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# NEUTRON TIME-OF-FLIGHT ION TEMPERATURE DIAGNOSTIC FOR INERTIAL CONFINEMENT FUSION EXPERIMENTS

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We are constructing a $T_i$ diagnostic for low neutron yield ($5 \times 10^7$ to above $10^9$) *d-d* and *d-t* targets in the Nova facility at Livermore. The diagnostic measures the neutron energy spread with 960 scintillator-photomultiplier detectors located 28 m from the target and operates in the single-hit mode. Each detector can measure a single neutron arrival with time resolution of 1 ns or better. The arrival time distribution is constructed from the results of typically 200-500 detector measurements. The ion temperature is determined from the spread in neutron energy $\Delta E_n \propto T_i^{1/2}$, which is related to the arrival time spread by $\Delta t/t = -(1/2)\Delta E_n/E_n$. Each neutron arrival is detected by using a photomultiplier tube to observe the recoil proton from elastic scattering in a fast plastic scintillator. The timing electronics for each channel consist of a novel constant fraction-like discriminator and a multiple hit time-to-digital converter (TDC). The overall system design, together with single channel performance data, is presented.

# I. Introduction

Neutron time-of-flight (TOF) detectors can provide important information about the fuel-ion burn temperature in various inertial confinement fusion (ICF) target designs. Conventional neutron TOF detectors measure the time history of the total light output from many neutron interactions in a scintillator. These detectors are useful for neutron yields above $10^{10}$, but are limited at lower yields by the finite emission time of the scintillator, the finite response time of the detector, and the statistics of neutron interactions and light production in the scintillator.[1]

We are constructing an ion temperature diagnostic based on timing measurements of single neutron interactions in many scintillators. This diagnostic is designed for low-yield targets on the Nova ICF laser facility at Livermore. The diagnostic measures the neutron arrival time distribution using an array of 960 scintillator-photomultiplier detectors (Figure 1) with about 1 ns time resolution and operated in the single-hit mode.[2] The arrival time distribution is constructed from the results of 100 or more detector measurements. The diagnostic will be located outside the Nova target chamber at a distance of about 28 m from the target.

The ion temperature is determined from the spread in neutron energy as denoted by the relation[3] $\Delta E_n(\mathrm{keV}) = C_{dd} T_i(\mathrm{keV})^{1/2}$ where $\Delta E_n$ is the energy spread (FWHM) and $C_{dd} = 82.5$ (for *d*-*t* reactions the coefficient is $C_{dt} = 176$). The energy spread is related to the time spread by $\Delta t/t \simeq -(1/2)\Delta E_n/E_n$. The quantities of interest are summarized in Table 1. Corrections to the raw data must be provided to account for the system time resolution (about 1 ns) and target burn time (about 100 ps).

The neutron arrival times are detected by using a photomultiplier tube (PMT) to observe the photons produced by recoil protons in a plastic scintillator. The recoil proton energy is dependent on the proton recoil angle $\theta$ through the kinematic relation $E_p = E_n \cos^2\theta$, where $\theta$ is measured with respect to the incident neutron direction. Since *n*-*p* scattering is isotropic in the center-of-mass frame, the proton recoil energy distribution is uniform up to the neutron energy. The pulse height distribution contains no information about the incident neutron energy except through its arrival time, but can be useful for monitoring the system gain or in some pulse pile-up rejection methods.

The dynamic range of the diagnostic must cover *d-d* neutron yields from $5 \times 10^7$ to above $10^9$. This range can be obtained through variation of the number of array channel hits (from 100 to 500) and scintillator volume (from 0.8 cm$^3$ down to 0.2 cm$^3$). Operation at yields above $10^9$ will provide overlap with results obtained from current-mode *d-d* time-of-flight detectors[1] and below $10^7$ with estimates of $T_i$ obtained from first-hit analysis[4] of data from the Large Neutron Scintillator Array (LaNSA) on Nova.

Another way to extend the dynamic range is by operating the array in the multiple hit regime. An acceptable fraction (10%) of the channels will provide single hit data even when the average number of hits per channel is three. Thus a dynamic range of about 30 is possible provided that channels affected by pulse pile-up can be rejected. Data reduction based on first-hit analysis[4] can also be considered.

