Multi-Scale Turbulent Interactions between Tearing Modes and Microturbulence in Magnetically Confined Plasmas

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Multi-Scale turbulent interactions

Multi-scale turbulence: nonlinear coupling of fluctuations over a range of scales, such as

- ion $\leftrightarrow$ electron gyroradius scales
- MHD $\leftrightarrow$ ion gyroradius scales
- MHD $\leftrightarrow$ electron gyroradius scales

Multi-scale interactions can influence

- saturation mechanisms
- driving gradients
- transport quantities

Consider multi-scale MHD $\leftrightarrow$ ion-scale interactions in reversed-field pinches (RFPs) and tokamaks

RFPs are susceptible to tearing modes (TMs)

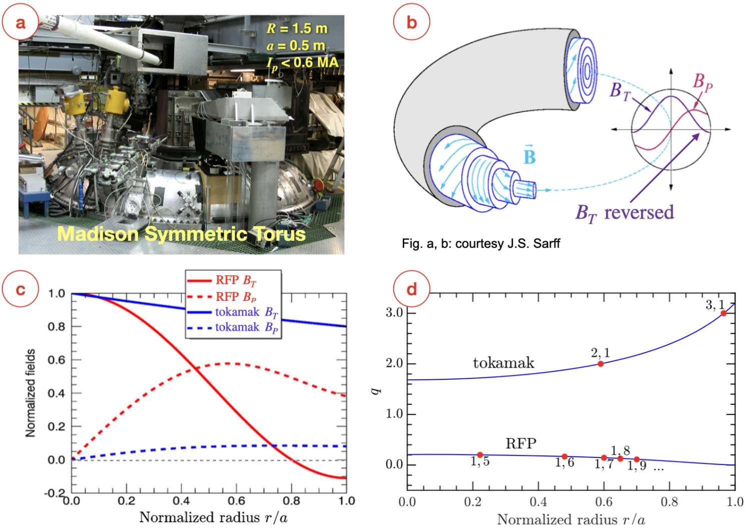
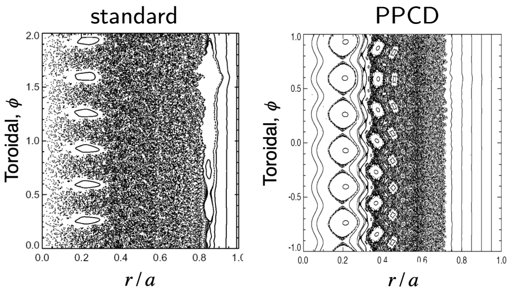


Fig. a, b: courtesy J.S. Sarff

L. Marrelli *et al.*, *Nucl. Fusion* **61**, 023001 (2021)

RFP confinement improved in a current-controlled discharge

- Standard RFPs:
  TMs → robust transport → low confinement

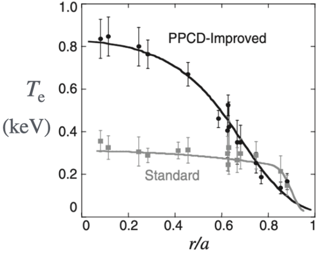


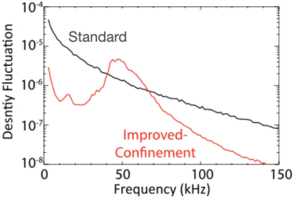
J.S. Sarff *et al.*, *Nucl. Fusion* **43**, 1684 (2003)

- Pulsed parallel current drive (PPCD): suppress TM activity → enhanced confinement

J.R. Duff *et al.*

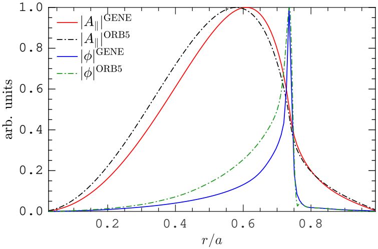
Phy. Plasmas **25**, 010701 (2018)

