Standard Profiles for NCSX Flexibility Studies

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This document describes a collection of measured density, temperature, and pressure profiles taken from four stellarators, ATF, CHS, LHD, W7-AS, and two tokamaks which bracket NCSX in size, PBX-M, DIII-D. These empirical profiles are expected to span the range that could plausibly be expected to occur in NCSX. These can be used in NCSX flexibility studies to assess the impact which a variety of profile shapes would have on a host of inter-related characteristics:

1) Magnetic surface quality,
2) Quasi-axisymmetry, and quasi-omnigeneity,
3) Bootstrap current,
4) Fast-ion orbits,
5) MHD stability limits

The work of assessing the impact of any particular set of profiles will be carried out by a number of codes which share the ability to make use of VMEC equilibria as their input. The pressure and temperature profiles can therefore be made available to these codes through the standard VMEC variables for polynomial fit coefficients of the pressure (AM in the INDATA namelist) and temperature (AT in the OPTIMUM namelist). See below for more detail on automated VMEC input file generation. The standard profiles are also available through a set of Fortran-77 subroutine (see below) for those who prefer or need an alternate method of access.

The experimental stellarator profiles come from a variety of published papers (cited in SPROF.DAT, and condensed in SPROF.REF). The DIII-D profiles come from the International Profile Database (formerly known as the ITER Profile Database). The PBX-M profiles come from TRANSP runs recommended by Benoit Leblanc and Stan Kaye.

Profiles based on analytic formulae as well as real profiles from ATF, CHS, DIII-D, LHD, PBX-M, and W7-AS are included. The analytic profiles are all described – and used for flexibility studies – in Martha Redi's paper "Robustness and Flexibility in Compact Quasiaxial Stellarators: Global Ideal MHD Stability and Energetic Particle Transport". The polynomial representation of the 'standard' NCSX pressure profile (P00 in Redi's paper) was supplied by Long-Poe Ku (as used in c82a calculations); it is based on the ARIES pressure profile. The polynomial representation of the 'standard' NCSX density profile was also supplied by Long-Poe Ku; the NCSX Te profile is simply the ratio P_e/n_e.

Brief descriptions of the discharges are given in SPROF.DAT (and duplicated in SPROF.REF). These were taken from the original papers, and they provide some idea of the plasma regime, heating method, and any reported unusual features of the discharges. None of the discharges is reported to be pathological or unrepresentative of its regime, but not all are relevant to any particular NCSX operational scenario, e.g, high beta. Thus, users should search the collection for discharges that are more likely to be relevant to the matter at hand.

Eleven discharges have been selected to cover the full range of pressure peakedness/broadness and to include several profiles with regions of lower pressure gradient near ρ=0.5 a; see below for descriptions and table of some parameters.

The radial variable is square root of normalized toroidal flux, and each profile is normalized to 1.0 at the peak of its spline fit. Some information concerning the absolute normalization is included in the comments in SPROF.DAT (duplicated in SPROF.REF). Both spline fits and polynomial fits are available for all profiles.

The flexibility studies also need the inductively driven rotational transform. There appear to be no stellarator experiments which are directly relevant to the NCSX scenario (which is intended to provide unique capabilities in this area!), so simulations of NCSX startup and steady state will be relied on to provide estimates of the inductive transform. That work will begin soon and be described separately.

General Characterization of Electron Pressure Profiles

Real profiles cannot be simply categorized by one (or only a few) measures, so users of this collection are urged to study the summary plots in order to become familiar with the available shapes. The following is only intended to provide a crude characterization.

The analytic pressure profiles (P00 through P05) cover roughly the same range of pressure profile shape as those found in experiments, but with two exceptions:
1) P04 is broader than any experimental pressure profile. 2) The experimental profiles (particularly from LHD) tend to have higher pressures in the outer 10-20% than the analytic profiles (except P04).