The electronics for each channel consist of the PMT voltage divider base, a discriminator, a multiple hit time-to-digital converter (TDC), and a gated charge-sensitive analog-to-digital converter (ADC). The multiple hit capability of the TDC is valuable to observe the gammas from neutron interactions with materials along the neutron flight path and thus to correct for timing differences between channels. ADCs can be valuable for recording the pulse height distribution of the recoil proton scintillations to monitor the overall health of the PMT array.

## II. Scintillator

The scintillator volume is chosen to give neutron sensitivity appropriate to the yield predicted for a particular Nova shot. In all cases the scintillator thickness should be restricted to about 1 cm to keep the *d-d* neutron transit time across the scintillator less than 0.5 ns (0.2 ns for *d-t* neutrons). With the above restriction, the probability of a neutron interaction in the scintillator is given by

$$P = Y(A/4\pi R^2)(x/\lambda)$$

where $Y$ is the neutron yield, $A$ is the detector area, $R$ is the distance from the Nova target to the scintillator (28 m), $x$ is the detector thickness. and $\lambda$ is the neutron mean free path for elastic scattering (7.7 cm). For the minimum neutron yield of $5 \times 10^7$ and a minimum detection probability of 10% (to obtain 96 measurements), the scintillator volume $Ax$ is 0.8 cm$^3$. For the maximum neutron yield of $1 \times 10^9$ and a maximum detection probability of 50%, the scintillator volume drops to 0.2 cm$^3$. If the array is operated at a detection probability of 300%, the dynamic range is increased six-fold at a given scintillator volume.

The scintillator itself should be relatively fast and bright, similar to BC400 or NE102. The light output of this scintillator is about 64% of anthracene. The light production in NE102 for electron energy deposition is 0.01 photons/eV.[5] The relative production efficiency for protons in NE102 has been measured[6] and can be expressed as

$$T_E = 0.95T_P - 8.0\{1 - \exp(-0.10T_P^{0.90})\}$$

where $T_P$ is the proton energy (in MeV) and $T_E$ is the equivalent electron energy (in MeV). The number of photons varies from 110 for a 0.25 MeV recoil proton up to a maximum of 7433 for a full-energy recoil. For comparison, a full-energy recoil from $d$-$t$ neutrons produces 80,300 photons. A useful amplitude calibration can be provided by gammas from $^{137}$Cs, which produces a Compton edge at two-thirds of the recoil proton edge from $d$-$d$ neutrons.

Light coupling efficiency of about two-thirds can be obtained by using optical coupling grease between the scintillator and the photocathode together with titanium dioxide paint on the uncoupled surfaces. However, the use of optical coupling grease is prohibited by the need to change the scintillators. Instead, silicone coupling pads can be employed. These coupling pads permit coupling efficiency close to that of coupling grease (about 50%). Bare coupling efficiency is around one-third.

## III. Photomultiplier Tube

The PMT converts scintillation photons into electrons and amplifies them in the electron multiplier. Bialkali photocathodes provide a good match for plastic scintillator emission spectra and have quantum efficiency of about 25%. Thus 10–15 photoelectrons can be expected from a 0.25 MeV recoil proton. The multiplier structure should be a linear focused type to obtain good time resolution. Inexpensive side-viewing PMTs are unsuitable because of inefficient light coupling between scintillators and the recessed photocathode.

Time resolution of PMTs is quoted in terms of the single-photoelectron transit time spread (SPTTS). These SPTTS values are 2–3 ns for PMTs of the type considered. The time resolution improves inversely as the square root of the number of photoelectrons compared with the SPTTS. This dependence indicates the importance of efficient light coupling. An SPTTS of 3 ns or better is needed to obtain time resolution of 1 ns for *d-d* measurements with as few as 10 photoelectrons. Even better time resolution is obtained with the brighter *d-t* scintillations.

The anode output must be compatible with the discriminator threshold. Assuming a minimum of 10 photoelectrons, a gain of $10^6$, and a triangular anode pulse with FWHM of 5 ns, the peak anode current is 320 $\mu$A. This represents 16 mV into a 50 $\Omega$ load, which provides a reasonable minimum voltage for the discriminators. In addition, the PMT output should remain linear up to the recoil proton edge (about 20 mA).

A variety of small 10-stage end-viewing PMTs were considered for this diagnostic. The Philips XP1911 19 mm tube was selected, primarily based on cost. This PMT provides the required gain (at a nominal voltage of 1600 V) and linear current (up to 130 mA).

