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Measurement of 14 MeV neutrons at TFTR with Si-diode detectors

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A detector system based on partially depleted silicon surface barrier detectors and fast front-end electronics has been built and cross calibrated to a set of absolutely calibrated ^{4}He recoil detectors. The cross-calibration factor for the channel with the widest dynamic range is 2.5×10^{-13} counts per 14 MeV source neutron. These data agree well with the independent neutron activation data. The new detector system covers a large dynamic range (corresponding to 10^{13}–10^{18} neutrons/s). The response is linear, except at the highest count rates where the detector dead time (~200 ns) causes departure from linearity. The noise discrimination against 2.5 MeV neutrons and γ pileup is excellent. Measurements of D-T neutrons from a tritium gas puff experiment as well as from a high-power D-T discharge in the TFTR tokamak are presented. © *1995 American Institute of Physics.*

I. INTRODUCTION

Since the startup of D-T operations at TFTR, in December 1993, accurate measurement of 14 MeV neutrons is of paramount importance. Time-resolved measurements of 14 MeV neutron emission are essential for insight into the tritium transport in tokamak plasmas and for determination of the peak fusion power.

The main challenge concerning D-T neutron measurements is the γ ray and D-D neutron backgrounds. A recent paper[1] surveys different techniques employed for neutron measurements of tokamak plasmas. Silicon diodes were used for time-resolved measurements of D-T neutrons produced by 1 MeV tritons on JET[2] and DIII-D.[3] They provided clear 14 MeV neutron emission data from the first trace tritium experiments at JET,[4] when the D-D neutron emission was about five times stronger than the D-T emission. Such measurements are possible because the $^{28}\mathrm{Si}(n,p)^{28}\mathrm{Al}$ and $^{28}\mathrm{Si}(n,\alpha)^{25}\mathrm{Mg}$ nuclear reactions have an effective threshold of ~7 MeV, thus being insensitive to the 2.5 MeV D-D neutrons.

Silicon diodes in conjunction with charge sensitive preamplifiers were used for neutron measurements at TFTR previously.[5] Although some useful data were obtained,[6] the diagnostics proved unreliable, possibly due to pileup of pulses produced by neutron-induced γ rays.[7] In our installation, based on a similar DIII-D system, we used fast front-end electronics (150 MHz bandwidth), which proved to be sufficient for avoiding γ pileup. The new system simultaneously covers the dynamic range of two other 14 MeV neutron diagnostics systems at TFTR: the ^{4}He recoil detectors,[8] which saturate at count rates of 25 000 c/s, and the fission chambers,[9] which accurately measure D-T neutrons only when they are more numerous than the D-D neutrons. The Si-diode detector system is especially useful in the intermediary range of 14 MeV neutron emission, such as in the case of trace tritium experiments, tritium wall recycling studies, and tritium gas puff experiments.

II. DETECTOR DESIGN

The system has two detectors and their sight lines point between the toroidal field coils of the tokamak. One is placed about 4 m away from the plasma center. The other is placed about 15 m away, in the empty space of a neutron collimator (NC), and benefits from the neutron and γ-ray shielding that the massive collimator structure provides.

We use partially depleted silicon diodes[10] with 500 μm depth and 300 mm^2 (closer diode) and 600 mm^2 (NC) surface area. Each detector box contains a diode, a preamplifier, and a 15 V power supply. We modified the preamplifier[12] to accommodate the 150 V bias on the diode.

The overall scheme of the detector system with its typical signal waveforms is shown in Fig. 1. The long distance between the detectors and the processing electronics as well as the lack of double shielded coaxial cables demand signal

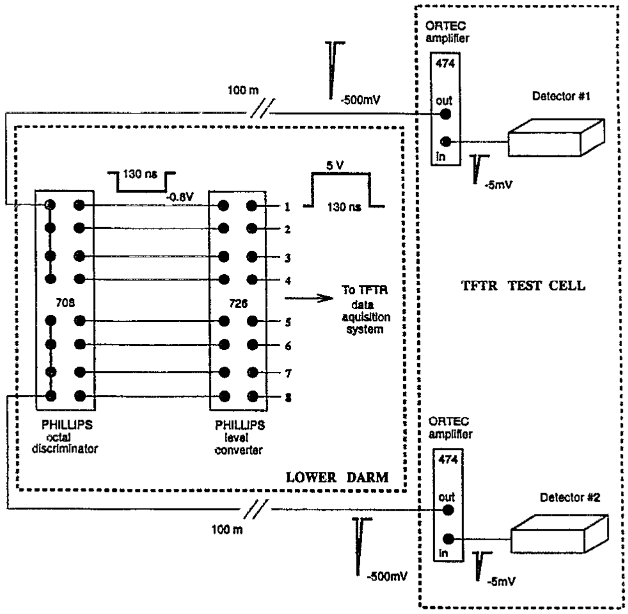

FIG. 1. Si-diode detector system (schematic). For clarity, eight unused channels of the Philips 726 level converter, as well as the HV power supplies for diode bias, are not shown.

