Spontaneous tokamak rotation: observations turbulent momentum transport has to explain

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Outline

What is spontaneous rotation?

Scaling with plasma parameters.

Edge and core rotation.

Transients, Heuristic Transport, Variability.

Remarks about Mechanisms.

Tokamaks have near-perfect Axisymmetry

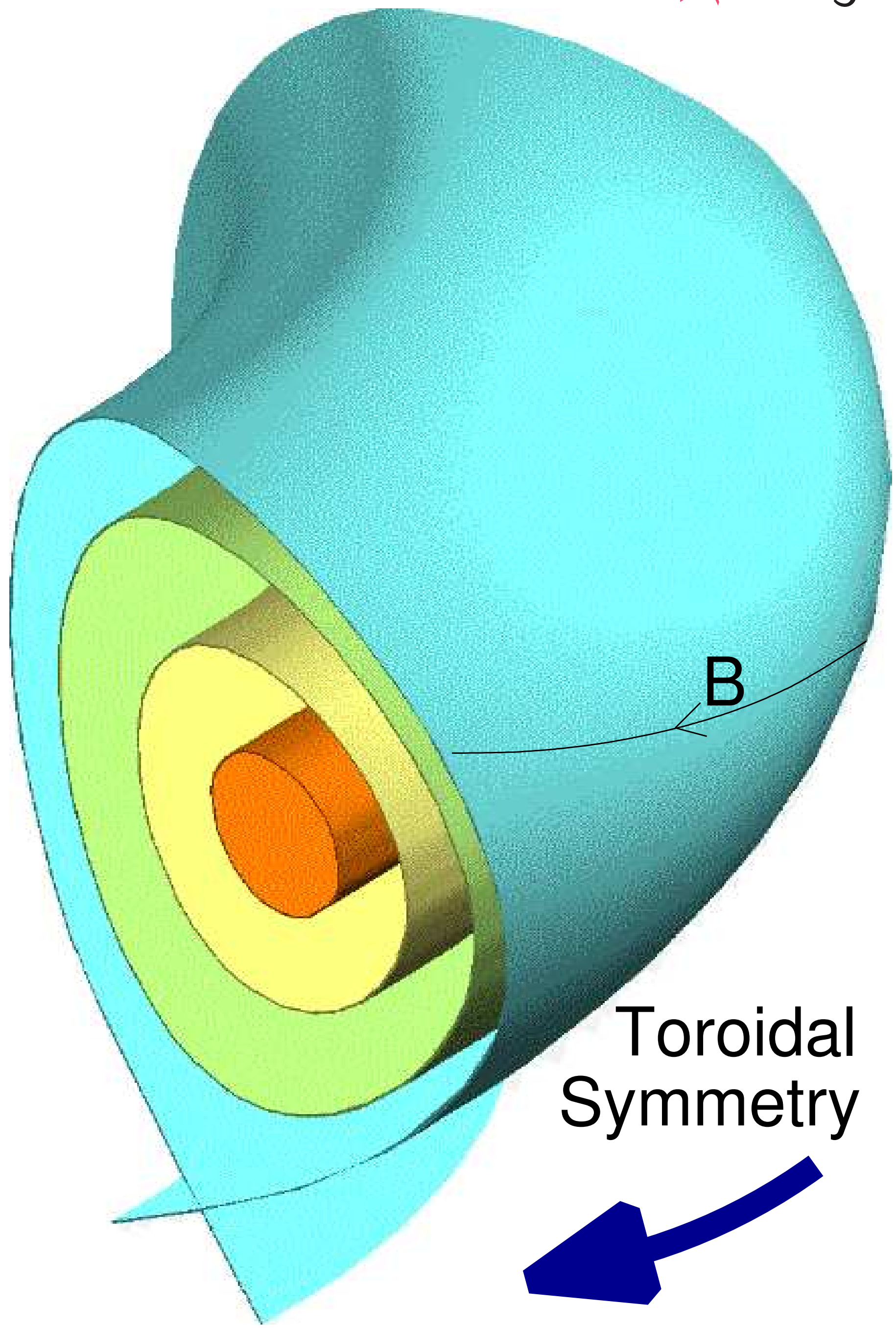
To the extent that axisymmetry is perfect, toroidal angular momentum is conserved.

There are nearby fixed structures to which momentum could be transfered (unlike astrophysics!), but it can only be transfered by non-axisymmetric fields or by particles.

We know that sometimes non-axisymmetric B-fields arise that transfer momentum (Perturbations, Locked modes, Wall modes).

Most of the time these are absent (AFAWK).

Poloidal Rotation is rapidly damped by the 1/R magnetic field variation (not symmetric in poloidal direction).



Neutral Beams Inject Momentum: Driven Rotation

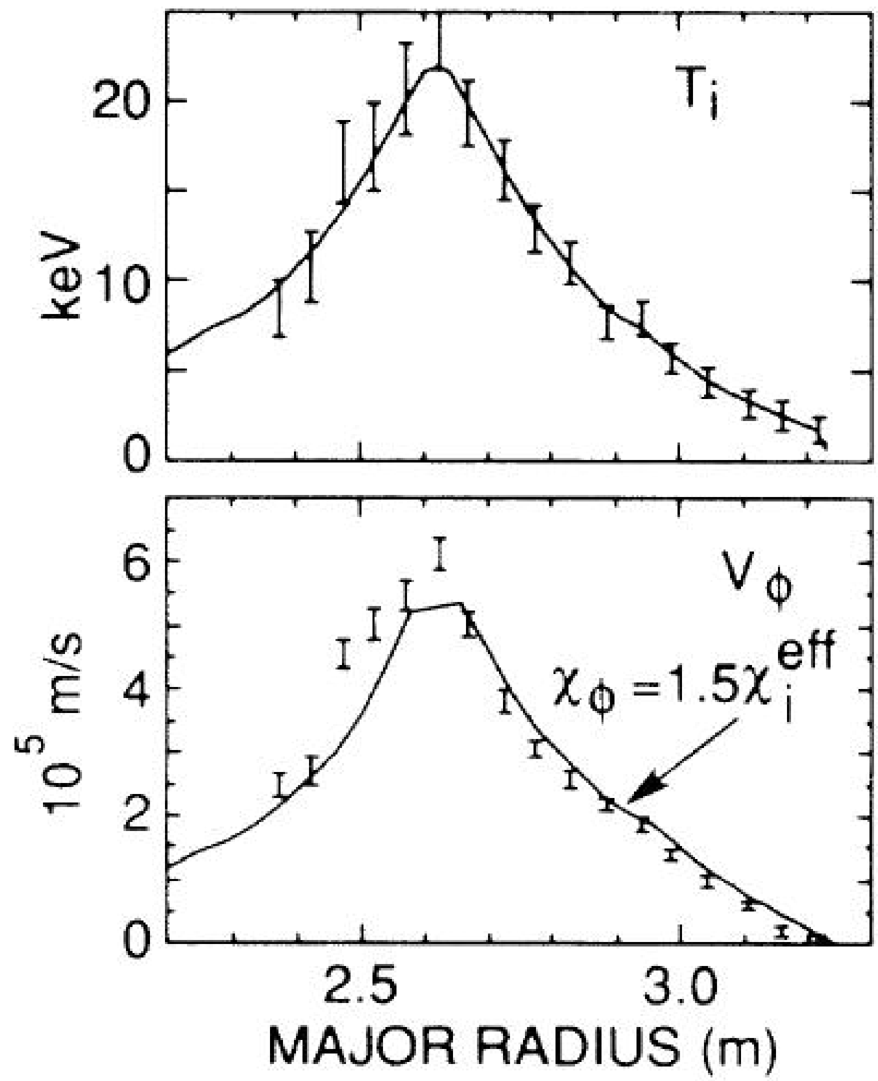
Heating beams are generally tangential, and asymmetric. They impart large amounts of particle momentum.

This is observed to be transported out of the plasma at roughly the same rate as heat.

In mid-90s a common view was simply that Tokamaks rotate because of beams, and momentum transport is roughly diffusive (shear viscosity) but due to turbulence.

This was a big oversimplification even then. The H-mode barrier was known to be a region of big velocity shear, E_r-reversal.

TFTR beam momentum transport

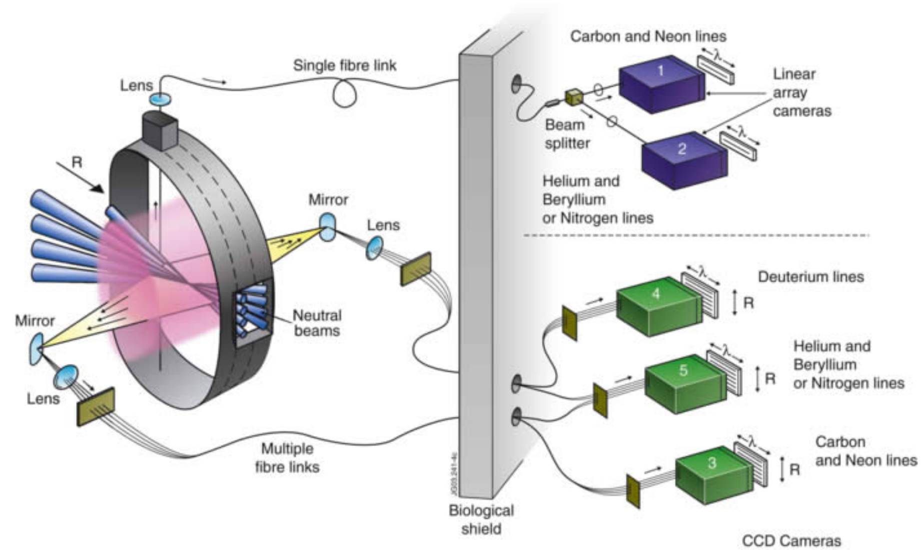


S.Scott et al PRL 64, 531 (1990)

Diagnostics of Velocity

Charge Exchange Spectroscopy needs beams, which usually cause a big perturbation.

There are subtleties to do with differences between bulk ion (D) and impurity velocity. For light ions (e.g. Carbon often used for CXS) there can be major differences.



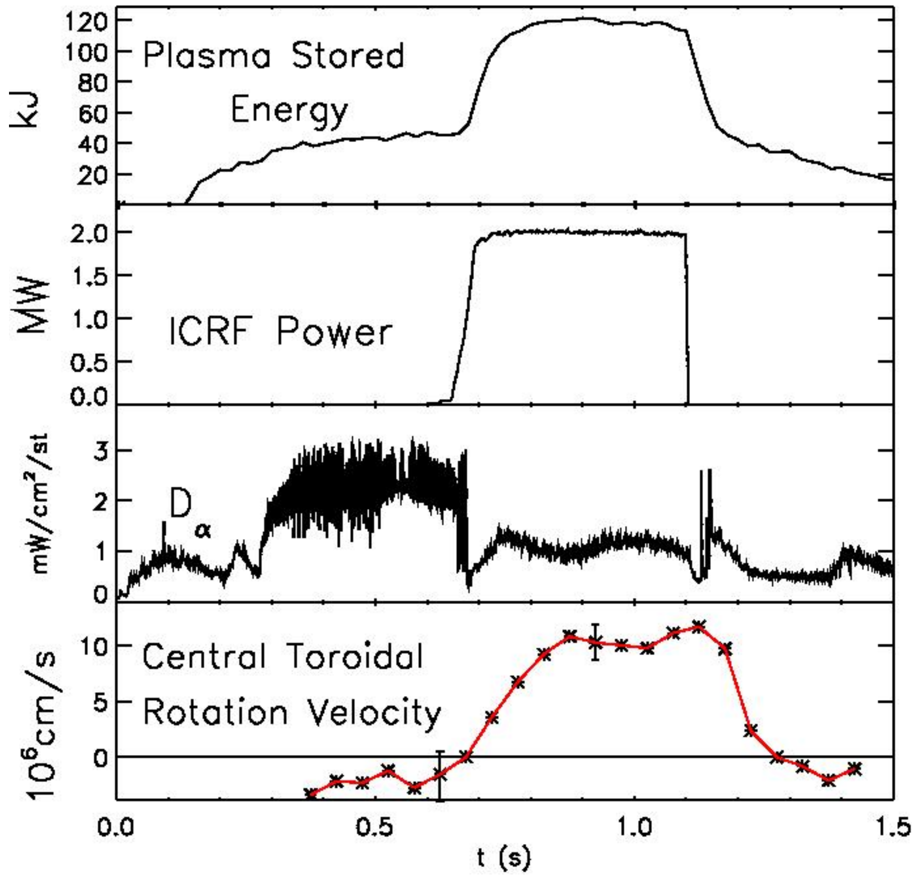
Doppler spectroscopy of intrinsic higher-Z impurity ions (like Ar) don't have crossed-beam localization, but are advantageous for velocity diagnostics because

- Diamagnetic term is smaller ($\propto 1/Z$)
- Collisional coupling of $v_{||}$ to bulk is greater ($\propto Z^2$)

MHD events known as Sawteeth give rise to central helical perturbations whose toroidal velocity can be measured.
This is a completely independent way to verify the velocity.
Agreement with Ion-Doppler is generally quite good.
(Edge magnetic perturbations can also be used.)

