Theory of Non-Axisymmetric Vertical Displacement Events

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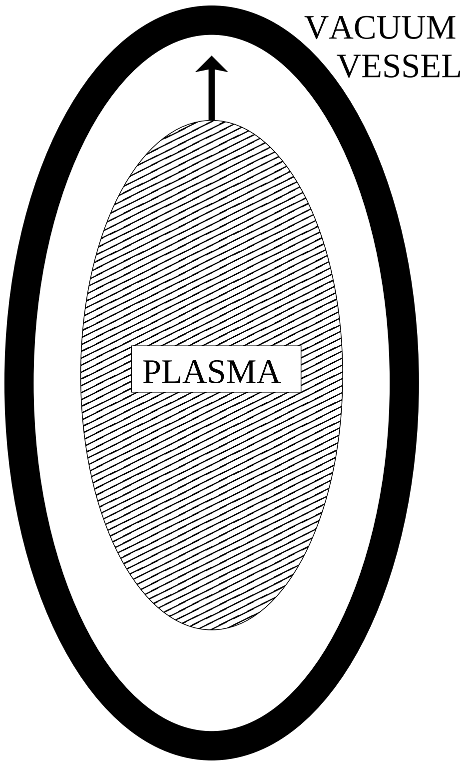
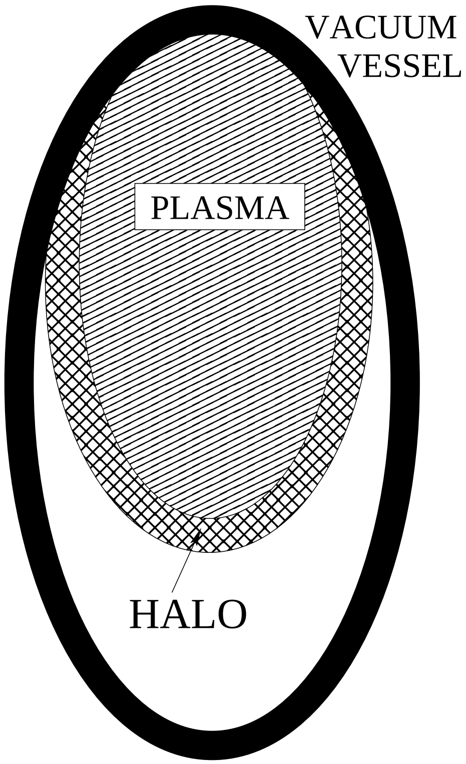
Vertical Displacement Event



- Elongated plasma loses vertical stability (i.e., control system and eddy currents in vacuum vessel unable to prevent ideal instability of $n = 0$ mode). Plasma moves upward on Alfvenic timescale.

Halo Formation



- Plasma strikes vacuum vessel. Plasma that comes into contact with v.v. neutralized, leaving outer flux-surfaces partly occupied by cold plasma, and partly occupied by v.v. This is so-called "halo."

Halo Current

- Poloidal cross-section of plasma shrinks as it moves upward. Halo cross-section also shrinks.
- Decreasing toroidal magnetic flux linked by halo gives rise to poloidal emf.
- Emf drives current in halo. Current constrained to flow parallel to magnetic field-lines in section of halo occupied by (force-free) cold plasma. Current flows along path of least resistance (i.e., poloidally) in section of halo occupied by v.v.
- Poloidal current in v.v. crossed with toroidal magnetic field gives rise to upward force on v.v.

Halo Current Moderation of $n = 0$ Mode

- Vacuum vessel exerts downward reaction on plasma, thereby affecting plasma vertical stability.
- Halo current magnitude adjusts itself such that force renders $n = 0$ ideal mode marginally stable. Allows plasma to move upward on resistive, rather than Alfvenic, timescale.
- Growth-rate of moderated $n = 0$ mode determined by halo current circuit equation. (We know what current we need, so growth-rate must be such that associated poloidal emf drives this current.)
- Halo current moderation of $n = 0$ mode more effective than eddy current moderation: i.e., moderated growth-rate less than τ_v^{-1}, where τ_v is L/R time of v.v. Roughly speaking, $\gamma \sim (\delta/a)\,\tau_v^{-1}$, where δ is radial thickness of halo, and a is plasma minor radius.

