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RADIATION STUDIES AT A MEDIUM ENERGY ACCELERATOR

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RADIATION STUDIES AT A MEDIUM ENERGY ACCELERATOR

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Berkeley, California

October 1969

ABSTRACT

The 88-Inch Cyclotron is one of the new generation of sector-focused cyclotrons which has been built since 1960. These third generation machines combine the advantages of the high beam intensities of the conventional first-generation cyclotrons with the high energies of the second-generation synchrocyclotrons. In addition, the ability to accelerate different particles to various energies has been incorporated into the 88-inch machine. These two features, initially tried on older machines, have been designed into many of the newer cyclotrons. Careful orbit calculations and engineering design have been combined to produce beams of excellent quality and stability. These features now make possible certain nuclear physics and nuclear chemistry experiments which were formerly impossible.

The ranges of energies available with this machine are from 2 to 60 MeV for protons, 0.5 to 130 MeV for alpha particles, and 1 to 170 MeV for ^3He . Other energies and ions are also possible.

Originally the cyclotron was designed for a beam current of 1 mA. The shielding was designed to provide protection to personnel outside the vault with the full 1 mA beam of deuterons on a Be target in the vault.

The design work for the 88-Inch Cyclotron was begun in 1958. Construction was nearly completed in 1961, and experimental work was begun as soon as external beams were obtained in 1962.

Monitoring of the radiation outside the shield as well as inside the vault areas was done concurrently with the beam development. Work was also begun on a determination of the neutron yield from thick targets at various angles. We believe this is a necessary step for the development of economical and safe shielding which would soon be necessitated by the continuing development of the cyclotron facility.

Effective attenuation lengths were measured through the shielding walls at several angles from a target. Attenuation of neutrons was measured for walls composed entirely of concrete, as well as of concrete and iron, or of concrete, iron, and sand. Variations in shielding efficiency were determined and are available for present and future use.

Neutron flux measurements have been made along an extended beam line in an effort to improve beam transport and reduce personnel irradiation.

Whenever beams of precisely defined energy are required, we find that there are several possible combinations of magnet and collimator settings. The total beam at the target can be optimized by the use of neutron radiation detectors which detect unwanted beam loss along beam lines.

We have also made extensive activation studies of many accelerator parts. These studies prove their worth in maintenance planning, for which it is desirable to minimize personnel exposures.

Another useful piece of information is a nearly complete picture of the external radiation field produced by the accelerator. We present here a sampling of these measurements:

1. External surveys during machine operation for personnel protection and for compliance with AEC requirements.
2. Internal surveys and activation studies, both for improved machine maintenance and for personnel protection from induced activity during machine shutdown.
3. Target yield and angular distribution studies, and studies of shielding materials, for cyclotron development programs.

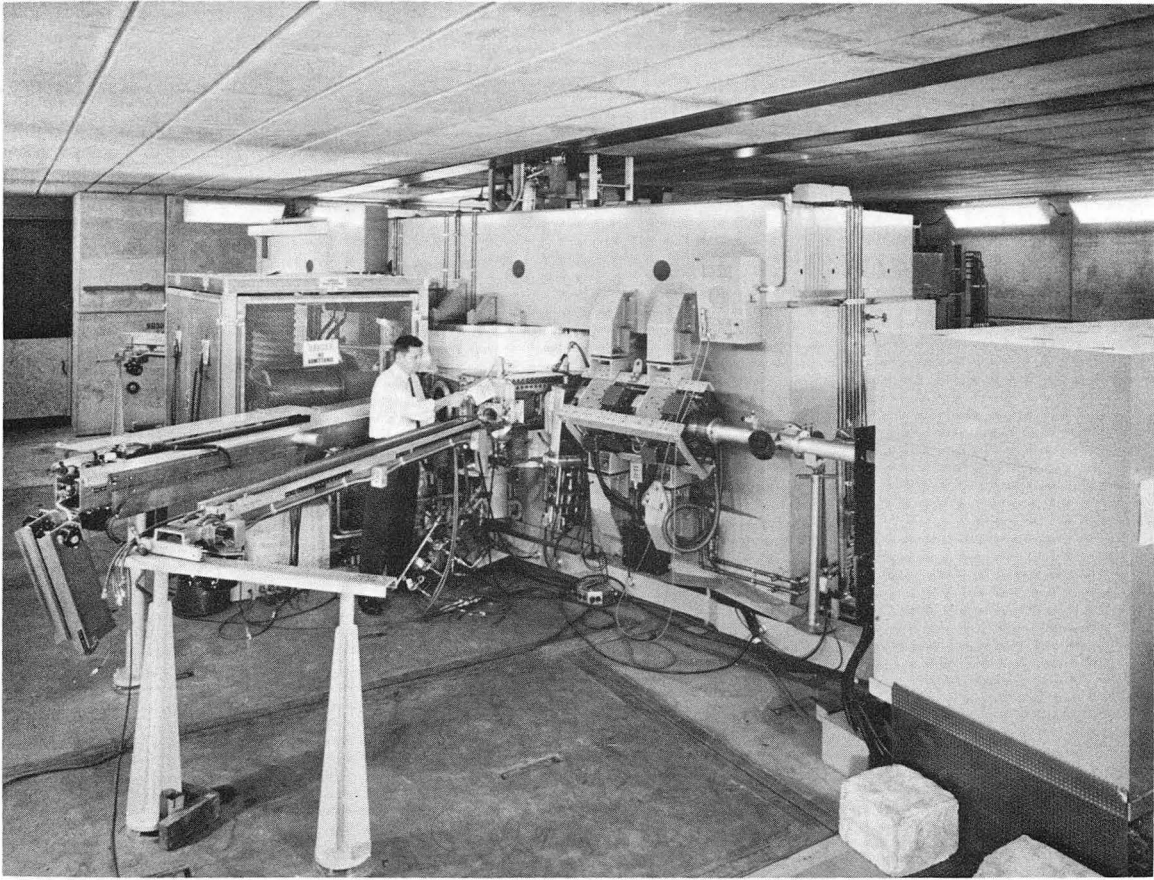
INTRODUCTION

The 88-Inch Cyclotron, Fig. 1, is one of the new generation of sector-focused cyclotrons built since 1960.¹⁻³ These third-generation machines combine the advantages of the high beam intensities of the conventional first-generation cyclotrons with the high energies of the second-generation synchrocyclotrons. In addition, the ability to accelerate different particles to various energies has been incorporated into the 88-inch machine. These two features, initially tried on older machines, have been designed into many of the newer cyclotrons. Careful orbit calculations and engineering design have been combined to produce beams of excellent quality and stability. These features now make possible certain nuclear physics and nuclear chemistry experiments that were formerly impossible.

The range of energies possible with this machine are from 2-60 MeV for protons, 0.5-130 MeV for alpha particles, and 1-170 MeV for ³He. Other energies and ions are also possible, as shown in Fig. 2.

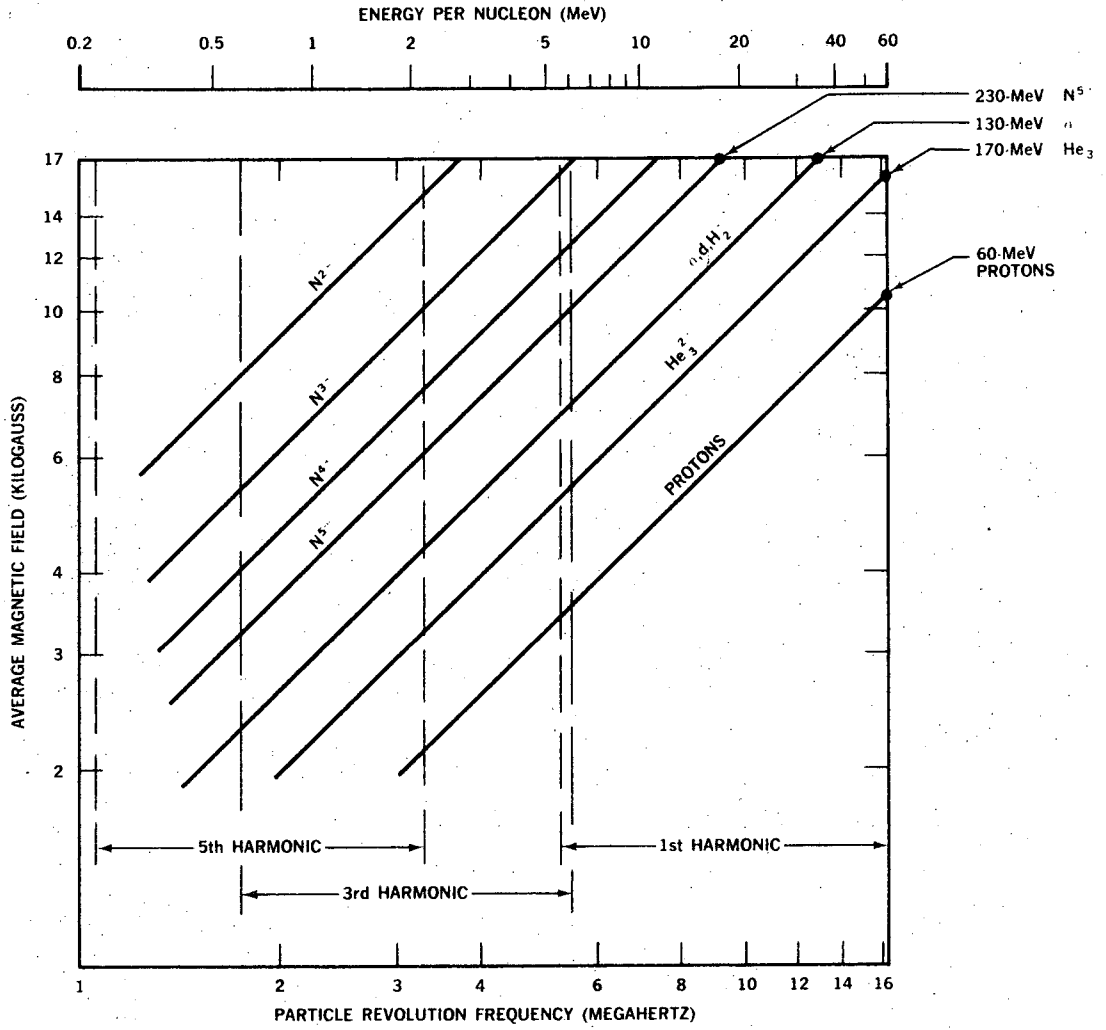
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Fig. 1



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Fig. 2

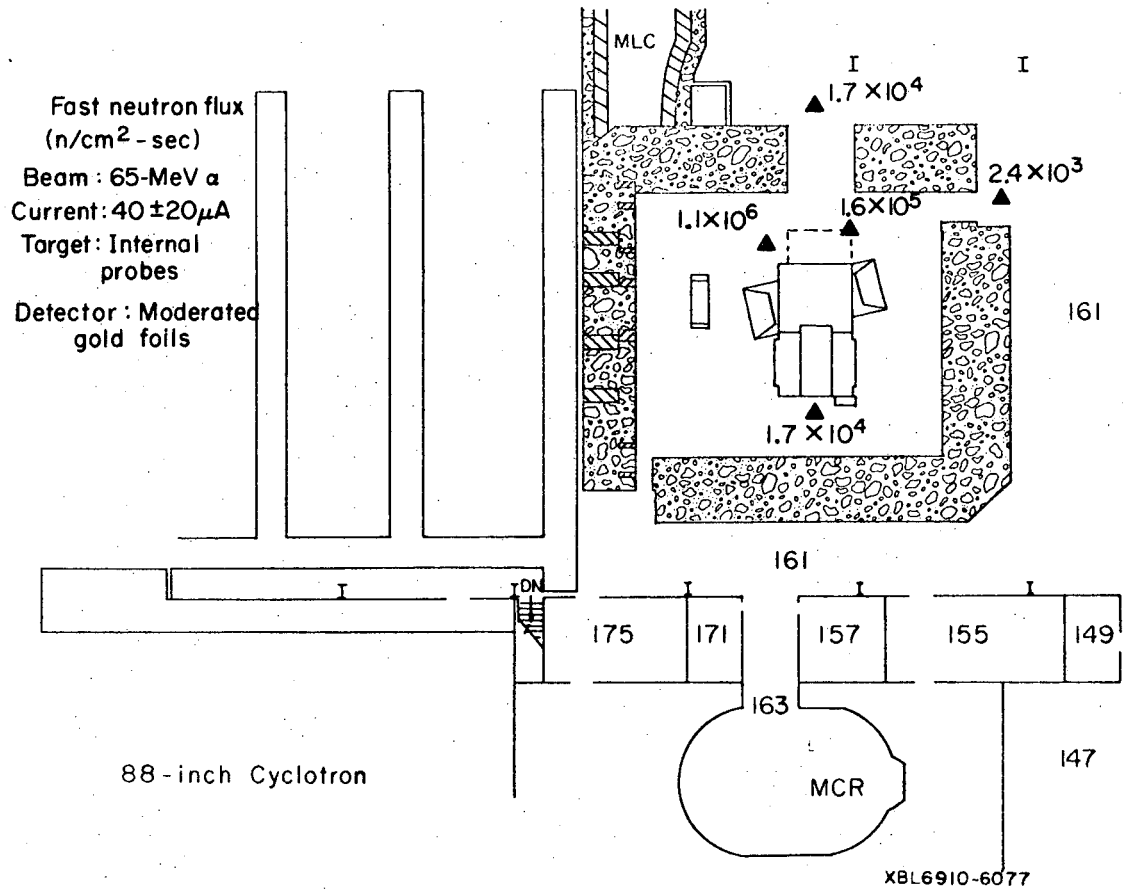


Fig. 3

Radiation Patterns and Experience

We are concerned with four separate radiation areas: the cyclotron vault and pit areas; the external beam caves; the cyclotron, including control room, shops, and offices; and the adjacent area surrounding the cyclotron out to the site boundary.

Vault and Pit Areas

During early phases of the construction and testing many radiation measurements were made in the vault and pit areas. Access was restricted during actual running, therefore we made use of gold foils in the paraffin-filled cadmium moderator.⁴ This allowed us to make simultaneous measurements. Figures 3 and 4 show some typical results.

External Beam Caves

Caves for the cyclotron were constructed as money became available. Concurrent with the solutions of beam optics problems, temporary caves were established and experiments were run. During this time many surveys were made which had value only at the time due to the uniqueness of conditions. No effort is made here to catalog or otherwise list these. One example only will be shown, Fig. 5. This survey provided us with an answer to the specific request, "Is this experiment safe to run?"

In 1963 the high level cave (HLC) and caves 1, 2, and 3 were completed. Cave 1 has since undergone some modification. The result is a cave in which larger beams can be handled. Cave 5 has recently been finished and the shielding added in final form. The present shielding for vault and caves is shown in Fig. 6. One simplified example of radiation measurements made during an actual operating condition is shown in Fig. 7.

