Final Scientific/Technical Report

USDOE Award **DE-FG-02ER54684**

Recipient: CompX

Project Title: **Fokker-Planck/Ray Tracing for Electron Bernstein and Fast Wave Modeling in Support of NSTX**

Principal Investigator: Dr. R.W. Harvey

Period of Performance: 08/15/2002 through 11/14/2009

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Executive Summary

This DOE grant supported fusion energy research, a potential long-term solution to the world's energy needs. Magnetic fusion, exemplified by confinement of very hot ionized gases, i.e., plasmas, in donut-shaped tokamak vessels is a leading approach for this energy source. Thus far, a mixture of hydrogen isotopes has produced 10's of megawatts of fusion power for seconds in a tokamak reactor at Princeton Plasma Physics Laboratory in New Jersey. The research grant under consideration, ER54684, uses computer models to aid in understanding and projecting efficacy of heating and current drive sources in the National Spherical Torus Experiment, a tokamak variant, at PPPL. The NSTX experiment explores the physics of very tight aspect ratio, almost spherical tokamaks, aiming at producing steady-state fusion plasmas. The current drive is an integral part of the steady-state concept, maintaining the magnetic geometry in the steady-state tokamak.

CompX further developed and applied models for radiofrequency (rf) heating and current drive for applications to NSTX. These models build on a 30 year development of rf ray tracing (the all-frequencies GENRAY code) and higher dimensional Fokker-Planck rf-collisional modeling (the 3D collisional-quasilinear CQL3D code) at CompX. Two mainline current-drive rf modes are proposed for injection into NSTX: (1) electron Bernstein wave (EBW), and (2) high harmonic fast wave (HHFW) modes. Both these current drive systems provide a means for the rf to access the especially high density plasma --termed high beta plasma-- compared to the strength of the required magnetic fields. The CompX studies entailed detailed modeling of the EBW to calculate the efficiency of the current drive system, and to determine its range of flexibility for driving current at spatial locations in the plasma cross-section. The ray tracing showed penetration into NSTX bulk plasma, relatively efficient current drive, but a limited ability to produce current over the whole radial plasma cross-section. The actual EBW experiment will cost several million dollars, and remains in the proposal stage.

The HHFW current drive system has been experimentally implemented on NSTX, and successfully drives substantial current. The understanding of the experiment is to be accomplished in terms of general concepts of rf current drive, and also detailed modeling of the experiment which can discern the various competing processes which necessarily occur simultaneously in the experiment. An early discovery of the CompX codes, GENRAY and CQL3D, was that there could be significant interference between the neutral beam injection fast ions in the machine (injected for plasma heating) and the HHFW energy. Under many NSTX experimental conditions, power which could go to the fast ions would then be unavailable for current drive by the desired HHFW interaction with electrons. This result has been born out by experiments; the modeling helps in understanding difficulties with HHFW current drive, and has enabled adjustment of the experiment to avoid interaction with neutral beam injected fast ions thereby achieving stronger HHFW current drive. The detailed physics modeling of the various competing processes is almost always required in fusion energy plasma physics, to ensure a reasonably accurate and certain interpretation of the experiment, enabling the confident design of future, more advanced experiments and ultimately a commercial fusion reactor.

More recent work entails detailed investigation of the interaction of the HHFW radiation for fast ions, accounting for the particularly large radius orbits in NSTX, and correlations between multiple HHFW-ion interactions. The spherical aspect of the NSTX experiment emphasized particular physics such as the large orbits which are present to some degree in all tokamaks, but gives clearer clues on the resulting physics phenomena since competing physics effects are reduced.

Comparison of Actual Accomplishments with Goals and Objectives of the Project.

The project title summarizes goals and objectives: Fokker-Planck/Ray Tracing for Electron Bernstein and Fast Wave Modeling in support of NSTX. The goal was to apply, and further develop as necessary, the GENRAY ray tracing and the CQL3D Fokker-Planck codes (http://www.compxco.com) for prediction and interpretation of the NSTX experiment. The range of publications below supports that this was fully accomplished. A Google search on PI+NSTX, as below, reveals 1600 references, certainly many effective duplications, but almost all related to the present contract. Selected references below (29) evidence direct input from CompX codes, GENRAY and/or CQL3D.

