UCRL--87766

DE83 000709

DYNAMIC GAS FLOW DURING PLASMA OPERATION IN TMX-U

W. L. Pickles, M. R. Carter, C. A. Clower, R. P. Drake, A. L. Hunt,
T. C. Simonen, and W. C. Turner,

Lawrence Livermore National Laboratory, University of California
P. O. Box 5511, Livermore, CA 94550.

ABSTRACT

Control of the neutral density outside of the plasma radius is essential for proper operation of the various plasma configurations in TMX-U. TMX-U excess-beam, stream-gun, gas-box, and beam-reflux gases are pumped internally in regions defined by 73^0 Ti-gettered liners and warm Ti-gettered plasma liners. The array of fast and slow ion gauges--a large TMX-U diagnostic--has been used to measure the dynamic pressure in many of the liner-defined regions on three time scales. The natural divertor action, or plasma pump effect, of mirror plasmas has been measured using the ion gauge diagnostics on a fast time scale during operation of TMX-U with ECRH start-up. Routine operation of TMX-U is enhanced by the ability to verify the effectiveness of gettering and to locate leaks using pressure data collected on the two slow time scales. A computer code, DYNAVAC 6, which treats TMX-U as a set of conductance-coupled regions with pumping and sources in each region, has been used to successfully model the overall gas dynamics during all phases of TMX-U operation.

INTRODUCTION

Reducing the amount of neutral gas outside the plasma radius, characterizing the species present, and increasing the reliability of the vacuum system were among the goals for TMX-U. Installing warm plasma liners and upgrading the vacuum system components, particularly the getter system and pressure-measuring diagnostic system, has allowed us to achieve much higher reliability, much shorter cleanup times for plasma operation, and a much better understanding of gas dynamics in TMX-U.[1]

This paper concentrates on the use of the diagnostic system that measures gas pressures in the TMX-U vacuum-vessel regions before, during, and after the plasma shot. We also discuss the use of the DYNAVAC 6 computer code, which provides a complete simulation of the dynamic gas flows in all TMX-U regions during the plasma shot.

SLOW PRESSURE MEASUREMENTS

The pressure measurement diagnostic system has two major sub systems. The first, which includes slow ion gauges (SIG) and medium ion gauges (MIG), consists of 19 unshielded and 3 magnetically and direct-ion-flux-shielded Bayard-Alpert ion gauges, 9 controllers, a Camac-based data acquisition system, and HP 1000 computer processors (programs) to archive the recorded pressures in the TMX-U data base and plot the pressures as functions of time. The gauges are located in all the vacuum regions of TMX-U (Fig. 1), and the pressures are acquired and plotted in two distinct time records.

The SIG records 9 gauge pressures every 6 minutes, 24 hours a day, 7 days a week. The MIG records the same gauge pressures every second for 4 minutes immediately before the plasma shot. This period includes the three radially staged Ti getter cycles used before each TMX-U plasma shot.[1] Figure 2 shows the pressure measurements during the 4 minutes before a shot as acquired by the MIG. The TMX-U getter system was redesigned to getter for 1 minute each in the first injector region, the second injector region, and finally inside the plasma region defined by the warm plasma liner. The getter wires are kept hot at all times by a 20-A minimum current. This reduces wire failure due to current over-shoot during turn on, maintains a temperature of 100^{0} C on the plasma liner, and prevents pumping of gas by the getter wires between shots. All getter power is off for 30 seconds just before the plasma shot to allow methane pump-out to the cryo pumps. The species are measured by the RGA diagnostic. The gas present in the vessel just before the plasma shot is almost entirely methane and the pressure is about 5×10^{-9} Torr. The CH_4 pressure rise during each getter cycle is also only 1×10^{-8} Torr. The very low pressures, even during gettering, indicate the excellent base vacuum conditions in which TMX-U plasmas operate. We feel this accounts for the extremely short "clean-up" plasma operation time required on TMX-U as compared to TMX. Using the operating procedures in Ref. 1, we were able to produce full-duration (75-ms) plasmas after one day of operation with the new getter cycle. More information on the glow discharge cleaning of TMX-U is found in Ref. 2. The MIG diagnostic is also used to spot small vacuum leaks that are otherwise unmeasurable. A small leak will contaminate a local region of the gettered surface. When the getter cycle begins, an anomalously large gas burst occurs, which is observed in one or more detectors. This establishes the location of the leak and the shot during which it developed.

