and in Duct walls is released (outgasses) under particle bombardment and heating. The reduction of Duct outgassing by conditioning increases injected power and provides more reproducible results. Fig.4 shows the measured PDX East NBI system Duct outgassing versus the cumulative power absorbed over several months. It is seen in Fig.5 that, initially at the beginning of 1-2 week Run, the Duct outgassing was high but decreased steadily during the Run. Interruption of the Run for Maintenance resulted in the return of high outgassing rates due to fresh gas adsorbed on Duct walls from the vessel, and volume diffusion of fresh gas to the surface of the Duct walls to replenish the outgassed surface region.

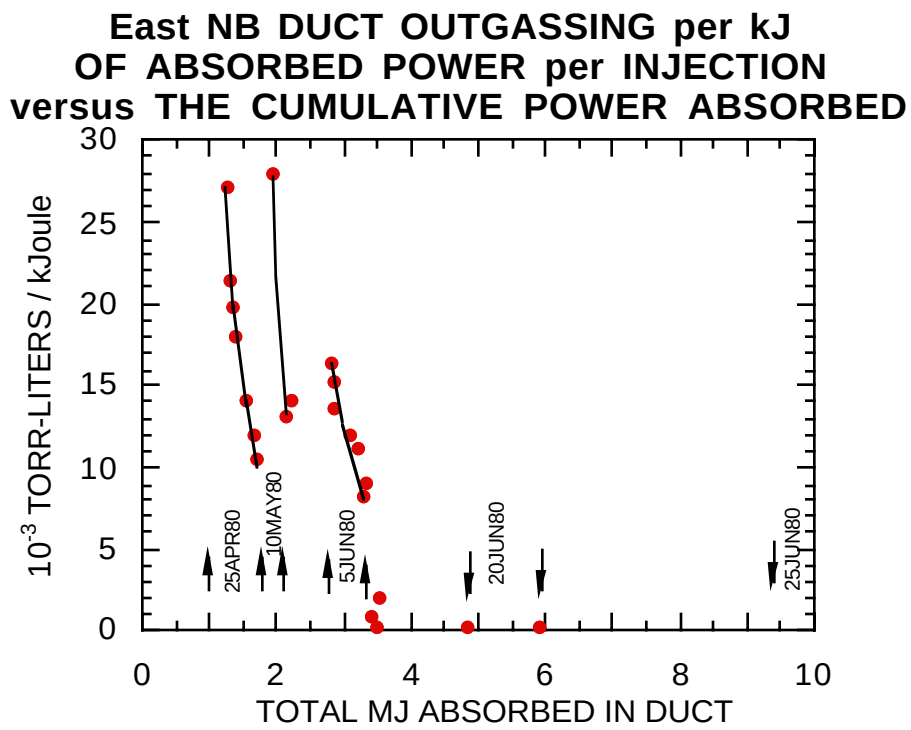

Fig.5. Measured Duct outgassing during several months of operation. H_2GDC was used to clean the vessel immediately after Pump-down from a vent. No H_2GDC or other GDC was applied thereafter. The application of HeGDC in the Transition Duct prior to NCSX daily operations and between discharges would reduce Duct conditioning time significantly.

Duct outgassing can be reduced by high conductance geometry, with walls far from the beam, appropriate materials, baking, and HeGDC between discharges. The effects of Duct outgassing can be reduced or eliminated with high-speed cryopumping at the entrance to the Duct.

10. NBI Duct Design Optimization and Port Access Requirements

The NBI port access requirements discussed above can be summarized by reference to Fig. 6, which shows a schematic diagram of the principal elements of a high conductance NBI Transition Duct. The beam, after passing through the beamline Torus Interface Valve (TIV), enters a rectangular section which is usually connected to a cylindrical section attached to the vessel. In the case of PBX-M, reionized power loss due to residual process gas in the Duct is steered to the Duct side wall by the predominantly vertical fringe field at the entrance to the Duct, and eventually to the top of the Duct by the predominantly horizontal fringe field at the

vessel entrance. The Duct has a least one ceramic break providing 5 KV isolation and a bellows at the vessel to decouple vessel motion during operation and bakeout. The bellows is usually shielded with a metal sheet fastened to the vessel and floating on the beam side. Diagnostic ports are provided to provide viewing of the beam in the Duct for NBI and plasma related measurements (e.g., BES calibrations).

