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By

S.S. Medley et al.

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PLASMA PHYSICS LABORATORY

PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY

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NEUTRAL BEAM INTERLOCK SYSTEM ON TFTR USING INFRARED PYROMETRY

S.S. Medley, H.W. Kugel, T.A. Kozub,
J.L. Lowrance, V. Mastrocola, G. Renda,
and K.M. Young

Plasma Physics Laboratory
Princeton University
Princeton, New Jersey 08544

ABSTRACT

Although the region of the TFTR vacuum vessel wall which is susceptible to damage by neutral beam strike is armored with a mosaic of TiC-clad POCO graphite tiles, at power deposition levels above 2.5 kW/cm^2 the armor surface temperature exceeds 1200° C within 250 ms and itself becomes susceptible to damage. In order to protect the wall armor, a neutral beam interlock system based on infrared pyrometry measurement of the armor surface temperature was installed on TFTR. For each beamline, a three-fiber-optic telescope views three areas of ~ 30 cm diameter centered on the armor hot spots for the three ion sources. Each signal is fiber-optic coupled to a remote 900 nm pyrometer which feeds analog signals to the neutral beam interrupt circuits. The pyrometer interlock system is designed to interrupt each of the twelve ion sources independently within 10 ms of the temperature exceeding a threshold settable in the range of 500-2300° C. A description of the pyrometer interlock system and its performance will be presented.

I. INTRODUCTION

The neutral beam injection (NBI) system for auxiliary plasma heating on the Tokamak Fusion Test Reactor (TFTR) consists of four horizontal beamlines.[1] Each beamline contains three ion sources mounted centrally on the torus midplane with an azimuthal angle of ~4° between the beam axes of adjacent sources. Injected neutral deuterium power up to 20 MW - 120 keV with 0.5 s pulse length is expected from existing ion sources and extension to 26 MW, 2.0 s pulses using upgraded ion sources is planned later this year.

To protect the vacuum vessel against damage by excessive neutral beam power deposition, the region of the inner wall subject to beam impact is armored by a mosaic of TiC-clad, POCO graphite tiles[2] as illustrated by the photograph in Fig. 1. Under normal TFTR operating conditions, the power deposition on the armor due to beam shinethrough does not exceed 0.5 kW/cm^2 corresponding to a calculated maximum surface temperature increase of 330° C for a pulse duration of 0.5 s. In the absence of a plasma discharge, the peak power density of 2.5 kW/cm^2 delivered by a single source increases the surface temperature by ~ 1700° C within 0.5 s, which could possibly damage the graphite armor as a result of thermal stress or contaminate the plasma from outgassing of impurities. Due to the orientation of the TFTR beamlines, an overlap of power deposition from two sources is possible in certain areas of the wall armor which exacerbates the damage hazard. To avoid armor damage or plasma contamination, it is necessary to terminate the pulse from any ion source which causes the armor surface temperature to exceed an adopted operational limit of 1200° C.

A neutral beam interlock system has been implemented on TFTR which uses infrared pyrometry[3-5] in the 900 nm range to measure remotely the temperatures of the armor hot spots for each of the twelve NBI ion sources. A latched interrupt signal is generated when the temperature exceeds a preset threshold in the range of 500–1800° C which terminates the pulse from the offending ion source within 10 ms. A description of the neutral beam pyrometer interlock system and initial test results will be presented.

II. *PYROMETER INTERLOCK SYSTEM*

The neutral beam pyrometer interlock (NBPI) system was designed to satisfy the following requirements for application to TFTR:

a) individual interruption of 12 ion sources to minimize injected power reduction during a plasma pulse,

b) interrupt time $\lesssim$ 10 ms after surface temperature exceeds threshold,

c) temperature operating range of 500–1800° C,

d) small field of view ($\lesssim$3°) to minimize temperature errors due to spatial averaging of the measurement,

e) insensitivity to environmental interference (magnetic fields, neutron flux, etc.).

