EUROfusion

# Evolution of $v_\perp$ shear along slow power ramp towards L-H transition

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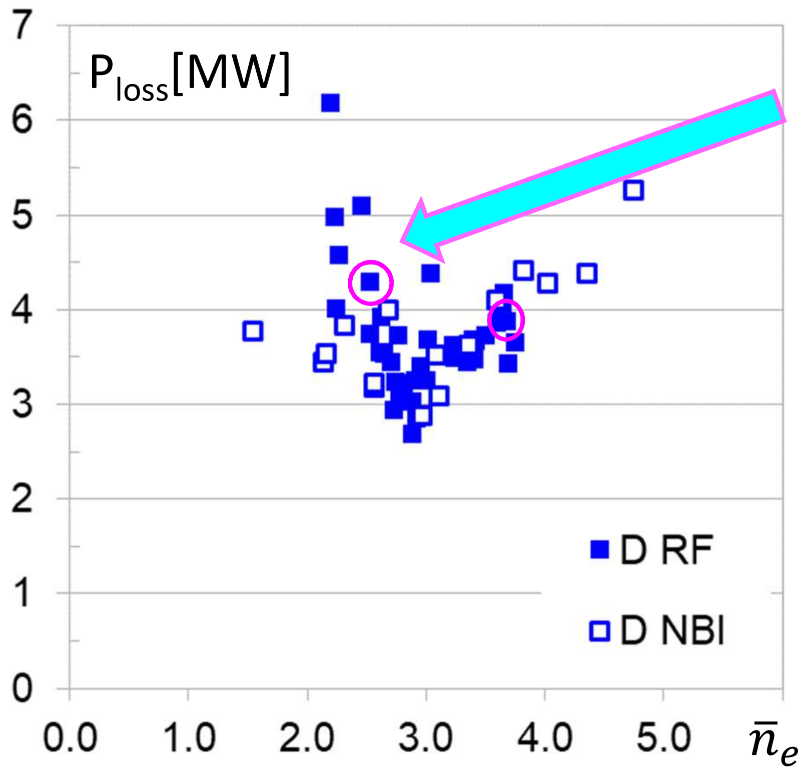
# Typical results of $P_{L\text{-}H}$ density scan in Deuterium

JET **Deuterium** HT 2.4 T 2 MA



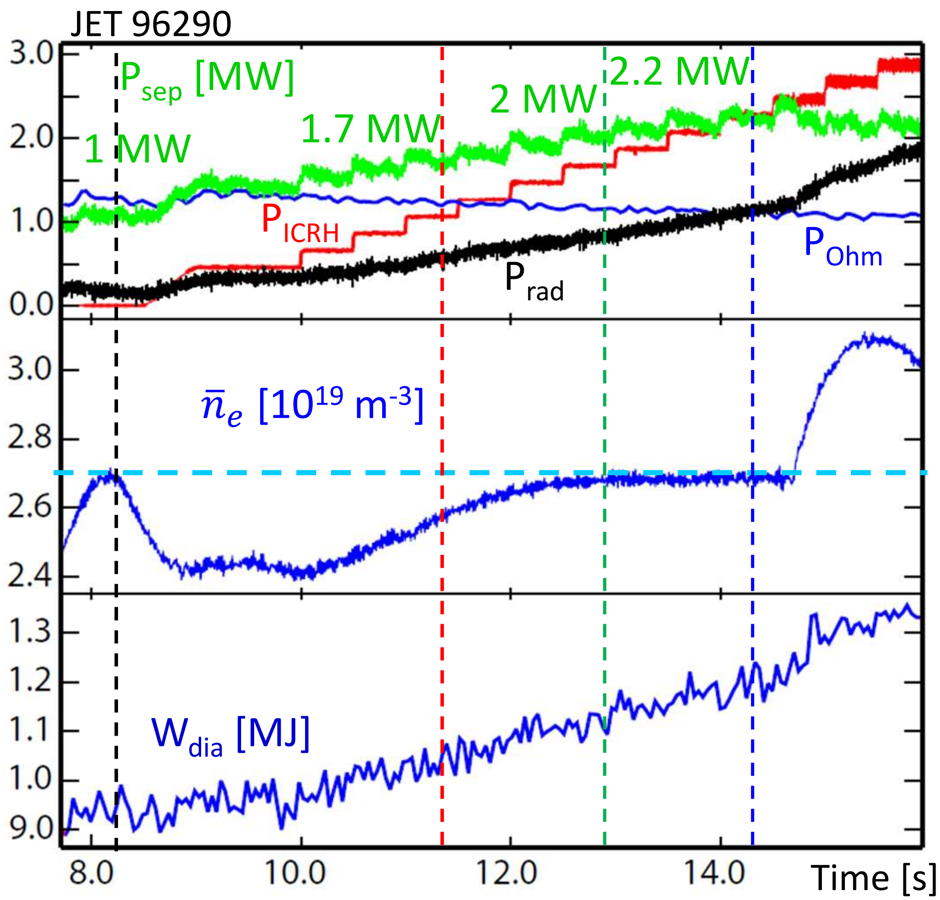

Focus on L-H transition with very detailed Doppler reflectometry measurements

Doppler reflectometry measures $v_\perp$, rotation of fluctuations perpendicular to B

$v_\perp$ shear is exactly what will tear or stretch turbulence eddies', if that is the mechanism for L-H transition

$v_\perp \sim ExB/B^2$

# New: evolution of $E_r$ along power ramp in Deuterium




The dominant understanding of the L-H transition:

