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Fast time-scale radiometry of DIII–D disruptions

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Introduction

Plasma disruptions in medium-size tokamaks such as DIII–D are characterized by loss of the stored thermal energy on a time scale as short as 10^{-4} s (thermal quench or TQ), followed by a dissipation on a 10^{-3} s time scale of the energy stored in the poloidal field (current quench or CQ). In both the thermal quench phase and the current quench phase, radiation is thought to be an important energy loss channel, but little is known about this to date because of the absence of diagnostics to measure radiated power on these time scales. The standard diagnostic for measurement of radiant heat is the metal foil bolometer, whose temporal response is limited to ~10^{-2} s. In order to better understand disruptions and the role played by radiative energy loss, a faster sensor is needed for this measurement.

A disruption radiometer ("DISRAD") diagnostic in use at DIII–D is described here, which uses a silicon "absolute XUV" (AXUV) photodiode detector [1], allowing measurements on a 10^{-6} s time scale. These devices are free of the "dead layer" that commonly desensitizes Si photodiodes to ultraviolet radiation; their application to radiometry in high-temperature plasma experiments has been described previously [2–4]. A weakness of these detectors in such measurements is that the responsivity varies considerably with photon energy below 22 eV—a spectral region in which considerable power can be radiated by impurities and atomic hydrogen. To address this issue, the diagnostic described here uses UV filtering to provide spectral information, allowing the spectral response to be accounted for in deducing the radiant power from the measured photocurrent.

The Diagnostic

The sensor used in this diagnostic is a monolithic linear array of AXUV diodes. The use of an array makes possible the inclusion of filtered channels, needed for decomposition of the emission spectrum (see below). The view is limited to a single chord in the poloidal plane, due to the diagnostic being mounted on a gate valve that allows isolation from DIII–D vacuum (Fig. 1). Three of the array elements are able to view of the plasma; the array is oriented such that the three views fan out toroidally (angle between views is about 2°).

The responsivity of the AXUV photodiode (amperes of photocurrent per irradiant watt) is fairly constant at 0.24 A/W (±2%) for photon energies from 22 eV to 4 keV, as seen in Fig. 2. Below 22 eV, the responsivity falls off—roughly by a factor of two. In DIII–D, a sizable fraction of the radiated power generally is emitted in the CIV resonance (8.0 eV or 155 nm) and in the deuterium Lyman α (10.2 eV or 122 nm). Because of the spectral variation of the responsivity, the ability to discriminate these lines from higher-energy XUV radiation is valuable for making an accurate determination of the radiated power.

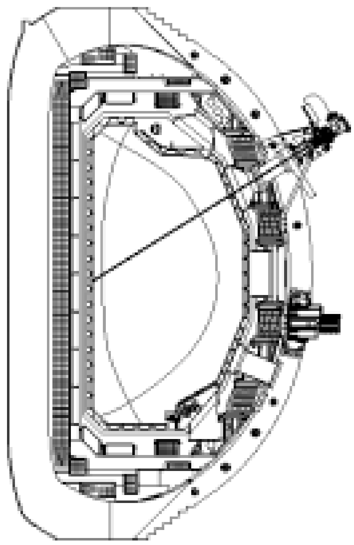

Fig. 1. The present DISRAD diagnostic has a single viewing chord through the DIII–D plasma.

To achieve this, different window materials (acting as short wavelength absorption filters) are placed in front of two of the array elements, and the third element has an unfiltered view. The MgF_2 filter (array element "M") transmits ~83% at 155 nm and ~55% at 122 nm. The cultured quartz filter (element "Q") transmits ~79% at 155 nm but blocks at 122 nm. Element "V" receives the full emission spectrum. In addition, a blind element ("B") is used to monitor for signals unrelated to optical radiation (e.g. hard X-rays, or external electronic influences).

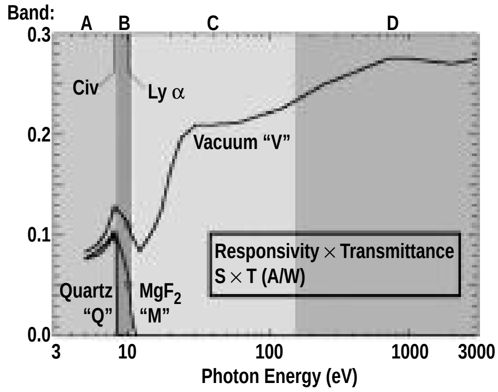

Fig. 2. The AXUV photodiode responsivity (V curve) varies significantly below 22 eV photon energy. The M and Q curves include the filter transmittance. Four spectral regions (A, B, C, D) are identified for analysis.

