SMC-TR-92-30

AEROSPACE REPORT NO.
TR-0090(5940-05)-4

Bevalac Ion Beam Characterizations For Single Event Phenomena

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16 July 1992

Prepared for

SPACE AND MISSILE SYSTEMS CENTER
AIR FORCE MATERIEL COMMAND
Los Angeles Air Force Base
P.O. Box 92960
Los Angeles, CA 90009-2960

Contract No. F04701-88-C-0089

425669

23p

Engineering and Technology Group

THE AEROSPACE CORPORATION
El Segundo, California

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This report was submitted by The Aerospace Corporation, El Segundo, CA 90245-4691, under Contract No. F04701-88-C-0089 with the Space and Missile Systems Center, P.O. Box 92960, Los Angeles, CA 90009-2960. It was reviewed and approved for The Aerospace Corporation by A. B. Christensen, Principal Director, Space and Environment Technology Center. Capt. Tyron Fisher was the project officer for the Mission-Oriented Investigation and Experimentation (MOIE) Program.

This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) TR-0090(5940-05)-4	5. MONITORING ORGANIZATION REPORT NUMBER(S) SMC-TR-92-30

6a. NAME OF PERFORMING ORGANIZATION The Aerospace Corporation Technology Operations	6b. OFFICE SYMBOL *(If applicable)*	7a. NAME OF MONITORING ORGANIZATION Space and Missile Systems Center
6c. ADDRESS *(City, State, and ZIP Code)* El Segundo, CA 90245-4691		7b. ADDRESS *(City, State, and ZIP Code)* Los Angeles, Air Force Base Los Angeles, CA 90009-2960
8a. NAME OF FUNDING/SPONSORING ORGANIZATION	8b. OFFICE SYMBOL *(If applicable)*	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER F04701-88-C-0089
8c. ADDRESS *(City, State, and ZIP Code)*		10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.

11. TITLE *(Include Security Classification)*

Bevalac Ion Beam Characterizations for Single Event Phenomena

12. PERSONAL AUTHOR(S) Koga, R.; Katz, N.; Pinkerton, S. D.; and Kolasinski, W. A. (The Aerospace Corporation) and Oberg, D. L. (Boeing Aerospace Company)

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT *(Year, Month, Day)*	15. PAGE COUNT
	FROM ______ TO ______	1992 July 16	17

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

Linear Energy Transfer (LET) distributions of Bevalac ion beams were measured. Subsequent analysis has called into question the standard assumption of a monoenergetic, single-species beam at Bevalac. Both high LET contaminants in the primary beam and very broad LET peaks in degraded beams were observed. High energy ion beams at other accelerators may possess similar characteristics. The existence of beam impurities may have important ramifications for the interpretation of single-event phenomena observed at high energy accelerator sites.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE *(Include Area Code)*	22c. OFFICE SYMBOL

DD FORM 1473, 84 MAR

83 APR edition may be used until exhausted.
All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

PREFACE

The authors would like to thank M. A. McMahan (LBL Bevalac) and T. L. Criswell (Boeing Company) for providing technical assistance during preparation of the experiment.

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FIGURES

I. INTRODUCTION

The Lawrence Berkeley Laboratory (LBL) Bevalac has been used to characterize the susceptibility of microcircuits to ions in space [1-4]. This susceptibility is usually measured in terms of such phenomena as single-event latchup (SEL), single-event upset (SEU), and single-event burnout (SEB). An accurate determination of ion beam properties such as fluence, spatial distribution, ion species, and energy is essential to ensure the validity of these measurements.

The ions at Bevalac can be accelerated to the order of 1 GeV/nucleon, which leads one to expect them to share characteristics with galactic cosmic rays (high energy nuclei that reach the Earth from outside the solar system). On the other hand, it has long been assumed that, unlike cosmic rays, the Bevalac ions can be extracted as a monoenergetic, single-species beam [1-3]. Because of this assumption, the purity of the beam has not been directly determined as part of single-event phenomena (SEP) studies. However, since the higher the energy of an ion, the greater its capability to produce low energy ions through interactions with matter in its path, high energy beams are more likely to contain contaminants than are low energy beams.

Most SEP experiments call for several dE/dx values in order to fully characterize the microcircuits under study. Multiple dE/dx values may be obtained either by successively retuning the accelerator, or by reducing (degrading) the ion energy with a degrader placed between the end of the beam pipe and the device under test. Water columns as well as slabs of metal have been used as degraders at various accelerator sites [1-4]. (The dE/dx of an ion is the specific energy loss of the ion in the medium and is inversely related to the energy through much of the ion's energy range. The terms dE/dx and linear energy transfer [LET] will be used interchangeably here.)

