Plasma Turbulence in Magnetic Fusion: What Is Needed to Predict and Reduce It?

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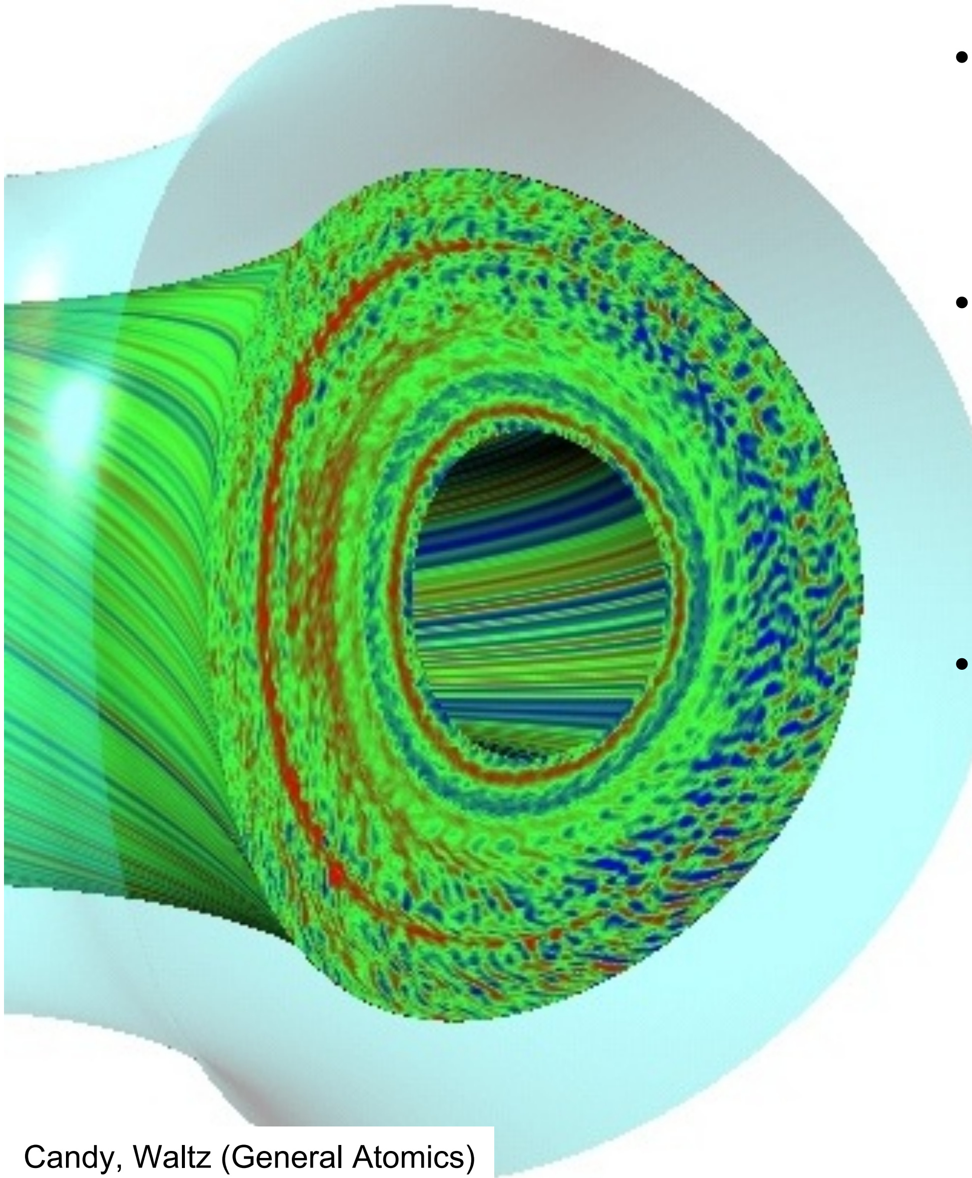
First: Happy Birthday Nat!

- Enjoyed co-teaching Intro to Plasma Physics graduate course with Nat for a number of years
- The first year, I sat in on some of his half of the class. He always has an interesting way of looking at things. Many insights he has passed to students and to our plasma physics community.
- Example: Amazed at his explanation of how one could use RF waves to heat particles in one direction, and get currents in another direction.

