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**Recent Improvements in
Thomson Scattering
Data Analysis**

M. S. Tillack
E. A. Lazarus

**OPERATED BY
UNION CARBIDE CORPORATION
FOR THE UNITED STATES
DEPARTMENT OF ENERGY**

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FUSION ENERGY DIVISION

RECENT IMPROVEMENTS IN THOMSON SCATTERING

DATA ANALYSIS

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ABSTRACT

A new profile analysis package for use with the Thomson scattering data on ISX-B has recently been implemented. The primary feature of this package is a weighted least squares fitting of temperature and density data to generate a representative curve, as opposed to the previous hand-fitting technique. The changes will automate the manner in which data are transmitted and manipulated, without affecting the calculational techniques previously used. The computer programs have also been used to estimate the sensitivity of various plasma quantities to the accuracy of the Thomson scattering data.

1. INTRODUCTION

SCAT PAK has been operating reliably for many years as an automated Thomson scattering data collection system. Currently, the electron temperature and density are scanned through 11 positions across the plasma radius (although the system has continuous scanning capability), yielding a profile with approximately 25 reproducible tokamak discharges. Through CAMAC hardware, these profiles are immediately available on the operating PDP-8.

However, until now the subsequent analysis of data has been delayed by the need to hand-fit and manually enter data for the calculational routines.* This procedure can be tedious and time-consuming. Features of the new data handling procedure that improve this condition are: automatic transmission of profiles from the PDP-8 to the PDP-10, computer fitting of profiles, and computer-assisted preparation of data for calculations.

Significant operational advantages are realized by automating the Thomson scattering data analysis. The time required for the analysis of a single profile has been reduced at least a factor of 5. With the SCAT PAK-II system (single-shot profiles), this increased speed will be a necessity. In addition, because most of the data input for calculations are now handled automatically,[†] the probability of reanalysis due to erroneous entry of data is virtually eliminated.

Besides the operational advantages, several other benefits come from the application of least squares fitting. (1) The fits are weighted by combining statistical and calibration uncertainties to place errors on each data point in a laser sequence (both temperature and density).

*These data are classified into two categories: gross plasma conditions and plasma profiles. Gross plasma conditions include properties measured by diagnostics other than Thomson scattering; i.e., loop voltage, plasma current, toroidal field, etc. Plasma profiles are spatial measurements of electron temperature and density that result from scanning the Thomson scattering apparatus across the plasma in the radial direction.

[†]Exceptions are ion temperature and neutral beam power.

Weighting the fits improves their accuracy and allows for the transmission of uncertainties to all calculated quantities. (2) The consistency of approach implies more uniform results. The subjective properties of data analysis have been removed while still retaining the ability to make human decisions. (3) Least squares fitting to a recognizable analytical expression results in the generation of useful parameters concerning the shape of the profiles, which can be used to describe the plasma (see Appendix A).

2. COMPARISON OF RESULTS

Most important to the conversion from one system to another is the fact that the final results are not drastically affected. To verify this the analysis of data has been repeated for experiments performed, and Table 1 summarizes some of the parameters of interest.

In addition to the final results, a comparison of the fits themselves determines the success of computer fitting (see Appendix C). In most cases the computer fit is very close to, and at least as good as, the previously drawn hand-fit curves. It is important to note that the process of analysis is now capable of considerable flexibility for change and improvement. This approach is a step toward more sophisticated and (hopefully) better data analysis procedures.

Table 1. Comparison of results (hand-fit profiles vs computer-fit profiles)

Profile	Z'_{eff}		τ_E (ms)	
	Hand	Computer	Hand	Computer
052291-1	3.68	4.54	18.1	18.8
052291-2	3.59	3.42	14.7	15.8
052492-1	1.87	1.78	53.0	47.8
052492-2	1.62	1.23	85.7	92.7
060591-1	1.92	1.79	21.7	20.9
060591-2	1.49	1.51	23.4	27.7
060791-1	2.58	3.10	19.7	21.8
060791-2	1.94	1.37	18.1	19.1
060792-1	2.53	1.92	30.6	30.6
060792-2	2.39	1.77	18.0	16.5
060792-3	3.41	2.82	9.5	10.3
061091-1	1.77	1.23	105.3	97.4
061091-2	1.10	1.09	57.0	53.3

Table 1 (continued)

Profile	W_e (kJ)			W_i (kJ)	
	Hand	Computer		Hand	Computer
052291-1	3.38	3.78		1.40	1.19
052291-2	3.54	3.67		1.58	1.35
052492-1	3.25	3.14		3.62	3.32
052492-2	3.65	3.21		4.84	5.97
060591-1	1.68	1.53		1.72	1.74
060591-2	1.93	1.88		2.21	3.03
060791-1	2.07	2.24		1.15	1.33
060791-2	2.16	1.90		1.69	2.18
060792-1	2.47	2.24		1.20	1.43
060792-2	1.66	1.44		0.65	0.68
060792-3	1.18	1.13		0.25	0.42
061091-1	3.25	2.79		2.72	2.73
061091-2	1.58	1.52		2.12	1.91