A plan-view schematic of the TFTR torus in Fig. 2 shows the general layout of the NBPI system. At each of the beamline ports (G,I,K, and O) the triplet of solid lines shows the injection axes of the three ion sources. The NBPI viewing ports (J,N,Q_1, and Q_2) are identified by solid triangles and the hatched regions depict the envelope of the field of view. Within each envelope are three separate NBPI sightlines which view the individual beam impact points on the wall armor (not shown).

The NBPI apparatus consists of the following principal components: 1) a reentrant, compound mirror mounted on the torus port cover, 2) a telescope/fiber optic assembly positioned immediately behind the mirror, and 3) a remotely located pyrometer detector module which is fiber-optic coupled to the viewing telescope. Each of these components will be described in further detail below.

Within the constraints of available diagnostic access on the torus, the NBPI ports were chosen to provide an incident viewing angle not exceeding ~45° from normal to the armor surface which, in turn, required using ports located off the midplane of the torus. Under these conditions, obtaining the desired view required using a reentrant, compound mirror system shown by the photograph in Fig. 3. Two highly polished, nonmagnetic, stainless steel mirrors are located in-vacuo with a quartz vacuum window mounted in the reentrant, cylindrical body. Different compound mirror angles were required at each of the four viewing ports to provide viewing angles from the normal to the port cover of up to ~ 40° in azimuth and ~ 4° in elevation.

The mirror module is coupled to a telescope/fiber optic assembly as illustrated in Fig. 4. Three, 600 μm diameter, anhydrous, fused-quartz, optic fibers are located in the focal plane of the telescope with each fiber optic accepting an image of the hot spot from one of the three ion sources. The fiber bundle and the output lens of the telescope can be translated axially within the nested barrel assembly for field-of-view alignment by means of micrometers identified in Fig. 4, and provision exists to rotate the fiber bundle around the axis of the telescope (not shown). Alignment of the viewing optics on the torus was accomplished by backlighting each fiber optic with a HeNe laser and adjusting the position of the telescope/fiber optic assembly using separate micrometer adjustment seen in the photograph of Fig. 4 to center the field of view on the appropriate hot spot for each ion source. At the same time, the half-angle of the fiber-optic field of view was determined to be ~ 1.7° which corresponds to a viewing region about 30 cm in diameter at a typical distance of 5 m from the telescope to the armor. The power deposition profile of the hot spot on the armor varies slightly due to differences in the beam incidence angle from various ion sources. Representative hot spot dimensions are ~70 cm full-height by ~40 cm full-width at the e-folding value of the peak power density. Errors in the peak temperature measurements due to spatial averaging over the field of view are therefore not negligible, but should not exceed ~10% based on simple, calculated estimates.

The fiber optic cable transmits the optical signal a distance of ~100 m to the detector and signal processing electronics which are located in the NBI control room. A block diagram of the overall system for one interlock channel is given in Fig. 5. The primary signal path is denoted by a heavy line. The fiber optic transmits the optical data to an IRCON Model 22Z00 detector having a peak spectral response in the wavelength region of ~900 nm. The detector feeds a logarithmic amplifier whose output is fed to a transient digitizer for recording the temperature time history. In parallel, the amplified pyrometer signal is fed to a comparator which sends a trip gate signal to the neutral beam interlock control if the output exceeds a preset threshold. A peak detector is used to monitor the peak temperature via input to a scanning ADC. Also shown in the block diagram is the control and monitoring circuitry for a test lamp housed in the telescope assembly. This feature allows the NBPI to be remotely checked for operational integrity prior to a beam injection discharge on TFTR using computer control of CAMAC modules.

