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ABSTRACT

Vertical elongated 1.3:1 elliptical plasmas in which the outermost flux surfaces are magnetically expanded and diverted by external coils into the lower half of the Doublet III vacuum vessel are described. Approximately 5 cm of the nominal 45 cm plasma minor radius is diverted to the lower chamber. The diverted flux is expanded by more than a factor of ten before reaching the vessel wall. Photographic measurements show diffused hydrogen recycling light in the lower half of the vessel, with greatly reduced recycling at the normal limiters, and no evidence of localized particle flow to the vessel wall. A significant amount (∿ 50%) of the ohmic power is radiated in the expanded boundary region. Comparison of similar low density plasmas (∿ 2×10^{13} cm^{-3}) with and without the expanded boundary shows that 1) the expanded boundary reduces the influx of nickel and oxygen impurities by an order of magnitude, 2) the boundary also reduces the influx of injected argon and helium by a similar factor, and 3) the concentration of argon in a non-diverted plasma is reduced by a factor of 10 when the expanded boundary is turned on. The central radiated power falls by an order of magnitude, to less than 0.01 W/cm^3. Similarly, $Z_{eff}(0)$ drops from 3.2 to 2.1.

1. INTRODUCTION

The poloidal divertor [1-4] has been proposed as an impurity control means for future tokamak reactors. However, conventional divertor geometries result in at least two serious technological drawbacks: 1) the power loading on the divertor plate will be very high, and 2) the requirement for a multi-megampere divertor coil located inside the vacuum poses difficult engineering problems.

The expanded boundary divertor concept proposed by Ohyabu [5] avoids these difficulties by magnetically expanding the diverted flux surfaces with coils external to the vacuum region and first wall. Several of the anticipated properties of this type of simplified divertor have been confirmed experimentally with ohmically heated plasmas in Doublet III. With the boundary expanded, the main plasma is well-separated (∿ 5 cm) from the

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normal limiters and hydrogen recycling shifts to the divertor region. A significant fraction of the total ohmic input power is radiated from the expanded flux region.

The influx of naturally occurring oxygen and nickel impurities and artificially injected noble gas impurities is reduced by up to an order of magnitude. Argon present in a normally limited discharge decreases by a similar factor when the expanded boundary is turned on dynamically.

2. MAGNETIC CONFIGURATION AND CONTROL

Elliptical plasmas with and without an expanded boundary were produced in the top half of the Doublet III vacuum chamber (Fig. 1). The plasma current of 350 kA (at $B_T = 2$ T) was intentionally limited in order to avoid damage to the vessel wall if a concentrated divertor channel was inadvertently formed. Feedback control of the plasma height and radial position ensured constant plasma position during the experiment. The expanded boundary is established by increasing the poloidal flux ψ ($\equiv\phi/2\pi$) linking coils 1B, 2B, 6B and 7B relative to that linking coil 8A. Additional control of the flux on coils 1A and 6A results in further expansion of the boundary layer and maintains vertical stability of the discharge.

The control circuits for the boundary expansion coil power supplies were arranged to cause ψ_{1B}, ψ_{2B}, and ψ_{7B} to follow ψ_{6B}, which serves as the master control parameter in determining the magnetic configuration. The value of ψ_{6B} can by dynamically programmed, allowing experiments in which the boundary is turned "on" or "off" during a single discharge.

3. EFFECT OF EXPANDED BOUNDARY

Increasing ψ_{6B} results in a significant change in the discharge characteristics, as shown in Fig. 2. The Hα hydrogen recycling light shifts from the normal limiters at the upper plane to the midplane and lower half of the vessel. Simultaneously, the midplane line-average density rises and the loop voltage drops. The transition occurs at ψ_{6B} = 65 mV-sec, which corresponds to the separatrix barely touching the limiter. For the expanded boundary "on" case (ψ_{6B} - 80 mV-sec), the plasma is separated from the normal limiters by about 5 cm, and the limiter recycling light virtually disappears. Framing camera photographs of the plasma show that the hydrogen recycling light is diffused over the lower half of the vessel, with no evidence of a concentrated divertor channel. Bolometers viewing the central and expanded boundary regions of the discharge show a decrease in the central radiation and an increase in the expanded boundary region radiation. The intensity of 354 A Ar XVI line radiation due to injection of a small amount of argon drops when the boundary forms (see Section 4).

