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# FILTERED AND BARE VACUUM PHOTODIODE DETECTORS FOR VUV MONITORING OF TOKAMAK PLASMAS*

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## 1. INTRODUCTION

THIS PAPER describes the use of filtered and unfiltered or 'bare' vacuum photodiodes as broadband vacuum ultraviolet radiation detectors for Tokamak plasmas. Filtered vacuum photodiodes are currently being used in laser fusion research as a temperature diagnostic (DAY *et al.*, 1979; SLIVINSKI and KORNBLUM, 1978; TIRSELL *et al.*, 1980) however, up to now only bare vacuum photodiodes have been used for monitoring Tokamak plasmas (ZWEBEN *et al.*, 1979). The bare photodiodes have a broad response to VUV in the wavelength range from less than 100 Å to greater than 1200 Å, and with filtering these same photodiodes can be used to monitor selected wavelength ranges within this spectral region. We have used polypropylene filters to obtain a transmission in the wavelength range approx. 50–150 Å, and aluminum silicon alloy (Al:Si) foil filters for obtaining a transmission in the range approx. 150–750 Å. The results obtained with these three types of photodiodes on the Macrotor (TAYLOR *et al.*, 1980) and Microtor (OREN and TAYLOR, 1977) Tokamaks are described below.

Vacuum photodiode detectors are simple and inexpensive and can provide useful information on Tokamak radiation profiles in the VUV where conventional soft or ultra-soft solid state X-ray detectors (EAMES *et al.*, 1979; PETRASSO *et al.*, 1980) are insensitive. We have found in particular that the plasma impurity level in the Tokamaks can be readily monitored and evaluated by using the bare and Al:Si filtered detector signals. It should be noted, however, that neither the bare nor the filtered vacuum photodiodes can easily replace bolometers (BUSH and LYON, 1978; BOL *et al.*, 1978) for a precise measurement of the total radiated power, since the vacuum photodiodes generally have a complicated spectral response function and because the exact sensitivity vs wavelength for our detectors and filters is not well known. Therefore the applications described here for Tokamaks rely mainly on the relative response of these detectors to various plasma conditions.

Nevertheless, a useful approximate calibration can be obtained by comparing the normal photodiode signals to those obtained when the discharge is intentionally contaminated to the point that most of the energy loss is by radiation. For example, this procedure can reliably show that the oxygen radiation loss in a clean plasma can be reduced to approx. 1 per cent of that in a heavily contaminated plasma, i.e. that the oxygen radiation loss in the former case is negligible.

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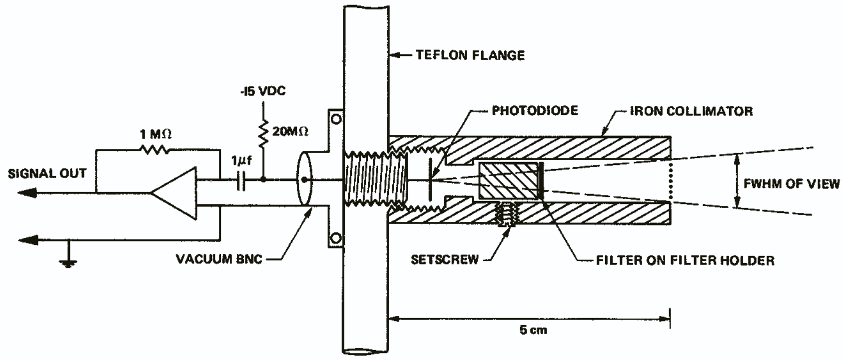


FIG. 1.—Construction of the vacuum photodiode. The detector is a 0.6 cm × 0.6 cm metal disk attached to the end of a vacuum BNC feedthrough. The filters are epoxy-mounted onto the removable filter holder. An optional mesh can be placed at the end of the collimator to reduce plasma flow into the diode. The detector is normally biased −15 volts and the signal is amplified with conventional op-amp.

