

# Momentum transport and self-acceleration in tokamaks

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# Tokamaks have near-perfect Axisymmetry



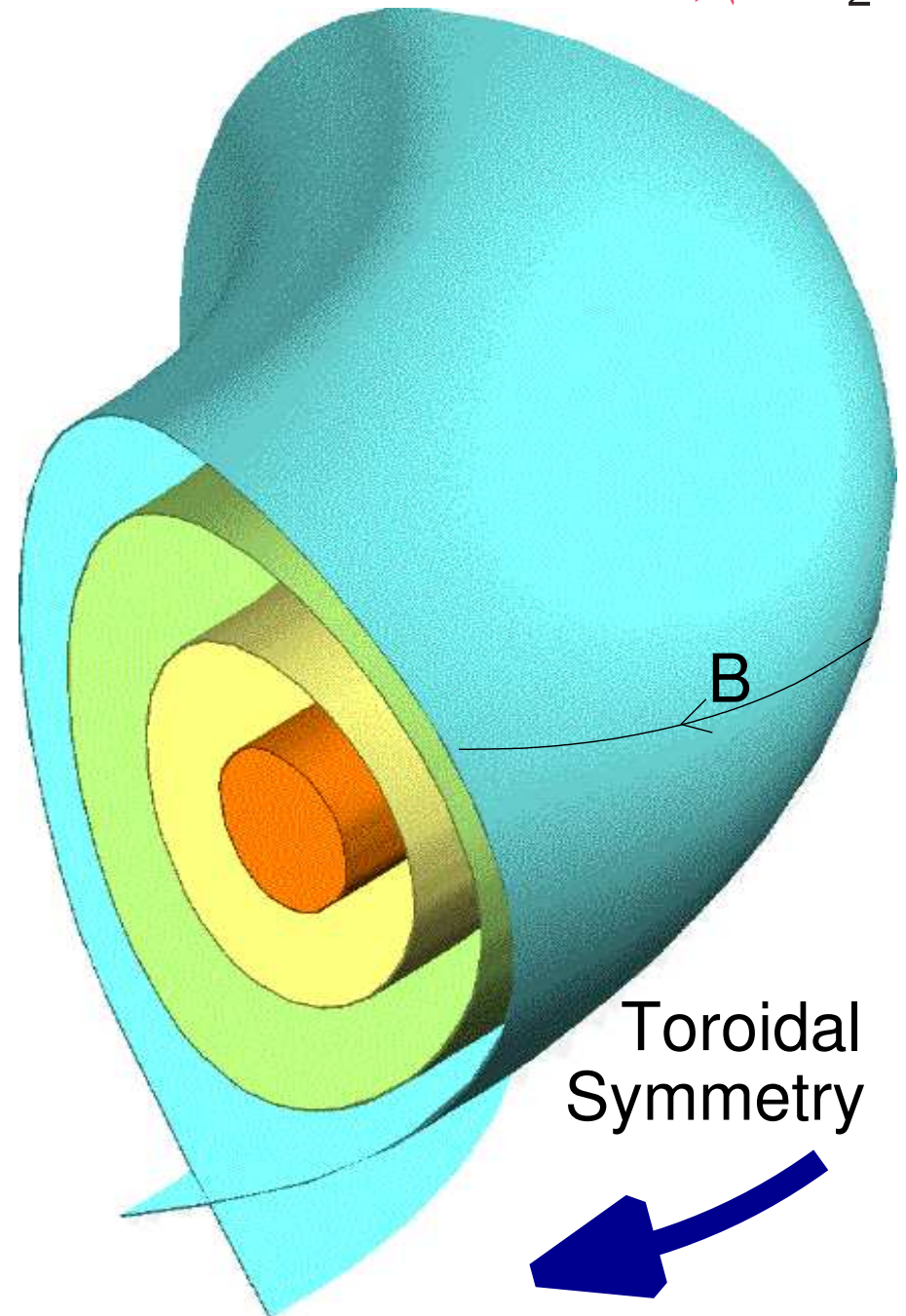
To the extent that axisymmetry is perfect, toroidal angular momentum is conserved.

There are nearby fixed structures to which momentum could be transferred (unlike astrophysics!), but it can only be transferred 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, Lost on confinement timescale

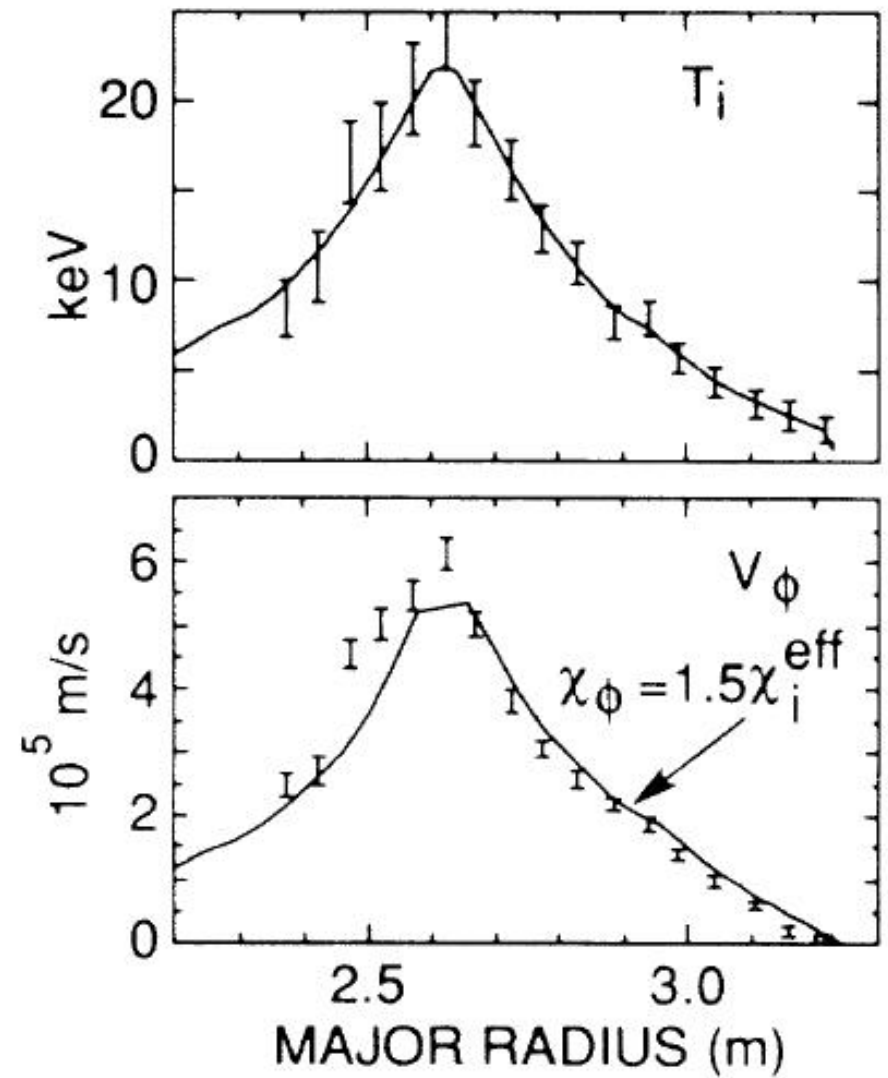
Heating beams are generally tangential, and asymmetric. They impart large amounts of particle momentum.