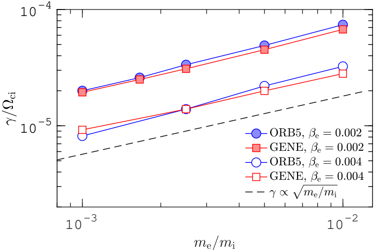




GENE implementation and benchmarking with ORB5

- Model dynamic global TMs and microturbulence $\rightarrow$ global gyrokinetics
- Use GENE with shifted Maxwellian distribution $\rightarrow$ current-gradient drive
- Compare with ORB5 using zero pressure-gradient

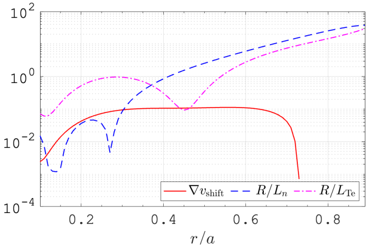


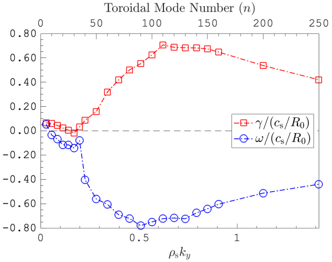


T. Jitsuk *et al.*, *Nucl. Fusion* **64**, 046005 (2024)

- Successful modeling of TMs in gyrokinetics

- Linear analyses of TMs of an RFP discharge



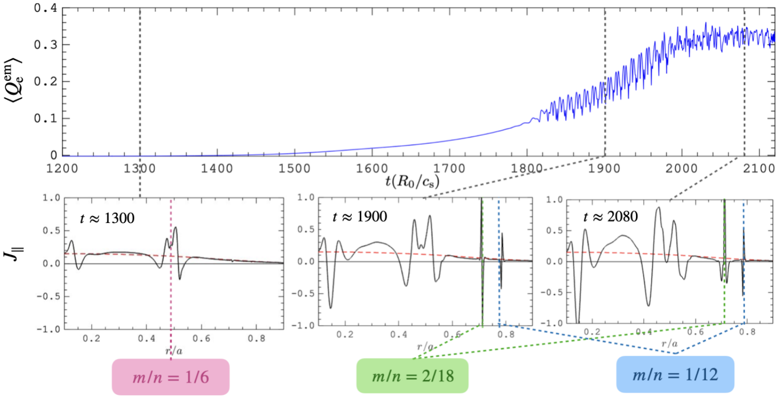


$$B_0 = 0.5\,\mathrm{T},\ m_\mathrm{i} = m_\mathrm{D},\ \beta_\mathrm{e} = 0.7\%,\ n_0 = 0.7\times10^{19}\,\mathrm{m}^{-3},\ T_0 = 0.6\,\mathrm{keV}$$

- Radial domain includes TMs and ∇P-driven microinstabilities
  - Low k_y: slow-growing core TMs
  - High k_y: fast-growing ∇n-TEM, close to edge

