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

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Many Challenges to Whole Device Models in Fusion Energy Science

- Resistive and Extended MHD & Disruptions
- RF Heating
- ITER Modeling
- Kinetics & Reduced Dimensional Models
- Plasma Control
- Energetic Particles
- Model Development Validation
- Edge Power and Particle Balance, Pedestal Stability, PMI, Liquid Wall, ...

Fusion Optimization

Optimization

Kinetics

Reduced

Dimensional

Models
We can make progress in the near term with a Plasma “Wind Tunnel”: The \textit{Simplest} Plasma Torus

- No parallel currents \textit{(no disruptions; no kinks; no tearing modes; no density limits; ...)}
- Axisymmetry \textit{(simplicity; omnigenous drifts;...)}
- Simple kinetics \textit{(similar dynamics for passing and trapped particles allow accurate reduced dimensional models)}
- Steady state \textit{(without time-evolving geometries or transients)}
- Good particle, energy, and momentum confinement; \textit{High-beta}
- Boundary layer physics \textit{between Open/Closed field lines (e.g. SOL, PMI, ...)}
- Non-trivial, fusion-relevant physics \textit{(sources & sinks; nonlinear turbulent cascade; up-gradient pinch; high-temperature and density; small $\rho^*$; ...)}
- First-principles understanding \textit{(without the need for \textit{ad hoc} assumptions)}
Simplest Fusion-Relevant Plasma Torus: Axisymmetric, Levitated Current Ring

Simple Geometry and Kinetics:
- Axisymmetric
- Omnigeneous “Classical” Orbits
- Small $\rho^*$ and Adiabatic Dynamics
- No transients and Steady State

Fusion Relevant Physics:
- Particle and Heat Sources
- Confined Pressure, Particles, Momentum
- Boundary Layer Transport
- SOL Flows
Axisymmetric Levitated Current Ring

- Dynamics dominated by interchange and entropy modes
  
  *because plasma is stabilized by compressibility and magnetic field tension*

- Relatively easy kinetic closures
  
  *because passing and trapped particle dynamics are similar*

- Demonstrated first-principles simulations using bounce-averaged kinetic and gyrokinetic codes
  
  *showing fascinating nonlinear physics and quantitative agreement with some observations*

- Leverages decades of space weather modeling

- *Existing experimental facilities for validation studies*
  
  *LDX at MIT and RT-1 at University of Tokyo*
Comparing to the Familiar Tokamak...

(a) Dipole Interchange-Entropy Modes

(b) Tokamak ITG-TEM Modes

Weak gradients: $\omega_p^* \sim \omega_d$

Stable by compressibility and field line tension

Steep gradients: $\omega_p^* >> \omega_d$

Stable by average curvature and magnetic shear

X. Garbet, Comptes Rendus Physique 7, 573 (2006)
What is known...
(giving confidence in this “wind tunnel” approach)

✓ Classical, adiabatic particle orbits
✓ Linear electrostatic and magnetostatic waves and instabilities at arbitrary beta (\(\beta \sim 1\))
✓ Energetic particle stability and nonlinear drift-resonant transport \textit{without adjustable parameters}
✓ Structure of gradient driven interchange and entropy mode turbulence in steady-state (and also during rapid toroidal rotation)
✓ We know how to create, sustain, and control the plasma torus but only at low power (~ 20 kW) and only with \(T_e \gg T_i\)
✓ Rate of global turbulent self-organization (inward pinch) equals measured quasilinear diffusivity \textit{without adjustable parameters}
✓ Self-organization and turbulent pinch reproduced by nonlinear gyrokinetic simulations and understood with bounce-averaged fluid equations with drift-kinetic closure
Measurement of Density Profile and Turbulent Electric Field Gives Quantitative Verification of Bounce-Averaged Gyrokinetic Pinch
Rate of Global Self-Organization Agrees with Space Weather Models & Measured Turbulence Intensity \textit{without Adjustable Parameters}

Quasilinear Flux using 2D Bounce-Averaged Fluid Equations with Drift-Kinetic Closure

[Note: Different Scales]

(a) Particle Flux  (b) Temperature Flux  (c) Entropy (P∂V^γ) Flux

Nonlinear Turbulent Flux using 5D Gyrokinetic (GS2) Simulations

Particle flux  Ion temperature flux  Electron temperature flux

Kobayashi, Rogers, and Dorland, Phys Rev Lett 105, 235004 (2010)
What is *not* known and needed...

- Can we use reduced dimension nonlinear models (e.g. bounce-averaged fluid equations with drift-kinetic closures), with sources and sinks, and reproduce the saturated turbulence levels?
- How do we model the edge boundary interface and SOL flows?
- How do particle and heat sources influence the self-organized profiles?
- What are the roles of momentum input? Flow shear? $T_i/T_e$ ratio? Ionic mass and impurities?

➡️ We need to apply the 1 MW RF heating source now available at LDX. *This will increase heating power by more than 30 times and produce steady-state fusion relevant parameters.*

➡️ We need improved diagnostics for non-perturbing observation of plasma profiles and the turbulent spectrum.

*Using existing facilities, this is not an expensive program.*
Achieving our long-term goal...

will require many development steps and will benefit from low-cost, simple “wind tunnel” tests
Wright Brother’s Wind Tunnel
> 200 Wing Shapes
Low Cost Validation
We should use a “wind tunnel” approach for whole device modeling for Fusion Energy Science:

**Step 1:**
First, understand and validate using the **simplest possible** plasma torus

*By using existing facilities, this is not an expensive program.*