The time resolution was measured by comparing the anode pulses from two XP1911 PMTs viewing the same scintillator. Neutral density filters between the scintillator and each PMT provide an attenuation of 200, ensuring that each scintillation produces at most a single photoelectron pulse. Ortec VT120C linear preamps provide an amplification of 10 for each anode signal. A 50 ns coax line was used to delay one of the signals. Ortec 473A discriminators and an Ortec 567 Time-to-Amplitude Converter were used to obtain the raw timing spectrum shown in Figure 2. The time spread $\Delta t$ can be expressed as

$$\Delta t^2 = \Delta t_A^2 + \Delta t_B^2 + \Delta t_{scin}^2$$

where $\Delta t_A$ and $\Delta t_B$ refer to the SPTTS of the two PMTs and $\Delta t_{scin}$ refers to the FWHM emission time of the scintillator (1.3 ns). For identical A and B channels, the SPTTS of each tube is 2.9 ns. Measurements without the neutral density filters confirm the expected improvement of time resolution with light level.

The PMT voltage divider is designed for bleeder current equal to the average anode current rating of the tube. The manufacturer's recommended string for maximum linear current output is employed. Capacitive stabilization of the latter dyrode stages is provided to limit voltage changes to less than 1% for 10 full-energy proton recoil scintillations. Positive high voltage is supplied to the anode to permit the cathode region to be grounded. Anode output is capacitively coupled to the discriminator.

## IV. Discriminator, ADC, TDC, and Data Acquisition

The anode signals are connected to novel constant-fraction-like discriminators based on a simple RC network and a fast voltage comparator.[7] No walk correction is required with this discriminator. An updating output of 10 ns minimum duration is provided to allow pulse pile-up to be detected by the TDC. This discriminator has low power dissipation and can be made quite compact.

The discriminator provides a buffered version of the anode signal for connecting to a LeCroy 1885F 15-bit charge ADC. This is a 96 channel FASTBUS module. The 1885F can be gated for a time as short as 50 ns and can be used to measure the amplitude of the *d-d* neutron pulses with a sensitivity of 50 fC per count.

The discriminator output is connected to LeCroy 1879 96-channel multihit TDC FASTBUS modules. These are 2 ns TDCs with double edge resolution of 10 ns. Up to 16 edge timing measurements per channel can be obtained. For $d$-$t$ measurements, the TDCs will be upgraded to the 0.5-ns LeCroy 1877 when that product becomes available.

A DEC MicroVax II computer is used to control and read out the FASTBUS modules and to analyze the data. A CAMAC-based Starburst LSI-11 mediates the control functions through a CAMAC-FASTBUS interface. The software needed for this diagnostic has already been developed for LaNSA array.

## V. Testing

The two general areas of testing are amplitude and timing tests. The overall gain of the scintillator-PMT system must be monitored routinely, perhaps prior to each Nova shot, and the PMT voltage or discriminator threshold adjusted to correct for gain shifts or changes in PMT coupling efficiency. Small $^{137}$Cs radioactive sources are used for this calibration. Timing tests will be performed using a 1-ns, blue, unfocused CRT light pulser developed at EG&G.

Once in operation, correct system performance will be checked by monitoring the recorded data in a number of ways. Timing can be routinely checked on Nova by observing x-ray generating targets or by using the gamma fiducial provided by neutron interations in the target. Spare channels are included in the array. PMT failures can be discovered by detecting a change in the divider string current, the appearance of excessive noise, or by the absence of signal in a particular channel for a series of shots. Discriminator and TDC problems will be detected by comparing the average detection probability in each channel with the average detection probability in the whole array. An overall alignment check can be performed by computing the average arrival time as a function of two orthogonal dimensions across the detector array. Individual channel timing variations can also be detected by comparison with the average arrival time.

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[6] Richard Madey, Frank M. Waterman, Alan R. Baldwin, James N. Knudson, J. D. Carlson, and J. Rapaport, Nucl. Instrum. Meth. **151**, 445 (1978).

[7] B. Turko, R. C. Smith, "A Precision Timing Discriminator for High Density Detector Systems," LBL-30602.