ATF profiles, as a group, are the most peaked among the stellarators, but there are some W7-AS profiles that are similarly peaked. Several ATF profiles have singularly low pressures in the outer 20-30% of the minor radius. This may be due to a large island in this region.

Profile C_MC2 is broadest among the experiments, but otherwise CHS profiles are similar to the general stellarator population.

LHD pressure profiles are generally similar to the general stellarator population, but they are among the highest in the outer 10-20% of the minor radius.

W7-AS has the widest range of profiles of any single device in this collection.

DIII-D pressure profiles are generally more peaked than most of the stellarator profiles. They are roughly similar to the ATF profiles and the most peaked W7-AS profiles.

Documentation of the Profiles

The following profiles are in the PPPL Unix cluster directory /u/dmikkels/ncsx/SOURCES .

PROFILE_LIB.PDF is this file.

SPROF_DESC.TXT Contains detailed descriptions of the layout of:

SPROF.DAT, the input file used by SPRF_INIT.
SPROF.REF, which has all description lines in SPROF.DAT
SPROF.OUT, which has profiles of all types, organized by type.
SPOUT_xxx., each contains all the profiles of type 'xxx'.
SELECT_xxx., each contains the selected eleven profiles of type 'xxx'.
SPROF.SUM, which has all summary info (organized by profile type) such as profile peakedness, profile 'width', and the size and location of the maximum of the first derivative.

Eleven Selected Pressure Profiles

DIII-D	78109_1
	77559_1
PBX-M	3113_1
LHD	L_lrcy
	L_Wdc05
	L_Sdc05
CHS	C_tECH
	C_H1
	C_MC2
W7-AS	W_coEld
	W_tHP

These eleven discharges have been selected to cover the full range of pressure peakedness/broadness found in the complete collection of profiles, and to include several profiles with regions of lower pressure gradient near ρ=0.5 a; see below for figures of the normalized electron density, temperature, and pressure profiles.

The most peaked profiles are from DIII-D; shots 78106 (RF heated, part of an L-mode ρ^* scan), 78109 (NBI heated, part of a different L-mode ρ^* scan), and NCS shots 84682 & 87031. The chosen representative with a steep core gradient is 78109, it is the most 'vanilla' of this group. 78109 has 1.9 MW of NBI, ne-bar=3.1E19, 1.0 MA, 2.0 T (78106 has 2.0 MW of ECH & FW, ne-bar=3.8E19, 1.0 MA, 2.0 T)

Some DIII-D pressure profiles have steep peripheral pressure gradients. The chosen example is 77559 1.0 MA, 2.0T H-mode 13.6 MW NBI, ELMing H-mode; the experiment used divertor pumping to decouple core density and NBI power (D. Schissel, et al Plasma Phys. and Control Fusion 38 (1996) 1487). Some LHD profiles also have large peripheral pressure gradients, but they have shallower gradients in the core. Other DIII-D shots have more peaked pressure profiles that most stellarator profiles, but there are a few stellarator profiles that are as peaked as the remaining DIII-D profiles. (82183 has a slightly broader profile, but is not 'typical': it is the high Kappa end of a Kappa scan and had higher tau_E than the usual scalings would predict. It has 1.33 MA, 1.6 T, 3.9 MW NBI, ne-bar=6.3E19.)

PBX-M TRANSP run 3113 is of shot 53944, a high-beta ($\langle\beta_{tor}\rangle$=6.8%), high-$T_i$ (T_{io}=5.0 keV) shot.

CHS and W7-AS exhibit a wider range of profiles than are observed in the two tokamaks. LHD may have less range because they have had far less run time and the reported data is all from discharges which are dominantly heated by NBI, while the peaked temperatures profiles in CHS and W7-AS employed ECH.

