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**CONTINUED DEVELOPMENT OF MODELING TOOLS
AND THEORY FOR RF HEATING**

Final Report for Grant Number DE-FG05-91ER54129

September 1, 1998

**Prepared by:
David N. Smithe
Mission Research Corporation
8560 Cinderbed Rd., Suite 700
Newington, VA 22122-8560**

**Prepared for:
Department of Energy
Oak Ridge Operations Office
P. O. Box 2001
Oak Ridge, TN 37831**

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INTRODUCTION

This report, assembled nearly seven years after the completion of work, has been prepared to meet the requirement of a final report, so that the grant may be formally closed out. The work performed during the grant has been reported long before this date, specifically in:

- 1) the grant's annual performance report for 1991, MRC/WDC-R-277,
- 2) the published **AIP Conference Proceedings #244, Radio Frequency Power in Plasmas, Charleston, SC 1991**, "Evaluation of Wave Dispersion, Mode-Conversion, and Damping for ECRH with Exact Relativistic Corrections," by D. N. Smithe and P.L. Colestock, and *-Removed for separate processing*
- 3) an unpublished paper entitled "Temperature Anisotropy and Rotation Upgrades to the ICRF Modules in SNAP and TRANSP," presented at the 1992 ICRF Modeling and Theory Workshop, at the Princeton Plasma Physics Laboratory. *-Removed for separate processing*

This final report contains copies of all three. The specifics of the grant's final months' activities, which have never been reported to the DOE, to the best of my recollection, are as follows. The original grant, which was to terminate August 15, 1991, was extended without additional funds to October 31, 1992. The primary reason for the extension was to permit attendance at the 1992 ICRF Modeling and Theory Workshop at the Princeton Plasma Physics Laboratory (PPPL), which was finally held August 17-18, 1992, after having been rescheduled several times during the summer of 1992.

As reported in the 1991 annual performance report, MRC/WDC-R-277, the work was largely completed by January 1992, with 90% of Task 1 complete, 70% of Task 2 complete, Task 3 satisfied, and Task 4 no longer being possible due to personnel changes at ORNL. At about this time in early 1992 it was decided that the remainder of the work should be completed, with the proviso that sufficient funds be left remaining to attend the workshop later in the year. That is exactly what was done.

The additional work performed, as reported in the workshop paper, pertains to Task 2:

- 1) the upgraded RF-heating program was inserted into the TRANSP code, in addition to its previous use in the SNAP code,
- 2) additional TFTR case studies were performed, utilizing the new rotation upgrade to the dielectric tensor, and
- 3) collaboration and assistance was provided to PPPL personnel in the use of the upgraded tools.

The body of this report contains copies of the 1991 annual report, which gives detailed discussion of the work accomplished, and a copy of the 1992 workshop paper, which discusses the remainder of work performed after the 1991 report came out.

BODY

- 1) Copy of 1991 Annual performance report, detailing most of the work completed.
- 2) Copy of the 1992 workshop paper, documenting additional work after 1991.

Annual Performance Report for DOE Grant DE-FG05-91ER54129

SECTION 1

EXECUTIVE SUMMARY

MRC is nearing completion of the specified tasks of the "Continued Development of Modeling Tools and Theory for RF Heating" project. The start date of the grant was August 15, 1991, about six months ago, hence this "annual report" covers only a six month period. The end date of the grant is August 14, 1992, about six months from now. As of January 31, 1992, 72.4% of the contract was expended. The technical progress of the contract towards successful completion of the specific tasks outlined in the grant proposal is consistent with the expenditures. The following tasks are either successfully completed or nearing successful completion.

