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Abstract

Successful operation in NSTX of two prototype fast-response micro ionization gauges during plasma operations has motivated us to install five gauges at different toroidal and poloidal locations. These have a nitrogen equivalent lower pressure limit of a conventional ion gauge (~3 x 10^{-10} Torr) and an upper pressure limit of 50 mTorr. On NSTX, they have a useful operating range of 1 x 10^{-5} Torr to 4 mTorr in deuterium. The modified PDX-type Penning gauges are well suited for pressure measurements in the NSTX divertor where the toroidal field is relatively high. It is capable of operation over a pressure range of 1 x 10^{-5} Torr to 4 mTorr in deuterium. The gauge calibration has been stable for two years and the gauges have required no maintenance. Behind the NSTX outer divertor plates where the field is lower, an unshielded ion gauge of a new design has been installed.

I. Introduction

The National Spherical Torus Experiment [1] (NSTX) is designed to explore the physics of low toroidal aspect-ratio plasmas combining high beta and high confinement simultaneously. NSTX has a major radius of 0.85 m, minor radius of 0.68 m and plasma elongation up to 2.5. The nominal range in toroidal field is 0.3 to 0.6 T and plasma current up to 1.5 MA. The device is fueled using gas injection from piezo valves at four different locations on the machine, from two locations on the center stack, and from the lower divertor plate region. Neutral pressure gauges are needed for routine plasma operations and to provide edge neutral pressure data as input parameter for transport codes such as DEGAS2 and TRANSP. Neutral pressure measurements will also facilitate analysis of divertor pumping requirements. Because NSTX operates with several gas injection sources while exploring numerous plasma configurations, an understanding of neutral pressure behavior at different locations in the machine is needed. Eventually these measurements will be needed for future machines such as ITER. Because fast time scale measurements require the gauge to be present close to the plasma boundary, fast neutral pressure measurements – especially to establish edge neutral pressures is difficult as most gauges do not operate under conditions of strong magnetic fields. Because different types of gauges are suited for specific applications we are investigating the use of three different types of gauges for the purpose of exploring the operating range and capability of these gauges. These are shielded ion gauges, Penning gauges and unshielded ion gauges. These are described in the subsequent sections.

II. The Penning Gauges

Modified PDX-type Penning gauges [2,3] were installed on the upper and lower divertors of NSTX. The gauge, shown in Figure 1, has a cylindrical anode measuring 1.27 cm in diameter and 1.26 cm long. 2.6 cm^2 steel plates separated from the cylinder ends by 2.6

mm act as the cathode. Penning gauges were operated at bias voltages ranging from 2 kV to 5 kV. The maximum operating pressure increases with decreasing bias voltage. At a bias voltage of 2 kV, the gauge can operate at a pressure of up to 4 mTorr, however discharge initiation is unreliable at pressures below 5 x 10^{-4} Torr. A bias voltage of 3.12 kV was chosen as at this voltage the discharge initiation is reliable at a pressure of 1 x 10^{-4} Torr, while providing access to an upper pressure of 1.5 mTorr. The numerical value for the pressure range for the gauge is 1 x 10^{-5} Torr (at 5 kV) to 4 x 10^{-3} Torr (at 2 kV). Capability to remotely adjust the bias voltage should allow the gauge to operate over the pressure range of 1 x 10^{-5} to 4 mTorr. All numerical pressure values mentioned in this paper, unless stated otherwise, refer to deuterium neutral pressure.

Since installing them more than two years ago, these gauges have required no maintenance. The calibration data, shown in Figure 1, at a toroidal field of 0.45 T at the machine axis shows the calibration to have remained essentially unchanged over the past two years [4] even though NSTX has undergone four machine bakeout cycles and twenty five boronization cycles [5]. During bakeout the plasma facing components are maintained at 300 to 350^0 C for 4.5 days. The outer vessel is maintained at 150^0 C. During boronization 10 grams of deuterated trimethylboron (TMB) are deposited over a 140 minute period. This is followed by four hours of helium glow discharge cleaning [5]. These gauges are not isolated from the machine during these machine conditioning events. Components of the Penning gauge can be subjected to 250^0 C, however, the cable connections to the gauge will require modification to handle the higher temperature. The electrode dimensions and spacing are the same as that for Penning gauges used on PDX