The most peaked stellarator profiles in the deep core region are C_tECH (CHS typical ECH profiles) and W_coEld (co-ECCD, low density). They differ in the periphery, where W_coEld has much higher pressure. (Both have higher peripheral pressure than the most peaked of the DIII-D profiles.) The break in the slope of the pressure profiles of C_tECH is caused by the 'two component' structure of Te , which is clearly seen in the data (S. Okamura, et al., Nuclear Fusion, 39, (No. 9Y) 1337, 1999). This 'two component' structure is also seen in W_coEld; its higher peripheral pressure is caused mainly by its very flat density profile (G. A. Mueller, et al., in 11th Top. Conf. on RF Power in Plasmas, p. 133).

A 'kinky' CHS profile is C_H1, which has a lower pressure gradient for ρ=0.5-0.7, highest P/P(0) at ρ=0.8, and the highest pressure gradient for ρ>0.8 (K. Toi, IAEA 1992, Vol. 2, p. 461). Although the kinkiness is questionable (moving a couple data points could remove it), this is clearly the broadest pressure profile of all (with highest P/P(0) for ρ>0.8). The temperature profile is quite broad and the density profile is slightly hollow with a peak at ρ=0.9. (C_H2 is also kinky, but the reality of the kink is similarly ambiguous).

C_MC2 (H. Iguchi, Plasma Phys. Control. Fusion, 36 (1994) 1091) has a low pressure gradient out to ρ=0.6, and represents what C_H1 should be if its kinkiness is not real. For C_MC2 the magnetic axis is shifted outwards, and this causes an 'outward particle pinch' on the inside of the density peak. B=1.4 T, $\langle n_e\rangle$=2.3E19, NBI heating, gas puffing.

LHD discharges generally have the highest P/P(0) for ρ>0.8; they have very broad T_e profiles and very broad (or hollow) density profiles. The broadest of these is L_lrcy, 'pump out low recycling phase'; while it has broad temperature and density profiles, the absolute pressure is low (M. Fujiwara, et al., Nucl. Fusion, 11Y (1999) 1659). Two more LHD profiles are from a 1999 EPS poster: K. Tanaka, et al., 1999 EPS, poster P3.101. The favored 'kinky' LHD profile is L_Wdc05, with a typical Te(r) and a hollow ne(r) giving a region of low pressure gradient near ρ=0.5 (L_Hy10 is kinkier, but I 'm even less sure we can trust the data). The other end of the steepness range for LHD is L_Sdc05, which has an appreciable pressure gradient at ρ=0.4 and maintains it all the way to the edge.

W_tHP, a "typical high pressure (<β>=0.14%) ECRH discharge", has a low pressure gradient around ρ=0.5, and a steep gradient inside ρ=0.5 (H. Renner, et al., IAEA 1990, Vol. 2, (1991) 439). Its mildly kinked nature is produced by a modest reduction in temperature gradient for ρ>0.4 and a mild off-axis density peak near ρ=0.6.

ATF profiles are not included because C_tECH is as peaked as any ATF profile. Some ATF profiles have lower peripheral temperatures, but these may be due to large islands which should not be expected for NCSX.

Device	Name	Heat	Pheat (MW)	fueling	mode	neo E19	$\bar{n}_e$ E19	Teo KeV	Ip MA	Bo T
DIII-D	78109_1	NBI	1.9	puff?	L		3.1	2.7	1.0	2.0
DIII-D	77559_1	NBI	13.6	puff?	H		4.7	3.9	1.0	2.0
PBX-M	3113_1	NBI	4.3			6.8	4.7	2.1	0.5	1.0
CHS	C_tECH	ECH	0.3			1.0		1.9		1.9
CHS	C_H1	NBI		puff	H	4.0		0.4		1.2
CHS	C_MC2	NBI		puff	not H	1.8	2.0	0.3		1.4
LHD	L_lrcy	NBI?				1.0	1.0	1.3		
LHD	L_Wdc05	NBI		puff		1.2	1.4	1.1		2.5
LHD	L_Sdc05	NBI	2.7	puff		1.6	1.3	1.2		1.5
W7-AS	W_coEld	ECCD	0.6	puff		1.8	1.6	2.8		1.3
W7-AS	W_tHP	ECH	0.6	puff		3.5	3	2.4		2.5