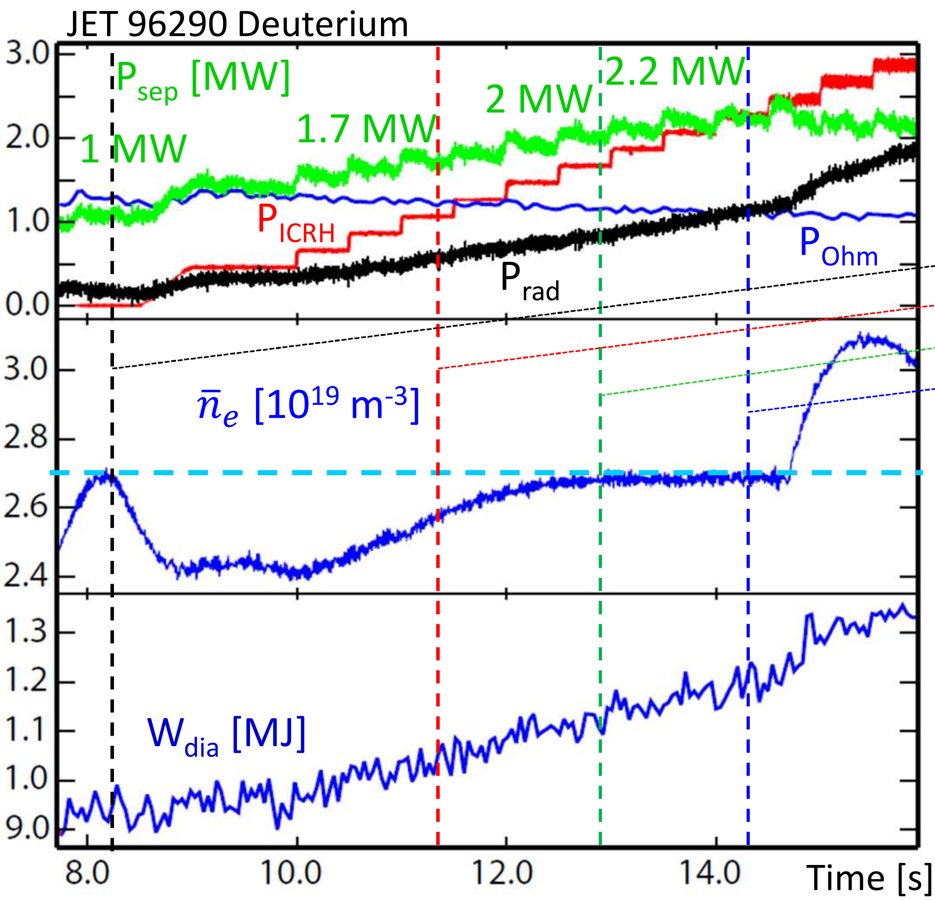
- the interaction between turbulence and radial electric field leads to an eventual critical electric field (shear) that stabilizes the turbulence

  KC Shaing, Biglari&Diamond, Hahm&Burrell, etc

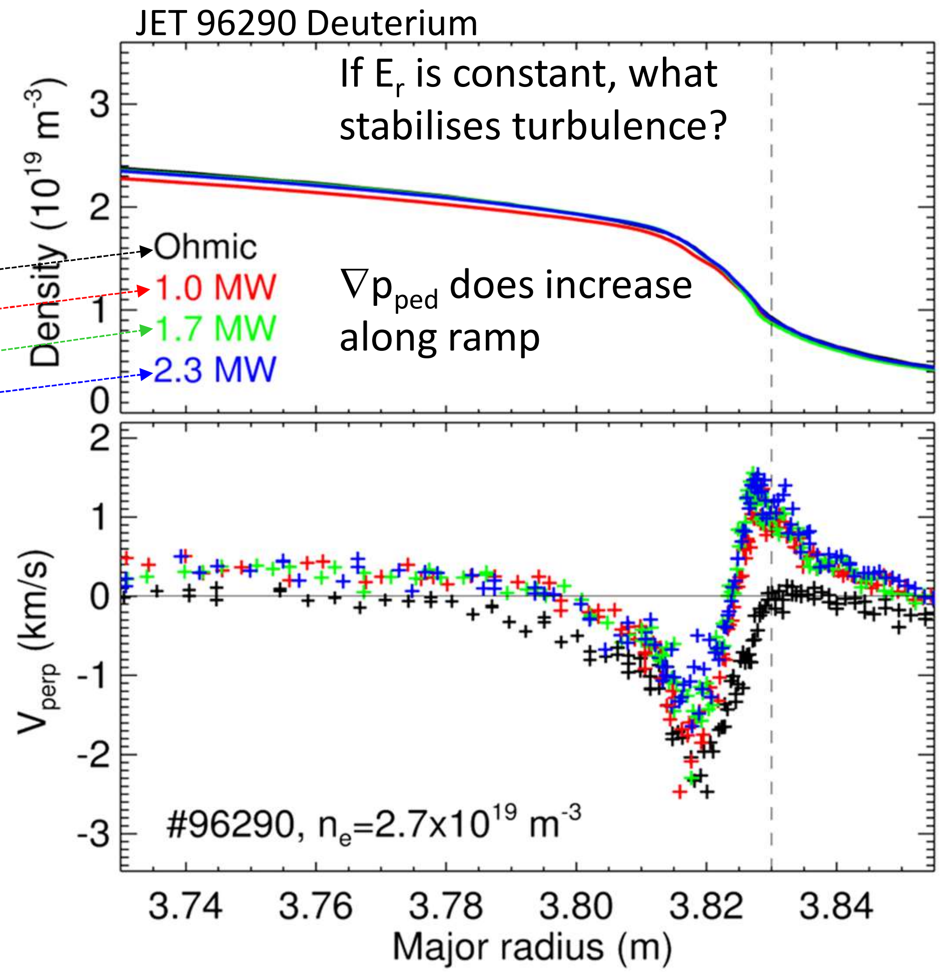
- The expectation is that the $E_r$ profile evolves along the power ramp, as $\nabla p$ or $\nabla p_i$ [ Ryter NF 2014] increases, until a critical $E_r$ well can stabilise turbulence

ER Solano et al, Nucl. Fusion **62** (2022) 076026 https://doi.org/10.1088/1741-4326/ac4ed8