[3], which operated at a toroidal field of about 2.5 T. This may suggest that these gauges could be used in the 5 T fields in ITER, however testing in a higher magnetic field device is needed to confirm this. The primary ionizing radiation sensitive material in the Penning gauge is an alumina insulator. Neutron and gamma dose rates of about 2 x 10^3 Gy/s are expected at the first wall of ITER [6] and less than this in regions that are shielded from direct line of sight from ionizing radiation. In a study conducted by Noda et al., it was concluded that from an electrical conductivity standpoint, the increased conductivity in alumina, under fusion reactor operating conditions is not considered to pose any significant problems [7]. This gauge may therefore be suitable for the harsh conditions encountered in ITER.

III. The Micro Ion gauges (MIG)

The Granville Phillips Micro Ion Gauge (MIG) No. 355001 is about 10 cm long with a maximum diameter of 7.3 cm. 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 configuration for fast pressure measurements during plasma operation. These have proved especially valuable for routine NSTX operations. Very successful operation of two of these gauges motivated us to install a total of five of these gauges at different toroidal and poloidal locations. The gauges installed two years ago have maintained their calibration. The calibration procedure involved emptying a pre-calibrated 5 Liter plenum containing gas into the NSTX vacuum vessel, which was isolated from the pumping system. The gas pressure in the 5 Liter plenum was accurately measured (to within 0.1%) using a new MKS baratron whose calibration was under warranty. The NSTX vessel pressure was measured using another new MKS baratron whose calibration was also under warranty. The pressure reading of the standard NSTX vessel pressure baratron agreed to within 0.1% of the pressure reading of new baratron. All pressure gauges were then calibrated based on the NSTX vacuum vessel volume and the fill pressure of the 5 Liter plenum.

The magnetic shielding is effective for the full 0.6 T on axis field capability of NSTX. These gauges, however, become contaminated if they are not isolated from the vacuum vessel during bakeout. This is probably because of the deposition of hydrocarbons on the gauge surfaces as the cold gauge (with respect to the high temperature vessel surfaces) acts as a pump collecting impurities. Contamination is exhibited by signal dropouts, which result is an overall noisy signal. A Granville Phillips 307 ion gauge controller with the Micro-Ion adapter (Granville Phillips Cat. No. 355002) was used to degas the gauge using the electron bombardment process. While degassing is able to restore most of its capability, the gauge never fully recovers to its original specifications. We have not investigated the possibility of keeping the gauge hot during bakeout. However, they do not seem to be affected by boronization and helium glow discharge cleaning. The micro ion gauge, if operated with the appropriate Granville Phillips ion gauge controller, has a useful nitrogen equivalent lower pressure limit a conventional ion gauge (~3 x 10^{-10} Torr) and an upper pressure limit of 50 mTorr. This controller was not chosen as it does not provide a fast system time response of about 5 – 20 ms that is desirable for real time pressure measurements. The operating range of the gauge with a modified Granville Phillips 270 controller is from 1 x 10^{-5} Torr to 4 mTorr (deuterium pressure) [4]. The 5 ms time response provided by the modified GP270 controller has allowed us to measure real time flow rates of the different gas injection systems on NSTX. In one experiment the NSTX outer mid plane gas injection valve was programmed to produce the same gas flow rate as that obtained from the center stack mid plane gas injection system to show that H-modes can be reliably initiated from the outside gas injection system if it can provide the same gas injection history as the center stack gas injection system [8]. A fast (5 – 20 ms) time response of the gauge has also been useful for neutral particle balance studies [9]. Edge neutral pressure measurements have also been used in yet unpublished TRANSP code calculations. A near term objective is to use the pressure measurements from the different gauges in DEGAS2 code calculations.

IV. The In-Vessel Neutral Pressure gauge (INP)

The advantage of the micro ion gauge is that it provides accurate neutral pressure measurements during plasma operations, but it is limited by the magnitude of the magnetic field that can be effectively shielded. This gauge cannot be installed inside the vacuum vessel as it is not designed to work in the magnetic fields within the vessel. The Penning gauge requires the presence of an external magnetic field for operation, so it can be installed inside the vessel but it is less accurate than the ion gauge. In order to improve pressure measurements inside the vessel, we have investigated both in laboratory setups as well as testing gauges on NSTX, the possibility of using an unshielded ion gauge. The In-Vessel Neutral Pressure gauge (INP) is a gauge configuration we have successfully used in NSTX during plasma discharges.

