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BEAM INDUCED PRESSURE VARIATIONS IN A TFTR NEUTRAL BEAM INJECTOR

James E. Willis and Klaus H. Berkner

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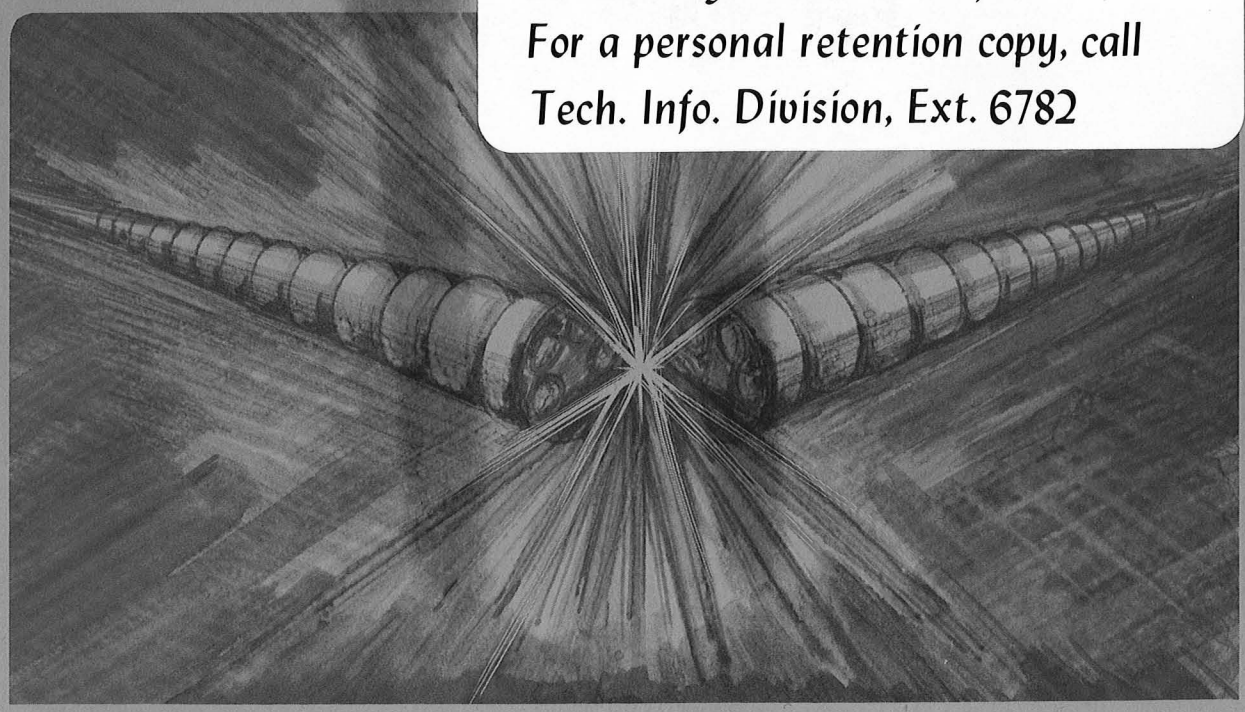

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BEAM INDUCED PRESSURE VARIATIONS IN A

TFTR NEUTRAL BEAM INJECTOR

James E. Willis and Klaus H. Berkner

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

Abstract

In neutral-beam injection systems either all or part of the gas flow into the neutralizer comes from the plasma source. When the beam is switched on, ions from the plasma source, which used to contribute to the gas flow, are converted to an energetic beam and are "pumped" away: hence reducing the gas input to the neutralizer. The large volume of the neutralizer and its high conductance damp out rapid changes; for example, when the gas to the source is first turned on, there is a 230 msec exponential rise time associated with pressure in the neutralizer. The neutralizer in turn acts as a source of gas to the first chamber and the first chamber to the second and so on. Beam dumps become additional sources of gas in the second chamber and target tank as gas molecules are collisionally desorbed from the surface of the dump. A simple analytical model (the equivalent of an electrical RC circuit) of the volumes and conductances of the system has been used to describe the pressure variations. The use of time dependent source terms in the model gives an estimate of the desorption rate from the dumps and its time variation during a beam pulse.