In order to study both degraded and primary ion beams, a series of tests was conducted at the "Irradiation station" (cave) of Bevalac. The following sections describe the experimental setup, the results of the beam measurements, and implications of these results for SEP studies, including a brief summary of relevant high energy SEP studies.

II. EXPERIMENTAL SETUP

A. ION DETECTION TELESCOPE

An ion telescope was used to eliminate the edge effects often observed in charged-particle detectors consisting of a single silicon surface barrier detector. (The coincidence requirement to eliminate the edge effects is described in the following section.) The dE/dx (or linear energy transfer [LET]) ion telescope consists of two circular surface barrier detectors, mounted in parallel, like the lenses of an optical telescope (see Fig. 1). The large area (25 mm^2) detector was 10 microns thick, while the small area (10 mm^2) detector was 2 microns thick.

B. DE/DX (LET) ANALYZER

The telescope was interfaced with the electronics as shown in Fig. 1. Standard laboratory equipment was used, with the exception of the preamplifier and the NIM stretcher. A homemade stretcher and preamplifier were used to provide the high degree of linearity and the high speed commercially available units could not.

The ion pulse heights of ions incident on the 10 μm-thick detector were measured using a standard pulse height analyzer. Only those ions for which the output of the 10 μm-thick detector appeared within a time window created by the same ion traversing the 2 μm-thick detector were recorded. This coincidence requirement ensured that outputs generated by ions hitting the edges of the 10 μm-thick detector (where the thickness of the sensor was not uniform) were not collected.

The front-end electronics were placed in the cave, with the remaining electronics housed in the control room (about 100 feet away). The pulses in the connecting cables were periodically monitored to ensure proper transmission quality.

C. TEST APPARATUS ARRANGEMENT IN CAVE

The beam of ions traveled in an evacuated, 7.5-in. diameter brass pipe, as shown in Fig. 2. After passing through a thin foil at the end of the pipe, ions continued to move in the air, mainly along a straight line. Ions penetrated the wire chamber, the first ion chamber, the degrader, the second ion chamber, and the device under test (DUT) during a run to observe SEP. The wire chamber was used to observe the uniformity of the beam, whereas the ion chambers were used to measure the fluence. The binary degrader (made of a set of brass sheets that can be individually inserted in the beam via remote control) was used to degrade the energy so as to increase the LET of the ions while *maintaining* the purity of the exiting beam energy (i.e., all exiting ions from the degrader were expected to have the same energy). The telescope was mounted in a hole cut into the last sheet of the degrader so that the telescope measured the dE/dx of ions after they had passed through the degrader. Obviously, an SEP observation could not be made when the telescope was placed in the beam line; a remote-controlled extractor was used to remove the telescope from the beam line as required.

Periodically, a set of photographic emulsions was placed in the beam line to measure the uniformity of the beam.

Data were collected at various degrader settings for the three ion species: La (600 MeV/nucleon), Fe (600 MeV/nucleon), and Ne (425 MeV/nucleon). For each run, the pulse height (dE/dx) of each ion impinging on the detector was measured. Beam uniformity was assessed using the wire chamber, and the fluence was calculated from readings of the ion chamber.

Primary ions that had not passed through the degrader exhibit a rather tight velocity distribution, as shown in Fig. 3 for Lab ions (similar results for Fe are shown in Fig. 4). In Fig. 3, the peak occurs at an LET of ~6.2 MeV/(mg/cm^2) and has a width of less than 1.6 MeV/(mg/cm^2). However, a substantial proportion of events (0.5%) had higher LET values than those in the peak. In Fig. 4, the peak corresponds to an LET of about 1.4 MeV/(mg/cm^2) and has a full width at half maximum of about 0.8 MeV/(mg/cm^2). About 0.6% of events had higher LET values than those in the peak.

Degraded ions exhibit a very wide distribution of events about the peak, as shown in Fig. 5 for a 0.42-in. thick degrader. The peak corresponds to an LET of 28 MeV/(mg/cm^2). Figures 6 and 7 show degraded Fe (via 0.843-in. thick brass) and Ne (via 1.23-in. thick brass) ion beam results. The Fe and Ne peaks correspond to LET values of 7.8 and 2.1 MeV/(mg/cm^2), respectively. Neon ions with LET values near 2.1 MeV/(mg/cm) (the Bragg peak) had lost most of their original energies through interactions with the degrader and therefore exhibit a wide distribution. A comparison of the LET distributions of the ions in Figs. 3-7 is presented in Table 1.

