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

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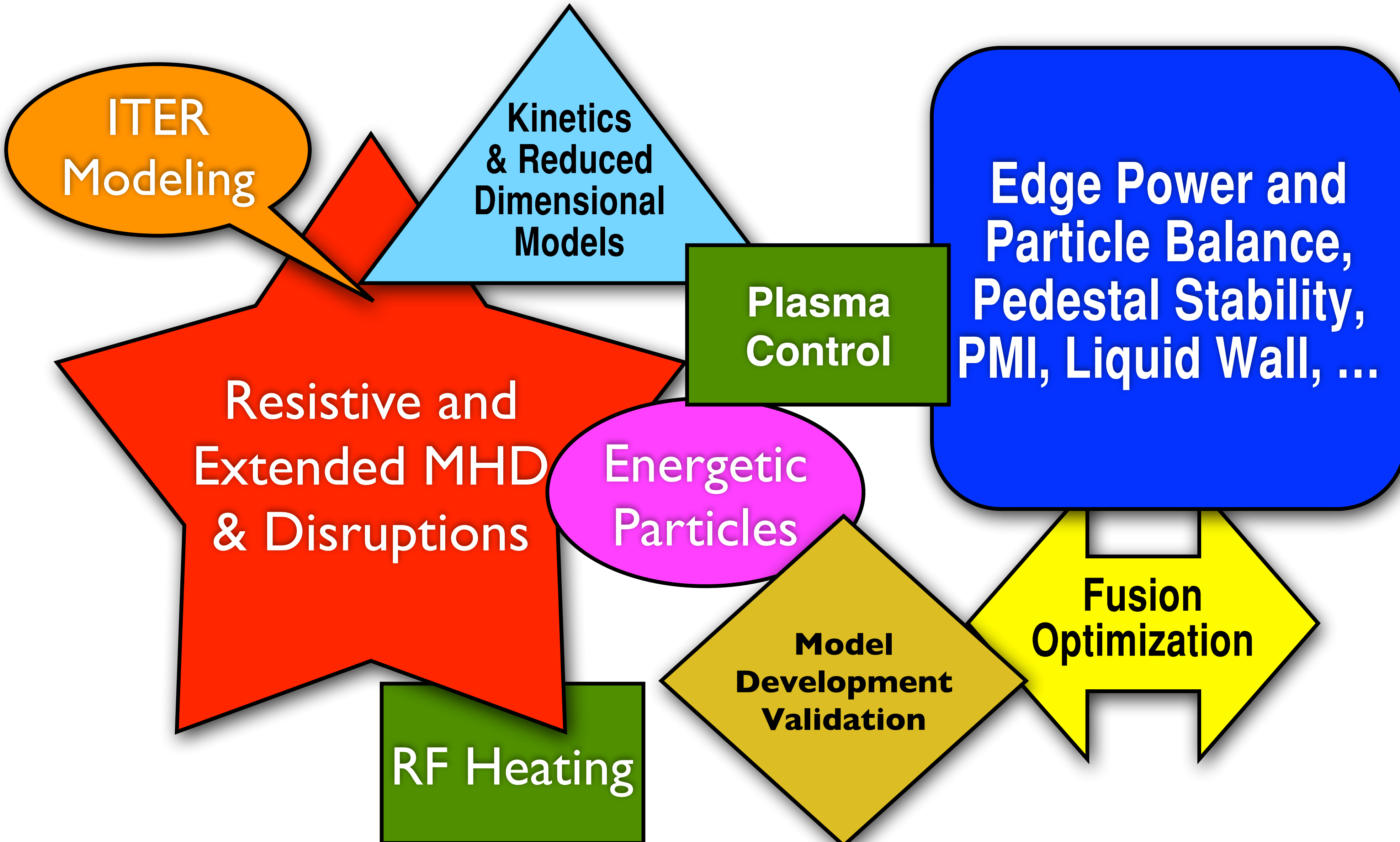
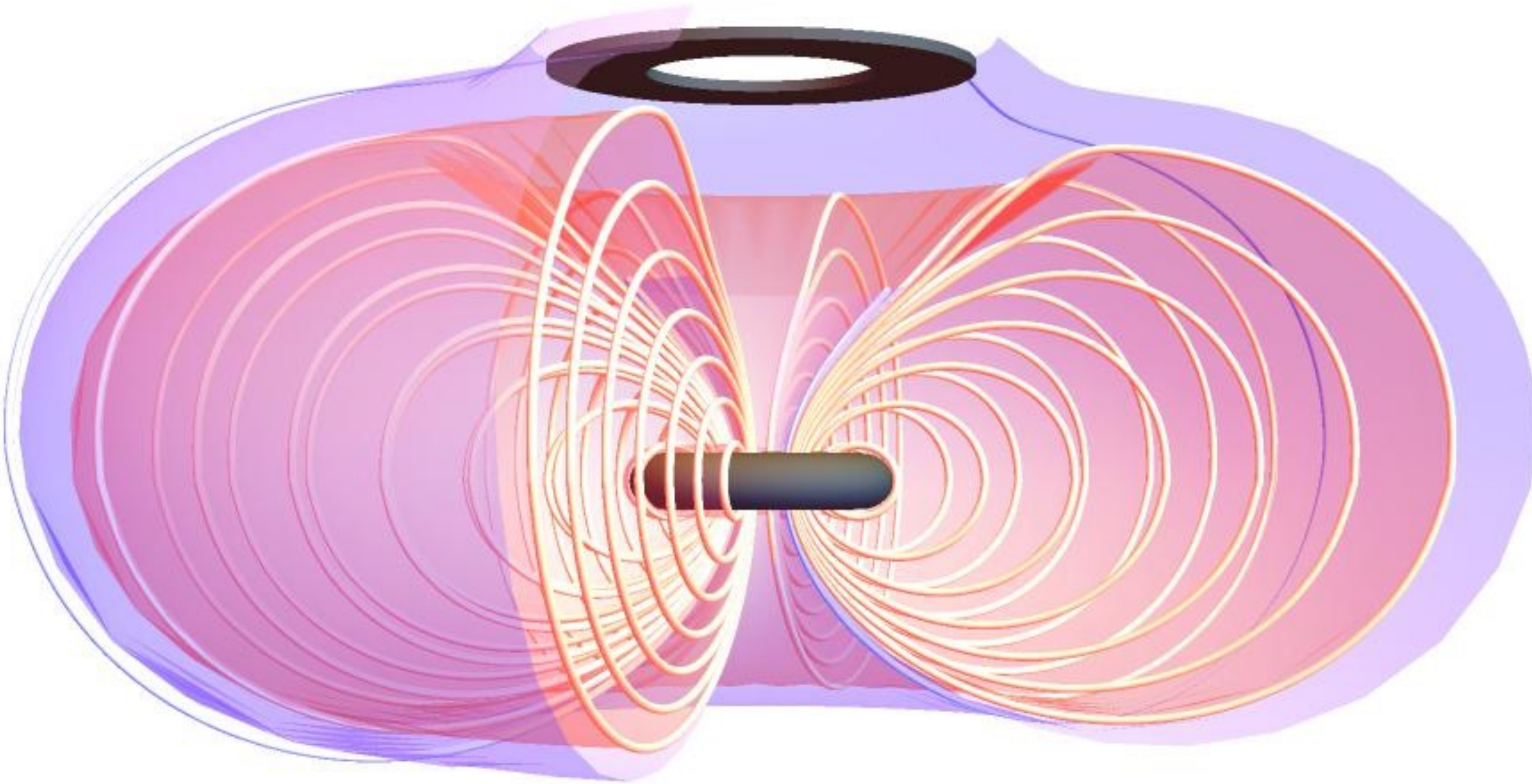
Many Challenges to Whole Device Models in Fusion Energy Science



