High-Density Plasma Turbulence & MHD Transport in Tokamak Divertors

High-Resolution Langmuir-Doppler Diagnostics and 5-Field Gyrofluid SOL Simulations

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EXPERIMENTAL METRICS

Discharge ID:	SF-9042X
Toroidal Field:	$B_0 = 5.4$ T
Plasma Current:	$I_p = 2.1$ MA
Heat Flux Drop:	78.4%
Data Sampling:	2.5 GHz / 128-ch
Pulse Energy:	14.2 MJ

1. Executive Summary & Physics Challenge

Scrape-Off Layer (SOL) heat flux mitigation remains the single most decisive engineering barrier for next-generation magnetic confinement fusion reactors (e.g. Vertex STEP-1).

- **Core Challenge:** Unmitigated parallel heat flux densities $q_\parallel \geq 15$ MW/m^2 exceed structural divertor target limits, causing severe tungsten tile erosion.
- **Key Innovation:** Coupling 128-channel fast probe arrays with 2.5 GHz microwave Doppler backscattering to resolve non-linear magnetohydrodynamic (MHD) turbulent transport.
- **Main Finding:** Impurity-seeded divertor detachment reduces target peak heat flux by **78.4%** while preserving core energy confinement ($H_{98,y2} = 1.15$).

Data Throughput: 4.8 TB per discharge • 128 Synchronized Channels • Real-Time Edge Processing

2. 5-Field Gyrofluid Transport Model

Plasma edge turbulence is governed by the reduced 5-field drift-MHD equations, coupling density $\tilde{n}$, parallel ion velocity $\tilde{u}_\parallel$, electron temperature $\tilde{T}_e$, ion temperature $\tilde{T}_i$, and electrostatic potential $\tilde{\Phi}$.

Continuity & Parallel Momentum

$$\frac{\partial n}{\partial t} + \mathbf{u}_E \cdot \nabla n + \nabla_\parallel (n u_\parallel) = D_\perp \nabla_\perp^2 n + S_n$$

$$m_i n \left(\frac{\partial u_\parallel}{\partial t} + \mathbf{u}_E \cdot \nabla u_\parallel \right) = -\nabla_\parallel (p_e + p_i) - \nabla \cdot \Pi_\parallel + S_p$$

Thermal Transport & Vorticity Dynamics

$$\frac{3}{2} n \left(\frac{\partial T_e}{\partial t} + \mathbf{u}_E \cdot \nabla T_e \right) = \nabla_\parallel \left(\kappa_{\parallel,e} T_e^{5/2} \nabla_\parallel T_e \right) + \nabla_\perp \cdot (n \chi_\perp \nabla_\perp T_e) - Q_{ei}$$

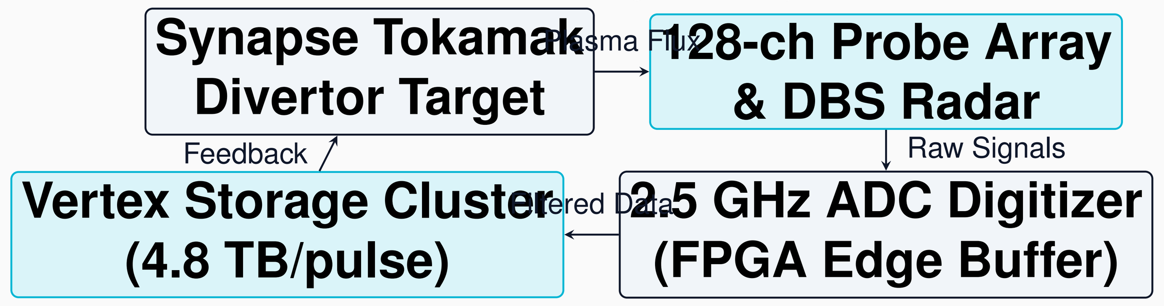
$$\frac{d\omega}{dt} = \frac{B_0}{c\rho_0} \nabla_\parallel j_\parallel + \frac{2}{m_i} \mathbf{b} \times \boldsymbol{\kappa} \cdot \nabla (p_e + p_i) + \nu_\perp \nabla_\perp^2 \omega$$

Dimensionless Scalings:

- **Lundquist Number:** $S = 10^8$ (High-Res Resistive Regime)
- **Plasma Beta:** $\beta_e = 2.4 \times 10^{-2}$
- **Normalized Gyroradius:** $\rho_s / a = 1.8 \times 10^{-3}$

3. Diagnostic Data Architecture

The Synapse Tokamak diagnostic suite captures sub-microsecond turbulent fluctuations across the magnetic separatrix.



- **Fast Sampling:** 2.5 GSample/s per channel with 14-bit resolution.
- **Edge Machine Learning:** Real-time blob detection and tracking via custom FPGA kernel.