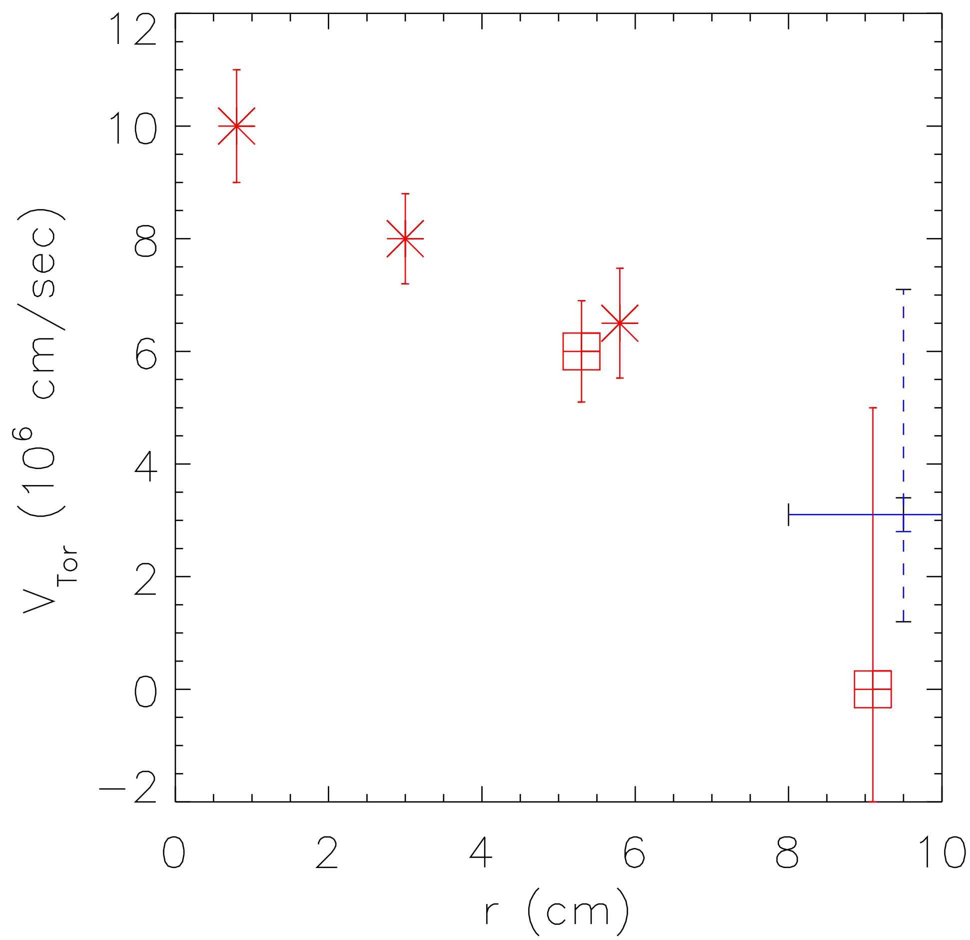
C-Mod has no heating beams: no direct momentum input

But it does have quite good plasma rotation measurements based on Doppler spectroscopy of Ar^{+16} (and magnetic fluctuations).



Velocity up to 100 km/s $= 0.3c_s$.

Swings positive on H-mode transition



Velocity peaked in the center.

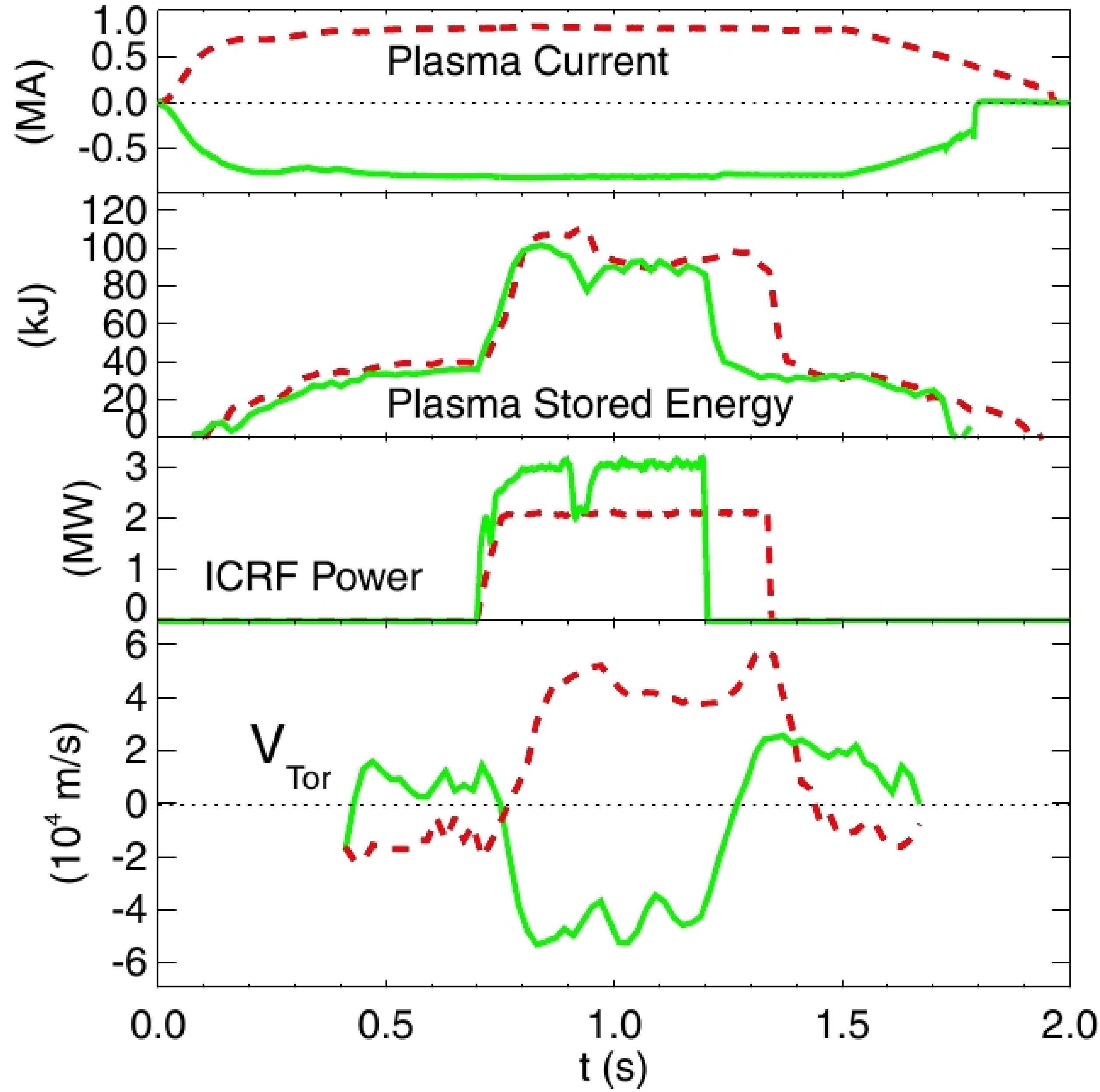
J.E.Rice et al Nuclear Fusion 38, 75 (1998)

Spontaneous Velocity in H-mode is in Co-Current Direction

When current is forward (Red) or reversed (Green)

Then during the high confinement period (ICRF heated, Energy Enhanced)

Toroidal velocity is correspondingly forward or reversed.



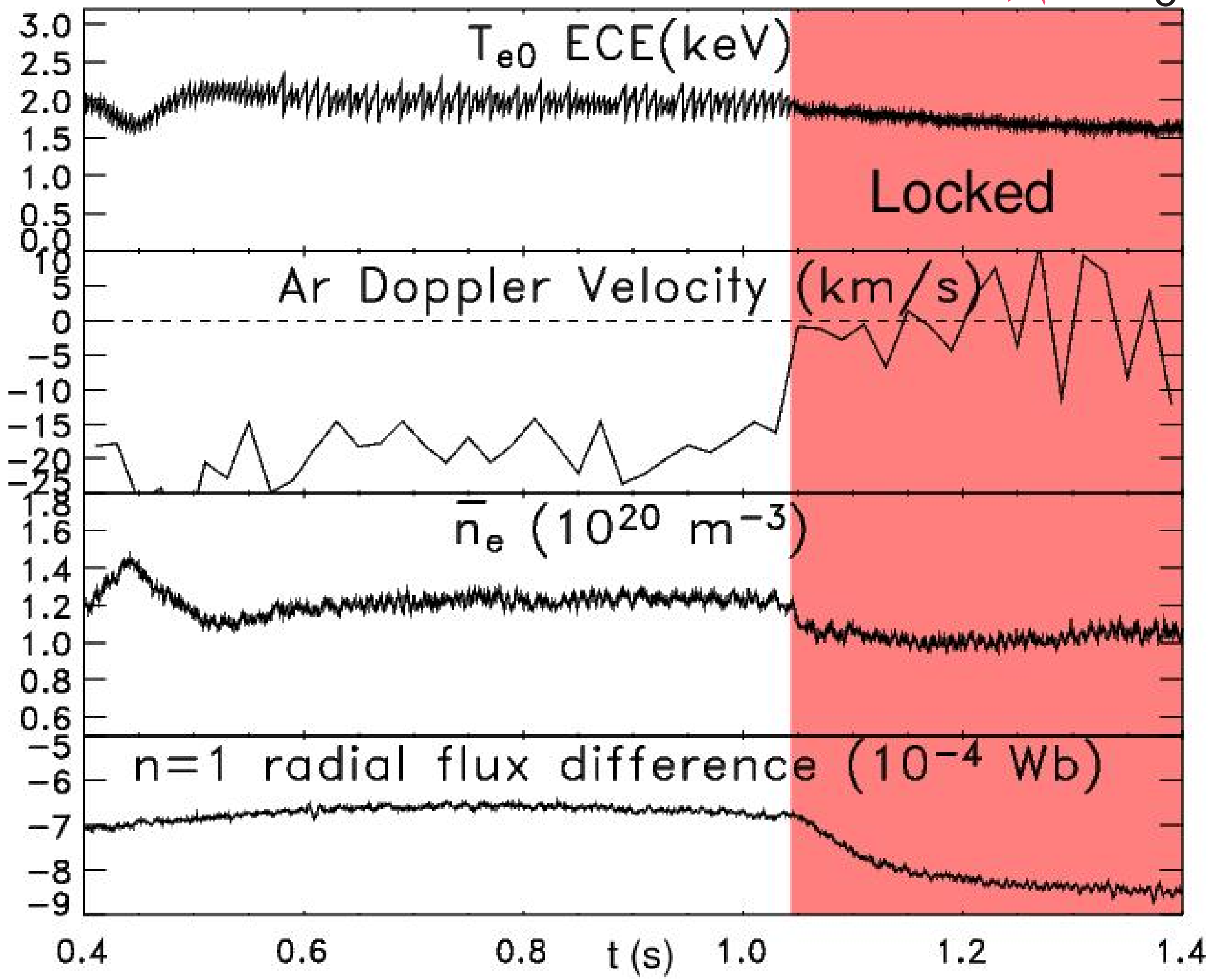
"Mode-Locking": Velocity goes to zero.