## 2. DETECTOR DESIGN

The vacuum photodiode emits a photoelectric current which is proportional to the incident UV flux. An uncollimated metal plate located outside the plasma but inside the vacuum vessel emits typically $>1\ \mu\text{amp cm}^{-1}$ in Macrotor or Microtor; thus the signal is easily measured by a single operational amplifier. In Fig. 1 we show details of the detector design and electrical circuit (see also ZWEBEN *et al.*, 1979). The detector plate is biased typically −15 V with respect to the soft iron or stainless steel collimator. The collimator serves to define the solid angle with which the detector views the discharge, and also helps shield the detector and filters from the plasma particles near the Tokamak edge. We have found that charged particle flow into the detector can be eliminated by placing the photodiodes >15 cm behind the vacuum vessel inner wall so that they are well outside the plasma edge.

The photodiodes are electrically insulated from the Tokamak by mounting the collimator onto a glass or Teflon plate with a vacuum BNC connector. Electromagnetic and hard X-ray backgrounds are negligible. The bare detectors can in principle also respond to the neutral particle efflux from the Tokamak; however the secondary electron emission coefficient for neutrals is small enough (BARNETT, 1977) so that at least for ohmically heated Tokamaks (ZWEBEN *et al.*, 1979; VOSS and COHEN, 1980) it constitutes a negligible background to the photoelectric emission.

The filter materials* are mounted on removable filter holders inserted into the collimator structure. The filters have a nominal thickness of 8000 Å for the polypropylene and 1500 Å for the 99 per cent, 1 per cent Si alloy filter (the latter is mounted on an electroplated nickel mesh).

We have used both tungsten and stainless steel for the detector element with little apparent difference in the results. The detector plates were cleaned in

* Obtained from Luxel, Inc., Friday Harbor, Washington, U.S.A.

solvents to remove oil and grease, but no attempt was made to remove any oxide layer from the surfaces. The filters are also routinely exposed to air before installation. This procedure has resulted in a relative response among a batch of similarly prepared photodiodes which appears to be constant to well within ±20 per cent, and this similarity of response has persisted over more than one year including thousands of Tokamak discharges and several openings to air. This stability has been obtained both with the bare and the filtered detectors. The variability in the response of a single photodiode over time has been difficult to evaluate without a calibration source; however, it appears reasonably stable in that the response of photodiodes which have been in use for a year is again within about ±20 per cent of that for newly prepared photodiodes placed in a similar location. Although VUV transmission of the filters has not appreciably varied with use, some of the oldest filters have tended to become clouded in appearance; thus there is evidently some surface deterioration which might eventually affect the performance of these filters.

The approximate sensitivity vs wavelength for the bare detector, and the transmission vs wavelength for the two types of filter materials are shown in Fig. 2. The bare detector response is that given by SAMSON (1974) for tungsten; it is quantitatively the same as the response for most other metals in this spectral range. Note that these transmission curves are for filter thicknesses different than those of our experiment. We expect the spectral sensitivity for our detectors and filters which have been exposed to air to be roughly given by these curves. Actually, it is more useful for our purposes to have a stable set of detectors and filters which will not be affected by exposure to air, rather than a carefully characterized clean surface which can deteriorate. An extensive discussion of the stability of the VUV response of bare photodiodes and filters have been given by DAY *et al.*, 1979), MOSS *et al.* (1979) and WALKER *et al.* (1955). The use of photodiodes for VUV radiometry has also been the subject of recent workshops sponsored by the U.S. National Bureau of Standards. It can be seen that the bare detector is sensitive over the whole range from 50 to 1200 Å, that the Al:Si filtered detector is sensitive mainly in the region from 150 to 750 Å, and that the polypropylene filtered detector is sensitive mainly from 50 to 150 Å. We have called these detectors *soft* UV, *medium* UV and *hard* UV, respectively.

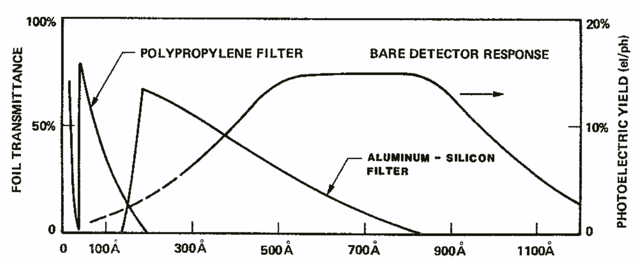


FIG. 2.—Detector sensitivity. The approximate photoelectric yield of tungsten in the VUV (SAMPSON, 1974) is shown along with the transmittance of an 1760 Å polypropylene film (CARUSO, 1974) and of a 800 Å aluminum foil (HUNTER *et al.*, 1965).

