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EXPERIENCE WITH POSITION-SENSITIVE NEUTRON DETECTORS AT THE INTENSE PULSED NEUTRON SOURCE*

R. K. Crawford, J. R. Haumann, J. E. Epperson, P. Thiyagarajan, A. J. Schultz,
G. P. Felcher, D. G. Montague, and R. J. Dejus
Argonne National Laboratory, Argonne, IL, USA

Abstract

At the Intense Pulsed Neutron Source (IPNS) pulses of protons accelerated in a synchrotron produce pulses of fast neutrons via the spallation process in an enriched uranium target. After moderation, the resulting pulses of slow neutrons are directed into beams which serve a variety of neutron scattering instruments. Currently there are thirteen neutron scattering instruments in operation or under development at IPNS, and six of these use position-sensitive neutron detectors (PSDs). These PSDs are: a 30 cm x 30 cm, ~3 mm resolution, neutron Anger camera area PSD with ^{6}Li-glass scintillator; a 2.5 cm dia, ~0.7 mm resolution, microchannel-plate area PSD with ^{6}Li-glass scintillator; a 20 cm x 20 cm, ~5 mm resolution, ^{3}He proportional counter area PSD; a 40 cm x 40 cm, ~4 mm resolution, ^{3}He proportional counter area PSD; a flat 20 cm long, ~1.6 mm resolution, ^{3}He proportional counter linear PSD; and 160 cylindrical ^{3}He proportional counter linear PSDs, each of which is 1.27 cm in dia 60 cm long and has ~14 mm resolution. These detectors, in addition to being position-sensitive, resolve the time of the neutron capture with ~1 μs precision for neutron time-of-flight measurements. This paper will discuss these various PSDs with emphasis on the instrumental specifications and the reasons for the selection of the different types of PSDs, and will also discuss the observed performances of these PSDs.

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Introduction

The Intense Pulsed Neutron Source (IPNS) [1] at Argonne National Laboratory began operation as a National User Facility for neutron scattering in 1981, following a decade of pioneering development of pulsed spallation neutron sources at Argonne. In such a source the pulses of protons accelerated in a synchrotron produce pulses of neutrons via the spallation process (effectively a nuclear "evaporation") in a heavy-element target. These neutrons are then moderated to yield spectra peaked at thermal or subthermal energies, and directed into beams which serve a variety of neutron scattering instruments. At IPNS there are three separate moderators, each of which is designed to produce neutron pulses with somewhat different spectral and time dependences, and each of these moderators serves several neutron beams. Figure 1 shows a layout of the accelerator, the target system, and the beamlines and instruments currently installed or under development at IPNS.

The goal in a neutron scattering experiment is to determine the differential scattering cross-section of the sample, since this cross-section is directly related to the crystalline (or magnetic) structure and dynamics of the sample. The measurement is performed by detecting how many neutrons of each energy are scattered by the sample at each angle. Since neutrons are non-ionizing particles, detection requires that the neutron first be captured by a nucleus, and that this nucleus then promptly decays with one or more ionizing products which can be detected by the usual proportional counter or scintillation methods. Since the luminosity of neutron sources is rather poor and neutrons interact only weakly with most samples, adequate counting statistics can be achieved only by using relatively large samples, ranging from a few mm^3 to a few cm^3 in volume. This in turn requires that the detectors be located at some distance from the sample (of the order of 1 m) in order to provide adequate resolution of the scattering angles. In order or measure the cross-section at many scattering angles with satisfactory counting statistics, the detector or array of detectors must usually cover a significant fraction of the available 4π solid angle, and because of the large distances from the sample this means that rather large detectors or arrays of detectors are often required.

Neutron scattering results are usually expressed as functions of the wave-vector Q and energy E transferred in the scattering process. In order to determine these quantities, the energies (or wavelengths) of the incident and scattered neutrons must be determined. (In neutron "reflection" or "diffraction" measurements it is assumed that there is no change in neutron energy in the scattering process, in which case only one determination of the neutron energy is required.) Since typical velocities of thermal neutrons are of the order of 10^3 m/sec, these can be readily determined by measuring the time-of-flight (TOF) of the neutron from the source to sample and/or from the sample to the detector. The neutron kinetic energy and de Broglie wavelength are both directly related to the neutron velocity, so these velocity measurements along with the measurement of the scattering angle are sufficient to determine both Q and E for each detected scattered neutron. The necessary kinematic equations are:

$$Q = k_{inc} - k_{scat} \quad (1)$$

$$|k| = k = 2\pi/\lambda = 2\pi mv/h \quad (2)$$

$$E = m(v_{inc}^2 - v_{scat}^2)/2 \quad (3)$$

where h is Planck's constant, m is the neutron mass, λ is the wavelength of the neutron, v is the magnitude of the neutron velocity, the vector **k** is directed along the line of travel of the neutron, and "inc" and "scat" refer to the neutrons before and after the scattering process, respectively.

Currently IPNS has ten fully-scheduled neutron scattering instruments in operation, each optimized for a different type of science, with three more instruments under development. Six of these instruments use position-sensitive neutron detectors (PSDs). This paper will briefly discuss the properties of the neutron source and scattering instruments which are relevant to the choices of detectors, and will then turn to the various PSDs used. The discussion will focus on the reasons for the selection of the different types of PSDs and the observed PSD performance characteristics.

