By

J. Schivell

SEPTEMBER 1986

**PLASMA
PHYSICS
LABORATORY**

**PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY**

**PREPARED FOR THE U.S. DEPARTMENT OF ENERGY,
UNDER CONTRACT DE-AC02-76-CBO-3073.**

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

RECONSTRUCTION OF PLASMA RADIATION FEATURES FROM PROJECTIONS
MEASURED WITH TWO BOLOMETER ARRAYS

PPPL--2382

J. Schivell

DE87 000670

Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08544

ABSTRACT

A specialized method has been developed to maximize the two-dimensional detail obtained from two perpendicular bolometer arrays. The technique relies on the assumption that poloidal variation exists only near the plasma surface. The cross section is divided into appropriate zones, and the emittance is reconstructed by a numerical method. The position, intensity, and width of large features are clearly displayed. A marfe is tracked as it drifts around the plasma and evolves into a radiating shell detached from the limiter. A central peak, plus inner-wall radiating layer, plus a marfe appear in a high-density case reached by pellet injection.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

INTRODUCTION

In the TFTR tokamak the power losses through impurity radiation are measured with several bolometers, among which are two fan arrays of 19 chords each [1]. The coverage of these arrays is diagrammed in Fig. 1. The field of view of each detector is approximately 0.1 m. It was expected, and usually found, that the profiles of chord-integral power measured with the two arrays are at least approximately symmetric about the plasma center. However, when the plasma density is high for the operating conditions, an intense, narrow peak appears and seems to be superimposed on the normal profiles (Fig. 2). From its behavior in the radiation profiles and its behavior in the observations of other diagnostics, this phenomenon has been identified as the edge-plasma effect first seen on Alcator C and named "marfe" [2]. A marfe is an intensely radiating, cold, dense, region of plasma on the inner side of the discharge. It is toroidally symmetric; that is, it has no helicity. Marfe observations on TFTR have been described in Ref. 3. New features observed (Fig. 3) are that the band drifts up or down the inner side of the plasma and that, if the density is pushed higher, the band evolves into a bright shell surrounding the whole plasma and radiating all of the energy throughput.

The bolometer array measurements are central to these observations. In the radiated-power profiles the marfe is typically a large feature, with an intensity which is as great, or greater, than the intensity of the normal part of the plasma. The coverage provided by the two arrays allows the marfe drift to be tracked continuously (while it drifts in and out of the field of view of other diagnostics), and the absolutely calibrated measurements can tell the power radiated by the marfe and its role in the plasma power balance. By locating the peaks on a diagram such as Fig. 1, one can see that the marfe has little or no rotational transform. In fact, one can also make a rough

estimate of the power radiated per unit volume and the width of the band. However, it is clearly worthwhile to make a proper reconstruction of the emittance as a function of radius and angle. With a well-specified procedure the reconstruction can be done routinely by computer. Also, one can check the consistency of the peaks from the two arrays and put an upper limit on possible helicity of the bright band. Finally, there are other features of radiation profiles which call for two-dimensional reconstruction: One, when the plasma is run in contact with the so-called inner bumper limiter, there is apparently a bright sheet of radiation on the whole inner side of the plasma. Two, when the density is very high as a result of pellet injection, there is evidence of a sharp central peak which needs to be distinguished from that bright background.

RECONSTRUCTION METHOD

The profiles from the two bolometer arrays constitute two projections of the cross section of the radiated power. Two projections give only limited information. For example, if the emittance in two dimensions is represented by harmonics in angle [4, 5],

$$E(r, \theta) = E_0(r) + \sum_m E_{c,m}(r) \cos(m\theta) + \sum_m E_{s,m}(r) \sin(m\theta) \quad (1)$$

two projections are sufficient to determine only terms through $\cos 2\theta$. If, on the other hand, one adopts a representation, say, of a grid with a large number of divisions and a constant emittance in each box, and applies the

method of Maximum Entropy [6] to select a solution from the underconstrained possibilities, then the result is to spread out the emittance over the widest possible area consistent with the measurements.

