A TALE OF TWO (VISCO)CITIES

see D. Kennedy – Fri 9:10 oral

ELECTROMAGNETIC TURBULENCE AND TRANSPORT BIFURCATIONS: IMPLICATIONS FOR NEXT-GENERATION FUSION POWER PLANTS

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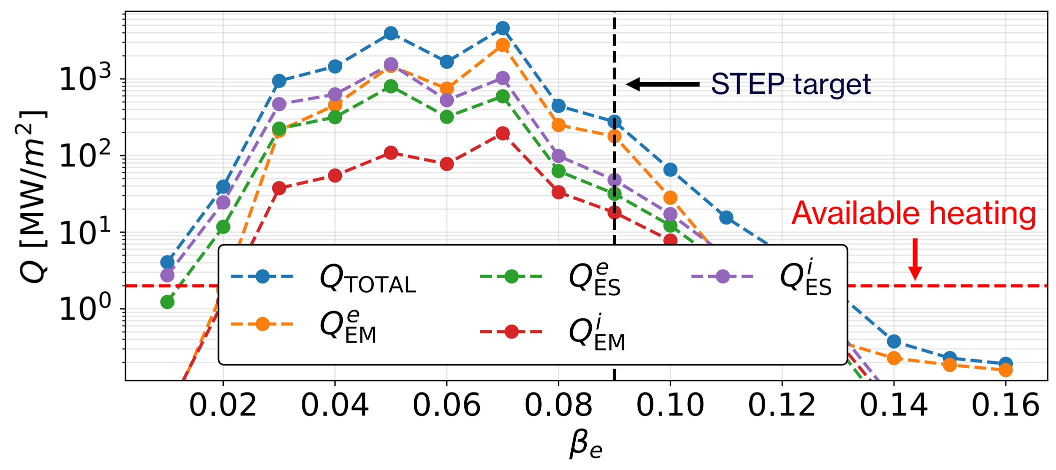
1. PRESSURE PROFILE SCALING

- **Turbulent heat fluxes** from **local gyrokinetic calculations** of an early **STEP-FTOP** [HM24] [ET24] [DK23] [MG24].
- $\beta[\equiv nT/(B^2/2\mu_0)]$ scan on reference mid-radius surface with $\beta \propto \beta'$ (i.e., consistent with scaling the pressure profile).



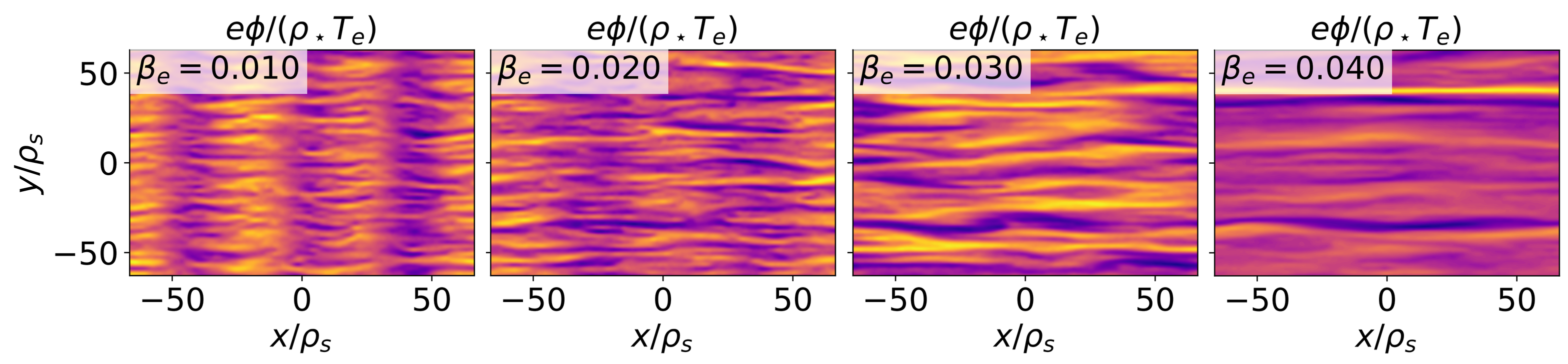
KEY QUESTIONS

1) What causes the transition to extreme heat fluxes? SEC 2-7
2) What causes the return to more modest fluxes and how might this be exploited in the design of next-generation fusion power plants? SEC 8
3) Can this theory be tested on modern-day high-performance experiments? SEC 9

- **No** (equilibrium) **flow shear.** Reasonable given no external momentum sources in STEP (electron heated).
- **Representative** of a more general trend. Nothing here is specific to STEP or spherical tokamaks [MJP08] [MJP13].

