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for Plasma Diagnostics***

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AN ULTRAHIGH-SENSITIVITY THRESHOLD NEUTRON DETECTOR FOR PLASMA DIAGNOSTICS*

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Abstract

An ultrahigh-sensitivity fast fission counter was developed to selectively detect high-energy neutrons ($E_n > 1$ MeV) produced by D-D and D-T fusion reactions in thermonuclear plasmas. Discrimination against slow and epithermal neutrons produced by scattering or electro-dissociation of deuterium was achieved by sensitizing the detector with 100 g of highly depleted $^{238}\text{UO}_2$, which has a fission threshold for neutron energies $E_n > 1$ MeV. The capacitive signal loading effects of the detector's large electrode area (5 m^2) were mitigated by using a transmission-line electrode configuration. Wideband, low-noise preamplifiers were developed to match the 25- Ω characteristic impedance of the transmission line. The neutron sensitivity of the detector was shown to be $0.07 \text{ counts} \cdot \text{s}^{-1} \cdot [\text{neutron}/(\text{cm}^2 \cdot \text{s})]^{-1}$ for $E_n > 2$ MeV in initial laboratory testing.

Introduction

An ultrahigh-sensitivity fast fission counter (UHSFFC) was designed and fabricated to selectively detect neutrons emitted by fusion reactions in thermonuclear plasmas. The design of the UHSFFC is based on the technology developed for the source range neutron flux monitoring channels of the Clinch River Breeder Reactor (CRBR) Project.¹ The sensitive volume and outer gas envelope (13.5 cm OD by 80 cm long) are nearly identical to those designed for the CRBR source range instrument thimbles, with the major difference being the substitution of highly depleted uranium for highly enriched uranium in the neutron-sensitive electrode coatings. The UHSFFC is sensitized with 100 g of highly depleted $^{238}\text{UO}_2$ to provide inherent discrimination of neutrons having energies below the ^{238}U fission threshold (i.e., for $E_n < 1$ MeV) such as those dissociated from deuterium by energetic electrons ($0 < E_n < 0.2$ MeV).

Fission Counter Construction

All of the desirable features of the prototype built for the CRBR were incorporated in the design of the UHSFFC. The electrodes were fabricated from 0.5-mm-thick aluminum sheet stock by premachining the profiles and then rubber-die forming them to produce a curvature (i.e., an r - θ relationship) given by

$$\theta = \left(\frac{r^2}{k^2} - 1 \right)^{1/2} - \cos^{-1} \left(\frac{k}{r} \right) \quad (1)$$

where k is a constant shape factor. Electrodes with curvatures described by Eq. 1 can fill completely an annular volume while maintaining a constant normal interelectrode gap (Fig. 1), thus maximizing specific sensitivity for the cylindrical geometry. After forming, the electrodes were coated with $^{238}\text{UO}_2$ to a thickness of $2 \text{ mg}/\text{cm}^2$ via the electrodeposition process. The UHSFFC contains 236 electrodes which are assembled into four identical sections. With a total electrode area of 5 m^2 and an interelectrode gap of 1.5 mm, the

Fig. 1. An end view of a UHSFFC mockup section shows the curved electrodes arranged to provide a constant normal interelectrode gap.

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total interelectrode capacitance is 15,000 pF. To reduce the capacitive signal loading to an acceptable level, the 29 signal electrodes of each section are connected with a copper helix whose pitch and diameter are adjusted to produce a 25- Ω lumped-element transmission line composed of 29 m-derived filter sections² having an m-value of 1.35 and a total propagation delay of 90 ns (Fig. 2). In the UHSFFC, the four sections are configured as two independent 180-ns-long transmission-line fission counters (TLFCs)³ by series connections of paired sections. With this arrangement, the input impedance seen by each signal electrode consists of two parallel 25- Ω transmission lines (12.5 Ω) rather than the low impedance of the full 7500-pF capacitance of two sections (~ 1 Ω at 20 MHz).

Experience gained through fabrication and testing of the prototype indicated the need for the modifications implemented in the design of the UHSFFC. In particular, the need for complex, machined ceramic electrode support rings was eliminated by supporting each high-voltage signal electrode with four slotted

alumina pins. This modification reduced the assembly cost and complexity and provided a more rigid structure. Also, the aluminum-to-aluminum compression connections between the signal electrodes and aluminum helices of the prototype were abandoned in favor of aluminum to indium-tinned-copper compression connections. This modification enabled us to consistently produce electrical connections with low contact resistances in the m Ω range.

