The Filterscope

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The filterscope is a diagnostic for monitoring visible light emission from plasmas. Light from a plasma is conducted to the filterscope via optical fibers. This light is split into multiple paths, and optical bandpass filters in each path pass the light from visible wavelengths, including D_α, D_β and various impurities. The filtered light is then detected by compact photomultipliers and the resulting data digitized and stored. Because of the large number of data channels employed, the filters and electronics are designed to be compact. Measured light intensities are absolutely calibrated. Filterscopes are presently employed on the DIII-D, the National Spherical Torus Experiment, and the Current Drive Experiment-Upgrade tokamak plasma devices. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1537038]

I. INTRODUCTION

Calibrated D_α measurements are an important diagnostic for many plasma devices.[1–3] D_α light comes primarily from the plasma edge and divertor regions, and it is desirable to view this light at multiple locations to quantify plasma edge conditions, recycling sources, and as a calibration for plasma edge modeling codes. The multiplicity of required measurements dictates the need for a compact detection system. These requirements are fulfilled by the filterscope, which can detect not only D_α, but also visible lines of plasma impurities. Key to this compact design is the use of photomultiplier tubes with built-in, high voltage power supplies. The phototubes and associated electronics are built into compact modules, with each module capable of handling up to five phototubes. Light from the plasma is imaged onto optical fibers and transferred from the tokamak to a low radiation background area which may be as far as several hundred meters from the tokamak. The light is then split into three or five paths, each of which is terminated by an optical bandpass filter and a photomultiplier tube. This allows signals from the same plasma viewing chord to be simultaneously recorded at several wavelengths. The DIII-D tokamak, the National Spherical Torus Experiment, and the Current Drive Experiment-Upgrade tokamak are presently equipped with filterscopes employing a total of 105 phototubes. Spectral lines from D_α, D_β, D_γ, C III, Li I, O II, B II, and He II are recorded throughout tokamak discharges. Signals are digitized at rates up to 100 kHz, allowing the study of edge localized modes (ELMs) and scrape-off layer (SOL) turbulence. D_α data from a tangential array of eight detectors on the midplane of DIII-D have been inverted, yielding neutral densities and ionization rate profiles in the plasma edge and SOL, as well as snapshots of edge turbulence with high time resolution.

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II. FILTERSCOPE DESCRIPTION

A. Light collection

A lens is used to focus plasma light onto a linear array of optical fibers in its image plane. The lens is located outside the DIII-D vacuum chamber, vacuum isolated by a window. This arrangement is shown in Fig. 1 for the DIII-D upper and lower divertor filterscopes. Lenses of 25 and 50 mm focal length are used to focus light onto the upper and lower divertor filterscope fibers, respectively. This results in spot sizes (diameter of the light cone at termination on a wall) of 3.6 and 7.1 cm.

The midplane filterscopes are located in a horizontal plane, as shown in Fig. 2. Optical dumps consisting of holes bored in carbon tiles and backed by stacked razor blades are used to prevent light reflected off the walls from contaminating light from the plasma source. At the tangency points, the light cones are 1 cm in diameter and spaced 1 cm apart, so that they just touch. Their location with respect to the separatrix and scrape-off-layer (SOL) is determined by the position of the plasma boundary, but typically they span the separatrix.

B. Light sensing electronics

The optical fibers run a distance of ~35 m from the machine chamber to an electronics annex, where the light detection electronics are located. Light from each fiber is then split into several channels by a fiber-optic splitter. Light from the DIII-D divertor filterscope fibers is split into five channels, as shown in Fig. 3. In the case of the midplane filterscope, light is split into three channels. After being split, the light is imaged onto a 1-in.-diam optical bandpass filter. The filters are located in specially designed holders that are attached to the photomultiplier tubes. The full width at half maximum (FWHM) of the D_α and D_β filters is 1 nm and that of the C III and He II filters is 2 nm. The filtered light is then

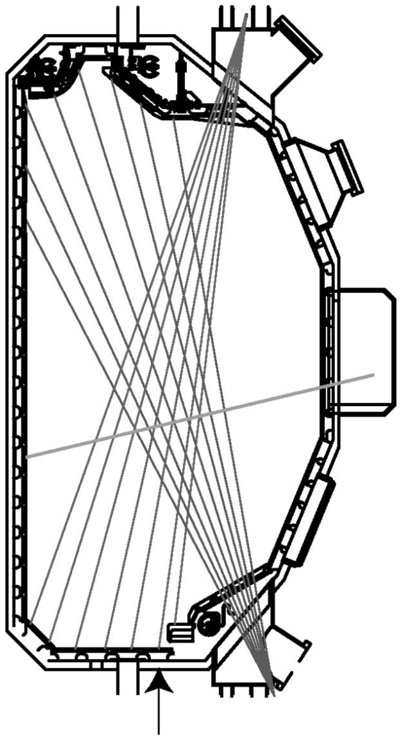

FIG. 1. Arrangement of the filterscope sight lines of the DIII-D. Lower divertor sightlines end on the lower carbon tiles, and upper divertor sightlines on upper tiles. One view is directed toward the inner wall.

detected by Hamamatsu (Bridgewater, NJ) H5783 photomultiplier tubes and amplified for output to the data acquisition system. Photomultiplier anode coatings are selected for high sensitivity at detected wavelengths.

