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Lh. 61

NOVEMBER 1981

PPPL-1852
UC-20A,F

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PRESSURE MEASUREMENTS IN MAGNETIC-FUSION DEVICES

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ABSTRACT

Accurate pressure measurements are important in magnetic fusion devices for: (1) plasma diagnostic measurements of particle balance and ion temperature; (2) discharge cleaning optimization; (3) vacuum system performance; and (4) tritium accountability. This paper reviews the application, required accuracy, and suitable instrumentation for these measurements. Demonstrated uses of ionization-type and capacitance-diaphragm gauges for various pressure and gas-flow measurements in tokamaks are presented, with specific reference to the effects of magnetic fields on gauge performance and the problems associated with gauge calibration.

Presented at the 28th National Symposium of the American Vacuum Society held at Anaheim, California, November 2-6, 1981.

Introduction

There are a variety of pressure and gas flow measurements that have been identified as necessary or useful for the operation of magnetic fusion devices. Accurate pressure measurements are important for fundamental measurements of particle balance and ion temperature; (2) discharge cleaning optimization; (3) vacuum system design and testing; and (4) tritium accountability. The inaccuracy and variability (to conditioning, environment, gas type, etc.) of commonly used thermal conduction gauges for low vacuum measurements (10^{-1} -10^{4} Pa) and ionization gauges for high vacuum ($\leq 10^{-1}$ Pa) measurements can complicate the application of these gauge types for measurements in fusion devices. Capacitance diaphragm manometers offer an attractive alternative to the conventional gauges because of the insensitivity of the transducer elements to magnetic field effects. However, problems of mechanically or thermally induced noise must be dealt with. Capacitance manometers are also useful as secondary standards for calibrating other types of pressure gauges over the pressure range of 10^{-3} -10^{6} Pa.

The first section of this paper reviews the various applications and relative importance of pressure measurements in magnetic fusion devices. In Section II, a brief review of the relevant literature is presented, followed by a comparison of the various gauging methods which have been applied. In Section III the application problems associated with the use of ionization gauges and capacitance manometers in fusion devices are presented. Included in Section III are a discussion of magnetic field effects, transient response, calibration methods, plasma-induced noise, and tritium effects. In Section IV, examples of important gas-flow and pressure measurements from several presently operating tokamaks are presented.

I. Categorization of Vacuum/Pressure Measurements in Fusion Devices

A considerable range of pressure, vacuum, and gas flow measurements are required for the design and operation of magnetic fusion devices and the associated vacuum hardware (pumping systems, neutral beam injectors, diagostics, etc.). A tabulation[1] of these measurements with estimates of the required accuracy and range is given in Table 1. The listed measurements in Table 1 have been grouped according to the level of accuracy required in the measurement. It should be noted for comparison that standard commercially available ionization gauges for the high vacuum range ($\leq 10^{-1}$ Pa) have absolute accuracies[2] which can vary by as much as ±100%.

The class of measurements requiring the highest accuracy in the fusion program is supporting surface physics measurements. Because of safety reasons it is desirable to measure the tritium retention in solids, the tritium pressure in gas-handling systems, and the total stored hydrogen-isotope content in cryopanels as accurately as possible. A level of ±1% is suggested.

The second class of vacuum measurements have a suggested accuracy of ±5%, and concern the measurement of fill pressures, and gas injection quantities and rates within the primary vacuum vessel of a fusion device, and supporting vacuum hardware, such as neutral beam injectors (NBI) and charge exchange (CX) diagnostics. The gas fill quantity is a fundamental parameter affecting the plasma performance of a fusion device and necessary for proper calculation of the particle balance.[3] The desired accuracy of these measurements (±5%) is no more than routinely required for other basic plasma parameters such as plasma density and temperature. Accurate measurement of the fill pressure in transition ducts of neutral beam injectors is necessary to properly evaluate and minimize reionization losses.[4,5]

A third class of measurements concerns diagnostics of fusion device systems, and here the required accuracy can be relaxed to ±10%. However, within this class of measurements, inaccuracies in pressure measurements can be straightforwardly translated into direct project costs. For example, residual gas analyzers (RGA) have proven to be the most useful diagnostics for optimizing and quantifying vacuum vessel conditioning procedures such as discharge cleaning.[6] RGA's should be calibrated over the entire operating range (10^{-10} -10^{-2} Pa) for accurate measurement for machine leak rates, outgassing rates, discharge cleaning effectiveness and endpoint observation.

The accuracies of the remaining class of measurements listed in Table 1, including base pressures, outgassing and leak rates, can be relaxed to ±100%, which is more than likely the accuracy to which such parameters are presently measured. If these quantitites are substantially below the values where vessel recontamination rates become significant, there is no justification of higher accuracy.

II. *Review of the Literature*

Most of the existing literature on pressure measurements in fusion devices is outdated. A recent article by Berman[7] published in this journal discussed the use of ionization-type gauges for neutral density measurements. Unfortunately, all of the measurements quoted in this article were performed on 1960-era devices. An important concern in the attempts to obtain pressure measurements on the first-generation plasma devices was the need for high transient response. Since discharge durations were only of the order of 1 ms, gauge response times of 10-100 μs were desired to infer the neutral density temporal behavior during the discharge. The fast response requirement also necessarily required close-coupling of the gauge to the plasma vacuum vessel which exacerbates the problem of plasma-induced noise on the gauge ion collection electrode. Therefore, much of the early (1960-era) literature in this field is concerned with ionization-type gauges with gauge tube structures that minimized response time, and required suppression or modulation electrodes to minimize spurious signals. In addition, there was no attempt in these early evices to instrument the gas fill systems; in view of the short discharge duration, simple steady gas fills were sufficient.

In contrast, the discharge duration has been extended to beyond 1 s for the present generation of large tokamaks, relaxing transient response requirements to 1-10 ms for vacuum vessel pressure measurements. The addition of programmed gas injection systems for plasma density control,[8] and neutral beam injection systems with programmed gas inputs[9] have given rise to the need for instrumented gas flow measurements with similar response-time (~10 ms) requirements.

Relatively few gauge-types have been applied to pressure measurements in fusion devices. For vacuum vessel total pressure measurements in the range of (10^{-1} -10^{-5}) Pa: hot filament ionization gauges,[10-14] cold cathode Penning-type[15,16] and magnetron gauges[17] have been used. Capacitance manometers have been applied to pressure measurements larger than 10^{-3} Pa. For partial pressure measurements over the range of 10^{-10} -10^{-2}) Pa, quadrupole-type mass spectrometers have been used,[18-22] usually for diagnosis of discharge cleaning effectiveness. For quantitative gas flow measurements, hot-filament ionization gauges[23] and thermal conductivity gauges[24] have been used on the downstream side of gas-injector assemblies, and capacitance manometers have been used for both upstream[25] and downstream[26] gas injector measurements.

