Microtearing turbulence saturation via electron temperature flattening at low-order rational surfaces

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Abstract. Microtearing instability is one of the major sources of turbulent transport in high-$\beta$ tokamaks. These modes lead to very localized transport at low-order rational magnetic field lines, and we show that they can saturate by flattening the local temperature gradient. This saturation process depends crucially on the density of rational surfaces, and thus the system-size, and gives rise to a worse-than-gyro-Bohm transport scaling for system-sizes typical of existing tokamaks and simulations.
1. Introduction

Confinement in tokamaks is enabled by magnetic field lines that trace out nested toroidal surfaces. On rational surfaces, the field lines connect back to themselves after integer numbers of poloidal and toroidal turns; certain electromagnetic plasma instabilities, such as the microtearing modes of interest here, are localized near these rational surfaces, and break the nested topology by forming magnetic islands \cite{1, 2, 3}. Therefore, microtearing modes have a significant impact on confinement in high-$\beta$ islands \cite{4, 5, 6}. Understanding microtearing transport is crucial for designing large spherical tokamak reactors such as STEP \cite{7}. In general, gyro-Bohm transport scaling may be applied when the turbulence is primarily electrostatic and allows extrapolation of predictions and observations to reactor-scale, but microtearing turbulence is less well-understood - for instance, first-principles gyrokinetic simulations often fail to saturate. We report a microtearing saturation mechanism that clarifies certain computational difficulties and provides insight into system-size scaling.

Microtearing modes are characterized by radially-narrow parallel electron current layers that are driven resonantly at the rational surface and associated magnetic islands. While various branches of microtearing modes have been identified, including those driven by the time-dependent thermal force \cite{8} or by curvature \cite{9, 10}, and are present in various collisionality regimes \cite{11, 12, 13, 14, 15}, the electron temperature gradient remains a necessary condition for instability in all cases. Previous works have reported various microtearing saturation mechanisms: via energy transfer to long wavelengths \cite{2} or to short wavelengths \cite{16}, via cross-scale coupling with electron temperature gradient modes \cite{17}, by background shear flow \cite{5} or zonal fields \cite{18}, etc. However, despite these advances, predicting saturation levels remains a challenging task. We therefore investigate the most basic case of a microtearing-only turbulence with no cross-scale interactions, background flow shear etc., and demonstrate a saturation mechanism where the magnetic islands associated with the resonant current layers flatten the electron temperature gradient, thereby reducing the linear drive at the rational surfaces.

The radial width of the resonant region at the rational surfaces is generally of the order of few ion Larmor radii and is set by the parallel correlation length in linear theory which scales with the square root of the mass ratio between ions and electrons \cite{19}. Nonlinearly, the flux associated with these modes, although slightly broadened, is still localized at the rational surfaces. This is already known to be important in setting global flux levels in the pedestal \cite{20}. In the most extreme case, if turbulent diffusivity is sufficiently large and localized near low-order rational surfaces, the system will remove the local driving gradients, increase the gradients away from the low-order rational surfaces, and saturate in a zero-flux state. In this work, we find a less extreme version of this process occurring in a standard microtearing regime. We make a scaling argument to quantify this effect and suggest that future reactor-size devices subject to microtearing turbulence may perform worse than expected.

We proceed by demonstrating the strong electron-temperature-gradient flattening at low-order rationals in gyrokinetic simulations, and showing that this allows saturation by reducing mode drive. We test the impact of the various saturation mechanisms by suppressing zonal modulations and show the dominance of the temperature corrugations. Lastly, we consider system-size scaling and explain the origin of a non-gyro-Bohm scaling.