## 3. SIGNALS FROM MACROTOR

Typical signals from a Macrotor discharge for the three different types of vacuum photodiodes are shown in Fig. 3. The major radius of Macrotor is 90 cm, the minor radius is 45 cm, and in this case each of these detectors is located in a top flange and views the center of the plasma with a field of 15 cm FWHM at the minor axis. The relative signal amplitudes at $t \approx 50$ ms are here approx. 1, 0.1; and 0.01 for the soft, medium and hard photodiode detectors each having the same solid angle of $3 \times 10^{-2}$ str and plate area of $0.36\ \text{cm}^2$.

Two features of these signals are evident. Firstly, the burnthrough phase of the discharge at $t \lesssim 10$ ms has a different signature for each detector. Secondly, the density increase due to gas puffing during the flat-current phase at $t \gtrsim 20$ ms is accompanied by a monotonic increase in all three signals. The latter behavior is as expected for detection of radiated power which, in general, increases with $n_e$ if the source is either an unchanging impurity concentration or hydrogen recombination radiation (see Section 4).

The burnthrough signatures have been observed to depend upon the cleanliness of the discharge in a simple way. In Fig. 4, we show the soft and medium UV trace for three different discharges which vary only in the impurity level. The 'dirty' type is obtained after leaving the machine overnight without discharge cleaning or Ti gettering. The 'clean' case is obtained after light (~1 monolayer) Ti gettering, and the 'ultra-clean' case is obtained after heavy (~100 monolayers) Ti gettering with simultaneous discharge cleaning.

The soft UV signal can be interpreted simply as the sum of two components, namely, the hydrogen burnthrough which peaks at $t \lesssim 1$ ms and the oxygen burnthrough which peaks at $t \approx 3$ ms. We have previously observed (ZWEBEN *et al.*, 1979) that for dirty discharges the soft UV peak at $t \sim 3$ ms is proportional to the oxygen content of the plasma. What is new in Fig. 4 is the extent to which this oxygen radiation can be reduced by Ti gettering. In the ultra-clean case the second peak in the soft UV signal has disappeared, and the time dependence of this signal is now quite similar to that of $H_\beta$, indicating that in this case the contribution of oxygen to the UV radiation is negligible. Thus the relative level of

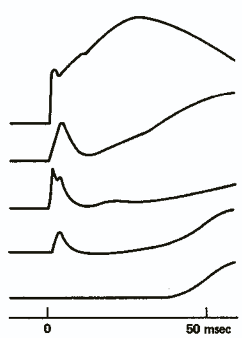


FIG. 3.—Photodiode signals from Macrotor. The response of the three types of photodiodes to a Macrotor Tokamak discharge is shown. Each of the three diodes is viewing the center of the discharge; in this case the photodiode current signals at $t = 50$ ms are in the ratio 1 : 0.1 : 0.01 for the soft, medium and hard UV channels, respectively.

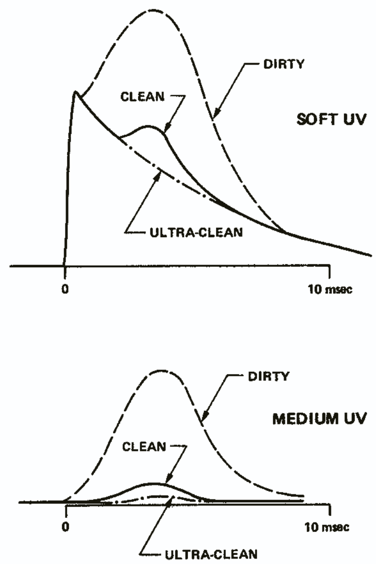


FIG. 4.—Burnthrough signatures for Macrotor. The relative cleanliness of Macrotor discharges can be monitored using the soft and medium UV signals. Dirty discharges show are characterized by a large peak at $t \sim 3$ ms due to oxygen burnthrough; ultra-clean discharges show only the hydrogen burnthrough peak at $t < 1$ ms in the soft UV.

oxygen contamination in a Macrotor discharge can be qualitatively diagnosed by the shape of the soft UV signal during the burnthrough phase of the discharge.

