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COMPUTATIONAL SIMULATION OF SPHEROMAK PLASMA HEATING

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Recent conceptual design studies in the U.S. and Japan underline the inherent attractive features of compact tori (CT) reactor systems. At the same time, considerable progress has been made in both experimental and computational demonstrations of the formation and gross stability of compact tori (especially spheromak) plasmas.

A general assumption involved in the conceptual reactor studies has been that a compact toroid can achieve thermonuclear-level temperatures without the use of auxiliary heating methods. Laboratory CT plasmas are still quite cold so heating has yet to be studied experimentally. The purpose of the present study is to help fill this "gap" by identifying some of the important questions connected with the heating of a spheromak plasma.

Computational simulations of the spheromak formation phase have taken advantage of a reduced set of one-fluid equations in which the pressure gradient and convective derivative terms in the momentum equation are dropped.⁽¹⁾ These assumptions are, of course, well justified for the formation of a cold, very low β plasma. In the heating phase, however, we are interested primarily in effects that are intimately related to cross surface convection, a significant pressure gradient, and a two-fluid (i.e., electron-ion) interaction. Hence, our approach in the heating study has been to develop and utilize a 1 1/2-D model⁽²⁾ in which poloidal flux profiles of electron and ion pressure are advanced independently (together with the

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equations for particle and toroidal flux conservation). This code (named SPTR for spheromak transport) makes use of arbitrary aspect ratio, integral transform solutions of Grad-Shafranov equilibrium equation to determine the 2-D spacial positioning of the poloidal flux surfaces within the plasma separatrix. These solutions are then coupled with a computational package that solves the 1-D ψ -dependent flux surface averaged moment equations for advancing the electron and ion temperatures and densities with time. The moment equations are self-consistently solved via a 4x4 block tridiagonal setup and the results are utilized in a 2-D repositioning of the poloidal flux surfaces.

From a heating standpoint, there are two features of the spheromak equilibrium solution that are quite noticeable--first, that current densities are $\sim 10\times$ greater than in a comparable tokamak equilibrium; and second, that the lack of hardware in the center of the plasma "doughnut" makes it possible to compress the plasma in the toroidal direction. Consequently, the computational model has been set up in a fashion that will allow simulation of both ohmic decay with a static applied field and/or adiabatic compression via a rapid buildup of the applied equilibrium field.

We have begun the study with an attempt to computationally simulate two of the small experimental plasmas presently under study (the PS-1c at Princeton⁽³⁾ and the Beta-II at Livermore⁽⁴⁾), and, particularly, to explain the observed clamping of electron temperature and rapid decay of the poloidal flux surfaces. Computational simulation of these experiments with a purely classical transport model and static applied fields predicts that the plasma should exist for times exceeding 100 μ s with temperatures approaching the 100

eV level--a behavior quite different from what is actually observed. To explain this discrepancy, we have considered several models that could account for enhanced losses. The first model, and the most likely candidate for explaining the early PS-Ic and Beta-II results, includes heavy impurity radiation. With a modest (.5% Fe, 1.5% O) impurity level we observe an electron temperature that is clamped at levels below 20 eV with complete poloidal flux surface decay occurring on a $\sim 30\mu\text{s}$ timescale. This is in line with actual experimental results. Plasma cleanup, of course, could remove such barriers.

With an eye towards future developments, we have also pursued two additional enhanced energy loss mechanisms--soft beta limit losses and resistive interchange transport. The soft beta limit model anomalously dumps energy from a flux surface region in which the increase in pressure gradient leads to a local violation of the ideal Mercier criterion. The resistive interchange model depicts a random walk transport across a locally braided magnetic field.

The ability to simulate a time dependent applied equilibrium field allows us to propose and study a combined heating scenario in which time-stepped adiabatic heating and ohmic heating are used to overcome enhanced losses of the type described above. Preliminary studies, for example, indicate that any of the above three temperature clamps could be overcome in a S-1 size plasma by means of a staged adiabatic and ohmic heating scenario. In fact, our earlier global studies of heating in a reactor-size spheromak indicated that an ohmic heating to ~ 1 keV followed by an adiabatic compression could tolerate significantly enhanced loss rates ($\propto 1/100\tau_E$ Bohm) and still lead to thermonuclear-level temperatures.⁽⁵⁾

In summary the examination of spheromak plasma heating provides a logical bridge between the present-day experimental studies of compact torus formation and the futuristic conceptual studies of the spheromak and moving ring reactors. In the near term, the work helps in understanding the temperature clamping in experiments and provides some insight into how to overcome this obstacle (e.g., via impurity cleanup). In the longer term, the work also provides some insight into other possible temperature clamping problems (i.e., soft beta limit and resistive interchange) and allows us to propose and study methods for overcoming them.

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