MEASUREMENT OF RADIATION FIELD AROUND HIGH-ENERGY ACCELERATORS

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## ABSTRACT

We measure the slow neutron, fast neutron, and $\gamma$-ray fluxes as three separate components of the radiation field around an accelerator. Instrumentation used to perform these measurements responds in physical terms; resultant data can then be converted to biological hazard terms by use of the best current values for appropriate conversion factors. We describe the instrumentation, its use at pulsed accelerators, and typical results obtained near the 6.3 Gev Bevatron at Berkeley.

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Our responsibilities at the Berkeley Laboratory fall naturally into four broad categories:

(a) Evaluation of radiation hazard and protection of personnel.

(b) Calculation and design of shielding for accelerators.

(c) Consultation on and evaluation of shielding enclosures for experimental equipment.

(d) Development of instrumentation and techniques needed for the above tasks.

We approach these responsibilities as physicists; we therefore employ the tools and techniques of experimental physics wherever possible. Radiation fields are measured in strictly physical terms. For evaluation of health hazard, we then rely upon interpretation of these meaurements according to the best available data on biological effectiveness.

Our responsibilities include design and evaluation of shielding--both for personnel and for experimental equipment. A necessary corollary is a clear understanding of the characteristics of the stray radiation field and their relationship to accelerator performance. Although some rather simple "rem"-response instrumentation may provide adequate evaluation of health hazard, such equipment clearly cannot fulfill these other requirements. Thus, from natural inclination as well as in an effort to meet our responsibilities most effectively, we have developed the techniques and have applied them as I will now describe.

The basic approach is to view the stray radiation field as consisting of several components, each of which can be separately investigated with suitable instrumentation. For example, one might measure the flux intensity, energy spectrum, and directional characteristics of a component and then apply this information to the specific problem.

We normally consider that three components constitute the radiation field. This concept is particularly useful for work done outside accelerator shields.[1] The most important component is the fast neutron flux and to this we give our greatest attention. Of lesser importance is the slow-neutron component. Of roughly equal importance in normal situations is the component we term "γ-ray and charged-particle flux." The utility of this concept will become apparent from examples cited. First, there should be a few general remarks concerning the instrumentation.

We deal primarily with pulsed accelerators, and are thus confronted with both high instantaneous radiation intensity and low average count rate. We employ detectors that either integrate with respect to time naturally, or deliver discrete pulses which can be summed with digital counting equipment. Examples are:

(a) gold or indium foil, which integrates neutron exposure, within half-life restrictions;

(b) ionization chamber with open-grid electrometer tube circuit, which integrates charge collected;

(c) $BF_3$ counter or fission counter, which produces discrete pulses that can be summed.

We exercise great care to insure that pulse counters yield correct information in high instantaneous flux intensities, and either that integrating devices are leakproof, or that their leakage is correctly evaluated. Decay of foil activation during exposure is here termed "leakage." Careful attention is given the problem of relating measured quantities to accelerator operation, and of relating measurements taken at different times to one another. The concept of a monitor counter is implied here; we normally employ such a counter, either to supplement or, in some cases, to supplant accelerator beam-intensity information, in order to achieve data correlation.

There is not time to describe our techniques in detail, so I have chosen several examples to illustrate particular techniques and to indicate their usefulness in solving the problems we face. These relate to the fast-neutron component--the component that is at once the most difficult to measure, the most serious health hazard, and the most difficult to shield against.

## Applications of Prompt Counters

We find that the fast-neutron component usually delivers 60 to 80% of of the biological dose to areas outside shields around our high-energy accelerators. The other two components, of nearly equal magnitude, contribute the rest. We regularly employ two counters for fast-neutron detection:

(a) moderated $BF_3$ proportional counter, with response to fast neutrons independent of energy in the range 0.050 to 20 Mev;

(b) polyethylene-lined (PE) proportional counter, with response proportional to the density of fast-neutron energy flux in the range 0.100 to 20 Mev.

Patterson and Moyer have shown that approx. 80% of the biological dose delivered by cosmic-ray neutrons lies within the region of the energy response of these two detectors.[2] Furthermore, there is good reason to expect the energy spectrum of stray neutrons outside the accelerator shield to resemble closely the cosmic-ray neutron spectrum. Thus these two detectors are seen to be powerful tools for the purpose.