The medium UV detector, on the other hand, is not sensitive to hydrogen line radiation at ~1000 Å but sees only the impurity radiation at wavelengths between about 150 and 750 Å. The peak of the medium UV signal is always observed to correspond with the second peak in the soft UV channel provided that the second peak is present. Thus the amplitude of the peak of the medium UV signal is proportional to the oxygen (or low-$Z$) contamination present in the beginning of the discharge, and can therefore provide a relative indication of the impurity level in very clean discharges. Note that the hard UV detector signal is generally absent in the burnthrough phase, most likely because the temperature is too low (<50 ev) to radiate in its bandpass.

Based on many consistent observations of this pattern, we have developed a simple criterion for the cleanliness of Macrotor: an ultra-clean discharge will show only the hydrogen burnthrough peak in the soft UV and will show nearly zero on the medium UV, whereas dirtier discharges will show a delayed peaking in the soft UV which coincides with an enhanced peak of the medium UV signal. The ratio of the second (oxygen) peak to the first (hydrogen) peak in the soft UV is a measure of the discharge cleanliness; another measure is the height of the medium UV peak. It should be noted incidentally that for Macrotor the 'dirty' case shown here still has $Z \cong 1$, since the oxygen level can be further increased at least a factor of three before affecting the discharge resistivity.

## 4. UV PROFILES

An array of six each of the soft, medium and hard UV detectors has been operated on Macrotor. All detectors view the plasma vertically from the top of the machine with a spacing of 15 cm between detectors of each type; thus the FWHM of the views of adjacent detectors of each type are just about overlapping at the midplane. A typical set of UV profiles for a moderately dirty Macrotor discharge is shown in Fig. 5.

It has been found in general that the soft, medium and hard UV profiles are progressively more peaked. We interpret this to be due to the temperature dependence of the spectrum of radiation from Macrotor, in which only the central part of the plasma at $T_e \approx 100$ ev can radiate at $\lambda \lesssim 150$ Å in the hard UV channel, and in which the edge region radiates in the soft UV channel due to hydrogen or low ionization states of oxygen. Note that these profiles have not

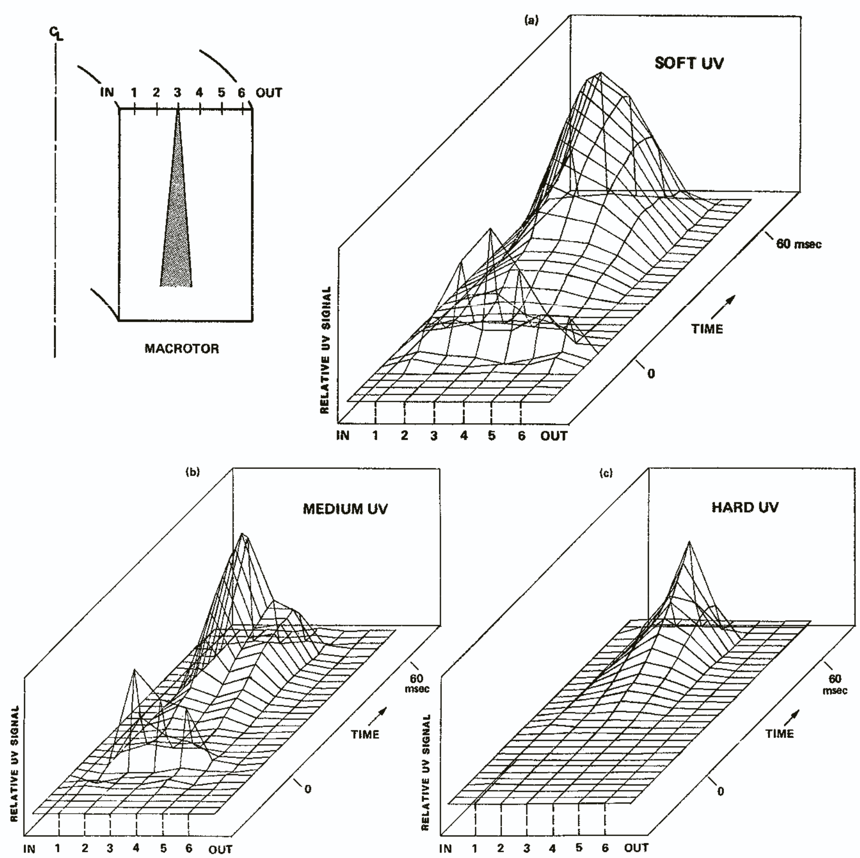


FIG. 5.—Macrotor UV profiles. The uninverted radial profiles of soft, medium and hard UV emission are shown here vs time in a Macrotor discharge. Each of the six detectors in each wavelength range views a conical volume as shown in the sketch at the left.

