Letter

Local dependence of ion temperature gradient on magnetic configuration, rotational shear and turbulent heat flux in MAST

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Abstract

Experimental data from the Mega Amp Spherical Tokamak (MAST) is used to show that the inverse gradient scale length of the ion temperature $R/L_{T_i}$ has its strongest local correlation with the rotational shear and the pitch angle of the magnetic field. Furthermore, $R/L_{T_i}$ is found to be inversely correlated with the gyro-Bohm-normalized local turbulent heat flux estimated from the density fluctuation level measured using a 2D beam emission spectroscopy diagnostic. These results can be explained in terms of the conjecture that the turbulent system adjusts to keep $R/L_{T_i}$ close to a certain critical value (marginal for the excitation of turbulence) determined by local equilibrium parameters (although not necessarily by linear stability).

Keywords: MAST, turbulence, magnetic configuration, rotational shear, turbulent transport, BES, critical ion temperature gradient

(Some figures may appear in colour only in the online journal)

1. Introduction

A key physics challenge posed by magnetically confined fusion plasmas is how their internal energy can be kept from being transported too fast from the core to the periphery. The problem is primarily turbulent transport, the temperature gradient between the edge and the core of a toroidal plasma driving turbulent fluctuations, which enhance the effective thermal diffusivity and relax the gradient. It is the ion-temperature gradient (ITG) that causes the most virulent instabilities (on ion Larmor scales) and is self-consistently limited by the resulting turbulence [1]. If we view the edge temperature as fixed by the aspects of tokamak physics that will not concern us here, the question is how to maximize the ITG. We therefore wish to inquire, experimentally, what this gradient depends on and how. Motivated by the fact (or conjecture) that the core turbulence is largely determined by the local (to a given flux surface) equilibrium conditions [2–4] and in turn acts back to adjust them locally, we ask what local parameters are most strongly correlated with the corresponding value of $R/L_{T_i}$, the inverse radial gradient scale length of the ion temperature ($L_{T_i}^{-1} = |\partial \ln T_i / \partial r|$) normalized to the major radius $R$ of the torus at the measurement location.

How universal are any such measured dependences for situations with different global conditions, e.g., different neutral-beam-injection (NBI) heating powers? It has
been recognized for some time that the turbulent fluid flux tends to increase very steeply with $R/L_{T_i}$ in ITG-dominated confinement, a phenomenon known as ‘stiff’ transport [5–8]. If (or when) the transport is stiff, any experimentally measured relationship between $R/L_{T_i}$ and other equilibrium parameters should be close to some critical manifold in the parameter space separating dominant turbulent transport from a non-turbulent state (the ‘zero-turbulence manifold’) [9]. This critical manifold would be independent of the power input and can be represented as a local parameter dependence of the critical gradient $R/L_{T_i} = f(q, \phi, i, T_i, \beta_i, \ldots)$, where $q$ is the safety factor (number of toroidal revolutions per poloidal revolution of the magnetic field around the torus on a given flux surface), $\phi$ is the inverse aspect ratio (i is the minor radius of the flux surface), $i = \delta \ln q/\delta \ln r$ the magnetic shear, $U_{\phi}^i = \partial U_{\phi}/\partial r$ the radial shear of the mean toroidal rotation velocity $U_{\phi}, L_n$ and $L_T$ the gradient scale lengths of the plasma density and electron temperature, $v_B$ the ion collision rate, $T_e/T_i$ the ion-to-electron temperature ratio and $\beta_i = 8\pi T_i/B^2$ the ion-to-magnetic pressure ratio. \ldots stand for other parameters, e.g., effective atomic number $Z_{\text{eff}}$, magnetic shape parameters, fast-ion pressure and its gradient. We choose to ignore them because either the variation in these parameters in our database is small, as is the case for $Z_{\text{eff}}$ (typically $\leq 1.5$ on MAST) and for the shape parameters of triangularity and elongation, or because they are measured or estimated reliably, as is the case for the fast-ion pressure profile. Note that $R/L_{T_i}$ need not be the same as the threshold for the existence of linearly unstable eigenmodes. Two known examples when it is not are the ‘Dimits upshift’ above the linear stability threshold [10–12] and the case of sufficiently large $U_{\phi}$ when the system is linearly stable but transient excitations [13, 14] lead to sustained subcritical turbulence [15, 16].