Optimization of the Duct design consists in maximizing the width W, the height H, and the diameter D, while minimizing lengths Lr and Lc. The use of electropolished 304-SS reduces the ratio of the atomic-to-geometric surface areas of the walls, which reduces outgassing. If possible, the use of rectangular ceramic break and a rectangular bellows to maximizes vacuum pumping conductance. If all vacuum seals are bakeable to 150°C, it is possible to implement 150°C bakeout capability, and possibly, to operate with the Duct walls at 150°C. There should be a port for a Duct ion gauge to monitor reioned power losses, and other diagnostic ports with spool pieces so as to avoid the direct impingement of reionized power on port flanges.

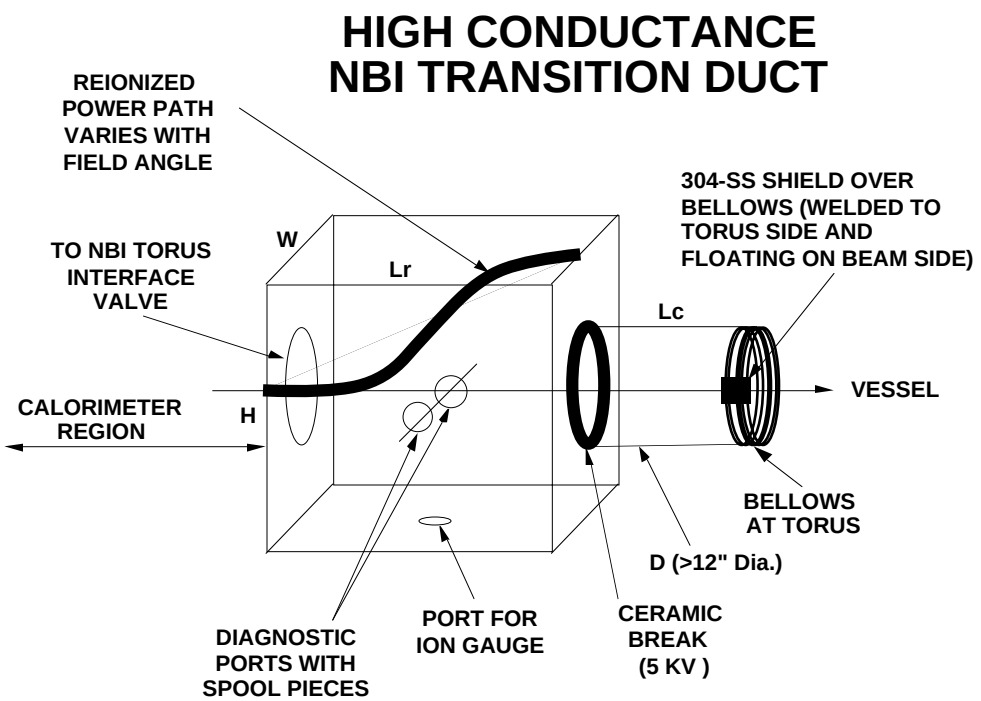

Fig.6 A partial schematic diagram showing the principal elements of a high conductance NBI Transition Duct.

One of these ports should be dedicated to a GDC electrode to facilitate Duct conditioning. a summary of the NBI Transition Duct and port access requirements. The far-wall beam armor should also provide for beam power and position diagnostics. Table 4 gives a summary of the NBI Transition Duct and port requirements.

