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Design of Neutron Diagnostic for MTX

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A neutron diagnostic system was designed for the Microwave Tokamak Experiment being carried out at the Lawrence Livermore National Laboratory. High speed measurements are important to this experiment. Plastic scintillator is used for this fast response detection of neutron. Proportional counters and fission counters are used for the total neutron emission rate measurements.

Keywords: Neutron Diagnostic, Tokamak Plasma, Microwave Tokamak Experiment, Free Electron Laser, High Speed Measurements, Plastic Scintillator, Proportional Counter, Fission Counter, Alcator C Tokamak

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MTX計画用中性子検出装置の設計

日本原子力研究所那珂研究所核融合研究部
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小田島和男・前田　彦祐

（1990年6月11日受理）

ローレンス・リバモア研究所で行われている，マイクロ波によるトカマクプラズマ加熱実験に使用するための中性子計測システムの設計を行った。この実験には高時間分解能の測定が重要であるが，そのためにプラスチック・シンチレータを使った早い時間応答の検出系と，比例計数管や核分裂計数管を用いた全中性子発生率測定系を準備している。

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1. Introduction

Tokamak plasma heating using intense microwave pulses from a Free-Electron Laser (FEL) is being carried out at the Lawrence Livermore National Laboratory (LLNL), in an experiment called the Microwave Tokamak Experiment (MTX)1). The MTX project is a collaborative program between LLNL and JAERI, and a neutron diagnostic is one of JAERI's contributions. This paper describes the design of this neutron diagnostic system.

The FEL is a pulsed system and the microwave pulse from the FEL is much shorter (<50ns) and stronger (>1GW) than that of a standard plasma heating system (e.g. neutral beam injection, ion cyclotron heating, and electron cyclotron heating using a gyrotron). Therefore high speed measurements are important to evaluate the physics on MTX. We propose a plastic scintillator system for fast response observation. A total neutron production rate monitor is also used for the ion temperature measurement.

The target plasma device is the Alcator C tokamak which was designed in 1976 and began operation in 1978 at the Massachusetts Institute of Technology (MIT). This tokamak has a high toroidal magnetic field (up to 13T) and has the ability to operate in a region of high plasma current (800kA) and high density ($10^{21}m^{-3}$) with major radius R=0.64m and minor radius a=0.165m2).

This paper is organized as follows. In section 2 we present typical data from neutron measurement and plasma parameters in Alcator C. In section 3, model calculations of a neutron intensity and flux in MTX are shown and the time scale is also described. Our neutron diagnostic system is shown in section 4, and a summary is given in section 5.

2. Alcator C Experiment at MIT

For the MTX plasma, there is considerable data on ion temperature and neutron measurements in Alcator C3), so it is useful to know those data for a design of diagnostic system on MTX. In this section the neutron measurements on Alcator C are shown and typical plasma parameters are described on ohmic heating, lower hybrid heating, ICRF heating and pellet injection experiments.

1. Introduction

Tokamak plasma heating using intense microwave pulses from a Free-Electron Laser (FEL) is being carried out at the Lawrence Livermore National Laboratory (LLNL), in an experiment called the Microwave Tokamak Experiment (MTX)$^{1)}$. The MTX project is a collaborative program between LLNL and JAERI, and a neutron diagnostic is one of JAERI's contributions. This paper describes the design of this neutron diagnostic system.

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2. Alcator C Experiment at MIT

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2.1 Neutron measurements

The BF_3 proportional counter system was used for neutron flux measurements on Alcator C. Three long counter assemblies with three BF_3 proportional counters were placed around the tokamak.

When the Alcator C was first operated, run-away electrons produced many photoneutrons with a maximum neutron rate about 10^9n/s at the end of the discharge. In subsequent operations, photoneutron production was reduced to less than 10^6n/s by fine-tuning of the gas injection system4).

Neutron spectrum measurements were made using a NE213 liquid organic scintillator5) and a ^{3}He ionization chamber6). The ion temperatures of 0.78 and 1.05keV were obtained from the spectrum with the sum of many plasma discharges7).

2.2 Plasma parameters in Alcator C

The maximum plasma parameters produced in the ohmic heating were as follows. The electron density is $n_e=2\times10^{21}m^{-3}$, the electron temperature is T_e=3keV, and the ion temperature is T_i=1.6keV at the toroidal magnetic field is B_t=13T and the plasma current I_p=800kA2).

Hydrogen and deuterium pellet injection experiments were carried out on Alcator C8). A pneumatic injector fired four independently-timed pellets with velocities close to 1 km/s. Each pellet contained 6×10^{19} particles corresponding to a volume-averaged electron densities $<n_e>=2\times10^{20}m^{-3}$ in Alcator C. The target plasma for pellet experiments had B_t= 8-12T, I_p=400-800kA, T_e=1.4-2.0keV, T_i=1.0-1.4keV, and line-averaged electron densities $\bar{n}_e=2\text{-}6\times10^{20}m^{-3}$. Highly peaked density profiles were produced and line-averaged densities up to $\bar{n}_e=1\times10^{21}m^{-3}$ were achieved with central densities near $n_e=2\times10^{21}m^{-3}$. The best pellet discharges showed T_i=1.5keV and the energy confinement time τ_E=50ms. Neutron rates in the range $1\text{-}2\times10^{13}$n/s were measured with a single deuterium pellet injected into a deuterium discharge.

Lower hybrid experiments at 4.6GHz resulted in T_i=1.85keV and T_e= 3.0keV at an input power of approximately 1.0MW, $\bar{n}_e=1.3\times10^{20}m^{-3}$ B_T=9T and I_p=400kA9).

Fast wave ion cyclotron heating experiments at 180MHz were carried out at B_t=12T, which corresponds to the proton minority regime in a deuterium background plasma. With approximately 3% minority ion concentration, injection of 400kW of RF power caused the bulk deuterium temperature to increase to T_i=1.75keV at a maximum line-averaged electron density of $\bar{n}_e=1.9\times10^{20}\text{m}^{-3}$ 10).

Ion Bernstein waves were launched at 183MHz. Typical data are T_i= 1.2keV, $\bar{n}_e=1.0\times10^{20}\text{m}^{-3}$ for P_{RF}=125kW at B_t=7.6T11).

