DIII-D Research Advancing the Physics Basis for Optimizing the Tokamak Approach to Fusion Energy



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Performance of High-q_{min} Plasmas Improved by Increased Off-Axis NB Power Reducing AE Drive and Fast Ion Losses



 New off-axis NBI current drive matches simulations





 10% higher confinement, 15% higher β_N

Optimization to classical fast ion confinement possible in steady state reactor scenarios



Top Launch Doubles Off-axis ECCD by Stronger Damping on Higher Energy Electrons



- Experiments validated top-launch ECCD predictions
 - Long absorption path
 - Damping on high energy e- by larger Doppler shifts
 - Optimized mid-radius for absorption and CD

 2X higher top launch mid-radius ECCD consistent with TORAY and CQL3D

Path to optimized off-axis ECCD for reactor steady state scenarios



Xi Chen et al., PRL submitted 2021 Xi Chen et al., NF submitted 2021

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Techniques for Continuous Avoidance of Vertical Displacement Events Demonstrated Experimentally



Proximity detection algorithm qualified for VDE avoidance in ITER



High-Z SPI Effectiveness for Disruption Mitigation Set by Particle Assimilation and Energy Balance, Not MHD



particle assimilation fractions and CQ rates

predictable from global energy balance

High-Z Shattered Pellet Injection (SPI)

and from empirical scaling laws

- Dependence of dual pellet high-Z assimilation and CQ rates reproduced
- Heat load peaking factors close to ITER limits
- D₂ SPI disruption dynamics set by MHD

Global behavior of multi-(high-Z)-SPI optimization for ITER now predictable



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Kink Instability Provides Novel Path to Runaway Electron Mitigation For High Current RE Beams



- Final large MHD burst at q_a=2 dissipates RE beam in pure D₂ background
- Magnetic energy dissipates Ohmically without generation of new REs



• MARS-F identifies large 2/1 resistive external kink gives increased RE loss orbits and wetted area

Path to RE energy dissipation over large area on resistive timescale, without CQ regeneration

C. Paz-Soldan et al., PPCF (2019)

M.E. Fenstermacher, DIII-D Overview, 2020 IAEA FE Paz-Soldan (poster, rapp). EX/5, Fri AM 8





TM1 Non-linear Plasma Response Model Predicts Narrow Isolated q₉₅ Windows of RMP ELM Suppression



Prediction and optimization of threshold field and Ip range for ELM suppression in ITER



Q. Hu et al., NF (2020) Q. Hu et al., Phys Plas (2020)

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Inter-ELM Variations of Electron and Ion Heat Fluxes Are Consistent With Evolution of Multi-scale Pedestal Turbulence



- TEM-scale ES fluctuations have potential to substantially explain anomalous Q_e
 - TEM-scale \tilde{n} shows $\nabla T_{e,crit}$ and saturates with ∇T_e and ExB shear
- Identification of MTM-like modes is not yet conclusive for these conditions

Significantly advances ability to understand inter-ELM pedestal thermal transport

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Techniques Identified to Reduce L-H Transition Power Threshold in ITER-Similar-Shape Hydrogen Plasmas

Experiments run at ITER-like low torque with balanced H-NBI and ECH



Identifies actuators to reduce P_{L-H} in ITER non-nuclear phase



Large Variations of Impurity Concentration in Multi-Charge-State Measurements Validate Models of Divertor Dissipation





A. McLean et al., RSI (2020) C. Samuell et al., RSI (2021)

Path to Optimize Detachment and Pedestal by Target Geometry and Impurity Species Demonstrated in SAS Divertor



Increased confidence in predictions of divertor detachment optimization by geometry and choice of impurity



L. Casali et al., PoP (2020)

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ExB Drifts Important to High-Z Divertor Erosion and Redeposition Both in L-mode and During ELMs



ONAL FUSION FACILIT



 Intra-ELM W gross erosion reduced with pellet pacing but increased with RMP

Validated W erosion and redeposition models increase predictability for ITER

T. Abrams et al., Phys Plas (2019)





Large Radius ITB in High β_p Scenario Compensates Pedestal Reduction in Detachment for Excellent Core-Edge Integration



Super H-mode Achieved in JET Compatible LSN Shape and DN Shows Promise of Coupling to Radiative Divertor



- Stationary Super H achieved in a JET-compatible ITER-like shape
- Predict 50% p_e^{ped} increase for ITER
- Divertor OSP at detachment onset using N₂ with peeling limited pedestal at SH channel entrance

Integrated core-edge solution with a Super H pedestal and dissipative divertor may be possible for ITER



Broad Current Profile Sustained in High- β Hybrid Without Anomalous Current Diffusion Using Off-Axis Current Drive

- Steady-state hybrids with on-axis ECCD have anomalously broad current profile
- Hybrids using off-axis ECCD have naturally broad current profile as predicted by TRANSP
- Both types of hybrids give similar sawteethfree, high-β, high-H₉₈ performance

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Increases confidence in steady-state Q ≥ 5 ITER hybrid scenario using off-axis current drive



High Power, Diverted Negative Triangularity Plasmas: A Promising Candidate for Reactor Core-Edge Integration



Good H-mode quality parameters ($H_{98y2} \le 1.2$, $\beta_N \le 3.0$) but no ELMs (L-mode edge) up to 5x P_{L-H}

 Ballooning modes close access to 2nd stability and prevent pedestal growth¹



• Stored energy increase stronger with P_{inj} than L-mode • Promising for coreedge integration with 30-50% broader λ_{q} , low Zeff~1.5 and impurity τ_{p}/τ_{F} ~1

Points to possible transformational characteristics of negative triangularity shapes for reactors



A. Marinoni et al., PoP 2019 M. Austin et al, PRL 2019

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1. Saarelma PPCF submitted





Future Plans Target Integrated Core-Edge Solutions for ITER and a Fusion Pilot Plant



Closure

Magnetic

strücture

Runaway Coil

Near term: Foundations

- Current drive: HHFW Helicon, HFS LHCD, Top-ECCD
- Re-optimized Tungsten slot divertor
- Increased 3D & divertor magnetic flexibility
- High power divertor negative triangularity

Long term: Proposed Performance Upgrade

- Shape, field, H&CD increases
- Modular divertor eg. long leg
- Reactor relevant materials
- Innovative transient control

Develop solutions and physics basis to project future reactors



Presen

Shape

M-Coils