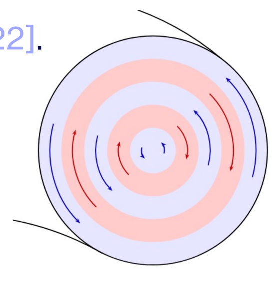
2. ELECTROMAGNETIC RUNAWAY AND NON-ZONAL TRANSITION

- How does the turbulence change as we cross the threshold?
- Transition from a state of **strong zonal flows** to a state dominated by **streamers. Non-zonal transition** [MJP08].



- Zonal flows and their radial shear are **critical for saturation** of electrostatic turbulence [PI20] [PI22].

$$v_{\mathrm{ZF}} \propto \frac{\mathrm{d}\phi_{\mathrm{ZONAL}}}{\mathrm{d}x}, \quad S = \frac{\mathrm{d}^2\phi_{\mathrm{ZONAL}}}{\mathrm{d}x^2}$$



- Physics of the non-zonal transition [FR22] [YZ24] [YZ25a] [YZ25b] [DK24] [DK25a].

4. THEORY AND NUMERICAL DIAGNOSTICS

CONJECTURE that the saturation, or otherwise, of electromagnetic gyrokinetic turbulence is determined by the ability of the system (or lack thereof) to form sufficiently strong zonal perturbations to shear apart any streamer structures that attempt to be established by the linear instabilities present.

- Starting from the standard gyrokinetic ordering we can derive an equation for the evolution of the zonal flow energy at long-wavelength

$$\frac{\mathrm{d}}{\mathrm{d}t}\int \mathrm{d}x \left(\frac{\mathrm{d}\phi_{\mathrm{ZONAL}}}{\mathrm{d}x}\right)^2 = -\nu_{\mathcal{R}} - \nu_{\mathcal{M}} - \nu_{\mathrm{lin}}$$

- Introduced turbulent zonal-flow viscosities

$$\nu_{\mathrm{lin}} \equiv -\int \mathrm{d}x\, S\,\Pi_{\mathrm{lin}}, \quad \nu_{\mathcal{R}} \equiv -\int \mathrm{d}x\, S\,\Pi_{\phi}, \quad \nu_{\mathcal{M}} \equiv -\int \mathrm{d}x\, S\,\Pi_{A_\parallel}, \quad S \equiv \partial_x^2\phi_{\mathrm{ZONAL}}$$

- Arising from torques that **DAMP** ($\nu > 0$) or **DRIVE** ($\nu < 0$) the zonal flow energy.

CONDITIONS FOR SATURATION VIA ZONAL FLOW SHEARING

- **ROBUST ZONAL SATURATION** when $\mathrm{E_{ZF}} \Uparrow$: i.e. $\nu < 0$.
- **FEEBLE ZONAL SATURATION** when $\mathrm{E_{ZF}} \Downarrow$: i.e. $\nu > 0$.
- **STEADY STATE** $\nu = 0$.

