Computations of temperature profiles in spheromak configurations with open field lines

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The NIMROD zero-β spheromak simulation results have mostly open field lines for parameters producing significant flux amplification. This would certainly affect the temperature profile, but to what extent is not obvious without computation. To begin addressing this issue, I have performed two thermal diffusion problems. I have solved

$$\frac{1}{\gamma-1}\frac{\partial T}{\partial t} = \kappa_{iso}\nabla^2 T + \kappa_{\|}\nabla\cdot\hat{\mathbf{b}}\hat{\mathbf{b}}\cdot\nabla T + \frac{1}{nk}\eta J^2 \ ,$$

using the geometry, magnetic fields, and current density from the flux-core simulation with S=5000, H/R=1.5, and uniform electrode B_z. [Density, n, is uniform.] One computation incorporates anisotropic thermal diffusivity, $\kappa_{\|}\neq 0$; the other uses isotropic diffusivity, $\kappa_{\|}=0$. The boundary condition is T=0 at all wall, and I have run the problem until the temperature approaches a steady state. No other evolution is allowed--these are not complete simulations.

Though performed in the unity-radius can, I chose the diffusivities to be somewhat relevant to the SSPX parameters, expecting the source term to be in the correct ballpark for a resistive diffusion time of 1s. In particular, I used

$\kappa_{\|} = 1\times 10^7 \ \mathrm{m}^2/\mathrm{s}$, ~ based on electrons

$\kappa_{iso} = 1\times 10^3 \ \mathrm{m}^2/\mathrm{s}$, ~ based on ions

I have not tried tying diffusivity values to temperature, and that may have a significant impact on the final temperature, especially since the parallel diffusivity value is based on something close to peak SSPX temperatures. Here, I'm just trying to get an idea of what profiles may result.

Results from the isotropic problem are shown in Figs. 1-2. The symmetric part of the solution looks like a textbook result, though the Ohmic heating source from the helical current path (Fig. 7 of our long manuscript, or the yellow isosurfaces in Figs. 5-6 below) is off center. This off-center source shows up more in 3D isosurfaces (Fig. 2, for example), but the structure of the current path is washed-out.

When large parallel conduction is added, the thermal energy content drops by two orders of magnitude. This is a factor of 10 less than the ratio of parallel to isotropic diffusivities, indicating that the magnetic configuration is providing some insulation. In addition, the peak of the symmetric part of the solution moves off center (Fig. 3), due to the anisotropic diffusion combined with the looping magnetic field line trajectories. This is clear in the temperature isosurface shown in Fig. 4. In Figs. 5 and 6, I plot a parallel current isosurface for a large value of λ together with the temperature isosurface to show that they are not coincident. The current tends to favor the short field lines (as described in the long manuscript), unlike the temperature. The current path seems to heat magnetic field lines near the end caps, and there is a confined region between. Though the field lines are not closed, this is very different than the result with

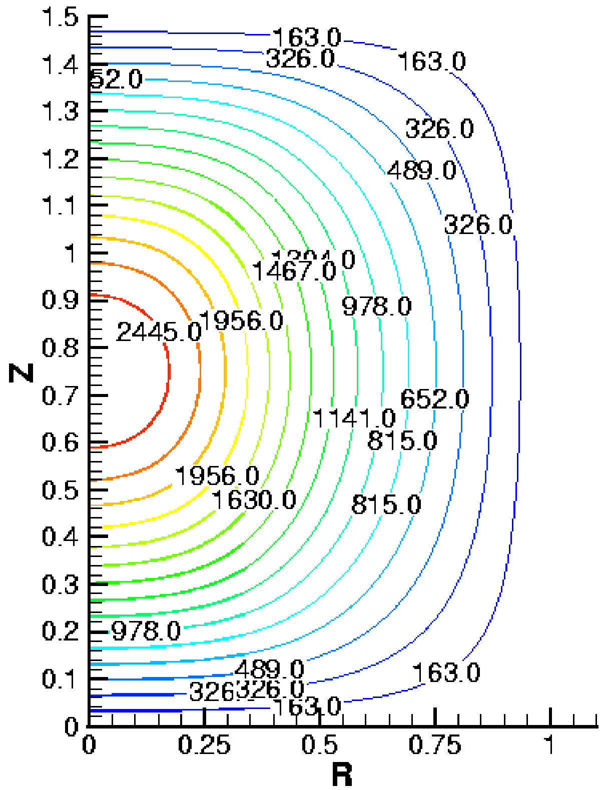

Fig. 1. n=0 Fourier component of temperature (times nk=16) from the isotropic problem.