The width of the transition region from boundary "off" to "on" indicates that the scrape-off layer is about 4 cm thick. It is necessary to divert at least this much of the plasma for the expanded boundary to be effective.

Reflux of hydrogen is reduced with the boundary on (Fig. 3). The time constant for the density to decay with no injected gas drops from 600 msec with boundary "off" to 300 msec with boundary "on". The injected gas must be increased by a factor of 2 to maintain equal steady-state densities for the "on" and "off" cases.

4. IMPURITY EFFECTS

Waveforms for typical boundary "on" and "off" discharges are shown in Fig.4. The expanded boundary reduces the influx of naturally occurring impurities. Turning the expanded boundary "on" reduces the influx of oxygen, monitored by the intensity of OV (193 Å), and both the influx and ultimate concentration of nickel monitored by Ni XI (148 Å) and Ni XVII (249 Å).

Artificially injected argon gas shows a similar effect. Here a short (∿ 5 msec) puff of argon is injected at t = 500 msec. Without the expanded boundary, the intensity of the 354 Å Ar XVI line reaches a constant value after 30 msec. With the expanded boundary on, the initial peak of the Ar line falls by a factor of 3, and the steady-state value falls to about 1/6 of the boundary-off steady-state.

The shielding effect is independent of the quantity of argon injected (Fig. 5). With boundary off, the maximum amount of argon that the plasma could tolerate without disruption was 6×10^{17} particles, compared with 1.9×10^{18} for boundary on. The absolute amount of argon in the plasma can be estimated from soft X-ray line radiation intensity measurements. The ultimate argon concentration with boundary off and on corresponds respectively to about 50% and 10% of the total argon injected. However, the uncertainty in the absolute calibration is at least a factor of two.

The concentration of argon present in a normally limited plasma is reduced after the boundary is turned on (Fig. 6). Here a 5 msec duration Ar puff preceeded the turn on of the boundary by 120 msec. With boundary off, the steady-state Ar XV line intensity rises in proportion to the electron density. Turning the boundary on causes an immediate reduction in the Ar XV intensity, which ultimately falls by an order of magnitude.

5. POWER BALANCE AND ENERGY CONFINEMENT

Parameters of similar plasmas with and without the expanded boundary are summarized in Table I. The electron temperature profiles are identical within ±10%. The principal effect of the expanded boundary is to reduce Z_{eff} and the central radiation power. The observed confinement improvement is consistent with the reduction of radiation from the plasma core. The energy confinement time with the boundary on is similar to the best values obtained with a non-diverted plasma under cleaner wall conditions [6].

6. CONCLUSIONS AND DISCUSSION

The expanded boundary configuration has a number of potentially useful features for reactor impurity control. The magnetic configuration is stable and reproducible. The boundary layer is effective in shielding the plasma from low- and medium-Z impurities, and also appears to exhaust argon impurities from established plasmas. Particle recycling moves from the limiter to the divertor region and the net hydrogen reflux is reduced. Significantly enhanced radiation from the expanded boundary region is observed.

The physical mechanism responsible for the shielding and exhausting actions of the expanded boundary is not yet clear. Ohkawa [7] has suggested that ion flow along the boundary flux surfaces would have the observed effects, and that injection of hydrogen into the top of the discharge and gettering in the divertor region (as was the case for the plasmas described herein) would increase the effectiveness of the anticipated impurity "pumping" effect.