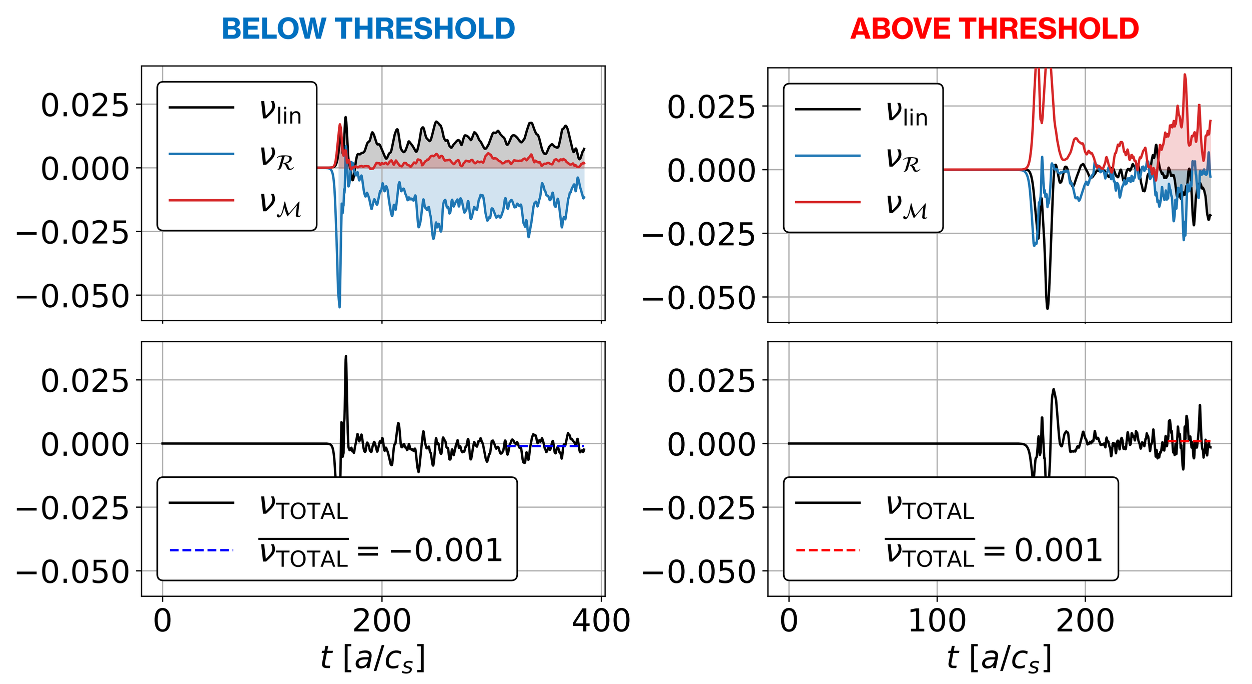
$$\Pi_{\phi} \equiv -\left\langle q_s \int \mathrm{d}^3\boldsymbol{v} \left\langle \left(\frac{c}{B}\boldsymbol{b} \times \frac{\partial}{\partial \boldsymbol{R}_s}\langle\phi\rangle_{\boldsymbol{R}_s}\right)\cdot\nabla h_s \right\rangle_{\boldsymbol{r}} \right\rangle_{\psi},$$

$$\Pi_{A_\parallel} \equiv -\left\langle q_s \int \mathrm{d}^3\boldsymbol{v} \left\langle \left(\frac{c}{B}\boldsymbol{b} \times \frac{\partial}{\partial \boldsymbol{R}_s}\left\langle -\frac{v_\parallel A_\parallel}{c}\right\rangle_{\boldsymbol{R}_s}\right)\cdot\nabla h_s \right\rangle_{\boldsymbol{r}} \right\rangle_{\psi},$$

$$\Pi_{\delta B_\parallel} \equiv -\left\langle q_s \int \mathrm{d}^3\boldsymbol{v} \left\langle \left(\frac{c}{B}\boldsymbol{b} \times \frac{\partial}{\partial \boldsymbol{R}_s}\left\langle -\frac{\boldsymbol{v}_\perp \cdot \boldsymbol{A}_\perp}{c}\right\rangle_{\boldsymbol{R}_s}\right)\cdot\nabla h_s \right\rangle_{\boldsymbol{r}} \right\rangle_{\psi}.$$

5. TURBULENT VISCOSITIES IN SIMULATIONS

- Turbulent zonal flow viscosities calculated using STELLA [MB16].
- Non-zonal transition accompanied by change in sign of total viscosity [DK25a].



