Difficulty of Plasma Steering and Constraints from the Greenwald Limit

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Disruptions and runaway electrons cannot be tolerated in a fusion power plant.

Plasma steering is the primary method for avoidance but resembles driving at high speed through a dense fog on an icy road [1].

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To avoid disruptions, tokamaks must operate below the Greenwald density, $n_G \propto I/a^2$.

This limits the plasma $\beta, < \beta_G \propto T/(q_{95}BR)$, and hence the fusion power density, unless T is far above the optimal temperature for confinement, ≈10 keV.

For a DT burn [2], confinement needs to be ∼10 times better relative to gyro-Bohm at 35 keV than at 10 keV.

Controls (actuators) for Steering [1]

Three are fast in present experiments, only one in a power plant.

1. **Changes in the externally produced B field**

   Fast in JET and other existing tokamaks: 10's of ms.

   Slow in ITER and power plants: ≈ 0.6 s for wall penetration, ≈ 6 s due of voltage limits on superconducting coils, ≈ 60 to shutdown plasma without a disruption [3].

2. **Changes in power Input**

   Fast in non-DT burning plasmas; not directly controlled in DT-burning plasmas.

3. **Particle or pellet injection**

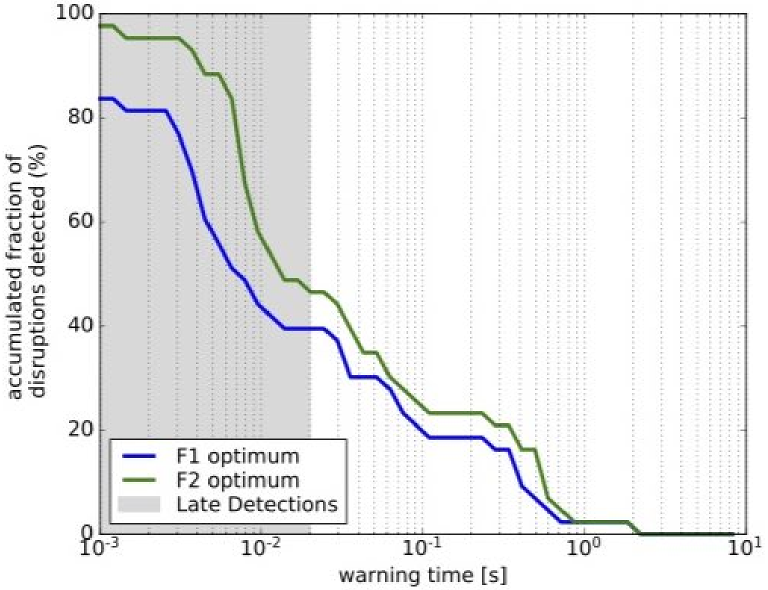
   Fast ≈ 20 ms, but penetration to core difficult and provides only limited control.

Which Actuators Control Critical Profiles

1. What actuators control the current profile, which evolves in $< 10^3$ s?
2. What actuators control the pressure profile, which evolves < 5 s?

Changes in either profile can create a disruptive state. A fleck of wall material can initiate a disruption in ~ 30 ms.

Required Warning Time and Reliability



Rea, Montes, Erickson, Granetz, & Tinguely Nuclear Fusion 2019

Required time for reliable predictions in ITER is 60 s for a disruption-free shutdown [3], 6 s for consistency with voltages on superconducting coils, and 0.6 s for externally produced magnetic fields to affect the plasma—similar in a power plant.

The longest internal time constant of an ITER-scale, 10 keV plasma is 10^3 s $\approx$ 17 min for poloidal flux dissipation by resistivity.

A power plant must operate years between major-maintenance shutdowns, which means $\sim 10^5$ flux-dissipation time scales. The ITER mission is compromised if even one in a thousand discharges results in major machine damage from a disruption or electron runaway.

Existing prediction techniques can reach 98 % reliability for a millisecond warning of a disruption but the reliability drops precipitously for a 10 ms warning.

Both the warning time and the reliability fall many orders of magnitude short of what is needed—a power plant has far fewer diagnostics.

