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TPX Neutral Beam Injection System Design

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ABSTRACT

The existing Tokamak Fusion Test Reactor (TFTR) Neutral Beam system is proposed to be modified for long pulse operation on the Tokamak Physics Experiment (TPX). Day one operation of TPX will call for one TFTR beamline modified for 1000 second pulse lengths oriented co-directional to the plasma current. The system design will be capable of accommodating an additional co-directional and a single counter directional beamline. For the TPX conceptual design, every attempt was made to use existing Neutral Beam hardware, plant facilities, auxiliary systems, service infrastructure, and control systems. This paper describes the moderate modifications required to the power systems, the ion sources, and the beam impinging surfaces of the ion dumps, the calorimeters, the various beam scrapers, and the neutralizers. Also described are the minimal modifications required to the vacuum, cryogenic, and gas systems and the major modification of replacing the beamline-torus duct in its entirety. Operational considerations for Neutral Beam subsystems over 1000 second pulse lengths will be explored including proposed operating scenarios for full steady state operation.

INTRODUCTION

The TFTR Neutral Beam Injection System (NBIS) has been a physics workhorse in support of TFTR operations since 1984. In 1986, the 0.5 second magnetic field free ion sources were replaced with long pulse ion sources (LPIS's) developed at the Lawrence Berkeley Laboratory (LBL) providing the capability for 2 second full power injection operations and up to 5 second operations at reduced power [1]. The TFTR Neutral Beam System, over the past six years, has reliably and routinely provided greater than 30 MW neutral injections [2] into TFTR plasmas with record power levels in excess of 33 MW.

The conceptual design of the TPX Neutral Beam system has incorporated existing TFTR equipment wherever feasible. Suitability of existing equipment has been determined by both analysis and testing. Every effort has been made to upgrade the TFTR design using commercially available field proven components to minimize research and development costs and to allow for a quick and predictable system start-up.

DESIGN CRITERIA

The TPX design requires a neutral beam injection system to provide ion heating and plasma core fueling, to accommodate bulk current drive, and to support diagnostic requirements. The TFTR NBIS upgraded to support TPX operations will provide 8 MW of deuterium neutrals at 120 kV of accelerating potential for pulse lengths up to 1000 seconds, of which 5.5 MW will be in the full energy component, or 4 MW of hydrogen at 90 kV of which about 2 MW will be at full energy. The specified duty cycle for the neutral beam system requires one 1000 second full power pulse every 4500 seconds for a maximum of ten pulses in 24 hours or one 100 second full power pulse every 1200 seconds for a maximum of 30 pulses in 24 hours.

The present beamline configuration featuring three ion sources and beam flight paths arranged in a horizontal fan array, and aimed through a common duct into the tokamak, is to be retained. A support structure is required to elevate the existing beam box to the desired height for TPX. A new neutral beam/torus connecting duct is necessary to provide a vacuum boundary aperture of ample size through which the beams of energetic particles can pass into the TPX torus without deleterious effects from the beams striking the duct walls. Since the heat loads on beam impinging surfaces of a TFTR beamline can be in excess of 1 kw/cm² during a full power pulse, active cooling for all beam heated surfaces is required for 1000 second pulse lengths.

SYSTEM MODIFICATIONS REQUIRED

The TPX Neutral Beam design has utilized most of the existing TFTR power systems, hardware, plant facilities, auxiliary systems, service infrastructure, and control systems. Retained in the beamline are the ion sources, vacuum enclosure, cryo panels, and three gap bending magnet. The nitrogen supply system, helium refrigerator, auxiliary gas systems, gas injection system, and vacuum system are also retained with little or no modification except for pipe rerouting to accommodate the new TPX beamline position. The major change in the beamline is the conversion of what are now inertially cooled power deposition components such as the beam dumps, calorimeters, and scrapers to actively cooled components using the hypovapotron technology [3] developed for and successfully used on the Joint European Tokamak (JET) Neutral Beam System.

An overview of the modifications required to TFTR Neutral Beam equipment to support 1000 second operation

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Fig. 1 Proposed TPX Neutral Beam Injection System Layout

on TPX follows. The proposed layout of the TPX NBIS is shown in Fig. 1.

Power Supplies:

The TPX NBIS requires power supplies capable of energizing each of the LPIS's filaments, arcs, decel grids, gradient grids, and accel grids [4]. The heart of this power system is the high power tetrode in the accel modulator/regulator (M/R). In addition to providing voltage regulation, the rapid response of this tube protects the ion source from grid faults, allowing conditioning and operation up to 120 kV. The power tetrodes have operated very reliably and can be commercially repaired or reproduced. They are constructed of low mass, short time constant components which reach thermal equilibrium during present 2 second operations. A recent and successful full power test of the tetrode for one hour demonstrated it's 1000 second capability.