Fairly Successful 5-D Gyrokinetic Turbulence Codes Have Been Developed for the main core region



Candy, Waltz (General Atomics)

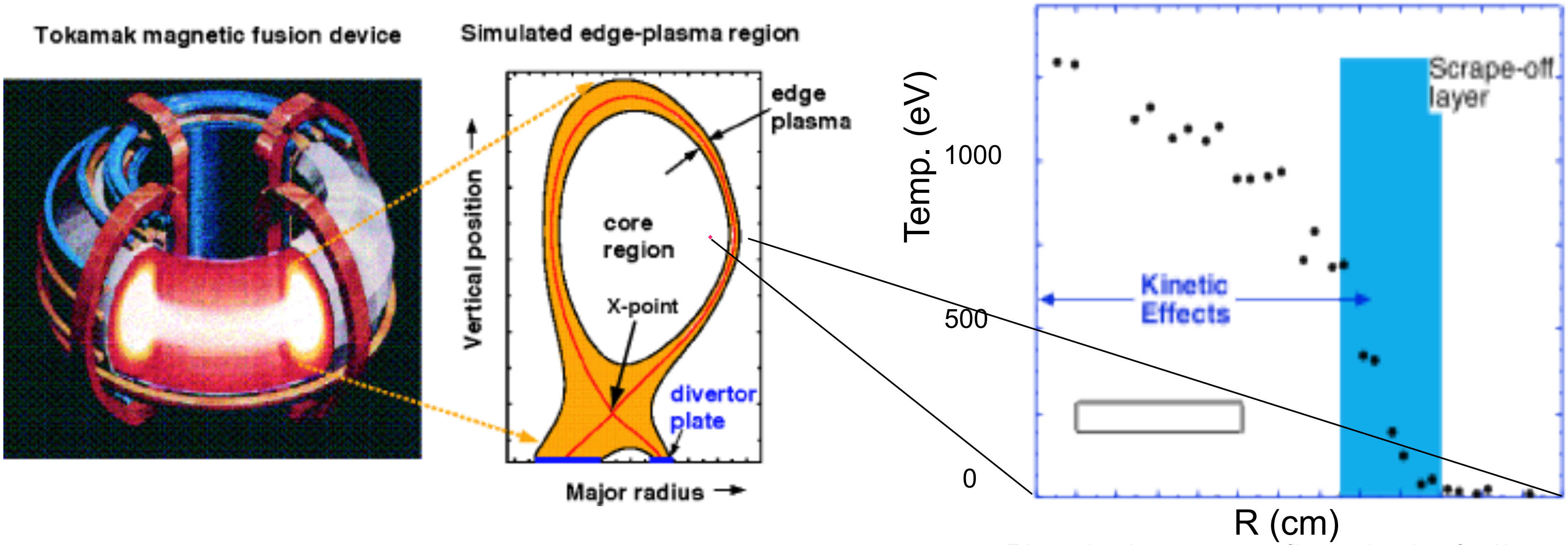
- Gyrokinetics solves for the particle distribution function $f(r,\theta,\alpha,v_{||},\mu,t)$ (avg. over gyration: 6D → 5D)

- Comprehensive codes, including kinetic electrons with full electromagnetic fluctuations, sophisticated algorithms (field-aligned coordinates, pseudo-spectral / high-order finite difference)

- 3 most widely used comprehensive codes all use "continuum"/Eulerian algorithms:

  GENE (Jenko, Goerler, Told, et al.)
  GYRO (Candy, Waltz, et al.)
  GS2 (Dorland, et al.)

Edge region very difficult



Edge pedestal temperature profile near the edge of an H-mode discharge in the DIII-D tokamak. [Porter*2000*]. Pedestal is shaded region.

Present core gyrokinetic codes are highly optimized for core, need new codes to handle additional complications of edge region of tokamaks (& stellarators):

open & closed field lines, plasma-wall-interactions, large amplitude fluctuations, (positivity constraints, non-Maxwellian full-F), atomic physics, non-axisymmetric RMP / stellarator coils, magnetic fluctuations near beta limit…

Hard problem: but success of core gyrokinetic codes makes me believe this is tractable, with a major initiative

Improving Confinement Can Significantly ↓ Size & Construction Cost of Fusion Reactor

Well known that improving confinement & β can lower Cost of Electricity / kWh, at fixed power output.

Even stronger effect if consider smaller power: better confinement allows significantly smaller size/cost at same fusion gain Q ($nT\tau_E$).

