FUSION and PLASMA PHYSICS

My objectives:

to explain why Nuclear Fusion is worth pursuing

to describe some basic concepts behind magnetic confinement

to summarize the history of fusion

to describe some of the problems associated with designing a power plant

> (confinement, wall loading, magnetic field, machine size)

to describe the role of the U. TX. Fusion Research Center

> (confinement, machine size, EPEIUS, TEXT)
>
> > Edge turbulence, Interior turbulence, inside $q = 1$

WHY BOTHER WITH ALTERNATE ENERGY SOURCES?

WORLD POWER USAGE, 1990

- 1 TW =10^{12} W ≈ 2000 power stations.
- 1 TW-year = 31.5 EJ (i.e. x10^{18}) ≈ 1 billion tonnes of coal, or 5 billion barrels of oil.

Date	Power
1850	0.6 TW
1950	3 TW
1970	8.4 TW
1990	13 TW (10 from fossil fuels)
2050	30 TW (10 billion people)

ESTIMATED ABUNDANCE

Oil, gas	3,000 TW-y
Coal	10,000 TW-y
Oil shale	30,000 TW-y
Uranium	3,000,000 TW-y
D-T fusion	150,000,000 TW-y
D-D fusion	250,000,000,000 TW-y

- There is no immediate problem
- Nuclear power offers one long terms solution

PER CAPITA ENERGY CONSUMPTION

Canada	19,000 kW-hours
India	250 kW-hours

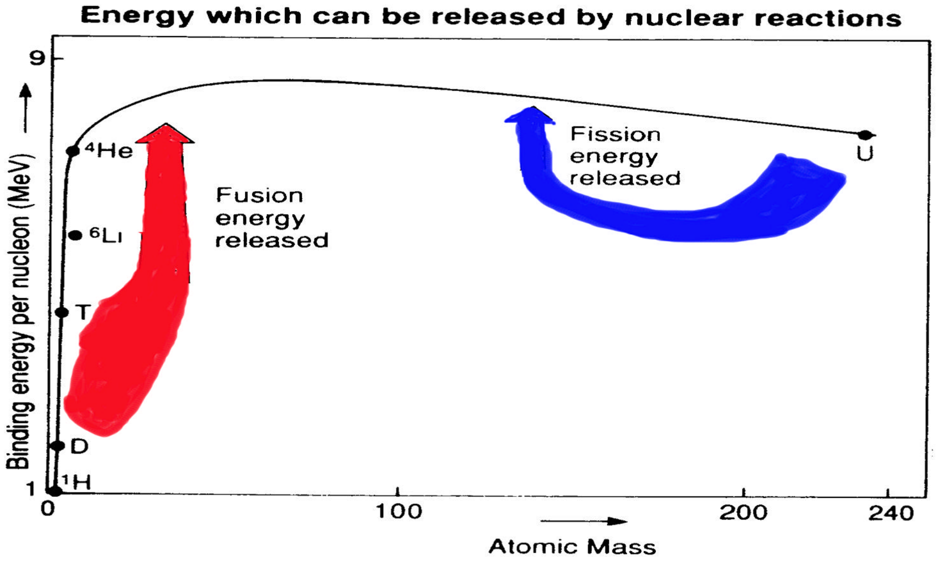
- India uses 4% of that of the developed word.

- China and India are on a path to bring their energy consumption up to the average (1500 kW-h per capita) by 2020.

- i.e. in the next 25 years they plan an additional 1,000 new fossil fuel burning power stations.

- Fusion may offer a clean alternative.

FUSION ENERGY



THE SUN

H used at 6×10^{18} tons/second.

$T = 1.5$ keV, $\rho = 100$ gm/cm^3, $p = 10^{11}$ atmos. contained by gravity.

OTHER REACTIONS

$D^2 + D^2$ He^3 (0.82 MeV) + n (2.45 MeV)

$D^2 + D^2$ T^3 (1.01 MeV) + H^1(3.02 MeV)

$D^2 + T^3$ He^4 (3.5 MeV) + n (14.1 MeV)

$D^2 + He^3$ He^4 (3.6 MeV) + H^1 (14.7 MeV)

Tritium ($\tau_{1/2} = 12$ years) from n + Li

A BRIEF HISTORY of FUSION

1929: Atkinson and Houterman proposed that Fusion might explain the energy of stars.

Beam target interactions demonstrated reality, but $E_{in} >> E_{out}$ (Rutherford: Fusion Energy is ‘Moonshine’).

early 1940’s: discussions of possible laboratory experiments.

late 1940’s: possible geometry discussed.

early 1950’s: H bomb.

1951: Peron claimed Richter solved problem.

< 1958: Classified programs by USA, USSR, UK (because copious neutrons might be used to create fissile material for bombs).

1957: Lawson’s criterion for useful energy production (and a yardstick of our progress):

for D-T

$T \approx 20$ keV ($2 \times 10^{8}\ {}^{0}K$),

$n\tau \approx 2 \times 10^{14}\ cm^{-3}s$.

for D-D

$T \approx 50$ keV ($5 \times 10^{8}\ {}^{0}K$),

$n\tau \approx 6 \times 10^{15}\ cm^{-3}s$.

late 1950's: Mirror machines (didn't work).

1959: The Harwell conference.

1960's: Toroidal pinches, stellarators.

1970's: Success of tokamaks.

1980's: TFTR and JET.

1990's: First D-T experiments, and the design of ITER.

December 1993: 6 MW of power from TFTR.

FROM THE DEBATE ON THE JET NUCLEAR FUSION PROJECT

THE HOUSE OF LORDS, 1987

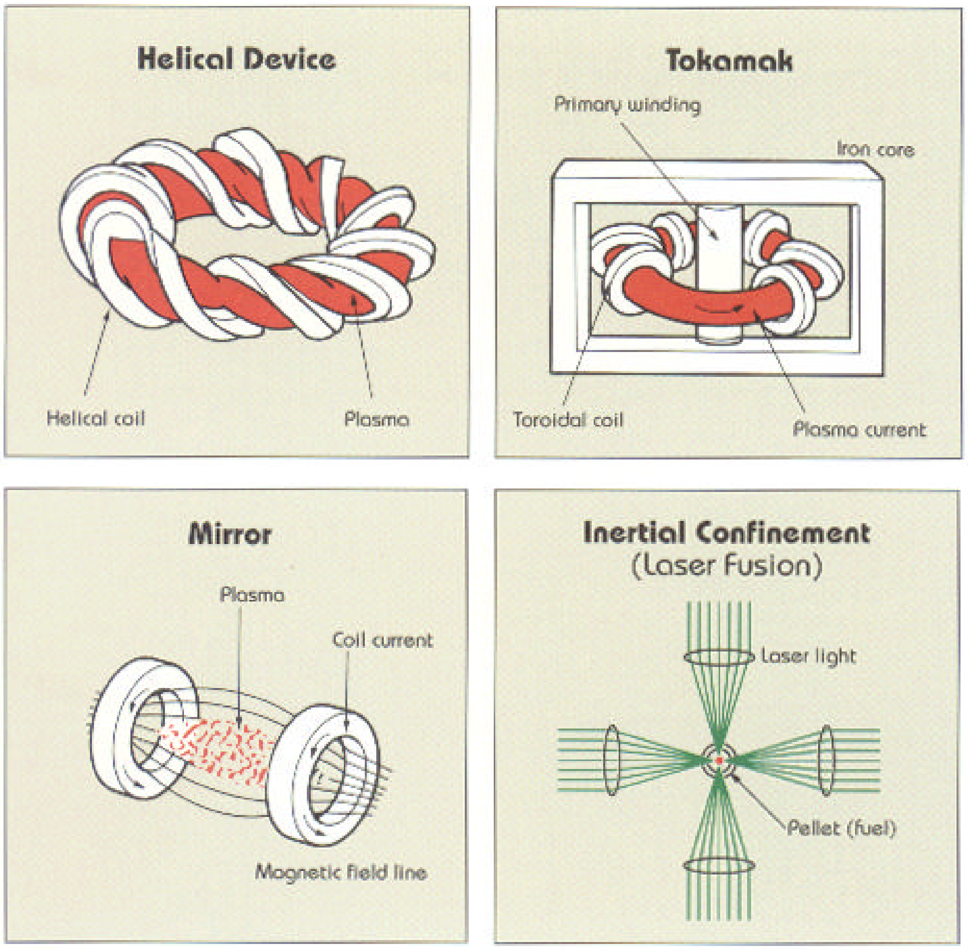
Earl Ferrers:

My Lords, what kind of thermometer reads a temperature of 140 million degrees centigrade without melting?

Viscount Davidson:

My Lords, I should think a rather large one.

THE MACHINES



Mirrors: need $p_{||} > p$ (Van Allen belt).

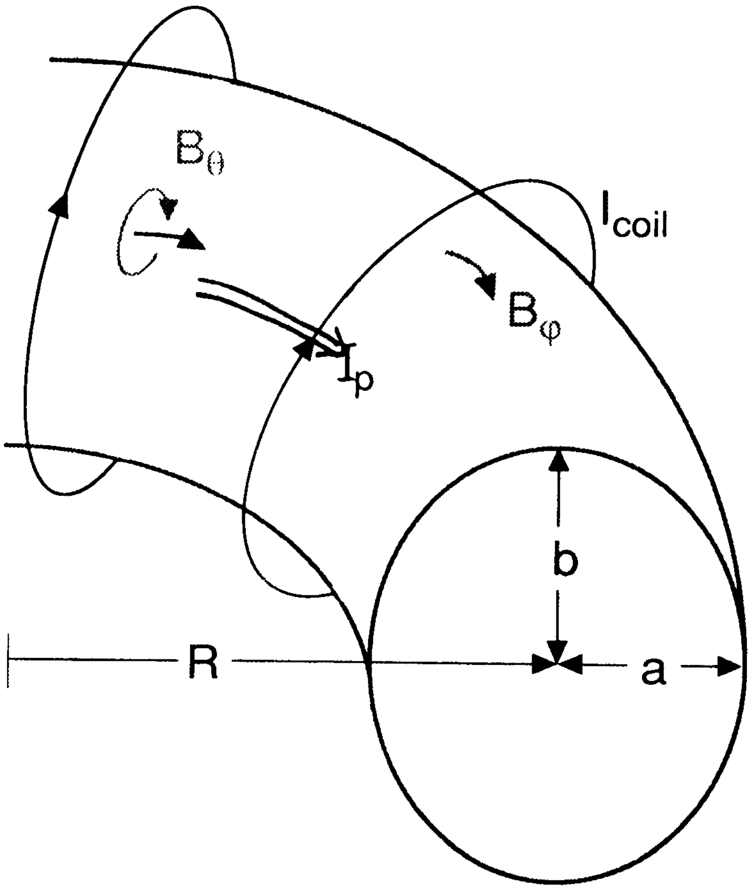
Inertial: high n, low τ (from $a/v_{expansion}$).

