CONF-860324-23

UCRL-94241
PREPRINT

Received by OSTI

APR 22 1986

NEUTRAL-PARTICLE DENSITIES OUTSIDE THE TMX-U PLASMA EDGE

W. L. Pickles
R. A. Jong

This paper was prepared for submittal to the
Proceedings of the 6th Topical Conference on
High Temperature Plasma Diagnostics,
American Physical Society,
Hilton Head Island, South Carolina,
March 9-13, 1986

March 4, 1986

Lawrence
Livermore
National
Laboratory

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

JS3 WeA12

NEUTRAL-PARTICLE DENSITIES OUTSIDE THE TMX-U PLASMA EDGE

W. L. Pickles and R. A. Jong
Lawrence Livermore National Laboratory
University of California
Livermore, California 94550

UCRL--94241

DE86 009404

ABSTRACT

Neutral molecular densities just outside the plasma edge are measured at 11 axial locations in Tandem Mirror Experiment-Upgrade (TMX-U). These densities are time dependent and vary greatly with different modes of TMX-U plasma operation. The densities are low in the ion-cyclotron resonance heated central cell because of plasma pumping. The density is high in the plug near the sloshing-ion turning point. These densities are measured with a combination of new retractable, and fixed, magnetically unshielded Bayard-Alpert gauges that can be oriented to provide calibrated operation in the high (7-kG) TMX-U magnetic fields. The role of the neutral density in simultaneously fueling and charge exchanging away the plug density is modeled using SMOKE, a Fokker-Planck code.

I. INTRODUCTION

We have successfully operated standard Bayard-Alpert gauges for several months in 0.3 to 0.7 Tesla (T) magnetic fields at eleven locations near the plasma edge of the TMX-U. We studied one of these eleven gauges extensively and it maintained calibration within 12% during this period of operation. All gauge filaments are tungsten and are heated with direct current. The gauge housing allows operation in the low-density plasma outside the limiter radius by thermalizing the neutral gas that enters the gauge and by preventing plasma from entering the gauge. Changing the orientation of the gauge with respect to the magnetic field changes the gauge calibration, or effective sensitivity, by as much as a factor of 100. Only some orientations of the filament-collector plane with respect to the magnetic-field direction allow calibrated operation as a pressure gauge. This range of angles is approximately from 20 to 50 deg. Each of the eleven gauges (Fig. 1) was oriented to produce a usable sensitivity, then calibrated for the magnetic-field effects at that position. The measured magnetic recalibration factor to the gauge sensitivity for D_2 , CH_4 , X_e , and Kr gas varied only 16% in the same high magnetic field. Repeated measurement of the magnetic recalibration for each of the species over a one month period showed less than 12% variation. The details of the calibrations of these Bayard-Alpert gauges in high magnetic fields are published in Ref.1.

II. GAUGE SYSTEM AND OPERATING ENVIRONMENT

Standard Bayard-Alpert commercial gauges were used in the work described here. The gauges were unshielded from the local TMX-U magnetic field and were

housed in stainless-steel cylinders. These cylinders had 80-mesh stainless-steel screen on the open end and were covered by a stainless-steel pipe cap spaced 10 mm from screen. Figure 2 shows one of the gauge housings on a long pipe, which allows the gauge to be inserted to its operating position at 40 cm from the plasma axis in the west plug of TMX-U. The housing design ensures that no plasma can enter the gauge, and that the gas in the gauge will be molecular and in thermal equilibrium with the housing. Because of housing design, a molecule must bounce a minimum of three times before entry into the housing. The ratio of the volume to entrance conductance of the housing assembly is 1.2 ms. The long pipe, which inserts the gauge in the TMX-U vacuum vessel, positions the gauge with the axis of the gauge perpendicular to the local magnetic field. Rotation of the pipe about its axis rotates the gauge around its collector for the operation in the field.

In routine operation, we find that our Bayard-Alpert gauges can be rotated with respect to the local magnetic field until we obtain a usable response of the collector and emitter currents. After the unshielded gauge is inserted and rotated to approximately the proper operating orientation, several shots with the magnetic field are taken. If the filament survives, the gauge is rotated slightly so that when the field is on (1) the emission current is reduced to about half of normal, (2) the collector current is positive, and (3) no parasitic oscillations exist in the emitter current. (We have observed 80 to 140 Hz oscillations in a gauge at 0.7 T.) After this initial operation in the magnetic field, a small recalibration of less than 10% for permanent filament distortion was necessary. The gauges can be calibrated in a constant local magnetic field using a multiplicative correction $S_m(\vec{B})$ to the normal gauge species sensitivity S_s in the following expression for pressure:

$$P = \frac{I_+}{I_- S_s S_r S_m(\vec{B})} \quad (1)$$

where P is the pressure in Torr, I_+ is the collector current, I_- is the emission current, S_s is the species sensitivity measured in zero magnetic field, S_r is the correction to S_s caused by the permanent distortion of the filament after operation in the magnetic field, and $S_m(\vec{B})$ is the correction for magnetic-field effects.

