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Nuclear Engineering Program
University of Illinois
Urbana, Illinois 61801

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User's Guide for
SLWDN9, a Code for Calculating Flux-Surfaced-Averaging of
Alpha Densities, Currents, and Heating in Non-Circular Tokamaks

Prepared for the
Fusion Studies Laboratory
Nuclear Engineering Program
University of Illinois
Urbana, Illinois 61801

by

L. M. Hively
G. H. Miley†

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†Persons interested in further details should contact this author at the Laboratory address or via 217-333-3772 (FTS 958-5533).

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APPENDIX G: SLWDN9 USER'S GUIDE

G.1 Code Description

The code, SLWDN9, calculates flux-surfaced-averaged values of alpha density, current, and electron/ion heating profiles in realistic, non-circular tokamak plasmas. See Figure G.1 for program flow diagram. The code is written in FORTRAN and executes on the CRAY-1 machine at the Magnetic Fusion Energy Computer Center (MFECC) sponsored by the U. S. Department of Energy, in Livermore, CA. The typical run time is 1-1.2 cpu hours. This guide will assume familiarity with the MFECC machines, with the system architecture, and with the utility routines. Online documentation can answer system-related questions and is available on the MFECC CDC-7600 by using the DOCUMENT utility.

There are two files required to execute the code. The FORTRAN source is obtained by using FILEM:

FILEM RDS 1352 SLWDN9

The input data file describes the tokamak equilibrium; two examples are available by using FILEM:

FILEM RDS 1352 TNS008 TNS075

The first data file, TNS008, is for a D-shaped, ETF equilibrium with $\bar{\beta} = 0.008$, a major radius of 5.04 m, and a elongation of 1.6. The second data file, TNS075, is for a D-shaped, ETF equilibrium having $\bar{\beta} = 0.075$, a major radius of 5.36 m, and an elongation of 1.6.

Section G.4 describes the formats and data for the input file. The default input/output filenames are TNS008 and L032 respectively.

Figure G.1 SLWDN9 Flow Chart.

To change these filenames, the "CALL LINK" statement on line 62 of SLWDN9 must be appropriately changed. To compile and execute SLWDN9, use

RCFT I = SLWDN9, L = 0, GO, LIB = (F')/T V

where the allotted time, T, should be ≥ 90 min. The time value, V, should be chosen keeping in mind that this code requires $\sim 1200K$ octal words of memory. Section G.5 discusses the output, including an example which corresponds to the input file, TNS008.

G.2 Inherent Limitations of the Code

There are several restrictions on the use of this code. First, the model which describes fast alpha guiding-center motion is accurate to first-order in gyroradius, requiring $\bar{b} < 0.1$. Also, the restrictions on code runtime and memory require that the various alpha profiles (density, current, etc.) be accumulated in no more than 16 intervals in ψ . For example, the flux-surface-averaged alpha density is computed for $0 \leq \psi \leq \psi_1$, $\psi_1 \leq \psi < \psi_2$, etc., and similarly for the other profiles. The approximations used in this allotment among ψ -bins place inherent limitations on the numerical accuracy of the parallel component of alpha current, $\langle I_{||} \rangle$. The value of $\langle I_{||} \rangle$ computed using 16 ψ -bins (i.e., $0 \leq \psi/\psi_{\text{edge}} \leq \frac{1}{16}$, $\frac{1}{16} \leq \psi/\psi_{\text{edge}} \leq \frac{1}{8}$, etc.) is typically 8% larger than when the whole plasma is spanned by a single ψ -bin. The latter value is more accurate because the approximations used to apportion the contributions among each ψ -interval create $\sim 0.5\%$ error per ψ -bin. Only the convergence of the total alpha current is affected by these

limitations. If the total current is important, rather than profile information, line 170 should be changed to

$$\text{NPSI} = 1$$

The whole plasma is then spanned by the single ψ -bin described above.

