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Abstract

An instrument for measuring neutron spectra in the approximate energy range of 30 to 300 MeV and protons spectra from 30 to > 300 MeV has been built in our laboratory. The instrument is intended for performing measurements in weak radiation fields, such as those encountered behind the shielding of high energy accelerators.

1. Introduction

Detailed knowledge of the energy distribution of the particles in radiation fields is essential for calculating shielding as well as for assessing the risk[1,2]) in high-energy radiation health physics.

Present measurement techniques commonly used around nuclear reactors provide precise measurement of neutron spectra up to about 10 MeV[3]). Proton recoil measurements in nuclear emulsion allow quite precise measurements in fields of neutrons of up to about 20 MeV of known angular distribution. Above this energy, track loss corrections become difficult and the method is not reliable[4]). Nuclear emulsions are useful at higher energies only for giving some indication of the slope of a smooth neutron spectrum assumed to be of the form of E^{-n} [5]). Threshold activation detectors have extended this range up to about 100 MeV and over[6]). However, their low sensitivity makes their use in stray radiation fields very difficult.

Theoretical calculations show that the energy of the neutron and charged-particle fields behind the shielding of high energy accelerators extends up to the energy of the primary beam. [See bibliography in reference[1]).] Theory also suggests that the shape of these spectra behind a thick shielding has to be similar to that of cosmic rays. The few data collected for neutrons seem to confirm this assumption[1]). No attempts to measure proton or other charged-particle spectra have been noted in the literature.

Radiation fields in which protection measurements have to be performed are very seldom geometrically defined, i.e., the spatial distribution of the field is generally unknown or only broadly defined. With the exception of activation detectors, the instruments used for neutron spectral measurements have a response which depends on the spatial distribution of the neutrons. For neutrons of energies < 10 MeV behind the shielding of high energy accelerators, we assume from theoretical considerations in the transport theory that they are isotropic, although we do not know of experimental measurements confirming this assumption. At higher energy, isotropy cannot be assumed even on a theoretical basis; here, measurement or theoretical calculation of the angular distribution is required for correcting the response of the spectrometers.

The apparatus we describe in this paper has a broad range of applications. It can be used as:

a. A high-sensitivity neutron spectrometer in the energy range from about 30 to 300 MeV when the spatial distribution of the neutrons is known. Its characteristics for this mode of use are described in section 3.1.

b. A charged particle spectrometer in the energy range for protons, between about 30 to 300 MeV where it determines also the angular distribution of these particles. This use is described in section 3.2.

c. A neutron spectrometer in the energy range from about 30 to 150 MeV in a field of unknown spatial distribution where it also detects the direction of the incoming neutrons. Its efficiency is much lower than in case a. This use is described in section 3.3.

2. Description of the Apparatus

The sensitive part of the spectrometer consists of a stack of 12 multiwire spark chambers, 13 sheets of hydrogenous material, and 15 plastic scintillators (fig. 1). The multiwire spark chambers have a sensitive area of 50×50 cm^2 and are composed of two wire grids spaced 1 cm apart. The wires of the grids are spaced 1 mm apart and are supported by a metal-reinforced plastic frame. A mixture of 90% Ne and 10% He is circulated inside the chamber. The hydrogenous material, which we shall call the converter, is made of polyethylene sheets 52×60 cm^2 and either 0.635 or 2.54 cm thick. This converter has the double purpose of generating recoil protons and of slowing them down. The scintillators, 52×56 cm^2 and 0.317 cm thick are connected through light pipes to photomultipliers, and are used for triggering the spark chambers simultaneously following a logic scheme that depends on the chosen use of the apparatus (fig. 2).

The two spatial coordinates of the spark in each chamber are determined through the typical magnetostrictive readout system[7]) and recorded on a magnetic tape. A detailed description of the apparatus is reported in[8]).

3. Uses of the Spectrometer

3.1. High-Sensitivity Neutron Spectrometer

The neutrons which reach the converters or the scintillators undergo an elastic scattering reaction with the hydrogen nuclei. The spark chambers record the tracks of the scattered protons. The spectrum of the single scattered recoil protons is then used for unfolding the incident neutron spectrum. The logic for this use of the apparatus is set in the following way: a coincidence of any three or more contiguous scintillators and an anti-coincidence of the first or last or external scintillator is required for triggering the high voltage to the 12 spark chambers. In such a way we detect the protons generated inside the spectrometer which have enough energy to cross at least two units "converter plus scintillator" and complete their trajectory inside the spectrometer. When the spectrometer is used in this way, its efficiency depends on the energy and angular distribution of the incoming neutrons.

