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TITLE DIAGNOSTIC TECHNIQUE FOR MONITORING HIGH TEMPERATURE PLASMA DYNAMICS

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SUBMITTED TO Proceedings for presentation at AIAA 19th Fluid Dynamics,
Plasma Dynamics, and Lasers Conference, Honolulu,
June 7-10, 1987

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Diagnostic Technique for Monitoring High Temperature Plasma Dynamics

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ABSTRACT

A preliminary design for the adaptation of a pinhole experiment (PINEX) technique to the monitoring of the dynamics of high temperature plasmas is described. Specifically, this imaging technique uses a thick aperture, an efficient radiation converter, and highly intensified television cameras to provide real-time viewing of radiation sources such as the neutron emissions from d-d and d-t fusion reactions in controlled thermonuclear research devices. The neutron emission strengths, $R \sim 5 \times 10^{15} \text{ n/s}$, recently achieved at the Tokamak Fusion Test Reactor (TFTR) and the Joint European Torus (JET) should be sufficient for 3 to 6-cm spatial resolution and 10 to 100-ms time resolution using such a system. Such information should be useful for on-line optimization of the plasma and for quantitative evaluation of its performance.

Introduction

An improved understanding of the time-evolution of d-d and d-t fusion reaction rates in magnetically confined plasmas may be attained by visualization of the neutron source with advanced radiation imaging techniques.⁽¹⁾ In particular, the application of a pinhole experiment (PINEX) technique would provide real-time viewing on a television monitor of the radiation source that in turn reflects the plasma dynamical behavior. PINEX uses a thick aperture, an efficient radiation converter, and a highly intensified television camera. The images can be digitized in both on-line and off-line modes to yield spatially and temporally resolved information about the plasmas. In this paper, the d-d mode of operation in some Tokamaks is shown to be a case similar to that of a fissioning test pin (driven by a thermal neutron test reactor) that was successfully imaged several years ago.^(2,3) Present operational parameters of controlled thermonuclear research devices, such as the Tokamak Fusion Test Reactor (TFTR) at Princeton and the Joint European Torus (JET) at the Culham Laboratory, result in production of copious amounts of neutrons sufficient in magnitude for measurement using this imaging technique.

It is estimated that the recently reported^(4,5) neutron emission strengths $R \geq 5 \times 10^{15} \text{ n/s}$ will allow the system to provide 3 to 6-cm spatial resolution and 10 to 100 ms time resolution for these types of sources. As higher neutron emission rates are attained in fusion reactors, one can anticipate reducing the spatial and/or time sampling size. The system can also work for a d-t neutron source and, hence, could be applied in future d-t operation of TFTR or the Compact Ignition Tokamak (CIT). These measurements can be

made under a wide variety of plasma operating conditions in Tokamaks, including 1) normal ohmic heating; 2) neutral beam and/or RF heating; 3) pellet injection; 4) RF current drive. The system described below will contribute to the detailed physics base required for the study and understanding of the dynamics of this type of high-temperature plasma source.

Progress in High-Temperature Plasma Source Development and Neutron Diagnostic Requirements

Since magnetic fusion energy research began in the early 1950s, a great deal of effort has been applied toward developing and exploiting a wide range of fusion device configurations. This goal continues today, although the bulk of fusion research funding is directed toward the Tokamak effort. From the earliest days in the program, neutron diagnostics have played a central role. Even though the neutron rates observed were very small (and that some experimenters were overly optimistic of their being of thermonuclear origin) registration of these neutrons proved that in some cases the plasmas in question were, in fact, of thermonuclear grade.⁽⁶⁾

This progress in achieving large neutron rates now allows more sophisticated neutron diagnostics to be employed, which in turn, allows the potential for better understanding of plasma dynamical behavior. In fact, in contrast to the early days of fusion research when neutron rates were very low (thus causing large statistical uncertainties with the measurements), the high neutron fluxes expected from the d-t operating of TFTR and CIT now present diagnosticians with the problem of having such high count rates that pile up and potential radiation damage must be addressed.