To summarize the Alcator C experiments at MIT, the typical plasma parameters are $\bar{n}_e=1\text{-}3\times10^{20}\text{m}^{-3}$, T_i=1keV and maximum parameters are $\bar{n}_e=1\times10^{21}\text{m}^{-3}$, $T_i<2$keV.

3. Neutron Emission in MTX

3.1 Calculation of total neutron intensity and flux

The thermonuclear neutron emission rate N from a Maxwellian plasma can be written as a function of the ion temperature and the deuteron density as

$$N = 4\pi\ R \cdot \int_0^a \frac{1}{2} n_D(r)^2 \cdot \langle\sigma v\rangle r dr,$$

where $\langle\sigma v\rangle$ is the reaction rate averaged over the ion Maxwellian distribution function,

$$\langle\sigma v\rangle = \frac{\alpha_1}{T_i(r)^{2/3}} \cdot [1+\alpha_2 \cdot T_i(r)^{\beta}] \cdot \exp[-\frac{\alpha_3}{T_i(r)^{1/3}}] ,$$

$\alpha_1 = 2.72\times10^{-14}$,

$\alpha_2 = 5.39$,

$\alpha_3 = 19.8$,

$\beta = 0.917$,

a = 0.165 m (minor radius),

R = 0.64 m (major radius),

$n_D(r)$ is the deuterium density,

$T_i(r)$ is the ion temperature in keV.

Figure 1 shows the calculated neutron source strength as a function of the center ion temperature. In this calculation, the deuteron density profile and the ion temperature profile were taken to be

$$n_D(r) = n_D(1 - (\frac{r}{a})^2),$$

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This calculation shows that the range of the neutron intensity from 10^9 to 10^{13} n/s corresponds to the peak ion temperature 0.5keV to 2.0keV at $n_D=5\times10^{20}m^{-3}$.

The estimation of the neutron flux range at the detector positions is important for determination of the neutron detector sensitivity. We have calculated the neutron flux using two models. Both models neglect the radial distribution of neutron emission and only use the values on the plasma axis.

Model 1

In this model we neglect any damping by the coils, the vacuum vessel, and the other structures. The neutron flux is determined using the detection geometry shown in Fig.2. The neutron flux is given by

$$\Gamma_1 = \frac{N}{2\pi R} \cdot \frac{Rd\theta}{4\pi\ l^2} = \frac{N}{S},$$

$$S = 4\pi[Z^4+2(R^2+(R+X)^2)Z^2+((R+X)^2-R^2)]^2.$$

When the neutron detectors are set up just beside the MTX side port, the neutron flux at X=100cm, Z=0, R=64cm becomes

$$\Gamma_1 = 3.5\times10^{-6}\cdot N \quad [n/cm^2].$$

Model 2

In this model fast neutrons are completely damped by the Bitter magnet plates and collimated by the side port keyhole as shown in Fig.3. The neutron flux is given by

$$\Gamma_2 = N \cdot \frac{D}{2\pi R} \cdot \frac{1}{4\pi X^2}.$$

Since the width of the MTX side port is D=4cm, the neutron flux at X=100cm, R=64cm becomes

$$\Gamma_2 = 7.9\times10^{-8}\cdot N \quad [n/cm^2].$$

We expect the neutron flux to be less than Γ_1 and more than Γ_2. Therefore the order of the attenuation rate is assumed 10^{-7} and the neutron flux is

$$\Gamma = 10^{-7}\cdot N.$$

The neutron flux range from this calculation is also shown in Fig.1.

3.2 Time scale in MTX

The FEL produces a pulse train at pulses less than 50ns long with an interpulse spacing of 200μs. The pulse length is less than the thermal electron transit time (~300ns) in MTX, so the microwave energy couples only electrons which stream past the microwave port during the FEL pulse. Since the electron-ion collision time (~10μs) is less than the interpulse spacing, ions can get energy from the electrons and the neutron emission rate will change in the period between FEL pulses. Therefore it is desirable to have the time resolution of 10μs or less to study the intense microwave absorption process between FEL pulses.

We are also interested in the time evolution during the FEL pulse (<50ns). It requires nanosecond time resolution. In inertial confinement fusion (ICF) experiment, a typical neutron measurement has nanosecond resolution[12]. Unfortunately, conventional ICF detectors are inappropriate for the measurement we need to make, because the target plasma size, the neutron flux intensity, and the time scales involved are very different between tokamak experiments and ICF experiments.

4. Neutron Diagnostic System for MTX

4.1 Neutron measurements and detectors

Several kinds of neutron diagnostic have been carried out in tokamak experiments and different types of neutron detectors are used for each measurement.

A total neutron production rate measurement is a standard diagnostic for deuterium plasma discharge experiment in both medium and large tokamak. In this measurement, proportional counters are generally used combined with a neutron moderator, because the proportional counters have high sensitivity to thermal neutrons and are able to have varying sensitivity. The proportional counters, however, have long time constant and are usually saturated at less than 10^6counts/s, so the time response is limited to about 1ms by the counting statics. Fission counters are used instead of proportional counters in large tokamak[13], because they have shorter time constant, lower neutron sensitivity and better x-ray discrimination than proportional counters. The time response in this measurement is limited to about 0.2ms by the transit time of a thermal

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A radial profile measurement with a neutron collimator becomes routine operation in large tokamak14). This measurement gives important informations on ion temperature profiles and ion behaviors. A high space resolution needs a strong source intensity, and a large and massive neutron collimator needs to shield against fast neutrons, so this measurement is not popular in small tokamak. A liquid organic scintillator or a ZnS(Ag) scintillator15) with a plastic proton recoil radiator is used to detect neutrons by the requirements of high count rate, good x-ray rejection, rejection of low-energy scattered neutrons.

A neutron spectrum measurement has been carried out in some tokamaks16). An ion temperature can be obtained from a Doppler broadening of a neutron energy spectrum. This measurement also needs a collimator and a high neutron emission, because any scattered neutron must be rejected. The detector is usually a ^{3}He ionization chamber or a liquid organic scintillator for 2.5MeV neutron. The ^{3}He ionization chamber has high energy resolution (1.5%) and low efficiency (10 ^{3}counts/n·cm^{-2}), so it is standard detector in large tokamak neutron spectrometry.

