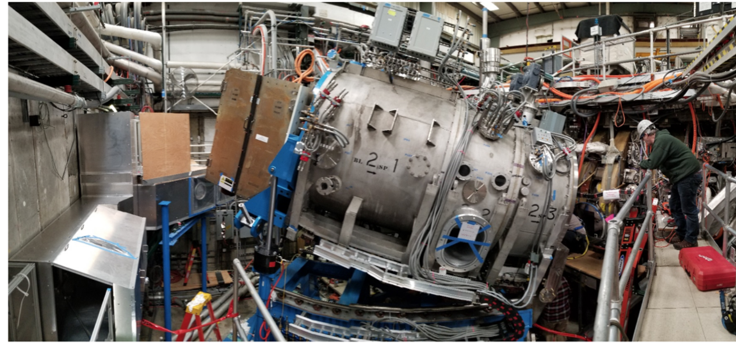
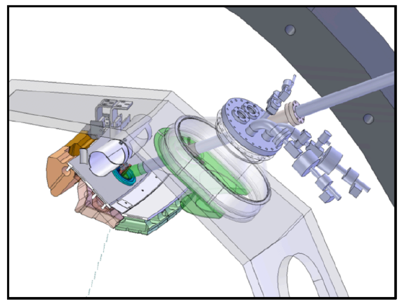
DIII-D Research Advancing the Physics Basis for Optimizing the Tokamak Approach to Fusion Energy



M.E. Fenstermacher (LLNL)

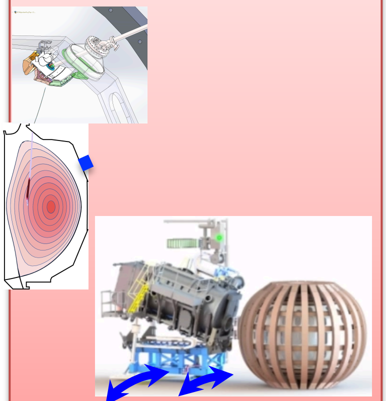


28th IAEA Fusion Energy Conference
Nice, France (Virtual)
May 10-15, 2021

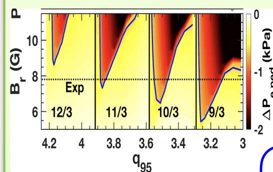
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344, and under Contracts DE-FC02-04ER54698, DE-FG02-07ER54917, DE-FG02-05ER54809. LLNL-PRES-820809

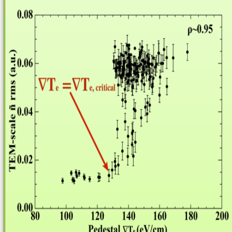
DIII-D Research Advances the Physics Basis for Optimizing Future Fusion Reactors