# Doppler reflectometry along power ramp in Deuterium

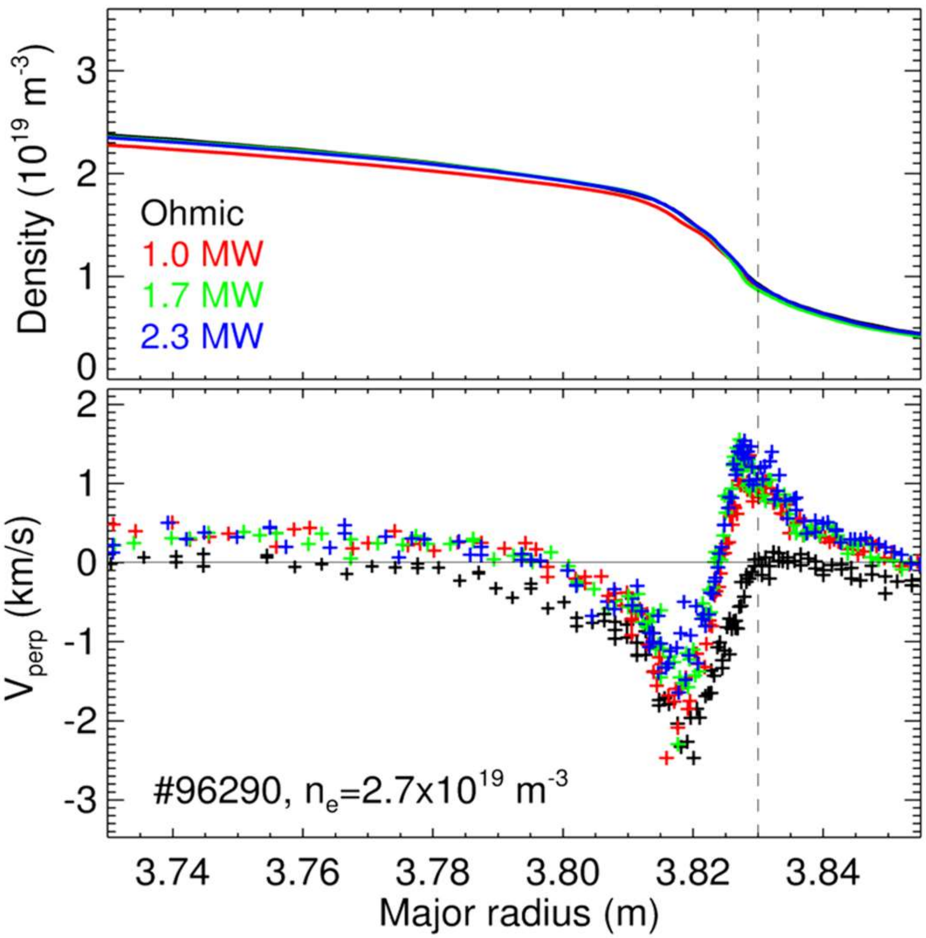



*C. Silva, Nucl. Fus. 61 126006 (2021)*



# Deuterium: $E_r$ measurements along ICRH power ramp, at $n_{e,min}$(D)

JET 96290, 2.4T, 2 MA, ICRH




**Evolution** of $v_\perp$~$E_r$/B measured with Doppler reflectometry along **especially slow** RF power steps (200 kW every 0.5 s). Time resolution: 300 ms (no momentum input)

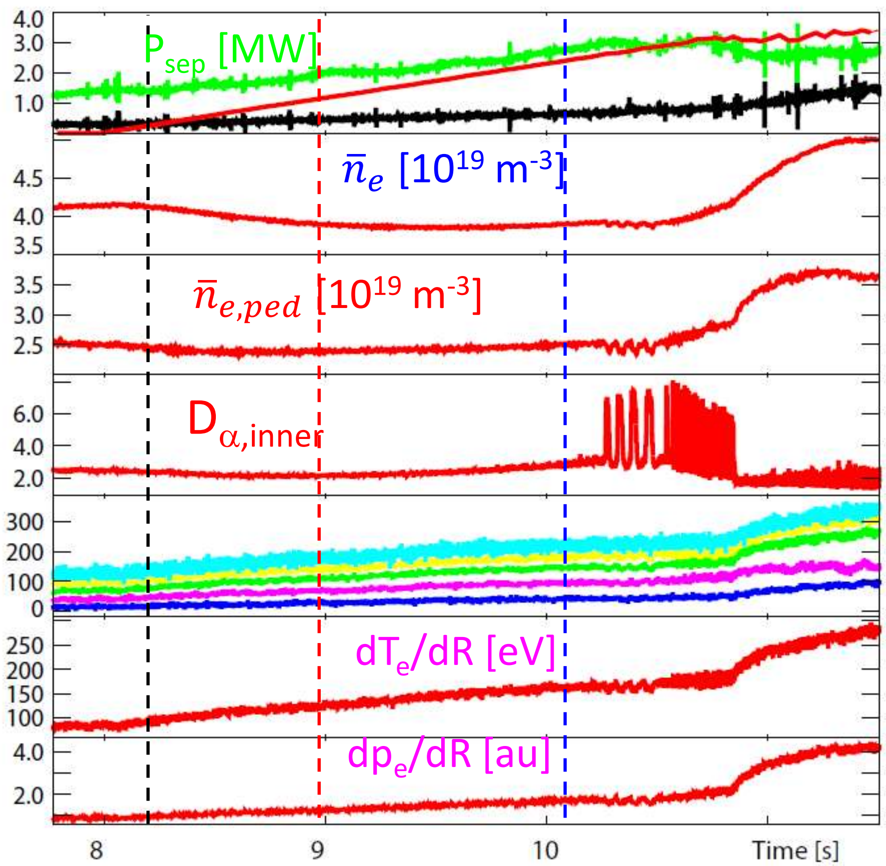
**Ohmic:** low $v_\perp$ at separatrix/SOL, deep well