The ratio (PE counts) ($BF_3$ counts) yields a quantity we term average neutron energy (referred to henceforth as "average energy"). One important use of average energy is as a guide in determining the magnitude of the health hazard of a fast-neutron field. A second important use is related to shielding problems, and is illustrated here.

The 730-Mev Berkeley cyclotron is a completely shielded accelerator. Two-counter surveys indicate average energy values in the range 1 to 2 Mev. The 6.3-Gev Bevatron, on the other hand, is only partially shielded. There is a complete outer ring shield, slightly taller than the magnet structure, but the entire top is open except for roof shields placed directly over the four straight sections.

The average energy values measured at great distances from the accelerator--300 meters or more--are 1 to 2 Mev. The average neutron energy decreases as one approaches the Bevatron, until surprisingly low values of 0.1 to 0.2 Mev are observed inside the accelerator building but outside the shield. We interpret these observations as follows:

(a) Neutrons lose energy rapidly by inelastic collisions as they penetrate the magnet structure, until their energy drops below 2 Mev. Some of these upward-directed neutrons are then scattered downward from above the accelerator, thereby suffering additional energy loss before they reach floor areas outside the main shield. The very low average energies observed close-by are thus reasonable.

(b) The low-energy groups are more strongly attenuated with passage through many meters of air; thus we observe "hardening" of the spectrum with distance--the average energy of the surviving neutrons increases.

(c) Beyond, say, 300 meters we have reached the region of equilibrium;

the spectrum is no longer changing, and we do not observe continued change in average energy values.

Steady improvement in Bevatron performance produced a steadily increasing stray radiation field. Early in 1959 the fast-neutron flux had risen to such an intensity that continuous occupancy of the entire experimental area was no longer a wise policy. The experimental physics program, on the other hand, required continuous occupancy of this area. By use of the two-counter techniques, we were able to show that 1 ft of wood shielding for temporary shelters reduced the fast-neutron biological hazard by a factor of 5 to 10. Accordingly, a system of quickly adaptable shelters, employing modular construction principles, was designed and built.

Figure 1 portrays one of the definitive tests that led to adoption of the wood shield. We see here a two-counter study of the attenuation in plywood of the Bevatron stray neutron flux at a station in the experimental area outside the main shield. The counters were shielded by 2-ft-thick heavy concrete on all sides except for one open side on which standard 4-by-8-ft sheets of plywood could be placed. The enclosure opened upward, the direction from which most neutrons reach these areas.

At this same time, the fast-neutron hazard both in the accelerator control room and in the adjoining support shops reached a significant fraction of the long-term occupational tolerance; similar 1-ft-thick wooden shields, applied in proper fashion, reduced the hazard here by a factor of five.

Figure 2 illustrates the effect of wood shielding in these areas as measured in 1959 by the same two counters. We show radial profiles of the fast neutron field at floor level outside the main shield. The first set shows conditions at an azimuth unaffected by the wood shield structure. The second set shows conditions at the Control Room azimuth before installation of the wood. Note that a thin concrete roof affords some protection for the Control Room itself. The third set shows conditions at the same azimuth with the wood shield in place. All three sets are normalized to the same fast-neutron flux intensity at a station close to the main shield, for ease of comparison. We have omitted a plot of energy flux density for the sake of clarity. Although the Bevatron is capable of a sustained beam of $4\times10^{10}$ $p^+$/sec, this slide portrays radiation intensities as they now exist, because the shielding added to straight-section top areas since the time of these surveys has almost exactly compensated for the increase in beam intensity.

Such shields are a stopgap measure, to be sure; however, they are extremely inexpensive and have proved quite effective in our situation.

Through their use, we are able to have the Bevatron operate continuously at its maximum beam intensity without subjecting those associated with the accelerator to excessive radiation exposure. The shields will be used until installation of the new roof shield late this year, and then presumably will no longer be needed.

We have made extensive studies of the intensity of fast-neutron flux inside the shield, with moderated indium foils. The foil technique is the main method through which we have learned the relative importance of different parts of the machine in neutron emission. As a direct consequence of such information we installed concrete roof shields above straight sections, the areas of greatest neutron emission. Fast-neutron flux intensity outside the shield in experimental areas was thus reduced by a factor of 5. Total emission from the accelerator as observed at a distance was reduced by a factor of 4.