Gauge orientations, having sensitivity corrections $S_m(\vec{B})$ for the magnetic field of approximately 5 to 15, produced stable operation over several months. The values of the multiplicative correction $S_m(\vec{B})$ that we measured is constant for pressures between 10^{-7} and 10^{-4} Torr for a particular gauge in one magnetic field.

III. TMX-U MEASUREMENTS

Pressure measurements are made at nine axial locations during each TMX-U plasma shot. These pressures show dramatic response to the actual plasma conditions at each axial location and as a function of time during the shot. Figure 3 shows pressures at various axial locations at 42 ms into two plasma shots 12/5/85 (shot 35) and 12/11/85 (shot 11). These shots are high-density, plugged, and have high ICRH power (300 kW) and 15 keV beams in the central cell. Pressure and plasma-parameter equilibrium are usually established by 40 ms into the shot. The pressures are normally uniformly low, 1 to 3×10^{-6} Torr, everywhere except at the inner sloshing-ion turning point in the plug where the pressure reaches 2×10^{-5} Torr. This measured high pressure could be due to local wall reflux of charge exchange neutrals or

might possibly have some contribution from gas flowing in the gauge insertion pipe which connects to the higher pressure first injector region. This cannot be verified until the next operating sequence.

IV. MODELING

We used SMOKE,² a relativistic, multiregion, bounce-averaged Fokker-Planck code to model the end-cell plasma buildup in TMX-U. This code provides numerical solutions to a Fokker-Planck equation that describes collisional processes in a mirror plasma confined in axially varying magnetic and potential wells. In addition to the Coulomb collision process, the code can include a synchrotron radiation term, a quasilinear rf-diffusion operator, source terms due to gas and/or neutral-beam inputs, and loss terms such as those resulting from collisions or charge exchange.

The axial variation of the plasma is included by bounce-averaging the Fokker-Planck equation.^{2,3} This technique assumes an ordering of the characteristic times such that the bounce time of a confined plasma particle is much shorter than its collision time. In addition, the presence of more than one magnetic and/or potential well produces in general, a multivalued distribution function. This code is the first Fokker-Planck code that can solve for the distribution function in a multisheeted phase space. In practice, this means that SMOKE can treat several groups of trapped particles that may be separated spatially, but which can interact with each other through Coulomb collisions.

The numerical method used to solve the bounce-averaged Fokker-Planck equation was developed by Fyfe et al.⁴ This method consists of a mapping from

the (μ, ϵ) (i.e., magnetic moment, energy) phase space to a rectangular (x, y) space, followed by a Galerkin finite element method.²

For the present calculations, we modeled the magnetic-field profile and a typical potential profile expected in the TMX-U plasma. The particle sources resulting from neutral-beam injection and neutral penetration from the background gas were included. Good agreement between the calculated and measured total-ion density and sloshing-ion density in the end-cell was obtained if, and only if, an anomalous loss process $\tau_{anom_{SI}}$ with a characteristic time of about 1 ms was included.

Charge exchange rates at the plug inner sloshing-ion turning point are high but the bounce averaged $\langle \tau_{ce} \rangle_{total}$ calculated by SMOKE is still only about 5 ms. This is true even for the high pressure simulation of 1×10^{-5} Torr. The total charge exchange rate ν_{ce} on axis in the plasma is the sum of the molecular and atomic rate.

$$\nu_{CE} = \nu_{atomic} + \nu_{molecular}$$

Using $\sigma \nu$ atomic as $1.5 \times 10^{-7} \text{ cm}^3 \text{ s}^{-1}$, and $\sigma \nu$ molecular as $9 \times 10^{-8} \text{ cm}^3 \text{ s}^{-1}$, and for Shot 35 N_0 molecular as 6×10^{10} at 25 ms, and using the SMOKE result of 75% attenuation of molecules and 5% attenuation of energetic neutrals at the inner turning point, then the charge-exchange rates at the inner turning point are

$$\nu_{molecular} = 1400, \quad \tau_{ce_{mole}} = 0.7 \text{ ms},$$

$$\nu_{atomic} = 450, \quad \tau_{ce_{atomic}} = 2.2 \text{ ms},$$

with

$$\tau_{ce, total} = 0.53 \text{ ms}$$

at the plug inner sloshing-ion turning point. However, since the sloshing-ion bounce time is approximately 20 μ s, the important rate for confinement is the bounce-averaged rate of 5 ms for charge exchange in the whole plug, which is both calculated and measured.

