Intrinsic momentum transport in up-down asymmetric tokamaks

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**Abstract**

Recent work demonstrated that breaking the up-down symmetry of tokamaks removes a constraint that limits intrinsic momentum transport and toroidal rotation to be small\cite{1}. We show, through MHD analysis, that tilted ellipticity is most effective at introducing up-down asymmetry throughout the plasma. Then, we detail an extension to GS2\cite{2}, a local 6f gyrokineic code that self-consistently calculates momentum transport, to permit up-down asymmetric configurations. Accordingly, tokamaks with tilted elliptical poloidal cross-sections were simulated to determine nonlinear momentum transport. The results are consistent with TCV experimental measurements\cite{3} and, for a tilted elliptical machine with ITER-like parameters, suggest rotation with an Alfvén Mach number in excess of 1%. It appears that up-down asymmetry is the most feasible method to generate rotation in reactor-sized devices.

**The value of intrinsic rotation**

- Rotation shear has been shown to reduce turbulence, the limiting factor for confinement time, by decorrelating turbulent eddies. Rotation stabilizes the resistive wall mode allowing the same magnetic field confine more plasma pressure.
- Externally induced rotation becomes impractical in large devices because of the higher plasma densities.

**MHD equilibria of up-down asymmetry**

- Expand the Grad-Shafranov equation to lowest order in aspect ratio, $\epsilon = a/R_0 \ll 1$:
  \[
  R^2 \frac{\nabla \psi}{R} = -\mu_0 R^2 \frac{dp}{dy} - \frac{dI}{dy}
  \]
- Taking the right-hand side to be linear, solutions are given by
- \begin{itemize}
  \item $\Pi_{m=2}$ mode
  \item $\Pi_{m=3}$ mode
  \item $\Pi_{m=4}$ mode
\end{itemize}

**Contours of $\psi_0$**

- Lowest poloidal mode number perturbations, like elongation, penetrate throughout the plasma most effectively\cite{4,5}.
- Hollow toroidal current profiles allow asymmetry to the magnetic axis, while peaked current profiles limit asymmetry to the plasma edge\cite{1,6}.

**Modification of GS2 for the tilted ellipse**

- To support up-down asymmetric configurations, a new elongation tilt parameter $\Theta$, was added to the analytic geometry specification, which also required updating the numerical differentiation scheme.

**Nonlinear momentum flux results**

- The quantity $(\Pi_{m=4} / \Pi_{m=2}) / R_i$ is an estimate of the ratio of the velocity gradient to temperature gradient and seems to be relatively independent of geometry.
- A tilt of $\pi/8$ is optimal for maximizing rotation.
- The peak corresponds to a maximum toroidal velocity gradient, $(1/\psi_0) \partial v_T/\partial \psi$, of 5% of the temperature gradient, $(1/T) \partial T/\partial \psi$.

**Comparison to experiment**

- TCV experimental results for tilted elliptical flux surfaces from roughly agree with numerical results.

**Effect of Shafranov shift and $\beta'$**

- Initial investigations have found that a Shafranov shift increases momentum flux, but including $\beta'$ reduces it.

**Poloidal distribution of momentum flux**

- Diagnostics were implemented in GS2 to determine the poloidal structure of the momentum flux.

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**References**


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