Table 1 (continued)

$\langle T_e \rangle$ (eV)			q(a)	
Profile	Hand	Computer	Hand	Computer
052291-1	3.42	4.00	2.72	2.56
052291-2	3.31	3.04	2.56	2.86
052492-1	5.74	5.58	3.83	4.00
052492-2	6.13	4.85	3.76	4.00
060591-1	2.37	2.28	3.89	3.57
060591-2	2.39	1.84	4.01	4.01
060791-1	3.36	3.43	3.95	3.70
060791-2	2.67	2.47	3.91	3.81
060792-1	3.83	3.53	3.95	3.95
060792-2	3.86	3.21	3.67	3.67
060792-3	4.15	3.78	3.63	3.51
061091-1	5.44	5.25	4.40	4.03
061091-2	4.04	3.92	4.27	4.05

Table 1 (continued)

$\beta_T(0)$ (%)			$\langle\beta_T\rangle$ (%)	
Profile	Hand	Computer	Hand	Computer
052291-1	1.10	0.96	0.57	0.65
052291-2	1.31	1.13	0.56	0.57
052492-1	3.02	2.99	0.43	0.39
052492-2	2.59	2.91	0.53	0.53
060591-1	0.97	0.85	0.36	0.39
060591-2	1.61	1.15	0.42	0.50
060791-1	1.45	1.06	0.33	0.40
060791-2	2.68	2.49	0.39	0.42
060792-1	1.51	1.65	0.38	0.38
060792-2	1.17	1.31	0.26	0.23
060792-3	0.99	0.62	0.16	0.18
061091-1	4.24	4.35	0.62	0.61
061091-2	3.67	3.26	0.41	0.39

3. ERROR ANALYSIS/SENSITIVITY STUDY

One of the purposes for developing the computer fitting routines was to systematically generate uncertainties in calculated quantities, using the uncertainties in temperature and density values. Three methods of varying complexity were considered. The best method involves mapping the surface in parameter space that represents those combinations of parameters that increase χ^2 by one over its minimum value. Each of these combinations must be used individually to generate profiles that are used in the calculations. Many sets of plasma properties would have to be calculated to procure the extreme values and this method would be prohibitively time-consuming.

The correlations between the parameters could be overlooked by simultaneously extending each one by a standard deviation. However, this upper bound on the uncertainties is far too large.

Another method that still yields an upper bound (although a lower one than obtained from the above method) is to fit the error bars on the data. This is done by adding a standard deviation once to all of the data and also by subtracting. These two fitted curves provide an envelope bounding the best profile estimate. An upper bound is still produced as errors in real life should occur randomly in the positive and negative directions. However, it was observed that these limits are much more reasonable. It is this latter method that was employed to test the data taken and the results of which are compiled in Table 2. "Nominal" is the best fit. The other four combinations are also listed (temperature and density plus standard deviation, temperature plus density minus, temperature and density minus standard deviation, and temperature minus density plus). Some typical profiles are shown in Figs. 1 and 2.

Table 2. Results of error analysis

	<u>Profile 052291-1</u>				
	$T^- n^+$	$T^- n^-$	Nominal	$T^+ n^+$	$T^+ n^-$
Z_{eff}	3.69	3.69	4.58	5.54	5.53
τ_{Ee} (ms)	12.60	12.50	14.20	15.90	15.80
$\langle \beta_T \rangle$ (%)	0.67	0.65	0.70	0.75	0.73
W_e (kJ)	3.33	3.30	3.76	4.20	4.16
W_i (kJ)	1.98	1.87	1.81	1.70	1.61
	<u>Profile 052291-2</u>				
	$T^- n^+$	$T^- n^-$	Nominal	$T^+ n^+$	$T^+ n^-$
Z_{eff}	2.79	2.82	3.42	4.04	4.08
τ_{Ee} (ms)	9.40	9.90	10.80	11.70	12.20
$\langle \beta_T \rangle$ (%)	0.55	0.56	0.59	0.61	0.62
W_e (kJ)	3.14	3.28	3.60	3.89	4.06
W_i (kJ)	2.22	2.20	2.10	1.99	1.99
	<u>Profile 080791-1</u>				
	$T^- n^+$	$T^- n^-$	Nominal	$T^+ n^+$	$T^+ n^-$
Z_{eff}	3.95	3.99	5.14	6.04	6.08
τ_{Ee} (ms)	9.00	9.40	10.60	11.90	12.40
$\langle \beta_T \rangle$ (%)	0.38	0.37	0.38	0.40	0.40
W_e (kJ)	2.15	2.24	2.53	2.82	2.95
W_i (kJ)	1.92	1.77	1.57	1.42	1.36
	<u>Profile 080791-2</u>				
	$T^- n^+$	$T^- n^-$	Nominal	$T^+ n^+$	$T^+ n^-$
Z_{eff}	2.72	2.74	3.65	4.37	4.42
τ_{Ee} (ms)	11.00	11.40	13.00	14.40	15.00
$\langle \beta_T \rangle$ (%)	0.48	0.50	0.52	0.52	0.54
W_e (kJ)	2.45	2.56	2.92	3.22	3.35
W_i (kJ)	2.79	2.87	2.73	2.36	2.47

POWER FUNCTION FIT : CENTER AT -4.75
 $Y=A1<1-((X-X0)/A2)**(2A3)>**(2A4)+20$

SEQUENCE 052291.DXX - 1

Fig. 1. (a) Typical power function fit of temperature profile.