A neutron fluctuation measurement using a plastic scintillator17) has been used to study a sawtooth instability, a fishbone instability, and pellet injection experiments. A plastic scintillator has a fast time response of less than 100ns. X-ray discrimination is a matter of concern in a neutron fluctuation measurement, because a plastic scintillator also sensitives to x-rays.

A high speed measurement is the most important measurement to study the intense FEL microwave absorption process in MTX. Several diagnostics are prepared to observe the electron response but the neutron diagnostic is the only diagnostic to observe the ion behavior. A conventional neutron source intensity measurement technique can not use to obtain the ion response measurement to the FEL pulse because the response time of detection is not enough fast. A plastic scintillator has fast response and has a weak point of x-ray rejection. Therefore we have designed a neutron diagnostic system for MTX combining two different type measurement systems.

4.2 Neutron production rate measurement

Neutron production rate measurement systems must have a wide dynamic range for neutron flux detection. Our diagnostic measures the flux of neutrons without any energy discrimination using a polyethylene moderator. The assembly is capable of detecting neutron flux over a range of five order of magnitude in pulse count mode. Mean square voltage mode is planned to measure more orders of neutron flux. The standard sampling time is 10ms.

Five neutron detectors are used inside each moderator in order to cover the entire range of neutron source strength. The detectors are listed in Table 1 starting with the most sensitive, and the counting ability of the detectors is shown in Fig.4.

The design of the moderator is illustrated in Fig.5. The 1mm layer of cadmium strongly absorbs slow neutrons. Higher energy neutrons surviving the cadmium layer pass into 10cm of polyethylene on the way to the detectors. In this layer fast neutrons are converted into thermal neutrons. The 5cm of lead reduces any hard x-ray noise effect on the neutron signal. At the center of each moderator are five detectors of varying sensitivity. Figures 6 and 7 show the location of neutron detector around the MTX device.

There are two fixed limiter in the MTX vacuum vessel located at port B and port E. The two detector assemblies are in front of port B and Port F. Since one detector assembly (port B) has a limiter and one detector assembly (port F) does not, the photoneutron rate can be estimated from the difference between the counting rate of these two detector assemblies.

A typical circuit for one detector assembly is illustrated in Fig.8. The electronics selected by the requirement of high speed and high count rates capability. TC170/171 preamplifier is a fast-rise time charge-sensitive preamplifier. It has separate energy and timing outputs. The timing output is differentiated with a 100ns time constant. ORTEC 579 is a fast filter amplifier with 5ns rise time and 250 × gain. The 4608C is an eight channel high speed discriminator which has 150MHz count rate capability and has three negative outputs per channels. The T8590 scaler has also eight channel inputs. Double scalers are used for different sampling rate measurements.

4.3 High temporal resolution neutron measurement

This system has a high temporal resolution so as to observe the ion response to a microwave pulse from the FEL. A plastic scintillator

(NEA102A) with a nanosecond response is used for neutron detection. Since the scintillator is also sensitive to x-rays, it needs to be shielded from or somehow otherwise against x-rays. The scintillator will be located inside the MTX top port close to plasma (Fig.9). The size of the ports on MTX is limited by the Bitter magnet plates (Toroidal Field coil) and is much smaller than that of standard tokamaks. We have designed three types of detectors. The smallest one is placed inside the keyhole which is the port inside the TF coil. It is nearest to the plasma and has the fastest response. The largest detector is 5cm in diameter and is placed outside of the keyhole. The lead shielded detector which is 1cm in diameter, is also placed outside of the keyhole. Photons generated by incident fast neutrons in the scintillator are transmitted to a photomultiplier through a light guide and fiber-optic bundle. The magnetic shielded photomultiplier shown in Fig.10 is set in a region where the stray magnetic field is weak enough. The electrical circuit is shown in Fig.11. The pulse and DC amplifier shown in Fig.12 can make use of current-mode operation, in addition to the pulse count mode operation. The pulse output is used for the pulse counting by CAMAC scalers in a low flux regime. The DC output signal transfers to a CAMAC digitizer using in a high flux regime.

5. Summary

We have described a neutron diagnostic system that combines plastic scintillators for fast response (about microsecond) together with standard proportional and fission counters for total emission measurements. These systems have been constructed and shipped for use in the Microwave Tokamak Experiment at the Lawrence Livermore National Laboratory.

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Table 1 Neutron detectors for neutron production rate measurement

Detector No.	Model No.	Neutron sensitive material	Fill pressure or Total quantity	Active length (cm)	Diameter (cm)	Thermal neutron sensitivity (cps/nV)
1	RS-P4-1609-201	^{3}He	5 atm	22.9	5.1	80.9
2	RS-P4-0809-203	^{3}He	2 atm	22.9	2.5	19.6
3	RS-P1-0809-205	BF_3	40 cmHg	21.1	2.5	4.1
4	RS-P6-1608-110	^{235}U	1.7 g	18.1	5.1	0.74
5	RS-P6-1608-125	^{235}U	1.7 g	18.1	5.1	0.23
6	RS-C3-2510-114	^{235}U	1.3 g	23.5	7.9	0.64