• Maximize dimensions W, H, and D (min. ~12”).
• Use electropolished 304-SS.
• If possible, use rectangular ceramic break and bellows to maximize conductance.
• All vacuum seals bakeable to 150°C.
• Provide 150°C bakeout capability.
• If possible, useful to operate at 150°C.
• Provide ion gauge port.
• Provide diagnostic ports with spool pieces.
• Provide port for GDC electrode.
• Far-wall beam armor should have beam diagnostics

Table 4. Summary of NBI Transition Duct Design Optimization and Port Access Requirements.

11. Torus Vacuum Pumping System Port Access Options

There are two choices for achieving and maintaining the NCSX vacuum base pressure. Either a) the vessel can have its own stand-alone turbomolecular pumping system, or b) the vessel can rely on the large high pumping speed cryopumps in the Neutral Beamlines. Decoupling the vessel and Neutral Beam pumping systems allows the NCSX to operate during NBI maintenance, special tests, calibration, and cryopump regeneration that, normally on all of the major fusion experiments, require a closed NBI Torus Interface Valve (TIV). Relying on the

Neutral Beam pumps to maintain vessel base pressure, therefore, would be very inefficient and restrictive for the NCSX Experimental Physics Program.

The present PBX-M Torus Vacuum Pumping System (TVPS) consists of four 1500 l/s turbomolecular (TM) pumps suspended from the bottom of the torus to give a total H_2 pumping speed of 2600 l/s. These pumps have operated in the fringe magnetic field of PDX, PBX, and PBX-M for about 18 years, about 1.5 m from the vessel wall. The field at those locations can be identified from the fringe field calculations and used to design similar systems for NCSX. Using this TVPS hardware, there are at least three options and several variations thereof for an NCSX Torus Vacuum Pumping System:

a) Suspend the four PBX-M, 1500 l/s turbomolecular (TM) pumps from the bottom of the torus for a total pumping speed of about 2600 l/s for H_2. (e.g., PBX-M method, ~2600 l/s H_2).

A primary issue with this method is that it requires four 16 inch O.D. flange (or larger) ports, which are difficult to locate amid the NCSX coil system and Diagnostic requirements.

b) Suspend four PBX-M TM pumps from a large midplane Pump Duct for ~ 3000 l/s H_2 (e.g., TFTR, NSTX).

The primary issue with this method is similar to that of 11.1, it requires at least one, or possibly more, large midplane ports which are difficult to locate amid the NCSX coil system and Diagnostic requirements.

c) Suspend 2 TM pumps from each of 2 Neutral Beam Transition Ducts for ~3000 l/s,

This design, or a variation that involves one TM pump on each of the four Transition Ducts, provides pumping speeds in the desired range with no additional burden on the vessel port allocation.

d) Initially, or as a future option, suspend 2 TM pumps from each of 4 Neutral Beam Transition Ducts for ~4-6000 l/s H_2.

This design, or a variation that involves one TM pump on each of the four Transition Duct, provides pumping speeds in the desired range with no additional burden on the vessel port allocation, and could be designed so as to accommodate (c) as the Baseline, and then upgraded at a later time if helpful to the Experimental program.

Hence, synergies accrue from combining duct requirements of the Neutral Beam and Torus Vacuum Pumping Systems. Fig. 7 shows a schematic diagram of the principal elements of a high conductance NBI Transition Duct that combines the design requirements for the Neutral Beam and Torus Vacuum Pumping Systems.

