Power threshold of the L-H transition in tokamaks from first principles

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Experimental observations heavily constrain LH theories

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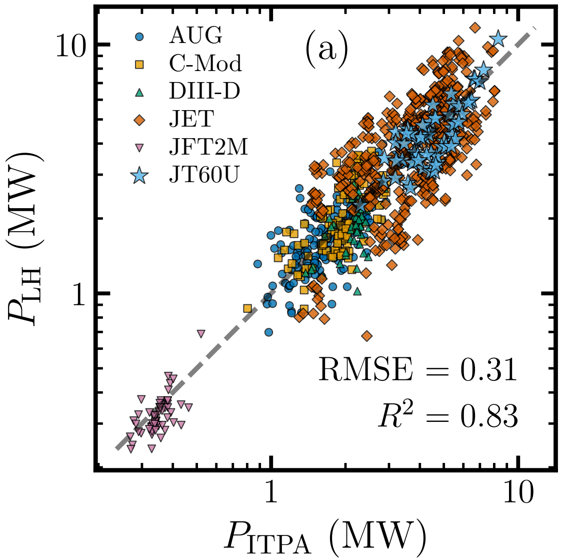
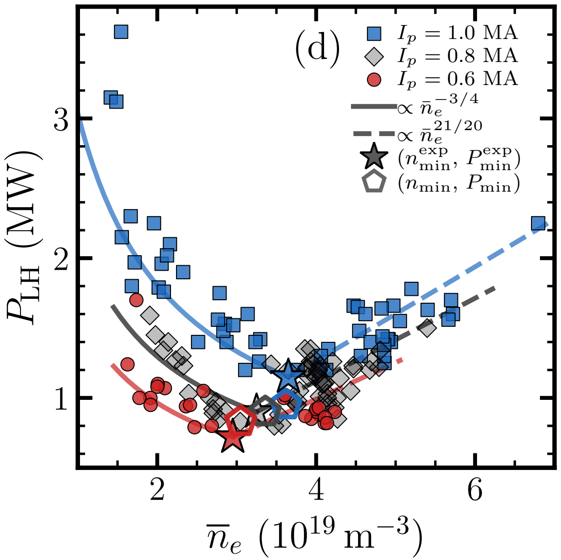
- Wealth of experimental observations strongly constrain LH theories
- Martin scaling, U-shaped power threshold, fav/unfav asymmetry effect