We can make progress in the near term with a Plasma "Wind Tunnel": The ***Simplest*** Plasma Torus

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

Simplest Fusion-Relevant Plasma Torus: Axisymmetric, Levitated Current Ring



Simple Geometry and Kinetics:

Axisymmetric
Omnigeneous “Classical” Orbits
Small ρ^* 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

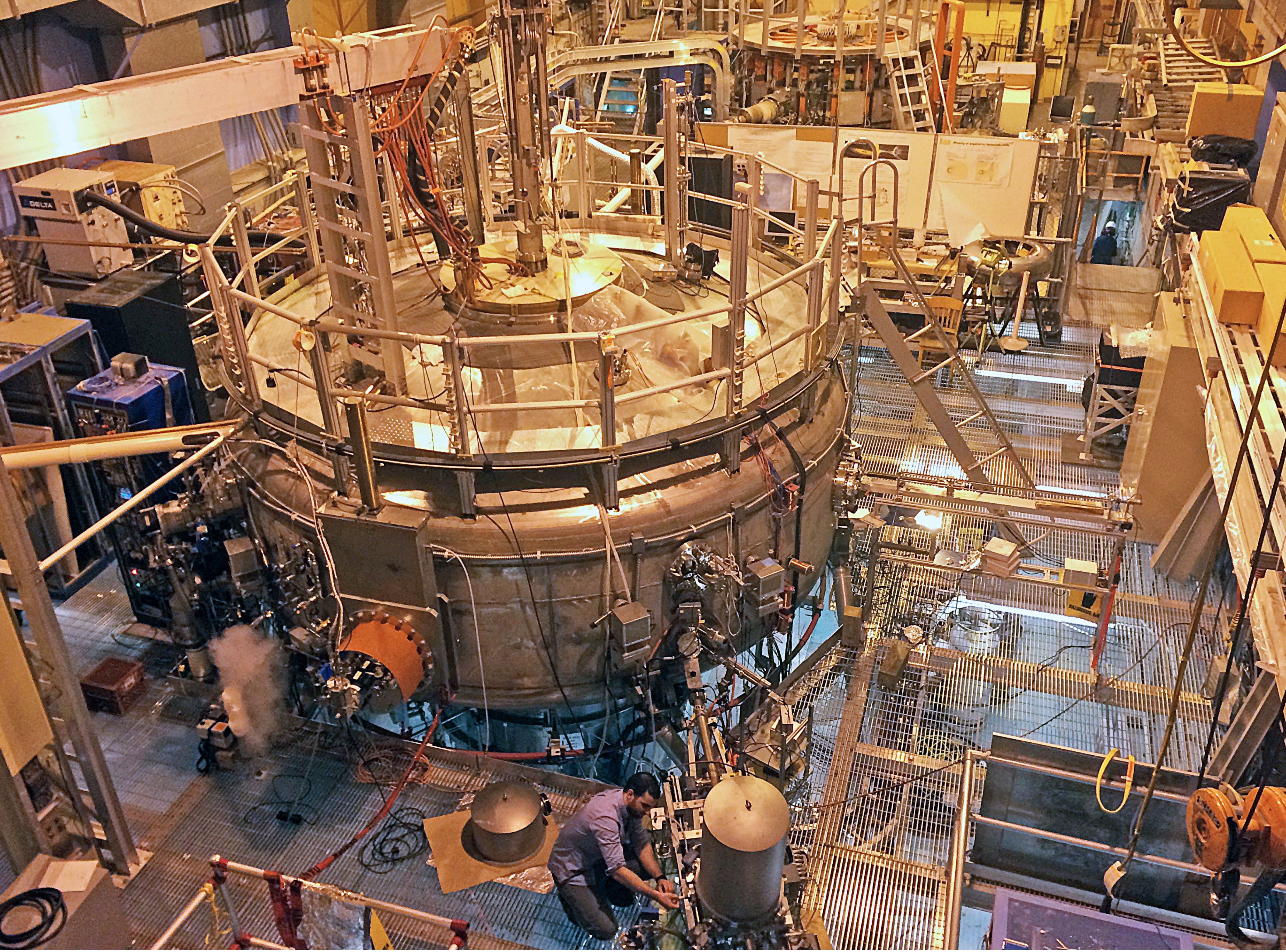
- **Demonstrated first-principles simulations using bounce-averaged kinetic and gyrokinetic codes**

  showing fascinating nonlinear physics and quantitative agreement with some observations

