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MARCH 1995

PRINCETON
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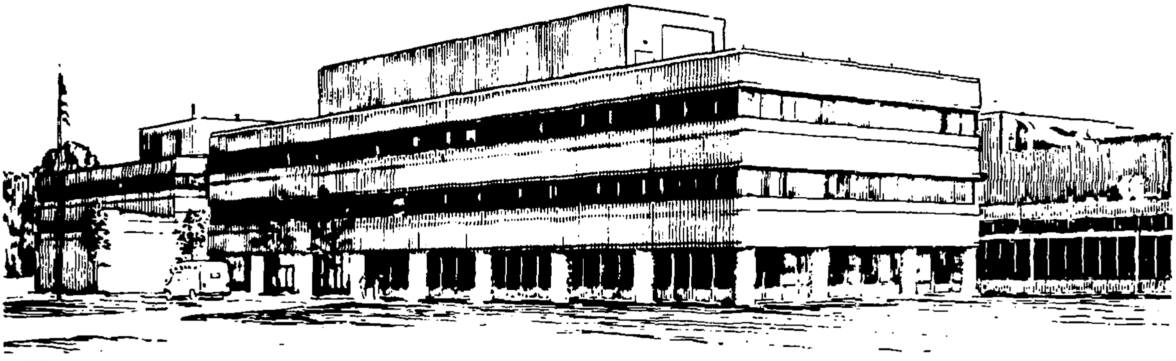

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Princeton University
Plasma Physics Laboratory

Cross-Calibration of Neutron Detectors for Deuterium-Tritium Operation in TFTR

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During the initial deuterium-tritium experiments on TFTR, neutron emission was measured with ^{235}U and ^{238}U fission chambers, silicon surface barrier diodes, spatially collimated ^{4}He proportional counters and ZnS scintillators, and a variety of elemental activation foils. The activation foils, ^{4}He counters and silicon diodes can discriminate between 14 MeV and 2.5 MeV neutrons. The other detectors respond to both DD and DT neutrons but are more sensitive to the latter. The proportional counters, scintillators, and some of the fission chambers were calibrated absolutely, using a 14-MeV neutron generator positioned at numerous locations inside the TFTR vacuum vessel. Although the directly calibrated systems were saturated during the highest power deuterium-tritium operation, they allowed cross-calibration of less sensitive fission chambers and silicon diodes. The estimated absolute accuracy of the uncertainty-weighted mean of these cross-calibrations, combined with an independent calibration derived from activation foil determinations of total neutron yield, is ±7%.

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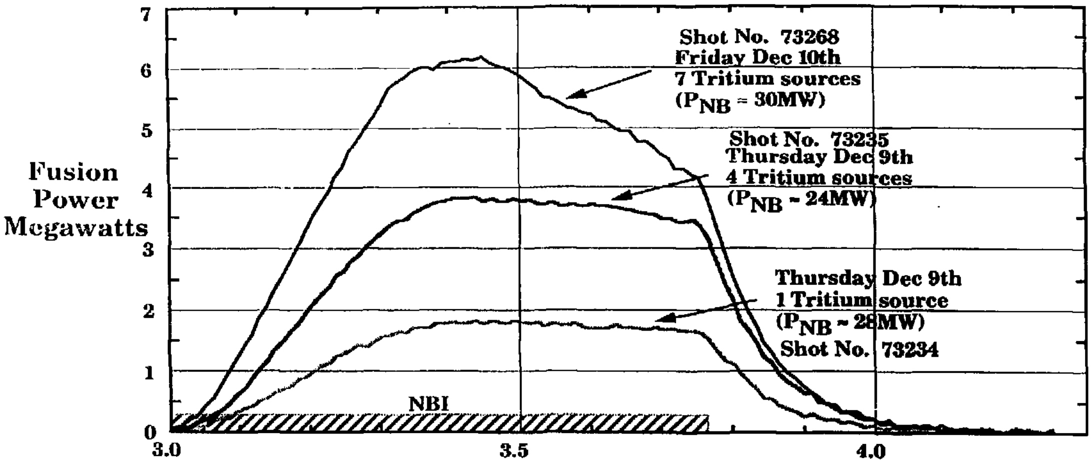
[c] University of California Irvine.

