CONF-810606--33

CONFINEMENT REQUIREMENTS FOR OHMIC-COMPRESSIVE IGNITION OF A SPHEROMAK PLASMA

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The Moving Plasmoid Reactor (MPR) is an attractive alternative magnetic fusion scheme in which Spheromak plasmoids are envisioned to be formed, compressed, burned, and expanded as the plasmoids translate through a series of linear reactor modules(1). Although auxiliary heating of the plasmoids may be possible, the MPR scenario would be especially interesting if ohmic decay and compression alone is sufficient to heat the plasmoids to an ignition temperature. In the present work, we examine the transport conditions under which a Spheromak plasmoid can be expected to reach ignition via a combination of ohmic and compression heating.

Simple estimates of the effectivess of ohmic heating in a Spheromak plasma can be obtained by writing the power balance in the form

$$\frac{W_M}{\tau_M} = \frac{\langle\beta\rangle W_M}{\tau_E} , \qquad (1)$$

in which W_M is the total plasmoid magnetic energy, $\langle\beta\rangle$ is a measure of the average local plasma beta, τ_M is the classical magnetic decay time, and τ_E is the plasma energy confinement time. Since the Spheromak's MHD-stable beta is likely to be limited to the 4-6% range (2), Equation (1) implies that for plasma heating:

$$\tau_E \gtrsim \frac{1}{20}\tau_M \ . \qquad (2)$$

This criterion is somewhat more informative when expressed in terms of a "quality of confinement" parameter, Q_c, necessary for heating of the plasma:

$$\frac{\tau_E}{\tau_B} \equiv Q_c \gtrsim 3 \times 10^{-3} \frac{\langle \beta \rangle T_{(ev)}^{5/2}}{\langle B \rangle_{(T)} \, z \ln \Lambda} , \qquad (3)$$

where τ_B is the Bohm time, $\langle B \rangle$ is a globally averaged magnetic field strength, and Q_c is the minimum number of Bohm times required for power balance.

A parameter study of Q_c vs. T_e (Figure 1) indicates that a typical reactor scale Spheromak plasma is expected to heat rapidly (i.e., when $Q_c \lesssim 1$) into the 100-500 eV range due to a classical ohmic decay of W_M. At some point just past this level, however, Q_c rises quickly into the 10-100 Bohm time range and it is conceivable that an ultimate temperature limit might be imposed by transport limitations. In addition, electron runaway limitations on current density (indicated in Figure 1 by regions of streaming-to-thermal electron velocity ratio $\gtrsim$ 3%) might impose further restrictions on the ohmic heating capability.

One possible method of overcoming such heating constraints is adiabatic plasma compression. It can be shown that, as the externally applied magnetic field B_e is raised, W_M increases proportional to $B_e^{1/2}$, T_e increases in proportion to B_e, and $n\tau_M$ increases as B_e^2.(3) Our power balance during compression then becomes

$$\frac{W_{M_o}}{\tau_{M_o}} + \frac{(f_B^{1/2} - 1) \langle \beta \rangle W_{M_o}}{\tau_c} = \frac{\langle \beta \rangle W_{M_o} \; f_B^{1/2}}{\tau_E} , \qquad (4)$$

where the zero subscripts indicate values before compression, τ_c is the compression time, and the compression factor, $f_B \equiv B_e/B_{e_0}$. The quality of confinement parameter including compession becomes

$$Q_c \gtrsim Q_{c_0} \left\{ \frac{f_B^{-1/2}}{1 + \frac{\tau_m}{\tau_c} (f_B^{1/2} - 1) \langle\beta\rangle} \right\} . \tag{5}$$

Here, it can be seen, for example, that with an adiabatic compression of $f_B = 4$ and $\tau_c = .001\ \tau_M$, the plasma can be ignited under much poorer confinement conditions (i.e., $Q_c \sim .01\ Q_{c_0}$.) than would be possible with ohmic heating alone. Also, it appears possible to increase B_e in a manner such that the electron runaway regions of Figure 1 would be avoided. For this type of scenario, we envision an example in which the plasma is formed with B_e = 2T and allowed to ohmically heat up to a presumed limiting temperature of about 1500 eV (where Q_{c_0} = 200 Bohm times). When the limit is achieved, an adiabatic compression with $f_B = 4$ and $\tau_c \sim .001\ \tau_M$ is begun. At the point at which the 200 Bohm time level is once again reached, Equation (5) indicates that the limiting plasma temperature has risen to about 7 keV. Possibly, at these higher temperatures, the transport scalings will have improved substantially (e.g., confinement might scale such that $D_\perp$ decreases as T_e increases) and, as B_e approaches 8 T, the temperature might rise well above the 7 keV level.

