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Limiter and RF Antenna**

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Photon activation of the Alcator C-MOD limiter and RF antenna

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Abstract

This paper summarizes the results from activation measurements of the limiter and the RF antenna in Alcator C-MOD. The measurements were taken after the run period from May to October of 1993, during which hydrogen and deuterium discharges were studied. We conclude that Bremsstrahlung photons generated by runaway electrons striking these materials induced most of the high threshold activation reactions. This means that electrons with energies higher than 10 MeV must have been generated in runaway discharges.

INTRODUCTION

The Alcator C-MOD tokamak has recently completed its second experimental campaign from May to October of 1993. The tokamak operated for a period of 6 months at plasma currents in the range from 100 kA to 1 MA, peak electron densities $\gtrsim 10^{20} \text{ m}^{-3}$ and ion temperatures $\gtrsim 1 \text{ keV}$.

Following these experiments, a vacuum break allowed access to internal components of the machine. The RF antenna and a limiter to protect it were removed and placed in a cage of restricted access. The activation measurements started one month after the last day of operation.

Fig. 1 shows the limiter and the antenna. The limiter tiles at the front surface are made of TZM (99% Mo, 0.5% Ti) and are fixed with stainless steel pins and screws to the tile mounting plate which is Inconel (80% Ni, 18.4% Cr). Some of the central tiles on the midplane of the torus were melted as a consequence of excessive energy deposition by the runaway electrons. A dose rate of 5 mRem/h at contact with the melted spot was measured after a cool-down period of one month following the last day of operation. Only the melted region showed activation levels exceeding background.

The antenna and its Faraday shield are made of Inconel. There are TZM protection tiles on the sides, top and bottom of the structure, located 5 mm in front of the Faraday shield and placed typically 5 to 10 mm behind the shadow of the limiter. No physical damage was observed on the shielding. The measured dose rate was a factor of 10 smaller than at the limiter.

In order to identify the source of radiation from the limiter and the antenna, gamma-ray spectra were obtained with a high-purity germanium (HPGe) detector.

We believe that most of the radiation from these two components has been caused by Bremsstrahlung photons produced by runaway electrons with energies $\gtrsim 10$ MeV. Understanding the runaway phenomenon is of great interest in the study of plasma stability ¹ and also because these high energy electrons can seriously damage the machine components.^{2,3}

DESCRIPTION OF RADIATION MONITORING

The neutron production is measured with fission chambers and BF₃ counters, while bubble dosimeters and TLD's provide neutron dose rates. Several monitors (TLD's, self reading dosimeters, film badges) have been used to report x- and γ -ray doses. A detailed description of the Alcator C-MOD radiation detection system has been previously reported.⁴

Fig. 2 shows a top view of the machine where the two neutron stations (containing fission chambers and BF₃ detectors) are inside moderators 1 and 2. The limiter is placed in the tokamak through E-port to protect the RF antenna situated in D-port. Radiation dosimeters are distributed over different locations in the experimental cell.

During the first four months of operation (mainly with hydrogen plasmas), the measured photoneutron peak-rates were of the order of $2 \times 10^{11} \text{ s}^{-1}$ and even higher when the discharges were dominated by runaway electrons. We should, though, take into account that the neutron detectors were calibrated with a Cf²⁵² source that has an average neutron energy of 2.14 MeV, which is close to the energy of thermal neutrons but significantly greater than the photoneutrons energy. Thus, the measurements are only a lower limit on the actual photoneutron flux.

As a result of the deuterium operation during the month of September 1993, the total neutron emission was 10^{13} , half of it coming from photoneutrons. When the discharges were dominated by runaway electrons, neutron and γ detection was much higher at E-port, where the limiter is located, than at KT-port. Fig. 3 shows neutron and hard x-ray measurements from a runaway dominated hydrogen discharge.