Plot Files

Summary plot files of a number of normalized profiles (in PDF format) have names such as ne_W7AS.PDF, Pe_LHD.PDF. These are in the PPPL Unix cluster directory /u/dmikkels/ncsx/PLOTS

Scatter plots showing the ranges (and possible correlations) of summary characteristics have names such as Pkdns_FusPk.PDF and SteepR_SteepF.PDF.

VMEC Namelist Input File Generation

A VMEC namelist input file (c.f., VMS file MIKK$:{NCSX]INPUT_V.QAS3_C82A;1 copied from PPPL Unix cluster file /u/zarnstor/QAS/input.qas3_c82a) has been used as a template for automatically generating a series of new VMEC input files which have a new pressure profile. The profiles are approximately normalized to meet a target toroidal beta value

(VBETA in PREP.FOR); the normalization needs the "Average b**2/(2 mu0)" value found in the THREED1 file written by VMEC for the template input file (VBSQOMU in PREP.FOR is used in the normalization; set it to the value of "Average b**2/(2 mu0)"). In the new VMEC input files the polynomial fit coefficients of the normalized pressure (in Pascals) replace the 'AM' array in the INDATA namelist in the original template VMEC input file. The polynomial fit coefficients of the normalized temperature (the target density-weighted-volume-average of Te is given by VTEAVG in PREP.FOR) are written as the 'AT' array in the OPTIMUM namelist in the VMEC input file.

The new VMEC input files have names of the form INPUT.QAS3_C82A-C_H1, INPUT.QAS3_C82A-W_tHP, etc. They are placed in the PPPL Unix cluster directory /u/dmikkels/ncsx/VMEC_inputs .

Fortran Source Files, Summary Plots, Descriptions, Etc.

The released versions of the files can be found on the PPPL Unix cluster in /u/dmikkels/ncsx/SOURCES.

The Fortran-77 source files are PREP.FOR and SPROF.INC, which contains the COMMON blocks. Users will need to call subroutines SPRF_INIT,SPRF_TYP,SPRF_VEC and function SPRF_ONE. The subroutine arguments of these are described in STDPRF.INTERFACE.