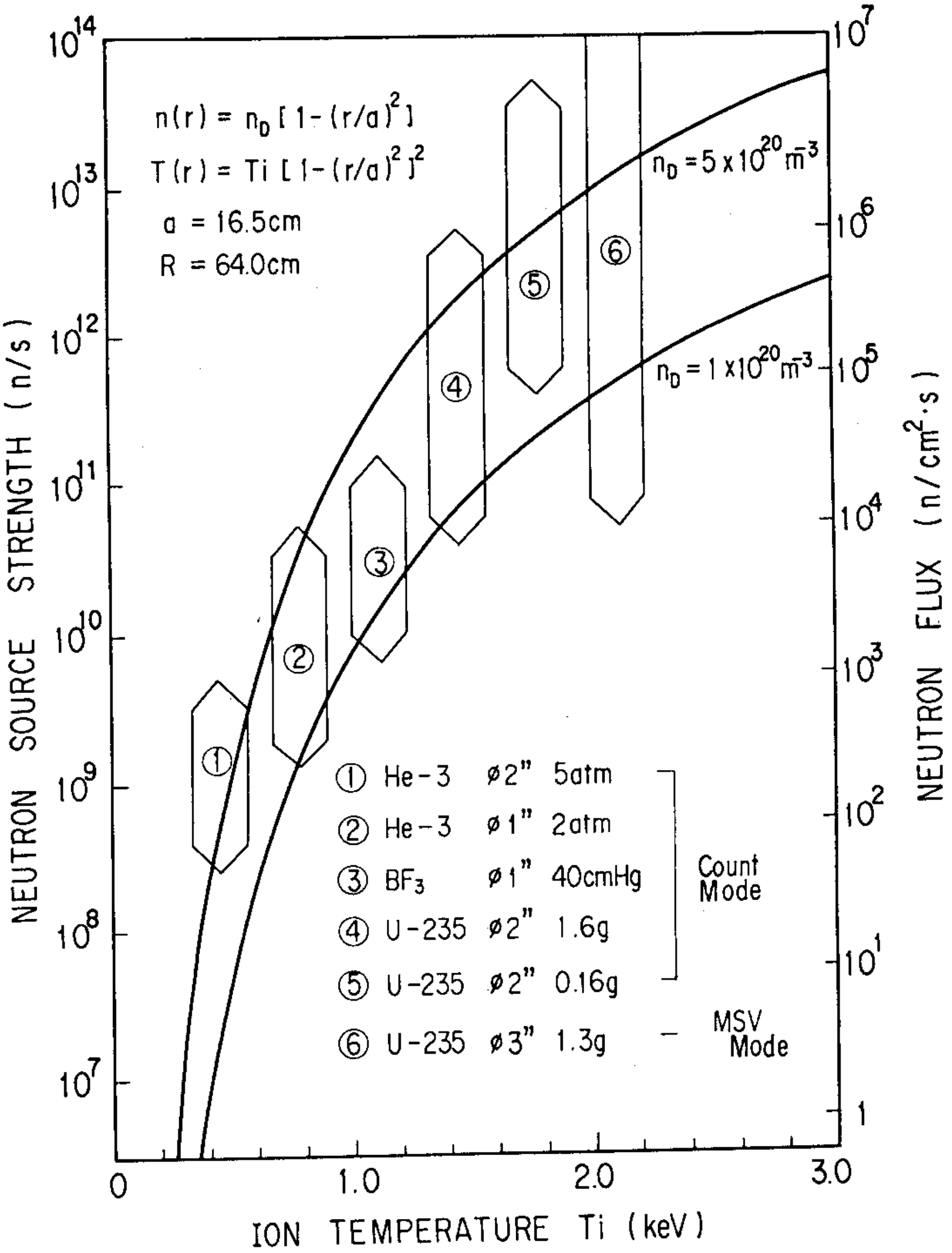

Fig. 1 Calculated neutron source strength from MTX plasma. The neutron flux at the detector position and the flux range corresponding to each detector are also shown.

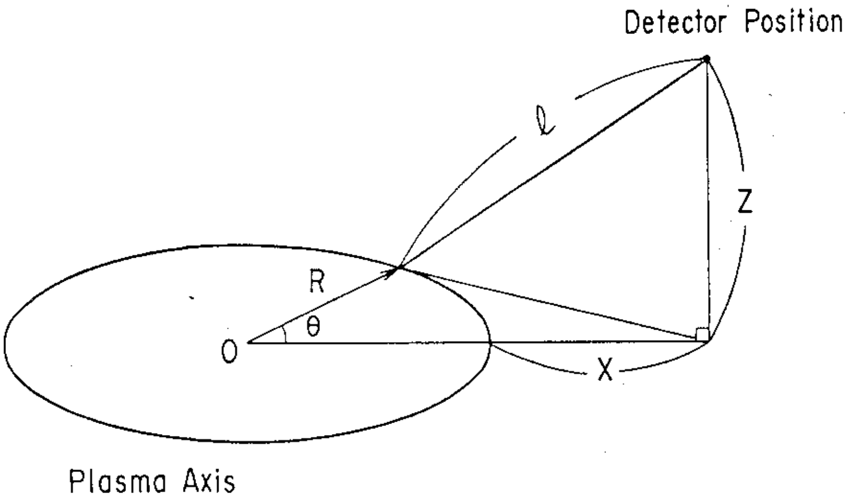

Fig. 2 Model calculation geometry showing the detector position.

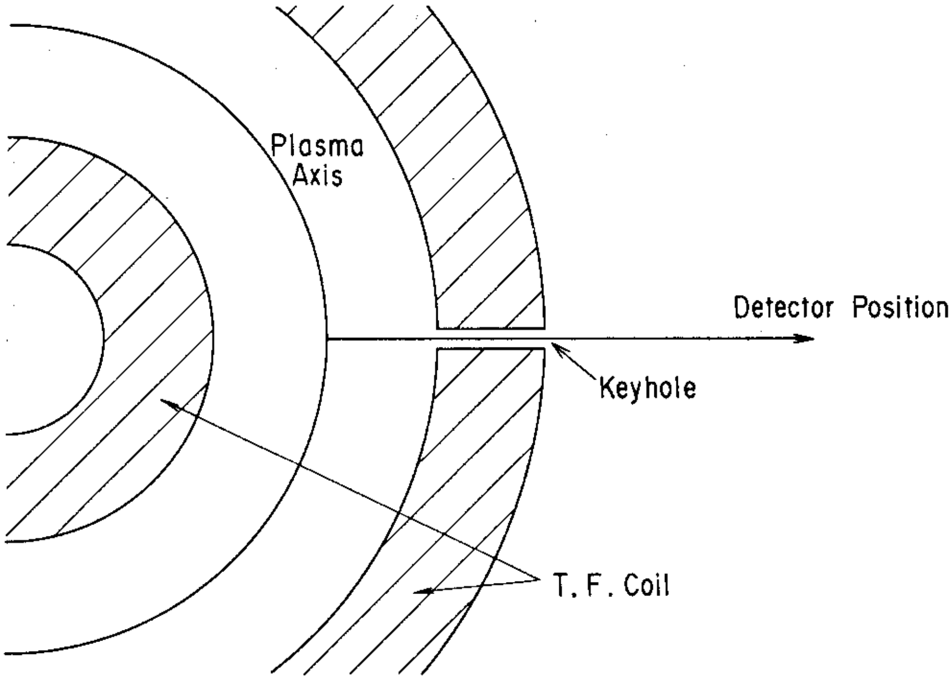

Fig. 3 Schematic diagram of the geometry used in the calculation. The detector is placed on the horizontal plane.