ACTIVATION MEASUREMENTS

Upon completion of the experimental campaign in the fall of 1993, the antenna and the limiter were removed from Alcator C-MOD. Radiation levels above background were found at the melted region of the limiter and the left central part of the antenna. One month after the end of operation their dose rates at contact were 5 mRem/h and 0.5 mRem/h respectively. No measurable activation was found on any other internal component of the tokamak.

The limiter is made of TZM tiles (99% Mo, 0.5% Ti, ...) that are fixed with stainless steel pins and screws to an Inconel mounting plate (80% Ni, 18.4% Cr, ...). The antenna is made of silver plated Inconel and is surrounded by TZM protection tiles coated with TiC/TiN. The antenna is behind an Inconel Faraday shield.

A series of γ -ray measurements were carried out using the HPGe detector to identify the remaining γ peaks from activation. The half-life of the radioisotopes was checked, when it was not too long, taking consecutive measurements over 10 days.

The detector was placed 3.5 inches away from the melted spot at the center of the limiter. We also took a spectrum of one of the limiter sides, where there is some Inconel, by turning the detector.

For the antenna, the detector was placed 3.5 inches away from its Inconel Faraday shield. However, it was still viewing part of the TZM lateral tiles.

Several measurements of different duration (from 300 s to 10 h) were taken, each with its corresponding background.

RESULTS

Representative spectra obtained from the limiter and the antenna are shown in Figs. 4 and 5 respectively. Unfortunately, these measurements were taken 1 month after the last operational day, so the short-lived radioisotopes had completely decayed. Some possible photonuclear processes to explain the peaks of these figures are listed in Tables I and II. Alternative neutron-induced reactions that would give rise to some of the peaks are given in table III. The cross sections for these neutron reactions are of the order of a few mb around 2.5 MeV^{5,6}, except for the Ni⁵⁸(n,p)Co⁵⁸ (120 mb at 2.5 MeV) in which case part of the activation could have been caused by thermonuclear D-D neutrons. However, no other activated Inconel was found in the experiment. Doses above background were measured only at the limiter and at the antenna. The radiation was mainly localized at the melted region of the limiter. This is strong evidence that neutron induced reactions have not contributed significantly to the activation.

Knowing that most of the activation processes were induced by Bremsstrahlung photons generated by high energy electrons, we tried to obtain some information about the energy and intensity of the incident runaway electrons by relating them with the intensity of each peak:

$$C_i = A_i \times \int_{E_{th}}^{E_{max}} N(E_\gamma, E_{max}) \times \sigma(E_\gamma) \times dE_\gamma$$

where C_i is the number of counts under the activation peak labeled "i", A_i includes the decay constant and the detector efficiency, σ and E_{th} are the cross section and threshold energy of the photonuclear process and $N(E_\gamma, E_{max})$ is the Bremsstrahlung spectrum generated by electrons of energy E_{max} . The fact that the activation could have occurred any time during the run period and the lack of data for most of the cross sections were the main reasons why we could not get this information. We can say, however, that some of these electrons have energies higher than 10 MeV by looking at the thresholds of the reactions that they can induce. Therefore, this technique has allowed us to obtain some information concerning the energy of the runaway electrons in the absence of other diagnostics. In previous studies on Alcator C.7, the Mo reactions were also found, but the activation of Ni, Ti and Cr was not observed. The presence of Co^{56} provides evidence of electron energies as high as 20 MeV.

We could see Ni and Cr activation at the limiter because there is a thick piece of Inconel supporting the molybdenum tiles by stainless steel bolts. At the melted region, these elements are close enough to the surface for the runaway electrons to cause their activation. In a different spectrum for which we turned the detector to see the side of the limiter, the intensity of the two Co^{57} peaks from the $Ni^{58}(\gamma, p)$ reaction was much higher than in cases where the detector was viewing the front of the limiter.

The activation of the antenna was much smaller, but enough to see the Co and Cr radioisotopes as well as the strongest Nb peaks.

CONCLUSIONS AND FUTURE WORK

Photons from runaway electrons with energies around 10 MeV and up to 20 MeV

are believed to cause most of the activation of the materials inside the Alcator C-MOD vacuum vessel.