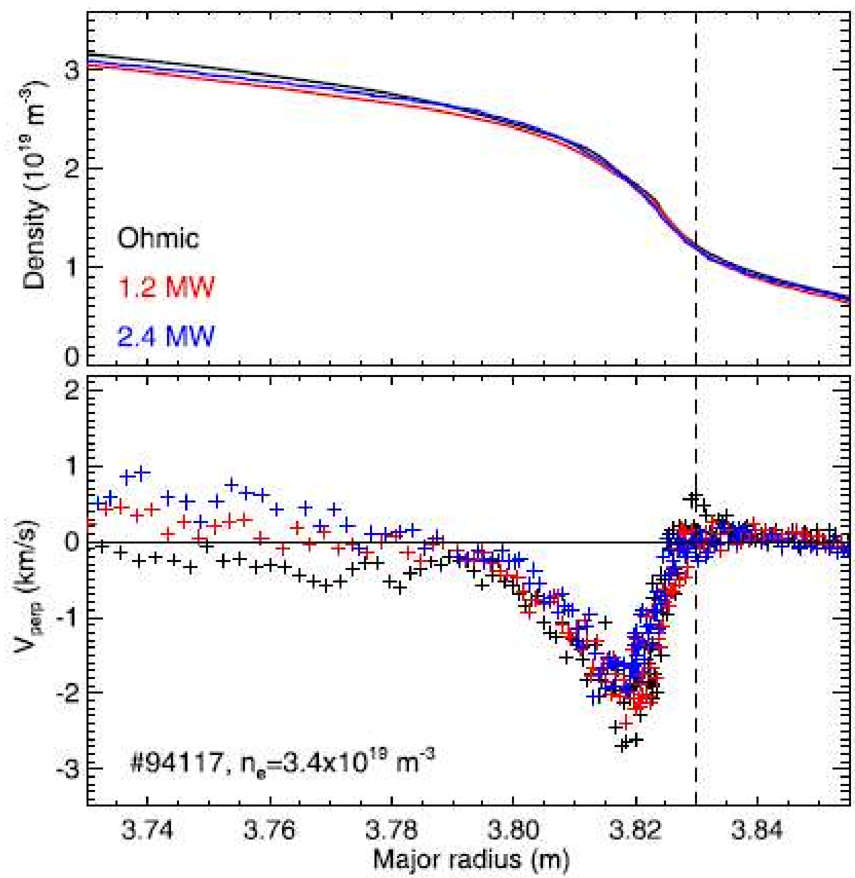
**During power ramp:**

- high $v_\perp$ at separatrix/SOL when ICRH on
- reduction in depth of $v_\perp$ well with ICRH
- similar $v_{\perp\ maximum}$ shear during power ramp
- L-H: 200 ms after last $v_\perp$ profile, 2.5 MW

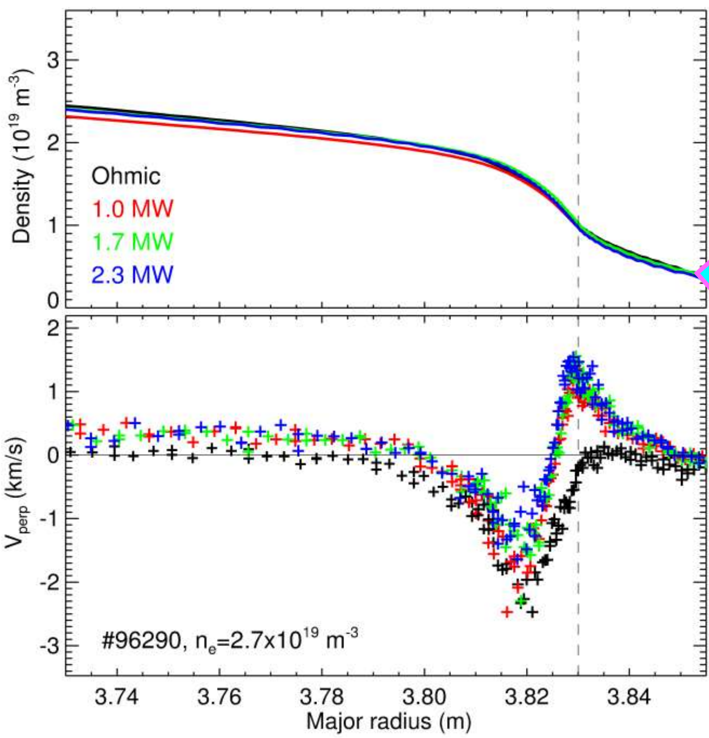
**Neither $E_r$ well nor $E_r$ shear appear to increase during the power ramp.**
**Is this $E_r$ shape characteristic of L-mode?**
**If so, what triggers the L-H transition?**

