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# Intrinsic momentum and current drive by almost-rational surfaces in tokamaks

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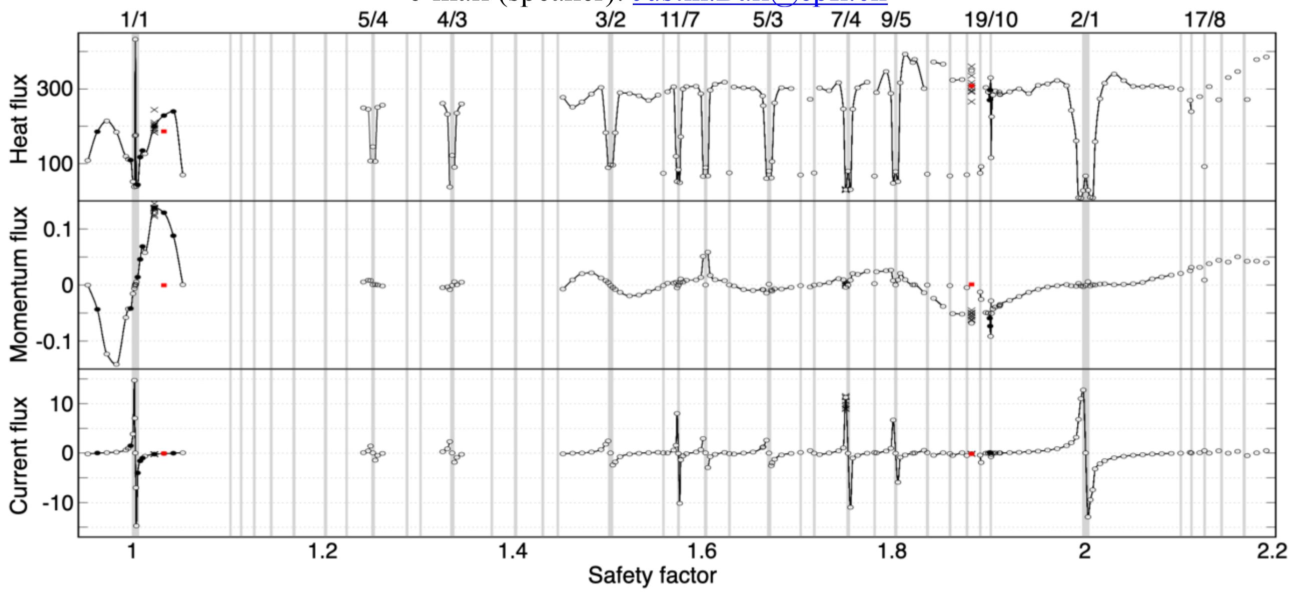


In tokamaks, toroidal plasma *rotation* is generally beneficial, stabilizing MHD modes as well as turbulence. At the same time, the toroidal plasma *current* is essential for stability but is difficult to sustain in steady state. A priori, turbulence can drive both: rotation from a turbulent ion momentum flux and current from a turbulent electron momentum flux. Unfortunately, strong turbulent momentum fluxes are not observed experimentally. Past work has explained this through the symmetry properties of the gyrokinetic equation[1,2], which is thought to accurately model core turbulence. Specifically, the gyrokinetic equations were shown to be invariant under the transformation[1,2]

$$f_s(x, y, z, v_{||}, \mu) \rightarrow -f_s(-x, y, -z, -v_{||}, \mu)$$

$$\phi(x, y, z) \rightarrow -\phi(-x, y, -z)$$

This means that any solution to the gyrokinetic equation can be used to generate a second solution, which has a momentum flux that cancels that of the first. Thus, the time-averaged turbulent momentum flux must be zero.

There was only one known mechanism that breaks this symmetry and enables an initially stationary plasma to spontaneously start to rotate: up-down asymmetry in the flux surfaces. This mechanism has been experimentally demonstrated[3] and numerically optimized[4], but strongly asymmetric flux surfaces are not practical for most existing tokamaks.

In this work, we demonstrate a second symmetry-breaking mechanism: almost rational values of the safety factor $q$ when the magnetic shear $\hat{s}$ is low. While previous works focused on the gyrokinetic *equations* themselves, we consider the *boundary conditions* and show that the parallel boundary condition[5] contains a term that breaks the symmetry. This term corresponds to how the field lines are shifted in the binormal direction as they pass through the parallel boundary condition. When $q$ is exactly rational, this term vanishes. However, even when it is finite, it is only important when turbulent eddies extend far enough along the field lines to perceive the boundary condition. This occurs when $\hat{s} \lesssim 0.1$, as low magnetic shear allows individual eddies to be long enough to wrap around the device and "bite their own tails"[6]. This is called "parallel turbulent self-interaction", and it is the fundamental mechanism responsible for this symmetry-breaking mechanism. This process is fundamental as it does not require radial inhomogeneity in the equilibrium, is present in slab geometry, and appears in the standard lowest-order gyrokinetics.

The plot above shows the turbulent fluxes calculated from ~200 nonlinear gyrokinetic flux tube simulations with $\hat{s} = 0$ and different values of $q$. We see that the heat flux is very sensitive to $q$, which is consistent with experimental measurements on the W7-AS stellarator[7]. In the middle panel, we numerically verify that almost-rational surfaces indeed drive a turbulent momentum flux. Around q=1, the momentum flux is significantly stronger than that produced by up-down asymmetry[4] and could explain experimental observations of rotation reversals[8]. Most interestingly, the current drive is substantial, appearing comparable to the plasma resistivity in the core of high-temperature devices. This could explain observations of anomalous current in KSTAR[9] and EAST[10].

**References**

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