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STUDIES OF NEUTRON EMISSION DURING THE START-UP PHASE OF THE ALCATOR C TOKAMAK

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ABSTRACT

Alcator C operations commenced with discharge cleaning and tokamak operation using hydrogen filling gas. Prior to and during these experiments no deuterium gas was allowed into the device. The earliest operation resulted in dosimeter readings of a few Roentgen per shot in the vicinity of the limiter and a localized source of neutron emission of up to 10^9 neutrons per shot which were subsequently identified as having photonuclear origin. After seven months of operation, conditions were achieved that resulted in substantially less photonuclear activity. Subsequently, deuterium fill gas was allowed into the device and measurement of neutron flux and energy spectra indicated that the majority of neutron emissions in Alcator C high density deuterium discharges were consistent with having thermonuclear origins.

1. INTRODUCTION

Studies of neutron emissions in present day fusion devices have gained wide acceptance as being an important aid in the understanding of processes that take place in fusion grade plasmas. In both ohmically heated and supplementary heated (neutral beam and RF heated) deuterium plasmas, the neutron emission provides a measure of the fusion reactivities. Furthermore, the emissions can be used to deduce ion temperatures, a technique that has in general been found to be in good agreement with standard ion temperature diagnostics, i.e., charge exchange and Doppler broadening techniques.

A prerequisite for the validity of the neutron deduced ion temperature determinations lies in the certainty that the measured neutron emissions are due to thermonuclear processes, since it is known that significant contributions to the total neutron emissions can be due to non-thermonuclear processes [1-7]. The dominant sources of spurious neutron emissions in present day ohmically heated tokamak devices result from electrodisintegration or photodissociation processes [8].

The reactions for these processes are given by

$D(e,e'n)H$ threshold = 2.2 MeV (Volume process)

$^{97}Mo(\gamma,n)^{96}Mo$ threshold = 6.8 MeV (Localized process)

The former process results when runaway electrons (whose energies exceed the binding energy of the deuteron) confined in the plasma volume interact with deuterons or impurities, thus producing a non-localized source of neutron emission. The cross section for this process is rather small [9] and the presence of measureable e-d neutron emissions are expected when

large fluxes of photonuclear emissions are present. The photonuclear effect arises when runaway electrons that are poorly confined collide with the plasma limiter. In the latter expression above, molybdenum is used as the target atom since molybdenum is used as the limiter material in Alcator C. Photodisintegration processes occur in other materials as well and it has been found that the photonuclear yields scales roughly with Z for a given incident electron energy for thick targets [10,4]. Photonuclear processes in tokamaks are thus localized at the plasma limiter and are independent of the filling gas used.

In section 3 we describe studies of the neutron emissions which arose from the photodisintegration process. The measurements were made during the start-up phase of Alcator C using hydrogen fill gas alone. Deuterium gas was not introduced into the machine prior to these experiments to ensure that electrodisintegration or fusion neutron emissions would not contribute to the measured neutron flux.

In section 4 we describe the next phase of experiments which utilized deuterium as the filling gas. This involved measurement of neutron energy spectra as well as the total global neutron rates resulting primarily from d-d fusion reactions.

2. EXPERIMENTAL DESCRIPTION

The design parameters for Alcator C are given in Table I.

TABLE I

R	a	B_T(max)	I_p(max)	n_o	$T_i \approx T_e$
64 cm	17 cm	14T	1 MA	2×10^{15}cm^{-3}	1.5 keV

For the experiments reported here the machine was generally operated at plasma currents of approximately 400 KA and toroidal magnetic fields of 6 T.

Figure 1 shows a schematic view of Alcator C. The system is completely surrounded by a liquid nitrogen cryostat. The Bitter magnet winding which provides the high magnetic field capability almost completely surrounds the vacuum vessel. Three long counter assemblies are placed about the device for the neutron flux measurements. Within each of the three assemblies are placed three BF_3 proportional counters in order to cover a broad range of rates of neutron emission. The two side assemblies are separated by 180° toroidally, one of which is adjacent to the limiter port, the other on the opposing side of the device. A radionuclide neutron source (PuBe) placed inside the limiter port resulted in a 30 times larger count rate registered by the limiter port long counter than as registered by the long counter on the opposing side of Alcator. Thus it was expected that a localized source of neutron emission which could arise during plasma operation would be easily recognizable as such. The upper long counter assembly was used for determination of the absolute rates of neutron emission. This assembly was calibrated using a PuBe neutron source and a Cf^{252} neutron source. For each calibration the source was placed within the torus and moved along the major and minor axis of Alcator C to simulate a spatially distributed (or localized) source of neutron emission as would be expected in tokamak operation.

3. NEUTRON MEASUREMENTS IN HYDROGEN DISCHARGES

3.1 Evidence that suggests that the neutron emissions observed were of photonuclear origin is described below.

1. Localization of the Neutron Emission. Figure 2 shows the outputs of the two side long counters (each voltage spike corresponds to a single neutron event in the detector). The data shows that the limiter long counter registers a significantly larger neutron flux than the opposing long counter, thus indicating that the neutron emission was localized in the vicinity of the limiter. The digital display of the neutron events was routinely used in the early operations as a check that the events were not due to hard X-ray emissions (i.e., by using pulse height analysis). The hard X-ray emissions were monitored in the forward (energetic emissions) and perpendicular (low energy) directions with 3" x 3" NaI scintillators in 3" thick lead collimators. The collimator apertures do not view the limiter directly because of the continuous Bitter magnet winding.

2. Correlations of Neutron Emissions with Hard X-Ray Emissions and Synchrotron Emissions. Figure 3 shows the neutron rate (in analog form) as measured by the calibrated top long counter. The maximum neutron rate (at the end of the discharge) was about 10^9 neutrons/sec. This type of discharge was routinely accompanied by a large flux of perpendicular hard X-ray emissions early in the discharge and by non-thermal features in the synchrotron emissions (as indicated by the arrows in the figure). Forward (or energetic) hard X-ray emissions rates (not shown in the figure) also showed a strong correlation with the neutron emissions late in the discharge.

3. Limiter Activation and Analysis. A schematic view of the molybdenum limiter is shown in Fig.4. It consists of twenty separate segments of molybdenum supported by two stainless steel support arms. The lower portion of the figure shows the activated portion of the limiter three days after the last tokamak operation.

A γ spectrum of the sample was then performed using a Ge(Li) diode and

several peaks in the spectrum were observed. Analysis of these peaks resulted in identification of sixteen radionuclides as shown in Fig.5. Table II shows the isotopic percentages of natural molybdenum and the corresponding γ,n separation energies.

