Ideas on Research Areas for Gyrokinetics, & GS2 Studies of Stellarators

Greg Hammett, PPPL
Madrid GK 2012 workshop, June, 2012

Possible research ideas to reduce turbulence: lithium, shaping, spinning, stellarators

Need to understand edge turbulence, related to shortfall in outer region of cold L-modes?

Selected highlights from Jessica Baumgaertel's Ph.D. thesis research on GS2 studies of stellarators

- code modifications to make GS2 more robust, particularly for stellarators
- NCSX / elongated tokamak comparison
- quasilinear comparisons with W7-AS

- thesis defense presentation at: http://w3.pppl.gov/~hammett/talks/2012/Baumgaertel_GS2_stellarators_thesis_talk.pdf
- dissertation at: http://w3.pppl.gov/~hammett/papers/2012/jbaumgaertel_thesis_online.pdf

Interesting Ideas To Try To Improve Fusion

* Liquid lithium coatings on walls: (1) protects solid wall from erosion, ELMs (2) absorbs incident plasma, reduces recycling of cold neutrals back to plasma, raises edge temperature & improves global performance. TFTR: ~2 keV edge temperature. NSTX, LTX: more lithium is better, where is the 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, studies of methods to controls Edge Localized Modes, alternative regimes (reversed shear, hybrid scenarios with flattish q profiles) to improve performance

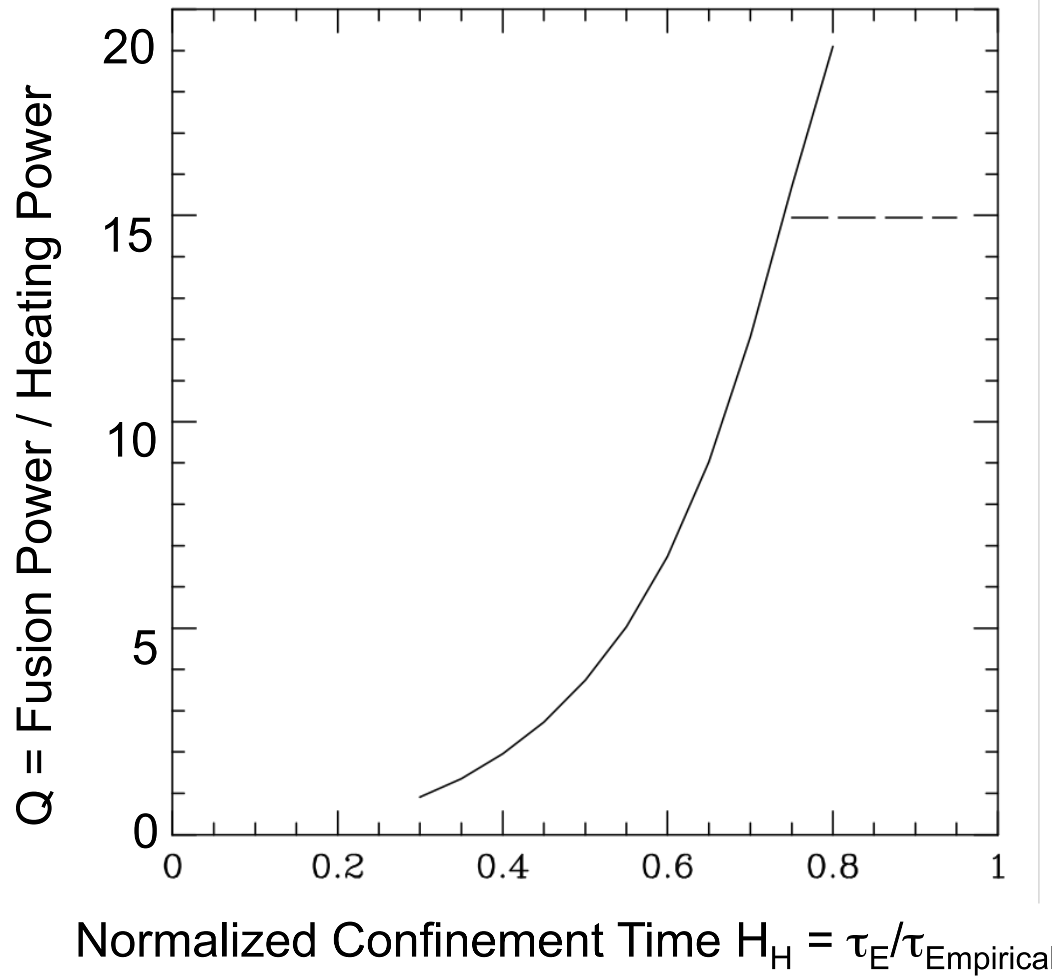
* Tokamaks spontaneously spin, and this sheared flow can reduce background turbulence and improve MHD stability. Can we enhance with updown-asymmetric tokamaks or non-stellarator-symmetric stellarators with quasi-toroidal symmetry?