The induced activity was sharply localized at the melted region of the limiter and doses above background were found only at the limiter and at the antenna. Furthermore, some of the identified radionuclides could not have their origin in reactions induced by neutrons of reasonable energy (below 3 MeV). These two facts point to the presence of photoreactions induced by high energy Bremsstrahlung generated inside the limiter and the antenna by runaway electrons.

For future runaway dominated discharges a calibrated detector should be used to determine the energy spectrum of the hard x-rays. As soon as any internal component of the machine is removed, its activation should be studied by taking consecutive spectra to try to infer some information about the intensity and energy of the runaway electrons.

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FIGURE CAPTIONS

Table I. Possible photonuclear reactions responsible for the observed activation at the limiter.

Table II. Possible photonuclear reactions responsible for the observed activation at the antenna.

Table III. Neutron induced reactions that could generate some of the radioisotopes found on the activation of the limiter and the antenna.

Fig. 1. Antenna (front and side views) and Limiter (side view) of Alcator C-Mod in 1993.

Fig. 2. Top view of Alcator C-Mod showing the location of the neutron detectors.

Fig. 3. Neutron and hard x-ray measurements from a runaway dominated hydrogen discharge with a plasma current $I_p=0.485$ MA. The neutron detectors were calibrated for D-D neutrons with a Cf^{252} source which has an average energy of 2.14 MeV.

Fig. 4. γ spectrum from the limiter activation obtained with a HPGe detector during 300 s.

Fig. 5. γ spectrum from the antenna activation obtained with a HPGe detector during 300 s.

Table I.

Element	Reaction	Threshold (MeV)	Half-life	E_γ (MeV)
Nb ^{91m}	Mo ⁹² (γ ,p)	7.5	62d	0.103, 1.205
Zr ⁸⁸ /Y ⁸⁸	Mo ⁹² (γ , α)	5	85d/105d	0.392/0.899, 1.836
Nb ^{92m}	Mo ⁹⁴ (γ ,np)	17.3	10 d	0.935
Nb ^{95m} /Nb ⁹⁵	Mo ⁹⁶ (γ ,p)	9.3	90h/35d	0.234/0.766
Mo ⁹⁹ /Tc ^{99m}	Mo ¹⁰⁰ (γ ,n)	8.3	67h/6h	0.181, 0.740/0.139
Cr ⁵¹	Cr ⁵² (γ ,n)	12	27.8d	0.320
Sc ⁴⁶	Ti ⁴⁷ (γ ,p)	10	84d	0.889,1.120
Co ⁵⁸	Ni ⁶⁰ (γ ,np)	20	71d	0.811
Co ⁵⁶	Ni ⁵⁸ (γ ,np)	19.6	77d	0.847, 1.238, 1.771

Table II.

Element	Reaction	Threshold (MeV)	Half-life	E_γ (MeV)
Nb ^{91m}	Mo ⁹² (γ ,p)	7.5	62d	1.205
Nb ^{92m}	Nb ⁹³ (γ ,n)/Mo ⁹⁴ (γ ,np)	8.8/17.3	10d	0.935
Nb ⁹⁵	Mo ⁹⁶ (γ ,p)	9.3	35d	0.766
Cr ⁵¹	Cr ⁵² (γ ,n)	12	27.8d	0.320
Co ⁵⁸	Ni ⁶⁰ (γ ,np)	20	71d	0.811
Co ⁵⁷	Ni ⁵⁸ (γ ,p)	8.2	270	0.121, 0.136
Co ⁵⁶	Ni ⁵⁸ (γ ,np)	19.6	77d	0.847, 1.238, 1.771

Table III.