The final limitation on the use of SLWDN9 is related to convergence of $\langle I_{\parallel} \rangle$ as the number of phase space intervals changes. The phase space labels used to parameterize each orbit are v (ion speed), ψ_x (the maximum value of the poloidal flux function along the guiding-center orbit, where ψ is increasing from the magnetic axis), and ζ (the cosine of the angle between the parallel component of plasma current $\vec{J}_{\parallel}$, and the ion velocity, $\vec{v}$). The various alpha particle profiles are obtained by integrating moments of the α distribution function over this phase space. In particular, convergence of $\langle I_{\parallel} \rangle$ is demonstrated in Table G.1 as the number of phase space intervals (N_v , N_{ζ} , N_{ψ_x}), corresponding to (v , ζ , ψ_x), is successively doubled.

Table G.1: Convergence of $\langle J_{\parallel} \rangle$ (kA)

	N_v	N_{ζ}	N_{ψ_x}	$\bar{B} = 0.008$	$\bar{B} = 0.075$
I_1	8	16	8	10.01	67.85
I_2	16	32	16	8.399	52.36
I_3	32	64	32	7.480	42.63
I_{∞}	(limit $\rightarrow \infty$)			6.3	26.2

For $(N_V, N_\zeta, N_{\psi_x}) = (4, 8, 4)$ the numerical methods are too crude to give meaningful results. For phase space intervals greater than $(32, 64, 32)$, the runtime of the code is prohibitively long.

For successive doubling of the number of phase space intervals, there is a geometric convergence (refer to Table G.1):

$$I_2 = I_1 - \Delta I, \quad (G.1)$$

$$I_3 = I_1 - \Delta I - \xi \Delta I, \quad (G.2)$$

$$\vdots$$

$$I_\infty = I_1 - \Delta I - \xi \Delta I - \xi^2 \Delta I \dots = I_1 - \Delta I / (1 - \xi). \quad (G.3)$$

Solving (G.1) and (G.2) for ΔI and ξ yields:

$$\xi = \frac{I_2 - I_3}{I_1 - I_2}, \quad \Delta I = I_1 - I_2. \quad (G.4)$$

The value of I_∞ is obtained by applying (G.3) and (G.4) to the data in Table G.1; this is the "converged" value for $\langle I_n \rangle$. The default values for $(N_V, N_\zeta, N_{\psi_x})$ are $(32, 64, 32)$ yielding convergence to better than 1% for the alpha particle density, and heating profiles. To use a different number of intervals, lines 166-168 should be changed. For example, to determine I_3 in Table G.1, these lines become:

NV = 8

NZ = 16

NPM = 8

The program can then be compiled and run as described above.

G.3 Additional Options

There are other options available for user control of SLWDN9. Different fuel cycles and fusion products can be investigated by making

the appropriate alterations. For example, to calculate 3-MeV proton slowing down effects in a deuterium plasma, change lines 145-147. The new fusion-product is described by its mass (MASS) in amu, charge (Z) in multiples of the protonic charge, and birth energy (EN) in MeV:

$$\text{MASS} = 2.$$

$$Z = 1.$$

$$\text{EN} = 3.03$$

To select the deuterium plasma and corresponding fusion rates, change line 158 to

$$\text{ISV} = 3$$

The settings of ISV are as follows: 1 for D-³He, 2 for D-T, 3 for DD → p + T, and 4 for DD → n + ³He. The background ion density profile is parameterized by $n_i/n_{i0} = (1. - \text{GN} * (\psi/\psi_{\text{edge}}) ** \text{NN}) ** \text{SN}$. Here GN, NN, and SN are all real, so to model a profile like $n_i/n_{i0} =$

$[1 - .9(\psi/\psi_{\text{edge}})^2]^{1/2}$, lines 155-157 become:

$$\text{GN} = 0.9$$

$$\text{NN} = 2.0$$

$$\text{SN} = 0.5$$

Finally, the default value of central ion temperature (15 keV) can be modified at line 159; for example, to use 20 keV:

$$\text{TMAX} = 20.$$

The corresponding T - profile is determined from the pressure profile (used to generate the equilibrium) and the chosen n-profile, using the ideal gas law with $n_i = n_e$.