Of special interest to both health physicists and experimenters is cave 4. This cave contains a beam line which is unshielded for more than half of its 86 feet. The dimensions of this beam line are called for by the resolution requirements. Under normal conditions the 88-Inch Cyclotron is capable of producing a beam with 0.08 % energy spread. The requirements for this particular system were to be less than 0.02%. Normal energy spread is shown in Fig. 8a and the cave 4 analyzed beam is shown in Fig. 8b. The determination here is measured by $^{12}\text{C}(p, p)^{12}\text{C}$

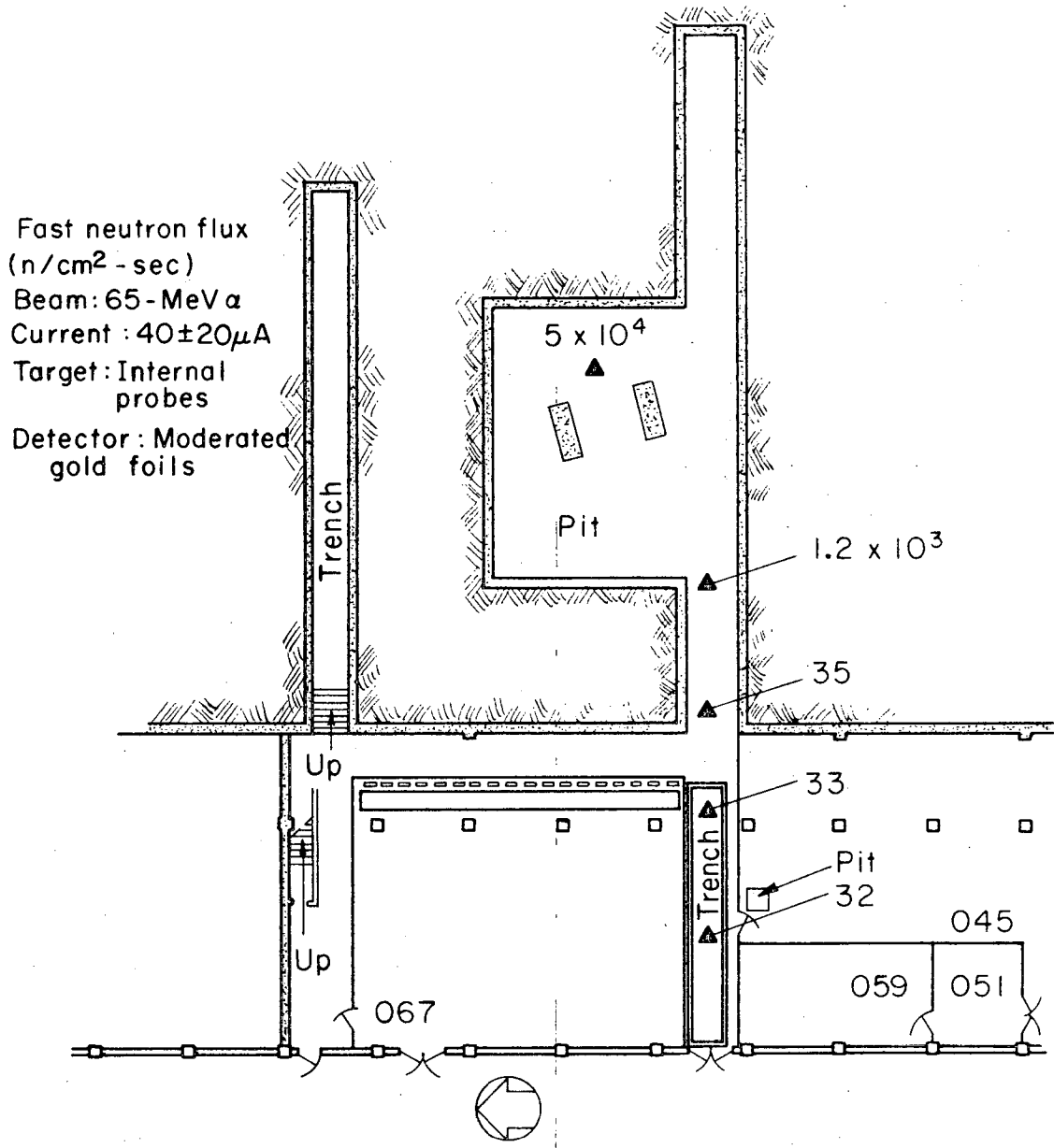


Fig. 4

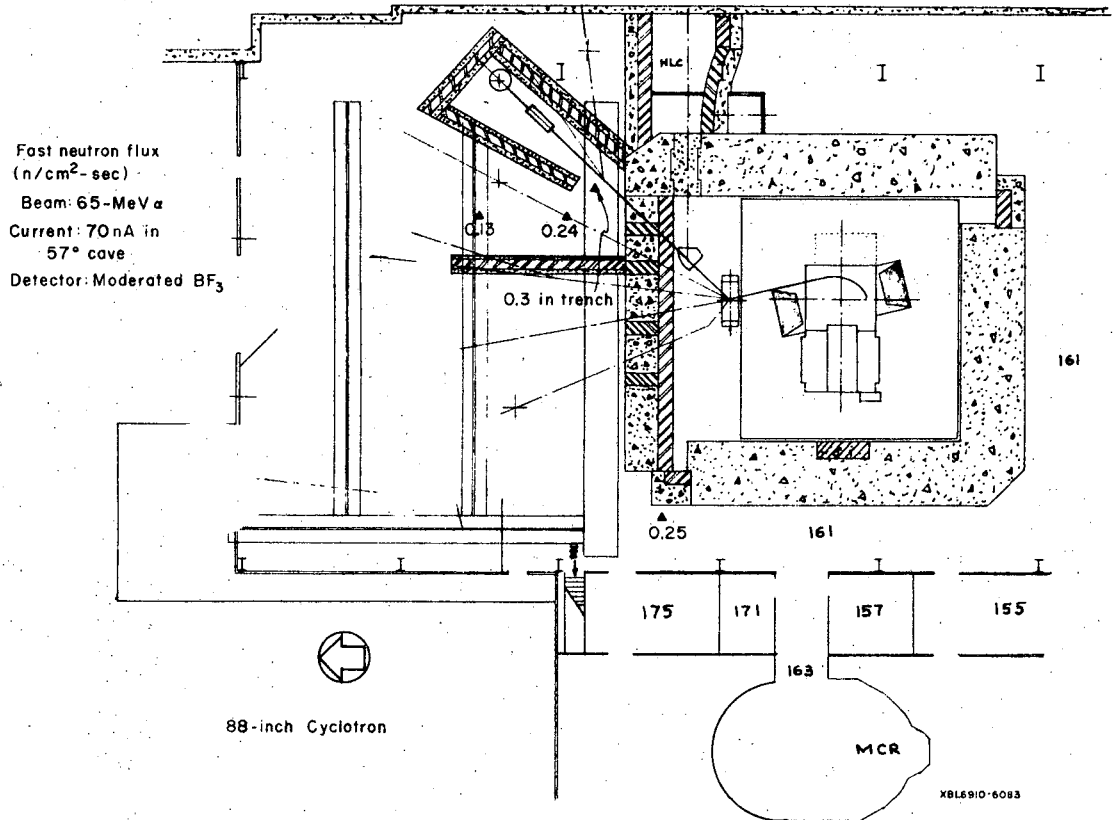


Fig. 5

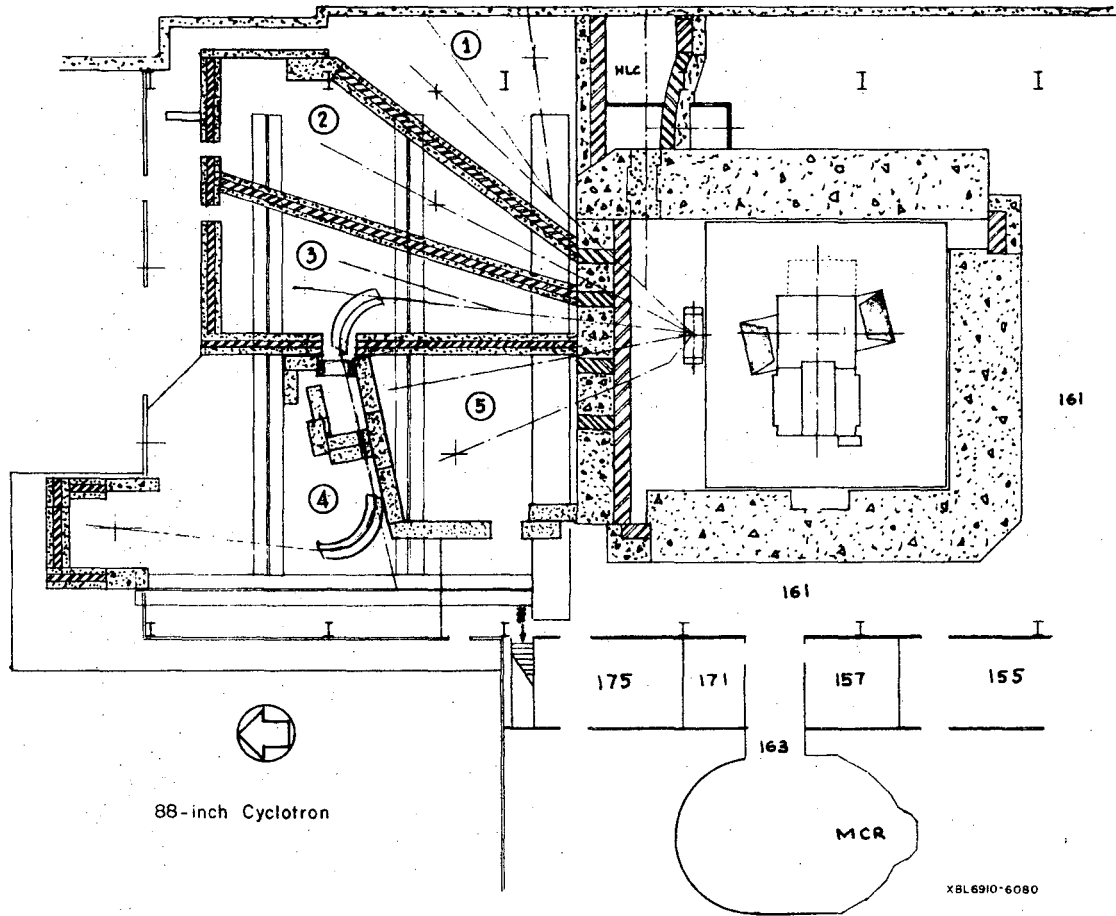


Fig. 6

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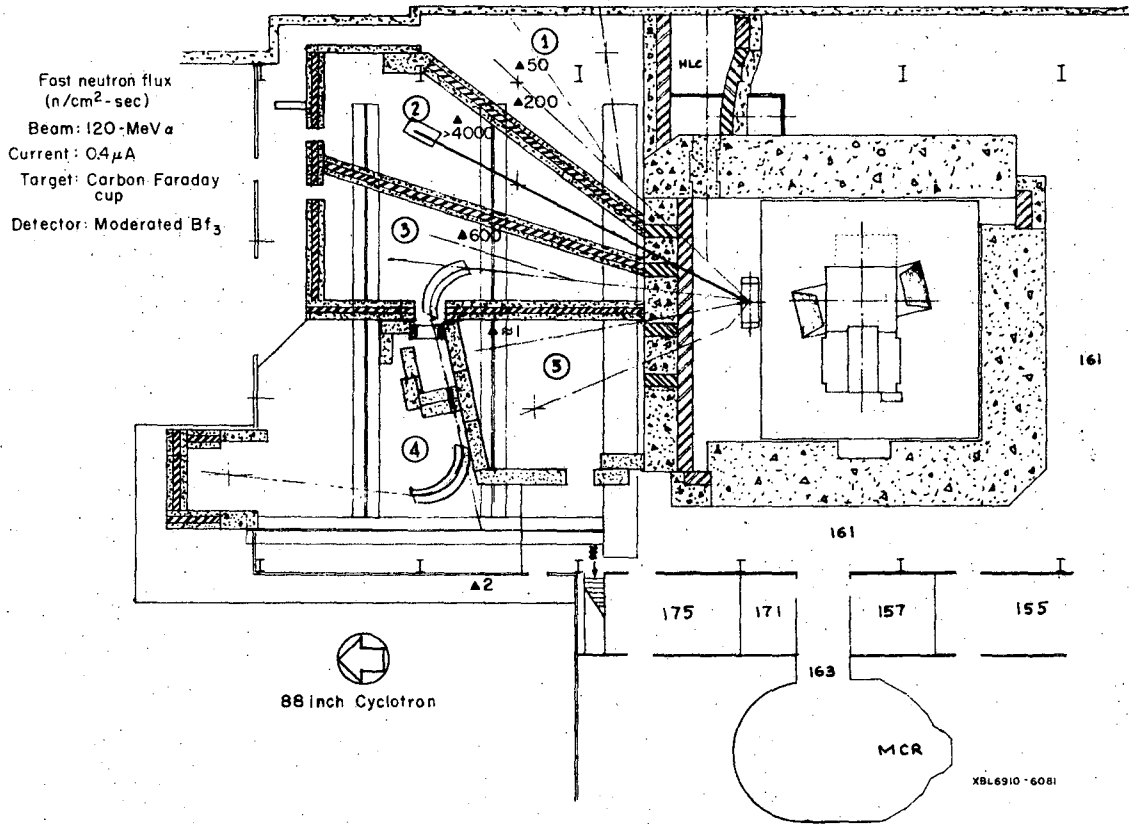
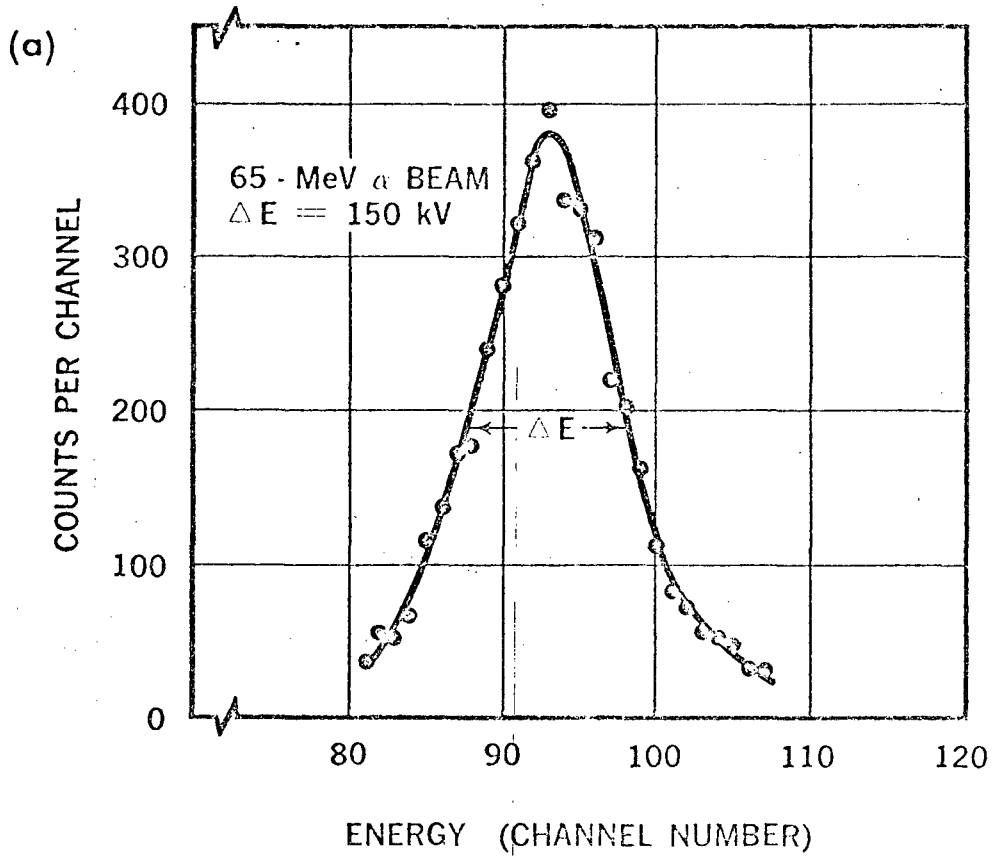