Stellarators: no plasma current needed.

Tokamaks: ....

THE TOKAMAK

Object: to confine particles in a magnetic field system without ends. Because the particles are tied to field lines we need nested magnetic surfaces (B is tang. to a surface). Poincare toroidal.



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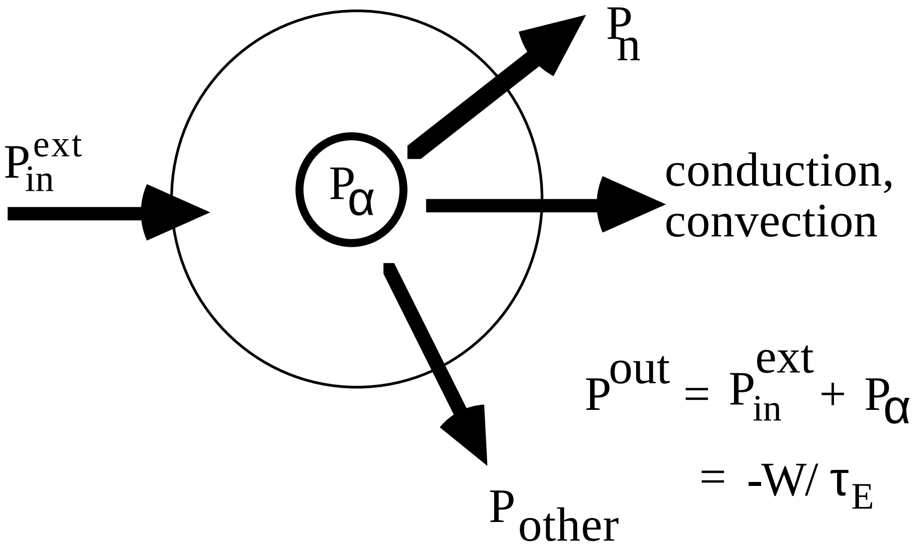
$B_{\phi} >> B_{\sim\theta}$

b\a=K

$$q = \frac{a^2}{2R}\,\frac{K B_{\phi}}{I_p}$$

> 2–3
for stability

A TOKAMAK REACTOR



$$P^{out} = P_{in}^{ext} + P_\alpha$$
$$= -W/\tau_E$$

$$P_\Sigma = P_\alpha + P_{in}^{ext} = \text{Power out} = -W/\tau_E$$

Energy confinement time τ_E:

$$\frac{\partial W}{\partial t} = P_\Sigma - \frac{W}{\tau_E} = 0$$

A Figure of merit is

$$F = \frac{P_\alpha}{W/\tau_E} \quad \text{or} \quad Q_\alpha = \frac{F}{1-F}$$

Ignition: F = 1 or $Q_\alpha = \infty$: no external heating required.

For a D-T Maxwellian plasma with 5 < T < 20 keV (where $\langle \sigma v \rangle \quad T^2$) and volume V:

$$P_\alpha = 1.5x10^{-37}\left(\bar{n}\bar{T}\right)^2 V g_{dilution} g_{profile}$$

Using energy balance and W = $3k_b nTV$

$$F = \frac{2P_\Sigma \tau_E^2}{3V} g_{dilution} g_{profiles}$$

i.e. confinement is important.

Confinement scaling.

Consider the tokamak engineering variables B_φ, I_p, n_e, P_Σ, a, R, κ, ... Regression analysis of data from all tokamaks shows (e.g.)

$$\tau_E \approx c h I_p^1 P_\Sigma^{-0.5} \kappa^{0.5} R^{1.75} a^{-0.37}$$

(But where is the physics?)

Then

$$F = \frac{2c^2 h^2 I_p^2 \kappa R^{3.5} a^{-0.74}}{3V} g_{dilution} g_{profiles}$$

i.e. F determined by geometry and plasma current. Write geometry in terms of aspect ratio A = R/a, so that

$$F \quad I_p^2 A^2$$

i.e. large I_p, large A are good. But large A implies large machine. A small machine (small A) requires large I_p.

Constraints.

Plasma current I_p

limited (stability) by the safety factor q, written in terms of geometry and toroidal field B_φ. Large currents are possible at low A = R/a

Toroidal field B_φ

limited by forces (materials, geometry)

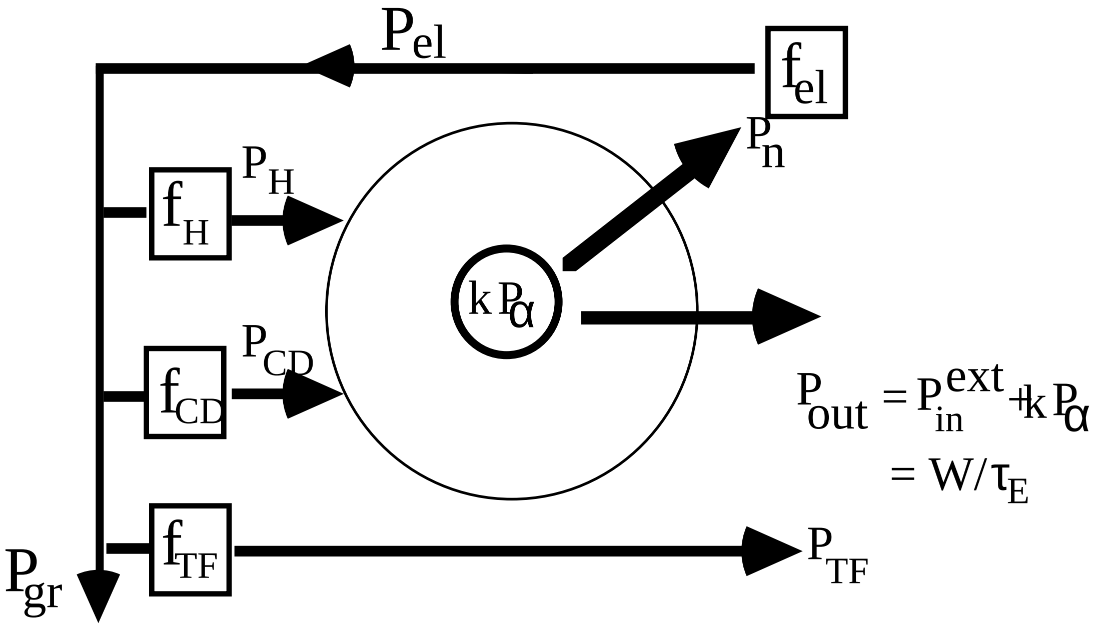
i.e. the maximum I_p and therefore F is determined only by the geometry (a, R, shape)

Therefore *assuming we have used the correct confinement* scaling the smallest machine to achieve a given F or Q_α is uniquely determined

i.e. choosing $Q_\alpha = 1$ (ignition) then the smallest machine is uniquely determined by the choice of aspect ratio A = R/a.

But neutron wall loading is crucial.

Power Flows and Efficiencies



1. Solve power balance with tokamak (Goldston) or stellarator [U. Stroth et al., Nucl. Fus. 36, 1063 (1996)] scaling.

2. Restrict q, B_{Tleg} by stability and recirculating power limits, $\chi = P_{TF}/(f_{TF} f_{el} P_n)$. For s/c coils specify maximum B_{Tleg}. Limit Γ_n, β.

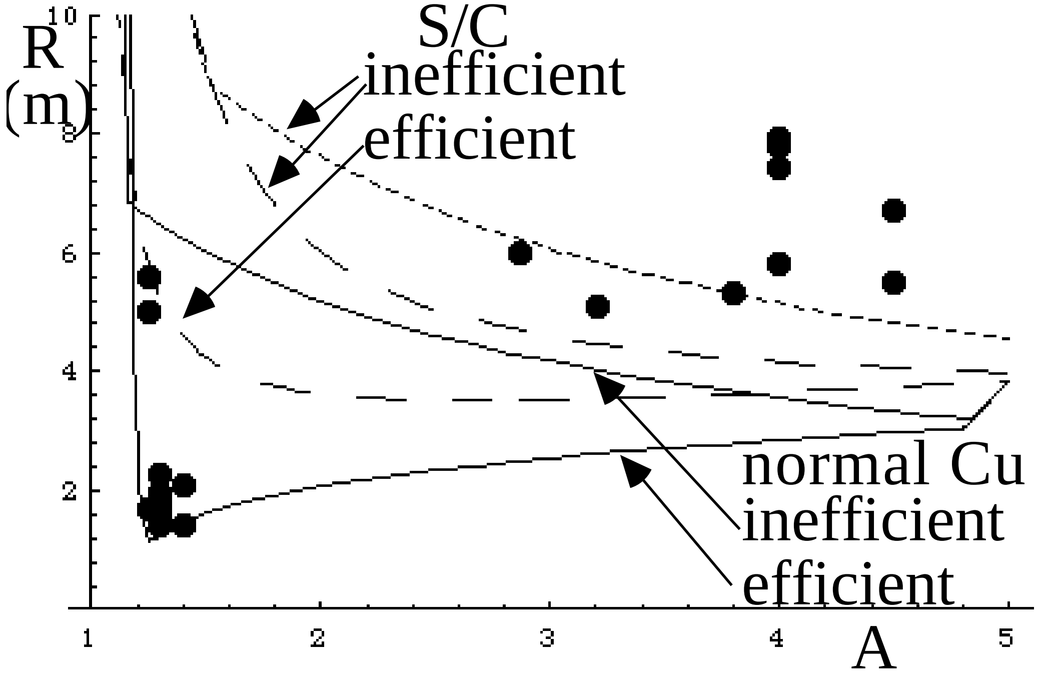
3. For tokamak, consider extremes of η_{CD}. Arbitrary values considered numerically.