L-mode plasma

Core ion velocity

Density loss at lock

Magnetic perturbation.



An example of momentum transport by non-axisymmetric fields.

Confirms the zero of Doppler diagnostics etc.

Rotating modes are measured to have too small a torque for relevance.

I.H.Hutchinson, IAEA Portugal, paper EX/P5-6, (2004).

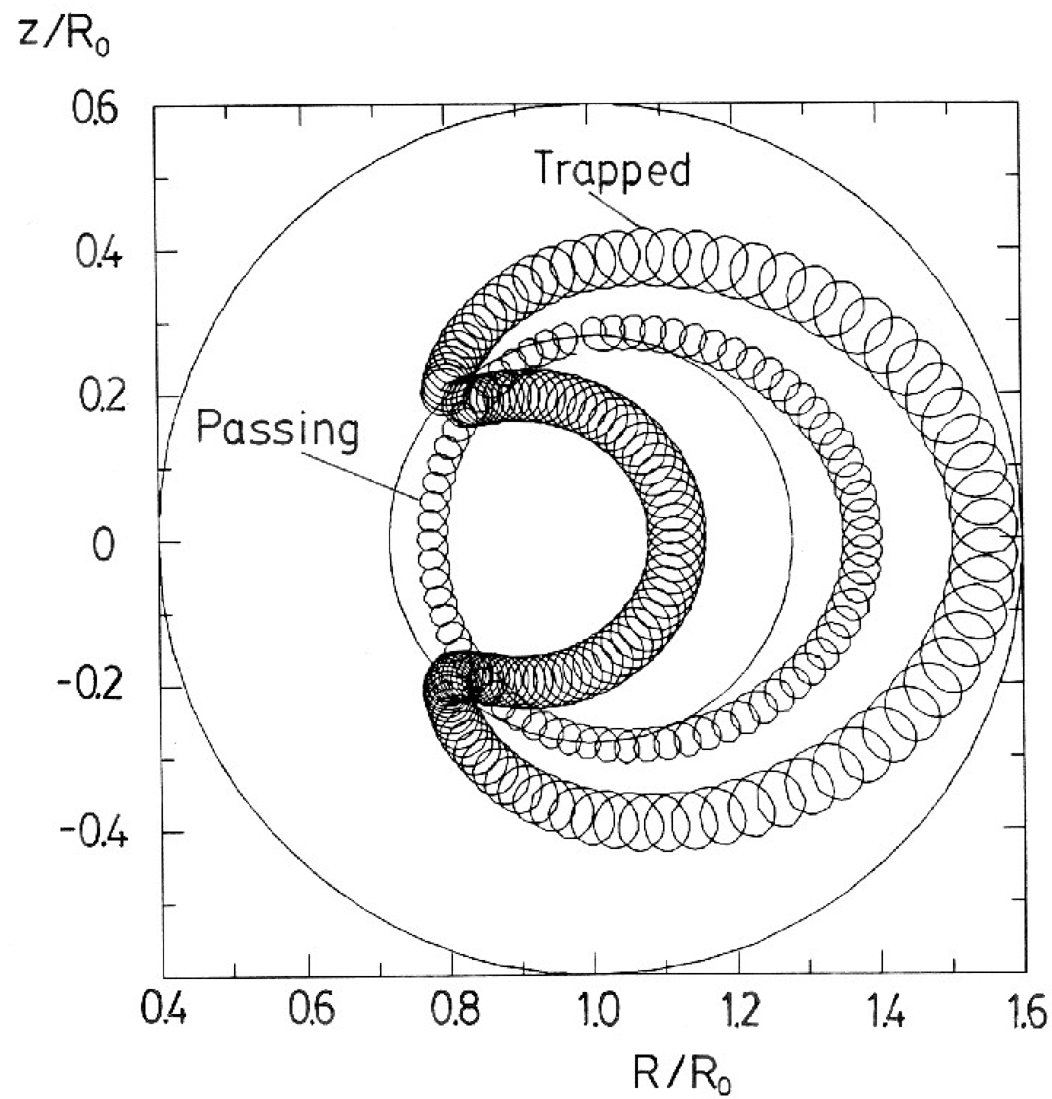
Energetic Ion Orbit Momentum Transfer

Initially suspected as an ICRF flow-drive mechanism

Co-moving ions are shifted outward, counter inward.

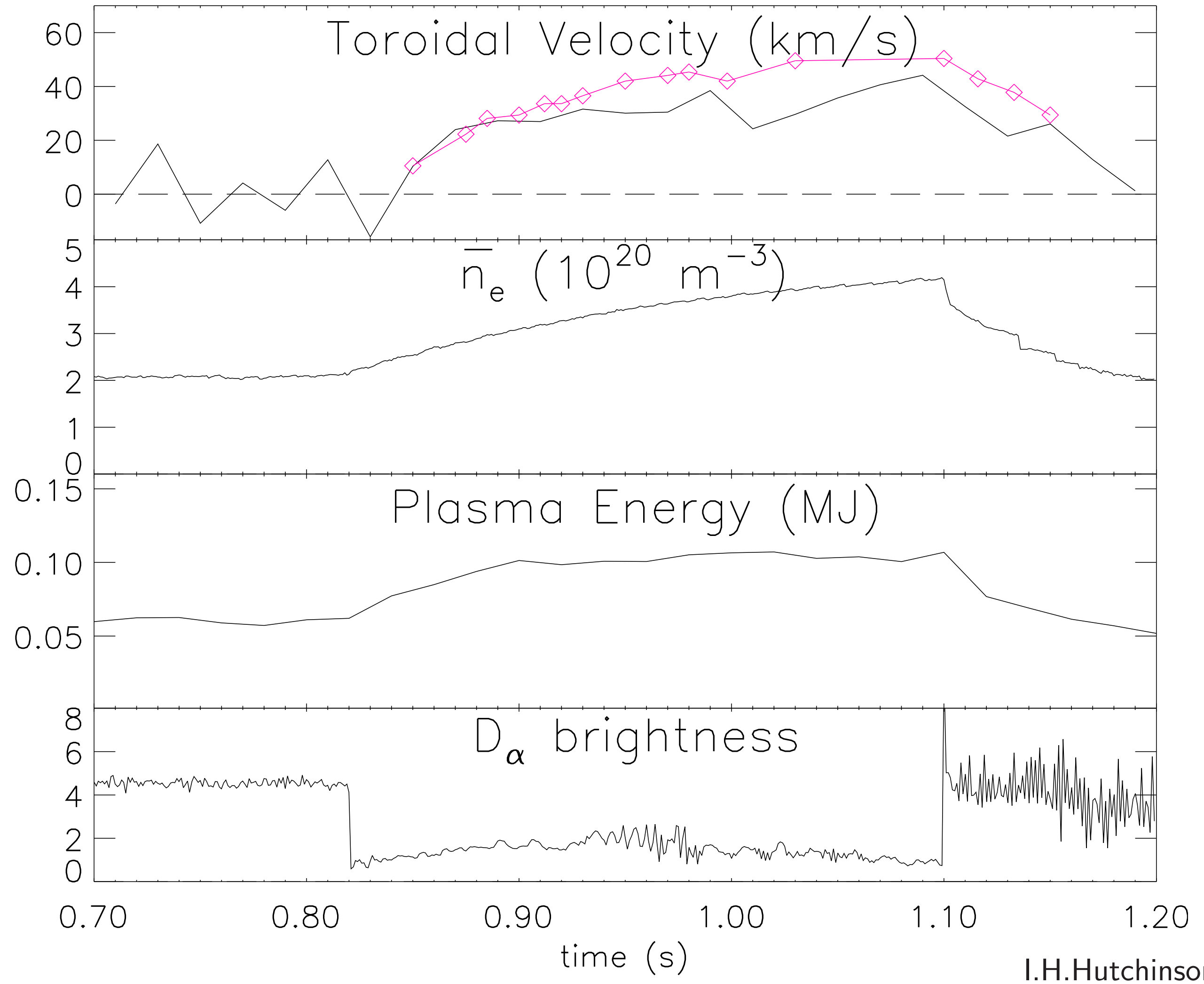
Systematic toroidal momentum transport can occur if ions are scraped off or accelerated in preferential positions.

Was initially considered to be a likely mechanism to generate rotation of the ICRF heated H-modes.



So a key experiment was pursued: to measure rotation without ICRF or Beams.

Spontaneous Rotation in Ohmic H-Modes



I.H.Hutchinson PRL 83, 3330 (2000)

Rules out ICRF-induced energetic ions as cause of rotation. (No RF!)

Sawtooth velocity (pink points) agrees with Argon (within errors)
in magnitude, direction, and time-dependence.

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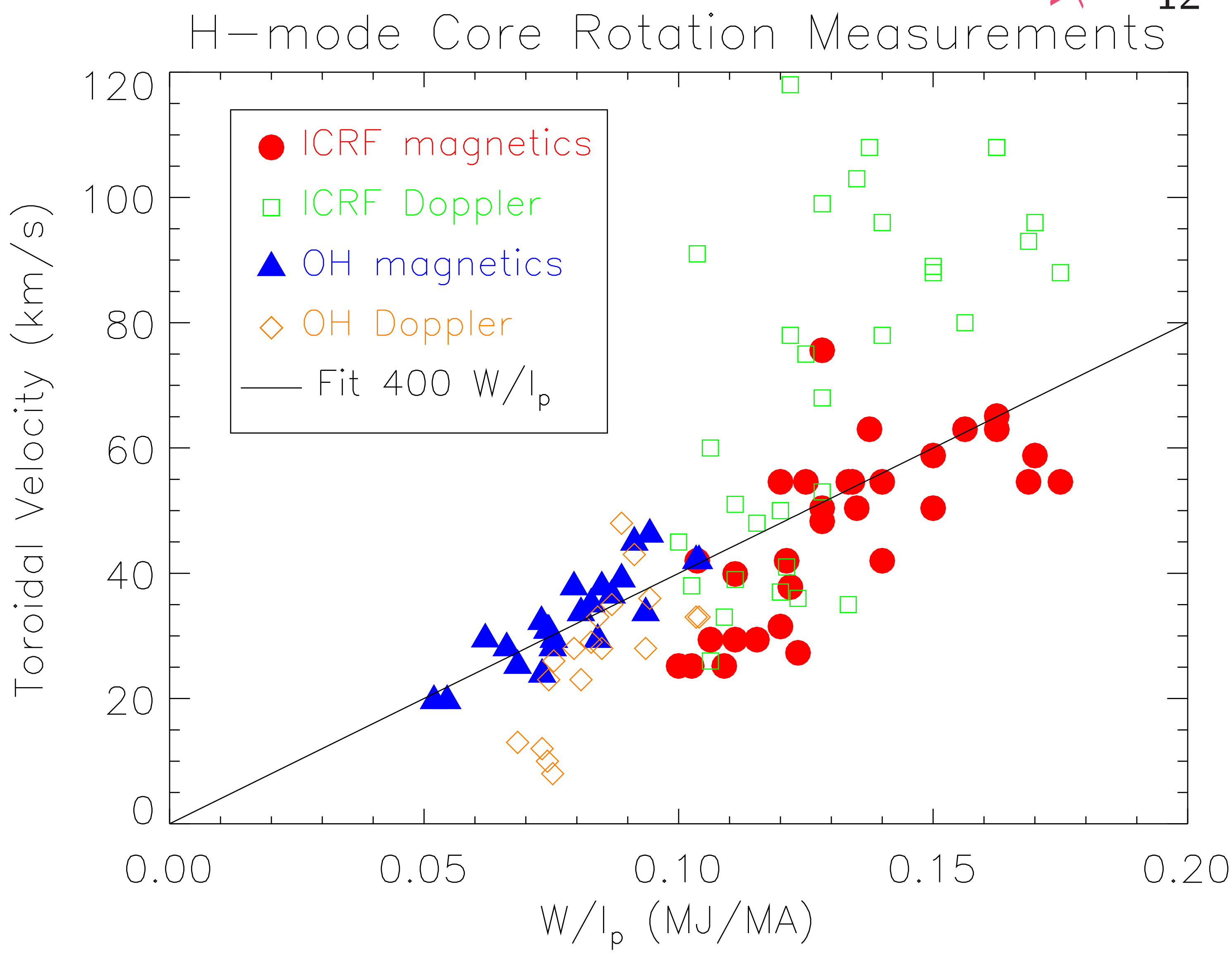
Ohmic Rotation Scaling is like ICRF

Database of observed central rotation.