III. Application Problems

A. Hot-filamant Ionization Gauges

The most commonly-applied gauge-types for pressure measurements in fusion devices, are the various forms of hot-filament ionization gauges, because of their large pressure range and short-transient response. Measurements have been performed with three common electrode geometries: The conventional triode, Bayard-Alpert, and Schulz-Phelps configurations. With the use of ion gauges, the most troublesome application problems are the effects of magnetic fields and plasma-induced spurious signals. The effects of magnetic fields for the various ion-gauge configurations have been discussed by Berman[7] and Martin[27]. Generally, ion gauge operation is quite sensitive to an arbitrarily applied magnetic field because of the effect of the B-field on the low energy electron trajectories. Trajectory calculations for typical electrode configurations without external B-fields have been performed by Pittaway[28], and the effect of low intensity (<100 gauss) fields has been investigated by Hseuh.[29] For the conventional triode and Bayard-Alpert (B-A) gauges the sensitivity is a strong function of both the magnitude and direction of the applied field. For B-fields applied transverse to electrode E-fields, sensitivities are affected by fields as low as a few gauss, and are reduced to impractical levels at fields of ~100 gauss. For operation of the triode or B-A gauge at low fields that vary in magnitude or direction, and for operation in fields higher than 100 gauss, external magnetic shielding is required.

Figure 1a shows the shield configuration used for B-A gauges installed on the PDX tokamak to monitor the torus pressure. The gauges are located on a high conductance duct to the torus at a radius equal to the outer circumference of the toroidal field coils. The ambient fields at this location include toroidal field components up to 7 kG and vertical field components up to 0.5 kG. These relatively high fields require a compound shield, where the outer shield is a medium permeability material (soft iron), that can withstand a high degree of magnetization before saturation, and the inner shield is a material (mu-metal) with a very high permeability (μ = 85,000). The cylindrical shield was designed[30] with a length/diameter ratio $\gtrsim 3$ to minimize stray-field effects at the open ends of the shield where the vacuum and electrical connections are made. Such a shield is necessarily most effective for B-fields directed perpendicular to the cylindrical axis. In Section IV torus pressure data measured with the gauge/shield configuration of Fig. 1a are shown.

Ionization gages of the Schulz-Phelps type[31], i.e., with a linear electrode geometry with minimal electrode spacing (Fig. 1b) can be operated in B-fields without external shielding if the B-field is oriented parallel to the gauge E-field.

In general the sensitivity of the Schulz-Phelps gauge will not be independent of the ambient field because the ionizing electron path will be lengthened by Larmor-orbiting about the B-field axis. Martin[27] has shown that the field dependence of a Schulz-Phelps gauge with 0.2 cm electrode spacings is negligible up to a parallel applied field of 1.5 kG. A similar gauge, constructed by Lewin and Martin[32] with larger electrode spacings (1-2 cm) to increase sensitivity, showed a relatively small drop in sensitivity (30%) over the investigated range ot applied B-field; however, the gauge showed a factor of three drop in sensitivity over the pressure range of (10^{-3} -10^{-1}) Pa. A more recent test of a commercially available Schulz-Phelps gauge in a static applied B-field by Mioduszewski and Edmonds[33] showed a sensitivity which was independent of the field up to 200 gauss and then decreased by 70% at 700 gauss. The gauge sensitivity decreased by 20% over the pressure range of (10^{-2} -1) Pa.

An important practical consideration with the use of unshielded hot filament ionization gauges in magnetic environments is the need to protect the filament against breakage by induced Lorentz forces. Usually the filament is heated with an a.c. current (1-20 kHz), however, it is then necessary to filter this frequency component from the ion current when a high bandwidth electrometer is used for a fast-response gauge.

B. Cold Cathode Gauges

An alternative to the hot filament ionization gauge, which sacrifices accuracy and reproducibility for simplification of hardware, is the cold-cathode ionization gauge. Of the three basic configurations, the Penning gauge,[34] magnetron gauge,[35] and inverted magnetron,[36] only the Penning gauge has the broadest range of applicability as a function of applied B-field. For the magnetron gauge the sensitivity will decrease to zero when the applied B-field is sufficient to entrap the electrons within the vicinity of the cathode on small radius cycloidal orbits, such that the energy attained by orbiting electrons is below ionization thresholds.[37] In contrast, investigations of the Penning discharge[38] show that the discharge current (which is proportional to the pressure) is strongly dependent on the applied B-field at low fields but at higher fields the dependence is small with no evidence of a high-field limit to operation. The transition field (B_{tr}) between the field-dependent mode and the field-independent mode is a function of the anode radius (r_a), anode-cathode potential (V_a), and weakly dependent on the pressure (P)[39]:

$$B_{tr} = \frac{7.63 \sqrt{V_a \text{ (volts)}}}{r_a \text{ (cm) } P^{.05} \text{ (Torr)}}$$

A disadvantage of cold-cathode discharges (particularly the Penning discharge) is that depending on the electrode geometry, applied fields, and pressure range, the discharge current is not a linear function of the pressure. Plasma oscillations and varying electrode surface conditions, giving rise to different mode structures in the discharge, cause the non-linearities.[38] A second problem concerns the well-known difficulty of igniting a Penning discharge (particularly at low pressures) since field emission is the original source of electrons in the discharge. When used for vacuum gauging a source of external ionization such as a pulsed filament,[40] RF pulse,[15] or radioactive foil,[41] has been applied to trigger the discharge.

The simplest cold-cathode gauge-type to apply to fusion applications is the Penning configuration where the magnetic field necessary to sustain the Penning discharge is supplied entirely by the confining B-field of the fusion device. Thus, the need for magnetic shielding or external support of magnetic material is eliminated. Figure 1c shows a Penning gauge designed for monitoring the pressure at multiple locations in the divertor chamber of the PDX tokamak.

The stainless steel housing of the gauge serves as the cathode, and the pressure signal is monitored by measuring the anode power supply. A ceramic break and a grounded grid serve to isolate the gauge from spurious pick-up from vacuum vessel currents and plasma particles, respectively. Figure 2, which shows calibration curves of this gauge for various applied magnetic fields, indicates that an accuracy of ±20% is achieved for D_2 over the range 10^{-3} -10^{-1} Pa. Data taken with an array of these gauges is given in Section IV.

C. Gauge Location

An important concern with regard to the application of ionization gauges on fusion devices is the placement of gauges on the vacuum vessel. The nature of the connection of the gauge to the vacuum vessel can affect the time-response and the susceptibility to spurious pick-up. A direct conection of the gauge to the vacuum vessel would minimize vacuum time constants to the minimum value of approximately V/C, where V is the gauge volume and C the conductance of the gauge aperture. However, this configuration is highly susceptible to plasma-induced spurious signals if ion-collection electrodes are exposed to line-of-sight (or glancing incidence line-of-sight) to the plasma volume. Grounded grids can suppress charged-particles but do not impede photon or charge-exchange neutrals, (where typical soft x-ray[42] and charge-exchange[43] fluxes in tokamaks would be ~10^{15} cm^{-2} $.s^{-1}$ and 10^{14} cm^{-2} $.s^{-1}$ respectively). Location of the gauge such that plasma emissions must reflect from more than one surface before entering the gauge, is the simplest method for minimizing spurious pick-up. The sacrifice in response time is acceptable for the present generation of large devices. (See Section IV).

