Thoughts About Ways To Improve Confinement For Fusion

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Thoughts on improving confinement

- $ vs. H (cost vs. confinement) scaling is very strong, improving confinement could help a lot.

- Some methods of improving confinement:
  – is beam-driven rotation stronger at ITER/reactor scales than we thought?
  – can spontaneous rotation be made stronger?
  – how much can lithium improve confinement? (Can recycling of cold neutrals back into main plasma also be reduced enough with super-X divertor?)
  – new stellarator designs (quasi-symmetry / omnigenity), vast design space for further optimization

Interesting Ideas To Try To Improve Fusion

* Liquid metal (lithium) coatings on walls: (1) protects solid wall (2) absorbs incident plasma, 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 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, alternative operating regimes (reverse magnetic shear or “hybrid”), methods to control Edge Localized Modes, higher plasma shaping. Will beam-driven rotation be more important than previously thought?

* Tokamaks spontaneously spin: can reduce turbulence and improve MHD stability. Can we enhance this with up-down-asymmetric tokamaks or non-stellarator-symmetric stellarators with quasi-toroidal symmetry?

* Many possible stellarator designs, room for further optimization: Quasi-symmetry / quasi-omnigenity improvements discovered relatively recently, after 40 years of fusion research.   Stellarators fix disruptions, steady-state, density limit.

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

Improving Confinement Useful Even at Large Reactor Scales

Sometimes hear the claim that confinement isn't a problem for large reactor scales. 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 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 (has reversed shear) (R=5.2m, Ip = 12.8 MA, H_{98} = 1.5, H_{89} = 2.65, β_N = 5.4).

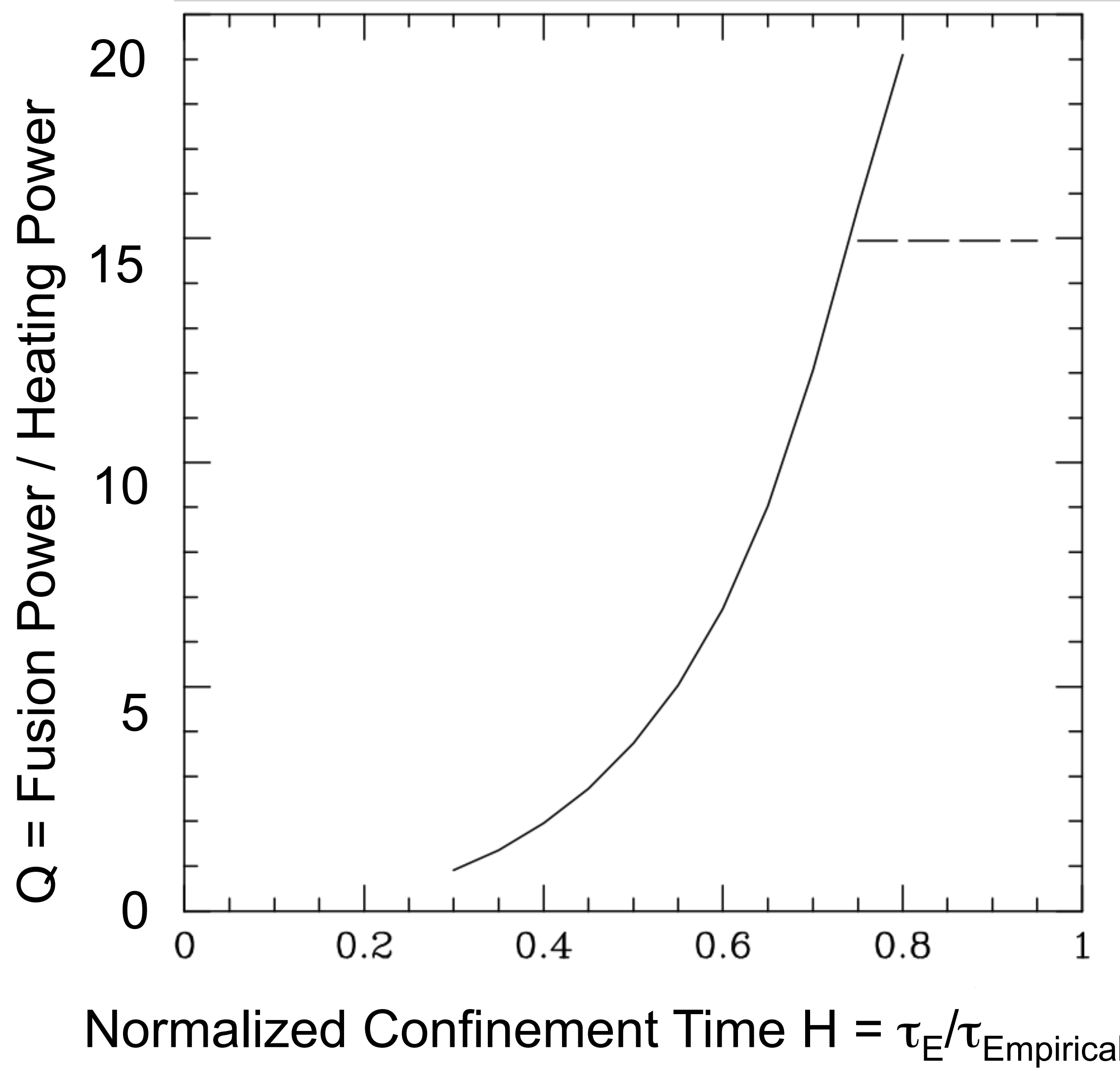
Fusion performance depends sensitively on confinement

Improving confinement factor H can lead to significantly smaller & cheaper fusion devices:

Start with ITER 98 H-mode empirical scaling for τ_E. Minimize capital cost by building smallest machine possible, while keeping fixed the fusion gain Q ($nT\tau_E$), beta, shape, $n/n_{\text{Greenwald}}$:

$$\text{Cost} \sim R^2 \sim 1 / H^{4.76}$$

a 26% improvement in confinement reduces cost by factor of 3.
a 16% improvement in confinement reduces cost by factor of 2.



Caveats: lower bound in size set by blanket thickness. Lowering net COE best if MHD pressure limits also improve with improved confinement.

Lots of properties improve with plasma current and thus with elongation κ and triangularity δ:

Empirical Greenwald density limit:

$$n_{Gr} = \frac{I_p}{\pi a^2}$$

Troyon pressure limit:

$$\beta \propto \beta_N \frac{I_p}{a B_T}$$

Confinement time:

$$\tau_{E,th}^{IPB98(y,2)} \propto H I_p^{0.93} P^{-0.69} R^{1.97} \ldots$$

Plasma current increases with stronger shaping:

$$I_p = \frac{a^2 B_t}{R q_{95}} f_s(\kappa_{95}, \delta_{95})$$

$$f_s \approx \frac{1 + \kappa_{95}^2 (1 + 2\delta_{95}^2)}{2} \approx \kappa_{95}^{2.5}$$

rough scaling with δ increasing with κ

Use $nT\tau_E \sim (P\tau_E/V)\tau_E$, eliminate P at fixed $nT\tau_E$ (fixed Q). Fix β_N, operating T, a/R, B_T, q_{95}, find

$$\text{Capital Cost} \sim R^2 \kappa \sim \frac{1}{\kappa^5}$$

At fixed fusion power, COE still improves significantly: COE $\sim 1/\kappa^{1.3}$.