CUBIC FIT : CENTER AT -4.75
 $Y=A1+A2(X-X0)**2+A3(X-X0)**3$

SEQUENCE 052291.DXX - 1

Fig. 1. (b) Typical cubic fit of relative density profile.

FIXED CENTER SUPER GAUSSIAN
 $Y=A1*EXP-((X-X0)/A2)**2**A3+20.$

SEQUENCE 052291.DXX - 2

Fig. 2. (a) Typical fixed center super Gaussian fit of temperature profile.

FIXED CENTER SUPER GAUSSIAN
 $Y=A1*EXP-((X-X0)/A2)**2**A3+ 0.416$

SEQUENCE 052291.DXX - 2

Fig. 2. (b) Typical fixed center super Gaussian fit of relative density profile.

4. SUMMARY

Testing of the Thomson scattering profile analysis package has proven it to be a reliable alternative to the hand fitting of data. The time spent analyzing sequences has been reduced substantially without drastically altering the results. Error analysis has provided estimates of the sensitivity of plasma parameters to the typical uncertainties in Thomson scattering data. Furthermore, the changes in plasma properties due to the conversion to automated fitting fall within this range of uncertainty. For the future, the computing package may serve as a starting point for more thorough calculations.

APPENDIX A

DETAILED DESCRIPTION OF THE DATA ANALYSIS PACKAGE

The Thomson scattering data analysis group now has an area of disk on the PDP-10 reserved solely for execution of routines and storage of data related to Thomson scattering. Described here are the purpose and operation of each routine in this area. This is to include the generation of data to the final output of plasma properties from ZORDIC.¹

Data analysis routines to be referenced in this section include:

- (1) LASMIT — transfers profiles from the PDP-8 to the PDP-10 (file extension .DA)
- (2) SEQDAT — plots and averages gross plasma conditions at laser firing times (including BT, PC, VX, ENMX, with standard deviations)
- (3) PROFIT — parametric fits of profiles
- (4) ZIN — prepares output from PROFIT and SEQDAT (files with .ZN extension) into ZORDIC input form; auto/manual entry of data and update capability
- (5) PROFIL — plots ZORDIC input profiles (may be data or fits); creates plots suitable for publication
- (6) ZORDIC — the primary data analysis code that uses profiles plus gross plasma conditions to generate various plasma properties such as q , β , W , etc. for both ohmic and beam-injected discharges
- (7) ERRFIT — version of PROFIT that fits error bounds on data to produce error envelope
- (8) TEST — accepts fitting parameters with uncertainties to produce an error envelope, assuming no correlation between parameters

Table A.1 lists the data file names used in these routines.

1. SEQDAT (Sample output in Appendix D)

SEQDAT is an averaging routine, like PROFIT, that is designed to feed ZORDIC with input through ZIN. In this case, the gross machine characteristics are to be averaged over all shots used in the profile, at the times corresponding to ruby laser pulses. The essential data are

toroidal field, loop voltage, plasma current, and line-averaged density. For these data, standard deviations are calculated. In addition to averaging the shots in a sequence, some amount of smoothing in time is done via a Gaussian filtering technique. The degree of smoothing is an option available for each parameter.

Table A.1. Data file names

Example: Sequence #2 deuterium plasma, hydrogen pellets, no beams	
File name	Purpose
052492.DA	Profile data points sent to PDP-10 from PDP-8
052492.ZN5	SEQDAT output of gross plasma conditions
052492.ZN1 through 052492.ZN4	PROFIT output of fitted temperature and density profiles for four laser pulses
052492.DHX	ZORDIC input file created by ZIN
Z05249.2D1 through Z05249.2D4	ZORDIC output files for all four pulses
TIL.D13 through TIL.D16	ZORDIC output files that are immediately printed out and deleted from the disk (part of TIL.D14 appears as Appendix G)

2. PROFIT (Sample output in Appendix E)

In PROFIT, both the electron temperature and the relative electron density profiles are fitted with smooth, analytic curves (see Fig. B.1). Table A.2 lists the files that make up PROFIT and the subroutines in each file. Before fitting these profiles, the electron kinetic pressure,