What was done in this work, instead, was to assume that the interesting features are all in the outer layers of the plasma, and, further, on the inner side of these outer layers. These assumptions are not rigorously justified, but are indicated by all of the other observations [2, 3]. Actually, when the radiation peak is centered on channel 3 of the vertical view, there is little doubt about where the bright band must be or its thickness. When it is in the lower part of the plasma, it is natural to guess that it is no thicker. Observations by other diagnostics, such as the visible-light, tangentially viewing plasma TV [7], and the multichannel infrared interferometer [8], support this assumption. Finally, it seems plausible that poloidally local effects are much more likely to occur in the outer portion of the plasma, which is closer to the influence of edge perturbations.

The assumptions allow one to utilize the available resolution in the interesting region. The cross section of the plasma is divided into zones as shown in Fig. 4. The emittance in each zone is a single value. The inner zones are annuli, while the outer ones are annuli subdivided into sectors on the inner side. Zone boundaries were chosen so that at least one chord from each view passes through each zone. Due to the difficulties of our particular geometric arrangement, it was not possible to have zones nicely centered around each chord in many places. The effect is extra noisiness in the result, since the emittance in some zones is not well determined. To allow for the possibility of emittance in areas of the vacuum vessel outside of the nominal plasma boundary, additional rings were added, sectorized as shown in the figure.

The length of each chord, i , in each zone, j , was calculated to make up a matrix, L_{ij} . (To take into account the finite field of view of each detector, L_{ij} was actually calculated by averaging over a number of chords distributed over a small range around each chord, i .) If the integral of the emittance along chord i is C_i , and the emittance in zone j is E_j , then the C 's and E 's are related by

$$C_i = \sum_j L_{ij} E_j \quad (2)$$

and, of course, the reconstruction consists of finding the $\{E_j\}$. A linear, additive algebraic reconstruction technique (ART) [9] was used. The procedure is the same as that described in Ref. 10. The chords are stepped through, one by one, and the E_j along each chord are adjusted to reduce the difference between the C_i from Eq. (2) and the measured C_i . The adjustment to each E_j is proportional to the length interval of the chord in the j -th zone. There is a convergence factor to specify what fraction of the difference is to be eliminated in each pass, and a large number of passes is used. Negative E_j values are set to zero, and the other E_j along the same chord are reduced to keep the sum unchanged. (There are two differences from Ref. 10. An error was corrected, so that in effecting the constraint that no E_j be < 0 , the non-negative E_j are replaced by $E_j + N L_{ij} / \sum_m L_{im}^2$, where m ranges over all j such that $E_j > 0$. The other difference is that there is a tolerance and a cutoff in the adjustment procedure for $E_j < 0$.)

This procedure is resilient. It does not demand that there be an equal number of chords and emittance zones. The numbers used here are 38 chords and 41 zones. When the solution is underconstrained, the emittance is distributed over all possible zones, consistent with the observed $\{C_i\}$. On the other

hand, when the input data contains inconsistencies, such as a different average intensity in the two projections, the procedure averages among them, as long as the convergence factor is small. This averaging property is particularly useful on TFTR, since the bolometer arrays are on opposite sides of the torus. Finally, however, one must keep in mind that it is possible to converge on a fit that is good, but that does not correspond to reality.

RESULTS

The results of reconstructing a typical set of profiles are given in Figs. 2 and 5. Deviations from the observed profiles are mostly less than a few percent. The height of the marfe is 200 kW/m^3 , and it is at least two zones (approximately 0.15 m) thick. (If the zones were to be sectorized in the smaller-radius rings, the reconstruction could yield a thicker marfe at some times, with correspondingly smaller height. However, the narrowness of the peak when the marfe is in the upper half, e. g., at 2.5 s (Fig. 2), indicates a small thickness.) The upward motion of the marfe along the inner side of the plasma is clearly seen. Beginning at 3.5 s the dominant pattern of radiation loss changes to a bright shell surrounding the plasma, steadily shrinking in diameter. At these times the symmetry in the chord-integral profiles is clear. The reconstruction, since it uses inner rings which are not divided into sectors, does not prove the symmetry of the emittance, but makes use of it. The origin of the small peaks outside the bright ring is not clear. They may be an example of an unreal fit, as mentioned above.

As a test, this reconstruction procedure has been generalized to the case in which all of the rings are subdivided into sectors. As expected, the resulting emittance distributions showed streaks across the plasma along the chords with high signals. Since the two projections available cannot

distinguish between this kind of result and the edge concentration assumed above, it is up to the user to choose which result is preferable in light of other information.