Destabilization of $n = 1$ Mode

- Poloidal cross-section of plasma shrinks on timescale $(a/\delta)\,\tau_\nu$.
- This timescale much less than toroidal L/R time of plasma. Hence, toroidal plasma current remains approximately constant.
- Shrinking plasma cross-section combined with approximately constant plasma current implies decreasing edge safety-factor.
- As edge-q approaches unity, $n = 1$ ideal external-kink mode destabilized.

Effect of $n = 1$ Mode

- The $n = 1$ mode also requires moderation to prevent it from growing on Alfvenic timescale. This leads to significant increase in vertical force exerted between vacuum vessel and plasma, and, hence, in halo current.

- As $n = 1$ mode grows in amplitude, region of contact between plasma and vacuum vessel becomes toroidally asymmetric. Eventually, contact region becomes toroidally localized. This implies toroidal localization of halo current, and halo current force. However, net force still has to be large enough to moderate $n = 0$ and $n = 1$ modes. Assuming that net force remains approximately constant, this implies significant increase in force density in contact region.

Critical Questions

- What is peak vertical force exerted on vacuum vessel during VDE?
- What is maximum toroidal peaking factor of this force?
- What is maximum sideways force exerted on vacuum vessel during VDE?

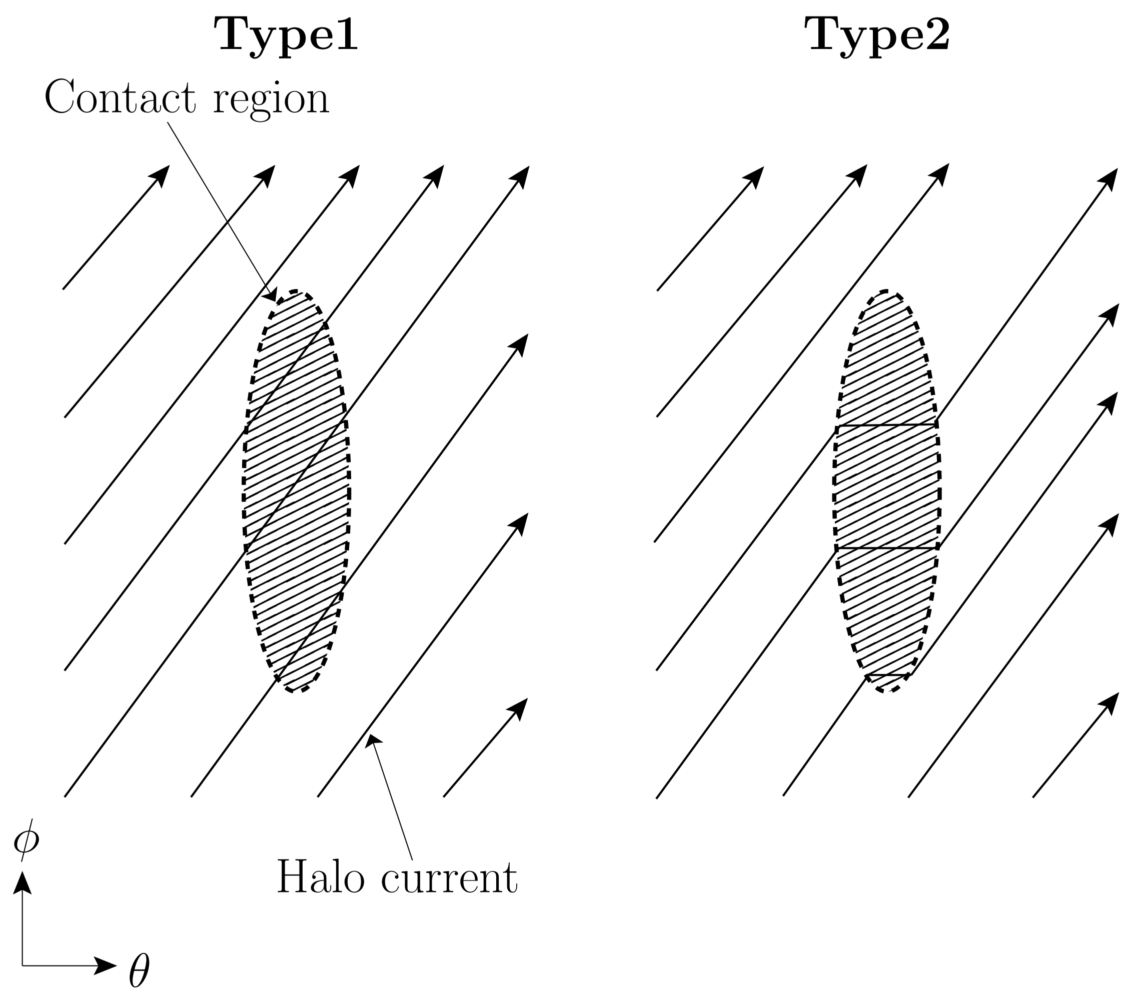
Sharp-Boundary Plasma Model

- Strongly elongated, large aspect-ratio, high beta (i.e., $\beta \sim \epsilon$) plasma with uniform internal pressure. All equilibrium currents flow on plasma boundary.

- Model allows fairly realistic treatment of $n = 0$ and $n = 1$ external modes.

- $n = 0$ and $n = 1$ stability calculations involve matching of vacuum-like solutions at plasma boundary. Can explicitly include effect of halo current force in matching process. Allows self-consistent calculation of effect of halo currents on $n = 0$ and $n = 1$ stability.