An arrangement of the gauge such that hot-gas particles must reflect off one or more metal surfaces before entering the gauge ionization volume also simplifies the calibration procedure. An ionization gauge is a density (n) detector[44] and not a fundamental measurement of the system pressure (nkT). The usual calibration procedure relies on correlating the ion current produced by the density of a room temperature gas in the ionization volume. Therefore, for such a calibration to remain valid when interpreting data measured on a fusion device, hot particles emitted by the plasma must thermalize by wall collisions before entering the gauge volume. This would not be a concern for a gauge which measured the true kinetic pressure such as a capacitance manometer.

D. Calibration Procedures

The calibration procedure is an important practical concern in the application of any gauging method to fusion devices. Because of the hostile electromagnetic and physical environment of a fusion device, it is prudent to incorporate an in-situ method of gauge calibration of the device. Primary high vacuum standards[45] are inappropriate for this purpose because of their complexity and inconvenience of operation. However, a secondary transfer standard such as a high accuracy capacitance diaphragm manometer[46] or the newly-developed spinning rotor gauge[47] is useful for in-situ calibrations. With certain types of capacitance manometers, 10% calibrations are possible over the range (10^{-3} -10^{-1}) Pa, and with the spinning rotor gauge a 2% calibration is possible over an extended range (10^{-5}-1) Pa.

For proper calibration of any of the ionization-type gauges discussed above, it is important to check for possible changes in calibration caused by the applied magnetic fields or spurious signal pick-up on the ion collection electrode during exposure to plasma. The former effect can be checked by establishing a static pressure in the device and measuring the gauge response as various magnetic systems are tested through the operational range. Field-effects for all systems except the stray-field induced by circulating plasma currents can be checked in this manner. Spurious signal pick-up in the case of hot-filament ionization gauges can be checked by comparing the gauge response during plasma exposure with or without emission current.

E. Capacitance Diaphragm Manometers

An alternative gauge-type for pressure measurements in fusion devices is the present generation of capacitance diaphragm manometers (CM). The CM gauges have several distinct advantages over the use of ionization-type gauges in the intermediate vacuum range ($\lesssim 10^{-1}$ Pa) and thermal-conductivity based gauges in the low vacuum range ($\gtrsim 10^{-1}$ Pa): (1) high accuracy and reproducibility; (2) measurements independent of the gas specie or composition; and (3) sensor elements which appear to be insensitive to interference from magnetic fields, although the conditioning electronics require proper shielding.

The latter effect (3) has not been extensively tested. However, the author has tested several types of capacitance manometers for the effects of static magnetic fields prior to the selection of these gauges as gas-flow monitors in the PDX gas injection system.[25] The tested gauges were commercially available[48] with the sensor head separated from the conditioning electronics with shielded cables, so that the sensor head or the electronics package could be separately exposed to the magnetic field. No magnetic materials were used in the construction of the sensor heads, the diaphragm material was either stainless steel or Inconel. The details of the test procedure are described in Ref. 49. The results are the following: no deviation in pressure reading above the short-term readability was measured for exposure of the sensor heads to static fields of 6.25 kG. However, the conditioning electronics package was found to be quite sensitive to magnetic fields because of the presence of an inductive bridge circuit which translates the diaphragm deflection to an electrical signal. Thus, for most applications of such gauges on fusion devices, the electronics package would require magnetic shielding. Subsequent use of the same type of capacitance manometer in the PDX gas-injection system showed that the sensor heads are insensitive to the normal magnetic environment in the near-field of the tokamak where B-fields as high as 8 kG are present.

For use of capacitance manometers as secondary standards the time-response of the sensor is not an important factor since most calibrations involve static measurements. However, for the application described above, as a sensor for gas-flow measurements, a reasonable response-time is desired. With proper choice of the dimensions of the associated piping, time-constants of the order of 10 ms can be achieved.

There are several important characteristics which constrain the use of capacitance manometers on fusion devices: (1) the sensor heads are microphonic and need to be vibration isolated in many cases to insure optimum performance; (2) the ultimate accuracy is limited by the thermal fluctuations of the sensor head. Temperature control is required for optimum performance.

E. Tritium Effects

A final application problem with pressure measurements in fusion devices concerns the possible effects of tritium on any of the gauging methods thus far considered, as the next generation of fusion devices will include two fueled with D-T (TFTR, JET). For measurement of tritium pressures higher than 10^2 Pa with capacitance manometers, it is necessary to use absolute sensors with the deflection electrodes located on the reference (unexposed) side of the diaphragm. Otherwise, β-emission will effect the dielectric constant of the diaphragm-electrode capacitance and thus influence the pressure reading.[50] Where absolute sensor heads are inappropriate, differential sensors of the wet-wet type are available wherein the deflection of a dual diaphragm is measured by a strain gauge bonded between the two elements.[51]

There appear to be no serious effects of tritium exposure on the operation of hot-filament ionization gauges. A recent study by Malinowski[52] showed that the combined effects of soft x-ray emission and ^{3}He ion collection within a Bayard-Alpert gauge exposed to 10^{-4} Pa of tritium are equivalent to a pressure reading of less than 10^{-9} Pa.

IV. Recent Pressure Measurements in Tokamaks

A. Gas-Fueling Measurements in PDX

The PDX tokamak[53-54] at Princeton Plasma Physics Laboratory is a large magnetic fusion device which went into operation in 1979 to study magnetic divertor physics, plasma impurity behavior, and plasma heating by high power neutral beam injection. An important diagnostic measurement for any of the above studies is the total gas injection quantity and rate required to fuel a particular discharge. A schematic of the gauging on the PDX gas injection system[25] is shown in Fig. 3. Gas for plasma fueling (usually H_2, D_2, or He) is injected into the torus at four midplane locations through piezoelectrically-controlled fast-valves (PV_1, PV_2). The gas injection valves are normally programmed to fill the torus to a preset pressure (typically 10^{-2} Pa) prior to discharge initiation, followed by feedback control of the gas injection to maintain a particular plasma density or density waveform. The total quantity of gas which flows through an injection valve is recorded by measuring the decrease in absolute pressure with capacitance manometers D_1 or D_2 in a fixed ballast volume on the supply line of the injection valves. The gas injection rate is obtained by differentiating the gas flow measurement. The two capacitance manometers (MKS type 221A) span different full scale ranges by a factor of ten; thus D_1 is used for monitoring lower flow rates of (0.5-50) Torr-liters/sec and D_2 is used for monitoring flow rates of 5-500 Torr-liters/sec. Fig. 4a shows an example of PDX gas flow data where one gas injection valve is pulsed with a two-step waveform into the vacuum vessel without plasma interaction. Figure 4b shows the subsequent response of the torus pressure as measured by one of two fast ion gauges. These ion gauges are configured according to the design given in Fig. 1a and are located on high conductance vacuum pumping ducts connected to the torus at the elevation of the divertor chambers. The net pumping speed within the torus can be extracted from the exponential decay of the torus pressure signal. These gauges have been absolutely calibrated for the injection gas (H_2) by comparison with an additional high sensitivity capacitance manometer system (MKS type 310 BHS-1) also connected to the torus volume. Figures 5a and 5b show PDX gas flow and pressure data during a typical high power discharge. The first plateau in the gas fill waveform (Fig. 5a) is the quantity injected for the torus prefill pressure, and the remainder of the waveform is the quantity required by the plasma density programming.

