Axisymmetric, High-β, Steady-State Plasma Torus: A "Wind-Tunnel" to Develop Whole Device Models

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Motivation

The development of experimentally-validated whole device models is a grand challenge of fusion energy science and a major goal of integrated simulation research. As explained in the 2009 Joint FES/ASCR Workshop Report [1], extreme-scale computing power will allow "improved versions" of large-scale simulations "to produce an experimentally validated integrated simulation capability for scenario modeling of the whole device." Whole device models will integrate multi-scale physics (*e.g.* turbulence and transport, local and nonlocal coupling), magnetic geometry (*e.g.* anisotropy between parallel and perpendicular dynamics, interfaces between closed and open field lines), nonlinear and electromagnetic dynamics (*e.g.* instability-induced energy transfer, particle kinetics and resonances), and carefully designed validation experiments. This scientific challenge is unquestionably "grand." Workshop participants called integrated predictive modeling both "urgent" and "one of the most difficult and least understood problems in fusion energy research" [1].

This white paper presents a cost-effective and near-term research step that makes progress towards this grand challenge by considering the simpler task of experimentally validated integrated simulation of a steady-state, high-β plasma torus confined by a simple axisymmetric current ring. *Using our nation's only toroidal confinement device with superconducting magnets, we can now make unparalleled measurements of fusion-relevant plasmas confined for several minutes and use these measurements for critical validation studies.* We call this approach a "plasma wind tunnel", because it is analogous to using low-cost instrumented objects in wind tunnels to validate CFD and turbulent hydrodynamics for various aerodynamical applications. In a manner of speaking, we want to follow in the footsteps of the Wright brothers. Just as the Wright brothers validated the means to predict lift and drag in their wind tunnel, we should build confidence in our whole-plasma capabilities by first demonstrating success with a fusion-relevant plasma torus that has the least complicated magnetic geometry and the least complicated particle kinetics.

We believe the axisymmetric current ring is both the simplest magnetized plasma torus that can be used for whole-plasma modeling, and, also, the simplest plasma torus that incorporates features of any fusion device: multi-scale and boundary layer physics, nonlinear stability and turbulence phenomena, and important kinetic effects and particle resonances. Steady-state high-β plasmas have proven to be relatively easy to produce in the laboratory [2-7], and gyro-kinetic and gyro-fluid models have been successfully applied to this geometry, yielding important insights into the fundamental nonlinear turbulent transport processes [8-12]. *Like a tokamak*, the plasma torus confined by a current ring is sustained by sources of heat, particles, and toroidal momentum and involves turbulent transport across boundary layers, up-gradient turbulent pinches [13,14], nonlinear fast particle dynamics [15], filamentary "blobs" [16], and turbulent cascades [17]. *Unlike a tokamak*, turbulent transport does not always lead to plasma loss. Instead turbulence causes self-organization, centrally-peaked profiles, and *either* an inward particle *or* an inward thermal pinch [11, 12] as the plasma approaches a state of minimum entropy production [18].

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Without a toroidal field, low-frequency interchange dynamics is especially simple [19-22], allowing the use of bounce-averaged models with reduced dimensionally and complexity [23-25]. When compared to tokamaks, whole-device modeling of a steady-state axisymmetric current ring will be less challenging because (*i*) the magnetic geometry does not evolve in time, (*ii*) the absence of parallel currents eliminates an entire class of current-driven instabilities, (*iii*) the absence of a toroidal field makes all particle drifts omnigeneous without the kinetic distinctions between trapped and passing particles, and (*iv*) the achievement high-beta ($\beta \sim 1$) stability allows leveraging related efforts in magnetospheric physics and integrated space weather simulation [26, 27].

Approach

Our approach builds on research conducted during the past decade and combines cost-effective laboratory measurements with state-of-the-art plasma simulations. Presently, our collaborative research team consists of students and scientists from three universities, MIT, Columbia University, and Dartmouth College, who have lead the development of the basic physics of the plasma torus in the “magnetospheric configuration.” The laboratory effort make full use of one of our nation’s newest research facilities: the levitated dipole experiment (LDX) located at MIT. LDX is the first U.S. fusion science research facility built and operated as a multi-university collaborative research project. With its high-field superconducting magnets and 5 m diameter plasma torus, *LDX is also our nation’s only steady-state facility for the study of toroidally confined plasma* and the largest of three facilities worldwide making the steady-state plasma torus in the magnetospheric configuration available for laboratory investigations [28, 29]. The simulation effort is now extending previous gyro-kinetic simulations of bounded annular drift surfaces [10, 11] to global gyro-fluid simulations that are capable of (*i*) representing the nonlinear dynamics driven by ideal interchange instabilities and drift-like entropy modes and (*ii*) incorporating realistic models for particle and heat sources. Recently demonstrated techniques to regulate the turbulence spectrum [30] and to make transient changes to plasma profiles [31] provide scientists unparalleled control over validation tests.

With sufficient resources, validated integrated modeling of the steady-state axisymmetric torus could become a focus of a larger national effort with near-term milestone. In addition to non-fusion support provided by the NSF/DOE Partnership for Plasma Science, funding of at least $2.0M/year for three years is needed for the LDX facility to install improved plasma diagnostics and the RF antenna needed to access higher plasma density and to complete controlled study of the effects of ion-electron temperature ratio, $\tau = T_i / T_e$. When the 1 MW HF Band (4 to 26 MHz) short-wave transmitter is switched-on, *the 20-fold increase in heating power will maintain plasma parameters as required for fusion-relevant validation studies.* Higher plasma density will also allow new investigations like: (*i*) electromagnetic Alfvén wave dynamics at high plasma β, (*ii*) finite ion temperature modifications to bounce-averaged gyro-kinetics and turbulent self-organization, (*iii*) turbulent cascades and possible zonal flow generation at high power flux, and (*iv*) integrated models of heat and particle SOL flows at high power.

Impact

Experimentally validated whole-plasma simulations of the steady-state plasma torus is both an urgent research need and grand scientific challenge. The axisymmetric “plasma wind tunnel” provided by a current ring is simplest plasma torus that incorporates multi-scale and boundary layer physics, nonlinear stability and turbulence phenomena, and the important kinetics and particle resonances characteristic of any fusion-relevant device. Recent laboratory and computational studies have been successful. They show a readiness to conduct a larger validation and development program that can meet a low-cost near-term milestone using existing laboratory facilities and computational expertise. If we succeed in validating integrated whole-plasma simulations of a steady-state plasma torus confined by a current ring, we will have performed our first “plasma wind-tunnel” test and gained confidence and know-how applicable to any steady-state toroidal fusion configuration.

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