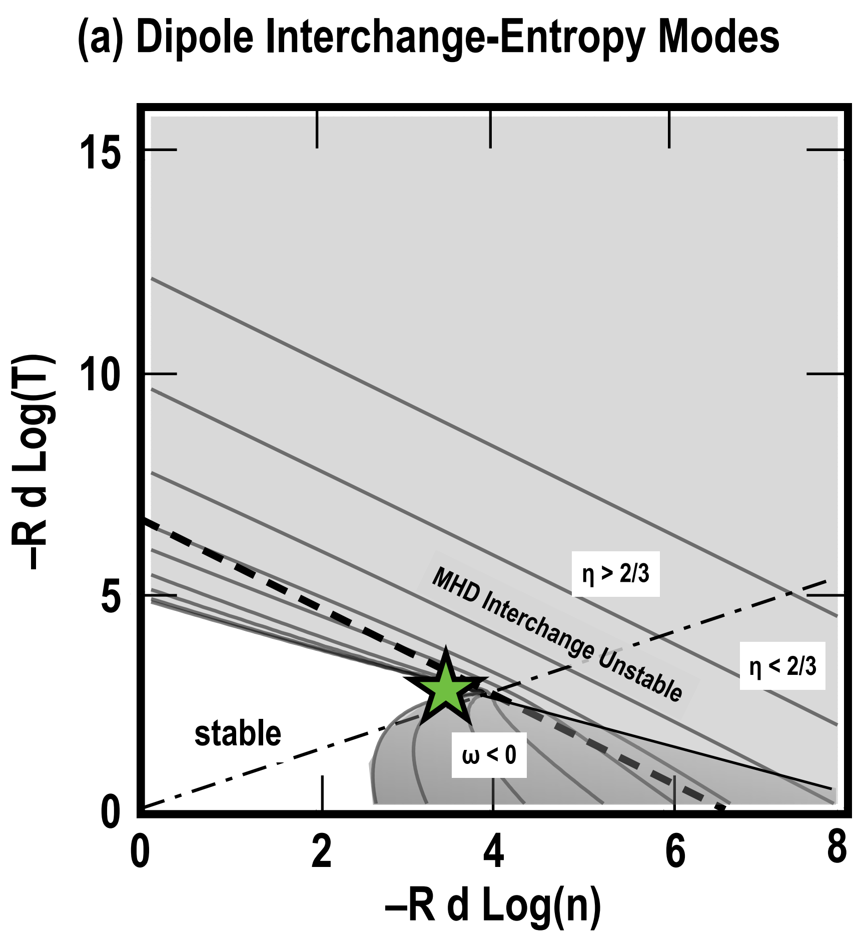
- **Leverages decades of space weather modeling**

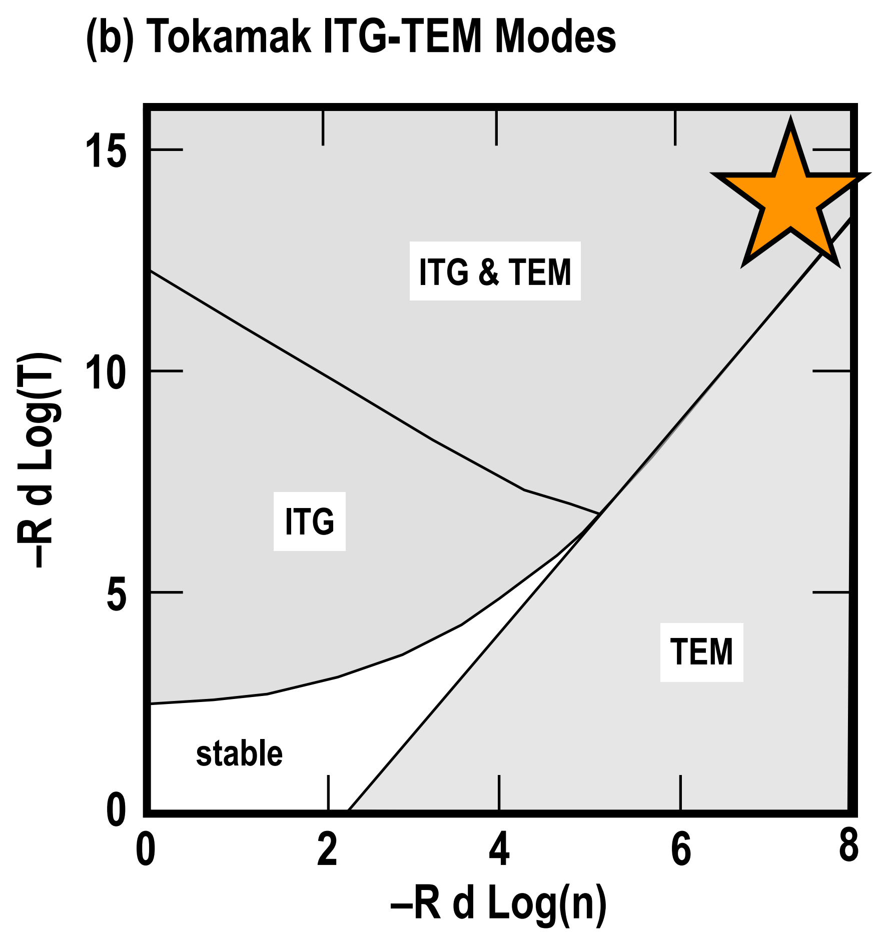
- ***<u>Existing experimental facilities for validation studies</u>***

  LDX at MIT and RT-1 at University of Tokyo


DELTA

Comparing to the Familiar Tokamak...





