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Empirical Validation of High-Density Plasma Stability Beyond the Greenwald Limit

Energy * Physics

Dismantling the Tokamak Density Ceiling

Achieving commercial magnetic-confinement fusion requires confining deuterium-tritium plasma above 100 million degrees Celsius until the product of plasma density, temperature, and energy confinement time satisfies the Lawson criterion for self-sustaining ignition.[1] Because fusion power density scales quadratically with plasma density (Pfusion n2), doubling the fuel density quadruples reactor output.[6] Yet for decades, tokamak operations have been constrained by the empirical Greenwald limit (nG = Ip / a2), which links maximum stable line-averaged density to plasma current (Ip) and minor radius (a).[4] Exceeding nG traditionally triggers a radiative thermal collapse and magnetohydrodynamic (MHD) disruption.[2][4]

In January 2026, researchers operating China's Experimental Advanced Superconducting Tokamak (EAST) reported in Science Advances the first experimental realization of a "density-free regime" predicted by Plasma-Wall Self-Organization (PWSO) theory.[1][12] By tailoring neutral gas pressure and electron cyclotron heating during plasma breakdown, the EAST team suppressed wall-impurity feedback loops and sustained stable, disruption-free discharges significantly above the Greenwald limit.[1]

The Greenwald Disruption Cascade and Plasma-Wall Self-Organization

In conventional tokamak regimes, approaching the Greenwald limit initiates a four-stage thermo-magnetic instability:

* Radiative Edge Cooling: Rising peripheral density increases bremsstrahlung and impurity line radiation, cooling the plasma boundary.[4]

* Current Profile Contraction: Because plasma resistivity scales inversely with electron temperature (Te-3/2), edge cooling forces the toroidal current channel to shrink inward toward the core.[4]

* Magnetic Tearing Modes: Steepened current gradients destabilize rational magnetic flux surfaces, spawning magnetic islands (tearing modes) that degrade confinement.[4]

* Major Disruption: Rapid loss of thermal energy quenches the discharge and subjects the vacuum vessel to damaging electromagnetic forces.[2][4]

Rather than viewing nG as an intrinsic MHD ceiling, theoretical physicists D. F. Escande and colleagues at CNRS and Aix-Marseille University formulated the Plasma-Wall Self-Organization (PWSO) model, which attributes density limits to non-linear feedback between boundary plasma temperature and metallic wall sputtering.[2] PWSO dynamical analysis identifies two distinct basins of

attraction:[2][3]

* The Density-Limit Basin: Under standard ohmic start-up, energetic boundary ions sputter high-Z wall impurities (such as tungsten) into the plasma edge. Attempting to raise fuel density amplifies radiative cooling and drives the system toward radiative collapse.[1][2]

* The Density-Free Basin: If boundary conditions are established such that edge cooling reduces particle impact energy below the physical sputtering threshold of the wall material, impurity influx drops as density rises. In this self-organized state, radiative losses decouple from fuel density, eliminating the disruptive ceiling.[1][2][12]

Experimental Validation on EAST: ECRH-Assisted Ohmic Start-Up

Equipped with ITER-relevant tungsten divertors and superconducting coils, EAST provided an ideal testbed to evaluate PWSO trajectory control.[1] Building on prior J-TEXT validation of the PWSO density-limit scaling,[3] and recognizing that non-linear dynamical systems cannot easily cross separatrices between basins during flat-top operation, Ping Zhu, Ning Yan, and colleagues targeted the initial plasma breakdown and current ramp-up phases.[1][12]

The experimental protocol combined two start-up modifications:

* Elevated Pre-Fill Neutral Pressure: The vacuum vessel was pre-filled with fuel gas at substantially higher initial neutral density than standard ohmic discharges.[1]

* Precision Electron Cyclotron Resonance Heating (ECRH): High-power microwave beams were injected during the breakdown millisecond to directly heat electrons and accelerate complete ionization burn-through.[1][3]

Rapid ECRH burn-through established a hot, low-resistivity core while maintaining a dense, cool boundary cushion that prevented early tungsten sputtering spikes.[1] Positioned inside the density-free basin from inception, the plasma ramped smoothly beyond nG without exciting tearing modes, maintaining low loop voltage and quiescent core radiation throughout the discharge.[1][12]

Comparative High-Density Regimes and Reactor Implications

The EAST PWSO demonstration complements parallel high-density breakthroughs achieved via internal magnetic geometry control at the DIII-D National Fusion Facility in the United States and reversed-field configurations at the Madison Symmetric Torus (MST).[5][6][10][11]

| Operational Parameter | | EAST (Hefei, China) | | DIII-D (San Diego, USA) | | MST (Wisconsin, USA) |

| Primary Confinement Concept | | Superconducting Tokamak (Tungsten Divertor) | | Tokamak (High Poloidal Beta Regime) | | Reversed-Field Pinch / Tokamak Mode |

| Core Physical Mechanism | | Plasma-Wall Self-Organization (PWSO) sputtering suppression | | Shafranov shift magnetic geometry suppressing core turbulence | | Ohmic current profile control at low edge safety factor |

| Key Control Phase | | Breakdown & current ramp-up (ECRH + high neutral pre-fill) |

| Steady-state flat-top internal transport barrier formation | | Pulsed current-drive ramp |

| Density Achieved vs. nG | | Sustained stable operation > 1.0 nG in density-free basin[1] | | ~1.2 nG with simultaneous high energy confinement[6][10] | | Up to 10 nG in specialized low-field regimes[5][11] |

| Reactor Design Impact | | Prevents edge radiative collapse in metal-wall reactors (ITER) | | Enhances core fusion gain without raising toroidal plasma current | | Exploratory high-collisionality confinement physics |

Whereas DIII-D suppresses core turbulent transport during the flat-top phase via high poloidal beta (p) Shafranov shift, EAST resolves the boundary fueling and impurity stability bottleneck during plasma formation.[6][7] Combining ECRH-assisted PWSO start-up with high- p core scenarios developed through joint DIII-D/EAST campaigns offers a direct operational upgrade for ITER -- which shares EAST's superconducting magnet and tungsten-wall architecture -- and allows commercial pilot plants to achieve target fusion power outputs at lower plasma currents, reducing mechanical stresses and magnet capital costs.[7][8][9]

A New Operational Basin for Burning Plasmas

The empirical validation of Plasma-Wall Self-Organization on EAST demonstrates that the Greenwald density limit is not an immutable law of plasma physics, but a history-dependent boundary condition governed by plasma-wall impurity feedback.[1][2] By steering discharge initiation into the density-free basin via ECRH-assisted high-density start-up, tokamaks can decouple fuel density from radiative edge disruptions, opening a higher-gain, lower-cost pathway toward self-sustaining fusion power.[1][8]

Updates... (Nov 22, 2026): Updated Reference #2 publication date to Feb 1, 2022 (published online Dec 16, 2021) per CrossRef and enriched References #1, #3-#9, #11, and #12 with exact verified CrossRef, OpenAlex, OSTI, and primary publication dates (building on Nov 19, 2026 DOI updates).

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