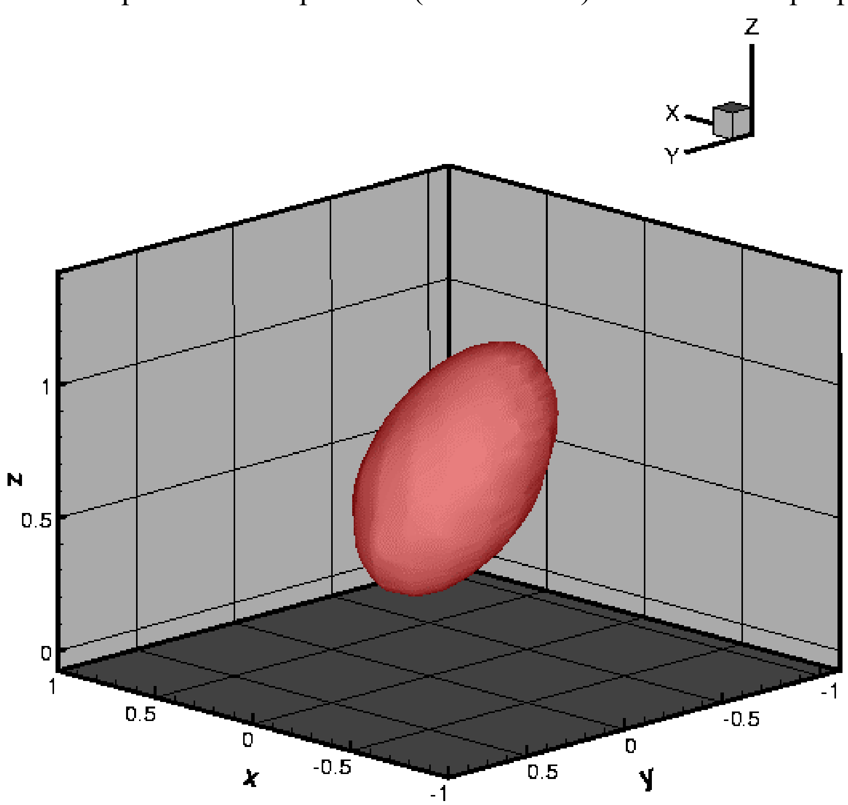

Fig. 2 nkT=2000 isosurface from the isotropic problem.

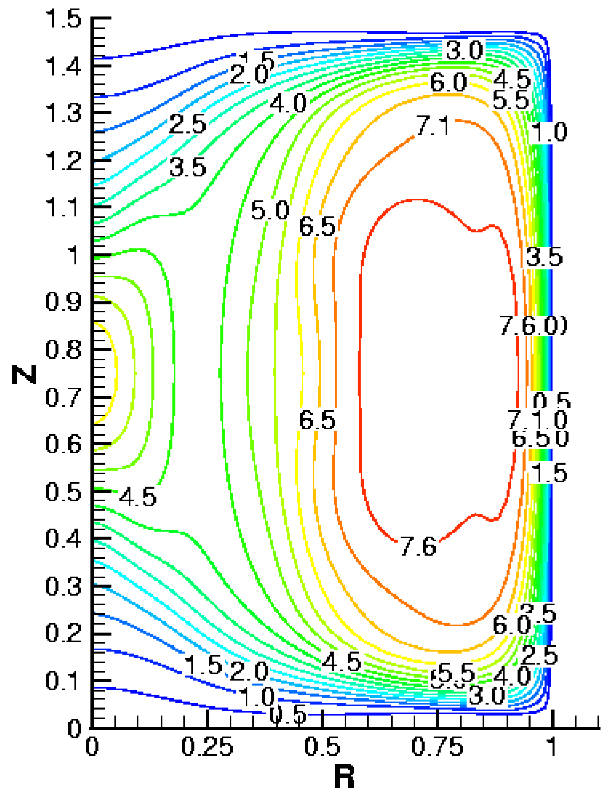

Fig. 3. n=0 Fourier component of temperature (times nk) from the anisotropic problem.