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

Stable by compressibility and field line tension

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

Stable by average curvature and magnetic shear

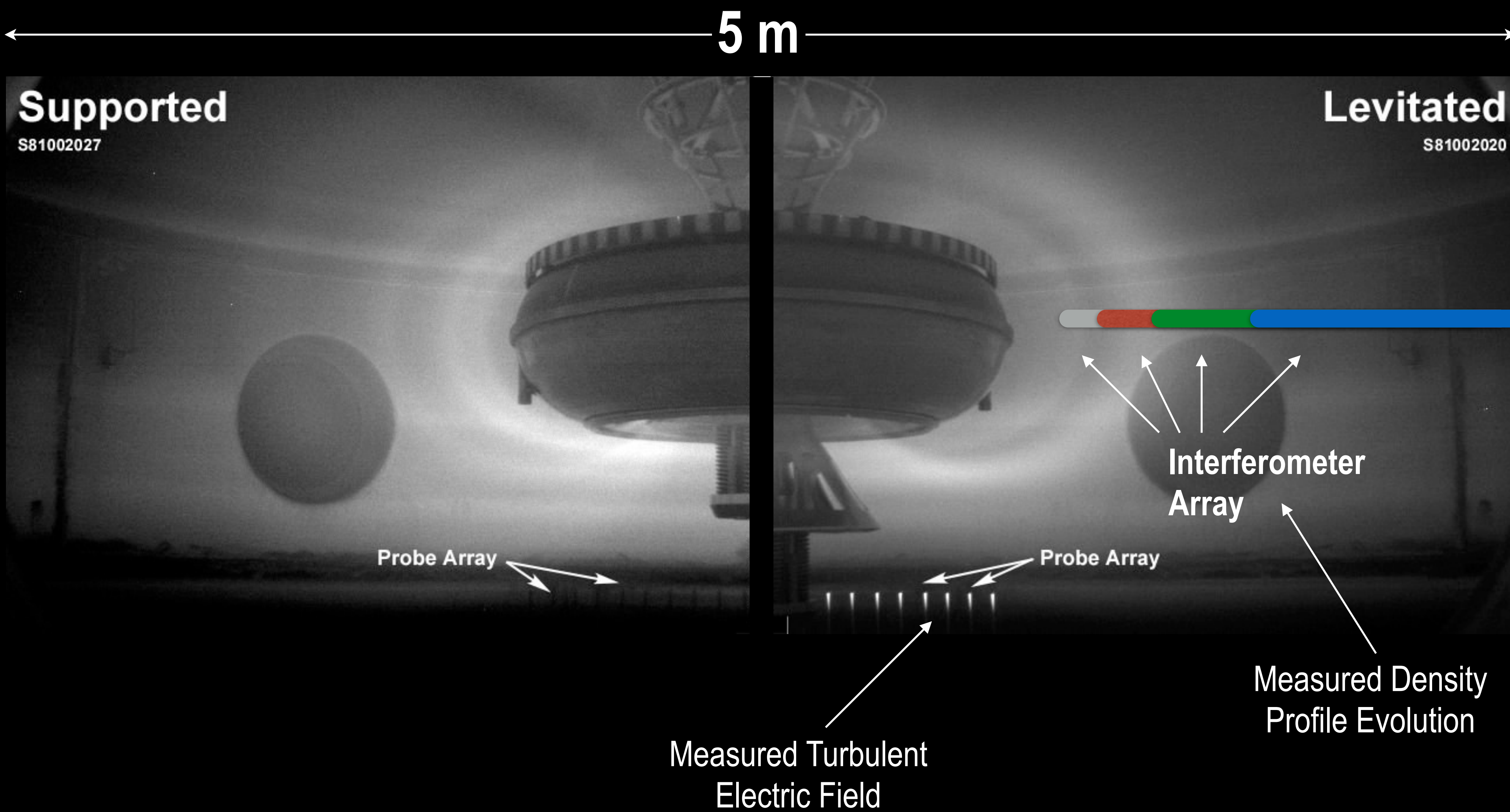
X. Garbet, *Comptes Rendus Physique* **7**, 573 (2006)

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 *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 *without adjustable parameters*
- ✓ Self-organization and turbulent pinch reproduced by nonlinear gyrokinetic simulations and understood with bounce-averaged fluid equations with drift-kinetic closure