* Josephine Proll, Per Helander, et al. (Germany) studying a recently discovered “quasi-isodynamic” stellarator configuration in which all trapped particles have averaged good curvature (PRL 2012). Shuts off trapped particle modes. Combine with Lithium to completely shut off all turbulence?

Fusion performance depends sensitively on confinement

Sensitive dependence on turbulent confinement causes some uncertainties, but also gives opportunities for significant improvements, if methods of reducing turbulence extrapolate to larger reactor scales.

$$\frac{dW}{dt} = P_{ext} + P_{fusion} - \frac{W}{\tau_E}$$



Caveats: best if MHD pressure limits also improve with improved confinement. Other limits also: power load on divertor & wall, …

ITER09 (n_e/n_Greenwald = 0.85) more conservative than
ITER95 (n_e/n_Greenwald = 1.5) and
tau_H98P(y,2) / (0.85 tau_H93P) = 0.81

Improved new fusion designs ↓ uncertainties

Density and pressure limits improve with elongation κ & triangularity δ:

Empirical Greenwald density limit

$$n_{Gr} = \frac{I_p}{\pi a^2} \propto \frac{B_T}{Rq_{95}}\left[1+\kappa^2\left(1+2\delta^2\right)\right]$$

Pressure limit

$$\beta = \frac{p}{B^2/8\pi} \propto \frac{I_p}{aB_T} \propto \frac{a}{Rq_{95}}\left[1+\kappa^2\left(1+2\delta^2\right)\right]$$

New ITER-FEAT design uses segmented central solenoid to increase shaping.

FIRE pushes to even stronger shaping (feedback coils closer) & reduced size with high field cryogenic CuBe (achievable someday with high-Tc superconductors?)