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TABLE I
PLASMA PARAMETERS FOR EXPANDED BOUNDARY

	Boundary OFF	Boundary ON
V_{loop} (V)	1.4	1.0
I_p (kA)	360	360
B_T (T)	2.0	2.0
q (0)	1	1
$T_e(0)$ (KeV)	1.0	1.0
$T_i(0)$ (KeV)	0.4	0.4
$Z_{eff}(0)$	3.2	2.1
$\bar{n}_e$ (0) (10^{13} cm^{-3})	2.2	1.9
τ_{Ee} (msec)	24 ± 8	28 ± 8
$\tau_E^{(1)}$ (msec)	35 ± 12	39 ± 13
P_{rad} (0) (W/cm^3)	0.12 ± 0.04	0.01 ± 0.01
$P_{rad}^{(2)}/I_pV_{loop}$	0.75 ± 0.15	0.44 ± 0.1
$P_{rad}^{(3)}/I_pV_{loop}$	--	0.5

NOTES:
(1) Assumes $T_i(r) = 0.4\ T_e(r)$
(2) Inside last closed flux surface
(3) Boundary region

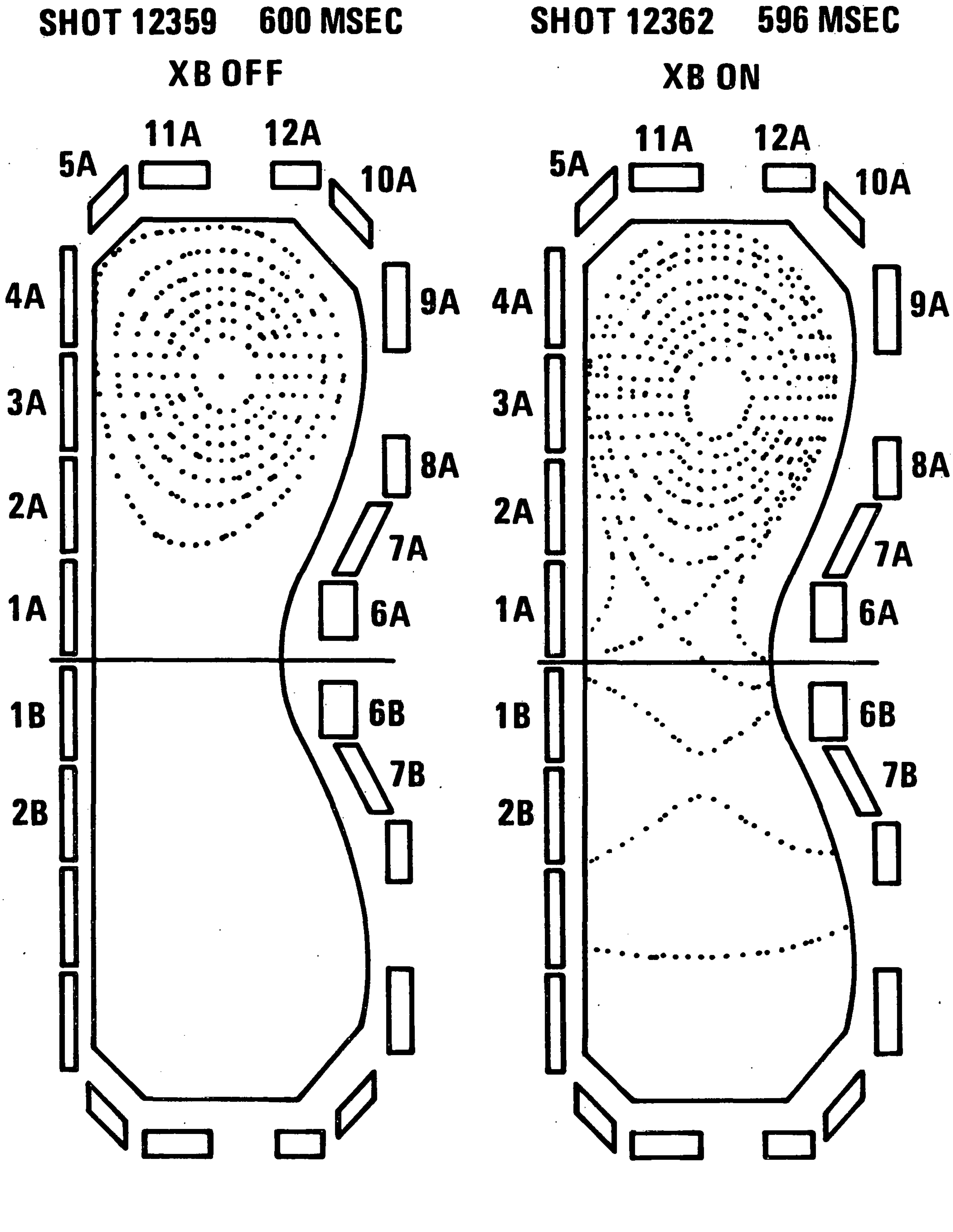

Fig. 1. Contours of constant flux for expanded boundary "on" and "off"