The torus pressure waveform in Fig. 5b shows the rise in system pressure from a base pressure ($<10^{-5}$ Pa) to the prefill pressure (A-B), followed by a decrease during the ionization and current build-up phase of the discharge (B-C), followed by the steady-state portion of the discharge (C-D), where the pressure signal images the plasma density behavior. At point D, the gas-flow was turned off and the torus pressure decays as the plasma density decays. From the density decay following point D, and the gas-flow rate immediately preceding point D, the gas fueling efficiency can be extracted for the achieved plasma density.[3]

Comparison of Figs. 4a, b and 5a, b shows that there are no significant magnetic field effects on the capacitance manometer performance. The time-response of the capacitance manometers for fill/flow measurements is quite acceptable. Figure 6 shows the response of the fill/flow manometer and the torus pressure ion gauge to the same gas pulse. From these data it is estimated that the time-response of the combination injection-valve orifice and torus pressure gauging is of the order of 10 ms, and the time-response of the fill/flow gauging and associated piping is of the order 50 ms. The latter time-response could easily be improved if larger diameter (>1 cm), shorter length (<25 cm) piping were used to connect the fill/flow gauging to the injection valves.

B. Comparison of Exhaust Pressures in Diverted Plasmas

An important parameter affecting the efficiency of a magnetic divertor is the exhaust pressure, since the removal rate of any divertor pump will be proportional to this pressure. Preliminary measurements are shown in Fig. 7 for the dependence of divertor (exhaust) pressure as a function of plasma density for three large tokamaks: PDX, ASDEX[55] and DIII[56] operated in the divertor mode. The sharp-rise in exhaust pressure occurs at a density where the plasma scrape-off becomes opaque to incident neutral gas.

A concern in the measurement of exhaust pressures in the divertor chambers of the PDX tokamak was the possibility of toroidal variation due to non-uniform titanium sublimation. A series of Penning gauges configured to the design of Fig. 1c was distributed throughout the divertor chamber to monitor spatially varying exhaust pressure. Figure 8 shows the output from the Penning gauge array during a 4-null-diverted discharge, where little spatial variation in chamber pressure is expected. Of the 15 Penning gauges installed on the PDX torus, typically 6-8 of the gauges will trigger before the initiation of the discharge as the toroidal field is ramped to the steady-state value (15 kG at the gauge location). The agreement between the operating Penning gauges and the pressure measurement with the shielded Bayard-Alpert gauges is good.

C. Duct-Pressure Measurements in Pumped-Limiter Experiments

An important development in tokamak physics has been the recent demonstration of the passive pumped-limiter concept for removing particles from the plasma volume. The neutral pressures which build up behind such a limiter are in a range (~10 Pa) beyond the linear region for ion gauges but ideally suited for capacitance manometers.

On the Alcator-A tokamak,[57] a capacitance manometer (MKS type 317 BHS-1) is located on a diagnostic duct which is partially occluded by a poloidal limiter. Figure 9a shows the time-evolution of the duct pressure during a high density discharge. A similar experiment has been performed with a moveable "scoop" limiter installed on the PDX tokamak.[58] Figure 9b shows the increase in duct pressure (also measured with a capacitance manometer) as the limiter is moved toward the plasma separatrix.

V. Summary

Pressure measurements on fusion devices serve a variety of purposes including: fundamental measurements of the edge-neutral density and neutral particle balance; and parameter mesurements necessary for quantification and calibration of neutral beam injectors, charge-exchange diagnostics, and vacuum-pumping components. Hot-filament ionization gauges can be adapted for these measurements with proper care for magnetic field effects and plasma-induced spurious pick-up. Penning ionization gauges, though less accurate, can be used on fusion devices without magnetic shielding. Finally, capacitance manometers have a demonstrated utility for many of the pressure measurements encountered on fusion devices and have the advantage of high accuracy, measurement independent of gas composition, and insensitivity to magnetic field effects.

Acknowledgement:

The author wishes to acknowledge helpful discussion of this subject with S. Cohen, J. De Grassie, R. Ellefson, M. Malinowski, D. Meade, D. Overskei, K. Owens, W. Poschenrieder, C. Tilford, F. Wagner, and thanks T. Bennett, W. Blanchard, T. Provost, W. Rauch, and M. Waldman for technical assistance. This work was supported by U.S. DOE Contract #AC02-76-CHO-3073.

TABLE 1: PRESSURE MEASUREMENTS IN FUSION DEVICES

MEASUREMENT	ACCURACY	RANGE	IMPACT
BASIC OPERATION			
Fill Pressure	±5%	10^{-4} -10^{-1} Pa	Plasma Performance; Particle Balance
Fill Quantity/Rate	±5%	10^{-1} -10^{5} Pa-1/s	Plasma Performance; Particle Balance
NBI AND CX DIAGNOSTICS			
NBI Fill Quantity/Rate	±5%	10^{2} - 10^{3} Pa-1/s	Source Performance
NBI Neutralizer Pressure	±5%	10^{-3} -1 Pa	Neutralization Efficiency
NBI Transition Duct Pressure	±5%	10^{-3} -1 Pa	Reionization Efficiency
CX Diagnostic Neutralizer Pressure	±5%	10^{-3} -1 Pa	Stripping Efficiency
CX Diagnostic Duct Pressure	±5%	10^{-3} -1 Pa	Reionization Efficiency
VACUUM SYSTEM OPERATION			
RGA Calibration	±10%	10^{-10} -10^{-2} Pa	Discharge Cleaning Efficiency; End Points
Pumping Speeds	±10%	10^{2} -10^{6} 1/s	Vacuum System Costs; Discharge Cleaning Efficiency; Vacuum System Performance
Base Pressures	±100%	$\leq 10^{-5}$ Pa	Vacuum System Peformance
Outgassing Rates	±100%	$\leq 10^{-6}$ Pa-1/s • cm^{2}	Vacuum System Performance; Materials Evaluation
Leak Rates	±100%	$\leq 10^{-3}$ Pa-1/s	Vacuum System Performance
SUPPORTING SURFACE PHYSICS			
Hydrogen Isotope Retention	±1%		Recycling Rates; Tritium Accountability
Getter Performance	±1%		Surface Pumping Development
Total H Flow into Cryopanels	±1%		Safety (H_2 Explosion Limit)

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Figure Captions

Figure 1. Schematic diagrams of ionization gauge configurations useful for fusion device applications: (a) the magnetically-shielded Bayard-Alpert gauge used for torus pressure measurements on the PDX tokamak; (b) the Schulz-Phelps gauge configuration which can be operated unshielded in external B-fields when oriented as shown; and (c) the Penning cold-cathode gauge which can be operated in high B-fields parallel to the anode axis.