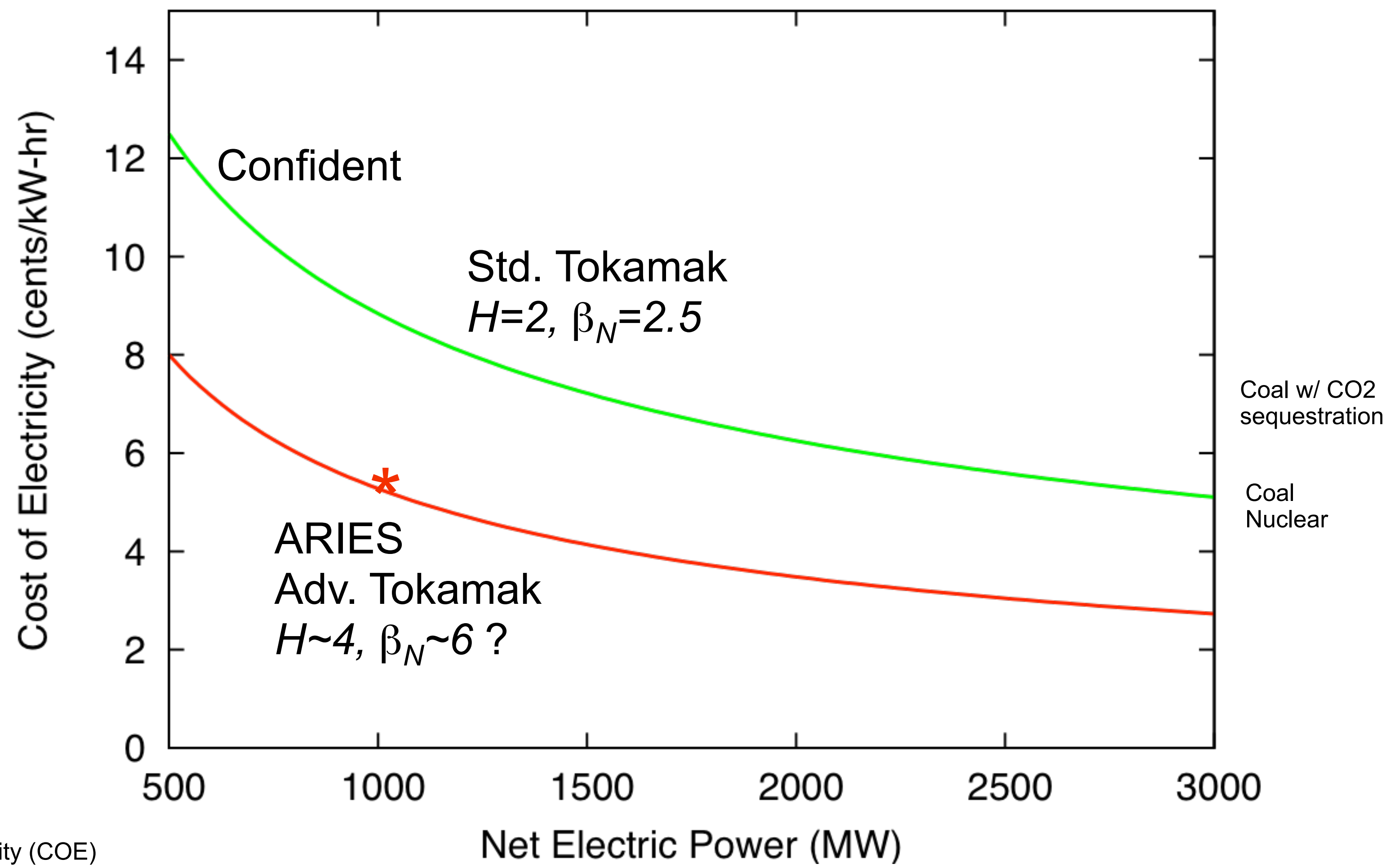
	R (m)	a (m)	B (T)	I_p (MA)	n_{Gr} $10^{20}/m^3$	$\langle n_e \rangle / n_{Gr}$	κ_x	δ_x	P_{fusion} MW	$P_{\alpha(}$/ $2\pi R$	τ_E / τ_{98H}	β_{norm}
ITER-96	8.14	2.80	5.68	21.0	0.85	1.50	1.75	0.35	1500	5.9		
ITER-FEAT	6.20	2.00	5.30	15.1	1.19	0.85	1.85	0.48	400	2.0	1.0	1.8
FIRE	2.14	0.60	10.0	7.7	6.92	0.66	2.00	0.70	150	2.2	1.0	1.8
Aries-AT	5.20	1.30	5.86	12.8	2.41	1.00	2.18	0.84	1760	9.0	1.4	5.4

Caveats: remaining uncertainties regarding confinement, edge pedestal scaling, ELMs, disruptions & heat loads, tritium retention, neoclassical beta limits, but also good ideas for fixing potential problems or further improving performance.

Need rigorous gyrokinetic theoretical explanation of improvement in confinement time at high elongation & triangularity?

- Some studies done (e.g. Belli & Hammett 2008) but gyrokinetic shaping effect not as strong as in experiment.
- Is it primarily an edge effect raising the edge temperature, and then propagating into the core by marginal stability?
- Other important shaping factors? Squareness, reverse-D, ...