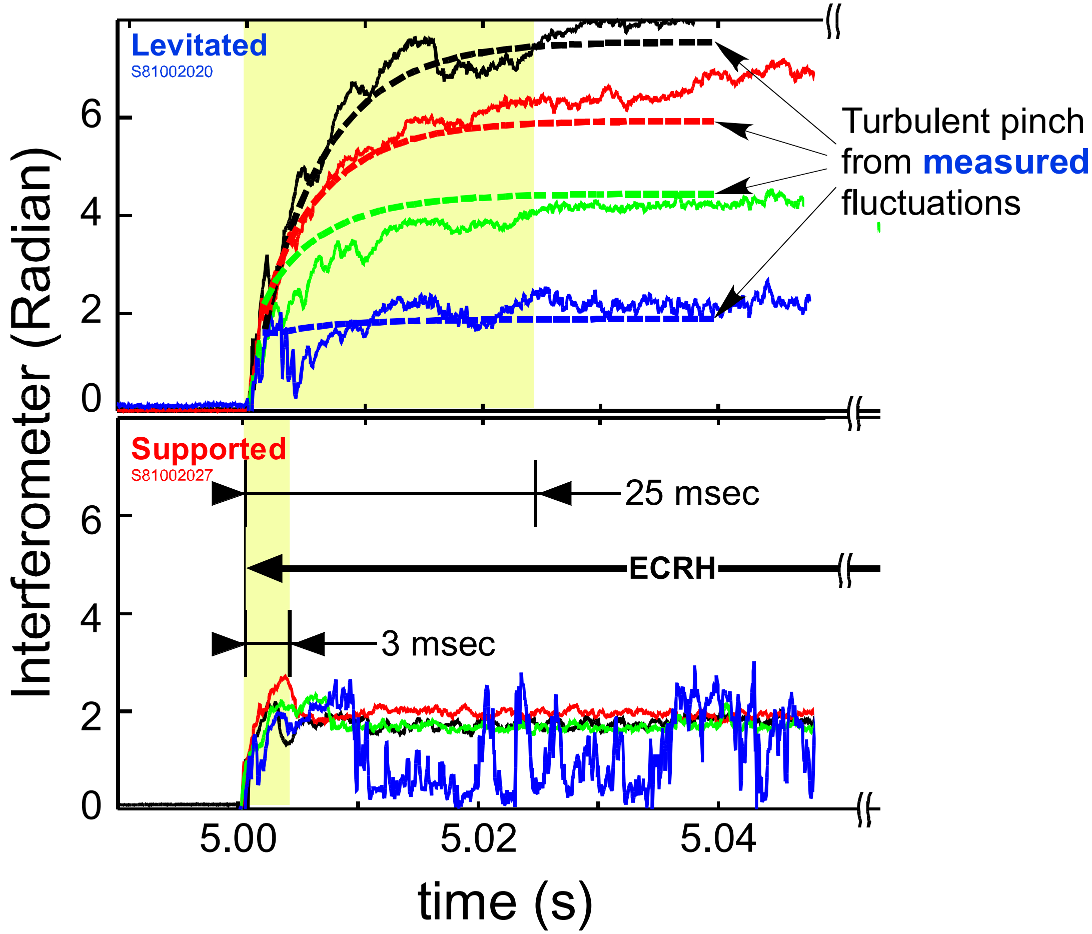
Measurement of Density Profile and Turbulent Electric Field Gives Quantitative Verification of Bounce-Averaged Gyrokinetic Pinch

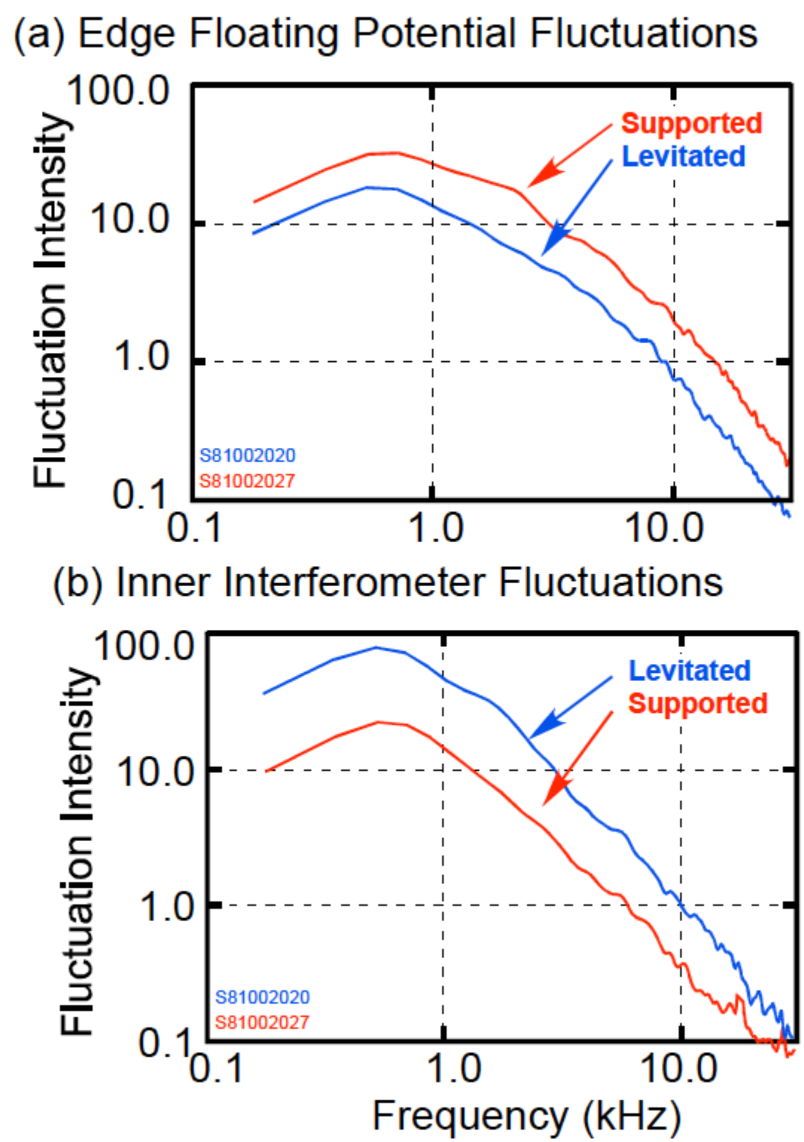


Rate of Global Self-Organization Agrees with Space Weather Models & Measured Turbulence Intensity ***without Adjustable Parameters***

Thomas Birmingham, "Convection Electric Fields and the Diffusion of Trapped Magnetospheric Radiation," *JGR*, 74, (1969).
Alex Boxer, *et al.*, "Turbulent inward pinch of plasma confined by a levitated dipole magnet," *Nature Phys* 6, (2010).