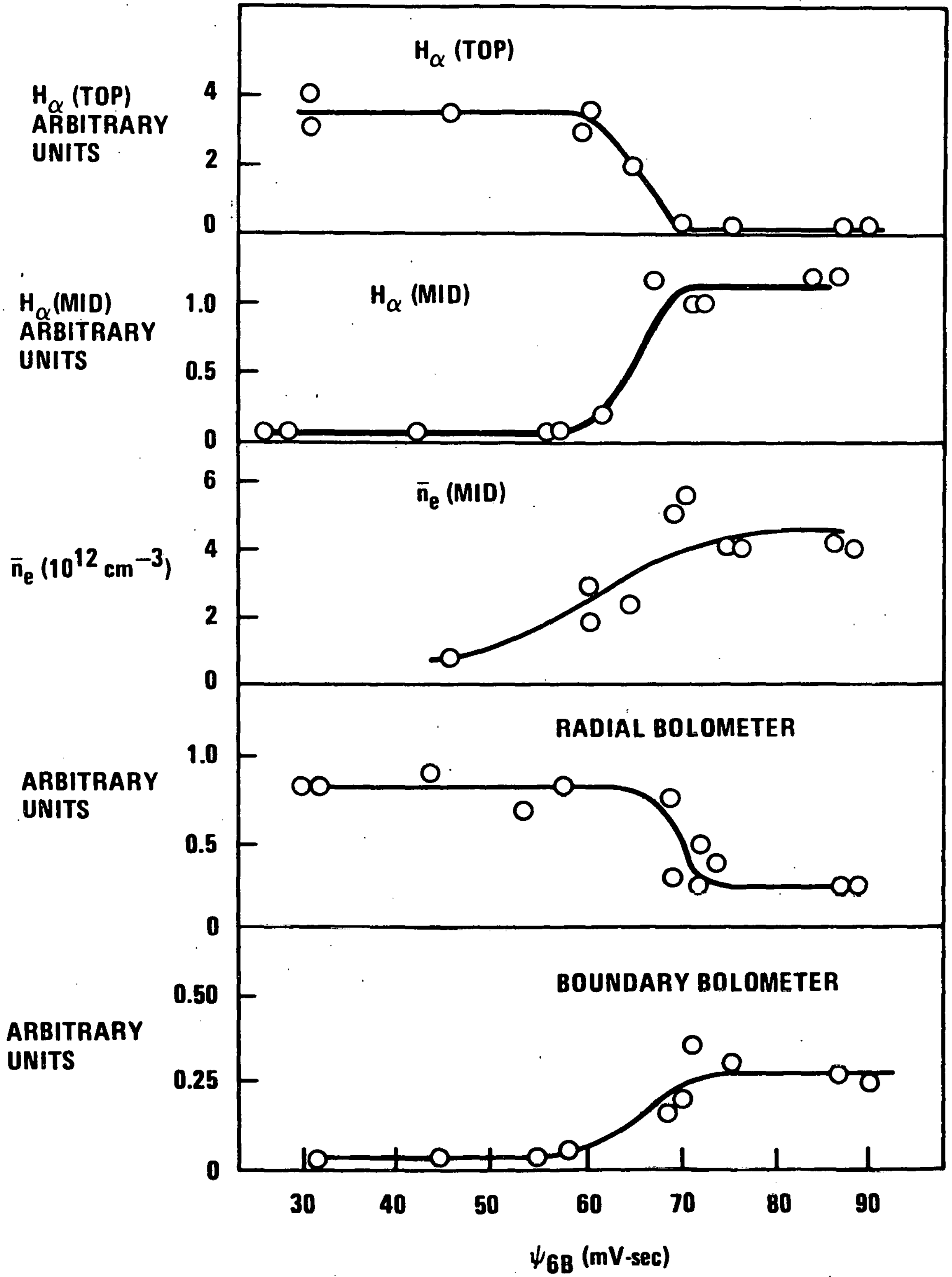

Fig. 2. Effect of ψ_{6B} discharge characteristics. The expanded boundary is established for $\psi_{6B} \geq 65$ mV-sec.