# Similar lack of $v_\perp$ evolution in high density branch

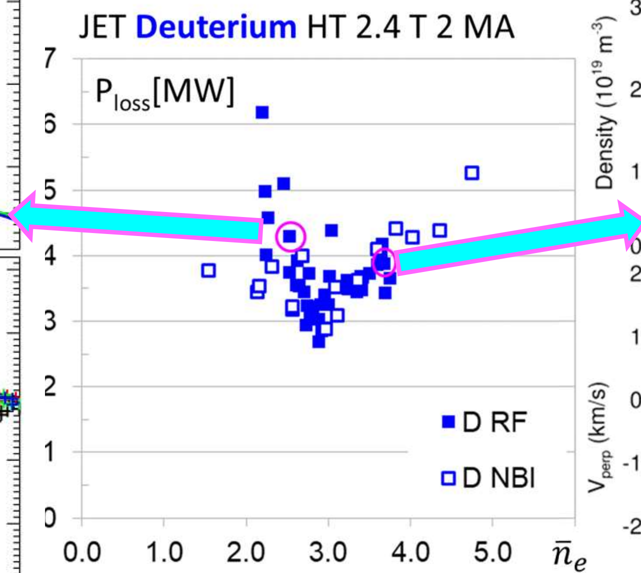


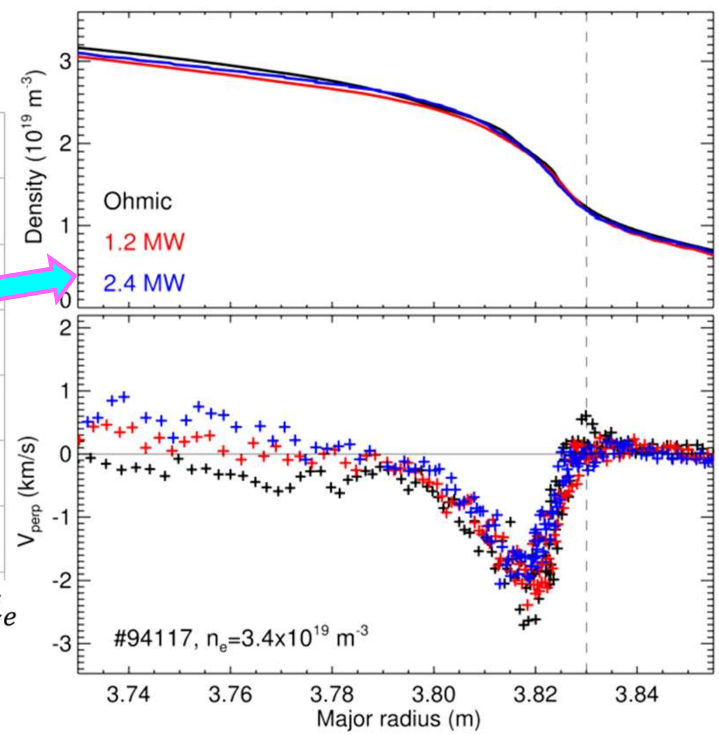
Low density branch




**ICRH: no momentum input**




High density branch




Same result in high density

# Conclusions

If $E_r$ profile barely evolves along power ramp, why didn't the transition happen earlier?

We propose $\nabla$p or F' drive a magnetic phase transition from para- to dia-magnetism.

Note: after the L-H transition both $\nabla$p and $E_r$ increase and ExB shear can reduce turbulence and further improve confinement

Technical note:

in the **Grad-Shafranov** equation the sign of F' (poloidal current density) matters

$$\underbrace{\frac{1}{\mu_0 R}\left(R\frac{\partial}{\partial R}\frac{1}{R}\frac{\partial \Psi}{\partial R}+\frac{\partial^2\Psi}{\partial Z^2}\right)}_{L(\Psi)}+\underbrace{\left(Rp'+\frac{(F^2)'}{2\mu_0 R}\right)}_{J(\Psi)}=0$$

F' sign affects magnetisation interchange transport, drives magnetization phase separation, maybe L-H transitions.

Different from Shafranov shift dependence

Related to $\tilde{B}_{||}$ Facundo Sheffield Heit's talk?

E.R. Solano, *PPCF* ***46*** *(2004) L7–L13*

E R Solano, R D Hazeltine (2012) *NF* ***52*** *114017*

# JET L-H experimental results

- Critical profiles $n_e$, $T_e$, $T_i$ determine access to L-H transition
- $P_{LH}$ depends on isotope due to L-mode isotopic dependencies
  - L-mode $\tau_E$ scaling is VERY old (1989), needs revisiting, especially isotope effect
- Effective mass orders threshold, but not good scaling parameter
- $v_\perp$ profile doesn't evolve along power ramp

**And what about theory?**

***Magnetization phase transitions***: explored in
Equilibrium criticality when $j_\theta$=0: ER Solano, PPCF 46 L7 (2004)
Diamagnetism and ITB formation: J Garcia, G Giruzzi PRL 104 205003 (2010)
Magnetic phase transition, transport barriers: ER Solano & RD Hazeltine NF 52 114017 (2012)

# Plasma magnetization in a tokamak

Plasma force balance: $\nabla p = \vec{j} \times \vec{B} = \vec{j}_\zeta \times \vec{B}_\theta + \vec{j}_\theta \times \vec{B}_\zeta$

In cylindrical approximation $\frac{d}{dr}\left(p + \frac{B_z^2 + B_\theta^2}{2\mu_0}\right) = -\frac{B_\theta^2}{r\mu_0}$

$$\frac{dB_z}{dr} = -\mu_0 j_\theta$$

Integrating:

$$\beta_\theta \equiv \frac{\int_0^a p\,dS}{B_{\theta a}^2 / 2\mu_0} = \frac{B_{za}^2 - \langle B_z^2 \rangle}{B_{\theta a}^2} \simeq 1 + \frac{2B_{za}\left(B_{za} - \langle B_z \rangle\right)}{B_{\theta a}^2}$$

$\beta_\theta$ related to volume averaged plasma magnetization

$\beta_\theta < 1$

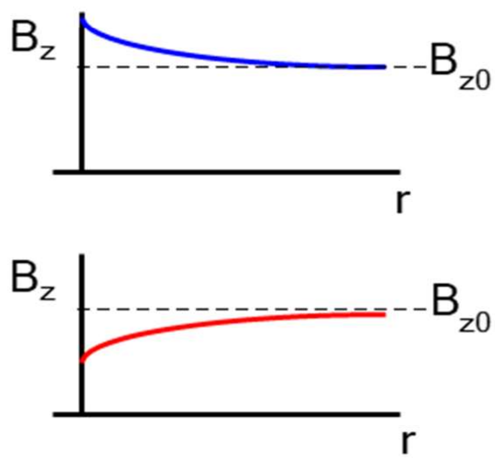
$\nabla p < j_z \times B_\theta$

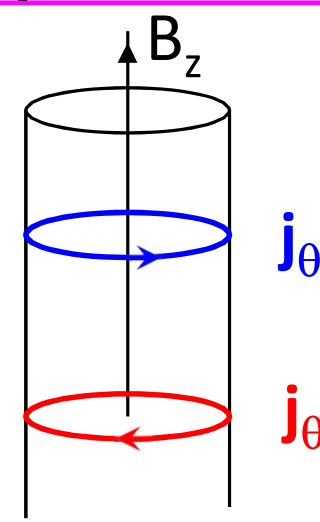
$B_z$ increased by $j_\theta$, paramagnetism, low pressure

$\beta_\theta > 1$

$\nabla p > j_z \times B_\theta$

$B_z$ reduced by $j_\theta$ diamagnetism, high pressure



# Plasma Magnetisation

The tokamak plasma is a magnet

$$\langle B_z \rangle - B_z^{vac} \cong \mu_0 \left( B_{\theta a}^2 / 2\mu_0 - \int_0^a p\,dS \right) \Big/ B_z^{vac}$$

The difference between poloidal magnetic and kinetic pressure determines if it is a para-magnet or a dia-magnet

Paramagnets

increase the background magnetic field

move towards high field

Diamagnets

increase the background magnetic field

move towards low field

*Diamagnetic frog levitating in magnetic field*
Berry, Geim (Ig-Nobel)
*Eur. J. Phys.* **18** 307 1997