Figure 3 compares the total fast-neutron flux intensities for two different shield configurations. The detectors are moderated foils, stationed along the circular craneway, a catwalk located about 30 feet above the main floor level and about 100 feet away from the Bevatron center. The upper set of points represents flux intensities observed in 1959, when top shields were in place at only the east and south straight sections. The lower set of points shows flux intensities observed in 1961, after top shields had also been installed on the west and north straight sections--the main experimental target positions. Both sets are normalized to the same value of Bevatron beam intensity.

## Moderated-Foil Detectors

Extensive use is made of the moderated-foil detector, a fast-neutron detector with energy-response characteristics similar to those quoted previously for the moderated $BF_3$ counter. We now use a cadmium-clad paraffin moderator in the shape of a right circular cylinder 6 in. in diameter and 6 in. high. Indium foils[3] are most often used when we require data relating to particular accelerator operating conditions. Gold foils are used to measure integrated exposures for periods of several days; these data more nearly represent actual exposures in the day-to-day work environment than we can obtain from indium foils. Indium and gold foil activities are measured with a methane-flow $\beta$ counter operated in the proportional region. Count rates of 4 counts/min from indium and 1.5 counts/min from gold are obtained when our 1-in.-diameter foils are irradiated to equilibrium in a 1-n/cm$^2$ sec fast neutron flux, while typical counter background is 10 counts/min.

Another moderated detector is the cobalt fast-neutron integrator, fully described elsewhere.[4] A 2-in.-diameter cobalt disc weighing approx.

56 grams is the active element of this detector. The amount of $Co^{60}$ produced in a disc during detector irradiation is taken to be the measure of integrated fast-neutron exposure. A $\gamma$-ray scintillation spectrometer is used to assay $Co^{60}$ content. Only the narrow energy region of the spectrum containing the two total-absorption $\gamma$-ray peaks is accepted as valid $Co^{60}$ information; thus spectrometer background is reduced to the practical minimum. An integrated exposure of $1.0 \times 10^{7}$ n/cm$^{2}$ produces 1.80 counts/min the the selected energy interval with a 4-in.-diameter 2-in.-thick NaI(Tl) crystal detector; BKG in this interval is 14 counts/min. Thus an exposure of $10^{7}$ n/cm$^{2}$ can be measured accurately when spectrometer BKG is precisely known and closely controlled.

A network of cobalt integrators has been in continuous operation at our Laboratory since December 1959. The original number of eight stations has recently been increased to twelve, to include locations at the Laboratory boundary. Integrator discs are counted either monthly or quarterly. Exposure times of at least one year can be employed without introducing serious error in computed flux integrals. A steady flux of 0.3 n/cm$^{2}$ sec produces an integrated exposure of $10^{7}$ n/cm$^{2}$ in 1 year.

A very significant point emerges from comparison of results obtained with the short- and long-term integrators, namely: that we correctly estimate long-term exposures from short-term measurements--always, of course, taking into account accelerator operating conditions. Furthermore, results obtained with prompt detectors are in agreement with the various integrator data. Thus we are able to apply whichever technique appears most suitable for a specific situation and at the same time can look to the resultant data with equal confidence. The significance of being able to predict long-term exposures from short-term measurements cannot be emphasized too strongly; this is one of the most important areas in which we must provide consistently accurate information for the Laboratory. Another vital capability is to be able to predict exposures accurately from specific accelerator operating conditions, especially from increased beam intensity; again all the above remarks apply to our treatment of this problem.

Another version of the moderated-foil detector partially bridges the gap between prompt counters and integrator foils. This detector was designed specifically for the Bevatron, but can be modified for use at other pulsed accelerators where the duty cycle is low. We again employ a moderator, but the detector is now a halogen-quenched Geiger-Müller (G-M) tube with a silver foil wrapped tightly around it. In operation, foil activation produced by a Bevatron beam pulse is measured during the quiescent period between beam pulses. Our present instrumentation is synchronized with the accelerator cycle to provide a 3-second count time on a digital scaler followed by a 2-second static readout time, and then to reset and repeat. We obtain a sensitivity of 1 observed count per 3-second sampling interval from a flux intensity of 1 n/cm$^2$ sec with a G-M tube of the size commonly used in portable survey instruments. The 23-second silver activity predominates, therefore changes in flux intensity are quickly reflected in detector response. This system completely bypasses the problems of high instantaneous flux intensity, while it still retains many advantages of the prompt detector, and in addition its sensitivity can be widely varied by simple adjustment of the size of the silver foil. One possibly serious disadvantage--sensitivity of the G-M tube to $\gamma$ rays--has not proved to be a difficult problem yet, although one must be constantly alert to the threat. We generally find the $\gamma$-ray component to be only 5 to 10% of the gross count rate, and it can therefore be neglected. This detector, when used in conjunction with prompt counters, has provided much valuable information regarding count loss in the prompt counters. G-M tube circuitry is inherently simple; this simplicity, plus the extensive use of solid-state, components has resulted in the creation of a flexible and dependable neutron-monitoring system that demands little finesse in operation and requires a minimum of maintenance.