During final assembly, the four preassembled sections were clamped together to form a single rigid unit (Fig. 3), and the serial connections between paired sections were made. The TLFC output signals were routed through the central support column to insulated feedthroughs in the header on 25- Ω stainless-steel-sheathed coaxial cables. Welding a 0.75-mm-thick cylindrical stainless steel envelope to the header completed the assembly.

CF₄ Counting Gas

The UHSFFC was filled to 1520 torr with an Ar+20% CF₄ gas mixture having an electron drift velocity of ~ 12 cm/ μ s. This mixture provides very short electron collection times of 12 to 15 ns and produces large amplitude current pulses of short duration which result in high signal-to-noise ratios and extended rate capability. The pressure is lower than that of the prototype (2000 torr) to decrease the charge density in fission fragment tracks, thus permitting operation at lower voltages (450 V versus 600 V for the prototype).

The performance of CF₄ gas mixtures used in fission counters is known to degrade with neutron irradiation, making these mixtures unsuitable for many fission reactor flux-monitoring applications.⁴ However, subsequent measurements by the authors show that performance is essentially unaffected by neutron exposures resulting in $\leq 10^{14}$ fissions per gram of CF₄. Thus, if the UHSFFC were providing 10^6 counts per plasma discharge, it would provide reliable data for at least 10^8 discharges.

Instrumentation

Each end of both TLFCs is terminated with a newly developed shunt-feedback preamplifier⁵ having an active input impedance of 25 Ω , a bandwidth of 60 MHz, and an input-referenced noise density of ~ 20 pA/ $\sqrt{\text{Hz}}$. The preamplifiers were mounted directly on the counter

Fig. 2. This side view of a preassembled UHSFFC section shows the ground plates retained by slotted aluminum rings. The signal electrodes are connected by a continuous helical inductor to form the lumped-element transmission line.

Fig. 3. The four sections of the UHSFFC are clamped together on a common axis. The first and second sections constitute an independent TLFC, as do the third and fourth sections.

header, thus eliminating the need for long interconnecting cables with the attendant signal losses and noise pickup. This was possible because the average radiation levels (and hence the radiation damage rate) associated with pulsed operation of fusion test reactors are three to five orders of magnitude lower than the CRBR ex-vessel design values of 10^5 R/h and 10^{10} neutrons/(cm²-s).

The balance of instrumentation was very similar to that described in Ref. 1 for the prototype. Because of the lower alpha activity of the $^{238}\text{UO}_2$ coatings (compared to $^{235}\text{UO}_2$ coatings), the pulse duration from the shaping amplifiers was increased from 20 ns to 40 ns for improved signal-to-noise ratio. However, even with the longer pulse duration, the rate capability of the UHSFFC is 5 MHz per TLFC with 10% counting losses. As shown in Fig. 4, the shaping amplifier outputs drive leading-edge (LE) discriminators, which in turn drive either a time interval analyzer for measurements

requiring spatial sensitivity or a bilateral coincidence gate for integral counting.

Performance Characteristics

The UHSFFC can be used to perform integral counting in either of two modes. In coincidence mode, output pulses from the bilateral coincidence gate are counted. In noncoincidence mode, output pulses from either LE discriminator are counted. Both types of data are plotted in Fig. 5 as integral pulse height distributions (i.e., plots of positive threshold level

Fig. 4. A TLFC has two signal outputs, each of which is instrumented with a preamplifier (PA), a shaping amplifier (SA), and a leading edge (LE) discriminator. The position of a fission pulse (i_f) is decoded from the time difference between discriminator outputs by a time interval analyzer. The output of the bilateral coincidence gate (resolving time $\sim 1.1T$) is used for integral pulse counting and provides improved rejection of spurious pulses from uncorrelated noise sources.