↓ turbulence & ↑ β could significantly improve fusion

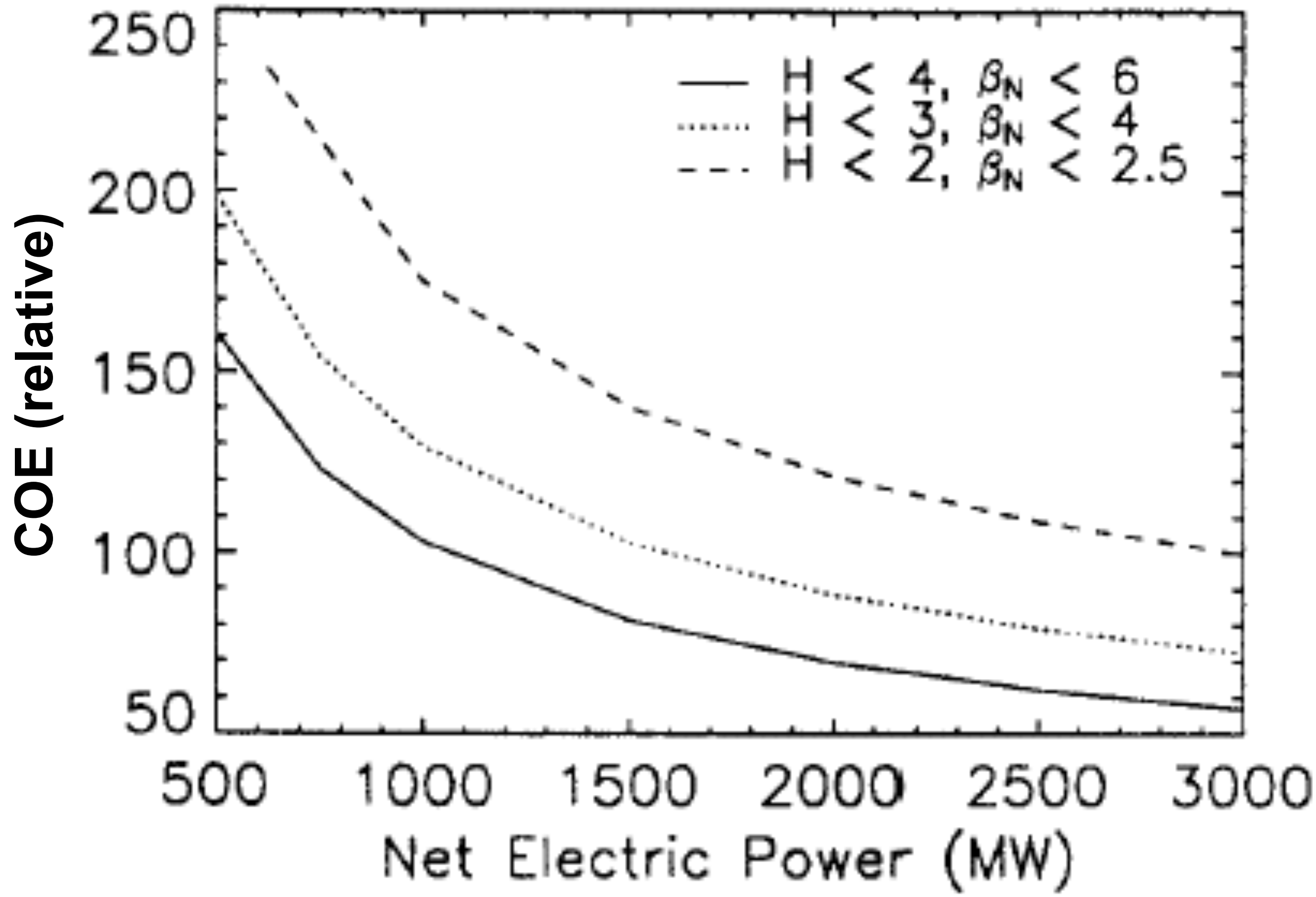
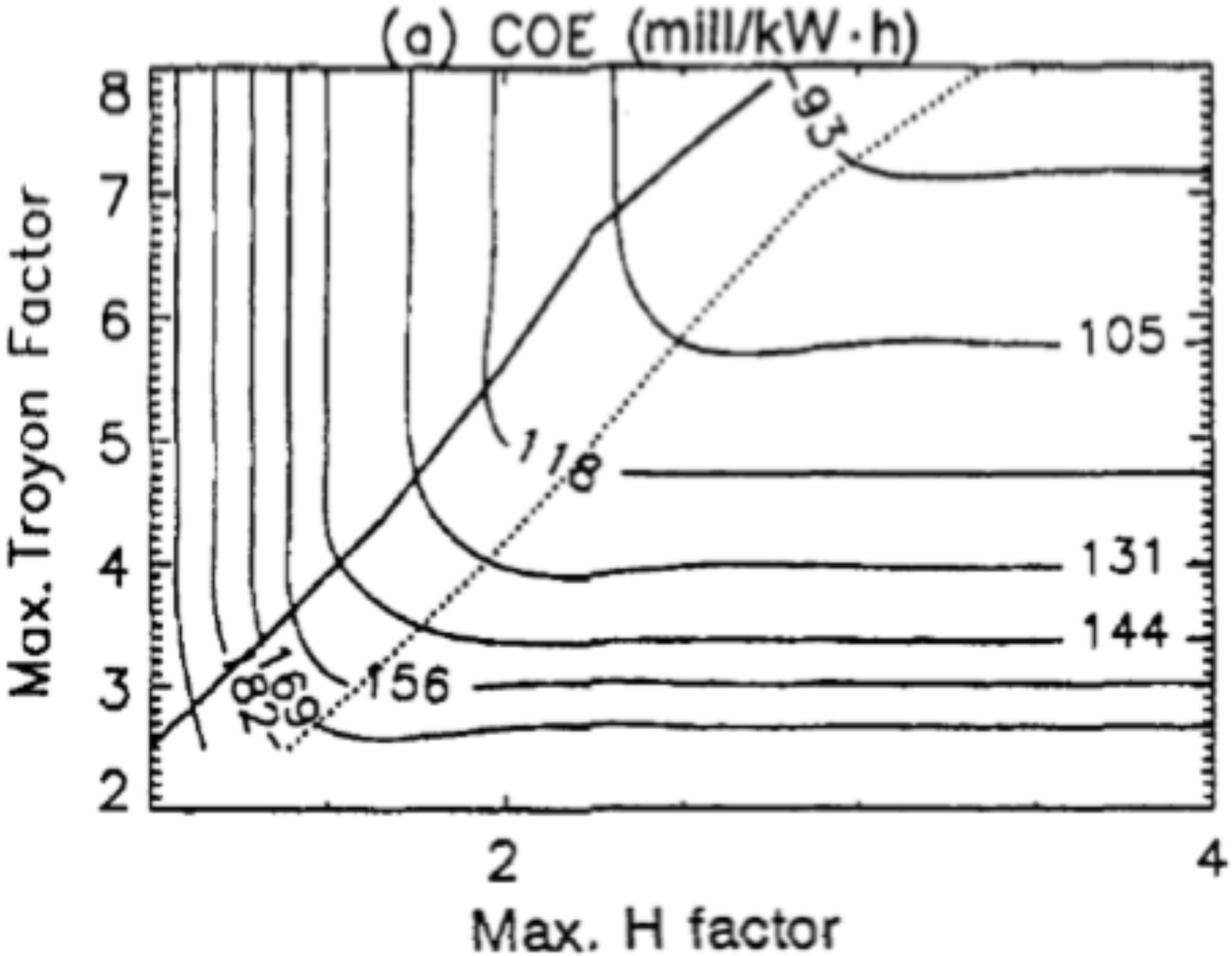


FIG. 4. Minimum COE steady state reactor parameters versus the net electric output. Cases are shown for three physics levels: (a) present day levels that would be sustainable in a non-transient manner in a conservatively designed system ($H \leq 2, \beta_N \leq 2.5$), (b) moderately improved physics ($H \leq 3, \beta_N \leq 4$) and (c) advanced physics ($H \leq 4, \beta_N \leq 6$).

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

Fusion Reactors benefit from improving Confinement Time and Beta limits simultaneously



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

Fusion devices improve at higher shaping

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

Empirical Greenwald density limit
$$n_{Gr} = \frac{I_p}{\pi a^2} \propto \frac{B_T}{R q_{95}} \left[1 + \kappa^2 \left(1 + 2\delta^2\right)\right]$$

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

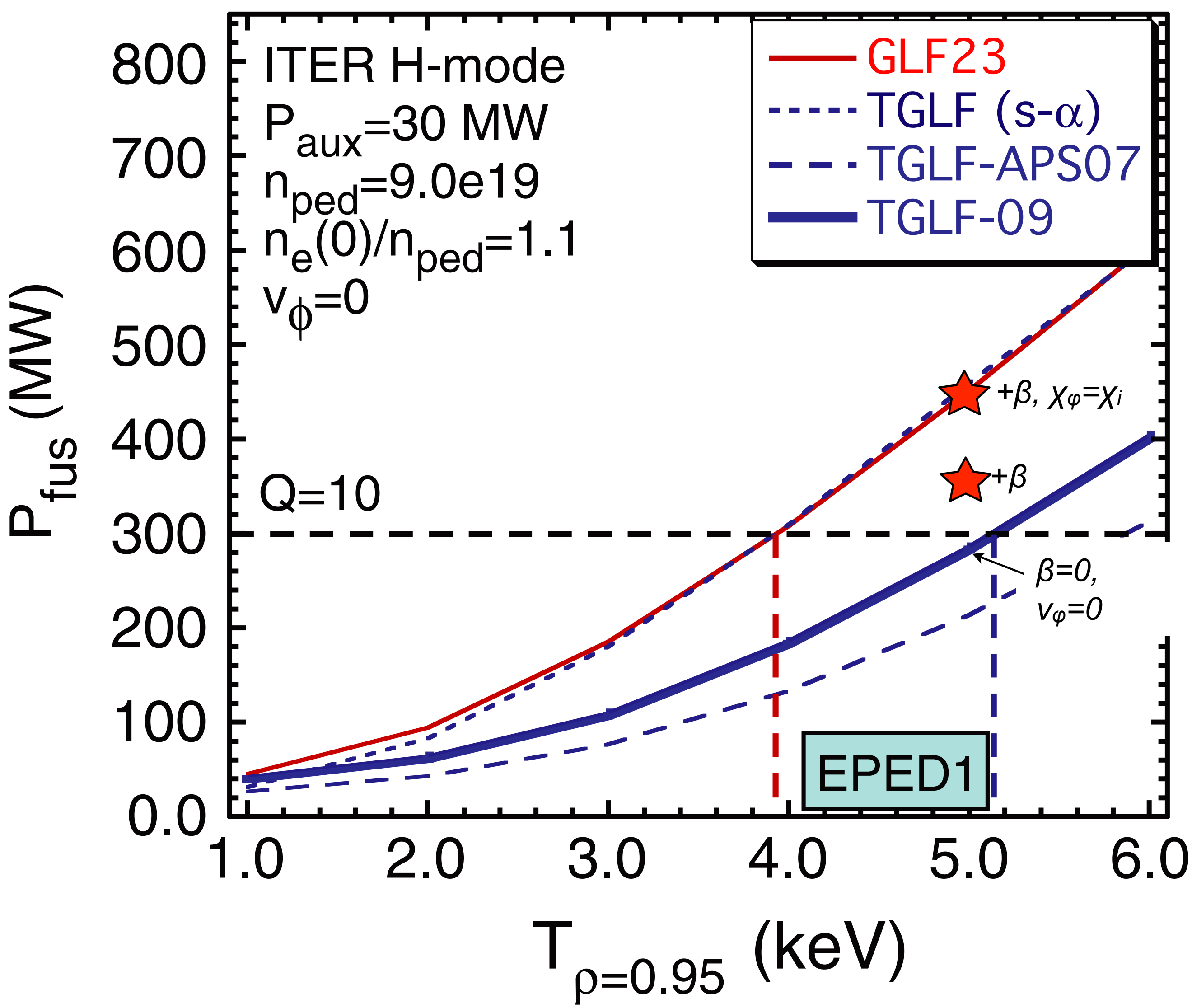
Current ITER-FEAT design uses segmented central solenoid to increase shaping.