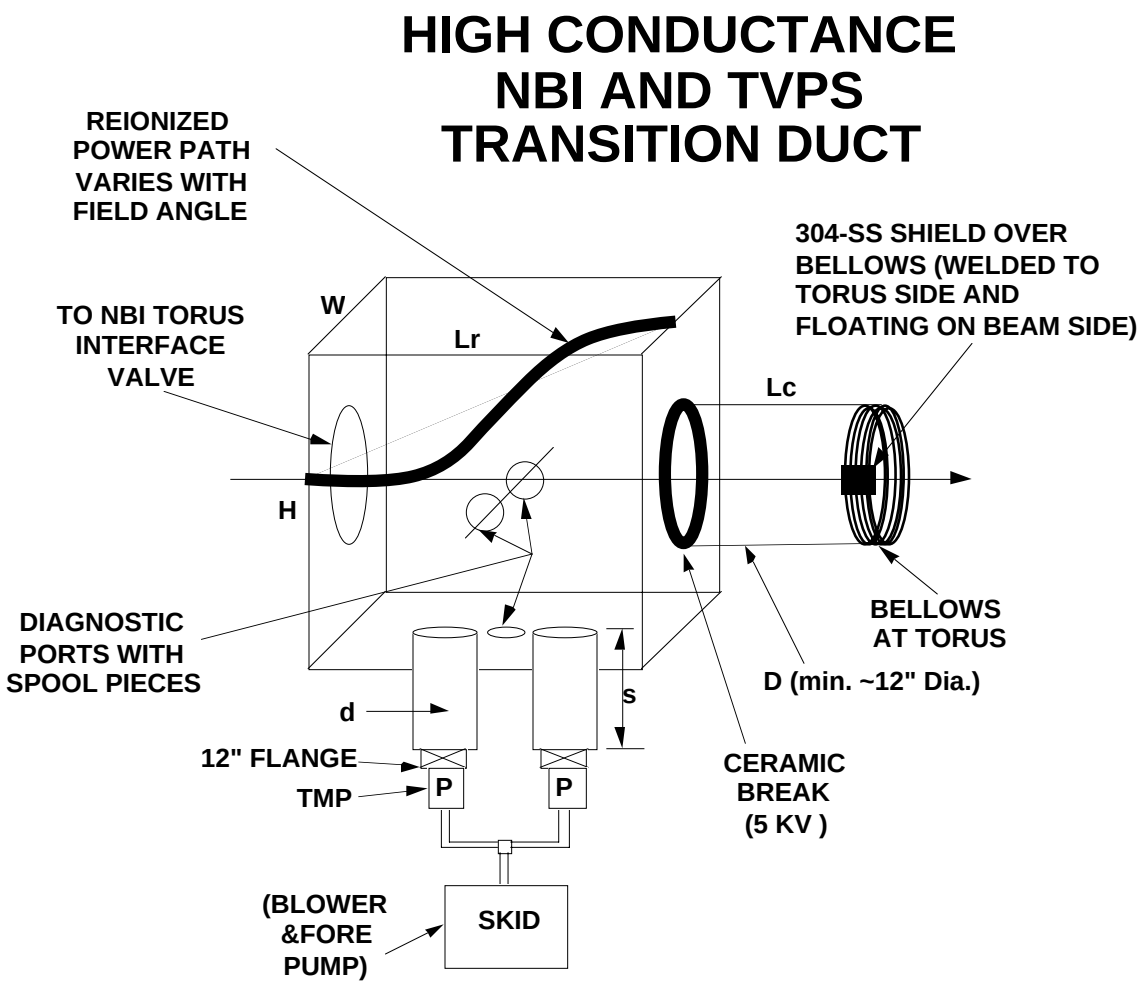

Fig.7. A partial schematic diagram showing the principal elements of a high conductance Transition Duct that combines the requirement of both Neutral Beam and Torus Vacuum Pumping System requirements.

Optimization of the Duct design is essentially that discussed in Sec.10 with the addition of the TM pumping station. It consists in maximizing the width W, the height H, the diameter D and the diameter d, while minimizing lengths Lr and Lc. Length S is selected for high conductance reaching a fringe field region comparable to that at the pumps during their PBX-M service. In addition, S should be sufficiently long to provide occlusion from beam sputtering. The other requirements discussed above in Sec. 10 are also applicable (electropolished 304-SS walls, 150°C bakeout capability). Table 5 gives a summary of the NBI Transition Duct, Torus Vacuum Pumping System, and port access design optimization requirements.