Table A.2. File structure of PROFIT

Contents				
PROFIT	PLOTN	FITT	FUNCTN	RUN.MAC
PROFIT	PLOT1	NEWRAP	FUNCL	(assembly language routine)
SETUP	PLOT2	FITT	FUNC	
MINCHI	PLOT3	MATINV		
EVALUE	PLOT4			
UNVALU	AVPLOT			
	PLOTCH			
Brief descriptions				
<u>PROFIT</u>				
PROFIT	main calling routine, all input/output, logical control and decisions			
SETUP	sets up .ZN files in a format compatible with ZIN			
MINCHI	controls the actual fitting, determines the function with the best χ^2			
EVALUE	shifts data from the storage arrays to the working arrays			
UNVALU	stores the working arrays (YFIT, BB, AA) into storage arrays (SAVY, SAVA, SAVB)			
<u>PLOTN</u>				
PLOT1	single plot with parameters and standard deviations displayed			
PLOT2	overlap plot used by PLOT4 for multiple graphs			
PLOT3	establishes the first graph for the multiple graph, for AVPLOT, and for the pressure plot			
PLOT4	controller for plotting of multiple graph with χ^2			
AVPLOT	produces average values at each station with uncertainties, calls PLOT3 or PLOT1 depending upon which average is being performed			
PLOTCH	places the values of χ^2 on PLOT3			
<u>FITT</u>				
NEWRAP	nonlinear least squares fitting routine producing parameter array and covariance matrix; the diagonal of the covariance matrix is the variance array			
MATINV	inverts matrices and performs the vector operation $\underline{C} = \underline{A}^{-1} \cdot \underline{B}$			
FITT	linear least squares fitting routine; functions that can be linearized, such as Ae^{ax} , may be fitted with FITT, if the proper calculations are performed in FUNCL			

Table A.2 (continued)

Brief descriptions	
<hr/>	
<u>FUNCTN</u>	
FUNCL	sets up the fits by defining the function and giving initial guesses to NEWRAP; FUNCL calls either FITT or NEWRAP and evaluates the fit after parameters are passed
FUNC	a subroutine used only by NEWRAP; it computes values of the derivatives of χ^2 with respect to the parameters (i.e., the Taylor expansion coefficients)
<u>RUN.MAC</u>	is used to begin execution of system program TKFVER to output plots onto the PDP-10 Versatec

$$nT = a_1(x - a_2)^2 ,$$

is fitted with a symmetric parabola in order to fix the plasma center. The fits will all be forced to have zero first derivatives at the plasma center. In this way the peak in the temperature, the density, and the pressure will all coincide at each instant of time.

After fixing the center, the user selects a fit from one of four curves that are currently being displayed. These functions are:

(1) Gaussian	$a_1 \exp - \left(\frac{x - x_0}{a_2} \right)^2 ,$
(2) cubic	$a_1(x - x_0)^3 + a_2(x - x_0)^2 + a_3$
(3) "super Gaussian"	$a_1 \exp - \left(\frac{x - x_0}{a_2} \right)^{2a_3} ,$
(4) "power function"	$a_1 \left[1 - \left(\frac{x - x_0}{a_2} \right)^{2a_3} \right]^{2a_4} ,$

where x_0 is the plasma center. These functions were chosen to give a maximum of flexibility in fitting anticipated shapes.

The reduced χ^2 (χ^2 per degree of freedom) is calculated in each case to aid, or even control, the selection. At this point, the chosen function is evaluated at 1-cm increments, and a ZIN-input file is created that contains these values as well as the parameters of the fit. The chosen function is then displayed to the user for closer inspection.

Some of the specific features of PROFIT derived from this procedure are:

- (1) The determination of parameters for the fits is done in either FITT or NEWRAP, using the standard technique of weighted least squares (see Fig. B.2). Except for the cubic polynomial fit, a nonlinear least squares routine is used. The definition of χ^2 is

$$\chi^2 \equiv \sum_{i=1}^n \frac{[y_i - f(\chi_i; \underline{\alpha})]^2}{\sigma^2},$$

where $\underline{\alpha}$ is the parameter array. χ^2 is Taylor expanded with respect to the parameter array, and successive iterations serve to locate the local minimum. Good initial guesses are required, particularly as the number of parameters goes up and χ^2 becomes considerably more structured. In order to assist the power function, a crude grid search is performed initially to locate the global minimum. In the case of the cubic, a linear least squares routine solves exactly for the minimum χ^2 with a single matrix inversion.

- (2) Due to the modular structure of the subroutines FUNCL and FUNC, other functions not appearing above may easily be added without upsetting any of the logic or program flow. There is no interplay between the modules in FUNC and FUNCL. Additions must also be made in SETUP and in the plotting routines to properly encode the functional form.
- (3) AVPLOT can be used to replot any graph with only one ordinate for each abscissa. The ordinate is a weighted mean defined by

$$\bar{y} = \frac{\sum \frac{y_i}{\sigma^2}}{\sum \frac{1}{\sigma^2}},$$

and the standard deviation is reduced by $\sqrt{n}$

$$\bar{\sigma} = \frac{1}{\sqrt{n}} \sum \sigma_i.$$

- (4) Some constraints based on intuition and some physics have been added to the fits. Symmetry about the center is required, except for the cubic, which is penalized in the calculation of a reduced χ^2 by having a degree of freedom subtracted for every point inside of center. Although real plasmas need not (indeed are not) be

symmetric, since data is taken between $-6 \text{ cm} \geq x \geq 24 \text{ cm}$, insufficient data is present on the inside of the plasma to allow arbitrary fittings.