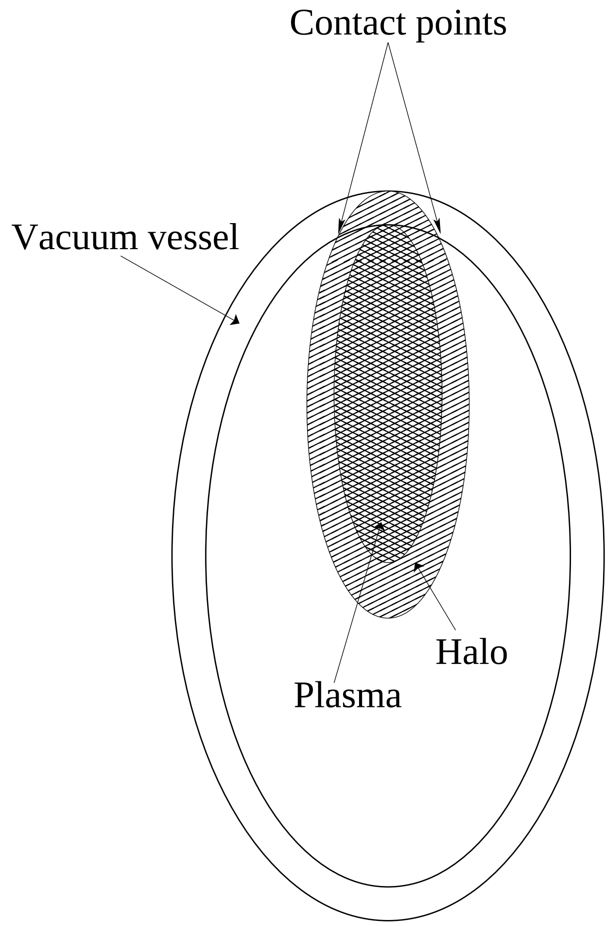
Halo Current Patterns



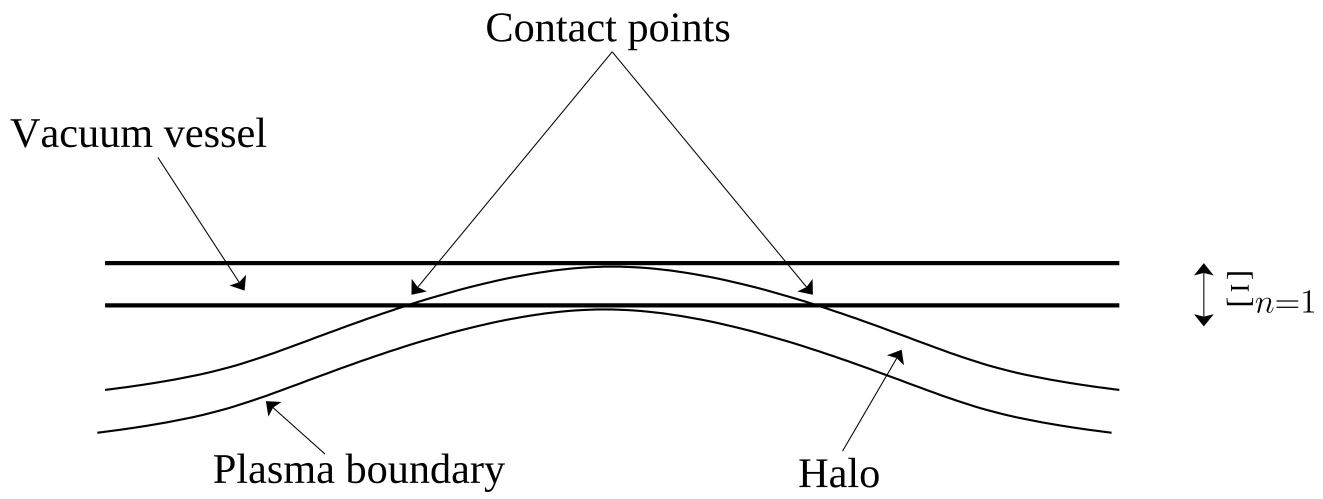
Circuit Equations

- Model allows for two types of halo current pattern. Type 1 gives rise to no halo current force. Type 2 maximizes force.
- Can calculate mean resistance of halo current circuit associated with each pattern (for specified SOL and v.v. resistivities), as well as mean emf generated by plasma shrinkage. (Assuming that circuit path covers LCFS ergodically.) Associated circuit equations determine relative mix of Type 1 and Type 2 patterns.
- Net halo current force adjusted such that $n = 0$ (and $n = 1$, when it is unstable) mode marginally stable. Circuit equations then give $n = 0$ (and $n = 1$) growth-rate.