Considerable uncertainties remain in the understanding of the confinement scaling of a Spheromak plasma. In the present work, therefore, we have made only very general statements concerning what might be possible in terms of ohmic-compressive Spheromak ignition under various scaling laws. Experimental evidence from RFP experiments(4), however, seems to indicate confinement limits ~100-300 Bohm times for temperatures in the 200-600 eV range. If Spheromaks could do this well or better, the model presented here suggests that a combination of ohmic and compression heating might be sufficient to raise the MPR plasma temperature to an ignition level.

References

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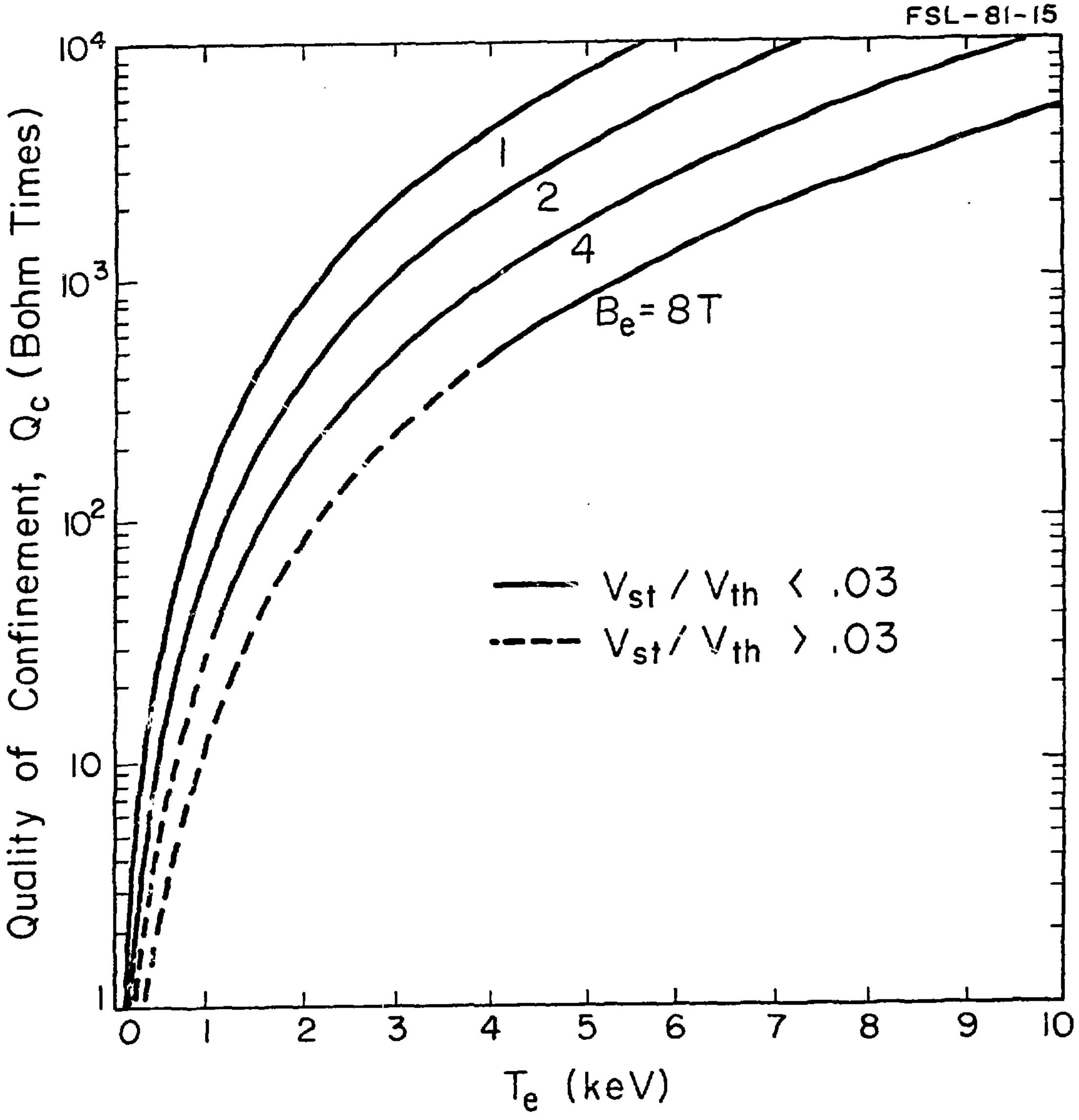

Figure 1: Q_c (Bohm Times) vs. T_e (keV) For Ohmic Heating with Electron Runaway Limits Indicated.