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.

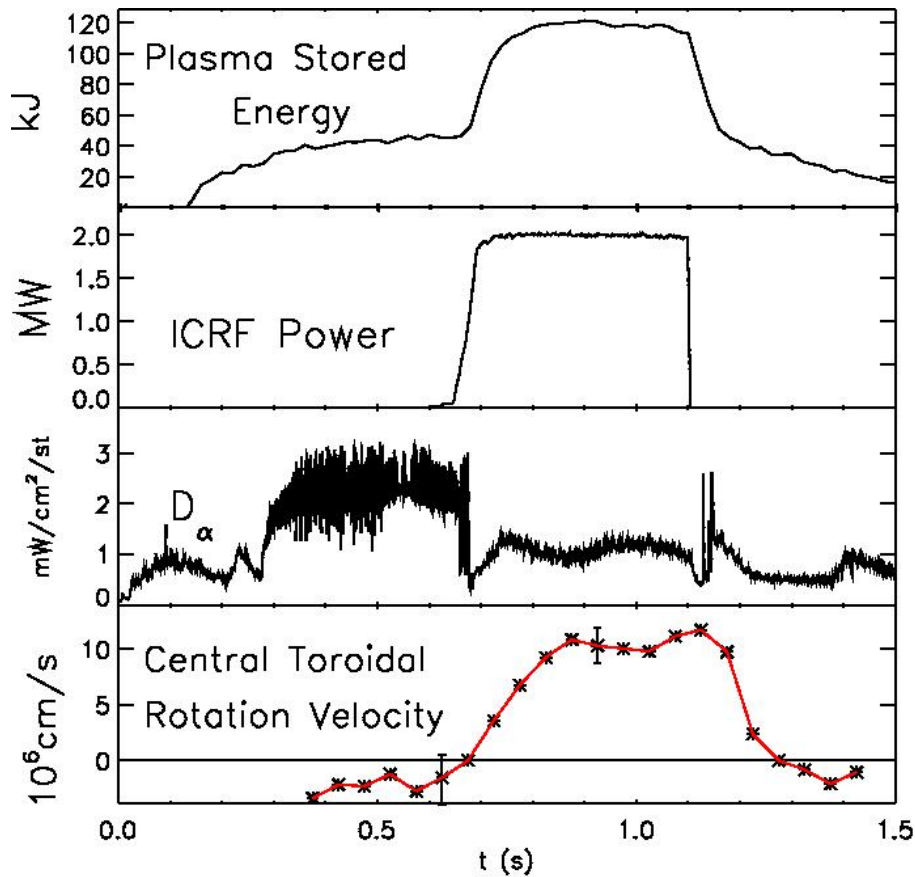
TFR beam momentum transport



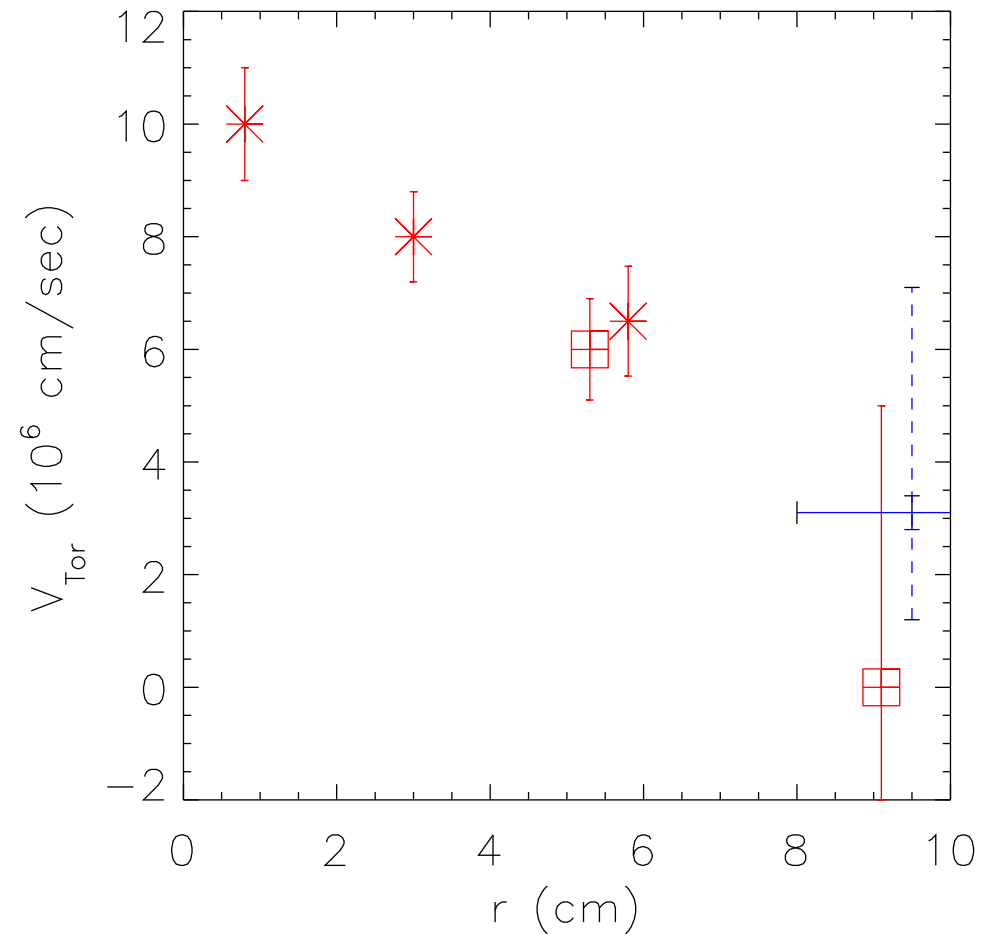
# C-Mod has no heating beams: no direct momentum input



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



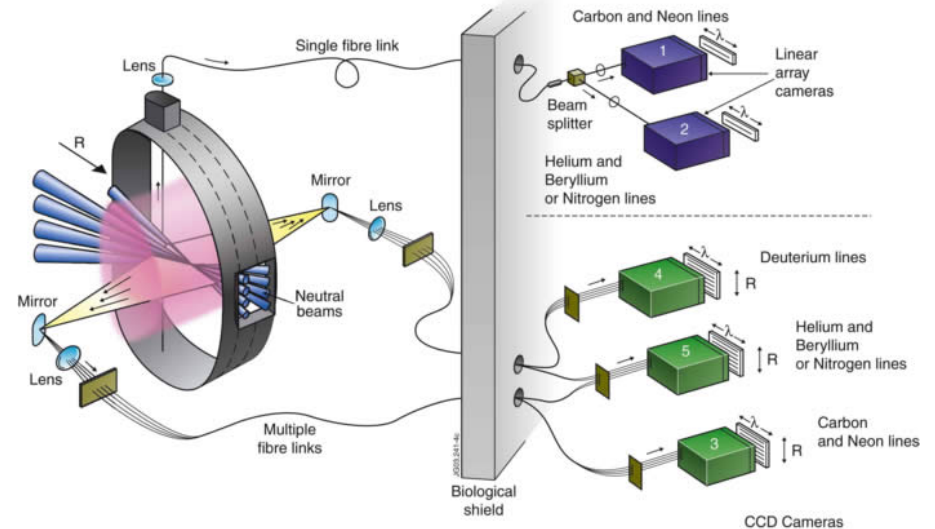
Velocity up to  $100 \text{ km}/\text{s} = 0.3c_s$ .  
Sign reverses on H-mode transition



Velocity peaked in the center.