The performance of the NBPI system was determined using a calibrated blackbody source mounted at the compound mirror input to the telescope/fiber optic assembly shown in Fig. 5. The pyrometer/amplifier output signal, v_o (volts), is related to the temperature, T(°K), of the source by

$$v_o = \frac{1}{2.303}\left[\ln \frac{\varepsilon C_1}{\lambda^5 K_\lambda I_R} - \frac{C_2}{\lambda_T}\right] + \alpha \qquad (1)$$

where $\lambda = 900$ nm, $C = 3.74 \times 10^{-12}$ W/cm^2, $C_2 = 1.43 \times 10^7$ nm°K, $K_\lambda = 2.6 \times 10^{-26}$, $I_R = 1 \times 10^{-3}$ A, and $\alpha = 7$ is a calibration factor associated with the maximum detector output voltage. With unity emissivity, ε, the measured temperature agreed with the blackbody temperature to within 3% over a range of 500-1800° C. The pyrometer system has an input signal dynamic range of 1×10^7 corresponding to a temperature operating range of approximately 500-2300° C. Using a square-wave input current test signal, the NBPI time response was measured to be ≤10 ms over the operating temperature range.

III. DISCUSSION

The role of the pyrometers is supplemented by an infrared camera diagnostic on TFTR which views several of the ion source hot spots on the armor. Using single wavelength temperature measurement in a wavelength band of 1.7 ± 0.4 microns, the infrared camera has a temperature range of 350-2300°C, time resolution of 20 ms and spatial resolution at the armor surface of ~ 0.5 cm. The camera views the beam hot spot through a flexible optical periscope system described elsewhere.[6] Among the applications of the infrared camera diagnostic in support of the NBPI system are: 1) confirmation of the pyrometer alignment on the ion source hot spots, 2) corroboration of the pyrometer temperature measurement, and 3) detection of anomalous armor heating patterns that could distort the pyrometer temperature measurement. In addition, the infrared camera provides power deposition profile data for characterization of the beam power and divergence.

At present, the full twelve-channel NBPI system has been installed and aligned on TFTR. Using the test lamps housed in the telescope assembly, the functinal integrity of the optics and electronics was verified. Tests during plasma and neutral beam operations which are now in progress indicate satisfactory performance, though a need for plasma light rejection using infrared-pass insert filters was demonstrated.

ACKNOWLEDGMENT

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FIGURE CAPTIONS

1. Partial view of the wall armor inside the TFTR vacuum vessel. The major components appearing in the photograph are: A) TiC-clad POCO graphite mosaic of tiles comprising the wall armor, B) bare graphite inner bumper limiter, and C) ZrAl bulk getter pumping panels.

2. Plan view of the TFTR torus illustrating the NBI ion source deployment (triplets of solid lines at locations G, I, K, and O) and the envelopes of the NBPI viewing fields (hatched regions emanating from locations J, N, Q_1, and Q_2).

3. Photograph of the reentrant, compound mirror assembly which enables oblique viewing of the beam hot spots through ports which are flush with the diagnostic access cover plates.

4. Schematic (top) and photograph (bottom) of the telescope apparatus used to image the armor hot spots onto a fiber optic bundle which transmits the optical signal to remotely located pyrometer detectors.

5. Overall electrical block diagram of the NBPI system. The primary signal path is shown by a heavy line. The mirror/telescope assembly focuses the optical image onto a fiber optic which feeds a pyrometer detector backed by a logarithmic amplifier. The amplifier signal is recorded with a transient digitizer to obtain the time evolution of the hot spot temperature. A comparator issues an interrupt gate signal to the neutral beam ion source if the temperature exceeds a present threshold.