Recent theoretical [13, 14] and numerical [9] investigations suggest that $q_{\phi}$ and $U_{\phi}^i$ may be the most important of the parameters. It is well known, both from experiments [17] and theory [3, 18], that finite-Mach flows in a tokamak are predominantly toroidal (certainly when plasma is heated by tangential neutral beams, which produce a toroidal torque)\(^7\). Therefore, any radial shear in the toroidal flow results in sheared flow in both the perpendicular ($U_{\perp}^i = (B_{\parallel}/B)U_{\parallel}, B_{\parallel}$ is the poloidal field) and parallel ($U_{\parallel}^i = (B_{\parallel}/B)U_{\phi}^i, B_{\parallel}$ is the toroidal field) directions. While perpendicular fluid shear is known (theoretically [15, 16, 22–26] and experimentally [8, 27, 28]) to suppress turbulence, parallel fluid shear can drive it via the ‘perpendicular-velocity-gradient’ (PVG) instability [13, 14, 29]. The average ratio of these two shearing rates on a flux surface, $U_{\parallel}/U_{\perp}^i = B_{\parallel}/B_{\phi}$, can be approximated by $q/\phi$ and so the degree to which sheared equilibrium flow suppresses or drives turbulence should depend on this parameter. Indeed, numerical studies of ITG- and PVG-driven turbulence have shown that $R/L_{T_i}$, for any given $U_{\phi}^i$ increases with decreasing $q/\phi$ (at least for low $\delta$ [9]); at any given $q/\phi$, $R/L_{T_i}$ increases with increasing $U_{\phi}^i$ provided the latter is not too large [9, 15, 16],\(^8\)

\(^7\) We do not suggest causality between these parameters and $R/L_{T_i}$—all local equilibrium characteristics, including $R/L_{T_i}$, jointly adjust to form the critical manifold.\(^8\) Typically the mean poloidal flow in MAST is below 10 km s\(^{-1}\) [19], and any mean poloidal flow exceeding the diamagnetic velocity is damped by collisions [20, 21].

A comprehensive parameter scan of the dependence of $R/L_{T_i}$ on all other potentially important local quantities is probably unaffordable in the near future. Faster progress can be made experimentally. In this letter, we first establish, based on a relatively sizable dataset for MAST, what the most important parameters are: we show that the local value of $R/L_{T_i}$ is most strongly correlated inversely with the local $q/e$ and positively with the local rotational shear—consistently with the result obtained in [9].

We then obtain an experimental signature that the measured $R/L_{T_i}$ is correlated with the local characteristics of the ion-scale turbulence, directly measured by the 2D beam emission spectroscopy (BES) diagnostic [30]. We show that not only does a strong correlation between $R/L_{T_i}$ and an estimated turbulent heat flux exist but its (at the first glance, counterintuitive) inverse nature is consistent with $R/L_{T_i}$ staying close to the critical threshold $R/L_{T_i}$, and hence with stiff transport.

2. Equilibrium parameters

Our database consists of equilibrium quantities (and turbulence characteristics; see below) from 39 neutral-beam-heated L-mode discharges from the 2011 MAST experimental campaign. They had a double-null diverted (DND) magnetic configuration, no pellet injection and no applied resonant magnetic perturbations. Mean electron density $n_e$ and temperature $T_e$ were measured with the Thomson scattering system [31], mean impurity ion (C\(^{6+}\)) temperature $T_i$ and the toroidal flow velocity $U_{\phi}$ via charge exchange recombination spectroscopy (CXRS) [32] (assuming the impurity and bulk ions had negligible differences in their temperature and flow velocities [33]). The local magnetic pitch angle ($\theta_{B_i}/\theta_{B}^\perp$) was measured with the motional Stark effect (MSE) diagnostic [34]; pressure- and MSE-constrained EFIT equilibria [35] were used to obtain the field strength $B$. All parameters were determined over 5 ms intervals either by averaging if the diagnostic’s temporal resolution was smaller or by interpolation if it was larger than 5 ms. Only data points from a limited range of minor radii $0.6 < r/a < 0.7 (r/a$ is the edge of the plasma) were used, in order to minimize any correlations between various quantities due to their profile dependence alone (thus, we did not attempt to prove locality here; see, however, [4]). In total, 879 data points were available.