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.



Higher-Z ions (like Ar) are better for velocity diagnostics because

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

MHD events known as Sawteeth give rise to central magnetic perturbations whose toroidal velocity can be measured.

Edge magnetic perturbations can also be used.

This is a completely independent way to verify the velocity.

Agreement with Ion-Doppler is generally quite good.

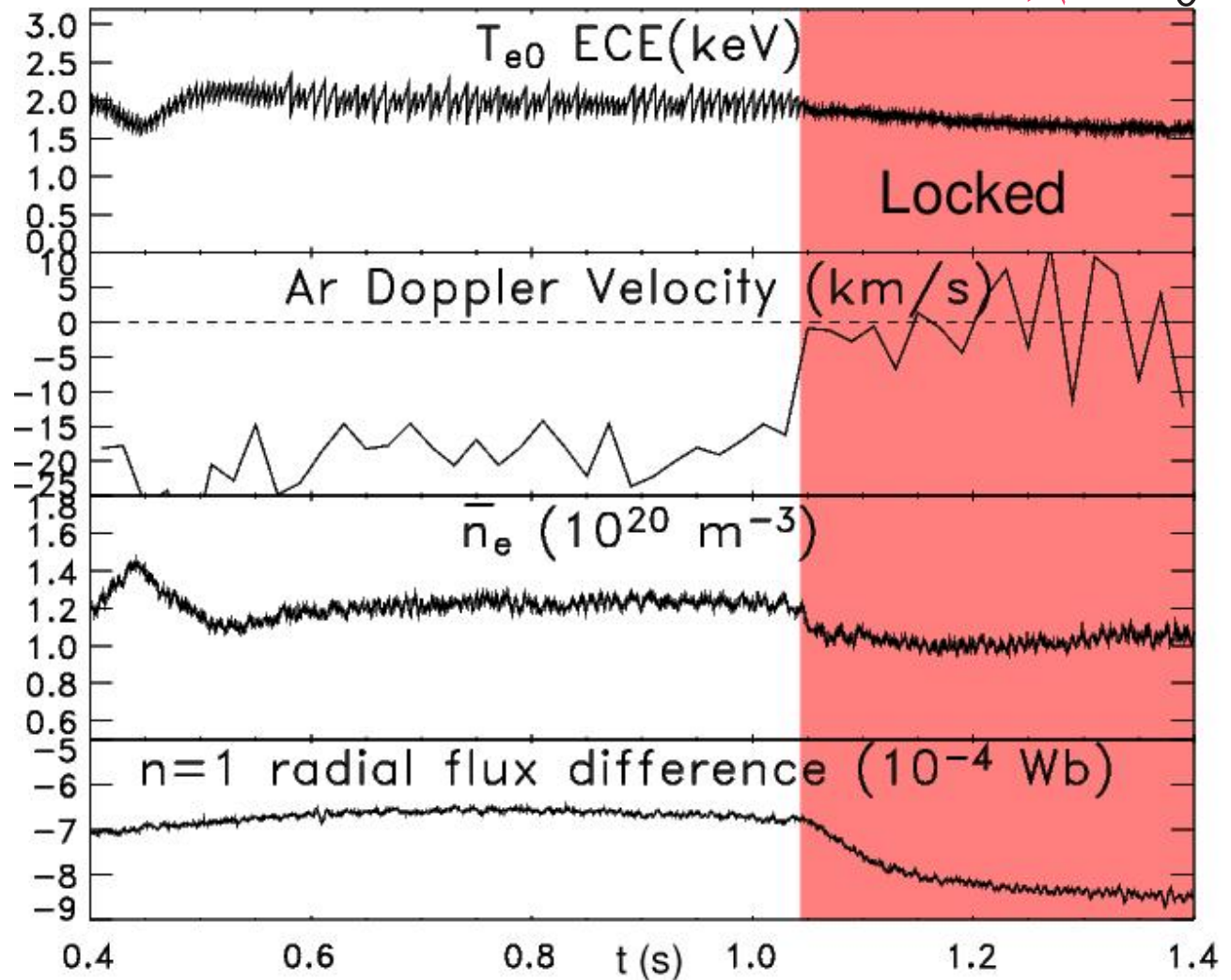
# “Mode-Locking”: Velocity goes to zero.

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.