High ICRF power have more peaked rotation.

I.H.Hutchinson PRL 83, 3330 (2000)

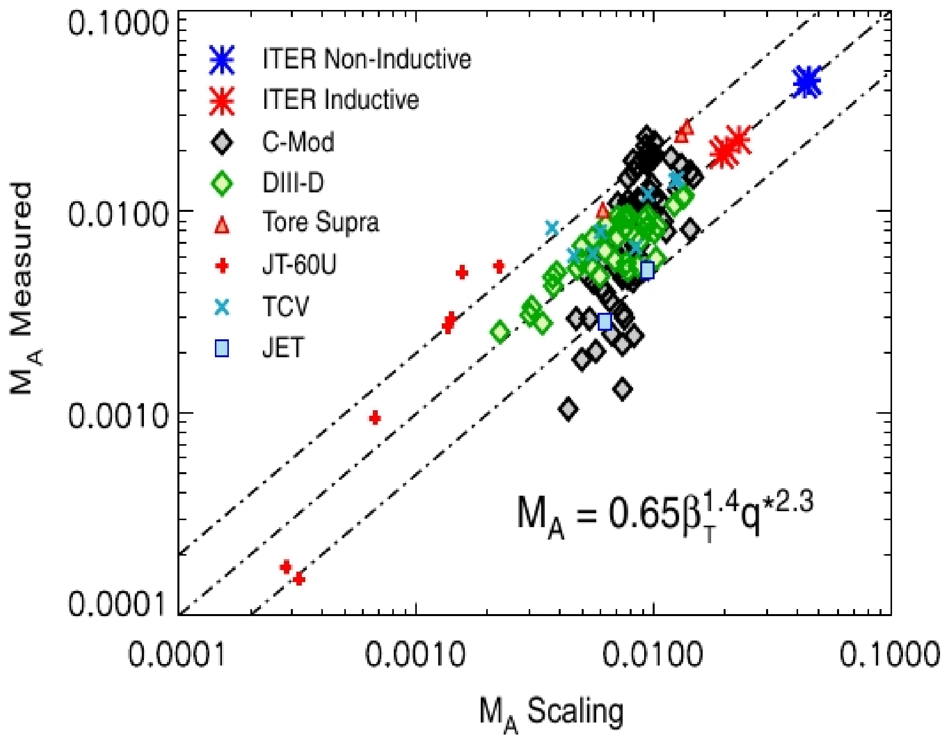


Both Ohmic and ICRF rotation velocities scale proportional to stored energy divided by plasma current $\propto W/I_p$.

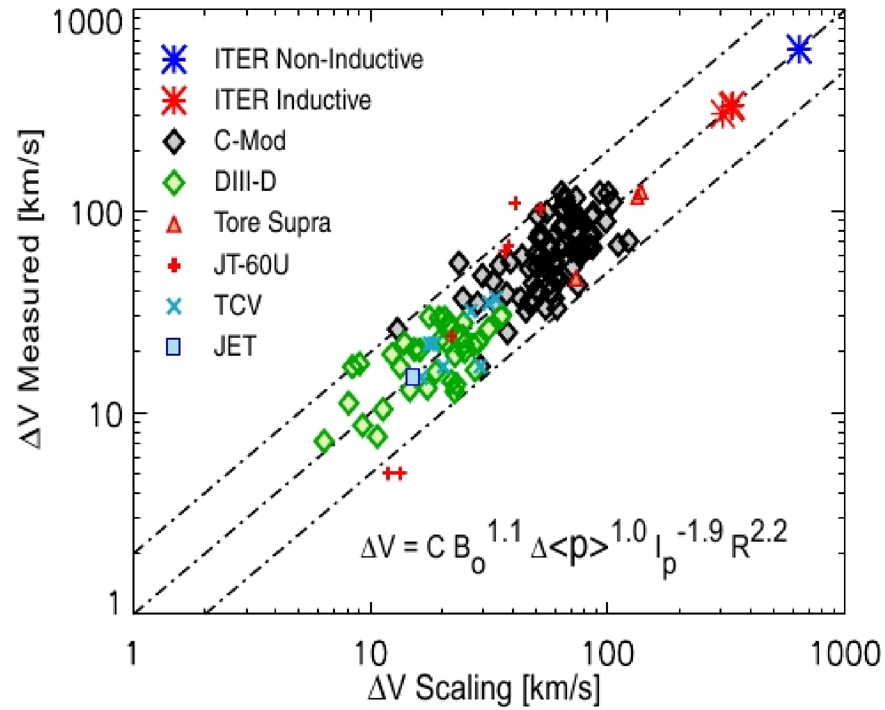
The bulk of the rotation is the same mechanism: “spontaneous”.

Scaling Observed in Many Tokamaks

Dimensionless



Dimensional



J.E.Rice et al., Nucl. Fusion 47 (2007) 1618.

Spontaneous (co-)rotation increases ∼ (stored energy)/(current)

Can be expressed as some kind of Mach number varying like beta.

If this scaling holds up (and it is far less well established than confinement) then ITER will spontaneously rotate quite rapidly.

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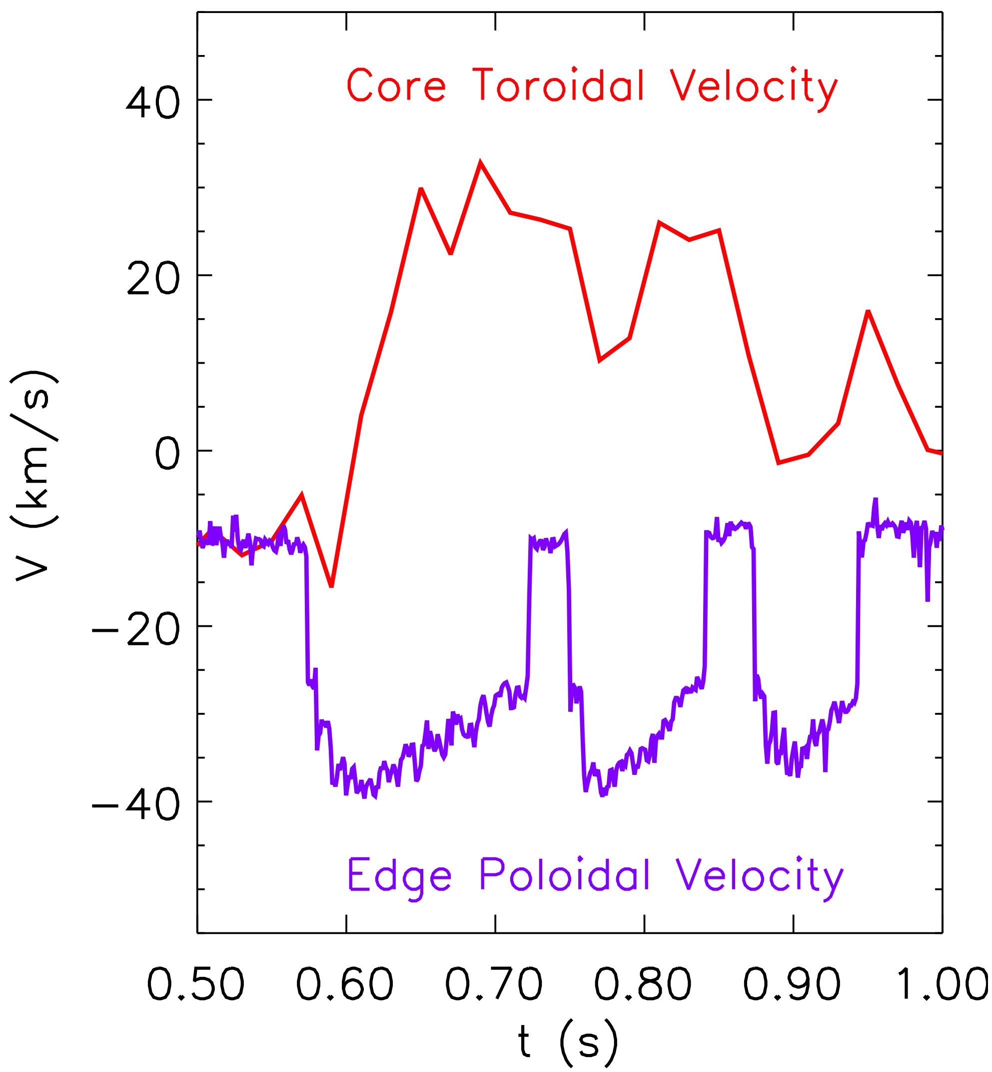
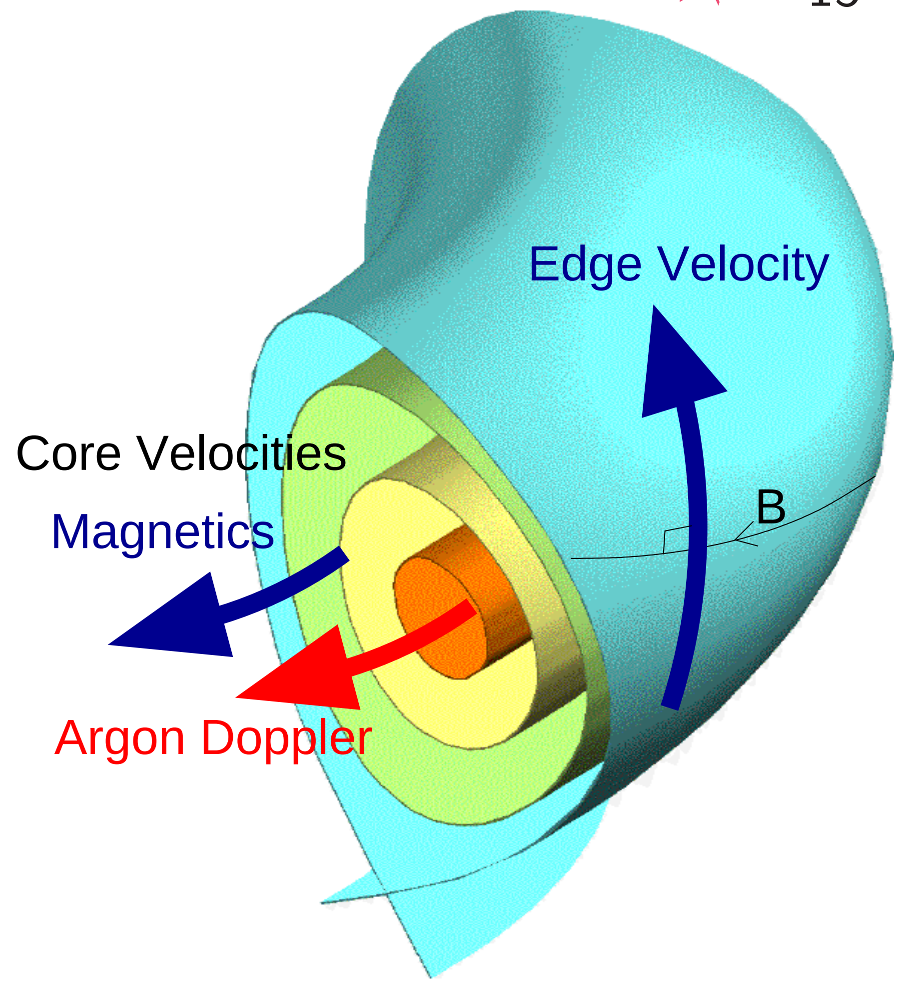
Plasma Edge rotates in opposite direction





At H-mode transition:

abrupt negative edge-velocity transition,

slower positive core-velocity increase.