• Port Access and external constraints need to be varied to: • Maximize dimensions of H,W, D • Minimize dimensions of Lc, Lr • Select S for high conductance, B-field operation, and occlusion from beam sputtering • Provide Bakeability

Table 5. Summary of the NBI Transition Duct, Torus Vacuum Pumping System, and port access design optimization requirements.

12. Port Access Requirements for Fuelling

Fuelling is performed by Gas Puffing, and possibly Cryogenic Pellet Injection and Compact Toroid Injection.

12.1 Gas Puffing

Gas Puffing is the primary fuelling method. The parameters that determine port access requirements for Gas Puffing are adequate gas conductance, sufficient number of toroidal locations, and the locations of Torus Fast Neutral Pressure Gauges (refer to Sec.15.1 below). At this time, pending a detailed design, it should be sufficient to designate 3 ports equally spaced toroidally with 4.5 inch O.D. flanges close to the vessel wall for outboard fuelling, and 3 ports equally spaced toroidally, with 4.5 inch O.D. flanges close to the vessel wall for inner wall fuelling. If the available ports are on longer spool pieces, at a greater distance form the vessel wall, then larger ports will be needed. The injection of different gases can be performed with the same injection port (but not simultaneously) by switching gases via a remotely controlled gas handling manifold. In the case of special experiments requiring a small admixture of another gas, this could be accommodated using one of the available injection ports, or using a spare port configured with a Torus Isolation Valve (TIV).

12.2 Cryogenic Pellet Injection

Fuel Pellets are most easily injected radially inward from an outer midplane port. Recently, there have been interesting results obtained by injecting Pellets radially outward from the inner wall. This is accomplished using long guide tubes with gentle radii of curvature to transport Pellets to the inner wall midplane from the apparatus more radially outward. A midplane port with a 6 inch OD flange, and inner wall port with a 2.75 inch flange should be sufficient should be for these applications. The desired toroidal location may need to be located opposite to a plasma cross section of sufficient width.

12.3 Compact Toroid Injection

Compact Toroid Injection is a promising technique central fuelling, pressure profile control, and facilitating start-up. A proposed Compact Toroidal Injector for the National Spherical Torus Experiment (NSTX) required a radial midplane port with 8-10" inch I.D. flange. This port access requirement can be adopted for NCSX pending additional design.

13. Port Access Requirements for He Glow Discharge Cleaning

NSTX presently uses two fixed GDC anodes; other experiments (e.g., JT-60U) use 2 or more GDC anodes. Given uncertainties about GDC in the NCSX geometry, the Glow Discharge Cleaning (HeGDC) design should plan for 3 ports with 4.5 inch O.D. flanges equally spaced toroidally for fixed anode wall probes, and if desired, an additional 3 anode ports to service Gaseous Boronization (Se. 14.1). These six anodes need not be separate but could be used for both GDC and Gaseous Boronization. The poloidal angle of these ports is not critical. In addition to the anode ports, it is desirable to have 3 ports with 4.5 inch OD flanges located near to the anode ports (preferably within line-of-sight) for preionization filaments to facilitate GDC breakdown at the actual operating pressure and voltage. These prionization filaments might also be useful for helping to initiate NCSX plasmas. On NSTX, preionization filaments are used routinely to initiate HeGDC between discharges, and in conjuction with ECE, to initiate plasma discharges.

14. Port Access Requirements for Wall Conditioning

Wall conditioning may be performed with boronization and lithiumization using several different techniques depending on experimental goals and convenience.