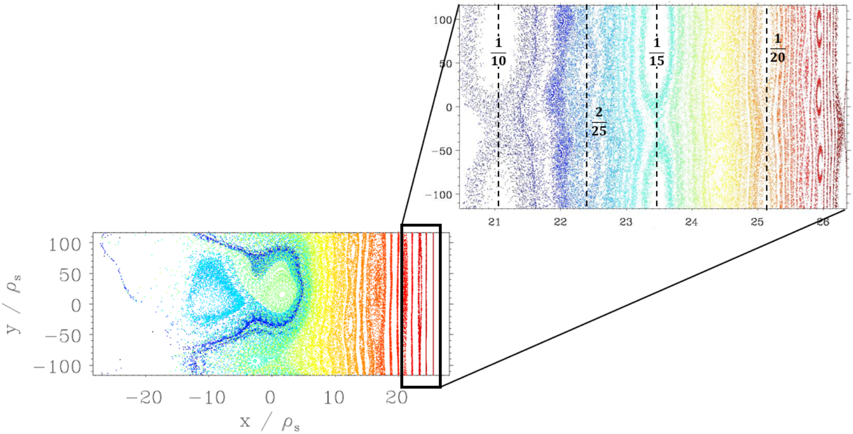
Nonlinear TM evolution

- Nonlinear coupling → saturation



- Core unstable modes excite smaller-scale stable modes close to edge

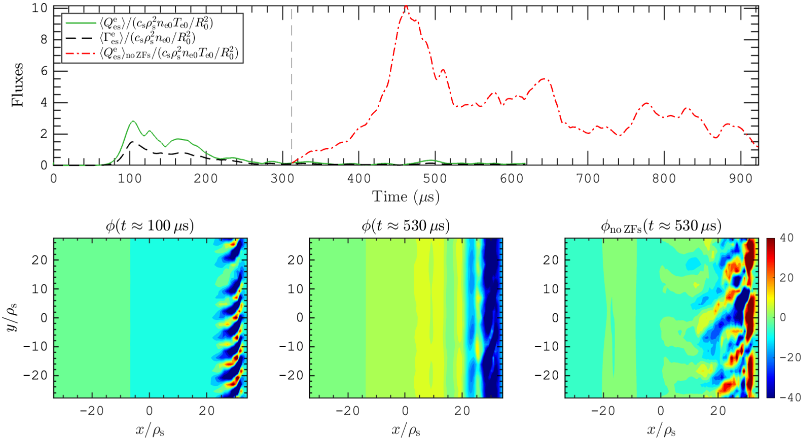
Diffusion of magnetic field lines due to nonlinear TMs

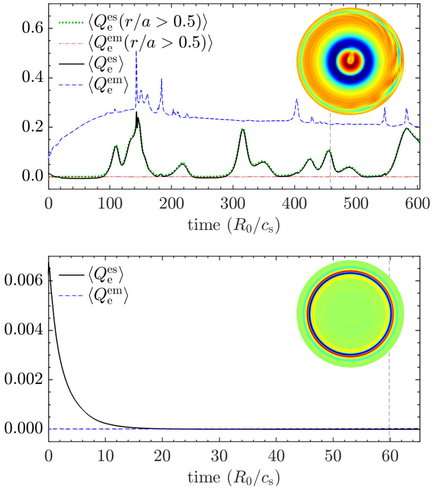


- Smaller-scale stable TMs get excited, form small islands near the edge
- Allows possible interactions with edge microturbulence

Microturbulence and saturation mechanism (no TMs)

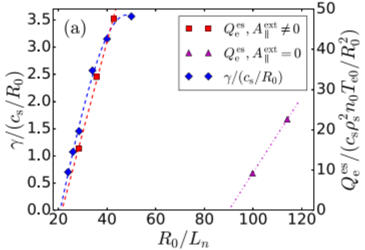
- Nonlinear TEM saturation by nonlinearly-generated ZFs
- At experimental gradients, fluxes are suppressed $\rightarrow$ Dimits regime





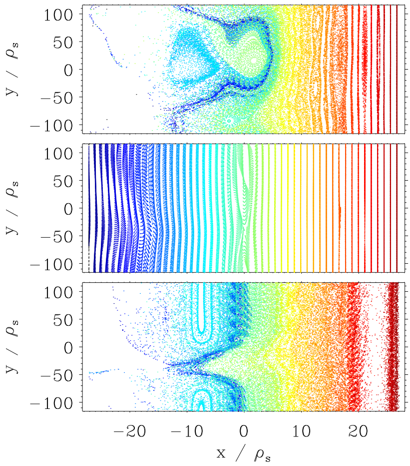
T. Jitsuk *et al.* (submitted)

- Multi-scale system saturates with higher average fluxes
- TMs suppress TEM-driven zonal flows
- System is moved close to marginality $\rightarrow$ flux bursts



Z.R. Williams *et al.*, *Phys. Plasmas* **24**, 122309 (2017)

Field-line diffusivity



TMs only

TEMs only

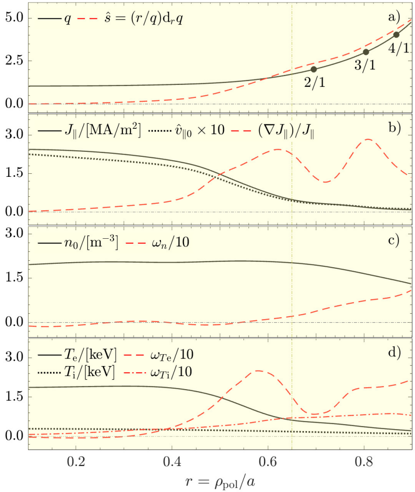
Multi-scale

- Nonlinear TMs → stochastic field lines → field line diffusion
- Stochasticity near edge → erosion of zonal flows