Fig. 7



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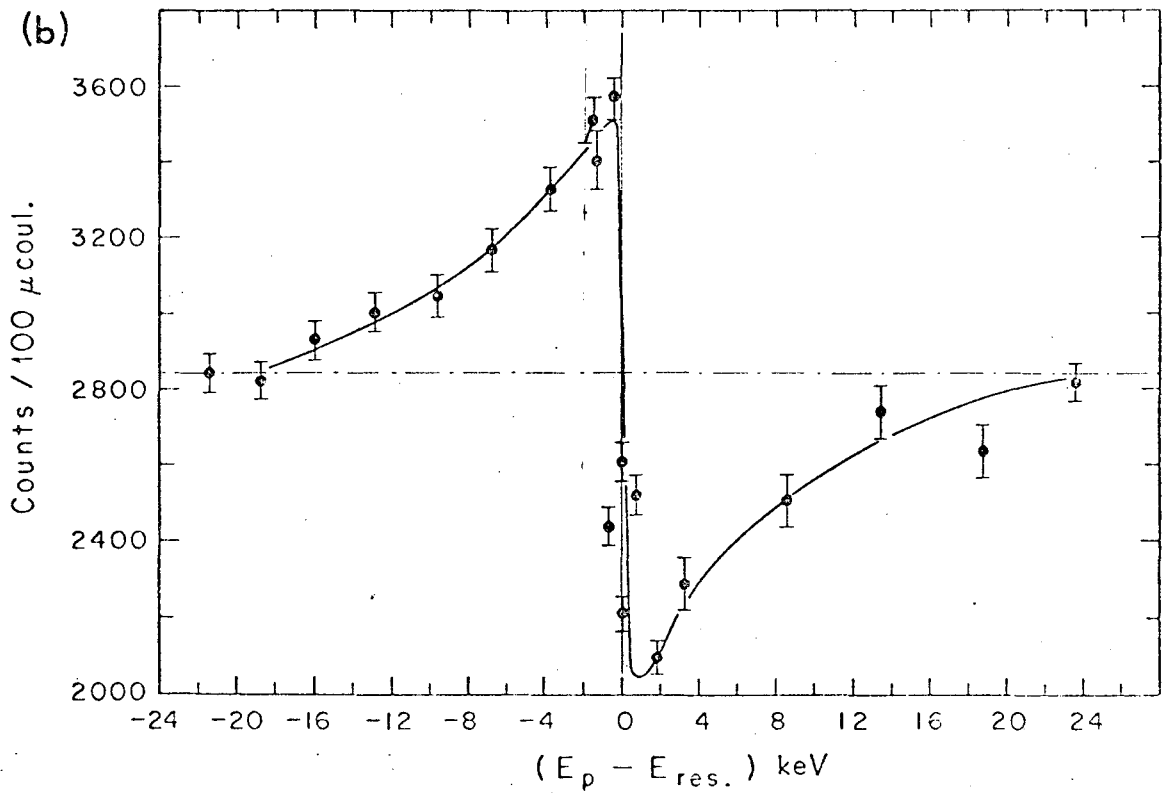


Fig. 8

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resonance at 14.233 MeV (lab).⁵ The measured energy spread is in fact 0.015%. The processes required to produce a beam such as this also produce a potentially troublesome radiation problem. "Analysis" of the beam—that is, selection of desired energies—occurs at several points along the beam line, Fig. 9. The points of special interest with respect to radiation sources are the entrance slit, magnet 1, the analyzing slit, magnet 2, and the clean-up slit. There are many combinations of parameters which can get beam through the entire beam line, but relatively few which produce a minimum amount of radiation.

As soon as this beam line began operation we initiated an investigation of the beam-loss locations. We attempted to correlate these with actual current measurements taken from the various slits.

The detection technique we employed is one of relative simplicity.⁶ After initial tuning we placed aluminum threshold detectors along the entire beam line. The results are shown in Fig. 10a, b, c, d. There is generally good correlation between measured beam currents and neutron radiation detected.

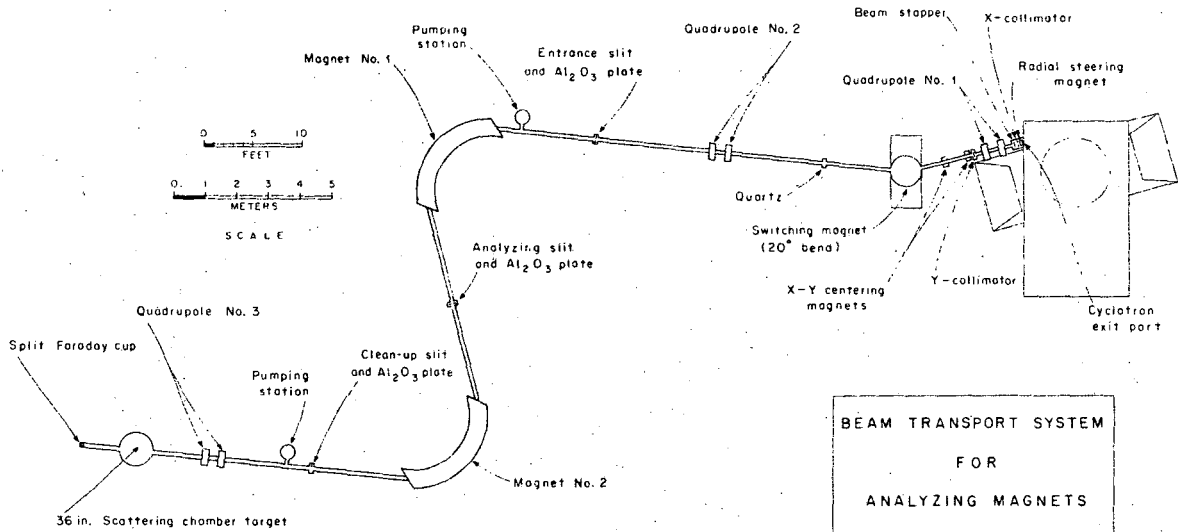
Subsequent measurements made with active neutron detectors have shown that there are more desirable optical solutions to be achieved. Future plans are for somewhat greater use of active detectors to give the desired beam with a truly minimized radiation source.

The analyzing slit required special shielding, which was designed for this purpose as a result of early tests. The local shielding gave a maximum amount of protection with a minimum amount of expense. A smaller shield was considered, but other factors were also to be considered. Among the most important was ease of access for repair or adjustment.

Localized shielding is used in cave 2 (Fig. 11) to reduce the radiation level both in the cave vicinity and in the experimental detectors. This shielding was designed by William Wadman specifically for this purpose. Very large beams are routinely permitted to be used in this cave because of the special shielding.

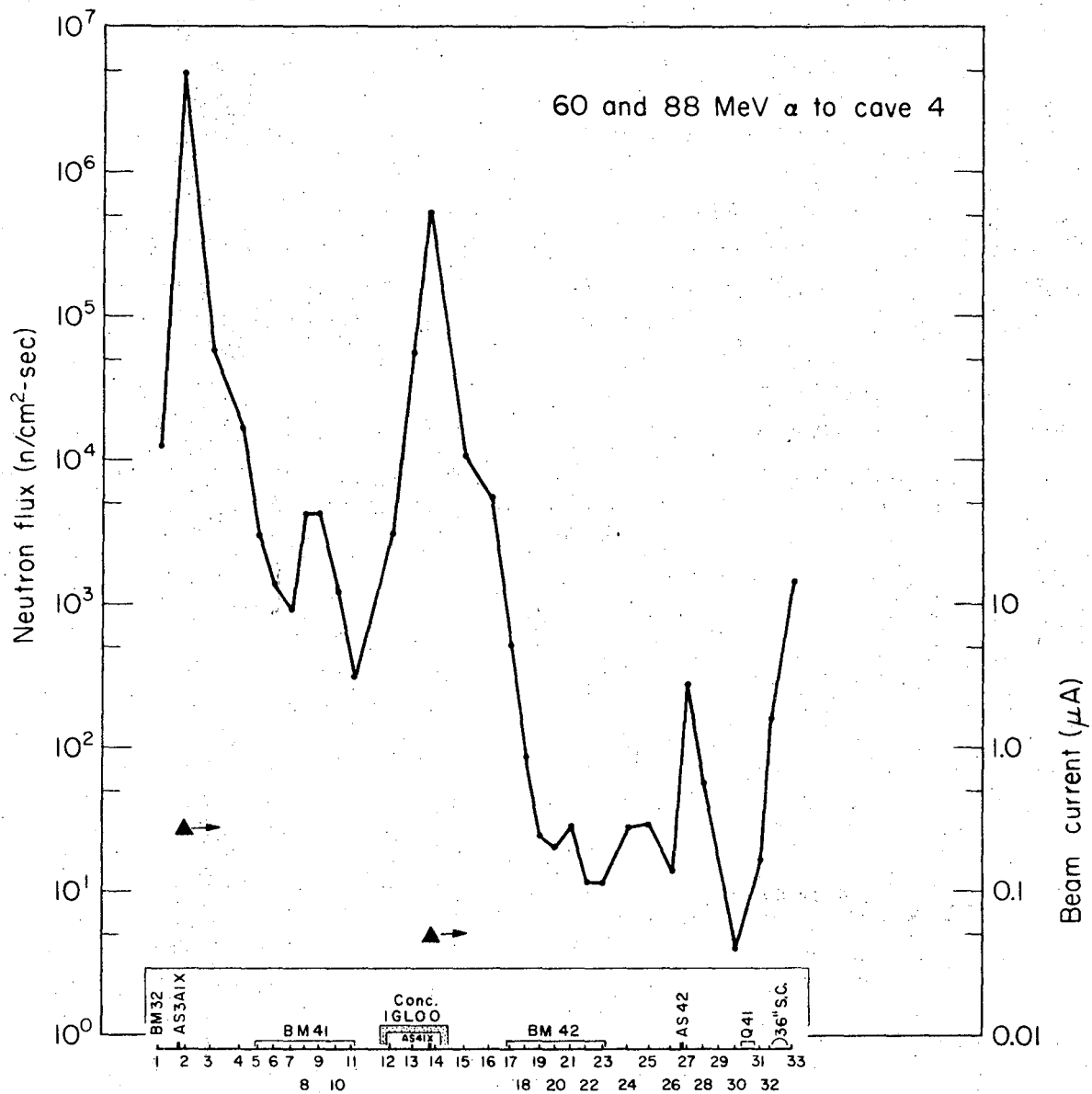
Construction is well along on the still longer beam line designated as the high-resolution spectrograph, Fig. 12.

The total amount of radiation produced is the limiting factor of this particular beam line. Temporary buildings were located near the cave 4 area, and, the laboratory boundary is approximately 500 feet west of the cyclotron. We solved a portion of the problem by scheduling long, high-level runs only during weekends and off hours. Level



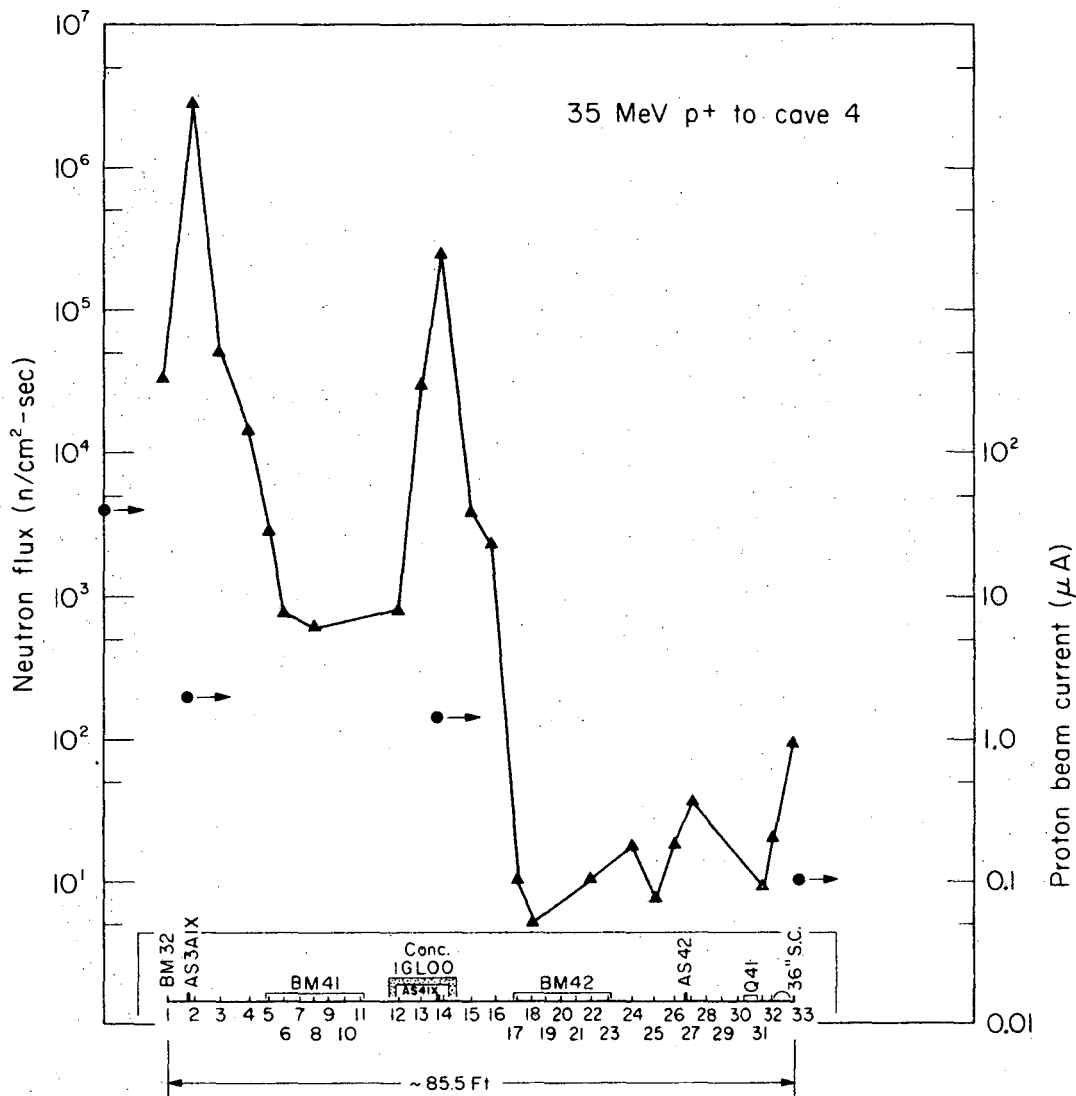
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Fig. 9



