

# TIME RESOLVED NEUTRON SPECTRUM MEASUREMENTS\* AT THE MIRROR FUSION TEST FACILITY

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## Abstract

An advanced neutron diagnostic system has been developed for spectrum measurements on MFTF. Its collimated field of view allows spatially resolved neutron spectrum measurements. The 10 Mhz pulse height analysis and particle identification capability allow spectrum measurements in intervals as short as 10 ms. These capabilities will be used for space and time resolved determinations of ion energy from measurements of neutron Doppler width.

## Introduction

The Mirror Fusion Test Facility (MFTF) is a tandem mirror fusion experiment directed toward the study of thermonuclear energy production in a magnetically confined plasma. Hot deuterium plasma is confined in a large solenoid where the plasma volume is roughly 1 m diameter by 32 m long. Within that volume the peak plasma density is about  $2 \times 10^{13} \text{ cm}^{-3}$  and the mean energy is expected to be about 20 keV. Radial confinement of the plasma is accomplished by the 1-2 T axial magnetic field. Loss of plasma at the ends of the solenoid (or Central Cell) is reduced by magnetic mirrors and by the roughly 30 kV electrostatic potential barrier developed in plasma endplugs beyond the mirrors. The endplugs consist of mirror confined plasma at densities as high as  $5 \times 10^{13} \text{ cm}^{-3}$  and mean energies up to 80 keV.

Heating of these plasmas is accomplished by a combination of energetic neutral deuterium beams, rf power resonant with the ions, and rf power resonant with the electrons. One of the principle purposes of the experiment is to study and understand the energy balance in the plasma, the mechanisms by which plasma energy is increased or lost, and the time constants for those processes.

The Center Cell and endplugs of MFTF are each expected to generate about  $10^{16}$  neutrons per second by the  $D(d,n)^3\text{He}$  reaction. The neutrons are produced at a nominal energy 2.45 MeV. There is a second reaction,  $D(d,p)^3\text{T}$ , which is equally abundant. To the extent that the reaction product tritium is confined in the latter case, there may also be some fusion neutrons produced at 14 MeV by the  $T(d,n)^4\text{He}$  reaction. Monitoring the intensity of those may aid in the understanding of fusion product confinement in MFTF as has been done at PLT<sup>2</sup>. Finally, the energetic neutral deuterium injected by the heating beams will react with the target plasma to produce neutrons. Neutron measurements will be used, first to determine the fusion rate in the plasma, and second to monitor the temporal and spatial variation of ion energy.

Knowledge of the neutron energy spectrum will play an important role in identifying and quantifying these reactions for the study of fusion in the MFTF plasma. Crude spectrum measurements which distinguish 2.5 and 14 MeV neutrons will be helpful in the study of triton confinement. High resolution measurements may be used to identify beam-target reactions and to determine mean ion energy from the Doppler width caused by ion center-of-mass motion. In a Maxwellian plasma the neutron Doppler width due to ion motion is<sup>3</sup>:

$$\Delta E_n (\text{FWHM}) = 2.35 \sqrt{\frac{m_n m_0 Q T_i}{(m_n + m_0)^2}} \quad (1)$$

where  $m_n, m_0$  are the masses of the neutron and recoil nucleus  
 $Q$  is the reaction energy  
 $T_i$  is the plasma temperature

or,

$$\Delta E_n (\text{FWHM}) = 67 \text{ keV} \sqrt{\langle E_i \rangle (\text{keV})} \quad (2)$$

for the  $D(d,n)$  reaction. The same parametric relation between Doppler width and mean ion energy is seen in non-Maxwellian plasmas, but the scale factor depends on the functional form of the speed distribution as will be seen below. High resolution measurement of the fusion neutron spectrum then provides a sensitive and absolute measurement of the ion energy which is independent of other plasma parameter measurements. To the extent the spectrometer may be collimated, the ion energy may be determined with good spatial resolution. To the extent that the spectrometer can obtain a good spectrum measurement in a short time interval, the ion energy determination may be time resolved. In that case, increases and decay in ion energy may be observed directly. Indirect measurement of ion energy decay has also been obtained from neutron yield measurements<sup>4</sup>.