I. Introduction

Pressure variations in a neutral beam injector play an important part in determining the amount of neutral beam injected into an MFE device. For example, to maximize neutralization of the ion beam, a thick-gas target is needed in the neutralizer. At the same time, to minimize re-ionization losses, a low gas density is required between the magnet which sweeps out the ions and the injection port of the fusion device. To meet these conflicting requirements, neutral-beam injectors are divided into chambers to provide differential pumping. The resulting neutral beam injector system is a complicated maze of ducts, chambers, grids, baffles and cryopanels.

The primary source of gas for the injector is located in the ion source and provides gas for running the arc. During beam operation some of this gas is ionized in the arc chamber and accelerated as beam, which in effect acts as a pump in the arc chamber. The arc chamber acts as a source of gas to the neutralizer, the neutralizer acts as a source of a gas to the first chamber and so on.

About half of the ion beam is converted to atoms by charge-exchange collisions in the neutralizer and is available for use in the tokamak; the other half, a mixture of full-, half-, and third-energy ions, are removed from the beam by a sweep magnet and are directed to an ion dump. These energetic ions are absorbed by the dump and heat the surface. The dump then acts as a source of gas during beam operation. In the Neutral Beam System Test Facility (NBSTF) at the Lawrence Berkeley Laboratory, the energetic neutral beam from the TFTR prototype beamline strikes a target plate inside a cryogenically pumped target tank. As with the ions, the dump is heated by the beam and acts as a source of gas during beam operation.

To study the performance of the TFTR neutral beam injector system, we have measured the pressure variations in the various chambers under beam-on conditions and developed a simple model (similar to an RC electrical circuit) with seventeen volumes, conductances and pumping speeds and with three time dependent sources. We show here a comparison of the observed and calculated pressure variations.

The instrumentation and the beam-off pressure distributions are described in a separate paper by J. H. Feist.[1]

II. Conductances and Pumping Speeds

The design of the TFTR beamline is described in Refs. 2 and 3, and a simplified schematic diagram is shown in Fig. 1.

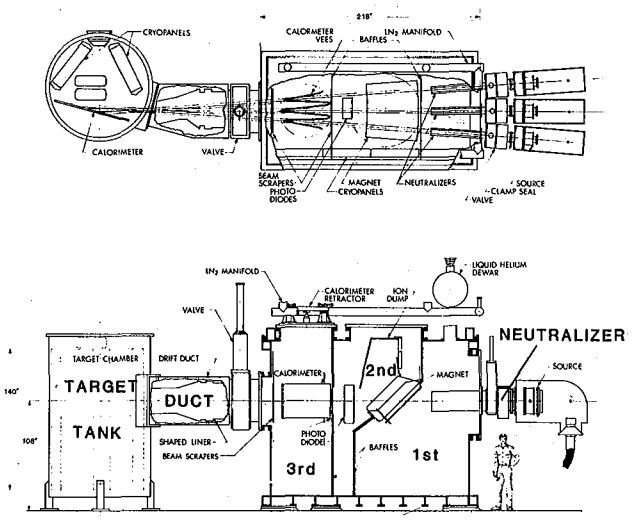

Figure 1: Schematic of the TFTR Neutral Beam Injector showing the location of the various chambers and differential pumping baffles.