been Abel inverted; thus, for example, the soft UV emissivity profile would actually be rather flat across the plasma cross section.

It has been found that these profiles can be used to monitor the discharge radial equilibrium and to study the development of low frequency instabilities in the same manner as X-ray diodes. However, it is not always easy to identify the source of the radiation seen by the detectors. In particular, the hard UV source in Macrotor may be either highly ionized low-$Z$ impurities, metal lines or Bremsstrahlung. Therefore a simple relationship between the broadband UV profiles and plasma temperature or density profiles cannot be established without a spectroscopic study of the impurity species and the locations of their various ionization states.

Nevertheless one can attempt an estimate of the absolute level of radiated power emitted from the discharge. For example, if in the cleanest cases the soft UV signal is due mainly to hydrogen, and if we take the quantum efficiency of the bare photodiode to be 10 per cent at 1000 Å where hydrogen radiates in the UV, then the total radiated power $P_{rad}$ for hydrogen UV can be calculated from the photoelectric current $i$, the detector plate area $A$, and detector viewing solid angle $\Omega$:

$$P_{rad} \cong i(\text{elect. s}^{-1})\left(10\,\frac{\text{photons}}{\text{elect}}\right)\left(10\,\frac{\text{ev}}{\text{photon}}\right)\frac{A_{wall}}{A\Omega}$$

where $A_{wall}$ is the area of the torus wall. For a typical steady state signal $i \sim 10^{-7}$ amps we find $P_{rad} \sim 100$ W for hydrogen UV radiation.

Similarly, one can estimate the radiated UV power in a moderately dirty discharge by assuming that a typical medium UV signal of $\sim 10^{-7}$ amps is due to radiation at a wavelength of approximately 500 Å; thus using a filter transmittance of 0.1 one finds $P_{rad} \sim 1$ kW in this bandpass. Taking the emissivity in the medium UV to be localized within a core of minor radius 15 cm, this indicates that for this type of discharge the level of radiated power in this bandpass corresponds to about 1 per cent of the central ohmic heating power input. For ultra-clean discharges the medium UV signal is lower by a factor of 10, while for discharges intentionally dirtied with oxygen the medium UV signal is higher by a factor of 10. This indicates the dominance of radiation in the latter case and the negligible influence of oxygen on the power balance in the ultra-clean case.

## 5. MICROTOR SIGNALS AND PROFILES

In Fig. 6 is a set of UV detector signals from Microtor, a small (minor radius 10 cm) but moderately hot ($T_e < 500$ ev) and dense ($n_e < 2 \times 10^{14}$ cm$^{-3}$) Tokamak. The soft, medium, and hard UV detectors are constructed like those shown in Fig. 1, and in this Microtor discharge they are viewing the central region of the plasma from a side port on the equatorial plane.

We see here the same two features of these signals as for Macrotor in Fig. 3; namely, all three UV channels increase monotonically with density during the flat-current part of the discharge, and they each show a different characteristic signature during the burnthrough phase.

In Fig. 7 is a better view of the burnthrough phase, which for Microtor occurs more rapidly than for Macrotor. For this discharge the soft UV hydrogen peak at

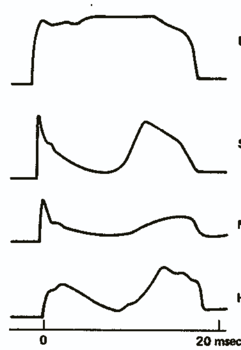


Fig. 6.—Photodiode signals from Microtor. The response of the three types of photodiodes to a Microtor discharge is shown. The UV signals increase after $t \sim 10$ ms due to a density increase at this time.