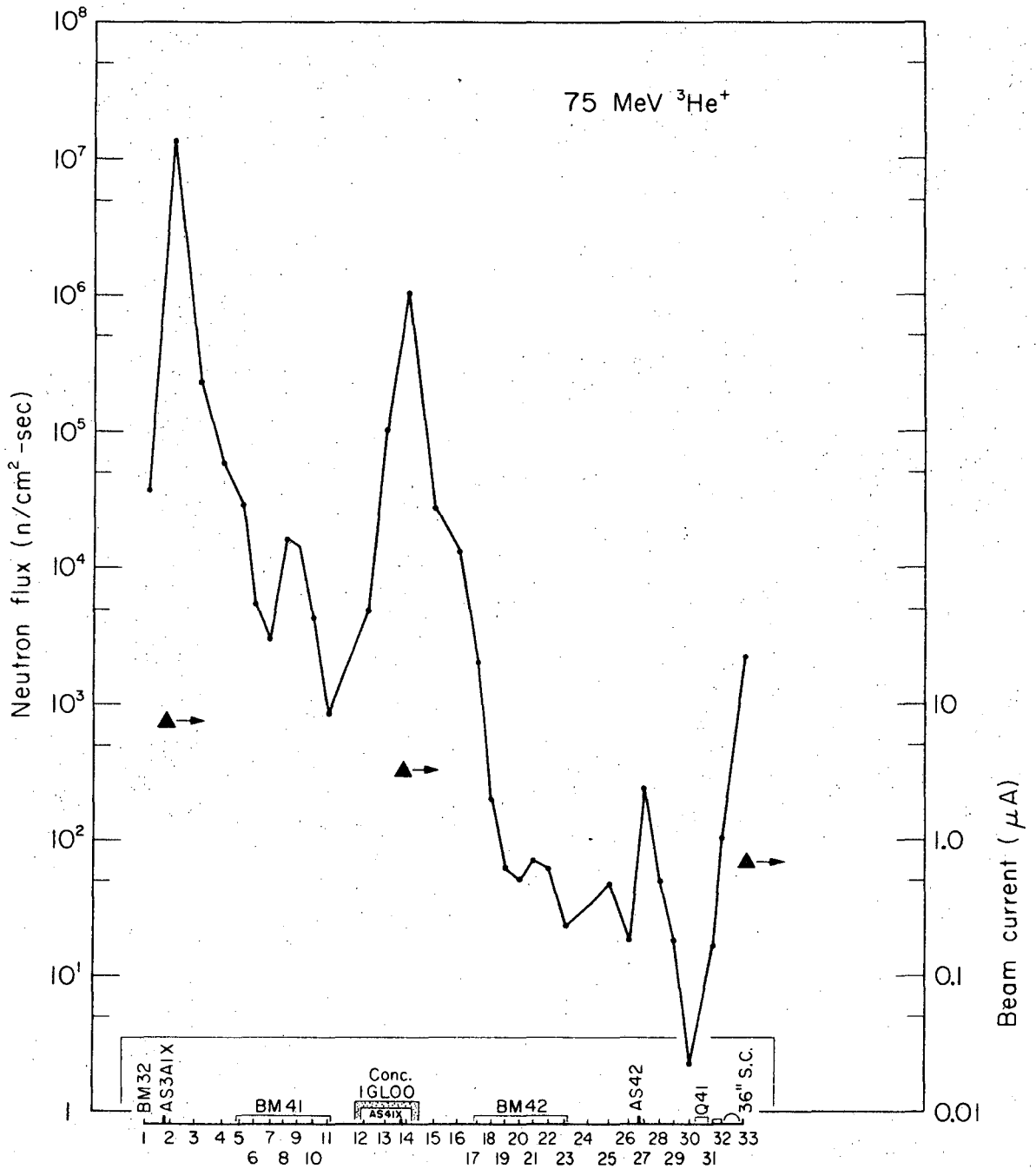
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Fig. 10a



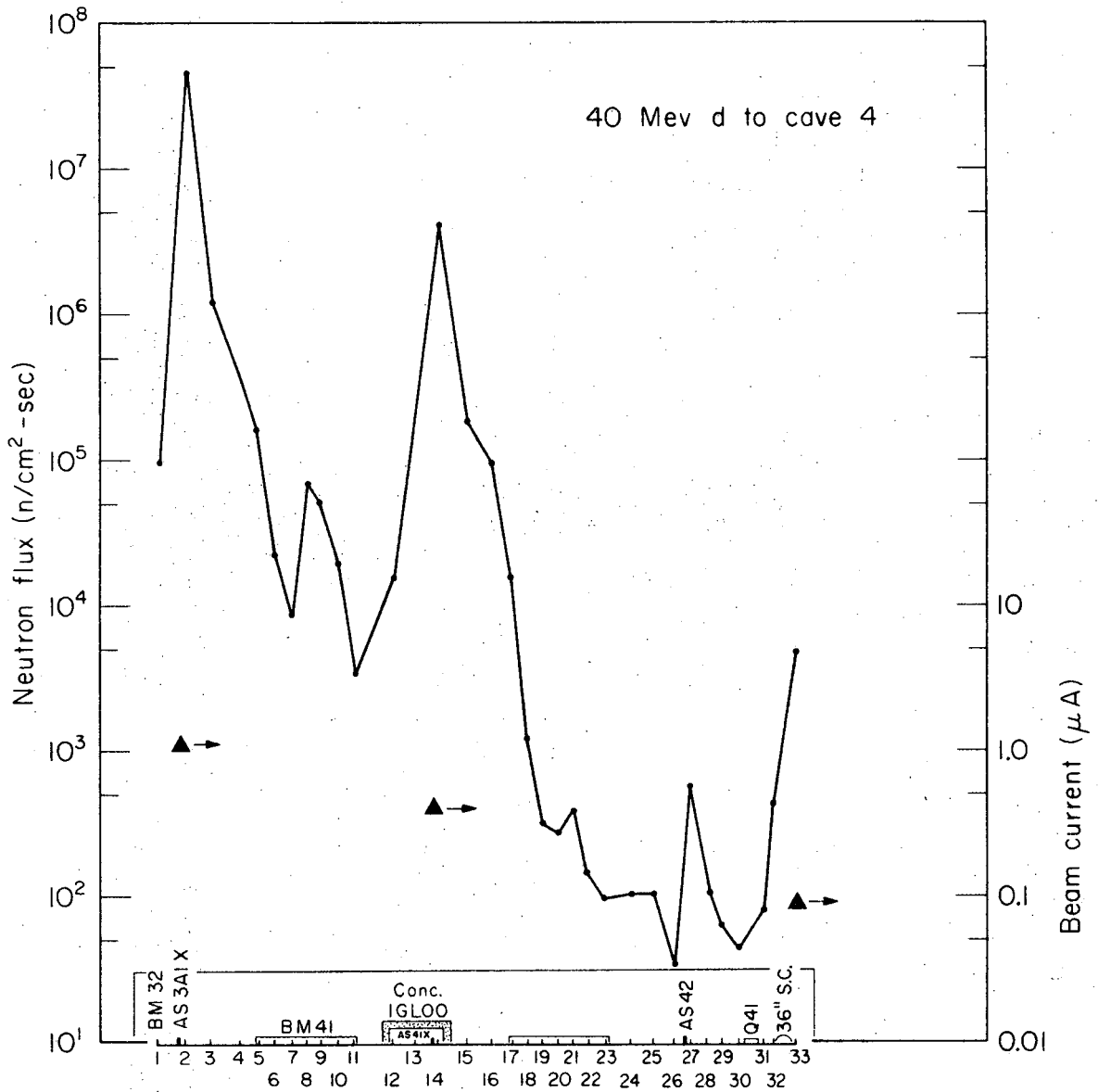
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Fig. 10b



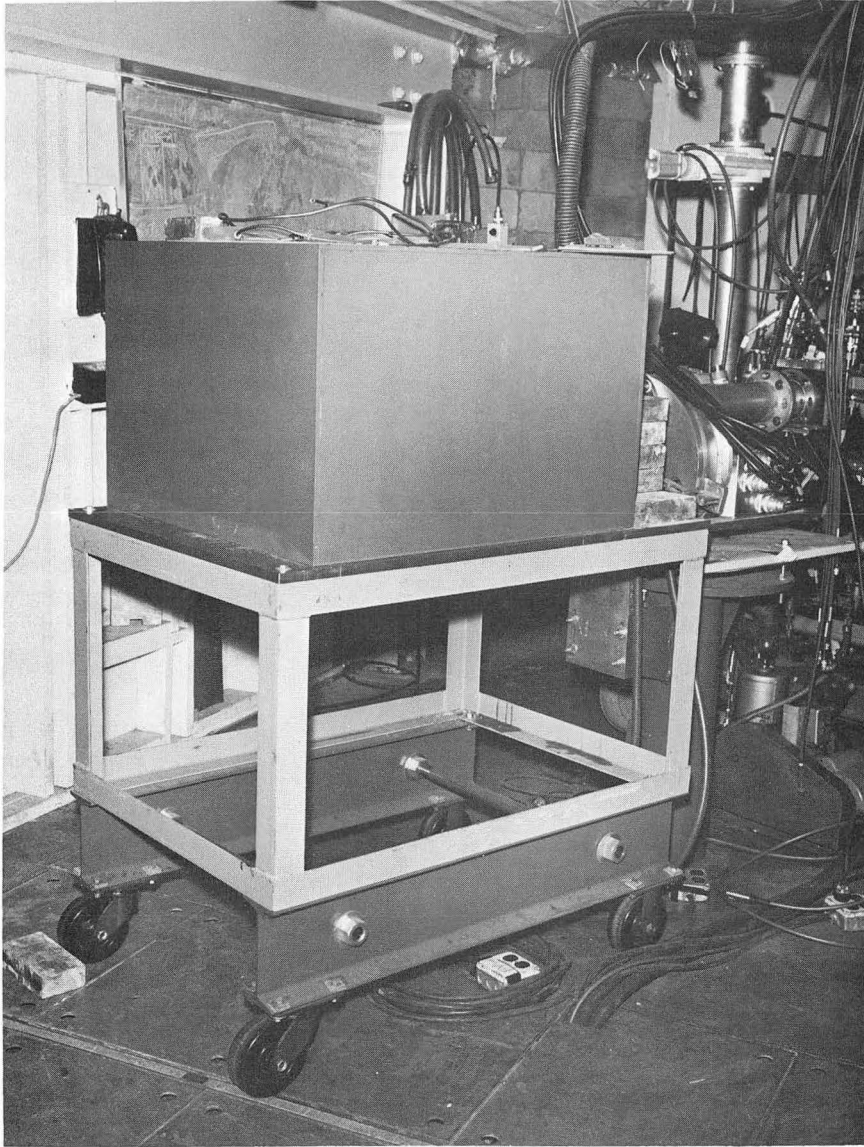
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Fig. 10c



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Fig. 10d



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Fig. 11

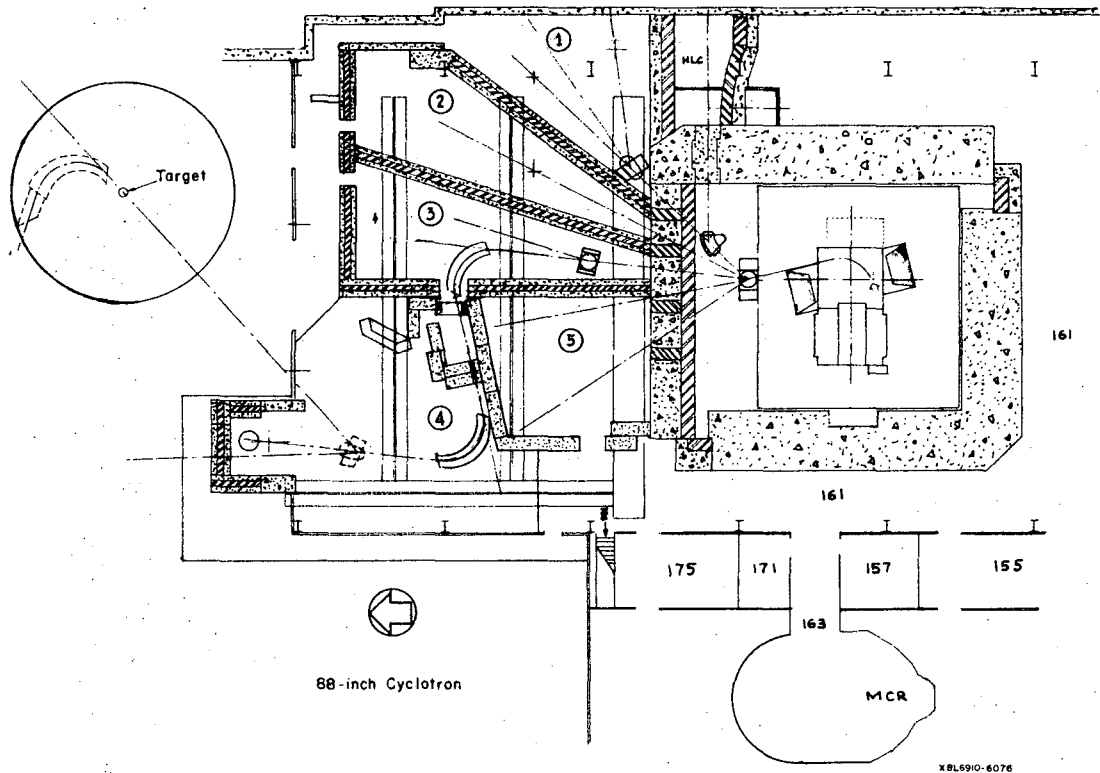


Fig. 12

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limits were set according to measured neutron radiation reaching the boundary monitoring station. In general, however, this did not prove too restrictive for the experimenters.

Cyclotron Building

During construction of the cyclotron, operational testing and initial calibration were carried out with limited shielding. Surveys were carried out as necessary, almost nightly in fact. Typical levels found are shown in Fig. 13. These measurements served as a guide for the determination of access limits. During this time the shielding doors were not installed, the roof was incomplete, and ports were left open for observation. Constant surveillance was a necessity. Most testing was carried on at night when only those persons required for the test were present.

Current radiation levels are shown for various ions at several locations on Fig. 14.

Original plans for the 88-Inch Cyclotron called for the use of an axial injection ion source. This required a large 10-by-5 ft hole through the entire roof shield directly above the magnet yoke. Since the machine was mechanically decoupled from the shield, a gap existed and allowed large numbers of neutrons to escape during operation.

Two measurements of the radiation primarily from this region, made at distances which were different by a factor of 30, give a source value in excess of 1.2×10^8 n/sec. This was therefore one source of personnel radiation which needed to be controlled, because access to the roof was required as well as crane operations that could not be suspended. A measurement at reduced beam intensity indicated that the average energy was in the region of 20 keV. The Laboratory had a supply of approximately 12 x 12 in. bridge timbers. We therefore fabricated a simple temporary cover for this source. The results of the measurement are shown in Table I.

These measurements gave us attenuation factors ≈ 550 for the first foot of wood and ≈ 780 for the two feet. Reducing the total neutron field allowed us access to the roof for maintenance and general use.

In an effort to further control this neutron radiation source, high-density concrete block shielding was placed along the lower edges between the magnet yoke and the roof shielding. This arrangement has allowed us to do installation work on the polarized ion source with a minimum of restriction for either machine operation or personnel.