ARIES-AT pushes to even higher shaping, by moving vertical feedback coils inside VV and stabilizing shell between split blankets (Kessel design).

	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_α / $2\pi R$	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.

Beam-driven rotation in ITER might enhance Q significantly



Including rotation predicted from ITER's beams assuming $\chi_\varphi = \chi_i$ leads to *M ~ 0.06* and 21% increase in P_{fusion}.

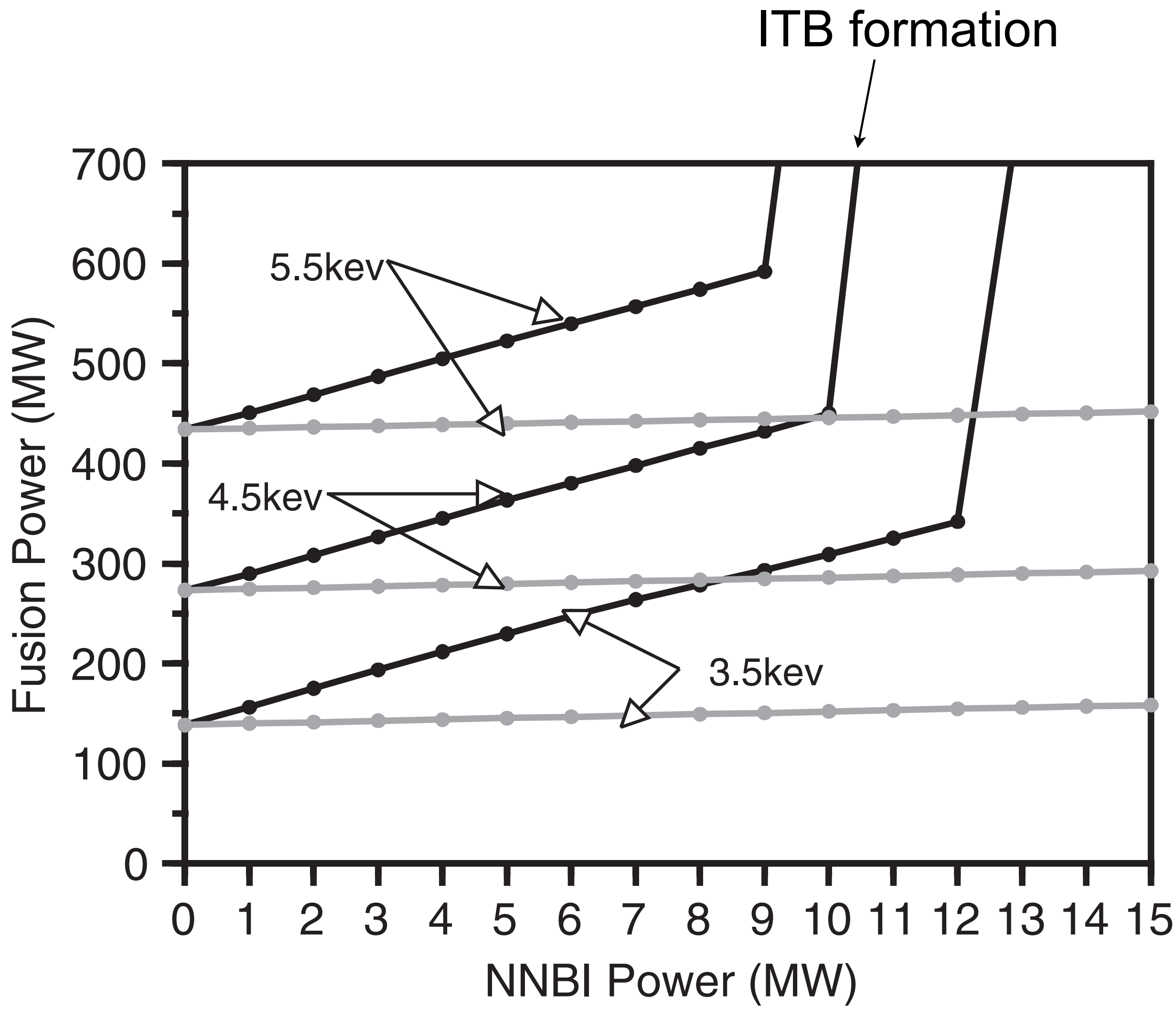
However, this neglects Coriolis pinch effects. JET experiments indicate the effective $\chi_\varphi = 0.2\, \chi_i$ including pinch effects. Could lead to a doubling of P_{fusion}.

GLF23 χ_φ predicts large rotation: ITB forms with just 10 MW of NBI (ITER will have 50 MW+) (Staebler 06, Budny 09)

Need full nonlinear GK simulations (GS2+Trinity) to handle subcritical turbulent momentum transport (Highcock, Barnes)

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

Beam-driven rotation in ITER might enhance Q significantly



Earlier rotation predictions (Staebler 2006) were done directly using the GLF23 transport model for χ_φ:

found a lower $\chi_\varphi \sim 0.2\, \chi_i$ (according to recollection) leading to $M = u_\varphi / v_{ti} = 0.18$ for Pnbi = 5 MW. But ITER capability is P_{nbi} = 33 MW initially, 50 MW eventually, so would extrapolate to $M > 1$ at full power?!! (I think the Coriolis pinch was ignored in those simulations so the rotation might get even stronger.)

Net result: GLF23 predicts that beam-driven rotation in ITER will greatly enhance fusion power.

Need to benchmark newer TGLF momentum transport predictions with experiments.

Eventually need transport codes coupled with full gyrokinetic turbulence simulations (like Trinity+GS2), because of possible nonlinear complexities ($du_\parallel/dr$ destabilization, subcritical turbulence)

Staebler et al. 2006 http://iopscience.iop.org/0029-5515/46/8/L02/

see also Budny 2009, http://iopscience.iop.org/0029-5515/49/8/085008/

(these calculations assumed 350 keV beams, so the rotation will be somewhat lower at the current MeV design of 1 MeV.)

Beam-driven rotation in ITER larger than one might expect at first

Expect that rotation in larger fusion reactors will be smaller than in present experiments because

(1) higher energy beams are used to penetrate into plasma, and the torque to power ratio of the beam drops with beam voltage. But drops only as *1/sqrt(E_{beam})*

(2) isotropic alpha heating is stronger so the beams are a smaller fraction of total heating. But alpha heating fraction is only *(Q/5)/(1+Q/5)*, so at moderate Q the beam torque is still significant.

Crude global power balance and momentum balance scaling arguments (ignoring critical gradients and edge boundary conditions), gives:

$$M \sim \frac{\chi_i}{\chi_\phi} 3 \sqrt{\frac{T}{E_{\text{beam}}}} \frac{1}{1+Q/5}$$

TFTR got *M ~ 1*, so scaling to ITER still gives fairly large M.
(Reactor designs that don't have NBI will of course need some other torque mechanism if they need rotation.)

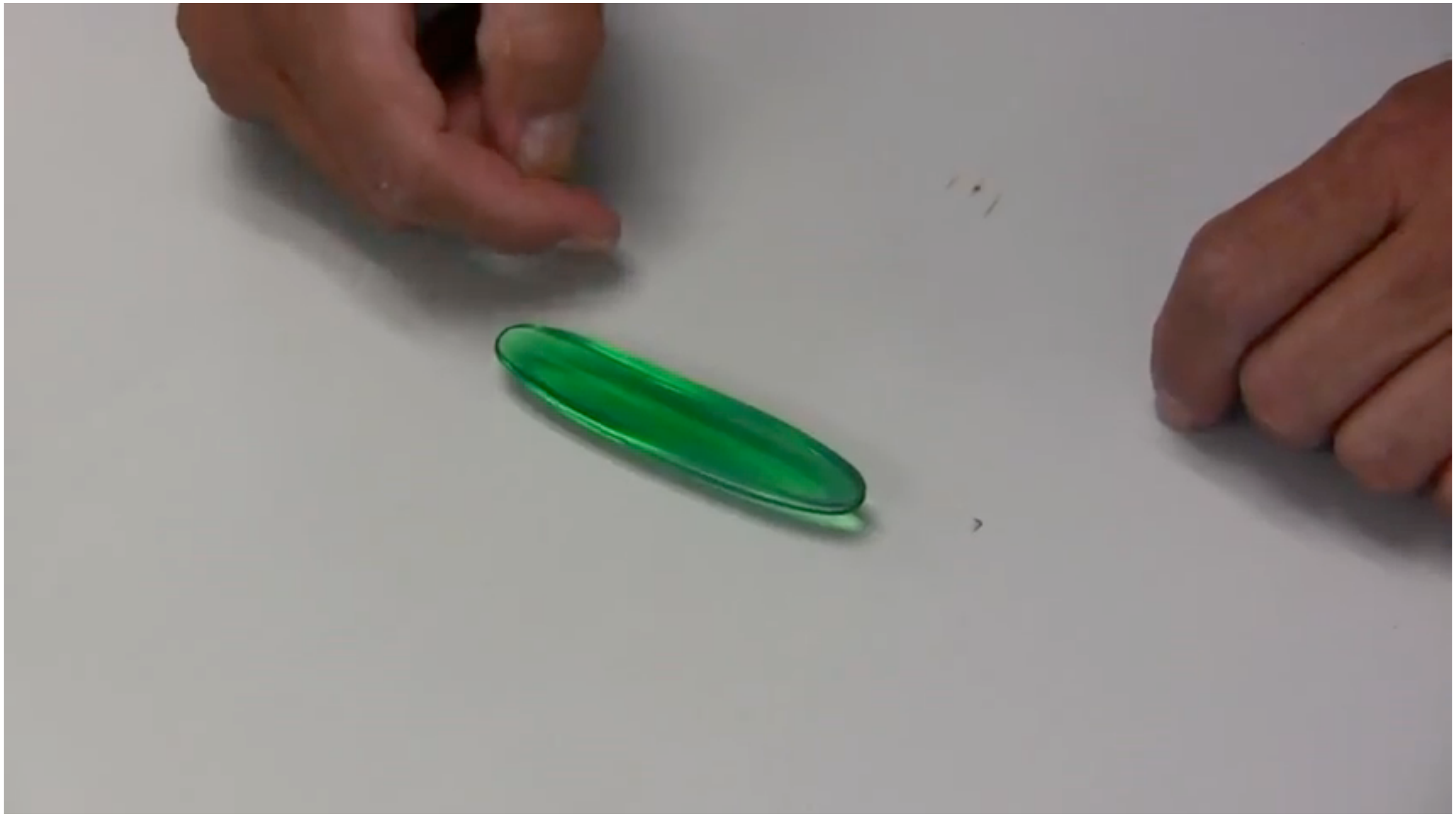
Examples of generating spin by breaking symmetries