Summary: multi-scale interactions in RFPs

- Linear RFP TMs: self-consistently reproduced in global gyrokinetics
- Nonlinear TM saturation via mode coupling, smaller-scale stable TMs get excited
- Linear and nonlinear TEM simulations using shifted Maxwellian confirm earlier results of TEM in Dimits regime
- Self-consistent multi-scale simulations of global tearing, ∇n-TEM, and zonal flows
- Core-edge coupling excites edge stable TMs, affecting TEM-generated ZFs
- Multi-scale: ZFs get partially eroded. Heat flux increases
- Outlook: full-spectrum simulations, detailed analyses of triplet energy transfer

Take tokamak equilibrium profiles from TCV shot #59151



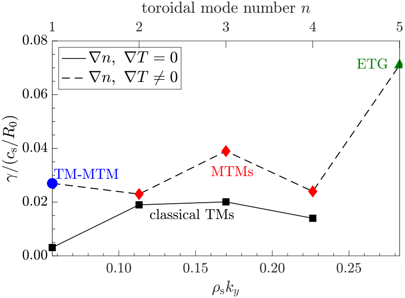
$$\omega_{Te} = R_0 \mathrm{d}_x \ln T_e > \omega_{Ti} \gg \omega_n$$

Plasma parameters

- $\beta_e = 8\pi n_e T_e / B_0^2 = 0.0061$
- $\rho^* = \rho_s / a = 0.014$
- $\varepsilon_a = a/R_0 = 0.317,\ R_0 = 0.88\,\mathrm{m}$
- $m_e/m_D = 2.73 \times 10^{-4}$
- $\nu_{ei} = 0.074\, c_s/R_0$
  with Landau coll. op.
- $Z_{eff} = 1$
- $J_\parallel = J_{\parallel e}$
- $q_0(r_a = 0) > 1$

Linear spectrum

- $*$ n: toroidal mode number, $k_y = nq_s/r_s$
- $*$ negative ω: electron direction

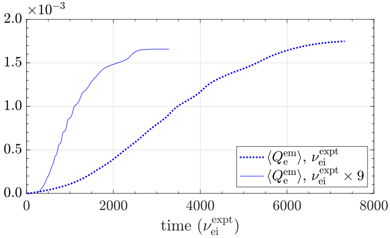


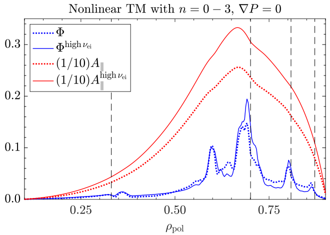
n	$\nabla P = 0$	$\nabla J_{\parallel 0} = 0$	all gradients
1	TM	MTM	TM-MTM
2-4	TM	MTM	MTM
≥5	stable	ETG	ETG

- Without pressure gradients $n = 1-4$: collisionless TMs, $n \geq 5$: stable
- Without current gradients $n = 1-4$: MTMs, $n \geq 5$: ETGs
- With all gradients, $n = 1$ shows signatures of both TM and MTM: hybrid TM-MTM, $n = 2-4$ are MTMs, and $n \geq 5$ low-k_y ETGs

Nonlinear TM only (with $\nabla P = 0$)

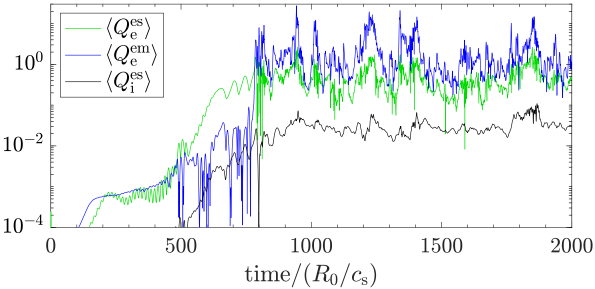
$\langle Q_e^{em} \rangle$: proxy of nonlinear tearing evolution (ETG=electrostatic)