## Threshold Detectors

Two types of threshold detectors are employed: prompt counters, and activation elements. Prompt counters have been more extensively used, and are discussed here in some detail. These counters are used near Bevatron targets, to measure flux intensity and spectrum shape. They have been used to study attenuation of target-produced neutrons in concrete and lead. We have also used them to study neutron emission from targets located either in a straight section or in a magnet quadrant.

The two counters most often used are a thorium-fission chamber, with a neutron energy threshold of 1.5 Mev, and a bismuth-fission chamber with a 50-Mev neutron energy threshold.[5] Both chambers operate as pulse ion counters, and therefore require high-gain low-noise electronic amplifiers.

The study of neutron emission upward from targets at two different locations illustrates well the utility of these detectors. Both fission counters, along with moderated-foil detectors, were employed at each survey point. In the first case, a target is located at the upstream entrance to a straight section, and is thus virtually unshielded for any detector position forward of 90° with respect to the target. In the second case, a target is located well within a magnet quadrant, and is thus shielded for all detector positions by iron at least 2 ft thick, with minimum shielding at 90° with respect to the target. Total fast-neutron emission measured with moderated foils is found to be about 10 times as great for straight-section location as for magnet-quadrant location: However, the bismuth fission counter, the highest-energy detector, shows straight-section emission to be about 150 times magnet-quadrant emission. In addition, magnet-quadrant emission is seen to be strongest at about 90°, whereas straight-section emission is clearly peaked in the forward direction. Information of this nature is very important in connection with shielding calculations and design. Although no new characteristics of beam-target interactions have been learned here, we have nevertheless provided some very important quantitative data, upon which much of the new design for the Bevatron shield depends.

Activation-element threshold detectors are also employed for measurements of flux intensity and energy spectrum. We propose to reach the flux intensity range of 1 to 10 $n/cm^2$ sec above reaction-energy thresholds. Kilogram quantities of elements may be required for such exposures; thus we have chosen the $\gamma$-ray scintillation spectrometer as the main analysis tool. A possible suite of elements includes aluminum, carbon, cobalt, nickel, and sulfur. We have obtained encouraging preliminary results with the first four elements, but do not have sufficient data to report quantitatively at this time.

## Conclusion

I have reviewed a few of the neutron-measurement techniques used at Berkeley. With these, and other techniques not described today, we do an adequate job at our Laboratory. However, we are by no means satisfied with our performance or the tools with which we work; we constantly seek to improve both. The threshold activation detector, a tool that shows great promise, needs particularly concentrated effort to bring it into practical usefulness. Solid-state detectors are in this same category. In these areas and others, we are actively engaged in development work.

We at Berkeley look forward to increased communication among the laboratories represented here as one of the most effective methods to bring about improvement in the equipment and techniques employed in our work. I wish to express my pleasure to be a participant of this Congress, a Congress that has surely provided great stimulus to this important, but often neglected, aspect of our professional experience.