2. Simulation set-up.

Our numerical investigation uses flux-tube and global GENE gyrokinetic simulations \cite{21, 22}. These simulations use a field-aligned coordinate system \cite{23} where $x$ is the radial coordinate, $y$ the binormal coordinate and $z$ the parallel coordinate. Parallel velocity $v_{||}$ and magnetic moment $\mu$ are the velocity space coordinates. The parameters are inspired from Ref. \cite{24} where a microtearing dominated turbulence case has been identified. Concentric circular flux-surface geometry \cite{25} is considered with an inverse aspect ratio $\epsilon = 0.15$. An electron-ion mass ratio of $m_e/m_i = 1836$, temperature ratio of $T_i/\epsilon T_e = 1$ and normalized pressure of $\beta = 0.4\%$ are considered. To model collisions, the linearised Landau operator is used with an electron-ion collision frequency $v_{ei}/(v_{th,e}/R) = 0.02$, where $v_{th,s} = (T_{s,0}/m_s)^{1/2}$ is the thermal velocity of species $s$.

In the flux-tube simulations, a safety factor of $q_0 = 3$ and magnetic shear $\delta = 1$ are considered. The inverse of the density, ion temperature and electron temperature background gradient scale lengths, normalized to the major radius $R$, are $R/L_n = 1$, $R/L_{T_i} = 0$ and $R/L_{T_e} = 4.5$, respectively. The standard nonlinear flux-tube simulation considered in this work has a minimum binormal wavenumber of $k_{y,\text{min}} R_i = 0.02 \left( L_y = 314.2 R_i \right)$, radial width of $L_x = 150 R_i$ and grid resolutions given by $N_x \times N_y \times N_z \times N_{v_{||}} \times N_{\mu} = 192 \times 48 \times 16 \times 36 \times 8$. It is run until normalized time 2000 $R_i/v_{th,i}$ and saturates to give a gyro-Bohm normalized electron electromagnetic heat flux of $Q_{e,em}/Q_{\text{GB}} = 7.9$ (see Fig. 5).

In the corresponding global simulations, a
quadratic q-profile of the form \( q(x) = 1.5 + 6(x/a)^2 \) is considered. These simulations, centered at \( x_0 = 0.5a \), span a radial width of \( L_x = 0.3a \), where \( a \) is the tokamak minor radius. The radial background temperature and density profiles are of the form \( A_s = \exp[-\kappa_A s \tanh((x-x_0)/(a\Delta A_s))] \) where \( A_s \) represents the temperature or density of species \( s \); \( \kappa_n = 1, \kappa_T = 0, \kappa_e = 4.5 \) and \( \Delta \kappa = \Delta T_i = \Delta T_e = 0.3 \). The numerical resolutions for the simulation with \( \rho^\prime = \rho_0/a = 0.004 \) are \( N_x \times N_y \times N_z \times N_{y\parallel} \times N_{y\perp} = 128 \times 36 \times 16 \times 36 \times 16 \). Krook heat and particle sources (see Ref. [26] for details) are also employed with a source rate of \( \gamma_b = \gamma_p = 0.015v_B,i/R \), and with radial smoothing over 0.09\( a \) applied so these operators maintain the global-scale profiles, but do not damp finer-scale corrugations. The result is a radially smooth heating profile, and thus a radially smooth quasi-steady state heat flux, as would be expected in experiment, and consistent with local simulations. Doubling or halving this source rate is found to have little effect on the time-averaged density and temperature profiles, and the heat flux-levels change only by 20% at most. This is unlike the global simulations of microtearing of [20] that had heat fluxes that were sensitive to the source level, and had very radially peaked heat fluxes near low-order rationals.

3. \( T_e \) flattening at low-order rational surfaces.

Modes at a specific toroidal mode number \( k_y \) create magnetic islands around the resonantly driven current layers at their respective mode rational surfaces (MRSs). Note that the distance between MRSs for a given \( k_y \) is \( (\delta k_y) \). The MRS of all \( k_y \) radially align at the lowest-order mode rational surface (LMRS), where the magnetic islands can persist even in the turbulent phase. For the standard nonlinear flux-tube simulation, this can be seen at the LMRSs at \( x/\rho_i = -50, 0 \) and 50 in the Poincaré plot in Fig. 1. The Poincaré plot records the positions where each magnetic field line crosses the outboard midplane on successive poloidal turns [27, 28]. Each color denotes an individual field line. Away from the LMRSs, the MRSs of each \( k_y \) are radially misaligned and the overlapping magnetic islands give rise to ergodic regions.