6. EXPENSIVE DIAGNOSTIC TO PREDICTIVE THRESHOLD

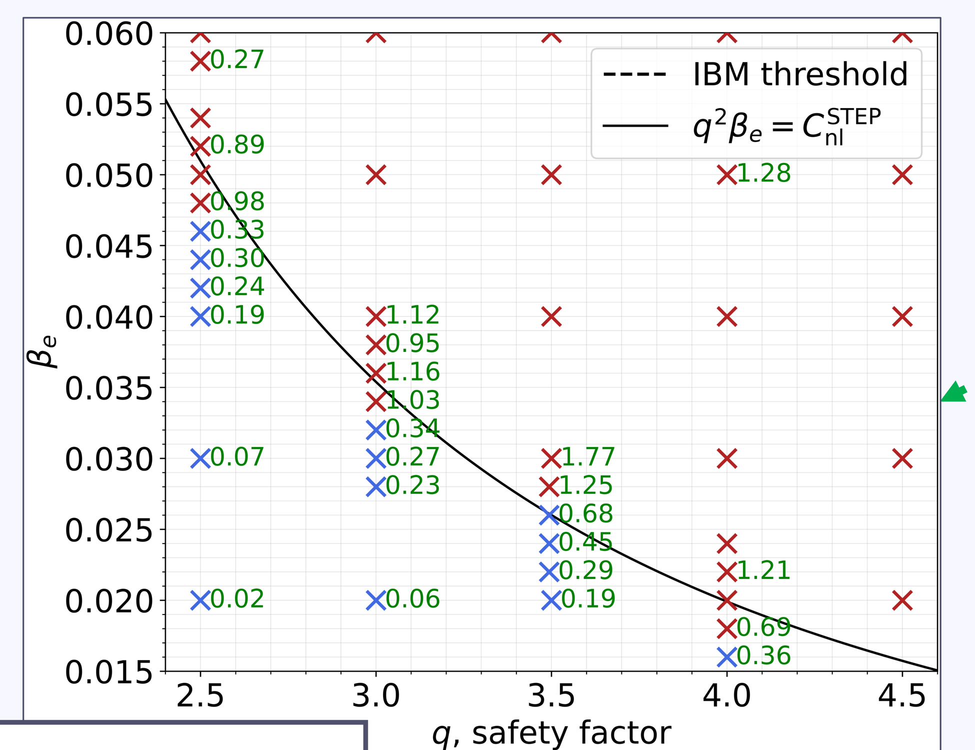
- We want to turn an **expensive diagnostic** into a **predictive tool**. Can we predict the threshold where the transition happens?

$$R \equiv \left|\frac{\nu_{\mathcal{M}}}{\nu_{\mathcal{R}}}\right| \simeq 1$$

- Intuitively expect **competition** between Reynolds stress and Maxwell stress to be controlled by a **critical-beta**.
- At **low-beta** the large Alfvén speed rapidly smooths magnetic perturbations, so magnetic-flutter stress is negligible, and saturation is set by electrostatic physics.
- As **beta is increased**, the **Alfvén speed decreases** until the Alfvén frequency matches the MHD interchange growth rate, defining a critical β where **electromagnetic effects become important.**

$$q^2\beta_e^{\mathrm{crit}} = C_{\mathrm{nl}}(\mathrm{geometry})$$

- Possible to recover the same result from QL scaling of R. Reasonably good approximation [YZ25b].
- **Predictive recipe for the transition!**
- Compute the ratio of viscosities in a low-β_e simulation and rescale.

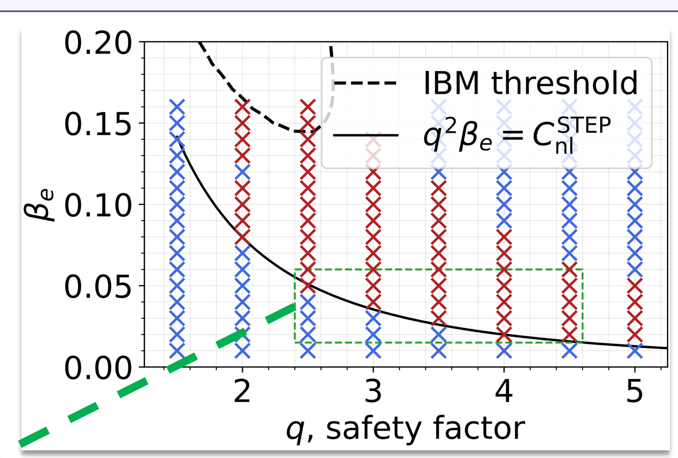


KEY

× Simulation does *not* saturate at $Q_{\mathrm{tot}} < 100$ MWm^{-2}

× Simulation *saturates* at $Q_{\mathrm{tot}} < 100$ MWm^{-2}

1.77 $R \equiv |\nu_{\mathcal{M}}/\nu_{\mathcal{R}}|$ (Maxwell/Reynolds viscosity ratio)