Element	Reaction
Nb ^{92m}	Mo ⁹² (n,p)
Nb ^{95m} /Nb ⁹⁵	Mo ⁹⁵ (n,p)
Mo ⁹⁹ /Tc ^{99m}	Mo ⁹⁸ (n, γ)
Cr ⁵¹	Fe ⁵⁴ (n, α)
Co ⁵⁸	Ni ⁵⁸ (n,p)

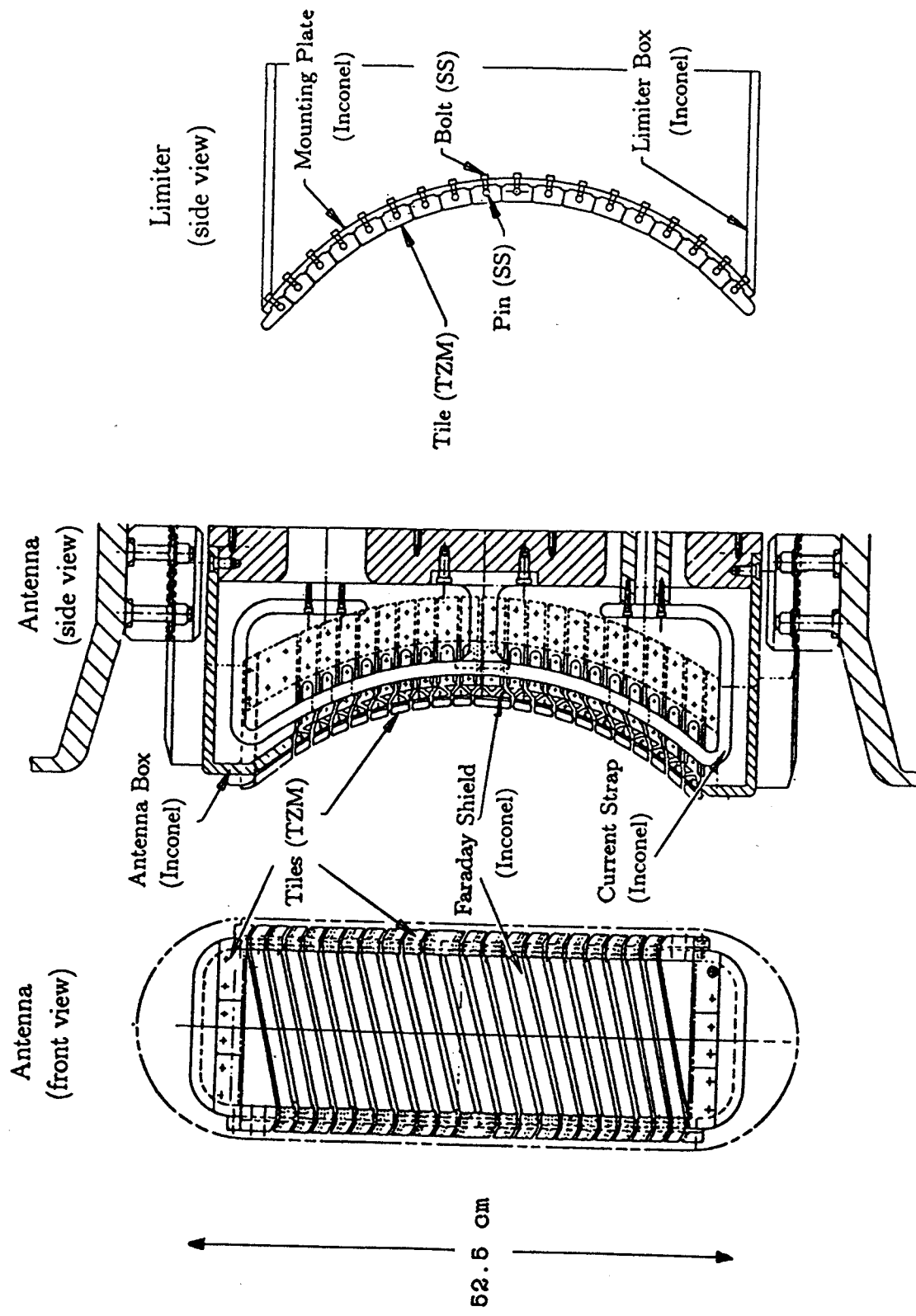


