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User's Guide for
FOKN-C; A Relativistic Fokker-Planck Code for Calculating
Distribution Functions in a Multi-Species Plasma
with Cyclotron Emission Included

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I. Introduction

FOKN-C is a modification of the code FOKN' to include cyclotron emission. This makes a convenient approach for studies of emission from non-Maxwellian electron distributions. The FOKN-C version of FOKN' employs a relativistic Fokker-Planck algorithm to evolve the distribution functions of the various mutually interacting components of a multi-species plasma forward in time, with the optional addition of radiation losses and high angle, large energy and momentum transfer interactions between the various charged species of the plasma. As a computational expediency, the latter process and all fusion reactions are handled by transfer matrices which are generated separately by another code, RNUX, so that once specific transfer matrices are generated, they can be used over and over by FOKN' provided the group structures are compatible. The transfer matrices are interaction probabilities of all the energy groups of one species with all the energy groups of another species. They are generated by a Monte Carlo technique with experimental cross-sections as inputs.

Before going further, several caveats should be explicitly issued:

- 1) The relativistic Fokker-Planck equation used in FOKN-C is applicable only to an infinite isotropic medium, i.e., the equation is one-dimensional in velocity space;
- 2) All charged particles are assumed to remain in the medium, while uncharged particles escape at birth without subsequent interaction.

Outputs of the code are separated into numerical outputs and graphical plots. The numerical outputs indicate the number density, energy density, temperature, distribution function of the various components of the simulated plasmas as a function of time. The graphical plots show the distribution functions in phase as a function of time.

Besides solving the relativistic Fokker-Planck equation, FOKN-C calculates radiation losses (bremsstrahlung and cyclotron radiation), charged particle losses, and accept charged particle injections at different energies.

FOKN-C has a wide range of applications. As examples the following types of problems have been studied using FOKN. First is the study of the deviation of the ion and electron velocity distributions from thermal equilibrium during the nuclear burn of light isotopes under conditions characteristic of those likely to be encountered in classical magnetic confinement CTR machines.¹⁻⁴ Second is the study of the fusion energy multiplication factors that can be obtained when beams of light ions are injected into a relatively cold target plasma ("wet-wood burner" reactors)⁵⁻⁶. Third is the study of energy transfer between electrons and ions under relativistic conditions which might arise from astro-physical studies⁷. Fourth is the study of radiation losses such as cyclotron radiation for non-Maxwellian electron distribution confined by magnetic fields⁸. Cyclotron emission is calculated separately from the Fokker-Planck equation. For details, please see Reference 8.

The present version of the code is set up to run in the CDC-7600 only (A machine of National Magnetic Fusion Energy Computer Center, NMFECC). RFOT29 is the most recent version of FOKN with cyclotron radiation and is the executable file. RFOT29F is the LLLTRAN listing of FOKN. LASLIBE is a private library needed to compile FOKN-C.

II. Inputs to FOKN-C

FOKN-C input cards (problem generator file).

Each card has at most 12 input words per line of at most 10 characters each.

All input formats are field free.

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All input formats are field free.

First card of the input file must be an identification card.

1. Identification card (required, must be the first card).

BOX.---^-----

First word is "BOX".

Second word is the box number (e.g. W98).

Third word is any name for identification up to 10 characters, but only the first 4 characters appear on FROG DD80 output (e.g. WMDT1).

2. Comment cards (optional).

C^-----

First word must be "C".

The rest could be anything up to 11 words.

3. Material cards (required, must be ≤ 3 kinds of materials).

M 1 5 18.37E-24

First word must be "M".

Second word is species number from 1-8, could be integer or floating point number.

Third word is the charge number, Z, of the corresponding species.

Use -1 for electrons and 1.E-30 for neutrons. The word could be integer or floating point but never zero.

Fourth word is the mass of the corresponding species in grams.

4. Group structure cards (required, 2 different kinds).

Group structure must be the same as in transfer matrix generator in order to use the transfer matrices.

There are two kinds of group structure cards.

One (ULIN cards) uses linear interpolation to set up the group structure.

The other (ULOG cards) uses logarithmic interpolation to set up the group structure.

First kind:

```
ULIN  1    2    .00242056    .00342319
```

First word must be "ULIN".

Second word is the lower group number of the range considered.

Third word is the upper group number of the range considered.

Fourth word is the u-upper boundary corresponding to the group in the second word.

Fifth word is the u-upper boundary corresponding to the group in the third word.

$u = \gamma B$

By definition u-lower boundary for group #1 is 0.