- Well-developed TMs serve as initial cond. for multi-scale simulations
- Experimentally, $Z_{\mathrm{eff}} \sim 3 \Rightarrow \nu_{ei} = 9\times$
- $3\times$ faster saturation at higher collisionality
- Dominated by 2/1 structure

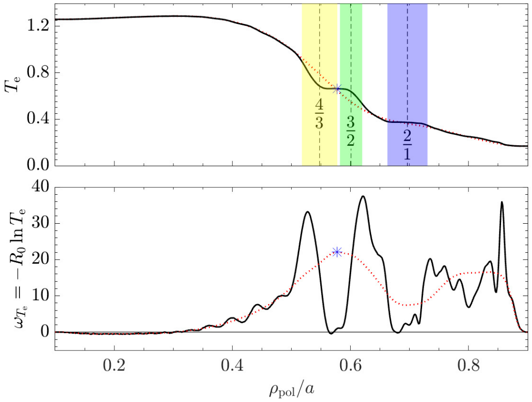
Nonlinear TM-MTM only (with $\nabla P,\ n = 0-3$)



$$\langle Q_e^{em} \rangle = 2.21$$
$$\langle Q_e^{es} \rangle = 0.48$$
$$\langle Q_i^{es} \rangle = 0.05$$

- Nonlinear spectrum shows active $n = 2, 3$ MTM
- $n = 1$ also contributes to electromagnetic heat flux Q_e^{em}

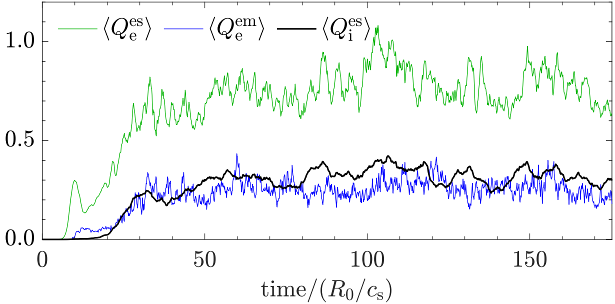
Flattening of T_e-profile



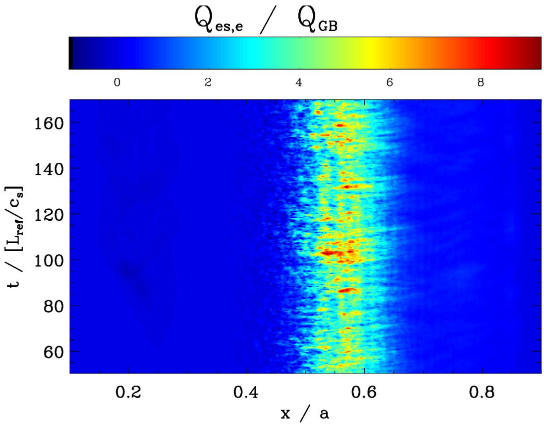
- TM-MTM $\Rightarrow$ profile flattening $\Rightarrow$ corrugation
- Flattening of T_e $\rightarrow$ perturbed bootstrap current $\rightarrow$ NTM $\rightarrow$ higher Q_e^{em}
- Flattening of T_e $\rightarrow$ affects ETG behavior
- Blue star: maximum drive of localized ETGs

Nonlinear ETG only (with $J_{\parallel} = 0$)

Low k_y ETGs	$\langle Q_{\rm e}^{\rm es} \rangle_{50 \le t \le 170} = 0.78$
Subdominant MTMs	$\langle Q_{\rm e}^{\rm em} \rangle_{50 \le t \le 170} = 0.26$
Subdominant ITGs/ETGs	$\langle Q_{\rm i}^{\rm es} \rangle_{50 \le t \le 170} = 0.32$

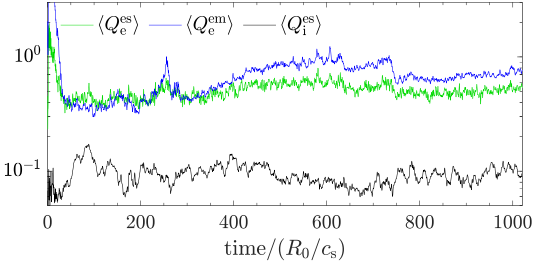


- Saturation: mode couplings to small scales
- Numerical elimination of ZFs $\rightarrow$ 10% increases in $\langle Q_{\rm e}^{\rm es} \rangle$ and $\langle Q_{\rm i}^{\rm es} \rangle$