Shown in Table I is a summary of types of neutron diagnostics now in use at various fusion facilities. The diagnostics listed are capable of registering useful information at intermediate levels of rates (10^9 - 10^{14} n/s), which are achievable by the high-performance Tokamaks in operation today. Additionally, when a single or multichannel collimator system is used in conjunction with one or more of the detector systems listed in Table I, the systems can be used to provide spatially-resolved neutron production rate information from which perpendicular (and/or parallel) ion energy distribution information can be inferred. Also achievable is registration of spatial and temporal behavior of neutron rate and ion temperature of the plasma in question. In sufficiently bright discharges, inferences can be made concerning MeV ion confinement, i.e., by measuring the 14 MeV neutron component in d-d plasma operation (produced by confinement high-energy ions in the triton branch of the reaction).

The above systems can be used during ohmically heated, rf and/or neutral beam heated, and pellet-injected discharges. In addition, these diagnostic systems can be used to study nonfusion neutrons arising from multi-MeV electrons through electrodisintegration and photonuclear processes, thus providing information concerning energetic electron populations in ohmic and RF current driven operating modes. Only recently during

neutral beam operation in TFTR and JET where neutron rates exceeding 5×10^{15} n/s have been achieved, has it become possible to employ advantageously the PINEX neutron imaging techniques that will be described in the following sections.

It should be noted that common to all of these diagnostic systems are the associated difficulties that arise because of operational and geometrical characteristics of the Tokamak. Specifically, the diagnostician must take the necessary precautions against interference due to neutron, x-ray, γ -ray background, and magnetic and electromagnetic fields. The PINEX electronics have been qualified in the fission reactor experiments in regard to ionizing radiation backgrounds and in linear accelerator experiments in regard to radiofrequency fields and magnetic fields. Additionally, the diagnostic system must be operable over a very wide dynamic range due to steep temperature and density profiles as well as the normal wide range of operational parameters of the device.

TABLE I
Commonly Used Neutron Diagnostic Systems In Fusion Research

<u>Technique</u>	<u>Measured Parameters</u>	<u>Features</u>
^3He Spectrometer	$T_i(r=0, t)$	Very high energy resolution
BF_3 (or U^{238} fission) long counter arrays	Total Neutron Flux, $T_i(r=0, t)$	No energy resolution
NE 213 Spectrometer	Energy Spectra of both D-D and D-T produced neutrons	Moderate energy resolution
Fission Foils	Time integrated neutron yield	Some energy resolution

Pinex Imaging Applications

The nature of the radiation source in regard to emission brightness, geometrical extent, type and energy of radiation, etc., plays a major role in the design of the imaging system. At the Transient Reactor Test Facility (TREAT), the fuel pin brightness (10^{17} n/cm²-s) when the reactor was at 100-MW power and the pin's 5-mm diameter by 0.75 m length guided our choice of number of apertures and the pin slit dimensions. Additionally, the spatial and time structure to be monitored such as the fuel diameter change and axial motion at pin failure in the time scales of interest must be considered. In the case of the plasma dynamics imaging experiment, the neutron rate, neutron energy (d-d or d-t fusion), the source dimensions, and the time scales of interest were considered.

Treat PINEX

As a reference example for imaging a time-dependent neutron source, we cite the successful PINEX imaging of a fissioning prototype liquid metal fast breeder reactor (LMFBR) fuel pin of only 5-mm diameter positioned in the test section of the Transient Reactor Test Facility (TREAT). The test pin's emitted neutrons were more representative of a fission neutron spectrum with average energy about 1-2 MeV than the thermalized driver neutrons of the TREAT core. A schematic of the imaging technique is shown in Fig. 1. In the example two apertures viewed different regimes. The experimental layout is illustrated in Fig. 2. Background neutrons and γ -rays from the reactor were reduced by the reactor wall and additional shielding around the thick aperture, the radiation converter, and the intensified television cameras.⁽⁷⁾ In the case of a 0.4-mm wide by 3-mm tall pin slit, effective spatial resolutions of about 1- and 6-mm, respectively, were achieved at the image plane with unity magnification. The test pin driven by 20 MW reactor power generated about 2×10^4 n/cm²-16 ms at the fluor, and this brightness was sufficient for imaging. Note the aperture was located about 2.7 m from both the object and image planes in Fig. 2. Sample video images are shown in Fig. 1 of Ref. 3 and reproduced here in Fig. 3. The vertical white band is the fuel pin as "seen" by its emitted neutrons and gamma rays using PINEX. At cladding failure the fuel diameter changed from 5 mm to 8 mm in filling the coolant channel surrounding it.