Table 1. LET Distributions for Ions in Figs. 3-7

		Degrader	Percentage of Ions		
	Ion	Thickness	< FWHM	FWHM	> FWHM
Fig. 3	La	None	0.9%	98.6%	0.5%
Fig. 4	Fe	None	0.0%	99.3%	0.6%
Fig. 5	La	0.42 in.	8.6%	87.5%	3.8%
Fig. 6	Fe	0.84 in.	16.6%	79.9%	3.5%
Fig. 7	Ne	1.23 in.	0.6%	93.4%	6.1%

The broad LET distributions for the degraded beams result from both Coulomb and nuclear interactions. Elastic scattering of ions against the inside wall of the Bevalac beam pipe can produce low energy ions, which may then be included in the primary beam. Since numerous experimental studies of elastic and inelastic scattering in various media have been published, it should be possible to calculate the expected LET distributions. However, since such an undertaking is beyond the scope of this report, we have limited our efforts to measuring the LET distributions only.

III. DISCUSSION

When a high energy beam is used for the study of SEP, some (or all) of the upsets may be caused by high-LET contaminants. Upset cross-section measurements often extend over several decades, hence a 0.5% contamination level (as observed above for the nondegraded La beam) can be a major cause of errors, especially in the area where the LET vs cross-section curve is very steep. A number of SEP studies using high energy (on the order of 1 GeV/amu) ions have been conducted over the past decade; a summary of results that may have relevance to the present findings is presented below.

A. HISTORICAL PERSPECTIVE

In 1984, an SEU study was conducted at Bevalac with 600 MeV/amu Fe and 425 MeV/amu Ne ions [1]. The energy of the ions was reduced using a water column degrader of variable thickness in order to increase the LET of the ions. The tester was set up in an experimental site called the "Biomed area." When an AMD27LS00 (bipolar 256x1 SRAM) was tested, the threshold cross-section values differed for Ne and Fe ions of the same LET. The deviation of the LET threshold values (both were below 2.5 MeV/(mg/cm^2)) was within 1 MeV/(mg/cm^2). Nonetheless, two clearly separated curves were observed. Fe ions produced larger cross sections than Ne ions of the same LET. However, at an LET of about 2.5 MeV/(mg/cm^2), the cross-section curves appeared to merge into one. The authors of this paper used the phrase "ion species dependence" to describe this phenomenon. A 1987 article, continuing the work begun in [1], described additional studies at Bevalac using both 27LS00 and 93L422 (bipolar 256x4 SRAM) as test devices [2]. As before, a water column degrader was used at the Biomed site. The authors summarized their results as follows: "It was found that the 27LS00 shows a pronounced ion species dependence, and may show a deviation of deposited charge from the usual inverse-cosine times a fixed depletion depth, while the 93L422 exhibited the expected inverse-cosine dependence and no ion species dependence." In this article, the cross-section curve for 27LS00 also appeared to differ from that presented in the earlier paper (at an LET of about 2.5 MeV/(mg/cm^2); the cross sections obtained with Fe and Ne ions no longer agreed with each other in the later article).

A detailed study of charge collection, employing high energy ions produced at the Argon National Laboratory ATLAS facility, was published in 1988 [4]. In this study, the charge collection resulting from ions of the same species and LET, but different energies, were compared. The authors found that, "Charge collection measurements in thin silicon structures have indicated that the charge collected is not the same for incident ions with the same LET but with different energies. More charge is collected for the higher energy ions than for the lower energy ions." They attributed this charge collection difference to the difference in ion energies.

The susceptibility of N-channel power MOSFETs to single-event burnout (SEB) was studied in a 1987 paper [3]. Experiments were conducted at the LBL 88-inch cyclotron and the University of Washington Van de Graaff facilities, as well as at Bevalac. In this study, the 600 MeV/amu Fe beam at Bevalac was degraded with the use of the same water column degrader as described in [1,2]. The authors note that "Distinctive features of the Bevalac data are the lower cross section at high values of V_{ds} and the apparently lower voltage threshold" (in comparison with data taken at either the cyclotron or the Van de Graaff facility).