## Spatially Resolved Spectrum Measurements

A neutron collimator has been constructed with four independently aimed apertures and housing four spectrometers. Details of its construction are given elsewhere<sup>4</sup>. The collimated spectrometers inside may be aimed at four volumes along the plasma radius in order to determine the radial dependence of ion mean energy, or along the plasma axis, or they may all be aimed at the same plasma volume with different sized entrance apertures in order to span a wider dynamic range in neutron intensity. The spectrometer field of view is limited to about one degree (FWHM) or about 10 cm for a plasma 6 m distant, and its out-of-field response is reduced by more than three decades<sup>4</sup>.

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## Energy Spectrum Measurements

Fusion neutron energy spectra have been measured for tokamak plasmas in Zeta<sup>5</sup>, in PLT<sup>6</sup> and in Alcator<sup>7,8</sup>. In most cases these measurements were made in plasmas where reactions between an injected beam and the target plasma were not important. Mean ion energies were relatively low so that the Doppler width was small, requiring very high resolution neutron energy measurements. Generally, high resolution has only been attained with ion chambers which must be used at low count rates so that data is obtained by accumulation over many plasma discharges and cannot be time resolved. Recent experiments have included large scale neutral beam heating where reactions with injected neutrals are important and calculations have been carried out to predict their effect on the fusion neutron spectrum<sup>9</sup>.

We report here recent development of a pulse-height-analysis (PHA) and particle identification system which allows the very efficient liquid organic scintillation spectrometers to be used at data rates up to 10 Mhz so that neutron energy spectra with good statistics may be obtained in intervals as short as 100 ms. We also report the development of a high resolution <sup>3</sup>He based Gas Scintillation Spectrometer (GSS) which may be used with the fast PHA system to obtain D-D fusion neutron spectra with good statistics in short intervals<sup>10</sup>.

Early work on the fast PHA system has been reported before<sup>4,11</sup>, and a spectrum measurement at a 5 Mhz data rate is reproduced from that report in Figure 1. Since that report, the PHA system has been upgraded in order to provide a modular design, to minimize the amount of radiation sensitive circuit near the detector, and to improve the software. At the time of this writing the hardware is complete and debugged, but the operational software is still incomplete and the system performance has not been characterized experimentally. A schematic diagram of the new system is shown in Figure 2. A low gain photomultiplier is used in order to avoid gain drift due to dynode fatigue and heating at high event rates. The low gain is compensated by a high gain

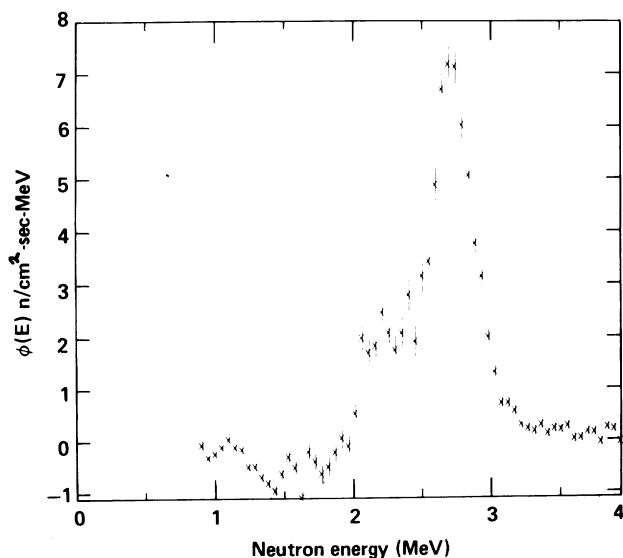


Fig. 1. Neutron energy spectrum obtained with NE213 detector at 5 Mhz input rate. Data shown was taken during a 200 ms acquisition period and corrected off-line for ADC non-linearity.