From this information, we constructed eight local dimensionless parameters, which, motivated by theoretical models and common sense, we deemed a priori the most important ones (we also give the range of variation of each parameter): $R/L_{T_i} \in [0.08, 20.3], q/e \in [4.0, 16.3], \delta \in [1.8, 6.0], \gamma_B \equiv U_{\perp}^i/T_a \equiv \pi r U_{\parallel}^i/v_{th,i} \in [0.005, 2.5], R/L_{\parallel} \in [0.1, 13.8], R/L_{T_i} \in [1.4, 22.7], v_{th,i} \equiv v_{th,i}T_a \in [0.004, 0.12], T_e/T_i \in [0.5, 1.5]$. The ion collision rate $v_{th,i}$ and the perpendicular velocity shear $U_{\perp}^i$ (used instead of $U_{\phi}^i$) were normalized, as in [4], to the ion parallel streaming time $\tau_{st} = \Lambda/v_{th,i}$, where $v_{th,i} = \sqrt{2T_i/m_i}$ and $\Lambda = \pi r B_{\parallel}/B_{\phi}$ is the connection length (the approximate distance along the field line from the outboard to the inboard side of the torus, expected to determine the parallel correlation scale of the turbulence [7]; if the flux surfaces had been circular, $\Lambda \approx \pi a R$). The local magnetic configuration is represented by $q/\phi$ and $\delta$. The choice
of \(q/\varepsilon\) was motivated by the physical considerations outlined in the introduction; since \(\varepsilon\) varied little in our database, we cannot distinguish any individual correlations of \(R/L_{T_i}\) with \(q\) and \(\varepsilon\). It is left for further study to determine whether other properties of the flux surfaces matter (e.g., Shafranov shift, triangularity, elongation, etc., which may affect the stiff-transport threshold [12, 36]). We have not included \(n, T_i, T_e\), which are not normalizable by any natural local quantities; note that \(R/L_{T_i}\) is found to have large correlation with \(T_i\) (cross-correlation coefficient of 0.56) within our database. This correlation might be explained by the dependence of collisionality on \(T_i\) which in turn controls the relative amplitude of the zonal component of the turbulence [4]. This is explained in more detail below. We also have excluded \(\beta_i = 8\pi n T_i/B^2\) because, in the absence of large variation of \(B\) in our dataset, \(\beta_i\) is simply the normalized ion pressure and, similarly to \(T_i\), has a large positive correlation with \(R/L_{T_i}\) (it remains to be investigated whether larger magnetic fluctuations at larger \(\beta_i\) are large enough to have an effect on turbulent transport [37–39]).

3. Correlation analysis

We perform a canonical correlation analysis (CCA) [40] with \(R/L_{T_i}\) treated as the dependent variable and the other seven parameters as independent ones. This amounts to finding the maximum correlations between \(\ln(R/L_{T_i})\) and linear combinations of logarithms of \(1, 2, 3, \ldots, 7\) other parameters, leading to an effective statistical dependence

\[
\frac{R}{L_{T_i}} = \left(\frac{q}{\varepsilon}\right)^{\alpha_1} \tilde{y}_E^{\alpha_2} \nu_{4i}^{\alpha_3} \left(\frac{R}{L_{T_i}}\right)^{\alpha_4} \tilde{z}^{\alpha_5} \left(\frac{R}{L_e}\right)^{\alpha_6} \left(\frac{T_i}{T_e}\right)^{\alpha_7}.
\]

(1)

This is of course not valid if the dependence of \(R/L_{T_i}\) on any of the parameters is non-monotonic. A non-monotonic dependence on \(\tilde{y}_E\) is, in fact, expected, with \(R/L_{T_i}\) first increasing, then decreasing at larger values of \(\tilde{y}_E\) due to increased transport from the P VG-driven turbulence [9, 15, 16]. However, \(\tilde{y}_E\) in our database does not extend to sufficiently high values for such a dependence to be observed (see figure 1).