As the electrons move swiftly along the parallel direction following the perturbed magnetic field associated with the islands at the low-order MRSs, they also undergo periodic radial excursions. This leads to a short-circuit of the perturbed \( T_e \) profile, leading to its flattening. This can be seen in Fig. 2(a), where the green curve denoting the time-averaged effective temperature gradient \( \omega^\text{eff}_{T_e} \) is plotted as a function of the radial coordinate for the standard nonlinear simulation. \( \omega^\text{eff}_{T_e} \) is defined as the sum of the contributions from the background temperature gradient and the time-averaged zonal perturbed temperature gradient, i.e.

\[
\omega^\text{eff}_{T_e} = -(dT_{0,e}/dx)/(T_{0,e}/R) - \langle \partial T_e/\partial x \rangle_{yz}/(T_{0,e}/R).
\]

The perturbed temperature is defined as \( T_e = (m_e/n_0) \int v^2 f_e \text{d}^3v - (T_{e,0}/n_0) \int f_e \text{d}^3v \), where \( f_e \) is the perturbed electron distribution function, and the flux-surface average, denoted by \( \langle \cdot \rangle_{yz} \), extracts the zonal part. Time-averaged \( \omega^\text{eff}_{T_e} \) (over the available turbulent steady-state) in global simulations too show similar flattening at low-order rational surfaces, as shown in Fig. 2(c).

One may also understand the temperature

\[
\omega^\text{eff}_{T_e} = \int (\partial T_e/\partial x)_{yz} \text{d}x/(T_{0,e}/R).
\]

Figure 1. Poincaré plot of magnetic field lines intersecting the outboard midplane for the standard nonlinear simulation at \( tv_{th,i} / R = 1750 \).

Figure 2. Time-averaged \( \omega^\text{eff}_{T_e} \) as a function of the radial coordinate. (a) Flux-tube simulation scan over \( k_{y,\text{min}} \rho_i \). Dashed lines denote position of LMRSs for the \( k_{y,\text{min}} \rho_i = 0.02 \) run. (b) Global simulation scan over \( \rho^\prime \). Dashed lines denote specific \( q_i = m/n \) rational surfaces. Solid black line denotes the background gradient.
flattening as a consequence of turbulence self-interaction - a mechanism where modes that are significantly extended along the field line 'bite their tails' at the rational surfaces \([29][30]\). In the case of microtearing modes, the parallel electron heat current density \(q_{e,\parallel}\) is given in Refs. \([30, 31]\) and can be summarized for convenience.

Taking the \(v_{\parallel}^2\) moment and the flux-surface average of the gyrokinetic Vlasov equation, one arrives at an equation for the time evolution of the zonal \(\delta T_{e,\parallel}\).

Considering only the electromagnetic (\(\propto A_{\parallel}\)) nonlinear term and ignoring the gyro-average over \(A_{\parallel}\), one obtains

\[
\frac{\partial (\delta T_{e,\parallel})}{\partial t} = -\frac{m_e}{n_0} \frac{e}{C} \frac{1}{\partial x} \sum_{k_y} k_y q_{e,\parallel,\perp,\parallel} A_{\parallel,\perp,\parallel}
\]

where the constant \(C = B_0/|\nabla x \times \nabla y|\). The linear structures of \(\delta T_{e,\parallel}\) and \(A_{\parallel,\perp,\parallel}\) for \(k_y \rho_i = 0.04\) are plotted with dashed lines in Fig. 3. The product of the two, proportional to a linear heat flux contribution, drives a zonal \(\delta T_{e,\parallel}\) that leads to the flattening of the parallel electron temperature at each MRS. The same process repeats for the perpendicular electron temperature.

However, note a significant broadening of the time-averaged \(\delta f_{e,\parallel,\perp,\parallel}\) in nonlinear simulation, also shown in Fig. 3 with a solid red line. A detailed description of this nonlinear broadening mechanism is given in Refs. \([30][31]\) and can be summarized as follows. The radially narrow linear eigenmode structures lead to extended tails in \(k_x\)-Fourier space and in ballooning representation (called 'giant tails' \([32]\)). However, in a nonlinear simulation, only the first few linearly coupled \(k_x\)-Fourier modes starting from \(k_x = 0\) of the eigenmode are able to retain their linear characteristics, i.e., their high amplitudes and relative phase differences with the \(k_x = 0\) mode, whereas the Fourier modes further away in the tail undergo a significant reduction in their amplitudes as a result of dominant nonlinear interactions, implying a broadening in real space. The width of the flattened electron temperature is therefore also broadened.

