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Analytical studies of PROTO-SPHERA equilibria

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Plasma tori formed around a 10 kA centerpost screw-pinch plasma discharge have been observed in phase-1 of PROTO-SPHERA experiments.
A simple model of plasma equilibrium has been developed, which reproduces the morphological features observed so far, in particular the bumpy shape of the centerpost discharge and the slim torus surrounding it.
The model is based on a generalization of the bumpy pinch equilibrium solution of the Grad-Shafranov equation by Taylor [Jensen T.H. and Chu M.S. 1980 J. Plasma Phys. 25 459], which allows reproducing both bumpy pinch and pinch-torus force-free configurations. The Taylor model in cylindrical coordinates is expressed as: $\psi = rJ_1(Kr) + crJ_1(\sqrt{K^2 - k_z^2}\, r)\cos(k_z z)$, where ψ is the poloidal flux function and K is the coefficient of proportionality between poloidal current and poloidal flux. The constant c determines the bumpiness of the pinch: bulgy pinches result for $c < 0$, while $c > 0$ gives pinch-torus combinations with squeezed pinch.
The above expression has been generalized along three lines. First, in order to describe low-current plasmas (including the vacuum case) it has been extended to $K < k_z$. Second, more z-dependent terms have been added, which allow obtaining bulgy pinches surrounded by slim tori. Third, a plasma pressure term $p = p_0 - \alpha\psi$ has been included. Plasma pressure in the pinch is not negligible, in fact it is sufficiently large to reverse the sign of the azimuthal current with respect to the force-free case.
Analytical solutions have also been found for the spherical G-S equation force-free conditions and with poloidal current proportional to poloidal flux (i.e. relaxed), in the form of combinations of Bessel functions of half-integer order in the spherical radial coordinate and Gegenbauer functions (for example solutions of hydrodynamical equations for symmetric Stokes flows) in the angular coordinate. These functions can be used to construct solutions of boundary-value problems for PROTO-SPHERA.

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