# Tables

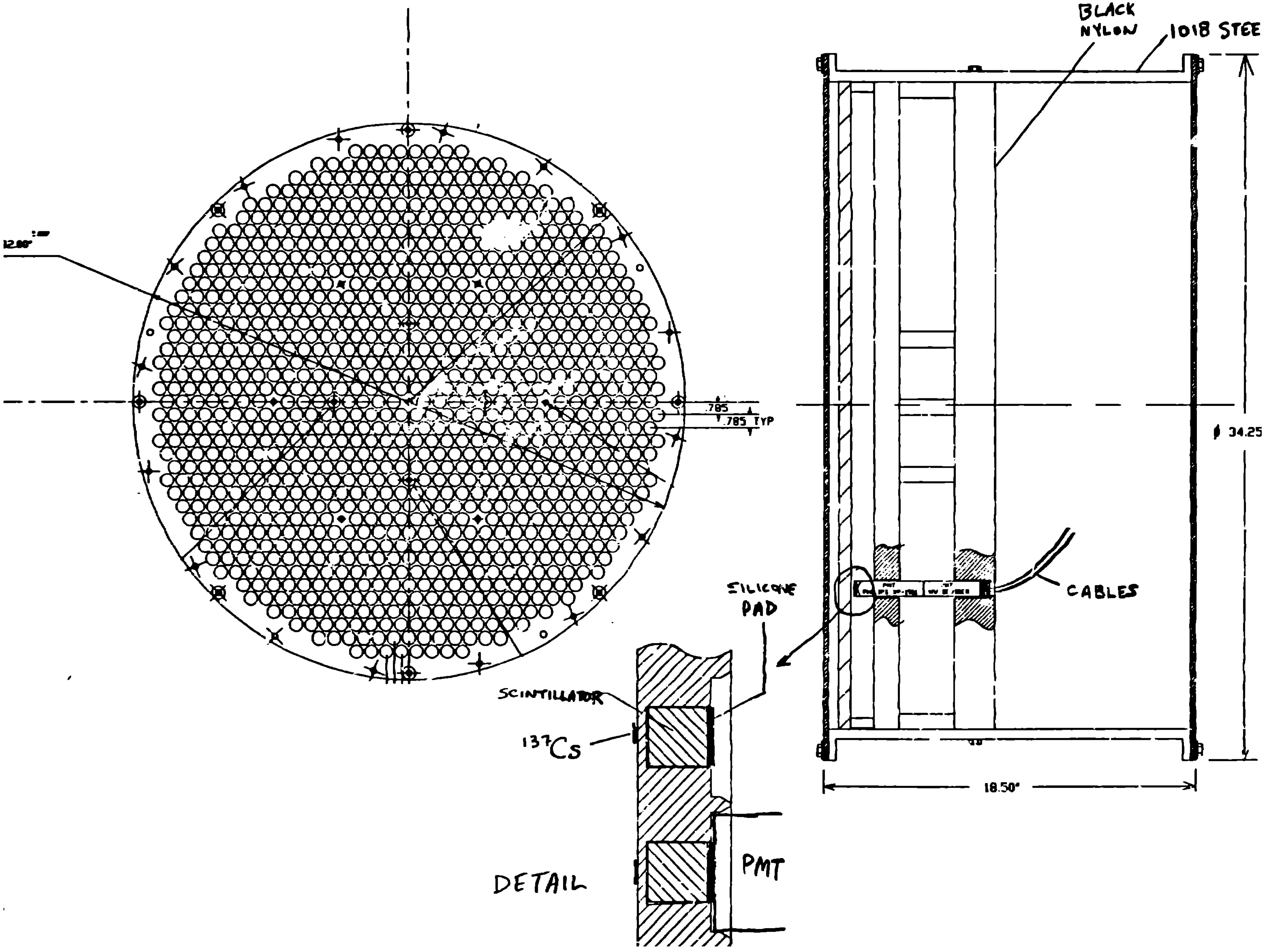
TABLE I. Characteristics of *d*-*d* and *d*-*t* neutron times-of-flight for Nova

| | *d*-*d* | *d*-*t* |
|---|---|---|
| inverse speed (ns/m) | 46.1 | 19.2 |
| distance (m) | 28 | 28 |
| time-of-flight (ns) | 1291 | 538 |
| $\Delta t$ for $T_i = 1$ keV (ns) | 21.7 | 3.4 |
| 1 ns distance (cm) | 2.2 | 5.2 |

## Figures

FIG. 1. Assembly drawing of the photomultiplier tube chamber, showing the $^{137}$Cs sources, scintillators, silcone coupling pads, PMTs, bases, and cables for the PMT array.