PLASMA REGION PRESSURE MEASUREMENTS

The second diagnostic subsystem, called FIG for fast ion gauges, consists of five magnetically and direct-ion-flux-shielded gauges, four pairs of controllers, a Camac data acquisition system, and HP 1000 computer processors to archive and plot the pressures from the plasma regions during each shot. The time response for pressure measurement is about 1 ms and is a conductance, not an electronic limitation. The FIG system is complex and is described in detail in Ref. 3. Pressure as a function of time is measured for 320 ms starting at the beginning of the 100-ms plasma shot in four plasma regions.

Typically, the regions are the east fan, east plug, center cell disc, and west plug (or west fan).

Figure 3 is an example of the pressures we measure on a shot. Shots 13 and 14 on 8/10/82 are overlaid for each of the three plasma regions shown. The shots are different in that in shot 13 the plasma is started by firing the stream guns, which inject target plasma down the axis of TMX-U and introduce about 25 Torr-liter/s of D_2 gas into the fan tanks. The large pressure rise of 2×10^{-5} Torr is typical for this type of plasma operation. In shot 14, plasma start-up is achieved by ECRH microwave power, which ionizes the gas in the plugs to provide a target for the beams. In this case, the stream guns do not fire and the much smaller pressure rise against pumping in the end fan regions is observed. This pressure rise is caused by the gas conductance from the plug plasma region ($< 1 \times 10^{-7}$ Torr), reflux from the 500-V end-loss ions near the axis ($< 8 \times 10^{-7}$ Torr), and low-energy end-loss ions at large radius (major component $\cong 4 \times 10^{-6}$ Torr). We have identified this large conductance of gas to the end fan tank from the plug and center cell as the plasma-pump effect. The pressure rise in the plug plasma region seems to be independent of the method of startup. Typical pressures are 8×10^{-6} Torr for these two modes of operation. A third mode of operation explored in October 1982 with fewer neutral beams in the plug and greater ECRH power (hot electron mode) gives pressure maxima of about 1×10^{-6} Torr in the plug plasma regions.

PLASMA PUMP EFFECT

The FIG diagnostic has already measured the ability of the TMX-U mirror plasma to pump large quantities of background neutral gas outside the plasma in the center cell and plug plasma regions to the end fan tanks. This effect has been assumed to operate but has never been measured before. The ability to operate TMX-U plasmas without stream guns allowed us to clearly demonstrate this effect. Figure 4 shows a clear example of the plasma pumping the center-cell plasma region and lowering its pressure while delivering gas to the end fan tanks, causing a significant pressure rise. Shots 17 and 18 on 8/6/82 are identical except that in shot 17, the ECRH power tripped-off early and plasma was not formed. Shot 18 shows the reduced center-cell pressure and increased end-fan pressure caused solely by the existence of the plasma. Investigations have shown that the pressures in the end-fan tanks in this mode of operation are independent of the end-loss ion currents measured near the axis. The pressure rises in the fan tanks are not due to reflux of high-speed ions hitting the end wall. The reflux coefficients of 100 to 500 V of H ions is on the order of 0.1 (Ref. 6). Note that there is no measurable pressure rise caused by conduction from the plug to the fan region (shot 17). The pressure rise in the fan is probably due to low-energy unconfined ions at large radius. These ions are created at the edge of the plasma in the center cell and plug and, because they are not confined, are then transported along the field lines directly to the fan tank. The wall reflection of these low-energy (10-eV) ions is calculated to be on the order of one.[7] The model offered here is that the cold plasma halo in fact is an effective pump for background gas in mirror machines. The amount of gas pumped in TMX-U is measured to be about 16 Torr-liter/s for each end. This converts to a pumping speed in the plug and center cell plasma regions of 1 or 2 x 10^6 liter/s. This makes the plasma itself the largest pump in plasma regions by a factor of 5. The warm Ti-gettered walls have pumping speeds of only a few x 10^5 liter/s. The integrated pumping speed of the plasma is measured by adding the pumping speed of the fan tank (measured separately by pump-out times and known gas source rates) to the rate of rise of the fan tank measured during the plasma. The same plasma pumping speed is obtained by assuming that one-fourth of the neutrals at the plasma surface are ionized and pumped.

