HEATING AND CURRENT DRIVE SYSTEMS FOR TPX

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ABSTRACT

The heating and current drive (H&CD) system proposed for the TPX tokamak will consist of ion cyclotron, neutral beam, and lower hybrid systems. It will have 17.5 MW of installed H&CD power initially, and can be upgraded to 45 MW. It will be used to explore advanced confinement and fully current-driven plasma regimes with pulse lengths of up to 1000 s.

I. INTRODUCTION

The H&CD system for TPX is an important part of the complete TPX experiment. It must provide the heating and current drive capability needed to:

- Achieve high β_N values
- Operate with steady-state current-driven plasmas
- Explore steady-state regimes with high bootstrap fraction and high β
- Modify the deposited heating power and driven current profiles to explore the effects of differing pressure and q profiles on confinement and stability.
- Do the above with both hydrogen and deuterium plasmas

One of the primary attributes that the H&CD system must have is flexibility. The control of the pressure and current profiles by judicious tailoring of the power deposition and the driven-current profiles is believed to be crucial to attaining the advanced tokamak modes that are desired, such as the VH-mode observed on DIII-D and elsewhere,¹ the supersonic modes on TFTR,² and the high-beta modes that should exhibit second stability.³

Because TPX is also designed to study long-pulse, fully current-driven operation, the H&CD system must

also be able to sustain the current using fully non-inductive means, either driven directly by the system or achieved from bootstrap current caused by high pressure gradients in the plasma.

There are three types of heating and current drive systems proposed for TPX: a neutral beam system, an ion cyclotron system, and a lower hybrid system. Each system has an initial configuration, and an upgrade path to provide more flexibility and power. Parameters for each system are given in Table 1.

TABLE 1. H&CD System Summary for TPX

System	Initial Config.	Upgrade Config.
Neutral Beam		
Power to plasma (MW)	8	24
Beam energy (keV)	120	120
Number of co-directed beamlines	1	2
Number of counter-directed beamlines	0	1
Ion Cyclotron		
Power to plasma (MW)	8	18
Frequency range (MHz)	40 - 80	40 - 80
Number of current straps	12	18
Ports used	2	3
Phase between straps	$-\pi$ to π	$-\pi$ to π
Lower Hybrid		
Power to plasma (MW)	1.5	3 (or 6)
Frequency (GHz)	3.7	3.7
Range of $n_{ }$ spectrum peak	1.7 - 3.0	$\pm (1.2 - 5.1)$

The specified duty cycles for the H&CD systems require one 1000-second full-power pulse every 4500

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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 initial configuration of the H&CD system is relatively cost-effective, providing significant "bang for the buck", while at the same time allowing a reasonable upgrade path so that experiments with higher power can be done with minimal major changes to the components inside the vacuum vessel. The conceptual designs for the systems and the tokamak have been done assuming that the components in the tokamak must withstand the full upgrade power capability of 45 MW, so that all initial components can be used in an upgraded system.

II. NEUTRAL BEAM SYSTEM

The initial neutral beam (NB) system will consist of one TFTR beamline modified for long-pulse (1000 s) operation. Existing inertially-cooled components such as the ion dump, calorimeter, and beam defining apertures will be replaced with hypovapotron-cooled components. The beam-torus duct must be replaced entirely and be actively cooled. Some of the elements of the existing power system must be upgraded for long-pulse operation.

The initial beam will be aligned for tangential co-injection, to take advantage of NB current drive capabilities. The 24 MW upgrade system would have two co-directed beams and one counter-directed beam; however, the beam ports are being designed to allow some flexibility in the choice of beam directions (e.g., three co-directed beams).

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.⁴ The TFTR Neutral Beam System, over the past six years, has reliably and routinely provided greater than 30 MW neutral injections into TFTR plasmas with record power levels in excess of 33 MW.⁵

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.

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. The system also will be able to provide 4 MW of hydrogen neutrals at 90 kV, of which about 2 MW will be at full energy.

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 magnets.⁶ 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 technology⁷ developed for and successfully used on the Joint European Tokamak (JET) Neutral Beam System. The proposed layout of the TPX NBIS is shown in Figure 1.

Figure 1. Proposed TPX neutral beam injection system layout.

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 will 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 impinged 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.

The cost for procurement and installation of the initial NB system is estimated to be approximately \$19.5M, with an additional \$1.6M for R&D. The development work consists primarily of testing the long-pulse modifications needed in the beamline.

III. ION CYCLOTRON SYSTEM

The initial ion cyclotron system will utilize the existing rf power sources at TFTR, consisting of four modified FMIT transmitters that cover the 40 – 80 MHz frequency range. Antennas will be installed in two adjacent ports. Each antenna has six current straps in a toroidal array, approximately equally spaced. Figure 2 shows a view of a single six-strap launcher. The plasma-facing surface of the antenna is covered by a single-layer, water-cooled Faraday shield, which is approximately 30% transparent. The Faraday shield is made of tubing that is plasma-sprayed with a coating of B₄C approximately 0.1 mm thick to provide a low-Z surface exposed to the plasma. The current straps are grounded at the center for mechanical support, and are fed at both ends as part of a resonant loop circuit. The resonant loop circuit is designed to help match the impedance of the antennas to the transmission lines.

