High Pressure Field Reversed Configuration with Anomalous Resistivity

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A high pressure field reversed configuration (FRC) will be the target plasma to demonstrate the physics of magnetized (MTF) target fusion. For MTF, a magnetized plasma is adiabatically compressed to fusion conditions intermediate between magnetic and inertial fusion. In the Field Reversed Configuration Experiment with a Liner (FRX-L), we have successfully created FRC's near the design goal for MTF, $\beta \approx 1$, temperature $T > 300eV$, density $n > 5 \times 10^{22} m^{-3}$, with plasma pressures exceeding 20-30 atmospheres. This FRC could benefit from a large *anomalous* resistivity to ohmically heat the plasma target prior to translation into the implosion region. In this and many other experiments, as well as in space, astro and solar physics plasmas, *collisionless* plasmas exhibit resistivity that is *anomalously* large. In FRX-L the Coulomb mean free path can be short compared to the plasma size, while the ratio of resistive diffusion to Alfven transit times (Lundquist number S) can be large ($S > 2 \times 10^4$). We are able to scale FRXL operating parameters over a wide range for both Coulomb and Lundquist collisionality estimates. We use FRX-L data to show that our resistivity anomaly is more consistent with wave scattering than Coulomb collisionality.

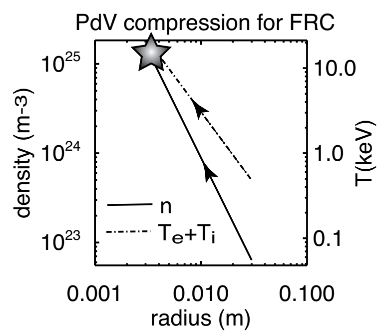

Figure 1: $\int PdV$ trajectory for FRC + MTF , $V \propto r^{2.4}$, $\beta \approx 1$, $PV^{\gamma} \approx const$.

Why a high pressure Field Reversed Configuration?

Magnetized Target Fusion (MTF) is a pulsed fusion energy concept that relies on adiabatic compression of a magnetized plasma. The embedded, closed magnetic flux surfaces improve particle and heat confinement compared to non magnetized inertial fusion approaches. For MTF to succeed, a magnetized target plasma must be created, transported to a compression region, and then adiabatically squeezed inside a flux conserving boundary "liner" [1]. Figure 1 shows adiabatic compressional work done on the plasma to decrease its volume and increase the plasma density and temperature to fusion relevant levels. Large density is useful, since fusion reactivity scales as the square of density. For our investigations of MTF target plasmas, we have selected the field reversed configuration (FRC). The FRC is a robust MHD like equilibrium with vanishing helicity, large diamagnetic flows, and a pressure balance requiring a large ratio of plasma pressure to magnetic pressure $\beta \approx 1$. This MTF scenario invokes a high density FRC ($10^{23} m^{-3}$) with temperature ($T_e \approx T_i > 200eV$) and large initial pressure ($nk_BT \approx 20 - 30$ atmospheres).

At Los Alamos National Laboratory the FRX-L experiment is used to study the physics of a suitable FRC plasma target [1] [2] and translation into a compression region. Flux conserving compression experiments on the FRX-L plasma using an imploding cylindrical liner will start by 2008.

Early theta pinch research showed that high density FRC's were possible, and we are attempting to improve the understanding and realizations of these plasmas for applications to MTF. Figure 2 shows a typical recent shot, with large plasma pressure of $nk_BT \approx 2 - 3MPa$ compared to other fusion devices. Increased confinement time through increased magnetic flux trapping during formation is one focus of ongoing investigations on FRXL.

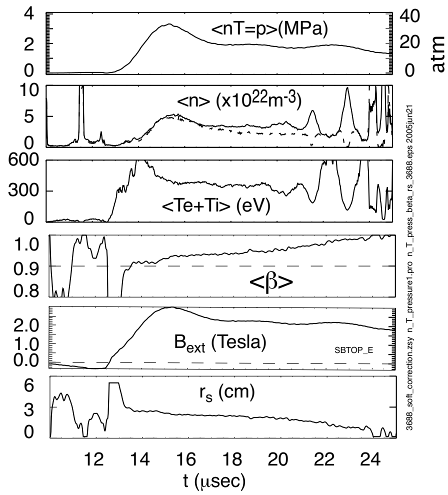

Figure 2: Typical recent shot showing high plasma pressure of $<nk_BT> \approx 2 - 3MPa$, average density $<n>$, temperature $<T>$, external magnetic field B_{ext}, and separatrix radius r_s.