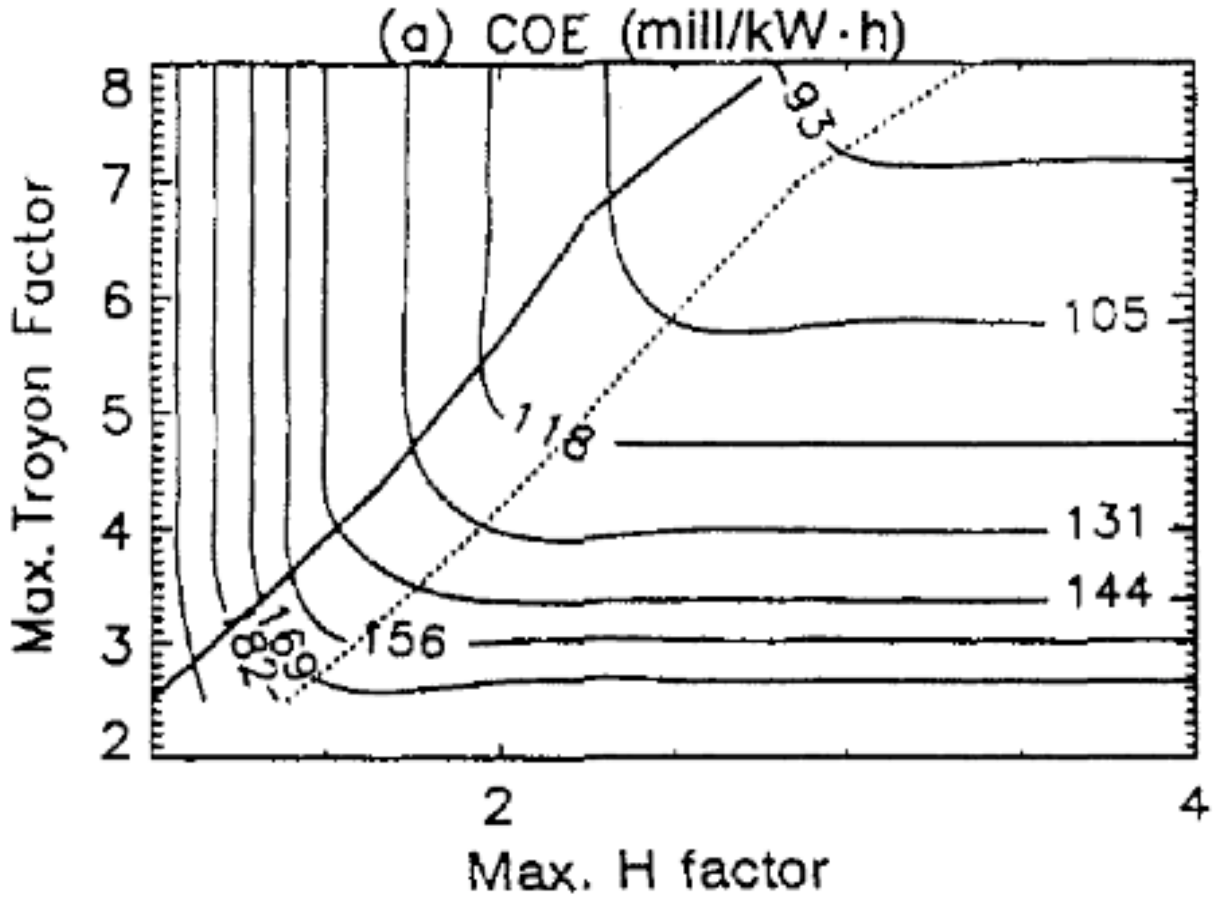
↓ turbulence (1/H) & ↑ MHD stability limits (β) could significantly improve fusion



(Relative Cost of Electricity (COE) estimates in Galambos et al. study, see ARIES reactor studies for more detailed costs estimates.)

From Galambos, Perkins, Haney, & Mandrekas 1995 Nucl.Fus. (very good), scaled to match ARIES-AT reactor design study (2001), http://aries.ucsd.edu/ARIES/

Fusion Reactors benefit from improving Confinement Time and Beta limits simultaneously