Fig. 1

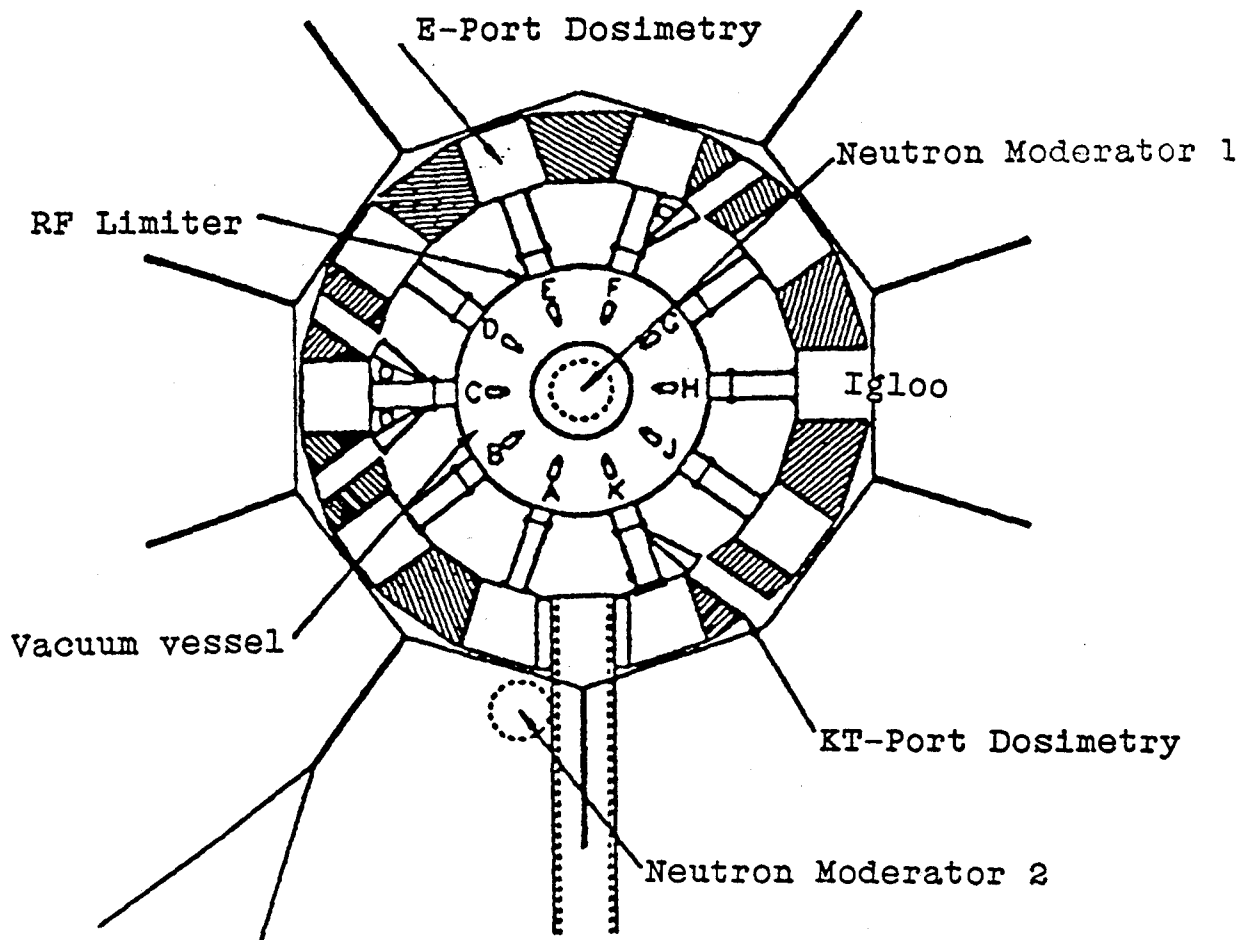


Fig. 2