COMPUTER MODEL OF DYNAMIC GAS PRESSURES

To understand how the pressures we measure relate to the complex regions, gas sources, beam-dump refluxes, pumping surfaces, and temperature-dependent molecular flow conductances of TMX-U, we have modeled the complete TMX-U vacuum system using the computer code DYNAVAC 6.[4,5] DYNAVAC 6 was written at LLNL and runs on the Magnetic Fusion Energy Computer Center's Cray computer.

DYNAVAC 6 allows a set of volumes to each have a time-dependent gas source and pumping speed and to have conductances to and from any other volume. The code assumes that the volumes have uniform pressure and that the conductances may have different values into and out of a particular volume. The code solves the set of coupled differential equations for viscous flow into and out of each volume at each time step for the new pressure of all the volumes, such that

$$\frac{dp_i}{dt} = Q_i - S_i P_i - P_i \sum_{j=1}^{N} C_{ij} + \sum_{j=1}^{N} P_j C_{ji} ,$$

where P_i is the pressure of the ith volume (Torr),

S_i is the pumping speed of the ith volume (liter/s),

C_{ij} is the conductance of the ith to jth volume (liter/s), and

Q_i is the gas source term for the ith volume.

The model used to simulate TMX-U pressures has 17 volumes connected by unequal conductances reflecting the realities of the TMX-U regional geometry and temperatures.

Figure 5 shows the volumes and the conductances used. The actual TMX-U volumes with large internal pressure gradients are modeled as coupled multiple volumes (first and second injector regions). Conductances between these regions were calculated using Monte Carlo estimates of annular flow probabilities for coaxial cylinders.[8] Annular flow was allowed only outside the solenoid magnet cases between the two second injector region volumes. The volumes and conductances are symmetric about the midplane of TMX-U. Molecular flow probabilities were also used to modify the conductances in the center cell disc region and solenoid plasma regions. All conductances C_{ij} were calculated using the temperature of the surface from which a molecule must reflect before exiting or entering a volume:

$$C_{ij} \equiv 0.25 \times 10^{-3} A_{ij}\sqrt{\frac{T_i}{m}} \times \text{molecular transmission probability},$$

where A_{ij} is the area between volumes (cm^2),

T_i is the reflection surface temperature (^{0}K), and

m is the mass of the molecule (Amu).

The 17-volume model and the conductances were arrived at by measuring regional pressure responses to pulsed gas sources before TMX-U was gettered. In addition, an extensive calibration procedure was used to guarantee that the pressure measurements in each volume were in Torr ± 15% absolute. Direct pressure measurement comparisons to code calculations can be made. The pressures measured and calculated can be used directly to obtain the neutral density outside the plasma for inclusion in models for mirror plasma parameters, such as the electron temperature, diamagnetism, halo shielding effects, and mirror reactor natural divertor effects.

Table 1 contains the conductances and pumping speeds used to model the TMX-U D_2 plasma operation during August 1982. The only external gas sources used were the measured 43.8 Torr-liter/s total gas input to each neutral beam and the 25 Torr-liter/s stream gun gas. These gas sources were introduced only in the first injector regions and fan tanks. A neutral beam-dump reflux of two was required to fit the data in the center cell disc region. Plasma charge-exchange neutral reflux from the warm plasma walls was not included. Figure 6 shows the results of the model when applied to the details of shots 13 and 14 on 8/6/82. Only the four plasma region pressures on the east half of the machine are shown. The pressures calculated in Fig. 6 have not been adjusted in any way to scale to the pressures measured by the FIG diagnostic shown in Fig. 3. Some data points from Fig. 3 are superimposed on the calculated pressures for comparison. The agreement between the independently calculated and measured pressures is close except for early times in the center cell disc region.

SUMMARY

The calibrated TMX-U pressure measurement diagnostics SIG, MIG, and FIG allow tracking of regional pressure at two slow sample rates for operational purposes and on a fast time scale (1-ms) for measuring pressures in the plasma regions during plasma operation. These regional pressure time histories are permanently archived in the TMX-U data base.