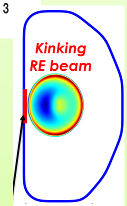
1. New Physics Actuators



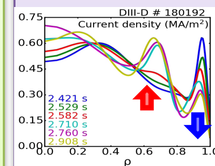
2. Key Physics Understanding

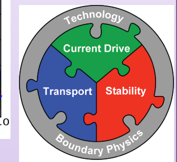


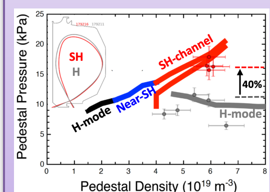




3. Integrated Core-Edge Scenarios

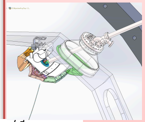


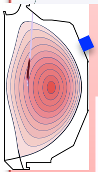


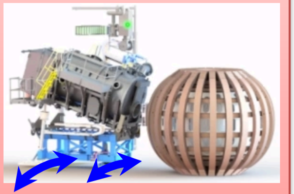


DIII-D Research Advances the Physics Basis for Optimizing Future Fusion Reactors

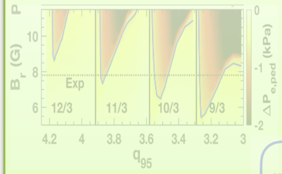
1. New Physics Actuators

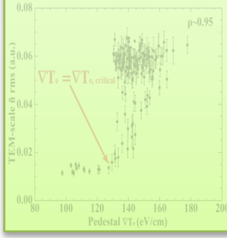




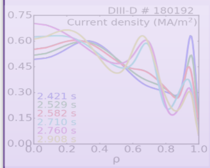


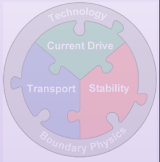
2. Key Physics Understanding

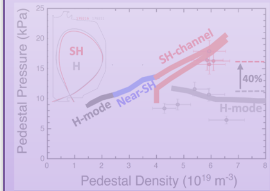




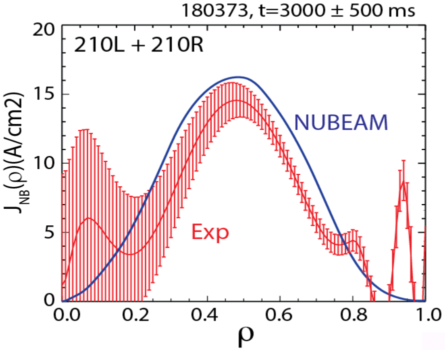
3. Integrated Core-Edge Scenarios



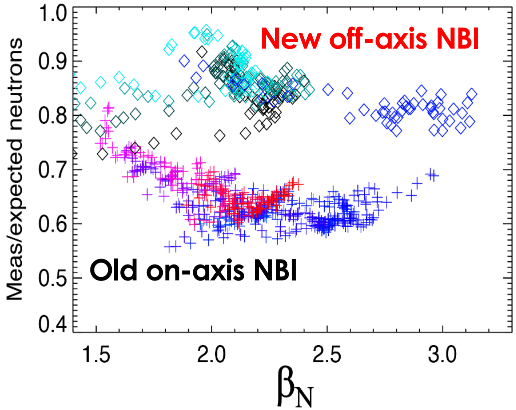




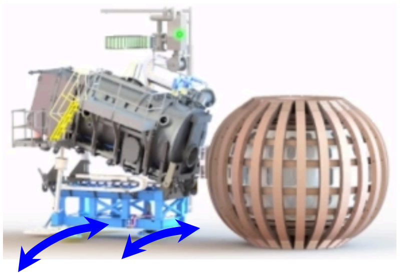
Performance of High-q_{min} Plasmas Improved by Increased Off-Axis NB Power Reducing AE Drive and Fast Ion Losses



- **Reduced beam pressure gradient at ρ_{qmin} gives higher thermal pressure and ratio of neutrons/ TRANSP(classical)**



- **New off-axis NBI current drive matches simulations**



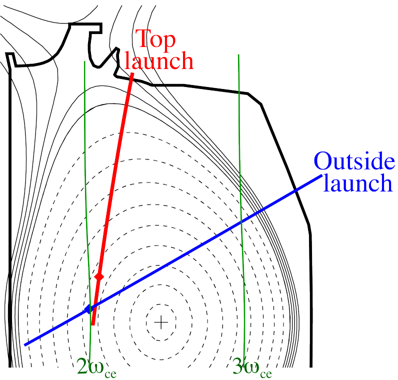
- **Recovered up to 25% of neutrons ratio (35% with added ECCD)**
- **10% higher confinement, 15% higher β_N**

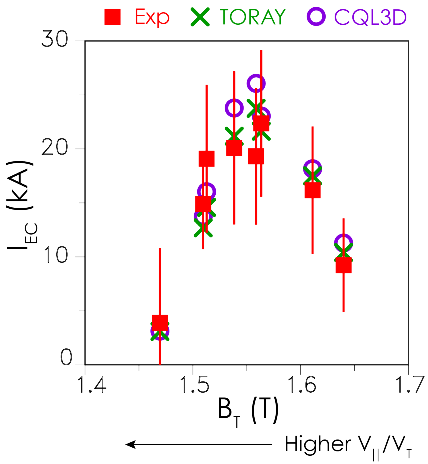
Optimization to classical fast ion confinement possible in steady state reactor scenarios