[d] JET Joint Undertaking.

Fusion Power of 6.2MW has been achieved on TFTR

TFTR



L. Johnson
J. Strachan

I. INTRODUCTION

High power deuterium-tritium experiments in TFTR began in December 1993. The highest fusion power attained up to the present is about 6.2 MW. This paper describes the detection systems used to measure DT fusion neutrons in TFTR and the procedures for calibrating those systems.

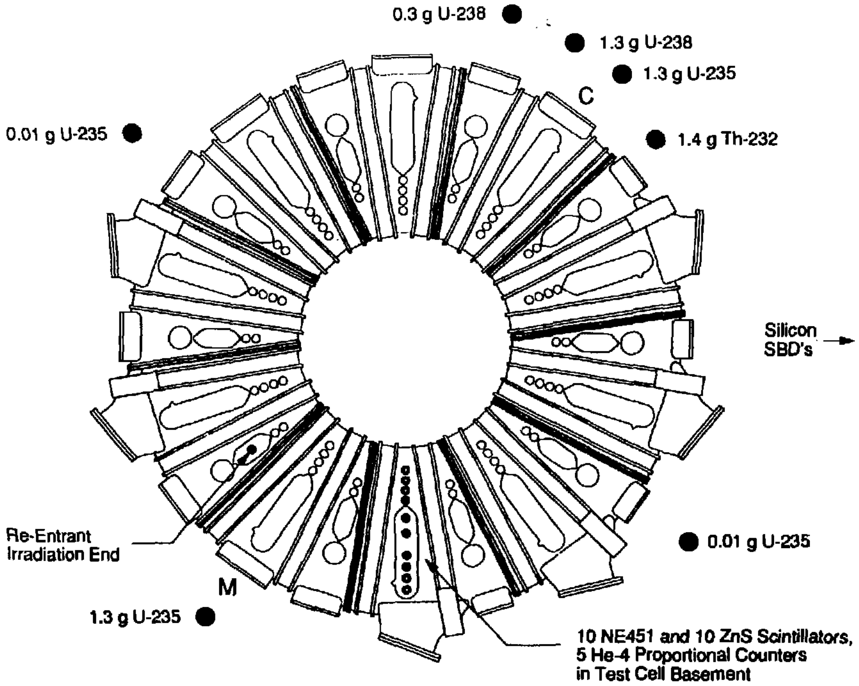
The principal neutron detection systems in use on TFTR during deuterium-tritium operation are listed in the accompanying table and figures. As indicated in the table, some of the detectors were calibrated *in situ* in February 1993 using a DT neutron generator inside the vacuum vessel to map the detector response functions. The directly calibrated detectors, together with independent activation foil measurements, were used to calibrate less sensitive detectors whose linear operating ranges extend beyond 10^{18} n/s. Analysis of the uncertainties of the individual cross-calibrations yields a weighted-mean efficiency for each of the less sensitive detectors and an estimate of the uncertainty of the resulting DT fusion power determinations.

Principal Neutron Detection Systems on TFTR

System		**Calibration**	**Energy Discrim.**	**Spatial Resolution**	**Temporal Resolution**
Fission Detectors					
U-235					
	2 @ 1.3 g	*in situ*	partial*	no	yes
	2 @ 0.01 g	cross	partial*	no	yes
U-238					
	1 @ 1.3 g	cross	partial*	no	yes
	1 @ 0.3 g	cross	partial*	no	yes
Th-232					
	1 @ 1.4 g	cross	partial*	no	yes
Neutron Collimator					
NE 451 (ZnS)		*in situ*	partial*	10 vertical chords	yes
ZnS wafer		cross	partial*	10 vertical chords	yes
He-4 proportional		*in situ*	yes	5 vertical chords	yes
Silicon Surface Barrier Diodes					
2 detectors		cross	yes	no	yes
Activation System					
1 re-entrant station		absolute via MCNP	yes	no	no
3 other stations		cross	yes	no	no