RESEMBLES DRIVING AT HIGH SPEED THROUHGH A DENSE FOG.

Resemblance to Driving on an Icy Road

1. When axisymmetric location-control is lost, it is usually impossible to regain control.

2. Even when the chamber walls are perfect conductors, a highly shaped plasma can be vertically unstable [4–7].

   Can cause unexpectedly large halo and induced currents—consistency with limits on forces in ITER is unclear.

3. Magnetic surfaces can be rapidly lost throughout the plasma:
   - *Causes rapid loss of energetic electrons, but magnetic surface breakage needs to last* ~ 15 *ms to eliminate trapped electrons as a runaway seed.*
   - *Flattens* $j_{||}/B$ *over full chaotic field line region, which makes rate of current decay proportional to the resistivity near the wall [8].*
   - *When sudden, can cause [8] collapse of electron pressure in* $\sim 50\ \mu$*s, as seen [9] on DIII-D.*

   For the theory of fast magnetic surface breakup, which depends only logarithmically on resistivity, see ⟨https://arxiv.org/pdf/2107.02717.pdf⟩.

Empirical Confinement Gyro-Bohm Like [10]

Gyro-Bohm transport gives $\boldsymbol{D_{gb} = \frac{\rho_s}{a}\rho_s C_s, \propto \frac{T^{3/2}}{aB^2}}$ where $C_s = \sqrt{T/m_i}$, $\rho_s = C_s/\omega_{ci}$, a is minor radius.

Customary in empirical energy scaling laws to replace the temperature by the thermal power P_{th}. $\mathcal{D}_e$ *is enhancement over gyro-Bohm*. Then [10]

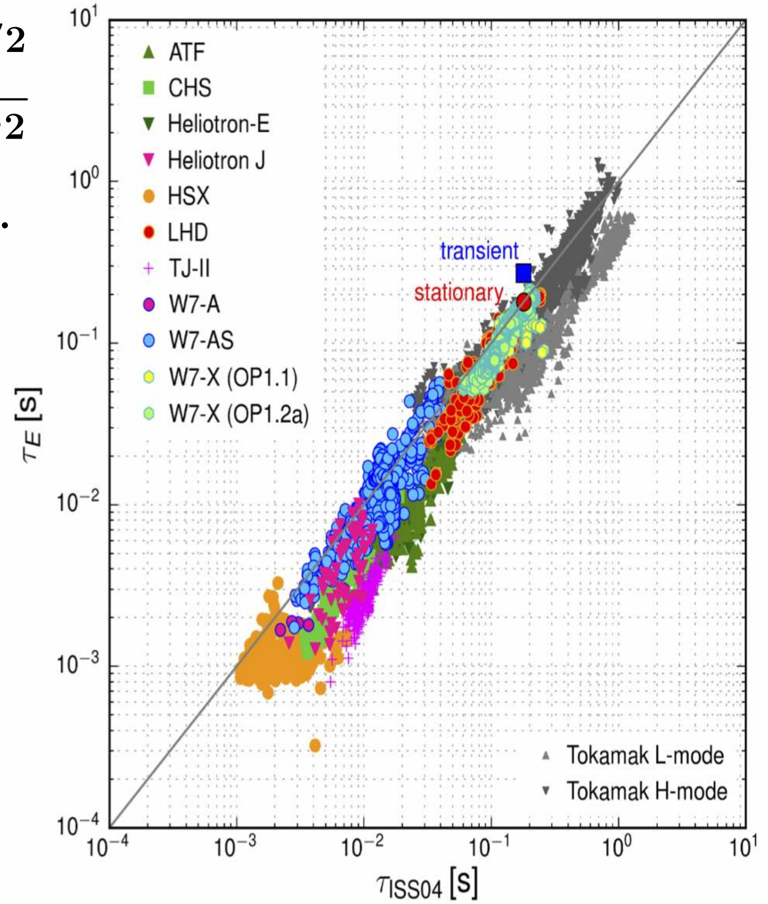
$$\tau_E \propto \frac{a^{12/5}R^{3/5}n^{3/5}B^{4/5}}{\mathcal{D}_e^{2/5}P_{th}^{3/5}}.$$

The standard stellarator empirical scaling law is

$$\tau_E^{ISS04} \equiv 0.134\frac{a^{2.28}R^{0.64}}{P_{th}^{0.61}}n^{0.54}B^{0.84}\iota_{2/3}^{0.41}$$

fits both tokamak and stellarator data within ~ 3.