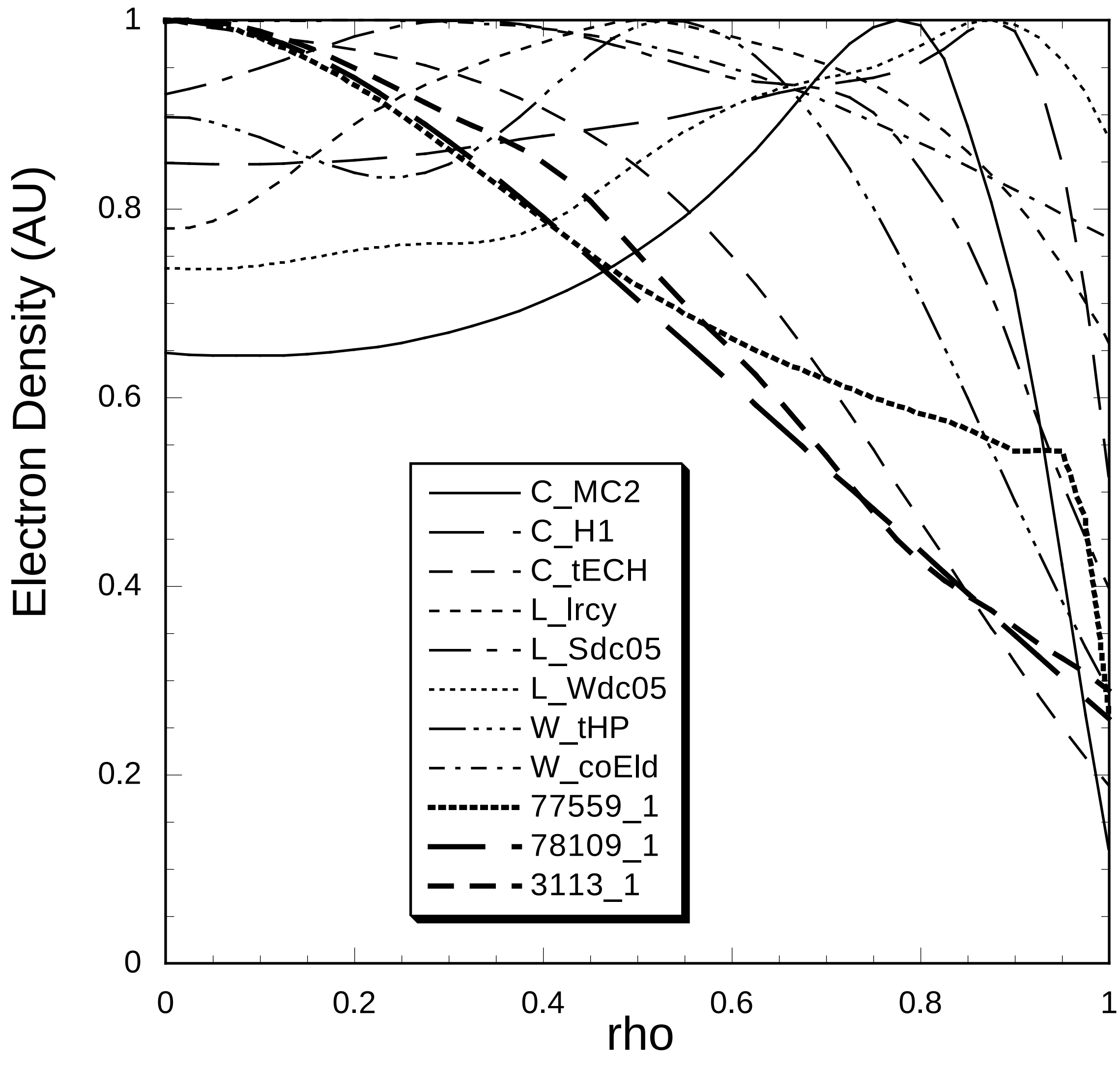
SPRF_INIT Reads the profile input file, makes spline fits, finds summary values for each profile, and initializes the COMMON variables.

SPRF_TYP Returns all the names of the requested type. Possible profile types are: ne, ni, Te, Ti, Pe, Pi, fPi, Ptot, fPtot.