4. Monitor

$$V_m = \pi(R+a)^2 .2\kappa a = 2\pi\kappa R_0^3 (A+1)^2 / A^3$$

Many aspects are not included (e.g. divertors, time dependence, thermal stability).

Major Radius of Smallest Tokamak Reactor



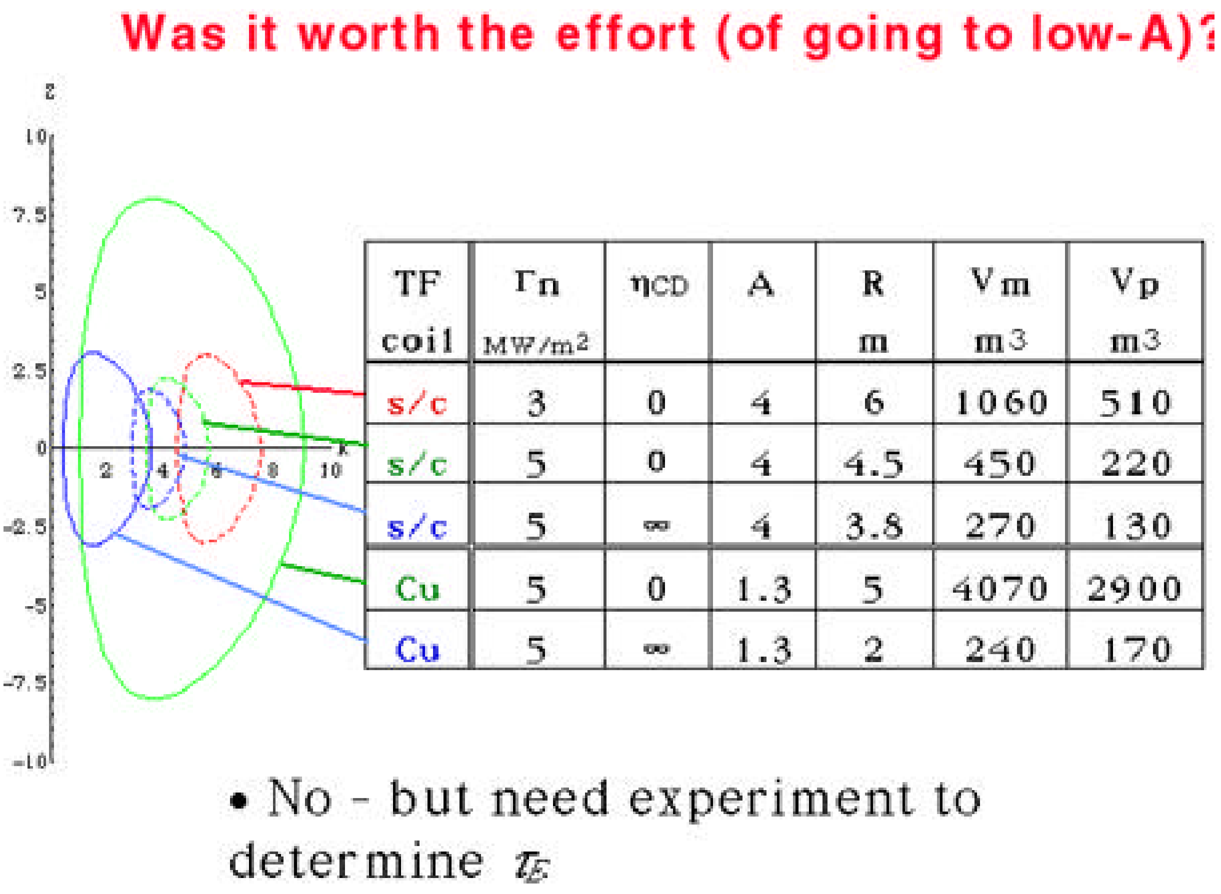
Efficient current drive:

$$R_{\Gamma} \quad q^{0.72} H^{-0.72} \Gamma_n^{-0.36} \ln(A)^{0.64} \kappa^{-1.13} \delta^{-0.15}$$

Inefficient current drive:

$$R_{\Gamma bs} \quad H^{-1.6} \Gamma_n^{-0.4} A^{-0.46} \kappa^{-1.18} \delta^{-0.15}$$

- Analysis consistent with published studies.
- Low-A more compact (smaller V_m) only if κ increases with decreasing A; also need completely efficient current drive.

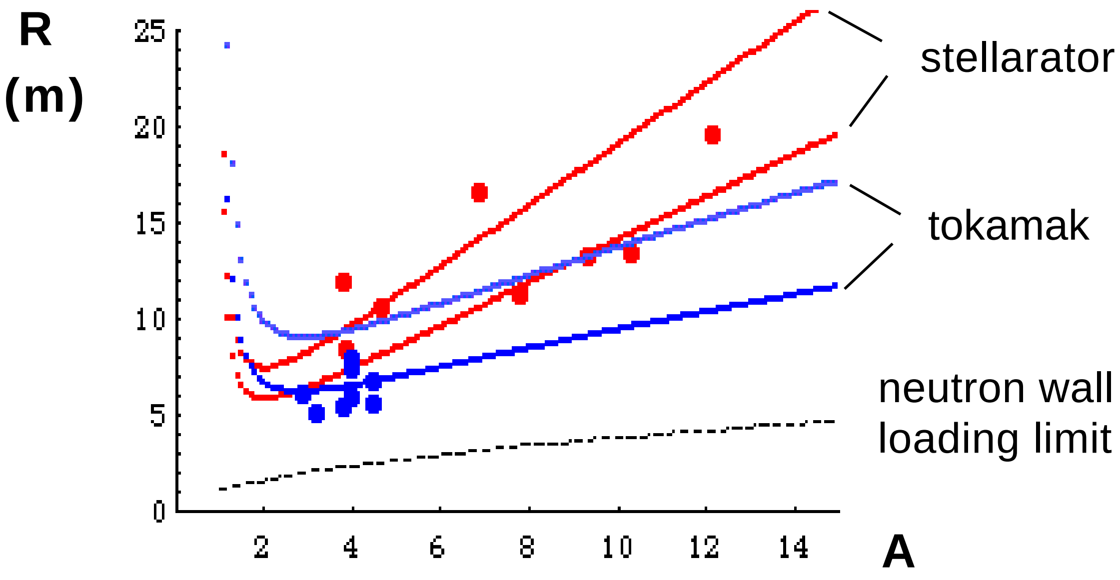


Was it worth the effort (of going to low-A)?

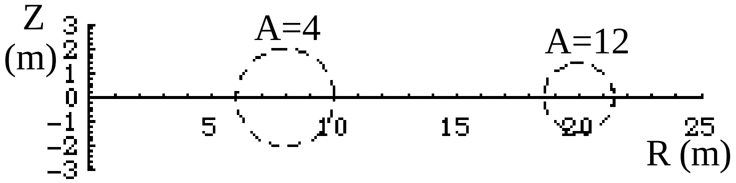
TF coil	Γ_n MW/m^2	η_{CD}	A	R m	V_m m^3	V_p m^3
s/c	3	0	4	6	1060	510
s/c	5	0	4	4.5	450	220
s/c	5	∞	4	3.8	270	130
Cu	5	0	1.3	5	4070	2900
Cu	5	∞	1.3	2	240	170

- No - but need experiment to determine τ_E

Low-*A* Stellarators? (s/c coils)



- Published stellarator reactor studies show same trend as simple model; a large increase in *R* with *A*:



i.e. a reduction in V_m is possible at low *A*, depending on confinement properties - see later.

Requirements for a low-A 3-D system

(In addition to power and particle handling, ...)

1. Space for a nuclear blanket

2. Higher β

$$P_n = \Gamma_n S_n \qquad \beta^2 \left(\frac{A-1}{A}\right)^4 V \qquad R_\beta \qquad \frac{\Gamma_n}{\beta^2}\,\frac{A^5}{(A-1)^4}$$

Theory I_p (a hybrid) works

3. $\tau_{n/c} > \tau_{scaling}$ for applicability of model.
$\varepsilon_{h,eff} = 0.5\%$ at $A = 3$

· Impossible? E_r?

- How far must B optimization be carried?

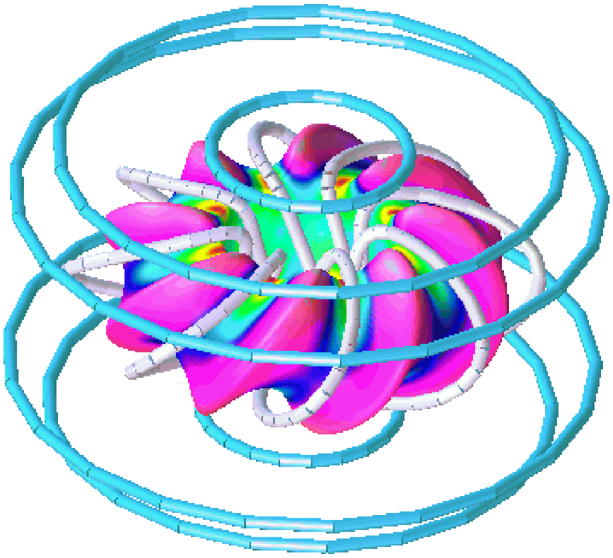
- $\boldsymbol{E}_r \times \boldsymbol{B}$ drifts can ameliorate the $\boldsymbol{B} \times \boldsymbol{B}$ drifts

- cf. W7A results.