I.H.Hutchinson, EPS Plasma Physics Conference, Budapest (2000)

Edge magnetic perturbation velocity is measured perpendicular to field.

[-ve ≡ electron-diamagnetic direction]

If toroidal, negative (& $\times 5$).

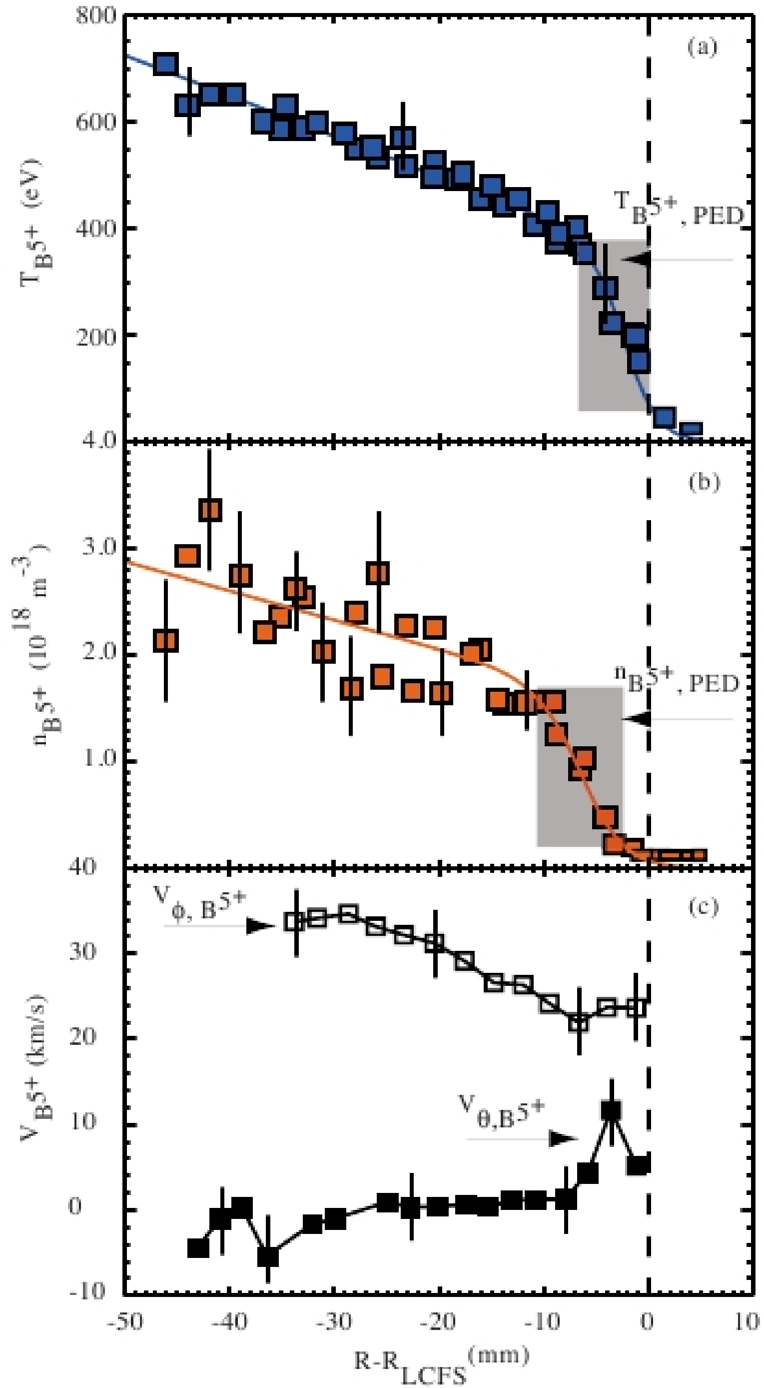
C-Mod Edge Boron Velocity Profiles

B^{5+} temperature $\approx$ D^{+} temperature profile (coupled by collisions at high density).

H-mode shows a "pedestal" and high-gradient transport barrier.
In C-Mod, barrier is very thin: $\sim$ 5mm.

Density profile of B^{5+} is similar in shape to the electron density profile.

Toroidal B^{5+} Velocity varies moderately and smoothly across the region.
Poloidal Velocity has a localized peak in barrier.
[positive v_θ is electron diamagnetic direction.]



R M McDermott et al, Phys. Plasmas 16, 056103 2009

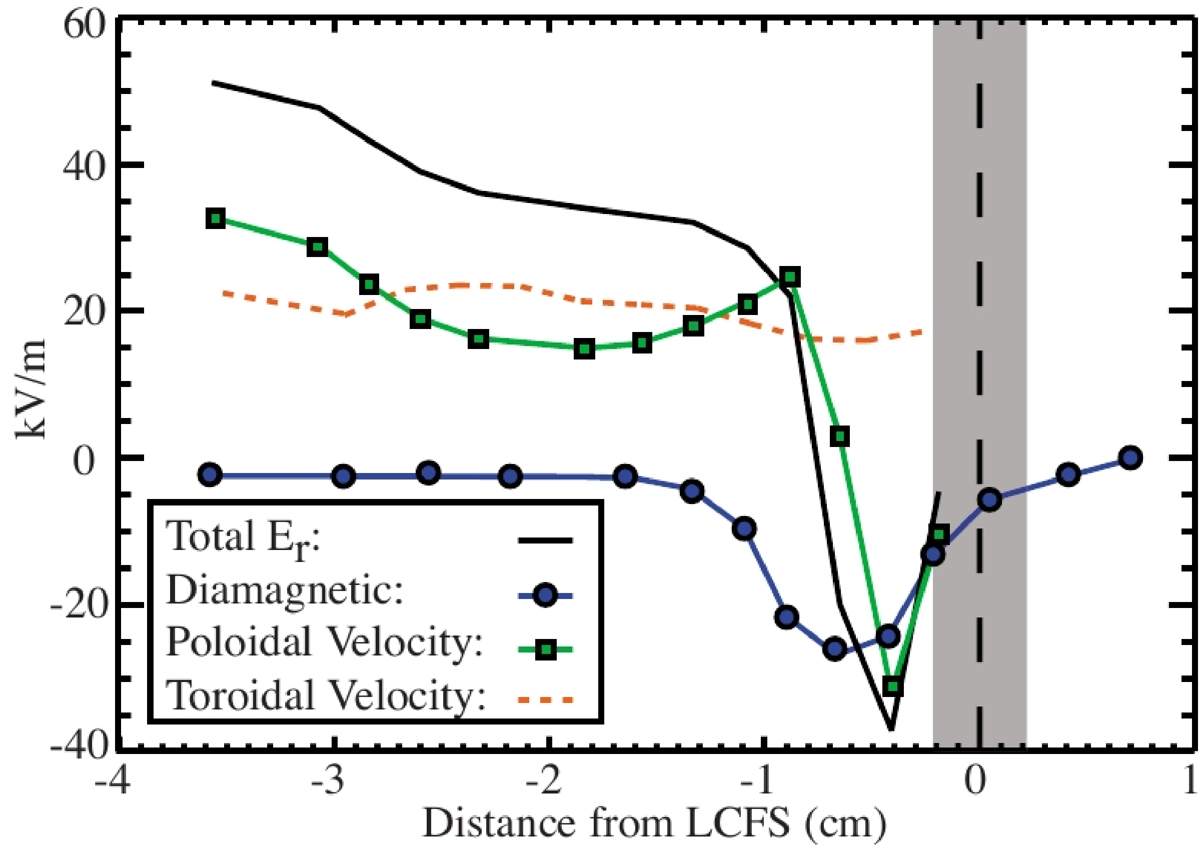
Radial Force Balance of B^{5+}

Radial Electric Field

$$E_r = \frac{1}{n_i Z_i e}\frac{dp_I}{dr} \quad \text{Diamagnetic}$$
$$+v_{\phi I} B_p \quad \text{Toroidal}$$
$$-v_{pI} B_\phi \quad \text{Poloidal}$$

Shows a narrow "well" at the transport barrier.

Turbulence suppression is attributed to shear in $E \times B$.



R M McDermott et al, Phys. Plasmas 16, 056103 2009

The narrow barrier region is just resolved.

B^{5+} pressure gradient and poloidal velocity both contribute to the E_r well.

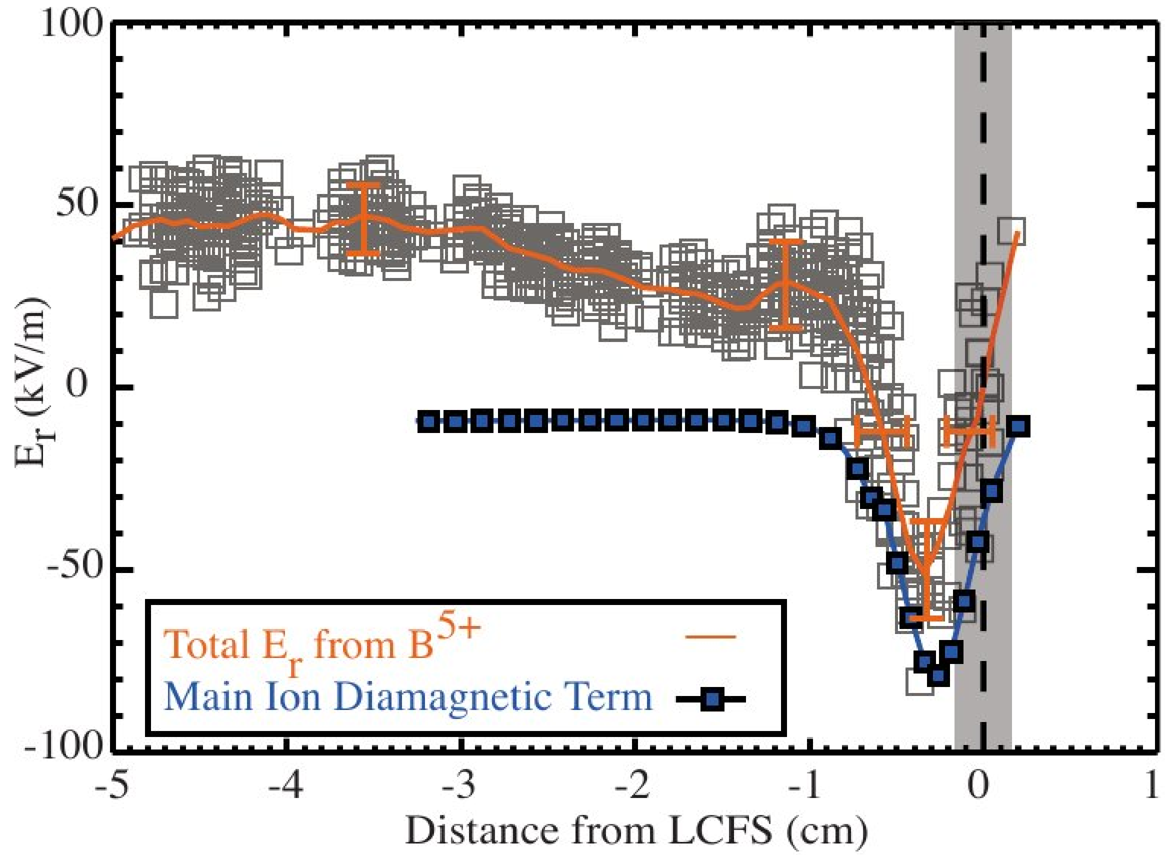
Thus, E_r force on the impurities *more than overcomes* ∇p_I.