Let ρ_s/a *in gyro-Bohm be* $\rho_s/\iota a$ *for* ι *scaling of* τ_E^{ISS04}. Passing particles departure from magnetic surfaces is $q\rho$.



Courtesy of G. Fuchert, IPP, Greifswald, Germany

Greenwald Limit $n < n_G \propto I/a^2$

1. **Complicates shutdown of tokamaks.** Must keep $na^2 < I$ as I drops.

2. **Limits $\beta < \beta_G$, [2] where $\beta_G \propto T/(q_{95}B)$.**

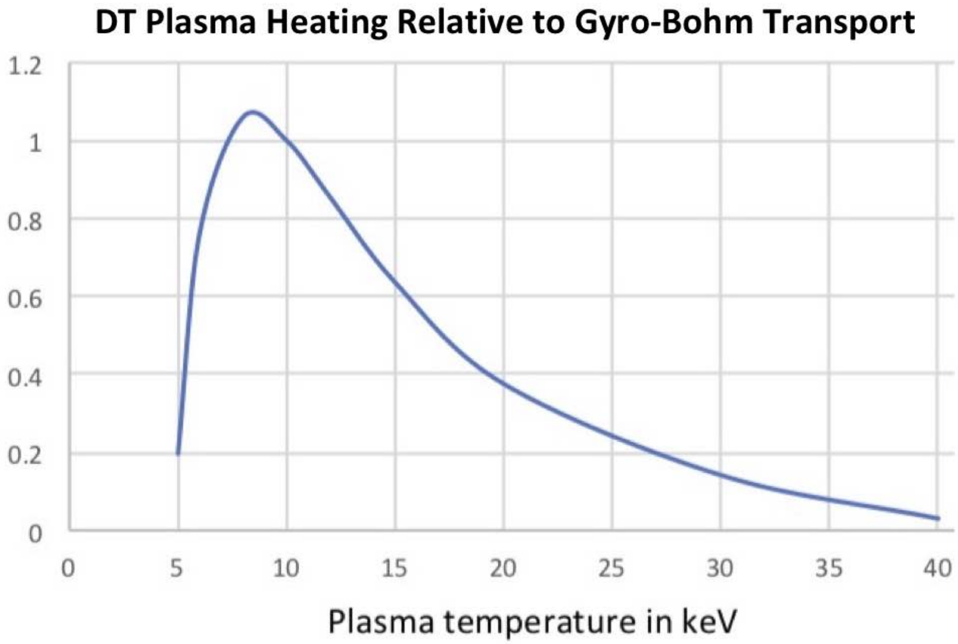
3. **Need a high $T \gtrsim 35$ keV for enough β to achieve an adequate fusion power density**.
   Fusion power density scales approximately as $\propto \beta^2$.

4. **By forcing T from approximately 10 keV to 35 keV, the Greenwald limit reduces the maximal acceptable transport in a power plant [2] by an approximate factor of ten.**

Energy confinement versus temperature issue

The DT power in α particles minus bremsstrahlung losses divided by gyro-Bohm energy transport is normalized to its value at 10 keV.

Synchrotron emission is ignored, which significantly degrades energy confinement for $T \gtrsim 35\ keV$.



Obtaining adequate energy confinement for fusion is far more demanding when the plasma temperature is far above 10 keV.

Implications

Before a tokamak power plant is possible, inventions are required:

- To ensure the disruptions and runaway electrons can be effectively eliminated.
- To overcome the tritium fuel-cycle issues reviewed [11] by Abdou et al in Nuclear Fusion in 2021.
- Possibly, in order to obtain the required energy confinement for $T \gtrsim 35$ keV.

A suitable invention is already known—the stellarator [2]. *Even expending a few percent of the U.S. or EUROfusion annual budget on reliable stellarator design is on indefinite hold. Needlessly limits the rapid development of fusion.*

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