Conventional ion gauges have the electron emitting filament displaced form the radial center, while the ion collector is located at the radial center. This causes a radial asymmetry when the gauge is operated in the presence of an external magnetic field because the ion trajectory would be aligned with the direction of the external field. In the design chosen here, shown in Figure 2, the filament is located at the radial center and the collector and grid are both circular spirals. This arrangement maintains radial symmetry so long as the external magnetic field direction is in the radial direction with respect to the axis of the gauge. The filament is the central tungsten wire, which is surrounded by a stainless steel spiral wire, which acts as the grid. The outermost spiral is the collector. The filament wire is .18 mm x 2.5 cm long. The collector spiral is about 2.2 cm long. To increase filament lifetime the filament is heated using an alternating current source. The filament is energized just before a shot cycle and turned off immediately following the shot. The gauge is driven at moderate emission current levels of about 2 mA. This is similar to the levels of emission current used for the micro ion gauge, which varies from 0.5 to 2 mA depending on the maximum pressure range that is desired.

V. Behavior of gauges in a vacuum magnetic field and during plasma operations

The time response of the different pressure gauges when subjected to a step function rise in vacuum vessel pressure in shown in Figure 3. Shown from top to bottom are the upper divertor Penning gauge located in bay K-top and the lower divertor Penning gauge located in bay G-bottom. The MIG gauges located in bays E, L, C-top and C-mid plane. The In-Vessel Neutral Pressure (INP) gauge located in bay C-top. The labels A to L correspond to the twelve different bays in NSTX. The pumping duct is located in bay L.

The MIG-E is the fastest responding gauge. The other micro ion gauges respond more slowly because of conductance limitations. The data was collected when gas was injected into a 0.45 T toroidal field on axis vacuum discharge. The higher noise levels in the INP gauge may be related to the fact that this gauge is located inside the vessel, so it cannot be isolated during machine bakeout and so it is subject to some level of gauge contamination. This is an inherent difficulty with any gauge that needs to be installed inside the machine. In general the response time of the micro ion gauges ranges from 5 ms (for the bay-E gauge) to about 20 ms for the bay-L gauge. The Penning and INP gauges have an effective response time of about 30 ms.

Figure 4 shows neutral pressure response during plasma operations at 0.45 T. Shown from top to bottom are the plasma current and the signals from the different neutral pressure gauges. This is a lower single null discharge fueled by both the NSTX center-stack gas injection and gas injection from the outer vessel region. Arrival of gas from the center stack gas injection system is clearly observed by the bay-E MIG at about 80 ms. In general, the time response of the bay-C top INP gauge is similar to that of the bay-C top MIG, but these are located in different regions. The MIG is mounted on an external port, while the INP is located directly behind a divertor plate in an area that is under consideration for a divertor cryo pump installation. The MIG-L is located on the pumping duct, therefore sees lower pressure than the other gauges. The lower divertor Penning gauge is located in a region that sees little plasma flows during this type of plasma operation, therefore it sees lower pressure than the upper divertor gauge.

VI. Conclusions

Several fast neutral pressure gauges are routinely used in NSTX. Modified, PDX-type Penning gauges have been very reliable and have required no maintenance for over two years. They also seem to be the most resilient as far as gauge contamination is concerned when subjected to high temperature machine bakeout. The micro ion gauges provide the most accurate pressure measurements on a fast time scale. These need to be isolated from the machine during high temperature bakeout but are not affected by boronization and helium glow discharge cleaning. Successful initial neutral pressure measurements have been made using a new design In-Vessel Neutral Pressure gauge (INP gauge). This is an unshielded ion gauge that can be operated in the presence of external toroidal and poloidal magnetic fields.