14.1 Gaseous Boronization via HeGDC or Fuel Gas

Boronization using Diborane (B_2D_6) using Plasma-aided Chemical Vapor Deposition via He GDC is used on DIII-D, and the same technique is applied on JT-60U using Decaborane ($B_{10}H_{14}$). These and other experiments have found that boron deposition occurs non-uniformly and predominantly within about 1 m of a GDC anode. Hence, (DIII-D) uses 4 anodes and JT-60U uses 12 anodes with multiple boron gas injectors to obtain uniform coverage. The Coaxial Helicity System (CHS) experiment at Nagoya has performed interesting boronization experiments for LHD using Decaborane as a fuel gas by injecting it into the edge plasma. This produced the desired improvement in performance with much greater efficiency of Decaborane usage than the GDC method. NCSX design can accommodate this potential Boronization methods by allocating 6 ports with 4.5” O. D. flanges for anodes, which can also service standard HeGDC described above (Sec. 13). The CHS fuelling method can be accommodated with the port discussed in Sec.14.2.

14.2 Solid Target Boronization

Solid Target Boronization (STB) is boronization by evaporating boron from a probe tip heated by insertion into the edge plasma. The STB probe consists of a graphite-felt probe tip containing 40-micron diameter boron particles. The plasma thermal deposition causes the boron to melt and to flow to tip surface. The boron evaporated into the plasma edge is ionized and flows field lines to divertors and limiters. One, 6 inch O.D. flange, preferably midway between Divertor regions should be allocated for STB on NCSX. STB is useful as a sole boronization method and for maintaining boron films deposited using Plasma-aided Chemical Vapor Deposition. This same port could be used for boronization using the Decaborane fuel gas method described above in Sec. 15.1.

14.3 Lithiumization

Lithium wall coatings have been found to improve performance significantly in clean graphite-clad machines. Lithium deposition has been performed using Pellet Injection, Effusion Ovens, and Laser induced ablation. Pellet Injection would require one midplane port with a 4.5-6 inch O.D. flange. This option would also allow boron and other impurity injection. An Effusion Oven approach would require at least 3 (or more) ports, one (or more) per sector, with 4.5-6 inch O.D, flanges for complete coverage. A Laser induced ablation approach could be implemented with 2 ports, at the top and bottom of the vessel, on the same vertical axis, with 6” O.D. flanges.

15. Port Access for Other Machine Physics Requirements

Machine Physics requirements involve diagnostic equipment and other hardware for optimizing machine operations and performance. These requirements include those mentioned above in Sec. 13-15. This Section emphasizes additional port access requirements for Machine Physics Diagnostics which should be included in the Baseline and available for Day-1 Operations.

15.1 Fast Neutral Pressure Gauges

Large fusion experiments use 3-6 Fast Neutral Pressure Gauges. These are located on the Midplane, Divertor, and Limiter regions. NCSX port access requirements should initially allocate 1 Midplane port with 4.5 inch O.D. flange and 2 Divertor region ports of the same size, one top and one bottom.

15.2 Vessel and Internal Hardware Thermocouples

It is not unusual for large high power fusion experiments to install several hundred thermocouples. Thermocouples are useful for calibrating IR Cameras, monitoring the uniformity of Bakeout, monitoring known energy deposition regions, and for monitoring unforeseen energy deposition as new regimes are explored. The NCSX geometry, bakeout requirements, operations, and Experimental Program will be facilitated by an adequate distribution thermocouples. The Thermocouple port access requirements involve finding suitable non-premium ports with 2.75 inch O.D. flanges for 20-36 pin thermocouple feedthru connectors (*i.e.*, 10-18 pairs). In the case of a modest 32 Thermocouples per sector, at least 2 such ports will be required per sector. Space for future expansion by x2-x4 should be included.

15.3 Plasma TV Views for Operators

Development of Control Systems, general optimizing of performance, and efficient exploration of complex magnetic geometries and new regimes is facilitated by providing operators with a Tangential Plasma TV Camera view of all plasma wetted surfaces (Divertors, RF Antenna Limiters, Armor, Probes, etc.). The port access requirements for this function on NCSX are to include tangential views of each long Sector (3) and each Inner Corner (3).