Anomalous resistivity

Our MTF experimental design calls for a flux conserving compression of 10 to 1 in radius for the FRC equilibrium, which is predicted to yield a 250 fold volume reduction[6] [1]. A final compressed density of $n_{MTF} \approx 10^{26} m^{-3}$ would yield fusion relevant conditions, which requires the initial target to have density of approximately $10^{23} m^{-3}$. This high target density results in a short Coulomb collision mean free path λ_{ei} compared to the plasma current sheet or separatrix size r_s of several cm. Figure 3(a) shows a survey of several different FRC experiments, spanning a large range of collisionality r_s/λ_{ei}. To compare different devices with differing fill pressure p_0 and vessel radius r_w, these data are scaled against a dimensionless line density $N_{ref} = 0.032 r_w^2(cm) p_0(mT)$. By this measure FRXL is very collisional, but also amenable to scans over a large range in fill pressure. Figure 3(b) shows that high Coulomb collisionality coexists with a large Lundquist number $S = \tau_R/\tau_A$ which usually corresponds to a *collisionless* regime, *i.e.* the Alfven transit time τ_A is much shorter than the resistive diffusion time τ_R.

FRXL intentionally operates in a regime where substantial ohmic heating is expected. After the initial shock heating during FRC formation, sustainment of the plasma temperature

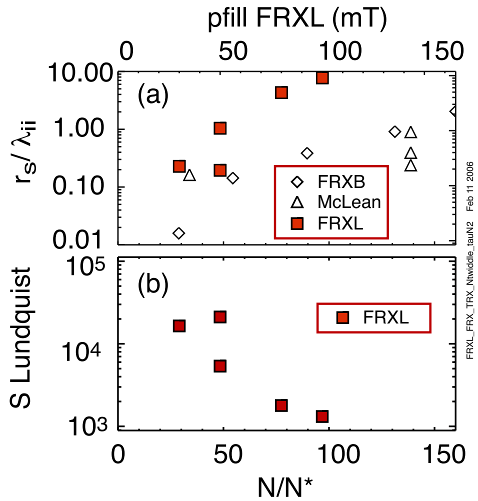

Figure 3: (a) Collisionality figure of merit r_s/λ_{ei} and (b) Lundquist number for several FRC experiments *v.s.* normalized line density N_{ref},

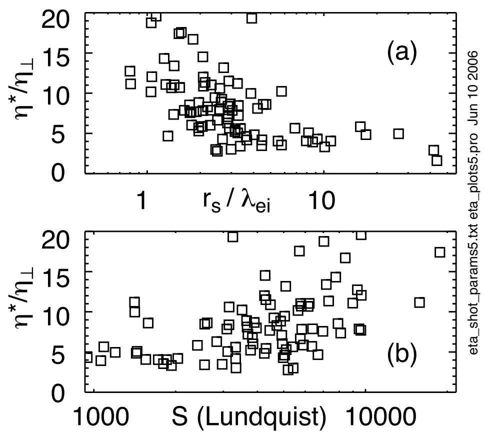

Figure 4: FRXL shot data showing the anomalous enhancement factor $\eta^*/\eta_\perp$ compared with (a) Coulomb collisionality and (b) Lundquist number.

requires large ohmic heating which could be increased by anomalously enhanced resistivity $\eta^* = \nu^*/(\omega_{pe}^2\varepsilon_0)$ over the Spitzer value $\eta_\perp = \nu_{ei}/(\omega_{pe}^2\varepsilon_0)$ where ν^* (ν_{ei}) is the anomalous (electron-ion) collision frequency and ω_{pe} is the electron plasma frequency. The anomaly factor for FRC's has traditionally been reported to be in the range of $\eta^*/\eta_\perp \approx 2-10$ [6]. The anomalous physics has never been explained, but ν^* is typically attributed to particle scattering from a wave energy density proportional to the internal poloidal magnetic field energy density. Here we calculate the resistivity using a rigid rotor model [3] that was benchmarked on FRXL using a multi chord interferometer [1].