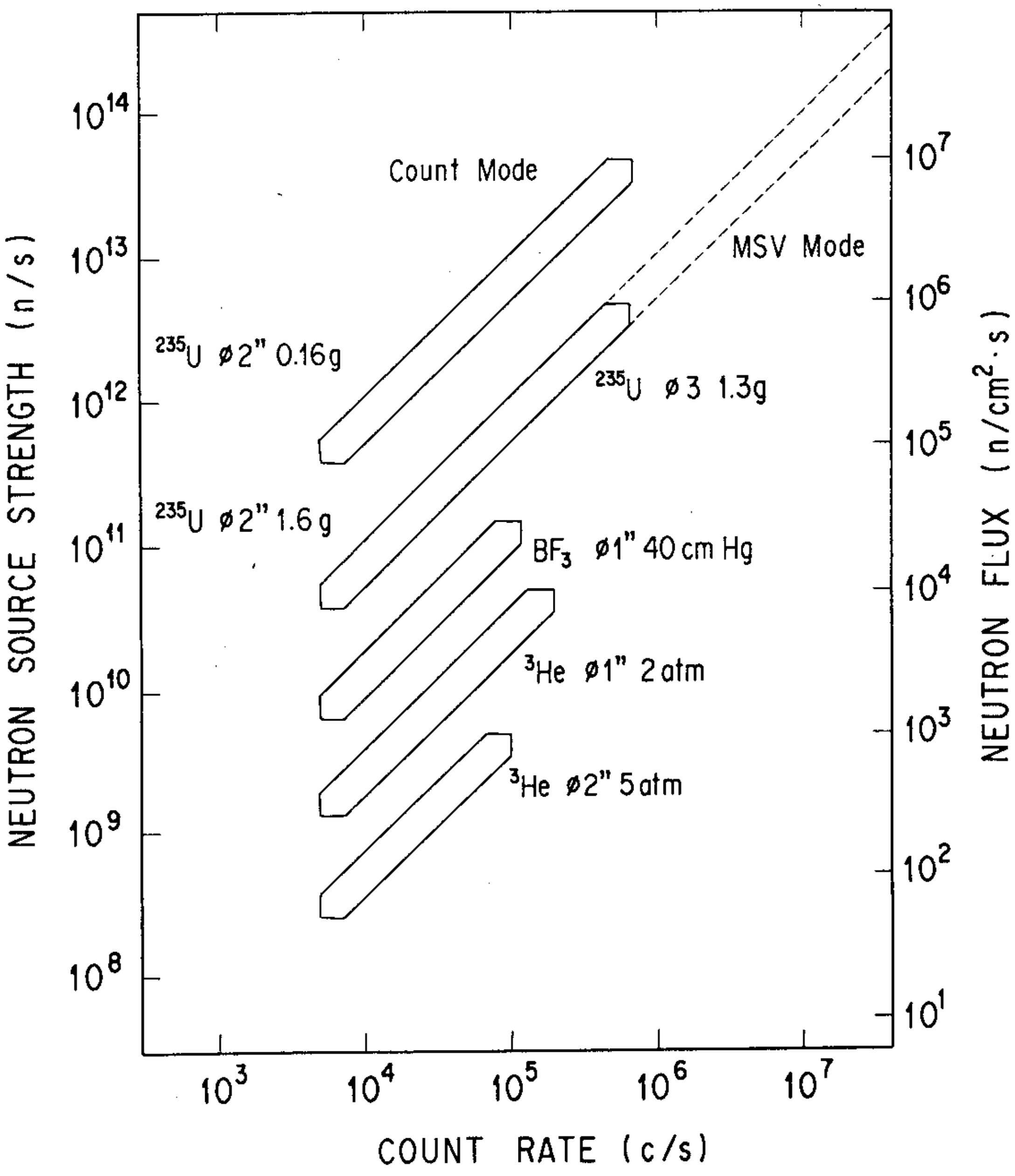

Fig. 4 Neutron detector count ranges. MSV mode is indicated in terms of equivalent count rates.

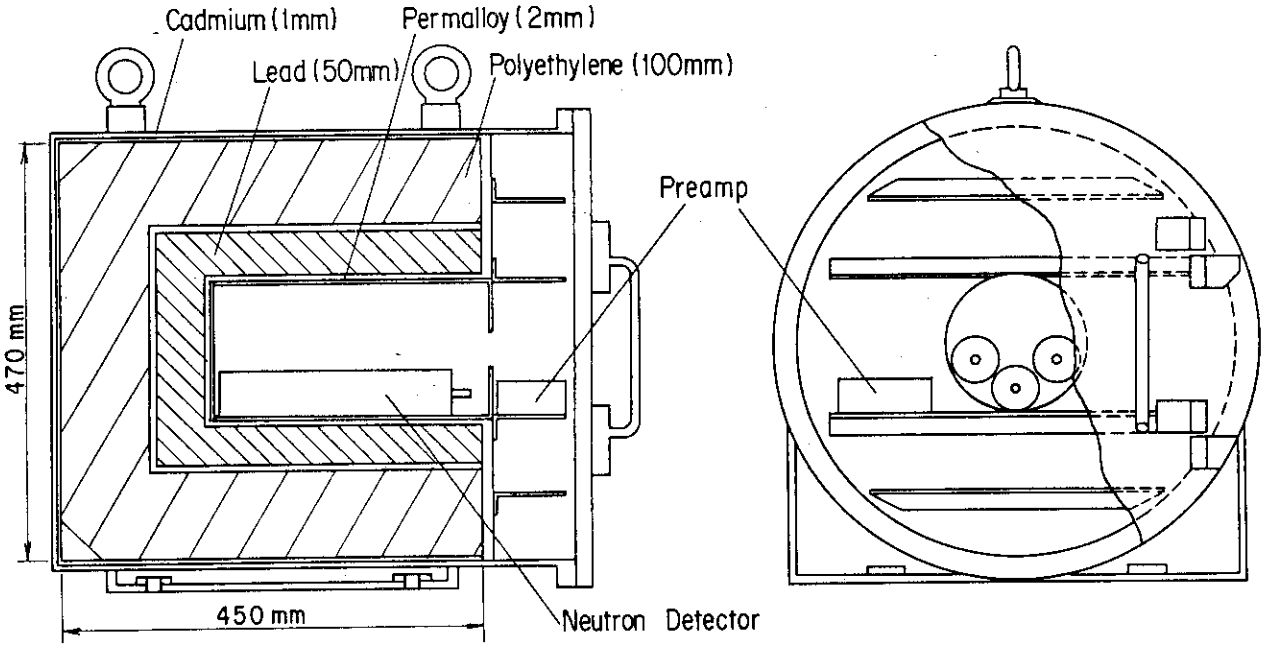

Fig. 5 Neutron Moderator consisting of 100mm thick polyethylene, 50mm thick lead, 1mm thick cadmium, 2mm thick permalloy and stainless steel. Neutron detectors and preamplifiers are set inside the neutron moderator.

