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by

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# NSTX High Field Side Gas Fueling System

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**Abstract** - Fueling NSTX plasmas with gas injected from the high field side (HFS) has produced earlier, more reliable transitions to the H-mode, longer H-mode durations, higher toroidal rotation, and higher edge  $T_e$  compared with similar discharges using the low field side (LFS) gas fueling injectors. The HFS gas fueling system consists of a Center Stack midplane injector, and an injector at the inner, upper corner of the Center Stack. The challenging design and installation constraints for the HFS gas system involved placing the control components as close as possible to the machine-vacuum interface, devising a special feed-through flange, traversing through vessel regions whose temperatures during bake-out range from 150C to 350C, adapting the gas transport tubing size and route to the small instrumentation wire channels behind the existing graphite PFC tiles on the Center Stack, and providing output orifices shielded from excessive plasma power depositions while concentrating the output flow to facilitate fast camera viewing and analysis. Design, recent performance, and future upgrades will be presented.

## I. INTRODUCTION

The National Spherical Torus Experiment (NSTX,) is evaluating the physics principles of spherical torus (ST) geometry, characterized by strong magnetic field curvature, high beta-toroidal, and close-wall passive plate stabilizers[1]. Fig.1 shows a schematic cross sectional view of NSTX. In the relatively brief operating time since first plasma in 1999, NSTX has achieved a  $\beta_T$  of  $\sim 35\%$  at  $I_p = 1.2$  MA and  $B_T = 0.3$  T using 6 MW of 90 keV neutral beam heating [2]. In the highest stored energy discharges (280 kJ), the central ion temperature was  $\sim 3$  keV and the central electron temperature  $\sim 1.4$  keV [2]. H-modes have been accessed routinely with confinement times up to 120 ms [3]. High Harmonic Fast Wave heating has achieved central electron temperatures of  $T_e > 3$  keV and discharges which exhibit apparent internal electron transport barriers [4]. In addition, Coaxial Helicity Injection (CHI) has been under investigation as a non-inductive current drive technique has achieved toroidal currents of 390 kA [5].

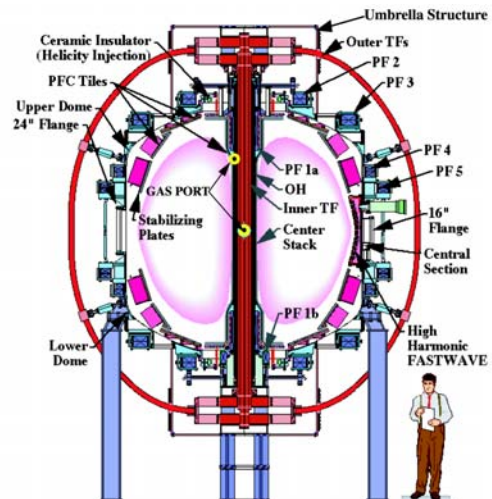


Fig.1. Schematic cross section of NSTX.



Fig.2. Photo of NSTX interior.

As this work progressed, it became evident that the outer vessel, low field side (LFS) gas fueling system used for the first NSTX plasmas was no longer adequate for providing sufficient plasma density control and for improving H-mode access. Coincident with this growing need, the Mega Amp Spherical Torus (MAST) demonstrated the effectiveness of fueling H-mode plasmas with gas injected from the high field side (HFS) [6]. This motivated the adoption of a similar system for NSTX.

The NSTX HFS gas fueling system consists of 2 gas injection assemblies with injection points at the Center Stack (CS) midplane, and the upper corner (shoulder injector) of the CS (Fig.1). When used to fuel NSTX plasmas, the CS midplane HFS injector has produced earlier, more reliable transitions to the H-mode, longer H-mode durations, higher toroidal rotation, and higher edge  $T_e$  in comparison to similar discharges using the LFS gas fueling injectors [3]. The 2nd injector at the CS shoulder was installed to give additional fueling control.