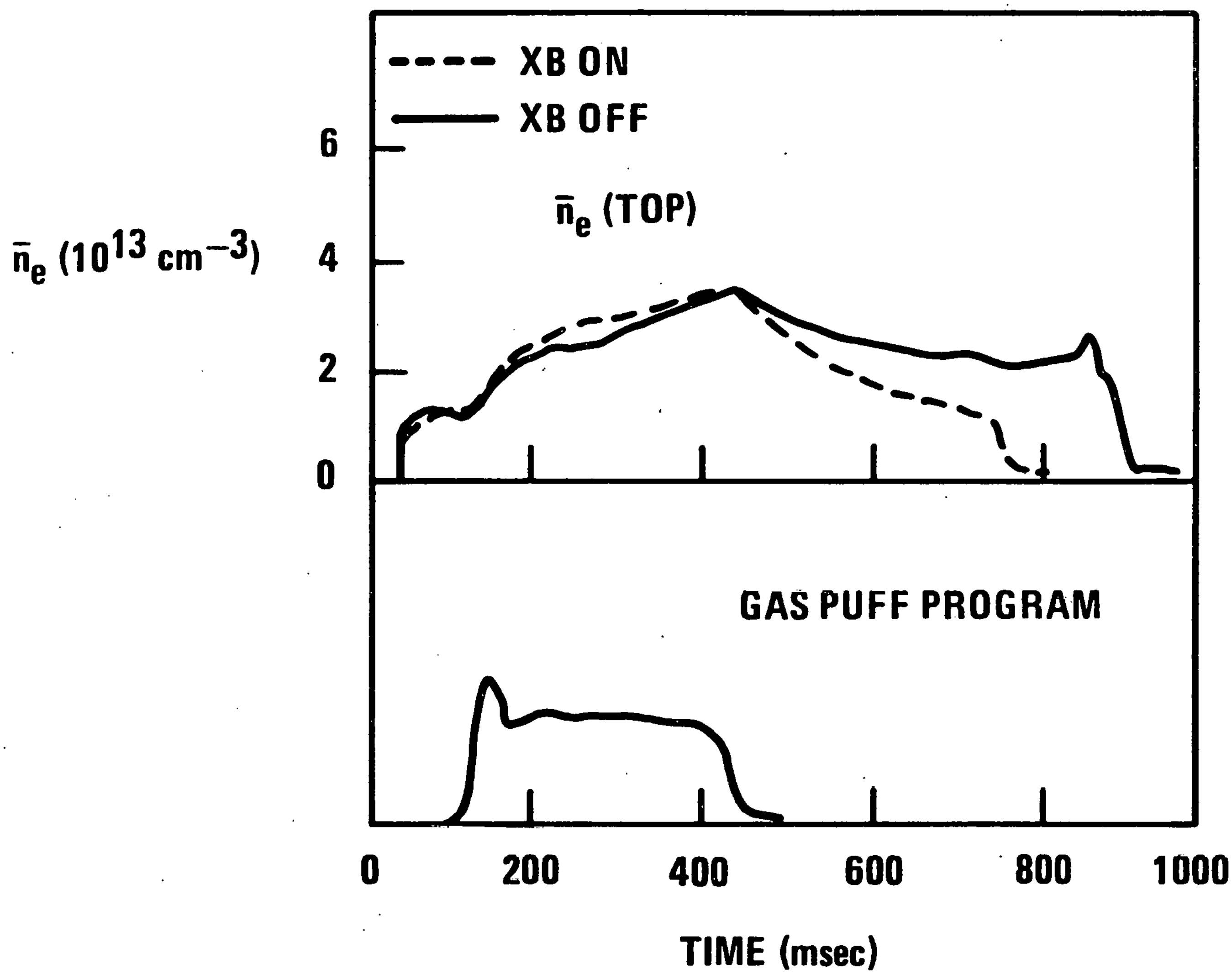

Fig. 3. Electron density decay for boundary "on" and "off"