- 1) Modeling for Relativistic ECRH, which utilizes a fully relativistic treatment of the RF - plasma interaction for electrons. Results of this study provide a correct picture of the absorption of RF power due to electron cyclotron resonance, and also Landau damping and TTMP, when the phase velocity of the RF waves is near or above the speed of light, a common occurrence both in Electron Cyclotron Resonance Heating and in the Fast Wave Current Drive experiments discussed below. This study also provided an improved picture of the mode couplings between the fast, slow, and Bernstein waves at the cyclotron and upper hybrid resonances.
- 2) Anisotropic Temperature and Rotation Upgrades, which provides to the SNAP and TRANSP RF modules a more advanced plasma description capability. The modeling codes now distinguish between perpendicular and parallel temperature, and allow for plasma rotation. These features are especially important for Ion Cyclotron Resonance Heating (ICRH), where hot ions are created with almost entirely perpendicular energy, and especially important for TFTR, where Neutral Beam Heating can spin up the plasma so that rotation velocities are comparable to the plasma thermal speeds.
- 3) Further Documentation of SHOOT and SPRUCE, which has provided additional writeups of the SNAP RF module (SHOOT) for an extensive review article on the SNAP code, currently in progress by PPPL staff member Dr. H.

Towner, and a writeup, at the request of PPPL staff member Dr. G. Hammett, of the TRANSP RF module's (SPRUCE's) technique of reducing the vector Maxwell equation to a scalar equation for $B_{\parallel}$, while still retaining the physics of the complete dielectric tensor.

A single adjustment to the original proposed work appears to be likely. This involves the proposed Task 4, in which technical expertise was to be provided to Oak Ridge National Laboratory's (ORNL) effort to install the parallel gradient dispersion function into the Brambilla full-wave RF modeling code. The personnel at ORNL tasked to perform this function was given new activities, so that this project is unlikely to be initiated prior to the expiration of this grant. Upon consultation with PPPL staff members, principally Dr. C. K. Phillips, the effort, albeit small, which Task 4 was to occupy will be reassigned to Task 2, if the ORNL project does not move forward.

Coordination with PPPL staff members also resulted in an emphasis on Task 2, which consisted of Anisotropic Temperature and Rotation Upgrades to the RF modeling modules in the SNAP and TRANSP data analysis and tokamak simulation packages. This resulted in a slightly more advanced model of temperature anisotropy than originally anticipated being added to the SNAP package. Nevertheless, the emphasis on Task 2 has been accomplished without jeopardizing the successful completion of Task 1, Relativistic Treatment of ECRH, and submission of the results of this task to a technical journal will proceed as planned.

An unexpected benefit from Task 2 is that the relativistic treatment of ECRH is also perfectly valid for electron Landau damping and Transit-Time Magnetic Pumping (TTMP) of RF waves with phase velocities near or exceeding the speed of light. Considerable interest in such RF waves, in the Ion Cyclotron Range of Frequencies (ICRF), has recently been concentrated on proposed methods of driving steady-state currents in tokamaks. A renewal proposal of this grant has been submitted which includes a possible installation of the relativistic dispersion function employed in Task 2 into the SNAP and TRANSP modules as part of an overall effort to endow the PPPL RF modeling codes with fast-wave current drive (FWCD) diagnostics.

The following summary indicates the progress towards the successful completion of the grant proposal's original four tasks as of January 31, 1992.

Task 1: 90% completed. Remaining work consists of preparing and submitting the results to a technical journal.

Task 2: 70% completed. Remaining work consists of further testing and characterization of installed temperature anisotropy and rotation models in the SNAP and TRANSP packages.

Task 3: Satisfied. Specific requests for additional documentation of the SNAP (SHOOT) and TRANSP (SPRUCE) codes have been satisfied.

Task 4: See above. Requests for technical expertise were not made due to redirected efforts at ORNL.

The following sections detail the progress made in each of the specific tasks.

SECTION 2

Task 1: Modeling for Relativistic ECRH

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Appendix A contains a paper that was presented at the 9th Topical Conference on Radio Frequency Power in Plasmas, in Charleston, South Carolina, during August of 1991, and will be published in the AIP Conference Proceedings series. This paper will be augmented with further dispersion relation studies performed during this contract and will submitted to a technical journal, probably *Physics of Fluids*, before the expiration of this grant.