Second kind:

```
ULOG  5    35    .00541253    .085
```

First word must be "ULOG".

Second to fifth words have the same meaning as those in the ULIN card.

5. Plasma background card (required, at most 1000/7 cards).

Background distribution is assumed to be

$$f = \kappa(\gamma-1)^\alpha e^{-[(\gamma-1)-\delta]MC^2/kT}$$

κ is automatically normalized to the range of u wished to be considered by user.

$\delta = 0$ and

$\alpha = 0$ force f to become a Maxwellian

$$kT = 0 \Rightarrow e^{-(\gamma-1)MC^2/kT} = 1$$

F card is of the form:

F 1 1.E14 40. 0. 0. 0. 0.

First word must be "F".

Second word is the species number corresponding to that in the M card.

Third word is the background particle density of this species in $\#/cm^3$.

Fourth word is the background temperature, kT , of this species in keV.

Fifth word (optional, default is 0.) is the lower boundary of the range of u wished to be considered by user.

Sixth word (optional, default is 0.) is the upper boundary of the range of u wished to be considered by user.

(Note: Defaults used in both the fifth and sixth words imply full range of u is to be used to set up the background distribution.)

Seventh word (optional, default is 0.) is " δ " as appeared in the above equation.

Eighth word (optional, default is 0.) is " α " as appeared in the above equation.

(Note: If words 5-8 are all zero, background distribution is a Maxwellian.)

Note The distribution for one species can be described by using several F cards. The resultant distribution is the sum of all the distributions described in the several F cards

6. Parameter cards (21 parameters to date, optional).

P 1 1.E-5

First word is "0".

Second word is the parameter number.

Third word is the value of the parameter.

The following is a list of the different parameters with defaults, modes, and units.

<u>Number</u>	<u>Default</u>	<u>Mode</u>	<u>Unit</u>
1	1.E-20	Float	sec
2	0	float	sec
3	100	int	---
4	0.1	float	---
5	1.1	float	---
6	1.E+20	float	sec
7	1.E+20	float	sec
8	100000	int	---
9	1000	int	---
10	1.E-8	float	---
11	100	int	---
12	10	float	---
13	0	float	---
14	0	float	---
15	0	float	---
16	1.E-30	float	---
17	1.0	float	---
18	1.0	float	---
19	1.E+20		

Parameter 1 is the initial time step.
 Parameter 2 is the time between edits.
 Parameter 3 is the number of cycles between edits.
 Parameter 4 is the maximum fractional change in distributions per cycle.
 Parameter 5 is the $\max \Delta t_{j+1}(\text{new})/\Delta t_j(\text{old})$
 Parameter 6 is the $\max \Delta t$.
 Parameter 7 is the stop time.
 Parameter 8 is the maximum number of cycles.
 Parameter 9 is the number of cycles between restart dumps.
 Parameter 10 is the convergence criteria for stopping iterations.
 Parameter 11 is the maximum number of iterations.
 Parameter 12 is the optimal number of iterations.
 Parameter 13 is the e-i bremsstrahlung multiplier.
 Parameter 14 is the e-e bremsstrahlung multiplier.
 Parameter 15 is the cyclotron radiation multiplier.
 Parameter 16 is the max fractional change in population per group.
 Parameter 17 is the ion over-relaxation parameter $1 \leq P17 \leq 2$.
 Parameter 18 is the electron over-relaxation parameter $1 \leq P18 \leq 2$.
 Parameter 19 is the source injection stopping time

Note: All 19 parameters can be changed while the program is running.
 See section on how to run the program. If parameters 13-15 are zero,
 the subroutines BREM and CYCLO will not be used so that there is no
 bremsstrahlung and cyclotron radiation.

7. Reaction enhancement cards (MULT cards, 2 kinds, optional)

First kind is multiplier of transfer matrix

MULT 30 2.0

First word must be "MULT".

Second word is the reaction number or the transfer matrix number.

Third word is the value of the multiplier, i.e. multiplier for the nuclear cross-sections.

Second kind is multiplier for the Fokker Planck scattering.

MULT 1 2 2.0

First word must be "MULT".

Second word is the scattered species number. This species is affected by the multiplier.

Third word is the scattering species number. This species is not affected by the multiplier.

Fourth word is the multiplier value.

Note: To conserve energy while using the second kind of "MULT" card, both permutations must be used.

8. Transfer matrix card (optional).

NUC T2DTNA ---

First word must be "NUC".

The rest are transfer matrices. Up to 10 transfer matrices can be used.

9. Source cards (optional, at most 10 source cards).

S 1 30 1.E+15

First word must be "S".