TABLE II

Isotope	M_o^{92}	M_o^{94}	M_o^{95}	M_o^{96}	M_o^{97}	M_o^{98}	M_o^{100}
Percent Abundance	15.86	9.12	15.7	16.5	9.45	23.75	9.62
γ,n Separation Energies (MeV)	12.6	9.7	7.4	9.2	6.8	8.6	8.3

Shown in Fig.6 are some of the possible schemes for γ,n , γ,p and γ,α reactions in molybdenum. The resulting radionuclides from these decay schemes [11] were then compared with the identified radioisotopes from the measured γ-spectrum and it was concluded that the limiter activation was consistent with photodisintegration (of molybdenum) processes.

3.2 Reduction of photonuclear neutron emission.

It has been reported elsewhere [12] that runaway electrons are born very early in the evolution of tokamak discharges. Consistent with these findings we observed that minor disruptions early in the discharge formation resulted in low levels of photonuclear neutron emission, low levels of hard X-ray emission and little or no non-thermal structure in the synchrotron emissions. Since this was not the most practical way to reduce runaway activity and hence photoneutron emission, another method was attempted.

During the latter period that these experiments were carried out, machine operation became more reliable and tests were performed to adjust the pulsed gas injection time in order that the density rise would occur at the earliest time without causing disruptions in the discharge. It was felt that large density levels very early in the discharge would reduce runaway production and hence photonuclear levels would be lessened. A reduction in the neutron and hard X-ray emissions is clearly shown in Fig.7 where we have used the early gas injection (early density rise) technique. Subsequent operations resulted in further reductions in photonuclear activity by fine tuning of the gas injection system. Photonuclear rates thereafter were less than 10^6 neutrons/sec, i.e., comparable to photonuclear rates observed during the majority of Alcator A high density discharges [13].

4. NEUTRON MEASUREMENTS IN HIGH DENSITY DEUTERIUM DISCHARGES

Measurement of neutron energy spectra can provide information concerning neutron origins as well as information on plasma properties. The results described in this section were the first D-D neutron spectra measurements from Alcator C and were obtained shortly after the first introduction of deuterium into the device. Since the thermonuclear yields were expected to be $< 10^{11}$ n/sec during the initial D-D operation, the spectrometer used for these experiments was chosen for its high efficiency rather than for maximum energy resolution. Specifically, the spectrometer consisted of a 5 cm x 5 cm NE 213 liquid organic [14,15] scintillator, optically coupled to an RCA 8850 photomultiplier tube using a two foot section of cast acrylic lucite plexiglass rod. The location of the spectrometer in relation to Alcator C is shown in Fig.1. Standard Ortec circuitry was used for n-γ pulse shape discrimination to allow pulse height analysis of only neutron pulses during the experiments.

RESULTS

Shown in Fig.8 is a predicted spectrum ($\Phi(E)$ vs. E where $\Phi(E)$ = neutron flux at energy E in neutrons/cm^2-sec, and E = neutron energy in MeV) for a 1 keV D-D maxwellian plasma. The velocity distribution of the reacting deuterons gives rise to a doppler broadening of the spectral peak. The energy spectra for maxwellian velocity distributions have been calculated by Faust and Harris [16]. For a maxwellian deuterium plasma, the width can be written as FWHM = 83.25 $(KT)^{1/2}$ keV, with KT in keV. The resolution of the high efficiency spectrometer used in this work was about 500 keV at 2.45 MeV. The efficiency of the detector was approximately 10^4 times the efficiencies of the usual (H_e^3 , Li-sandwich, etc.) high resolution spectrometers. For the neutron rates expected during the early D-D operation, verification of the fusion origin of the neutron emissions was possible from data averaged over approximately ten plasma discharges.

To unfold the measured proton recoil spectra, a derivative unfolding code [17] was used. Basically, the flux Φ is approximated by

$$\Phi(E) = \frac{-E}{VTn_H} \cdot \frac{1}{\sigma_{np}(E)} \cdot \frac{dP(E)}{dE}$$

where $\Phi(E)$ = neutron flux at energy E (n/cm^2-sec),

$\frac{dP}{dE}$ = first derivative of the proton recoil distribution,

V = detector volume (cm^3),

T = counting time (sec),

n_H = density of target protons (H atoms/cm^3),

and σ_{np} = n-p elastic scattering cross section (cm^2).

The unfolded measured neutron energy spectrum from a high density Alcator C D_2 discharge is shown in Fig.9. The spectrum indicates a large 2.5 MeV peak neutron emission from the $D(D,n)He^3$ fusion reaction. The ion temperature determined both by global neutron emission (using the moderated BF_3 detectors discussed in Section 2) and the spectrum of high energy neutral particles [18] was approximately 800 eV. The agreement between ion temperatures deduced by the neutron flux and the neutral particle spectrum together with the 2.45 MeV peak measured in the neutron spectra, is a clear confirmation that the majority of the neutron emissions for the typical Alcator C high density discharges are of thermonuclear origin.

5. CONCLUSIONS

Rates of neutron emissions of up to 10^9 neutron/shot were observed in hydrogen discharges during the start up phase of Alcator C. Prior to and during these initial experiments deuterium gas was not let into the machine. Localization of the neutron emission together with radioisotopic analysis of the limiter and correlations with non-thermal phenomena in the plasma indicate that the neutron emissions were of photonuclear origin. Runaway electron production was observed to be controllable at times early in the discharge by either minor disruptions or early pulse gas injection. The latter technique was used routinely during the latter part of the experiments and the observed photonuclear neutron rates were typically less than 10^6 neutrons/sec.

Subsequent measurements were performed with deuterium used as the filling gas. D-D neutron energy spectra indicated a peak at 2.5 MeV. Additionally, the central ion temperatures deduced from the measurement of the global neutron emission rate were in agreement with the ion temperatures

deduced from fast neutral spectra. These results confirm that the majority of the neutron emissions produced in high density Alcator C D_2 discharges were of thermonuclear origin.

ACKNOWLEDGEMENTS

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FIGURES

FIG.1. The Alcator C Device

FIG.2. Digital output of the two side port long counters showing localization of neutron emission at the limiter. Neutron rate at the end of the shot $\approx 10^9$ n/sec.

FIG.3. Analogue display of neutron emission as registered by the top long counter. The neutron emission was typically accompanied by large flux of hard X-ray emission and non-thermal feature of the cyclotron emission.