15.4 IR Camera Views

An early Experimental goal for NCSX during initial low power operations will be to benchmark thermal deposition simulations so as to allow simulations of sufficient accuracy to determine the adequacy of the power handling surfaces for high power operation. IR Camera views will be required for Neutral Beam Armor, RF Antennas, Divertor Regions, the toroidal

footprint of the Divertor Strike Points, and all unshielded regions. These ports need to have 4.5 inch O.D. flanges and have an appropriate Line-of-Sight to the target. Wide-angle lens and mirrors can allow more than one object to be observed by one camera view. About 2 ports per sector may be required.

16. Summary and Conclusions

16.1 Conclusions on Neutral Beam Injection System and Torus Vacuum Pumping System Port Access Requirements

The port access requirements for the Neutral Beam Injection (NBI) systems and Torus Vacuum Pumping Systems (TVPS) are usually approached as separate and independent design problems. Combining the respective duct requirements of the Neutral Beam Injection (NBI) and Torus Vacuum Pumping Systems (TVPS) eliminates separate port access requirements for NBI and TVPS (more access for RF and diagnostics), provides high conductance geometry for NBI and TVPS, minimizes NBI gas loading of torus during NBI conditioning, and minimizes Duct base pressure at start of next shot.

16.2 Conclusions on Machine Physics Requirements

The Machine Physics requirements discussed in Sec. 12-15 are summarized in Table 5.

Machine Physics System	Number of Ports	Flange O.D. (Inches)	Locations	Notes
Fuelling • Gas Puffing • Outboard Fuelling • Inboard Fuelling • Cryo Pellet Injection • Outboard Fuelling • Inboard Fuelling • Compact Toroid Inj	 3 3 1 1 1	 4.5" 4.5" 6" 2.75" 10-12"	 Outer Wall Inner Wall Outer Midplane Inner Midplane Outer Midplane	 • (Close to Vessel wall, with 1 per Sector)
HeGDC Anodes HeGDC Filaments Gaseous Boronization	6 3 6	4.5" 4.5" 4.5"	Outer wall Outer wall Lower or Upper wall	• Equally spaced toroidally • Near Anode ports • Between Anode ports, Same R
Solid Target Boronization	1	6"	Outer Midplane	
Lithiumization • Pellet Injection • Effusion Oven • Laser Ablation	 1 3 2	 4.5-6" 4.5-6" 4.5-6"	 Outer Midplane Lower wall 1 Top, 1 Bottom	 • One per Sector • Same vertical axis
Fast Neutral Pressure Gauges	1 1 1	4.5" 4.5" 4.5"	Outer Midplane Lower Divertor Upper Divertor	It may be of interest to locate one pair in a Bean Sector and one pair In an Oblate Sector
Thermocouples	6	2.75"	2 Feedthrus per Sector	• Allow for x2-x4 future expansion
Plasma TV Views	3 3	4.5" 4.5"	Outer wall tangential Outer wall radial	Viewing each long Sector Viewing each Inner Corner
IR Camera Views	4 4 1 1 1 1	4.5" 4.5" 4.5" 4.5" 4.5" 4.5"	NBI Armor views RF Antenna views Upper Divertor Upper Divertor Lower Divertor Lower Divertor	• (Wide Field of Views may allow some consolidation) • Bean Sector • Oblate Sector • Bean Sector • Oblate Sector

Table 5. Summary of Machine Physics Port Access Requirements.

16.3 NBI Port Access Interferences

Candidate NBI port locations that avoid power deposition on Diagnostic and RF ports by having beamlines interfere with neighboring beamlines, and, therefore, requiring extensive beamline modifications may not be acceptable. The technical, cost, and schedule implications of such modifications will be addressed in a future report, which may have to include the merits of armoring Diagnostic ports and relocating RF hardware.