4. Microtearing stability with corrugated background gradients

Now, we consider the linear stability of microtearing modes when the effective electron temperature gradient \(\omega_{e,\text{eff}}\) has local flattenings at LMRSs; the profiles are plotted in Fig. 4(a). This is equivalent to the tertiary instability analysis of zonal flows \([33]\), except with a fixed temperature corrugation rather than a zonal flow pattern.

Since the resonant current drive leading to the microtearing instability is also localized at the MRS, we expect the growth rate of the \(k_y \rho_i = 0.02\) modes considered in these tertiary instability simulations to be set mostly by the effective gradient \(\omega_{e,\text{eff}}\) at the MRS, i.e., the temperature gradient away from MRS is of little significance. This is verified in Fig. 4(b) by the close match between the growth rate obtained from the tertiary instability simulations plotted as a function of \(\omega_{e,\text{eff}}\) (magenta) and the growth rate obtained from standard linear simulations plotted as a function of \(R/L_{Te}\) (blue). The figure also suggests that the time averaged \(\omega_{e,\text{eff}}\) at the LMRSs in standard nonlinear simulation is set by the critical gradient of the instability. For \(k_y > k_{y,\text{min}}\), the modes at LMRSs are made almost fully stable, those at MRSs away from the LMRSs, with lesser flattenings, are made less stable. In general, by reducing the local drive of microtearing modes at the rational surfaces, the system saturates to a state with lesser flux.

5. Removing zonal modulations

To further investigate the role of electron temperature flattening on saturation, a nonlinear simulation is run while eliminating any local modifications to the temperature gradient. This is achieved by redefining the zonal component of the electron distribution function as \(\langle \delta f_{e,\text{mod}} \rangle_{yz} = \langle \delta f_{e} \rangle_{yz} - K(x) [m_e v^2/(2 e T_{e,0} - 1.5)] \langle f_{M,e} \rangle_{yz}\), where \(f_{M,e}\) is the electron background distribution function - a homogeneous local Maxwellian. Note that \(K(x)\) is only a function of \(x\) and is set at each time-step such that \(\langle \delta T_{e} \rangle_{yz} = 0\), and therefore \(\omega_{e,\text{eff}} = R/L_{Te}\) throughout the simulation. The heat flux \(Q_{e,\text{emp}}/Q_{GB} = 28.1\) in this simulation is many times higher than
The domain length along a field line at a scan using global simulations. In these simulations, to study this in detail, we first perform a system-size and the corresponding finite system-size effect is crucial. Surfaces, the separation distance between them and temperature flattening happens primarily at rational modes 'biting their tails') including temperature flattening mechanism(s). Deleting the zonal electrostatic potential $\Phi$ or the zonal $A_k$ in simulations changes the flux levels at most by 12%, implying that zonal flows and fields do not play a significant role in saturation in the case considered. For similar parameters, Ref. [16] shows that the free-energy flow to short wavelengths increases by weakening the self-interaction process. For similar parameters, Ref. [16] shows that the free-energy flow to short wavelengths increases by weakening the self-interaction process.

**Figure 4.** (a) Magenta: Various fixed $\omega_{Te}^{\text{eff}}$ considered for the tertiary instability simulations. Solid green: Time-averaged $\omega_{Te}^{\text{eff}}$ in the standard nonlinear simulation. Dashed green: Position of the MRS. (b) Magenta: Growth rate in tertiary instability simulations as a function of $\omega_{Te}^{\text{eff}}$ MRS. Blue: Growth rate in linear simulations as a function of $R/L_{Te}$.

$Q_{e,\text{em}}/Q_{GB} = 7.9$ in the original standard nonlinear simulation, as shown in Fig. 4, confirming that electron temperature flattening indeed plays a significant role in saturation.