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SECTION 3

Anisotropic Temperature and Rotation Upgrades

3.1 *The Upgraded Dielectric Tensor*

The most important feature of the Anisotropic Temperature and Rotation Upgrades is the use of a more general linear dielectric tensor in the Maxwell wave equation. Formulas for the more general tensor were readily available in existing literature, however, because of the complexity of the formulas, each authors formulas generally appeared quite different from the others. In addition, broad summation rules can be used to convert terms into radically different forms, which, of course, have the same actual numeric value. When choosing these forms, it is important to note that there is often cancellation of large numbers between positive and negative harmonic terms, particularly in the off-diagonal tensor elements. There can also be cancellation of large numbers between an unsummed term and the entire summation. When implementing the new formulas for the dielectric tensor into the existing modeling packages, forms were chosen to avoid cancellation of large numbers that depend on the complete summation of harmonics. It is still necessary, though, that when using these forms, both positive and negative harmonics be summed.

Ultimately chosen was the complicated dielectric tensor from the reference, "Hot Plasma in a Cylindrical Waveguide," by D. Gary Swanson, in *Physics of Fluids* 10 (1967), pg. 428. The primary reason for this was Swanson's choice of tensor elements, which coincided exactly with the coefficients of the six independent tensor basis elements for an arbitrary physical quantity that has knowledge of two directions in space (e.g., the direction of B_0 and the direction of k). Because the full-wave analysis must deal with an arbitrary direction of k , these same coefficients arise naturally in the computational algorithms. Use of other references would have led to intermediate steps to make alternative tensor elements compatible with the requirements of arbitrary spatial orientation.

A summary of the formulas used is contained in Appendix B. The formulas appear different from the original reference in two ways. They are longer because certain secondary variables have been written explicitly. They are generally neater, because of manipulations performed on certain terms which were summable directly, or canceled altogether. In particular, most of the new anisotropy and rotation terms can be included into a factor, P_n , which is common to all of the tensor elements. It is possible that this fact has never been noticed before. It clearly made implementation of the formulas into the FORTRAN source code much simpler and more reliable. To verify the formulas, considerable manipulation was performed to arrive at forms identical to

that found in a second reference, *Theory of Plasma Waves*, by Thomas Stix (McGraw-Hill, New York, 1962), with one exception which is detailed in the Appendix.

3.2 Additional Features of the Anisotropy Model

Because of the emphasis placed on this particular task, additional features were added to the model in SNAP to more completely account for temperature anisotropy. This primarily included features meant to calculate an estimated perpendicular / parallel partitioning of the stored energy in the RF tail population, so that diamagnetic and energy transport could be more accurately treated by SNAP. In addition, the partition is used to more accurately model the absorption of the RF onto the tail population.

The basis of SNAP's RF quasilinear energy deposition model is an isotropic Stix-type calculation (*Nuclear Fusion* 15, 1975, pg. 737; specifically the analysis contained in Sections 12 through 16) of the ion velocity distribution function. The solution for the velocity distribution function remains isotropic. However, theoretical modeling formulas (G. Hammett, PhD thesis, Princeton University, 1986) were used to estimate the partitioning of parallel and perpendicular stored energy in the tail, to improve the modeling of the tail population in the dielectric tensor. The conceptual basis of these theoretical formulas is that the perpendicular to parallel energy ratio goes roughly as v_{slow}/v_{pitch} , where v_{slow} is the slowing-down collision frequency and v_{pitch} is the pitch angle collision frequency. For energetic particles (> 100 keV) this ratio is quite large, on the order of 1000, but for thermal particles, this ratio is much closer to unity. Thus this model incorporates important nonlinearity with regard to the total RF power being absorbed.