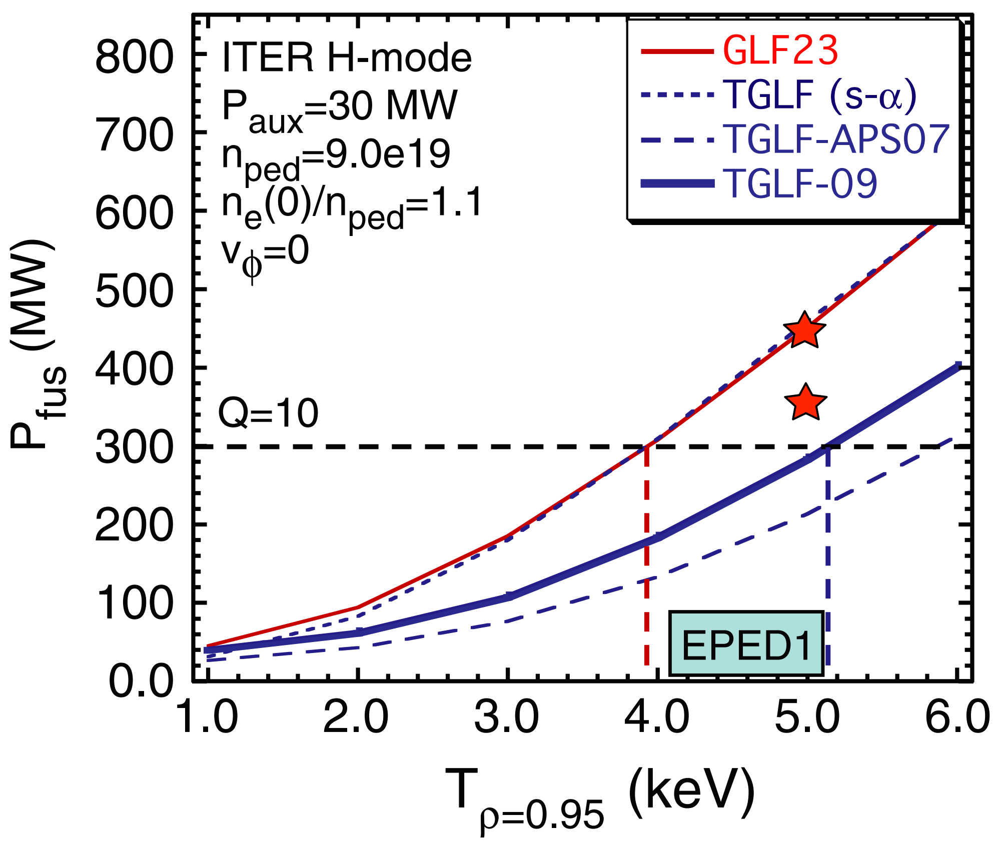
Galambos, Perkins, Haney, & Mandrekas 1995 Nucl. Fus.

Improving Confinement Useful Even at Large Reactor Scales

Sometimes hear the claim that confinement isn't a problem for very large reactors. However,

- ITER standard scenario (P_{fusion}=500 MW, R=6.2 m, Ip=15 MA, β_N=2.0) is H_{98} = 1, but its steady-state scenario (Ip=9 MA) assumes improved performance H_{98} = 1.57, β_N=3.0 with reversed/low magnetic shear, in part to reduce current drive requirements (in part by raising the bootstrap current fraction).
- Similarly, at reactor scales, improved confinement and β_N can increase fusion power, reduce the current drive requirements, reduce the recirculating power, and thus lower the COE.
- Also, raising H allows the minimum machine size to be reduced (at fixed Q), allowing smaller unit costs and reducing the capital cost barriers and risks. Accelerate rate of innovation with more, smaller machines.
- ARIES-AT (P_{fusion}=1719 MW) assumes advanced performance can be achieved with (R=5.2m, Ip = 12.8 MA, H_{98} = 1.5, H_{89} = 2.65, β_N = 5.4).

Need comprehensive simulations of edge turbulence: predicted fusion performance is a strong function of edge temperature



Need to understand and predict power threshold for H-mode transport barrier formation, height of the pedestal, spontaneous rotation mechanisms, ways to suppress ELMs, improvements with lithium walls.

Hard problem, but tractable: continuum gyrokinetic codes very successful in understanding tokamak core, but need extension to handle additional complexities of edge turbulence: large amplitude fluctuations, separatrix and open/closed field lines, ...