## II. DESIGN

Installation of a controlled HFS fueling system for low aspect ratio geometries is difficult to implement. This is due to the typically small space available at the inner wall that prevents the installation of fast, controllable valves at the output orifices. Under these constraints, the only available recourse has been to install long gas transport tubes of small diameter from the fast controllable valves located outside of the vessel. This results in the gas flow being restricted by the impedance of the gas transport tube yielding relatively slow fuel delivery rates and time constants that are longer than desired. At plenum pressures of a few bar, the initial gas flow in the tube is in the viscous flow range, which for a tube of internal diameter ( $D$ ) and pressure ( $P$ ) results in a flow rate dependence proportional to  $\sim D^4 P^2$ . Hence, maximizing the tube internal diameter, if possible, yields a strong increase in flow rate.

In addition to the limited space available along the CS, the installation of the HFS gas fueling system on NSTX required resolving many challenging design and installation constraints. First, space had to be located as close as possible to the machine-vacuum interface, for mounting the in order to maximize gas conductance to the output region. Two adjacent 3.375 inch vacuum flanges on the upper Center Stack Inner Divertor region at the inner most region of the upper dome were selected as the feedthroughs for the gas delivery lines. Since the Upper and Lower Umbrella structures at the top and bottom of the vessel (Fig.1) are highly congested with hardware that includes the TF busses as they enter the CS, the two gas injection assemblies had to be mounted on the outside of the Upper Umbrella at the closest point to the feedthroughs approximately 1 m away. Fig.3 shows the HFS gas injection assembly and components. The valve board base consists of 1.27 cm thick G-11 to maintain electrical isolation of the components. The assembly consists of an air actuated torus isolation valve, injection valve, fill valve, and plenum. The isolation valve allows for maintenance of the system

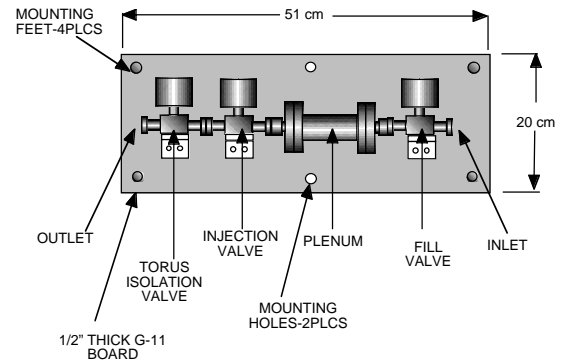


Fig.3. CS gas injection assembly.

and the fill valve isolates the plenum at a precisely known pressure and therefore a well defined amount of fuel gas prior to each discharge. The injection valve is a full open or closed valve that is timed to open at a pre-programmed time during the discharge. Calibration tests were run to measure both the time constants and flow rates of the system for various plenum pressures in order to optimize the fueling for HFS discharges.

A special gas tube feed-through for the vessel flange was designed to accommodate installation, possible leak maintenance, and thermal stresses during vessel bakeout. The design had to accommodate thermal effects as the gas transport tubes traversed through vessel regions whose temperatures during bake-out ranged from 150°C to 350°C. Therefore, it was desirable to select sufficiently ductile internal gas transport tubing, with the largest internal diameter (ID) allowed by the only available tubing route through the small instrumentation wire channels on back face of the existing graphite plasma facing components (PFC) tiles on the CS. Additionally, it was necessary to provide an output orifice shielded from excessive plasma power depositions while ensuring a direct line of sight from the orifices to the plasma region, and thereby concentrating the output flow to facilitate fast camera data acquisition and analysis.