* More sensitive to 14 MeV than to 2.5 MeV neutrons

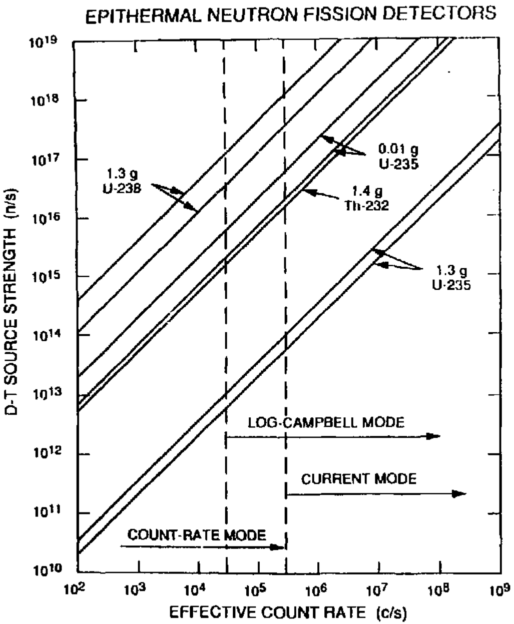
TFTR NEUTRON DETECTION SYSTEMS

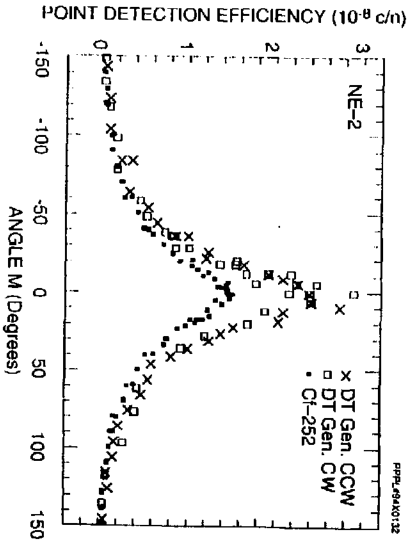


FISSION DETECTORS

Fission detectors have been used routinely for neutron source strength measurements on tokamaks for many years. The TFTR fission detectors can produce three electronic output signals: count rate mode, mean-square voltage (Campbell) mode, and current mode. In the case of the 1.3 g ^{235}U detectors, the directly calibrated count rate mode remains linear up to DT source strength $S_n \sim 10^{14}$ n/s, where it is limited by pulse pileup. Electronic noise and linearity characteristics limit the range of validity of the Campbell mode to $10^{13} — 3 \times 10^{17}$ n/s, while the range for the current mode is limited to $10^{14} — 3 \times 10^{17}$ n/s. Corresponding ranges for the 0.01 g ^{235}U detectors are somewhat more than 100 times higher. By taking advantage of overlapping linear ranges of the various data channels during DT operation, the *in situ* calibrations of the 1.3 g ^{235}U detectors may be extended to $S_n > 10^{19}$ n/s. Although fission detectors do not distinguish between 2.5 MeV and 14.1 MeV neutrons, their counting efficiency is higher for the latter. Plasma conditions with negligible contributions of DD neutrons relative to DT neutrons were selected for use during cross-calibrations.

The stability of the fission detector electronics between February and December 1993 was examined by periodically recording count rates of neutrons from small sources placed immediately adjacent to the detectors and by comparing relative counting efficiencies of the various fission detector data channels during several months of deuterium operation leading up to the tritium experiments. In this way, the effect of electronic instability on cross-calibrations was shown to be less than 5%.


EPITHERMAL NEUTRON FISSION DETECTORS
D-T SOURCE STRENGTH (n/s)
EFFECTIVE COUNT RATE (c/s)
10¹⁰
10¹¹
10¹²
10¹³
10¹⁴
10¹⁵
10¹⁶
10¹⁷
10¹⁸
10¹⁹
10²
10³
10⁴
10⁵
10⁶
10⁷
10⁸
10⁹
1.3 g U-238
0.01 g U-235
1.4 g Th-232
1.3 g U-235
LOG-CAMPBELL MODE
CURRENT MODE
COUNT-RATE MODE

