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by

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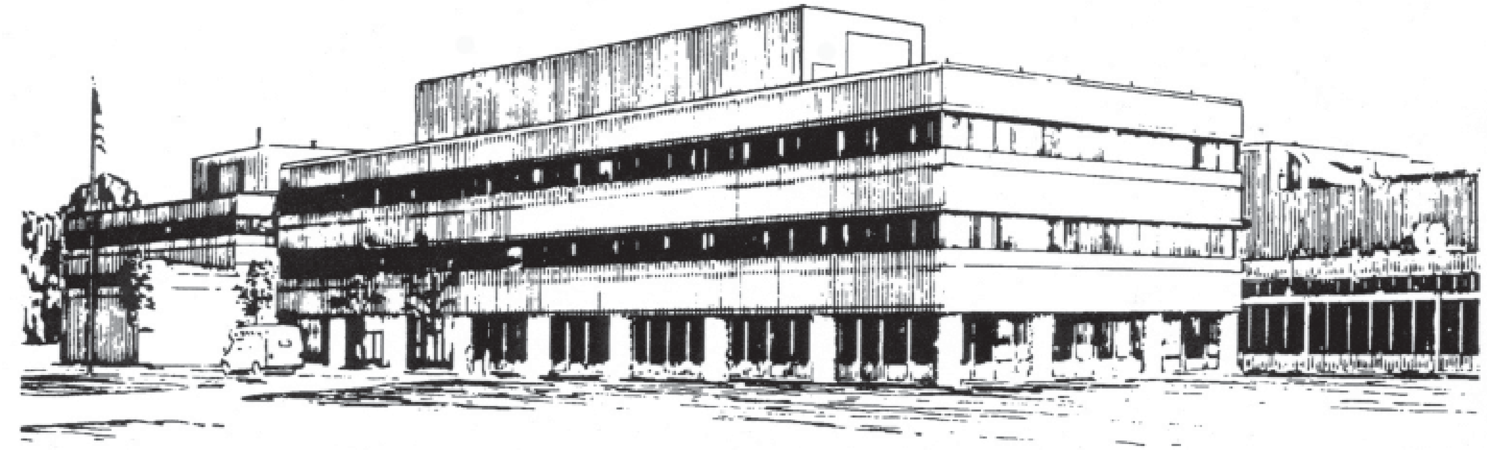

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Fast neutral pressure measurements in NSTX

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Several fast neutral pressure gauges have been installed on NSTX to measure the vessel and divertor pressure during inductive and coaxial helicity injected (CHI) plasma operations. Modified, PDX-type Penning gauges have been installed on the upper and lower divertors. Neutral pressure measurements during plasma operations from these and from two shielded fast Micro ion gauges at different toroidal locations on the vessel mid-plane are described. A new unshielded ion gauge, referred to as the In-vessel Neutral Pressure (INP) gauge is under development.

1. INTRODUCTION

The National Spherical Torus Experiment (NSTX) is designed to explore the physics of low toroidal aspect-ratio plasmas combining high beta and high confinement simultaneously[1]. NSTX has a major radius of 0.85m, minor radius of 0.68m and plasma elongation up to 2.5. The nominal range in toroidal field is 0.3 to 0.6T and the plasma current up to 1.5MA. Figure 1 shows the layout of the NSTX device, which contains the location of the poloidal field coils, divertor and passive plates, relevant to the discussion in this paper. The device is fueled using gas injection from piezo valves at four different locations on the machine, from a fifth location at the mid-plane of the center stack and, during CHI operations[2], from the lower divertor plate region. Understanding the edge neutral pressure changes on a fast timescale and at different locations on the vessel during various modes of plasma operations is necessary for establishing pumping and fueling requirements and eventually for controlling the edge neutral pressures at the desired level. For CHI discharges, it is useful to know the variation in the neutral pressure within the vessel and in both divertor regions during long pulse operation as the current that can be driven in the injector circuit is dependent on the number of available charge carriers. Implementation of fast neutral pressure gauges on NSTX and measurements conducted during plasma operations are described in subsequent sections.