G.4 Description of Input

The input file characterizes the $1\frac{1}{2}$ -D, non-circular tokamak equilibrium, determined on an R-z mesh. The first two lines of input summarize the equilibrium set and are displayed as a part of the output. The remainder of the file describes the profiles of plasma pressure, $p(\psi)$ and F-value, $F(\psi) = Rb_\phi$, plus the poloidal flux function $\psi(R,z)$. A detailed deliniation of the input data is shown in Table G.2 with a corresponding example shown in Table G.3. Sets of equilibrium data, other than the examples given here, can be obtained from Martin Peng or Dennis Strickler (ORNL).

G.5 Description of Output

The output file consists of two sections: a summary of the runtime and input information, and then the code results. Table G.4 discusses the details on a line-by-line basis and Table G.5 displays an example.

Table G.2: Input Variables for SLWDN9

Line(s)	Variable	Description
1	BETAT	Average toroidal beta
1	QPSI	q-value at the plasma edge
1	TIP	Total plasma current (amps/10.)
1	BT	Magnitude of the toroidal $\vec{B}$ -field (gauss) at R_0
2	RAXIS	Approximate value of major radius, R_0 (meters)
2	PAXIS	Value of poloidal flux function (webers) at $(R_0, 0)$
2	PWALL	Value of poloidal flux function (webers) at wall
2	BETAP	Average poloidal beta
3	NOCONS	Number of ψ -values used to tabulate $F(\psi)$, $dF/d\psi$, and $p(\psi)$; see below.
3	NCFT	Number of spline coefficients for $F(\psi)$
3	NCFT1	Number of spline coefficients for $p(\psi)$
4-44	PSITAB	Sequence of NOCONS ψ -values, ψ_i (in webers), used to tabulate $F(\psi)$, $dF/d\psi$, and $p(\psi)$; see above.
4-44	FTAB	Sequence of NOCONS F -values at ψ_i , i.e., $F(\psi_i)$ in webers/m
4-44	FPTAB	Sequence of NOCONS values of $dF/d\psi$ at ψ_i in m^{-1}
4-44	PTAB	Sequence of NOCONS $p(\psi)$ -values at ψ_i , i.e., $p(\psi_i)$ in newtons
45-54	XFSQ	Sequence of NCFT normalized ψ -values (ψ/ψ_{wall}) used to spline fit $F(\psi)$
45-54	CF	Sequence of NCFT spline coefficients for $F^2(\psi)$ in $(\text{webers})^2/m^2$
55-64	XPRS	Sequence of NCFT1 normalized ψ -values (ψ/ψ_{wall}) used to spline fit $p(\psi)$ in newtons
55-64	CPMKS	Sequence of NCFT1 spline coefficients for $p(\psi)$
65	JMAX	Number of equally spaced R -values, over which $\psi(R, z)$ is tabulated

Table G.2: (continued)

Line(s)	Variable	Description
65	KMAX	Number of equally spaced z -values, over which $\psi(R,z)$ is tabulated
66-69	RJ	Array of R_j -values (in meters) in ascending order over which $\psi(R,z)$ is tabulated
97-122	ZK	Array of z_k -values (in meters) over which $\psi(R,z)$ is tabulated: $-\Delta z/2, \Delta z/2, 3\Delta z/2, \dots$
123-4003	PSI	Array of ψ -values (in webers), $\psi(R_j, z_k)$, ordered like $\psi(R_{\min}, -\Delta z/2), \dots, \psi(R_{\max}, -\Delta z/2), \dots, \psi(R_{\min}, z_{\max}), \dots, \psi(R_{\max}, z_{\max})$

