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**PROGRESS REPORT OF THE PROPOSAL "STUDY OF
PLASMA ROTATION IN TOKAMAK CONFINEMENT"**

(June 1, 1997 -- February 28, 1998)

GRANT NUMBER: DE-FG03-97ER54416

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INSTITUTION: Prairie View A&M University

1. Summary of the research performance:

This proposal is a collaborative project between Prairie View A&M University and Princeton University. The proposed tasks have been established based on close collaboration between two institutions. We studied the tasks in two aspects: analytical theory of drift current in tokamak plasmas, and computer simulation of non-neutral plasma. Some preliminary results have been presented in the 1997 APS Division of Plasma Physics Meeting, Pittsburgh. Titles of the presentations were "Magnetic Moment of Bounce Motion in Tokamak Plasma" and "Numerical Simulation of Plasma Confinement in a Non-neutral Plasma". The papers for publication are in preparation.

In the coming year, we will further develop the analytic theory and simulation studies. The studies will be focused on understanding of edge electric field in TFTR experiments, and attention will be paid to the effect of the α particles resulting from DT fusion reactions. In addition, in order to establish a stronger fusion plasma research and education base at Prairie View A&M University, we plan to expand our current theoretical project into a coupled theoretical/experimental project. With the help of Oak Ridge National Lab we plan to build a plasma physics laboratory equipped with a small mirror machine.

For the second year budget of this proposal, including the funds for the previously proposed theoretical and the newly planned experimental tasks, we request a \$245,000 grant. A budget plan and its justification are included in this report.

2. Studies of particle drift and bootstrap current:

To start the task of investigating edge electric fields in tokamak plasmas, we have been working on the subject of particle drift motion and bootstrap current. A new description for particle drift based on the guiding field line motion, and an accurate calculation for bootstrap current are presented.

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We depict particle drift in a frame moving with bounce average drift velocity, in which a particle moves along a closed trajectory. Besides its banana shape projection on the poloidal cross-section, the trajectory has a projection on the magnetic surface which has a long narrow figure "8" shape. From this trajectory, we calculate the field-line distributed magnetic moment associated with the bounce motion, a new quantity recently introduced by the Principal Investigator of this proposal. Using this new quantity, the bootstrap current is expressed by the magnetization of plasma due to the bounce motion magnetic moment. The expression for the trapped particles is applicable to that of the transit particles by replacing a trapped particle by a pair of particles circulating in opposite directions.

In calculating the bootstrap current, we used the Clebsch coordinate system and plasma distribution function $F(\alpha, \beta, \mu, J)$, where α, β are the Clebsch coordinates of the magnetic field and μ, J are the first and second invariants of the particle motion. In an axisymmetric tokamak, α, β can be written as

$$\alpha = \frac{\Psi_{\text{pol}}^r}{2\pi}; \quad \beta = q\theta_f - \zeta$$

where Ψ_{pol}^r — poloidal flux, q — safety factor, and ζ — toroidal angle. Assuming circular cross sections of flux surfaces, θ_f is given as

$$\theta_f = \frac{rR_0 B_t(R=R_0)}{qB_p(\theta=0)(1+d\delta/dr)} \frac{1}{(R_0+\delta)^2-r^2} \left\{ \frac{[(R_0+\delta)d\delta/dr-r] \sin\theta}{R_0+\delta+r \cos\theta} + \frac{2[(R_0+\delta)-r d\delta/dr]}{\sqrt{(R_0+\delta)^2-r^2}} \arctan \frac{(R_0+\delta-r)\tan(\theta/2)}{\sqrt{(R_0+\delta)^2-r^2}} \right\}$$

where δ is the Shafranov shift. Use of the Clebsch coordinate system in this study is the first application of this coordinate system to a practical tokamak device, although it has been known as a very helpful tool for theoretical studies many years.