7. THRESHOLD ON β_{POL}?

- Threshold condition may be a constraint on β_{pol}

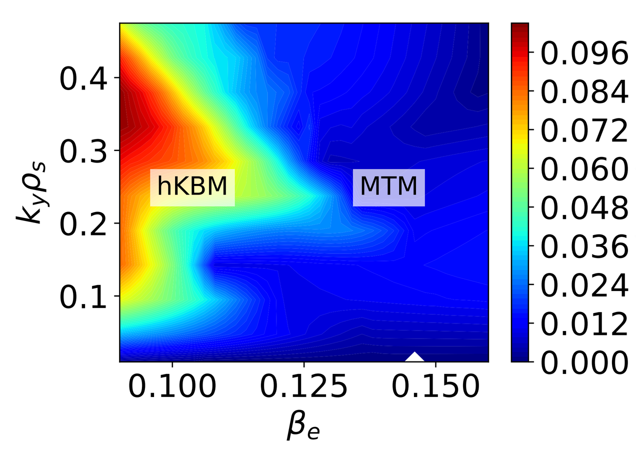
$$q^2\beta_e \sim \beta_{\mathrm{pol}}\left(\frac{a}{R}\right)^2$$

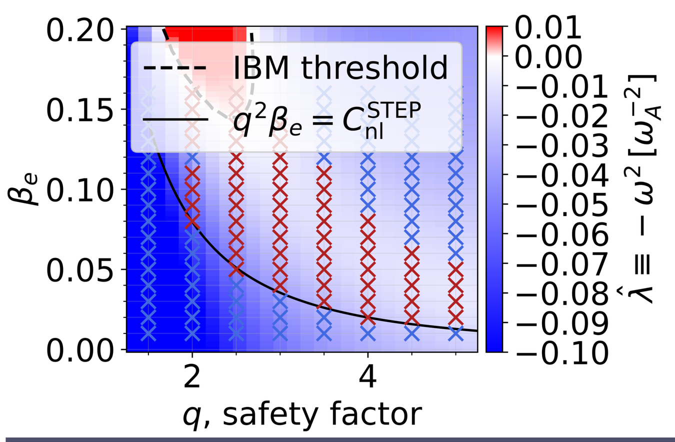
- Related to current continuity and Alfvén waves

$$\frac{\nabla\cdot\mathbf{J}_\perp}{\nabla\cdot\mathbf{J}_\parallel} \propto q^2\beta_e\left(\frac{R}{a}\right)^2$$

8. CONNECTION TO IDEAL BALLOONING MODES

- Second transition (return to modest fluxes) is **linear** and connected to second stability and ideal ballooning mode physics [RD22] [CB05] [DK25a].





KEY

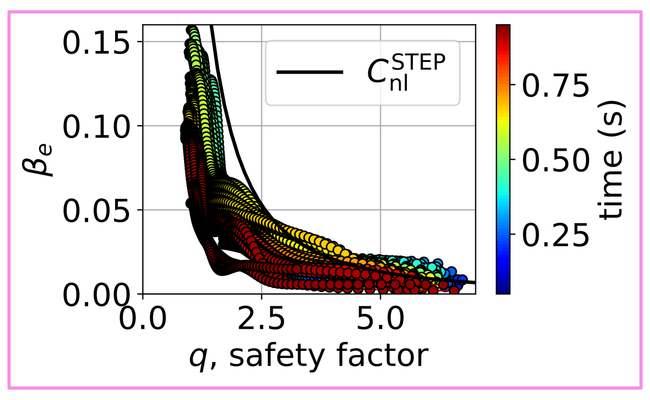
■ $\hat{\lambda} > 0 \longrightarrow$ IBM unstable $\longrightarrow$ growth rate of unstable IBM