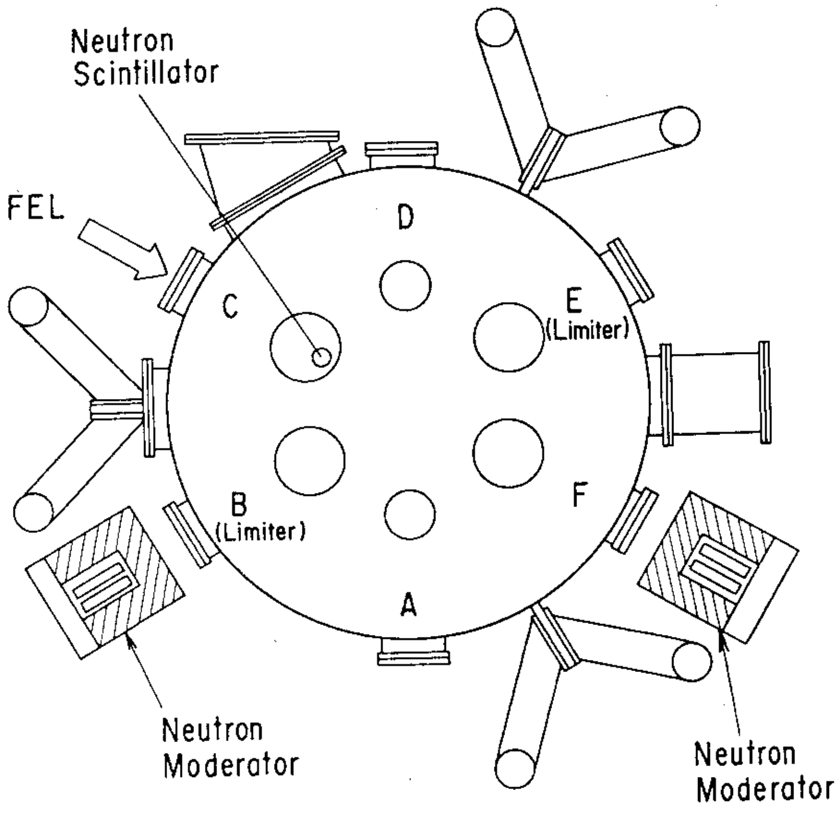

Fig. 6 Plan view of MTX, showing the locations of the two neutron moderators and the scintillator.

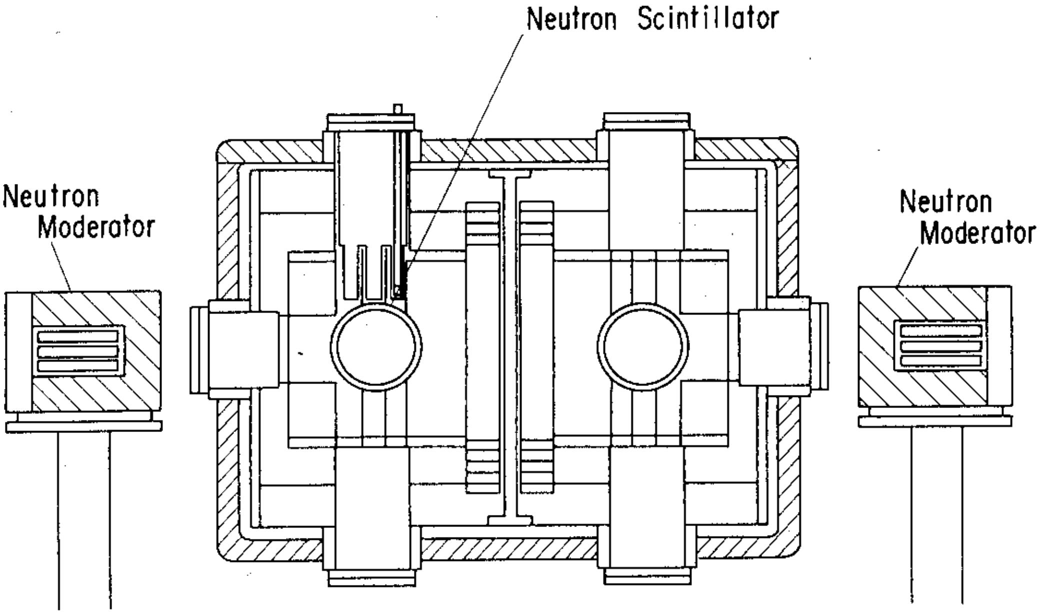

Fig. 7 Elevation view of MTX, showing the layout of the neutron detectors.