A paper presented by W. C. Bowman at the Seventh Symposium on Single-Event Effects (held in Los Angeles on 25 April 1990) is also relevant to the current discussion. This paper describes the results of a study of N-channel power MOSFETs, that were tested with ion beams generated at Bevalac using a brass degrader. The experiment was carried out at the same cave ("Irradiation station") where our beam measurements were performed. The test results for the N-channel MOSFETs resembled those obtained at the Bevalac Biomed area [3]. In his paper, Bowman states that the low voltage threshold seen in the Bevalac test results for N-channel MOSFETs results from displacement errors caused by high energy ions. (A displacement error is initiated by a displacement spike, which is a region where silicon atoms are displaced from their lattice positions. Nuclear interactions of the incident high energy ions with the silicon atoms of the device can result in a displacement spike [5]. If the spike occurs in the base-collector junction of an N-channel power MOSFET with sufficient electrical power, it may result in a second breakdown, leading to SEB.)

Several aspects of the above studies deserve further comment:

1. Testing at the Bevalac Biomed area revealed that one device type (27LS00) was more susceptible to lower energy ions (Ne) than to higher energy ions (Fe) of the same LET, whereas no such "ion species dependence" was found for a second device type (93L422) [1,2]. In contrast, the ATLAS charge collection study [4], which compared ions of the same species but different energies, produced the opposite results, with higher energy ions resulting in greater charge collection than lower energy ions of the same LET. (Incidentally, our own SEU measurements of 27LS00 taken at the LBL 88-inch cyclotron facility tend to agree with the Fe data published in References [1,2]. Also, the cross section of 93L422 given in [2] agrees well with our own measurements conducted at the LBL 88-inch cyclotron facility [6].)

2. The MOSFET test results obtained at the Biomed and Irradiation station sites are very similar. However, the impact of the two different degraders on SEP is not clear. High energy Bevalac ions have recently been reported to be capable of producing displacement errors in MOSFETs (see above). The apparent low voltage burn-out threshold in [3] can now be explained by this new phenomenon, but it is still not clear why Bevalac ions tend to produce lower cross sections at high values of V_{ds} than do low energy ions accelerated at cyclotron facilities.

3. The high energy ion beams at Bevalac and ATLAS were not directly measured for purity during the experiments described in [1-4]. A beam-averaged LET study using 670 MeV/amu Ne ions was included in [2]; however, such studies may not reveal the possible existence of small amounts of beam contaminants. While caution must be exercised when comparing results from studies utilizing protons with those involving heavy ions, a high energy proton study [7] showed that degraded protons were not monoenergetic, even though the beam-averaged LET curve was very smooth, like the one given in [2]. Thus a smooth beam-averaged LET curve is not necessarily indicative of beam purity.

B. EFFECTS OF CONTAMINANTS

The effect of beam contaminants will now be considered. If the ion beam used in the experiment is contaminated by ions of lower LET than those in the peak region, then cross-section calculations based on a monoenergetic beam assumption will tend to underestimate the true cross section. The degree of underestimation of the cross section depends on both the relative amount of contaminants and the sensitivity of the cross section to LET. As shown in Figs. 5-7, this condition may result when highly degraded ion beams are used. On the other hand, higher LET contaminants tend to raise the calculated cross section above the true value. We believe that some of the rather unusual observations described in References [1-4], and emphasized in the previous section, may be due, at least in part, to impurities in the ion beams. However, a detailed analysis of the precise effects of beam impurities in these studies is not possible based solely upon the limited information provided in the literature.

A major ramification of using impure ions is that each SEP run must be scrutinized very carefully. The saturation cross section and the LET threshold can no longer be conveniently read from a curve that was plotted under the assumption that the beam was pure. This semi-standard practice, which has been employed by many SEP researchers, may need to be re-examined.

C. CYCLOTRON-GENERATED IONS

A number of SEP experiments have been carried out with ion beams accelerated at cyclotron facilities. Cyclotron-generated beams tend to be nearly monoenergetic and relatively pure, provided that: (1) the cyclotron has been properly tuned, (2) the source is carefully maintained, and (3) the beam delivery system is properly controlled. In addition, effects of possible beam impurities tend to be minimal because the dE/dx of the primary ions is already in (or close to) the maximum region, hence a degrader has not been needed for cyclotron-generated ions.

Pulse height analyses of properly delivered N (67 MeV), Ar (180 MeV), and Cu (290 MeV) ions at the LBL 88-in. cyclotron facility are shown in Figs. 8, 9, and 10, respectively. Since the RF tuning frequency of Ar (14.295930 MHz) and Cu (14.297522 MHz) are very close, a mixture of Cu and Ar ions may inadvertently be delivered to a test device if the tuning frequency is set at some intermediate point -- it is the responsibility of the experimenter to carefully avoid such an occurrence.