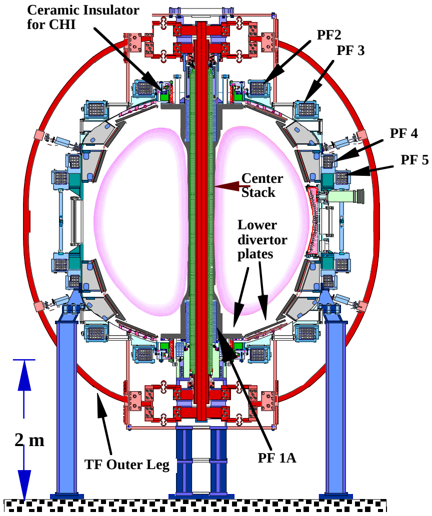

Figure 1: NSTX machine layout.

2. PENNING GAUGES

Since NSTX has a small aspect ratio (major radius / minor radius) and because the divertor region is located at small major radius, there is a steep gradient in the toroidal field in the vicinity of the divertor region. The toroidal field in combination with that from the PF2 coil results in a field pattern that has a strong curvature with both toroidal and poloidal components. While ASDEX type ion gauges[3] have been used in the divertor region of large aspect ratio tokamaks, it is not at all clear that they would work satisfactorily in the divertor of a tight aspect ratio machine. For this specific application, Penning gauges are an attractive option because of their simplicity, small size and ability to operate in the presence of strong variable fields. Modified, PDX-type Penning gauges were therefore tested on the HIT-II experiment at the University of Washington and then installed on the upper and lower divertors of NSTX. These gauges have a cylindrical anode measuring 1.27cm in diameter and 1.26cm long. 2.6cm^2 steel plates separated from the cylinder ends by 2.6mm, act as the cathode. Voltages in the range of 2 to 5kV were used for experimentation. A voltage of 3.12kV was selected in the final configuration. This increases the maximum operating range for the pressure while ensuring that the Penning discharge initiates at the lower pressures.

The gauges were calibrated at 0.3, 0.45 and 0.6T (at the nominal torus radius, 0.85m). A set of calibration data was also collected with the toroidal field at 0.3T and with 126kA·turns on the PF2 coils to simulate

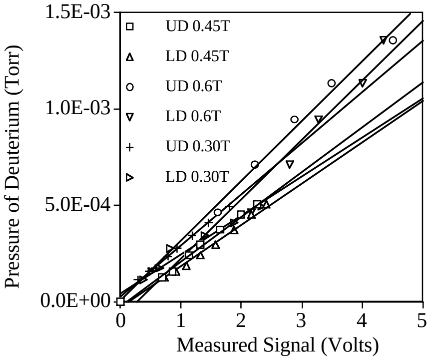

*Figure 2: Calibration curves for the upper and lower divertor penning gauges. A linear fit to all the data in the toroidal field range from 0.3 to 06T results in a calibration curve, P(Torr) = 2.98E-4*Volts-6.33e-5, that contains an error of +/-25%. This level of accuracy is at present sufficient for characterizing flows into and out of the divertor.*

field conditions in the divertor region during plasma operations. Adding current in the PF2 coils did not markedly alter the calibration. Results from this calibration are shown in Figure 2. The calibration data primarily shows that the calibration for the upper and lower divertor gauges is generally insensitive to the magnitude of the toroidal field. The absolute calibration for both gauges is however slightly different. For our purposes, a linear fit to all the data, irrespective of gauge or the magnetic field, results in a calibration curve with an error of +/- 25%, which is adequate for the type of studies these gauges would be used for. This is in agreement with the work of Dylla[4] in which the transition magnetic field for this type of gauge was estimated to be about 0.1T. This is a desirable result as it means that during plasma operations the divertor pressures can be measured within reasonable errors for a wide range of operating conditions. In general, the divertor pressure gauges show a reduction in divertor pressure during diverted lower single null ohmic operation. This is discussed in the section on experimental results.