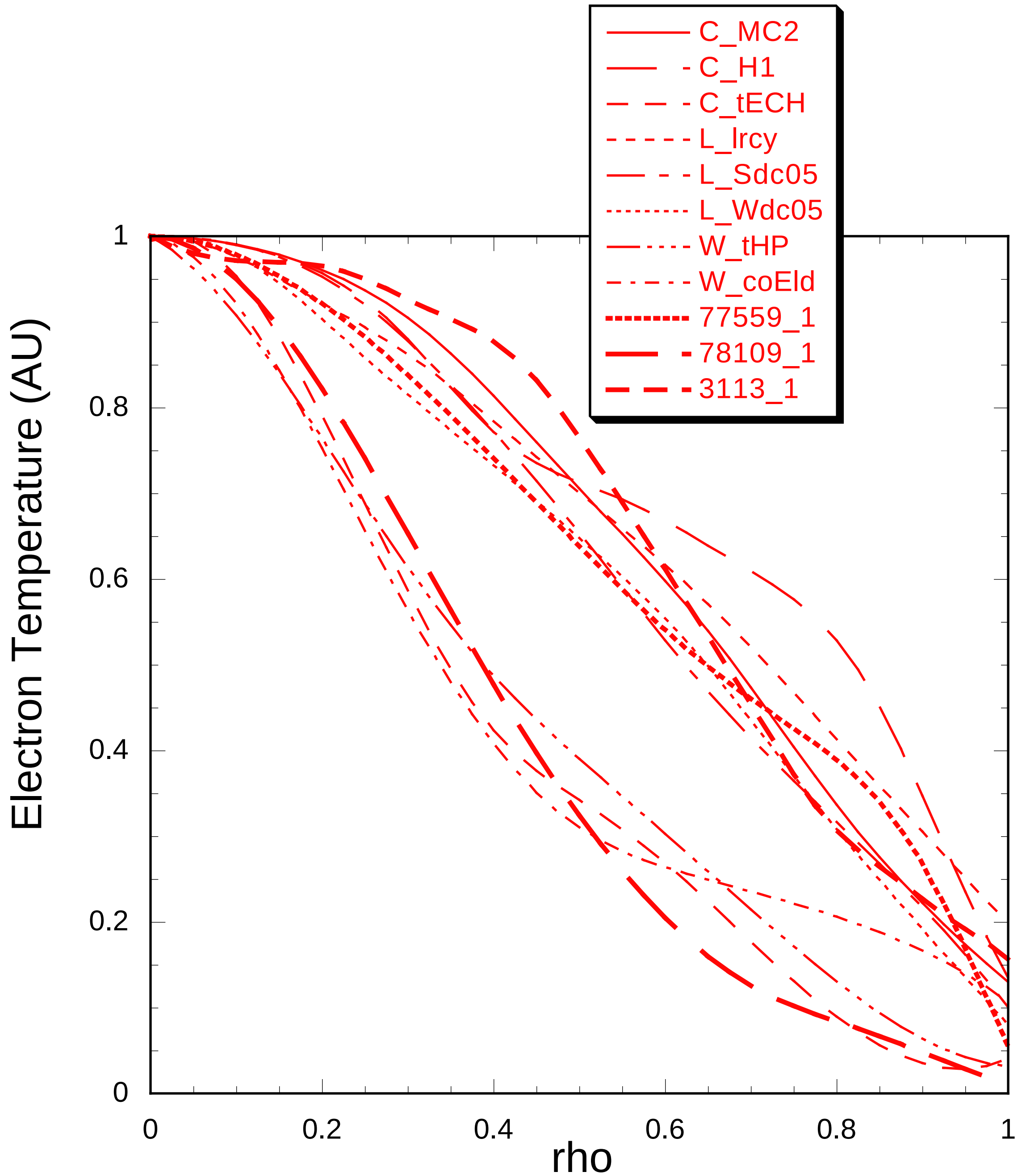
SPRF_VEC Evaluates a profile's spline fit for an array of ρ values.

SPRF_ONE Evaluates a profile's spline fit for one ρ value.