Martin *et al* J. Phys. Conf. Ser. 2008



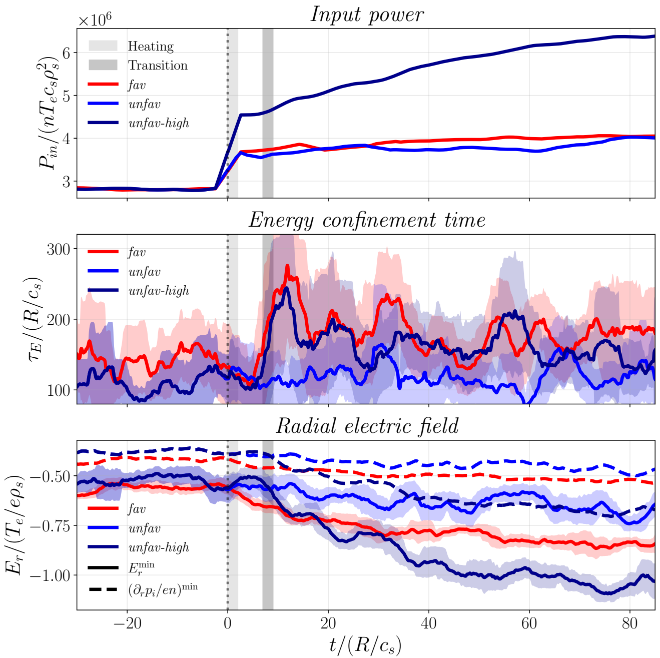


Ryter *et al* Nucl. Fusion 2014

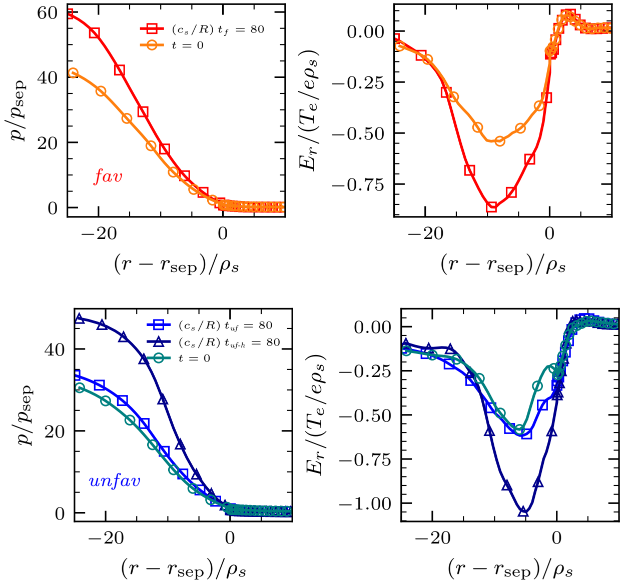
$$P_{\mathrm{LH}}^{\mathrm{ITPA}} = 0.0488\,\overline{n}_{e20}^{0.717} B^{0.803} S^{0.941}\ [\mathrm{MW}]$$

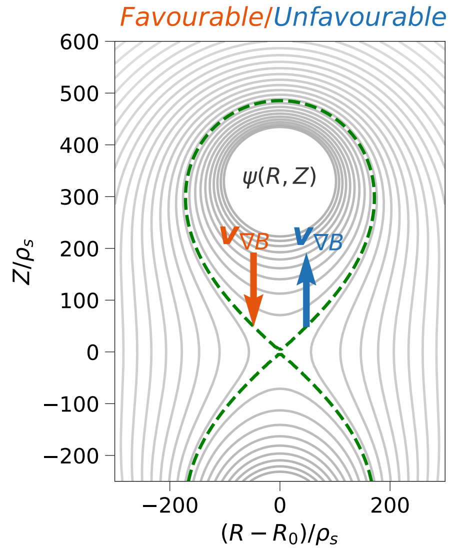
Confinement transitions in GBS simulations fav/unfav

- Power ramp simulations in a half-TCV-sized tokamak with GBS
- Increasing power transitions to suppressed confinement
- Unfavourable transitions only when ~1.5 more power is used



Pressure and radial electric field





Electromagnetic effects and ExB shear are key

- Electrostatic simulation shows no transition, plasma-beta is key
- Key role of beta and its interplay with ExB shear flow generation
- Fourier analysis reveals electron drift-waves

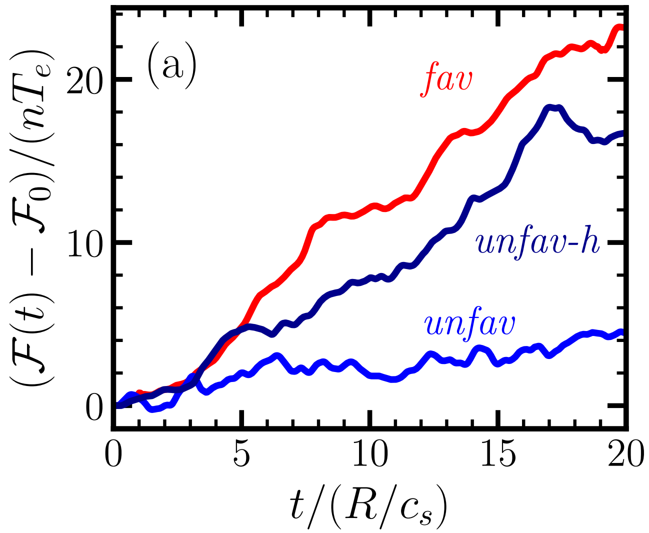
$$\frac{\partial n}{\partial t} + i\sigma_T \rho_s k_y \sqrt{\beta_A}\phi + \sigma_p \frac{\partial(\rho_s^2 k_\perp^2 A_\parallel)}{\partial \theta} = 0, \quad (2)$$