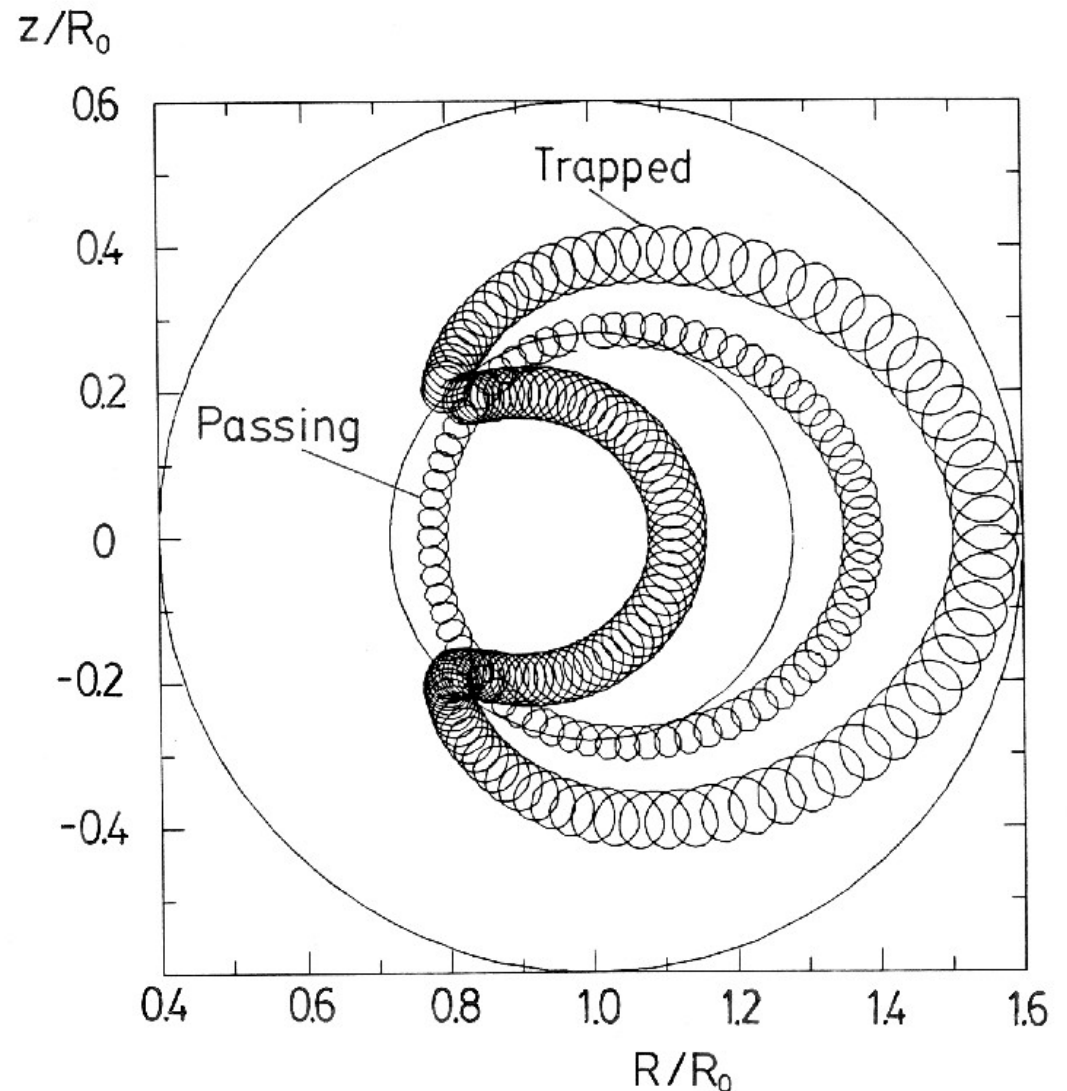
# Energetic Ion Orbit Momentum Transfer



Co-moving ions are shifted outward, counter inward.

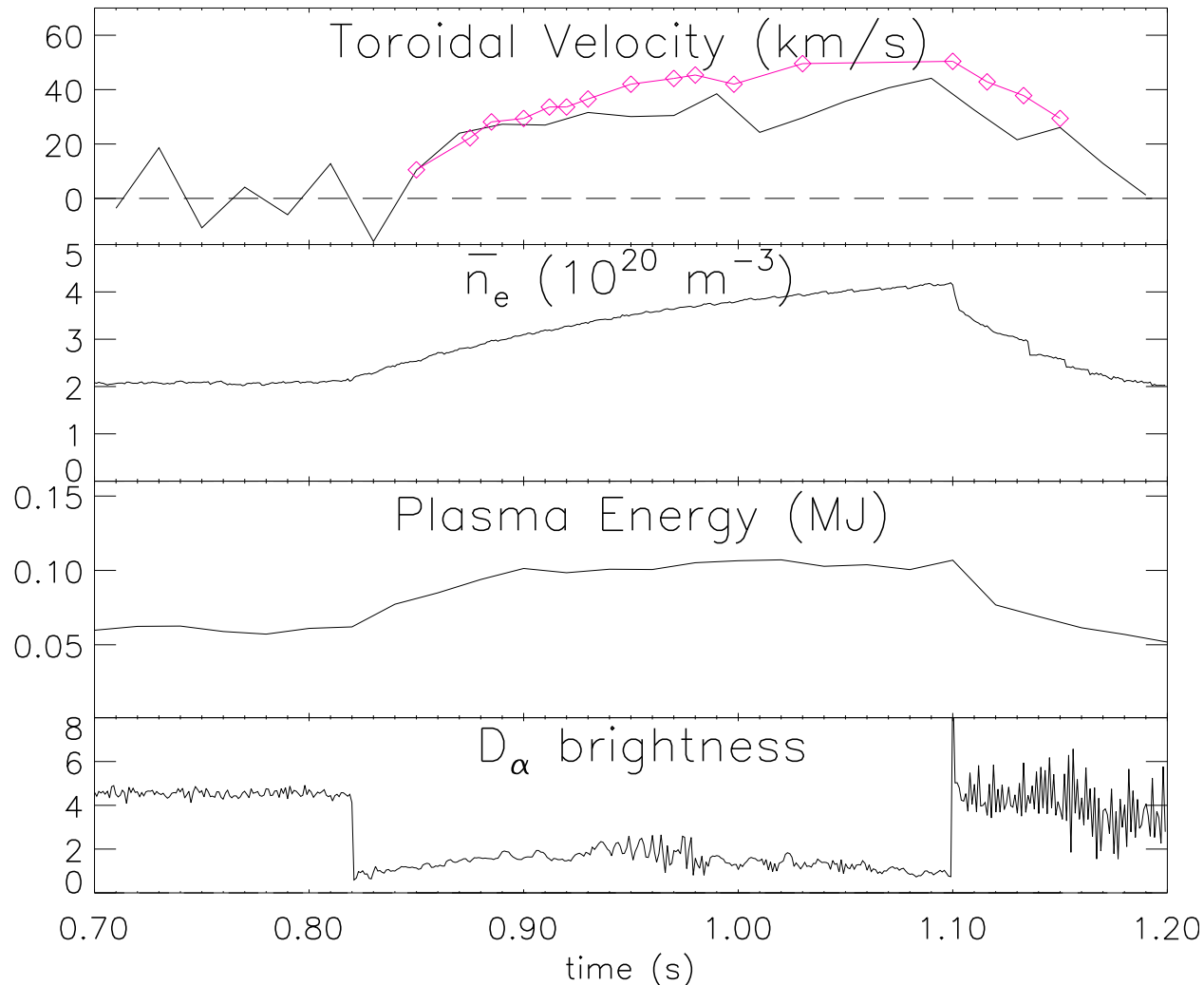
Systematic toroidal momentum transport can occur if ions are scraped off or accelerated in preferential positions.

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.

# Ohmic H-modes Spontaneously Rotate Too



Rules out ICRF-induced energetic ions as cause of rotation.