FIG.4. Top- schematic view of the segmented molybdenum limiter. Photograph shows the activated region (dark shiny region in center).

FIG.5. Gamma spectrum of the activated region. 16 peaks are identified as shown.

FIG.6. Thick target bremsstrahlung resulting from runaway electrons colliding with the limiter can produce photoneutrons by some of the above reactions. Various unstable isotopes that are produced can be identified by gamma spectrum of the activated sample.

FIG.7. Early pulse gas injection reduces hard X-ray emission and photoneutron production.

FIG.8. Calculated neutron energy spectrum for a 1 keV D-D (maxwellian) plasma.

FIG.9. Measured neutron energy spectrum from Alcator C high density deuterium discharge. The peak at 2.5 MeV together with the agreement between fast neutral spectrum and neutron flux deduced ion temperatures indicates that the neutrons are of thermonuclear origin.

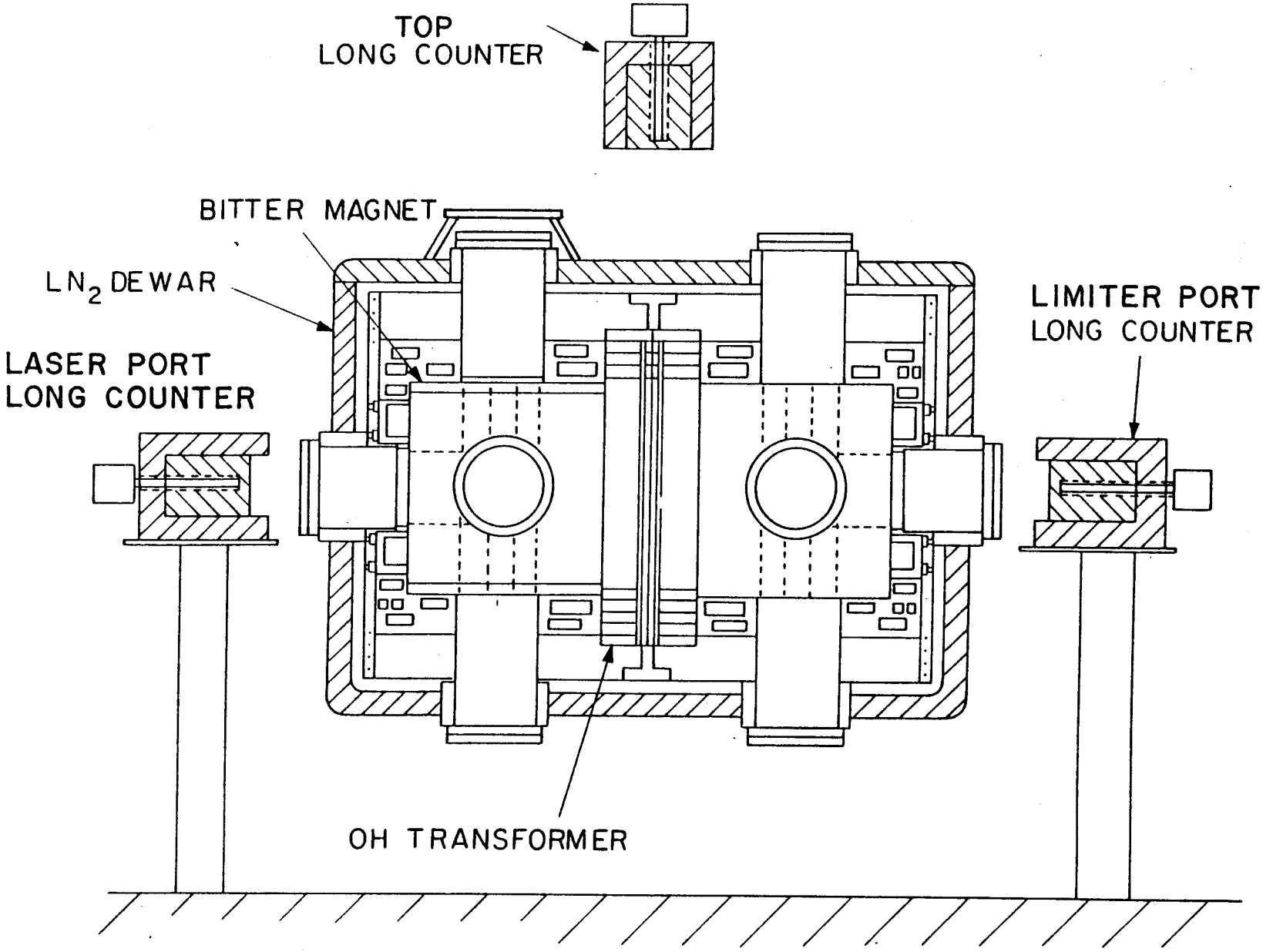

TOP
LONG COUNTER
BITTER MAGNET
LN_2 DEWAR
LASER PORT
LONG COUNTER
LIMITER PORT
LONG COUNTER
OH TRANSFORMER

Figure 1.