Preliminary Design for a Tokamak PINEX

As applied to the plasma dynamics problem, the neutron rate R_N as a function of space and time for d-d and d-t operation can be determined with the imaging technique. Then $R_N(x,t)$ can be combined with independent measurements of ion density and the effective impurity factor to deduce the temperature distribution $T(x,t)$. We initially assumed a 5×10^{15} n/s neutron production rate from d-d fusion, a spatial resolution requirement of 5-10 cm, time resolution of ≤ 100 ms, and a hot plasma diameter of 60 cm in the Tokamak.

The preliminary design then would be as follows:

- 1) Thick imaging aperture: One to three thick apertures located about 3.5 m from the plasma center with the image plane about 1.7 m beyond would provide a field-of-view (FOV) of about 1.6 m and a magnification of 1/2. The aperture(s) could be a pinhole of 2-cm diameter (6-cm resolution) (or a pinslit 1-cm by 4-cm with 3 cm radial resolution) depending on the horizontal FOV requirements. The optical efficiency would be about 2×10^{-6} for the 2-cm diameter pinhole. This value is about two orders of magnitude greater than that used in the TREAT experiments.
- 2) Radiation Converter: One could probably use an inorganic phosphor that has been previously characterized for MeV imaging applications.⁽⁸⁾ We would enhance the neutron sensitivity (x2) by adding a hydrocarbon layer on the side toward the aperture. Our inorganic fluor is about 15 times more efficient than a 1-mm thick piece of NE102 for 14-MeV neutrons.
- 3) Intensified Video Camera: One would minimize effects of stray magnetic fields on the video system by using a proximity-focused microchannel plate intensifier and a charge-injection device (CID) video camera. Both components are known to be relatively insensitive to magnetic field effects. It should be noted that the intensifier tube is a critical component. As shown in Fig. 4, this device consists of an input photocathode, a microchannel plate to amplify the electron number by a factor of 10^3 to 10^4 , and an output phosphor to convert the electron energy back into a visible image. This output is fiber-optically coupled to the CID sensor of the television camera. Net system gain is usually 10^3 for a single microchannel plate. Also, the coupled system would have about 100 resolution elements across the sensor so if one mapped 100 cm onto the sensor, 1-cm resolution would still be possible (the aperture is the limiting factor on this initial design). The camera would be positioned out of the direct beam by the use of a 45° mirror. It could then be shielded against penetrating background radiation, a key factor in the success of the experiment.

If we now consider the d-d operation (2.45 MeV neutrons) with a neutron rate $R_N(d-d) = 5 \times 10^{15}$ n/s, the brightness could be estimated:

t = thickness of source
 V = hot part of plasma volume
 $\approx 2\pi r_1(\pi r_2^2)$,
 r_1 = major radius = 2.5 m
 r_2 = minor radius = 0.3 m

$$B_{D-D} = 5 \times 10^{15} \frac{n}{s} \frac{t}{V} ,$$

$$B_{D-D} = 5 \times 10^{15} \frac{n}{s} \frac{(60cm)}{(2\pi 2.5 \times 10^2 cm) \pi (0.3 \times 10^2 cm)^2} ,$$

$$B_{D-D} = 5 \times 10^{15} \frac{n}{s} \frac{(60cm)}{(4.4 \times 10^6 cm^3)} ,$$

$$= 6.8 \times 10^{10} \frac{n}{cm^2 \cdot s} .$$

The brightness is less than that of the TREAT test pin but the volume and resolution requirements at TFTR are different so it will be shown that it is sufficient. (It is noted that for a future d-t operation at TFTR the neutron rate of 10^{19} n/s would imply 10^{14} n/cm²-s, assuming the same volume.)

The flux at the fluor would be the mapping of the object brightness onto it.