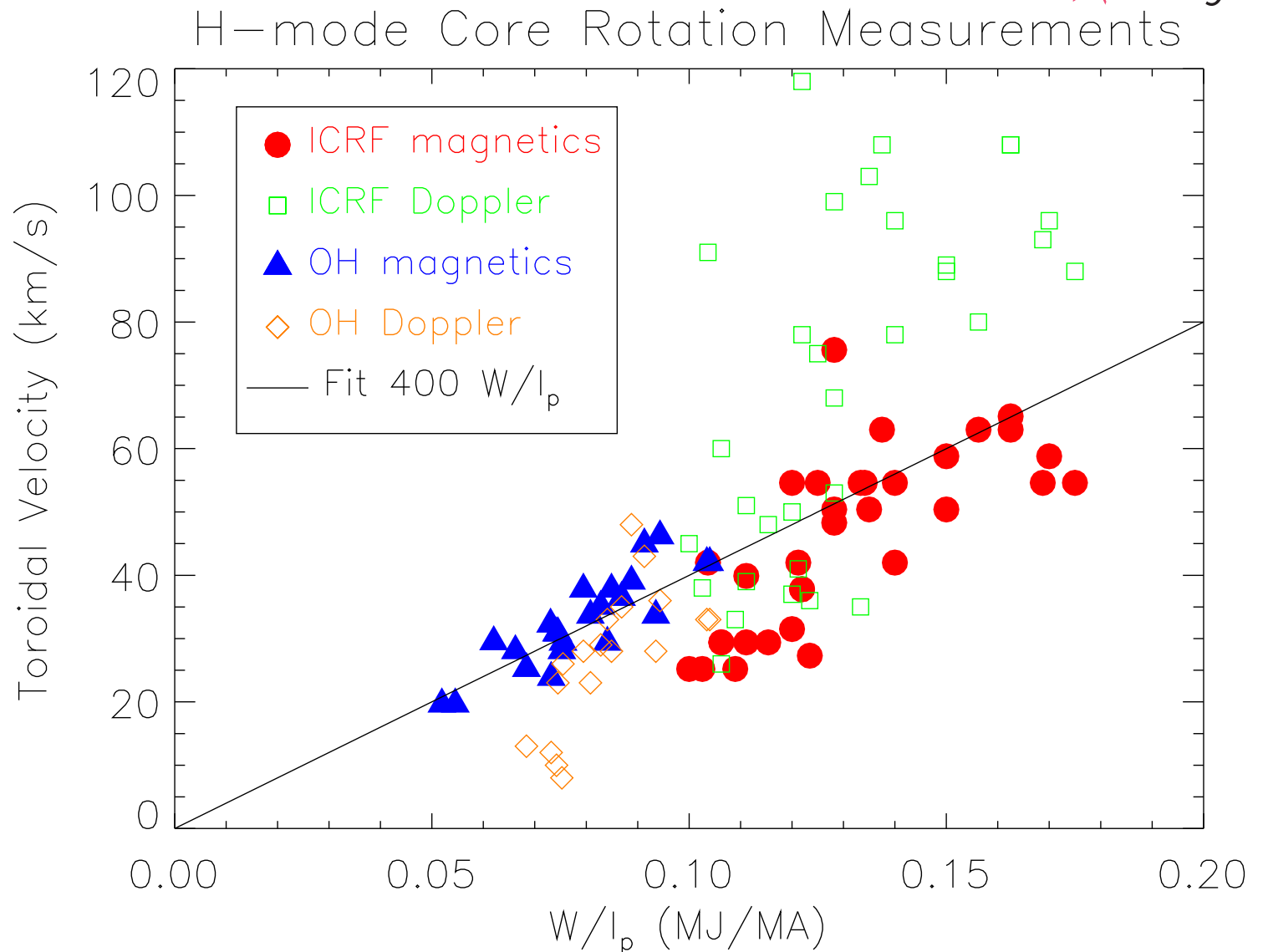
Sawtooth velocity (**pink points**) agrees with Argon (within errors) in magnitude, direction, and time-dependence.

# Ohmic Rotation Scaling is like ICRF

Database of  
observed central  
rotation.

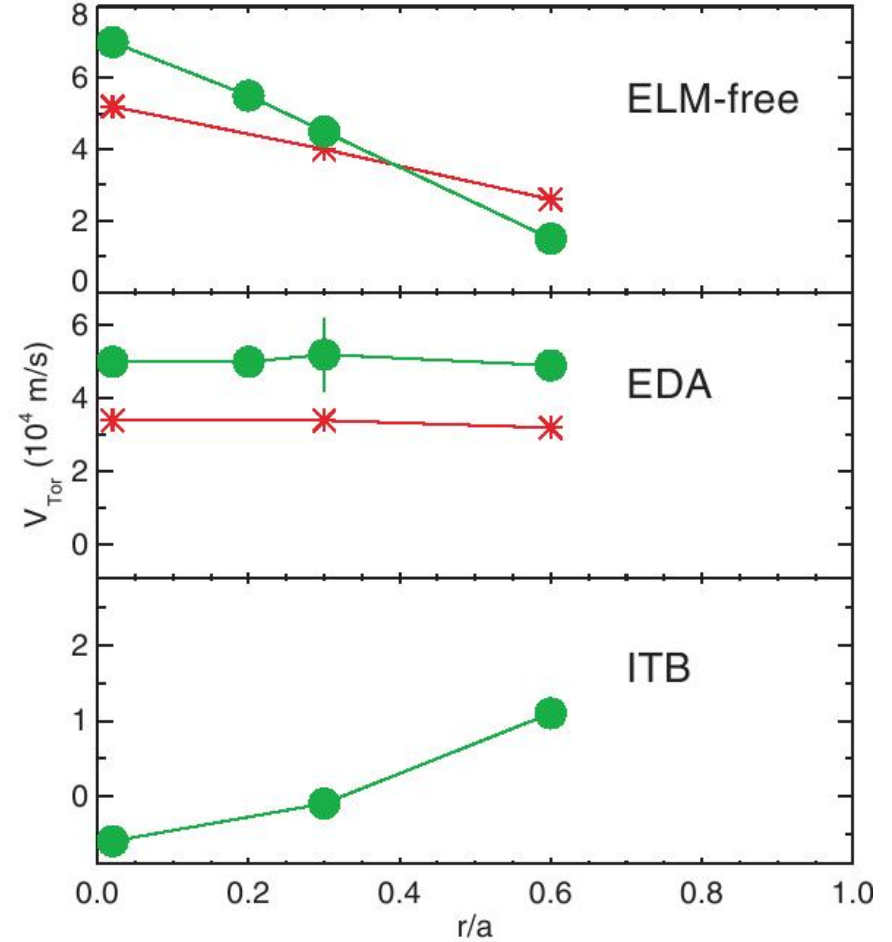
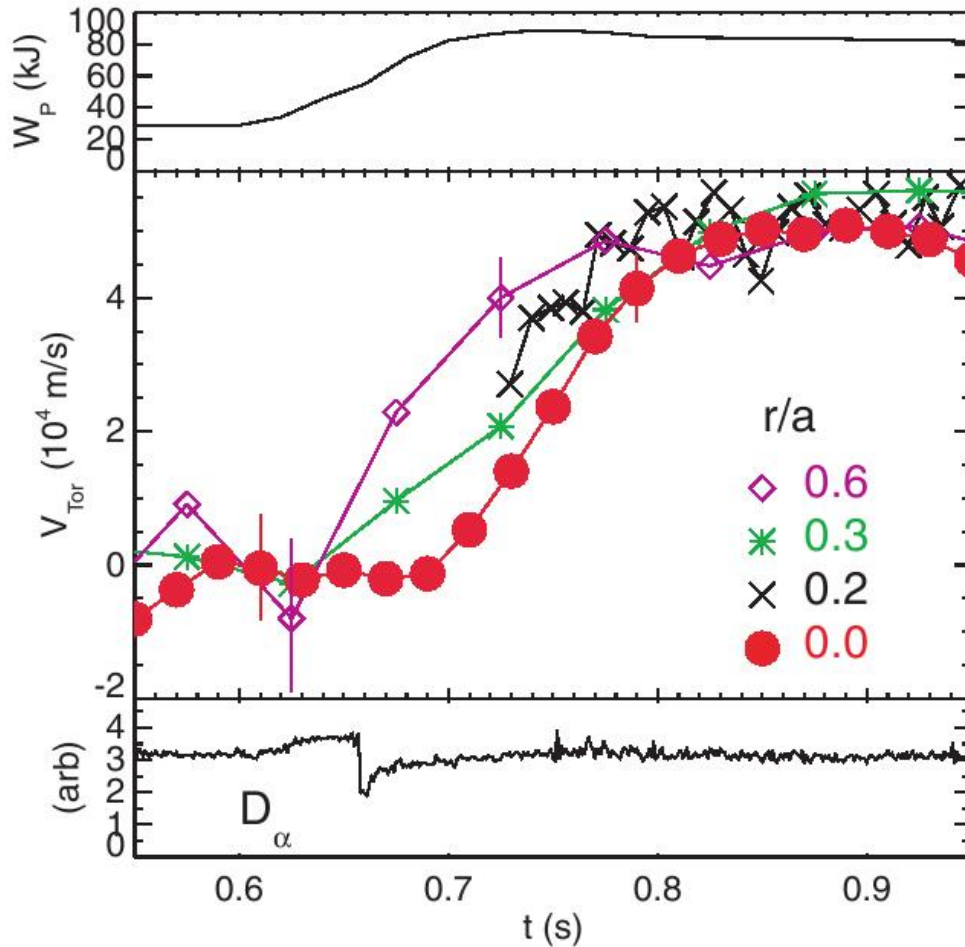
High ICRF power  
have more peaked  
rotation.