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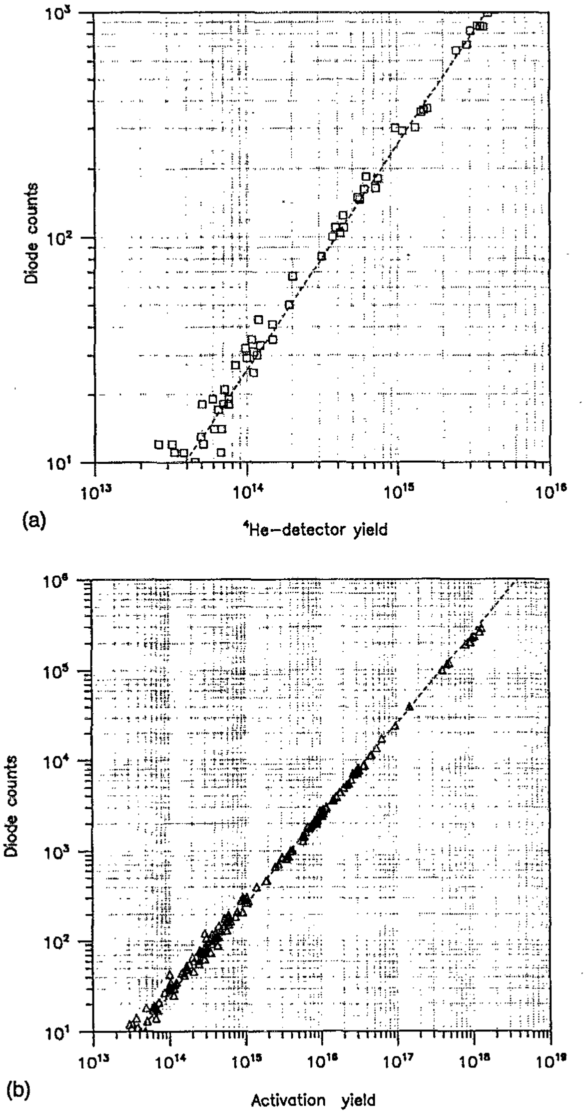

FIG. 2. (a) Diode calibration with the ^{4}He-detector system. The slope of the straight line is 2.58×10^{-13}. (b) Diode calibration with the NA system. The error bars are of the size of the symbols, or smaller, except for counts below 80. The slope of the straight line is 2.53×10^{-13}.

amplification near the place of origin. The two signals are then fed to a pulse height discriminator[11] set to discriminate at levels corresponding to neutron energies of 5.0, 7.5, 10.0, and 12.5 MeV. These multiple channels extend the dynamic range of the detector system and help detect contamination of the pulse spectrum. A 1 μCi Am-241 alpha source is used to set the discrimination levels. The alpha pulse height and detector leakage current are monitored for evidence of radiation damage to the detector. We replace the detector (and readjust the gain on the amplifier) when the leakage current has doubled or tripled. The last module in the system converts NIM signal levels to TTL levels without affecting the pulse duration.[11]

The preamplifier, the discriminator, and the level converter have bandwidths of 500, 300, and 150 MHz, respectively. We believe that, by avoiding γ pileup, they are the main reason for the successful operation of the Si-diode detectors.

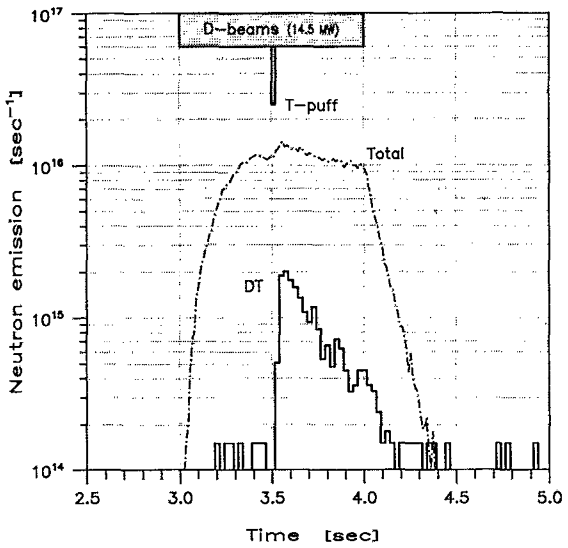

FIG. 3. Total neutrons measured with fission detectors, and D-T neutrons measured with Si diode, from a tritium gas puff experiment. The Si-diode counts are integrated over 25 ms. Deuterium beams (14.5 MW) heat this plasma, from 3 to 4 s.

III. DETECTOR CROSS CALIBRATION

The integrated count rate from each of the eight channels is entered into the MINGL database[13] and compared to the 14 MeV neutron yields from the TFTR neutron activation (NA) system[14] and the ^{4}He detectors.[8] The ^{4}He detectors were absolutely calibrated to an accuracy of 15% using an *in situ* 14 MeV neutron generator. The widest dynamic range is attributed to the signal from the diode in the neutron collimator, obtained by discriminating neutrons with energies lower than 7.5 MeV. The subsequent discussion refers to that particular channel. The cross calibration to the ^{4}He detector system is shown in Fig. 2(a). Analysis of the 83 dataset points result in a Si-diode response coefficient of $(2.58\pm0.05)\times10^{-13}$ counts per 14 MeV source neutron.