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Figures captions

Figure 1: (a) The NSTX Penning gauge, (b) Pressure calibration curves from 2002 and a recent calibration from 2004. No maintenance work has been performed on these gauges during the past two years. The squares are data points from a recent 2004 calibration. The circles are calibration data from 2002. The smaller solid square and smaller solid circle are data from the lower divertor gauge. The larger open square and larger open circle are data from the upper divertor gauge.

Figure 2: The In-Vessel Neutral Pressure gauge (INP).

Figure 3: Time response of the different pressure gauges when subjected to a step function rise in vacuum vessel pressure.

Figure 4: Neutral pressure response during plasma operations at 0.45 T. The top trace shows the plasma current. The remaining traces are from the neutral pressure gauges.

Figure 1

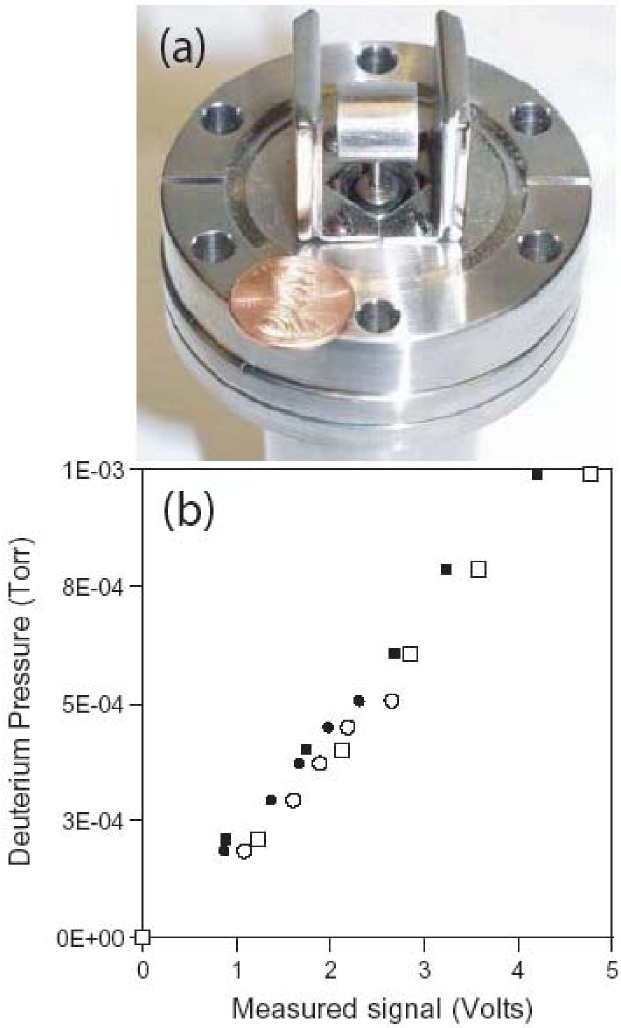
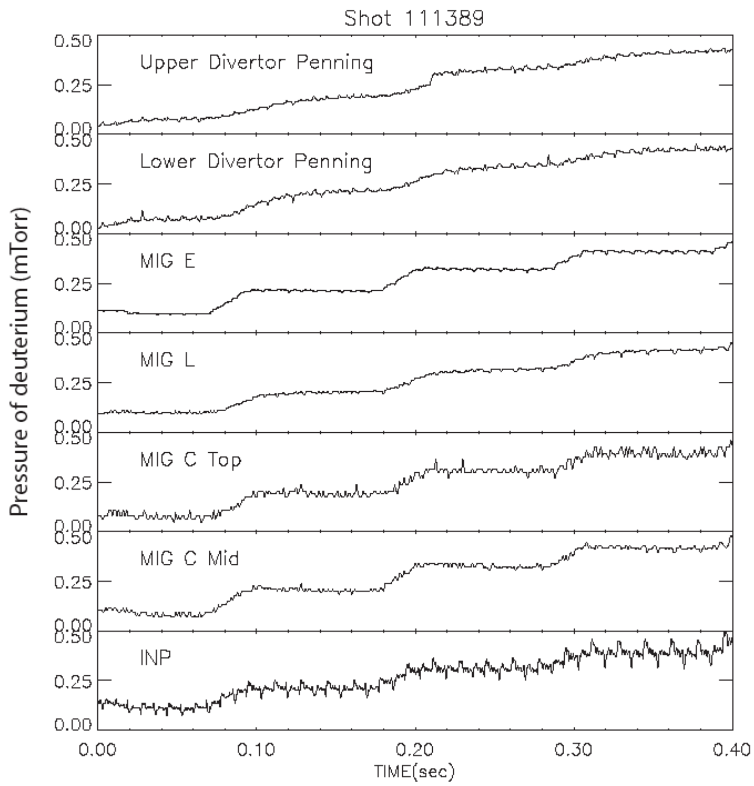