FIG. 2. Transit time spectrum obtaining from the two photomultiplier tube method using XP1911 tubes and a BC418 scintillator. The calibration factor is 155 channels per ns. The full width at half maximum corresponds to 4.3 ns.


12.88"
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CABLES
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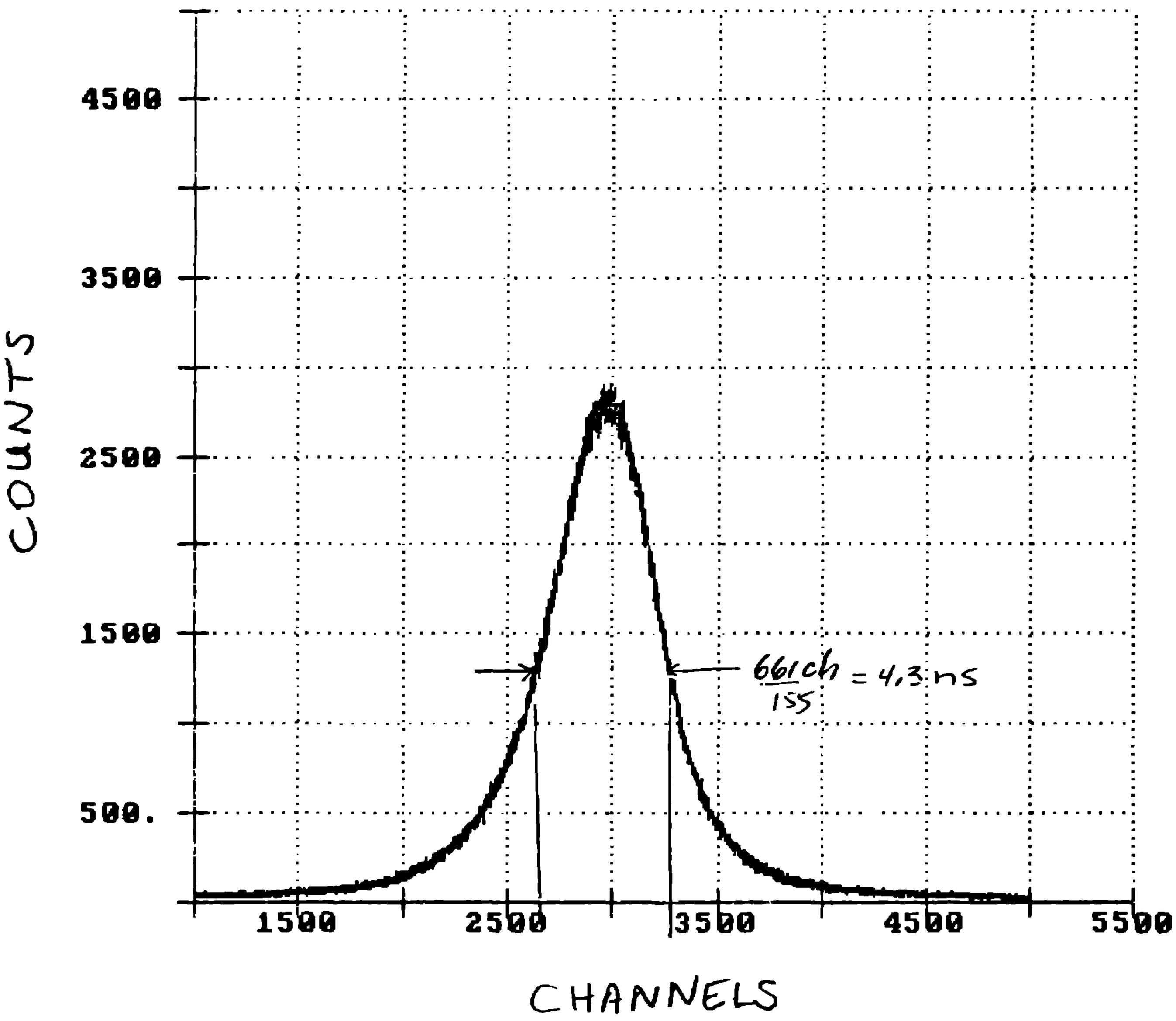

4500
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