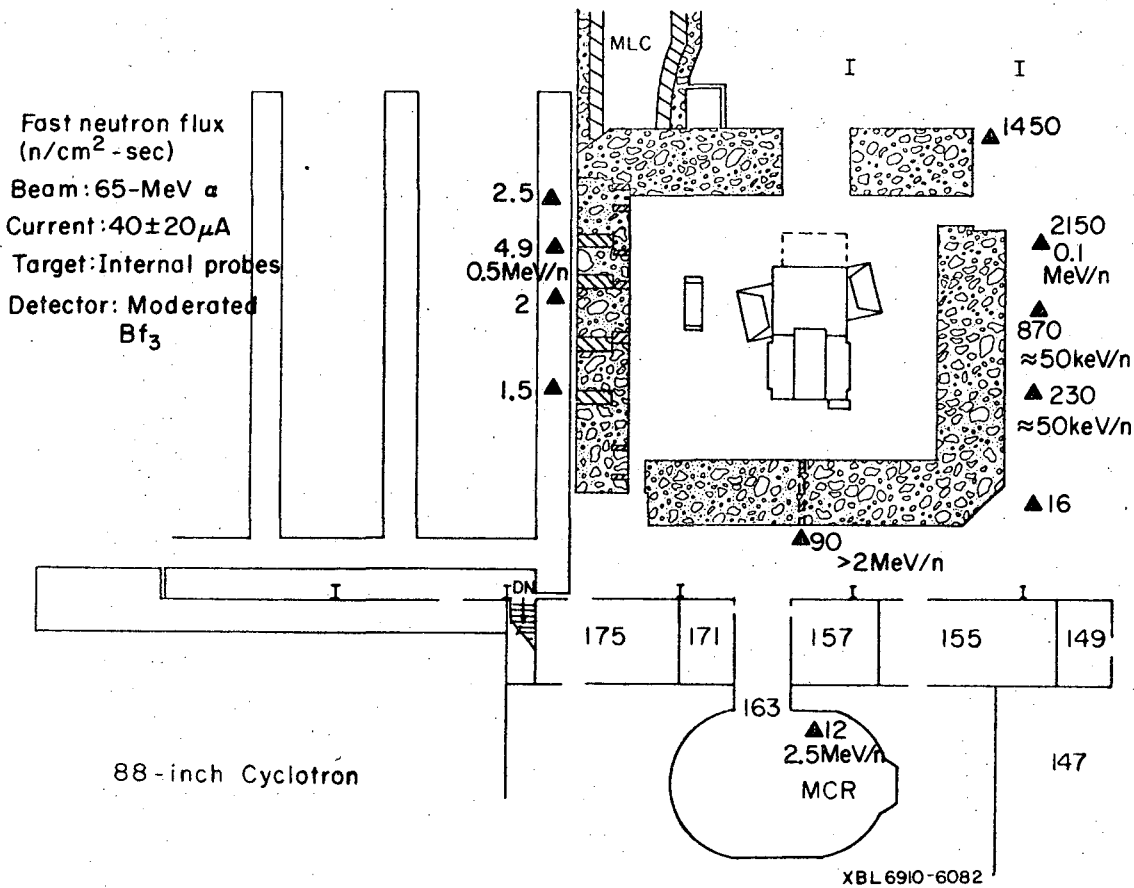


Fig. 13

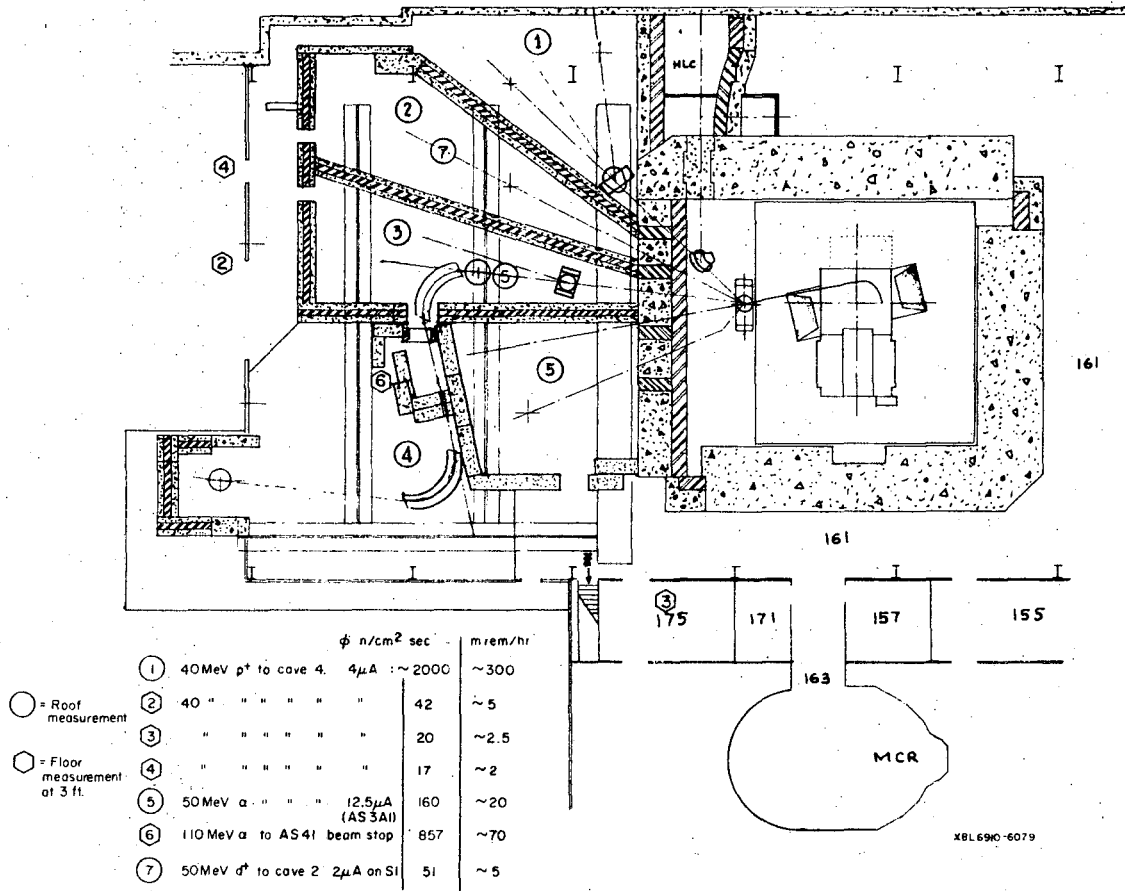


Fig. 14

Table I. Effect of bridge-timber shielding.

Condition	ϕ^a (n/cm ² sec)	\bar{E}_n (MeV)	γ (mr/h)
Open source hole	2380	0.020	3.7
1 ft of wood	4.3	1.15	---
2 ft of wood	3.1	2.14	---

^a40-MeV internal p⁺ beam.

Environmental Radiation

Environmental monitoring⁷ is carried out as a part of the AEC contract agreement. The result of this activity does give us a better understanding of machine radiation. Figure 15a is a plot of the daily environmental neutron levels; Fig. 15b is a similar plot from a monitor detector in the building. These do not necessarily correlate for two reasons: the monitor detector is moved to different locations, and the environmental station results are also affected by Bevatron operation.

Radiation levels on a yearly integrated basis at the site boundary are about 0.1 of the maximum permitted level, although the restrictions on the experimenters are not too severe.

Neutron Studies

Neutron yields from various target materials for various ions at various energies form a useful compilation of data for the practical health physicist. The gathering of such data from published literature and experimental results was a difficult task. Specific points are shown in Table II, and derived curves are shown in Fig. 16. The angular distributions of neutrons from thick tantalum targets of 40 and 80 MeV have been determined by Wadman.⁸ Specific values were desired for efficient design of the local shield.

The experiment as carried out by Wadman was basically the neutron irradiation of seven threshold detectors, located on a ring of 30 cm diameter. The preliminary studies were carried out at both the Heavy Ion Linear Accelerator and the 88-Inch Cyclotron.

The angular distribution of neutrons from 40-MeV α particles on a thick tantalum target is shown in Fig. 17.

Neutron Attenuation for Different Combinations of Shielding Materials

At the 88-Inch Cyclotron occasions arise when floor space and cost limitations make it desirable to locally shield machine-produced sources of radiation. Local shielding as mentioned here refers to shielding that is placed close to and around targets or other localized sources of radiation, i. e. beam-analyzing slits or areas of beam loss along the transport system.

In an attempt to find a shielding configuration which provided optimum radiation protection with a minimum of shielding material, an

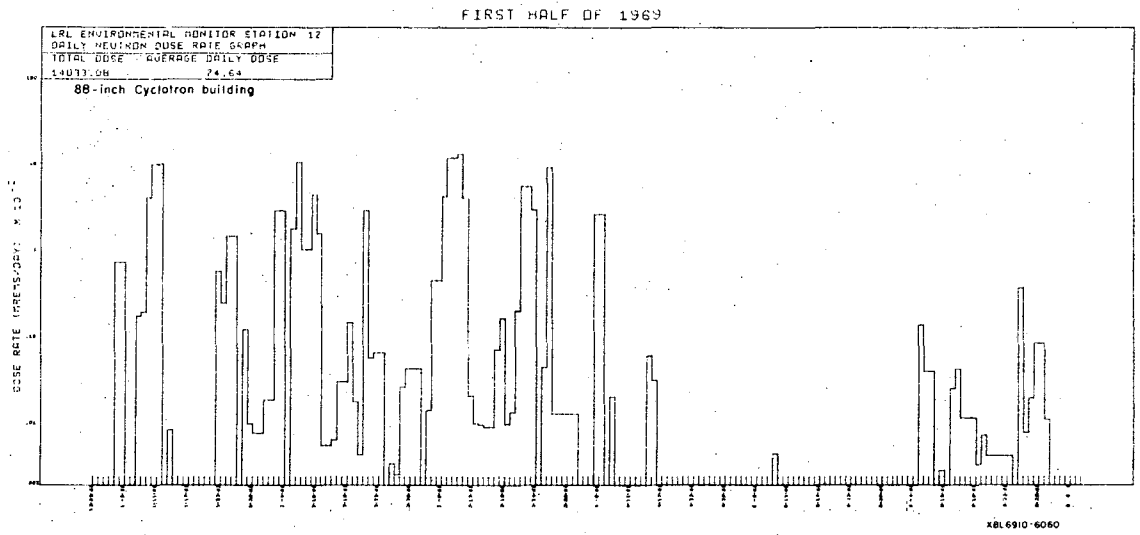
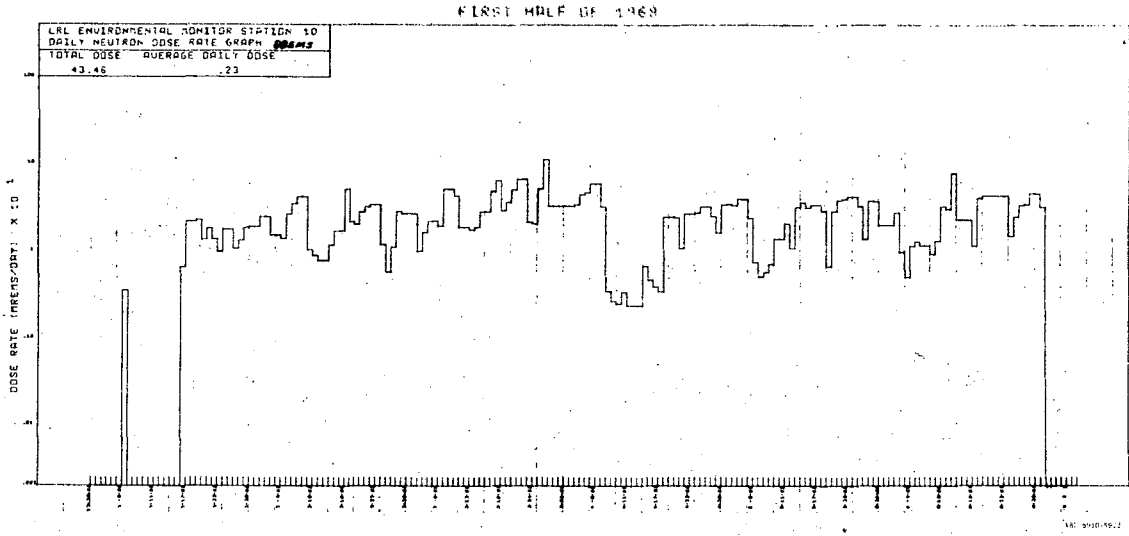
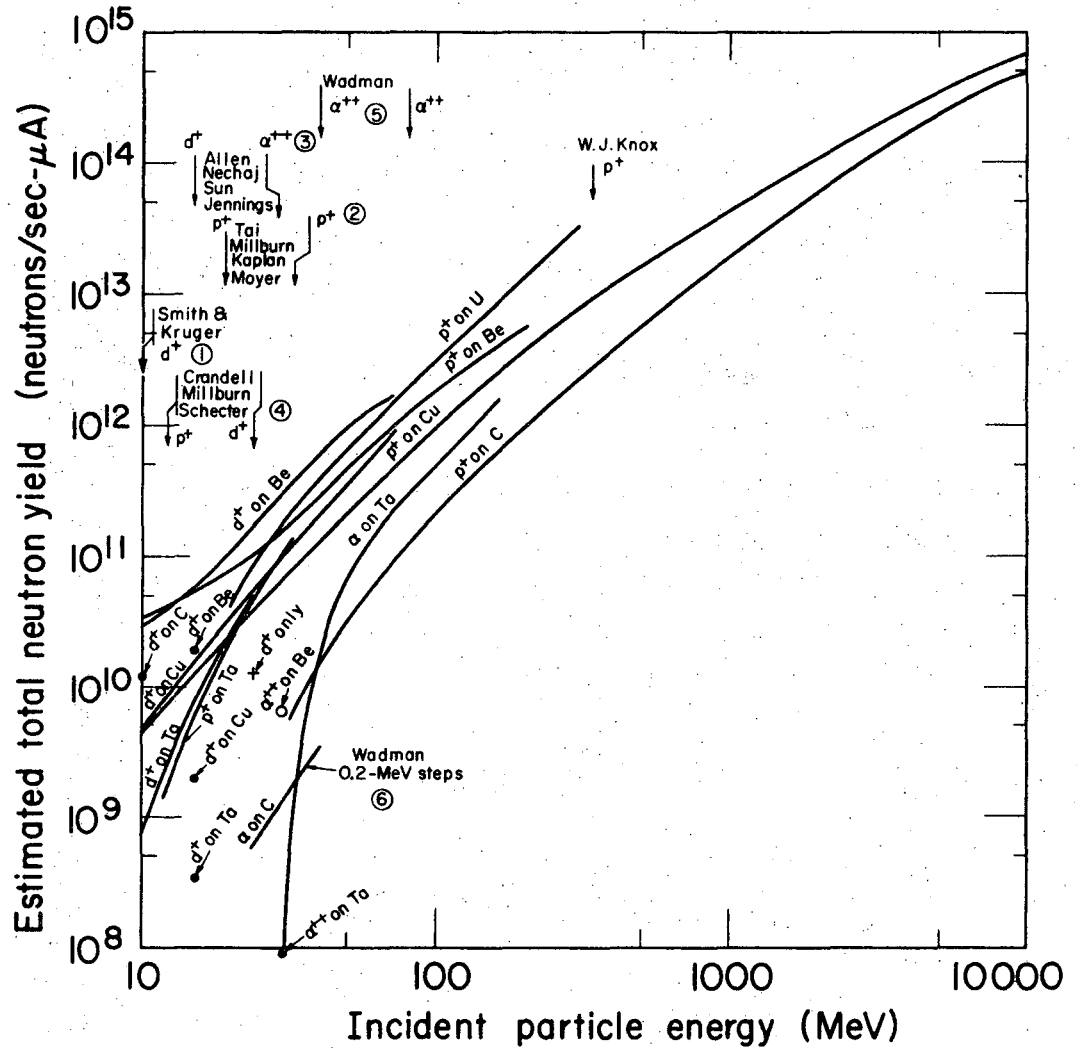
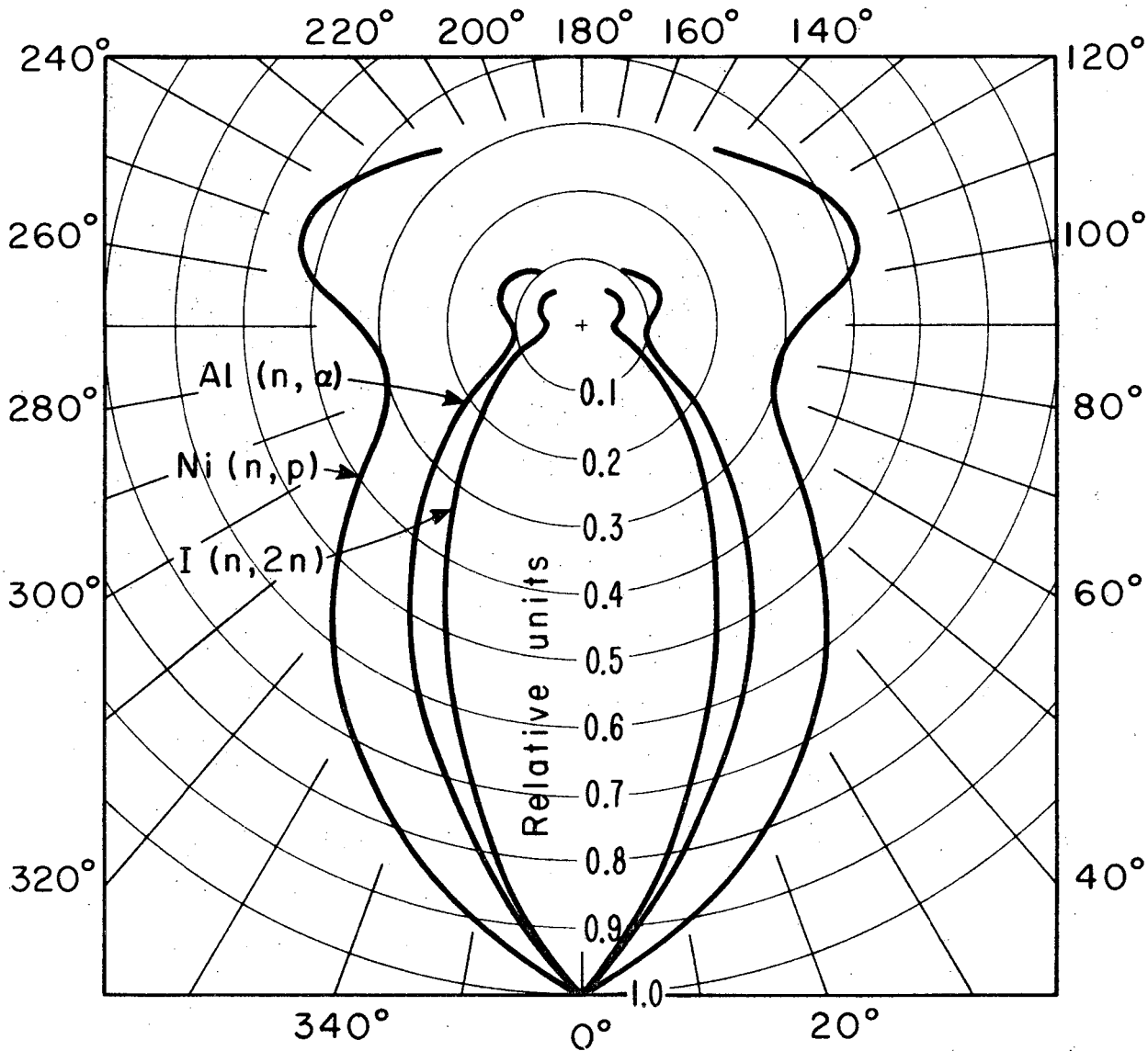