In table 1, the canonical correlation (the correlation coefficient between the logarithms of \(R/L_{T_i}\) and the right-hand of equation (1)) is given together with the corresponding exponents \(\alpha_1, \ldots, \alpha_7\). We start by calculating the individual correlations of \(R/L_{T_i}\) with each of the seven parameters and then include pairs, triplets, etc., only if the correlation improves. The strongest individual correlations of \(R/L_{T_i}\) are with \(q/\varepsilon\) (64%) and \(\tilde{y}_E\) (49%). The overall fit is measurably improved (70%) if both are included. Including further parameters does not make a significant difference; the third strongest (although not very strong) dependence is on \(\nu_{4i}\). The results from such a multi-variable scaling can be misleading if significant cross-correlations exist between the parameters formally treated as independent. The cross-correlations between all the parameters involved (including \(R/L_{T_i}\)) are shown in table 2. We see that there exist potentially meaningful correlations between \(q/\varepsilon\), \(\tilde{y}_E\), \(\nu_{4i}\) and \(\tilde{z}\), but they do not change the basic conclusion from the CCA results that much of the \(R/L_{T_i}\) variation can be accounted for by its dependence on \(q/\varepsilon\) and \(\tilde{y}_E\).

The dependence of \(R/L_{T_i}\) on \(q/\varepsilon\) and \(\tilde{y}_E\) is shown in figure 1. \(R/L_{T_i}\) generally increases with decreasing \(q/\varepsilon\) and increasing \(\tilde{y}_E\), broadly consistent with the intuitive physical reasoning explained in the Introduction and the numerical study of [9].

The conclusion is that, at least on a rough qualitative level, it is sensible to consider \(R/L_{T_i}\) to be a function primarily of \(q/\varepsilon\) and \(\tilde{y}_E\). Since the \(q\) profile tends to change more slowly than other equilibrium profiles [11], one may think of a critical curve \(R/L_{T_i}(\tilde{y}_E)\) [42] parametrized by \(q/\varepsilon\) [9], the latter quantity containing the essential information about the magnetic cage confining the plasma.

4. Collisionality dependence

Even though the dependence of \(R/L_{T_i}\) on \(\nu_{4i}\) is weaker than on \(q/\varepsilon\) and \(\tilde{y}_E\), a discernible inverse correlation between \(R/L_{T_i}\) and \(\nu_{4i}\) might be expected because zonal flows, believed to suppress turbulence [11, 43], are more strongly damped at higher ion collisionality [44–46]. To isolate this dependence, we selected data points for approximately fixed \(\tilde{y}_E\in [0.7, 0.8]\) and \(q/\varepsilon\in [5, 6]\) (the largest number of data points could be found within these narrow ranges, with no measurable correlation between \(R/L_{T_i}\) and \(q/\varepsilon\) or \(\tilde{y}_E\)). The resulting figure 2 confirms a degree of inverse correlation between \(R/L_{T_i}\) and \(\nu_{4i}\).

9 One of the discharges within our database has been analysed via TRANSP analysis [41], and it shows that the power flowing from the electrons to the ions is about 10% of the total ion heating power, which is consistent with the small degree of correlation between \(R/L_{T_i}\) and \(R/L_{T_e}\).

10 The broad scatter in figure 1(a) suggests that the correlation between \(q/\varepsilon\) and \(\tilde{y}_E\) is weak; the lack of higher values of \(\tilde{y}_E\) at large \(q/\varepsilon\) is due to the fact that the flow shear is weak at earlier times in the discharges, when the central value of \(q\) is high.

11 The functional dependence \(q(\psi)\), where \(\psi\) is the flux-surface label, only changes on the resistive timescale of the mean magnetic field.
turbulent 

and the BES measurements in MAST [4] suggest that the ratio of Q turbulence through a given flux surface can be estimated as $Q_{\text{turb}} \sim nT_\iota \delta T_i / \rho_i$, where the effective turbulent diffusivity $\chi_i \sim \delta u^2 \tau_i$, $\delta u \sim (c/B)\phi/\ell_y$ is the (radial) fluctuating $E \times B$ velocity, $\tau_i$ its correlation time, $\ell_y$ its poloidal correlation scale and $\psi$ the fluctuating electrostatic potential; using the approximation of Boltzmann electrons, $e\psi / T_e \approx \delta n/n \rho_i$ is the (radial) fluctuating ion temperature. This would indeed be the case if $\delta n/n \approx \rho_i$ (the drift time; $\rho_i$ is the ion Larmor radius). Collecting all this together, we estimate the gyro-Bohm-normalized turbulent heat flux $Q_{\text{turb}} = \rho_i \ell_y / T_e \left( \frac{R}{n} \right)^2 \left( \frac{R}{T_e} \right)^2 \delta n / n \tau_i$.

where $Q_{\text{turb}} = nT_\iota \delta T_i / \rho_i ^2 / R^2$.