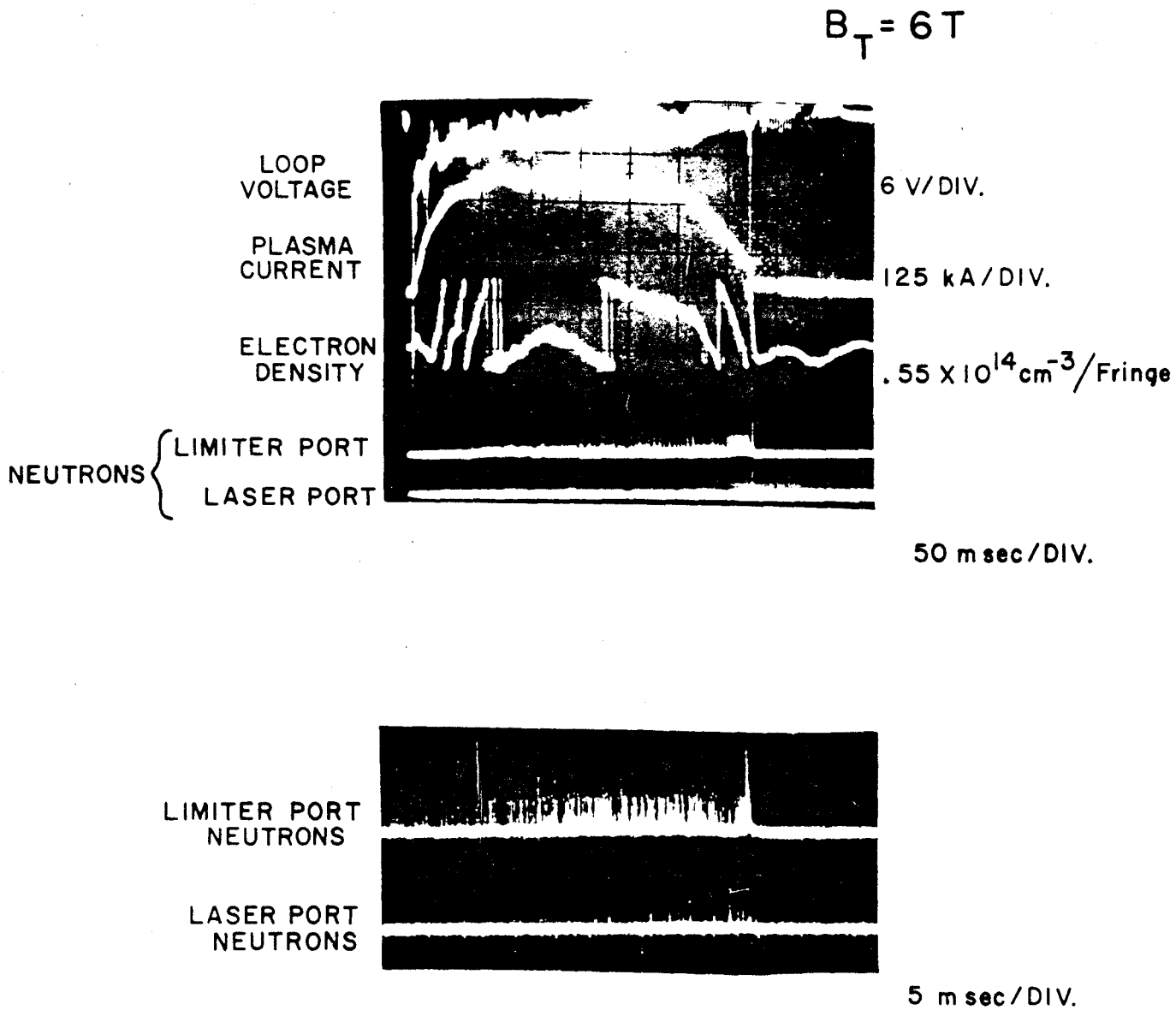

$B_T = 6\,T$
LOOP VOLTAGE
6 V/DIV.
PLASMA CURRENT
125 kA/DIV.
ELECTRON DENSITY
$.55 \times 10^{14} cm^{-3}$/Fringe
NEUTRONS
LIMITER PORT
LASER PORT
50 m sec/DIV.
LIMITER PORT NEUTRONS
LASER PORT NEUTRONS
5 m sec/DIV.