Also, the limiter point at +27 cm is forced to $T = 20 \text{ eV}$ and $n = 0^+ (n_{\text{max}}/1000)$. Placing a large weight ($\pm 10\%$) on the limiter ensures that the curves pass very close to these predetermined values. The effect on the remainder of the fit can be significant in some cases. Especially when the plasma is shifted out, this condition may lower the fit below the data points at the center.

- (5) There are two primary weaknesses associated with our current method. The first is caused by forcing the limiter. The second is slightly less well-defined. In some cases, it appears that the computer misses points due to limited degrees of freedom (between 2 and 4). For instance, a hollow profile is not possible except for the cubic, and even then it shows resistance. In these cases where the data are structured, the individual weights on the data points become quite important, because the computer will sooner miss one point than drastically alter its shape. Of course, in some cases the fit is bad simply because the data are spread and/or the errors are unreasonable. In these cases, even a hand-drawn fit would not be adequate.

3. ZIN

ZIN is used to manipulate files and accept data in order to produce a ZORDIC input file (see Fig. B.3). The files created by both PROFIT and SEQDAT are used. ZIN has the added features of optional manual entry of data and the capability of updating files. Manual interactive entry is always the default when no .ZN files can be found. Updating of profiles can be done in either mode, manual entry or reading PROFIT output files. However, updating of gross plasma conditions is currently available only through text editing of the ZORDIC input file.

4. PROFIL (Sample output in Appendix F)

PROFIL does not manipulate files or do calculations, but rather it produces graphs in an aesthetic and concise format. It will have the capability of viewing data either before or after the data have been fitted.

5. ZORDIC (Sample output in Appendix G)

ZORDIC is the primary set of calculations done on the experimental data to yield extensive information about the plasma. This program has not been modified.

6. TEST

TEST is a display and file writing routine very similar to PROFIT, except that fits are not done in TEST. This routine accepts nominal values of the parameters for the best fit and a standard deviation for each. It then plots the envelope of uncertainty about the best fit and writes a file containing the values of temperature and density that correspond to the envelope limits.

These new profiles can be used in ZORDIC to estimate uncertainties on the parameters calculated in ZORDIC. As discussed earlier, these represent an upper bound assuming no correlation between parameters.

7. ERRFIT

ERRFIT is a modified version of PROFIT that fits the data, and in addition fits the data plus and minus the error bars.

REFERENCE

1. D. L. Shaeffer and M. Murakami (Oak Ridge National Laboratory), private communication, September 30, 1976.

APPENDIX B

FLOW CHARTS OF PROFIT, ZIN, NEWRAP

Flow charts for the data analysis routines PROFIT, ZIN, and NEWRAP are shown in Figs. B.1, B.2, and B.3, respectively.

PROFIT FLOW CHART

Fig. B.1. PROFIT flow chart.

ZIN FLOW CHART

Fig. B.2. ZIN flow chart.

NEWRAP FLOW CHART

Fig. B.3. NEWRAP flow chart.

APPENDIX C

COMPARISON PROFILES

Hand-fit vs computer-fit profiles for Profile 052291 are compared in Figs. C.1 and C.2.

POWER FUNCTION FIT ; CENTER AT -4.75
 $Y=A1<1-((X-X0)/A2)^{A3}>^{A4}+20$

SEQUENCE 052291.DXX - 1

Fig. C.1. (a) Power function fits of temperature profile.

CUBIC FIT : CENTER AT -4.75
 $Y=A1+A2(X-X0)**2+A3(X-X0)**3$

SEQUENCE 0S2291.DXX - 1

Fig. C.1. (b) Cubic fits of relative density profile.

POWER FUNCTION FIT : CENTER AT -0.24
 $Y=A1<1-(((X-X0)/A2)**(2A3))>**(2A4)+20$

SEQUENCE 052291.DXX - 2

FIXED CENTER SUPER GAUSSIAN
 $Y=A1*EXP-((X-X0)/A2)**2**A3+0.416$

SEQUENCE 052291.DXX - 2

Fig. C.2. (b) Fixed center super Gaussian fits of relative density profile.

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APPENDIX D

SEQDAT SAMPLE OUTPUT

Sample output from SEQDAT is shown for Profile 052291 in Figs. D.1-D.5.