Fig. 15



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Fig. 16



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Fig. 17

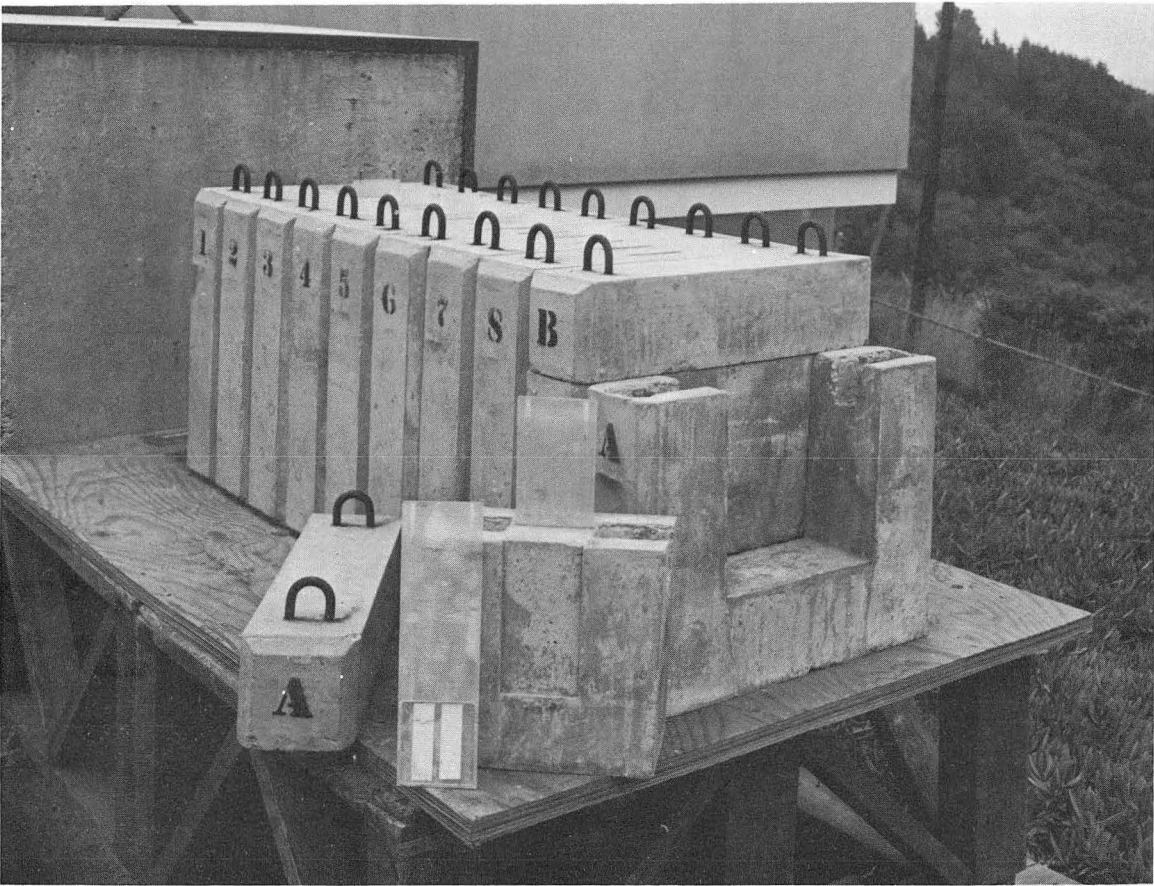
Table II. Neutron yields for selected ions, target particles, and energies.

Ion and target	Neutron yield energy (MeV)	10^{11} n/ μ coulomb
p^+ or d^+ on Ta	50	3.
p^+ on C	60	.55
α on Ta	60	1.3
p^+ on Cu	60	3.0
d^+ on Cu	60	5.5
p^+ on Be	60	7.0
p^+ on U	60	10.
d^+ on Be	60	15.
p^+ on C	100	2.3
d^+ on Be	100	30.

experiment was conducted which helped us to evaluate the effectiveness of different combinations of shielding materials, iron, depleted uranium, and ordinary concrete. For this study, ion beams of 110-MeV α particles, 50-MeV protons, and 55-MeV deuterons were transported to a totally shielded experimental cave and allowed to impinge on a thick elemental tantalum target. Located 6 in. from the target center, a 5 ft-thick stack of precision cast ordinary concrete blocks was placed along the beam axis (Fig. 18). The concrete blocks were fabricated so that the first 12 in. of concrete in the stack could be removed and replaced with iron or uranium. Fast neutron threshold detectors of Al, Ni, and Tl, and thermal and epithermal detectors of gold, were placed in the center of the concrete stack at 3-in. intervals along the beam axis. The properties of the threshold detectors are shown in Table III. From each detector the normalized activity as a function of depth in the concrete shielding array was determined.

Figures 19, 20, and 21 give examples of the attenuation data generated from three different neutron threshold reactions for deuteron-produced neutrons. It was interesting that regardless of shielding-face material or energy of threshold reaction, the half-value thickness is nearly the same after neutron equilibrium has been reached in the concrete. This demonstrates that it is the higher-energy component of the neutron spectrum that controls the half-value thickness or attenuation length of neutrons in concrete shields. It is also noteworthy that when compared with ordinary concrete, the heavy-element face materials—iron and depleted uranium respectively—reduced the total number of neutrons observed in the shielding array. Table IV summarizes the data in terms of half-value thickness for all the neutron energy threshold reactions and shielding combinations used in the study of neutron attenuation for neutrons from 55-MeV deuterons on a tantalum target.

The study demonstrated the benefits derived from the use of heavy-element face materials in combination with ordinary concrete when designing shielding for localized sources of medium-energy neutrons. Of particular usefulness is the iron-ordinary concrete combination, because of its ease of handling and its availability. In areas where nonmagnetic materials are desirable and space is limited, the depleted uranium-ordinary concrete combination would be an effective combination shield. Shielding neutron-attenuation measurements were made in the completed shields. These measurements were made for the purpose of comparing actual operating conditions, experimental work, and calculations.

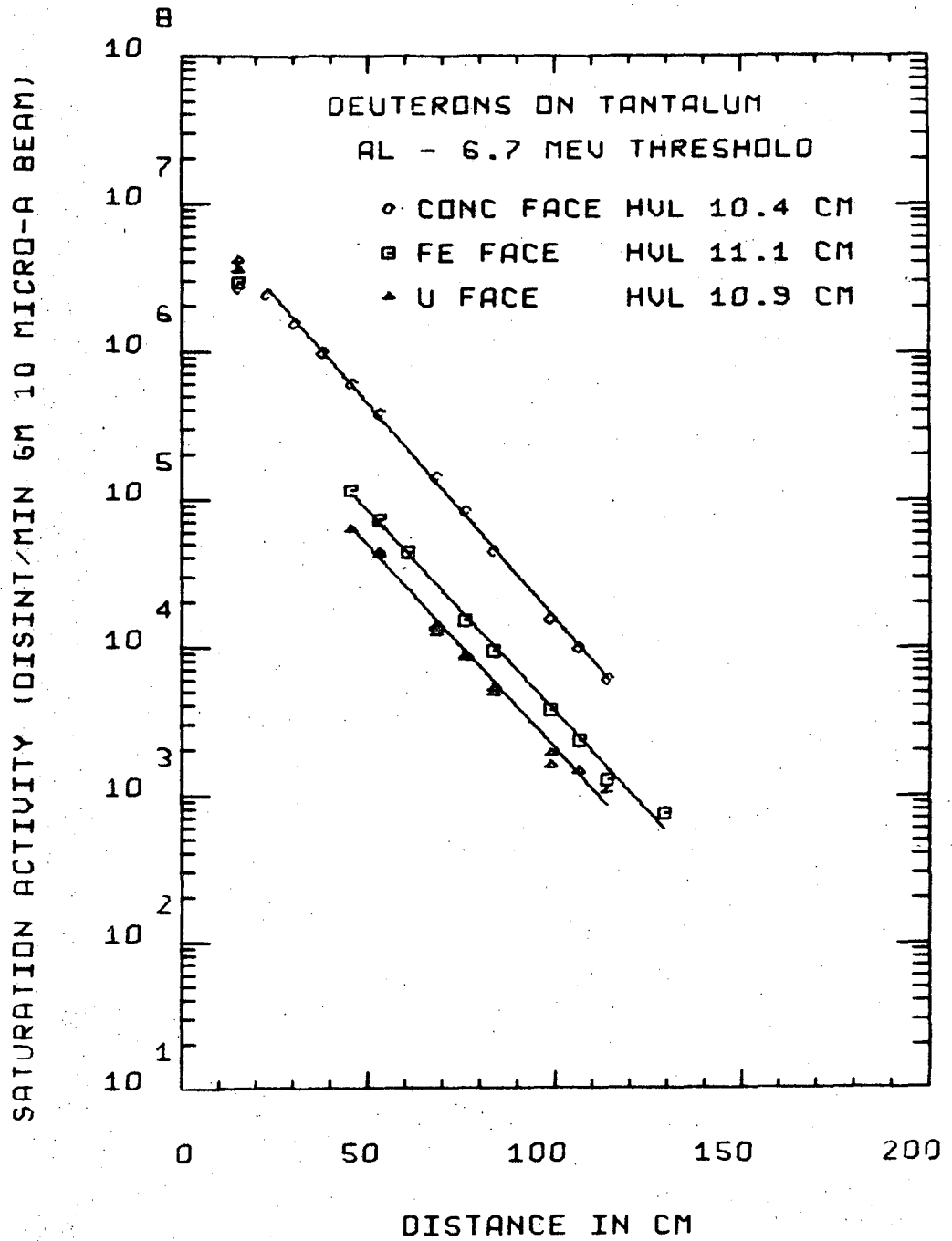


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Fig. 18

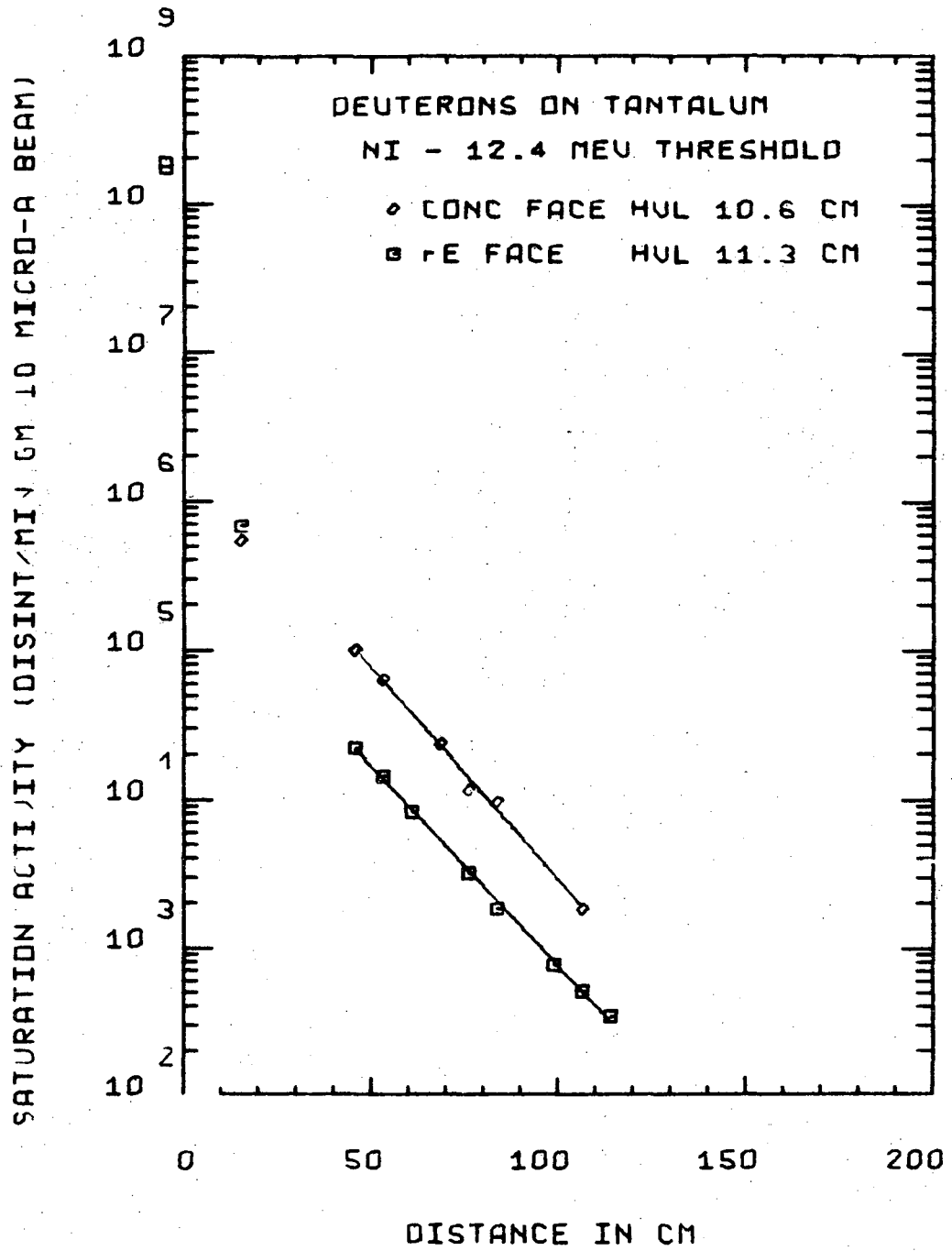
Table III. Threshold detector properties