The Accel modulators will, however, require upgraded gradient grid voltage dividers and secondary internal power supplies. The ion source power transmission lines will require heavier gauge conductors. The deflection magnet supplies, decel supplies, and surge rooms will be retained without modifications.

The most visible changes in the Neutral Beam Power System will be seen in the Neutral Beam Power Conversion (NBPC) building. Here new High Voltage Decks (HVD) will be constructed to replace the High Voltage Enclosures (HVE) presently located in the TFTR

basement. The HVE contains the arc and filament DC supplies, three isolation transformers to permit referencing these low voltage supplies to accel potential, passive inductor elements that protect the source from energy stored in transmission line capacitance, and high voltage to low voltage telemetry. Because the HVE is pressurized with sulphur hexafluoride (SF_6) and is difficult to maintain, and since larger isolation transformers are required for the long pulse lengths, the new isolation transformers, the DC power supplies, and the high voltage telemetry will be relocated to the 100 foot level of the NBPC building in the HVD enclosure. For ease of access and maintenance, the HVD will incorporate open air construction. The arc and filament supplies, which are currently unregulated, will be modified for feedback control using thyristors and phaseback controls already in place.

New high voltage transmission lines will be installed from the HVD in the NBPC building through the basement to the new beamline positions in the test cell. Because these new positions are fixed, the transmission lines will be rigidly constructed, as opposed to the present flexible TFTR lines, but like the TFTR lines will be filled with SF_6 to minimize size. Existing penetrations can be used from the test cell and through the basement, but the penetrations in the NBPC floor must be widened. Each transmission line will be routed through a new Ion Source Protection Equipment (ISPE) enclosure containing the inductive snubbers formally located in the HVE. The ISPE enclosure will be located directly under the ion source and will provide improved protection from energy stored in the

line during faults. At the ion source, the transmission line will terminate in new electrical connections designed to facilitate source installation and repair.

In the switchyard, all the switchgear and fast vacuum interrupters are usable as is. For initial operations with one beamline, the autotransformer and transformer rectifier sets will be paralleled to meet the 1000 second pulse requirement. Later, for an additional two beamline upgrade option, units would be rewound as necessary to keep current densities at conservative levels.

Neutral Beam Controls:

The TFTR NBIS has an extensive Instrumentation and Control (I&C) system consisting of local power control centers, Programmable Logic Controllers (PLC) for beamline vacuum and cryogenic controls, magnet controllers, ion source fault detection equipment, plasma fault protection systems, gas injection systems, beamline diagnostics, source steering controls, beamline thermocouple monitors, and timing controls. Also, the I&C system is connected to the computer system through an interface consisting of digital and analog input/output modules, multichannel digitizers, high speed transient digitizers and remote consoles and displays. For TPX, the entire I&C system can be used virtually as is with minor changes to increase the capacity of the beamline thermocouple monitoring system and to add a link interface to the upgraded computer system.

Advances in computer workstation technology would permit a more automated controls approach for the TPX NBIS, but the baseline does not include this feature. The downsized scope of the TPX NBIS does not warrant the investment in computer hardware and software development.

The TFTR NBIS also has an extensive personnel and equipment safety system consisting of Kirk-Key interlocks, emergency stops, test cell door interlocks, and hardwired power system status displays and permissives. All of these safety features will be retained for the TPX program.

Neutral Beam Beamline and Long Pulse Ion Sources:

The dumps for the residual unneutralized ions, the calorimeters, the various beam scrapers, and the neutralizers will be replaced with actively cooled devices, and the duct to the tokamak will also be lined with actively cooled devices [5]. The heat transfer technology chosen for all of the actively cooled components in the beamline and duct is the hypovapotron based on an optimum size and required flow for the TPX design and on JET's actual operating experience with this technology.

The ion dump will be enlarged vertically to increase the area of power deposition but will retain the existing plan view footprint to fit in the existing beamline port opening. The calorimeter will use the existing drive, frame, bellows, and beamline port opening but will require the replacement of all beam impinging surfaces. Apertures associated with the source isolation valve and the beamline's 90 inch flange will be enlarged and the layout

altered to permit sufficient clearance for the hypovapotrons and associated plumbing.

The beamline-torus interconnecting duct, which must have a clear aperture of greater than 40 cm, will reuse the existing Torus Isolation Valve and ceramic electrical break. Two bellows, a bi-metallic transition flange, a bolted vacuum seal section and support linkage form the structure and vacuum integrity of the new duct assembly. A hypovapotron lining will handle divergent and reionized beam power loading. Accommodation has been made for TPX vacuum vessel bakeout to 350°C, with concomitant dimensional expansions.