Fig. D.1. Sample output from SEQDAT showing plots of averaged plasma conditions.

```

SEQ 052291.OXX BT- 11.9 1STSHT- 13069 LSTSHT- 13090
AVG FOR CHAN 21 .14623035E+03 .14674577E+03 .13364771E+03
STD DEV CHAN 21 .93072067E+00 .92058631E+00 .12050076E+02
TIMES: 91 121 151
CHAN21 .14556938E+03 .14760532E+03 .13682255E+03 .00000000E+00 SN 13077.
CHAN21 .14627696E+03 .14680257E+03 .12028089E+03 .00000000E+00 SN 13076.
CHAN21 .14432652E+03 .14631145E+03 .14085691E+03 .00000000E+00 SN 13069.
CHAN21 .14604883E+03 .14546269E+03 .11951671E+03 .00000000E+00 SN 13084.
CHAN21 .14648259E+03 .14571401E+03 .13480895E+03 .00000000E+00 SN 13070.
CHAN21 .14629985E+03 .14969616E+03 .13360234E+03 .00000000E+00 SN 13074.
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CHAN21 .14712587E+03 .14680226E+03 .13715683E+03 .00000000E+00 SN 13066.
CHAN21 .14627696E+03 .14716043E+03 .11301473E+03 .00000000E+00 SN 13090.
CHAN21 .14735415E+03 .14630000E+03 .13273464E+03 .00000000E+00 SN 13078.
CHAN21 .14712594E+03 .14570242E+03 .15246583E+03 .00000000E+00 SN 13085.
CHAN21 .14775770E+03 .14679082E+03 .13745400E+03 .00000000E+00 SN 13079.
CHAN21 .14706140E+03 .14656261E+03 .11793965E+03 .00000000E+00 SN 13083.
CHAN21 .14541677E+03 .14738864E+03 .14585487E+03 .00000000E+00 SN 13080.
CHAN21 .14579766E+03 .14615189E+03 .13368614E+03 .00000000E+00 SN 13082.
CHAN21 .14580902E+03 .14593086E+03 .13652183E+03 .00000000E+00 SN 13081.
CHAN21 .14626552E+03 .14655125E+03 .14310666E+03 .00000000E+00 SN 13069.
CHAN21 .14737696E+03 .14679090E+03 .10576745E+03 .00000000E+00 SN 13068.

```

Fig. D.2. Sample plot of averaged plasma current.

```

SEQ 052291.DXX BT- 11.9 1STSHT- 13069 LSTSHT- 13089
AVG FOR CHAN 11 .18815177E+01 .21059776E+01 .35810934E+01
STD DEV CHAN 11 .50495084E-01 .31022182E+00 .27796002E+00
TIMES.          91          121          151
CHAN11 .18407411E+01 .18303570E+01 .36522986E+01 .00000000E+00 SN 13077.
CHAN11 .18964380E+01 .21288333E+01 .36094428E+01 .00000000E+00 SN 13076.
CHAN11 .18767117E+01 .18426080E+01 .40284353E+01 .00000000E+00 SN 13069.
CHAN11 .19150608E+01 .19130065E+01 .31497674E+01 .00000000E+00 SN 13064.
CHAN11 .19072788E+01 .23576376E+01 .35934407E+01 .00000000E+00 SN 13070.
CHAN11 .18870892E+01 .25019313E+01 .41814964E+01 .00000000E+00 SN 13074.
CHAN11 .18634237E+01 .21685675E+01 .33683907E+01 .00000000E+00 SN 13071.
CHAN11 .19588364E+01 .21216733E+01 .37353629E+01 .00000000E+00 SN 13073.
CHAN11 .18720566E+01 .19251242E+01 .36760707E+01 .00000000E+00 SN 13072.
CHAN11 .19399223E+01 .19040677E+01 .32009907E+01 .00000000E+00 SN 13087.
CHAN11 .18001581E+01 .18546375E+01 .31609144E+01 .00000000E+00 SN 13086.
CHAN11 .18937295E+01 .25480579E+01 .36964471E+01 .00000000E+00 SN 13090.
CHAN11 .18909128E+01 .18696331E+01 .33495437E+01 .00000000E+00 SN 13078.
CHAN11 .19066702E+01 .18586028E+01 .33055393E+01 .00000000E+00 SN 13085.
CHAN11 .19049684E+01 .19109527E+01 .35583990E+01 .00000000E+00 SN 13079.
CHAN11 .17577430E+01 .23099909E+01 .38090757E+01 .00000000E+00 SN 13083.
CHAN11 .18769650E+01 .18592935E+01 .32826981E+01 .00000000E+00 SN 13080.
CHAN11 .17603398E+01 .28763745E+01 .39018914E+01 .00000000E+00 SN 13082.
CHAN11 .18910743E+01 .19576418E+01 .37792193E+01 .00000000E+00 SN 13061.
CHAN11 .19220659E+01 .18727757E+01 .36375896E+01 .00000000E+00 SN 13069.
CHAN11 .19274652E+01 .26137595E+01 .36451476E+01 .00000000E+00 SN 13088.