The present baseline design has the antenna constructed of Inconel 625, a material with high strength and easy fabricability that has been used in several rf launchers. However, we are investigating the feasibility of fabricating the launcher of titanium. This would result in low-activation launchers, which are needed to permit hands-on access to the machine after operation begins. Ni or Cu coating will be used to seal the Ti surface and prevent hydrogen embrittlement. An R&D program is being carried out to demonstrate that a B₄C-coated, Ni-plated Ti Faraday shield can be fabricated that will withstand the H₂ exposure and elevated temperatures at which the TPX Faraday shield will operate.

Figure 2. Perspective view of a TPX IC antenna.

The IC system will be used for both heating and for fast-wave current drive, requiring that the phase between currents in adjacent straps be adjustable in order to change the current-drive direction and efficiency of the system. This will require a sophisticated matching and phase control circuit to meet these requirements under the different plasma configurations expected in TPX. A baseline system that will perform the required functions has been designed, but it is likely to be modified and improved because of knowledge that will be gained on presently-operating tokamaks doing FWCD experiments (e.g., JET, DIII-D). It consists of a number of power splitters, phase shifters, stub tuners, and resonant loops etc. that are located near TPX, as shown in Fig. 3.

Because there are 12 current straps and four transmitters, each transmitter must drive three current straps, which must have variable phasing between straps. Power from each transmitter is split three ways; the phase difference between legs is adjusted by the insertion of phase shifters in the legs. A number of tuning and matching components and rf diagnostics are included to insure proper operation of the system.

The initial two six-strap antennas can be upgraded to deliver 12 MW to the plasma with the addition of more rf power sources. For the full 18-MW upgrade, a third antenna will be required, as well as more rf sources.

The cost for procurement and installation of the initial rf system is estimated to be approximately \$21M, with an additional \$2.2M in R&D. The R&D funding is primarily for the development and testing of the low-activation Ti antenna.

Figure 3. Tuning and matching system for one transmitter and three current straps

IV. LOWER HYBRID SYSTEM

The lower hybrid (LH) system consists of four 500-kW, 3.7 GHz klystrons and associated power supplies, power splitting and phase control circuitry, and a single radially-moveable LH launcher. This system will deliver 1.5 MW to the plasma. Figure 4 shows a schematic of the system.

The DC power system for the LH generator will make extensive use of excess TFTR Neutral Beam power components. One beamline set of 13.8kV switchgear, tap changer and transformer-rectifier will be modified and rewired for LH use. The LH system capacitor bank and crowbar will be obtained from Neutral Beam surge-room components. All four klystrons will be fed from a common DC power bus to eliminate phase ripple induced from the power system. Fault protection will be provided by a fast crowbar and trigger system based on klystron overcurrent and other parameters.

Figure 4. Schematic of the lower hybrid system.

Diagnostics for the LH system will include RF phase and forward power for each group of four poloidal waveguides in the array. In addition, klystron voltages, klystron cooling water temperatures, load temperatures, and other signals will be digitized and monitored.

Waveguide isolators will be provided in the klystron outputs to remove power reflected back from the plasma. A low-reflection load allows the klystrons to generate additional output power (more than the loss of the isolators) without the plasma-induced power variations prevalent in other systems. The klystron amplifier outputs will be phase-locked and power-leveled to a single RF reference. This will correct for phase drift in the klystrons, isolators and output waveguide structure.

Although LH source power for 1.5 MW into the plasma will be available initially, the initial launcher will be designed to deliver up to 3 MW to the plasma, so that an upgrade of the LH power can be made without having to install a new launcher. Sufficient spare neutral beam equipment exists to allow complete duplication of the AC / DC power system for a second 1.5 MW system. Four additional klystrons with duplicate phase shifters, waveguides, diagnostics and control equipment will bring the total capability to 3 MW through one port.

The system could be upgraded to provide 6 MW to the plasma. A second launcher assembly will be needed in an additional port on TPX. This upgrade has not been studied in detail, but the existing DC power system has additional capabilities if the transformer-rectifiers are re-wound for lower voltage and higher current and the cooling capacity is increased. This may allow an additional eight klystrons to be powered by existing equipment.

The LH launcher will consist of two independent arrays mounted side-by-side; each array contains waveguides in a 32 (toroidally) by 4 (poloidally) grid, with adjustable phase control between adjacent toroidal waveguides to alter the spectrum of the launched LH wave. A view of the launcher is shown in Fig. 5.

The power splitting system consists of a series of conventional four-way power splitters. This configuration has several advantages: insertion of a phase shifter in each line permits a wide control of the $n_{||}$ -spectrum launched, including the 'counter' direction. It also allows the insertion of the vacuum window sufficiently close to the plasma so that a differential pumping system is not needed, and at the same time having the electron cyclotron resonance in the pressurized section of the launcher.

In the initial stages of operation the phasing system will be simplified in order to save costs. Instead of single phase shifters in each line, there will be four high power ones at one of the two outputs of the klystrons; these, coupled with the low power phase shifter before the amplifier tube will allow a 360° phase control between groups of four waveguides. Since the phase difference between the waveguides within these groups is fixed at 90° the result is a limited $n_{||}$ -spectrum range, from 1.7 to 3.0, without capability of reversing the direction of launch.

The estimated cost of the LH system is \$14 M, with an additional \$1.6 M for R&D. The main R&D item is development of a monolithic LH launcher assembly that will meet the low-activation requirements of TPX.

Figure 5. View of the lower hybrid launcher.

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