The emittance results are also produced as contour plots and plots in which the density of dots is proportional to emittance. The surface plots are the most useful for maximum visibility of the features.

Figure 6 shows results at a time 600 ms after the last in a series of 5 frozen deuterium pellets has been injected into a discharge; the density reached a record high level. The reconstruction algorithm fits, in addition to a marfe in the inner side, a sharp central peak. Evidence for this peak is seen directly in Fig. 6 (b) at vertical-view channel 9. In the horizontal view it is apparently submerged in the marfe peak. It is interesting to note that this peak is predicted by calculations of deuterium bremsstrahlung and impurity radiation for the density profile in this plasma [11].

The total power radiated from each zone can be found by multiplying the emittance by the toroidal volume of the zone, and the total for the whole plasma by summing over zones. In the drifting marfe case above, the marfe radiated power (taking a rough cut for the extent of the marfe) is 300 kW, the remainder of the power from the inner-side surface of the plasma is 200 kW, and the total from the rest, or "normal" part of the plasma, is 500 kW. It is worth noting that, if the marfe is truly concentrated as shown, then the emittance is five times the typical value radiated from the most intense region (near the surface) of the normal part of the plasma. The poloidal extent of the marfe (width at half maximum) is approximately 60° , but extends about 90° as it passes through the midplane. In the pellet case the peak marfe emittance is 600 kW/m^3 , and the central peak is 300 kW/m^3 . The integrated radiation losses are as follows: from the vicinity of the inner wall,

including the marfe, 1400 kW; from the central peak, 350 kW; and, from the rest of the plasma, 150 kW. In this case 100% of the input heating power is lost through radiation, but 75% of that is from the region near the inner wall. It is the case, however, that at the plasma center the local radiation loss is approximately equal to the local heating power.

Since the peaks in the two profiles are both fit, I find toroidal symmetry in the intensity, width, and poloidal location of the bright band. The amount of poloidal rotation of the band is less than 5° in going one-half the way around the torus. Of course, the peaks would also be consistent with a large poloidal rotation, e.g., 70° in this case between arrays. However, that amount of rotation is inconsistent with the rotational transform of the magnetic field lines, 32° , and with the picture from the plasma TV [7].

Sensitivity to noise was tested by adding normally distributed random errors to measured profiles and carrying out the reconstruction. A standard deviation of 10 kW/m^2 resulted in a standard deviation of 50 kW/m^3 in the emittance. This corresponds roughly to a doubling of the fractional error. An estimate of the sensitivity to the locations of the zone boundaries was made by comparing a case in which the L_{ij} were calculated for zero-width fields of view with the case of normal fields (4°). For almost all zones there was little difference in the result, but one zone on the upper, inner side developed an apparently spurious peak (200 kW/m^3 in the 4.00 s reconstruction of Fig. 5), which is small in the normal-field case. These tests, as well as experience with numerous reconstructions, indicate that the stability of the method is good.

CONCLUSIONS

The accuracy of the results is limited by the same sort of sensitivity to errors as the usual Abel inversion for cylindrically symmetric situations [12]. In the TFTR case, the accuracy is also limited by the fact that the two arrays are on opposite sides of the torus. The assumption of relatively large, discrete zones with uniform emittance in each leads to rough spatial variations in the results.

Often there are features which do not fit, such as bumps, edge cusps, and skewness in the two profiles, with amplitudes of about 20% or less of the main part of the profile. The ART tends to average between the two views. In many cases the reasons for these features are not known. One known cause is a plume of impurities which comes off the limiter rail [7] and apparently passes in front of the vertically viewing array, 36° around the torus. For this reason, with rail-limited plasmas the outer half of the vertically viewed profile is often excluded from the fit.

In any case, this method is successful. It finds a fit to the height and width of large peaks in the two views. It indicates that the model, with its sectorized zones on the inner side, is consistent with the measured profiles. The smaller bumps which result are generally not very reliable. They can suggest the existence of phenomena, to be confirmed by other evidence.

ACKNOWLEDGMENTS

I wish to thank C. E. Bush, M. Zarnstorff, and B. C. Stratton for helpful discussions. This work was supported by U.S. Department of Energy Contract No. DE-AC02-76-CHO-3073.

