Cross-cutting Connections between the Spheromak and the Reversed-Field Pinch (RFP)
[CT sub-sub-panel: McLean, Sovinec, Woodruff, Yamada]

Introduction

Like the tokamak and spherical torus (ST), the spheromak and RFP configurations use electrical current flowing within the plasma to confine heat and particles. However, the spheromak and RFP share important physical properties that distinguish them from other confinement schemes. The externally applied magnetic field is smaller than the magnetic field that is induced with plasma current, and this is beneficial from an engineering standpoint. While the absence of a large externally induced field allows macroscopic instabilities, nonlinear coupling to stable modes and natural relaxation of the profiles saturate the instabilities without disruption. Because these processes are fundamental to standard operating modes and with transient control already demonstrated, a number of the scientific and technical issues identified in the Toroidal Alternates Panel (TAP) report are very similar for the spheromak and RFP. Here, we highlight these commonalities, while noting some finer-scale differences, to help formulate initiatives that are both strategic and scientifically general.

Common Issues

- Achieving current drive with high confinement is a 'Tier 1' issue in the TAP report for both configurations. Electron temperatures and confinement indicative of low magnetic fluctuation levels has been demonstrated in both configurations through the application and tuning of transients (pulsed parallel current drive, PPCD, in the Madison Symmetric Torus, MST, and tailoring of the DC waveform in the gun-driven Sustained Spheromak Experiment, SSPX). The beneficial effects have been measured and computationally confirmed as being current profile control that reduces relaxation activity and magnetic-fluctuation-induced transport. RF and neutral beams may provide at least some form of steady-state profile control and need further study for both configurations, where common traits stemming from the low field require expansion from the tokamak knowledge base. Pulsed schemes are also being considered for both configurations, and optimizing cycle-average performance for quasi-steady sustainment is a common goal.
- Current sustainment is identified as a separate 'Tier 1' issue for the RFP, and it is implied through the previously noted issue of sustainment/confinement integration for both. AC-type current drive for the RFP (oscillating field current drive, OFCD or 'F-Θ pumping') is described as having promise if it scales well from present MST experiments to reactor-grade conditions without adverse effects on confinement. An analogous AC sustainment study for the spheromak is underway in the Helicity Injected Torus with Steady Induction (HIT-SI); scaling and confinement are also the primary issues. The 'Tier 1' issue of spheromak formation is related; standard DC helicity injection and multi-pulsed injection are being examined for both formation and sustainment. Progress in this area may also prove useful for other fusion concepts such as the ST.
- Transport and confinement scaling is listed as a 'Tier 1' issue for the RFP and as a 'Tier 2' issue for the spheromak. The significance of magnetic-fluctuation-induced transport has been measured in the RFP and identified for the spheromak through comparisons of measurements and theoretical computations for standard driven conditions. Scaling and the significance of two-fluid and kinetic effects are less well known. More importantly, the transport mechanisms and scaling of the respective high confinement states, where magnetic

fluctuations are suppressed through profile control, are essentially unknown. Estimates for transport during high confinement approach that of similarly sized and powered tokamaks, and drift-wave turbulence may dominate. However, the magnetic safety factor (q) is low in both configurations relative to the tokamak (Fig. 1), and shear ($q^{-1}dq/dr$) can be relatively large. Thus, a transport study that serves both the spheromak and the RFP is needed to extend the tokamak knowledge base, possibly starting with modification of gyrokinetic simulation codes to handle weak-toroidal-field conditions. It is likely that the physical results of this effort will strengthen our overall scientific understanding of plasma transport.