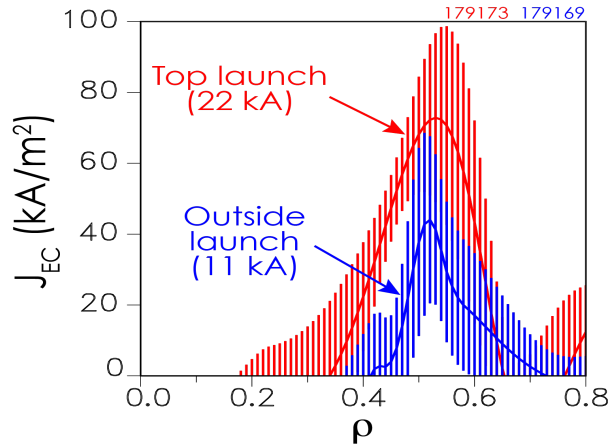
B. Grierson (poster), P/1, Tues AM

C. Collins (oral), EX/8 Sat AM

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**

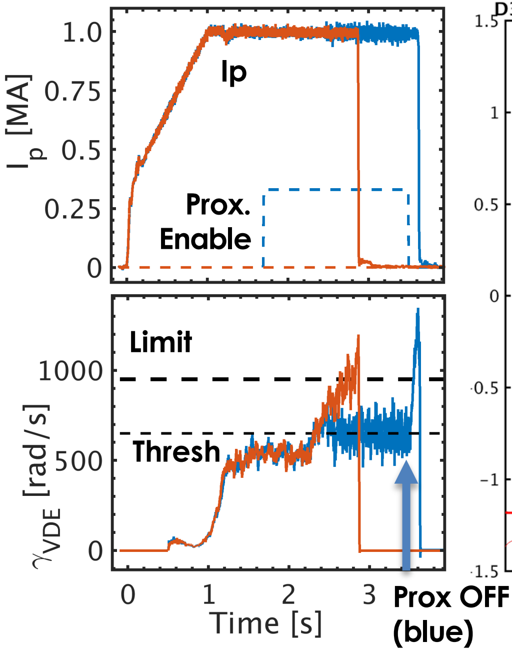
Path to optimized off-axis ECCD for reactor steady state scenarios

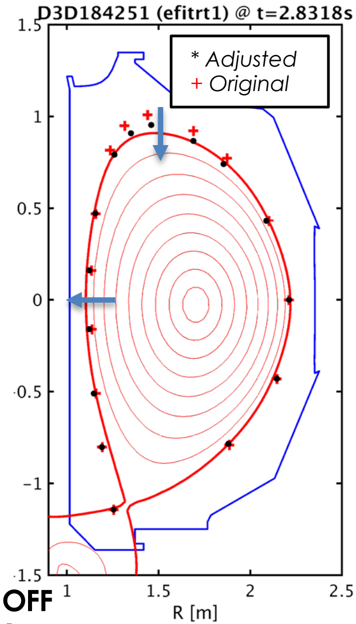
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

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

Xi Chen (oral), EX/1, Tues AM

Techniques for Continuous Avoidance of Vertical Displacement Events Demonstrated Experimentally





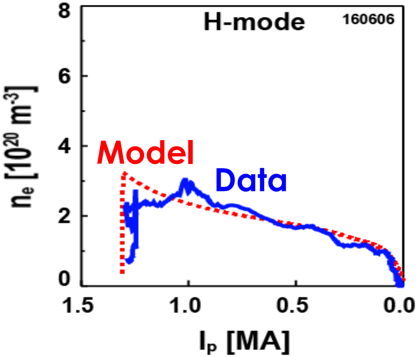
- **Real time proximity-to-instability controller provides robust VDE prevention**
- **Proximity evaluated from either real time linear stability or machine learning database techniques**
- **Real time κ and inner gap variation regulates VDE growth rate**