Fig. 5. Integral pulse height spectra of preamplifier noise (squares) and inherent alpha activity (triangles) demonstrate the superior rejection of uncorrelated random noise obtained during coincidence mode operation. Note also the flatness of the neutron counting plateaus (circles) and the very low level of inherent alpha activity.

crossing rates versus the threshold level). Since the slopes of the neutron plateaus are small, both modes provide about the same neutron sensitivity. The advantage of the coincidence mode, therefore, lies in the ability to operate at effectively higher threshold settings for greater immunity to random noise (i.e., preamplifier noise, inherent alpha pileup noise, and gamma pileup noise if present).

The data for Fig. 5 were obtained using an unmoderated Pu-Be neutron source emitting 10^7 neutrons $\cdot$ s $^{-1}$, so the absolute neutron sensitivity of the UHSFFC can be estimated as $S_{\text{fast}} = C(V_1)/\phi_{\text{fast}}$, where

$$\phi_{\text{fast}} = \frac{1}{V_s} \int_{V_s} \frac{10^7}{4\pi r^2} dV \text{ neutrons}/(\text{cm}^2 \cdot \text{s})$$

is the fast flux averaged over the sensitive volume, V_s ; r is the distance between the center of the source and dV ; and $C(V_1)$ is the integral count rate obtained at the threshold setting V_1 , which limits the spurious count rate to 1 s $^{-1}$. The result is 0.035 counts $\cdot$ s $^{-1}$ [neutron/(cm 2 $\cdot$ s)] $^{-1}$ for each TLFC, or 0.07 for the entire counter.

High-purity ^{238}U was used for the electrode coatings to minimize the thermal and epithermal sensitivities of the UHSFFC. The isotopic composition of the feed material was 999989 ppm of ^{238}U ; 11 ppm of ^{235}U ; and <1 ppm each of ^{233}U , ^{234}U , and ^{236}U . The fast-to-thermal sensitivity ratio is approximately equal to the ratio of the respective macroscopic fission cross sections; that is,

$$\frac{S_{\text{fast}}}{S_{\text{thermal}}} = \frac{0.55 \text{ barn}}{(570 \text{ barn}) \cdot (11 \times 10^{-6})} = 88.$$

Thus, if the fast and thermal fluxes were equal, an error of about 1% would result from attributing the total detector response to fast ($E_n > 1$ MeV) neutrons. A method based on the inherent position sensitivity of a TLFC was incorporated in the UHSFFC to detect a significant thermal flux component. Each fission event in a TLFC produces two current pulses that propagate toward opposite ends of the transmission line so the position of each fission is encoded as the difference between pulse arrival times at each end of the line. The time spectrum is easily decoded with a conventional time-to-amplitude converter and a pulse height analyzer (Fig. 6). In the UHSFFC, the first of 58 signal plates

in each TLFC was tagged with additional ^{235}U to increase its thermal sensitivity by a factor of 10. In the previously cited case of equal fast and thermal fluxes, the tagged plate would yield about 10% more count rate than untagged plates, thereby providing a correction factor to the total count rate.

Since the internal structure of the UHSFFC is similar to that of the prototype, both counters should have approximately the same gamma sensitivity. The sensitivity of the UHSFFC may be slightly higher ($<10\%$) than the measured prototypic value of $0.52 \text{ nA} \cdot (\text{R/h})^{-1}$ due to substitution of stainless steel for aluminum in the counter envelope. Again drawing from the data base obtained from testing of the prototype, the UHSFFC is estimated to lose no more than 10% of its neutron sensitivity in gamma fields up to 10^5 R/h.

Discussion

The UHSFFC has been successfully used for measurements at the EBT (Elmo Bumpy Torus) facility at Oak Ridge National Laboratory (ORNL) and is presently installed at the TFTR (Tokamak Fusion Test Reactor) facility at Princeton, where it should prove to be a useful complement to the ^{235}U fission counters already in use. The UHSFFC should be particularly useful during neutral beam heating experiments where its high rate capability, high neutron sensitivity, and inherent discrimination of electrodisassociated and thermalized

Fig. 6. A time spectrum of the UHSFFC permits measurement of individual fission rates from each signal plate. The shape of the peak height envelope is due to azimuthal position sensitivity to a small fast neutron source. In a neutron field having a significant slow component, the response of the tagged electrode would be relatively larger. The time separation between electrodes is 5.5 ns.

neutrons will more accurately measure ion temperatures and yield better time resolution of temperature oscillations during the -3-s discharges.⁶

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