Neutron Detection at Pulsed Neutron Sources

Pulsed neutron sources introduce several new types of problems for neutron detection systems, beyond those problems encountered in detection systems designed for steady-state instruments. Each short (<1 μs) pulse of protons from the accelerator produces a short pulse of high-energy neutrons in the target. Some of these neutrons travel to one of the moderators, are slowed down, and emerge in a neutron pulse with an energy-dependent time profile. The widths of the moderated neutron pulses typically vary with neutron energy from a few μs to a few hundred μs, and all these neutrons leave the moderator within a short time (again typically a few μs to a few hundred μs, depending on the neutron energy) after the proton pulse. Because the different energies or wavelengths correspond to different neutron velocities, the neutrons which were produced essentially simultaneously in the pulse from the target/moderator system arrive at the sample at different times, with the TOF spectrum reflecting the wavelength spectrum. Figure 2 shows a typical TOF spectrum measured at the beam monitor position at one of the IPNS instruments. Since the IPNS accelerator operates at 30 Hz, this neutron-arrival-time spectrum repeats every 33 ms. As seen in the figure, the instantaneous intensities within the first few hundred μs after the proton pulse can be orders of magnitude larger than the time-averaged intensities, so detection systems at pulsed sources must pay particular attention to overload, pulse-pileup, and dead-time problems. These detection systems must also have very low intrinsic background counting rates if meaningful results are to be obtained in the long wavelength, low intensity, portion of the spectrum. Another important feature of the pulsed source is the strong component of epithermal and fast neutrons in the incident beam, as indicated by the high intensity at short times (below ~2000 μs in Fig. 2). Depending on the particular instrument requirements, detectors may need to have appreciable efficiency for detection of neutrons in the epithermal range (neutron energies up to ~10 eV or wavelengths down to ~0.1 Å). On the other hand, good rejection of fast neutrons is desirable in all cases, since a significant portion of the background will be due to fast neutrons. Detectors must also have good rejection of gamma rays, similar to the situation at steady-state neutron sources.

IPNS Instruments Using PSDs

Since all IPNS instruments operate using the TOF principle, they all depend on neutron detectors which span significant fractions of the available useful range of scattering angles with moderate to good angular resolution. They must all have their resulting raw data binned into histograms with both time (neutron TOF) and spatial (angular) dimensions. (The data acquisition systems for the IPNS instruments have been described elsewhere.[2]) Thus the heart of each instrument is its detectors (usually a large number) and the corresponding electronics and software used to detect, encode (according to position and flight time), and histogram the neutron events from these detectors. IPNS instruments now utilize nearly 800 one-dimensional (TOF only) neutron detectors (^{3}He proportional counters or BF_3 pulsed ion chambers) of various sizes, and various PSDs summarized in Table I and discussed separately below.

Anger Camera

An area PSD (neutron Anger camera with ^{6}Li-glass scintillator) developed and built at Argonne is the primary detector for the Single Crystal Diffractometer (SCD) [3], which uses the time-of-flight Laue technique to obtain diffraction data from single crystals. Figure 3 shows this instrument schematically. The SCD is routinely used for structure determinations with single-crystal samples, as well as for a variety of problems relying on its ability to investigate quickly large regions of Q-space. The area detector and the range of wavelengths from the pulsed source provide a three-dimensional sampling of Q-space with a single orientation of the sample, and this is extremely useful in studies of diffuse scattering, in texture determination, in characterizing nuclear and magnetic phase transitions, and in the measurement of incommensurate satellite reflections.

Figure 3 also provides a schematic representation of the Anger camera detector, which has been described in detail elsewhere.[4] This detector has an active area of 30 x 30 cm, with a resolution of ~3.5 mm fwhm and a dead-time of ~3 μs per event. Use of the ^{6}Li-glass scintillator as the active neutron detection medium permits high detection efficiency with a thin detection volume. (The 2 mm thick glass on this detector provides a detection efficiency of ~66% for 0.5 Å neutrons.) Since the detector is operated only ~30 cm from the scattering sample, parallax would result in a serious degradation of the resolution if the detection volume were thicker. This high efficiency at short wavelengths, negligible parallax, and the short dead-time and good spatial resolution were the primary reasons a detector of this type detector was developed for this instrument. The electronics encode the active area as 128 x 128 pixels, and also provide sufficient additional information so that accurate dead-time corrections can be made on the data as a function of TOF. Although the scintillator is relatively sensitive to gamma rays, pulse-height discrimination along with careful attention to shielding materials has reduced both gamma and fast neutron backgrounds to quite acceptable levels.

Area Proportional Counters

The Small Angle Diffractometer (SAD)[5] and a second small angle diffractometer (SAD-II)[6] currently being developed both utilize rise-time-encoded ^{3}He proportional counter area PSDs at small scattering angles to make measurements to very small values of Q. This enables them to investigate relatively large structures (up to ~500 Å) in metallurgical, polymer, chemical, and biological systems. Figure 4 shows these instruments schematically. An important capability of these instruments is their large dynamic Q-range, which results from the use of the TOF method and permits collection of data from 0.005 $Å^{-1}$ to 0.35 $Å^{-1}$ in a single experiment with a single instrument setting. Over some parts of this range the scattering signal can be quite weak, so proportional counters were chosen because of their low intrinsic background counting rate and their relative insensitivity to gamma rays and high-energy neutrons.