The unfolding of the neutron spectrum is done by numerically solving the first-order integral equation

$$N(E_p) = \int_{E_p}^{\infty} A\,\Phi(E_n)\,K(E_n, E_p)\,dE_n, \qquad (1)$$

where $N(E_p)$ is the proton recoil spectrum as detected inside the spectrometer, $\Phi(E_n)$ is the neutron fluence incident on a face of the spectrometer of area A, and $K(E_n, E_p)$ is the kernel matrix of the system. The unfolding is executed by three computer programs for the CDC 7600.

The first program PTAPE uses as input the coordinates of the sparks in the various chambers for each triggering event as provided by the magnetic recording unit of the spectrometer, and generates the spectrum of the single scattered recoil protons which complete their track inside the spectrometer $N(E_p)$. This is done by determining, for each event, the length and the angle of the proton recoil track on a coordinate system associated with the spectrometer. Single scatter events are accepted if the proton track follows a straight line within a given approximation checked by a least-square method, and is contained inside the spectrometer volume. From the length and direction of the track inside the spectrometer, the energy of the recoil proton is determined and the recoil proton spectrum is calculated by a smoothing routine.

The second computer program (DEER) generates the matrix kernel $K(E_n, E_p)$. This is done in a simulation process through using the Monte Carlo method. For generating the kernel, an angular distribution of the incoming neutrons has to be assumed. Neutrons impinging on the spectrometer are followed through it. An analytical expression for the differential (n, p) elastic scattering cross section in the energy range of interest was derived by a least-square fitting of the available experimental data[9]). This expression is used in the program, which also considers the possible interactions with the carbon nuclei of the converter and of the scintillator and introduces appropriate corrections.

For every neutron of energy E_n entering the spectrometer, the program calculates the probability of generating a proton of energy E_p, whose trajectory is contained inside the sensitive volume of the spectrometer.

The third computer program (LOUHI) is used for numerically solving the integral equation (1): formal solution methods are not applicable in our case because the proton spectrum $N(E_p)$ and the kernel $K(E_n, E_p)$ are known only as a set of discrete points. The unfolding method utilized in the computer program LOUHI,[10, 11]) is a generalized least-square method with nonnegative solution. It has been used extensively in our laboratory for unfolding neutron spectra for threshold activation detectors. A detailed description of these three programs is reported in[8]).

The approximate values of efficiency range from 15% at the minimum detectable energy of about 30 MeV, to 0.5% at the energy of about 300 MeV (which is the maximum detectable with the present maximum converter thickness). . The upper limit of the energy of neutrons that can be detected is set by the energy up to which the n, p scattering may be considered elastic, namely the threshold for pion production (about 295 MeV).

3.2. Use as a Charged Particle Spectrometer

By modifying the logic of the coincidence system which triggers the spark chambers, the apparatus can be used for measuring spectra of charged particles, e.g. protons in the approximate energy range 30 to 300 MeV. If one requires a coincidence between the first two or three front scintillators, together with an anticoincidence of the last scintillator, or of the scintillators that surround the sensitive region, the spark chambers will record the tracks of the charged particles which enter the spectrometer from the front and complete their trajectory inside the sensitive volume.

The computer program PTAPE has been modified so that it provides directly the energy spectrum and the angular distribution of the incoming charged particles. A correction has also been introduced that takes into account the nuclear interactions of the charged particles inside the sensitive volume.

Theoretical studies on nucleon transport through shielding[12]) indicate a relationship between the angular distribution of protons and neutrons behind the shields. Knowledge of the angular distribution of the protons can then be used for inferring the angular distribution of neutrons to be used for calculating the kernel matrix required for the unfolding of the neutron spectrum in the use shown in section 3.1.

3.3. Isotropic Neutron Spectrometers

The triggering logic can be modified so that only two successive elastic scattering events of neutrons on protons are recorded. Knowledge of the location of the two scattering points and of the energy of the two scattered protons allows a precise measurement of the energy as well as the direction of the incoming neutron.

A detailed design study of a double-scattering spark chamber neutron spectrometer quite similar to the one described here was done by H. Göllnitz et al.[13]. Using Monte Carlo techniques they investigated different triggering geometries for finding the maximum efficiency. According to their calculation, efficiencies up to 0.1% for neutrons < 100 MeV can be achieved. We have not yet made any detailed study for our particular case.