Figure 2

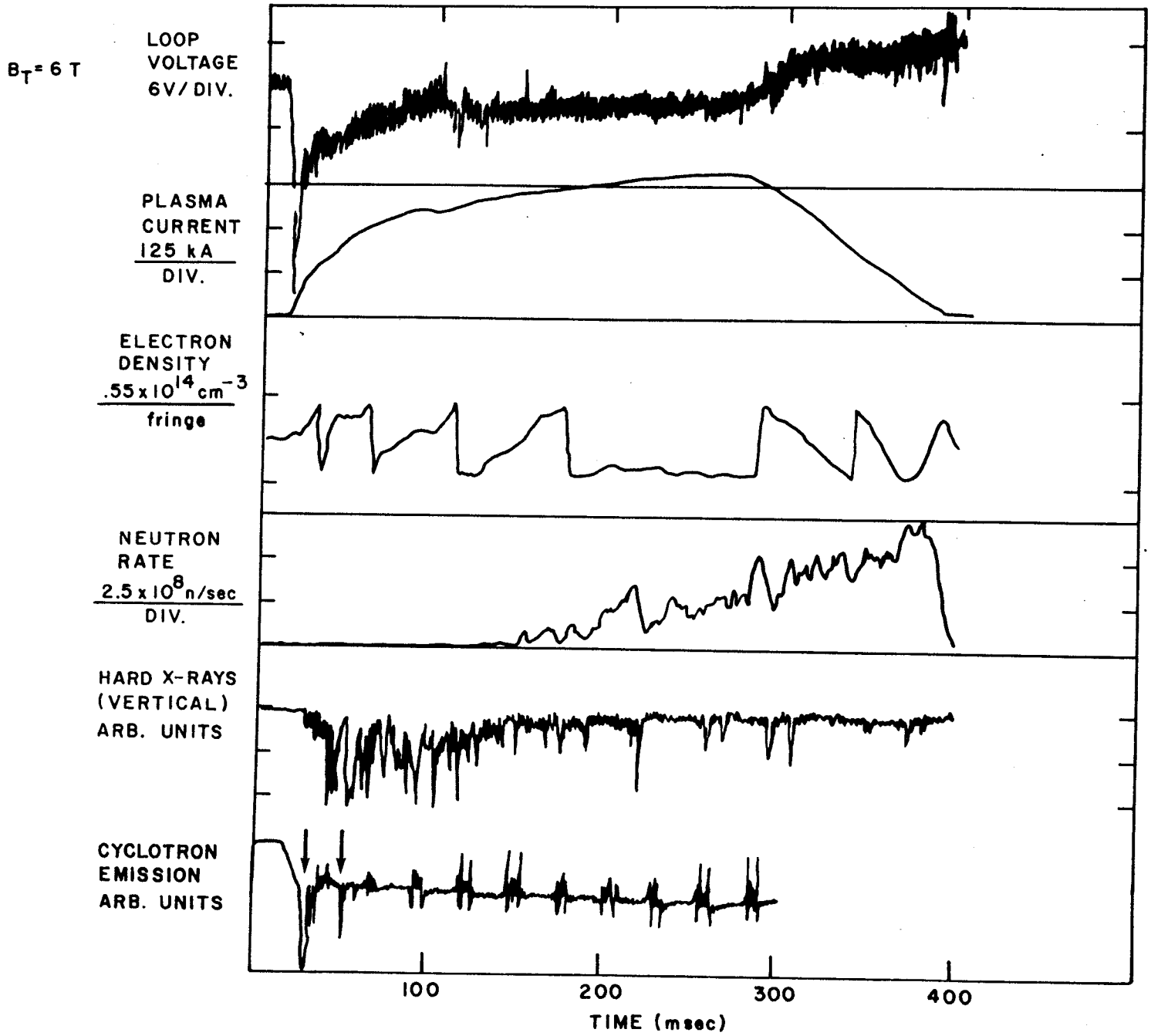
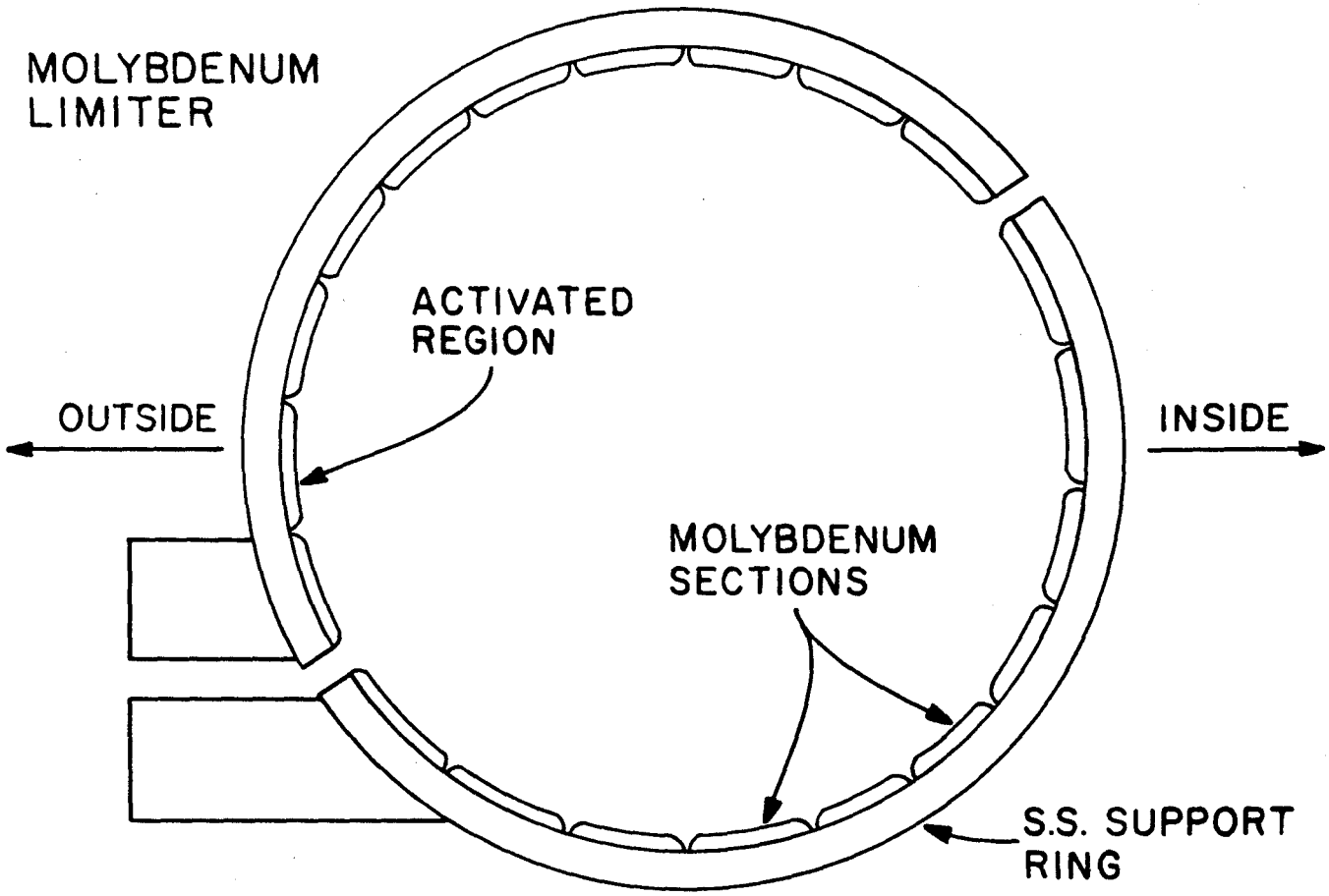

B_T = 6 T
LOOP VOLTAGE 6V/DIV.
PLASMA CURRENT 125 kA / DIV.
ELECTRON DENSITY .55x10^14 cm^-3 / fringe
NEUTRON RATE 2.5x10^8 n/sec / DIV.
HARD X-RAYS (VERTICAL) ARB. UNITS
CYCLOTRON EMISSION ARB. UNITS
100
200
300
400
TIME (msec)