The coupled-volumes computer code, DYNAVAC 6, has been used to develop a 17-volume model of TMX-U with conductances, pumping speeds, and volumes as nonadjustable parameters. The results of the modeling compare closely with the measured pressures and now form a basis for simulation of any contemplated

Table 1. Conductances and pumping speeds used in the 17-volume DYNAVAC 6 model of TMX-U regions.

TMX-U DYNAVAC Model 3 D2 Plasma Case Conductances

From	To	Conductance D_2 (liter/s)	Temp. (^{o}k)	Molecular probability	Area (cm^2)
EEF 1	EPP 2	6.2 E4	77	1	3.9 E3
EPP 1	EEF 1	1.32 E5	373	1	3.9 E3
EPP 2	ECP 3	1.32 E5	373	1	3.9 E3
ECP 3	EPP 2	3.3 E4	373	0.25	3.9 E3
ECP 3	CCD 4	7.06 E4	373	0.25	1.14 E4
CCD 4	ECP 3	1.33 E5	77	1	1.14 E4
EPP 2	EP2 8	6.5 E5	373	1	1.93 E4
EP2 8	EPP 2	3.08 E5	77	1	1.93 E4
EP2 8	EC2 9	4.16 E4	77	0.11	2.37 E4
EC2 9	EP2 8	4.16 E4	77	0.11	2.37 E4
ECP 3	EC2 9	1.06 E6	373	1	3.12 E4
EC2 9	ECP 3	9.40 E5	273	1	3.12 E4
EC2 9	EC1 11	9.40 E5	273	1	3.12 E4
EC1 11	EC2 9	4.97 E5	77	1	3.12 E4
EP2 8	EP1 10	2.64 E6	373	1	7.78 E4
EP1 10	EP2 8	1.24 E6	77	1	7.78 E4
EP1 10	EC1 11	1.45 E6	77	0.19	4.84 E4
EC1 11	EP1 10	1.45 E6	77	0.19	4.84 E4

TMX-U Model 3 Pumping Speeds East Volumes

Region	Cold area	S^1 = 0.22 (measured)		S^1 = 0.03	
		S_{cold} (liter/s)	Warm area (cm)	S_{warm} (liter/s)	STOT (liter/s)
EEF 1	2.77 E5	9.68 E5			9.68 E5
EPP 2			2.12 E5	2.16 E5	2.16 E5
EPP 2 Plasma pump nominal value					1.22 E6
ECP 3			1.57 E5	1.60 E5	1.60 E5
ECP 3 Plasma pump nominal value					2.16 E6
CCD 4	2.78 E5	9.51 E5			9.51 E5
EP2 8	2.05 E5	7.15 E5	2.12 E5	2.16 E5	9.3 E5
EC2 9	5.10 E5	1.78 E6	1.57 E5	1.60 E5	1.95 E6
EP1 10 in	2.05 E5	7.15 E5			1.7 E6
out	2.81 E5	9.85 E5			
EC1 11 in	5.10 E5	1.78 E6			2.48 E6
out	7.07 E5	2.48 E6			

machine reconfigurations and study of neutral beam dump reflux and charge exchange induced reflux. The natural divertor action of mirror plasma machines has been measured for TMX-U. The plasma acts as a high-speed (3 x 10^6 liter/s pump for background neutral gas in the center cell and plugs, and as a gas source for the end fan tanks.