Table G.3: Example of an Input Data File

Line					
1	7.53569315E-03	3.20692909E+00	5.78062641E+05	5.29872354E+04	
2	5.00000000E+00	-3.95362033E+00	-1.09311402E-01	3.88501212E-01	
3	41 10 10				
4	-3.95362033E+00	2.70183748E+01	-2.42677006E-01	2.99784001E+05	
...	...				
44	-1.09311402E-01	2.64936177E+01	-1.44062964E-03	0.	
45	0.	7.29992330E+02			
46	0.	7.74470036E+02			
47	0.	7.14880269E+02			
48	0.	7.04843659E+02			
49	3.33333333E-01	7.01904300E+02			
50	6.66666667E-01	7.01913795E+02			
51	1.00000000E+00	0.			
52	1.00000000E+00	0.			
53	1.00000000E+00	0.			
54	1.00000000E+00	0.			
55	0.	2.99796655E+05			
56	0.	2.41823371E+05			
57	0.	1.40451232E+05			
58	0.	3.27932142E+04			
59	3.33333333E-01	1.38877745E+02			
60	6.66666667E-01	-1.48443630E+01			
61	1.00000000E+00	0.			
62	1.00000000E+00	0.			
63	1.00000000E+00	0.			
64	1.00000000E+00	0.			
65	154 126				
66	3.79210526E+00	3.80789474E+00	3.82368421E+00	3.83947368E+00	3.85526316E+00
...	...				
96	6.16052632E+00	6.17631579E+00	6.19210526E+00	6.20789474E+00	
97	-7.98387097E-03	7.98387097E-03	2.39516129E-02	3.99193548E-02	5.58770468E-02
...	...				
121	1.90814516E+00	1.92411290E+00	1.94008065E+00	1.95604839E+00	1.97201613E+00
122	1.98798387E+00				
123	3.64325860E-02	-3.65162777E-02	-1.09855019E-01	-1.83597116E-01	-2.57687493E-01
124	-3.32071842E-01	-4.06695466E-01	-4.81505106E-01	-5.56448342E-01	-6.31473465E-01
...	...				

Table G.4: Output from SLWON9

Line(s)	Variable	Description
1	SLWON9	Version of code, as distinguished from earlier versions (e.g., SLWON8)
1	02/02/80C	Run 02 Feb 1980 on C-machine (CRAY-1)
1	07:37:46	Time of run (PST)
2	BETAT	Average toroidal beta of plasma
2	BETAP	Average poloidal beta
2	Q(A)	Q-value at plasma edge
2	IO	Total plasma current (amps)
2	BT	Magnitude of toroidal field at $(R_0, 0)$
3	RO	Major radius (meters) at magnetic axis
3	RIN	Major radius (meters) at inboard edge
3	ROUT	Major radius (meters) at outboard edge
3	PEDGE	ψ -value at plasma edge (webers)
4	Z	Fusion-product charge (multiples of proton)
4	MASS	Fusion-product mass (amu)
4	ENERGY	Fusion-product birth energy (MeV)
4	VEL	Fusion-product birth speed (m/s)
5	NV	Number of phase space intervals in speed, v
5	NPM	Number of phase space intervals in ψ_x
5	NZ	Number of phase space intervals in ζ
5	NINT	Number of ψ -intervals to span plasma
5	NPSI	Number of ψ -bins
5	NVOL	Number of ψ -intervals to obtain volume and area integrals
5	STOL	Search tolerance termination criterion

Table G.4: (continued)

Line(s)	Variable	Description
6-23	P/PWL	Normalized ψ -value (ψ/ψ_{wall}) at which subsequent variables are evaluated
6-23	DV	Amount of plasma volume (m^3) contained in this ψ -bin
6-23	T	Ion temperature (keV)
6-23	NI	Ion density ($\#/m^3$)
6-23	NP	Number of fusion products born ($\#/m^3$ -s)
6-23	NA	Flux-surface-averaged number of alphas ($\#/m^3$)
6-23	JA	Flux-surface-averaged current density (amps/ m^2)
6-23	GE	Flux-surface-averaged heating rate (keV/s-electron) of electrons, accounting for large banana-width orbits (LRG BANAN) and IN-SITU deposition
6-23	GI	Same as GE, but for ions
24	DV	Total plasma volume (m^3)
24	NP	Total fusion-product rate ($\#/s$)
24	NA	Total number of fusion products in plasma
24	JA	Total alpha particle current (amps)
24	GE	Total electron and ion heating rates for both the large banana-width (LRG BANAN) and IN-SITU deposition models
25	CPU	Central processing time (sec)
25	ID	Input/output time (sec)
25	SYS	System overhead time (sec)
25	TOT	Total execution time for this run (sec)

Table G.5: Example of an Output Data File

SLWON9 ON: 02/02/80C AT 07:37:46 PACIFIC TIME

PLASMA--BETAT=0.008, BETAP=0.389, Q(A)=3.207, IO(AMPS)=5780626., BT(G)=52987.