References

- [1] J. Schivell, Rev. Sci. Instrum. 56, 972 (1985).
- [2] B. Lipschultz, B. Labombard, E. S. Marmar, M. M. Pickrell, J. L. Terry, R. Watterson, S. M. Wolfe, Nucl. Fusion 24, 977 (1984).
- [3] F. P. Boody, C. E. Bush, S. S. Medley, H. K. Park, and J. Schivell, Proc. of the 7th Internat. Conf. on Plasma-Surface Interactions in Controlled Fusion Devices (May, 1986) J. Nucl. Mater. (in press).
- [4] P. Smeulders, Nucl. Fusion 26, 267 (1986).
- [5] J. F. Camacho and R. S. Granetz, Rev. Sci. Instrum. 57, 417 (1986).
- [6] G. A. Cottrell, E. S. Fairbanks, and R. E. Stockdale, Rev. Sci. Instrum. 56, 984 (1985).
- [7] S. S. Medley, D. L. Dimock, S. Hayes, D. Long, J. L. Lowrance, V. Mastrocola, G. Renda, M. Ulrickson, and K. M. Young, Rev. Sci. Instrum. 56, 1873 (1985), and S. S. Medley, private communication.
- [8] H. Park, D. K. Mansfield, L. C. Johnson, and C. H. Ma, Rev. Sci. Instrum. 56, 938 (1985), and H. Park, private communication.
- [9] G. T. Herman, A. Lent, and P. H. Lutz, Commun. Ass. Comput. Mach. 21, 152 (1978).
- [10] J. Schivell, IEEE Trans. on Plasma Sci. PS-8, 226 (1980).
- [11] B. C. Stratton, private communication.
- [12] K. Bockasten, J. Opt. Soc. Am. 51, 943 (1961).

Figure Captions

- [1] Lines of sight of bolometer arrays. The arrays are 162° apart toroidally. The solid and dashed circles represent the two largest plasmas allowed by the limiters.

- [2] Chord-integral intensity measured by the two bolometer arrays at 2.5 s in a discharge with a "marfe" [see text]. The part of the vertical-view profile outside of channel 10 is considered normal. The dashed lines are the results of integrating the reconstructed emittance.

- [3] Chord-integral intensity (horizontal view) as a function of channel and time for the same discharge as Fig. 2. The bright feature drifts from bottom to top. During the same time there is a peak in the vertical view which drifts from channel 7 to channel 2.

- [4] Division of plasma cross section into zones for emittance reconstruction. Dotted circle is the vacuum vessel.

- [5] Plots of emittance as a function of position for nine times, showing drift of the marfe and its evolution into a detached plasma limited by a radiating shell. The height of the surface is proportional to emittance. The view is looking inward toward the torus major axis; the top of the plasma is on the right. The chord integrals at 2.5 s are shown in Fig. 2.

- [6] Chord-integral intensity, horizontal view (a) and vertical view (b), and reconstructed emittance distribution (c) for a discharge with a central radiation peak as well as a marfe.