The total plasma current then is derived to be

$$\mathbf{j} = nq\bar{\mathbf{u}} + \mathbf{j}_{b||} + c\nabla \times \mathbf{M}_g$$

where $\bar{\mathbf{u}}$ is the averaged drift velocity over all particles, $\mathbf{M}_g$ is the magnetization vector due to gyro-motion, and

$$\mathbf{j}_{b||} \equiv -2q\mathbf{B} \int d\mu dJ \left[\frac{\partial}{\partial \alpha} \left(\frac{F\Delta\alpha}{\tau_b} \right) + \frac{\partial}{\partial \beta} \left(\frac{F\Delta\beta}{\tau_b} \right) \right]$$

The bootstrap current can be calculated by

$$\mathbf{j}_{bs} = \mathbf{j} - \mathbf{j} \cdot \hat{\zeta}$$

where $\mathbf{j} \cdot \hat{\zeta}$ is the current component along the toroidal direction.

We have completed all theoretical derivations on this subject, and all of the numerical calculations for particles trajectories and bounce-motion-magnetic moments. The trajectory projections, on poloidal sections and magnetic surfaces, and the components of the line density of magnetic moments are shown for trapped and transit particles respectively on two pages attached at the end of this report. The rest of this subject, including the calculation of the bootstrap current in tokamak plasmas and the work for paper publication will be completed before the end of June.

3. Computer simulation of non-neutral plasma:

In order to have a more comprehensive understanding of the role of the electron sheath resulting from the scrape off process of ions at the boundary of magnetically confined plasma, and the associate edge electric field in reducing the edge turbulence, we also conducted computer simulations of stability and transport in slab and cylindrical non-neutral plasmas.

In the simulation, a two-and-half-dimensional electrostatic particle model is employed for slab and cylindrical systems. The main magnetic field in the two systems is in the z-direction (ignorable coordinate), and the electrons are assumed to be guiding center particles while the ions follow full dynamics. Both cold and hot plasmas with and without rotational transform and magnetic shear are included. In the slab system, a plasma is bounded in the x-direction with conducting walls whose voltage is held at zero at both ends of the system

and pure electron sheaths exist at the two ends of a neutral central plasma. In the cylindrical system, a ring shaped sheath of pure electrons is assumed surrounding the neutral plasma.

The simulation for the two cases shows that in the absence of a rotational transform both cold and hot plasma support the instability leading to diffusion of core and edge plasma. In the presence of a rotational transform with or without a shear, the instability is found weakened substantially. Introduction of a plasma pressure weakens the instability somewhat but did not eliminate it. It is important in practical applications to consider coupling of the sheath electric field to the pressure-driven drift wave instability.

Scatter plots showing the time history of the sheath electrons in the slab system (x, y plane) at $t = 0, 8,000$, and $14,000$ (measured in the unit of the electron plasma frequency) are given in the attached sheet. It is clearly seen that the perturbations at the interface between the edge and core plasmas grow rapidly in time leading to mixing of the core and the sheath particles. The simulation for the slab system also shows that a hot plasma diocotron instability without a rotational transform indicates presence of ripples associated with the instability. On the other hand, with a finite $B_y = 0.01 B_z$ the instability is weaker as shown at $t = 8000$.

The simulation results for the cylindrical system also are shown in a figure attached at the end of this report. Again the presence of an edge electric field causes the edge electrons to rotate leading to a diocotron instability. Shown in the figures for a cold plasma without a rotational transform are scatter plots of the edge electrons at $t = 0, 4,000$ and $8,000$. Similarly but with a rotational transform $B_p = 0.01 B_z$ scatter plots are shown at $t = 4,000$ and $8,000$.

4. Experimental project:

For strengthening our fusion plasma research project and getting more students to be involved, we plan to build a plasma physics laboratory at Prairie View A&M University. The major equipment will be a small mirror machine. The mirror machine will be used for both research and education. The research will have components of basic plasma physics experiments, including plasma heating, pitch angle diffusion, and effect of electric field on the confined plasma.