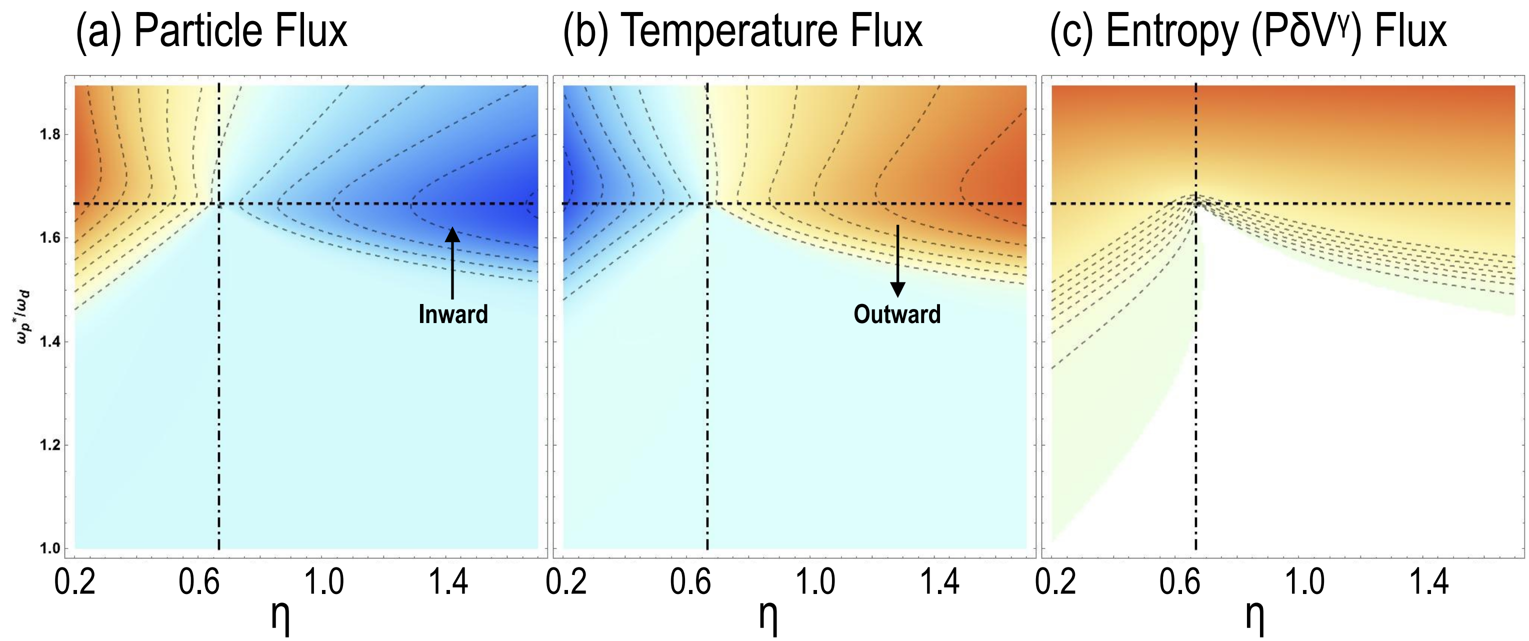
With levitated dipole, inward turbulent transport sets profile evolution



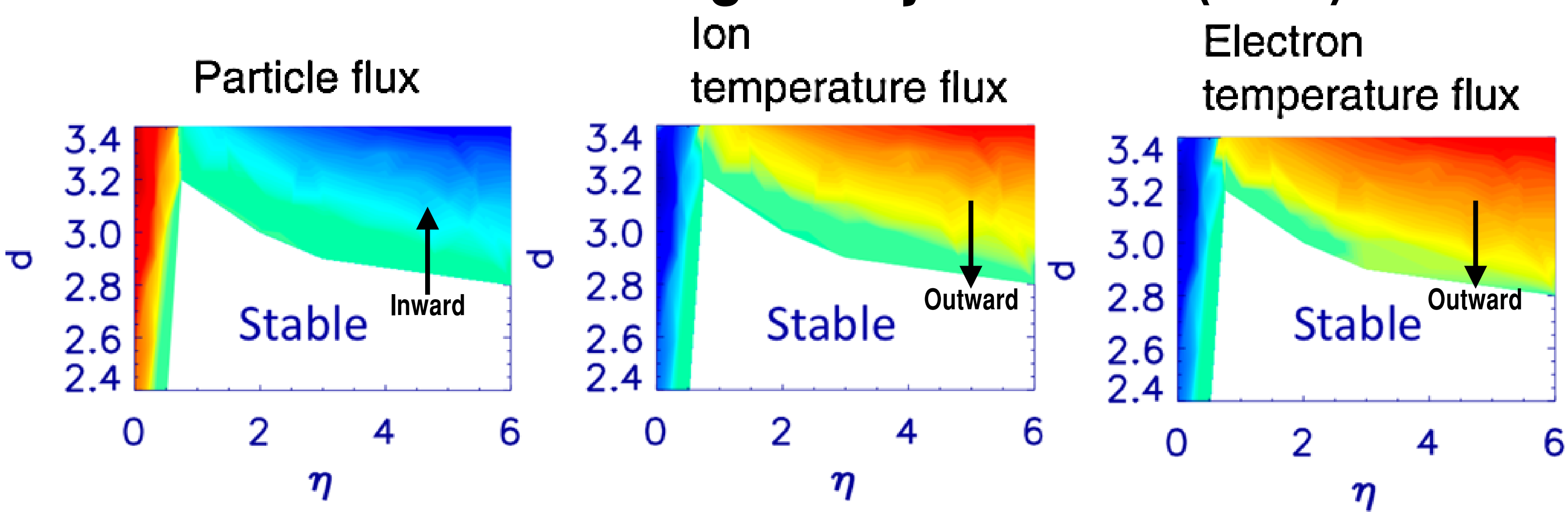


Quasilinear Flux using 2D Bounce-Averaged Fluid Equations with Drift-Kinetic Closure

[Note: Different Scales]



Nonlinear Turbulent Flux using 5D Gyrokinetic (GS2) Simulations



Kobayashi, Rogers, and Dorland, *Phys Rev Lett* **105**, 235004 (2010)

What is *not* known and *needed*...