3. MICRO ION GAUGES

Recent developments in ion gauge technology have resulted in the availability of a standardized miniaturized ion gauge. The Granville Phillips Micro Ion Gauge No. 355001 is about 10cm long with a maximum diameter of 7.3cm. These dimensions are sufficiently small that it allows a magnetically shielded gauge to be installed on the NSTX outer vacuum vessel, in a high conductance region for fast pressure measurements during plasma operation. Two shielded fast Micro ion gauges (MIG) were installed at different toroidal locations on the vessel mid-plane. The gauge installed on Bay-E is located behind the RF antenna and is shielded from direct line of sight from the plasma discharge. It is oriented along the radial direction with a spacer that is 1.5cm in ID and 7.5cm long. A magnetic shielding cylinder consisting of an outer layer of low permeability metal and two inner layers of high permeability metal completely covers the gauge. From crude conductance calculations, this gauge is estimated to have a response time of about 5ms, but results show, it may be faster than this. The second gauge is mounted on Bay H, but is mounted aligned to the vertical axis. The presence of additional vacuum fittings between the gauge and the vessel considerably reduces the conductance resulting in a much slower response time as compared to the Bay-E gauge. A modified Granville Phillips 270 controller is used to collect both the ion and electron current during the plasma discharge. The gauges provide a very useful operating range of 1E-5Torr to about 4mTorr. With a lower emission current setting the range could be extended to above 10mTorr. During high-pressure transients, the emission current can change, which can result in an incorrect ion current signal. We therefore measure and digitize the emission current signal by measuring the voltage across a 100Ohm resistor introduced in series in the emission current circuit. Calibrations show that these gauges are robustly shielded and are unaffected by toroidal fields up to 0.6T, which is the maximum capability of NSTX. The comparison of the gauge calibration with and without the toroidal field is shown in Figure 3. These gauges have been very useful and are routinely used as an edge neutral pressure diagnostic. Reliable operation has motivated us to incorporate the signal from this gauge into the NSTX plasma control algorithm to initially feedback control on the fill pressure during discharge initiation. This gauge has also been useful in characterizing the gas flow rates from the different gas injection systems used on NSTX.

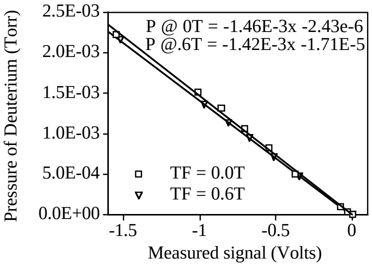

Figure 3: Micro Ion Gauge calibration curve at 0.6T. The magnetic shielding is remarkably effective for toroidal fields up to 0.6T, the maximum toroidal field capability of NSTX. Calibrations carried out in February 2002, during the start of NSTX FY02 operations are essentially the same as recent calibration in June towards the end of NSTX FY02 operations.

4. IN-VESSEL NEUTRAL PRESSURE GAUGE

For pressure measurements inside the vessel we are developing a new fast ion gauge that is insensitive to the magnetic field direction along the toroidal and poloidal directions in NSTX. After initial experiments on a test stand, a proto-type gauge, referred to as the In-vessel Neutral Pressure (INP) gauge was used for pressure measurements behind the lower passive plates. A consequence of using an unshielded ion gauge in a magnetic field environment is that the emission current is considerably reduced during the presence of magnetic field[5]. Consequently a high filament emission current is needed. On NSTX we have operated this gauge with an emission current of 5-10mA, which is considerably larger than the 0.5mA used by the MIG. To withstand the magnetic forces and to prolong the life of the filament, this level of emission current requires a filament that has a diameter larger than used in the MIG. The gauge we constructed is cylindrical in shape with a central 0.17mm thick tungsten filament wire that is 1.5cm long. This is surrounded by a spiral stainless steel grid wire located at a radius of 0.56cm. A second spiral located at 0.76cm acts as the collector. Since the gauge is cylindrical, any changes to the field orientation along the radial direction should not matter. Such a gauge mounted radially on NSTX would see a radial field produced by the toroidal field coil and the ohmic solenoid or the poloidal field. To operate the gauge at the high levels of emission current a special controller was developed. The controller uses an AC filament voltage to heat the filament. The grid bias is variable from 180VDC to 250VDC. The bias on the filament is 30VDC. The resulting emission current is measured and the filament voltage adjusted manually. A feedback loop to automatically correct the emission current was not employed as the resulting time constants to heat a thick filament are about 200ms, and not very useful on a machine that normally has a pulse length of about 500ms. Instead, the emission current is measured in real time and used to correct the ion current signal. Initial test have been conducted on NSTX. The gauge has been calibrated at toroidal fields of 0.45 and 0.6T. The calibration is field dependent at lower field, but is relatively constant in the 0.45 to 0.6T range as shown in Figure 4.