ACKNOWLEDGEMENT

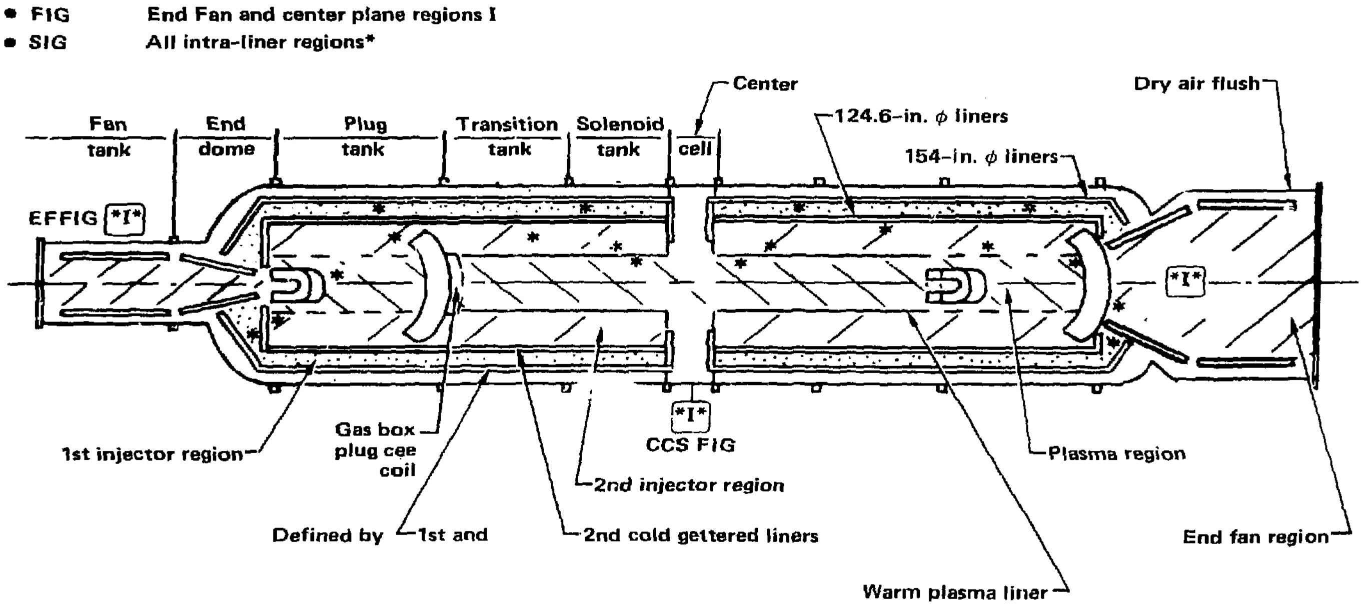
Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

REFERENCES

1. W. L. Pickles, A. K. Chargin, R. P. Drake, A. L. Hunt, D. D. Lang, J. J. Murphy, P. Poulsen, T. C. Simonen, T. H. Batzer, T. P. Stack, and R. L. Wong, *J. Vac. Sci. Technol.*, *20*(4), 1177 (1982).
2. S. L. Allen, C. Clower, R. P. Drake, E. B. Hooper, A. L. Hunt, and R. Munger, Lawrence Livermore National Laboratory, Livermore, CA, Rept. UCRL 87757 (1982).
3. A. L. Hunt, F. E. Coffield, and W. L. Pickles, Lawrence Livermore National Laboratory, Livermore, CA, Rept. UCRL 87756 (1982).
4. G. A. Deis, Lawrence Livermore National Laboratory, Livermore, CA, Rept. UCID 18717 (1980).
5. A. C. Hindarmarsh, *ACM-SIGNUM Newsletter*, *15*(4), 10 (1980).
6. O. S. Oen, M. T. Robinson, *Journal of Nuclear Materials*, *76* and *77*, 370 (1978).
7. O. R. Dean, S. O. En, M. T. Robinson, *Nuclear Instruments and Methods* *1321*, 647 (1976).
8. J. F. O. Hanlon, *A User's Guide to Vacuum Technology*, John Wiley & Sons, New York.