Reaction	Calculated threshold (MeV) ^a	Peak cross section (Barns)	Product half-life	Target isotope (%)	γ-ray energy of product (MeV)
$^{58}\text{Ni}(n, p)^{58}\text{Co}$	1.1	0.556	71 d	67.8	0.81
$^{27}\text{Al}(n, \alpha)^{24}\text{Na}$	6.7	0.243	15 h	100.0	1.37, 2.74
$^{203}\text{Tl}(n, 2n)^{202}\text{Tl}$	8.5	2.78	12 d	29.5	0.44
$^{58}\text{Ni}(n, 2n)^{57}\text{Ni}$	12.4	0.25	37 h	67.8	1.36
$^{203}\text{Tl}(n, 4n)^{200}\text{Tl}$	24.7	≈ 1.3	27 h	29.5	0.368, 1.207



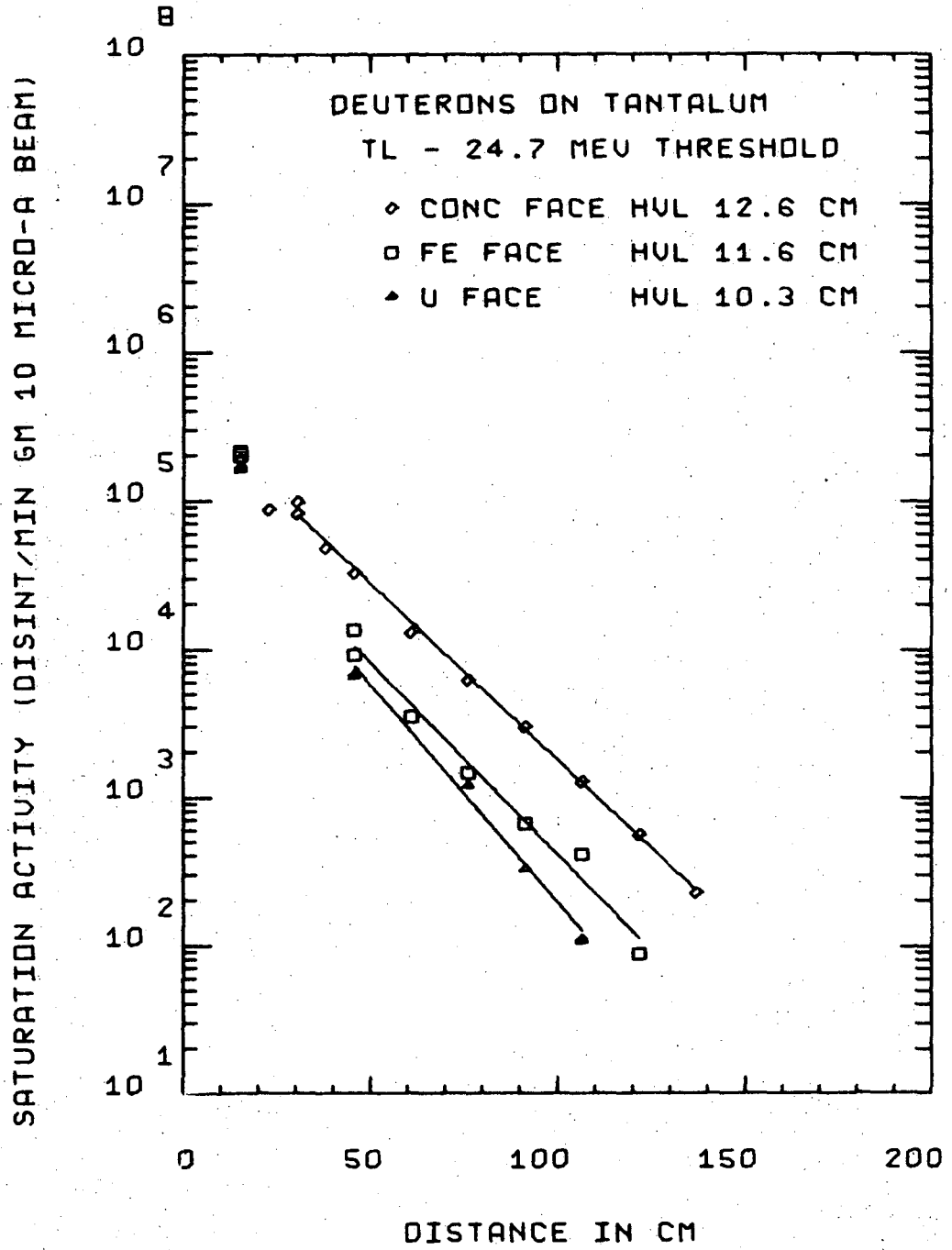
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Fig. 19



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Fig. 20



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Fig. 21

Table IV. Deuterons on tantalum
Measured half-value thickness summary

Detector	Threshold energy (MeV)	Shielding face material	Measured half-value thickness (cm)
Gold	Thermal and epithermal	concrete	11.1
		iron	7.2
		uranium	6.7
$^{58}\text{Ni}(n, p)^{58}\text{Co}$	1.1	concrete	11.3
		iron	11.6
		uranium	---
$^{27}\text{Al}(n, \alpha)^{24}\text{Na}$	6.7	concrete	10.4
		iron	11.1
		uranium	10.9
$^{203}\text{Tl}(n, 2n)^{202}\text{Tl}$	8.5	concrete	11.1
		iron	10.7
		uranium	10.3
$^{58}\text{Ni}(n, 2n)^{57}\text{Ni}$	12.4	concrete	10.6
		iron	11.3
		uranium	---
$^{203}\text{Tl}(n, 4n)^{200}\text{Tl}$	24.7	concrete	12.6
		iron	11.6
		uranium	10.3

One such experiment was performed in the composite iron-concrete shield wall housing the cave beam lines and through the roof blocks. Indium foils were secured in transflex tubing inserted in the spaces between shield blocks. The results are shown in Figs. 22 and 23. Corrections have been made for source-to-detector distances and are tabulated with the experimental attenuation measurements in Table V.

Induced-Activity Studies

Induced radioactivity has been the object of some detailed study at the 88-Inch Cyclotron since early in its history. In general there have been two approaches followed in the study.

The first approach, and perhaps the most useful, has been the ionization chamber measurements, begun just minutes after the accelerator was shutdown and continued at regular intervals for up to several days after the initial measurements.

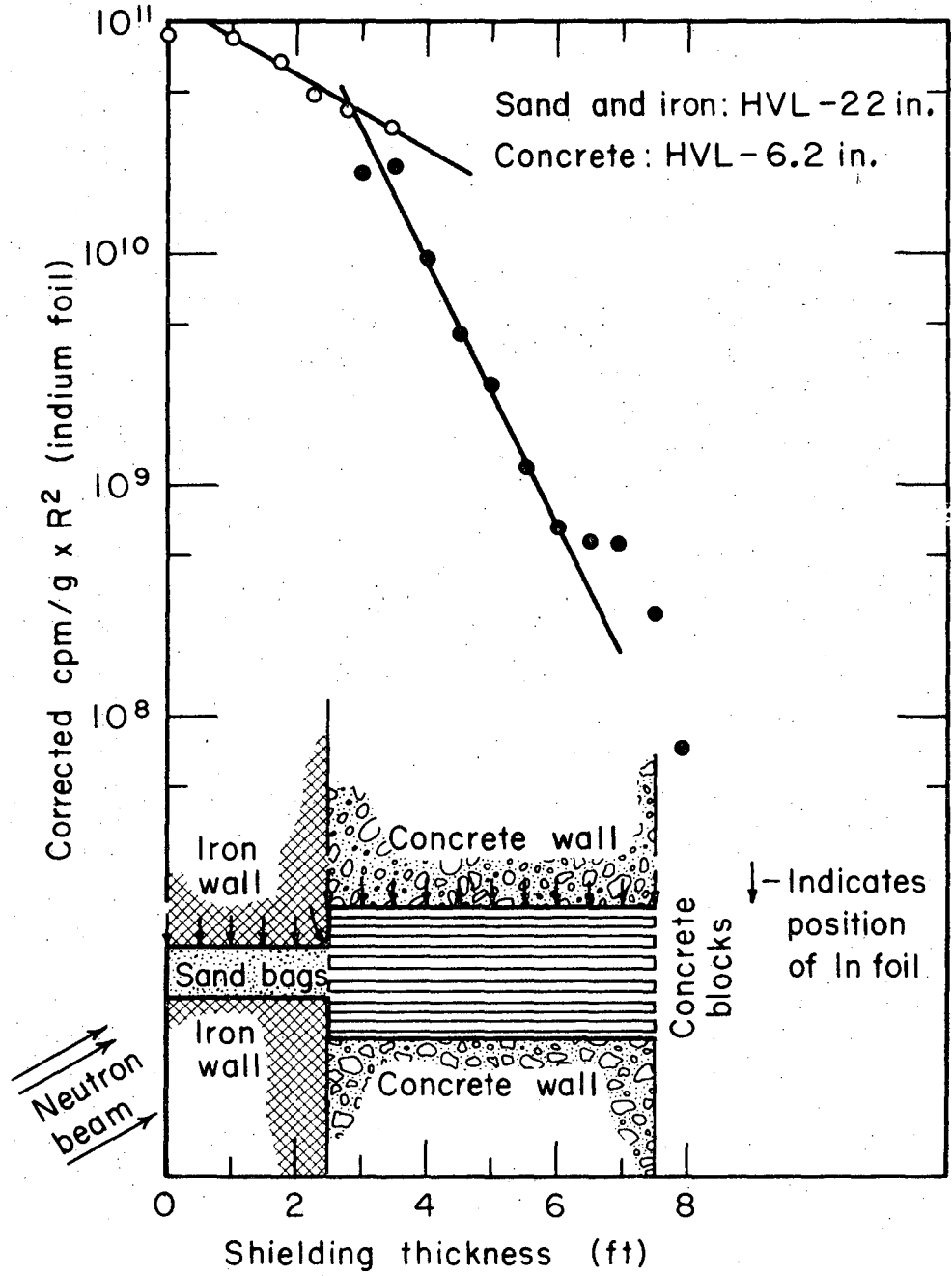
Figures 24 and 25 represent a sample of the ionization measurements made at three representative locations around the cyclotron. The figures include data taken 5 years apart in time, and thus represents the effect of buildup of long-lived radioisotopes. Figure 24 displays ionization chamber data recorded only minutes after cyclotron shutdown and at regular intervals for 3 to 5 hours. The important fact noted from this figure is that a maximum of 3 hours is required for the induced activity to fall to 50% of its initial value.

The ion-chamber measurements of December 22, 1962, were made approximately 9 months after machine operation began, therefore the data represent only a small contribution from the long-lived isotopes. The measurements of December 29, 1967, on the other hand, represent approximately 5.75 years of cyclotron operation, and with but one exception demonstrate the buildup of long-lived isotopes. The exception, at position # 2, is where external ion beams are passing and scattering whenever the cyclotron is running; the early activity measurements are no doubt dependent upon the ion last accelerated and the focusing and steering of the beam as it exits the cyclotron. Regardless of the initial activity of position # 2, after approximately 10 hours, the long-lived radioisotopes dominate (Fig. 25). From the 1967 data (presented in Fig. 25) we find that, regardless of the measuring position, the activity remains nearly constant 24 hours after the beginning of shutdown.

The second approach for the study of induced activities was the positioning of stacks of various metal foils inside the cyclotron vacuum

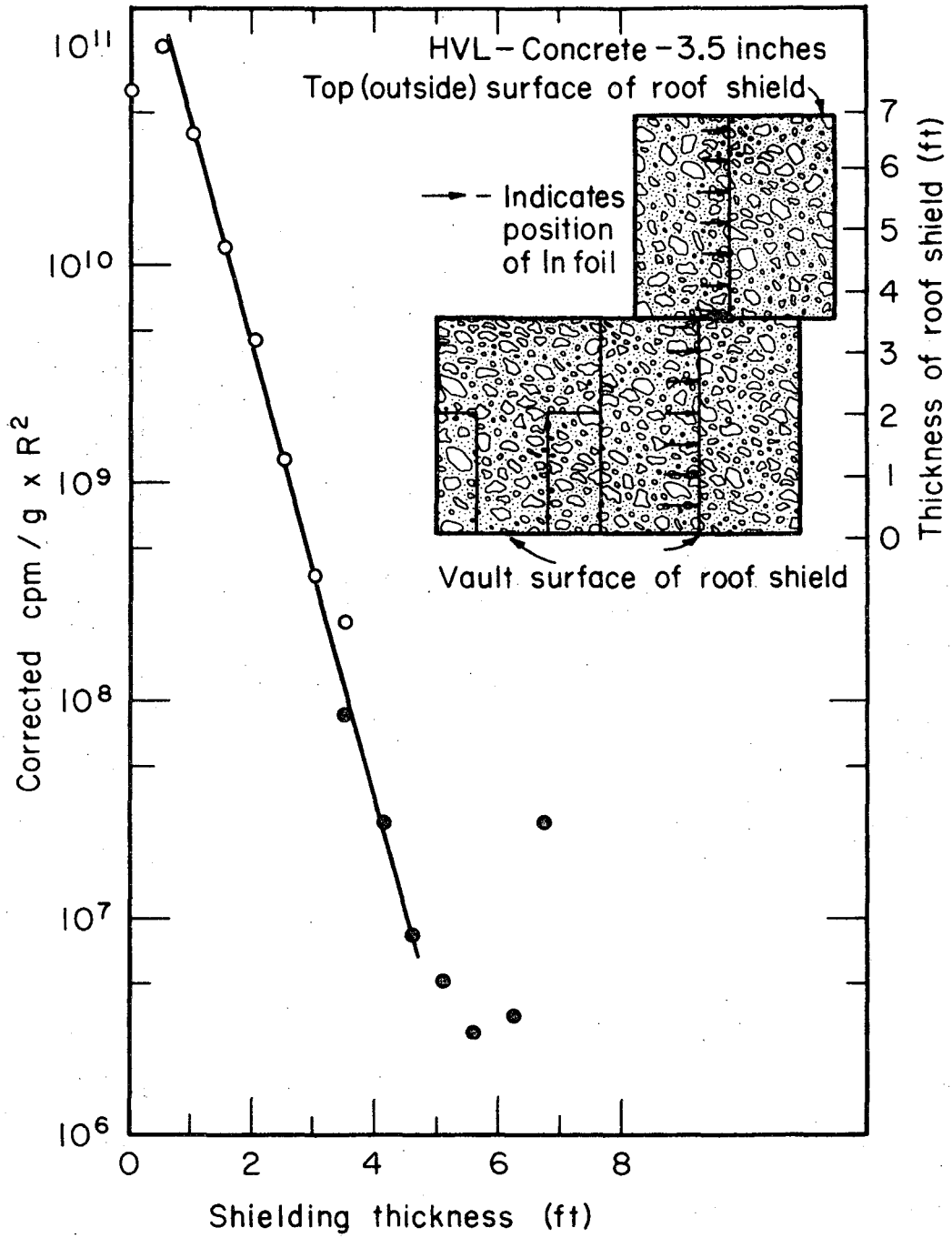
Table V. Measured and experimental half-value layers