$$\frac{\partial(\rho_s^2 k_\perp^2 \phi)}{\partial t} - \sigma_p \frac{\partial(\rho_s^2 k_\perp^2 A_\parallel)}{\partial \theta} = 0, \quad (3)$$

$$\frac{\partial}{\partial t}\left(1 + \frac{\rho_s^2 k_\perp^2}{\beta_\mu}\right) A_\parallel + i\sigma_T \rho_s k_y \sqrt{\beta_A} A_\parallel - \sigma_p \frac{\partial(\phi - n)}{\partial \theta} + \frac{\rho_s^2 k_\perp^2}{\beta_\nu} A_\parallel = 0, \quad (4)$$

$$k_\perp^2 = k_y^2 \left[\frac{1}{g} + \hat{s}^2 \left(\theta + r_0 \partial_x \theta / \hat{s} - \sigma_T \Omega_E t\right)^2 g\right]$$

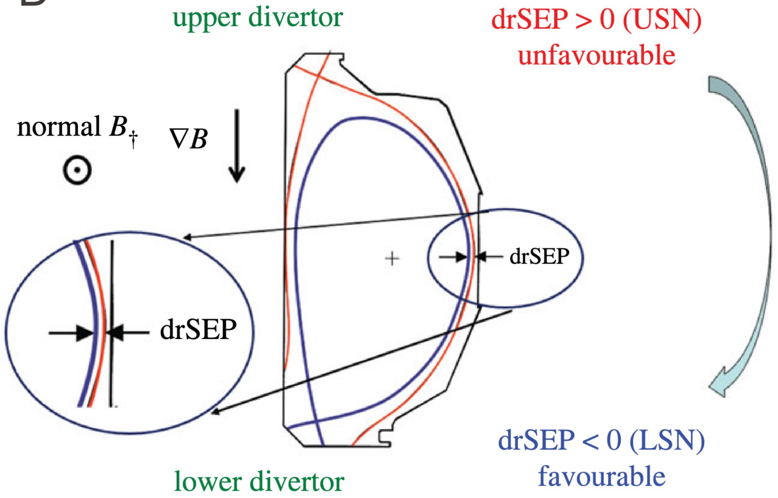
Turbulent drive of ExB rotation

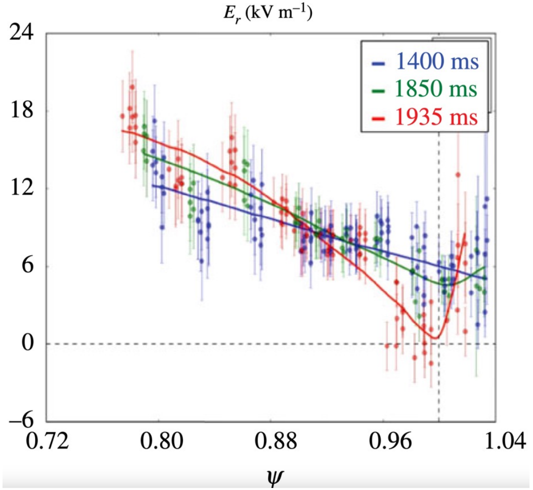


$$\sigma_p \equiv \text{sign}(\boldsymbol{I}_p \cdot \nabla\varphi) \qquad \sigma_T \equiv \text{sign}(\boldsymbol{B} \cdot \nabla\varphi) = -1$$

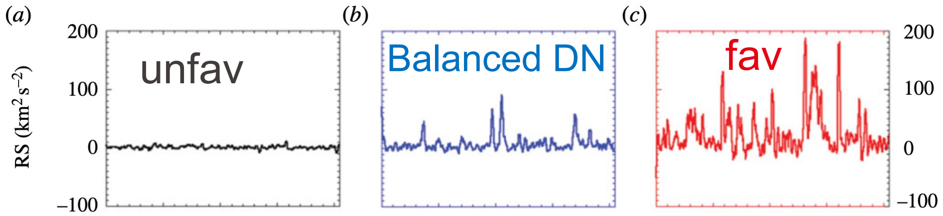
Asymmetry effect in DIII-D due to ExB shear by RS