Second word is species number.

Third word is the group number which is the intended energy for injection.

Fourth word is the injection rate in particles/cm³-sec.

10. Loss cards (optional).

The loss term is described by the following equation

$$\frac{df}{dt} = - f \left[\frac{c}{r} R / \left[(\tau_p + \tau_f + \frac{r}{v}) (\gamma - 1)^p + f_L \right] \right]$$

c = speed of light, r = radius of plasma, v = volume of plasma
default of v = 1 cm³, default of r = 0.62 cm.

L 1 2.1E-11 0. 1. 0. 0.

First word must be "L".

Second word is the species number.

Third word is the value of R.

Fourth word (optional) is value of p, default is 0.

Fifth word (optional) is value of τ_p , default is 1.

Sixth word (optional) is value of τ_f , default is 0.

Seventh word (optional) is value of f_L , default is 0.

Note: The term inside the big bracket is usually referred to as the particle confinement time.

11. New time, volume, and electron temp cards (optional, up to twenty cards).

TV 1. 2. 10.

First word must be "TV".

Second word is the value of time in seconds at which the volume of the plasma and/or electron temperature would be changed.

Third word is the value of the new volume of plasma.

Fourth word (optional, default is 0) is the value of electron temperature. If electron temperature as specified here $\neq 0$, then the electron distribution would remain a Maxwellian at this specified temperature, i.e., the electron distribution would not be evolved by the Fokker-Planck operator.

Note: If there are more than one TV card, logarithmic interpolation is used between cards.

12. DTBURN card (optional).

DTBURN 1 2

First word must be "DTBURN".

Second word is deuterium species number.

Third word is tritium species number.

Note: If this card is used, then transfer matrices or "NUC" cards should not be used. The function of this card is to list the number of $d(t,n)\alpha$ reactions only, so that the α particles will not deposit energy to the plasma.

13. Cyclotron radiation card (optional).

B 10000. 0. 1. 0.5 .333

First word must be "B".

Second word is the magnetic field strength in gauss.

Third word is the scale length in cm and can be zero, in which case the volume is used to determine the size.

Fourth word is the multiplier for the initial cyclotron radiation density, with respect to its equilibrium value.

Fifth word is the reflectivity of the wall.

Sixth word is the ratio of parallel kinetic energy to total kinetic energy. Default is 1/3 which is the value for a Maxwellian distribution.

14. Coulomb logarithm card (required when scattering transfer matrix is used).

CLOG 1 2 3.00

First word must be "CLOG".

Second and third words are species numbers involved in the collision.

The order of these words is not important.

Fourth word is the value of $\tan \psi$. See explanation below.

Coulomb logarithm (Ref: Spitzer, p. 122 and 127).

If two particles collide with a relative speed u and an impact parameter p , then the angular deflection, χ , of each particle is given by

$$\chi = \pi - 2\theta$$

where

$$\tan \theta = \frac{Mpu^2}{Z_1 Z_2 e^2}$$

where M is the reduced mass.

Coulomb logarithm, $\ln \Lambda$, is defined by

$$\ln \Lambda = \ln \left(\frac{\rho_m}{\rho_0} \right)$$

where $p_0 = \frac{Z_1 Z_2 e^2}{m_1 w_1}$ is the impact parameter for the lighter particle

to be deflected through 90° in the center of mass system with m_1 as the mass of the lighter particle and w_1 its speed in the center of mass system and p_m is the impact parameter beyond which the Coulomb field is screened. p_m is usually taken as the Debye length

$$p_m = \left(\frac{kT}{4\pi n_e e^2} \right)^{1/2} = 6.90 \left(\frac{T}{n_e} \right)^{1/2}$$

Now suppose that one wishes to do the scattering explicitly above a certain angle, θ_c , then

$$\ln \Lambda = \ln \left(\frac{p_m}{p(\theta_c)} \frac{p(\theta_c)}{p_0} \right)$$

and so the $\ln \Lambda$ one wants to use in doing implicit Fokker Planck scattering is

$$\ln \Lambda = \ln \left(\frac{p_m}{p(\theta_c)} \right) = \ln \Lambda - \ln \left(\frac{p(\theta_c)}{p_0} \right)$$

Now $\theta_c = \pi - 2\psi$ so that

$$\tan \psi = \tan \frac{\pi - \theta_c}{2}$$

So for $\theta_c = 20^\circ$, $\tan \psi = \tan 80^\circ = 5.67$.