IV. CONCLUSION

High energy ion beams are important for investigating various SEP that cannot be tested using the lower energy ion beams produced at existing cyclotron and Van de Graaff facilities. For example, an entire computer can be exposed to the Bevalac beam to investigate the susceptibility of the system as a whole to a cosmic ray like environment.

The present experiment calls into question the widely held assumption of a monoenergetic, single species beam at Bevalac. Both high LET contaminants in the primary beam, and very broad LET peaks in degraded beams were observed. High energy ion beams at other accelerators may possess similar impurities. Since most SEP studies utilize test setups similar to the one employed in the present experiments, these findings are unlikely to be unique, and may have important ramifications for the analysis and interpretation of SEP data. In particular, some conflicting observations made while testing microcircuits at high energy accelerator sites may be due, at least in part, to impurities in the beams. In any case, a thorough analysis of the ion beams should be a prerequisite to any SEP study undertaken at a high energy accelerator site.

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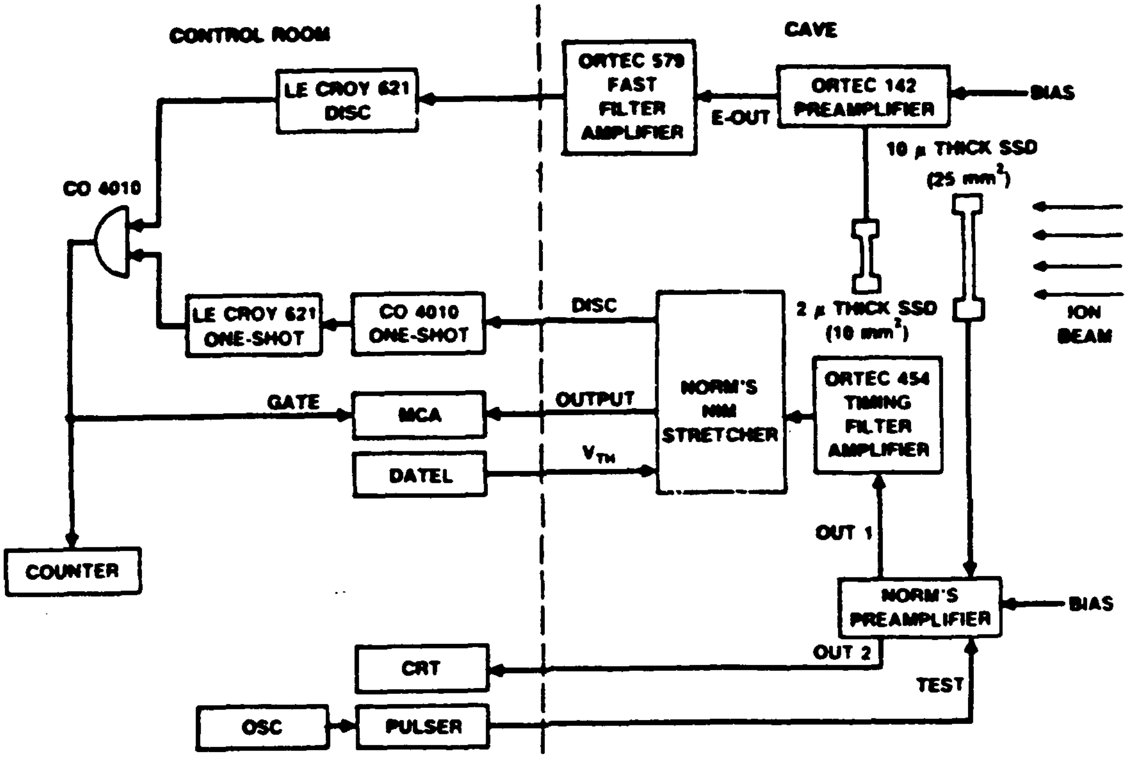