Toroidal velocity contributes a uniform positive (outward) offset to E_r.

Bulk Ion Diamagnetic Term Dominates

Comparison of E_r with the diamagnetic term of the bulk (D^+) ions.
Their shapes are very similar.

The vertical offset indicates an additional perpendicular D^+ flow of about 10 km/s.
(We can't separate ϕ from p components experimentally.)

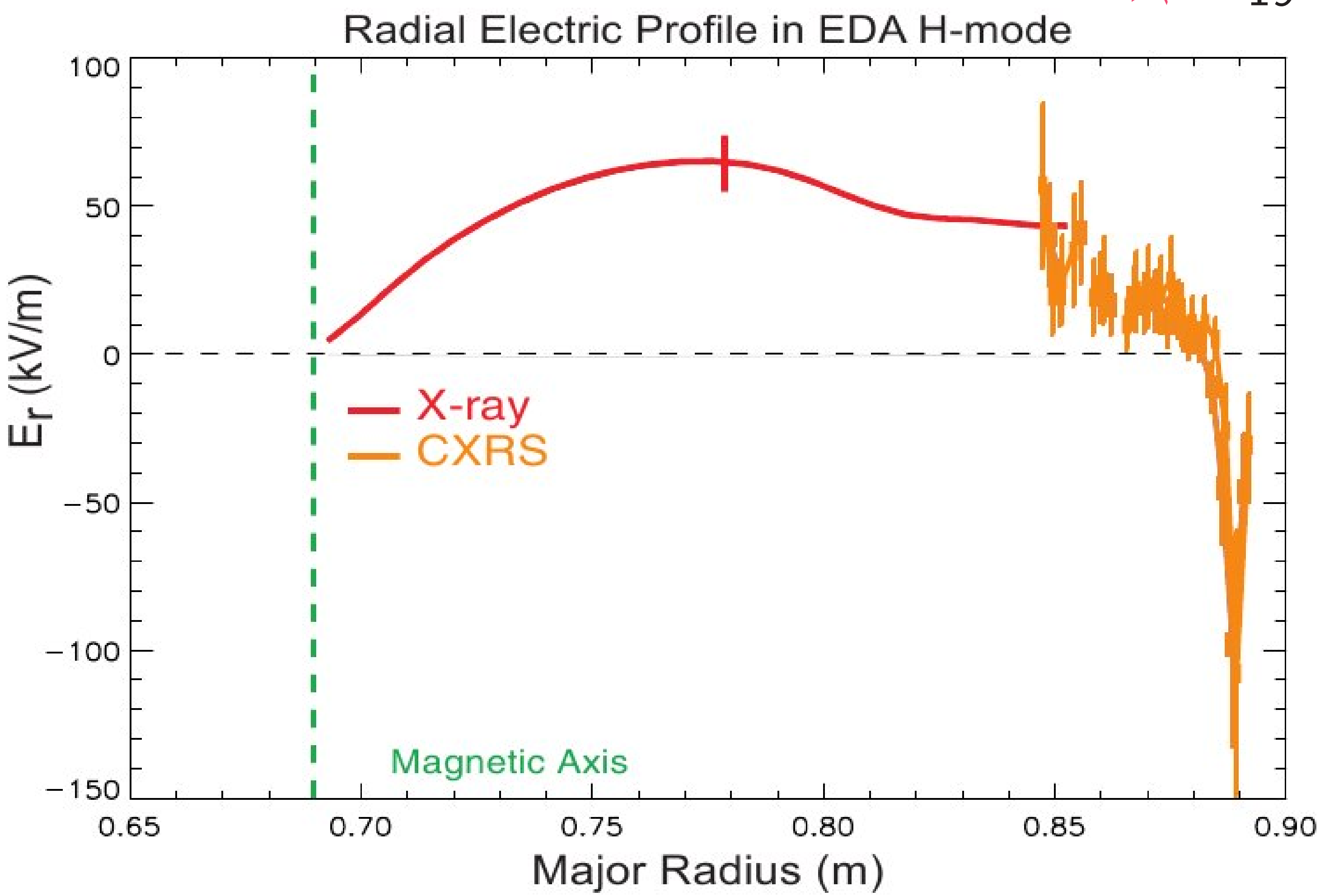


The H-mode barrier D^+ ions are mostly confined by the electric field, E_r giving rise to only moderate, uniform, perpendicular D^+ flow velocities.

Overall Typical E_r Profile

Combining the X-ray and CXS measurements.

Together cover the full minor radius of the plasma.



Gives typical overall flow structure, expressed as E_r.

However, this can be changed. Is not universal.

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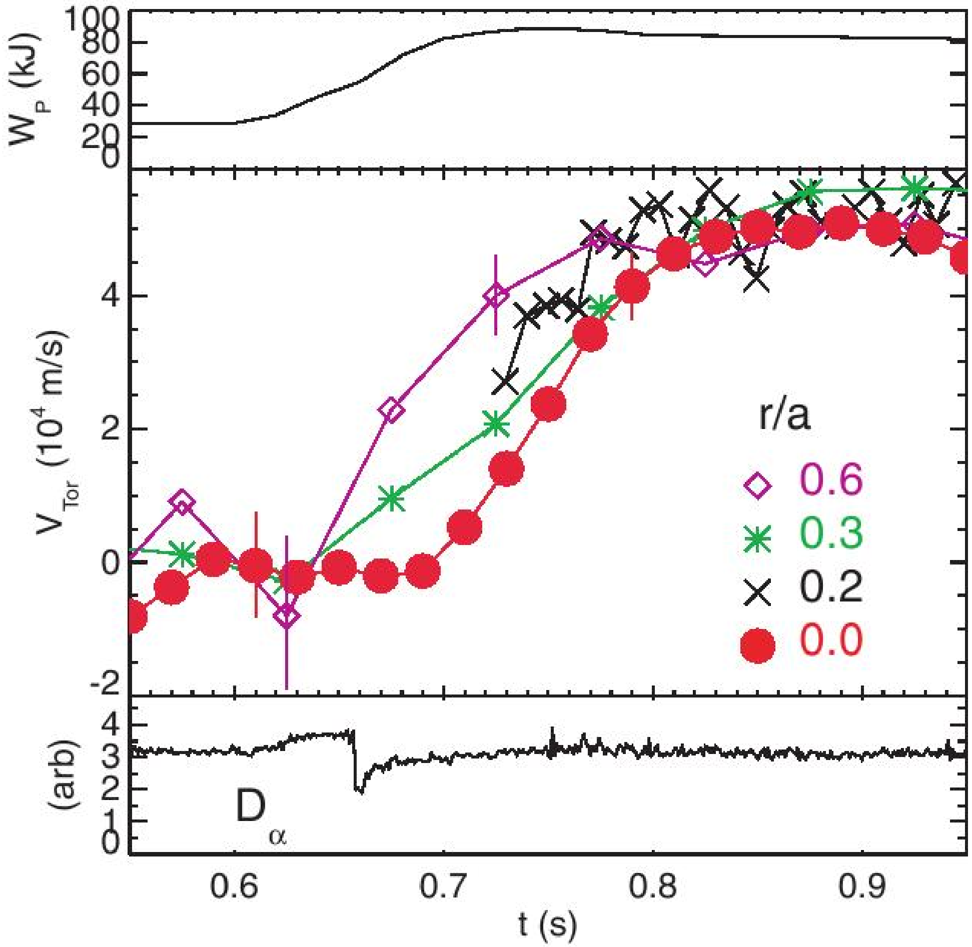
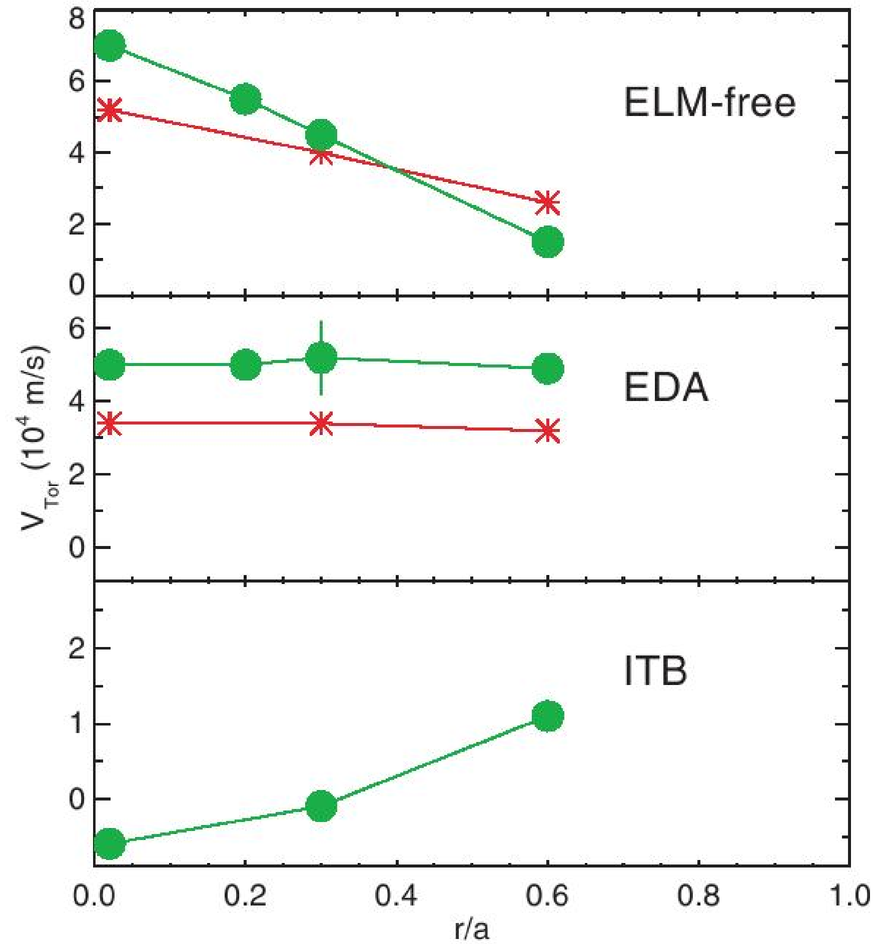
Flow Profile Transients and Variations





Transient velocity rises first near edge.

Then diffuses inward.

$D_\phi \sim 2 - 3\chi$

Profiles vary with discharge type.

Steady shapes: Peaked, flat, hollow.

Non-flat requires non-diffusive terms in the region of gradient.

J.E.Rice, W.D.Lee, et al, Nuclear Fusion 44, 379 (2004)

"Momentum Pinch" assumption

in the now-common form, is unjustified and can't explain spontaneous rotation.

Writing a heuristic momentum flux in the form of "momentum pinch":

$$\Gamma_v = nm\Big(\underbrace{D_v\frac{d}{dr}v_\phi}_{\text{diffusion}} + \underbrace{V_c v_\phi}_{\text{pinch}}\Big)$$

has very little to recommend it.

There's no good reason to make the non-diffusive term (pinch) $\propto v_\phi$.