Thus if the explicit consideration of elastic scattering between particle species 1 and 2 is cutoff at 200° the CLOG card has the form

```
CLOG      1      2      5.67
```

In fact, in order to avoid numerical problems, the explicit high angle scattering is not cut off sharply at θ_c but rolled off by the factor

$$\frac{1}{(1 - \cos \theta)^2 + \lambda_0^2}$$

where $\lambda_0 = 1 - \cos \theta_c$.

This factor is used in generating Rutherford cross-sections for inputs of transfer matrix generator. In particular λ_0 is the 2nd parameter of the "SET" statement, discussed in the RNUXN input file. For $\theta_c = 20^\circ$, $\lambda_0 = 0.060307379$ and using 9 Legendre polynomials involved in the fit, the "SET" card is

```
SET    9    0.060307379
```

When the integral is done to get the total cross-section, the effects of a cut-off and a roll-off are identical for the Rutherford component.

Note: The CLOG card must be consistent with the SET card when scattering transfer matrices are used. There should be no CLOG card if there is no scattering transfer matrices used.

III. HOW TO EXECUTE FOKN-C.

Suppose the latest compiled version of FOKN-C is called RFOT29 and the problem one wishes to run in called WWDT1. Before execution of FOKN-C, one needs to have the problem generator file (FOKN-C input file) for WWDT1. Usually the name of the problem generator file is the problem name with a "G" added at the end. In this case the problem generator file is WWDT1G. Also all the transfer matrices to be used in the problem must be on line. To execute FOKN-C, the execute line is:

```
RFOT29  WWDT1  WWDT1G  options / TV
```

First symbol is the latest version of FOKN-C.

Second symbol is the name of the problem to be run.

Third symbol is the name of the problem generator or G.

A list of options follows (discussed in the following section).

"T" and "V" have the usual meaning of time and value as used in the NMFECC computer system.

Note: In order to insure the program to run, "T" must be ≥ 1 minute. Program will stop when time left is about one minute.

Options for the execute line.

If there is not list of options in the execute line, all outputs go immediately to FR80 (microfiche) when the program stops.

1. S - Suspends program and waits for instructions from teletype.
2. K - Keeps numerical output so that it will not be sent by the program when the program stops running. Numerical output files have names like HX ----- A for HSP and FXRAD----- for FR80.
3. P - Sends numerical output to on-line printer rather than FR80.
4. H - Sends numerical output to High Speed Printer (HSP) rather than FR80.
5. KD - Keeps DD80 (graphics) output so that it will not be sent when program stops running. DD80 output files have names like DX-----AY.
6. DD - Send DD80 output to white paper output rather than microfiche.
7. Decimal number L (e.g. 40000L) - Specifies the size (number without the L) of storage of the program so that the program may run more efficiently. Default is 40000B.

8. NOFOK - Will not use the relativistic Fokker-Planck subroutine (RFOKP).

To restart a problem:

There are two ways to restart a problem. Suppose one wishes to restart a problem named WWDT1, one needs either the drop file or the Z file. If the drop file is available (i.e. +WWDT1), then the problem can be restarted by the line

+WWDT1 / TV.

If the Z file (i.e. WWDT1Z) is available, then the problem can be restarted by the line

RFOT29 WWDT1 / TV.

Suppose the program is finished due to no time left in the machine, the program can be restarted by typing first

RFOT29 WWDT1 S / TV

and then change parameter 7 to 6 by typing

6.

TTY options while running FOKN-C:

1. T (Carriage Return) - Reports cycle number, time, time-step, species number and group which limit the time step, and number of iterations.

2. S (carriage return) - Suspends program.
 S (carriage return) (again) - Program will run one more cycle and suspends.
 S number (carriage return) - Program will run the specified number of
 cycles before suspension.
3. G (carriage return) - Gets the program out of suspension and lets it run.
4. ED (carriage return) - Asks the program to make an edit.
5. FIN (carriage return) - Terminates the program.
6. D (carriage return) - Asks the program to make a dump.
7. P parameter number value (carriage return) - Will change the specified
 parameter to the specified value.
8. Species number (carriage return) - Outputs the energy density, number
 density, and temperature of the specified species on TTY.
9. Species number group number (carriage return) - Outputs the number
 density of the specified group and species on TTY.

IV. HOW TO PREPARE TRANSFER MATRICES FOR FOKN.

The latest version of the program which generates transfer matrices
 for FOKN-C is RNUX3.

Suppose the input data file is I2DDEL. To execute RNUX3, type

```
RNUX3  I2DDEL  options / T V
```

First word is RNUX3 which is the latest version.

Second word is the input data file.

A list of options follows (discussed in the following section).