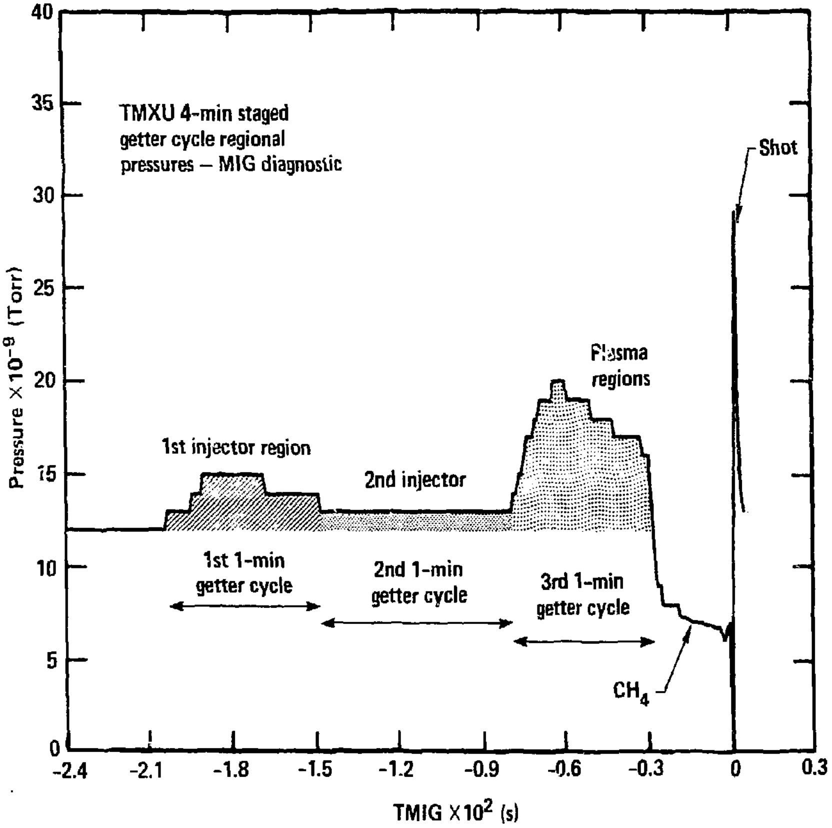
FIGURE CAPTIONS

1. Slow ion gauges are located in all TMX-U vacuum regions. Magnetically shielded fast ion gauges are located in all plasma regions.
2. Pressure in the center cell disc region during the TMX-U 4-minute radially staged Ti getter cycle--measured by the MIG diagnostic.
3. FIG pressure measurements in fan tank, center cell disc, and plug plasma regions during two TMX-U plasma shots: Shot 13 stream gun startup and Shot 14 ECRH startup.
4. Demonstration of mirror plasma pumping effect: Center cell disc region gas pressure in reduced and end fan pressure increased by the TMX-U plasma. Shots 17 and 18 are identical except that plasma was not formed on shot 17.
5. The 17-volume model of TMX-U regions used in DYNAVAC 6 code.
6. Results of DYNAVAC 6 pressure calculations of shots 13 and 14 on 8-10-82 using the TMX-U 17-volume model and measured neutral beam and stream gun gas input rates. The four plasma regions calculated and measured pressures are shown for shots 13 (stream gun startup) and 14 (ECRH startup).