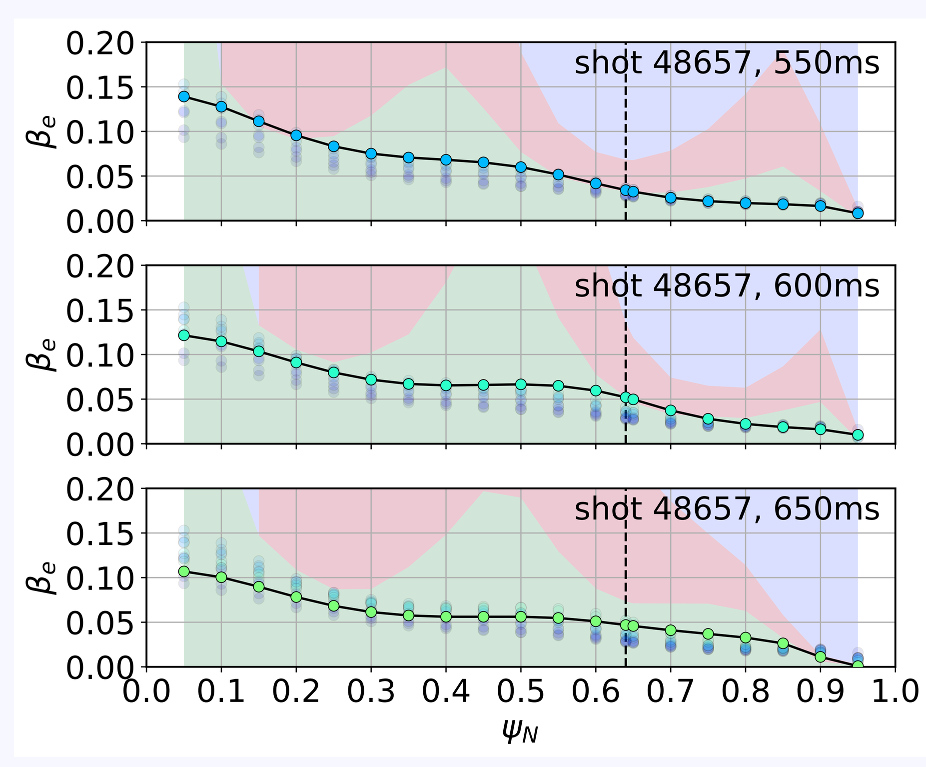
■ $\hat{\lambda} < 0 \longrightarrow$ IBM stable $\longrightarrow$ real frequency of shear Alfvén wave

- Insights can be used to guide scenario development.

9. TOWARDS EXPERIMENTAL VALIDATION ON MODERN-DAY EXPERIMENTS

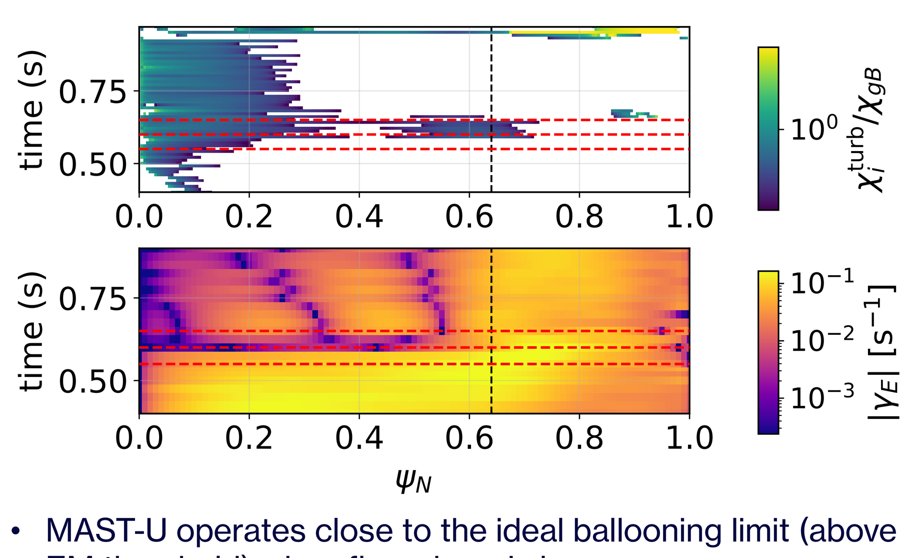
- How close have **modern-day experiments** been to the **threshold for the non-zonal transition?**
- MAST-U (Mega Ampere Spherical Tokamak Upgrade) is the UK national flagship facility for studying fusion plasmas.
- **Discharge #48657** two-beam, high-powered H-mode scenario achieving peak $\boldsymbol{\beta_N \sim 4}$ (one of the highest achieved on MAST-U) [BP25].
- **Ideal ballooning mode as proxy** for onset of large fluxes. SEC 8





KEY

• Experiment 1st stable IBM unstable 2nd stable



- MAST-U operates close to the ideal ballooning limit (above EM threshold) when flow shear is large.
- When the flow shear is lost the experimental performance degrades.
- MHD activity complicates analysis and interpretation.

10. CONCLUSIONS

- β_{pol} threshold triggers bifurcations to high-flux states (Maxwell stress vs Reynolds stress).
- Re-saturation possible (second-stability).
- Transport strongly initial-condition sensitive.
- Experiments can probe β_{pol} threshold but need γ_E. Loss of shear degrades confinement.
- STEP requires zonal flows, intrinsic rotation, or external drive to sustain shear and prevent electromagnetic runaway.

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