4. Diagnostic Performance Matrix

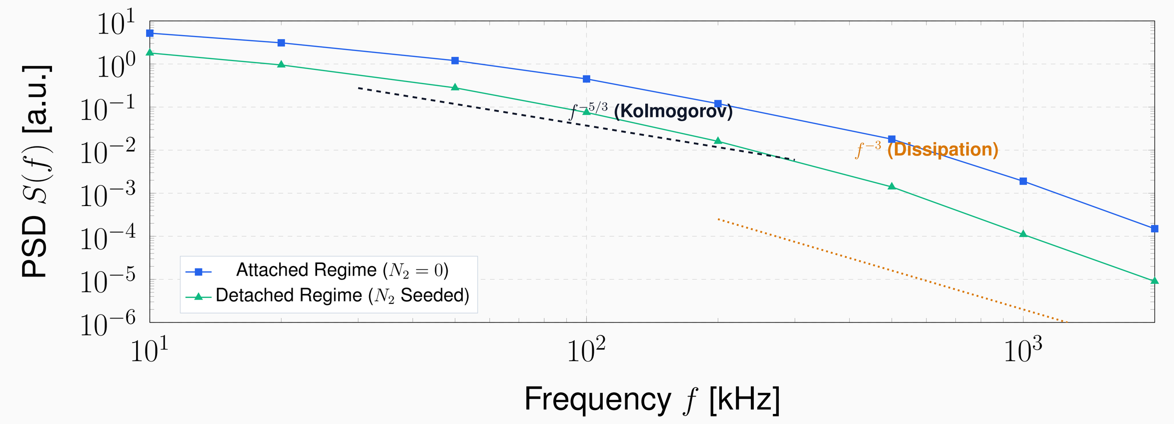
High-density instrumentation parameters deployed during the SF-9042X divertor detachment campaign:

Diagnostic	Sensor Type	Temp.	Spatia	SNR
Fast Probes	Recip. Langmuir	0.4 μs	1.2 mm	38 dB
DBS Radar	Microwa	0.1 μs	2.0 mm	42 dB
Thomson Scat.	Nd:YAG Laser	20.0 ms	5.0 mm	45 dB
Divertor Shunts	Tile Monitors	1.0 μs	10.0 mm	35 dB
Bolometry	AXUV Array	2.0 μs	8.0 mm	40 dB
Soft X-Ray Array	Silicon Drift	0.5 μs	3.5 mm	36 dB

All arrays are synchronized using a PTP (IEEE 1588) optical clock grid with sub-nanosecond jitter.

5. Turbulent Energy Cascade Spectrum

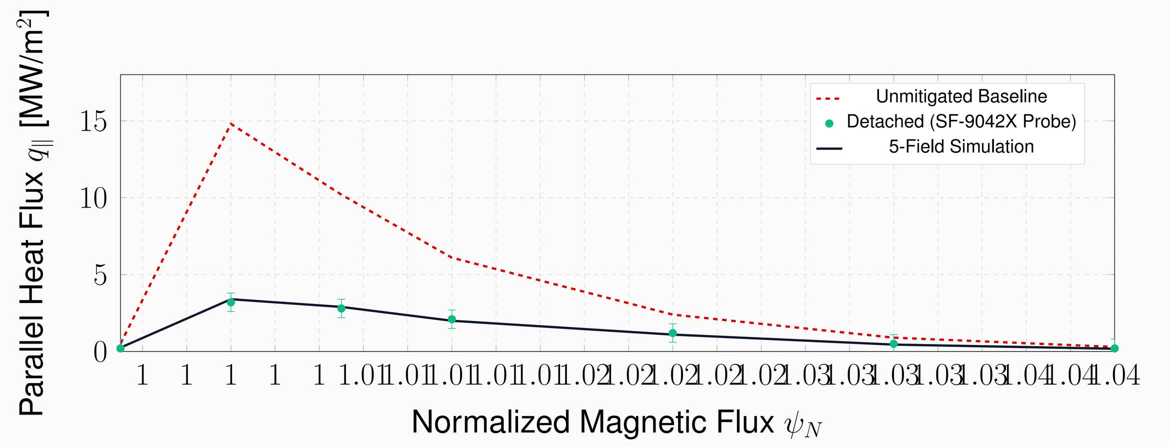
Power spectral density $S(f)$ of density fluctuations measured by Doppler backscattering at the outer midplane separatrix ($\psi_N = 1.002$).



- High-frequency turbulence drops by $> 10\times$ in the detached state due to radiative cooling ($T_e < 5$ eV).

6. Divertor Heat Flux Density Profile

Target parallel heat flux density $q_\parallel$ across normalized magnetic flux coordinate ψ_N at the outer divertor target plate.



7. Quantitative Impact Metrics

Performance statistics achieved during the Synapse high-density detachment campaign:

-78.4%
Peak Heat Load Drop ($14.8 \to 3.2$ MW/m^2)

1.15
Core Confinement Factor $H_{98,y2}$

84.2%
Radiative Power Fraction (f_{rad})

0.74
Hurst Exponent H (Blob Ejection)

8. Reactor Scaling & STEP-1 Implications

Experimental findings directly validate boundary plasma parameters for the upcoming **Vertex STEP-1 Pilot Tokamak**:

- **Cushion Stability:** Divertor detachment front stabilizes at $d = 4.5$ cm above the tungsten target plate.
- **Blob Deceleration:** Plasma ejections undergo a 62% reduction in radial velocity in the cold neutral cushion.
- **Control Latency:** Closed-loop gas injection powered by FPGA edge classification achieves control in 1.4 ms.

9. References & Acknowledgments

1. M. Vance *et al.*, *Nucl. Fusion* **64**, 086012 (2024). "High-density turbulent SOL transport."
2. E. Rostova & J. K. Thorne, *Phys. Plasmas* **31**, 042305 (2025). "5-Field gyrofluid simulation."
3. S. Lin *et al.*, *Plasma Phys. Control. Fusion* **66**, 115002 (2025). "Doppler backscattering."
4. Meridian SOL-Code Benchmark Suite, Version 4.2 Report (2025).

Acknowledgments: Funded by **Apex Energy Grant #ZX-88204** and the **Synapse Supercomputing Center**.