# Magnetism in cylindrical blob with pressure peak/hole

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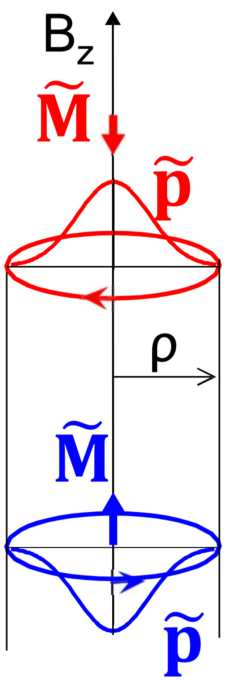
$$\mathbf{F} = mn\frac{d\mathbf{v}}{dt} = -\nabla\tilde{p} + \tilde{\mathbf{j}}\times\mathbf{B} = 0 \qquad \tilde{\mathbf{j}}_\perp = \frac{\mathbf{b}\times\nabla\tilde{p}}{B}$$




Diamagnetic current: if inside the tube there is a pressure peak, the associated $j_\perp$ reduces $B_z$: diamagnetism

Paramagnetic current: if inside the tube there is a pressure hole, the associated $j_\perp$ increases $B_z$: paramagnetism

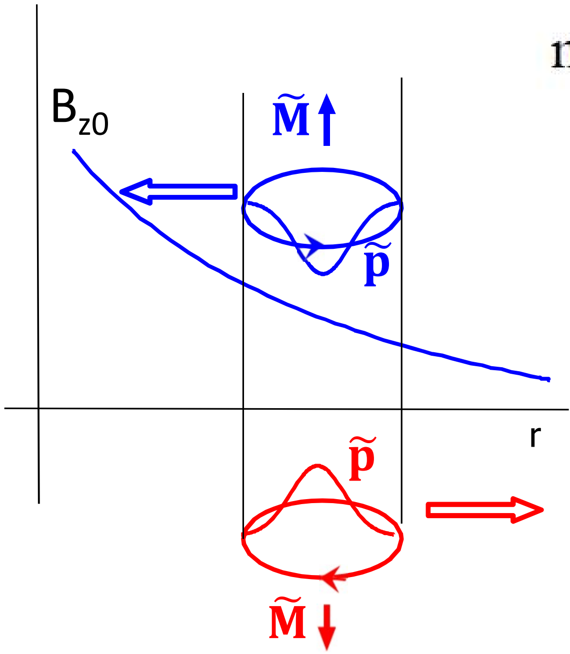
**Magnetization of the blob:**

$$\nabla\times\mathbf{M} = \mu_0\frac{b\times\nabla\tilde{p}}{B} = -\frac{dM}{dr}\hat{\mathbf{r}}$$

$$\tilde{\mathbf{M}} = \frac{1}{\lambda_\parallel}\int_0^\rho \frac{\mathbf{b}}{B}\frac{\partial\tilde{p}(\rho')}{\partial\rho'}\lambda_\parallel\, d\rho' \approx -\frac{\tilde{p}}{B}\mathbf{b} \quad \begin{cases} < 0, \text{ dia} \\ > 0, \text{ para} \end{cases}$$

# Movement of magnetised blobs in paramagnetic plasma

Jackson, Classical Electrodynamics




$$m_V \left.\frac{d\mathbf{v}}{dt}\right|_V = \int \left(\nabla(\tilde{\mathbf{M}}.\mathbf{B})\right) dV \simeq$$

$$\vec{B} = \vec{B}_0 + \vec{r}.\nabla\vec{B}_0 + \dots$$

$$\left(\int (r \times j_{mag}) dV\right) \int \nabla B_{0z} dV$$

blob magnetization

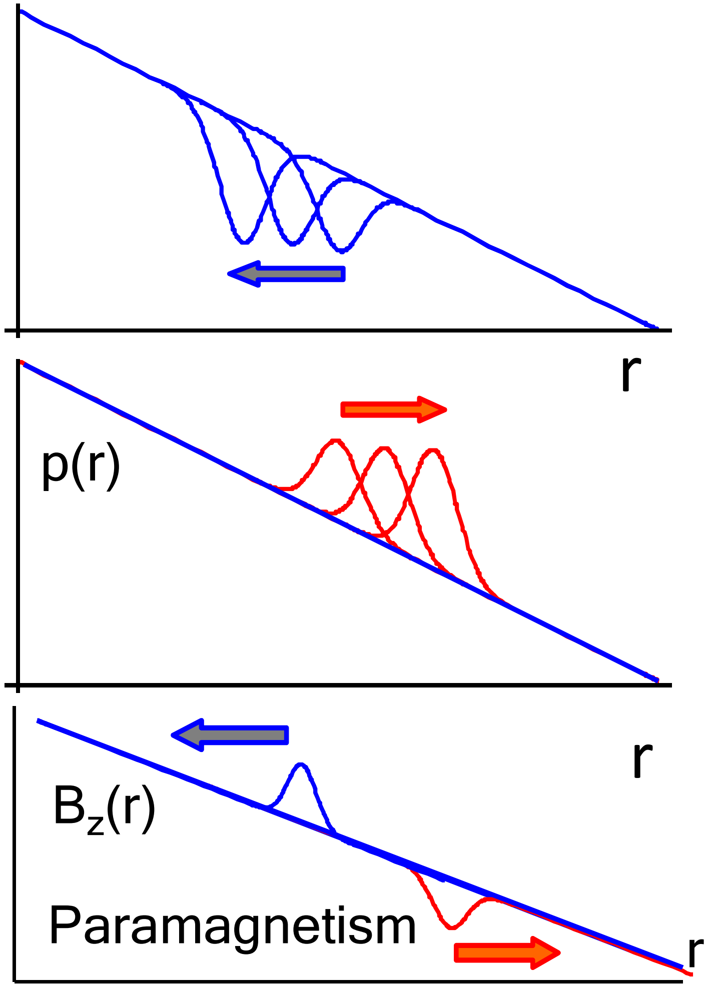
$$mn_V \frac{d\mathbf{v}_r}{dt} \simeq \tilde{M}_z \nabla \overline{B}_{z0}$$

the cold blob (paramagnetic) seeks high field

the hot blob tube (diamagnetic) seeks low field

Blob averaged $dB_z/dr$ controls motion of magnetised plasma blobs: <u>Anti-potential</u> leads to *magnetic phase separation*