```

Fig. D.3. Sample plot of averaged loop voltage.

```

SEO 052291.DXX BT= 11.9 1STSHT= 13069 LSTSHT= 13090
AVG FOR CHAN 35 .36543164E+14 .44901104E+14 .34124907E+14
STD DEV CHAN 35 .32517918E+13 .32387131E+13 .93763067E+13
TIMES: 91 121 151
CHAN35 .36434016E+14 .45197920E+14 .26691404E+14 .00000000E+00 SN 13077
CHAN35 .39619147E+14 .47707105E+14 .34880986E+14 .00000000E+00 SN 13076
CHAN35 .36681086E+14 .44176480E+14 .27939826E+14 .00000000E+00 SN 13069
CHAN35 .40710760E+14 .48716485E+14 .41422054E+14 .00000000E+00 SN 13084
CHAN35 .31643490E+14 .40584187E+14 .27495314E+14 .00000000E+00 SN 13070
CHAN35 .39554012E+14 .44175406E+14 .36253414E+14 .00000000E+00 SN 13074
CHAN35 .33930691E+14 .41369977E+14 .31114948E+14 .00000000E+00 SN 13071
CHAN35 .37258614E+14 .46452554E+14 .38898348E+14 .00000000E+00 SN 13073
CHAN35 .31399972E+14 .39228606E+14 .14405442E+14 .00000000E+00 SN 13072
CHAN35 .39827692E+14 .48977287E+14 .27457589E+14 .00000000E+00 SN 13067
CHAN35 .31094024E+14 .39665093E+14 .36674942E+14 .00000000E+00 SN 13056
CHAN35 .42887007E+14 .50889282E+14 .58606110E+14 .00000000E+00 SN 13090
CHAN35 .35656682E+14 .44138985E+14 .34352641E+14 .00000000E+00 SN 13078
CHAN35 .35241506E+14 .43914921E+14 .21811484E+14 .00000000E+00 SN 13085
CHAN35 .36829066E+14 .43241609E+14 .42017359E+14 .00000000E+00 SN 13079
CHAN35 .39617331E+14 .49509282E+14 .40122523E+14 .00000000E+00 SN 13063
CHAN35 .33776428E+14 .42799958E+14 .28339296E+14 .00000000E+00 SN 13060
CHAN35 .37190044E+14 .46168556E+14 .45695244E+14 .00000000E+00 SN 13062
CHAN35 .34836704E+14 .46539743E+14 .28003710E+14 .00000000E+00 SN 13061
CHAN35 .39257440E+14 .46531706E+14 .30907133E+14 .00000000E+00 SN 13069
CHAN35 .33960532E+14 .42916031E+14 .41323256E+14 .00000000E+00 SN 13068

```

Fig. D.4. Sample plot of averaged density.

SED 052291.DXX BT= 11.9 1STSH= 13069 LSTSH= 13090
 AVG V-L (DI/DT) 1.8915154E+01 2.1059767E+01 3.5810972E+01
 STD DEV V-L (DI/DT) .34912957E+00 .35029452E+00 .15835966E+01
 TIMES. 91 121 151

Fig. D.5. Sample plot of averaged corrected voltage.

APPENDIX E

PROFIT SAMPLE OUTPUT

Sample output from PROFIT is shown for Profile 052291 in Figs. E.1-E.5.

Fig. E.1. Sample output from PROFIT showing symmetric parabolic fit of pressure profile.

Fig. E.2. Sample output from PROFIT showing four temperature curves.

POWER FUNCTION FIT : CENTER AT -4.75
 $Y=A1<1-((X-X0)/A2)**(2A3)>**(2A4)+20$

SEQUENCE 052291.DXX - 1

Fig. E.3. Sample output from PROFIT showing a power function fit of the temperature profile.

Fig. E.4. Sample output from PROFIT showing four relative density curves.

Fig. E.5. Sample output from PROFIT showing a cubic fit of the relative density profile.

APPENDIX F.

PROFIL SAMPLE OUTPUT

Sample output from the PROFIL routine is shown for Profile 052291 in Figs. F.1-F.6.

SEQUENCE 052291.DXX - 1

TIME= 91. BT=11.1
NE=3.82 I=145.0
TI=290.0 V=1.82

Fig. F.1. Sample output from PROFIL showing temperature and density profiles.

SEQUENCE 052291.DXX - 1

(AVERAGES)

TIME= 91.	BT=11.1
NE=3.82	I=145.0
TI=290.0	V=1.82

Fig. F.2. Sample output from PROFIL showing averaged temperature and density profiles.

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APPENDIX G

ZORDIC SAMPLE OUTPUT

A small fraction of the sample output from ZORDIC for Profile 052291 is shown in Fig. G.1.