4. Conclusions

Figure 4 shows the sensitive part of the apparatus: the triggering scintillators, the spark chambers, and one of the converters are visible in the picture. Figure 5 shows the racks with the electronic coincidence circuits, the magnetostrictive readout system and the recording unit.

The spectrometer was tested by exposing it to a 600 MeV proton beam at the 184-Inch Synchrocyclotron. This allowed us (a) to time the triggering logic; (b) to measure the spatial efficiency of the spark chambers which has proved to be uniform over the sensitive area; and (c) to determine the accuracy in the determination of the particle tracks: for protons crossing the 12 chambers normal to the chamber plane, the average deviation of the recorded tracks from a straight line was 0.4 mm, and was 0.5 mm for particle crossing at an angle of 25°.

The apparatus is presently installed behind the shielding of the 184-Inch Synchrocyclotron where it records stray proton spectra under different accelerator uses. As a next step, we are planning to perform the following experiments:

1. Measure the proton spectra produced under controlled geometrical conditions: a 700 MeV p beam will be stopped on a copper target, a concrete block will be positioned beside the target and the instrument will be located behind the concrete block at different angles from the beam direction. This straightforward geometry will be simulated in a Monte Carlo program and the theoretical and experimental results will be compared.

2. Repeat the same procedure with the spectrometer logic set for its use as a neutron detector, for both the uses described in sections 3.1 and 3.3, and compare with theoretical data.

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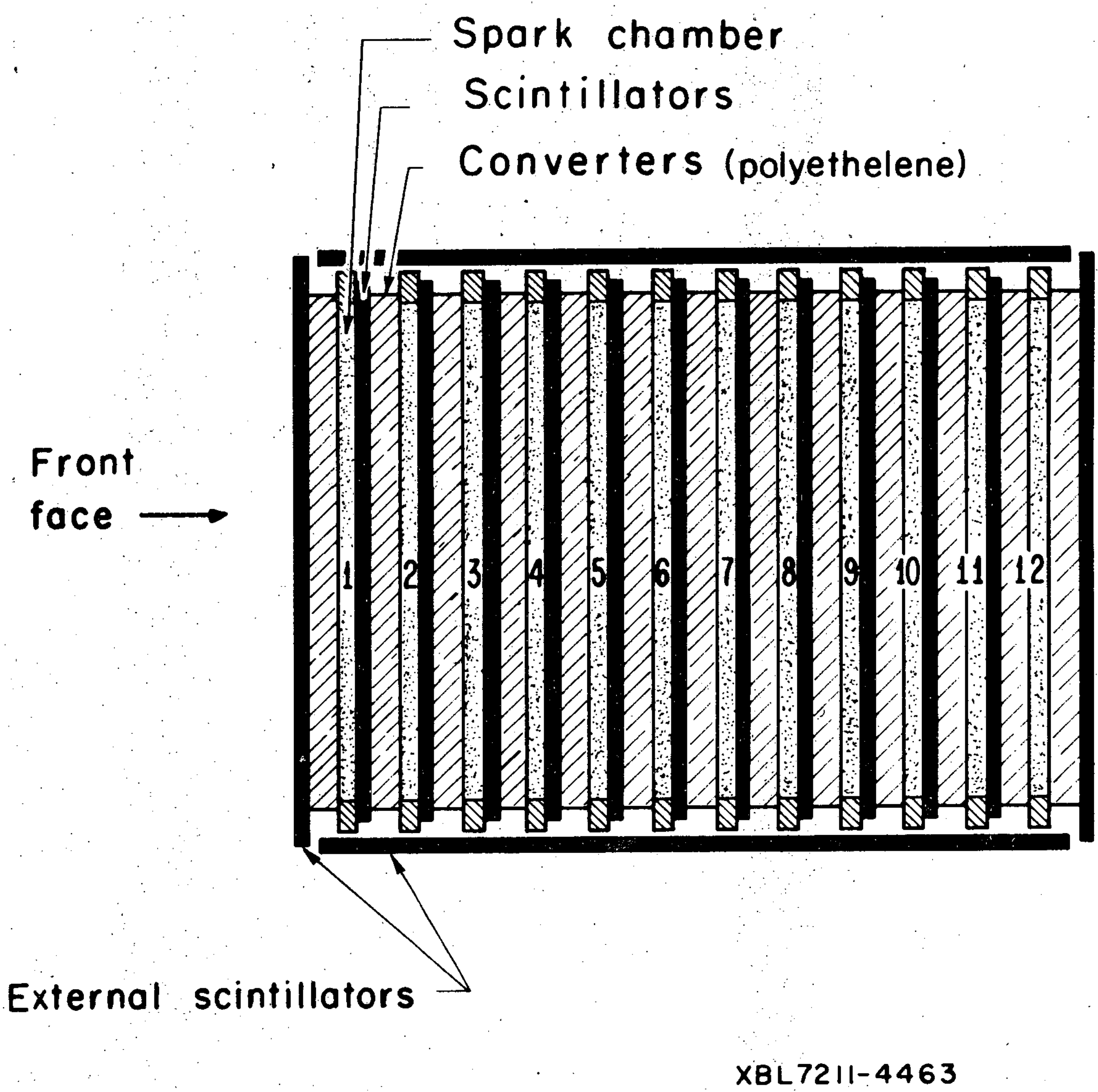