Figure 2. Calibration curves for the Penning ion gauge configuration of Fig. 1C as a function of the applied magnetic field in kilogauss. The voltage applied across the anode-cathode was 4 kV.

Figure 3. Gauge configuration for measurement of the total gas flow and flow-rate for the PDX tokamak gas injection system. PV_1 and PV_2 are piezoelectrically-controlled gas-injection valves. D_1 and D_2 are differential capacitance manometers for measuring gas-flow rates of (0.5-50) Torr-liters/sec. and (5-500) Torr-liters/sec., respectively.

Figure 4. Examples of the data generated by the gas-flow monitors and torus pressure ion gauges installed on the PDX tokamak. Figures 4a,b show data recorded when H_2 gas was injected into the torus without plasma to measure the torus pumping speed. A "gauge factor" is plotted with the ion gauge data to indicate the relative calibration of the torus pressure with respect to various gas species. The N_2 equivalent pressure is plotted for a gauge factor of 1.0 and the H_2 equivalent pressure is plotted for a gauge factor of 2.8.

Figure 5. Gas flow (a) and torus pressure (b) data recorded during a plasma discharge in PDX. The average plasma density $\langle n_e \rangle$ is shown in units of 10^{13} cm^{-3}.

Figure 6. (a) Time-response of the PDX torus fast ion gauge. (b) Time response of the PDX fill/flow capacitance manometers. Both curves were recorded as one of the torus gas-injection valves was pulsed for 10 ms at 405 ms.

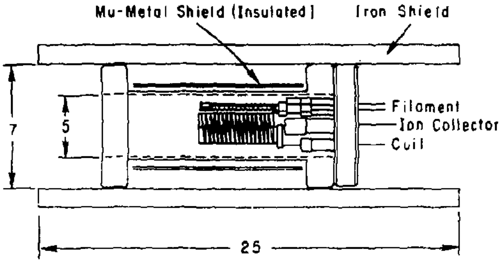
Figure 7. Divertor chamber pressures as a function of the average plasma density $\langle n_e \rangle$ for three large tokamaks operated in the divertor-mode.

Figure 8. The response to a diverted discharge of an array of Penning ion gauges distributed around the PDX torus. The plasma density $\langle n_e \rangle$ waveform for this discharge is similar to that shown in Fig. 5b.

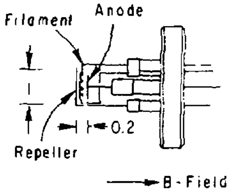
Figure 9. (a) Temporal evolution of the duct pressure behind the poloidal limiter of the Alcator-A tokamak.[57] (b) Variation of the duct pressure behind a moveable limiter in the PDX tokamak[58] as the limiter is moved toward the plasma separatrix at 176 cm.

81X0930

(a) Shielded Bayard-Alpert Gauge



(b) Schulz – Phelps Gauge



(c) Penning Ion Guage

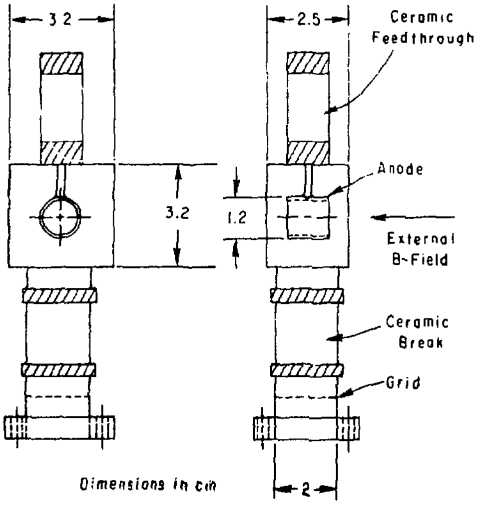


Fig. 1

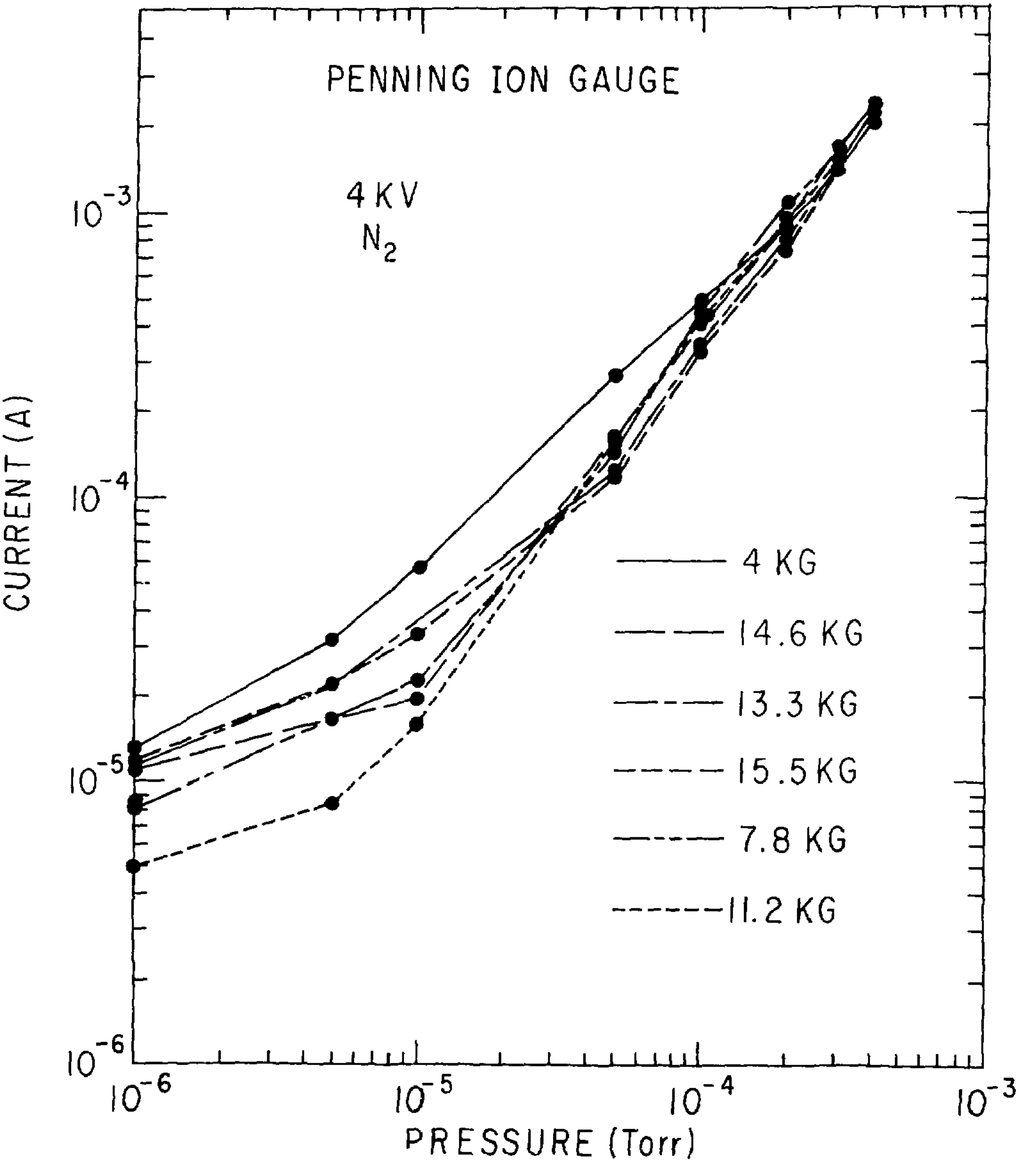

PENNING ION GAUGE
4 KV
N_2
CURRENT (A)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
PRESSURE (Torr)
10^{-6}
10^{-5}
10^{-4}
10^{-3}
4 KG
14.6 KG
13.3 KG
15.5 KG
7.8 KG
11.2 KG