Determination of Poloidal Extent of Contact Region



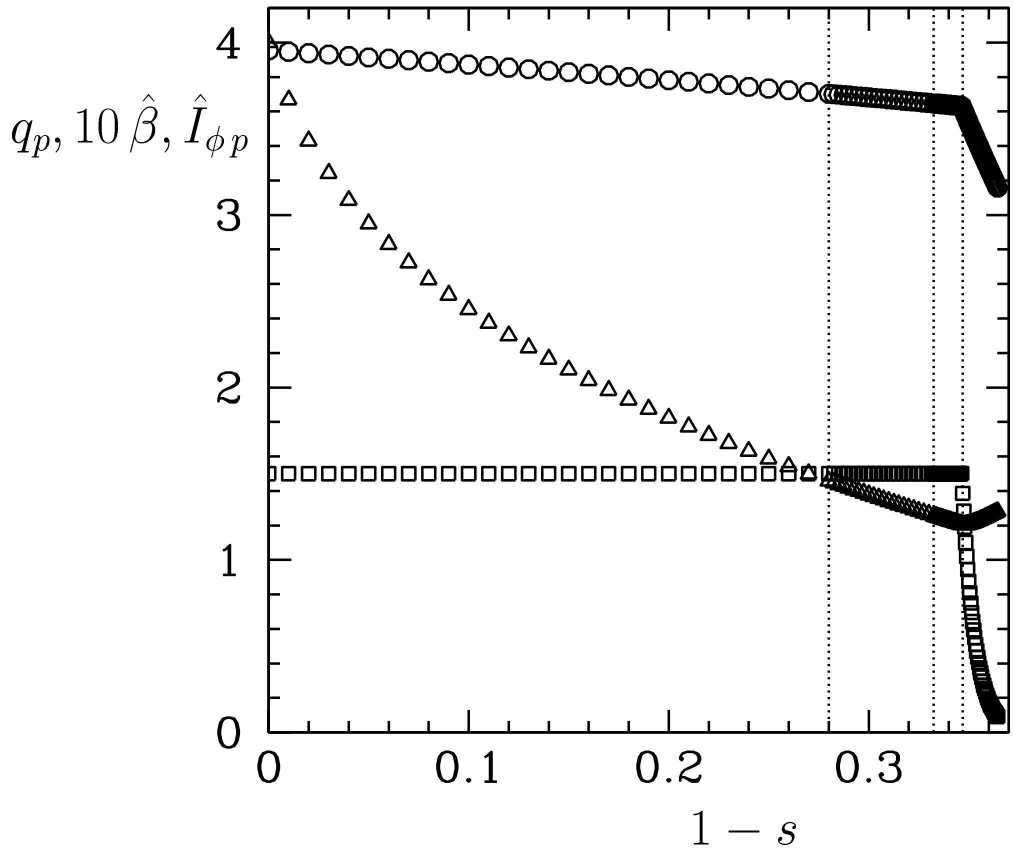
Determination of Toroidal Extent of Contact Region