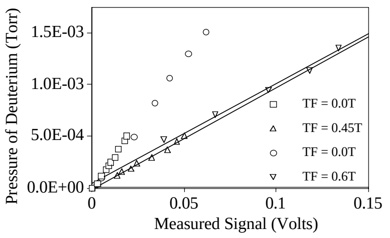

Figure 4: Calibration curves for the INP gauge. At a given pressure the signal output is higher during the presence of a magnetic field. In the 0.45 to 0.6T range, the calibration factor is approximately the same.

5. EXPERIMENTAL RESULTS

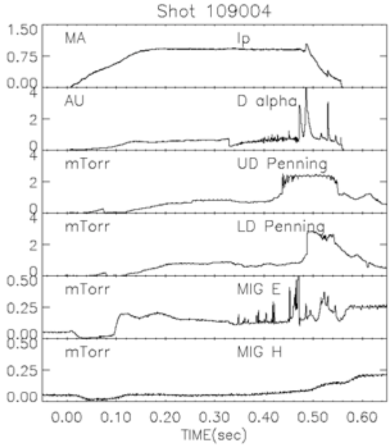

Figure 5: 900kA, 0.45T, double null fiducial discharge with no current in the PF2 coils. Shown from top to bottom are traces of plasma current, Dα line emission, upper divertor Penning gauge, lower divertor Penning gauge, the faster Bay-E micro ion gauge and the Bay-H micro ion gauge.

Figure 5 shows traces from a 900kA, 0.45T, double null, neutral beam heated inductive discharge with no current in the PF2 coils. The plasma discharge is initiated by gas fueling from the outboard side. At 95ms, gas injection from the high field side commences. This is clearly seen by the Bay-E MIG. This gas injection causes the upper and lower divertor pressures to increase, while the vessel pressure remains about the same or decreases slightly, indicating gas flow along the SOL (scrape off layer) into the divertor region. The discharge transitions to an H-mode at 328ms. A giant ELM is generated at 470ms, as shown by the spike in the Dα line emission. This as well as the smaller ELMs is also seen by the Bay-E MIG. Because of conductance limitations, the Bay-H MIG does not see these ELMs. At 478ms a Reconnection Event (RE) is initiated which causes the pressure in the lower divertor to rapidly increase. However, as shown by the upper divertor gauge, the pressure in the upper divertor region starts increasing as early as 400ms and increases rapidly at 435ms causing the divertor pressure to quickly saturate, well before the RE shows up on the plasma current trace. Interestingly, the plasma density as measured by an interferometer continues to increase until the time of the RE. Equilibrium reconstructions using the EFIT code show the plasma beta and confinement to degrade starting at about 400ms[6]. That there is an asymmetric behavior in an otherwise symmetric double null plasma is an important result for divertor pumping and heat load studies. Since NSTX generally operates in the lower single null configuration, there is far more diagnostic coverage of the lower divertor, however, such results indicate a need for improved understanding of differences in divertor behavior, and possible optimization of divertor configurations.

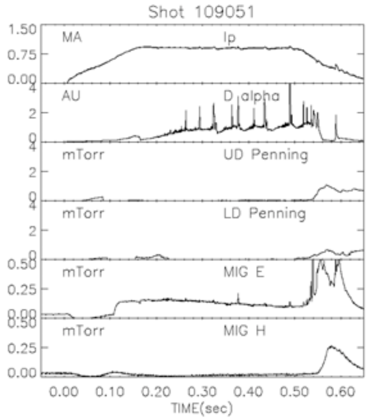

Figure 6: 900kA, 0.45T lower single null fiducial discharge with zero current in the PF1 coils. The sequence of traces is the same as in Figure 5.

In Figure 6, we show similar traces for a 900kA, 0.45T lower single null (LSN) discharge with zero current in the PF1 coils. An H-mode is initiated at 163ms. The sharp reduction in the Penning gauge signals is a feature seen in LSN discharges. This discharge is also fueled using the center stack gas injection system, but there is no buildup of divertor neutral pressure. This is probably because these discharges do not use the PF1 coils. Without current in the PF1 coils, at these times the SOL footprints are probably positioned away from the narrow gap between the divertor plates. The divertor Penning gauges measure pressure in the region behind the divertor plates which is a closed region, containing private flux. Since there is no SOL flow into this region, one expects the pressure here to drop. Because of the NSTX divertor geometry, the bulk of the SOL flow is exhausted into the vessel, at radii that are closer to the mid radius of the outer divertor plate or at radii much closer to the center stack, causing the NSTX divertor to resemble an open divertor configuration. Use of the PF1 coils seems to divert some of the outer SOL flows into the gap between the divertor plates as indicated by Figure 5. The increase in the lower divertor pressure during 150 to 230ms, is a feature reproduced in several of this sequence of discharges indicating that it appears to be a true pressure response and not an artifact of Penning discharge quenching, and also probably results from time variations in the SOL footprints that channel some flow into the divertor gap at these times.