The ion sources are already nearly rated for steady state operation and will require only minor changes. On TFTR, the LPIS has been operated repeatedly and successfully for 2 seconds at 120 kV and 4 seconds at 90 kV. Longer pulse length operation has been limited by the TFTR beamline ion dump and not by the source, but within this constraint the source has been essentially operated steady state since most of its construction consists of low mass components with short thermal time constants. However, for very long pulse operation at full power, the exit scrapers and the electron dump will require upgrades [6]. The source exit scrapers will use hypovapotron technology while the ion source's electron dumps (back plates) will require cooling channel modifications. In addition, the grid mask, which presently reduces the source aperture, will require design changes. On TFTR, the robustness and reliability of the basic ion source design has been extensively proven with availability approaching 95%. Similar performance is anticipated for TPX.

Neutral Beamline Subsystems:

As previously mentioned, the beamline cryogenic system will use the existing 1070 W liquid helium refrigeration plant and existing liquid nitrogen system, with changes to the transfer lines to accommodate the new beamline position and height. Similarly, the vacuum system will reuse major portions of the existing pumping systems, with extended piping for the new beamline height. A seismically rated support structure has been designed to position the existing beamline at 65 inches above the present level to match the beam path to the TPX torus mid-plane.

The Neutral Beam cooling water system will be upgraded and will provide local distribution of cooling water to beamline components, the duct, and the power systems, with appropriate interlocking and instrumentation. TPX Neutral Beam cooling water requirements will be significantly higher with approximately 12,000 gal/min of deionized water needed to dissipate the anticipated 40 MW of heat load on the beamline components, the ion sources and the power supplies. The SF₆ and compressed air systems will be reused as is.

COST ESTIMATE AND SCHEDULE

Maintenance and operational improvements to the TFTR NBIS over the years has required the removal, refurbishment, and recommissioning of ion sources, dumps, calorimeters, 90 inch flanges with neutralizer ducts, Torus Isolation Valves, and the various other equipment that will have to be upgraded for the TPX design. The TFTR work was accomplished within the constraints of tightly scheduled maintenance periods with limited time provided for reconditioning the neutral beam equipment back up to required operating levels. Based on this operating and maintenance history, it is believed that a TPX Neutral Beam design that incorporates existing TFTR equipment and operating routines upgraded with only well tested and commercially available equipment will require only a minimum amount of R&D activity and commissioning time.

The preliminary and final design along with the procurement, fabrication, and installation of the required Neutral Beam upgrades will be staggered to match the TPX funding profile, the lead times of equipment procurement, and to balance the manpower loading over a five year period. The longest lead item is the hypovapotron procurement activity which will be initiated in time to meet project schedule.

The estimated engineering, hardware, installation and contingency costs of upgrading the TFTR Neutral Beam system for TPX is as follows;

Neutral Beam Power Supplies	\$ 2.5M
Neural Beam Controls	1.5M
Beamline	11.4M
Beamline Subsystems	<u>2.9M</u>
	\$ 18.3M

Operating costs such as the conceptual design, research and development, mock-ups, spares, and preparations for operations are estimated to be an additional \$1.6M.

The above costs represent day one operation of TPX with a single 8 MW, 1000 second beamline. This estimate, however, would also cover most of the engineering costs associated with upgrading to the three beamline option.

PROPOSED OPERATING SCENARIOS

The essential function of the NBIS is to inject hot hydrogen or deuterium atoms into a hydrogen or deuterium plasma. The NBIS for initial operation on TPX will consist of one beamline with provisions made for a total of three beamlines. Steady state operations could be accomplished after upgrading to the three beamline option by staggering ion source and beamline operation.

For the three beamline option, the administrative limit for the amount of hydrogen or deuterium that may be stored on a beamline's cryopanel (and possibly provide an explosive mixture in air) determines the maximum beam pulse length. For deuterium beam operation, the helium cryopanel will reach their maximum allowable inventory

after 30K source-seconds (ten, full length, three source shots) and will have to be regenerated. For hydrogen operation, the cryopanel will have to be regenerated after 24K source-seconds. Hydrogen beam operation will require that the cryopumping panels operate at 3.8° Kelvin so as to achieve a H₂ vapor pressure at the cryopump of about 10⁻⁷ torr. As always, the hydrogen beams will realize little injected power gains above 65 keV due to the sharp falloff of the neutralization efficiency for hydrogen.

The calorimeters are designed to withstand the full beam power flux for 1000 second pulse lengths allowing full beam conditioning before the first TPX Neutral Beam injection. Beamline diagnostics at the neutralizer and the NB/torus duct will measure beam divergence and permit an accurate determination that the beam crossover is at the required position, and will also permit the species mix of the neutral beam entering the tokamak to be measured.

TFTR Beams have reliably provided 8 MW/beamline of deuterium neutrals to TFTR using ion sources and modes of operation virtually identical to those proposed for TPX. The TPX Neutral Beam Injection System will be able to follow the existing TFTR operating procedures with minor revisions to address monitoring beamline temperatures and adjusting setpoints in real time during a pulse. Ion source conditioning to required TPX operating levels will probably take place in just a few pulses.

ACKNOWLEDGMENT

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