Primary reporting on the project was through the NSTX research forums (presentation in 2003, 2004, 2005, 2007, 2008, 2009) and through publications in collaboration with NSTX team members as given in the list of publications below).

Summary of Project Activities for the Funding Period

The tight aspect ratio National Spherical Torus Experiment has a very small center-post region, as shown in Figure 1. This restricts the amount of toroidal current that can be electrically *induced* by transformer action in the machine giving, if this is the only current source, an inherently pulsed machine operation. The small center-post also restricts the confining toroidal magnetic field. However the advantage of the geometry is that it enables relatively high plasma pressure to magnetic pressure (beta) ratios and high intrinsic toroidal bootstrap current. In principle, it is possible to entirely sustain the toroidal current necessary for tokamak operation with 100% bootstrap current drive, giving a highly desirable steady state tokamak. For control purposes though, physics studies indicate that some of the toroidal current will need to be provided in addition to BSCD. Additional current drive by continuous injection of radiofrequency waves, provides a means to maintain the steady state. Given the plasma parameter regime that the device operates in, particularly the desired high plasma density which gives characteristic plasma frequency greater than cyclotron frequency, then, of many possible radiofrequency modes, there are two major preferred choices: electron Bernstein waves (EBW) and high harmonic fast waves (HHFW). Each has advantages and disadvantages for current drive and plasma heating purposes. Contributions of award ER54684 to these current drive systems for NSTX are reviewed below.

(A) High Harmonic Fast Wave Current Drive

The CQL3D Fokker-Planck code, along with GENRAY ray tracing, provides a comprehensive model for high harmonic fast wave (HHFW) power absorption and current drive within the plasma bulk. In the ECH current drive regime the calculations have been successfully benchmarked against experiment to the extent that the accurate current drive predictions enable further advances in the dependent physics, for example, tearing modes and radial transport. This level of confidence is sought for HHFW in NSTX. Initial applications to NSTX involved collaboration with Dr. Cynthia Phillips and graduate student Adam Rosenberg. Extensive benchmarking of GENRAY, which is needed for coupling to CQL3D, was conducted with Phillips and Rosenberg to ensure that the code provided an accurate basis for comparison with the NSTX experiment. Ultimately, good agreement was obtained with the Menard HPRT ray tracing code, as shown in Fig. 1. This provided confidence in further CQL3D/GENRAY modeling.