Figure 3


MOLYBDENUM
LIMITER
ACTIVATED
REGION
OUTSIDE
INSIDE
MOLYBDENUM
SECTIONS
S.S. SUPPORT
RING

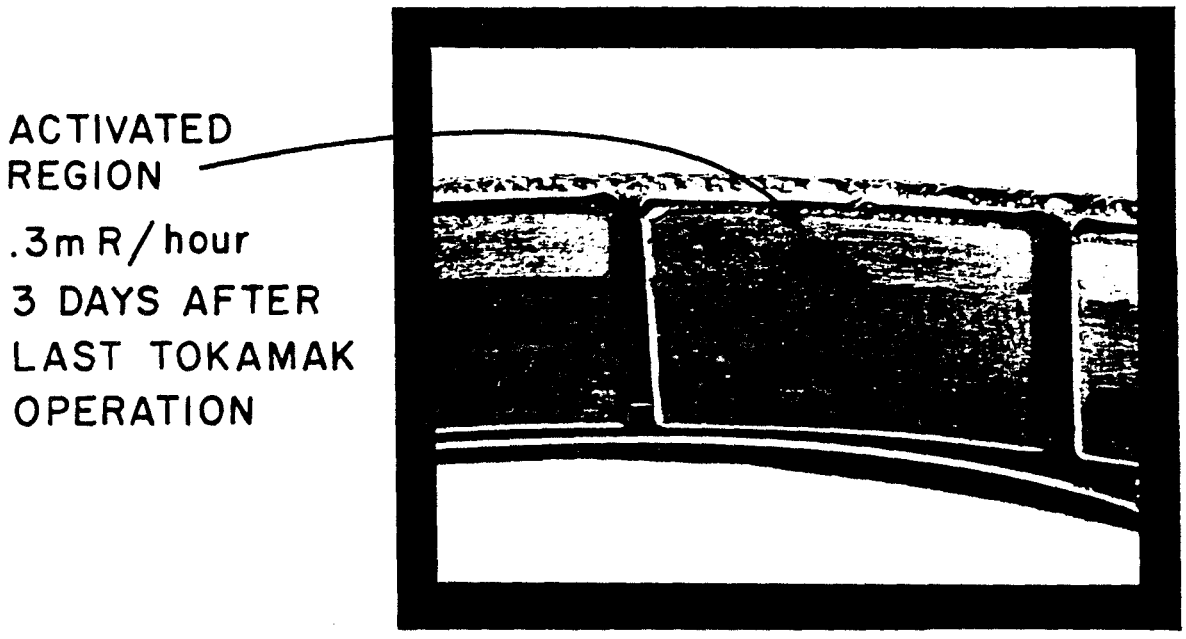
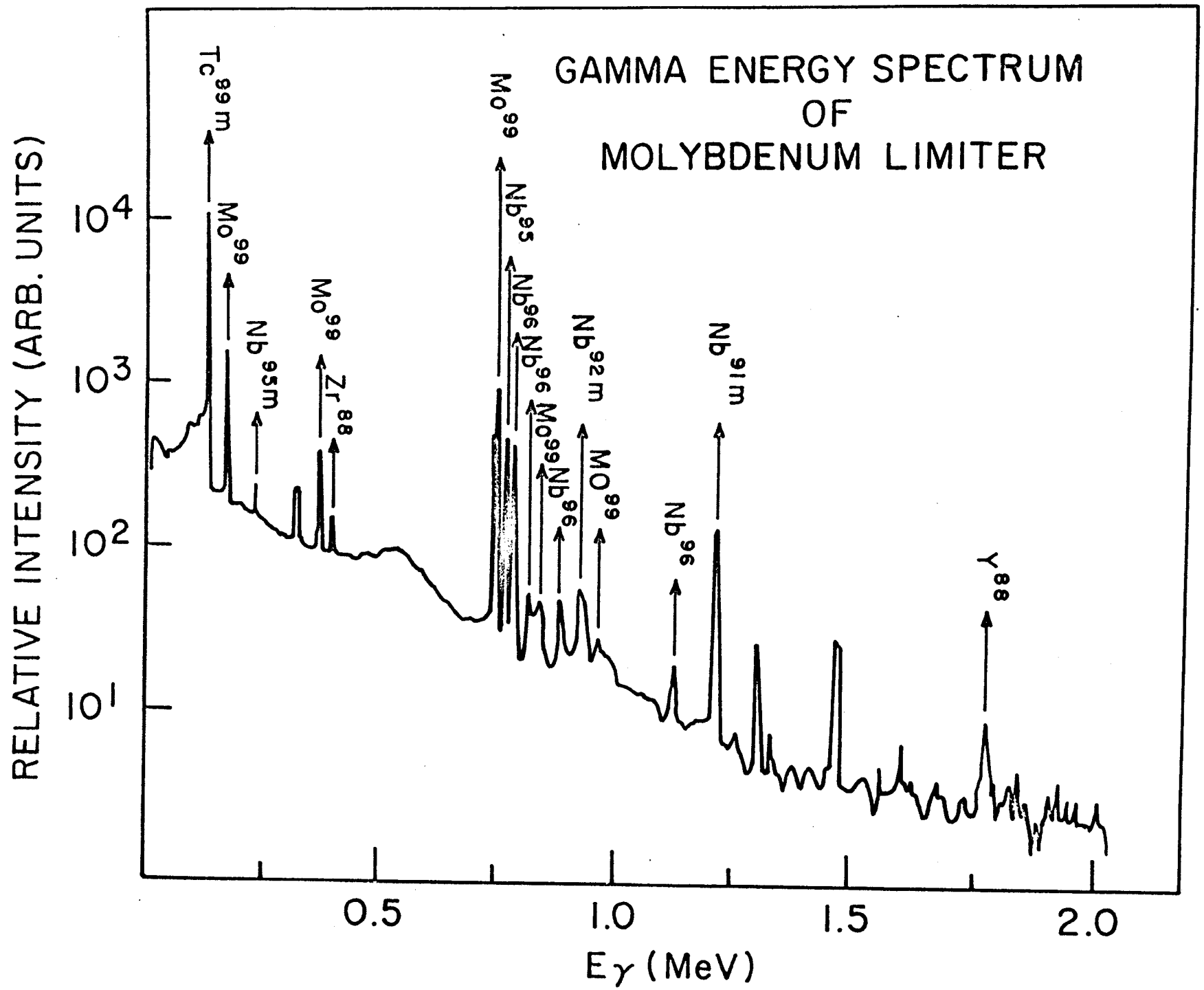

ACTIVATED
REGION
.3m R/hour
3 DAYS AFTER
LAST TOKAMAK
OPERATION

Figure 4.


GAMMA ENERGY SPECTRUM
OF
MOLYBDENUM LIMITER
RELATIVE INTENSITY (ARB. UNITS)
10^4
10^3
10^2
10^1
Tc^{99m}
Mo^{99}
Nb^{95m}
Mo^{99}
Zr^{88}
Mo^{99}
Nb^{95}
Nb^{96}
Nb^{96}
Mo^{99}
Nb^{96}
Nb^{92m}
MO^{99}
Nb^{96}
Nb^{91m}
Y^{88}
0.5
1.0
1.5
2.0
Eγ (MeV)