In addition, improvements to the basic model were made to account for the trapped particle effect whereby perpendicular energy is converted to parallel energy due to the mirror forces along a banana orbit. Thus, the tail population is given a poloidal variation in the ratio of perpendicular to parallel stored energy when calculating the dielectric tensor, and the tail populations' perpendicular and parallel stored energies are properly averaged over the drift surface before they are returned to SNAP.

To calculate collision frequencies (Coulomb collisions only), formulas are employed from the *NRL Plasma Formulary*, by D. L. Book, 1987 Revised Edition, and include exact Error Function evaluation, and include summation over all species, regardless of which species is the major contributor to collisions.

Three examples from test cases utilizing the advanced modeling features are included in the following pages. These examples are based on TFTR geometry, with a plasma of central electron density $n_e = 5 \times 10^{13} \text{ cm}^{-3}$, composition 97% deuterium and 3% hydrogen, all background central temperatures of 5 keV, center magnetic field around 2.7 Tesla, and 3 MWatts of RF at 47 MHz. The RF heating scenario is minority hydrogen and 2nd harmonic deuterium heating. The "minor radius" of the radial profiles in Figures 1-3 is actually the variable which indexes the poloidal flux surfaces, which are not concentric, since the plasma contains a 15 cm Shafranov shift, as illustrated by the dotted lines on the wave-absorption contour plots. The poloidal field of the plasma is derived from an assumed q-profile ranging from 1 on the magnetic axis to 5 at the plasma edge.

Shown are:

Figure 1. A typical run without the anisotropic temperature upgrade.

a) contour plot of RF wave deposition, b) radial profiles of perpendicular stored energy, and c) radial profiles of parallel stored energy. Note that ratio of perpendicular to parallel stored energy is exactly 2, for an isotropic plasma. The hydrogen tail stored energy is significant, effectively contributing an additional 1 keV to the hydrogen temperature of 5 keV. Plots b) and c) constitute an important input to the SNAP code, for purposes of evaluating energy confinement and MHD equilibrium of the plasma.

Figure 2. Same run as in Figure 1, but with anisotropy effects.

The radial profiles are seen to be narrower. The isotropic model improperly increased both perpendicular and parallel temperatures equally to account for the hydrogen tail stored energy, thus overestimating the Doppler broadening of the resonance due to the heated ions. The improved model increases the perpendicular temperature more to account for the actual velocity orientation of the majority of the tail ions. In this case, the hydrogen tail stored energy contributes an effective 5 keV to the perpendicular stored energy, which is greater than the previous figure because of the narrower resonance zone. The ratio of perpendicular to parallel stored energy of the hydrogen minority at the resonance layer is near 1000, yet the ratio of poloidally averaged stored energies, i.e., the ratio of curves b) to c), is only about 15. This value is smaller because the resonance layer is inside of the magnetic axis, hence the mirror forces along the particles' orbits convert perpendicular stored energy at the resonance layer to parallel energy, so that the surface averaged parallel stored energy is far greater than the parallel temperature at the resonance layer.

Figure 3. Run similar to Figure 2, except that the resonance is placed outside the magnetic axis.

Here there is no opportunity for the mirror forces to transfer tail perpendicular energy gains from the RF to parallel energy, because the resonant interaction is already on the low field side of the drift surfaces. The ratio of the flux surface averaged perpendicular to parallel stored energy for the hydrogen minority remains high, around 700. However, the picture is vastly different for the small deuterium tail pulled out by the 2nd harmonic resonance. On plot b) the deuterium stored energy is just barely off the zero mark, because of the large scale for hydrogen. A closeup would show it to peak at about 38 joules/m³, or just slightly greater than twice the parallel stored energy from plot c), i.e., the deuterium tail remains nearly isotropic because of the small amount of power absorbed by deuterium. Physically this is due to the fact that at low energies the pitch angle scattering and slowing down collision rates are comparable, while at high energies the slowing down collision rate is much larger than the pitch angle scattering rate. Thus, the stored energy anisotropy model accounts for the nonlinear changes to the tail ion population as the total amount of RF power is increased.