Standard H-mode empirical scaling:

$$\tau_E \sim H\, I_p^{0.93}\, P^{-0.69}\, B^{0.15}\, R^{1.97} \ldots$$

($P = 3VnT/\tau_E$ & assume fixed $nT\tau_{E,}\, q_{95},\, \beta_N,\, n/n_{Greenwald}$):

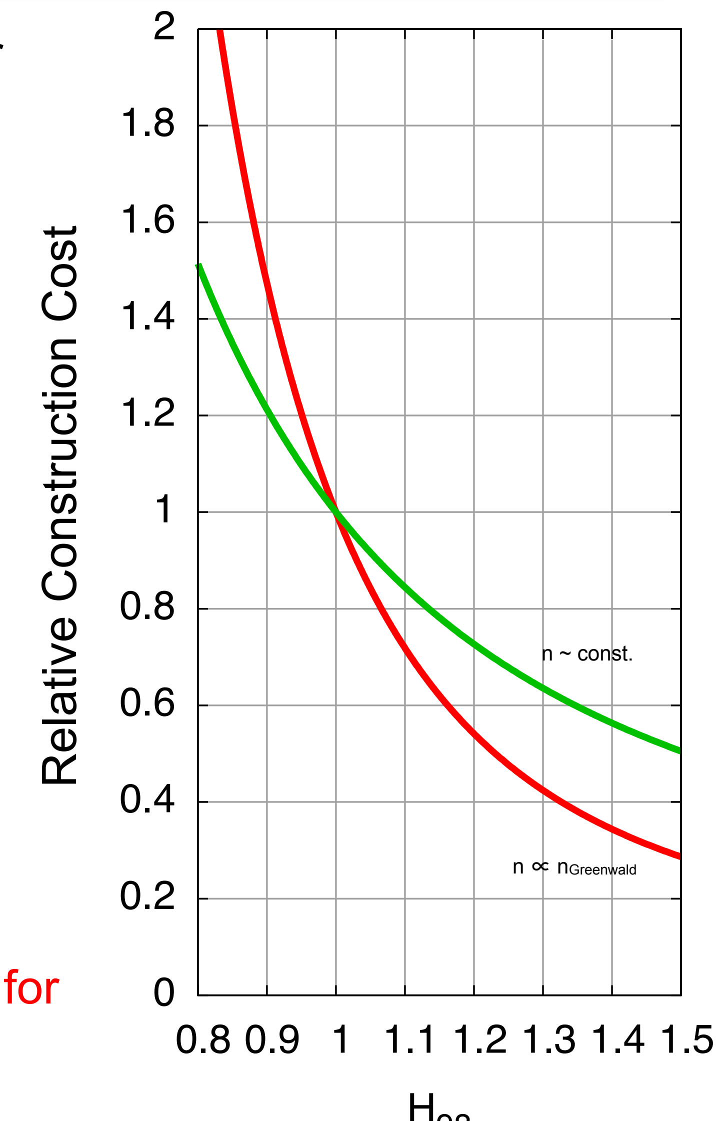
$$\$ \sim R^2 \sim 1 / (H^{4.8}\, B^{3.4})$$

ITER std $H=1$, steady-state $H\sim1.5$

ARIES-AT $H\sim1.5$

MIT ARC $H_{89}/2 \sim 1.4$

Need comprehensive simulations to make case for extrapolating improved H to reactor scales.



(Plots assumes cost ∝ R^2 roughly. Includes constraint on B @ magnet with ARIES-AT 1.16 m blanket/shield, $a/R=0.25$, i.e. $B = B_{mag}\,(R-a-a_{BS})/R$. Neglects current drive issues.)

Interesting Ideas To Improve Fusion

* New high-field superconductors (MIT). Dramatic reduction in size & cost (x1/5 ?)

* Liquid metal (lithium, tin) coatings/flows on walls or vapor shielding: (1) protects solid wall (2) absorbs hydrogen ions, reduces recycling of cold neutrals back to plasma, raises edge temperature & improves global performance. TFTR found: ~2 keV edge temperature. NSTX, LTX: more lithium is better, where is limit?

* Spherical Tokamaks (STs) appear to be able to suppress much of the ion turbulence: PPPL & Culham upgrading 1 --> 2 MA to test scaling

* Advanced tokamaks, alternative regimes (reverse magnetic shear / "hybrid"), methods to control ELMs, higher plasma shaping, advanced divertors.

* Tokamaks spontaneously spin: reduce turbulence & improve MHD stability. ITER spins more than previously expected? Up-down-asymmetric tokamaks/stellarators?