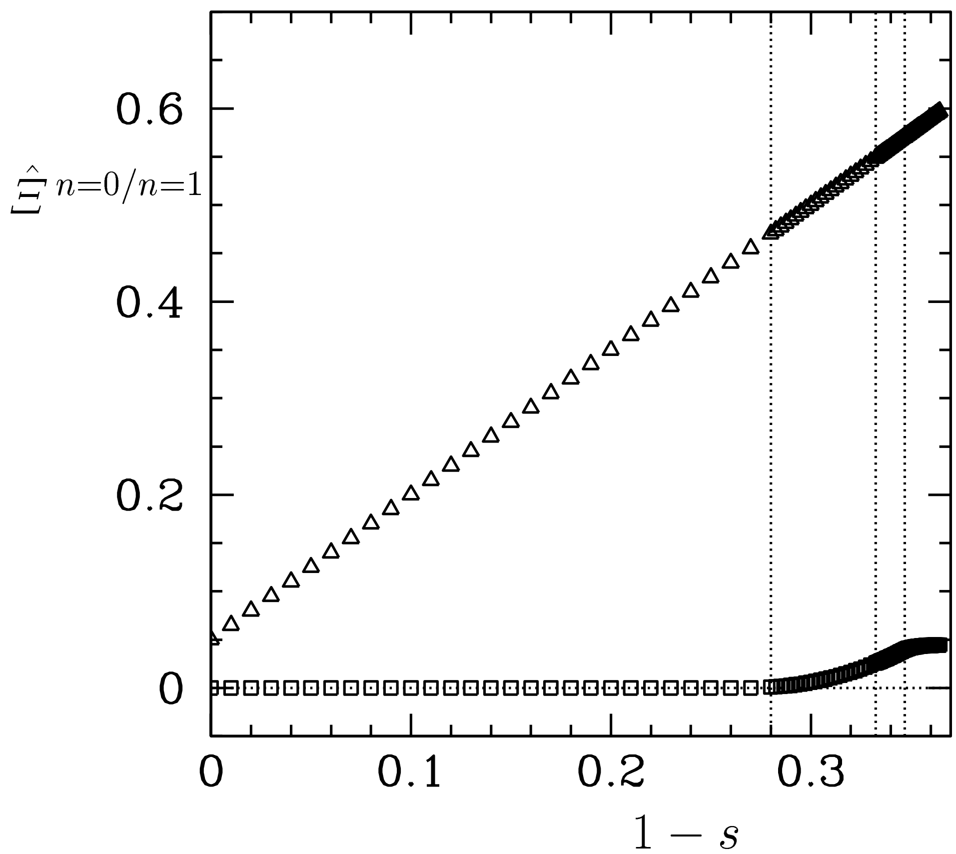
Inputs to Model

- Vacuum vessel shape and thickness.
- Initial edge-q.
- Plasma shape, current, and beta as plasma shrinks.
- SOL and vacuum vessel resistivities.
- Critical halo current fraction that triggers current quench.