EPEIUS

MOTIVATION

- The Small Aspect-Ratio Toroidal Hybrid (SMARTH) concept proposed by ORNL offers a possible route for improving the ST and/or the compact torsatron:
  - for tokamaks, reducing or eliminating disruptions, reducing current drive requirements, and easing the difficulty of non-inductive startup,
  - for torsatron/stellarators, providing an alternative to quasi-symmetry for confinement optimization through magnetic shear, electric field, and barrier formation, and by reducing the fragility of magnetic surfaces.



OBJECTIVES

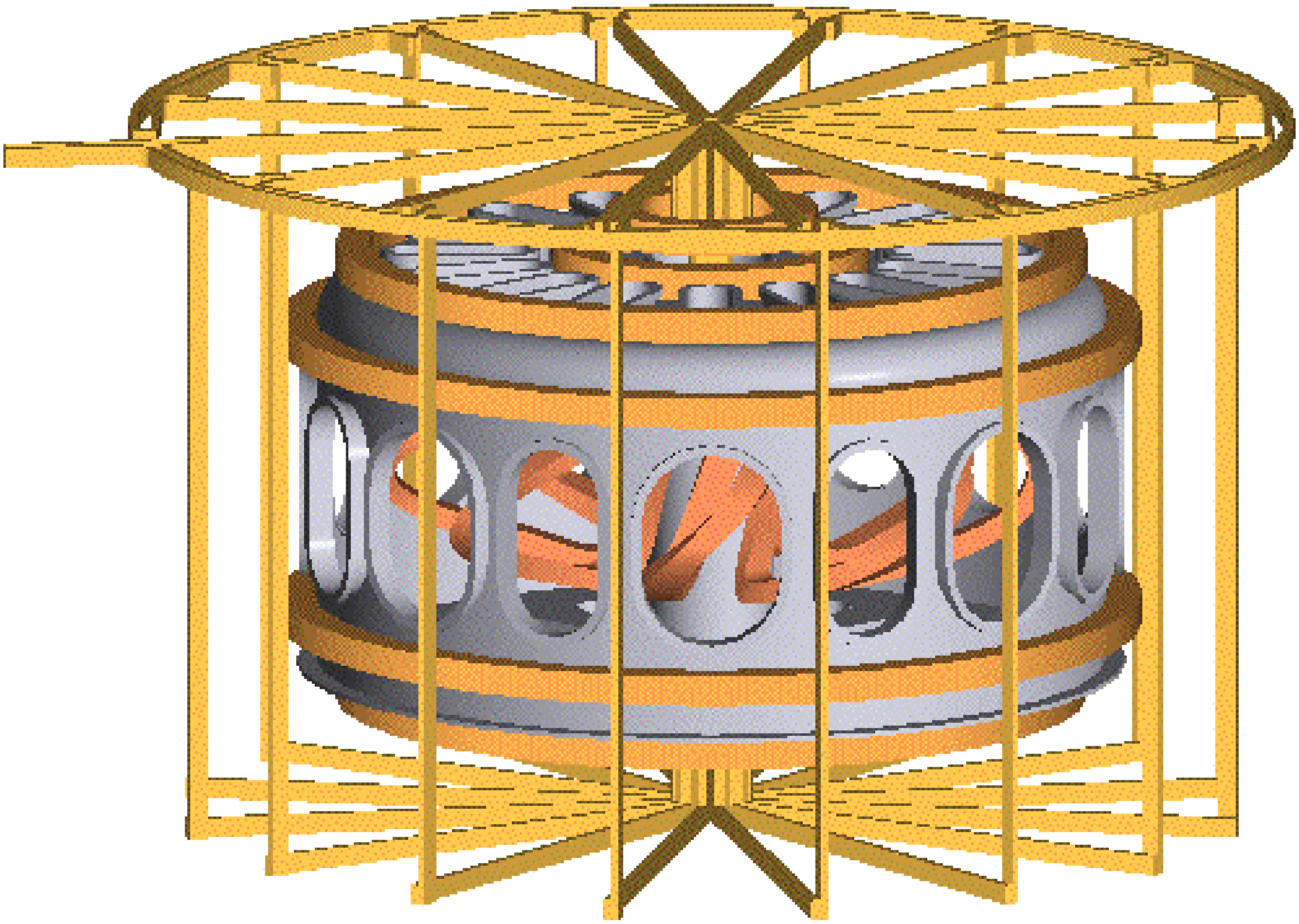
1. Can torsatron and torsatron-tokamak hybrid plasmas with acceptable magnetic surfaces be operated at $A \lesssim 3$?

2. Can E_r ameliorate the consequences for confinement properties of a helical magnetic ripple? Can E_r be controlled? Can an *H*-mode be achieved?

3. What are the tearing and kink mode stability properties associated with particular combinations of ƚ_{int} and ƚ_{ext}?

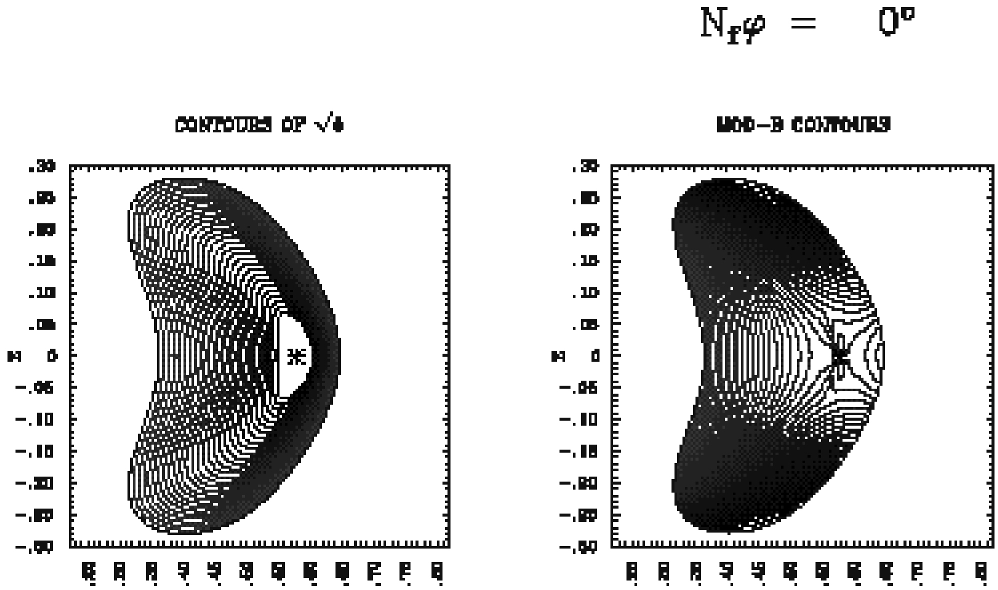
4. How do confinement properties relate to local stability properties?

5. "Generic" physics: disruptions, E_r effects (turbulence), bootstrap current simulation, torsatron/tokamak comparison.



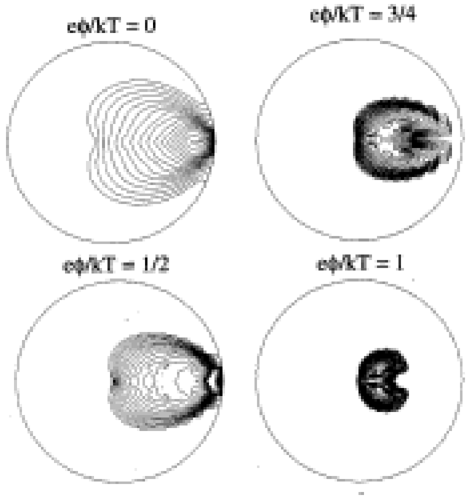
Equilibrium and Transport

Typical cross sections:



Orbits:

Ion root electric fields can close off the loss cone for trapped ions in Epeius (shown for 1 kev and ε/μ = 1)



(J* is approximation to invariant $J = \oint m v_{||} dl$: closed contours are good).

Reactor-development path

Very low A is achieved with partial magnetic optimization sufficient for α-particle confinement in the very low collisionality regime.

The α's will have closed trapped particle orbits with excursions Δr_α such that the diffusion coefficient is $D_\alpha = (\Delta r_\alpha)^2 \nu_\alpha$ and the confinement time can exceed the slowing-down time.

The thermal plasma, on the other hand, will be nominally in the $1/\nu$ regime, even with closed orbits, thus requiring naturally occurring or driven E_r to enter the ν / E_r^2 regime.

This scenario has the added benefit of providing an ash-removal mechanism: after the alphas give up most of their energy they enter the $1/\nu$ regime and are lost before being affected by E_r.

The ultimate objective is to design a compact reactor: Will it be a torsatron, a tokamak, or a hybrid?