An essential feature of the electronics is an over-current protection circuit, for protection of the photomuliplier tube anodes. If over current is detected, the high voltage of the photomultiplier is turned off. This causes the signal level to decay with an exponential time constant of ~66 ms. For continued operation, the high voltage must be reinstated. At present, all tube voltages are automatically reset before the

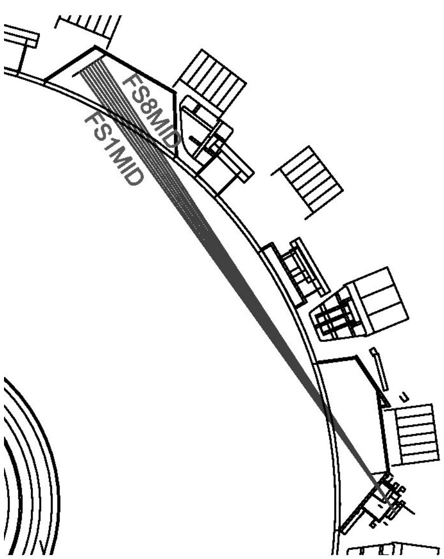

FIG. 2. Array of eight sight lines (FS1MID-FS8MID) located at the midplane of DIII-D, near the outer separatrix.

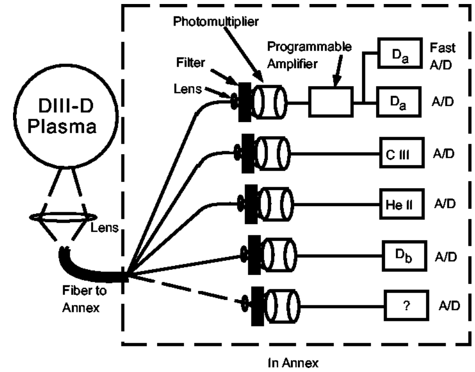

FIG. 3. Schematic of the filterscope system for one light fiber. Light imaged from the plasma onto one fiber is subsequently split five ways and filtered by optical bandpass filters. Light from the filters is sensed by photomultipliers and the resulting signal is converted to digital data. The fifth channel is presently a spare.

beginning of each discharge. It is also possible to manually reset the circuits by switches.

Each tube contains its own Cockcroft–Walton high voltage power supply. This supply is driven by an external +12 V power supply which is manually adjusted by a 20 turn 10 kΩ potentiometer. Although not presently implemented, it is also possible to adjust the voltage via an external programmable power supply or digital-to-analog device. Computer control of the voltage adjustment is planed for the future. Tube voltages are scaled and the digitized value is recorded using a computer automated measurement and control (CAMAC) analog-to-digital (A/D) converter, just before each discharge.

C. Data acquisition

Data are sent to either a CAMAC programmable amplifier (D_α only) or a CAMAC A/D converter (see Fig. 3). The programmable amplifier allows remote adjustment of the gains by factors of 0.5–256. A computer program is available to automatically adjust the gains to optimize D_α light intensities.

Data are presently digitized at variable rates during a discharge, in order to conserve CAMAC memory. As shown in Fig. 3, D_α data are sent to both "slow" and "fast" CAMAC A/D digitizers. Typical slow digitization rates are 1 kHz and fast digitization times are 20–100 kHz. Future plans are to digitize all channels using fast PC-based digitizers.

D. Signal calibration

All DIII-D filterscope channels are absolutely calibrated by means of a Labsphere (North Sutton, NH) or Optonics (Orlando, FL) calibrated light source. Calibration is routinely performed just before and just after each plasma campaign. The light sources in turn are calibrated at the factory in terms of the quantity $\Phi_{LS}(\mathrm{photons/s\,cm^2\,sr\,\AA})$. By integrating in wavelength over the filter's bandpass width W_{FWHM} the inherent number $I_h(\mathrm{photons/s\,cm^2\,sr})$ is obtained:

$$I_h=\int_0^\infty \Phi_{LS}(\lambda)e^{-4(\lambda-\lambda_0)^2\ln(2)/W_{FWHM}^2}d\lambda. \quad (1)$$