V. CONCLUSIONS

We find that Bayard-Alpert gauges can be operated as calibrated pressure gauges in magnetic fields between 0.3 to 0.7 T if the angle of the filament collector plane is within the range of 30 to 50 deg with respect to the local magnetic field. In addition, the emission and collector currents must be positive. The gauge sensitivity correction for magnetic field that gives the best overall reliability of the gauges is between 5 and 15. The magnetic-field sensitivity correction measured for one gauge at one field value varies 16% for the four species measured. A particular gauge set at one angle for one field has a linear correction from 1×10^{-7} to 3×10^{-5} Torr. The correction for permanent filament distortion is approximately 10% and constant. The gauge calibrations can be maintained for long periods if the gauge is not moved or the magnetic-field changed in magnitude or direction.

In the TMX-U central-cell, we find that ICRH power uniformly lowers the measured pressure during plasma operation to approximately 1×10^{-6} Torr. The pressure at the outer turning point and the midplane of the plug are moderately low, 1×10^{-6} Torr, but during plasma operation the inner turning

point pressure is high, 2×10^{-5} Torr. Fokker-Plank modeling of the plasma densities with molecular and energetic atomic fueling shows that this high inner turning point pressure does not have a strong effect on the plasma parameters. The measurements and modeling show that the charge-exchange rate at the exposed sloshing-ion turning points are high ($\tau_{ce} = 0.5$ ms), but the plasma is self shielding for most of the remaining plug and the bounce averaged τ_{ce} is 5 ms.

ACKNOWLEDGMENT

This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract No. W-7405-ENG-48.

REFERENCES

1. W. L. Pickles and A. L. Hunt, J. Vac. Sci. Technol. **4** (3), May 1986 (in press).
2. Y. Matsuda and J. J. Stewart, Jr., "A Relativistic Multiregion Bounce-Averaged Fokker-Planck Code for Mirror Plasmas," Lawrence Livermore National Laboratory, Livermore, CA, UCRL-92313 (1985), Journal of Computation Physics, 1986 (in press).
3. T. A. Cutler, L. D. Pearlstein, and M. E. Rensink, "Computation of the Bounce-Averaged Code," Lawrence Livermore National Laboratory, Livermore, CA, UCRL-52233 (1977).
4. D. E. Fyfe, A. Weiser, I. B. Bernstein, S. Eisenstat, and M. Schultz, J. Comp. Physics **42**, 327 (1981).

Table 1. In the SMOKE simulation of 12/5/85, shot 35 at 25 ms varying the pressure at inner turning points between extremes while holding all other parameters constant shows that $\tau_{anom_{SI}}$ of 1 ms was still required to fit the measured plug densities and pressures.

Case	Press	Press	Press	Midplane	Outer	N_{SI}	$\tau_{ce_{TOT}}$	$\frac{At\ z = -448^*}{v_{atomic}\ v_{mole}}$		$\tau_{anom_{SI}}$
	inner	mid	outer	N_e	N_e	mid				
	(μ Torr)	(μ Torr)	(μ Torr)	(10^{12})	(10^{11})	(10^{11})	(ms)	(Hz)	(Hz)	(ms)
18	0.5	0.5	0.5	1.9	11.5	3.4	4.7	150	467	1
19	0.5	0.5	0.5	5.5	110	39	18.1			∞
15	1.5	0.5	0.5	1.6	9.9	2.9	4.4	450	1400	1
meas.	1.5	0.5	0.5	1.5	3	2.1	5			
transition to 10										
14	1.5	0.5	0.5	5.4	109	38		450	1400	∞
29	1.5	0.5	0.5	4.7	107	3.7		inner ϕ peak		∞
16	10	0.5	0.5	2	6.4	2.0	1.0	3000	9300	1
17	10	0.5	0.5	2.5	22	6.5	1.5			∞

* $z = -448$ is the inner sloshing ion turning point in the east plug.

FIGURE CAPTIONS

Figure 1. The warm-wall plasma boundary and the locations of all the gauges available on TMX-U. The distance in centimeters along the z axis is also shown.

Figure 2. The west-plug warm wall, magnetic-field contours, and the location of the insertable unshielded ion gauge are shown at $z = 558$ cm , the axial location of the gauge.

Figure 3. The pressure in Torr D_2 measured by the unshielded ion gauges at various axial (z) positions is low (1×10^{-6} Torr) except at the plug inner turning point (2×10^{-5} Torr, $z = -448$ cm). The time is 42 ms into a high-density plugged-plasma shot when all pressure and plasma parameters are in equilibrium.

W. L. Pickles et al. - Figure 2

W. L. Pickles et al. - Figure 3