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

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

However, there can also be "spontaneous symmetry breaking", which generates spin even in a symmetric system...

Rattleback spinning toy



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

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

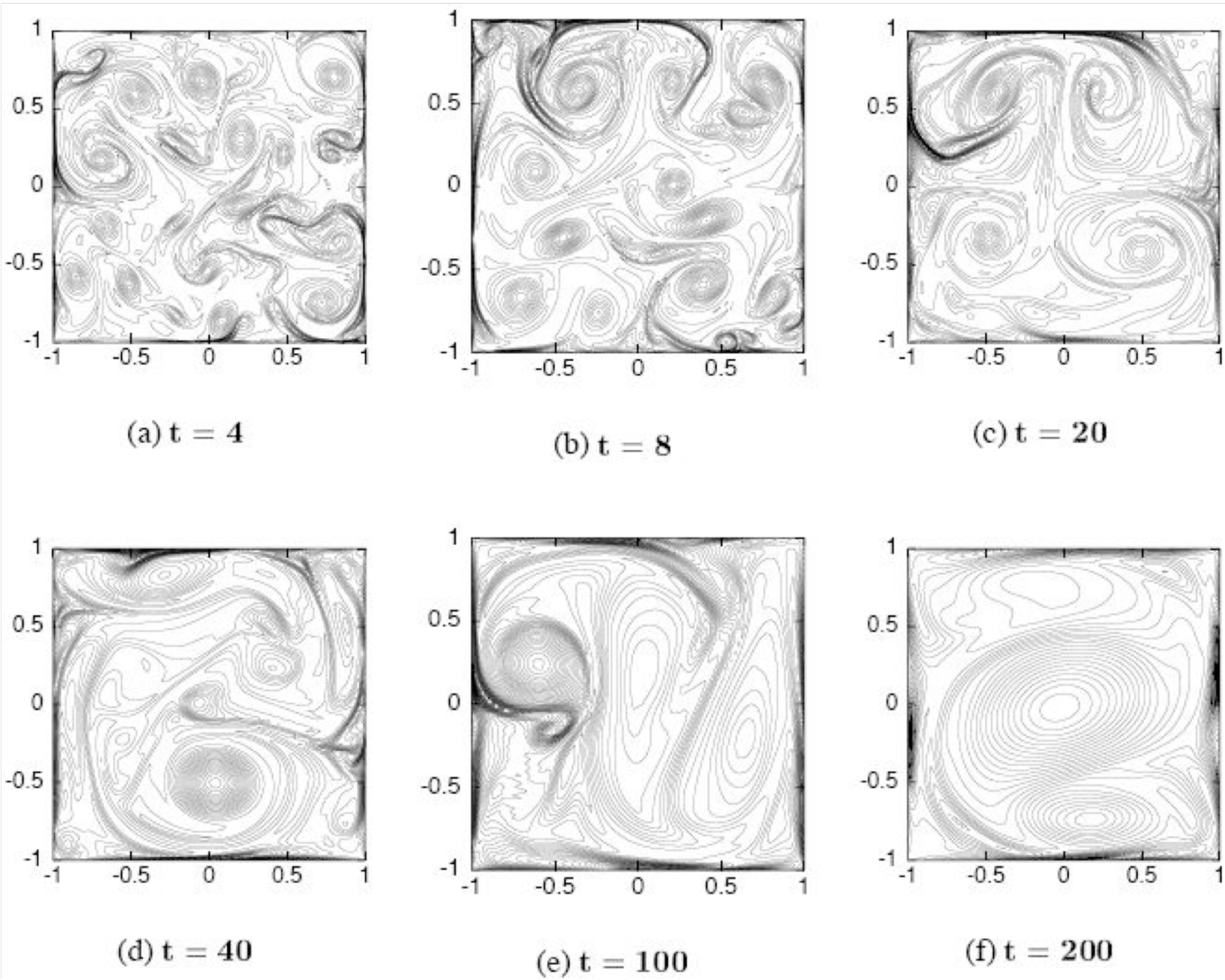
- San Jose Scientific rattleback (concise): http://www.youtube.com/watch?v=o2nURFQ-m5g
- longer, entertaining demo by Dr. Tadashi Tokieda (rattleback example starts at t=1:20. He mentions the general property of chirality and the example of the earth's geodynamo):
  - http://www.youtube.com/watch?v=AcQMoZr_x7Q