The TFTR neutral beam injector is divided into seven chambers: the ion source; the neutralizer; the first chamber which is betweeen the neutralizer and the magnet; the second chamber which includes the magnet and ion dump; the third chamber which is the drift section between the magnet and the duct; the duct; and the target tank. Each chamber is characterized by a volume and one or two conductances

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connecting it with its neighbors; some chambers are cryopumped and/or have time dependent source terms. The conductances considered were: the accelerator grids, the neutralizer, the sweep-magnet aperature between the first and second chambers, the baffle between the second and third chamber, and the conductance of the duct. The conductances were measured or calculated using standard techniques, as reported by J. Feist elsewhere in this conference.[1]

Cryopumps are located in the first, second, and third chambers and in the target tank. The pumping speed of a cryopanel may be estimated by the black hole pumping speed multiplied by the effective area of the cryopanel. We found by measurement of the gas density that the average gas temperature in the cryopumped chambers is about 100 K.[1] The dynamic response of the system was best described when the pumping speed of the cryopanels were calculated with an assumed average temperature of 100 K; this yields an effective pumping speed of 4.5 $l/sec/cm^2$ for deuterium. The pressure in the neutralizer was measured with a calibrated capacitance manometer. The pressures in the rest of the system were measured using ordinary ion gauges and referenced to the manometer. With the exception of the target tank, the ion gauges are located in the center of the chambers, near the beam path and away from the walls and cryopanels.

III. Calculation of the Pressure Profiles

The electrical analogue for the beamline vacuum system is shown in Fig. 2. The model used yields seven first-order coupled differential equations of the form:

$$\dot{P}_i = ((P_j - P_i)C_{j,i} + (P_k - P_i)C_{k,i} + I_i(t) - P_i S_i)/V_i$$

Where: P_i is the pressure in the i th chamber
V_i is the volume of the ith chamber
S_i is the pumping speed of the ith chamber
$C_{i,j}$ is the conductance from chamber i to chamber j
I_i is a source term in the ith chamber

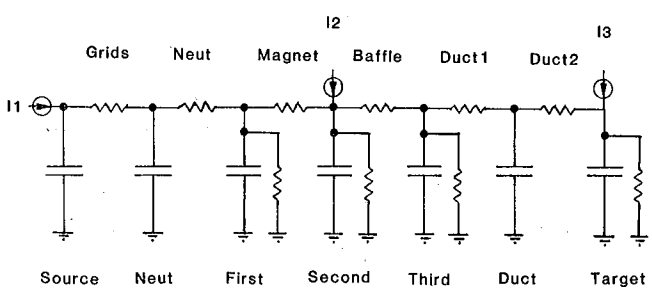

Figure 2: TFTR Neutral Beam Injector Gas Pressure Model. This model is our electrical analogue of the vacuum system.

A simple computer code, PvTIME, was written in BASIC and run on an HP-9845 to solve the seven equations using a finite difference technique. The volumes, conductances, and pumping speeds for the various chambers are given in Table I.

To test the model and the input parameters, we calculated the pressure distributions for the gas-only case, for which the only source term is the gas introduced into the plasma source. The calculated pressures agreed with the measurements within 30%.

IV. Results and Discussion

The measured pressure variations in the neutralizer are shown in Fig. 3 for a) gas only (22 T-l/sec D_2), b) arc, and c) beam (120 kV, 65 A, 0.5 sec). For reference the gas-only profile is reproduced as a dashed line for the arc and beam conditions. The neutralizer has a filling time of 230 msec (Fig. 3a). When the arc is turned on, there is a temporary drop in pressure followed by a temporary increase in pressure when the arc is turned off (Fig. 3b). The arc appears to pump initially; this pumping action quickly saturates for the duration of the discharge; the pumped gas is then released when the arc is turned off. When the beam is turned on, ions that used to collide with the grids and were thus reconverted to gas are accelerated (or pumped) from this part of the beamline (Fig. 3c); the result is a pressure drop in the neutralizer. For the conditions shown in Fig. 3c the gas efficiency of the source (nucleons in the beam/nucleons into the source) was 35%, and the measured pressure drop was also 35%. During the beam pulse there is a slight increase in the neutralizer pressure, possibly caused by outgassing of the walls of the neutralizer which intercept about 5% of the beam power. It is clear from this sequence of figures that "beam pumping" can significantly reduce the pressure, hence the neutralization efficiency. The neutralizer for NBSTF was designed[2,3] so that equilibrium neutralization can be achieved with the net flow during beam conditions.