- Experimental study of fav/unfav asymmetry in DIII-D
- Input power above fav P_{LH} but below unfav level
- Continuously change from unfav to fav by varying *drSEP* *[Z. Yan et al. Phil.Trans. R. Soc. 2022]*
- As one approaches the fav config:
  - Radial electric field well deepens due to
  - Strong Reynolds stresses





Reynolds Stress



Quasilinear theory of ExB flow generation by finite-beta DW

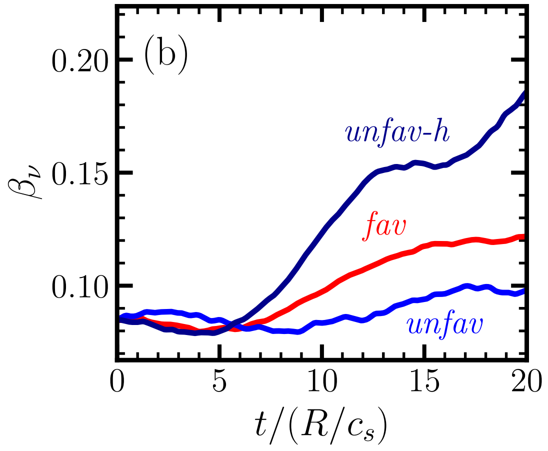
- DW linear system with electromagnetic effects (RDW and IDW)
- Coupled to zonal ExB flow equation (mean flow)
- Two parameters control growth depending on collisionality
- Here is the RDW case (from simulations)

$$\frac{\rho_s}{\sqrt{\beta_A} L_n} \frac{\partial}{\partial t} \frac{d\langle\phi\rangle}{dx} + \sigma_T \frac{d\Pi}{dx} = 0$$

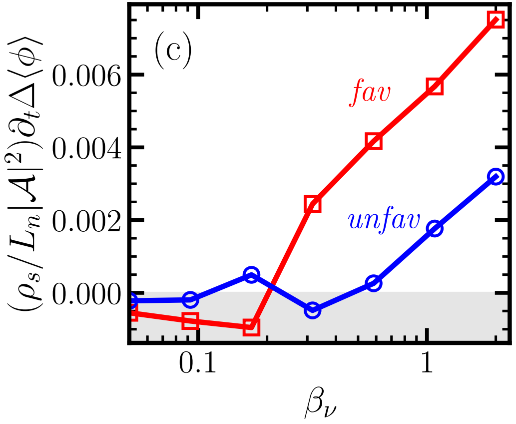
$$(\beta_\nu, \beta_\mu) = (\beta\omega_A/\nu, m_i\beta/m_e)$$