TEXT: Turbulence and Transport

- The machine parameters:

  $R = 1.05$ m

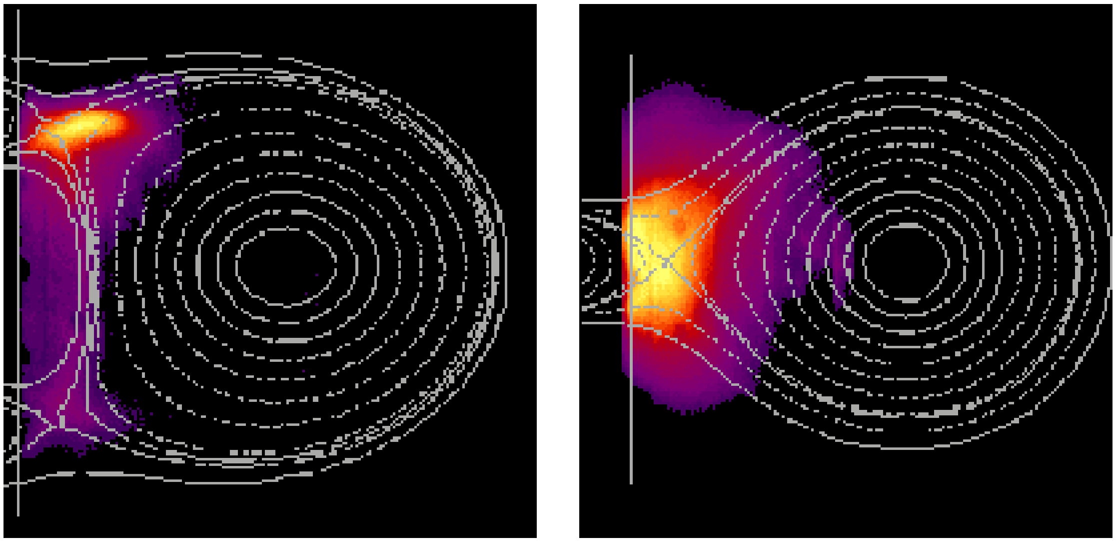
  $a < 0.3$ m

  $B_\varphi < 3$ T

  $I_p < 400$ kA

  pulse length < 500 ms

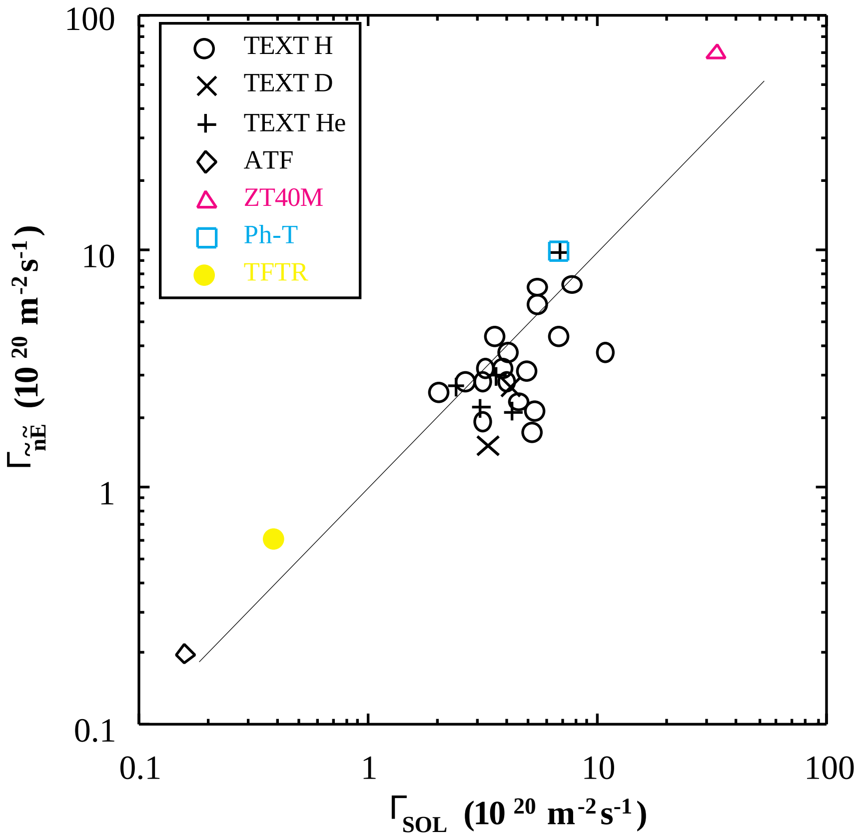
  400 kW ohmic, 600 kW ECRH



Edge Particle Flux

Tokamaks, RFP's and stellarators

$$\Gamma_{SOL} = \frac{n_e c_s L_n}{2 L_c}$$



- Electrostatic turbulence “explains” total.
- This is true for tokamak, RFP, stellarator.
- In RFP the density fluctuations associated with tearing modes do not cause any transport.
- Directly measure $\tilde{b}$ effects to be small.

Interior Turbulence and Transport (heat)

The possibilities

1. Magnetic perturbations: parallel particle motion along field lines with a component out of the flux surface.

2. Electrostatic *ExB* drifts across flux surfaces.

- Determine relevance of each: Compare total (heat) flux or (thermal heat) diffusivity with measured fluctuation driven (heat) flux or (thermal heat) diffusivity.

- Cannot do this, so resort to models and upper limits.

Electrostatic: Deduce maximum (electron) heat flux from measured turbulence.

$$Q_e = \frac{3}{2}\langle \tilde{p}_e \tilde{v}_r \rangle = \frac{3k_b n\langle \tilde{E}_\theta \tilde{T}\rangle}{2B_\varphi} + \frac{3k_b T\langle \tilde{E}_\theta \tilde{n}\rangle}{2B_\varphi}$$

conducted convected

i.e. $Q_{e,conducted} < \dfrac{3k_b n}{2B_\varphi}\tilde{E}_\theta \tilde{T}$ (rms fluct. values)

$$= \frac{3k_b n}{2B_\varphi} k_\theta \tilde{\varphi}\tilde{T} = \frac{3k_b n T^2}{2B_\varphi} k_\theta \left(\frac{\tilde{\varphi}}{T}\right)\left(\frac{\tilde{T}}{T}\right)$$

Usually find $\tilde{\varphi}/T \approx \tilde{n}/n$, so that

$$Q^{\max}_{cond\ e} = \frac{3}{2}\frac{k_b n T^2 k_\theta}{B_\varphi}\left(\frac{\tilde{T}}{T}\right)\left(\frac{\tilde{n}}{n}\right)$$

