189
6/24/78

LA-7273

UC-20f

Issued: June 1978

Dr. 192

MASTER

A Diagnostic for Measurement of Radiated Energy from a Toroidal Plasma

R. B. Howell
H. J. Karr*

* 1509 42nd Street, Los Alamos, NM 87544

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87545

An Affirmative Action/Equal Opportunity Employer

UNITED STATES
DEPARTMENT OF ENERGY
CONTRACT W-7405-ENG. 36

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

A DIAGNOSTIC FOR MEASUREMENT OF RADIATED ENERGY FROM A TOROIDAL PLASMA

by

R. B. Howell and H. J. Karr

ABSTRACT

Impurity line radiation can be a serious loss mechanism for a plasma. A diagnostic was needed for measuring the radiation loss on ZT-S, a toroidal reverse field pinch, so that the loss could be compared with total energy loss from the plasma. In the techniques described here the total number of photons emitted from the plasma and the average photon energy are found. The number of incident photons is measured by a calibrated detector that observes a limited region of plasma. By measuring the emission from two different chords and using the optical properties of the system, one can obtain the total number of photons emitted from the plasma per unit time and per unit length. To obtain the average photon energy one must know the relative sensitivity of both the spectrograph and film vs wavelength. Then the time-integrated radiated power is compared with the total energy loss from the plasma.

I. INTRODUCTION

A comparison of total radiated power with total energy loss is useful in establishing whether radiation is the dominant loss mechanism in a plasma. Impurities in plasmas can give rise to large energy losses through line radiation and bremsstrahlung. With the resulting lower electron temperature there can be an unacceptably higher magnetic field diffusion in the case of high-beta plasmas such as the reverse field pinch (RFP).

The RFP is a toroidal high-beta device that operates above the Kruskal-Shafranov limit and owes its predicted magnetohydrodynamic stability to wall and shear stabilization. This stability depends to a great extent upon obtaining certain magnetic field configurations and maintaining them. The ZT-S (toroidal RFP) experiment had the following parameters: $R = 40.4$ cm, $r = 7.7$ cm, $I_\phi \simeq 60.0$ kA, $\dot{i}_\phi \simeq 3 \times 10^{10}$ A/s, $B_\phi(r=0) \simeq 0.25$ T, $n_e = 2$ to

$5 \times 10^{15} \text{ cm}^{-3}$, $\tau \leq 30 \text{ } \mu\text{s}$, $T_e = 20 \text{ to } 25 \text{ eV}$ at 10 mtorr D_2 , and oxygen impurity concentration $\sim 0.85 \text{ at.}\%$ at 10 mtorr. The low electron temperature prompted the development of a diagnostic to measure the radiation energy loss.

To obtain an absolute measurement of radiated power on a microsecond time scale, the detector first must be calibrated for intensity. One must know also the emitting geometry of the source if the measured intensities from a limited region and solid angle are to be related to a total radiated intensity. In addition, the spectral sensitivity of the detector must be known. If the detector response is mainly due to number of photons and not to energy deposited by them, the average photon wavelength must be found. Similar diagnostic techniques were employed by Karr, Knapp, and Osher.¹

II. EXPERIMENTAL SETUP AND SPECTRAL RANGE DETERMINATION

The experimental setup is shown schematically in Fig. 1. The detector is an ITT FW 128 diode with a sodium salicylate phosphor for conversion of the uv radiation. The detector assembly is supported above one of the ZT-S pump ports by an X-Y translation mount so that the detector views the center of the toroidal discharge tube.

Figure 2 shows a typical radiation signal for a photodiode load resistor of $150 \text{ } \Omega$ and the ceramic plug removed from the pump port. The arrangement of the torus and the detector is shown in Fig. 1. The radiation signal started $\sim 2 \text{ } \mu\text{s}$ after the onset of the toroidal discharge current and rose to its maximum value after another $2 \text{ } \mu\text{s}$. A streak photograph of a typical pinch discharge (Fig. 3) shows that the pinch was stable for $\gtrsim 25 \text{ } \mu\text{s}$ --longer than the time interval over which the measurements were made.