#86X0414

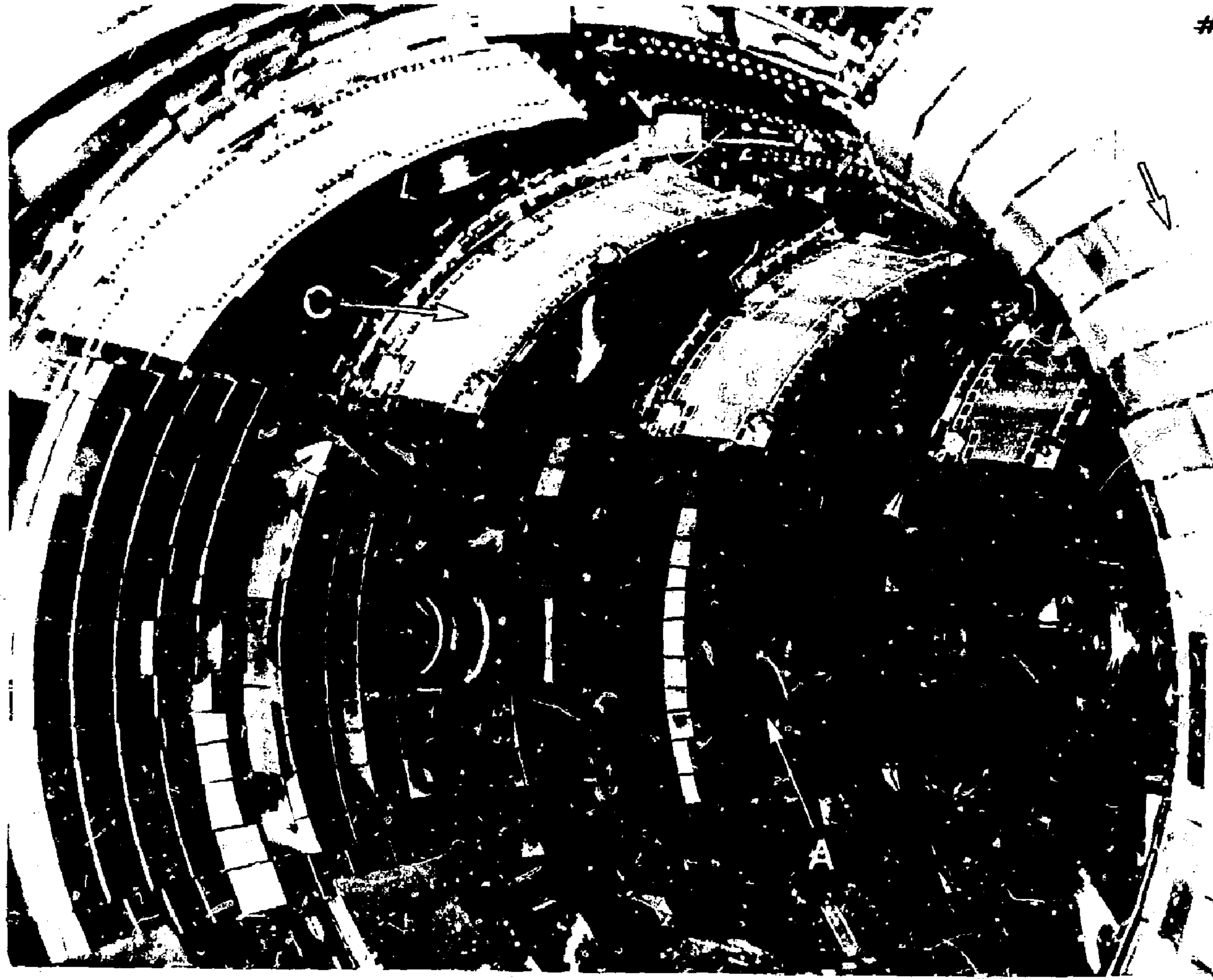

FIG. 1

#86X0348