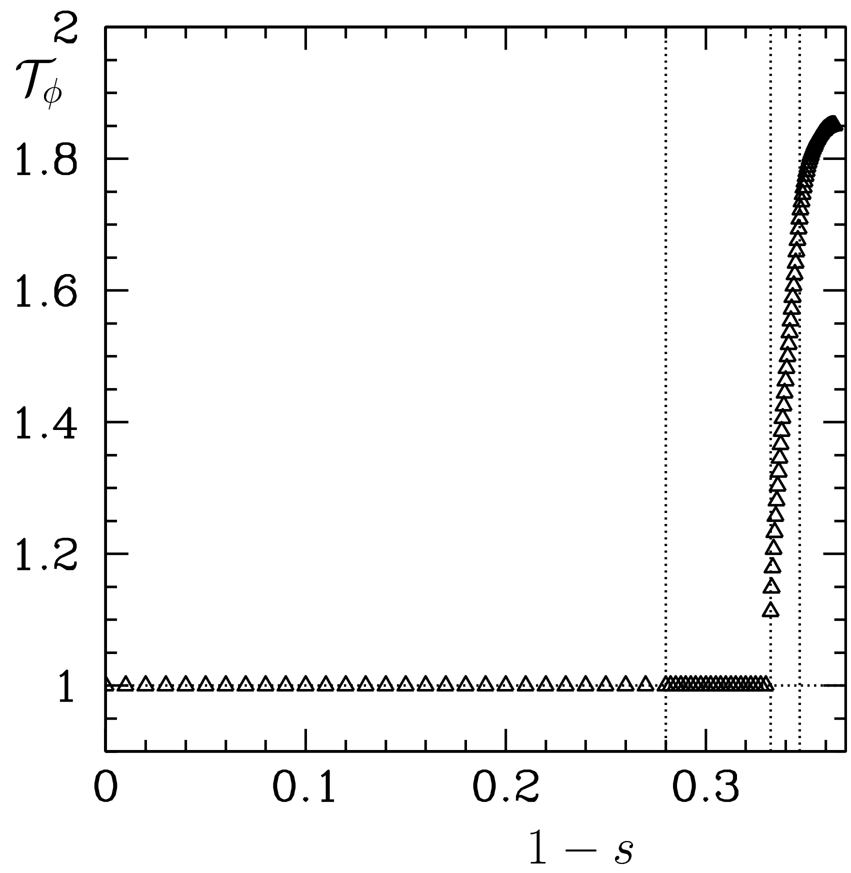
Example Calculation: Edge-q, Current



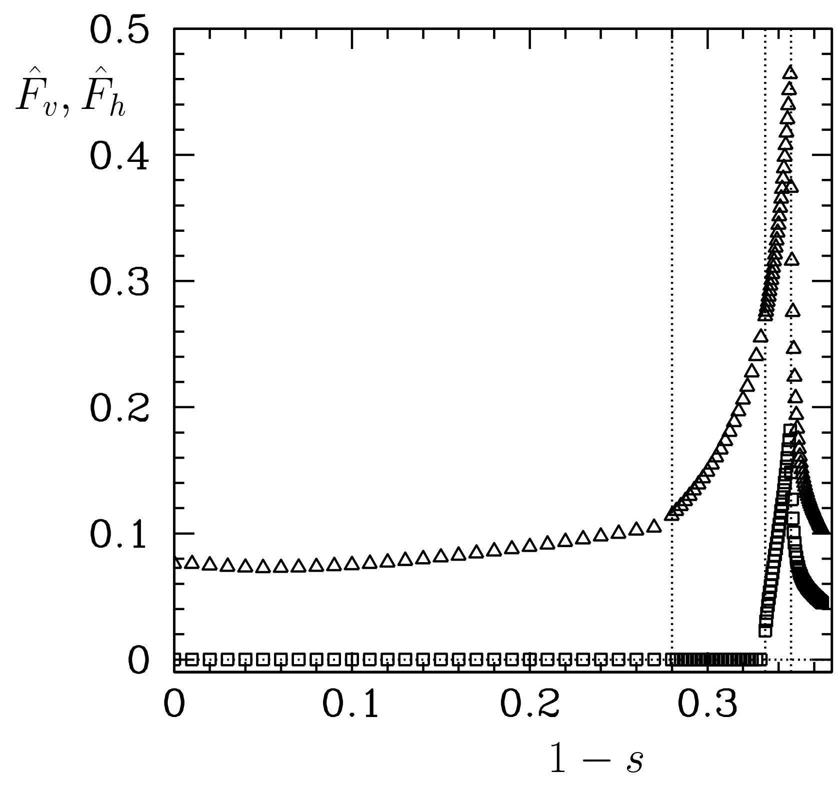
Example Calculation: $n = 0/n = 1$ Displacements



Example Calculation: Toroidal Peaking Factor

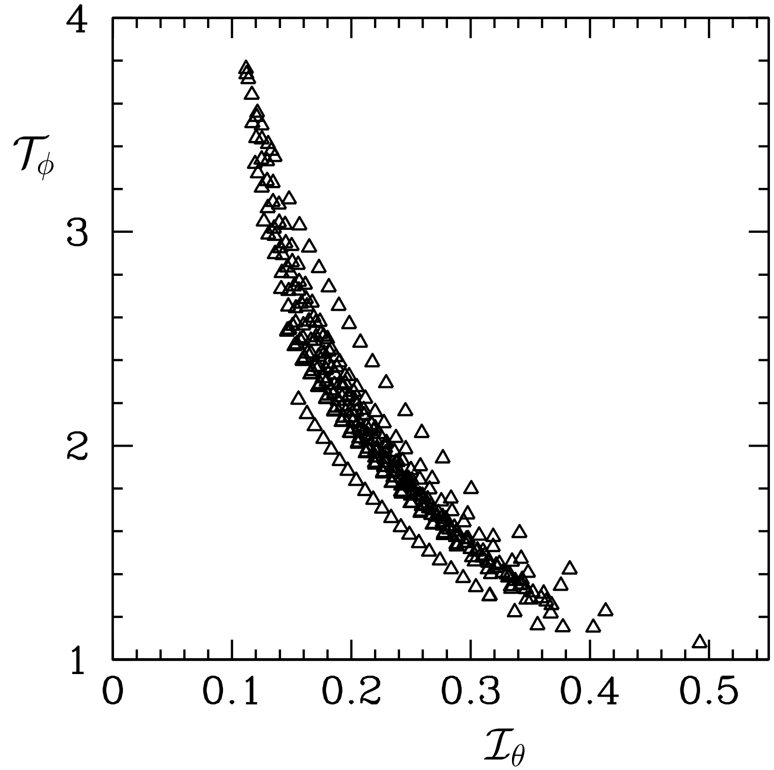


Example Calculation: Vertical and Sideways Forces



For typical ITER parameters, peak vertical and horizontal forces are 31 MN and 12 MN, respectively.

TPF vs Poloidal Halo Current Fraction



Ansatz that current quench triggered when halo current faction exceeds critical value reproduces inverse relation between TPF and poloidal halo current fraction seen experimentally.