Quasilinear calculation

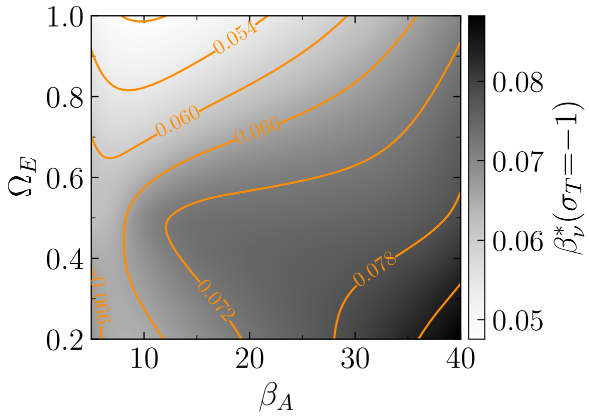
Simulation



Electric field growth rate



Critical parameter



First-principles threshold criterion

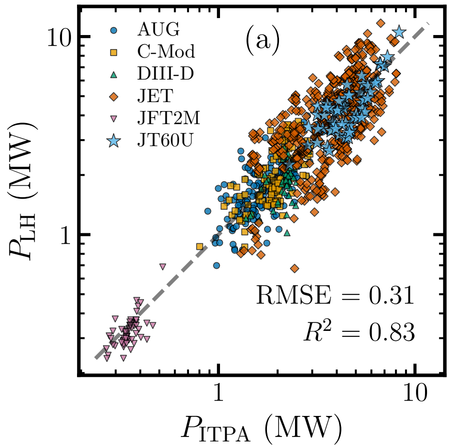
- First-principles expression for power from threshold criteria
- Cross-field losses dominated by ExB turbulence
- Mixing-length estimate for heat flux $Q_\perp \simeq \gamma |\partial_r p| / k_x^2$
- Obtain closed-form expressions for P_{LH} in high- and low-density branches
- HDB scaling improves Carbon wall scaling of Martin (via Z_{eff})
- Reproduces ILW scaling from *Delabie et al Nucl. Fusion 2026*

$$\beta_\nu > \beta_\nu^* \text{ (RDW)}$$
$$\beta_\mu > \beta_\mu^* \text{ (IDW)}$$

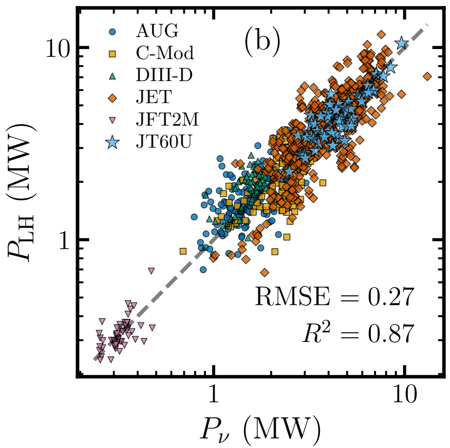
HDB
$$P_\nu = K_\nu \frac{\beta_\nu^* (\sigma_T)^{11/10} e^{19/10} \Lambda^{3/5} m_e^{3/10}}{\mu_0^{11/20} \epsilon_0^{6/5} m_h^{11/20}} \times \frac{a R^{11/10} B^{3/5} n^{21/20} Z_{\text{eff}}^{3/5} q^{1/10}}{M^{11/20}},$$

LDB
$$P_\mu = K_\mu \frac{\beta_\mu^{*11/4} \epsilon_0 m_e^{5/2}}{e^{5/2} \sqrt{\Lambda} \mu_0^{11/4} m_h^{11/4}} \frac{a B^5}{n^{9/4} q \sqrt{Z_{\text{eff}}} M^{11/4}}$$

Martin ITPA scaling



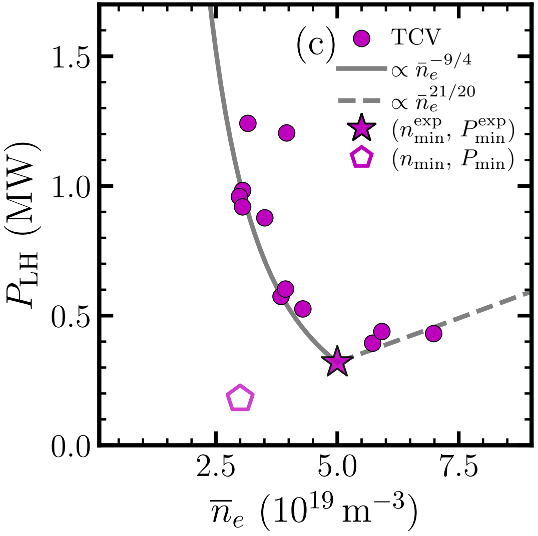
Analytical result
(1 fitted constant)