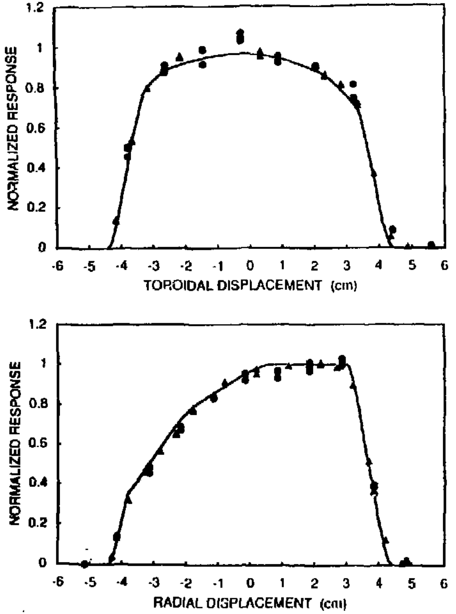

POINT DETECTION EFFICIENCY (10⁻⁸ c/n)
0
1
2
3
ANGLE M (Degrees)
-150
-100
-50
0
50
100
150
NE-2
× DT Gen. CCW
□ DT Gen. CW
• Cf-252
PPPL#94X0132

SPATIALLY RESOLVED MEASUREMENTS

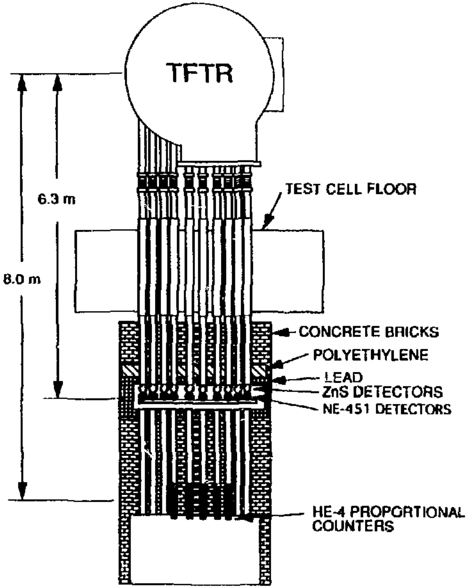
Spatial profiles of neutron emission from TFTR are monitored by arrays of detectors which view the plasma along ten vertical, collimated sight lines. The original configuration, which consisted of ten NE 451 (ZnS) scintillators, has been augmented by the addition of ten ZnS wafer scintillators developed in our laboratory and five ^{4}He proportional counters. Both the NE 451 scintillators and the ^{4}He counters were calibrated *in situ* for 14 MeV neutrons. The ^{4}He detectors use pulse height discrimination to reject counts from 2.5 MeV neutrons. Pulse height spectra from the scintillators do not permit complete rejection of counts from DD neutrons, but the detectors are more sensitive to DT neutrons by a factor ranging from 2 to 10, depending upon discriminator level.

For 14 MeV neutrons, the NE 451 detectors saturate for $S_n > 3 \times 10^{16}$ n/s. The low-sensitivity ZnS wafer scintillator system was designed to operate up to $S_n \sim 10^{19}$ n/s. By selecting appropriate plasma conditions, the ZnS wafer for each sight line may be cross-calibrated to the corresponding NE 451 detector. Similarly, after spatial integration, both the ^{4}He and NE 451 detectors may be used to cross-calibrate other detectors, e.g., fission chambers or silicon surface barrier diodes.