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”.



Velocity rises first near edge.

Then diffuses inward.

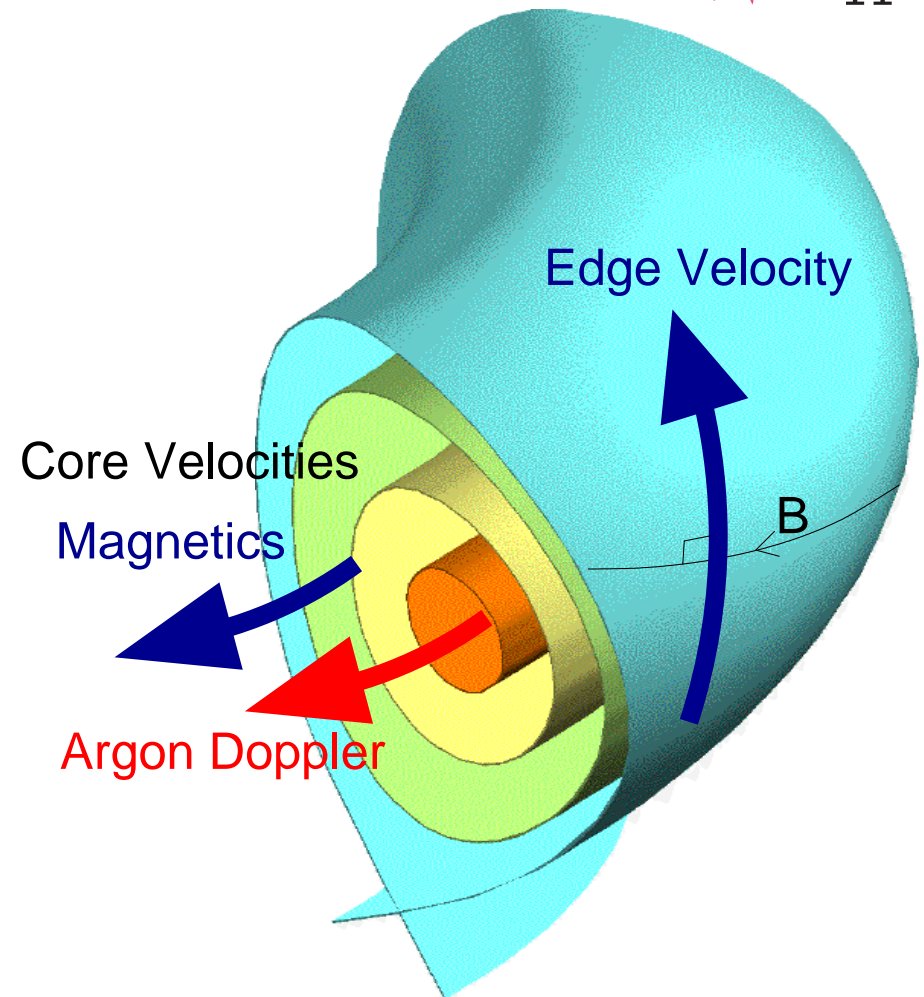
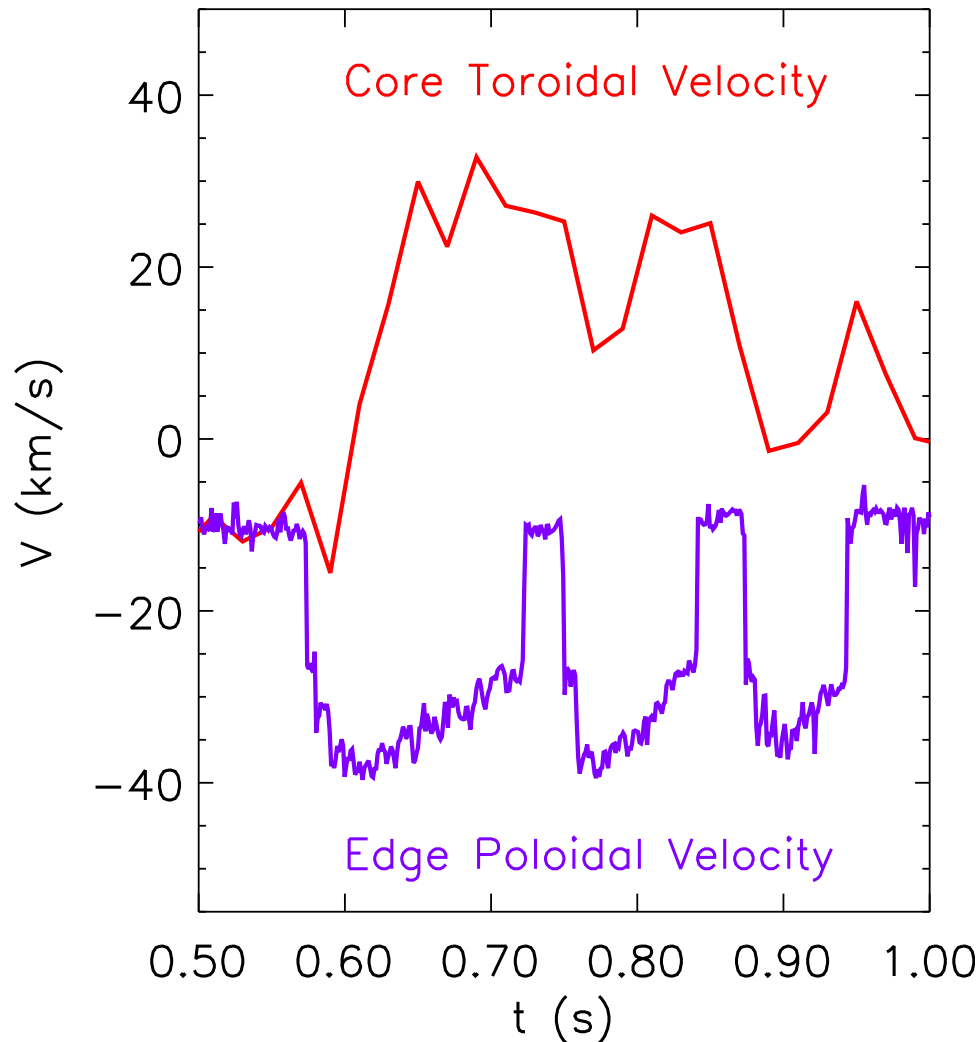
$$D_\phi \sim 2 - 3\chi$$

Profiles vary with discharge type.