In Fig. 4 we show the pressures for all chambers of the beamline for the same conditions as Fig. 3. The first chamber shows the same qualitative pressure variation as the neutralizer, but the pressure is lower due to the high pumping speed for this chamber. The ion dump is located in the second chamber; here there is a pressure rise associated with the beam. The drop in pressure due to beam pumping is initially masked, then exceeded by beam-induced gas desorption from the ion dump. The gas evolution in this chamber increases rapidly throughout the beam pulse and "cuts off" when the beam is turned off. A similar gas evolution is observed in the target tank where the neutral beam strikes a dump. The pressure rise is more dramatic in this chamber because very little gas from the neutralizer reaches the target tank. The connecting chambers, the third and the duct, also show beam-associated pressure increases; these are most likely caused by the pressure rise from the dumps in the adjacent chambers.

The beam-induced pressure variations shown in Fig. 4 are equilibrium values attained after a few dozen beam pulses at the 120 kV power level. Larger pressure rises have been observed when a new power level is attained. At lower power levels (90 kV, 40 A) we have operated with beam pulses as long as 1.5 sec. The same qualitative behavior was observed -- the pressure continues to increase throughout the beam pulse. There was no indication of a leveling off of the beam-induced gas evolution.

We had expected gas evolution caused by the beam striking the dumps to be constant in time and proportional to the flux of particles. This condition was used in the model and the results are shown in Fig. 5. It is clear that there is little correlation with the observed pressures.

The observed pressure variations during a beam pulse are best described with an exponentially increasing source of gas (for the period of the beam

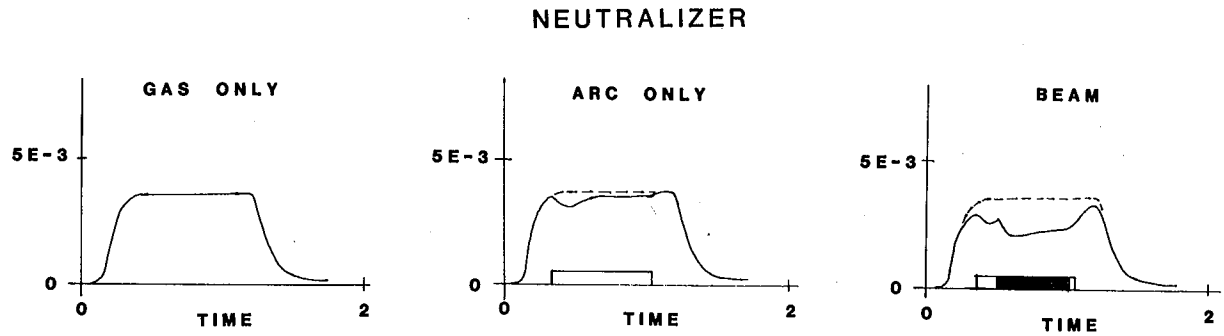

Figure 3a Figure 3b Figure 3c

Figure 3: Gas pressure variations in the neutralizer of the TFTR Neutral Beam Injector. The ordinate is pressure in torr; the abscissa is time in seconds. The open box in Fig. 3b indicates arc duration; the shaded box in Fig. 3c indicates beam duration.