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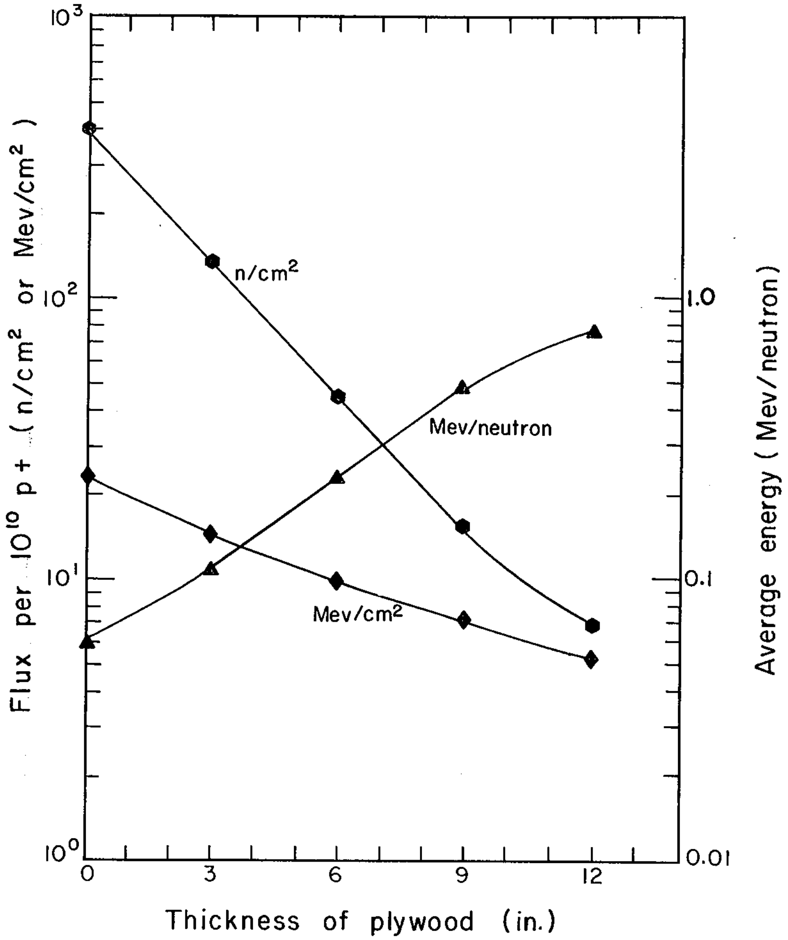
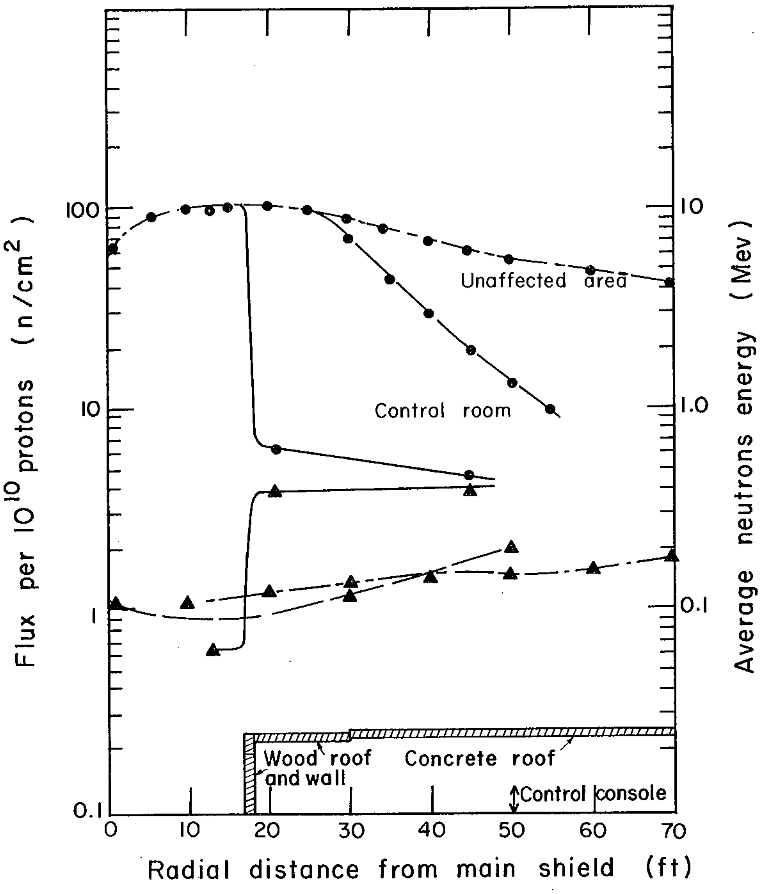


MU-26413

Fig. 1. Attenuation of Bevatron stray neutrons in plywood: two-counter study in experimental area.