Data analysis is carried out with the aid of the "core SPRED" VUV survey spectrometer in DIII–D. The spectrum from this diagnostic is used as a weighting function for averaging the AXUV responsivity curve over a certain spectral region (see below). The line of sight of the SPRED diagnostic is tangential in the equatorial plane of the tokamak. Although the view is different from that of the DISRAD, it does pass through the core plasma. The SPRED has a minimum integration time of 1 ms, and typically provides a few spectra in the course of a disruption CQ.

The DISRAD diagnostic needs to measure brightnesses up to ~10^3 W cm^{-2} sr^{-1}. The photodiode array views the plasma through a pinhole aperture in a stainless steel disk of thickness 50 μm. The pinhole diameter for the results shown here is 100 μm. The distance from the pinhole to the diode array is 50 mm.

The DIII–D vessel is typically baked out at 350°C. The DISRAD can be baked, but the photodiode detector limits the temperature to around 120°C.

The bandwidth of the photocurrent detection electronics is 170 kHz. Variable-gain amplifiers following the detection circuit allow measurements in quasisteady (non-disrupting) plasmas as well as during disruptions. The measured brightness is ~10^2 higher in disruptions.

DIII–D is equipped with a multi-chord foil bolometer diagnostic [5]. Bolometer measurements are shown here for comparison with DISRAD. Construction of a multi-chord DISRAD diagnostic for DIII–D is planned.

Analysis

For interpretation of the data, we identify four significant photon energy bands: "A" (photon energy up to 8.3 eV), "B" (8.3 to 11 eV), "C" (11 to 150 eV), and "D" (150 to 5000 eV). Band A is seen by all channels (V, M, and Q), band B by channels V and M only, and bands C and D are seen only by channel V. Band C is the domain of the SPRED. Above 5 keV, the photodiode sensitivity falls off as the X-ray absorption length approaches the thickness of the epitaxial layer that forms the photodiode (only 25 μm thick).

We seek to determine the radiation from each of these four bands (P_A, P_B, P_C, P_D) independently, using the equations

$$I_Q = S_A T_{QA} P_A \tag{1}$$

$$I_M = S_A T_{MA} P_A + S_B T_{MB} P_B \tag{2}$$

$$I_V = S_A P_A + S_B P_B + S_C P_C + S_D P_D \tag{3}$$

Here I is the measured current for each channel, P is the radiant power incident on the filter (or diode in the case of I_V), T is filter transmittance, and S is responsivity. Band A is predominantly CIV (8.0 eV), so S_A = 0.125 A/W, T_{QA} = 0.79, and T_{MA} = 0.83 are used. Band B is predominantly Lyman α (10.2 eV), so S_B = 0.11 A/W and T_{MB} = 0.55 are used. For band D, S_D = 0.26 A/W is used. For band C, S_C is taken as an average of the spectral responsivity, using the SPRED spectrum as a weighting function. When the total power has been calcaluted ($P_{tot} = P_A+P_B+P_C+P_D$), it is useful to refer to an effective responsivity, given by $S_{eff}=P_{tot}/I_V$.

There are four photon energy bands of interest, but only three measured photocurrent channels. Different assumptions are used to close the system in the disrupting and quasisteady plasma cases.

In the disruption CQ, the system is closed by assuming that the radiation above 11 eV is entirely in the C band – i.e., the plasma is cold enough that P_D = 0. In quasi-steady plasmas, the D-band emission is not negligible. An absolute calibration is available for the SPRED, providing a C-band brightness measurement (W cm^{-2} sr^{-1}) that is used in the analysis, taking account of the different lengths of the SPRED and DISRAD viewing chords in the plasma. Both viewing chords pass through the core plasma, but since they pass through in different ways, this determination of P_C is rather approximate. With P_A and P_B taken from I_Q and I_M, and with P_C provided by the SPRED, P_D is deduced from I_V.

The time scale of the disruption TQ is typically too short for useful information to be obtained from the SPRED. Brightness in the TQ can be calculated by assuming values of S_{eff}, in transition from the quasi-steady value of typically 0.18 A/W to the CQ value of typically 0.12 A/W.