Kinsey et al. Nucl. Fus. 2011 http://stacks.iop.org/NF/51/083001

Examples of generating spin by breaking symmetries

"Rattleback" toy: spin it one way, and it eventually reverses. See the discussion by Dr. Tadashi Tokieda (rattleback example starts at t = 1:20, he also mentions the earth's geodynamo):

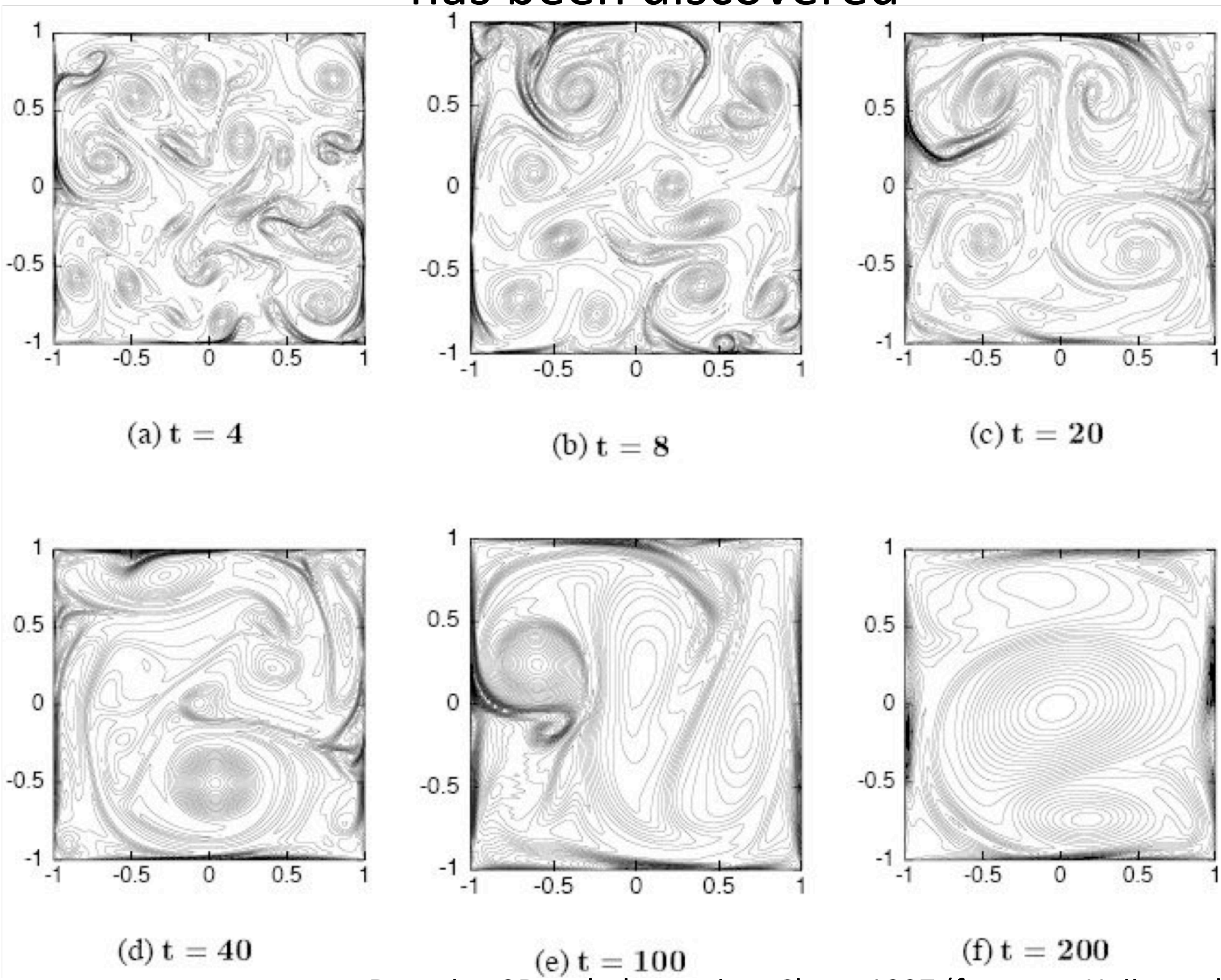
- http://www.youtube.com/watch?v=AcQMoZr_x7Q
- see also http://www.youtube.com/watch?v=CJzRuprW_cc

Japanese dentist (Hideki Watanabe) invents self-stirring pot:

- http://gizmodo.com/5913529/specially-sculpted-pot-creates-a-whirlpool-when-cooking-so-you-never-have-to-stir
- http://www.youtube.com/watch?v=uBKF6cl3Z9o