Another way to reduce the electron temperature flattening is by weakening the self-interaction process by increasing the parallel length $L_z = 2\pi N_{pol}$ of the simulation volume [29, 30, 34], where $N_{pol}$ indicates the number of times the flux-tube wraps around poloidally before connecting back to itself. Doubling $N_{pol}$ weakens the temperature flattening from $\sim 70\%$ to $\sim 20\%$ at LMRSs, leading to an increase in the flux level as shown in Fig. 4.

While these results confirm that the local flattening of electron temperature is crucial for correctly predicting the saturated turbulent state, the fact that these simulations, either with fully eliminated or weakened electron temperature flattenings, did saturate, indicates the presence of other, less dominant, saturation mechanism(s). Deleting the zonal electrostatic potential $\Phi$ or the zonal $A_k$ in simulations changes the flux levels at most by 12%, implying that zonal flows and fields do not play a significant role in saturation in the case considered. For similar parameters, Ref. [16] shows that the free-energy flow to short wavelengths could be another saturation mechanism.

6. Effect of system-size

Given that microtearing turbulence saturation via temperature flattening happens primarily at rational surfaces, the separation distance between them and the corresponding finite system-size effect is crucial. To study this in detail, we first perform a system-size scan using global simulations. In these simulations, to correctly capture the effects of self-interaction ($\sim$ modes 'biting their tails') including temperature flattening, the domain length along a field line at a rational surface must be correctly captured, and hence the minimum toroidal mode number $n_{\text{min}}$ is set to 1. In Fig. 5 orange markers denote $Q_{e,\text{em}}/Q_{GB}$ plotted as a function of $\rho^* = \rho/a$, where $a$ is the minor radius. For the two larger system sizes denoted by open squares, the fluxes saturate to a turbulent steady state for at least a duration of $400 R/v_{th,i}$, after which they undergo a 'runaway' similar to what has been reported in Ref. [20]. Although the origins of this runaway, which may be physical (as explained below) or numerical, are not yet clear, one can arrive at the general observation that the flux increases as system-size increases.

To further analyse this system-size dependence, we make use of flux-tube simulations. Given that the separation distance between the LMRSs is $1/(sk_{y,\text{min}})$, we can study this particular system-size effect through a scan in $k_{y,\text{min}}\rho_i = n_{\text{min}}(a/\rho_0)^2$, where $\rho_0$ is the radial position of the flux-tube. Note that by setting $N_{pol} = 1$ and by choosing $k_{y,\text{min}}\rho_i$ corresponding to the fundamental mode ($n_{\text{min}} = 1$) of the tokamak, the flux-tube framework offers the possibility to accurately capture the effect of self-interaction, while neglecting other finite $\rho^*$ effects such as profile shearing (see Ref. [30] for more details).

As $k_{y,\text{min}}$ is decreased, the radial density of regions with flattened electron temperature (see Fig. 2(a)), and hence weaker linear drive, at low-order MRSs decreases. Concurrently, flux increases, as shown by the blue asterisks in Fig. 4. That is, the temperature flattening mechanism becomes less effective in large systems. For the $k_{y,\text{min}}\rho_i = 0.02$ case, the $k_{y,\text{min}}\rho_i = 0.04$ mode contributing most to the flux has six MRSs, three of which at LMRSs experience $\sim 70\%$ flattening, and the other three at second-order MRSs experience $\sim 10\%$ flattening. Whereas for $k_{y,\text{min}}\rho_i = 0.04$, the $k_{y,\text{min}}\rho_i = 0.04$ mode sees a $\sim 70\%$ temperature flattening at every MRS, so mode stabilization is much more effective. When the electron temperature flattenings are eliminated, there is still some non-gyro-Bohm scaling (black markers in Fig. 4), but this is less consistent.

We suggest a crude model to understand the increase in flux with increasing system-size. In the turbulent steady state, when the electron heat flux $Q_e$ becomes radially constant, one defines the pointwise diffusivity via $\chi_e \equiv Q_e/(dT_e/dx)$ and the radial average

$$\langle dT_e \rangle_x = \langle Q_e \rangle_x = Q_e \frac{1}{\langle \chi_e \rangle_x}.$$

Boundary conditions impose zero average temperature fluctuation, thus $Q_e = dT_e/0/(1/\langle \chi_e \rangle_x^{-1})$, where $\langle 1/\chi_e \rangle_x^{-1}$ is the effective average diffusivity.