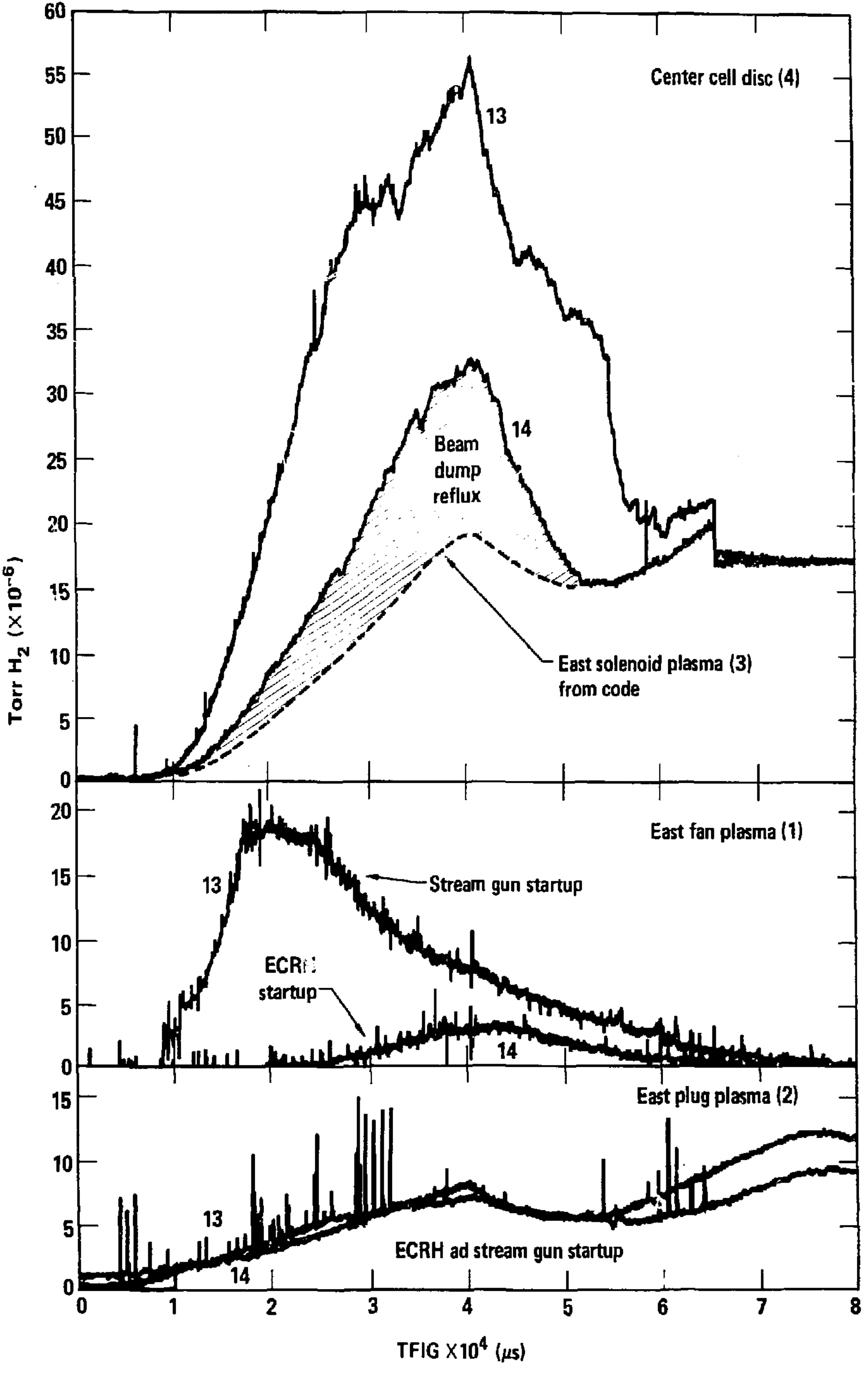


Pickles et al. - Fig. 1

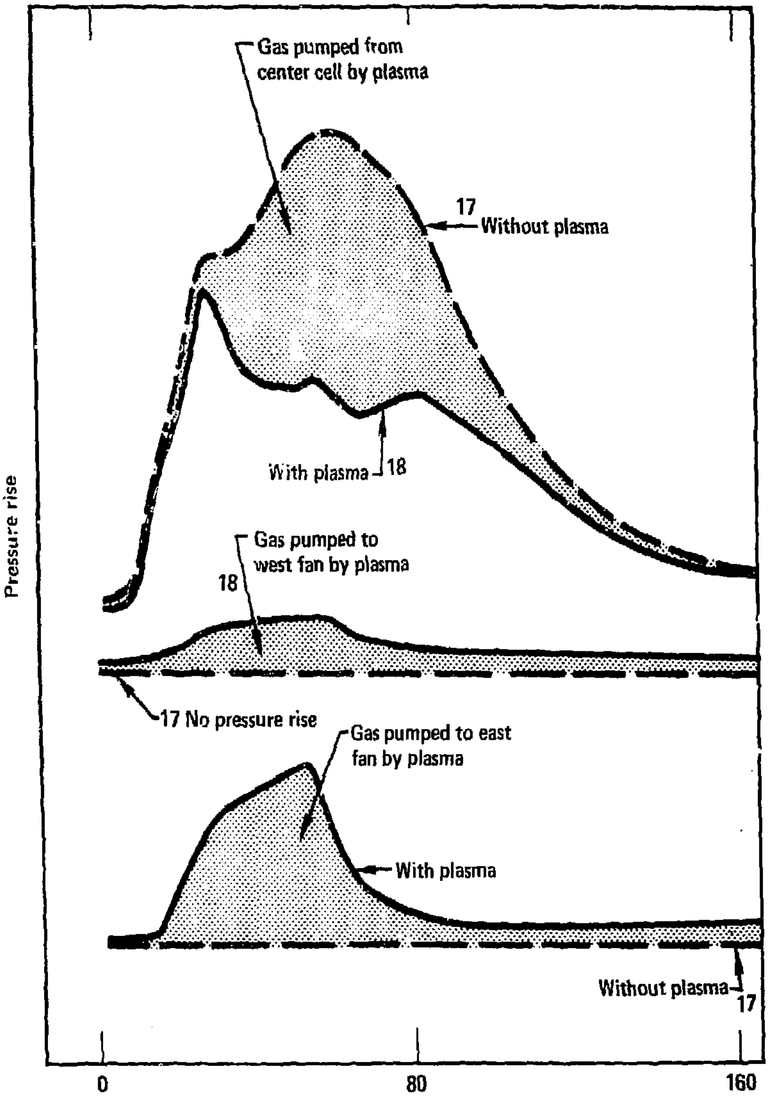
Pickles et al. - Fig. 2