Spark chamber
Scintillators
Converters (polyethelene)
Front face
1
2
3
4
5
6
7
8
9
10
11
12
External scintillators
XBL7211-4463

Fig. 1

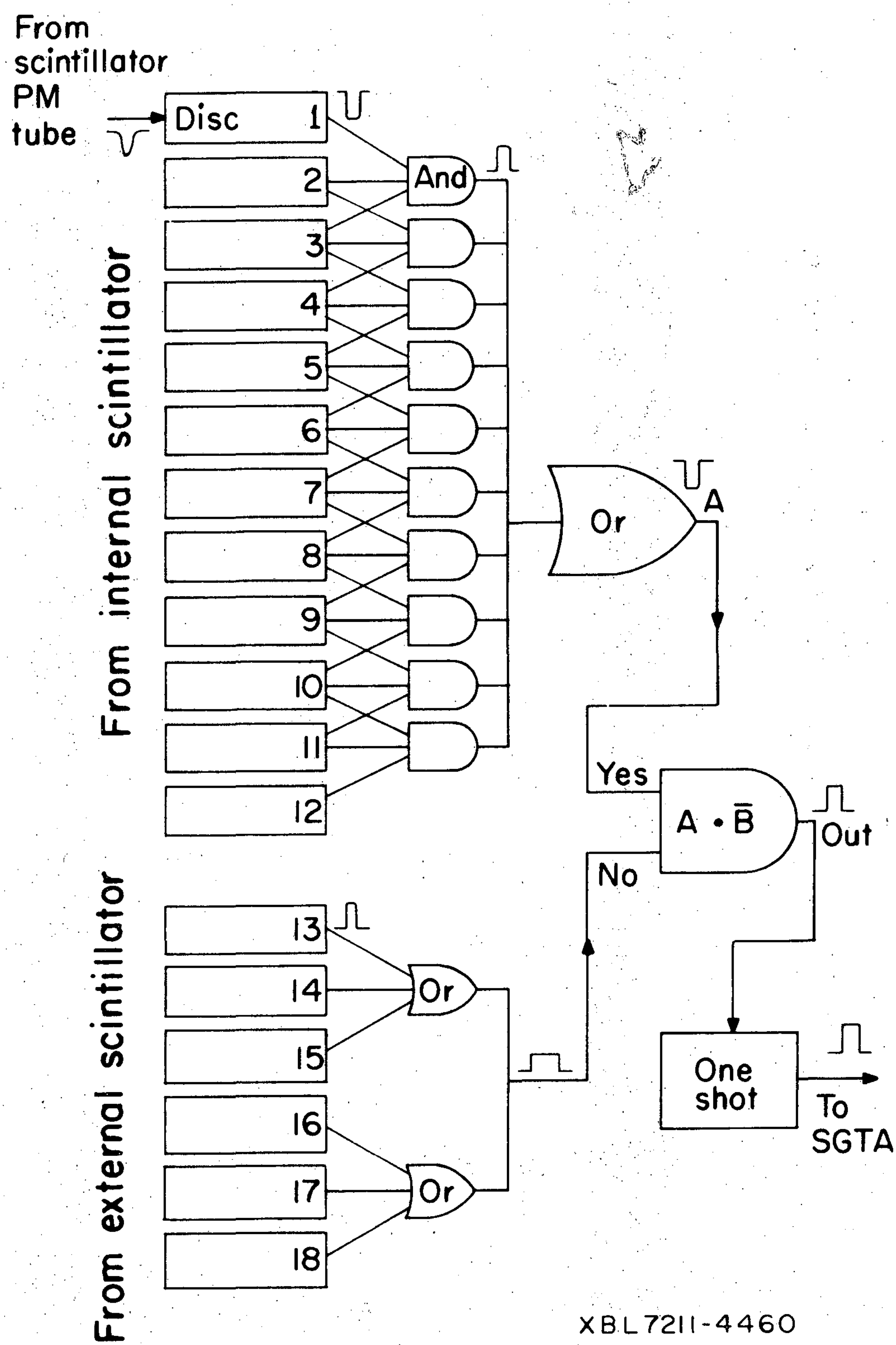
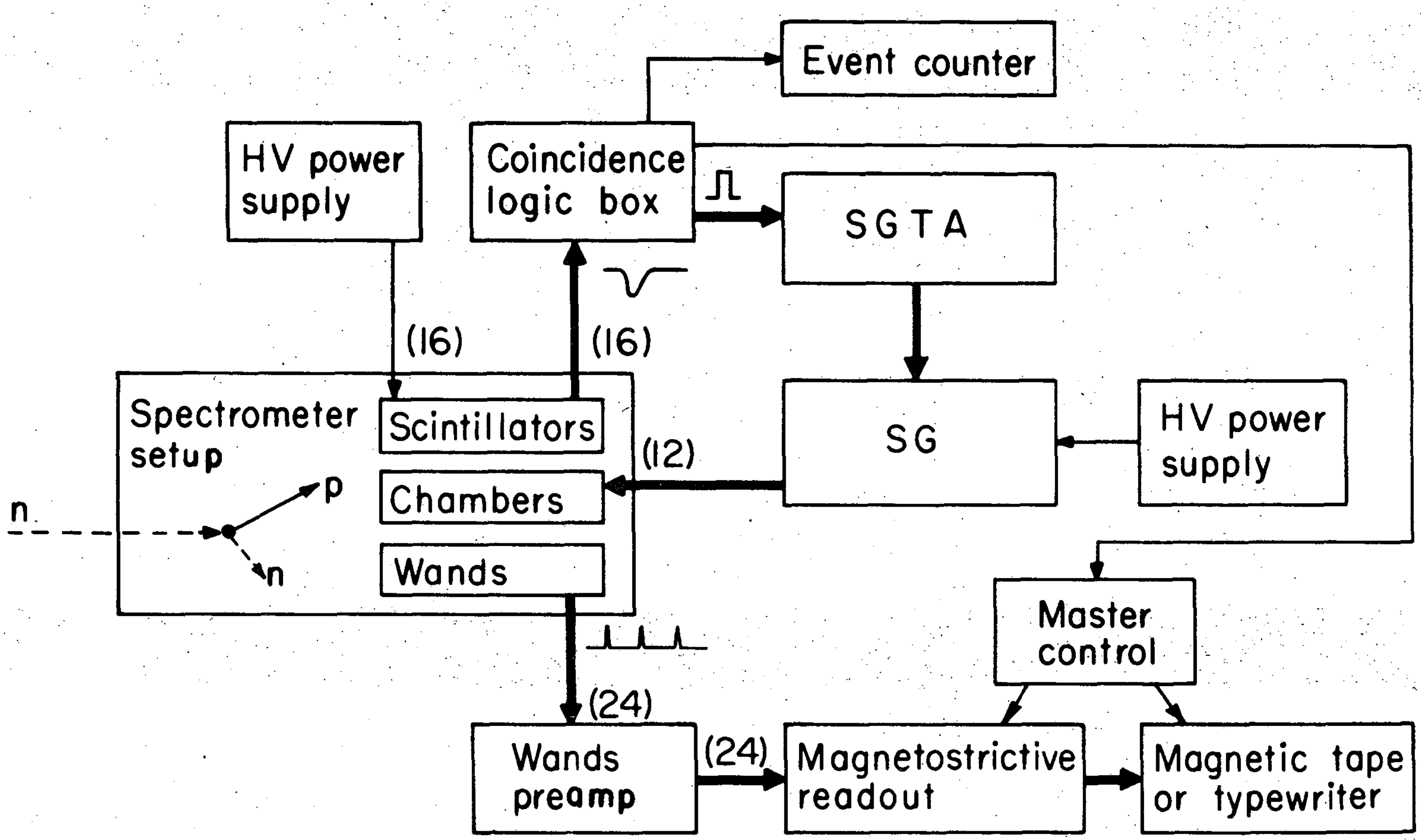