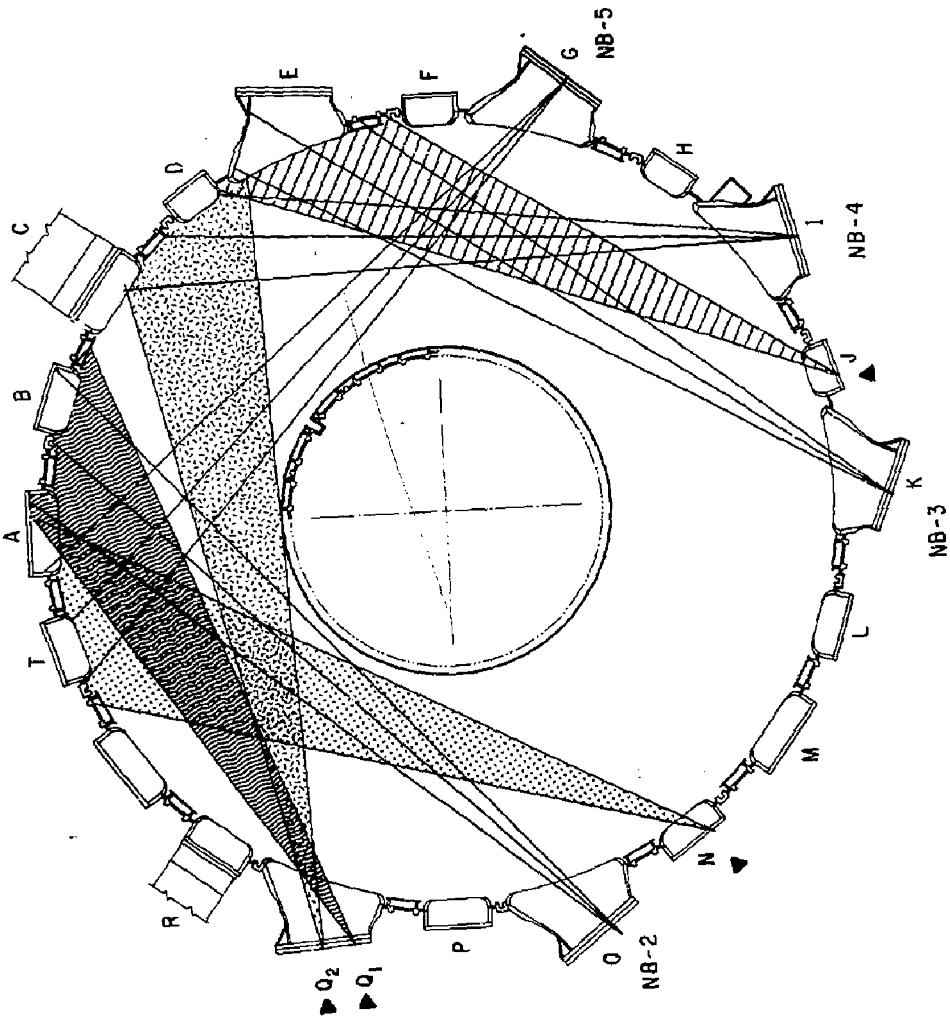

FIG. 2

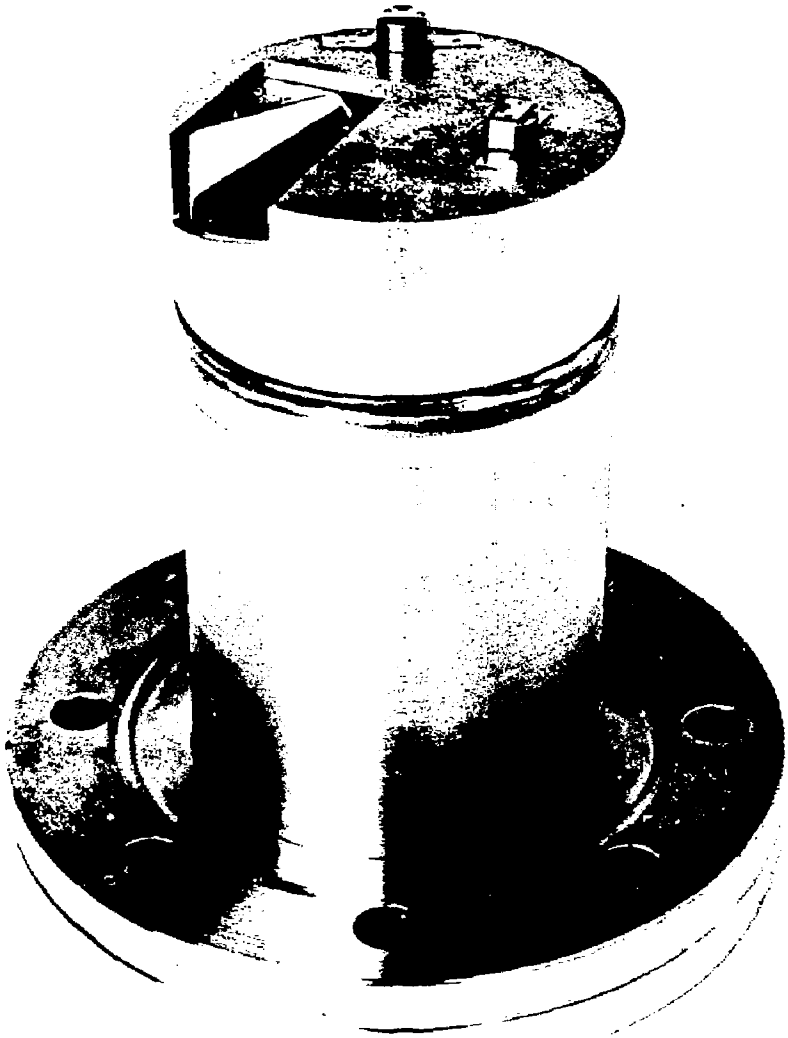

FIG. 3