COLLIMATOR POINT RESPONSE FUNCTION @2.68 m



TFTR MULTICHANNEL NEUTRON COLLIMATOR

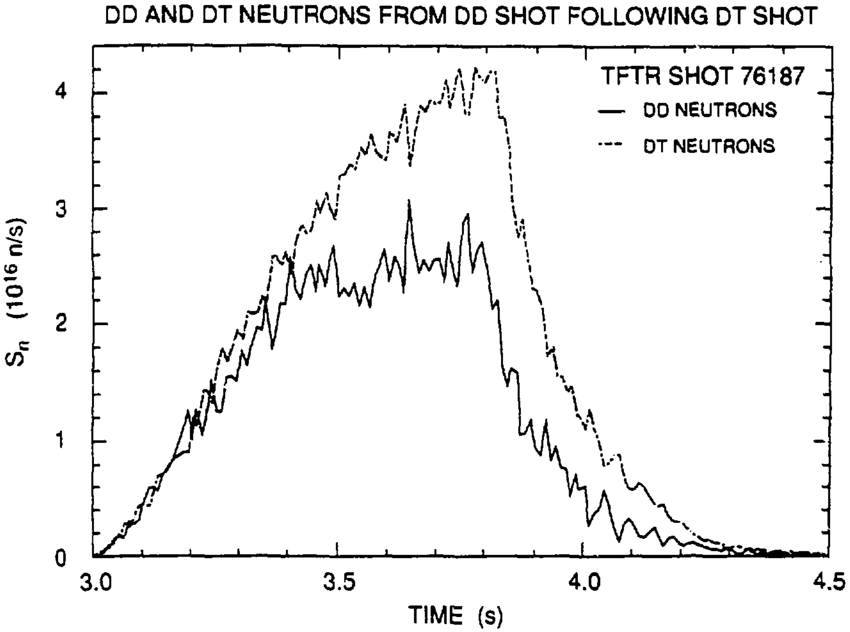


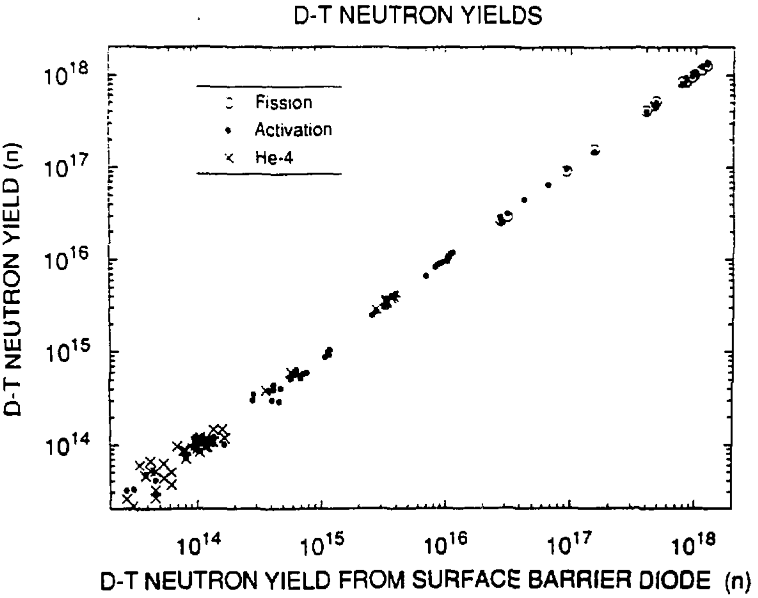
SILICON DIODES AND ACTIVATION FOILS

Two silicon surface barrier diodes have been installed near TFTR to enable unequivocal measurement of DT neutrons when DD neutrons are also present. One of the detectors is nearer to the plasma than the other, so that it has higher sensitivity and consequently lower statistical noise at small S_n, but it is also more susceptible to pulse pileup and radiation damage. Neither diode was in place during the February 1993 calibration.

For plasmas without tritium injection, separate determinations of DD and DT neutrons may be obtained by combining DT neutron measurements from the surface barrier diodes with DD + DT measurements from fission chambers.

A pneumatic transport system allows capsules containing various elemental foils to be irradiated at a number of stations near the TFTR vacuum vessel and then retrieved for analysis of the induced activation. One of the stations is a re-entrant irradiation end (REIE), for which most of the fluence consists of virgin neutrons. This minimizes errors in transport code modeling (MCNP) of the effect of scattered neutrons and allows a reliable determination of neutron yield for each plasma discharge. Since the neutron induced activation is intrinsically linear with respect to fluence, the yield may be compared to time-integrated signals from other neutron detectors to provide independent absolute cross-calibrations.