Include effects of

a) sample volume sizes

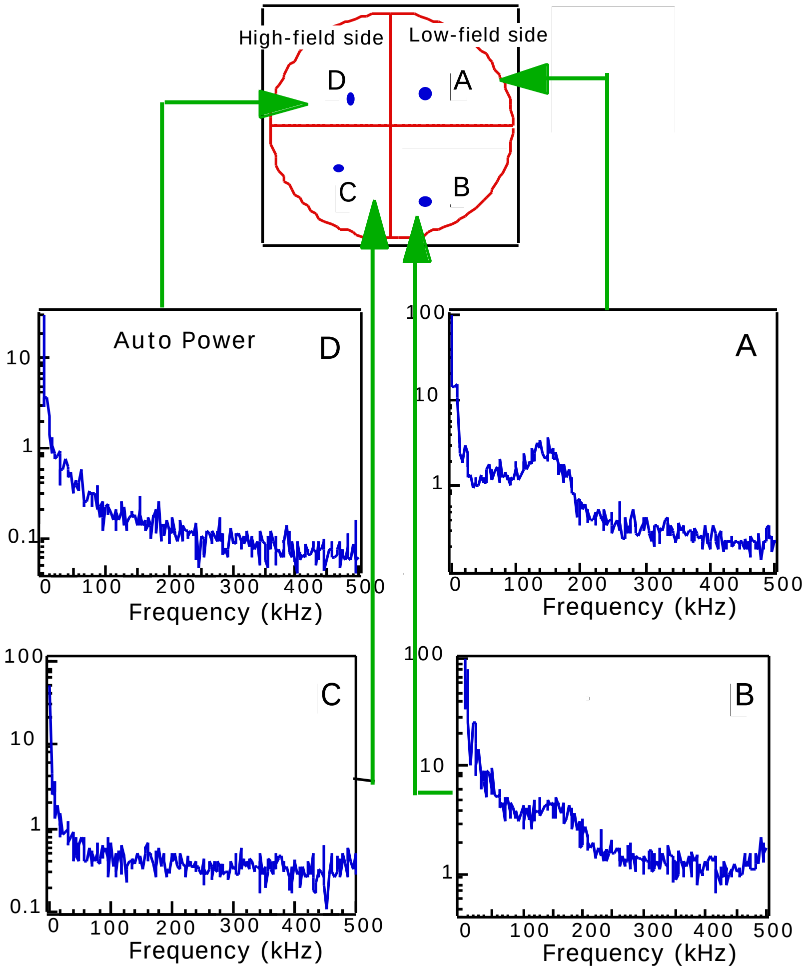
b) asymmetries

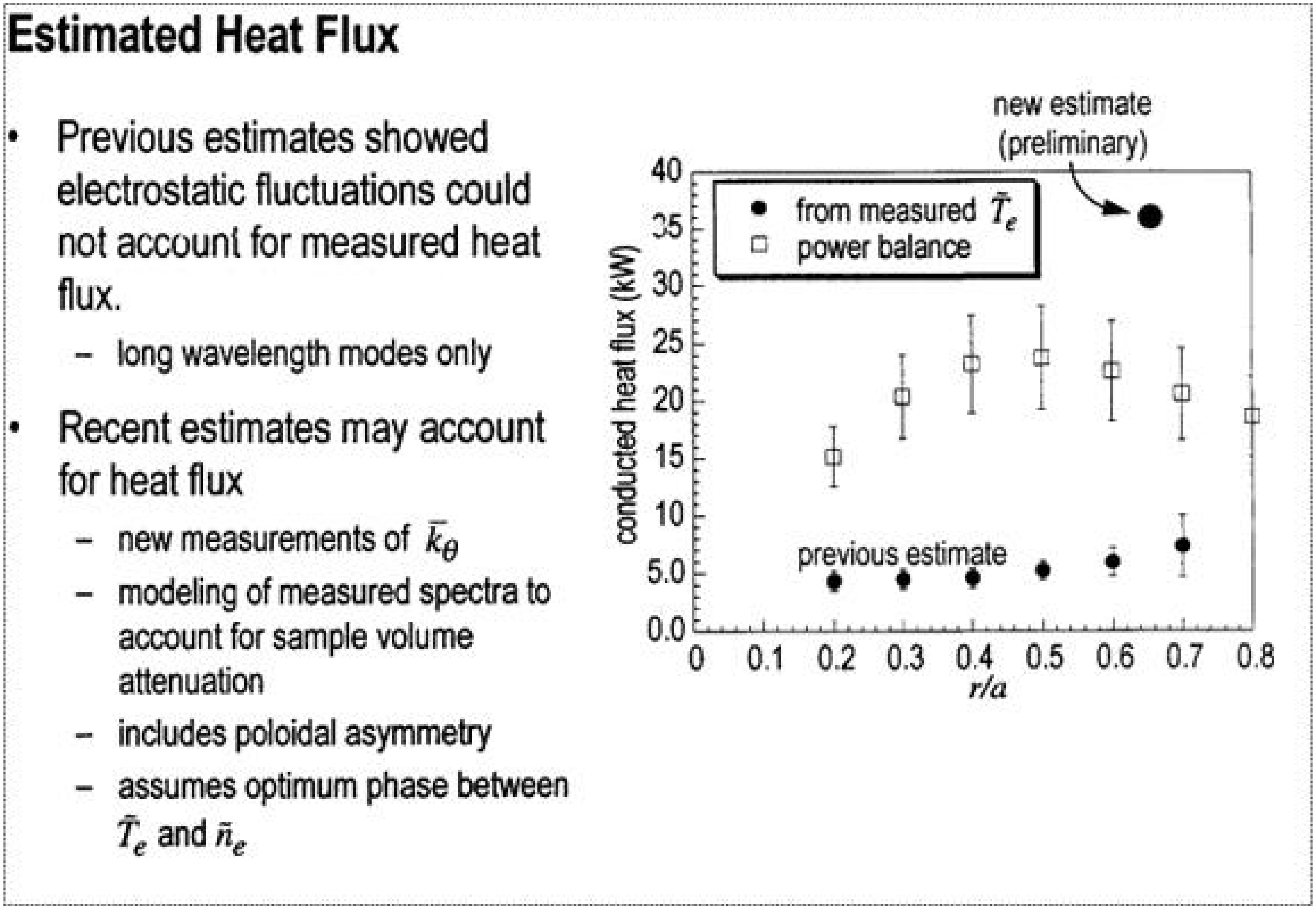
Asymmetries

The turbulence is poloidally asymmetric.

HIBP density and potential fluctuations

HIBP density fluctuation data

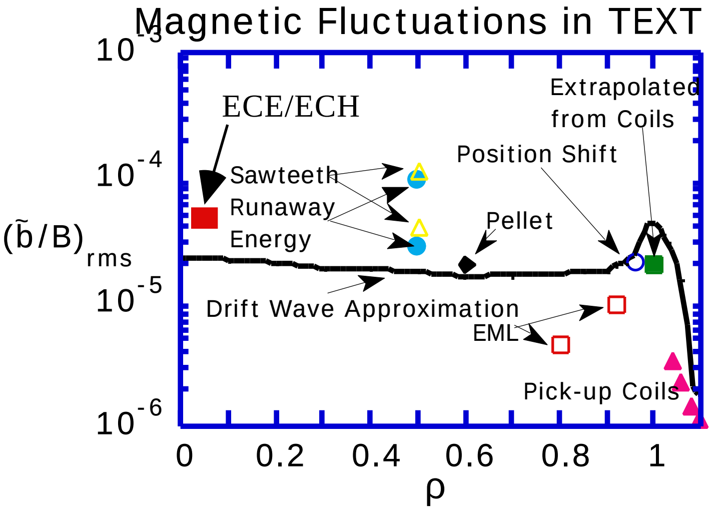


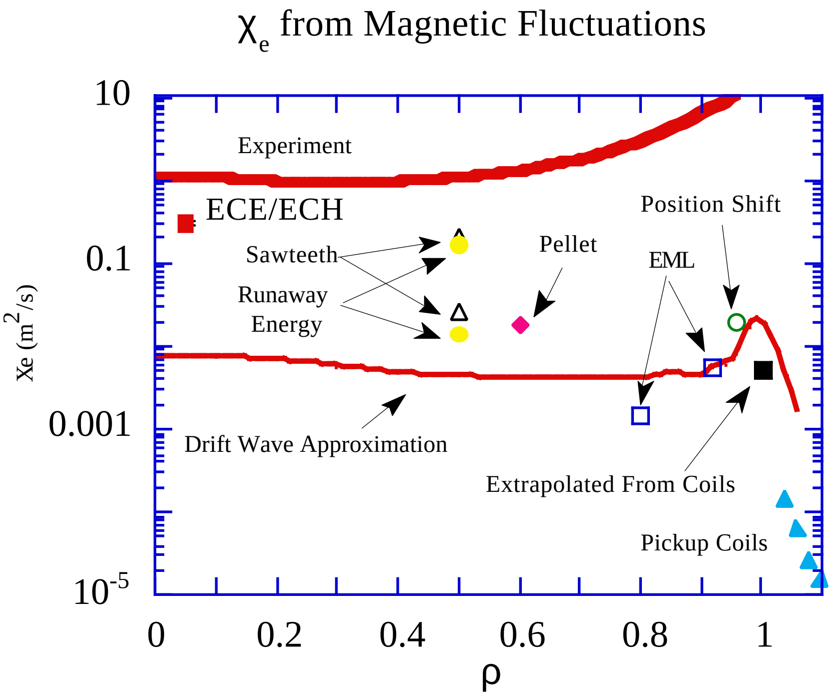


Estimated Heat Flux

- Previous estimates showed electrostatic fluctuations could not account for measured heat flux.
  - long wavelength modes only
- Recent estimates may account for heat flux
  - new measurements of $\bar{k}_\theta$
  - modeling of measured spectra to account for sample volume attenuation
  - includes poloidal asymmetry
  - assumes optimum phase between $\tilde{T}_e$ and $\tilde{n}_e$

Implications for $\tilde{b}$ and χ_e in TEXT





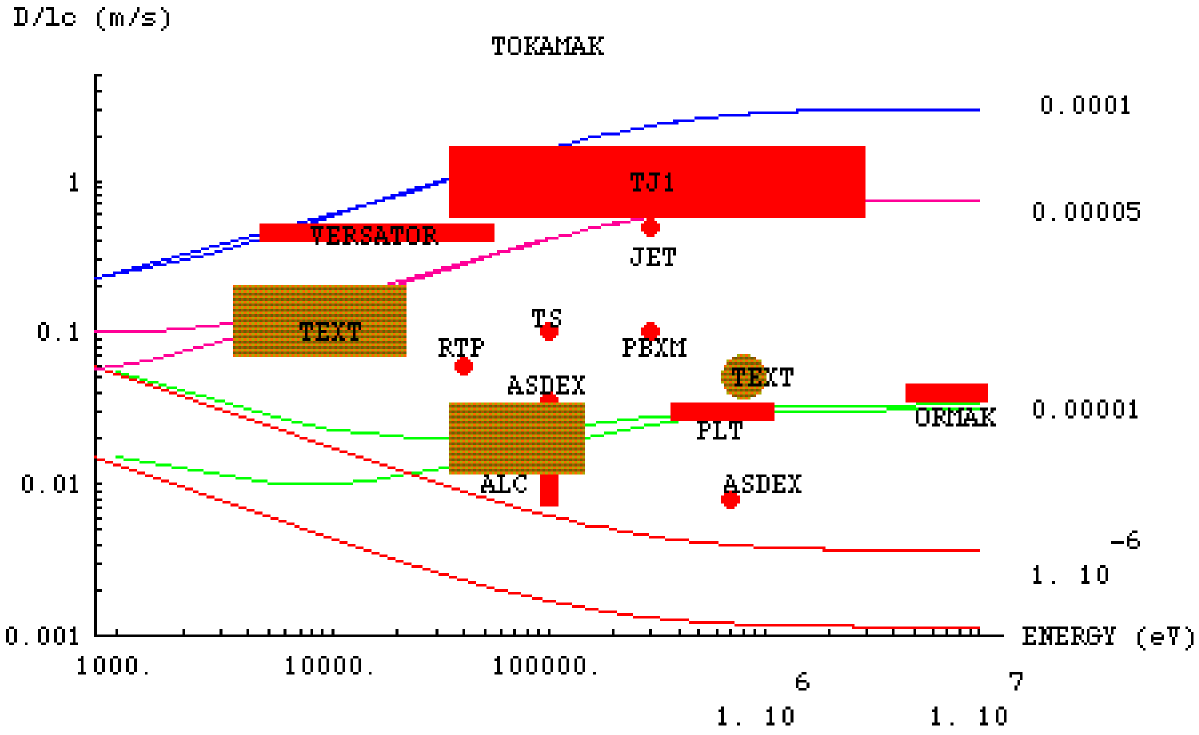
- Magnetic fluctuations are not important
- True for most other estimates from other devices.

Results from other machines

$$D \approx \pi q R \left[\frac{1}{v_\parallel}\left(\frac{\tilde{E}}{B_\varphi}\right)^2 + v_\parallel \left(\frac{\tilde{b}}{B_\varphi}\right)^2 \right]$$

- Show $D_{fe}/(\pi q R)$ in ms^{-1} as a function of energy.

- Show predictions for $v_0 = \frac{\tilde{E}}{B_\varphi}$ = 500 (lower) and 1000 ms^{-1}.