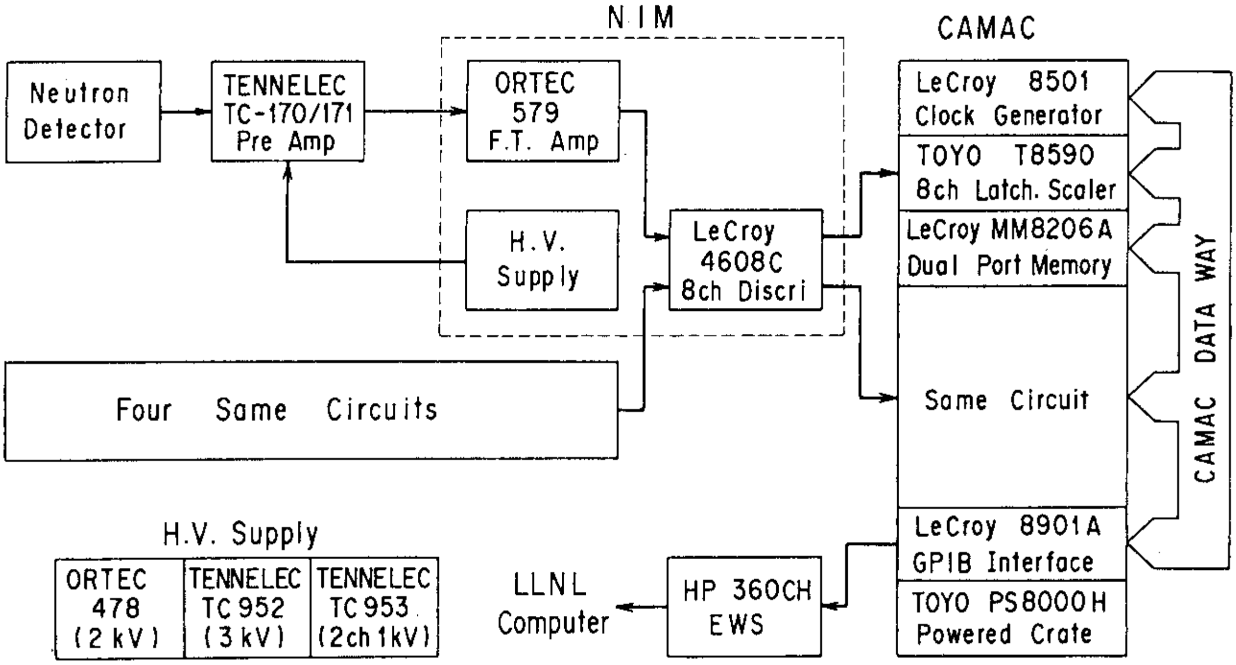

Fig. 8 Electronic system of the neutron production rate measurement.

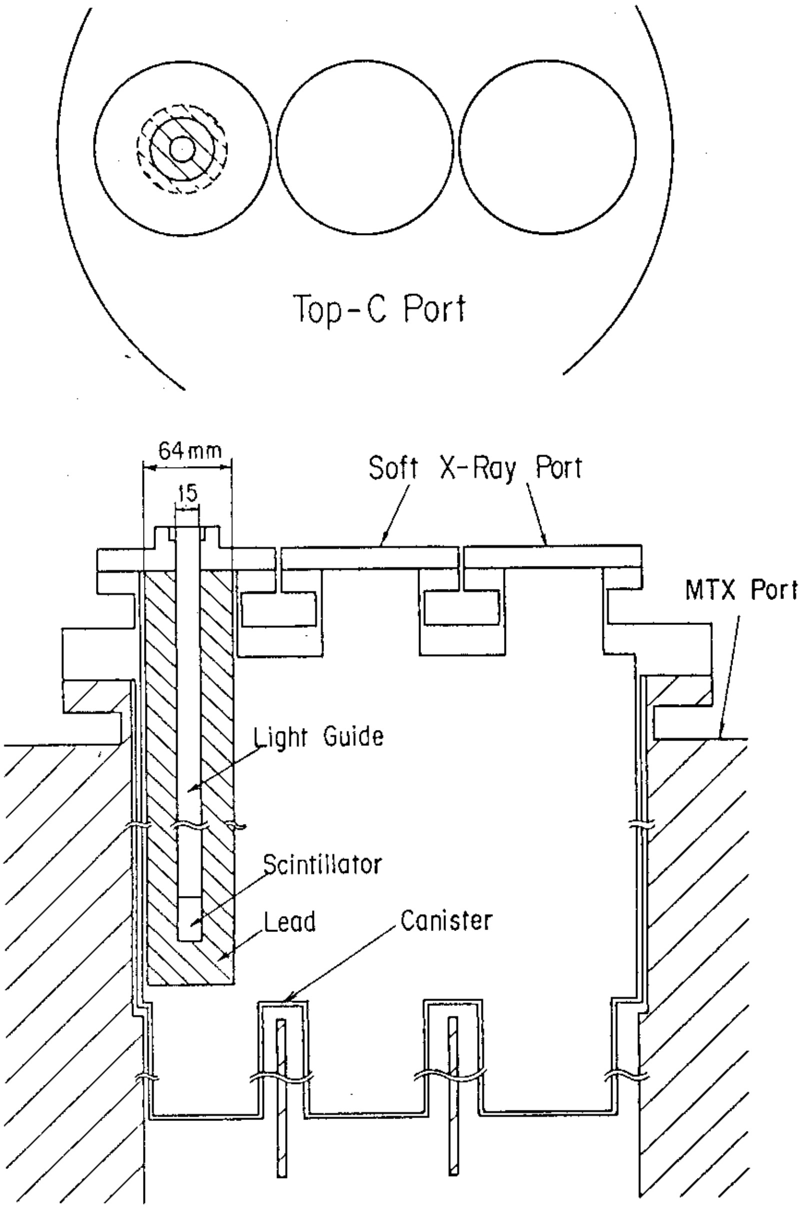

Fig. 9 Schematic diagram of the top port C, showing the layout the neutron scintillator.

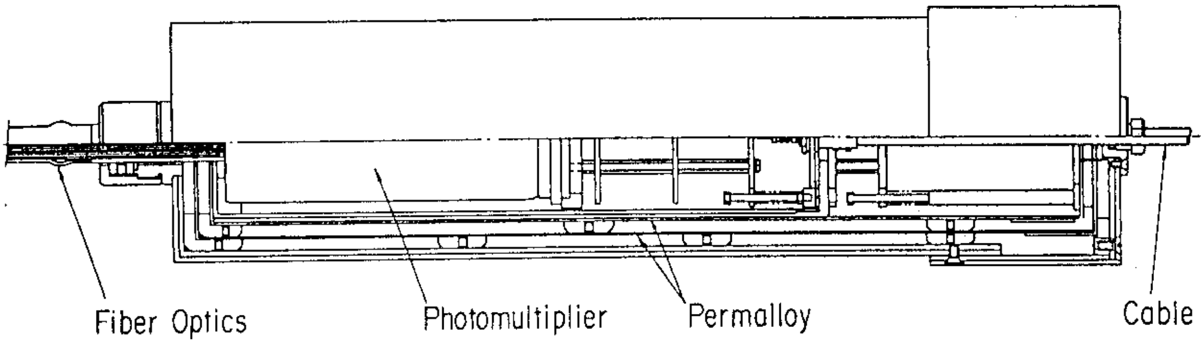

Fig. 10 Schematic drawing of the shielded photomultiplier.