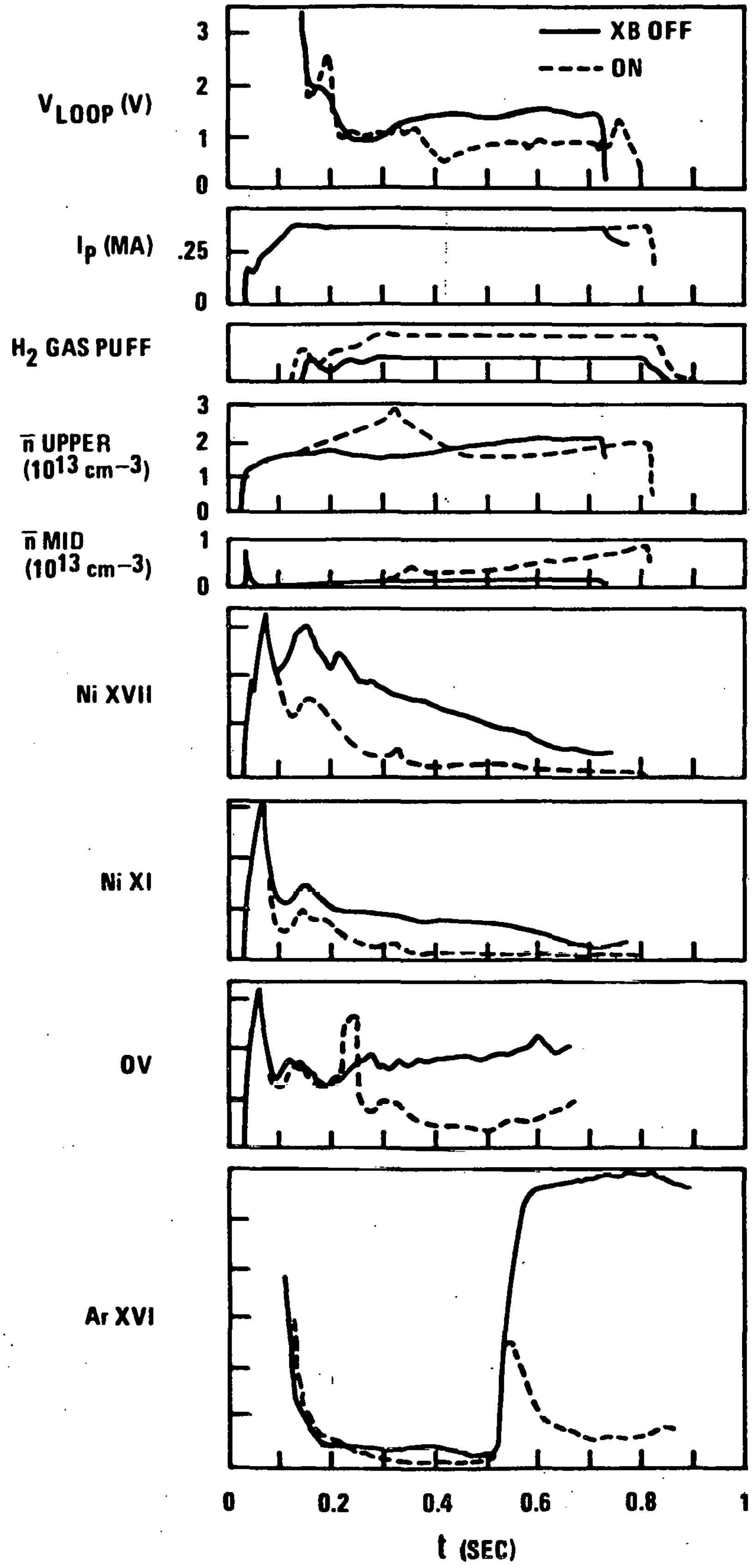

Fig. 4. Waveforms for boundary "on" and "off" discharges

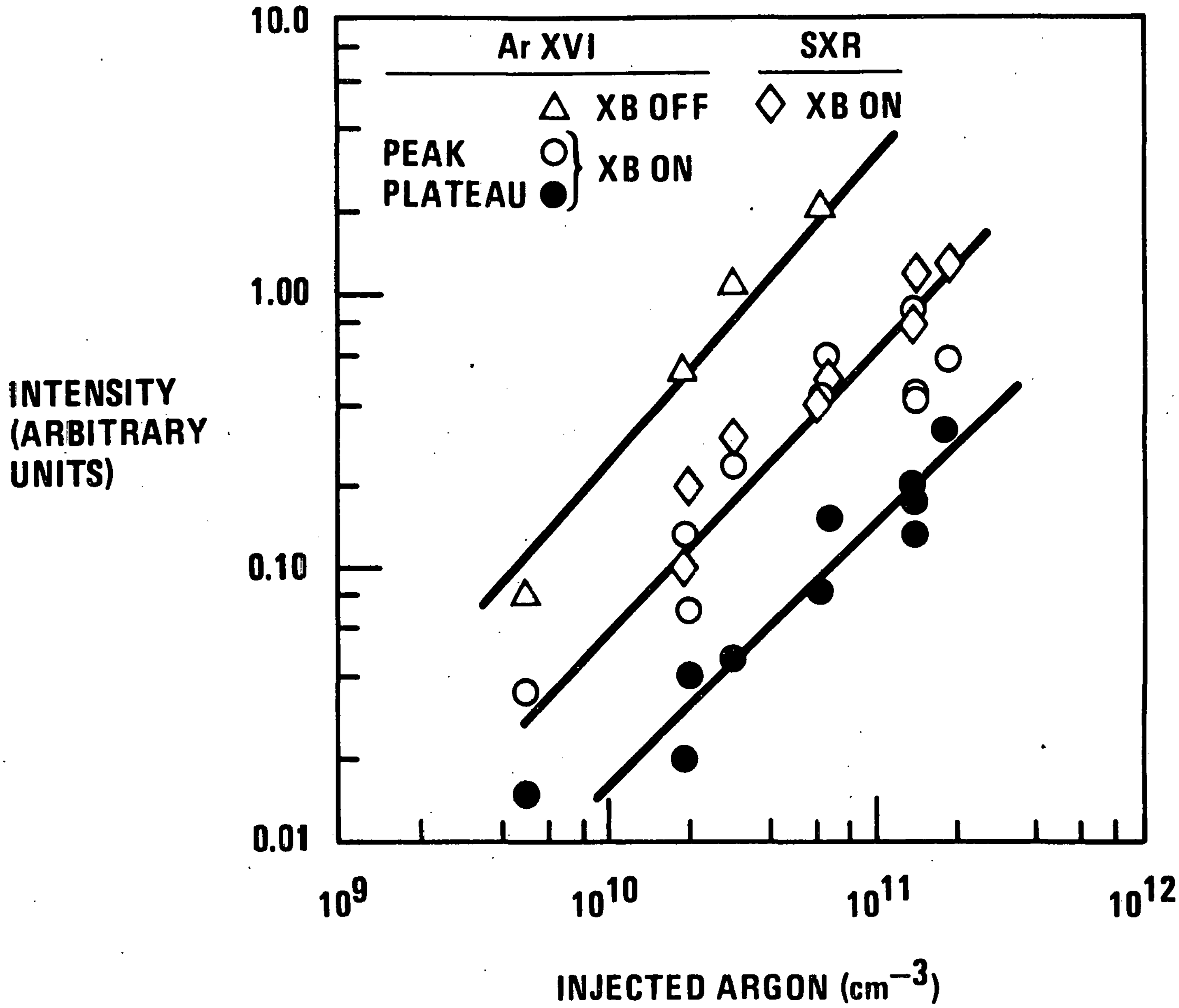

Fig. 5. Argon XVI line intensity (I.P. = 855 eV) vs injected neutral argon density (injected atoms/plasma volume). The shielding effect is independent of the quantity of argon injected.