The mirror machine we planned to build is different from the normal in two aspects: A very large ratio of vacuum chamber radius to its length, and two small caliber magnetic coils. The length and radius of the chamber will be about one meter; the radius of the magnetic coils is about fifteen centimeters. The magnetic field near the coils is roughly two

Teslas. RF waves will be used to heat the plasma, and poloidal limiters with electrical bias will also be included in the hardware. This fat mirror machine contains a new dimension — in radial, it will allow us to study not only the plasma confinement by mirrors, but also the transport of plasma crossing field lines. Particularly, by changing the voltages imposed by the limiters, the effect of electric field on the plasma transport can be studied.

Dr. Charles Bush of Oak Ridge National Laboratory (ORNL) will be the technical monitor of this experimental project. Dr. Bush is also an adjunct professor of Prairie View A&M University. In collaboration with him, an outline of the basic mirror machine has been made. We plan to finish the design of hardware (including magnetic coils, vacuum chamber, plasma source, RF waves, and diagnosis) and the simulation of plasma states within the first six months of the second year. In the following six months, we plan to obtain and/or fabricate, and then assemble and adjust the equipment. All work will be done with help of Scientists and Engineers from Oak Ridge National Laboratory.

5. The second year budget:

For the second year of the project, we request a \$245,000 budget. The part of budget for the theory component of the project remains the same as for the first year, \$145,000. An additional cost of \$100,000 is planned for establishing plasma experimental equipment, i.e. the small mirror machine. The \$100,000 cost includes \$10,000 for work by Oak Ridge National Laboratory.

The \$145,000 cost for theoretic studies includes funds of \$130,000 for work by Prairie View A&M University and \$15,000 for Princeton University. The \$130,000 cost of Prairie View A&M University is mostly personnel support, the Principal Investigator's quarter time, a full time effort by research scientist Dr. Yuri Petrov, and a graduate assistant. The travel cost is planned to cover two trips to scientific conferences and one trip to Princeton University. The \$15,000 cost for Princeton University supports the effort of Dr. Okuda on the simulation task.

The experimental project cost of \$100,000 is partially for personnel support — a half year technician, and partially for equipment. We plan to acquire the vacuum chamber and pumps, and some diagnostics devices from National Labs. The \$40,000 equipment cost will be used to purchase the mirror magnets and RF wave generators. The \$10,000 cost of Oak Ridge Lab is mainly for the Scientists' and Engineers' travels to Prairie View A&M University.

BUDGET PLAN
6/1/1998 -- 5/31/1999

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A. Personnel:		
Catalog I		
Principal Investigator (25%)		20,100
Research Associate (100%)		40,200
Lab Technician (50%)		17,000
Catalog II		
Graduate Associate		14,400
Fringe Benefits		
(23% for Stuff, 15% for Student)		19,900
Total Salaries and Fringe Benefits		111,600
B. Equipment		
Mirror machine's hardware		
(magnet, RF wave device, vacuum system etc.)		40,000
D. Travel		
(domestic travels)		3,300
E. Other Direct Costs		
computer software		1,800
publication and Page Charges		2,500
health Insurance		8,500
Total Other Direct Costs		12,800
F. Subcontract		
to PPPL		15,000
to Oak Ridge		10,000
Total subcontract Costs		25,000
TOTAL DIRECT COST		190,900
INDIRECT COST		
59% of Total Salaries		54,100
TOTAL PROJECT COST		245,000

CROSS-SECTION

SIDE VIEW (IN MOVING FRAME)

Trajectories of a trapped particle with different pitch angles in reference to a frame moving with bounce average drift velocity, and their corresponding magnetic moments.

CROSS-SECTION

SIDE VIEW (IN MOVING FRAME)

Trajectories of transit particle with different pitch angles in reference to a frame moving with the source average drift velocity, and the corresponding magnetic moments

Nonneutral plasma in slab system

without rotational transform

stability effect of rotational transform

hot plasma diocotron instability

Nonneutral plasma in cylindrical system

without rotational transform

without magnetic shear

with a magnetic shear