- Localized $Q_{\mathrm{e}}^{\mathrm{es}}$ blobs driven by ETGs at $r \approx 0.56$, spreading down both sides of T_{e} peak $\Rightarrow$ turbulence spreading
- No significant local/global profile flattening

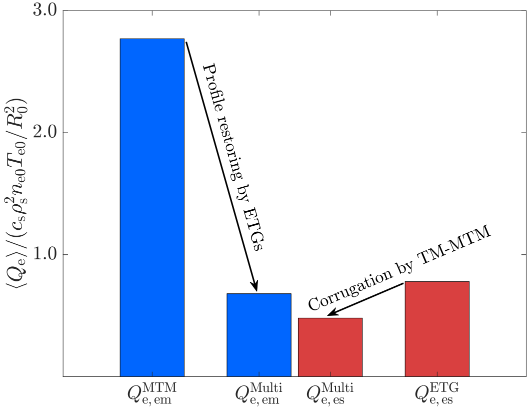
Multi-scale TM-MTM-ETG, adding ETGs into saturated TM-MTM



fluxes	ETG only	TM-MTM only	multi-scale
$\langle Q_e^{em} \rangle$	0.25 ± 0.05	2.21 ± 3.19	0.68 ± 0.03
$\langle Q_e^{es} \rangle$	0.78 ± 0.09	0.48 ± 0.40	0.48 ± 0.03
$\langle Q_i^{es} \rangle$	0.32 ± 0.04	0.05 ± 0.05	0.08 ± 0.01

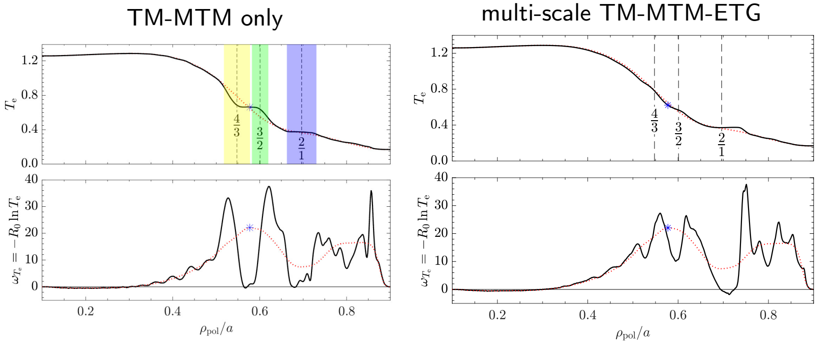
- Multi-scale $\rightarrow$ changes in flux levels
- Two possible factors: driving gradients and saturation mechanisms

Single-scale vs. Multi-scale Heat fluxes



- ETGs in multi-scale simulation removes the TM-induced corrugations $\rightarrow$ steepening profiles $\rightarrow$ reduces perturbed bootstrap current $\rightarrow$ less contribution from nonlinear TMs and NTM
- Profile corrugation $\rightarrow$ reduces local average gradients $\rightarrow$ reduced ETGs

ETGs restore the flattened (corrugated) T_e profile



- ETGs (micro-scale modes) smooth driving gradients ⇒ reduces EM heat flux from tearing modes
- TM-MTM flatten profile ⇒ reduces ES heat flux from ETGs

Summary: multi-scale interactions in a TCV discharge

- Linear simulations: TM, MTM and ETG
- Multi-scale fluxes are lower than those from single-scale simulations
- TM-MTM flatten T_{e} profile $\rightarrow$ lower average temperature gradient driving ETGs $\rightarrow$ lower $Q_{\mathrm{e}}^{\mathrm{es}}$
- ETGs steepen flattened T_{e} $\rightarrow$ less bootstrap current $\rightarrow$ reduced NTM activity $\rightarrow$ lower $Q_{\mathrm{e}}^{\mathrm{em}}$
- Ongoing: multi-scale effects on saturation mechanisms, measurement of actual levels of bootstrap currents and NTMs

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