Steady shapes: Peaked, flat, hollow.

Non-flat requires "momentum pinch".

# Plasma Edge rotates in opposite direction




At H-mode transition:  
abrupt negative edge-velocity transition,  
slower positive core-velocity increase.

Edge velocity is measured perpendicular  
to field.

If toroidal, then is 5 times faster.

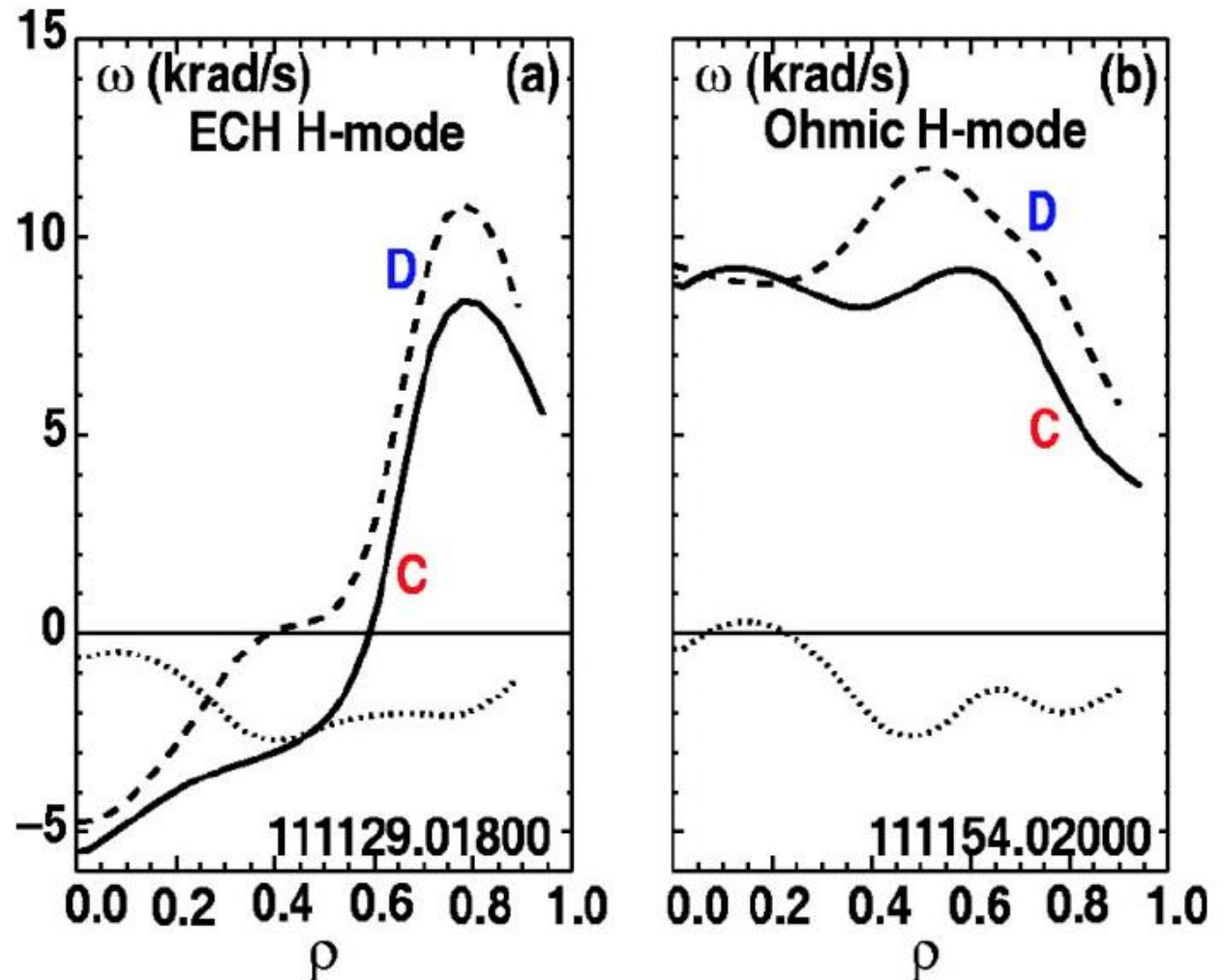
# DIID Ohmic and Electron Cyclotron Heating Velocity Profiles

 Central Direct Electron heating results in a hollow velocity distribution.

C impurity velocity is measured.

D velocity is inferred.

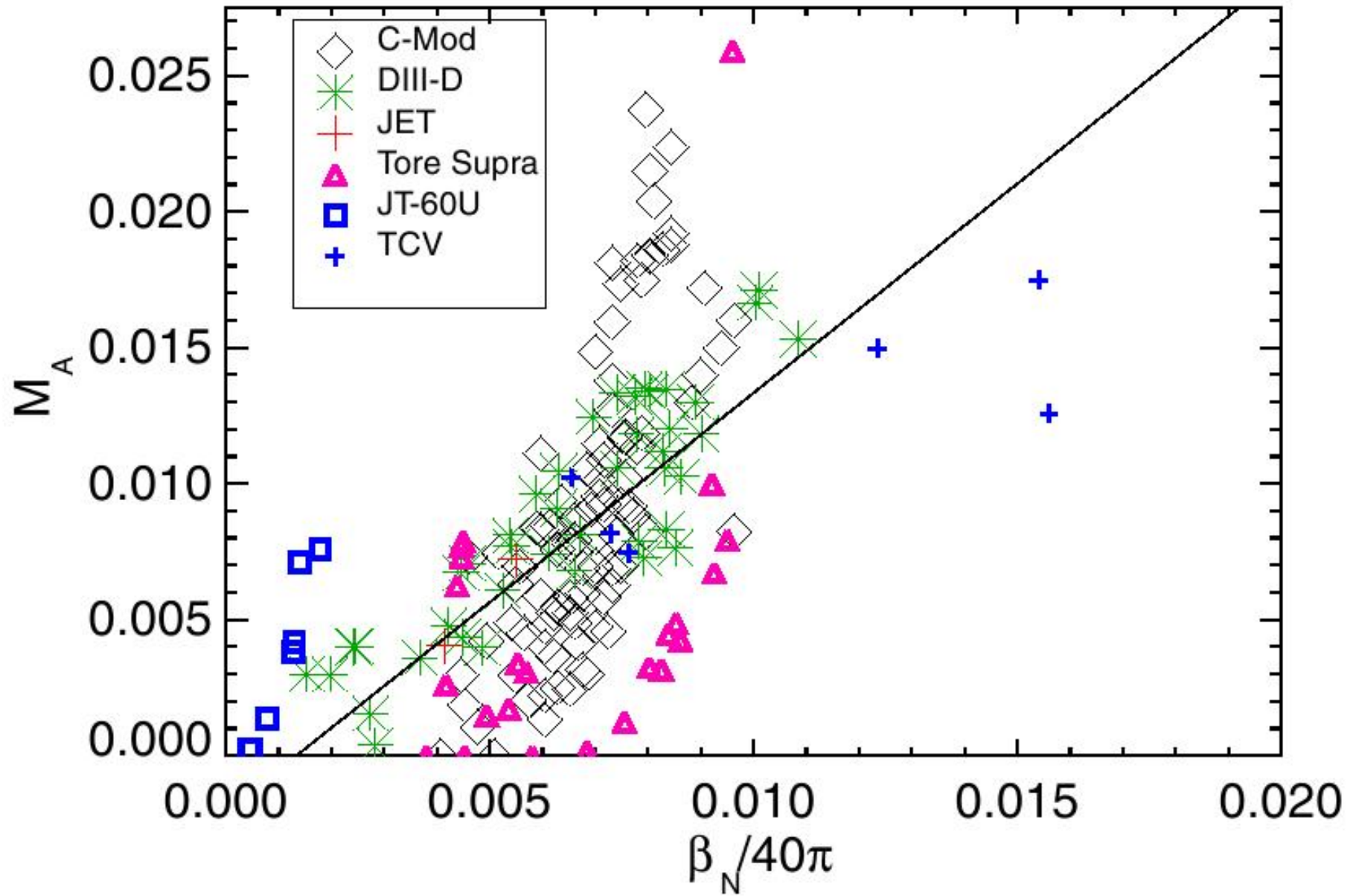
Inconsistent with flat momentum profile.