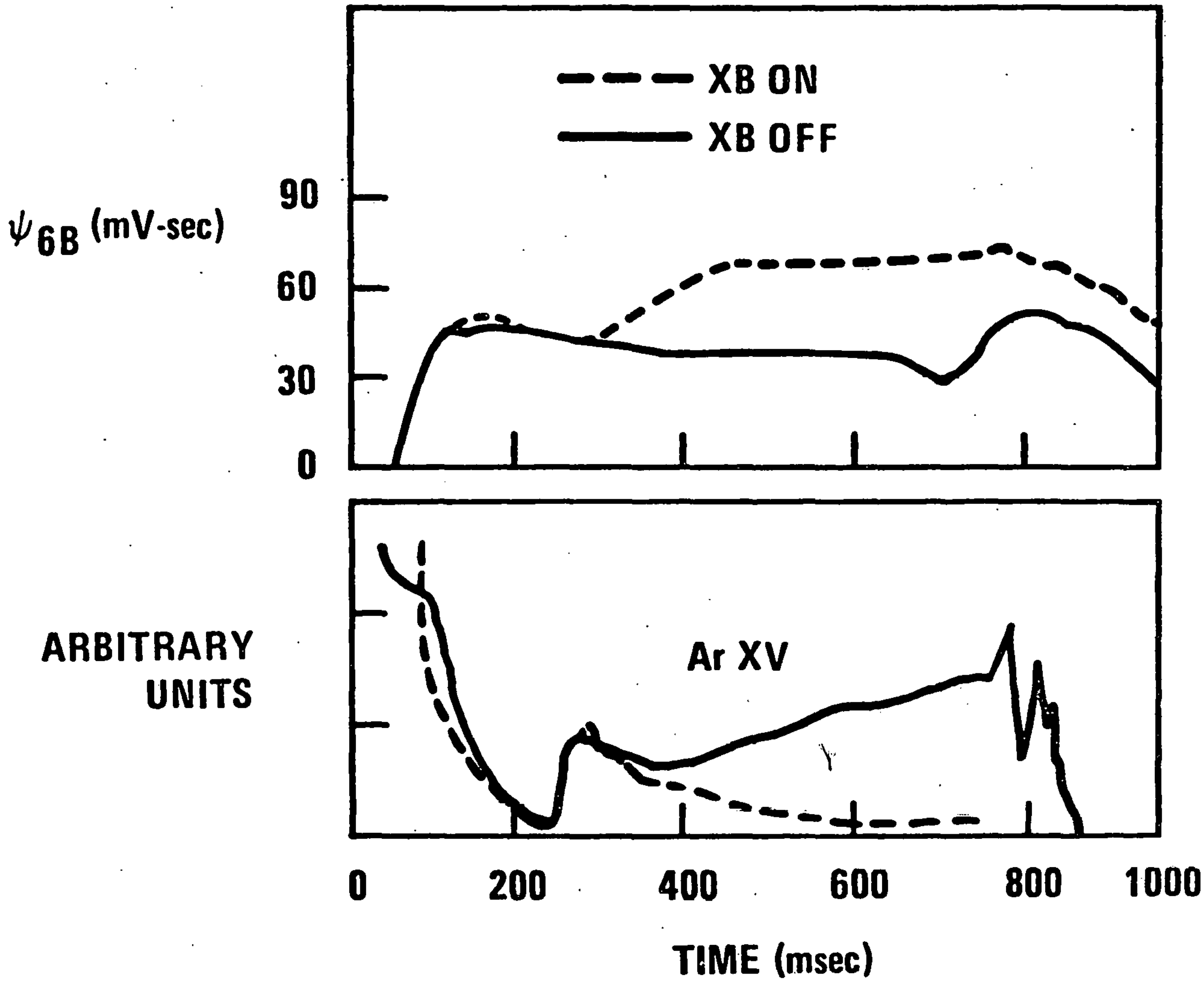

Fig. 6. Waveforms of Ar XV line and ψ_{6B} for expanded boundary "on" or "off". Argon is injected 120 msec before the boundary is turned on.