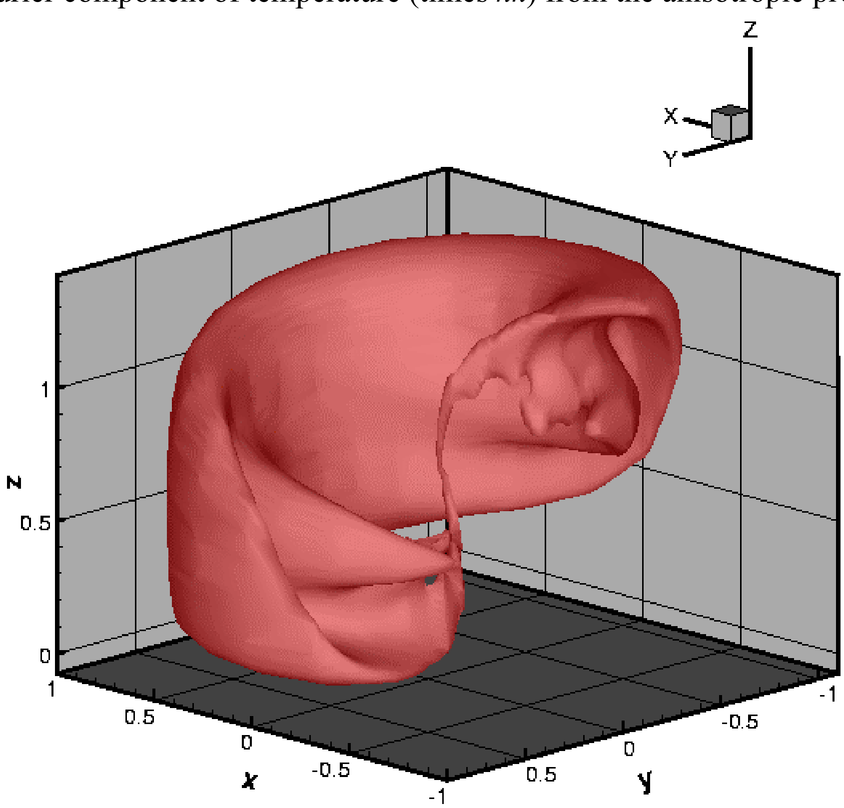

Fig. 4. nkT=8 isosurface from the anisotropic thermal conduction problem.