Particle and target	Energy (MeV)	HVL	approximate beam-to- detector angle (deg)
α on Ta	80	15.8 cm (measured in composite shield wall)	0
α on Ta	80	8.9 cm (measured in roof shielding)	90
α on Ta	110	12.0 cm (experimental pre cast stack)	0



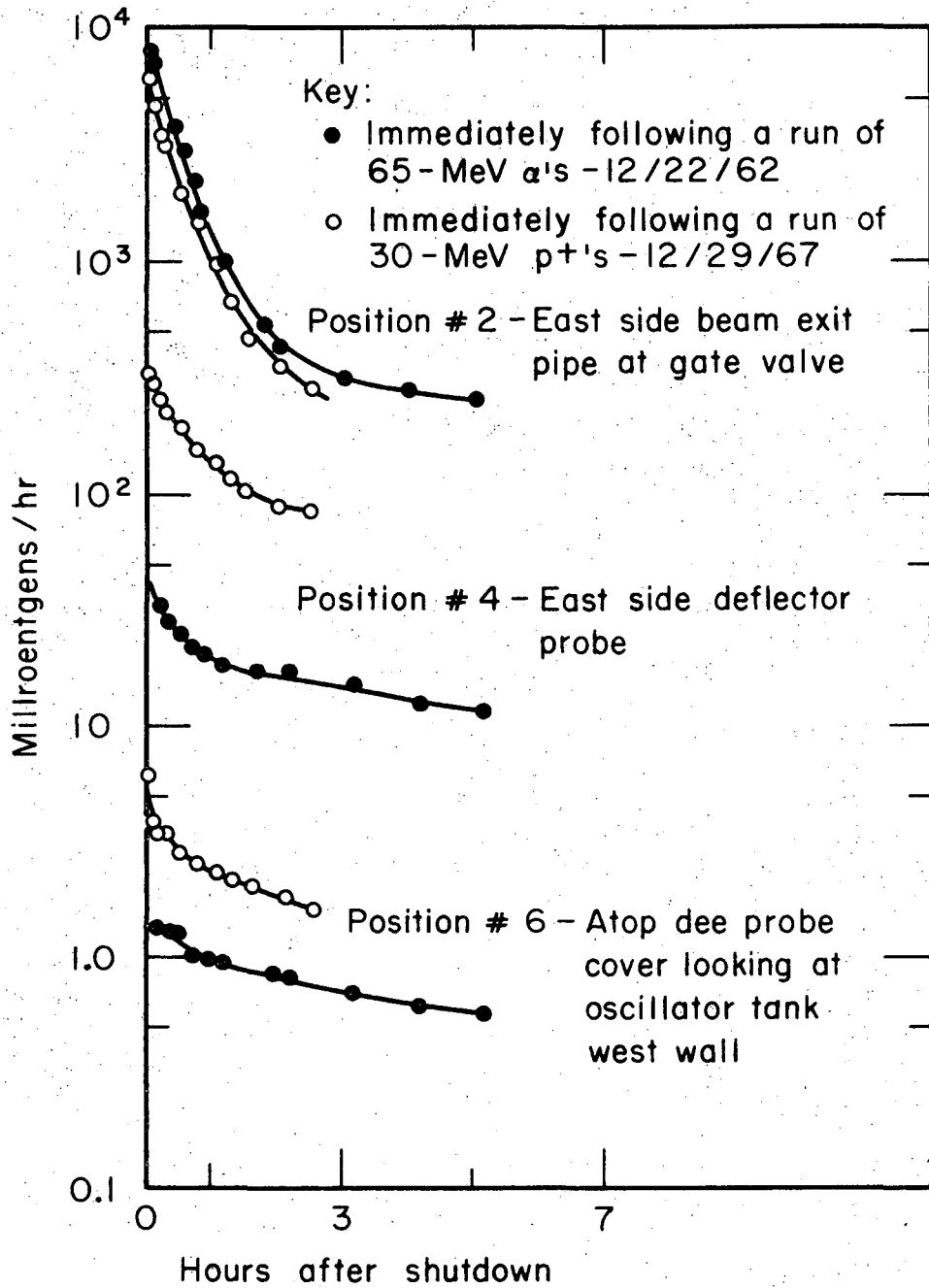
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Fig. 22



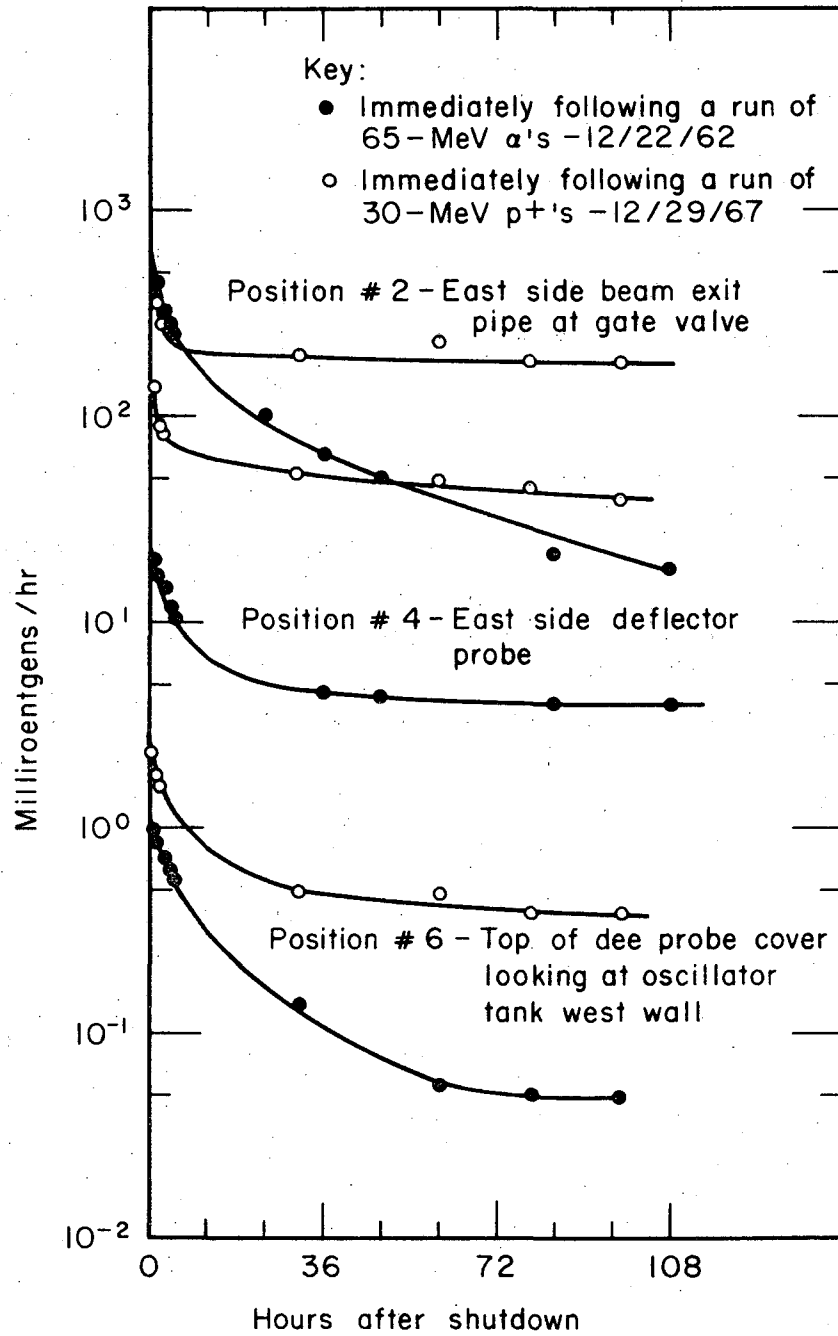
XBL 6910-6075

Fig. 23



XBL6910-6072

Fig. 24



XBL6910-6073

Fig. 25

tank. The foils used for this study represent the more important metals used in the construction of the 88-Inch Cyclotron: aluminum, brass, copper, cold rolled steel, stainless steel, Inconel, and K-monel. Each stack of foil was exposed for approximately 9 months and then removed and counted with a NaI(Tl) crystal spectrometer system.

This study began approximately 5 years ago, and is considered a continuing project. Although the foils have been counted numerous times since they were removed from the vacuum tank, the γ -ray pulse-height spectra generated have not been fully analyzed. Thus the information from this study is quite limited at this time.

In summary, the induced activity levels measured at the 88-Inch Cyclotron are quite reasonable and well within working levels after several hours of decay. It is important to note that the induced activity of the cyclotron is not uniform, but shows increasing levels of activity at locations of large beam loss, i. e., at the septum of the deflector and at collimator locations. This confirms our contention that the areas of highest activity are due to beam interactions with the accelerator hardware and not due to neutron-capture reactions.

Summary

The 88-Inch Cyclotron was designed to be a reliable, versatile, and safe accelerator. Eight years of operation have shown this to be true. Designs were chosen which allowed for ease of maintenance. Materials were selected with careful consideration given to future induced activities. Shielding was planned to allow personnel to work in all spaces where beams were not present. Special cases make this impractical— but not often. Roof areas are extensively used for experimental apparatus, with few restrictions.

During the entire period of operation no personnel radiation over-exposures have occurred.

There are but two problem areas which require special consideration, the ion source region and the exposed cave 4 beam. Experimenters are generally allowed to operate any desired beam at any time, with few exceptions. This freedom and the highly reliable and clean beams available make the 88-Inch Cyclotron a most useful accelerator for nuclear physics, nuclear chemistry, and biological studies.

REFERENCES

1. E. L. Kelly, General Description and Operating Characteristics of the Berkeley 88-Inch Cyclotron, in Proceedings of the International Conference on Sector-Focused Cyclotrons, Los Angeles, April 1962, Nucl. Instr. Methods 18, 19, 33 (1962).
2. H. Grunder and F. Selph, Operation of the 88-Inch Cyclotron (Lawrence Radiation Laboratory Report UCRL-11477, April 1964); earlier version published in International Conference on Sector-Focused Cyclotrons and Meson Factories, Geneva, April 1963 (CERN 63-19, Geneva, 1963,)p.8.
3. R. Burger, D. J. Clark, E. Close, and H. Kim, Machine Development at the Berkeley 88-Inch Cyclotron, in International Conference on Isochronous Cyclotrons, Gatlinburg, Tennessee, May 1966, IEEE Trans. Nucl. Sci. vol. NS-13 [4], 364 (1966).
4. Lloyd D. Stephens and Alan R. Smith, Fast Neutron Surveys Using Indium Foil Activation, Lawrence Radiation Laboratory Report, UCRL-8418, Aug. 1958.
5. R. E. Hintz, F. B. Selph, W. S. Flood, B. G. Harvey, F. G. Resmini, and E. A. McClatchie, Beam Analyzing System for a Variable Energy Cyclotron, Lawrence Radiation Laboratory Report, UCRL-18383, Aug. 1968.
6. Alan R. Smith, Threshold Detector Applications to Neutron Spectroscopy at the Berkeley Accelerators, in Proceedings of the First Symposium on Accelerator Radiation Dosimetry and Experience, Brookhaven National Laboratory, November 3-5, 1965.
7. H. S. Dakin and L. D. Stephens, Environmental Radiation Telemetry System, submitted to Health Physics.
8. William W. Wadman, Angular Distribution of Neutrons Produced by 40 - and 80-MeV α Particles on a Thick Tantalum Target, Lawrence Radiation Laboratory Report, UCRL-11375, May 1964.

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FIGURE CAPTIONS

- Fig. 1. General View of the 88-Inch Cyclotron.
- Fig. 2. Energy per nucleon available at the 88-Inch Cyclotron.
- Fig. 3. Vault neutron measurements made during construction phase.
- Fig. 4. Pit neutron measurements made during construction phase.
- Fig. 5. Temporary cave neutron measurements.
- Fig. 6. Present radiation shielding form for cyclotron vault and caves.
- Fig. 7. Some typical neutron measurements due to a beam in cave 2.
- Fig. 8. Cyclotron beam energy resolution (a) available to all caves, (b) available in cave 4 (see text).
- Fig. 9. Cave 4 beam-transport system.
- Fig. 10 a, b, c, d. Neutron beam-loss patterns along cave 4 beam line for four different ions.
- Fig. 11. Local shielding designed by W. Wadman as used in cave 2.
- Fig. 12. High-resolution spectrograph (under construction).
- Fig. 13. Early cyclotron building radiation measurements.
- Fig. 14. Current cyclotron building radiation measurements.
- Fig. 15. (a) Environmental neutron levels at the site boundary (see text) (b) neutron levels in 88-Inch Cyclotron building (see text).
- Fig. 16. Plot of neutron yields vs incident particle energy for several combinations of targets and ions. (1) Smith-Kruger, Mn SO₄, (2) Tai-Millburn, Kaplan, Moyer, Mn SO₄, (3) Allen, Nechaj, Sun, Jennings, ³²S (n, p) ³²P, (4) Crandell, Millburn, Schecter, Mn SO₄, (5) Wadman (40, 80 MeV α⁺⁺ on Ta) ⁵⁸Ni (n, p) ⁵⁸Co, (6) Wadman (23.2-40.8 MeV α on C) Moderated BF₃ curve shape accurate yield value probably high.

Fig. 17. Angular distribution of neutrons from 40-MeV α particles on a thick tantalum target.

Fig. 18. Concrete block experimental shielding stack.

Fig. 19. Experimental neutron attenuation data. (6.7 MeV threshold)

Fig. 20. Experimental neutron attenuation data. (12.4 MeV threshold)

Fig. 21. Experimental neutron attenuation data. (24.7 MeV threshold)

Fig. 22. Actual neutron attenuation measurements through a composite shield wall.

Fig. 23. Actual neutron attenuation measurements through the vault roof shield.

Fig. 24. Short-lived decay measurements of several specific locations on the 88-Inch Cyclotron. Effect of long-lived activity buildup can also be seen.

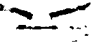
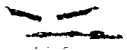
Fig. 25. Long-lived decay measurements at several specific locations on the 88-Inch Cyclotron. Effect of long-lived activity buildup can also be seen.

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