Testing of the anisotropy model is continuing, and evaluations of its ability to match the actual physical behavior of plasmas under intense RF heating are being made. Testing of the new model's ability to account for nonzero plasma rotation is just now beginning, and no examples are currently available.

Figure 1. A typical run without the anisotropic temperature upgrade.

a) contour plot of RF wave deposition,
b) radial profile of *perpendicular* stored energy,
c) radial profile of *parallel* stored energy.

The ratio of U_{perp} (plot b) to U_{par} (plot c) is exactly 2 for an isotropic plasma.

Figure 2. Same run as in Figure 1, but with anisotropic temperature.

- a) contour plot of RF wave deposition,
 b) radial profile of *perpendicular* stored energy,
 c) radial profile of *parallel* stored energy.

The ratio of U_{perp} (plot b) to U_{par} (plot c) is raised for an anisotropic plasma.

The power deposition profile is narrower because the effective tail parallel temperature is not artificially raised as in the isotropic case.

Figure 3. Run similar to Figure 2, except that the resonance is placed outside the magnetic axis.

- a) contour plot of RF wave deposition,
 b) radial profile of *perpendicular* stored energy,
 c) radial profile of *parallel* stored energy.

The ratio of U_{perp} (plot b) to U_{par} (plot c) is greatest for resonance outside the magnetic axis, since there is little mirror effect to convert U_{perp} to U_{par} .

The 2nd harmonic deuterium tail is very nearly isotropic because the small amount of power absorbed leads to low tail temperatures with nearly identical pitch angle scattering and slowing down collision rates.

SECTION 4

Task 3: Further Documentation of SHOOT and SPRUCE

Two activities have been completed which pertain to Task 3.

First, writeups consisting of computational and physical details of the RF module in SNAP was provided to Dr. H. Towner of PPPL, for the purpose of inclusion into an expansive review article on the SNAP code. A preview of parts of this article was presented at the 1991 Division of Plasma Physics of the American Physical Society (*Bulletin of the American Physical Society* 36 (9), 1991, pg. 2450, paper 7T10).

Second, a writeup detailing the mathematical manipulation involved in the SPRUCE code was prepared. This was done primarily at the request of Dr. G. Hammett of PPPL. The SPRUCE code is markedly different in its solution technique from most (probably all) other full-wave codes in existence. Because it serves as only one small piece of a quite large tokamak simulation code, TRANSP, a premium is set on its speed of operation. For this reason, it inverts a second order wave equation for only a single field component (B_z), rather than inverting a first order equation for two field components (E_θ and B_z , or E_θ and E_r), resulting in a speed-up factor of at least four. In doing so, it sacrifices no physics content, however it does result in added numerical difficulties for deriving the electric fields from B_z near cutoffs, because of the need to evaluate numerically the limit of a ratio of two quantities approaching zero. This writeup describes the mathematical manipulations involved in rewriting Maxwell's wave equations as a single scalar equation, and the special technique used to back out the electric field components near cutoff. This writeup is included in Appendix C.

SECTION 5

Remaining Activities

The following activities are expected to make up the remaining ~25% of the project. Except for the preparation of the final report in August 1992, and the RF Workshop at PPPL in May 1992, these activities are expected to be completed, and the project budget is expected to be expended at the end of February, 1992.

Task 1. Submit relativistic ECRH results to a technical journal.

Task 2. Complete testing of temperature anisotropy and rotation model.

Attend and present paper at the RF Workshop at PPPL on May 29, 1992 (1 day).

Prepare Final report (1-2 days).

APPENDIX A

ECRH Paper

This paper was presented at the 9th Topical Conference on Radio Frequency Power in Plasmas, in Charleston, South Carolina, during August of 1991.

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APPENDIX B

Upgraded Dielectric Tensor

The following formulation is based on "Hot Plasma in a Cylindrical Waveguide," by D. Gary Swanson, in *Physics of Fluids* 10 (1967), pg. 428.

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