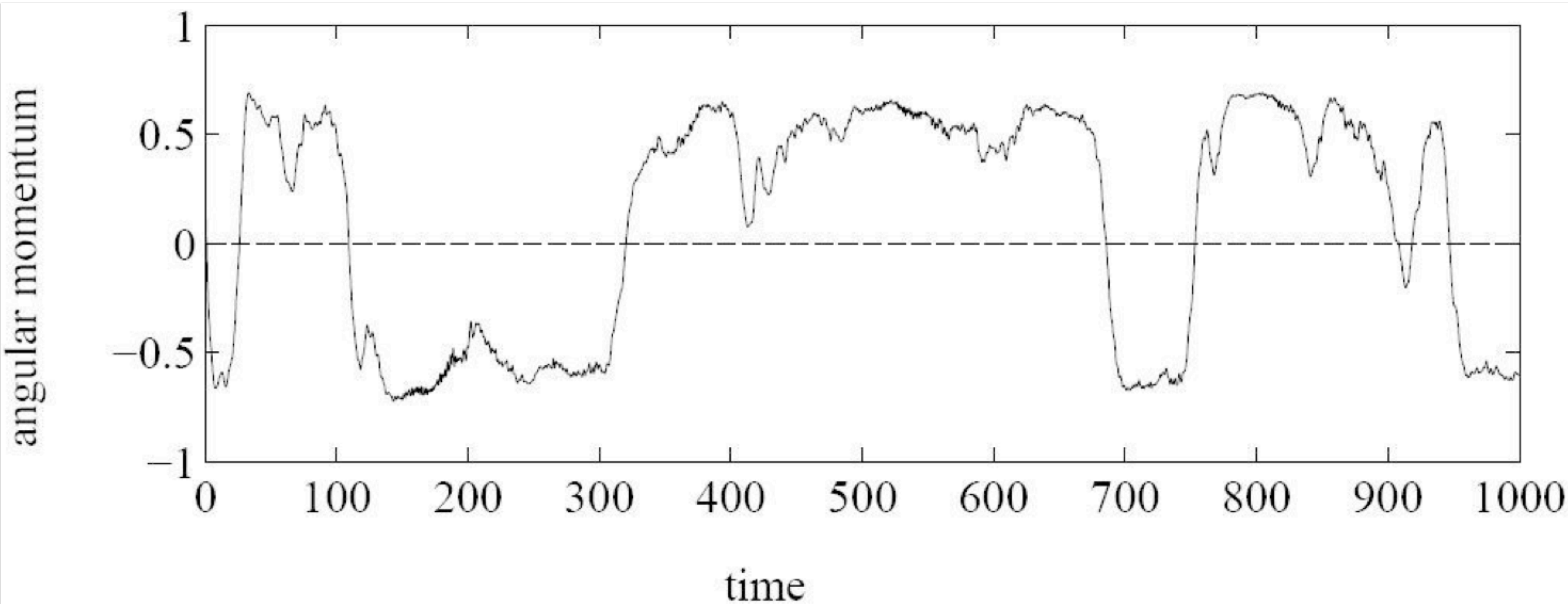
However, there can also be "spontaneous symmetry breaking", which generates spin even in a symmetric system... (next 2 slides)

Spontaneous spin-up in 2-D bounded hydro has been discovered



Decaying 2D turbulence sim., Clercx 1997 (from van Heijst and Clercx 2009)

Spontaneous spin-up in 2-D bounded hydro is large: ~50% of kinetic energy in net solid body rotation