From scintillator PM tube
Disc
1
2
3
4
5
6
7
8
9
10
11
12
And
Or
A
From internal scintillator
Yes
No
A • B̄
Out
13
14
15
16
17
18
Or
Or
From external scintillator
One shot
To SGTA
XBL7211-4460

Fig. 2

*Numbers in ( ) are the number of cables



XBL7211-4461

Fig. 3

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Fig. 4

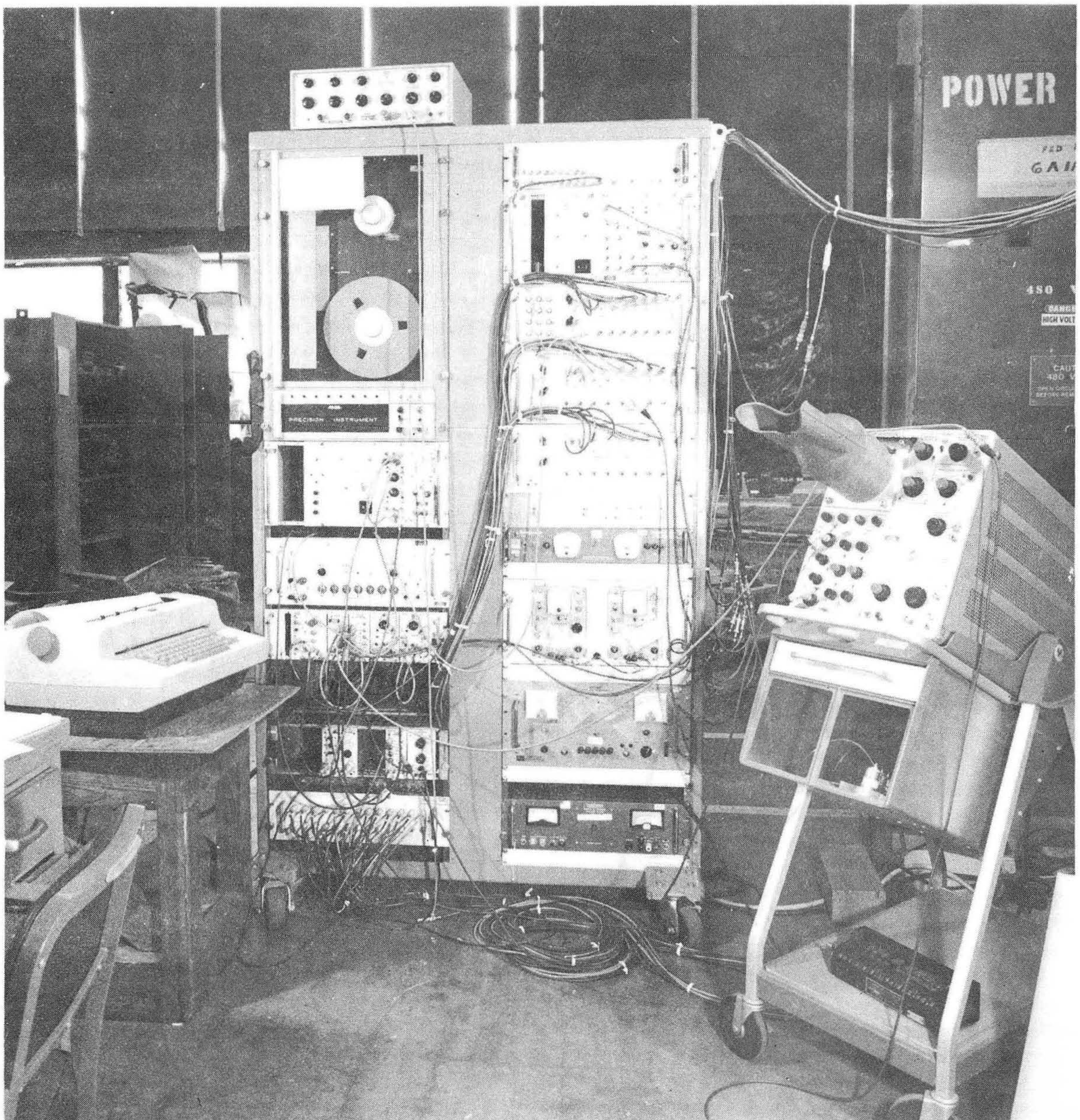

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Fig. 5

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