Since ion-scale density fluctuations are measured directly by the BES, $Q_{\text{turb}}$ can be obtained independently of any transport reconstruction models such as TRANSP [41]. The method of determining $\delta n/n$ and $\ell_y$ using the BES system on MAST (8 radial $\times$ 4 vertical channels with spatial resolution $\approx 2$ cm [30]) is explained in [4]. This is done from the covariance and correlation functions of the photon intensity fluctuations, averaged over the same 5 ms intervals for the same 39 discharges as the equilibrium quantities studied above, although not in all intervals there was good BES data. Restricted to the radial range $0.6 < r/a < 0.7$, there were 95 available data points for $\delta n/n$ and $\ell_y$.

### 6. Inverse correlation between $R/L_T$ and $\tilde{Q}_{\text{turb}}$

It is shown in figure 3(a) ($\tilde{Q}_{\text{turb}}$ versus $q/e$ and $\tilde{\gamma}_E$; see figure 1), figure 3(b) ($\delta n/n$ versus $R/L_T$) and figure 3(c) ($\tilde{Q}_{\text{turb}}$ versus $R/L_T$) that smaller $\tilde{Q}_{\text{turb}}$ and $\delta n/n$ are observed where $R/L_T$ is large and vice versa. This is perhaps counterintuitive as one might expect that the larger $R/L_T$, the more turbulent the plasma and so the larger the heat flux. This would indeed have been the case had $R/L_T$ been fixed, as in local flux-tube simulations, where $\tilde{Q}_{\text{turb}}$ does increase with $R/L_T$ [7, 10]. In contrast, in the real plasma, a certain amount of power flows through a flux surface and, if transport is stiff, the temperature gradient and other equilibrium quantities adjust to stay close to the critical manifold $R/L_{\text{T}}(\tilde{\gamma}_E, q/e)$. In plasmas with both power and momentum injection, there is a regime with $R/L_T$ close to $R/L_{\text{T}}$, where the turbulent and

| Canonical | $q/e$ | $\tilde{\gamma}_E$ | $v_{nu}$ | $R/L_{Ti}$ | $\delta$ | $R/L_{Te}$ | $T_i/T_e$ | $\alpha_L$ | $\alpha_e$ | $\alpha_s$ | $\alpha_g$ | $\alpha_{q/\varepsilon}$ | $\alpha_{\gamma E}$ | $\alpha_{R/L_T}$ |
|------------|-------|-------------------|---------|-------------|---------|-------------|----------|-----------|---------|---------|---------|-------------|-----------------|----------------|
| 4%         | 0     | 0                 | 0       | 0           | 0       | 0           | 0        | -3.29     |         |         |         | 0            | 0                | 0                |
| 6%         | 0     | 0                 | 0       | 0           | 0       | -1.93       | 0        | 0         | 0       | 0       | 0       | 0            | 0                | 0                |
| 17%        | 0     | 0                 | 0       | 0           | 0       | -3.58       | 0        | 0         | 0       | 0       | 0       | 0            | 0                | 0                |
| 39%        | 0     | 0                 | 0       | -0.99       | 0       | 0           | 0        | 0         | 0       | 0       | 0       | 0            | 0                | 0                |
| 49%        | 0     | 0                 | 0       | 0.94        | 0       | 0           | 0        | 0         | 0       | 0       | 0       | 0            | 0                | 0                |
| 64%        | -1.69 | 0                 | -0.27   | 0           | 0       | 0           | 0        | 0         | 0       | 0       | 0       | 0            | 0                | 0                |
| 67%        | -1.47 | 0                 | -0.27   | 0           | 0       | 0           | 0        | 0         | 0       | 0       | 0       | 0            | 0                | 0                |
| 70%        | -1.30 | 0.39              | 0       | 0           | 0       | 0           | 0        | 0         | 0       | 0       | 0       | 0            | 0                | 0                |
| 71%        | -1.17 | 0.36              | -0.20   | 0           | 0       | 0           | 0        | 0         | 0       | 0       | 0       | 0            | 0                | 0                |
| 72%        | -1.18 | 0.34              | -0.18   | -0.23       | 0.15    | 0.02        | -0.38    | 0         | 0       | 0       | 0       | 0            | 0                | 0                |

Table 1. Results of CCA assuming equation (1); 0’s mean that the CCA was performed without including the corresponding parameter.
The turbulent Prandtl number is order unity \[15, 25, 49\] while transport, while in the turbulent regime, they are comparable. The momentum transport is much less efficient than the heat transport, which is relatively easier and less expensive than increasing the shearing rate in tokamak operations\[14\].