Fig. 2

#81X0924

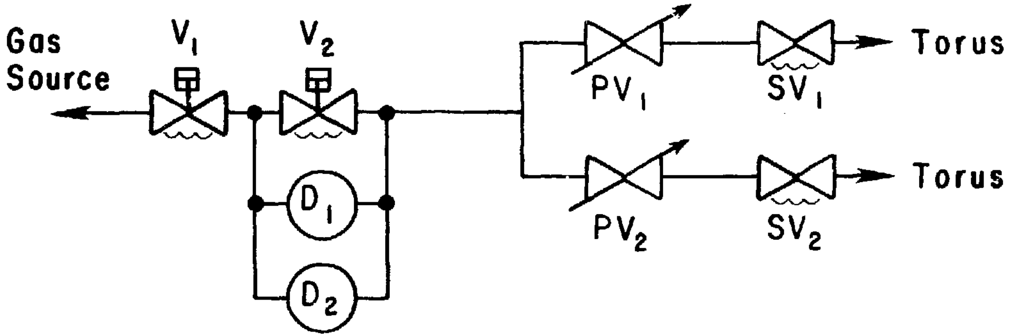
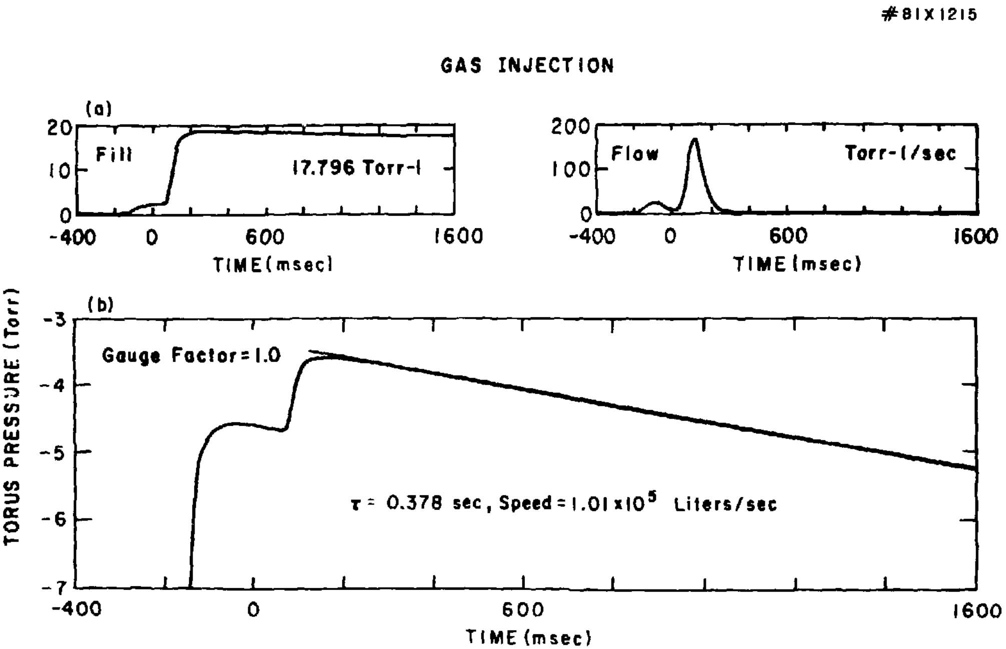


Fig. 3



#81X1215
GAS INJECTION
(a)
Fill
17.796 Torr-l
20
10
0
-400
0
600
1600
TIME(msec)
Flow
Torr-l/sec
200
100
0
-400
0
600
1600
TIME(msec)
(b)
TORUS PRESSURE (Torr)
Gauge Factor=1.0
τ = 0.378 sec, Speed=1.01×10^5 Liters/sec
-3
-4
-5
-6
-7
-400
0
600
1600
TIME(msec)

Fig. 4

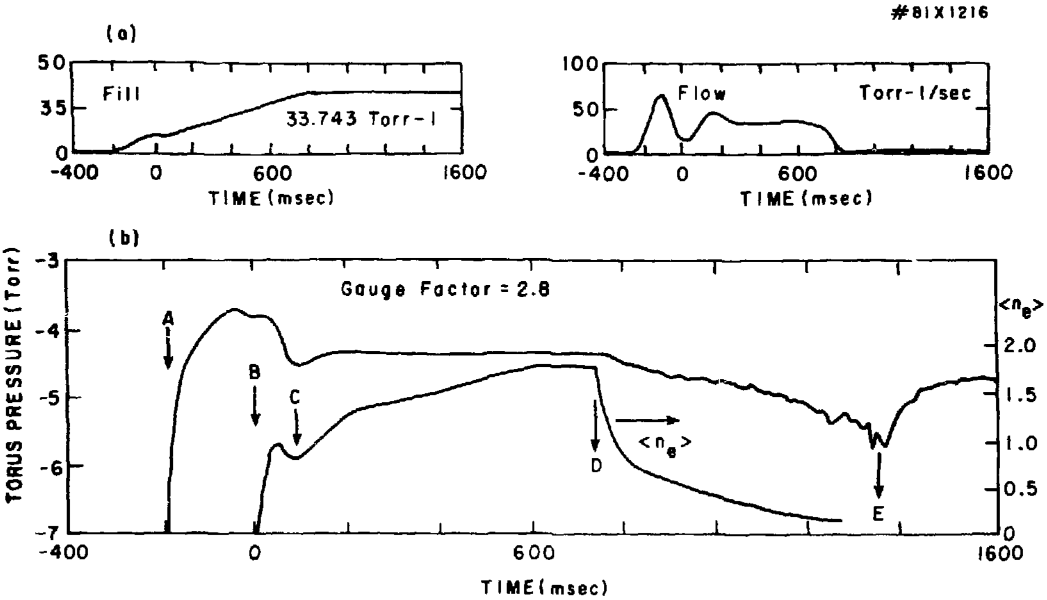

#81X1216
(a)
Fill
33.743 Torr-l
50
35
0
-400
0
600
1600
TIME (msec)
Flow
Torr-l/sec
100
50
0
-400
0
600
1600
TIME (msec)
(b)
Gauge Factor = 2.8
TORUS PRESSURE (Torr)
-3
-4
-5
-6
-7
A
B
C
D
E
$\langle n_e \rangle$
$\langle n_e \rangle$
2.0
1.5
1.0
0.5
0
-400
0
600
1600
TIME (msec)