Microtearing modes are modelled to lead to regions of high diffusivity near each MRS, which
reinforce at LMRSs, resulting in the temperature-gradient corrugations seen in simulations.

The set of ‘relevant’ MRSs, i.e. associated with all the modes contributing significant flux, becomes more radially dense with decreasing \( k_{y,\text{min}} \), because the number of toroidal modes increases, and each mode has associated rationals separated by \( 1/sk_y \). This is illustrated in Fig \( 6(b) \). In Fig \( 6(a) \), \( k_y \)-spectra of the electron electromagnetic heat flux for the flux-tube simulations are plotted for the three considered values of \( k_{y,\text{min}} \). \( Q_{e,\text{em},k_y} \) is defined such that the total flux \( Q_{e,\text{em}} = \sum k_y \hat{Q}_{e,\text{em},k_y} dk_y \), where \( dk_y = k_{y,\text{min}} \rho_i \). In Fig \( 6(b) \), the positions of all MRSs associated with \( k_y \rho_i \leq 0.1 \) (i.e. contributing significant flux) are marked for each of the three simulations, clearly indicating how the MRSs become radially dense with decreasing \( k_{y,\text{min}} \). The opposite is true for LMRSs (the MRSs common to all \( k_y \)s and separated by \( 1/sk_{y,\text{min}} \)), denoted by thicker markers in Fig \( 6(b) \), which become more spaced apart with decreasing \( k_{y,\text{min}} \).

As the harmonic mean of diffusivity sets flux levels, concentrating the diffusivity at widely-spaced MRSs (large \( k_{y,\text{min}} \), small system-size) leads to lower flux than distributing it more evenly at a larger number of closely-spaced MRSs (low \( k_{y,\text{min}} \), large system-size). In an extreme limit, microtearing creates infinite local diffusivity and completely flattens gradients near each MRS, but elsewhere the diffusivity is a small constant \( \chi_b \). The effective average diffusivity, crudely assuming no overlap between flattened regions, is \( \chi_b/(1 - WN) \), where \( W \) is the proportion of the radius flattened by each toroidal mode and \( N \) is the number of toroidal modes. This leads to a scaling \( Q_e \propto 1/(1 - w/\rho^*) \) with \( w \) a small parameter; note that the flux rises sharply at small \( \rho^* \). This is analogous to the avalanche transport arising when transport windows caused by fast-particle-driven modes overlap across much of the tokamak [35].

The width \( W \) of the high-transport region was assumed fixed in this simple picture, but actually may increase with higher flux, and the larger overlap may cause a runaway situation; this may be tied to failure to reach saturation in certain microtearing simulations.

Apart from system-size scaling, another possible consequence of electron temperature flattenings and magnetic islands at low-order rational surfaces is the potential to seed the growth of NTMs [36]. The possibility for microturbulence to excite NTMs via nonlinear coupling has been demonstrated in the past [37]. Furthermore, to experimentally verify our results, one may measure the electron temperature and look for flattenings near rational surfaces, similar to previous investigations of ITG turbulence [38]. One may also be able to measure low toroidal mode number magnetic perturbations associated with the microtearing islands in external magnetic coils; for instance, the radial magnetic perturbation associated with the islands is \( (dB_y/B_0)/(\rho_i/R) \simeq 0.14 \) in the standard nonlinear simulation.

7. Conclusions

In conclusion, the fast motion of electrons across the magnetic islands at the LMRSSs short-circuit the electron temperature, resulting in local electron temperature flattening, which then decreases the local...
linear drive of microtearing modes and allows lower saturated transport levels. The spacing and width of the low-confinement regions near low-order rationals are crucial, and this provides a pathway to understand microtearing saturation (or lack thereof); one direct consequence is that microtearing turbulent transport and its study are more important in larger future devices than previously thought.

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