Japanese Spinning Pot

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

Spontaneous spin-up in 2-D bounded hydro

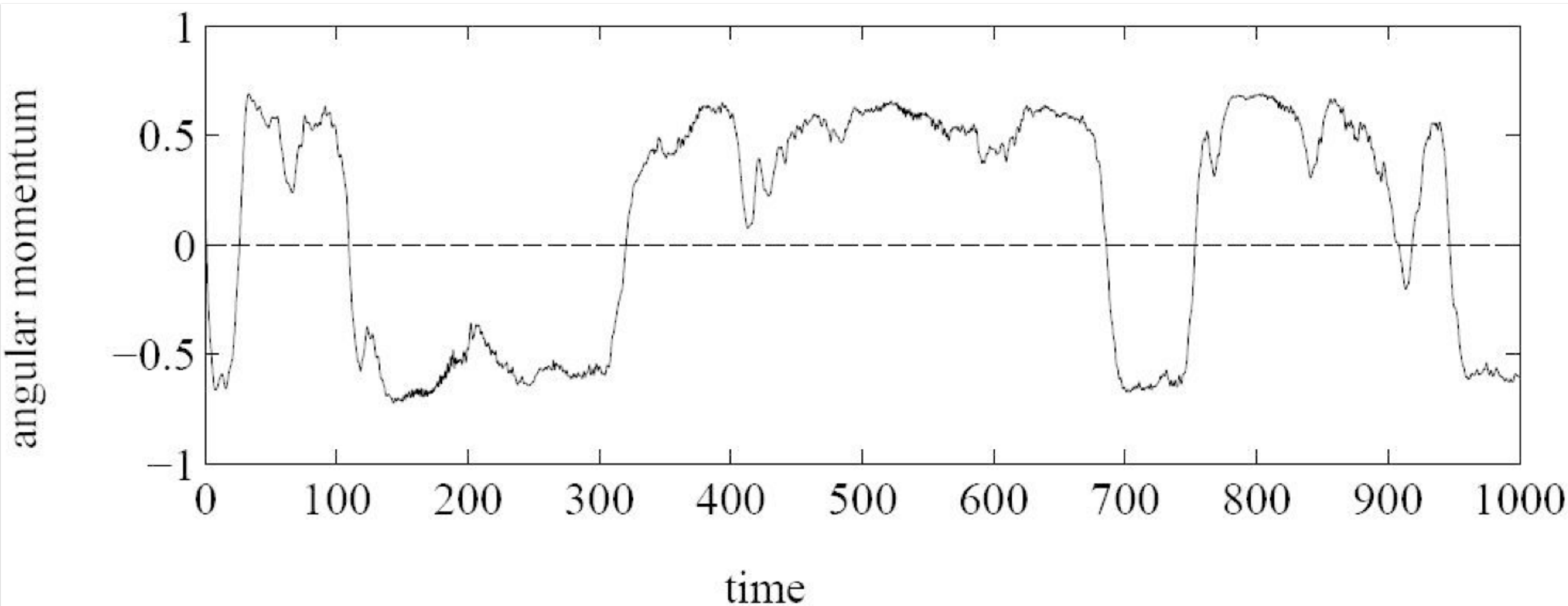


(a) t = 4 (b) t = 8 (c) t = 20

(d) t = 40 (e) t = 100 (f) t = 200

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

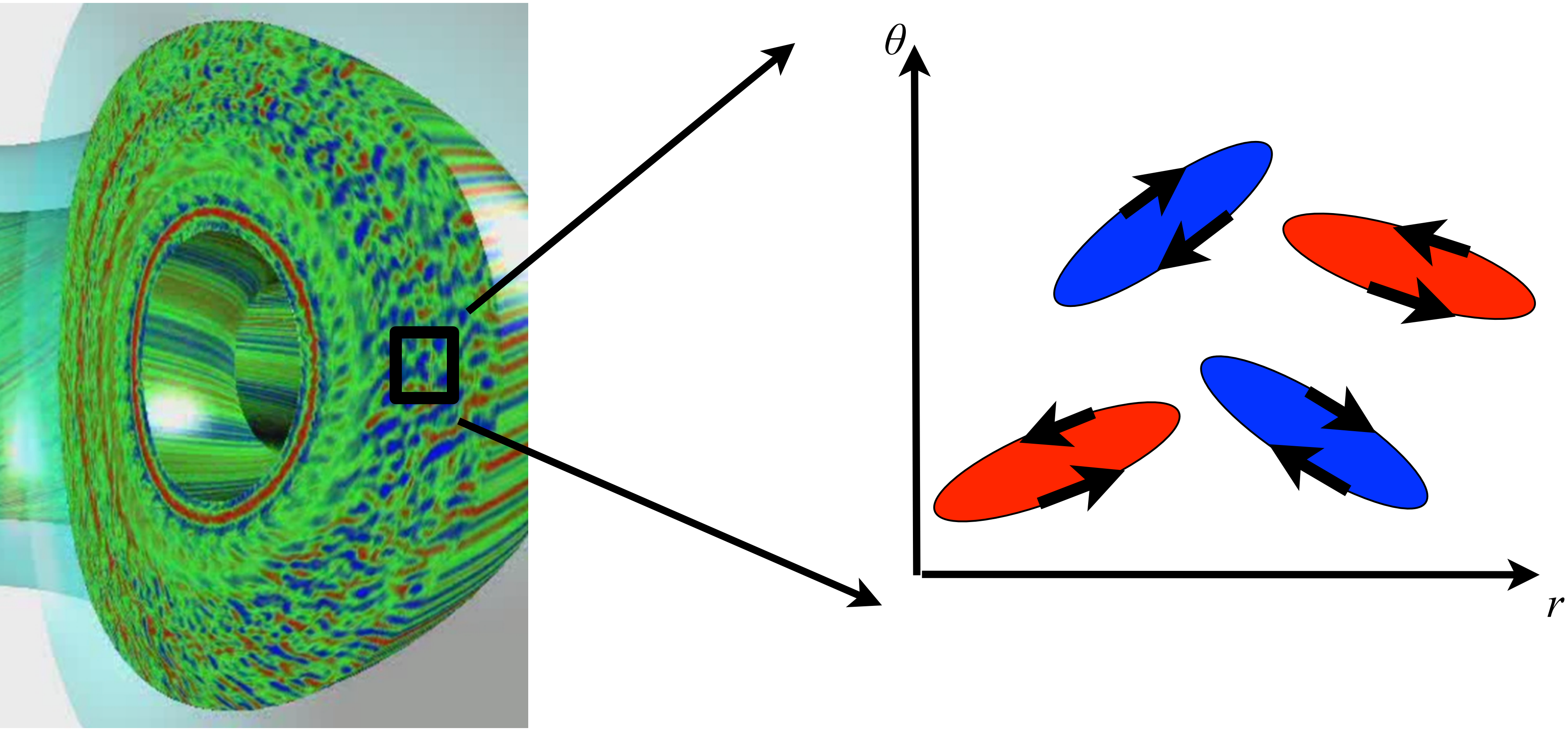
Spontaneous spin-up in 2-D bounded hydro is large: ~25% of kinetic energy in net solid body rotation



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)

Intuitive picture of Reynolds' stress: asymmetry needed to drive net rotation



Reynolds' stress radial transport of perpendicular momentum

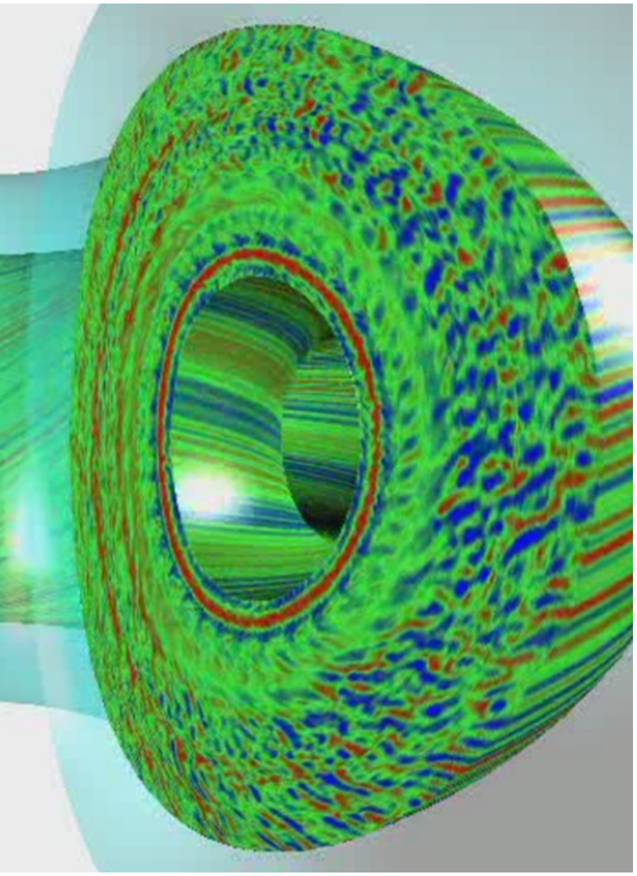
= $\langle v_r v_\theta \rangle$ > 0 for eddy tilted up

$\langle v_r v_\theta \rangle$ < 0 for eddy tilted down

$\langle v_r v_\theta \rangle$ averages to zero with up-down symmetry

Rigorous, complete proof by Parra et al. 2011

Can we design tokamaks or stellarators so they spontaneously spin at significant rates?



GYRO simulation, Candy & Waltz 2006

General theory of why intrinsic torques vanish in standard low-flow ordering in up-down symmetry:
Parra et al. PoP, 18, 062501 (2011)

Expt. demo of driving flows by breaking up-down symmetry:
Camenen et al., PRL 2010

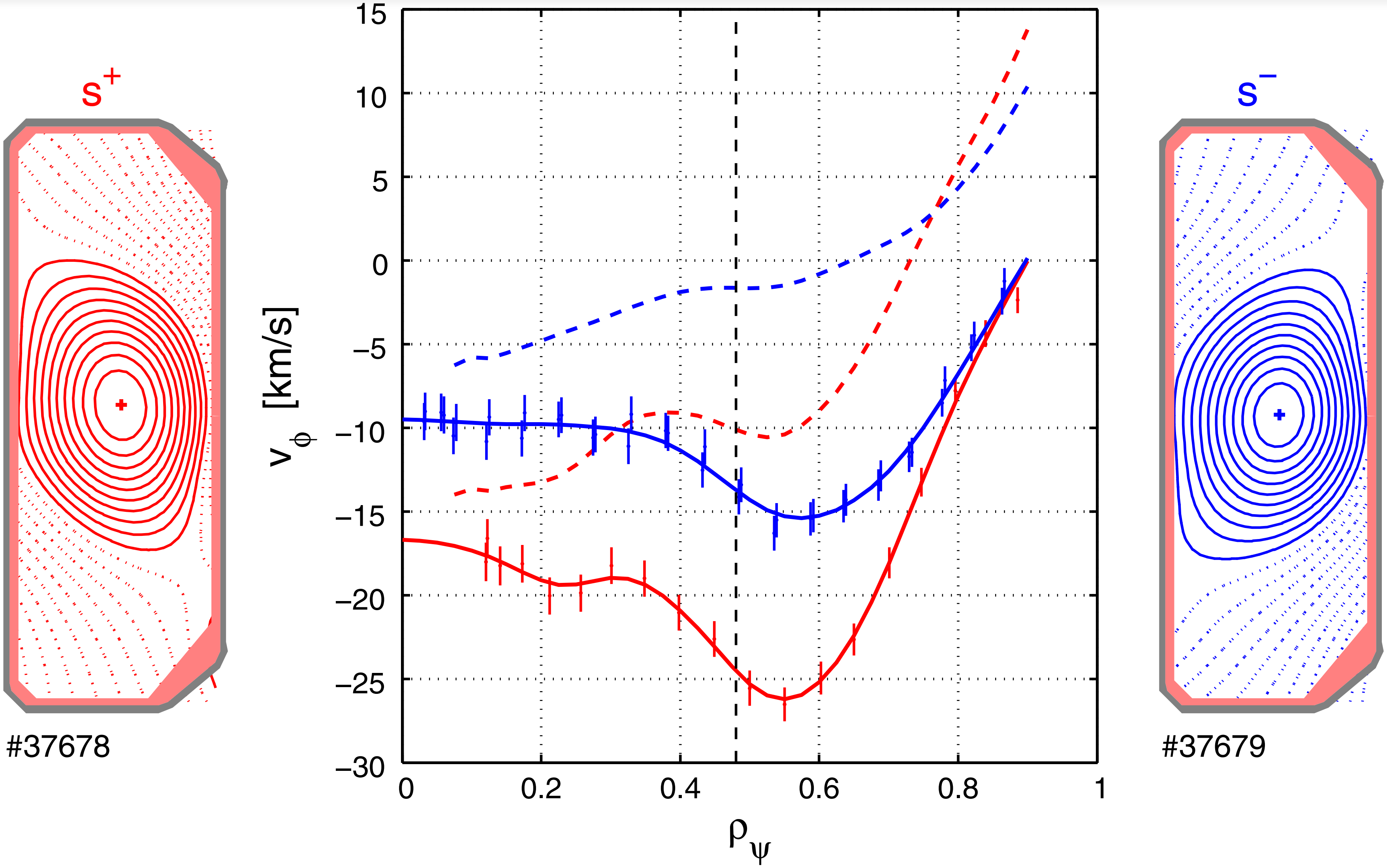
Barnes & Parra et al. using GS2 to study spontaneous spin with up-down asymmetry, but it might be weak (very preliminary)?