The area PSD used on SAD was built as a joint effort by Argonne and Oak Ridge personnel, and has been in continuous operation for more than 10 years.[5] It has an active volume 20 cm x 20 cm x 3.2 cm, and is currently filled with a mixture of 65% ^{3}He and 35% CF_4 to a total pressure of 2 atm. This detector is of the Borkowski-Kopp [7] type, with an anode plane in the center, sandwiched between front and rear single-wire cathode planes which produce the x and y signals (Fig. 4). The cathode wires are strung in a zig-zag pattern with 2 mm spacing, with the wire directions in the front plane being orthogonal to those in the rear. The intrinsic RC time-constant for each cathode is ~0.8 μs. Rise-time encoding [7] utilizing a direct-time-digitizer [8] produces digital x and y positions encoded with 8 bits each. Pulse height discrimination has been found to be adequate to eliminate most events due to gammas or to fast neutrons. The position resolution of this detector is nominally ~3 mm, but so far the lowest measured value is ~5 mm fwhm. This value results when short amplifier time constants (~0.5 μs) are used, with measured resolution increasing to ~9 mm fwhm with longer time constants (~10 μs). With the shorter time-constants, there is observable nonlinearity of the position encoding over the entire detector, which is particularly severe near the detector edges. The longer time constants produce essentially linear encoding over the central portion of the detector, but still leave large nonlinearities near the detector edges. These nonlinearities are sufficiently severe that the data from significant regions around the detector edges must be discarded (using software masks), leading to an effective area of ~17 cm x 17 cm. A detailed simulation of the detector and associated circuitry is underway to explore potential methods of eliminating the encoding nonlinearity and improving the spatial resolution.

The PSD being used on SAD-II is a commercial unit (Ordela, Inc, Oak Ridge, TN) with construction, fill gas, and encoding electronics quite similar to those of the SAD detector. The active volume is 40 cm x 40 cm x 2.5 cm. Resolution is nominally ~4 mm fwhm, but the best value so far achieved in actual neutron measurements is ~ 6 mm. Linearity problems are similar to those of the SAD detector, which seem to be inherent to the rise-time encoding method.

In order to achieve the small scattering angles, both of these area PSDs are operated with part of the active area in line with the direct beam (Fig. 4). This beam is mostly eliminated by a beamstop immediately in front of the detectors, but the beamstop is inadequate to eliminate all the high-energy neutrons which arrive at the beginning of the time frame. Thus there is an intense pulse which leads to a significant overload of the detector and electronics at the start of each time-frame. The overload problem has been temporarily alleviated by the use of a single-crystal MgO filter to remove most of the fast neutrons from the incident beam. However this results in some loss in the accessible wavelength range and data rate of the instrument, so electronic solutions are also being explored.

Microchannel-Plate

The Polarized Neutron Reflectometer (POSY) [9] utilizes polarized neutrons for obtaining magnetization density information in thin films or near the surfaces of bulk materials. The detector is a 2.5 cm dia, ~0.7 mm fwhm resolution, area PSD (microchannel-plate). The POSY instrument and detector are shown schematically in Fig. 5. Since the critical angle for reflection of neutrons is small, very good spatial resolution at the detector is required to provide the necessary angular resolution, and this was the primary reason for this particular choice of detector.

This area PSD [9] is based on a commercial microchannel-plate detector with integral photocathode and resistive anode readout (Surface Science Laboratories, Inc., Mountain View, CA). Its sensitive area is circular with a diameter of approximately 25 mm. This detector is supplied with charge-division position encoding electronics to provide a digitized x,y output (8-bits for x and 8-bits for y) from the resistive anode signal. Sensitivity to neutrons is obtained by the inclusion of a ^{6}Li-glass scintillator (0.5 mm thick) optically coupled to the photocathode of the microchannel-plate assembly (see Fig. 5). This scintillator has appreciable gamma-ray sensitivity and therefore the detector was shielded from stray neutrons by lithium carbonate enriched with ^{6}Li, which produces no gammas upon absorption of neutrons. This, combined with the use of pulse-height discrimination, has reduced the detected gamma background to quite low levels. The operation of a similar neutron detector for a somewhat different purpose has been described by Schrack [10].

Linear Proportional Counters

A second reflectometer (POSY-II)[6] constructed on the same beamline as POSY (see Fig. 5) uses unpolarized neutrons to study chemical density profiles in polymer and other thin films. POSY-II uses a commercial (Ordela, Inc., Oak Ridge, TN) rise-time encoded ^{3}He proportional counter linear PSD. This detector is planar, with an active area of 20 cm x 5 cm position-encoded along the long dimension. Use of a single carbon-coated quartz fiber as the anode provides sufficiently high anode resistance to achieve ~1.6 mm fwhm position resolution. The sample-detector distance is much longer than on POSY, so this spatial resolution yields adequate angular resolution for POSY-II, and the 20 cm active length provides a much larger range of angular coverage which is used to good advantage.

The most recent addition to the IPNS complement of instruments is the Glass, Liquids, and Amorphous Materials Diffractometer (GLAD),[11] which is optimized to obtain structural information from glasses and liquids. GLAD features high data rates with low-to-moderate Q-resolution and emphasizes low-angle detector banks to simplify inelasticity corrections to the scattering data. This instrument, shown schematically in Fig. 6, is just being commissioned, but preliminary measurements to test the new GLAD detector and data acquisition systems and some of the calibration and data analysis procedures have been made on a temporary flightpath over the past two years.

GLAD currently contains 160 commercial (Reuter-Stokes, Twinsburg, OH) linear PSDs (^{3}He proportional counters), expandable to 408. These detectors are mounted in modules with 38-53 PSDs per detector module (Fig. 6). Each PSD is a cylindrical proportional counter containing 10 atm of ^{3}He plus appropriate stopping gases (mostly Ar) and has a diameter of 1.27 cm dia and an active length of 60 cm. Each detector is encoded into 64 segments using charge-division encoding, with a position resolution of ~14 mm fwhm. (The encoding and data acquisition electronics for GLAD have been discussed in detail elsewhere.[12] These detectors and the mounting arrangements, but not the electronics, are similar to those used earlier on a steady-state instrument at the University of Missouri reactor.[13]) Both instantaneous and time-averaged data rates are expected to be relatively high (in extreme cases up to ~20,000,000 events/sec instantaneous and up to ~300,000 events/sec time-averaged, when the full detector complement is installed). Arrays of linear PSDs were chosen rather than area PSDs, because the latter typically have severe overall instantaneous data rate limitations and are difficult to fabricate with high efficiency for short-wavelength neutrons. A number of features have been incorporated into the detector mounting assemblies, preamplifiers, encoding modules, and operating software to facilitate initial tuning of the position encoding, absolute calibration of the encoded positions, and automatic testing for drifts in calibration. These have been described in detail elsewhere.[11,12]

Initially the charge-division encoding of the GLAD PSDs produced considerable (as high as 30 percent) integral nonlinearity near the PSD ends. This problem has now been fully understood and cured [14], so that the entire active length of the detectors can be routinely used.