# Paramagnetic plasma: L-mode




Motion of pressure blobs depends on $dB_z/dr$

$$mn_V \frac{d\vec{v}_r}{dt} \simeq \tilde{M}_\zeta \nabla_r \bar{B}_{\zeta 0}$$

paramagnetic cold blobs move inward,

diamagnetic hot blobs move outward

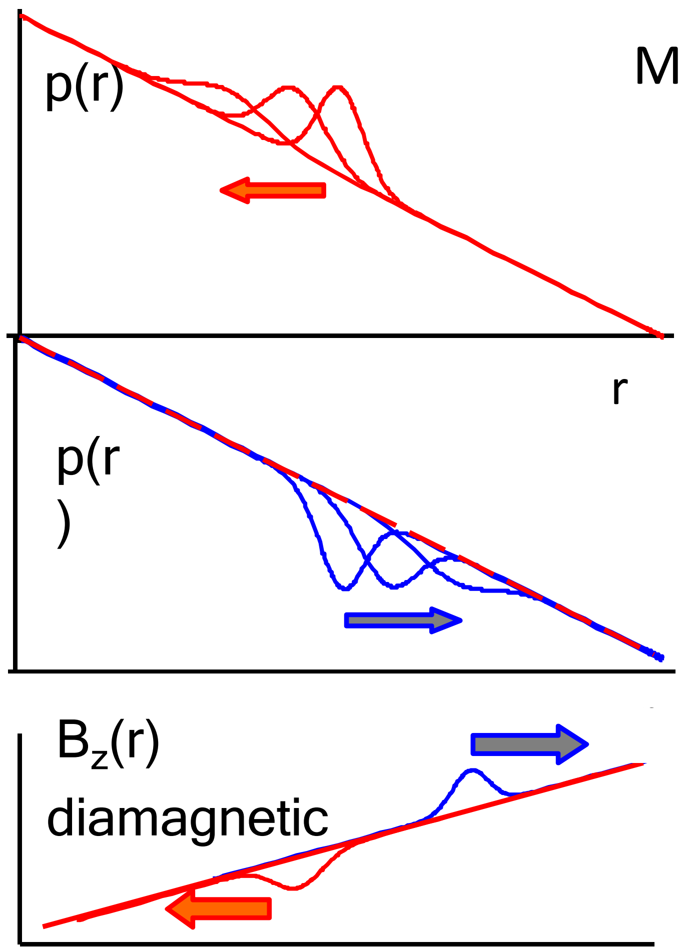
outward thermal energy convection at the expense of

inward magnetic energy convection

p blobs "grow", "instability"

**L-mode**

# Diamagnetic plasma: H-mode




Motion of pressure blobs depends on $dB_z/dr$

$$mn_V \frac{d\vec{v}_r}{dt} \simeq \tilde{M}_\zeta \nabla_r \overline{B}_{\zeta 0}$$

diamagnetic hot blobs move inward,

paramagnetic cold blobs move outward

inward thermal energy convection

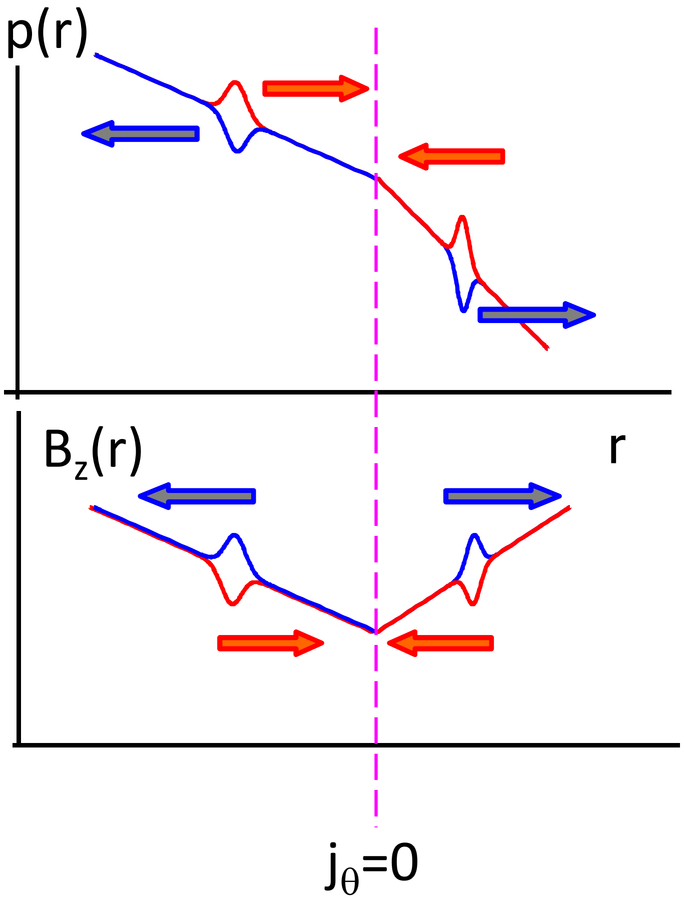
at the expense of

outward magnetic energy convection

p blobs “decrease”, “saturation”

**H-mode**

# Magnetic Boundary: phase transition




At a magnetic phase boundary blobs of the same type accumulate/separate

diamagnetic blobs (heat) seek magnetic wells
paramagnetic blobs seek magnetic hills