E_a = aperture efficiency
 m = magnification

$$B_{fluor} = B_{D-D} \times E_a \times \left(\frac{1}{m^2} \right) ,$$

$$= 6.8 \times 10^{10} \frac{n}{cm^2 \cdot s} (2 \times 10^{-8}) \left(\frac{1}{(\frac{1}{2})^2} \right) ,$$

$$= 5.4 \times 10^5 \frac{n}{cm^2 \cdot s} ,$$

or

$$B \approx 1 \times 10^4 \frac{n}{cm^2 \cdot 16ms} .$$

We have estimated the neutron flux at the radiation converter with this design to be about $1 \times 10^4 \text{ n/cm}^2\text{-}16\text{ms}$, which is a value close to the TREAT PINEX results with fission neutrons. It should be noted that any improvement in neutron rate such as a projected d-d rate of 10^{17} n/s would allow reduction of the time sampling and/or the spatial sampling. Since the aperture is removable (and changeable) from the shielding block, an additional flexibility is possible. Also, cascaded microchannel plate tubes have reported gain 10-100 times that of a single microchannel plate. Either way, it's probable that one could attain 10-ms sampling and probably at lower brightness than $10^{11} \text{ n/cm}^2\text{-s}$. The video recording equipment frame times would have to be considered before going beyond 8-ms field rates. Also, the dynamic range should be 50-100 for a single image, but the system gain can be varied by a factor of 1000 within a few-second pulse or from shot to shot.

Finally, it should be noted that although the neutron signal looks reasonable, it would be very important to know the expected neutron, x-ray, and gamma-ray backgrounds in the collimator area. It is expected that background problems can be solved by employing appropriate shielding. If the signal-to-background ratio is better than 1/5 on the Tokamak, then one would be in a more favorable situation than the TREAT application.

Summary and Conclusions

In summary, the PINEX technique for imaging the neutron emissions from reactor-grade, high-temperature plasmas is not only viable, but could be a valuable complement to the standard diagnostic coverage. The real-time monitoring of the neutron radiation profile with good temporal and spatial resolution and the video recording of the plasma performance should be a powerful means of optimizing the operation of the Tokamak. The full power of image processing techniques also becomes feasible: psuedo-three dimensional displays, psuedo-color contour plots, tomographic reconstructions from a few angles, etc. The detailed information that would be acquired from such a system could contribute significantly to the experimental database required for full understanding of the high-temperature plasma dynamical behavior of Tokamak reactors.

Acknowledgements

The authors acknowledge useful discussions with Dr. H. Hendel (TFTR) and Drs. O. Jarvis and J. Källne (JET).

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Figure Captions

- Fig. 1** Schematic diagram of the imaging in PINEX-2. Note the pinhole inversion of the fuel pin image and the vertical to horizontal transposition of the images as displayed by the TV monitor.
- Fig. 2** Early TREAT PINEX experimental layout showing the test pin, the reactor and its slot, the aperture location, the radiation converter (the plastic NE102), and the intensified vidicon and film (IF) cameras.
- Fig. 3** Representative television monitor displays of frames (a) before and (b) after cladding failure in a TREAT experiment. The image of the fuel is the narrow, white band in the center which has increased in width by 60% in frame (b). The remainder of the image (out to the fluor edge) arises from capsule background. The black tick-marks at the fluor edge define axial position, and the diagonal black lines arise from improper blanking during the "fly-back" of the camera's scan.
- Fig. 4** Schematic representation of an intensifier tube and its components. The photocathode, microchannel plate, phosphor, and fiber optics are indicated.
- Fig. 5** Schematic of the imaging aperture's potential field-of-view (FOV) from a Tokamak diagnostic port. (Figure adapted from a TFTR figure).
- Fig. 6** An expanded view of the Tokamak PINEX and the potential location of the aperture and the image plane. A magnification of 1/2 is suggested.

Fig. 1

Fig. 2

a)

b)

Fig. 3

GAIN: 10^4
SP. RESOL: $>20 \mu\text{p/mm}$

GATEABILITY: 1 ns
FIELD: kV/mm

Fig. 4

Fig. 5

Fig. 6