SIZE: RO(M)=5.035, RIN(M)=3.860, ROUT(M)=6.145 PEDGE(W)=3.675

FUSION PRODUCT: Z=2., MASS(AMU)=4.00 ENERGY(MEV)=3.52, VEL(M/S)=1.303E+07

NV= 32, NPM= 32, NZ= 64, NINT=1024, NPSI= 16, NVOL=128, STOL= 1.0E-05

#	P/PWL	DV:M3	T:KEV	NI:#/M3	NP:#/M3/S	NA:#/M3	JA:A/M2	GE:KEV/S/ELECTRON		GI:KEV/S/ION	
	0.0		15.00	6.24E+19	2.578E+17			LRG BANAN	IN-SITU	LRG BANAN	IN-SITU
1	0.030	8.95	14.24	6.23E+19	2.327E+17	2.216E+17	1.402E+03	9.462E+00	1.023E+01	2.346E+00	2.916E+00
2	0.090	9.19	12.84	6.19E+19	1.853E+17	1.735E+17	2.934E+03	8.329E+00	8.399E+00	1.875E+00	2.153E+00
3	0.149	9.45	11.58	6.10E+19	1.429E+17	1.262E+17	3.257E+03	6.898E+00	6.712E+00	1.392E+00	1.549E+00
4	0.209	9.72	10.42	5.97E+19	1.065E+17	9.013E+16	3.696E+03	5.581E+00	5.213E+00	1.015E+00	1.083E+00
5	0.269	10.02	9.37	5.79E+19	7.631E+16	5.836E+16	3.537E+03	4.364E+00	3.921E+00	6.600E-01	7.316E-01
6	0.329	10.34	8.39	5.57E+19	5.230E+16	3.681E+16	2.770E+03	3.100E+00	2.843E+00	4.302E-01	4.753E-01
7	0.388	10.68	7.47	5.31E+19	3.399E+16	2.283E+16	2.089E+03	2.285E+00	1.973E+00	2.661E-01	2.942E-01
8	0.448	11.07	6.61	5.00E+19	2.072E+16	1.308E+16	1.462E+03	1.533E+00	1.299E+00	1.569E-01	1.718E-01
9	0.508	11.50	5.80	4.64E+19	1.168E+16	7.343E+15	8.658E+02	1.046E+00	8.014E-01	8.807E-02	9.319E-02
10	0.568	11.99	5.02	4.25E+19	5.951E+15	3.876E+15	5.825E+02	6.431E-01	4.548E-01	4.890E-02	4.601E-02
11	0.627	12.56	4.28	3.81E+19	2.651E+15	1.788E+15	3.301E+02	3.995E-01	2.309E-01	2.197E-02	2.002E-02
12	0.687	13.23	3.56	3.32E+19	9.758E+14	8.268E+14	1.921E+02	2.313E-01	1.001E-01	1.057E-02	7.282E-03
13	0.747	14.05	2.85	2.79E+19	2.692E+14	2.895E+14	1.021E+02	1.168E-01	3.425E-02	3.681E-03	2.027E-03
14	0.807	15.07	2.16	2.22E+19	4.656E+13	8.113E+14	4.352E+01	5.932E-02	8.072E-03	9.300E-04	3.714E-04
15	0.866	16.43	1.47	1.60E+19	3.364E+12	1.458E+13	9.312E+00	2.339E-02	9.949E-04	1.418E-04	3.317E-05
16	0.926	18.40	0.80	9.41E+18	2.807E+10	1.003E+12	8.613E-01	5.662E-03	3.294E-05	7.140E-06	6.998E-07
		192.65			8.343E+18	7.172E+18	7.507E+03	4.751E+06	4.705E+06		
EXECUTION TIMES(CPU, IO,SYS,TOT):					3.668E+03	3.083E+00	4.053E+00	3.675E+03			