These linear PSDs have also been satisfactorily operated in the direct neutron beam, protected only by a semi-opaque beamstop (Fig. 6). This beamstop contains several small holes, allowing some of the beam to strike the detector directly. In this mode of operation the central detector segments (those behind the small holes in the beamstop) are used to measure transmission of the neutrons through the sample while the outer segments of the same detector are measuring the scattering from the sample. Recovery from the initial intense pulse is sufficiently fast and the pileup rejection is sufficiently good that operation in this mode has produced quite reliable results for both the beam spectral measurements and the simultaneous scattering results.

Summary

Neutron PSDs have proved to be quite useful in a variety of instruments at IPNS, and several different detector types have been adapted to meet the problems peculiar to pulsed-source usage. The position encoding from all of these types of detectors has been quite stable, showing little drift with time. The Anger camera and microchannel-plate area PSDs have been working quite satisfactorily for a number of years in their respective applications. The large number of linear PSDs in the GLAD instrument also perform satisfactorily, although some improvements in the resolution, deadtime, and differential linearity are still being explored. However the one linear PSD and two area PSDs which are rise-time encoded proportional counters all have significant encoding nonlinearities near the detector edges. At best, this poses a calibration problem, but for the area PSDs it is sufficiently severe that portions of the active areas of these detectors are effectively unusable. Improvements in the linearity, spatial resolution, and overload response of these detectors are under study.

TABLE I

Parameters of PSDs at IPNS

	SCD	SAD	SAD-II	POSY	POSY-II	GLAD
Number of PSDs	1	1	1	1	1	160
PSD type	Anger	Prop.	Prop.	Micro.	Prop.	Prop.
Encoding method[a]	Anger	RT	RT	CD	RT	CD
Encoded dimensions	2	2	2	2	1	1
Encoded channels (x,y)	128x128	256x256	256x256	256x256	256	64
Histogram channels (x,y)	85x85	64x64	128x128	128x1	256	64
Active material	^{6}Li glass	^{3}He	^{3}He	^{6}Li glass	^{3}He	^{3}He
Active area (cm)	30x30	20x20	40x40	2.5 dia	5x20	1.25x60[b]
Active depth (mm)	2	32	25	0.5	25	12.5[b]
Resolution (mm fwhm)	3.5	3-9[c]	4-6[c]	0.7	1.6[c]	14
Dead-time (μs)	~3	~10	~5	~8	~10	8
Efficiency at 1.8 Å	0.98	0.55	0.61	0.63	0.61	0.77[d]
Efficiency at 0.6 Å	0.73	0.23	0.27	0.28	0.27	0.39[d]

[a] RT stands for rise-time encoding, CD for charge-division encoding.

[b] GLAD detectors are cylindrical, 1.25 cm dia x 60 cm long.

[c] Depends on choice of amplifier time-constant. There is a tradeoff with linearity.

[d] Efficiency averaged over cylinder.

Figure Captions

1. Layout of the Intense Pulsed Neutron Source facility showing the synchrotron which accelerates protons to 450 MeV, the proton transport line, the neutron target system and shielding, the neutron beamlines, and the neutron scattering instruments. The lower-energy injection linac which feeds the synchrotron is not shown.

2. Variation with time of the neutron intensity measured at the beam monitor position in one of the IPNS instruments over most of one period of the pulsed source (IPNS accelerator operates at 30 Hz). The corresponding neutron wavelengths calculated from Eq. (2) are also shown.

3. Schematic representation of the Single Crystal Diffractometer and an exploded view of its associated Anger camera area PSD. When assembled, the light disperser plate is in direct contact with the face of the photomultiplier array, and the 2 mm thick glass scintillator plate is separated from the disperser plate by a thin air gap which serves to truncate the scintillation light cone. The output of each 5.1 cm square photomultiplier is resistor-weighted according to its x and y coordinates, and the normalized sums of the weighted signals give the centroid of the scintillation light cone from the neutron absorption event.

4. Schematic representation of the Small Angle Diffractometers SAD and SAD-II. The arrangement of the electrodes in one of the proportional-counter area PSDs is also shown schematically. Wire spacing is 2 mm for the actual cathodes.

5. Layout of the two neutron reflectometers POSY and POSY-II and a schematic representation of the microchannel-plate area PSD used on POSY. The scintillator glass is 0.5 mm thick and the 0.025 mm thick mylar gasket produces an air gap between the scintillator and optical coupler to provide better definition of the scintillation light cone. The alumina powder diffusely reflects some of the scintillation light to enhance the signal.

6. Layout of the Glass, Liquids, and Amorphous Materials Diffractometer. One of the detector modules is also shown schematically on an expanded scale to indicate the relative placement of the linear PSDs, preamplifiers, and absorbing bar used for calibration.