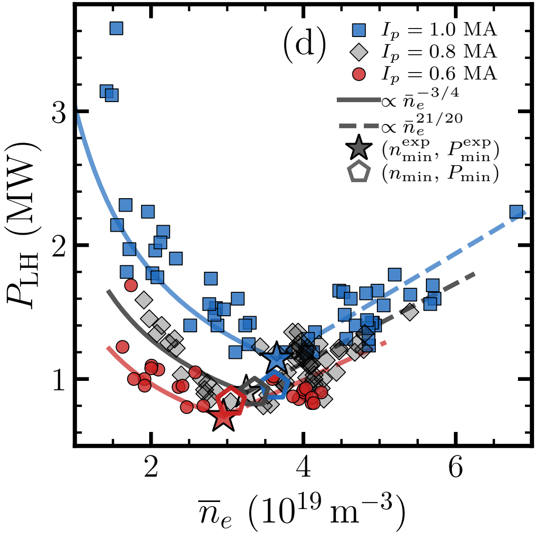


High-and-low density branches in TCV and AUG

- At low enough density, collisionality is weak
- RDW to IDW transition: threshold power scales inversely with n
- At high power (AUG and JET) sheath-losses set edge electron temperature at such low densities
- Different scalings in TCV and AUG

TCV data from Piras *et al* PRL 2010





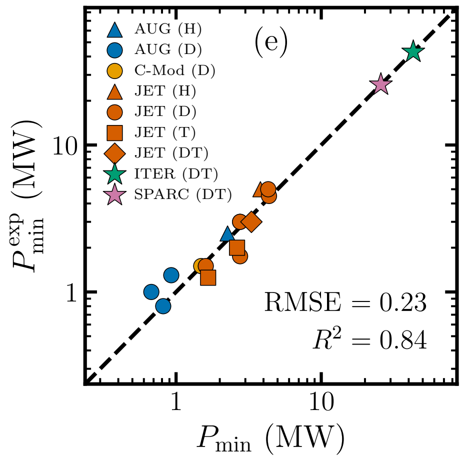
AUG data from Ryter *et al* Nucl. Fusion 2014

Crossover point for density minimum

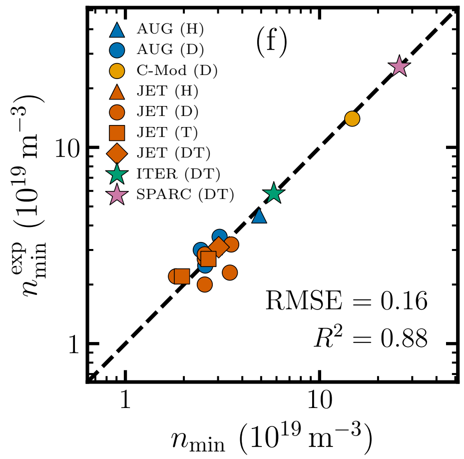
- In our theory the transition point occurs when IDW ~ RDW
- Resistive effects are comparable to inertial physics $m_e\omega_A/(m_i\nu) \sim 1$
- Yields a scaling for the density minimum and associated power

$$P_{\min} = K_P \frac{e^{1/2}\Lambda^{1/4} m_e}{\epsilon_0^{1/2} m_h^{5/4}\mu_0} \frac{a^{1/2} R\, B^{7/4} I_p^{1/4} Z_{\mathrm{eff}}^{1/4}}{M^{5/4}}$$

$$n_{\min} = K_n \frac{\epsilon_0^{2/3} m_e^{2/3}}{e^{4/3}\mu_0^{1/3}\Lambda^{1/3} m_h^{2/3}} \frac{I_p^{1/3} B}{Z_{\mathrm{eff}}^{1/3} a^{2/3} M^{2/3}}$$



Data from Delabie *et al* Nucl. Fusion 2026



Conclusion

- From flux-driven simulations we construct a theory of the LH transition
- Mechanism is self-organised, turbulent generation of sheared mean ExB flow
- Correctly reproduces:
  - Low and high density branches
  - Density minimum
  - Power minimum
  - Improves ITPA scaling and recovers new ILW scaling
  - Favourable/unfavourable asymmetry (time-reversal-symmetry breaking by collisionality)
- ITER implications: $n_{\min}^{\mathrm{ITER}} \simeq 5.8 \times 10^{19}\,\mathrm{m}^{-3}$ $\quad P_{\min}^{\mathrm{ITER}} \simeq 43\,\mathrm{MW}$