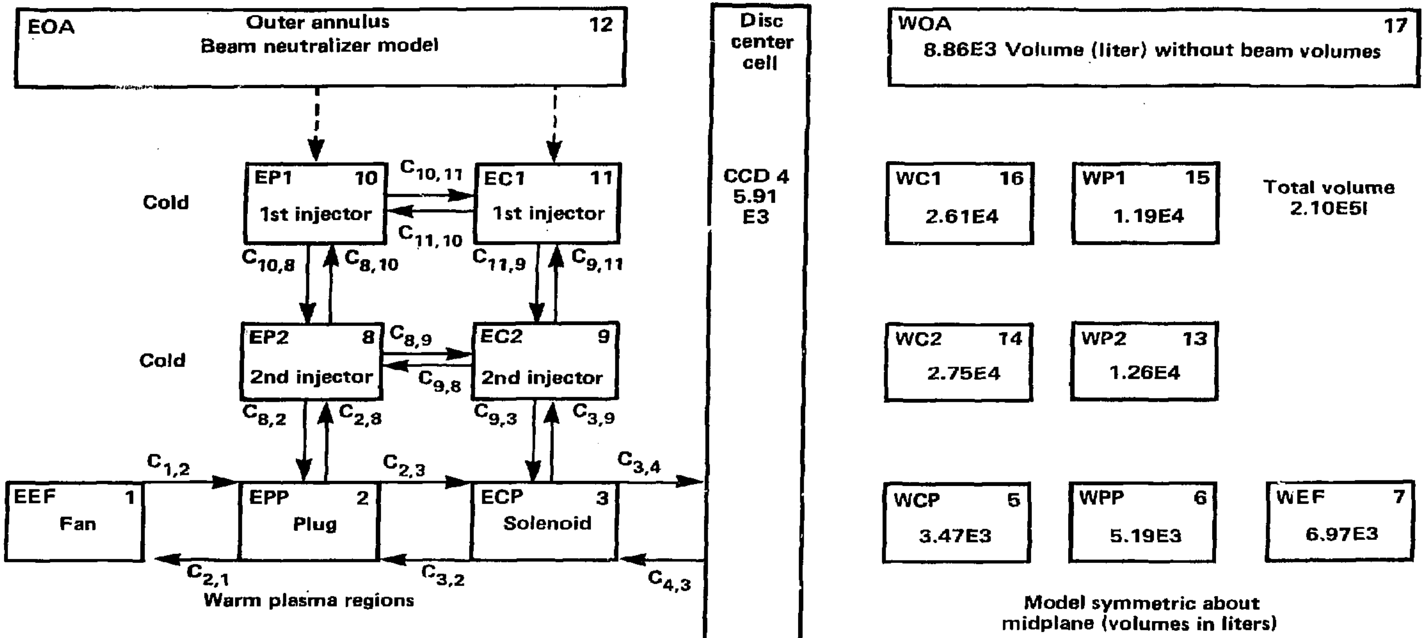


Pickles et al. - Fig. 3



Pickles et al. - Fig. 4





Pickles et al. - Fig. 5

Pickles et al. - Fig. 6