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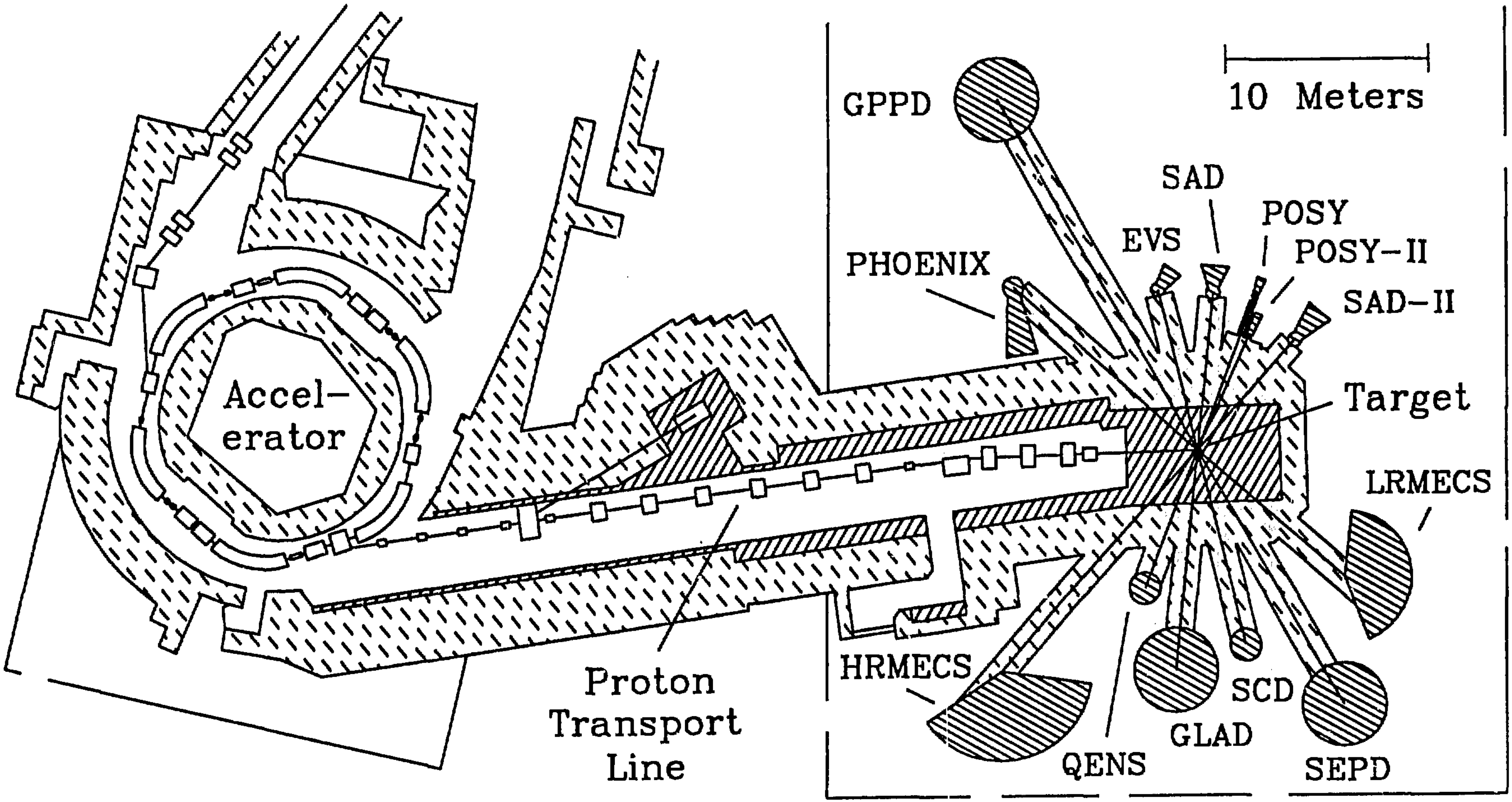

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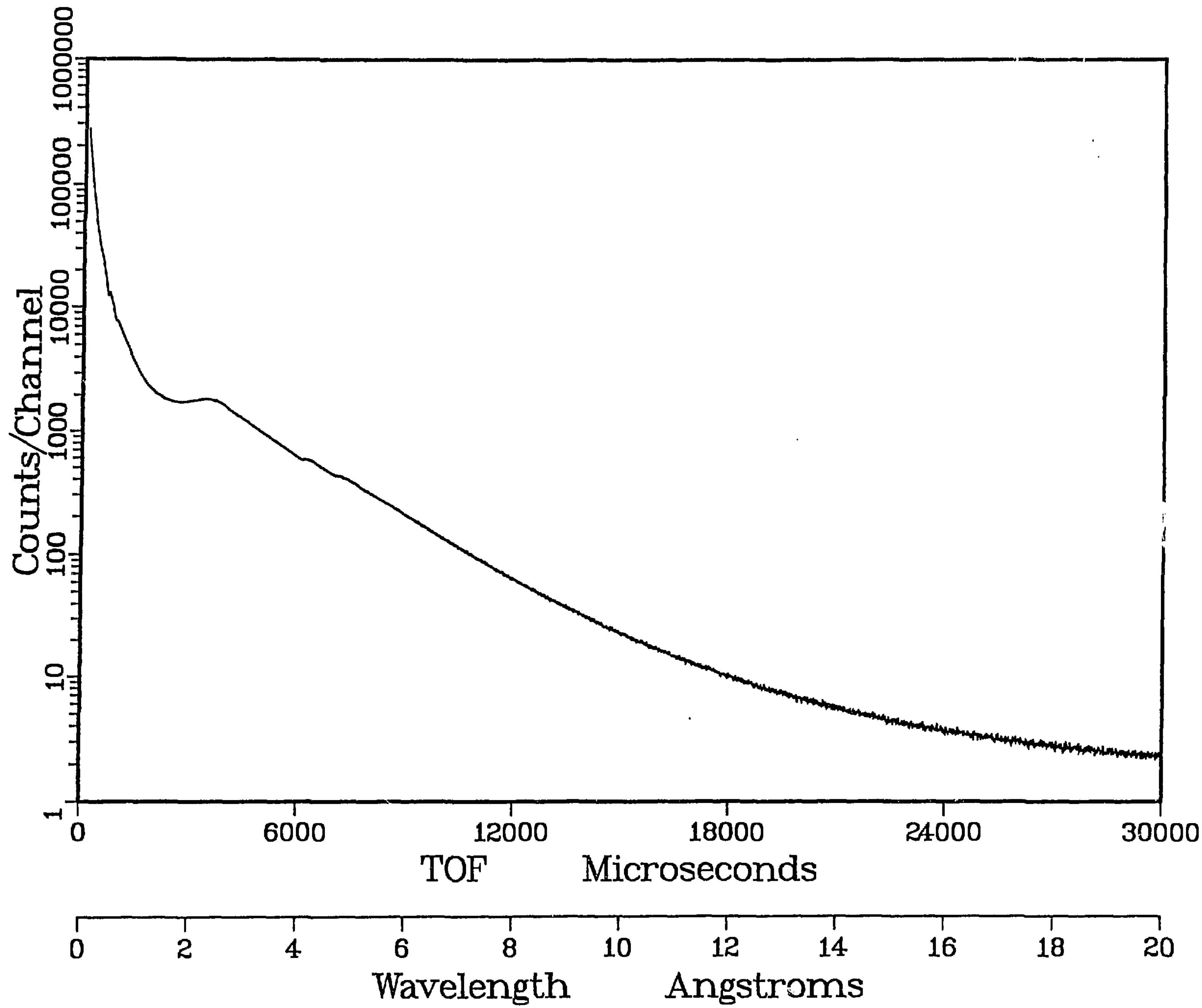