The first aperture (Fig. 1) mounted in front of the photodiode shield is recessed to hold quartz or LiF filters. When a 2-mm-thick quartz window was inserted, the signal fell to negligible amplitude, indicating that little of the signal was due to radiation when $\lambda > \sim 2000 \text{ } \text{\AA}$. When a 2-mm-thick LiF window was inserted, the signal decreased to ~ 0.1 that of the amplitude measured without a filter. From this we deduce that most of the radiation lies in the spectral range below $1050 \text{ } \text{\AA}$. Also, the use of various thin films as filters confirmed that uv was the radiation source. The spectrum was determined in detail with VUV spectrograph measurements which are shown in Fig. 4. This

Fig. 1. Photodiode radiation energy detector.

Fig. 2. Typical signal from uv radiation detector (shown in Fig. 1) with photodiode load resistor of 150 Ω . Upper trace: I_ϕ -0.1 V/div. (30 000 A/div.), 5 μ s/div. Lower trace: Photodiode signal-0.05 V/div., 5 μ s/div. Shot No. 24706: P_0 -20 mtorr D_2 , FB_ϕ -0.95 kV (600 G), RB_ϕ -10 kV, PI -5 kV, V_ϕ -7.5 kV, $I_{\phi max}$ -60 kA.

Fig. 3. Streak photograph for shot 24706. Total streak duration $\sim 50 \mu$ s.

Fig. 4. Plasma line emission below $\sim 50 \text{ \AA}$ for the ZT-S plasma.

spectrum was taken on SWR film and a photodensitometer trace was made of it. These measured intensities then were corrected for the relative film sensitivity vs wavelength. To determine an average photon wavelength an intensity calibration must be made for grating. With the assumption of a flat grating response, an average photon wavelength of 400 Å was determined for the spectrum.

III. INTENSITY CALIBRATION OF THE DETECTOR

1) The overall gain of the photodetector system from the diode load to the oscilloscope was 2.5×10^{17} photoelectrons/s for 1 V at the oscilloscope, which corresponds to 6 V at the diode across 150 Ω.

2) For known radiation (2537 Å Hg) incident on the sodium salicylate fluor coating on the diode window, the photoelectric current gave 92.9 photons/photoelectron. In measurements by Samson et al.² the photoconversion efficiency of sodium salicylate decreases by a factor of 1.45 from the 2537 Å wavelength to the 200 to 1200 Å region. Thus the conversion efficiency is 135 photons/photoelectron, and 1 V at the scope corresponds to 3.4×10^{19} photons/s incident on the fluor at the diode window.

IV. EFFECT OF THE EMISSION PROFILE ON THE MEASUREMENT OF RADIATED POWER

Consider the source-detector geometry as shown in Fig. 5. Here the plasma is considered to be cylindrically symmetric with its axis lying on the Z axis of the figure. The variables R and θ in Fig. 5 refer to the cylindrical coordinate system whose axis passes through the detector and which is at 90° to the axis of the plasma.

The plasma emission (intensity/unit volume) is $I = \sum_i I_i f_i(r)$ where $f_i(r)$ is the radial emission profile of a given spectral line, I_i is the peak emission for a given line, and the sum is taken over the important spectral lines. If each infinitesimal volume element that is radiating has a solid angle $d\Omega$ as seen by the detector, we can write the power incident upon the detector as

$$P(b) = \sum_i I_i \int_V d\Omega f_i(h) dv$$

where the volume integral is over the volume of plasma seen by the detector and where h is the radial distance from the plasma axis to the radiating volume element.