Fig. 1

Fig. 2

Fig. 3

#86XIII3

Fig. 4

Fig. 5

Fig. 6

EXTERNAL DISTRIBUTION IN ADDITION TO UC-20

Plasma Res Lab, Austra Nat'l Univ, AUSTRALIA
 Dr. Frank J. Paoloni, Univ of Wollongong, AUSTRALIA
 Prof. I.R. Jones, Flinders Univ., AUSTRALIA
 Prof. M.H. Brennan, Univ Sydney, AUSTRALIA
 Prof. F. Cap, Inst Theo Phys, AUSTRIA
 M. Goossens, Astronomisch Instituut, BELGIUM
 Prof. R. Bouclique, Laboratorium voor Natuurkunde, BELGIUM
 Dr. D. Palumbo, Og XII Fusion Prog, BELGIUM
 Ecole Royale Militaire, Lab de Phys Plasmas, BELGIUM
 Dr. P.H. Sakanaka, Univ Estadual, BRAZIL
 Lib. & Doc. Div., Instituto de Pesquisas Espaciais, BRAZIL
 Dr. C.R. James, Univ of Alberta, CANADA
 Prof. J. Teichmann, Univ of Montreal, CANADA
 Dr. H.M. Skarsgard, Univ of Saskatchewan, CANADA
 Prof. S.R. Sreenivasan, University of Calgary, CANADA
 Prof. Tudor W. Johnston, INRS-Energie, CANADA
 Dr. Hannes Barnard, Univ British Columbia, CANADA
 Dr. M.P. Bachynski, MPB Technologies, Inc., CANADA
 Chalk River, Nucl Lab, CANADA
 Zhengwu Li, SW Inst Physics, CHINA
 Library, Tsing Hua University, CHINA
 Librarian, Institute of Physics, CHINA
 Inst Plasma Phys, Academia Sinica, CHINA
 Dr. Peter Lukac, Komenského Univ, CZECHOSLOVAKIA
 The Librarian, Culham Laboratory, ENGLAND
 Prof. Schatzman, Observatoire de Nice, FRANCE
 J. Radet, CEN-BP6, FRANCE
 JET Reading Room, JET Joint Undertaking, ENGLAND
 AM Dupas Library, AM Dupas Library, FRANCE
 Dr. Tom Mui, Academy Bibliographic, HONG KONG
 Preprint Library, Cent Res Inst Phys, HUNGARY
 Dr. R.K. Chhajlani, Vikram Univ. INDIA
 Dr. B. Dasgupta, Saha Inst, INDIA
 Dr. P. Kaw, Physical Research Lab, INDIA
 Dr. Phillip Rosenau, Israel Inst Tech, ISRAEL
 Prof. S. Cuperman, Tel Aviv University, ISRAEL
 Prof. G. Rostagni, Univ Di Padova, ITALY
 Librarian, Int'l Ctr Theo Phys, ITALY
 Miss Ciella De Palo, Assoc EURATOM-ENEA, ITALY
 Biblioteca, del CNR EURATOM, ITALY
 Dr. H. Yamato, Toshiba Res & Dev, JAPAN
 Direc. Dept. Lg. Tokamak Dev. JAERI, JAPAN
 Prof. Nobuyuki Inoue, University of Tokyo, JAPAN
 Research Info Center, Nagoya University, JAPAN
 Prof. Kyoji Nishikawa, Univ of Hiroshima, JAPAN
 Prof. Sigeru Mori, JAERI, JAPAN
 Prof. S. Tanaka, Kyoto University, JAPAN
 Library, Kyoto University, JAPAN
 Prof. Ichiro Kawakami, Nihon Univ, JAPAN
 Prof. Satoshi Itoh, Kyushu University, JAPAN
 Dr. D.I. Choi, Adv. Inst Sci & Tech, KOREA
 Tech Info Division, KAERI, KOREA
 Bibliotheek, Fon-Inst Voor Plasma, NETHERLANDS
 Prof. B.S. Lilley, University of Waikato, NEW ZEALAND
 Prof. J.A.C. Casral, Inst Superior Tecn, PORTUGAL
 Dr. Octavian Petrus, ALI CLUZA University, ROMANIA
 Prof. M.A. Hellberg, University of Natal, SO AFRICA
 Dr. Johan de Villiers, Plasma Physics, Nucor, SO AFRICA
 Fusion Div. Library, JEN, SPAIN
 Prof. Hans Wilhelmson, Chalmers Univ Tech, SWEDEN
 Dr. Lennart Stenflo, University of UMEA, SWEDEN
 Library, Royal Inst Tech, SWEDEN
 Centre de Recherches, Ecole Polytech Fed, SWITZERLAND
 Dr. V.T. Tolok, Kharkov Phys Tech Ins, USSR
 Dr. D.D. Ryutov, Siberian Acad Sci, USSR
 Dr. G.A. Eliseev, Kurchatov Institute, USSR
 Dr. V.A. Glukhikh, Inst Electro-Physical, USSR
 Institute Gen. Physics, USSR
 Prof. T.J.M. Boyd, Univ College N Wales, WALES
 Dr. K. Schindler, Ruhr Universitat, W. GERMANY
 ASDEX Reading Rm, IPP/Max-Planck-Institut fur
 Plasmaphysik, F.R.G.
 Nuclear Res Estab, Julich Ltd, W. GERMANY
 Librarian, Max-Planck Institut, W. GERMANY
 Bibliothek, Inst Plasmaforschung, W. GERMANY
 Prof. R.K. Janev, Inst Phys, YUGOSLAVIA