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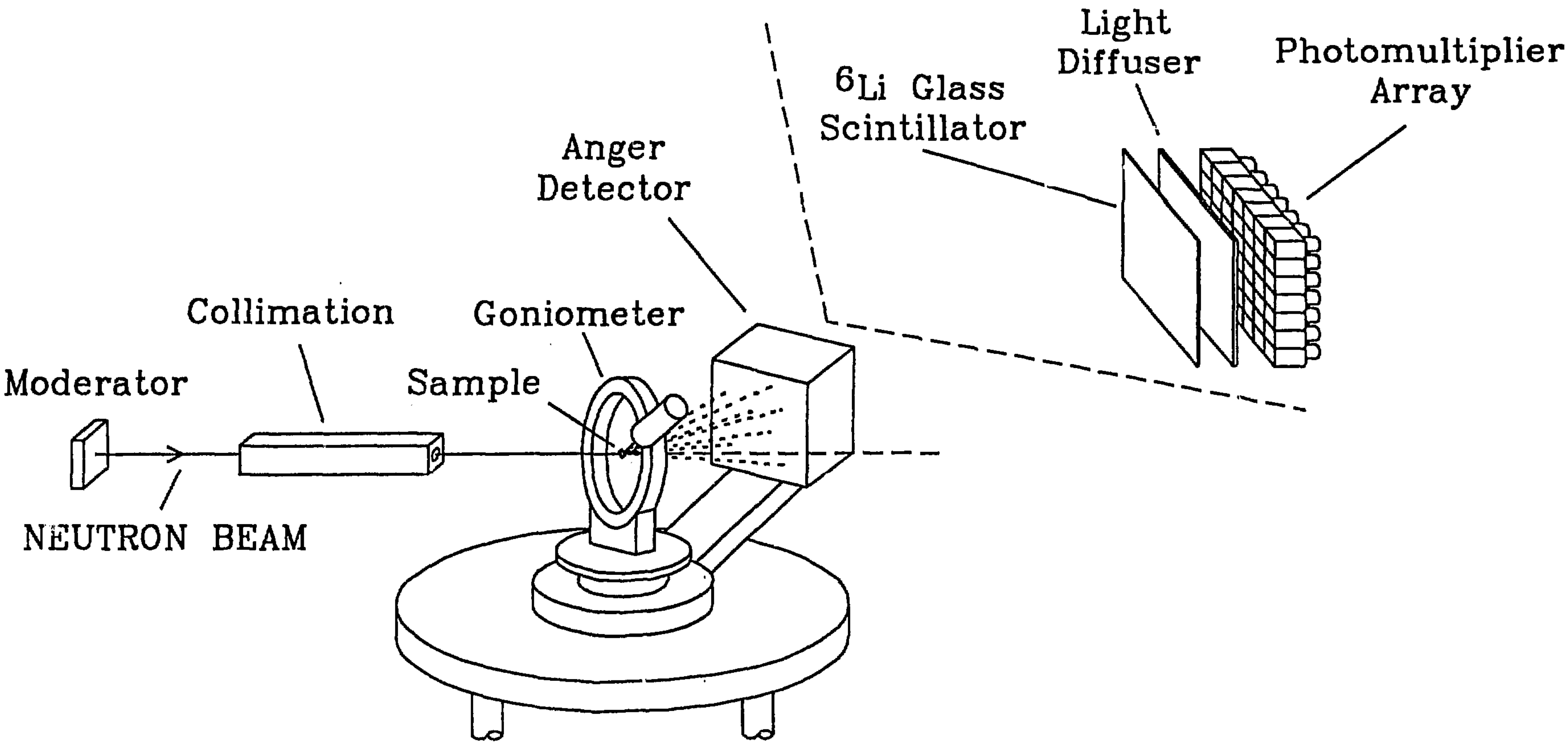
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