Let $A(R, X_S)$ be the area of the detector illuminated by a source at X_S whose distance from the detector axis is R . The solid angle for $|X_P - X_S| \gg R$ is

$$d\Omega \approx \frac{A(R, X_S)}{4\pi [R^2 + (X_P - X_S)^2]},$$

where X_P is the distance from the detector to the center of the plasma, as shown in Fig. 5. Hence the power incident upon the detector is given by

$$P(b) = \frac{1}{4\pi} \sum_i I_i \iiint_{XR\theta} A(R, X_S) [R^2 + (X_P - X_S)^2]^{-1} f_i(h) d\theta R dR dX_S \quad (1)$$

where

$$h = [X_S^2 + (R \sin\theta - b)^2]^{1/2},$$

The parameter b accounts for the detector viewing the plasma on an off-diameter chord. In Fig. 5, b is equal to zero. The incident power on the detector can be written $P = \sum_i I_i F_i$, where F_i is the cumulative illumination factor (source volume $\times$ solid angle) for a single spectral line. The power radiated per unit length of plasma for a single spectral line is

$$I_{li} \text{ (watts/unit length)} = I_i \int_0^r 2\pi f_i(r) r dr = I_i K_i$$

where K_i is the effective cross-sectional area of the plasma for a single spectral line emission profile. The total power radiated per unit length of plasma is

$$\begin{aligned}
I_{\lambda} &= \sum_i I_{\lambda i} \\
&= \sum_i P_i \frac{K_i}{F_i}
\end{aligned}$$

This can be approximated by the product of $\sum_i P_i$ and an average of K_i/F_i , giving

$$\begin{aligned}
I_{\lambda} &\approx \left\langle \frac{K}{F} \right\rangle \sum_i P_i \\
&= \left\langle \frac{K}{F} \right\rangle P \\
&= \frac{K}{F} P,
\end{aligned}$$

where K and F denote the effective cross-sectional area and the effective cumulative illumination factor, respectively.

To determine the effect of emission profiles on the emitted power I_{λ} when a power P is obtained at the photodiode detector, we considered three cases: (1) a flat emission profile, (2) a hollow emission profile, (3) a set of gaussian emission profiles. For the flat profile, $K = 78.5 \text{ cm}^2$ for $R = 5 \text{ cm}$, and $F = 1.25 \times 10^{-2}$. From this, $K/F = 6.28 \times 10^3$.

For the hollow profile we chose $f(r) = 1.189 (e^{-Ar^4} - 0.5 e^{-Br^4})$, where $A = 5.3 \times 10^{-3}$ and $B = 0.106$. For this case, $K = 39.94 \text{ cm}^2$ and $F = 6.98 \times 10^{-3}$, so $K/F = 5.7 \times 10^3$. If the detected signal had been attributed to a flat profile, the calculated amount of power radiated would be 10% higher than the power actually radiated as a result of this hollow profile.

Table I shows the results calculated for a set of gaussian profiles $f(r) = e^{-r^2/\delta}$. Here $K = \pi\delta(1 - e^{-R^2/\delta})$. The values of F were obtained from the Vignet code that calculates numerically the integrals in Eq. (1). The gaussian profiles are shown in Fig. 6.

TABLE I
CALCULATIONS FOR GAUSSIAN PROFILES

δ (cm ²)	K (cm ²)	F (cm ³)	K/F (cm ⁻¹)	$I_{\lambda}(\delta)/I_{\lambda}(\delta \rightarrow \infty)$
2	6.3	0.00255	2.47×10^3	0.39
4	12.5	0.00380	3.29×10^3	0.52
6	18.6	0.00474	3.95×10^3	0.63
8	24.0	0.00546	4.40×10^3	0.70
10	28.8	0.00632	4.55×10^3	0.72
12	33.0	0.00650	5.07×10^3	0.81
∞	78.5	0.01250	6.28×10^3	1.00

The last column of Table I gives the ratio of the actual radiated power to the radiated power calculated on the assumption of a flat emission profile. Large errors could be made by assuming a flat emission profile in the calculation.