At the vessel flange, the external gas transport tube is welded to a standard 1.33 inch OD mini conflat flange which is fastened to a 3.375 inch to 1.33 inch zero-length adapter flange. On the inside face of the 3.375 inch OD flange, a weldment supports the beginning of the internal gas transport tube which carries the gas to behind the existing graphite PFC tiles on the Center Stack. This two part feedthrough arrangement was designed to allow for maintenance and leak checking of the system and gas feed line if required. Fig. 4 is a photo showing the gas transport tube weld joint on the vacuum side of this flange and



Fig.4. Photo showing the gas transport tube weld joint on the vacuum side of this flange and nearby strain relief coil.

the nearby strain relief coil in the gas transport tube which accommodates the 350°C CS temperature and the 150 °C flange temperature during vessel bakeout. The tubing shown in Fig.4 is 6.35 mm O.D., 4.57 mm I.D. fully annealed 321-SS with Ti additive for ductility. This ductility was essential for installation of the tubing through the confined geometry of the vessel interior.

### III. INSTALLATION

The installation was dominated by the constraints imposed by the graphite PFC tiles on the CS. These graphite tiles, which range in thickness from 5 cm, on the inner horizontal divertor, to only 1.27 cm, on the

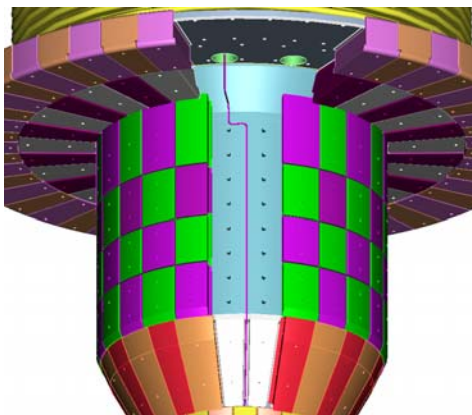


Fig.5. Schematic of a gas transport tube as it enters NSTX.

midplane, are fastened with hardware that prevented convenient modification for gas transport tubing. This restricted the available space to the narrow instrumentation wire channels which are along the tile edges in the divertor region, and in the tile centers in the midplane region. These channels behind the tiles typically contain instrumentation wiring for thermocouples, Langmuir probes, and magnetic sensors. Fig.5 is a schematic of the gas transport tube as it enters the vessel in the upper horizontal divertor, and undergoes three 90° bends as it proceeds downward toward the narrower midplane region. Fig.6 shows the gas transport tube during installation along the CS near the midplane.

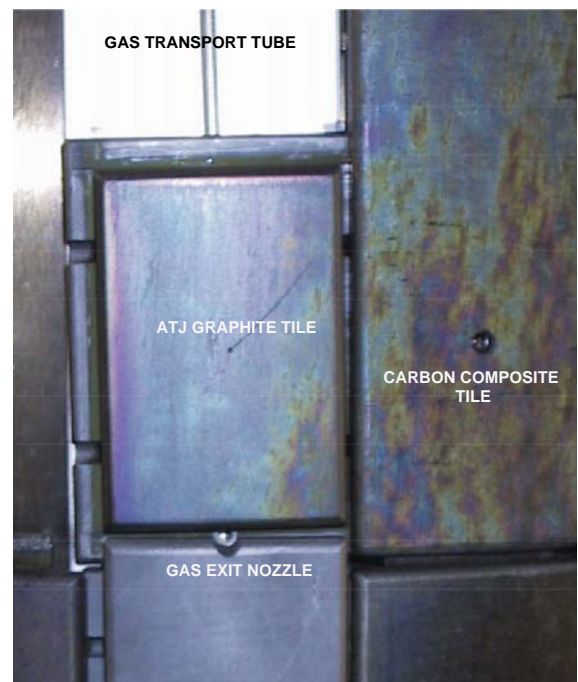


Fig.6. Photo of gas transport tube installation along CS near the midplane with some tiles removed.

At the top of Fig. 6, a graphite tile has been removed and the the gas transport tube is seen against a white background as it enters the instrumentation wiring channel on the back face of the midplane tile. The gas transport tube ends at the midplane where it is press-fit into a 304-SS elbow which provides the exit nozzle. The press-fit exit nozzle provides a simple, low conductance seal with the tube that allows for easy changes in the nozzle configuration. Additionally, the nozzle is recessed from the surface of the graphite PFCs to limit the plasma from impinging on the unit during discharges.