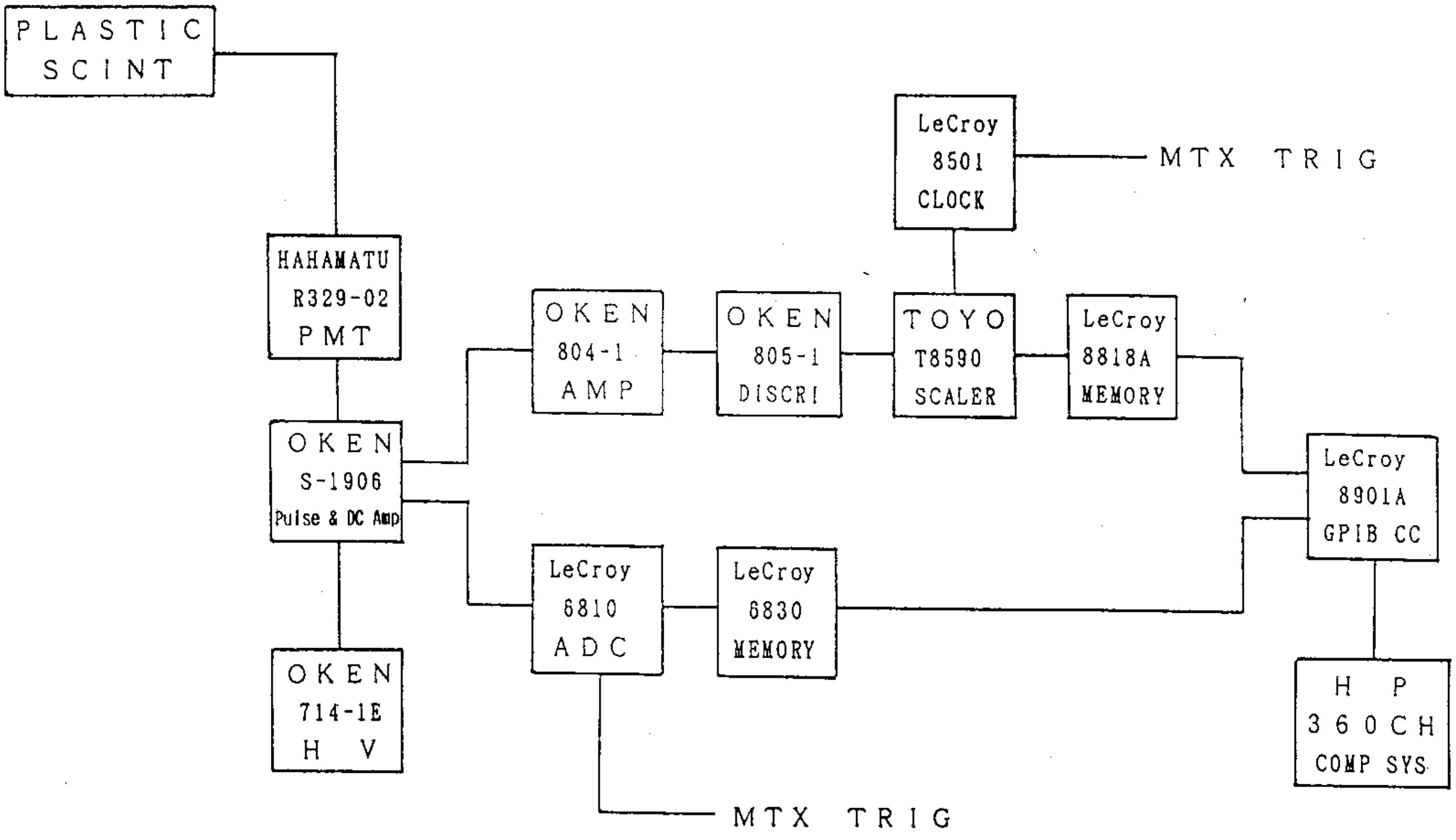

Fig. 11 Electronic system of the high temporal resolution neutron measurement.

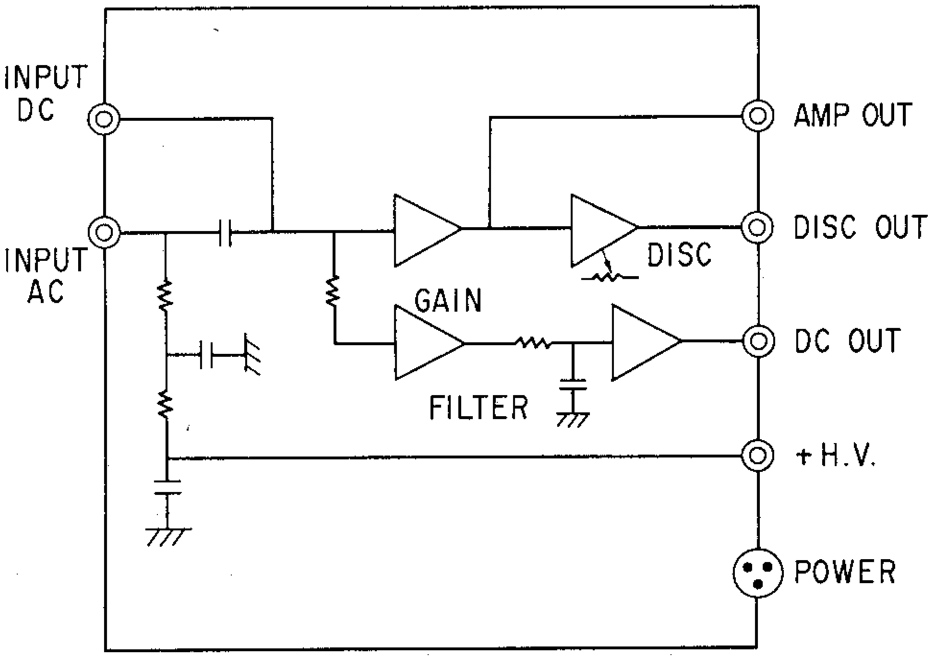

Fig. 12 Pulse & DC amplifier circuit diagram.