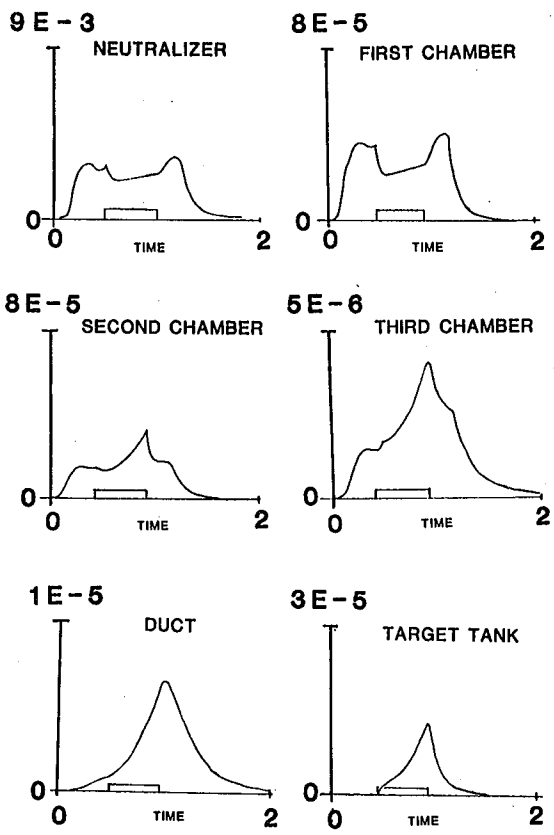

Figure 4: Measured pressure variations in the TFTR Neutral Beam Injector for 120 kV, 65 Amp, 0.5 sec beam for a gas flow of 22 T-l/sec D2. The open box indicates beam duration

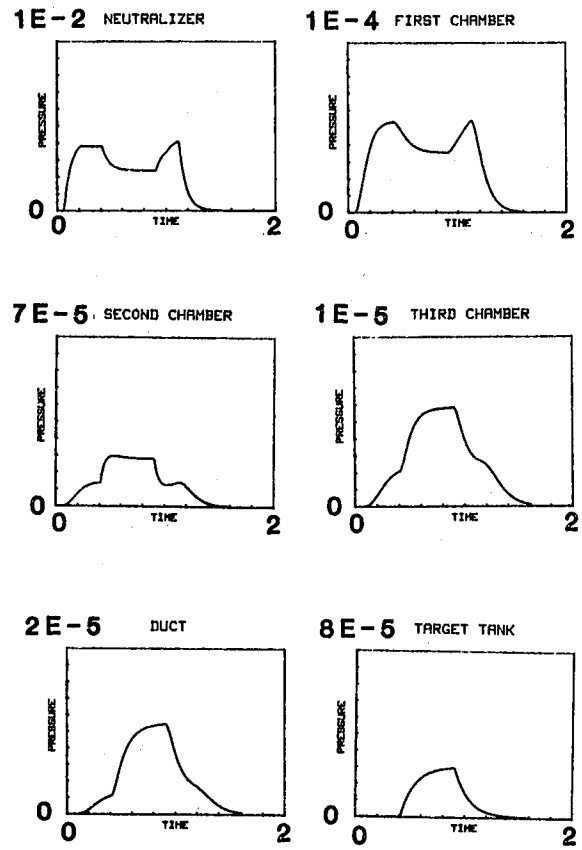

Figure 5: Calculated pressure variations for conditions listed in Fig. 4 and an assumed square wave desorption of gas from the dumps

pulse) in the second chamber and the target tank with a time constant of 0.25 sec. The exponential source term was normalized so that the total amount of gas desorbed was comparable to the fluence of beam on the dumps. The calculated pressure distributions obtained when these source terms were used are shown in Fig. 6. There is good agreement with the measured pressure shown in Fig. 4.

We have not yet performed a systematic study to determine how the beam-induced gas desorption varies with beam energy and flux, nor do we have a mass analysis to determine whether the desorbed gas is D_2. We postulate that the rate of gas desorption from the dump increases with the surface temperature. The beam dumps are thick Cu plates with cooling lines on the back surface, and the rise in the surface temperature is, to first order, proportional to the power density and the square-root of beam on-time. The surface temperature rise at the center of the dump, for a 120-kV, 1.5-sec pulse, is estimated to be approximately 900 K. Our results cannot be explained by diffusion of gas from the Cu,[5] since the observed drop in pressure after the beam pulse is much faster than the calculated decrease in the surface temperature.