This calibration factor is consistent with the one obtained from the cross calibration to the independently calibrated NA system. The accuracy of the NA measurement is determined separately for each shot; for most of the points it is ~10%. Silicon foils were used for the majority of NA measurements, while aluminum and iron foils were occasionally used. For improved cross-calibration accuracy, shots with absolutely calibrated NA data are chosen, and for reasonable counting statistics, shots with yields lower than 10^{13} are discarded. Thus a subset of 173 data points is created (the full set has 273 data points). The integrated count rate versus NA yield is shown in Fig. 2(b). Plots of the ratio of the diode counts to the NA yield versus NA yield show slight saturation for yields higher than 5×10^{17}. Analysis of the corresponding data subset indicates a 7% saturation, which is consistent with detector dead-time corrections. The response coefficient for the channel with the widest dynamic range is $(2.53\pm0.02)\times10^{-13}$ counts per 14 MeV neutron, in the

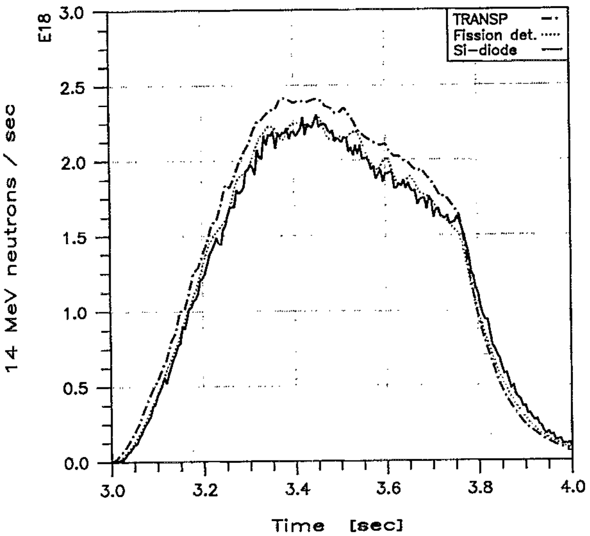

FIG. 4. Comparison of measured and TRANSP predicted D-T neutrons from a high-power discharge (30 MW NBI). Seven tritium and four deuterium beam lines heat this plasma, from 3.00 to 3.76 s.

10^{13}–5×10^{17} range, and $(2.35\pm0.05)\times10^{-13}$, for yields higher than 5×10^{17}. Therefore, in the operational range of the ^{4}He detectors (10^{13}–10^{16}), the Si-diode detector efficiencies, calculated by both methods, disagree by only 2%.

The highest point in Fig. 2(b) has a peak count rate of 500 000 c/s, which corresponds to a peak fusion power of ~6 MW. We expect that the channel under consideration is useful up to peak fusion powers of 10 MW, where the correction due to the detector dead time will be ~10%.

IV. MEASUREMENTS OF TFTR DISCHARGES

The Si-diode detectors were deployed at the end of August 1993, prior to the introduction of tritium into the TFTR vessel. Initial 14 MeV neutron data are from tritons produced in D-D reactions. The diode signals from these "burnup" measurements are delayed with respect to the 2.5 MeV neutron rate, as expected for classical deceleration of tritons. During the 1993 D-T operations, there were 59 trace tritium discharges (tritium content less than 2%), 13 tritium gas puff discharges (with 100% T-gas puff), and 27 discharges with mixed deuterium and tritium NB heating. The fusion power produced from these D-T discharges is discussed in Ref. 15. Here we present measurements from one gas puff discharge and one high power D-T discharge.

Gas puffing experiments are designed for fuel transport studies from the plasma boundary inward.[16] Total and D-T neutron measurements[17] from the first T-gas puff discharge in a series of eight such discharges are shown on Fig. 3. Diode counts start 200 ms after the deuterium beams are turned on, and they are attributed to tritium released from the walls of the vacuum vessel. On subsequent discharges, this early signal shifted closer to the beam startup time and grew larger as tritium accumulated in vessel components. At 3.5 s a short (20 ms) 100 Torr ℓ/s T-gas puff was introduced. The sharp increase of the diode signal and its subsequent decay are evident. All these details in the 14 MeV neutron signal are detected amidst 10–100 times stronger 2.5 MeV neutron background, and they demonstrate the insensitivity of the Si diode to D-D neutrons.

Figure 4 shows 14 MeV neutron measurements with fission and Si-diode detectors, together with a TRANSP code[18] prediction for the D-T neutrons in a plasma heated by seven T beams and four D beams (total power 30 MW). The Si-diode channel with the widest dynamic range, calibrated to the NA yield from this particular shot, was used. The two measurements agree very well. The simulation overestimates the rate by only 7%, which is within the uncertainties of the measurement and the simulation.

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