Stellarator equivalent of up-down tokamak symmetry is "stellarator symmetry". Only for convenience? (Weitzner?)
But need quasi-symmetry so $\partial|\vec{B}|/\partial\alpha \approx 0$ minimizes magnetic pumping and allows plasma to spin in that direction.

So do we want a non-stellarator-symmetric stellarator (to drive rotation) with quasi-symmetry (to minimize rotation damping)? (But recent papers by Sugama and by Helander indicate even a quasi-symmetric stellarator can't rotate very fast.)

Useful status report on rotation:
Peeters et al. Nucl. Fusion, 51, 094027 (2011)

TCV Tokamak verified that toroidal rotation can be affected by up-down asymmetry

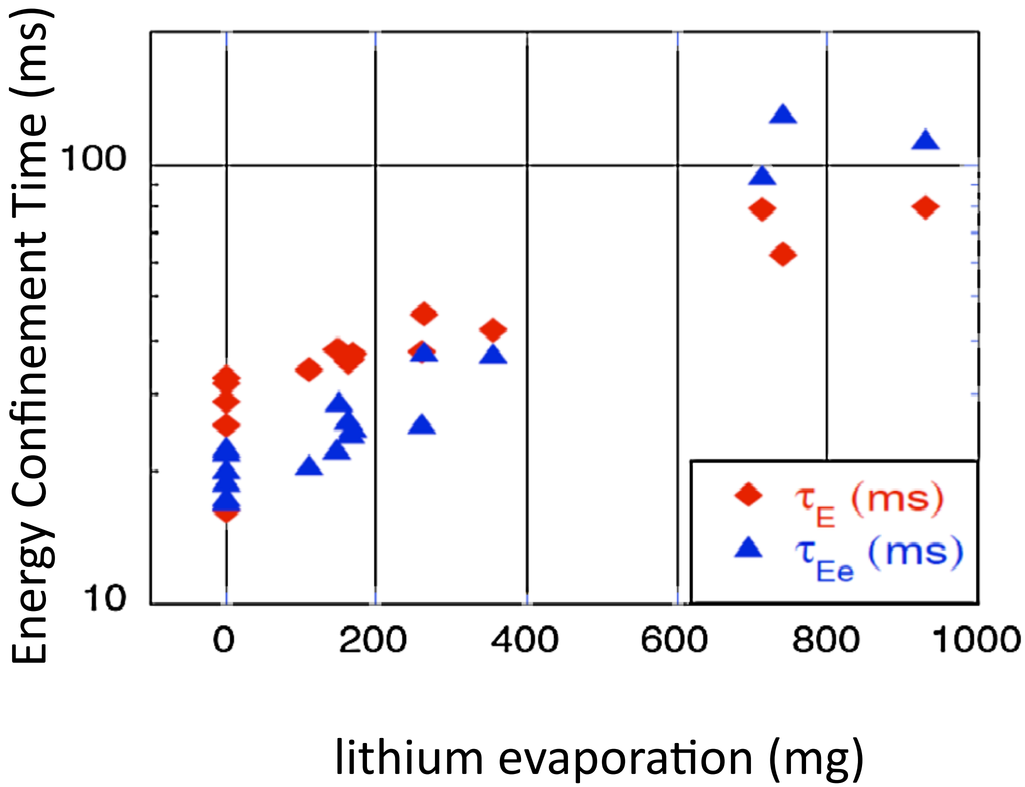


Only elongation propagates well to center, do we want an elongated tokamak tilted by 45 degrees?

Rotation of carbon (solid lines) & main ions (dashed)

Camenen et al., PRL 2010

How much can lithium improve plasmas?



NSTX (APS 2011) finds more lithium is still good. Can we raise edge temperature to ~4 keV or higher? (NSTX global τ_E went up as pedestal broadened and ELMs were suppressed, but $T_{e,\,SOL}$ didn't rise? Unlike TFTR, where T_{SOL} ~ 2 keV.)

Lithium on wall absorbs hydrogen, reduce recycling of hydrogen as cold neutrals that cool the edge, raises edge temperature. Liquid lithium coating protects wall, avoid melting divertor plates by ELMS? avoid melting wall in disuption? Potentially dramatic effect.

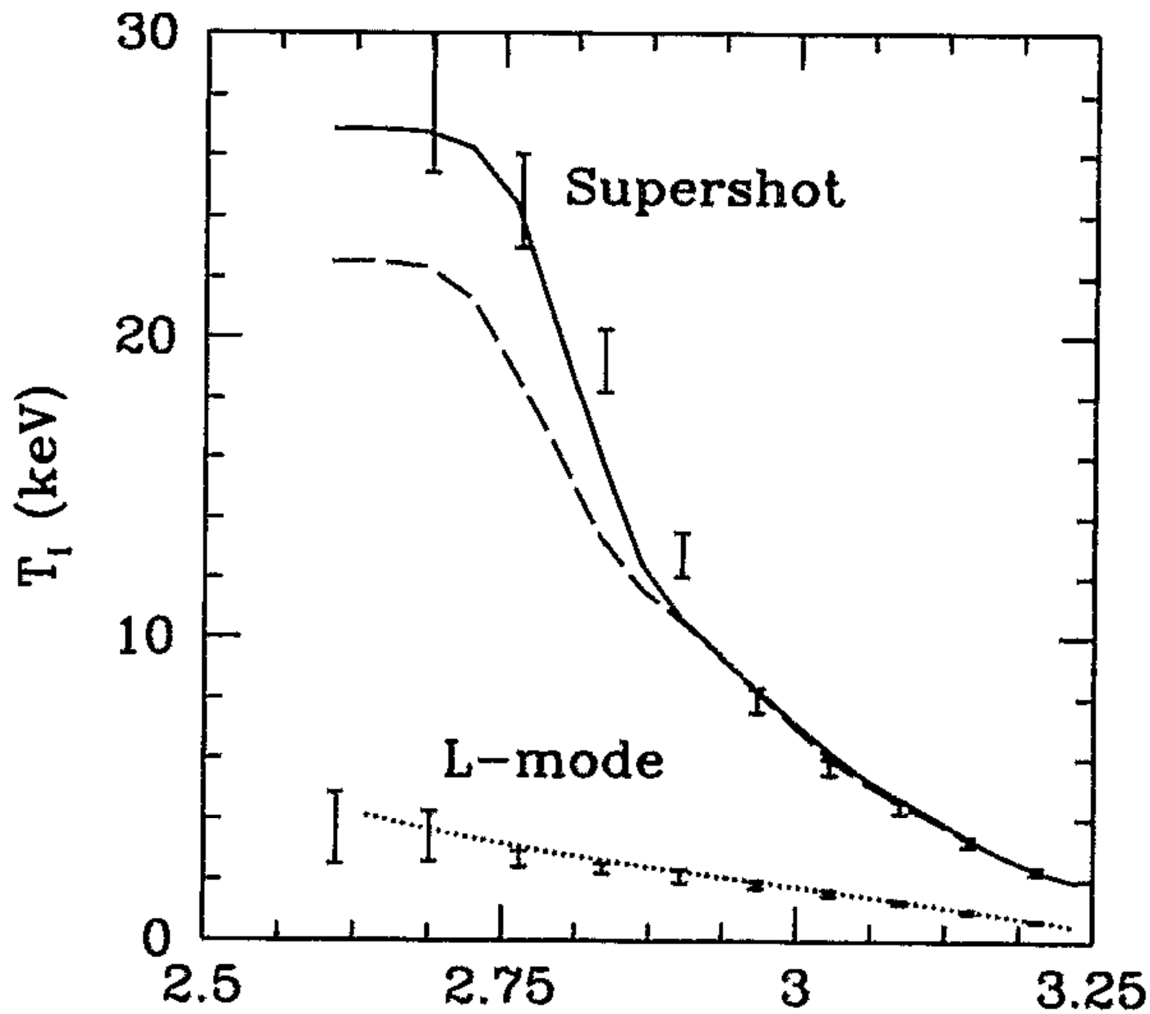
Gyrofluid Turbulence Simulations Explained Why TFTR Supershots (and Lithium Walls) are Super

* reduced recycling at wall, reduced influx of cold neutrals & raised edge T_i

* Profiles stiff for critical ITG:

  Core $T_i \propto$ Edge T_i

* high T_i/T_e , moderate density peaking, and beam-driven ExB shear raised R/L_{Tcrit}