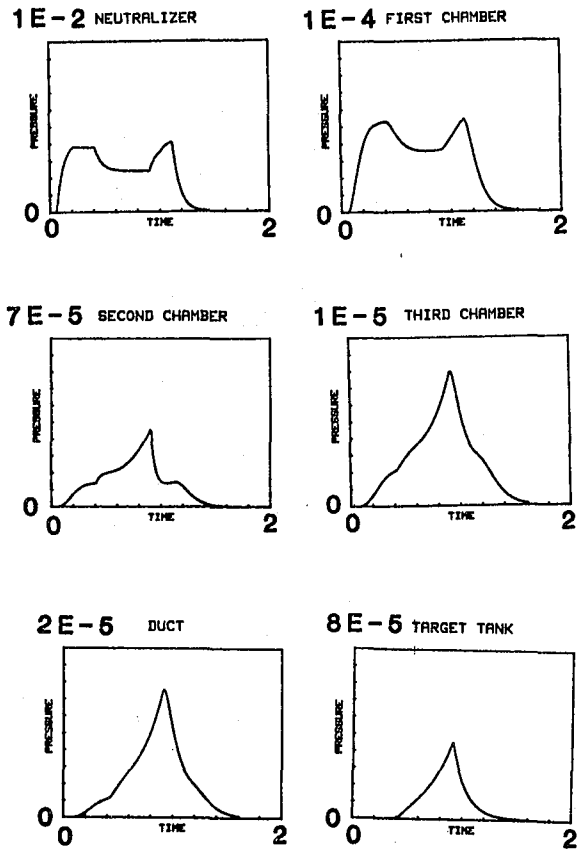

Figure 6: Calculated pressure variations for conditions listed in Fig. 4 and an assumed exponential desorption of gas from the dumps. Pressure is in torr and time in seconds.

The unexpected pulse-length-dependent pressure rise significantly increases re-ionization losses. From our measurements we estimate a re-ionization loss of 2%-3% for a 0.5-sec pulse on NBSTF where only one ion source is used. The TFTR beamlines will be operated with three sources each, tripling the gas load and the re-ionization losses. For longer pulses the re-ionization losses will be more severe. If our premise -- that gas desorption is enhanced by a rise in the surface temperature -- is correct, the pressure rise in beamlines designed with actively cooled beam dumps[6] may not be too severe, since the surface temperature rise will be limited to several hundred degrees.

V. Acknowledgements

The measurements reported here were a continuation of work started by J.H. Feist.

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Table I.

Volumes, pumping speeds, and conductances for D_2 gas in NBSTF.

VOLUMES (liters)		PUMPING SPEEDS (liters/sec)		CONDUCTANCES (liters/sec)	
Vsource =	9.00E+00			Cgrids =	2.40E+03*
Vneut =	3.00E+02			Cneut =	4.80E+03†
Vfirst =	2.30E+04	Sfirst =	3.06E+05	Cmag =	5.08E+04††
Vsecond =	1.30E+04	Ssecond =	2.31E+05	Cbaffle =	6.93E+04††
Vthird =	1.50E+04	Sthird =	1.85E+05	Cductl =	9.41E+04**
Vduct =	2.16E+03			Cduct2 =	1.69E+04**
Vtarget =	2.00E+04	Starget =	1.44E+05		

* The conductance of the grids was calculated with standard conductance formulas (3000 l/sec) and with a 2D Monte Carlo code (2500 l/sec). The measured value (Ref. 1) is 3700 l/sec. The capacitance manometer is located part way along the neutralizer and the conductance from source to neutralizer includes the conductance of the first section of the neutralizer.

† Measured and calculated (Ref. 1).

†† Calculated for a gas temperature of 100 K (see Ref. 1,4).

** The conductance of the duct is split into two parts; the first from the third chamber to the ion gauge, the second from the ion gauge to the target tank.

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