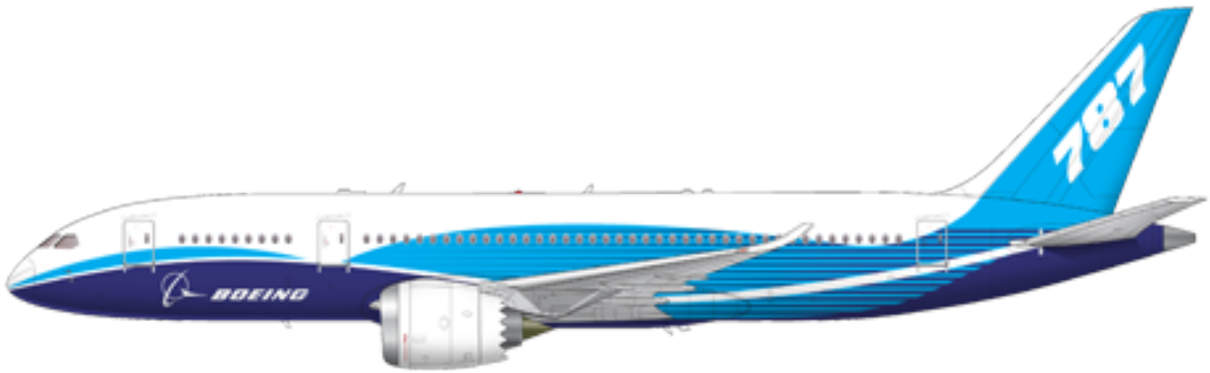
- Can we use reduced dimension nonlinear models (*e.g.* bounce-averaged fluid equations with drift-kinetic closures), with sources and sinks, and reproduce the saturated turbulence levels?
- How do we model the edge boundary interface and SOL flows?
- How do particle and heat sources influence the self-organized 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.

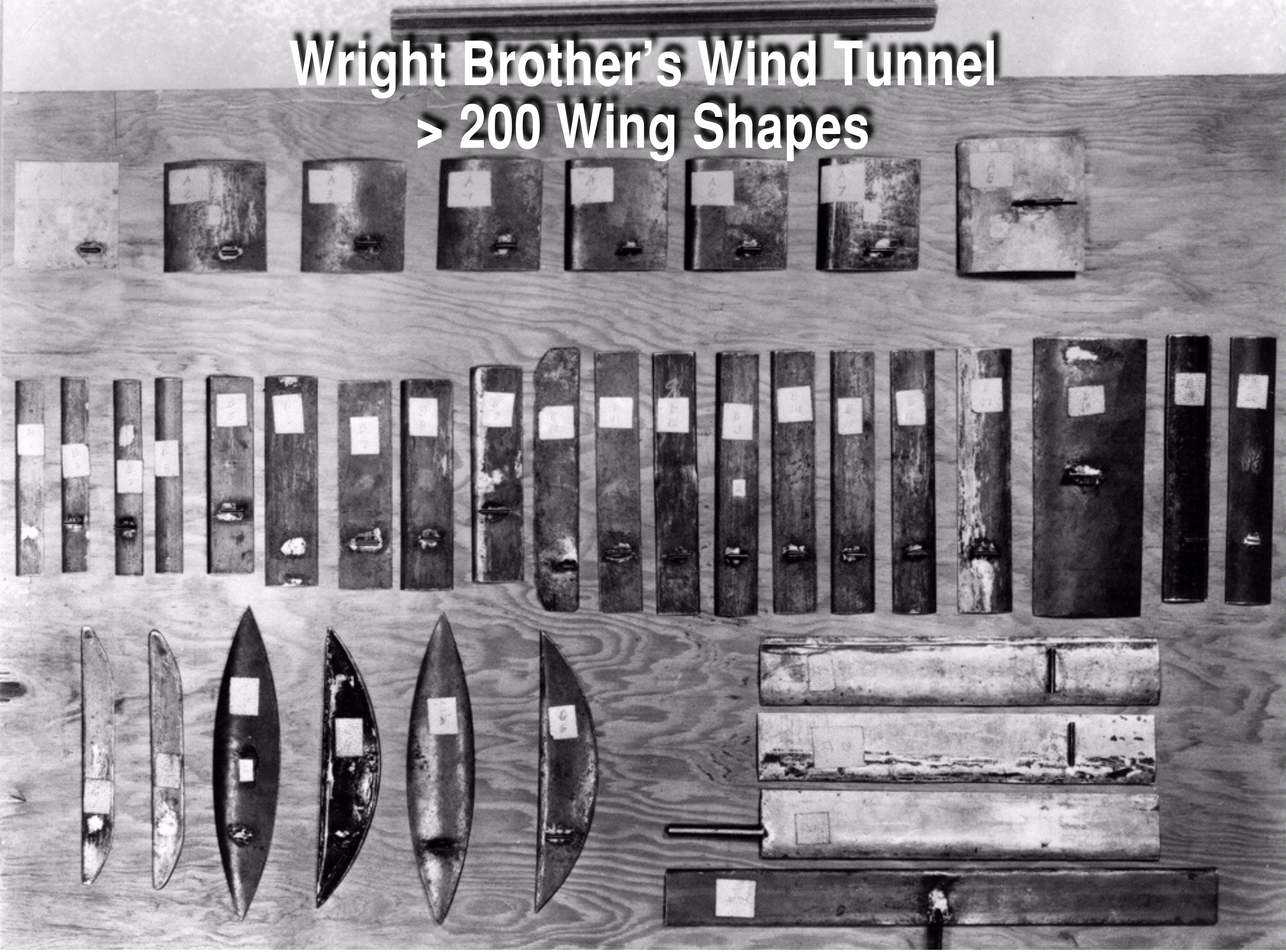
Using existing facilities, this is not an expensive program.