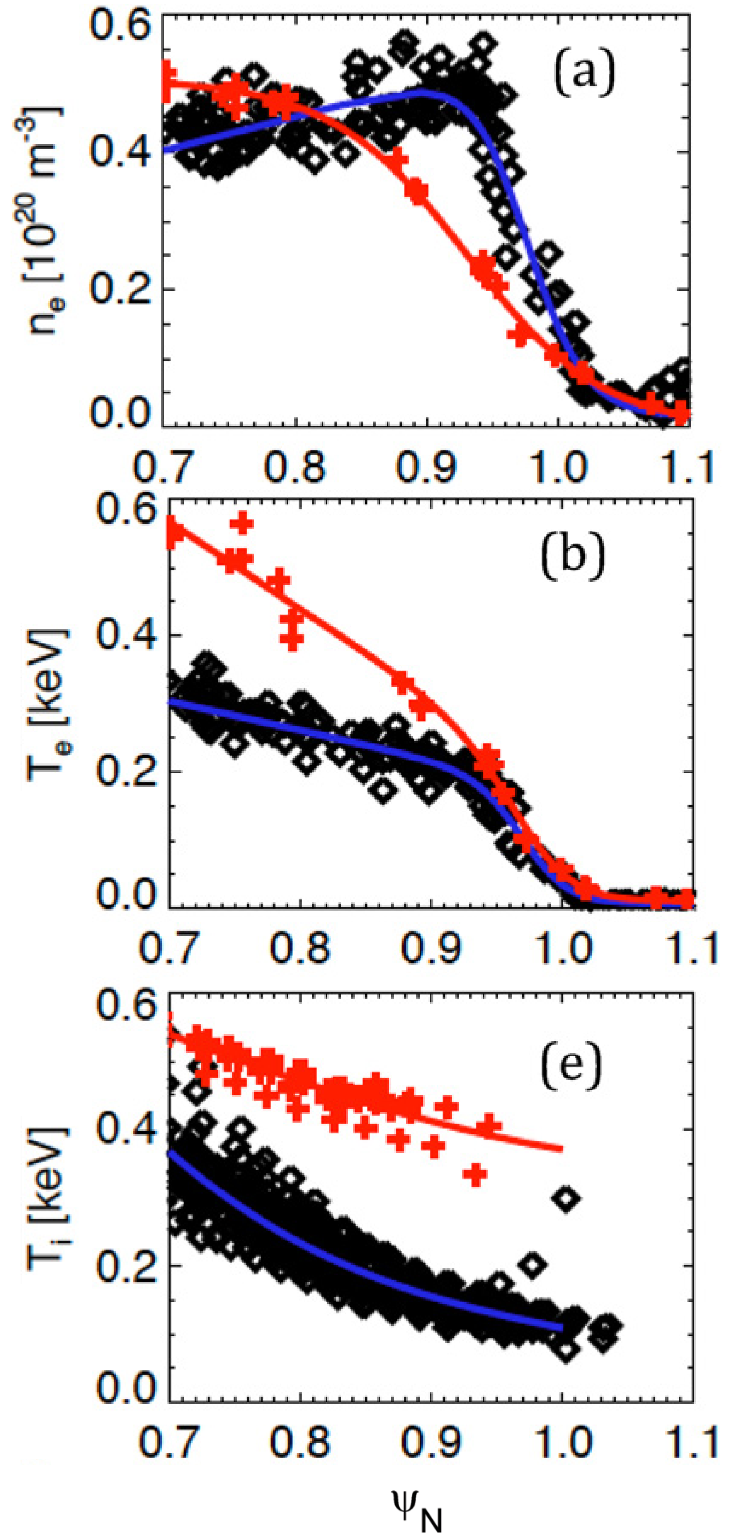


Kotschenreuther, Dorland, Beer, Hammett (1995)

Lithium wall coating reduces recycling of cold neutrals back into plasma: dramatically raises edge temperatures

with Li
w/o Li

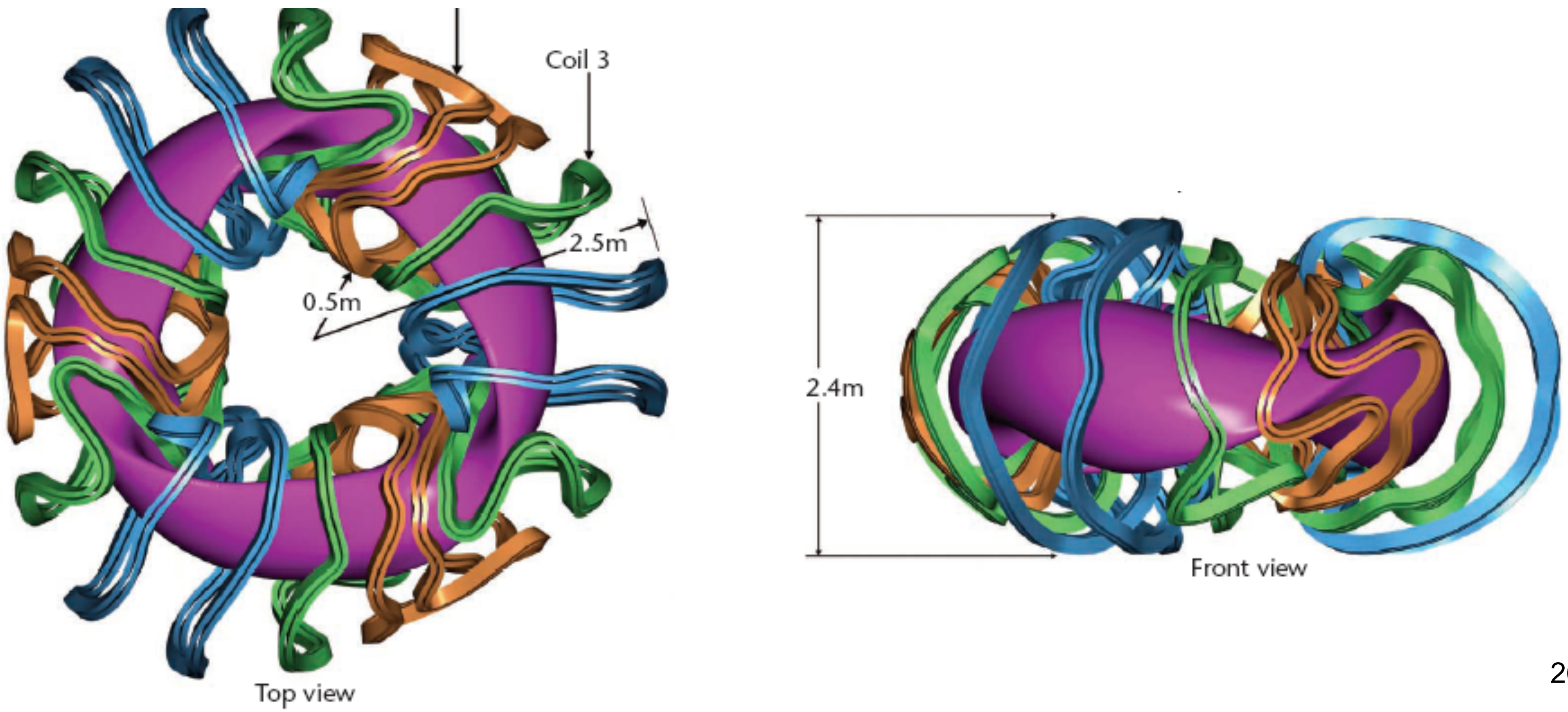
Same core temperature for ~1/2 the beam power in NSTX



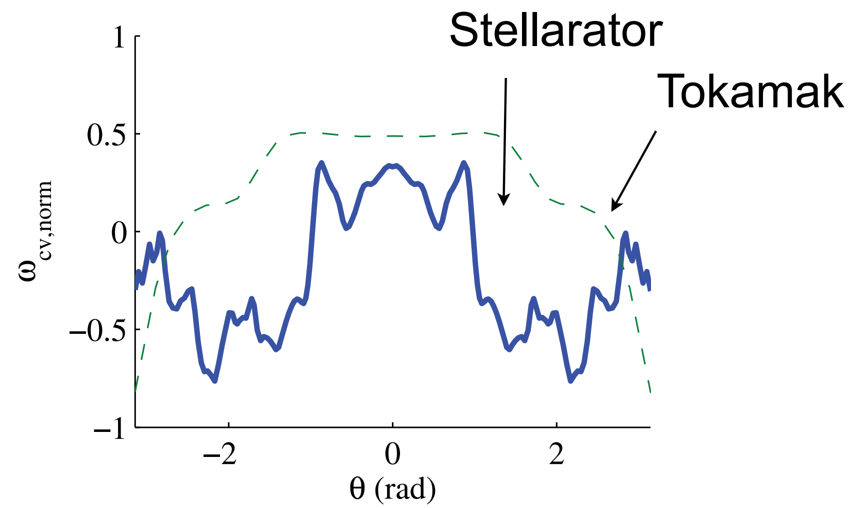
Bell et al, PPCF 51, 124054 (2009), Maingi PRL 2009, Maingi NF 2012