- Plasma-β limits are identified as a 'Tier 2' issue for both the RFP and spheromak. Experiments have achieved β-values of roughly 10% or more—and larger engineering-β with the magnetic field strength at the external coils. With q<1 in both configurations, there is no average good curvature from toroidal effects, and resistive-MHD predicts instability. While there has been analytical and computation work for pressure-driven modes, it is less well developed than the work for current-gradient-driven modes. Extended-MHD studies of linear stability properties of pressure-driven modes and their nonlinear consequences at low q-values are needed. While there are similarities, an important distinction is that RFPs have at least some region of high shear, but spheromaks can have either high or low shear. High shear is realized when current running along the geometric axis of a spheromak is small. However, gun and flux-core spheromaks have a separatrix (like diverted tokamaks) and usually have a reversed-shear q-profile (Fig. 1) when the open field carries current. In these cases, the shear is not large, and the importance of avoiding low-order rational surfaces for high confinement (demonstrated with SSPX and NIMROD simulations) is likely related to this characteristic. In contrast, high-β with low-order rational surfaces has been demonstrated for the RFP, so a comprehensive nonlinear study must address high, low, and reversed shear.
- Energetic particle effects is listed as a 'Tier 3' issue for the two configurations. Insensitivity to magnetic fluctuations has been demonstrated on MST, but relative to tokamaks, the use of neutral beams is in its infancy apart from some diagnostic applications. Heating and current drive are largely unexplored, and any progress for profile control would be important, as discussed above. Interaction of energetic particles with tearing-type instabilities is a new area of theoretical research. Excitation of Alfvén eigenmodes is also unexplored for these configurations but may eventually be important for burning plasma conditions.
- Resistive wall mode (RWM) effects is identified as a 'Tier 3' issue for both configurations. In the absence of a conducting wall or feedback, the RFP and spheromak are both unstable to virulent ideal MHD modes. Progress in other aspects of these configurations has largely been in experiments with highly conducting shells, but the resistive-wall behavior will be important if sustained operation is pursued. The Swedish and Italian RFP groups have made very substantial progress with feedback on multiple modes through a resistive shell; hence the less-urgent RFP classification. This has not been attempted with spheromaks, but the configuration will benefit from the RFP research.
- Plasma Boundary Interactions is listed as a 'Tier 2' RFP issue for its ITER-era goal of establishing the basis for a burning plasma experiment. Part of the issue is divertor design and performance. Gun and flux-core spheromaks characteristically have a separatrix, and existing spheromak results on relaxation and confinement with diverted field and low-q may prove helpful for the RFP.

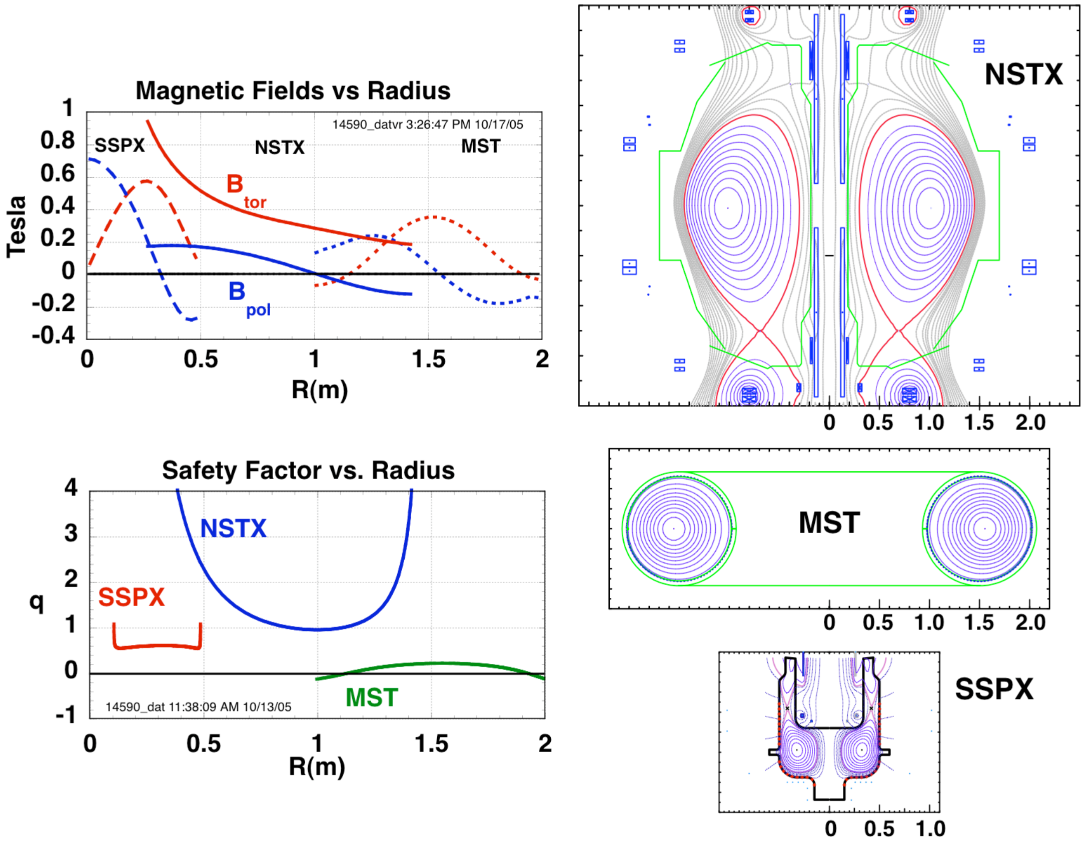

Figure 1. Magnetic fields, safety factor profile and relative size of the SSPX spheromak, NSTX spherical torus, and the MST reversed-field pinch. Spheromaks have been created with varying degrees of magnetic shear, which can approach that of an RFP in experiments without a flux core. SSPX has relatively low shear near its magnetic axis and reversed shear near the separatrix due to the current-carrying flux core.