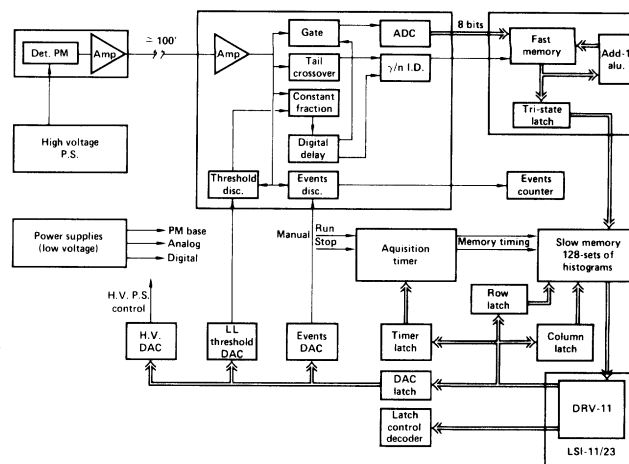


Fig. 2. Schematic of the high rate pulse height analyzer.

linear amplifier incorporated into the FET regulated high voltage divider string. A linear output is thus produced which has low output impedance, is fast, and is free of the usual sources of gain drift present in high event rate systems. The shaped linear signal is detected and digitized in an 8-bit "flash converter" with pulse pair resolution time roughly 80 ns. Simultaneously a cross-over timing circuit compares the pulse decay time with a digitally controlled delay line in order to identify short decay ( $\gamma$ -ray induced) and long decay (neutron induced) events in the detector. The result of the comparison sets the ninth and most significant bit at the ADC output. A fast memory is then incremented at the appropriate location so that neutron induced events produce a pulse height spectrum in the first 256 channels and  $\gamma$ -ray induced events produce a corresponding spectrum in the top 256 channels.

The fast memory is sufficiently large to store 128 pairs of pulse height spectra and a digitally controlled timer is used to regulate storage of sequential spectra in up to 128 time intervals during a plasma discharge. All controls including particle identification, linear gain, acquisition intervals, amplitude threshold, and system initiation are digital and are intended to be controlled by a diagnostics computer through fiber optic links.

Of course some processing of the spectral data is necessary after the plasma discharge. The ADC has poor differential linearity and the spectra must be corrected for this using the procedure described previously<sup>11</sup>. Data obtained with NE213 spectrometers must then be unfolded since the pulse height spectrum recorded is related to the energy integral of the neutron spectrum. This is accomplished using the FLYSPEC unfolding procedure<sup>12</sup>. Figure 1 shows a typical example of a neutron spectrum acquired in this way. A liquid scintillation NE213 spectrometer was used to measure the spectrum of neutrons produced by an accelerator source at a data rate of approximately 5 Mhz. At this rate approximately 5% of the  $\gamma$ -ray events were falsely identified as neutron induced events. The data shown in the figure were used to determine that the system energy resolution is about 270 keV at this data rate. Dispersion of the source was small by comparison. This spectrum was acquired in 200 ms.

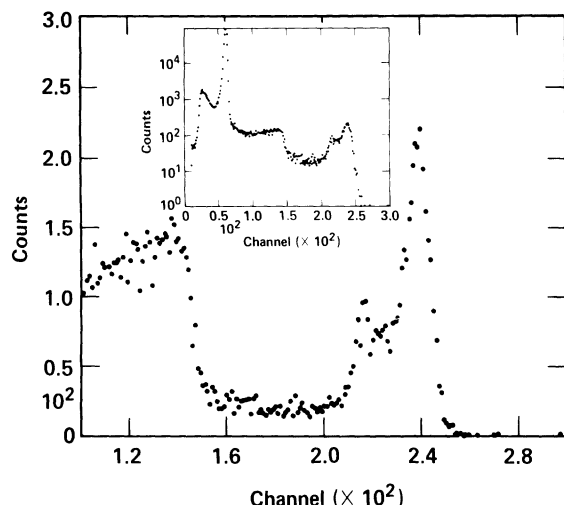


Fig. 3. Pulse height spectrum obtained with  $^3\text{He}$  gas scintillation spectrometer in the field of a 2.5 MeV accelerator neutron source.