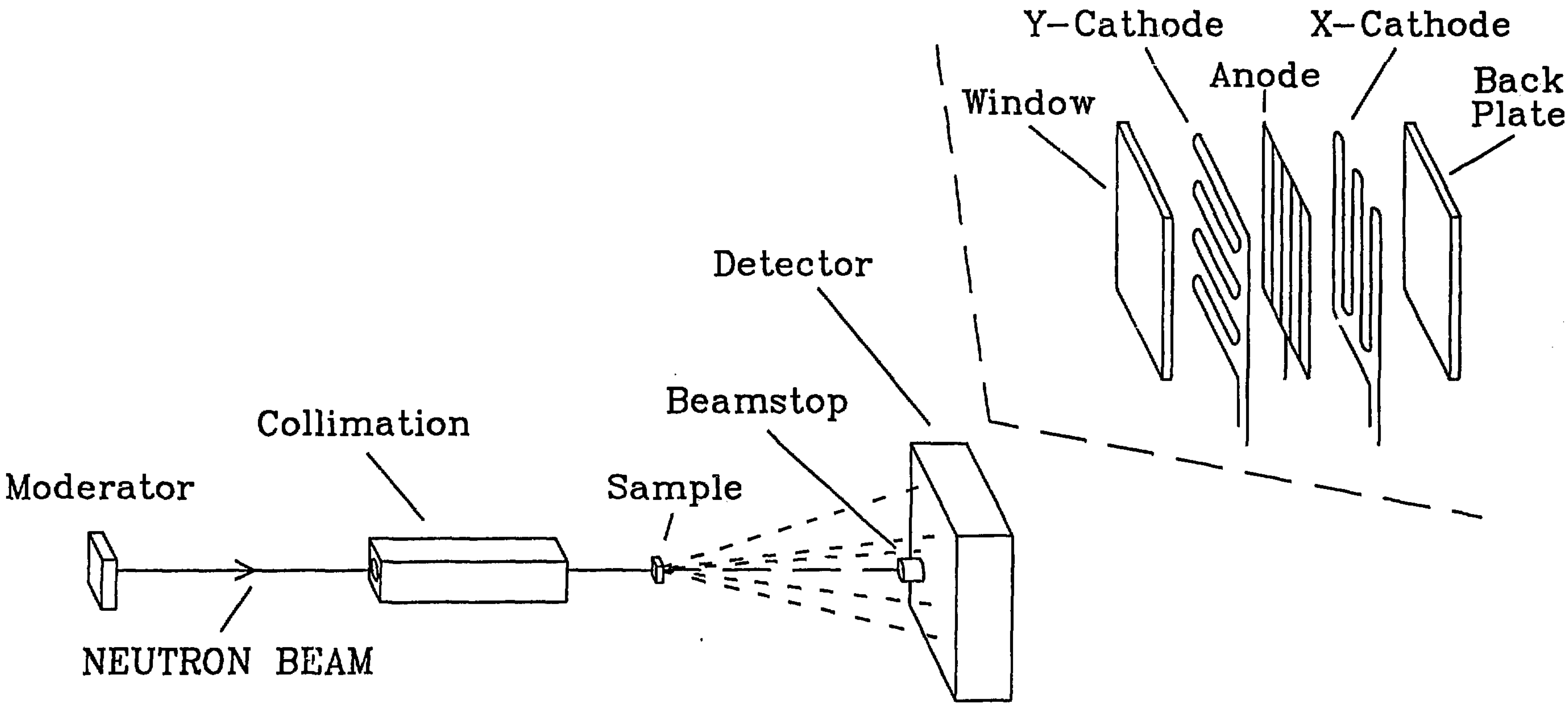
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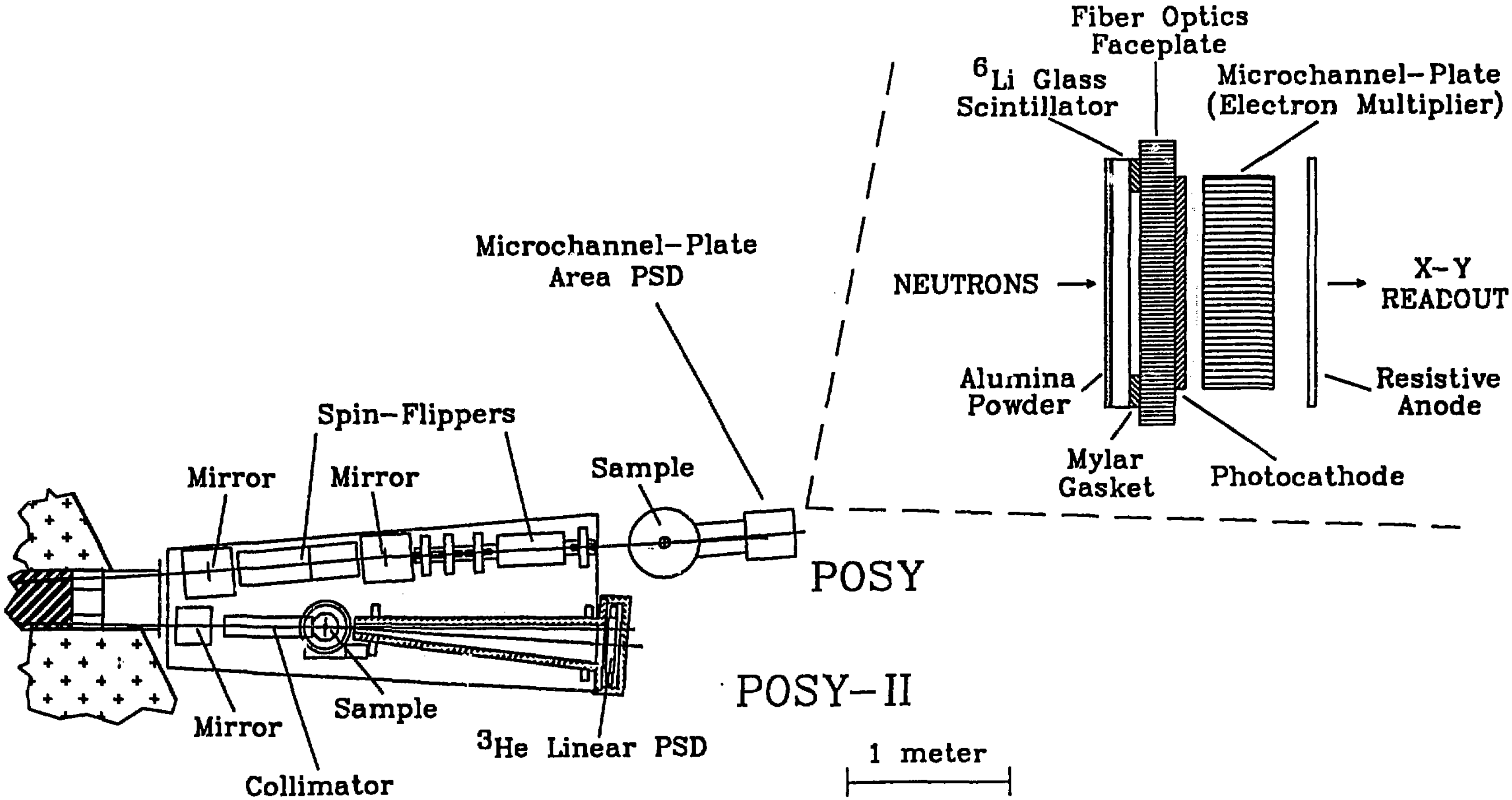