C: Carbon velocity. D: Deuterium velocity

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

# Multi-machine Scaling

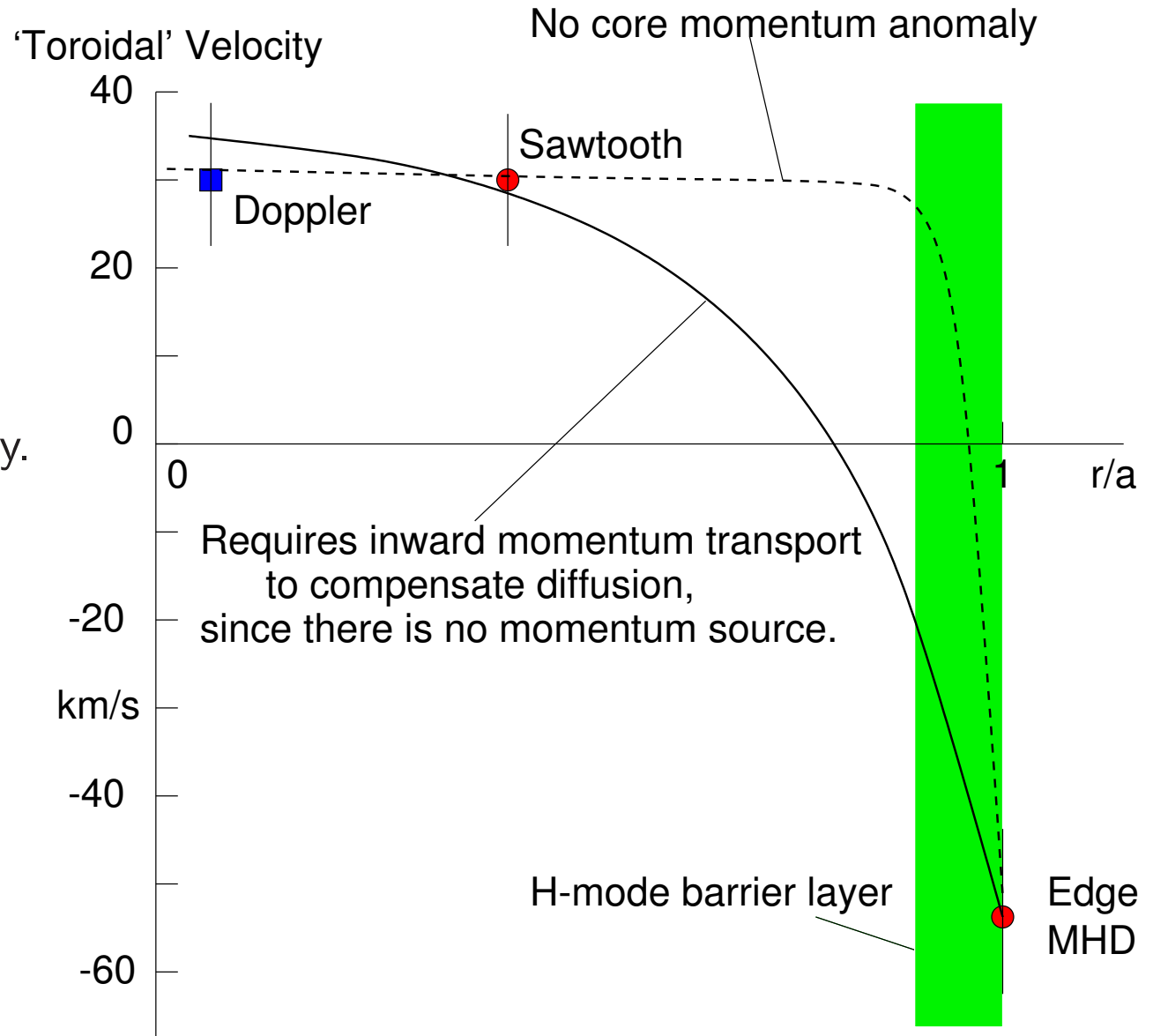


# Significance of Velocity Profiles



Flat Core profile:  
momentum transport  
anomaly is located in the  
edge barrier.

Peaked/hollow profile:  
Core momentum anomaly.



# 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
Fields	Stochastic Fields	R&R Parallel Transport
	$\tilde{B}$	Rotating modes
		Resistive wall modes
	$B_t$ ripple	Locked modes
	$E_\phi$	Charge Imbalance

# Theory Examples



## Summary

## Characteristics

### ICRF Energetic Particles:

Chang      Minority Tail orbit  
effect, analytic.

Trapped and passing particles give different flow direction.

Perkins & White      Tail Current,  
Monte-Carlo.

Direction depends on resonance position.  
[Not observed].

### Neoclassical Effects on Transport:

Rogister       $L_n \sim \rho_p$  in H-barrier

Edge agreement not established.  
Could not explain core  $v$ -gradient.

### Turbulent Transport:

Shaing      Momentum Pinch (Q-L)

Direction depends on edge term.  $\frac{dv_{\parallel}}{dr} - \frac{5}{2} \frac{T'}{T} v_{\parallel} = 0$

Coppi      Momentum Pinch (Q-L)

Direction determined by  $v'_{\parallel}$  ITG stability contribution.

# Summary



There are important mechanisms in tokamak **H-mode edge**, which give rise to a “boundary condition” (for the core) of finite velocity.

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

There are also clear examples where there are strong steady gradients of toroidal velocity in the **core**, when there is no direct momentum input.

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 momentum transport mechanism **up** the velocity gradient to counteract diffusion. This is loosely called a “momentum pinch”.

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

The most plausible mechanisms seem to be turbulent transport (giving rise to “Reynolds Stress”).