Fig. 1. The dE/dx Analyzer at Bevalac

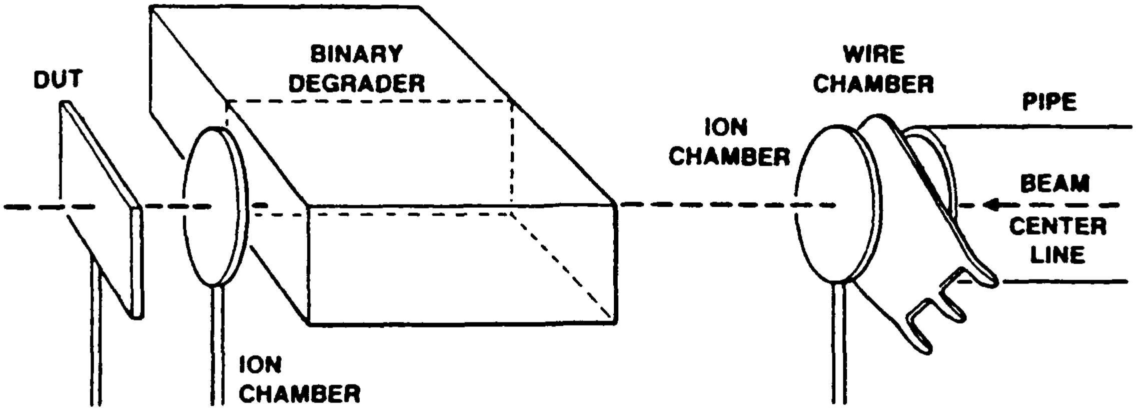

Fig. 2. Test Setup in the Cave

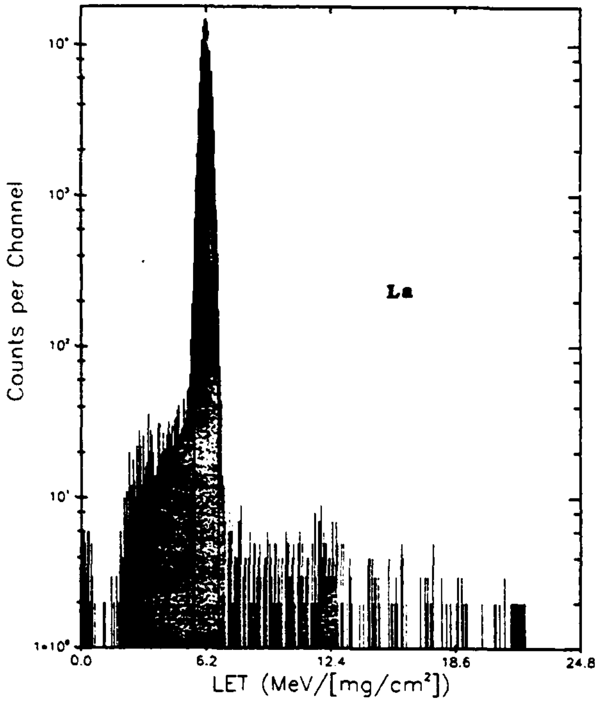

Fig. 3. LET Distribution of Primary La Ion Beam.

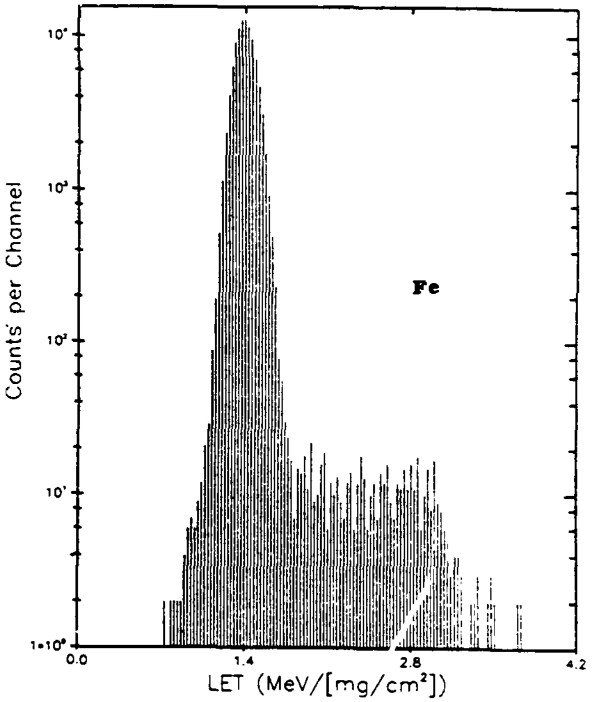

Fig. 4. LET Distribution of Primary Fe Ion Beam.