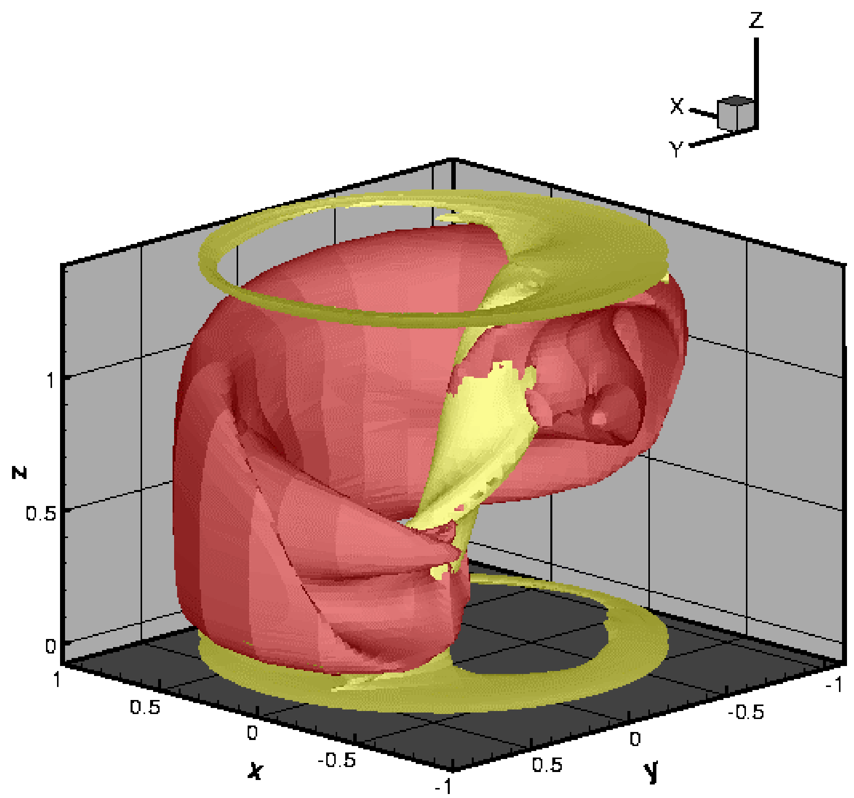

Fig. 5. *nkT*=8 isosurface (red) with the λ=6 (yellow--near maximum λ) isosurface.

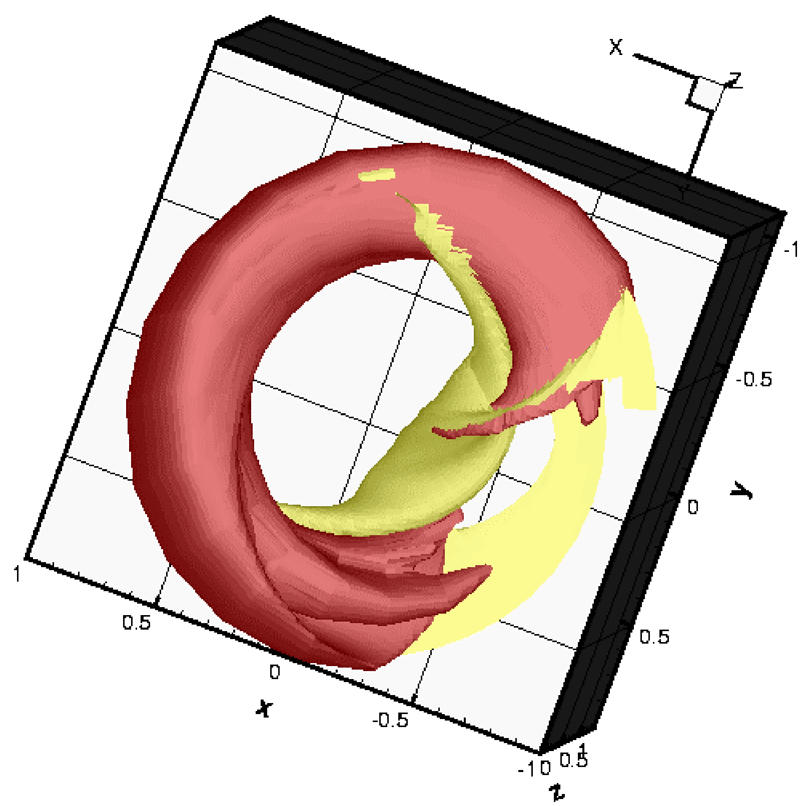

Fig. 6 Same as Fig. 5, but top view and clipping some data near the top.

isotropic diffusion, where the peak temperature coincides with the midpoint of the strong parallel current path.

The anisotropic result may be considered a demonstration that open configurations can produce a shaped temperature profile that is peaked off the geometric axis. [But no more than a demo.] This may have some bearing on the SSPX profiles, but Thompson scattering is effectively instantaneous, so there would be large shot-to-shot variation in the profile as the structure is caught at different phases. I still harbor suspicions that the SSPX discharges do not reflect sustained conditions, in which case, flux surfaces may form. One question I have for the experimentalists is, "What temperature profiles are observed when the n=1 mode dominates?" [Does it resemble the anisotropic results shown here?]

We may be able to get more accurate profiles for quantitative comparison by using the gun geometry and diffusivity values proportional to T (proportion to the n=0 part of T is tractable). However, one then starts to wonder about the importance of the temperature dependent resistivity. The worm can quickly becomes large.