DD AND DT NEUTRONS FROM DD SHOT FOLLOWING DT SHOT
TFTR SHOT 76187
DD NEUTRONS
DT NEUTRONS
S_n (10^{16} n/s)
0
1
2
3
4
3.0
3.5
4.0
4.5
TIME (s)

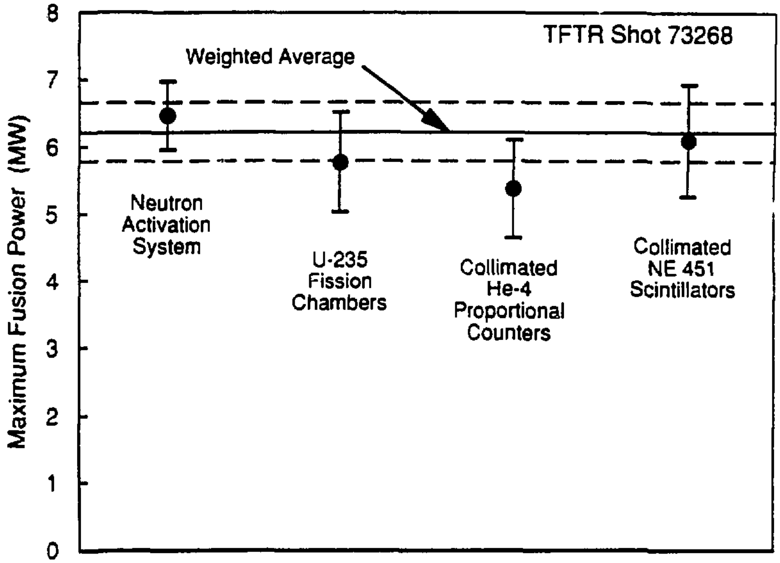

D-T NEUTRON YIELDS
Fission
Activation
He-4
D-T NEUTRON YIELD (n)
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
D-T NEUTRON YIELD FROM SURFACE BARRIER DIODE (n)

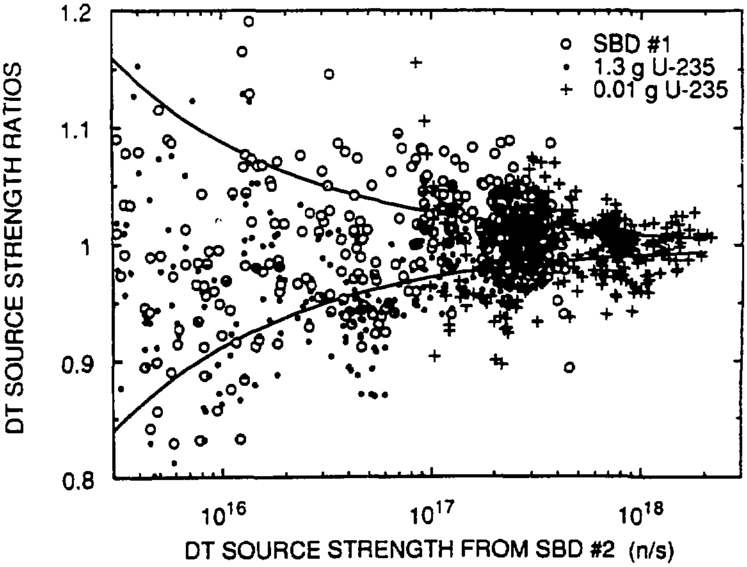
CROSS-CALIBRATION RESULTS

With three independently calibrated detector systems and an absolute determination of neutron yield from the activation foil system, there are a number of ways to cross-calibrate the less sensitive detectors. In order to obtain the most reliable values of S_n in high power deuterium-tritium experiments, we perform an uncertainty-weighted average of cross-calibrations, referred to a common data channel, namely, the current mode of a 0.01 g ^{235}U fission chamber. Except for cross-calibration from the activation foil system, intermediate steps are required to carry the *in situ* calibrations of 1993 into the range $S_n > 10^{17}$ n/s.

A figure below shows the maximum fusion power yet obtained in TFTR DT experiments, as determined by cross-calibration from the four systems just mentioned. Error bars represent overall uncertainties (one-sigma) for each determination. The solid and dashed lines represent the mean and its ±7% error bars, respectively, obtained by weighting the individual measurements by the inverse-squares of their independent uncertainties.