1

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(a)

**SHOT NUMBER	=13069-13090	
**TIME OF LASER SHOT PROFILE	= 90.030	MSEC
**PLASMA RADIUS	= 25.590	CM
**MAJOR RADIUS OF PLASMA CENTER	= 91.590	CM
**LIMITER RADIUS	= 27.000	CM
**MAJOR RADIUS OF THE DEVICE	= 93.000	CM
**PLASMA CURRENT	= 145.000	KAMPS
**PLASMA SPECIES	= 2	
**TOROIDIAL MAGNETIC FIELD	= 11.100	KGAUSS
**Q AT PLASMA EDGE, R=A	= 2.720	
**Q AT LIMITER	= 3.000	
LINE AVG. ELECTRON DENSITY	= 3.020E+13	CM3
CENTRAL ELECTRON DENSITY	= 4.448E+13	CM3
FITTED ANALYTIC FORM: NE(R)	= 2.797E+13*(1.-(R/A)2.)*.55 + 1.707E+13	
VOL.-AVG. ELECTRON DENSITY	= 3.447E+13	CM3
**PLASMA VOLTAGE AT EDGE	= 1.020	VOLTS
**EXPERIMENTAL PLASMA RESISTANCE	= 12.552	MICROOHMS
**CENTRAL ELECTRON TEMPERATURE	= 592.403	EV
FITTED ANALYTIC FORM: TE(R)	= 510.309*(1.-(R/A)2.)*1.22 + 70.905	
**DENS.-AVG. ELECTRON TEMP.	= 331.206	EV
**CENTRAL ION TEMPERATURE	= 290.000	EV
**EXPONENTS OF T1(R)	= 2.000. 0.553	(ASSUMED NE PROFILE)
**DENS.-AVG. ION TEMPERATURE	= 237.901	EV

50

Fig. G.1. (a) Sample output from ZORDIC (p. 1).

(b)

**ELECTRON ENERGY CONTENT	=	3.223E+03	J	
**ION ENERGY CONTENT	=	1.909E+03	J	
**TOTAL ENERGY CONTENT	=	5.131E+03	J	
**OHMIC HEATING POWER	=	263.900	KWATTS	
**TOTAL INJECTION POWER	=	0.000	KWATTS	
**INJ. POWER TO ELECTRON	=	0.000	KWATTS	
**INJ. POWER TO ION	=	0.000	KWATTS	
**ELE.-ION HEAT TRANSFER	=	74.196	KWATTS	
**RADIATION POWER LOSS	=	692.656	KWATTS	-- ASSUMING FE IMPURITIES RESPONSIBLE FOR ZEFF-1
**CHANGING RATE OF ELEC. ENERGY	=	0.000	KWATTS	
**ELECTRON BETA-POLOIDAL	=	0.355		
**BETA-POLOIDAL	=	0.569		
**BETA-POLOIDAL(Z=1)	=	0.609		
**PEAK BETA	=	1.220	PERCENT	
**AVERAGE BETA	=	0.596	PERCENT	
**BETA STAR	=	0.060	PERCENT	
**ELECTRON ENERGY LIFETIME(OH)	=	12.211	MSEC	
**ELECTRON ENERGY LIFETIME	=	12.212	MSEC	
**TOTAL ENERGY LIFETIME	=	19.444	MSEC	
**ION ENERGY LIFETIME(OH)	=	25.724	MSEC	
**ION ENERGY LIFETIME	=	25.724	MSEC	
**TAUE FOR TI(R) LIKE NE(R)	=	19.444	MSEC	
**TAUE FOR TI(R) LIKE TE(R)	=	17.211	MSEC	

Fig. G.1. (b) Sample output from ZORDIC (p. 2).

1

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(c)

**ZEFF	=	3.381	
**ZEFF(0) ASSUMING Q(0)=1	=	3.584	
**Q AT R=0	=	0.970	
**RADIUS FOR Q=1	=	1.381	CM
**RADIUS FOR Q=2	=	20.617	CM
**NU*E MINIMUM	=	1.332	
**RADIUS FOR NU*E MINIMUM	=	11.300	CM
**NU*I MINIMUM	=	2.565	
**RADIUS FOR NU*I MINIMUM	=	17.767	CM
**L I	=	1.012	
**L INEAR PROTON DEFICIENCY	=	0.836	
VOL.-AVG. ION DENSITY	=	2.842E+13	CM3
**NZ(0)/NE(0)	=	0.014E-03	
**PSUEDOCLAS. CONF. TIME	=	9.644	MSEC
CENTRAL NEUTRAL DENSITY	=	9.979E+07	CM3
EDGE NEUTRAL DENSITY	=	5.327E+10	CM3
**H(R) AT R=0 FOR E=E(0)/2	=	0.000	
**BEAM INDUCED CURRENT	=	0.000	KAMPS
**GAITIA	=	0.000	
**DRIFT-VEL./THERMAL-VEL.(AVGD)	=	1.191E-02	
**WIDTH OF MAGNETIC ISLAND	=	2.408	CM
**M,N MODE	=	2.1	
**R SURFACE	=	20.622	CM
**DELTA PRIME	=	0.586	
**B TILDA	=	0.299	PERCENT

Fig. G.1. (c) Sample output from ZORDIC (p. 3).

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