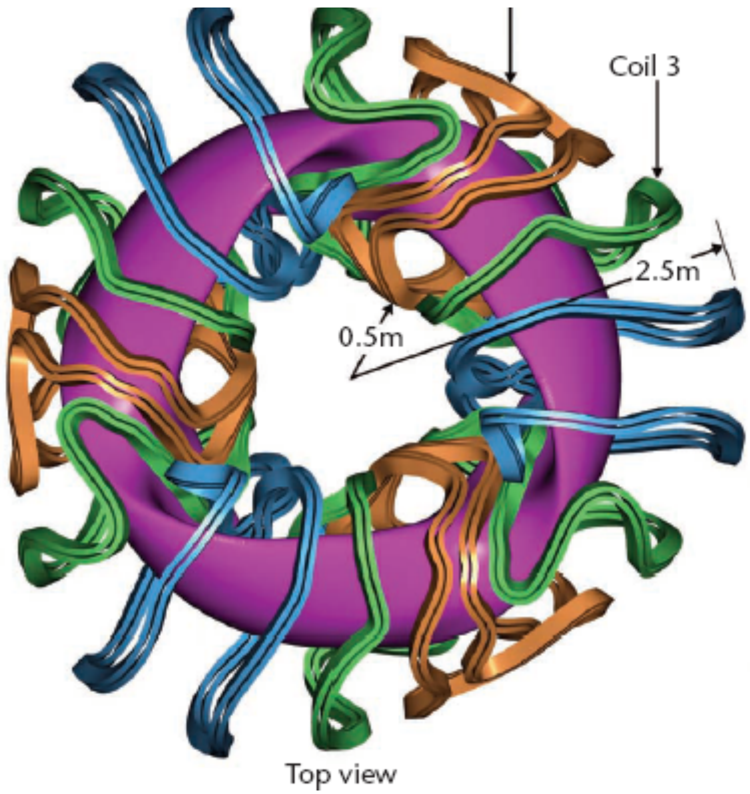


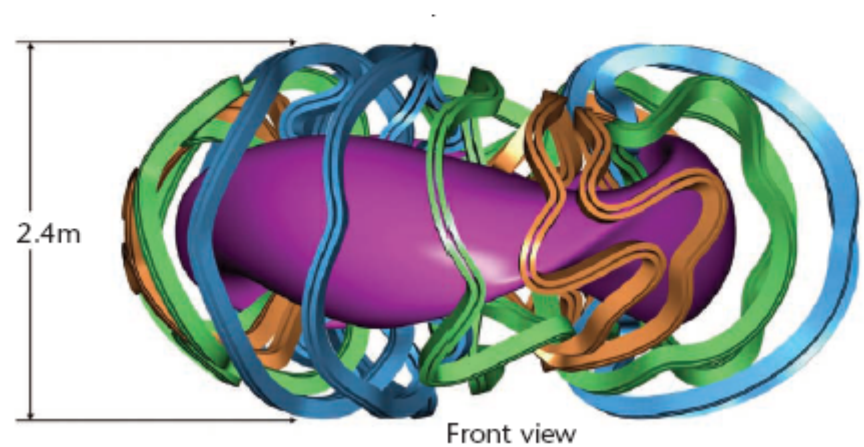
J.B. Taylor, Borchardt, & Helander PRL09: statistical equilibrium theory explains spontaneous spin-up, influence of boundary shape

Driven 2D turbulence sim., Molenaar et al. 2004(from van Heijst and Clercx 2009)

Improved Stellarators Being Studied

- Originally invented by Spitzer ('51), the unique idea when fusion declassified ('58)
- Mostly abandoned for tokamaks in '69. But computer optimized designs now much better than slide rules. Now studying cost reductions.
- Breakthrough: Quasi-symmetry discovered in late 90's: don't need vector ***B*** symmetric exactly toroidally, |***B***| symmetric in field-aligned coordinates sufficient to be as good as tokamak.
- Magnetic field twist & shear provided by external coils, inherently steady-state. Stellarator can exceed Greenwald density limit, don't have hard beta limit & don't disrupt. Quasi-symmetry allows plasma spin to reduce turbulence? Other ways to reduces turbulence?
- Robotics breakthroughs could reduce costs for large complex devices that can't be mass-produced.





Showed selected highlights from Jessica Baumgaertel's Ph.D. thesis research on GS2 studies of stellarators:

- code modifications to make GS2 more robust, particularly for stellarators
- NCSX / elongated tokamak comparison
- quasilinear comparisons with W7-AS

- For her full slides and dissertation, see:

  http://w3.pppl.gov/~hammett/talks/2012/Baumgaertel_GS2_stellarators_thesis_talk.pdf

  http://w3.pppl.gov/~hammett/papers/2012/jbaumgaertel_thesis_online.pdf