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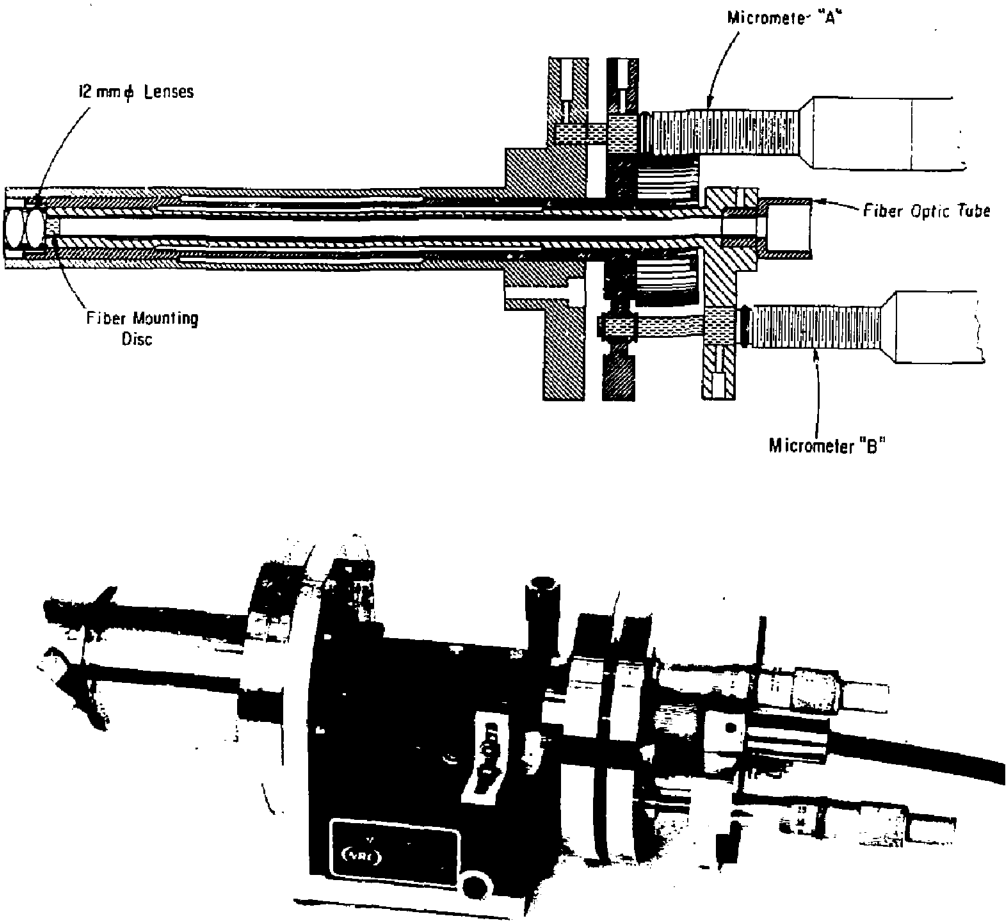