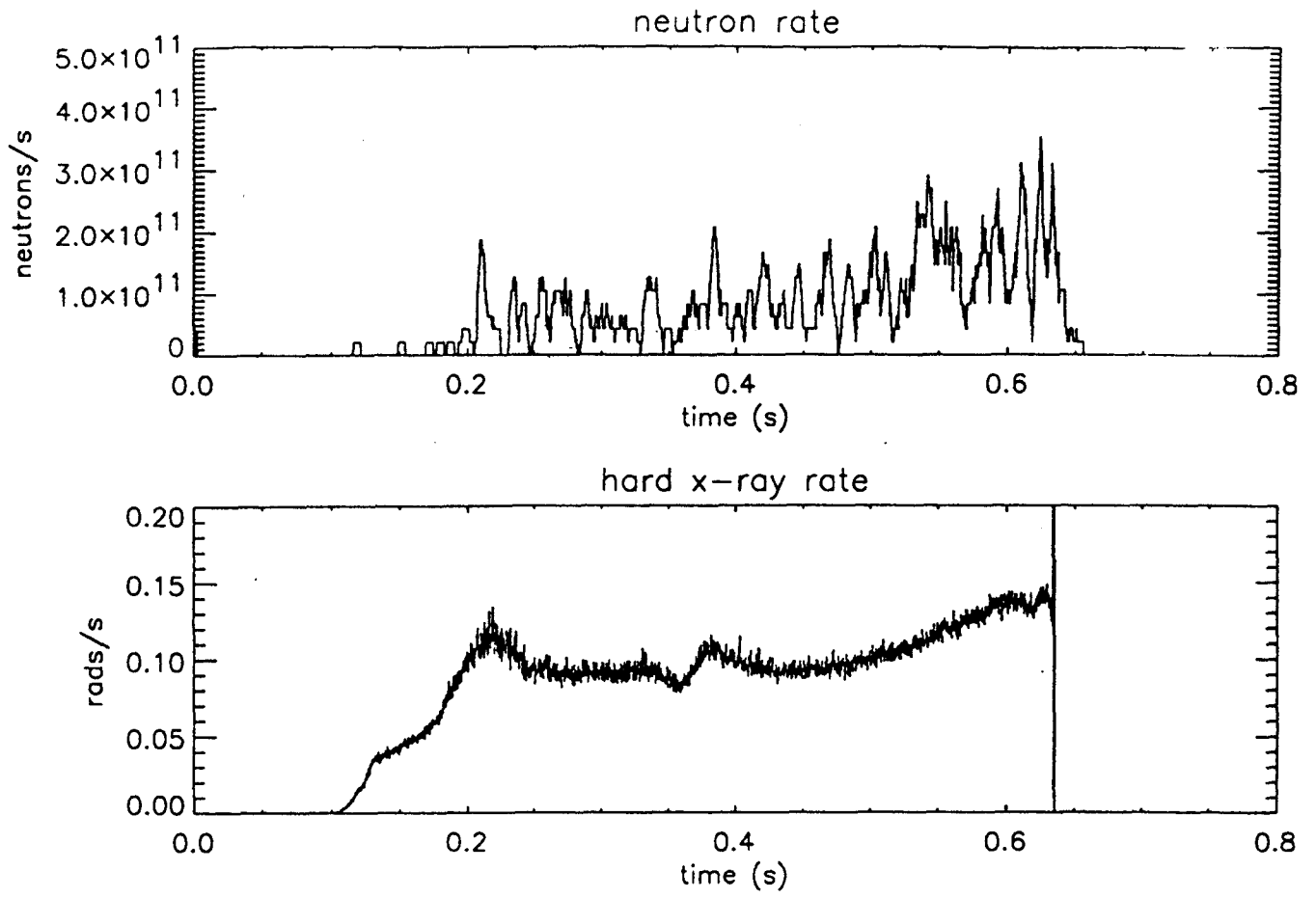
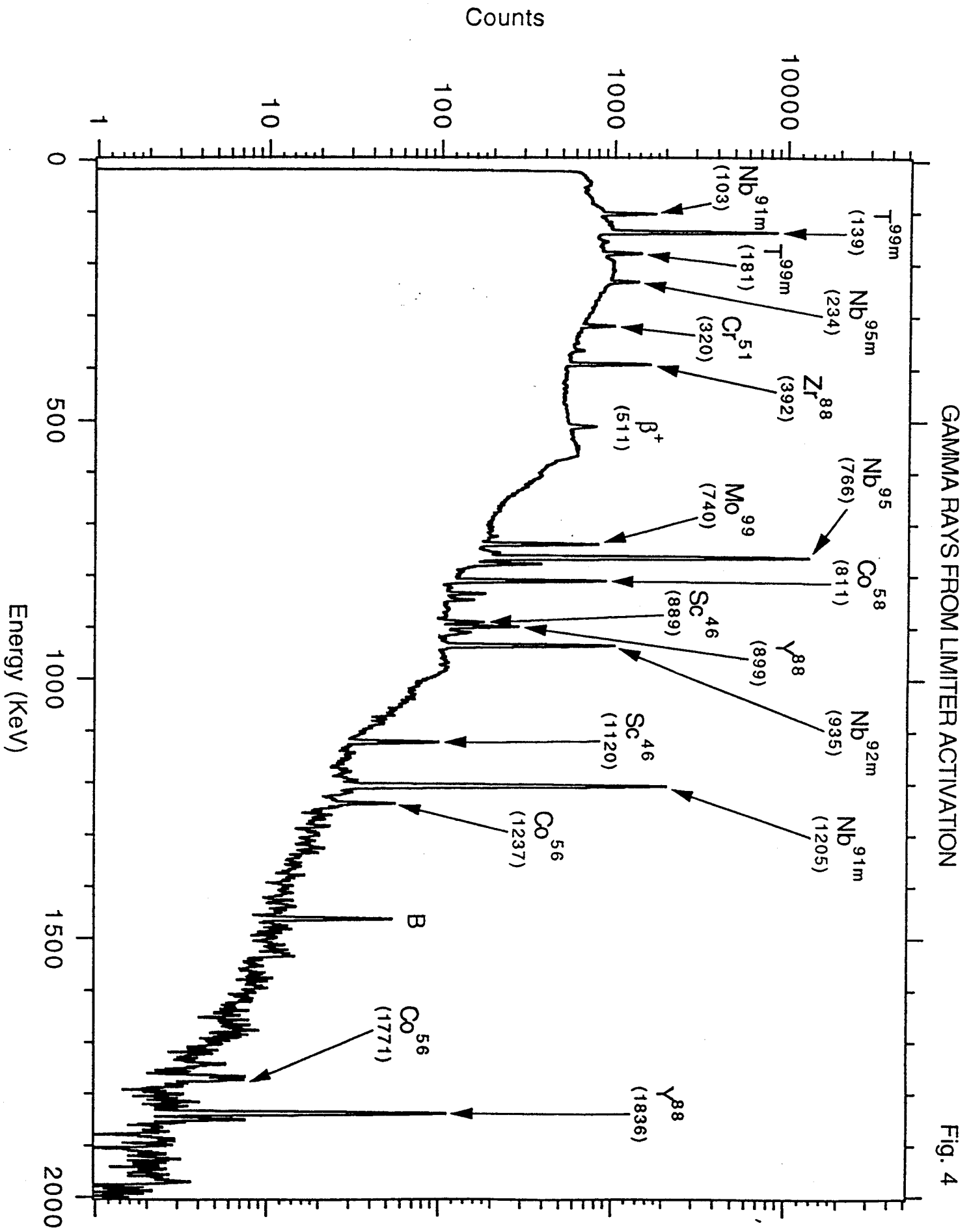