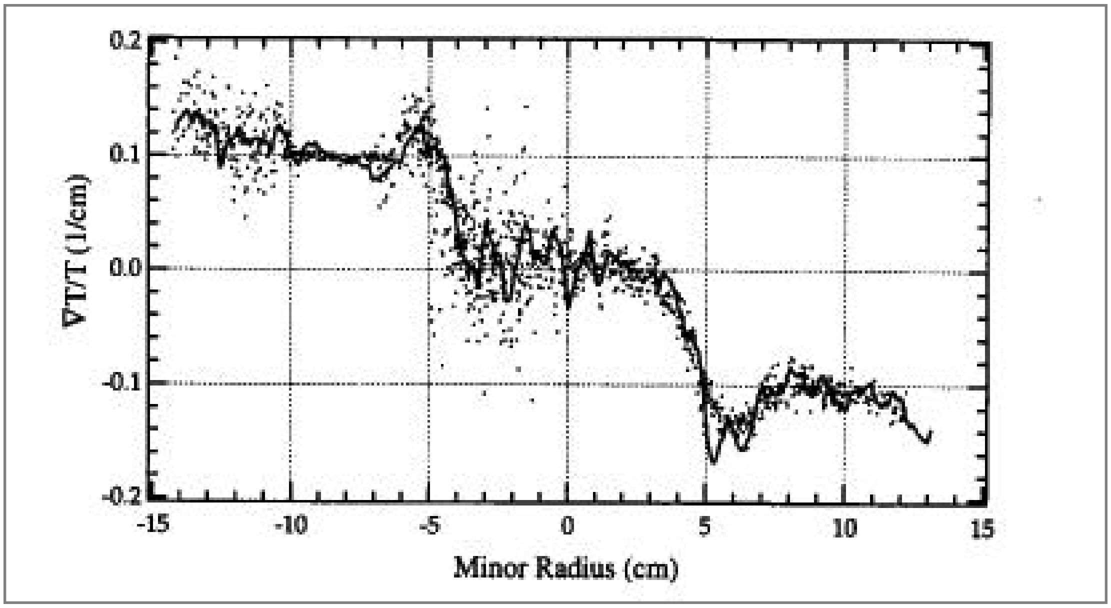


Generally $\tilde{b}$ is too small to explain χ_e.

What about mixed 'good' and 'bad' surfaces?

i.e. mixed stochastic, island and concentric surface regions ("bubbling islands") ?

No evidence for 'flat spots' in T_e.



Sweep plasma slowly under detector(s).

Stationary islands not present outside $q = 1$. (unless MHD) .

'Bubbling islands' (time dependent flat spots) not present unless width < 0.5 cm, duration <100 μs.

Are there any theories which predict islands growing and decaying with τ ≈ 100 μs?'.

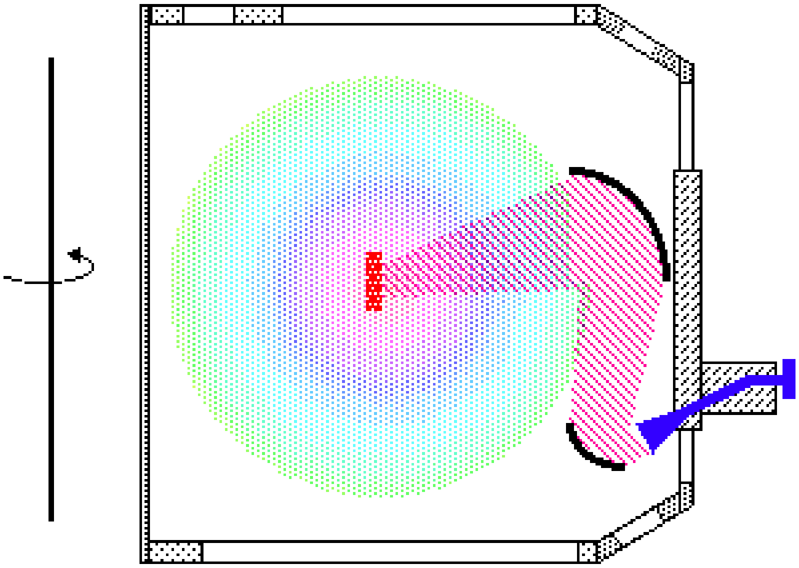
Inside the *q* = 1 surface, with ECRH

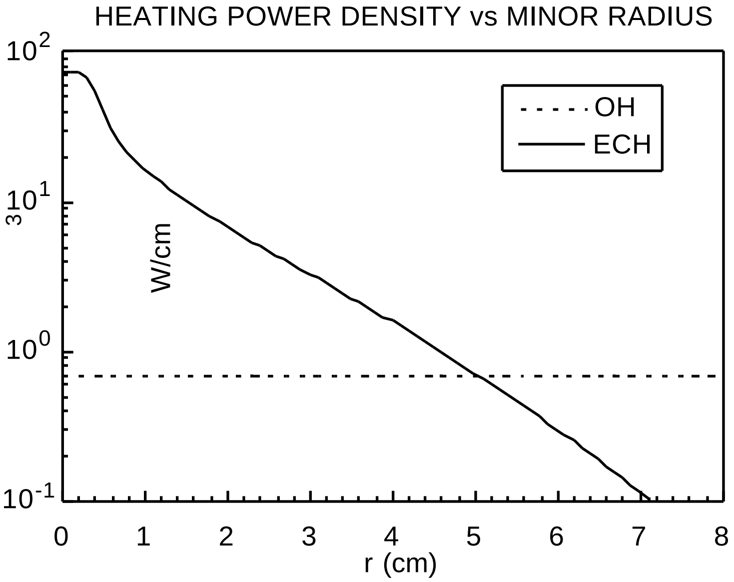
- Overall confinement
- Filaments

TEXT unique features:

1) high power density ECH

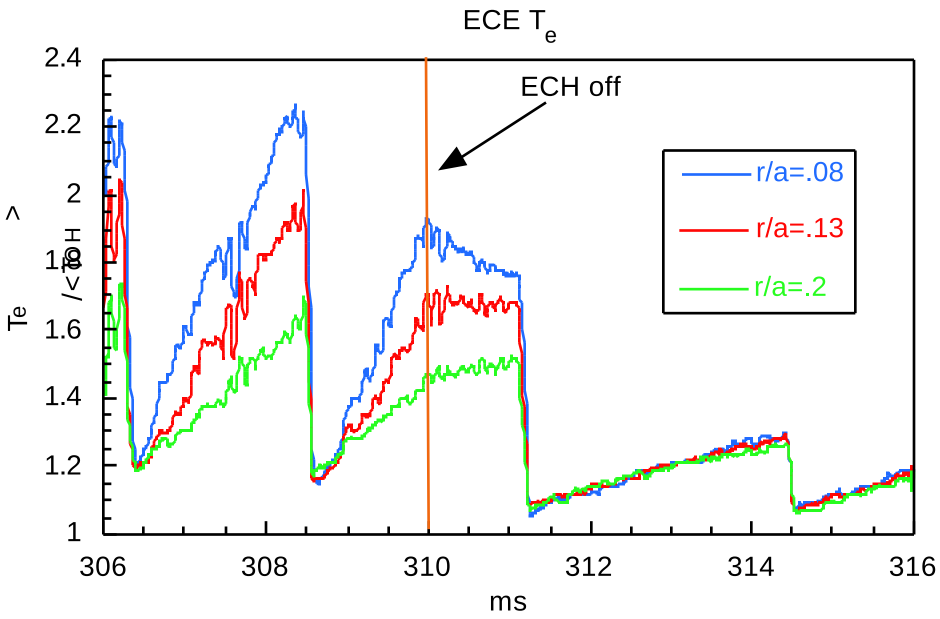
2) high resolution ECE (20 imaging channels)



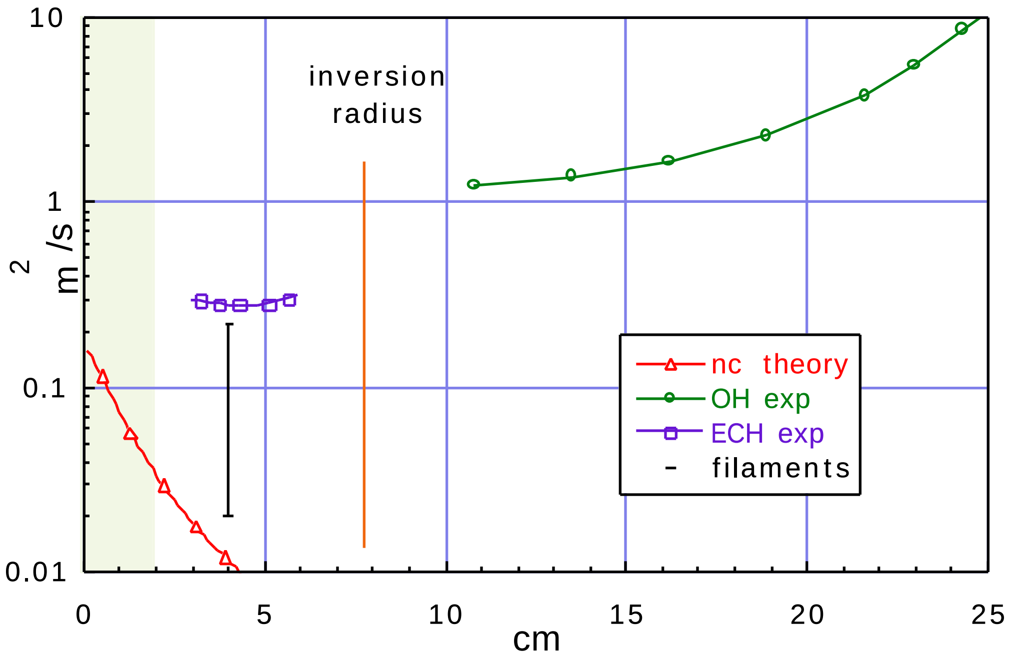


Overall Confinement Within $q = 1$

Time histories of T_e (over 10 ms)



Deduced χ_e



- χ_e can be very low.