Fig. 5

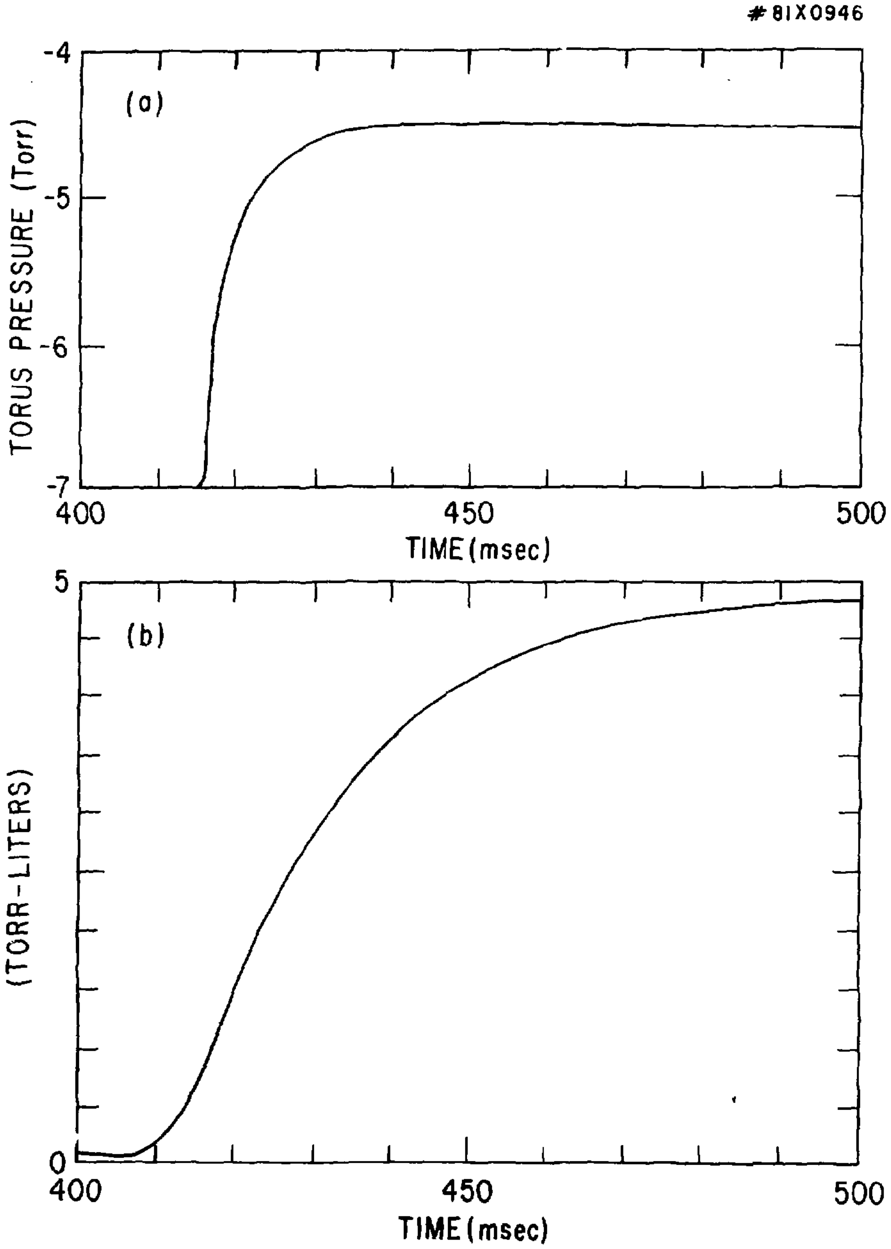
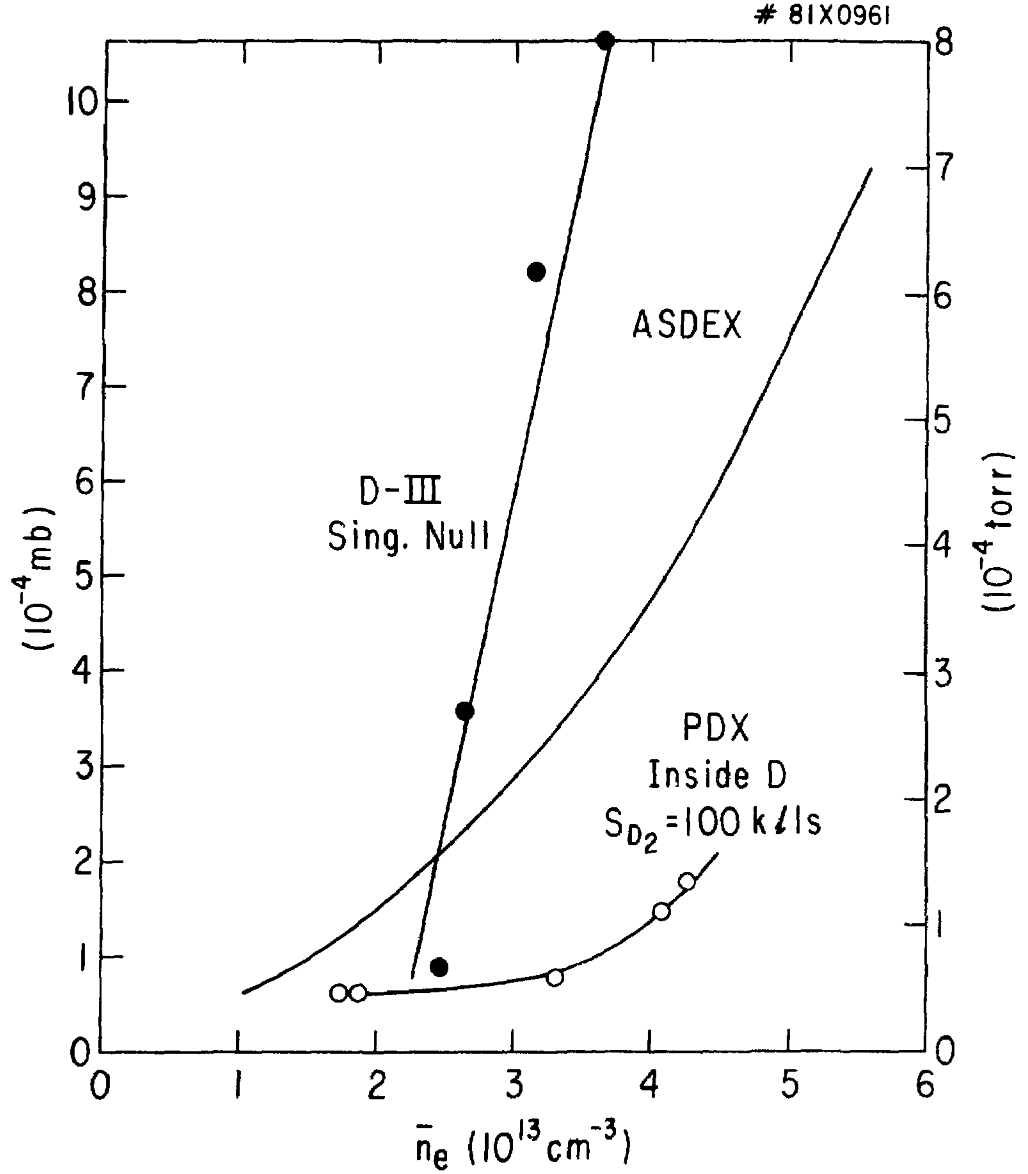

