Final Technical Report on DOE grant DE-FG02-98ER54469 : "Centrifugally Confined Plasmas for Magnetic Fusion Energy"

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Institution : Institute for Plasma Research, University of Maryland
Principal Investigator : Richard F. Ellis
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1. INTRODUCTION

The purpose of the research funded under this study grant was to investigate the feasibility of a small scale experiment to test the concept of centrifugal confinement as a magnetic fusion energy scheme and to develop conceptual designs for important components of such an experiment. This work falls in the category of Innovative Confinement Concepts, as defined by the Office of Fusion Energy. The results of the funded work were very successful in that various studies were conducted which showed the concept to be viable and these studies led to design improvements. In addition, the major components of an experiment were identified and designed at least to the conceptual stage. In September, 2000 the Maryland Centrifugal Torus was funded for construction, in no small part because of the progress made during the time period reported here.

The centrifugal confinement concept for fusion is based on three principles:

- centrifugal forces from supersonic plasma rotation perpendicular to a strong magnetic field can provide effective confinement along the field
- the concomitant large velocity shear will suppress even macro-MHD instabilities
- the sheared rotation will heat the plasma via viscous dissipation

Technical progress was made in clarifying and quantifying these concepts and designing a cost effective experiment. Below we briefly describe each area of progress and the implications for the MCT project.

The Basic Configuration The essentials of the centrifugal confinement configuration begin with a main magnetic field which is a straight solenoid with axisymmetric mirror-like geometry at the ends. There is a cylindrical, conducting core which is electrically insulated from the outer vacuum wall. A radial electric field is applied by biasing the inner core at high voltage with respect to the outer wall. The electric field causes the plasma in the annulus to rotate azimuthally in the **ExB** direction. As a result of the rotation, there is a radially outward centrifugal force which has a component along the magnetic field that points toward the equatorial plane, forcing particles towards the midplane. If the rotation speed is supersonic, the centrifugal forces are strong enough to contain the plasma pressure against expansion along the field.

DISCLAIMER

2. THEORETICAL AND MODELING RESULTS

Particle Orbits : Ions are predicted to be confined along the open field lines by a centrifugal potential. If the Mach number is large, the centrifugal potential overpowers the mirror force potential – the usual mirror loss cone is closed by the centrifugal potential and the Hamiltonian resembles that of a bead on a wire. It can be shown further that there are no banana orbits if the toroidal magnetic field is zero. We developed a numerical drift orbit solver and confirmed these ideas, both without and with a toroidal magnetic field.

MHD Equilibrium: We solved the ideal MHD equilibrium equations analytically for a simple case and developed a much more complete numerical simulation code. Our calculations included both toroidal and poloidal magnetic fields as well as toroidal rotation. The essential physics is that along the field the parallel pressure force is balanced by centrifugal force, which is proportional to R^2, where R is the plasma radius at a point on a field line. Both the analytic and numerical models showed that large rotation velocities ($M>1$, where M is the ion mach number) lead to equilibria with plasma pressure concentrated at large R. Thus the experiment must have a) supersonic rotation and b) large radius at the center compared to the ends(large mirror ratio). These became major design points. Our equilibrium calculations have been done both without and with a toroidal magnetic field, B_T. We have shown that B_T does not make a difference to the pressure profile above.

MHD Stability : Because of the curvature of the magnetic field lines the plasma would be unstable to MHD interchanges for a purely poloidal (axial) magnetic field. However, the plasma rotation will have a radial profile and the resulting velocity shear can stabilize the interchanges. We completed MHD stability studies, both analytic and numeric, to test this idea. To summarize, MHD interchanges can be all but completely stabilized by velocity shear if one can achieve Mach numbers of the order of 3-5. Results also show, however, that along the way to stabilization with increasing Mach number there may be a residual wobble in the plasma. Because of these possibly weak residual instabilities we incorporated in our experiment a toroidal magnetic field to provide magnetic shear to stabilize the flute type modes. MCT was conservatively designed for a toroidal field of the order of the poloidal field. Theoretical studies also indicated that plasma elongation(length along B much larger than width across B) aids in velocity shear stabilization. MCT was designed to have large elongation.

Transport : Velocity shear in the system is so large that all plasma microinstabilities should be suppressed and the crossfield transport should be classical. The heat transport for the system will therefore be dominated by electron heat loss along the open field lines. However, the electrons are held in by the self-consistent electrostatic potential generated when they try to separate from the strongly, centrifugal confined ions. For large mach numbers the potential well depth goes as M^2. We developed a simple 0-D transport model for the reactor regime including a variety of effects and the results show that for Mach numbers $M \sim 4$-5, the Lawson Criterion can be exceeded (at $T \sim 20$ keV). The foregoing discussion pertains mostly to transport in reactor regimes.. The MCT capability for MCT. The main bank is designed to achieve $V \leq 20\text{kV}$, Energy ≤ 1 MJ, Flattop $\tau > 5$ ms.

Wall conditioning: we completed a review of wall conditioning. MCT will use ultra-high vacuum components (hard seals) and turbomolecular and cryo pump and we expect base pressures in the $1\text{x}10^{-7}$ Torr range or better. To reduce recycling and impurity influx during a discharge we will use: a)*electropolishing* of the major interior metal surfaces especially the vacuum vessel, the core, and the shaped liner ; b)*bakeout to 150°C*, which will be accomplished by conventional resistive heaters on the vessel - baking is vital for removing water vapor; c)*discharge cleaning* with both hydrogen and helium; d)titanium gettering if needed. Provision for these is included in the MCT design.

Expected Parameters : From our design, from considering previous experiments, as well as transport studies with the 0-D code we concluded MCT will operate in the following parameter range :

$B \sim 0.2 - 0.5$ T (midplane), 1-2 T (mirror throat) $B_T \leq 0.2$ T Applied Voltage ≤ 20 kV, Energy ≤ 1 MJ $p_0 \sim 1 - 10$ mTorr (hydrogen fill pressure in static mode)	$n_e = 10^{13} - 10^{14}\ \text{cm}^{-3}$ $T_e \sim T_i \sim 10\text{-}50$ eV $M_s \sim 3\text{-}5$ # Larmor radii across a ~ 40