$t < 1$ms is much smaller than the low-$Z$ burnthrough peak at $t \approx 1$ ms. This indicates a fairly 'dirty' discharge by the criterion of Section 3; the shape of the soft UV signal for an ultra-clean discharge is shown by the dashed line. The medium UV signal peaks at the same time as the main peak in the soft UV as it did also in the case of the dirty Macrotor discharge of Fig. 4; however the hard UV signal for Microtor shows up more strongly during the burnthrough than it did for Macrotor. This most likely is due to the excitation of hard UV when the temperature during the burnthrough stage goes above $\approx 100$ ev. Note that the peak of the hard UV is delayed with respect to that of the medium UV signal.

In Fig. 8 is shown a soft UV profile obtained from an array of 12 bare detectors viewing the Microtor plasma vertically from the top. This profile is from a high current $I = 100$ kA shot in which $T_e = 500$ ev and $\bar{n}_e$ varies from $10^{13}$ cm$^{-3}$ to $10^{14}$ cm$^{-3}$ during this time. It can be seen that the soft UV profile in this case is hollow even without Abel inversion, indicating that at Microtor temperatures the soft UV emission due mainly to hydrogen and oxygen is localized near the plasma edge.

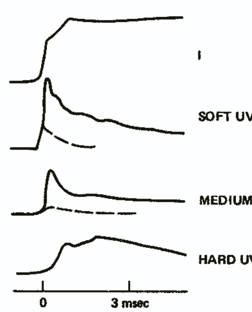


Fig. 7.—Burnthrough signatures for Microtor. The burnthrough phase of the Microtor discharge displays the difference between ultra-clean discharges (dashed line) and dirty discharges (solid line). In Microtor the hard UV signal also appears during burnthrough.

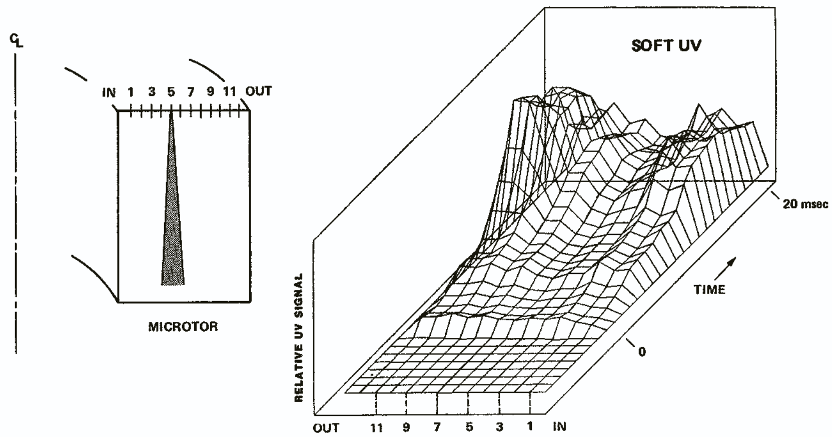


FIG. 8.—Soft UV profile in Microtor. A 12 detector uninverted soft UV profile shows a hollow shape indicating the central burnout of this emission at Microtor temperatures (c.f. Fig. 5).

## 6. CONCLUSION

A simple system for broadband VUV diagnosis of a Tokamak plasma has been described. Bare vacuum photodiodes sensitive to wavelengths in the range 50 to 1200 Å can be used as a monitor of discharge cleanliness by comparing the height of the hydrogen burnthrough peak to the height of the low-$Z$ burnthrough peak. Vacuum photodiodes filtered with an Al:Si foil having a transmission in the wavelength range 150–700 Å are sensitive mainly to low-$Z$ impurity radiation, and those filtered with polypropylene having a transmission in the range 50–150 Å are sensitive to the hotter $T_e \geq 100$ ev part of the plasma. Profiles in Macrotor are progressively more peaked in the soft, medium and hard UV channels, respectively.

These detectors may be used on hotter Tokamaks in the same way as conventional soft X-ray systems. Their advantage is simplicity, low cost, and a sensitivity in the VUV region where many impurities radiate. Of course, for use in future reactor-grade Tokamaks the possible effect of secondary emission due to fast neutral particles and the integrity of the thin filters will have to be reassessed; however, the natural insensitivity of the photodiode detector to hard X-ray and neutron backgrounds may make them attractive for use in that environment as well.

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