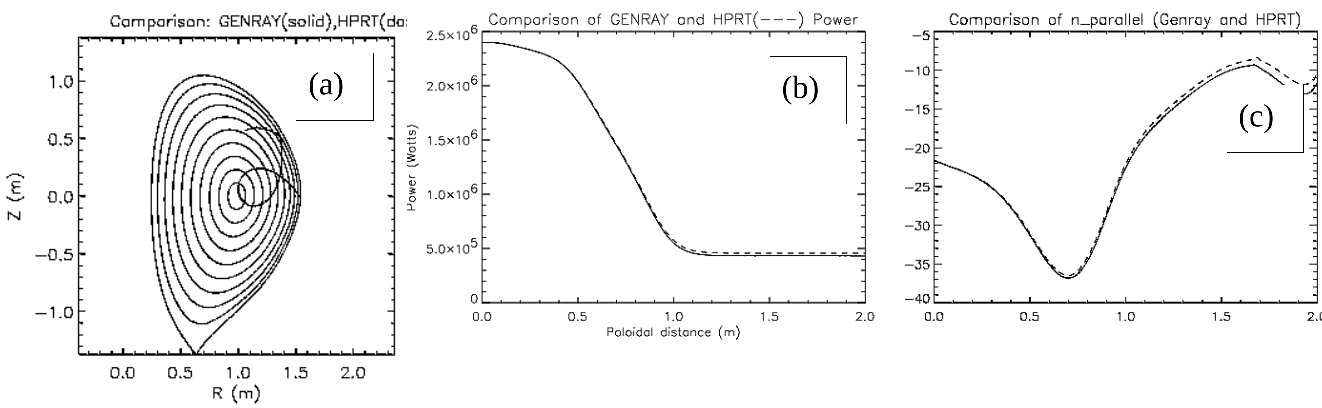

Fig. 1. Comparison between GENRAY and HPRT, verifying GENRAY for application within CQL3D. (a) Ray trajectories overlap for NSTX, (b) Power deposition along the ray on electrons and ions is nearly identical, (c) parallel refractive index variation agrees.

Working with Rosenberg and Phillips, good agreement was obtained between synthetic diagnostics in the CQL3D/GENRAY model and experiment. Model and experimental time-dependence of neutrons resulting from HHFW power agreed, indicating overall accuracy of this physics-based, no-free-parameter model. Agreement was particularly good for high toroidal mode number $n_\phi = 24$, as shown in Fig. 2. In this work, a discrepancy was found between modeling and experiment at lower values of toroidal mode number/parallel refractive index. On the basis of this, Rosenberg reported the results in an invited talk at the American Physical Society Fall '03 DPP Meeting, published results[3], and along with additional material, prepared his Ph.D. Dissertation for Princeton University[4].

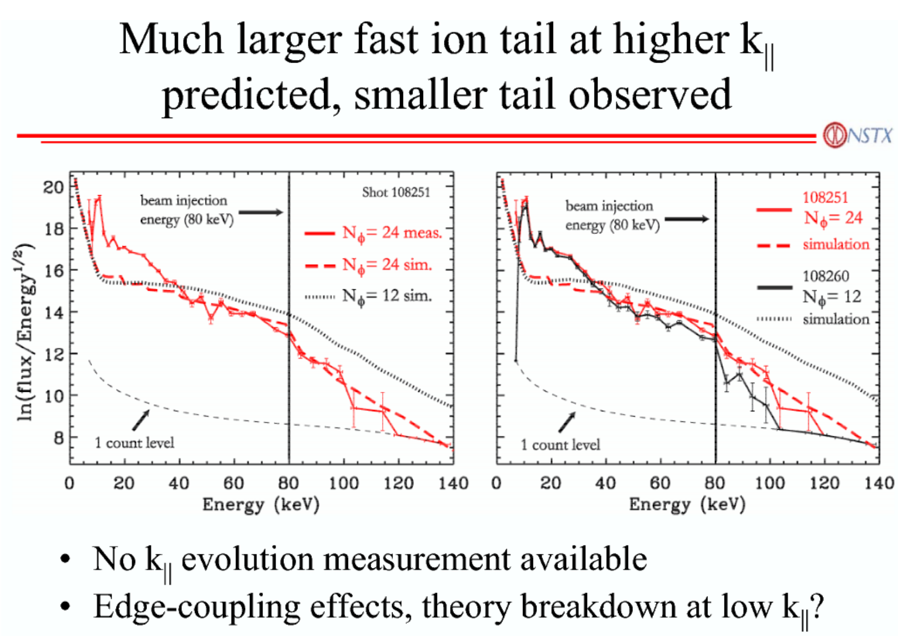

Fig. 2. Slide from Rosenberg invited talk at the APS/DPP Meeting, 2003, indicating a discrepancy at lower $n_{||}$ between CQL3D/GENRAY modeling of HHFW ion tail production and suggesting edge losses..

CQL3D/GENRAY distribution functions have been used in calculation of HHFW effects on NSTX MHD chirping modes[5].

More recently, comparison between CQL3D/GENRAY calculated neutrons production rates is being used as an indication of loss of coupling to the interior of the plasma at low-$n_{||}$ [6], as shown in Fig. 3. The CQL3D code is being further refined, to check that omitted physics effects such as finite ion orbit-width are not a major loss of energy: that is, finite-orbit losses, which can be accurately added to CQL3D, will provide modeling of additional losses, suggesting edge losses are not otherwise as large as could be inferred from Fig. 3.