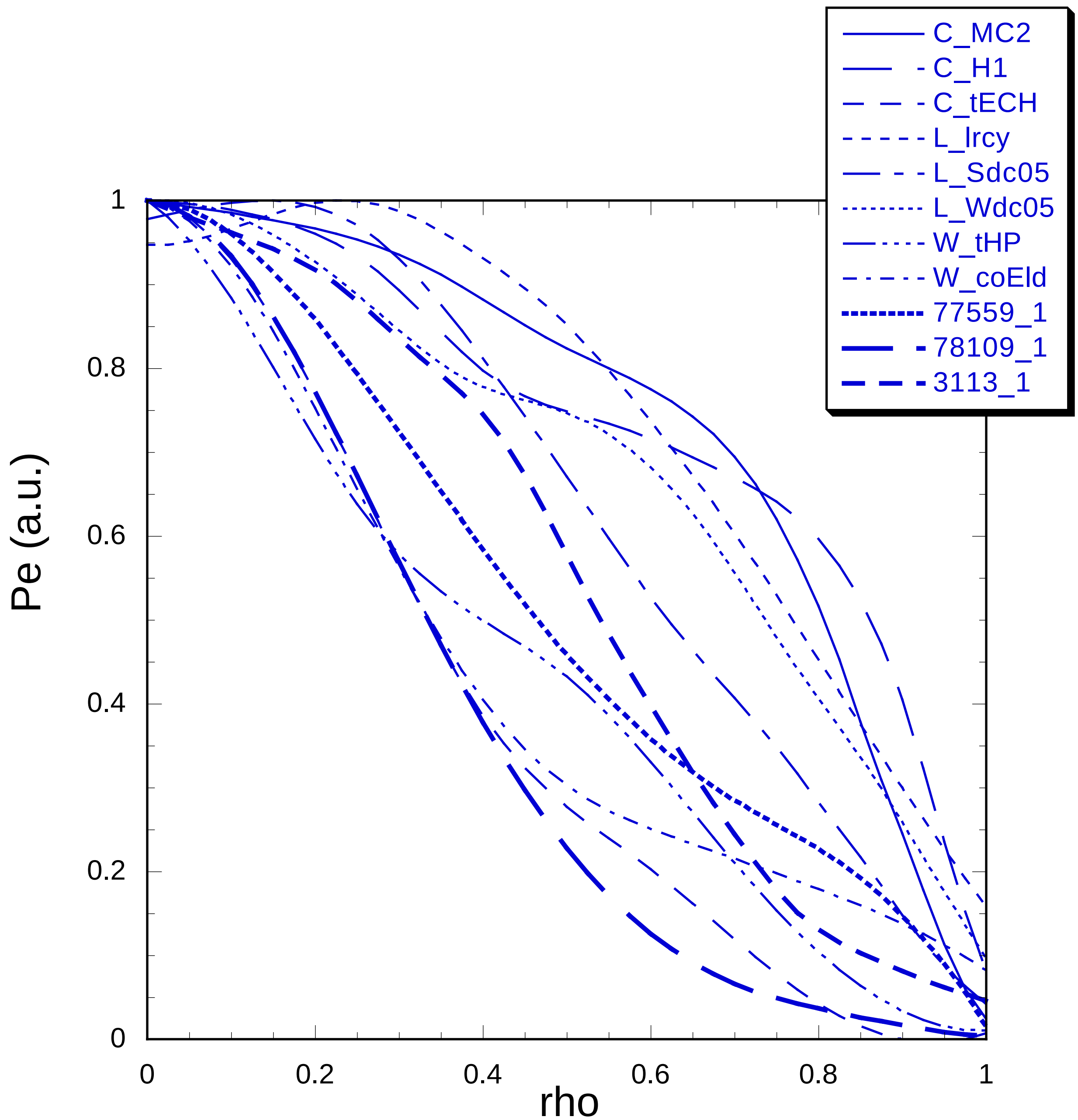
SPRF_PREP Is a driver program to allow testing of the routines. Users should use IPREP=0 to mimic a user code environment. (IPREP=1 is used to generate SPROF.OUT, SPROF.SUM, SPROF.REF, ...)



Electron Density (AU)
rho
0
0.2
0.4
0.6
0.8
1
C_MC2
C_H1
C_tECH
L_lrcy
L_Sdc05
L_Wdc05
W_tHP
W_coEld
77559_1
78109_1
3113_1



C_MC2
C_H1
C_tECH
L_lrcy
L_Sdc05
L_Wdc05
W_tHP
W_coEld
77559_1
78109_1
3113_1
Electron Temperature (AU)
rho
0
0.2
0.4
0.6
0.8
1


C_MC2
C_H1
C_tECH
L_lrcy
L_Sdc05
L_Wdc05
W_tHP
W_coEld
77559_1
78109_1
3113_1
Pe (a.u.)
rho
0
0.2
0.4
0.6
0.8
1