Comparisons of individual measurements of S_n from four detectors, cross-calibrated to the weighted mean, are also shown below. Each point represents a 0.1 second average of data from one of forty-one deuterium-tritium plasmas during the period 9 December 1993 to 11 March 1994. The plotted points show ratios of S_n from two fission detectors (current mode) and a surface barrier diode to values obtained from the second SBD. The solid lines show the (± one-sigma) statistical variations to be expected from the reference SBD alone.


TFTR Shot 73268
Weighted Average
Maximum Fusion Power (MW)
0
1
2
3
4
5
6
7
8
Neutron Activation System
U-235 Fission Chambers
Collimated He-4 Proportional Counters
Collimated NE 451 Scintillators


DT SOURCE STRENGTH RATIOS
0.8
0.9
1
1.1
1.2
○ SBD #1
• 1.3 g U-235
+ 0.01 g U-235
10^{16}
10^{17}
10^{18}
DT SOURCE STRENGTH FROM SBD #2 (n/s)

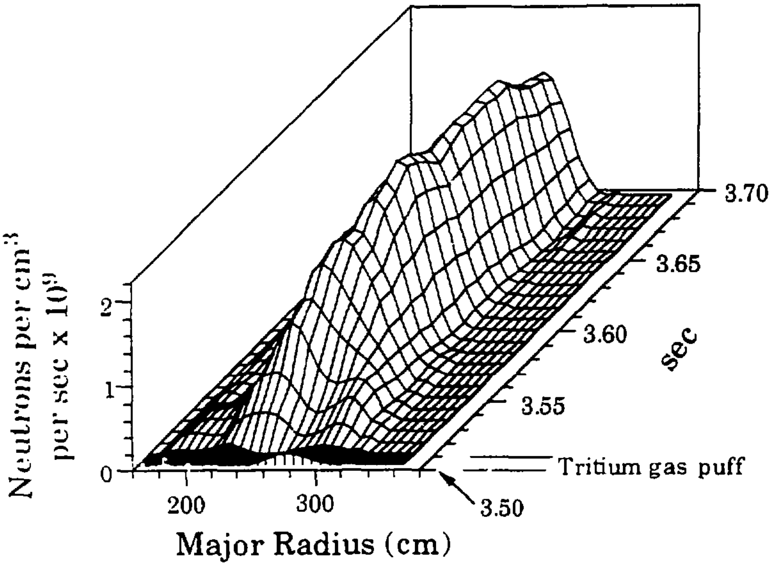
NEUTRON PROFILE RESULTS

Two examples of data from the ten ZnS wafer scintillators, cross-calibrated to the NE 451 (ZnS) detectors in the multichannel neutron collimator, are shown below. In the first case, pure tritium gas was puffed into a DD plasma, and tritium transport coefficients were deduced from temporal and spatial evolution of the excess DT neutrons.

The second figure below shows results from a recent high-β experiment. Values of S_n obtained by spatial integration of the neutron emission profile agree very well with measurements from a fission detector and a surface barrier diode. The neutron profile peaking parameter, i.e., the ratio of central to volume-average neutron emission, is also shown. The figure shows that both the global source strength and the profile peaking parameter increase until 2.95 s, when a central β-collapse occurs.