In fact there are good reasons NOT to do so: such a term CAN ONLY arise from coriolis (or centrifugal) forces. (By Galilean invariance when $\Gamma_n = 0$.)

And can't explain spontaneous rotation. (E.g. v_ϕ sign-reversal.)

A more plausible heuristic form of momentum conservation is

$$\frac{\partial}{\partial t}(nmv_\phi) - S_v = \frac{\partial}{r\partial r}\left[rnm\left(D_v\frac{\partial v_\phi}{\partial r} + \frac{\Gamma_n}{n}v_\phi + V_v v_0\right)\right].$$

where v_0 is just a convenient normalization (e.g. v_{thi}).

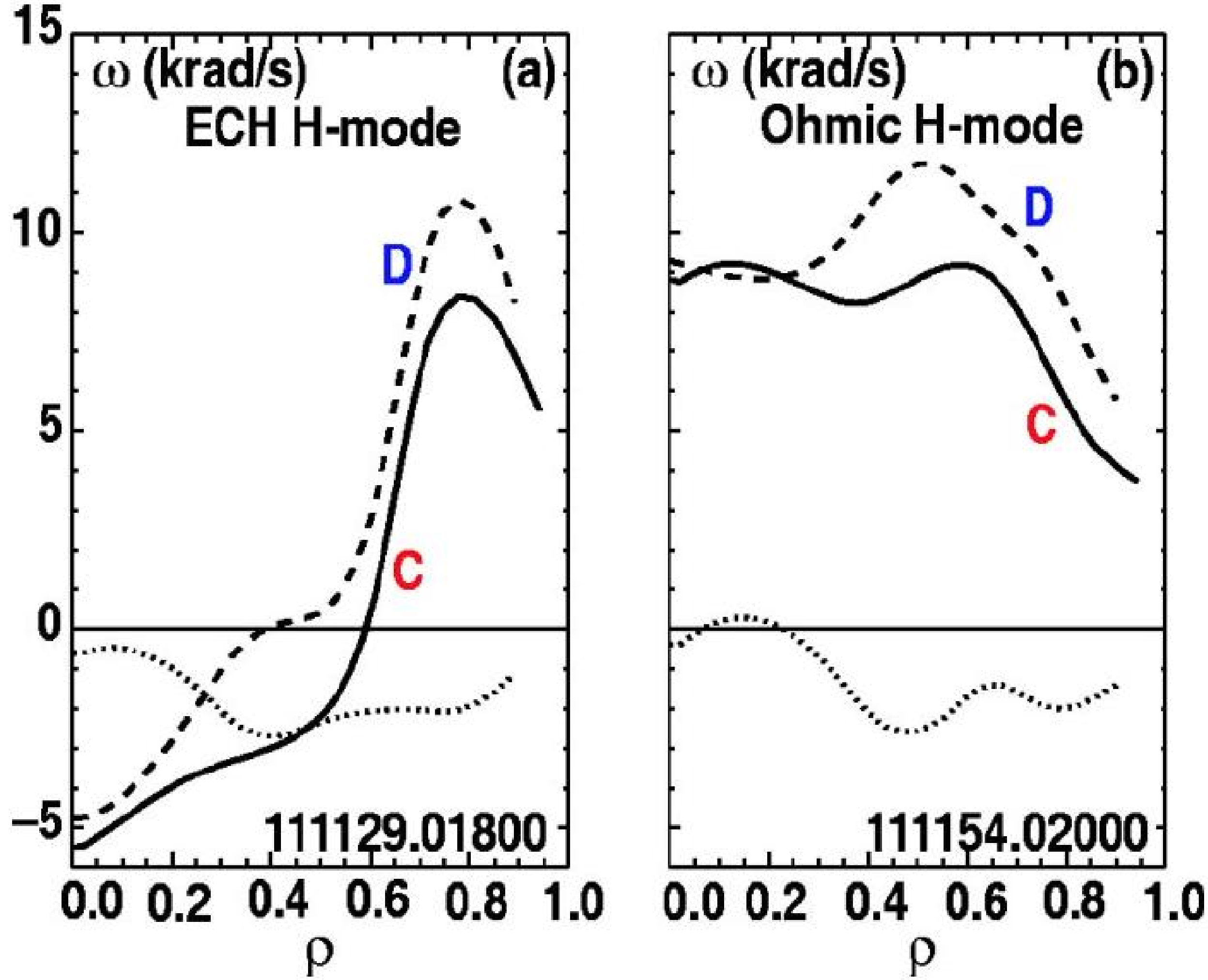
Then if invariance of D_v and V_v are assumed, they can deduced from transients (or sources S_v).

I H Hutchinson, http://arxiv.org/abs/0904.4003

Electron Cyclotron Heating Velocity Profiles on D-IIID

Central Direct Electron heating results in a hollow velocity distribution.

C impurity velocity is measured.
D velocity is inferred.
Inconsistent with flat momentum profile.

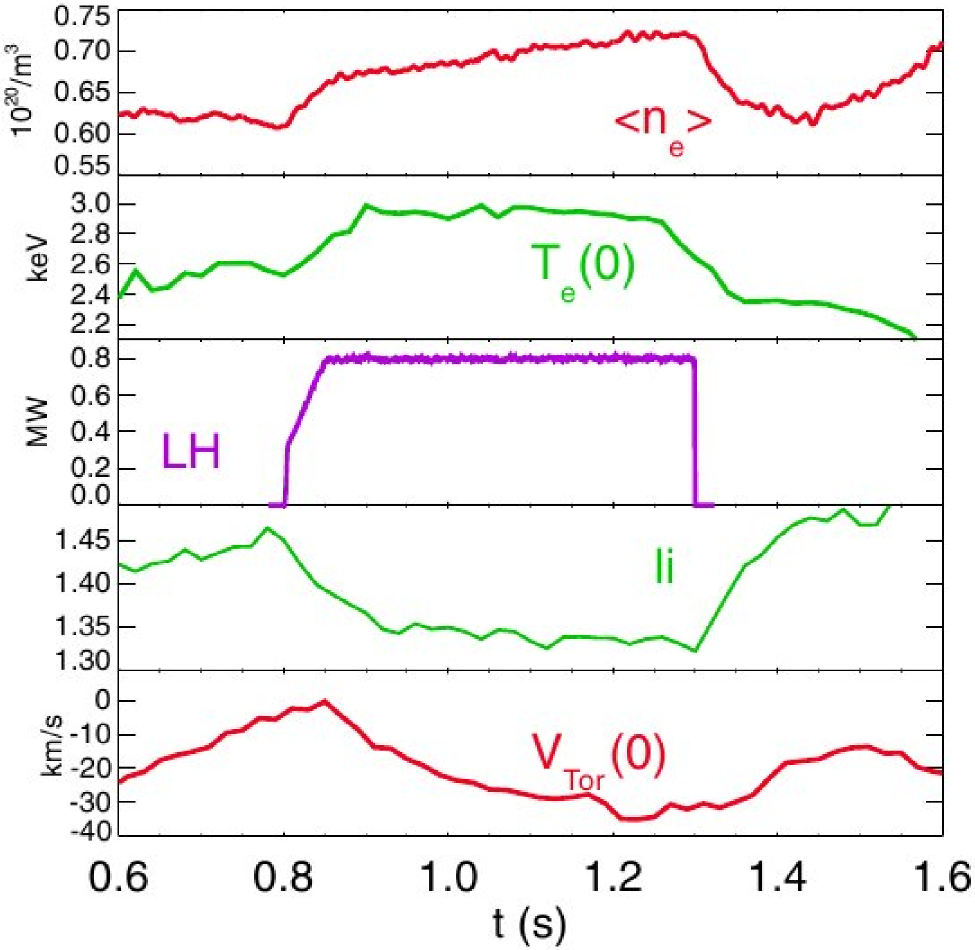


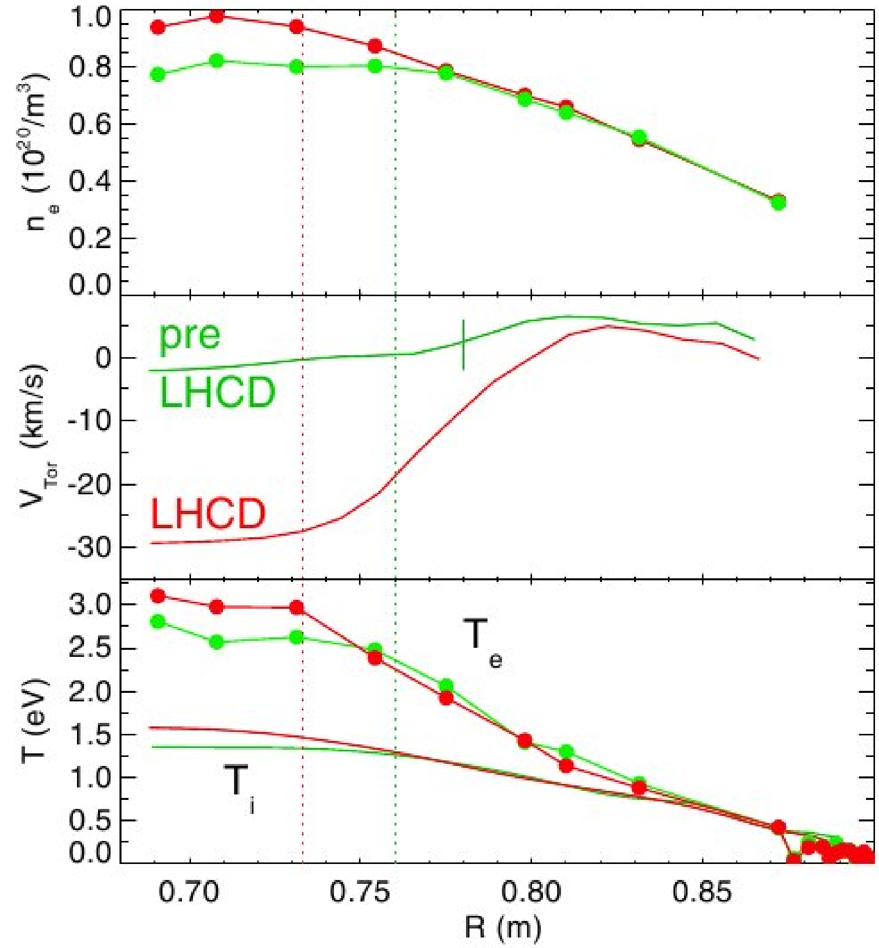
C: Carbon velocity. D: Deuterium velocity

Dotted: C velocity with assumed zero D. (Disagrees)

J.S.deGrassie Physics of Plasmas 11, 4323 (2004)

Lower Hybrid changes rotation





Application of LH current-drive makes the toroidal velocity (more) negative (counter-current).

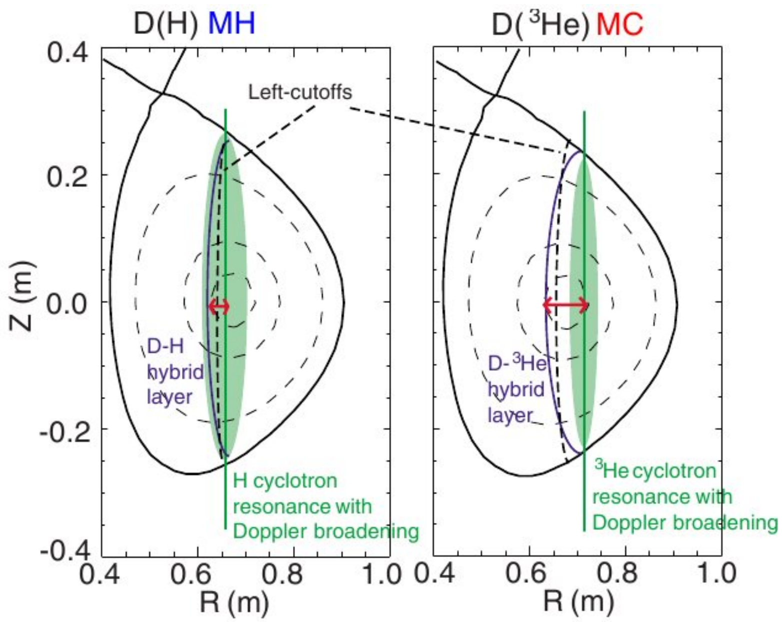
It is just the central rotation that is affected. Hollow, reminiscent of D-IIID ECH.