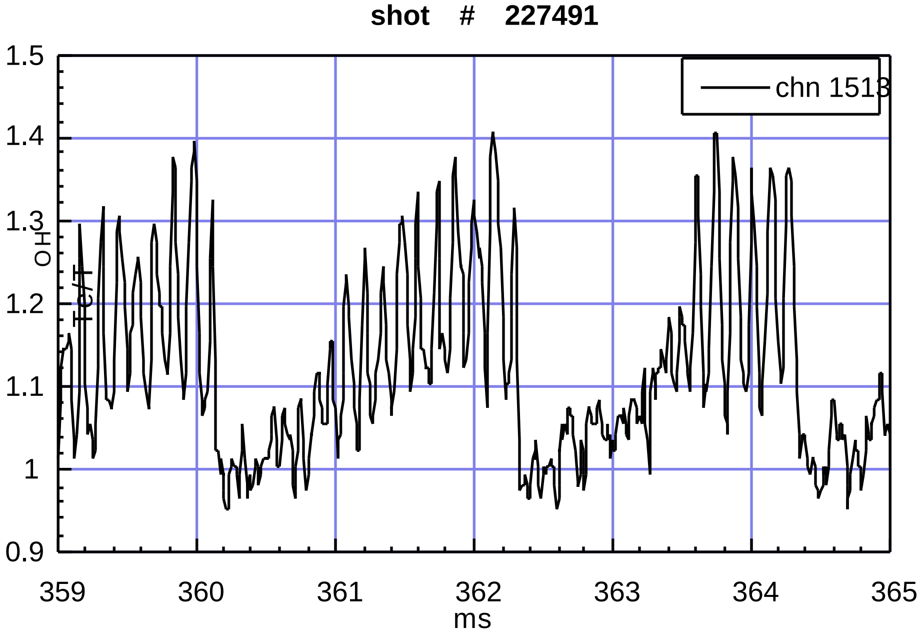
Inside the q = 1 surface - filaments (with ECRH)

Filaments (with ECRH)

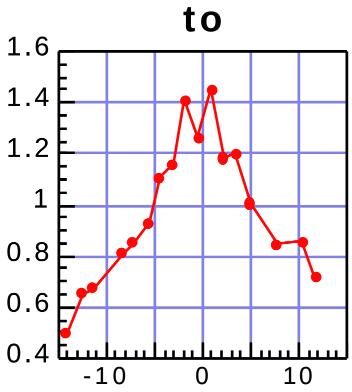
Remember RTP? Thomson scattering at a single time point during ECRH showed 'filaments'.

We also observe them during ECRH

20 μs/1 cm resolution ECE



'Filaments' not random - rather periodic in time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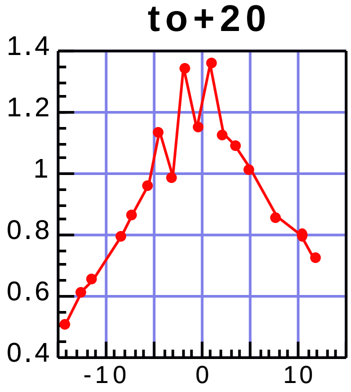
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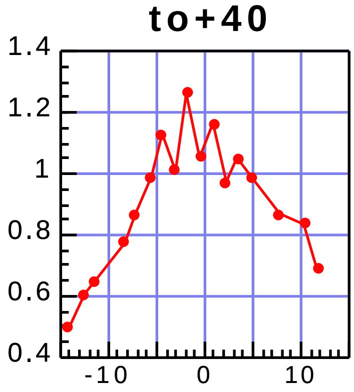
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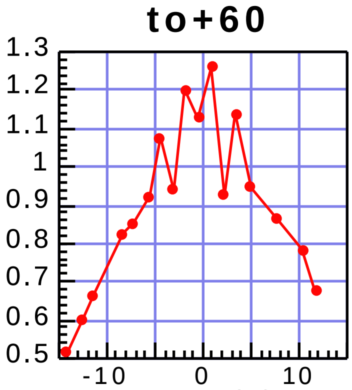
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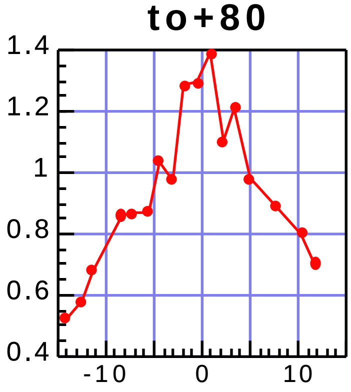
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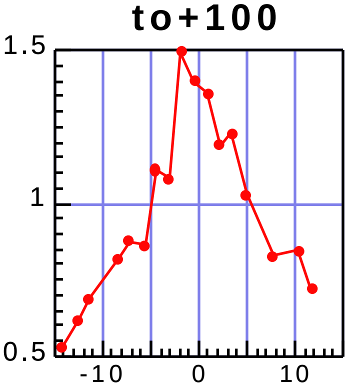
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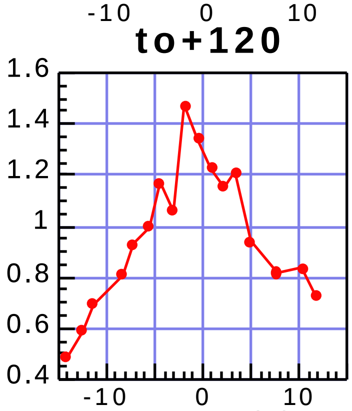
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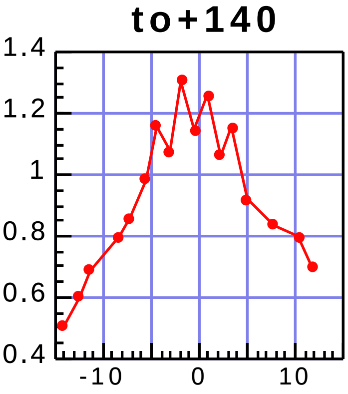
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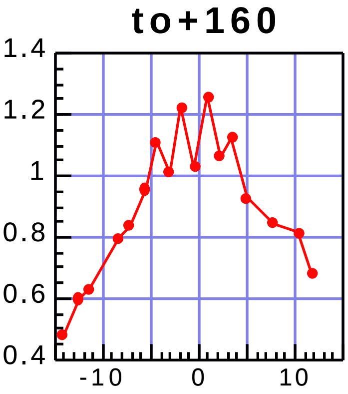
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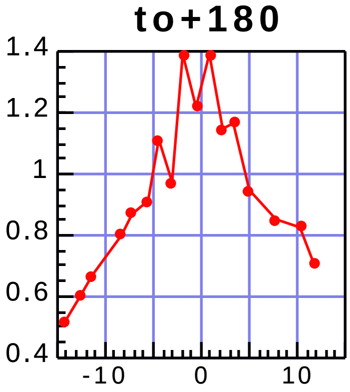
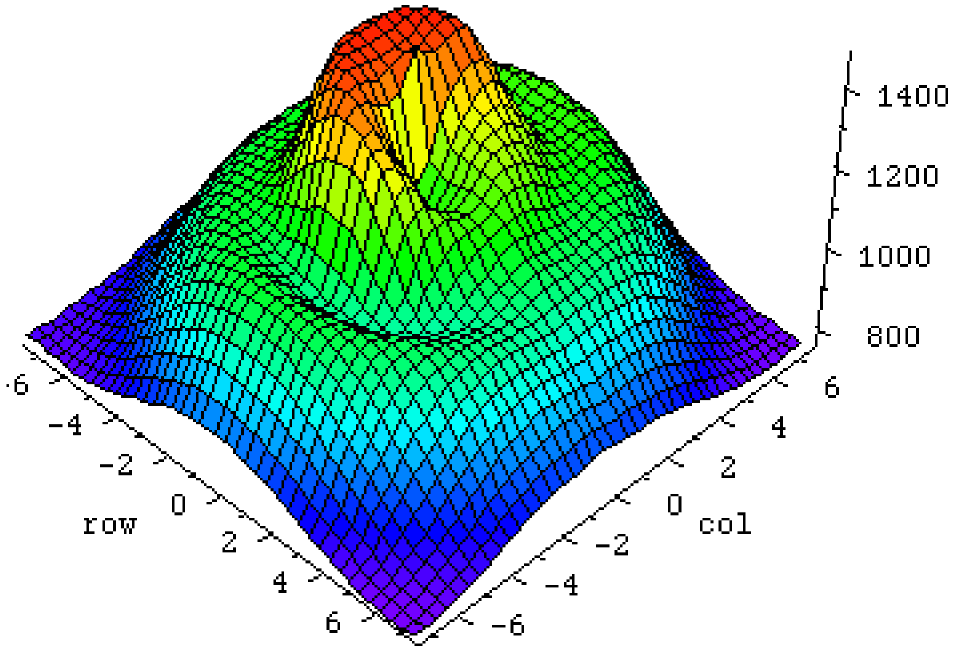

to+180

Sequence of vertical ECE Temperature profiles in 20μs time slices.

Reconstruction



Are we looking at MHD islands and a localized energy source interacting? χ_e is neoclassical.

Conclusions

Is low-A worthwhile?

Tokamaks: For an exothermic thermonuclear device, with accepted τ_E, κ and η_{CD}, there is no advantage in low-A. i.e. build a normal-A superconducting system. But it is an interesting experiment (a neutron source? an ignition experiment?), and τ_E may improve.

Stellarators: For an exothermic thermonuclear device, scaling relations show low-A is advantageous, but high β is required (use I_p?). How will $\tau_{En/c}$ be suppressed? Low $\varepsilon_{h,eff}$? E_r?

Is there an optimum hybrid device which uses I_p and E_r (self consistent and controlled)?

Is electrostatic or magnetic turbulence responsible for plasma transport?

The edge Electrostatic turbulence. But the drives are not fully understood.

The Interior With many caveats, it appears to be electrostatic with $k_\theta \approx 3\ \mathrm{cm}^{-1}$ (in TEXT). Perhaps the drive is something we do not measure well (T_i'?).

Inside q = 1 χ_e can be very low. 'Filaments' with ECRH may be the interaction of an MHD mode with the very localized heating source.