During vacuum openings, a calibrated light source is placed

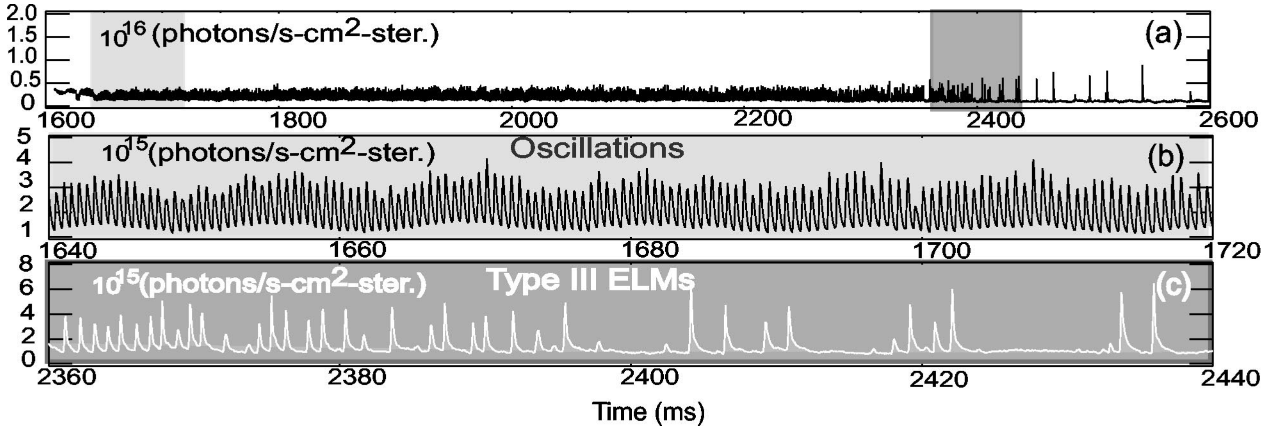

FIG. 4. Filterscope D_α data from DIII-D showing edge oscillations during time periods: (a) 1600–2600 ms; (b) 1640–1720 ms, ''predator-prey'' oscillations, lighter highlighted area in (a) and (c) 2360–2440 ms, type III ELMs, darker highlighted area in (a). Data were digitized at a 20 kHz sample rate.

inside the DIII-D vacuum vessel and the response, V_{cal} of each channel is recorded. The gain of the photomultiplier tube generally follows a power law dependence, but for improved accuracy it is fit by the equation

$$G_{cal}=e^{(a_0+a_1V_{pmt\,cal}+a_2v^2_{pmt\,cal}+a_3v^3_{pmt\,cal})}, \tag{2}$$

where $V_{pmt\,cal}$ is the voltage applied to the photomultiplier during the calibration and the coefficients a_n are obtained by fitting data obtained from a bench calibration of the tube over a range of tube voltages. The signal gain is calculated from a similar formula

$$G_{sig}=e^{(a_0+a_1V_{pmt}+a_2V^2_{pmt}+a_3V^3_{pmt})}, \tag{3}$$

where V_{pmt} is the voltage applied to the photomultiplier when taking plasma data. The photon flux Φ (photons/s cm^2 sr) is given by

$$\Phi=I_h\left[\frac{G_{cal}}{G_{sig}}\frac{V_{sig}}{V_{cal}}\right], \tag{4}$$

where V_{sig} is the amplified photomultiplier voltage that results from plasma light.

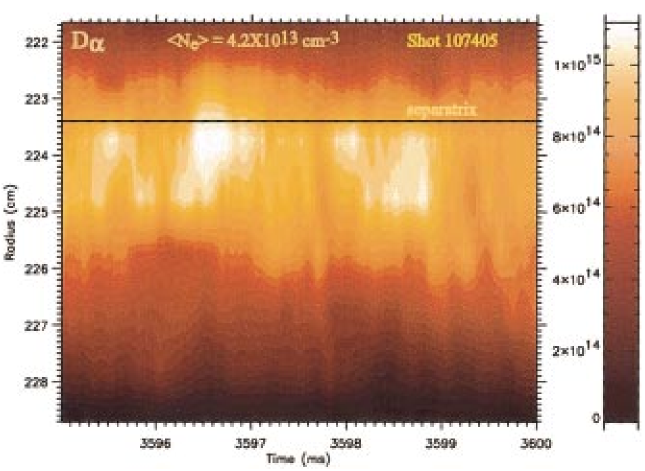

FIG. 5. (Color) Contour plot of the inverted D_α light intensity from the midplane filterscope. An intensity scale of the inverted D_α light is shown on the right (photons/s cm^3). These data were digitized at a 100 kHz sampling rate.

III. FILTERSCOPE RESULTS

Filterscopes have been useful in a wide array of plasma investigations, particularly those involving D_α light. Examples are shown below to illustrate some of the applications.

Figure 4 shows an example of ''predator-prey''[4] edge plasma oscillations viewed by divertor filterscope viewing chord FS05 (marked by an arrow in Fig. 1). The ''fuzzy''-looking portion of the Fig. 4(a) trace is comprised of edge oscillations, individual cycles of which are expanded in Fig. 4(b) [lighter highlighted portion of trace 4(a)]. During the darker highlighted portion of the Fig. 4(a) trace, shown in Fig. 4(c), the oscillations break up into type III ELMs.

D_α data from the midplane filterscope array have been inverted using an ''onion peeling'' model[5] to give a radial D_α profile. A contour plot of inverted midplane D_α data is shown in Fig. 5. The outer edge of the confined plasma (the separatrix), is shown as a horizontal line. Confined plasma lies above the line and unconfined plasma in the SOL between the plasma and the outer wall lies below the line. Spatially coherent variations with time in the D_α intensity reveal plasma turbulence.

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