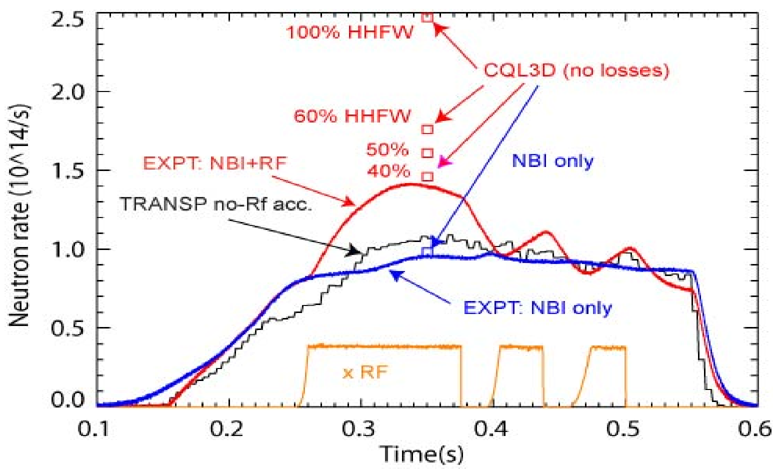

Fig. 3. The CQL3D code has combined neutral beam injection and HHFW quaslinear diffusion models, enabling a physics-based no-free-parameter calculation of combined NBI+HHFW distribution functions. A neutron rate synthetic diagnostic in the code thus obtains neutron rates, to compare with experiment. The above results indicate that only about 40% of the HHFW is being deposited in the bulk plasma [6].

The calculated ion distribution functions from CQL3D/GENRAY for NSTX NBI and NBI+HHFW shots have been combined with the FIDA (Fast Ion Diagnostic) calculation, for comparison with experiments. For these simulations, a long-standing restriction in CQL3D to three ion cyclotron harmonics was removed, enabling ion harmonics from 3 to 11 extending across the whole plasma cross-section, to be simultaneously simulated. The results[5] indicate that FI spatial distributions are broader than obtained with the zero-orbit-width CQL3D. A first order finite-orbit-width correction is being added to CQL3D, and this will undoubtedly resolve substantial uncertainty in prompt FI losses as a result of HHFW QL diffusion. However, there are important regions in velocity space where orbits extend from near the plasma center to the plasma edge. See Fig. 4, giving the guiding center and Lorentz force orbit for a 100keV deuterium ion, such as is produced by the HHFW in NSTX. This strongly supports development of a full finite-orbit-width CQL3D modification, proposed for future work in support of NSTX.

Further indication of the desirability of the full-finite-orbit-width Fokker-Planck calculation is clear from comparison of the ORBIT-RF finite orbit-width Monte Carlo simulations with CQL3D results[6]. An advantage of the CQL3D finite-difference approach over Monte Carlo methods is that statistical noise is eliminated, giving reliable computational results in much less computational time, and the dimensionality can readily be reduced to 3D (2-velocity/1-generalized-radius) by bounce-averaging.

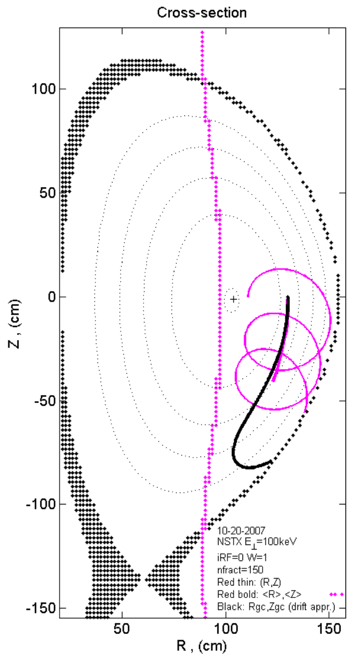

Fig. 4. Guiding center orbit(black) and the full Lorentz force gyro-orbit(magenta) for 100 keV deuterium ion in NSTX.