#81X0946
(a)
TORUS PRESSURE (Torr)
-4
-5
-6
-7
400
450
500
TIME (msec)
(b)
(TORR-LITERS)
5
0
400
450
500
TIME (msec)

Fig. 6



81X0961
D-III
Sing. Null
ASDEX
PDX
Inside D
S_{D_2}=100 kℓ/s
(10^{-4} mb)
(10^{-4} torr)
$\bar{n}_e$ (10^{13} cm^{-3})
0
1
2
3
4
5
6
7
8
9
10
0
1
2
3
4
5
6
7
8
0
1
2
3
4
5
6

Fig. 7

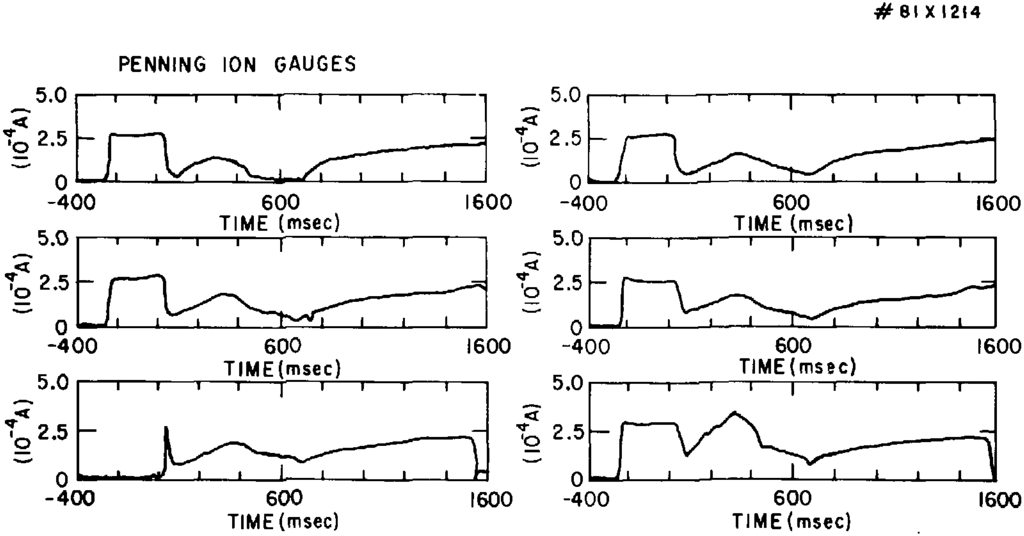

#81X1214
PENNING ION GAUGES
$(10^{-4}A)$
5.0
2.5
0
-400
600
1600
TIME (msec)

Fig. 8

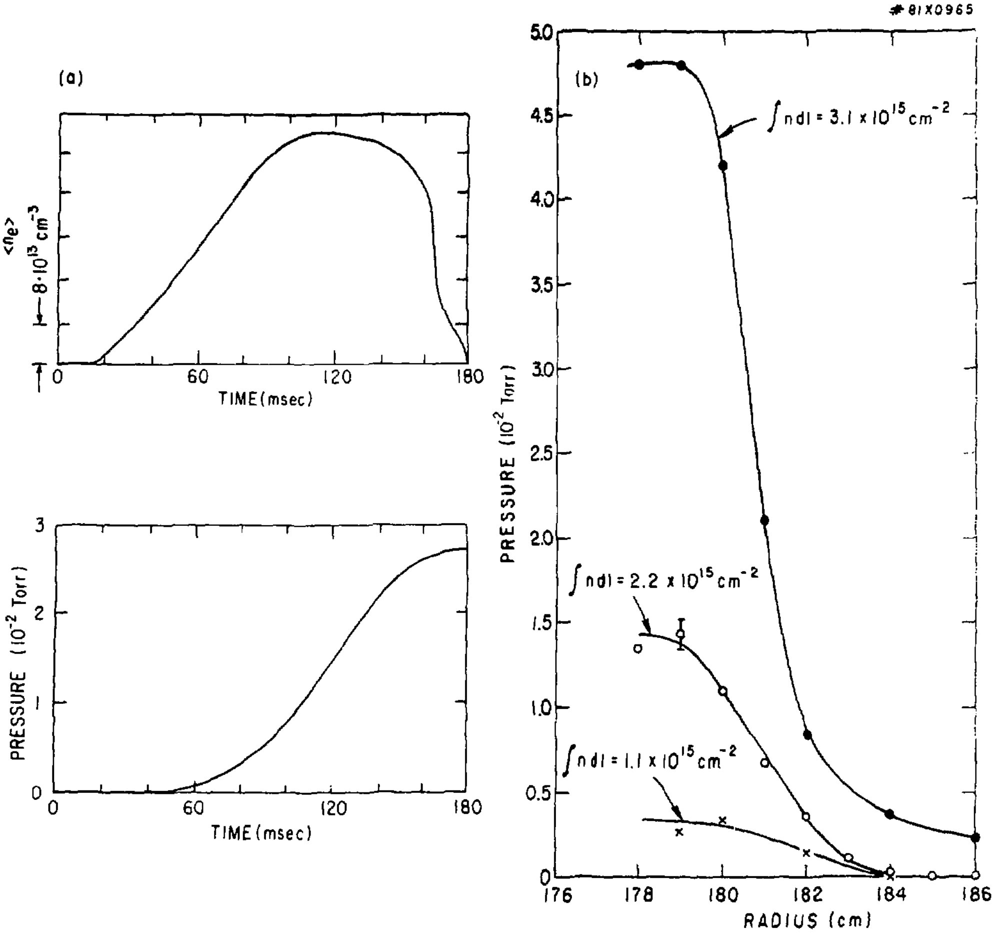

#81X0965
(a)
<n_e>
8·10^13 cm^-3
0
60
120
180
TIME (msec)
PRESSURE (10^-2 Torr)
3
2
1
0
0
60
120
180
TIME (msec)
(b)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
PRESSURE (10^-2 Torr)
∫ndl = 3.1 x 10^15 cm^-2
∫ndl = 2.2 x 10^15 cm^-2
∫ndl = 1.1 x 10^15 cm^-2
176
178
180
182
184
186
RADIUS (cm)

Fig. 9