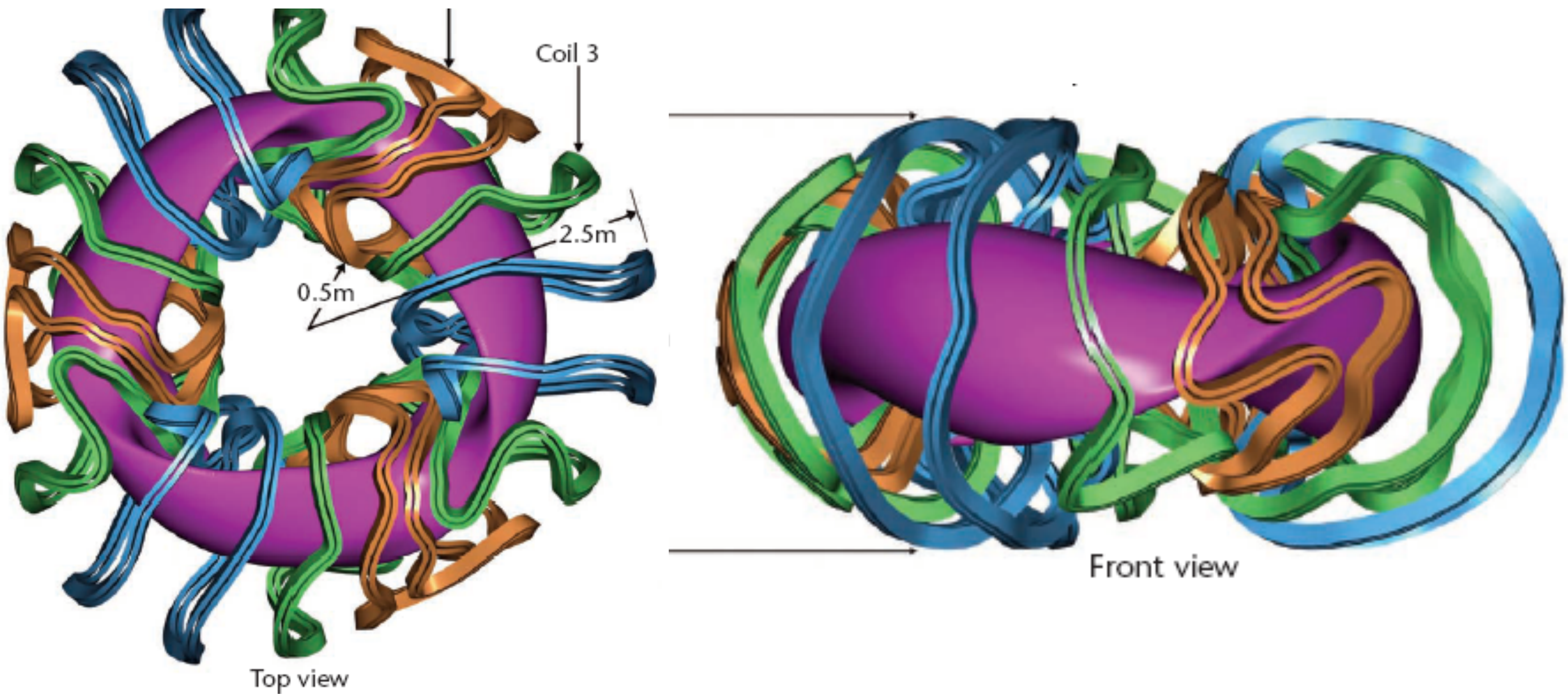
* New stellarator designs, room for further optimization: Hidden symmetry discovered after 35+ years of fusion research. Fixes disruptions, steady-state, density limit.