Transport modeling of NSTX using the TSC code, incorporating current drive estimates for EBWCD from CQL3D/GENRAY shows that a plasma which is completely sustained by non-inductive current can be achieved with 3 MW of HHFW and 3 MW of EBW power[7,8].

A primary goal for HHFW on NSTX is current drive, and recent improvements in coupling at low $n_{||}$ support that greater efficiencies can be achieved[9,10,11]. Phillips *et al.* [12] has successfully benchmarked full-wave and the GENRAY ray tracing codes against each other, to increase the reliability of calculated current drive and to enhance the interpretation of the HHFWCD experiments.

B) Electron Bernstein Wave Current Drive (EBWCD)

The NSTX device is designed to work at overdense conditions, where the usual lower hybrid and electron cyclotron current drive systems cannot drive current at positions substantially inside the plasma. There were preliminary indications that EBW CD would be useful under NSTX conditions. Earlier computational work by CompX in support of the University of Wisconsin Madison Symmetric Torus device had provided first toroidal geometry ray tracing/Fokker-Planck calculation of current drive by nonthermal electron distributions due to EBW [13]. MST is an alternative toroidal plasma geometry which operates in overdense conditions, and the modeling results indicated a level of credible modeling which was then applied to the NSTX tokamak. Under the present award, first tokamak ray tracing/Fokker-Planck calculations were applied to spherical tokamaks, in particular NSTX Device[14]. The GENRAY code was parallelized over rays, in order to speed up the otherwise computationally intensive, full, warm-plasma dispersion ray tracing.

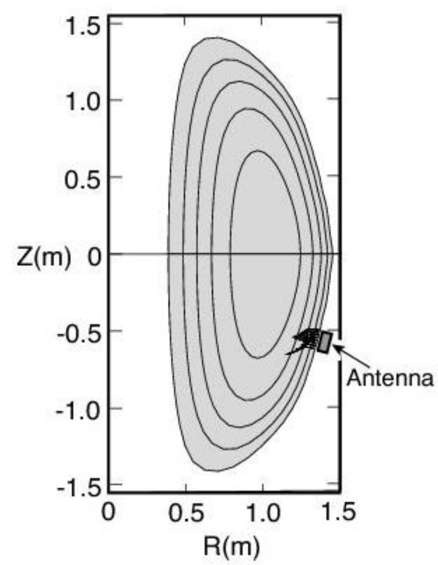

Fig. 5. Proposed location of NSTX EBWCD antenna, and inwards propagation of EBW until absorbed.

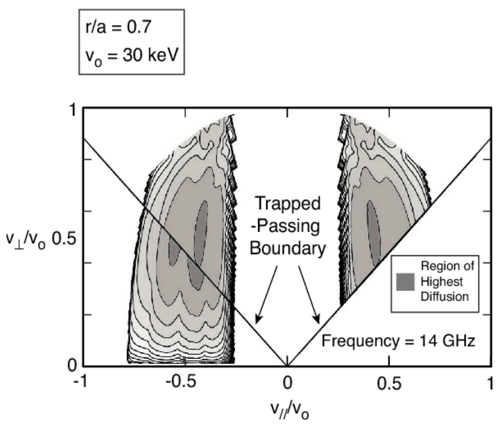

Fig. 6. The peak of the QL diffusion coefficient from EBW occurs near the trapped passing boundary, giving large Ohkawa current drive efficiency.

In Taylor *et al.*[14], a range of launch locations and wave frequencies were considered for NSTX. It was found that at 14 Hz, a frequency at which the necessary sources are available, that the target 100 kA of toroidal current can be driven with 3MW of launched power. Launch was off the midplane, as shown in Fig. 5, in order to obtain an $n_{||}$-variation compatible with current drive at the desired 0.7 of the minor radius. The current drive efficiency factor was 0.6, several times the maximum normally obtained by conventional electron cyclotron CD by O- or X-modes[15]. With GENRAY/CQL3D, this high efficiency was discovered to be due to dominance of the Ohkawa CD mechanism, involving enhanced trapping of electrons which removes transiting current carries in a given direction and giving a net electron current in the opposite direction. The conditions of EBW in NSTX turned out to be ideal for this type of CD. Fig 6 shows that the EBW diffusion coefficient in velocity space is maximum at the trapped-passing boundary, evaluated in the radial region of the peak current drive. The diffusion coefficient maximum occurs due to finite Larmor radius effects on cyclotron damping, modeled with the CQL3D full-Stix QL operator.