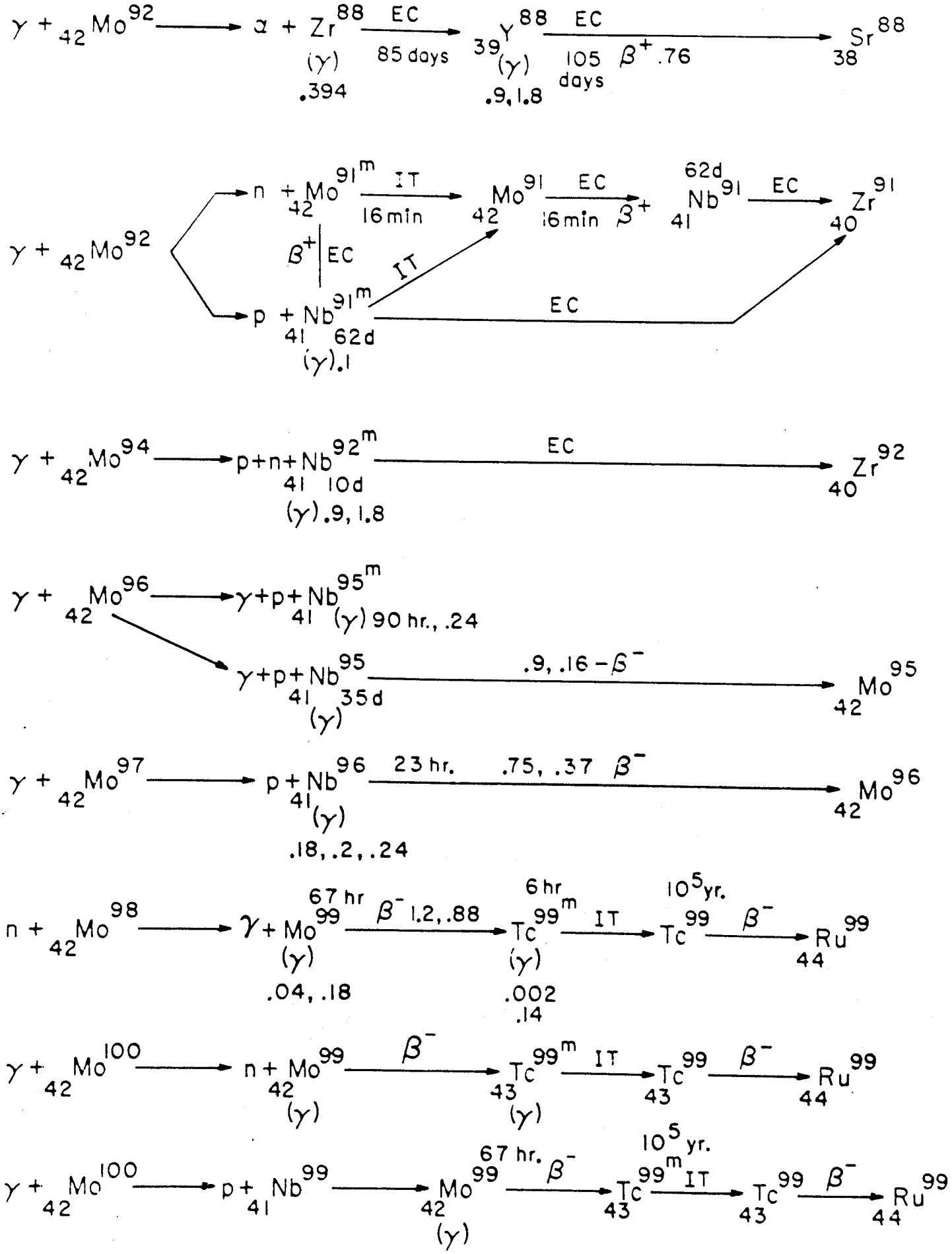

γ + 42Mo92 → α + Zr88 (γ) .394 EC 85 days 39Y88 (γ) .9, 1.8 EC 105 days β+ .76 38Sr88
γ + 42Mo92
n + 42Mo91m IT 16 min 42Mo91 EC 16 min β+ 41Nb91 62d EC 40Zr91
β+ | EC
IT
p + 41Nb91m 62d (γ) .1
EC
γ + 42Mo94 → p+n+41Nb92m 10d (γ) .9, 1.8 EC 40Zr92
γ + 42Mo96 → γ+p+41Nb95m (γ) 90 hr., .24
γ+p+41Nb95 35d (γ) .9, .16 −β− 42Mo95
γ + 42Mo97 → p + 41Nb96 (γ) .18, .2, .24 23 hr. .75, .37 β− 42Mo96
n + 42Mo98 → γ + 42Mo99 (γ) .04, .18 67 hr β− 1.2, .88 43Tc99m (γ) .002 .14 IT 43Tc99 6 hr 10^5 yr. β− 44Ru99
γ + 42Mo100 → n + 42Mo99 (γ) β− 43Tc99m (γ) IT 43Tc99 10^5 yr. β− 44Ru99
γ + 42Mo100 → p + 41Nb99 → 42Mo99 (γ) 67 hr. β− 43Tc99m IT 43Tc99 10^5 yr. β− 44Ru99

Figure 6.