#### IV. PERFORMANCE

Fig. 7 shows a comparison of the waveforms of the total deuterium gas injected into NSTX in the absence of plasma *versus* time using the HFS CS

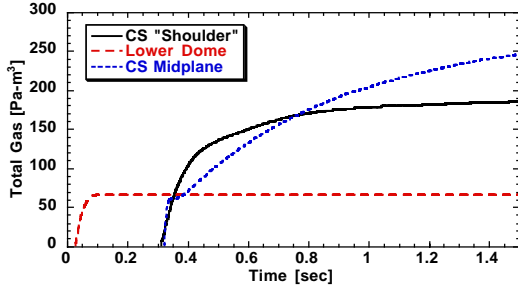


Fig. 7. Comparison of total injected gas ( $\text{Pa}\cdot\text{m}^3$ ) vs time for NSTX gas injectors.

midplane and CS shoulder injectors and gas injected from the lower dome divertor region. The rise of the HFS signals is later indicating a longer time constant than the Lower Dome signal due to their longer and smaller diameter gas transport tubes. The faster rate of rise of the HFS CS shoulder injector signal relative to that of the CS midplane injector is due to both the larger tube ID and shorter tube length. Fig.9 shows waveforms of the plasma current ( $I_p$ ), H-alpha luminosity ( $H_\alpha$ ), electron densities ( $n_e$ ), stored energy ( $W_{\text{MHD}}$ ), and confinement time ( $\tau_E$ ) for high performance 800KA, 10 MW, NBI heated H-mode discharge with combined HFS and LFS fuelling. The HFS CS midplane injector gives

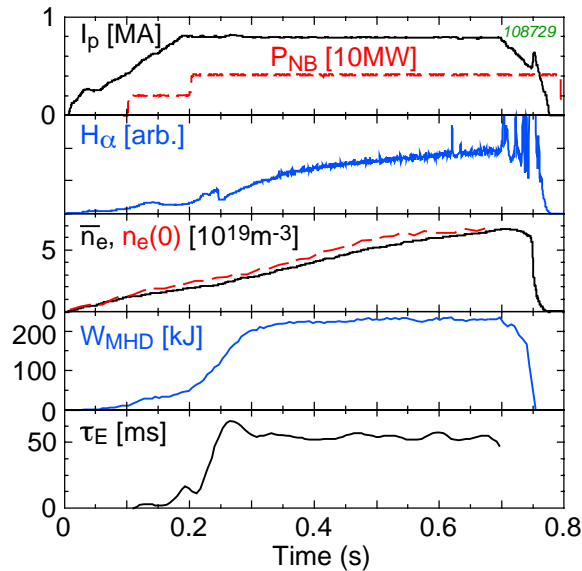


Fig.9. Plasma waveforms during H-mode.

large initial flow but then gives a continuing lower flow which contributes to the density rise. The  $H_\alpha$  signal exhibits a strong drop as the discharge transitions into the H-mode at 0.24 s and the stored energy rises and remains relatively constant during the  $I_p$  flattop. The ensemble of the 2 CS gas injectors, the lower dome and outer wall midplane injectors provide a poloidal array of gas injectors. An investigation of the dependence of the H-mode characteristics on the poloidal location of fueling was started in 2003. Initial results indicate that for Lower Single Null diverted plasmas, the easiest access to the H-mode was provided with the CS midplane injector, and for Double Null diverted plasmas, the CS midplane and CS shoulder injectors give similar responses. Work is in progress to further investigate these fueling characteristics.

#### V. SUMMARY AND CONCLUSIONS

The installed HFS gas injection system improved both the reproducibility and longevity of the H-mode. This upgrade in performance is a direct and visible result of adding HFS fueling to NSTX operating capability. The installation of the HFS gas fueling system required resolving many challenging design and installation constraints. Future work will focus on determining if adding additional poloidal HFS injectors will be required, and exploring methods for improving the response times and control of these injection systems.

#### ACKNOWLEDGMENT

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