FRXL anomaly factor $\eta^*/\eta_\perp$ data show substantial scatter, decreasing to small $\eta^*/\eta_\perp$ with Coulomb collisionality for $r_s/\lambda_{ei} > 10$ in Fig. 4(a) and increasing with Lundquist number $S = r_s v_A/(\eta_\perp/\mu_0) \gg 1$ in Fig. 4(b). For a range of densities and total temperature $T_{tot} = T_e + T_i$, we have assumed $T_e \approx T_{tot}/2$, and $T_e(T_i)$ are respectively the electron and ion temperatures. We note that MRX [5] reconnection experiments showed $\eta^*/\eta_\perp > 5-10$ for $\delta/\lambda_{ei} > 1$, where δ was a reconnection layer width.

Figure 5 data indicates reduced scatter when plotted against a wave scattering resistivity η^* proportional to internal poloidal magnetic field B_{pol} energy W. From force balance, $\eta^* Jen = -\nabla_\perp W(r)$ where $\nabla_\perp W(r) \approx \frac{1}{r_s}(B_{pol}^2/2\mu_0)$, and B_{pol} is proportional the external magnetic field B_{ext}. This is reminiscent of lower hybrid drift wave scaling [4] [6] and requires that $\eta^* \approx C_{wave} B_{ext} x_s^{1+\varepsilon}/n$, where x_s is the ratio of separatrix to coil radius, $\varepsilon \approx 0.25$ is an edge shape factor, and n is average density. The C_{wave} dependence is smaller for FRXL high density FRC's (squares) than a worldwide compendium of lower density FRC data (diamonds). Error bars for $\eta^*/\eta_\perp$ may be sensitive to impurities[6] $Z_{eff} \leq 1.5$, FRC profile deviation from the rigid rotor model, and whether $T_e \approx T_{tot}/2$.

Conclusion

High pressure plasmas have been created in FRX-L for use as a high density MTF target. The parameters we have achieved are approximately those required for the MTF liner implosion on plasma experiments which will be implemented in the next several years at AFRL Kirtland. These target FRCs benefit from substantial ohmic heating after formation, which may depend on resistivity that is found to be anomalous for a wide range of Coulomb collisionality. The behavior of this resistivity does not appear to depend on resistive diffusion in the usual sense.

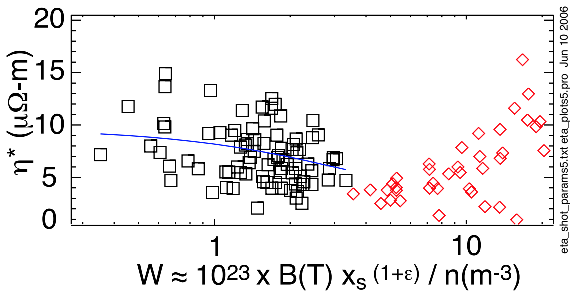

Figure 5: FRXL shot data (squares) and a survey of many other lower density FRC experiments (diamonds, courtesy L. Steinhauer) comparing anomalous resistivity η^* with a wave scattering quantity proportional to internal poloidal magnetic field energy.

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References

[1] T. Intrator, S.Y. Zhang *et. al.*, *A high density FRC target for magnetized target fusion: first internal profile measurements of a high density FRC*, Phys. Plasmas **11**, 2580 (2004)

[2] J. M. Taccetti, T. P. Intrator *et. al.*, *FRX-L: A field-reversed configuration plasma injector for magnetized target fusion*, Rev.Sci. Instrum., **74**, 4314 (2003)

[3] A.L. Hoffman, R. D. Milroy, and L. C. Steinhauer, *Poloidal flux loss in a field reversed theta pinch*, Appl. Phys. Lett, **41**, 31 (1982)

[4] R.D. Milroy and J. U. Brackbill, *Numerical studies of a field reversed theat-pinch plasma*, Phys. Fluds **25**, 775 (1982)

[5] F. Trintchouk, M. Yamada, H. Ji, R. Kulsrud, T.A. Carter, *Measurement of the transverse spitzer resistivity during collisional magnetic reconnection*, Phys. Plasmas, **10**, 319, (2003)

[6] M. Tuszewski, *Field Reversed Configurations*, Nucl. Fus, **28**, 2033, (1988).