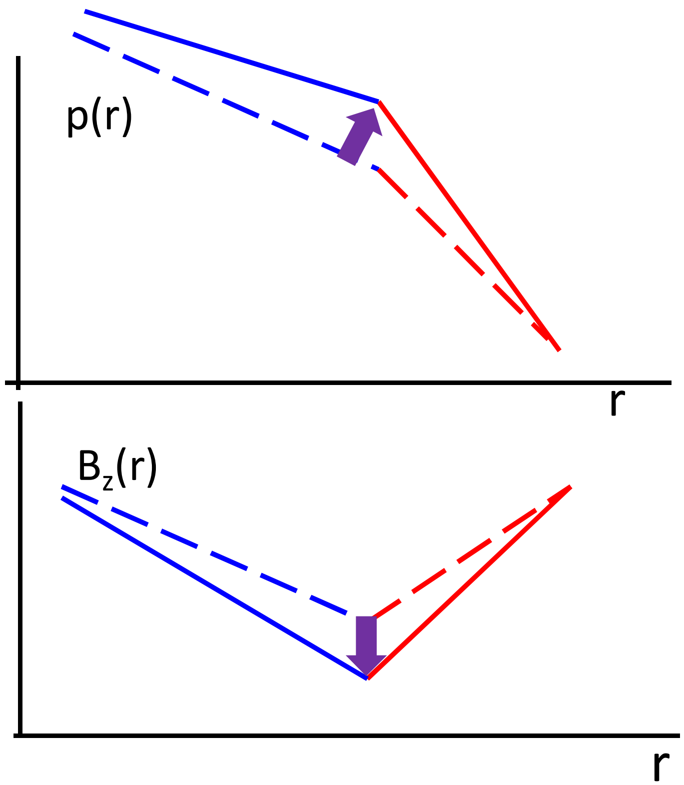
With multiple blobs moving,

p and $B_z$ profiles evolve,

steepening magnetic hills, digging magnetic wells

Developing pressure pedestal

# Magnetic Boundary: phase transition




∇p increases somewhere, creating diamagnetic region at plasma edge.

Magnetization, of both signs, increases.

Phase transition is self-reinforcing.

Pressure pedestal forms, grows.

# Pedestal formation at magnetisation boundary

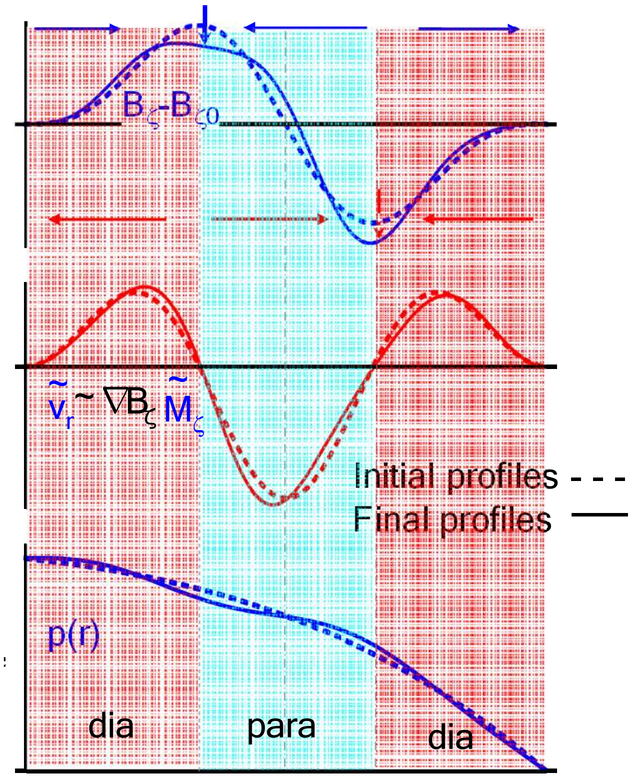
Assume dashed $B_z(r)$, $p(r)$ initial profiles

Ideal MHD with <u>magnetization force</u>

$$\bar{n}_V m_i \left.\frac{d^2\xi_r}{dt^2}\right|_M = \tilde{M}_\zeta \nabla \bar{B}_{0z}$$

$$\left.\frac{\partial B_z}{\partial t}\right|_M = \nabla \times (\tilde{v}_r \bar{B}_{0z})$$

$$\left.\frac{3}{2}\frac{\partial p}{\partial t}\right|_M = -\nabla(\tilde{p}\,\vec{v})$$




Integrating one temporal step

pressure steepens in diamagnetic regions, increases diamagnetism

flattens in paramagnetic regions, increases paramagnetism

*Magnetic <u>phase separation</u> drives pedestal formation*

## Interchange instability[1]

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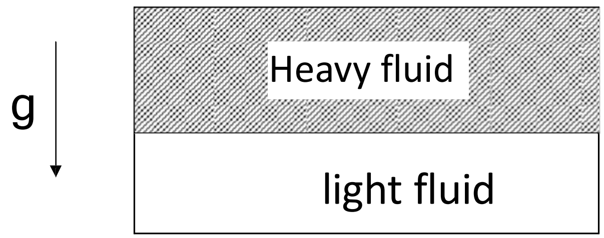
- present when radial force acts equally on electrons and ions
- equivalent to the Rayleigh-Taylor instability in a fluid.
- magnetization gradient acting on magnetized plasma blobs replace "gravitational field" or "curvature".




Magnetization interchange

$$\gamma = \sqrt{g\lambda_\perp} =$$

$$= \sqrt{-\frac{1}{m_V}\frac{\tilde{p}}{2B^2}\frac{\partial B_\zeta^2}{\partial r}\lambda_\rho}$$

Magnetization interchange growth faster for
high magnetisation, blob amplitude & radius, low field & mass

[1]M.N. Rosenbluth and C.L. Longmire, Annals of Physics, Volume 1, Issue 2, May 1957,120

# Suydam criterion for interchange instability

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B. R. Suydam, Proc. 2nd UN Conf. on Peaceful Uses of Atomic Energy, Geneva, 1958.

$$\beta'\left(\frac{Rq}{r_s}\right)^2\left[\frac{B^2\kappa_r}{\mu_0}\right] > \frac{q'^2}{4q^2}$$

magnetic shear opposes interchange of tubes driven by cylindrical curvature and $\nabla\beta$

Generalization: add magnetization force to cylindrical curvature

$$\beta'\left(\frac{Rq}{r_s}\right)^2\left[\frac{B^2\kappa_r}{\mu_0} + \tilde{M}_z\frac{dB_{0z}}{dr}\right] > \frac{q'^2}{4q^2}$$

In magnetically mixed states $\tilde{M}_z\frac{dB_{0z}}{dr} < 0$

magnetisation force adds to curvature, instability,

until the magnetic shear q' or the sign of $dB_z/dr$ changes.