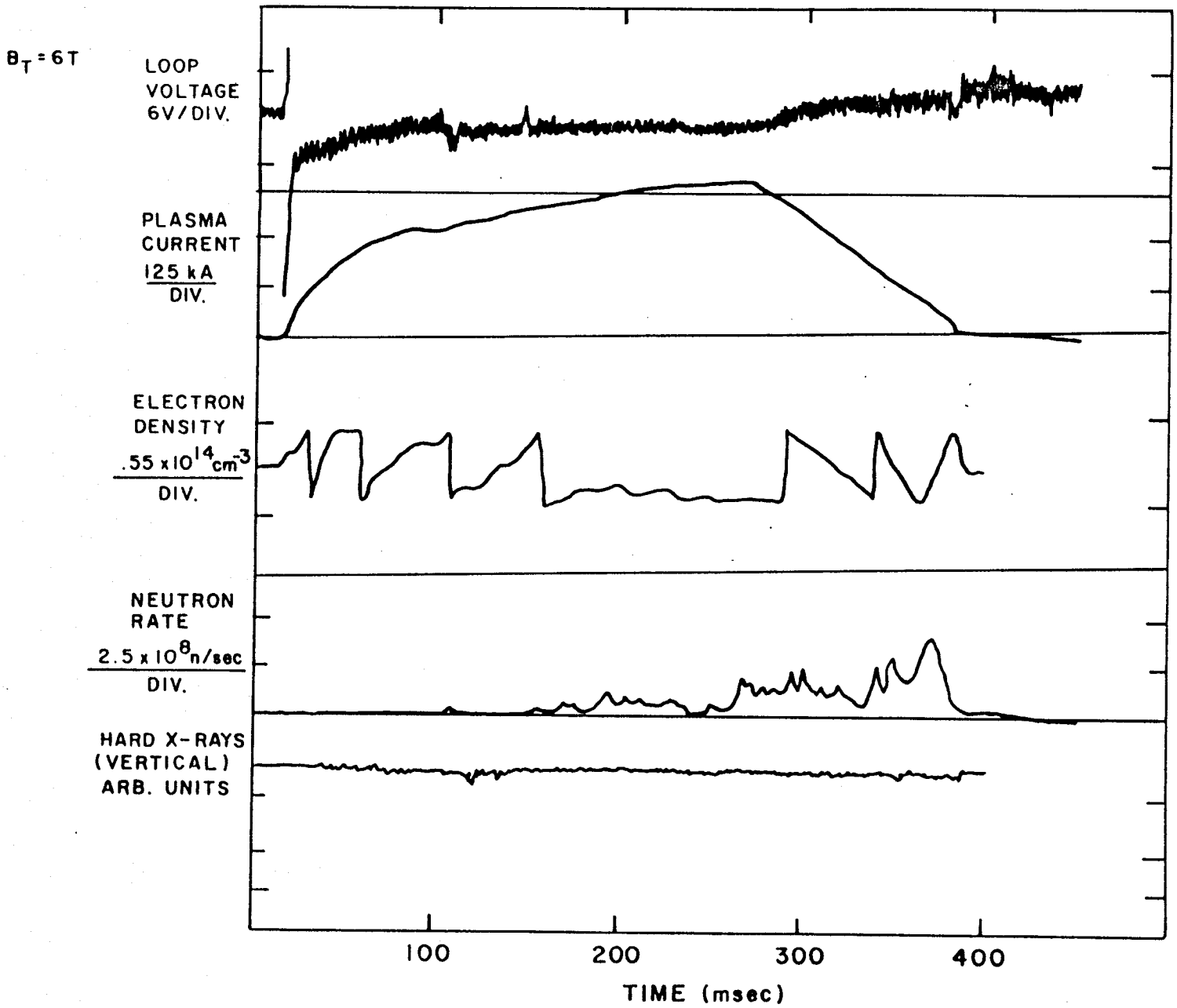

$B_T = 6T$
LOOP VOLTAGE 6V/DIV.
PLASMA CURRENT 125 kA/DIV.
ELECTRON DENSITY .55 x 10^{14} cm^{-3} DIV.
NEUTRON RATE 2.5 x 10^{8} n/sec DIV.
HARD X-RAYS (VERTICAL) ARB. UNITS
100
200
300
400
TIME (msec)

Figure 7

FIGURE 8

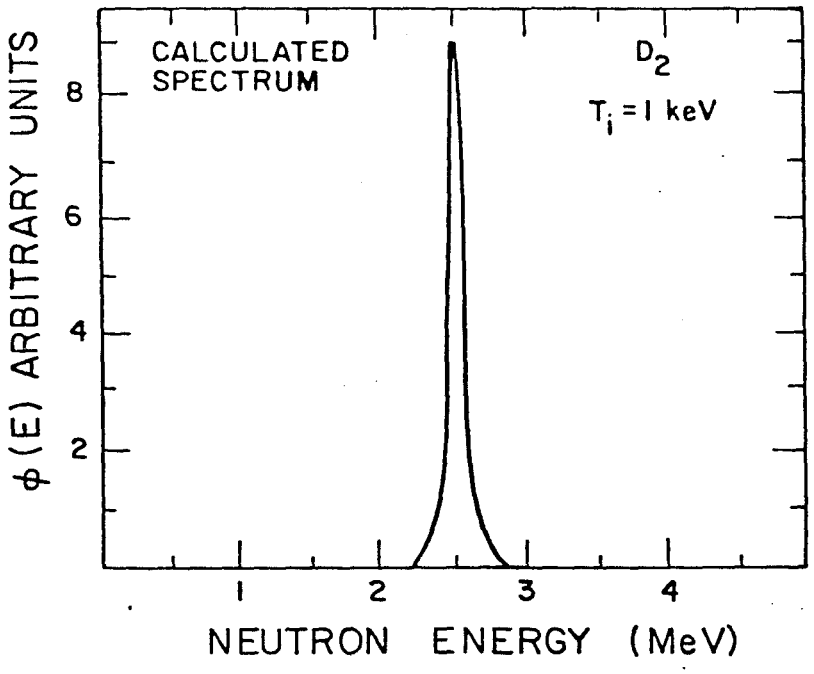
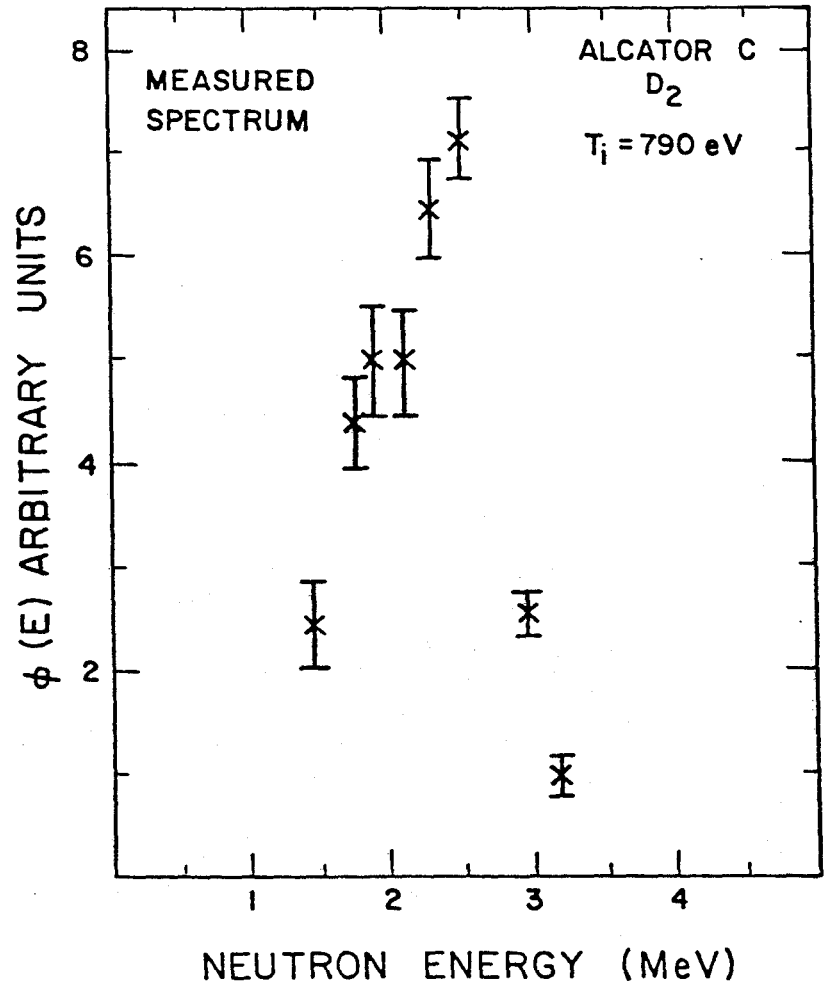



FIGURE 9