"T" and "V" have the usual meaning of time and value as used in the NMFECC computer system.

Execution options.

If there is not list of options in the execute line, default is FR80 so that all outputs are in microfiche.

1. K - Keeps numerical output.
2. KD - Keeps DD80 graphical output.
3. DD - Sets up DD80 graphical output for white paper output.
4. P - Sets up numerical output for the on-line printer.
5. H - Sets up numerical output for the high-speed printer (HSP).

Note: While RNUX3 is executing, type "carriage return" on the teletype will print out the pair of group numbers being processed.

To restart, one must use the drop file (file ended with a "+").

For example, to restart I2DDEL, simply type

I2DDEL+ options/ T V

RNUX3 input file.

Each card has at most 12 input words per line of at most 10 characters each.

All input formats are field free.

First card of the input file must be an identification card.

1. Identification card (required, must be the first card)

BOX ,--- ,-----

First word must be "BOX".

Second word is the box number.

Third word is any name for identification.

2. Comment cards (optional).

C ^-----

First word must be "C".

The rest could be anything up to 11 words.

3. Nuclear reaction identification card (required).

NUC 30 0. 10000 T2DDEL EEBREM

First word must be "NUC".

Second word is the identification number (S99) for the nuclear reaction, i.e. D-D elastic scattering in this case.

Third word is the Q-value of the reaction in MeV.

Fourth word is the number of MONTE CARLO particles per pair of groups.

Fifth word is the name of the transfer matrix for the reaction.

Sixth word (optional) can be anything but zero to indicate e-e bremsstrahlung is being done. Default is zero.

4. Material card (required).

There must be at least 4 material cards. The first two materials are reactants with the first one as the beam and the second one as the target. The last two materials are products with the first as the one whose center of mass angle is specified on 9 (THET) cards.

```
M      1      1.67E-24      1      35      NODEP
```

First word must be "M".

Second word is the charge number of the species.

Third word is the mass of the species in grams.

Fourth and fifth words are the first and last groups, respectively, to be set up by the ULIN and ULOG cards.

Sixth word (optional) can be anything but zero to indicate that the species is not deposited in plasma. Default is zero.

5. Group structure cards (required).

ULIN and ULOG cards. They are the same as those for FOKN. See section on FOKN input file.

(Note: The group structure as inputted here must be compatible with that set up for FOKN in order for FOKN to use the transfer matrices generated under this group structure.)

6. Cross-section fit card (required, must precede THETN and SIGE cards).

```
SET      9      .060307379
```

First word must be "SET".

Second word is the number of Legendre polynomials used for fitting the cross sections. "9" is the maximum number of Legendre polynomials allowed.

Third word is the Rutherford roll over parameter, x_0 .

$$x_0 = 1 - \cos \theta_c$$

where θ_c is the cut-off angle. See section on CLOG cards for FOKN input file. θ_c as used in SET card must be consistent with θ_c as used in CLOG card for FOKN.

7. Scattering angle card (required, must precede SIGE cards).

THETN 0. 10. 20.

First word must be "THETN".

The rest are scattering angles in center of mass system for the first product in degrees. If there are many angles, THETN card could be continued by

THET 70. 80.

Note: Continuation cards for THETN cards start with THET instead of THETN.

8. Differential cross-section cards.

The differential cross-sections corresponding to the angles in the THETN cards at different energies are inputted by the SIGE cards.

SIGE 0.300 31647. 31437

First word must be "SIGE".

Second word is the beam energy in lab system in MeV.

The rest are differential cross-sections at the specified energy corresponding to the angles in the THETN cards in mb/ster. The SIGE cards can be continued by

SIG 9325.

Note: Continuation cards for SIGE cards start with SIG instead of SIGE.

9. Total cross-section cards (SIGN cards).

THETN 0.

SIGN .094 .05 1.

First word must be "SIGN".

Second word is the beam energy in MeV in lab system.

Third word is the total cross-section in mb at the specified energy.

Fourth word (cross-section at 0 degrees) with a value of 1. signifies that the cross-section is isotropic and to be normalized to total cross-section.

Note: If the reaction is not isotropic, then the relative importance at different angles must be indicated and the result would be automatically normalized to total cross-section. For example:

THETM	0.					
THET	30.	60.	90.	120.	150.	180.
SIGN	10.	44.	1.			
SIG	.41	.44	.27	.25	.43	.56

10. Resonance well card (required if the reaction has 3 products).

Q2 2.9 1.1

First word must be "Q2".

Second word is the position of the resonance well in MeV in lab system of the secondary product state.

Third word is the half-width in MeV.

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