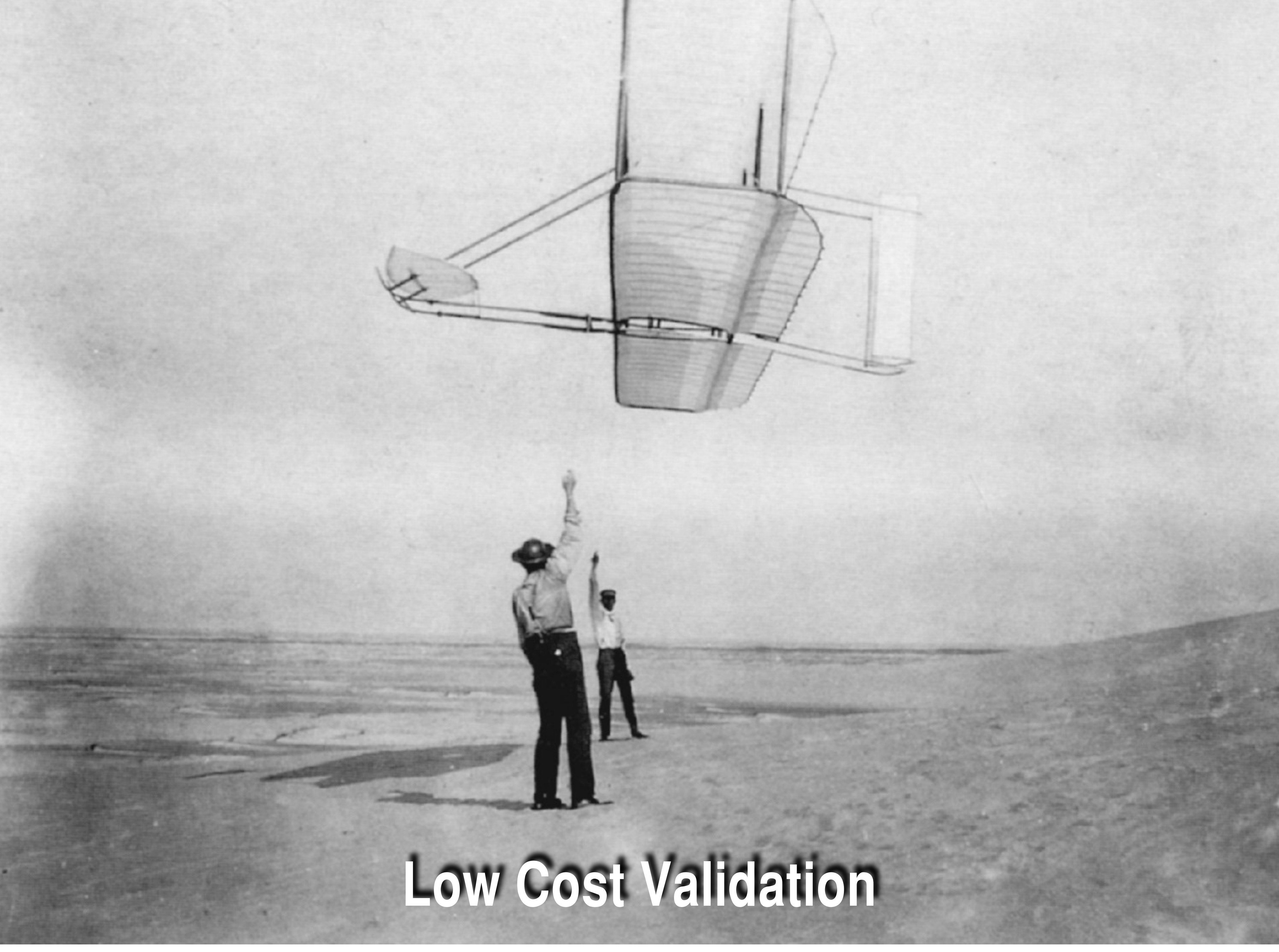
Achieving our long-term goal…



will require many development steps and will benefit from low-cost, simple "wind tunnel" tests

Wright Brother’s Wind Tunnel
> 200 Wing Shapes

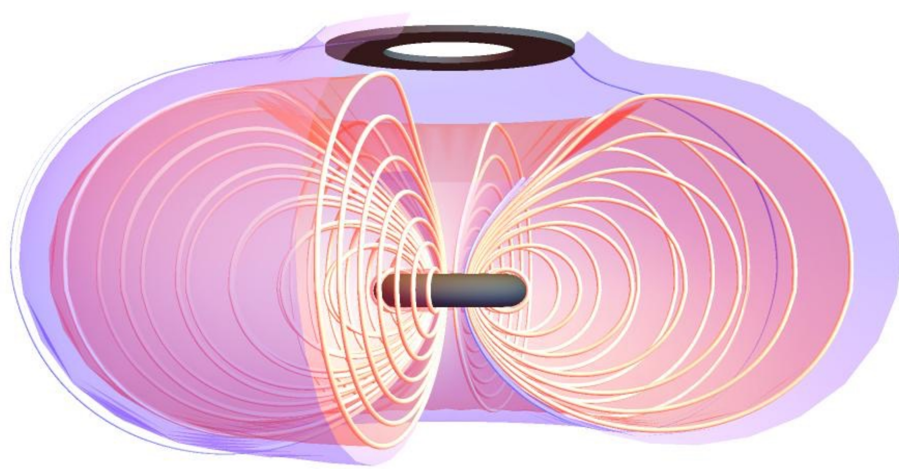



Low Cost Validation

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.