* More speculative concepts: RFPs, FRCs, …

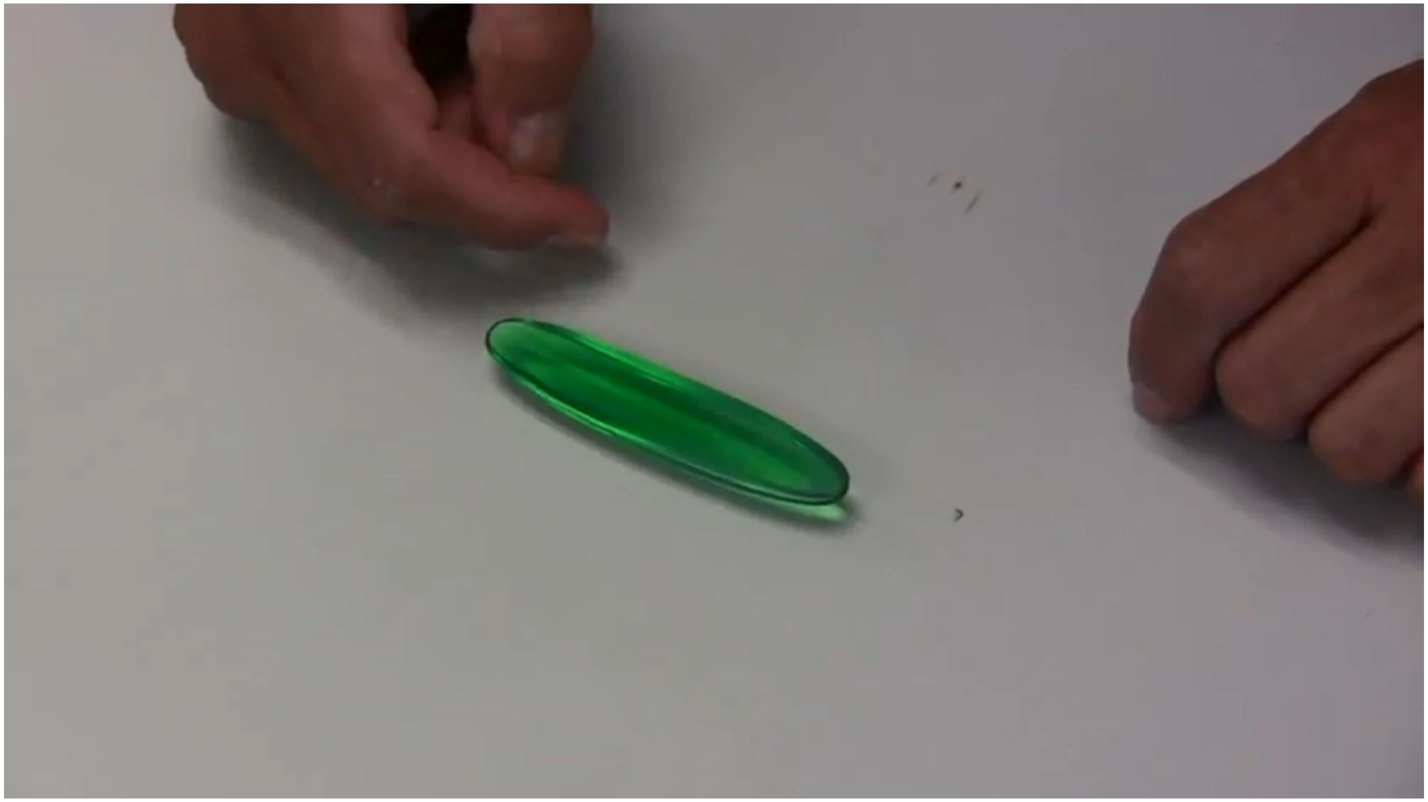
* Robotic manufacturing advances: reduce cost of complex, precision, specialty items

Improved Stellarators Being Studied

- Originally invented by Spitzer ('51), the unique idea when fusion declassified ('57)
- Mostly abandoned for tokamaks in '69. But computer optimized designs now much better than slide rules. Now studying cost reductions.
- Hidden quasi-symmetry discovered in 80's-90's: don't need vector ***B*** exactly symmetric toroidally, |***B***| symmetric in field-aligned coordinates sufficient to be as good as tokamak.
- Magnetic field twist & shear provided by external coils, inherently more stable? Stellarator expts. can exceed Greenwald density limit, no hard beta limit & don't disrupt. Princeton Quasar design + high B coils leads to much smaller stellarator?



A Virtual Birthday Present: Rattleback spinning toy



http://www.youtube.com/watch?v=o2nURFQ-m5g

"Rattleback" toy: spin it one way, and it eventually reverses:

- San Jose Scientific rattleback (concise): http://www.youtube.com/watch?v=o2nURFQ-m5g
- longer, entertaining demo by Dr. Tadashi Tokieda (rattleback example starts at t=1:20. He mentions the general property of chirality and the example of the earth's geodynamo):
  - http://www.youtube.com/watch?v=AcQMoZr_x7Q