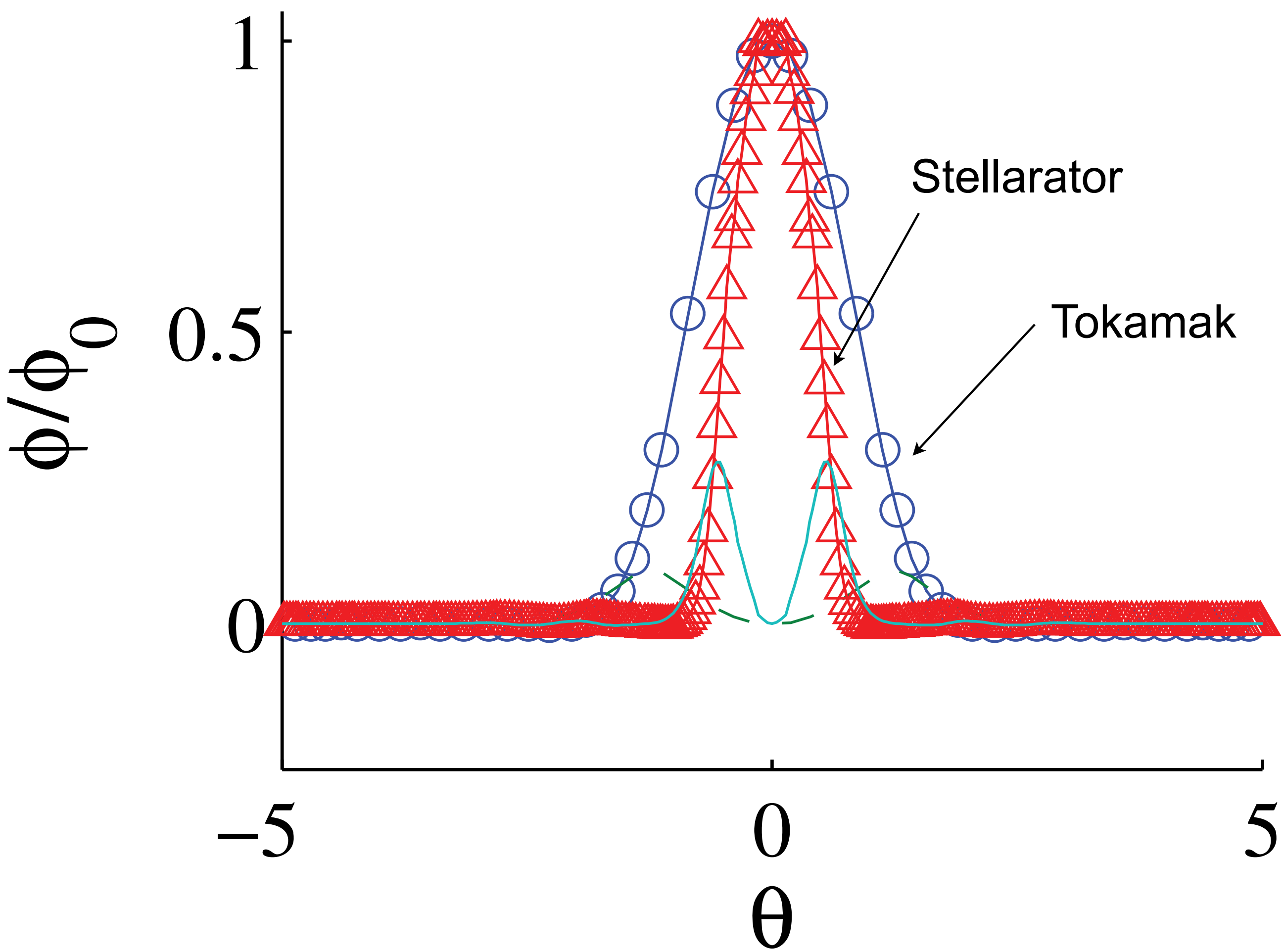
Improved Stellarators Being Studied

- Mostly abandoned for tokamaks in ’69 (in US). But computer optimized designs now much better than slide rules. Now studying cost reductions.
- Breakthrough: Quasi-symmetry (& omnigenity) discovered in 1990’s (after 40 years of fusion research): don’t need vector $\boldsymbol{B}$ symmetric exactly toroidally, $|\boldsymbol{B}|$ symmetric in field-aligned coordinates sufficient to be as good as tokamak.
- Magnetic field twist provided by external coils, not plasma currents, inherently steady-state. Stellarator expts. 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?
- Connection length to good curvature / high-shear region: in tokamak ~ $q\pi R$, in stellarator ~ $\pi R/3$, compensates for steeper gradients in narrow stellarator locations, so stellarator can be competitive with tokamak.



Short parallel distance to good curvature region in stellarators is very stabilizing, forces ITG mode to be narrow.





Parallel connection length to good curvature / high negative shear regions:

in tokamak ~ $q \pi R$

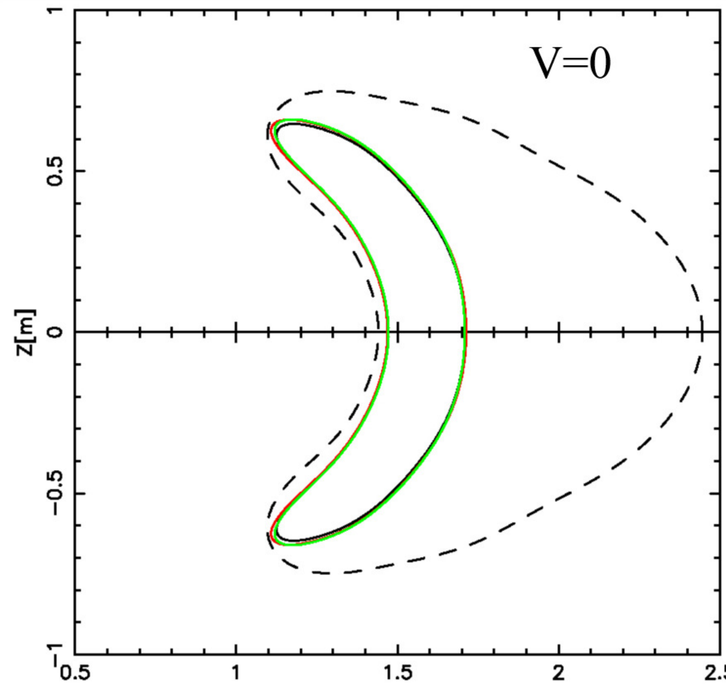
in stellarator ~ $\pi R / 3$

(Baumgaertel, Hammett, Mikkelsen, et al, Phys. Plasmas 2013)

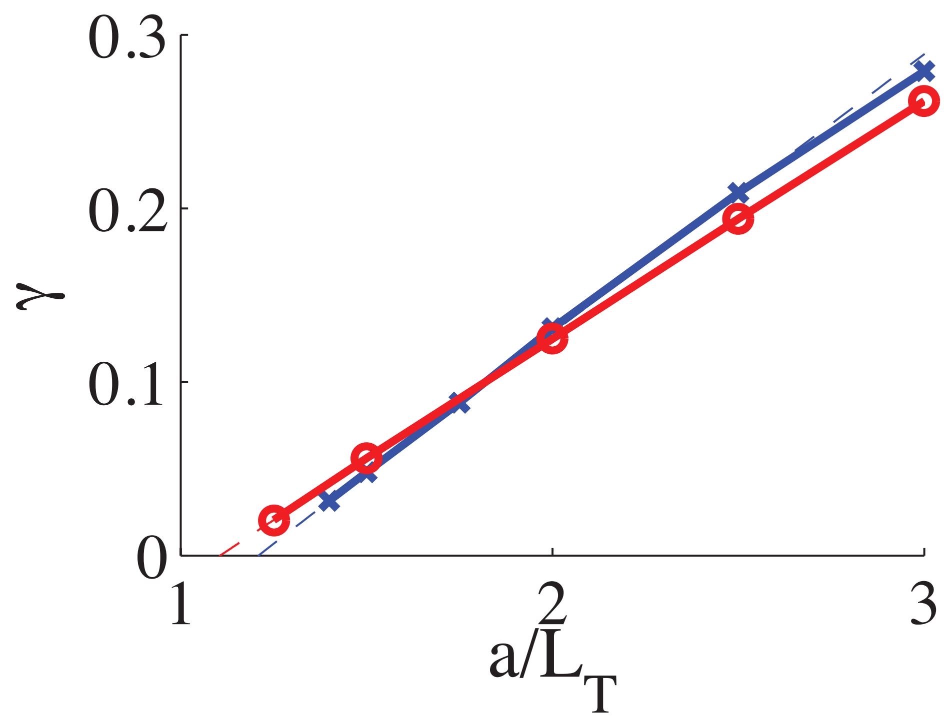
(stellarator even narrow in $z = \theta q R$)

Stellarator ITG Thresholds Can Be As Good as Tokamaks

Because stellarators have very narrow cross section at some toroidal locations, the local $|\nabla T|$ is very large, worry that ITG modes will be driven very hard.



However, the critical gradient scale length normalized to the local minor radius can be as good in NCSX (red) as in a highly-shaped tokamak (ARIES-AT, blue), due to stabilizing effects of short connection length to regions of good curvature & high local magnetic shear.
(Baumgaertel, Hammett, Mikkelsen, et al, Phys. Plasmas 2013)



Could explore optimizations of stellarator designs to further improve transport
(Mynick, Pomphrey, Xanthopolous, PRL 2010)

Many possible stellarator designs, room for further optimization

* Some initial turbulence optimization studies for stellarators:

- Mynick, Xanthopolous et al. (PRL, 2010).

- Proll, Helander, et al. (PRL 2012) demonstrate design where all trapped particles have averaged good curvature. Eliminates trapped-electron instabilities, combine with lithium to eliminate all turbulence?

- because $\gamma \propto \sqrt{\omega_d(\omega_{*T} - C\omega_d)}$, near marginal stability want larger $\omega_d \propto 1/R$, but far above marginal stability we want smaller ω_d.

- 2000's optimized degree of quasi-symmetry. Next optimize to reduce coil cost?

* Tokamaks spontaneously spin: (reduces turbulence and improves MHD stability). Can we enhance this with updown-asymmetric tokamaks or non-stellarator-symmetric stellarators with quasi-toroidal symmetry? (But Sugama, Helander say rotation is limited.)

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

Future Advances in Robotic Manufacturing Could Significantly Reduce Cost of Fusion Energy

* It seems that over the next 20 years there will be continued radical leaps forward in robotic manufacturing capabilities.

* Of course this would benefit other energy sources too, but perhaps it will benefit fusion more:

* Many key fusion components (superconducting coils, ...) are large & complicated & can't be mass-produced in a factory and shipped to a power plant.

* Instead of relying on robots in factories and shipping parts out, bring the robots to the construction site.

* Future robots could be quickly reconfigured from one task to another: complex, high-precision tasks that at present aren't done in high enough volume to justify robotic automation could be done robotically in the future.

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  - new stellarator designs (quasi-symmetry / omnigenity), room for further optimization