FIG. 4

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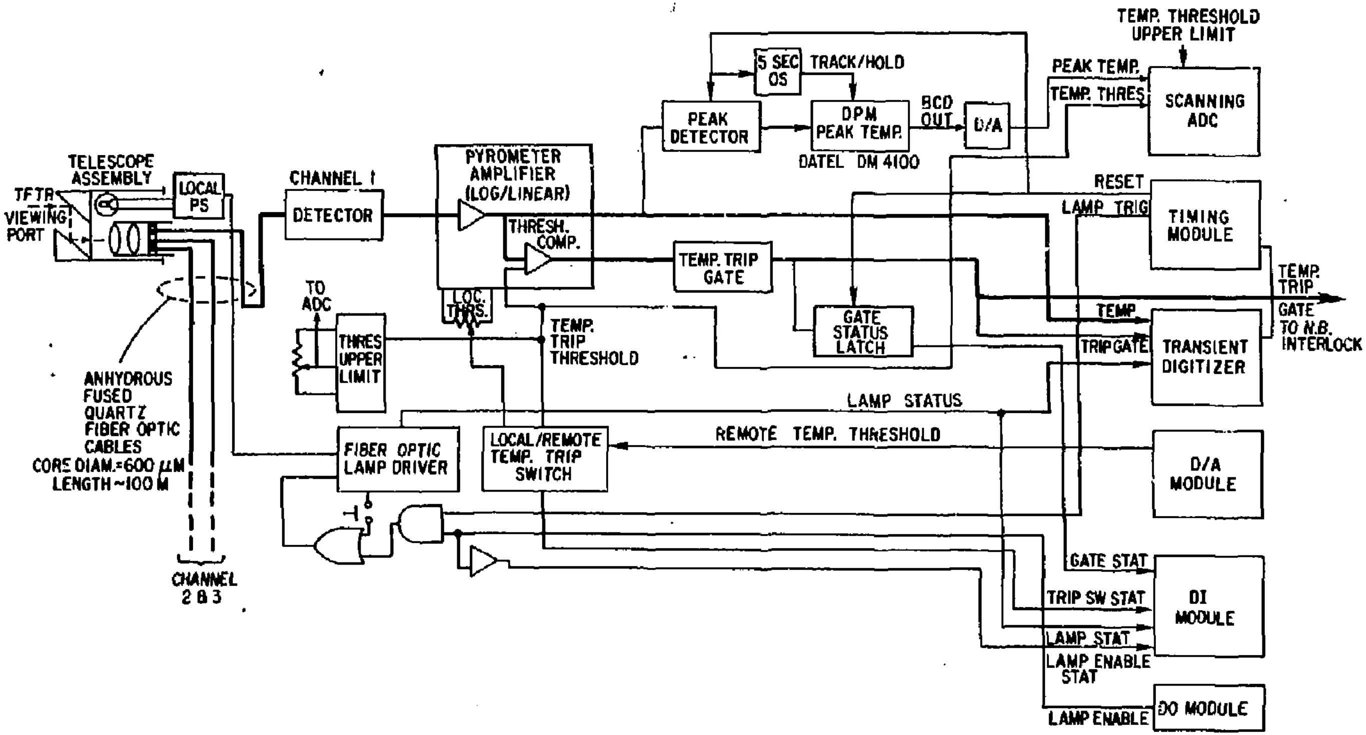

FIG. 5

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