(a)
(b)
1E-03
8E-04
5E-04
3E-04
0E+00
0
1
2
3
4
5
Deuterium Pressure (Torr)
Measured signal (Volts)

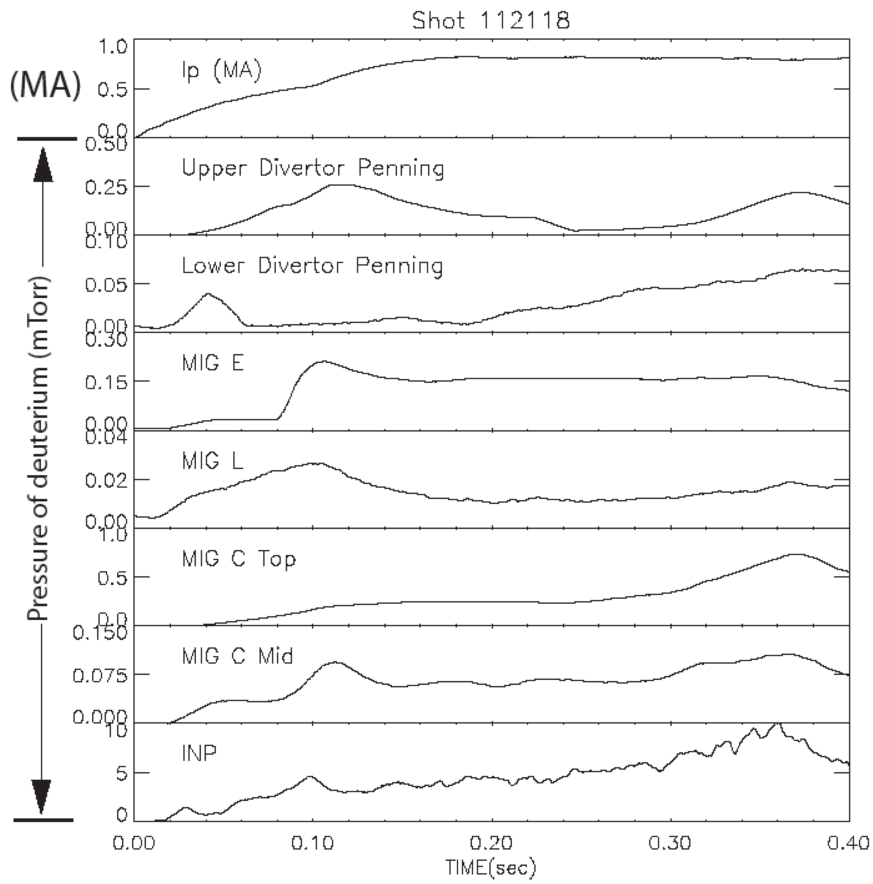
Figure 2

Figure 3



Shot 111389
Upper Divertor Penning
Lower Divertor Penning
MIG E
MIG L
MIG C Top
MIG C Mid
INP
Pressure of deuterium (mTorr)
0.50
0.25
0.00
0.00
0.10
0.20
0.30
0.40
TIME(sec)

Figure 4


Shot 112118
(MA)
Ip (MA)
Upper Divertor Penning
Lower Divertor Penning
MIG E
MIG L
MIG C Top
MIG C Mid
INP
Pressure of deuterium (mTorr)
1.0
0.5
0.0
0.50
0.25
0.00
0.10
0.05
0.00
0.30
0.15
0.00
0.04
0.02
0.00
1.0
0.5
0.0
0.150
0.075
0.000
10
5
0
0.00
0.10
0.20
0.30
0.40
TIME(sec)

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