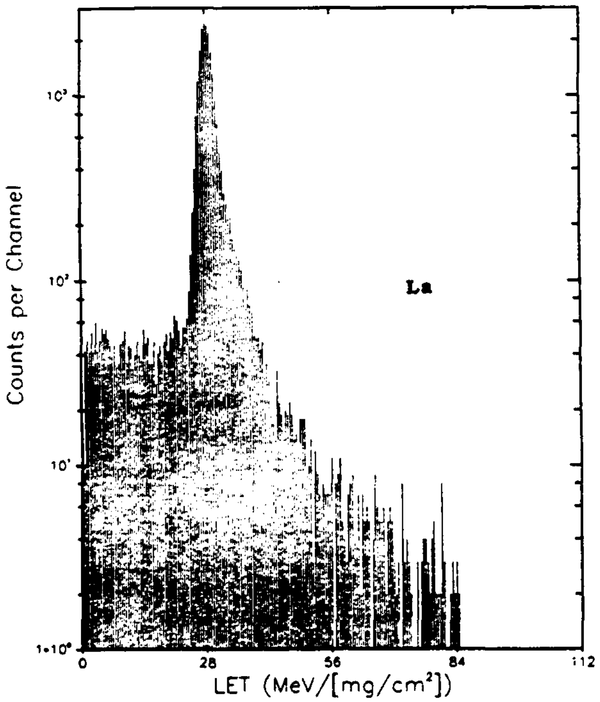

Fig. 5. LET Distribution of Degraded La Ion Beam (0.42-inch Brass Degrader).

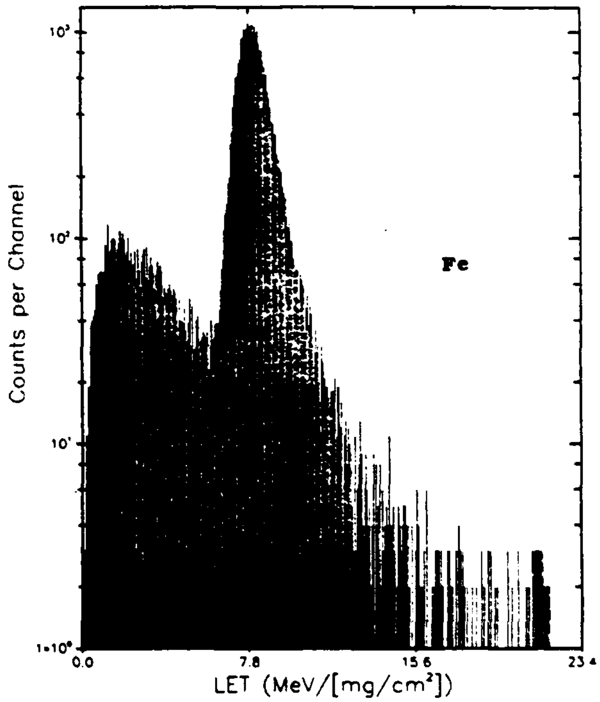

Fig. 6. LET Distribution of Degraded Fe Ion Beam (0.84-inch Brass Degrader).

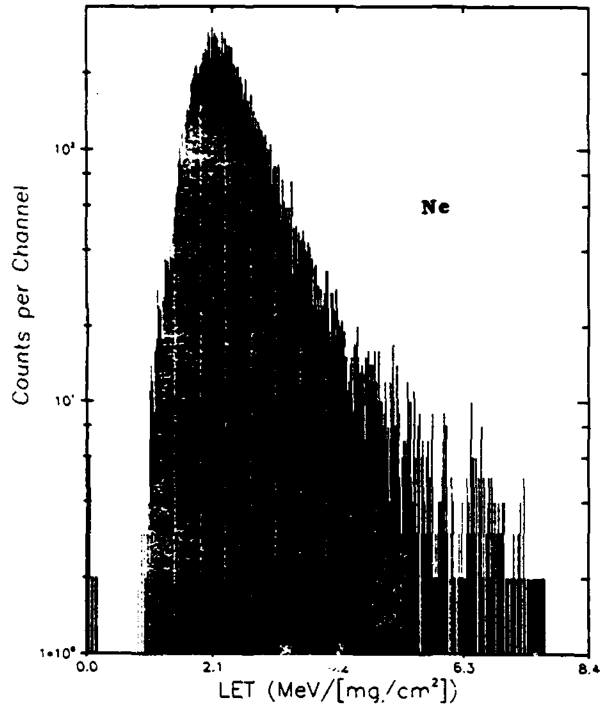

Fig. 7 LET Distribution of Degraded Ne Ion Beam (1.23-inch Brass Degrader).