![Figure 3](image.png)

Figure 3. (a) \(\tilde{q}_{\text{turb}}\) calculated from BES data according to equation (2) versus \(q/\varepsilon\) and \(\tilde{\gamma}_E\) (see figure 1); (b) \(\delta n/n\) versus \(R/L_T\); (c) \(\tilde{q}_{\text{turb}}\) versus \(R/L_T\) (see figure 4(b) of \[16\]); (d) \(\tilde{Q}_{\text{turb}}\) versus \(R/L_T\) and \(\tilde{\gamma}_E\) for a fixed range of \(q/\varepsilon\) in \[9, 11\], indicated by the dotted horizontal lines in (a); open squares are data from figure 1(a) for which BES measurements were not available (see figure 3(b) of \[42\]).

The correlation between \(q/\varepsilon\) and \(\tilde{\gamma}_E\) is also observed in JET, suggesting that the inverse correlation between \(R/L_T\) and \(q/\varepsilon\) is perhaps ubiquitous, as would be the case if \(R/L_T\) were generally fixed at some locally determined critical value \[9\]. Furthermore, we have found an inverse correlation between \(R/L_T\) and the gyro-Bohm-normalized turbulent heat flux (estimated via direct measurements of density fluctuations) and argued that this is consistent with \(R/L_T\) remaining close to a critical manifold \(R/L_T(q/\varepsilon, \tilde{\gamma}_E)\) separating the turbulent and non-turbulent regimes \[16, 42\] (stiff transport). It is thus plausible that we have essentially produced this critical manifold for the MAST discharges we investigated.

Practically, our results suggest that \(R/L_T\) can be increased by lowering the \(q/\varepsilon\), which is relatively easier and less expensive than increasing the shear rate in tokamak operations\[14\].

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7. Conclusion

We have found that the normalized inverse ion-temperature-gradient scale length \(R/L_T\) has its strongest local correlation with \(q/\varepsilon\) and the shear in the equilibrium toroidal flow: \(R/L_T\) increases with increasing shear, which is a well-known effect, and with decreasing \(q/\varepsilon\), which corresponds to increasing ratio of the perpendicular to parallel shearing rates. A similar dependence of \(R/L_T(q/\varepsilon, \tilde{\gamma}_E)\) is also observed in JET, suggesting that the inverse correlation between \(R/L_T\) and \(q/\varepsilon\) is perhaps ubiquitous, as would be the case if \(R/L_T\) were generally fixed at some locally determined critical value \[9\]. Furthermore, we have found an inverse correlation between \(R/L_T\) and the gyro-Bohm-normalized turbulent heat flux (estimated via direct measurements of density fluctuations) and argued that this is consistent with \(R/L_T\) remaining close to a critical manifold \(R/L_T(q/\varepsilon, \tilde{\gamma}_E)\) separating the turbulent and non-turbulent regimes \[16, 42\] (stiff transport). It is thus plausible that we have essentially produced this critical manifold for the MAST discharges we investigated. Practically, our results suggest that \(R/L_T\) can be increased by lowering the \(q/\varepsilon\), which is relatively easier and less expensive than increasing the shear rate in tokamak operations\[14\].

This situation is distinct from transport stiffness experiments on JET [8], where vigorous extra heating power was provided using localized ion-cyclotron-resonance heating (ICRH) to depart far from marginality.

\[13\] This is distinct from transport stiffness experiments on JET [8], where vigorous extra heating power was provided using localized ion-cyclotron-resonance heating (ICRH) to depart far from marginality.

\[14\] With tangential NBI, it is difficult to increase the toroidal Mach number—

and hence the equilibrium flow shear—because of the fixed ratio of injected torque to power at a fixed injection energy.
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