Alternatively, a  $^3\text{He}$  gas scintillation spectrometer may be used as the neutron sensor. Particle identification is not required due to the low  $\gamma$ -ray sensitivity of this spectrometer. In addition, the impulse response of the spectrometer produces a roughly Gaussian peak corresponding to full energy deposition within the active volume, as well as a distribution of events with less than full energy deposition. As a result, unfolding may not be required to determine the neutron Doppler width and the statistical requirements are much less demanding than with the NE213 spectrometer. Figure 3 shows the result when the GSS is exposed to an accelerator neutron source. The pulse height spectrum is relatively simple to interpret<sup>10</sup> and the neutron line width obtained in a very short acquisition time interval. This spectrometer is substantially less efficient than the NE213, but the relaxation of statistical requirements in the spectrum make it a very attractive alternative. Its efficiency is sufficiently high so that neutron yields expected in MFTF will be sufficient to drive it to high count rates and will allow time-resolved spectrum measurements.

#### Simulations

In order to assess the application of neutron spectrum measurements to MFTF diagnostics a number of Monte-Carlo simulations have been carried out to predict the neutron energy spectrum produced by a variety of plausible deuterium speed distributions. A code called LINE<sup>13</sup> was used in these simulations. Separate speed and angular distributions were given to each of the two reacting ions. The energy of a neutron emerging in a particular observation direction was calculated classically and the reaction is weighted according to the differential cross section corresponding relative velocity of the ions and to the center-of-mass angle for the outgoing neutron. Figure 4 shows a sample of the results. Included for comparison are simulated neutron energy spectra produced by deuterium plasmas with mean energies 15 keV and whose speed distributions are Maxwellian, mono-energetic, and a three-component Gaussian distribution characteristic of mirror confined beam driven plasmas<sup>14</sup>.

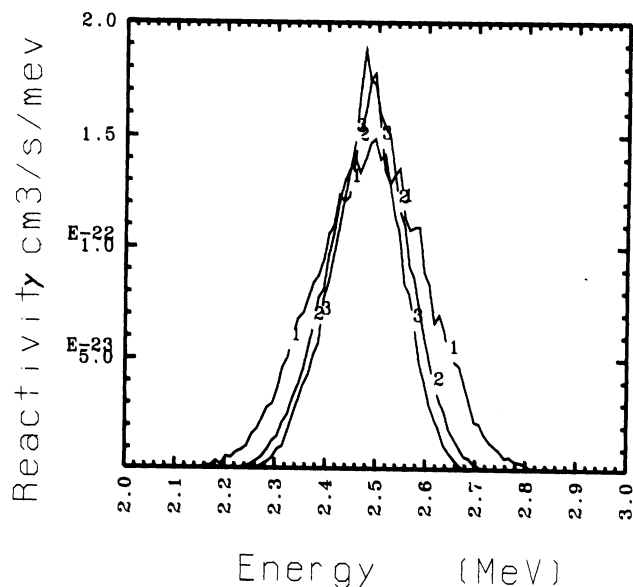


Fig. 4. Simulated neutron spectral line shapes for deuterium plasmas with mean energy 15 keV. Results shown are for plasmas with Maxwellian (1), three-component Gaussian (2), and mono-energetic (3), speed distribution functions.

Variation of the neutron spectral line width (FWHM) with mean ion energy was determined in the simulations and a few of the results are shown in Figure 5. The Doppler width increases roughly as the square root of the mean ion energy, which may be derived analytically in the case of a Maxwellian ion speed distribution<sup>3</sup>. However, the scale factor depends on the functional form of the ion speed distribution and is distinct for each of the

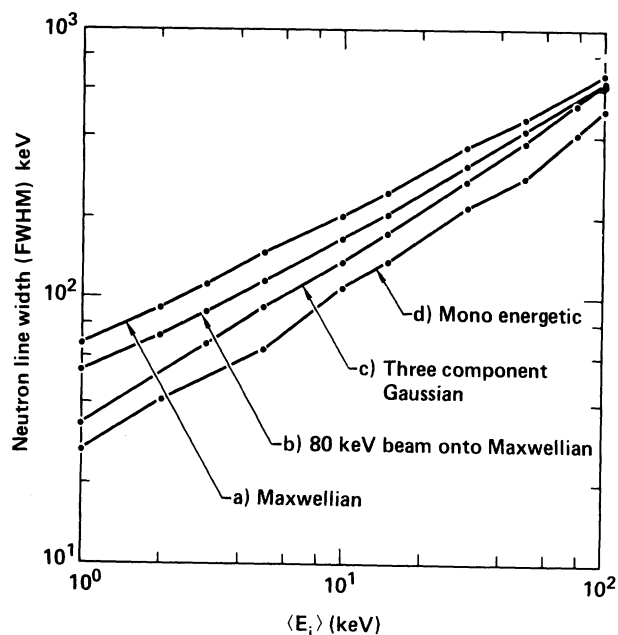


Fig. 5. Neutron line width (FWHM) determined from simulated neutron spectra. Results shown are for plasmas with a) Maxwellian, b) 80 keV onto Maxwellian, c) three component Gaussian, and d) mono energetic speed distribution functions.