We devised a technique to find the total radiated power when the exact emission profile is not known. K and F(b) have a similar dependence on the emission profile. Thus $K \cong \text{constant} \cdot F(b)$, and this constant can be determined approximately by computing K and F(b). Since $F(b)/F(o) = P(b)/P(o)$ we can determine K/F(o) by measuring P(o) and P(b). Using the Vignet code, we computed F(b) and F(o) for a set of centered gaussian profiles using the detector geometry that is being implemented on ZT-S. The ratio of F(b)/F(o) is plotted in Fig. 7. The emission profile for $\delta = 100 \text{ cm}^{-2}$ is close to a flat emission profile. Next, the radiated power coefficient K/F(o) was found for each of the gaussian and hollow profiles. The hollow profiles are shown in Figs. 8(a), (b), and (c). In Fig. 9 the values of K/F(o) are plotted against the chordal intensity ratio, P(b)/P(o). From that plot the power coefficient can be found once the chordal intensity ratio has been measured.

The value of K/F(o) is an effective value usually representing the intensity-weighted contribution of several different emission profiles. Thus this approximation introduces some uncertainty in K/F(o) for a given chordal intensity ratio. The bounds on the uncertainty have been evaluated and are

Fig. 5. The source-detector geometry of the experiment.

Fig. 6. Gaussian emission profiles.

Fig. 7. Chordal intensity ratio vs δ .

Fig. 8. Hollow emission profiles.

shown in Fig. 10. The percentage of uncertainty should be taken as both positive and negative uncertainty; consequently, chordal intensity ratios between 0.7 and 1.0 have uncertainties of $\pm 7\%$.

V. EXPERIMENTAL RESULTS

If a flat emission profile is assumed, the calibration factor for the present photodiode setup would be 110 J/ μ s·m.

The lower trace in Fig. 11 shows the cumulative radiation energy loss obtained by applying the above calibration factor to the ZT-S radiation signal shown in Fig. 2. The radiation loss rate per meter length varies from .5 to 8 MW during the .25- μ s stable period of the discharge.

Figure 12 shows the energy balance for the discharge. The lower trace in Fig. 12 represents the magnetic field energy and plasma energy contained within the torus plotted against time, and was calculated from probe data for a 1-m length of the ZT-S torus. The upper trace shows the total energy input obtained electronically by integrating the product of the current and voltage waveforms. The gap between the two traces (Fig. 12) represents the total energy loss (J/m), which is replotted in Fig. 11 for comparison with the radiation loss when a flat emission profile is assumed. The pinch exhibits bouncing and other dynamic effects that may invalidate the plasma energy content calculations for the first .5 μ s. After this dynamic period, the radiation loss probably represents a significant fraction of the total energy loss over the .20- μ s interval for which the calculations were made.

VI. CONCLUSIONS

The method for determining absolute energy losses attributable to radiation depends either on knowledge of the emission profile or use of the technique developed here of finding the chordal intensity ratio that is proportional to the radiated power coefficient. With the latter technique, the radiated energy loss can be obtained and accurately related to total energy loss. Here we made the comparison between radiated energy loss and total energy loss but assumed a flat emission profile for lack of better information.

Fig. 9. $K/F(o)$ vs chordal intensity ratio. The triangles denote hollow emission profiles and the circles denote centered gaussian profiles.

Fig. 10. Percent uncertainty in K/F vs the chordal intensity ratio.

Fig. 11. Energy loss in J/m vs time in time in μs after onset of I_0 .

Fig. 12. Energy balance in J/m for a typical shot on ZF-S.

REFERENCES

1. H. J. Karr, E. A. Knapp, and J. E. Osher, "Energy Loss from a Toroidal Pinch Discharge," *Phys. Fluids* 4, 424-437 (1961).
2. J. A. R. Samson, Techniques of Vacuum Ultraviolet Spectroscopy (John Wiley and Sons, Inc., 1967), p. 212.