MU-26414

Fig. 2. Effect of wood shielding on Bevatron stray neutrons: two-
______ with wood shielding in place
_ _ _ _ before wood shielding was added
_._._. unaffected area
counter survey in experimental area.

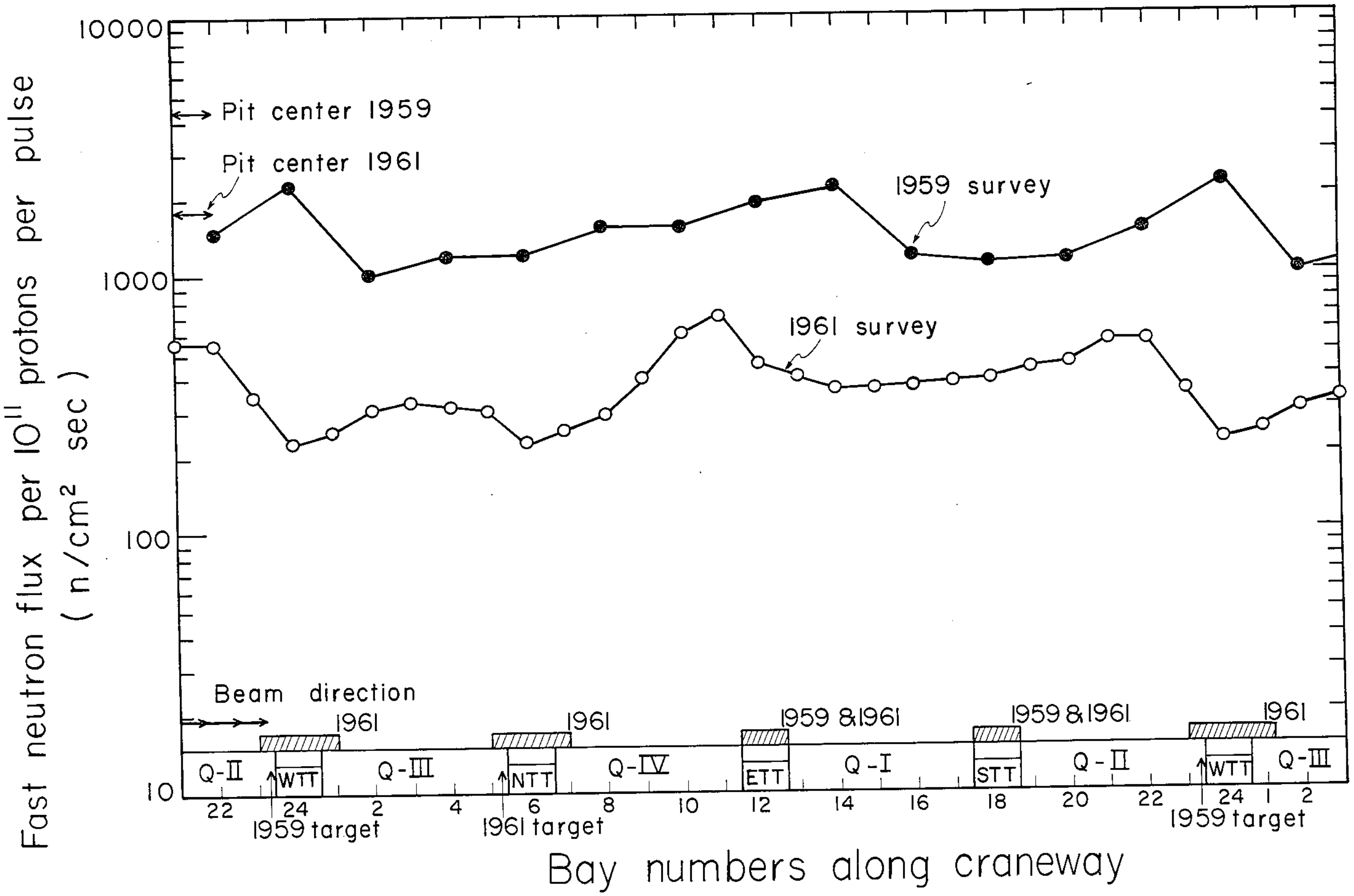


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Fig. 3. Effect of top shields above straight section on Bevatron stray neutrons: moderated-foil surveys along craneway.
(WTT = west tangent tank, etc.)
(Q-I, magnet quadrant I, etc.)