Fig. 3



GAMMA RAYS FROM LIMITER ACTIVATION

Fig. 4

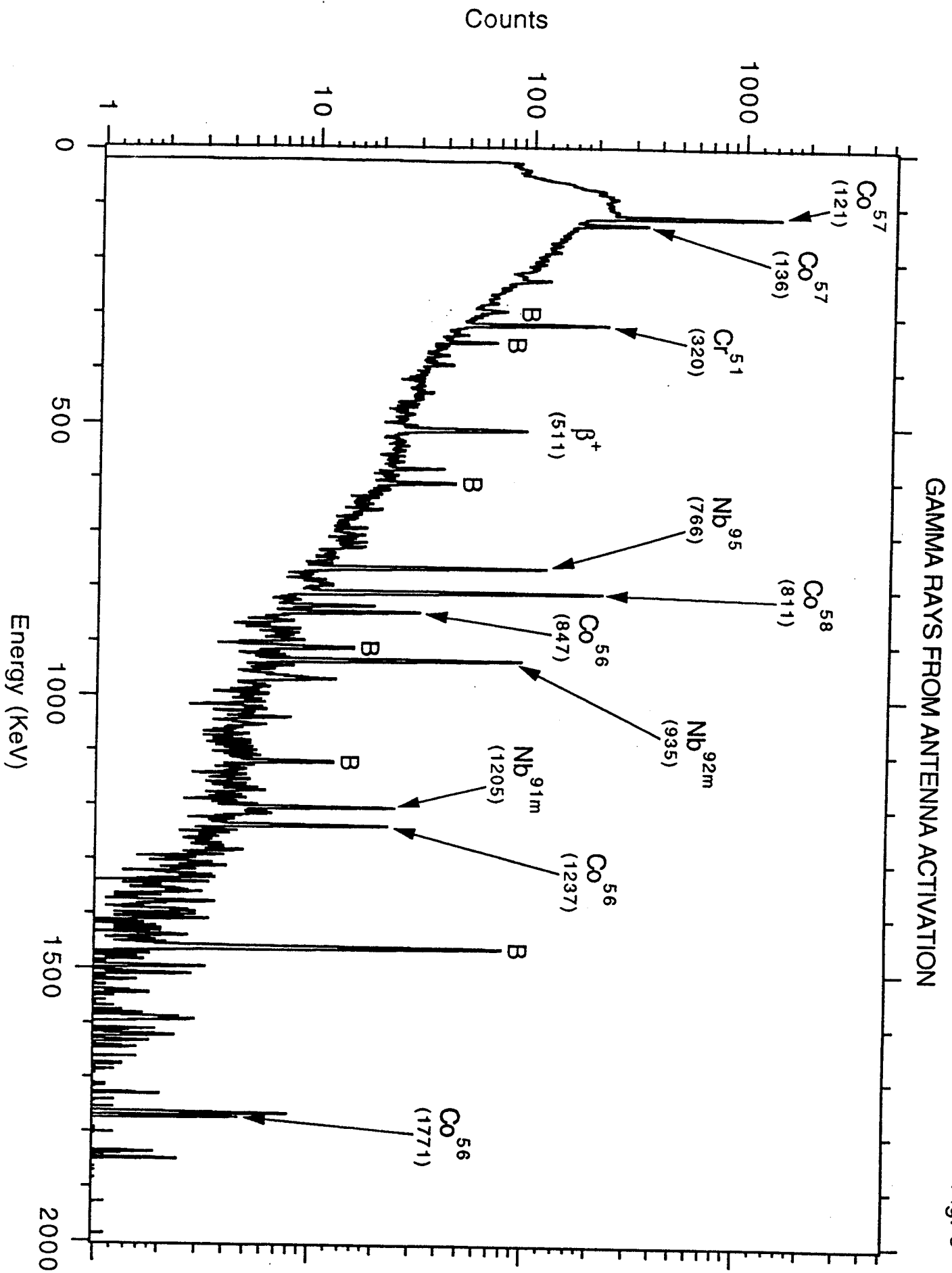


Fig. 5