distributions considered. Inspection of the figure shows that the differences are important, especially at mean ion energies less than 10 keV. The Doppler width of the D(d,n) neutron spectrum generated in the simulations is well approximated by:

$$\Delta E_n \text{ (FWHM)} = C \langle E_i \rangle^\alpha \quad (3)$$

where the values of  $c$  and  $\alpha$  are given in Table I below.

Table I

Distribution Function	C(keV)	$\alpha$
Maxwellian	65.9	.499
80 keV beam onto Maxwellian	49.3	.542
Gaussian	32.8	.634
Mono energetic	25.4	.632

If the form of the distribution is poorly known, the mean ion energy determined from a Doppler width measurement may be uncertain by up to a factor of four. Some knowledge of the functional form of the ion speed distribution will be required before neutron Doppler width measurements may be used to infer the ion mean energy directly. Results of the simulations indicate that the neutron spectral line shapes are Gaussian up to the 10th moment for all of the speed distributions considered. As a result, analysis of the high order moments of a measured neutron spectrum is not likely to be helpful in identifying the form of the speed distribution.

#### Conclusion

The system described above is fully computer controlled and its functions automated so that it need not be attended for data acquisition. Data interpretation is expected to be done off-line. The spectrometer is adequate for the determination of ion mean energy in either Central Cell or endplug deuterium plasmas in those cases where the functional form of the ion speed distribution is known. Expected neutron yields are sufficient to provide good statistics even with relatively strict collimation so that these data may be used to establish the spatial dependence of ion mean energy. The efficiency is high enough to provide very high count rates when the collimation is relaxed so that measurements with good statistics may be made in intervals as short as 10 ms. It appears, however, that the expected neutron yield is not sufficient for simultaneous space and time resolved measurements.

#### References

1. D. E. Baldwin, B. G. Logan, T. C. Simonen, "Physics Basis for MFTF-B", Lawrence Livermore National Laboratory, UCID-18496 (1980).
2. P. Colestock, J. D. Strachan, M. Ulrickson, R. Chrien, Phys. Rev. Lett. 43, 768 (1979).
3. H. Brysk, Plasma Physics 15, 611 (1973).
4. D. R. Slaughter, H. S. Spracklen, R. Delvasto, Nuc. Inst. Meth. 215, 443 (1983).
5. R. A. Coombe, B. A. Ward, Plasma Physics 5, 273 (1963).
6. J. D. Strachan, P. Colestock, H. Eubank, L. Grisham, J. Hovey, G. Schilling, L. Stewart, W. Stodiek, R. Stooksberry, K. M. Young, Nature 279, 626 (1979).
7. D. S. Pappas, R. J. Furnstahl, G. P. Kochanski, F. J. Wysocki, Nuc. Fusion 23, 1285 (1983).
8. W. A. Fisher, S. H. Chen, D. Gwinn, R. R. Parker, Nuc. Inst. Meth. 219, 179 (1984).
9. W. W. Heidbrink, Nuc. Inst. Meth. A236, 380 (1985).
10. M. S. Derzon, D. R. Slaughter, S. G. Prussin, "A High Pressure <sup>3</sup>He Gas Scintillation Spectrometer", this proceeding, 1985.
11. H. P. Spracklen, IEEE Trans. Nuc. Sci. NS-29, 896 (1982).
12. Dennis Slaughter, Robert Strout, II, Nuc. Inst. Meth. 198, 349 (1982).
13. Dennis Slaughter, "LINE: A Code Which Simulates Spectral Line Shapes for Fusion Reaction Products Generated by Various Speed Distributions", LLNL, UCID-20374, (1985).
14. Dennis Slaughter, J. Appl. Phys. 54, 1209 (1983).