The initial observation that EBWCD under NSTX conditions relied heavily on the Ohkawa current was further examined by Harvey and Taylor[16]. An enhanced Ohkawa current due to EBW pitch angle scattering around the trapped-passing boundary also implies enhanced bootstrap current. The direct synergy with bootstrap current was determined to be not a large effect[16]. Another issue regarding the Ohkawa CD mechanism related to steepening of the density profile due to inward pinch of the additional EBW trapped particles. Toroidal momentum considerations lead to that the resulting additional bootstrap may counteract the Ohkawa EBWCD[16,18]. This raises very interesting new physics issues for Ohkawa CD, but also introduces uncertainty into the calculations.

The EBW modeling in GENRAY/CQL3D utilized the full warm-plasma nonrelativistic (NR) dispersion relation for the ray propagation, but the damping was based on fully relativistic calculation anti-Hermitian damping correction to the dielectric tensor. This approximation reasonably supposes that the EBW wave is carried mostly by the non-relativistic bulk plasma, but the electron cyclotron damping in the tail of the distribution giving the anti-Hermitian dielectric contribution should be treated relativistically. Questions arose as to the accuracy of this approximation. A fully relativistic (A. Ram) dielectric tensor was installed in GENRAY under this contract and applied to the even hotter ARIES-ST tokamak in order to discern if the present model was adequate[19]. Although ray paths differed somewhat, the overall effect compared to the above mixed-NR-thermal/relativistic-damping model was not significant at NSTX temperatures.

There are concerns about achievable efficiency for coupling EBW waves into the plasma. Experimental evidence of coupling efficiency can be obtained by comparison of the observed EBW emission from thermal plasma with what is expected at the otherwise known plasma temperature (by ECE and Thomson scattering measurements). By reciprocity, the amount by which the EBW radiation is depressed from thermal values gives the fractional amount of injected radiation that can be expected (at least linearly) to penetrate the plasma. Coupling efficiencies up to approximately 80% were found in some cases, compared to theoretically expected value of ~65%[20,21]. However, in some higher edge density cases the coupling was indicated to be much lower, 20% of predicted[14].

The nonthermal emission calculation in the GENRAY code was generalized to include EBWE[22]. Application was made to NSTX, calculating nonthermal EBW emission as a diagnostic for quasilinear distortion of electron distributions arising from injected EBW power[23]. The results exhibited an interesting, very wide range of EBWE phenomena resulting from the poloidal dependence of observation points, very strong $n_{||}$-variation of EBW rays, and harmonic overlap.

The above theoretical and experimental studies indicated areas of uncertainty with regard to EBWCD. Consequently, the EBWCD program for NSTX, the EBWCD program was deemphasized in 2008 for NSTX in favor of the HHFW program which is making good experimental and theoretical progress.

Coupling GENRAY and CQL3D to the TRANSP code

Harvey has visited PPPL for direct collaboration with Drs. D. McCune and Keshavamurthy Indireshkumar with the aim to couple the GENRAY and CQL3D codes to the PPPL TRANSP transport code through the McCune Plasma State software. The PS coupling has been carried ou in 2007, and the initial coupling of GENRAY to TRANSP has been accomplished[24].

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Google of PI name plus NSTX ("R.W. Harvey", NSTX, or alternatively, "Harvey, R.W.", NSTX) gives about 1600 references, most representing work related to this contract. Besides the PI, four additional scientists have been partially supported with the present Grant. Some of the resulting publications are listed below.

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