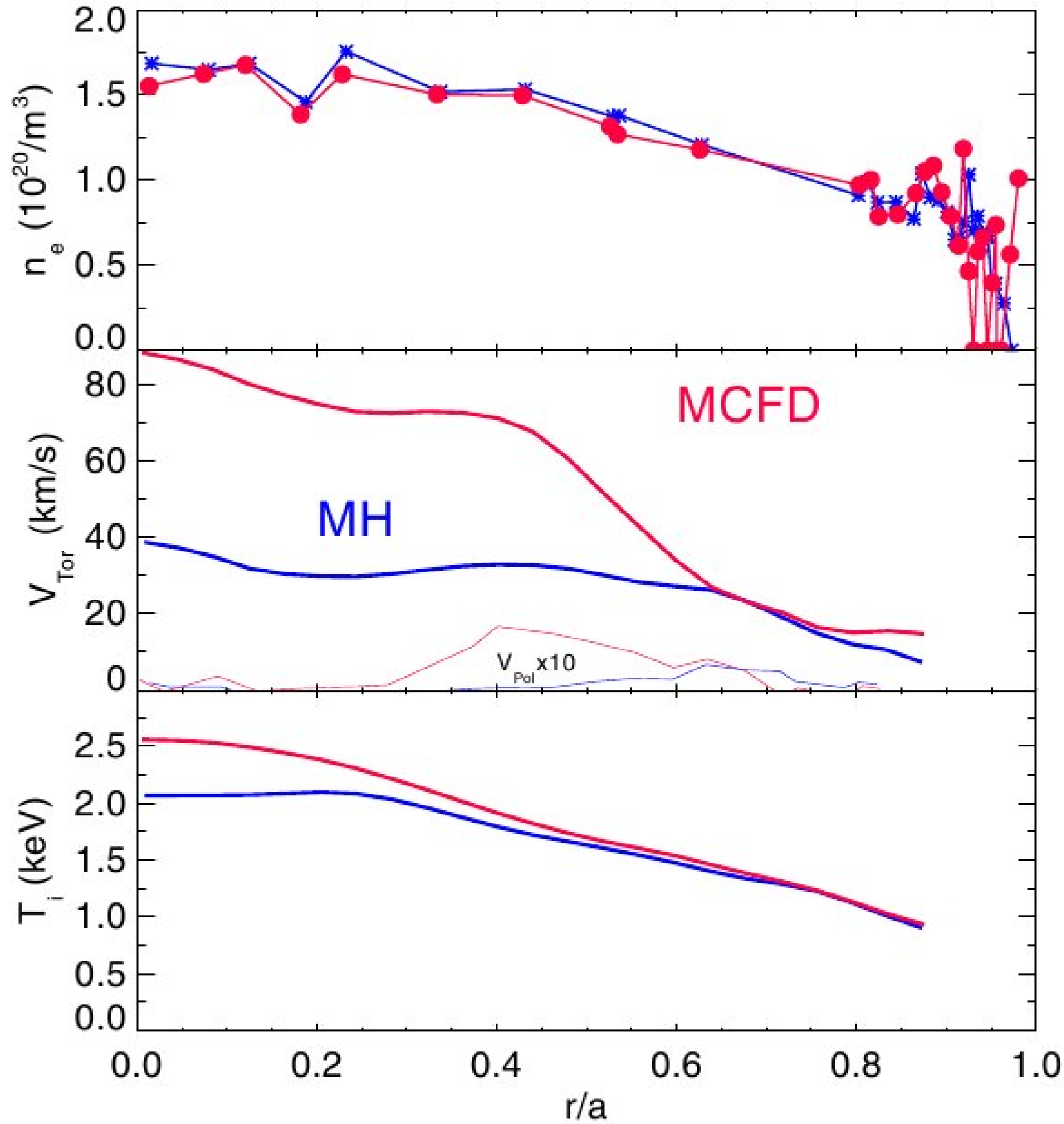
Evolution is on the timescale of the current-profile (l_i)

A. Ince-Cushman et al., Phys. Rev. Lett. 102 (2009) 035002. J.E.Rice et al., Nucl. Fusion 49 (2009) 025004.

Mode-Conversion Flow Drive

Has been clearly demonstrated in the plasma center.





D(He^3) Mode conversion, MC, more than doubles the toroidal velocity of the normal minority heating: MH.

The mechanism for this effect is as yet unproven.

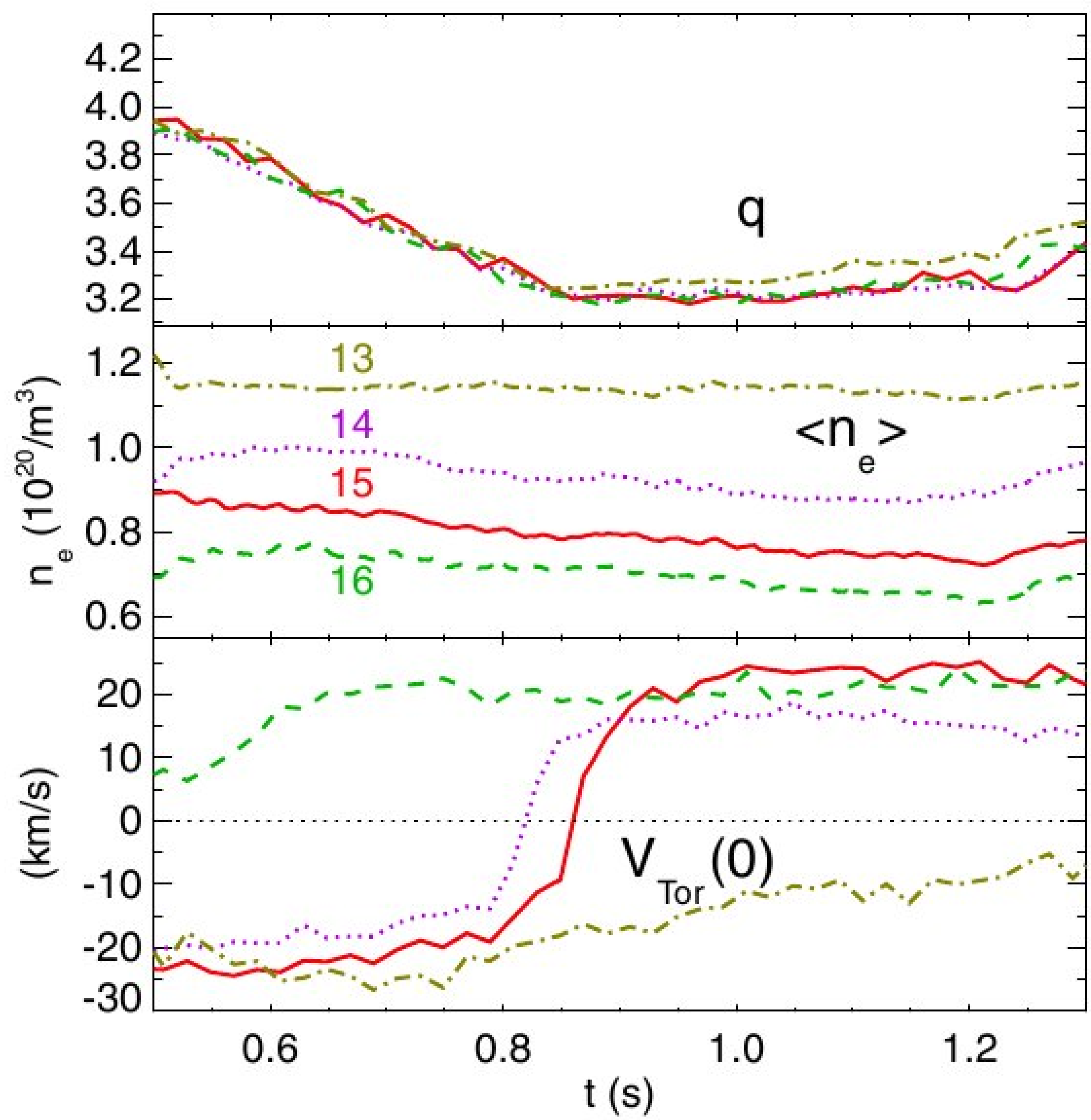
Y Lin, et al, Phys Plasmas 16, 056102 (2009)

Density-dependent profile transition

Like TCV*, C-Mod observes a transition from negative to positive rotation in limited L-modes. Governed by density (and safety factor).

Four different densities.

Show transition between negative and positive core rotation, sometimes during shot.



The changes occur only inside the surface q ≈ 1.5, not at edge.

*A.Bortolon et al., Phys. Rev. Lett. 97 (2006) 235003.

Courtesy J E Rice, B Duval, 2009

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Mechanisms for Toroidal Momentum Transport

Carrier	Mechanism	Example
	Neutral Atoms	NBI
		Edge Neutral Viscosity
	Energetic Ions	ICRF Minority
		NBI
Particles	Thermal Ions	Neoclassical
		Steep gradient $L_n \sim \rho_p$
	ES Turbulence	ITG
	Stochastic Fields	R&R Parallel Transport
	$\tilde{B}$	Rotating modes
Fields		Resistive wall modes
	B_t ripple	Locked modes
	E_ϕ	Charge Imbalance

Theory

I am leaving the review of theory that purports to explain all this to the later speakers. But I mention that there are quite a lot out there that say turbulence can do this. Here's a cross-section of references.

K.C.Shaing, Phys. Rev. Lett. 86 (2001) 640.
B.Coppi, Nucl. Fusion 42 (2002) 1.
A.G.Peeters et al., Phys. Rev. Lett. 98 (2007) 265003.
O.D.Gurcan et al., Phys. Plasmas 14 (2007) 042306.
T.S.Hahm et al., Phys. Plasmas 14 (2007) 072302.

However, there's nothing much that I can see in the way of really focussed confrontation between theory and experiment.
And I'm hoping this workshop will stimulate some.

Summary

H-mode tokamak plasmas spontaneously rotate in the co-current direction, increasing with W/I_p in a way that is **consistent across different machines**. Since this is observed with no auxiliary heating, it is **truly spontaneous**.

In the **edge barrier** region many mechanisms may be at work (neutrals, finite ion orbits, neoclassical violation, etc) and a proper understanding is still lacking.

However strong velocity gradients **also occur in the core**, even without direct momentum input, showing that the non-diffusive momentum transport is not just an edge barrier effect.

Transients without sources confirm the deductions from beam momentum source transport that **momentum diffuses at roughly the same rate as heat**.

These facts imply a mechanism **transporting momentum up** the velocity gradient to counteract diffusion. But there's no reason to suppose this is $\propto v_\phi$.

Electron heating by ECRH or LHCD leads to more **negative**, often hollow central velocity profiles. **Density** also seems to control central velocity transitions.

Although (energetic ion) **RF mechanisms** might sometimes be significant, they do not explain the Ohmic (or ECRH) results.

Unequivocal **flow-drive** by Mode-Conversion has been demonstrated. There is estimated to be enough wave momentum to explain this, but it is not proven whether the mechanism is really direct drive or turbulent transport modification.

The most plausible mechanisms for spontaneous rotation seem to be **turbulent transport** (giving rise to "Reynolds Stress").
But quantitative prediction still lacks a verified theoretical basis.

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