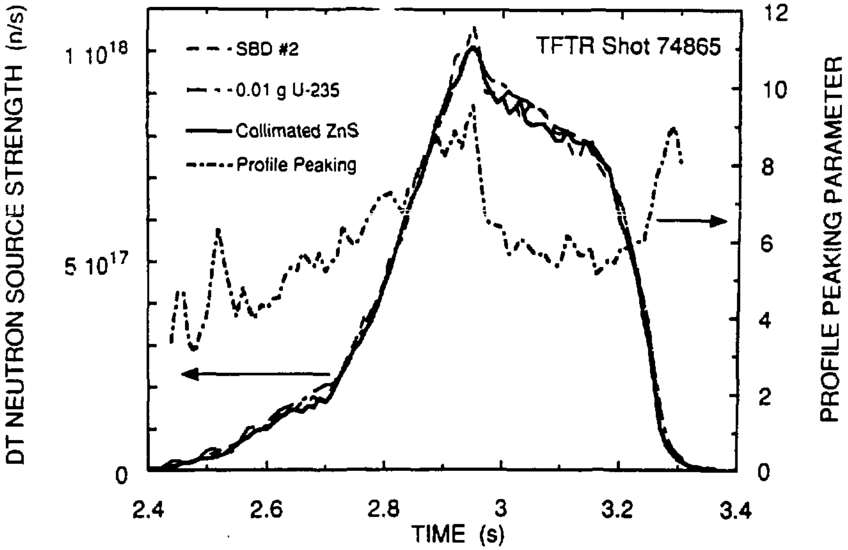
Abel Inverted D - T Neutron Profile

TFTR



- Rapid radial diffusion of tritium from the edge observed.

L. Johnson
P. Efthimion



SOURCE STRENGTH AND PROFILE PEAKING PARAMETER

CONCLUSIONS

TFTR has begun high power deuterium-tritium operation. A full complement of detection systems provides reliable and self-consistent measurements of DT neutron source strength and its spatial profile for all plasma conditions. The highest neutron source strength obtained to date is 2.2 × 10^{18} n/s. The estimated accuracy of the measurements, determined by an uncertainty-weighted mean of independently calibrated systems, is about ±7%. Statistical variations may be higher for individual measurements.

ACKNOWLEDGMENT

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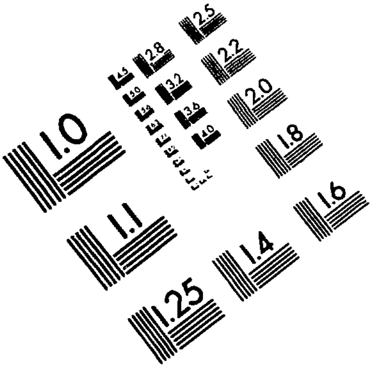

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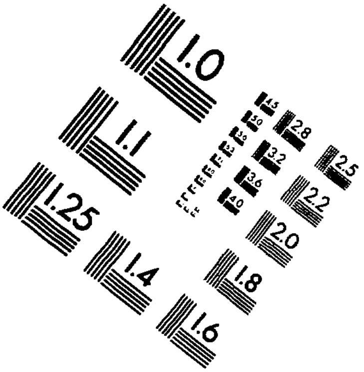

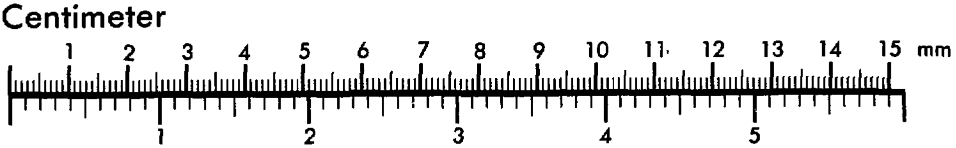

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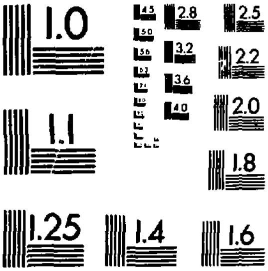

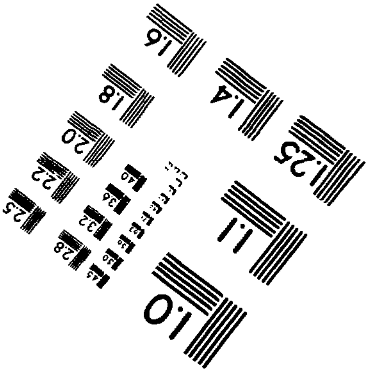

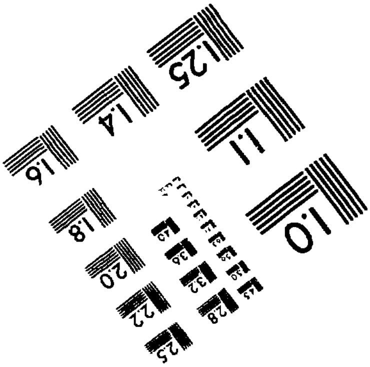

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