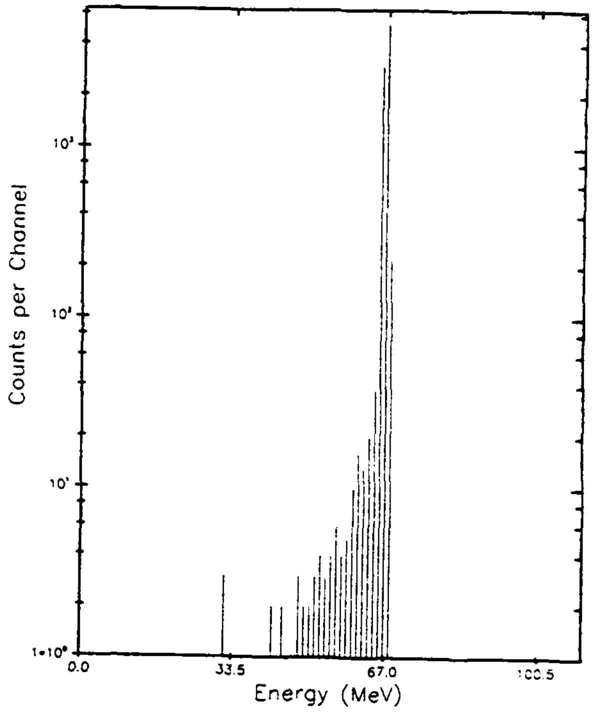

Fig. 8. LET Distribution of Cyclotron-Generated N (67 MeV) Ion Beam.

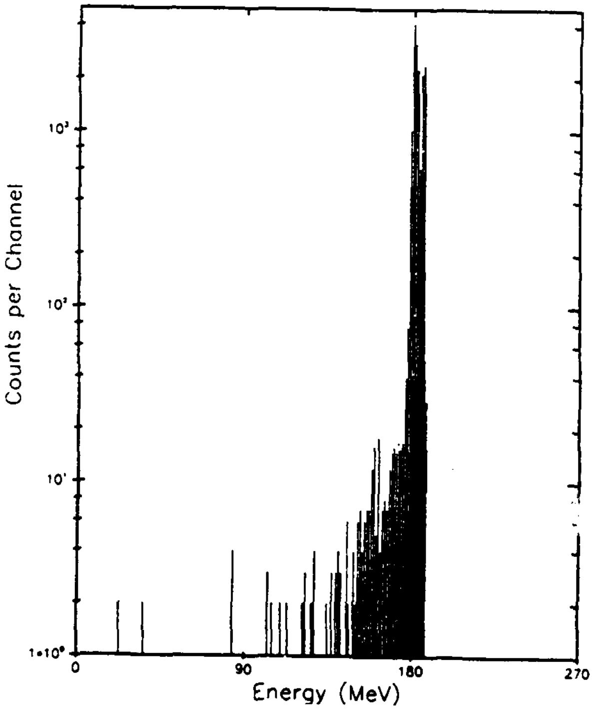

Fig. 9. LET Distribution of Cyclotron-Generated Ar (180 MeV) Ion Beam.

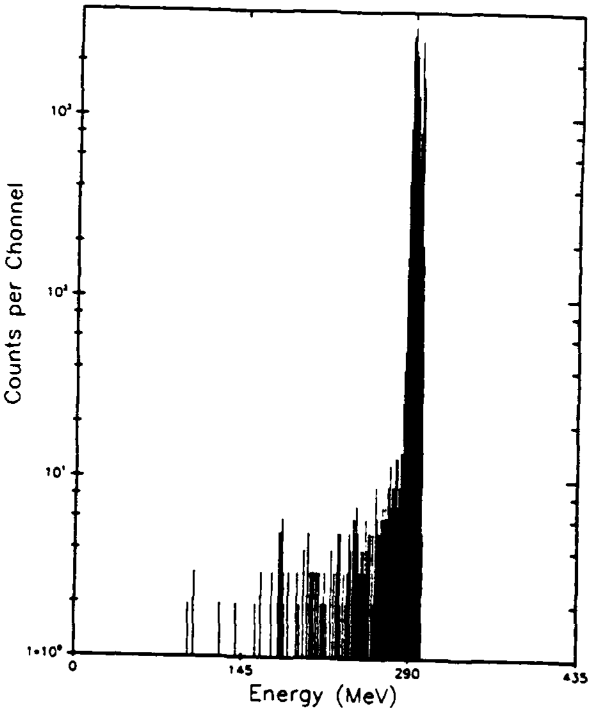

Fig. 10. LET Distribution of Cyclotron-Generated Cu (290 MeV) Ion Beam

TECHNOLOGY OPERATIONS

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