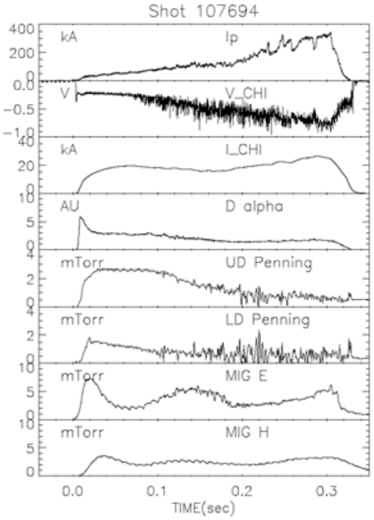

Figure 7: CHI produced discharge. The first three traces correspond to the CHI produced toroidal current, the CHI injector voltage and the injected current. The remaining traces show Dα line emission, upper divertor pressure, lower divertor pressure, Bay-E mid-plane and Bay-H mid-plane micro ion gauge pressures.

Discharge traces from Coaxial Helicity Injection (CHI) operation are shown in Figure 7. A general description of CHI discharges on NSTX can be found in Reference 2. In this discharge, from 50 to 300ms, the toroidal field is ramped up from 0.3 to 0.4T. At -20ms, a plenum containing gas is opened to the vessel using fast gas valves. This causes the gas to enter the vessel at about t = 0 through four ports located in the lower divertor plates. Soon after discharge initiation, there is a neutral pressure spike seen by the Bay-E and H micro ion gauges and the Dα signal monitor. Although gas is injected from the lower ports, the pressure in the upper divertor region saturates within the first 30ms. It stays saturated until 100ms. Thereafter the pressure in the upper divertor gradually decreases, even though the **E X B** drift is still into this region. After 250ms, the upper divertor pressure is similar in magnitude to that in the lower divertor. The initial fast drop in the upper divertor pressure is accompanied by an increase in the vessel pressure as seen by the mid-plane micro ion gauges. Presumably this gas fuels the plasma discharge, which continues to increase in current while the edge Dα signal continues to decrease. At present there is insufficient data to know how the density inside the discharge changes during the course of the 300ms long CHI discharge. The observation that the upper divertor pressure increases early on is an expected result. That during long pulses this pressure decreases and becomes closer in magnitude to that in the lower divertor is an unexpected new result. It is also useful to note that many CHI discharges end in an absorber arc at about 200ms (a condition when a localized discharge develops across the insulator in the top divertor), just when the pressure in this region has dropped sufficiently. This is the first experimental measurement of absorber neutral pressure during a long pulse CHI discharge and supports the previous conjecture that a combination of long field line length in the absorber region coupled with low gas pressure would satisfy a Paschen-like condition for breakdown. This suggests that intentional gas injection in the absorber region could suppress absorber arcs. This observation of upper divertor neutral depletion as well as mid-plane neutral pressure increases raises the question whether, once a CHI discharge has been initiated, subsequent gas injection could be provided by mid-plane gas injection, since SOL flows seem to provide the required charge carriers.

The INP gauge produces some of the features seen by the Bay-E MIG, such as responses to gas injection and ELM activity. It also shows differing behavior as operating conditions change. An interpretation of results from this gauge is beyond the scope of the present paper, as the gauge is still under development.

6. SUMMARY

Several fast neutral pressure gauges have started routine operations on NSTX. These are used to measure the edge and divertor pressure during inductive and coaxial helicity injected plasma operations. Modified, PDX-type Penning gauges have been quite helpful in characterizing divertor conditions during CHI, and ohmic operations. Two, shielded, fast Micro ion gauges at different toroidal locations on the vessel mid-plane are also routinely functional and are sensitive to fast pressure changes in the vessel. The magnetic shielding is remarkably effective for the full toroidal field capability of NSTX. For pressure measurements inside the vessel the new INP gauge is being developed, and has produced initial results during plasma operations.

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