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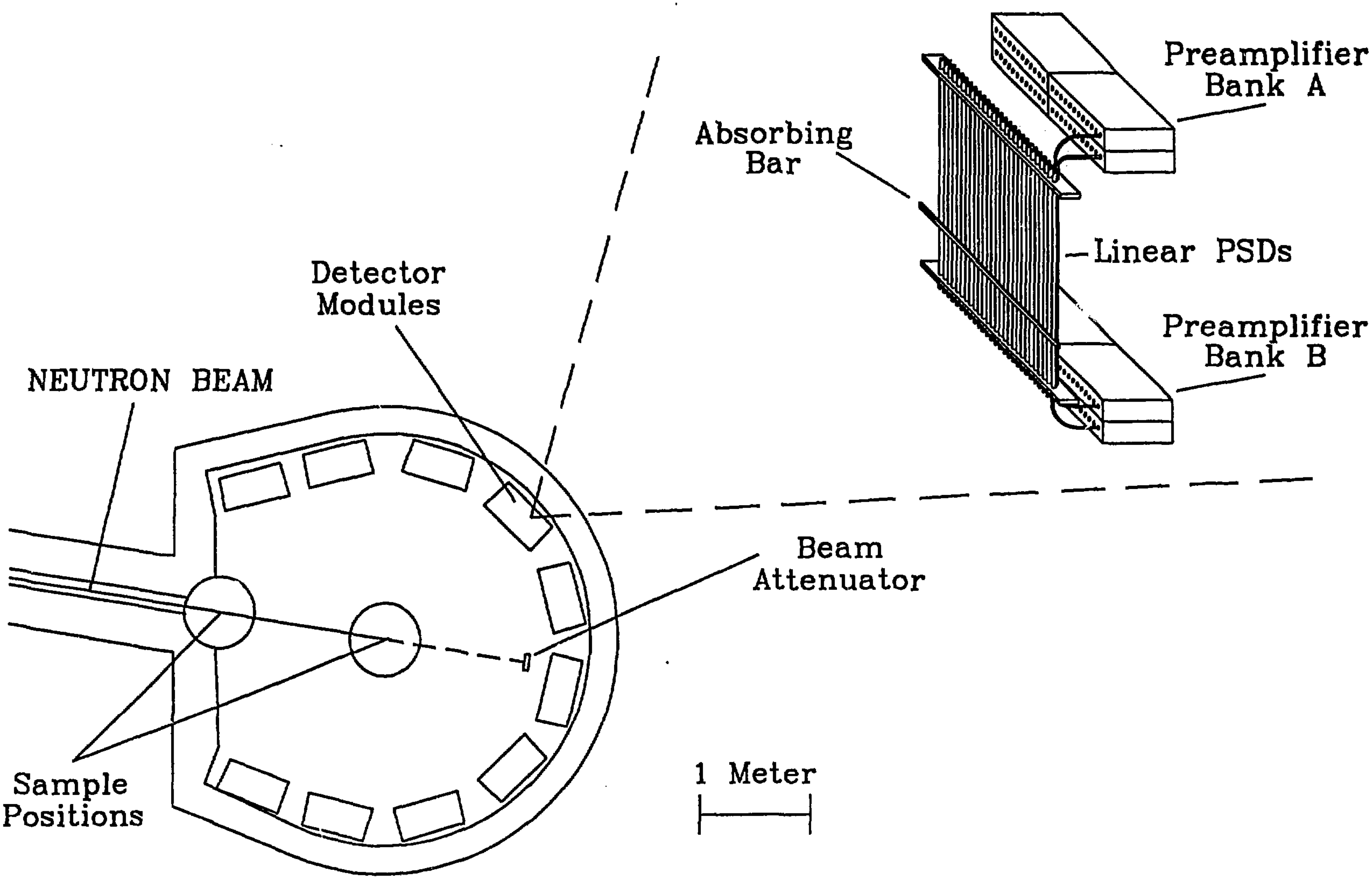
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