Results

The brightness measured during a disruption is shown in Fig. 3. The results shown take into account the AXUV spectral responsivity as described above. The peak photocurrents are a few microamperes; this corresponds to several million photons per microsecond absorbed in the photodiode, so photon statistics is not a concern. The brightness measured from the equivalent chord of the bolometer diagnostic is included for comparison; the areas under the two curves are in good agreement.

From the spectral decomposition of the radiation, we find that typically less than 3% of the radiated power is emitted at photon energies above 17 eV in the current quench. S_{eff} is found to be within 10% of 0.12 A/W throughout the CQ of the disruptions we have studied (Fig. 3). Since S_{eff} is essentially the same for all SPRED spectra in a given CQ, it is reasonable to assume that Seff is not varying within the SPRED integration time.

The brightness in the thermal quench of this disruption is shown in Fig. 4. The observed decay time of 0.13 ms is close to that seen in T_e as measured by electron cyclotron emission.

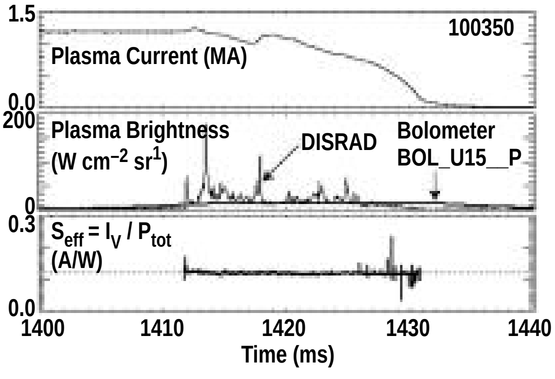

Fig. 3. The DISRAD diagnostic provides good temporal resolution of radiant power during disruptions. The time integral (radiated energy) agrees with the bolometer.

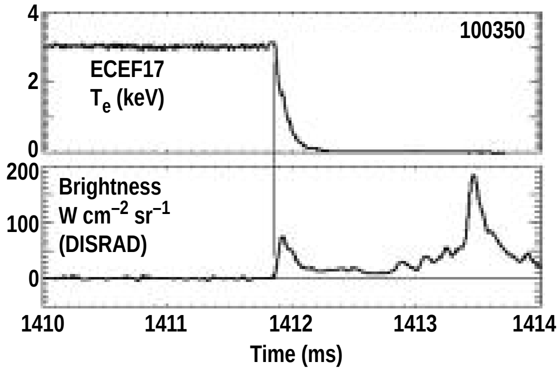

Fig. 4. In the thermal quench, decay time of T_e and radiant power are similar.

The brightness measured from a complete discharge (quasisteady plasma) is shown in Fig. 5. The brightness from the equivalent bolometer channel (same *r*-θ chord at a different toroidal location) is shown for comparison. The agreement is quite good, even though the photocurrents are small during quasisteady operation and magnetic pickup is sometimes significant in comparison to the signals produced by the small photocurrents. Increasing the aperture diameter is expected to improve the signal-to-noise ratio. The effective responsivity is found to be less constant than in the disruption CQ, due to varying fractions of the radiated power being emitted at higher photon energies.

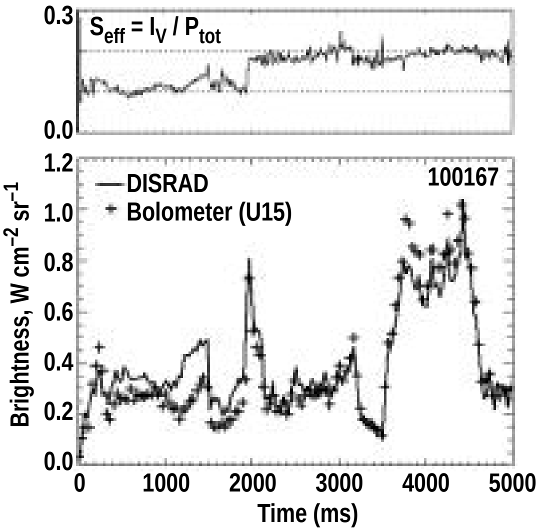

Fig. 5. Agreement with bolometer is found also in quasi-steady plasmas. The effective responsivity is less constant than in disruptions.

Conclusions

The use of optical filtering and fast current detection electronics have made possible the time-resolved measurement of radiant power from disrupting plasmas using a photodiode-based diagnostic. Agreement with foil bolometer measurements is good. A fast multi-chord diagnostic using these photodiodes is planned for DIII–D.

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