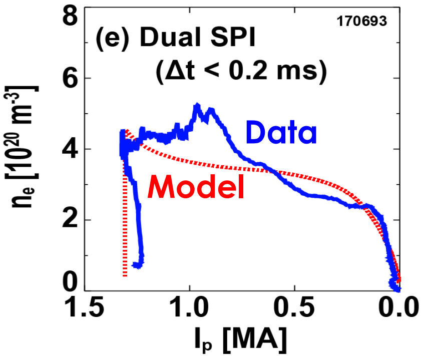
Proximity detection algorithm qualified for VDE avoidance in ITER

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

J. Barr (oral), EX/5, Fri AM

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



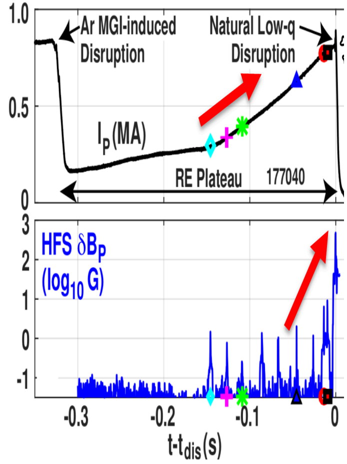


- Dependence of dual pellet high-Z assimilation and CQ rates reproduced
- Heat load peaking factors close to ITER limits
- D_2 SPI disruption dynamics set by MHD

- High-Z Shattered Pellet Injection (SPI) particle assimilation fractions and CQ rates predictable from global energy balance and from empirical scaling laws

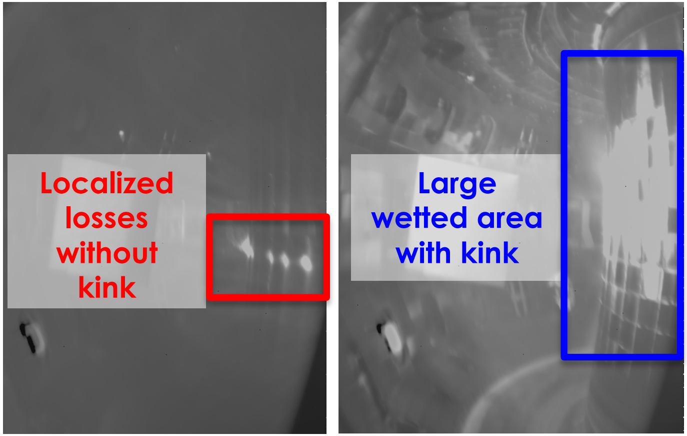
Global behavior of multi-(high-Z)-SPI optimization for ITER now predictable

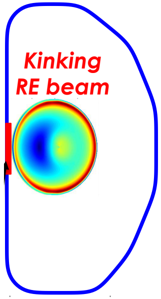
Kink Instability Provides Novel Path to Runaway Electron Mitigation For High Current RE Beams



- Final large MHD burst at q_a=2 dissipates RE beam in pure D_2 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

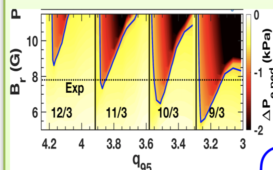
C. Paz-Soldan et al., PPCF (2019)

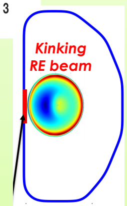
Paz-Soldan (poster, rapp). EX/5, Fri AM

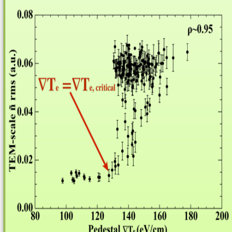
DIII-D Research Advances the Physics Basis for Optimizing Future Fusion Reactors

1. New Physics Actuators

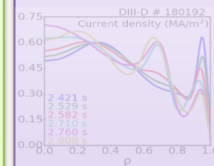
2. Key Physics Understanding

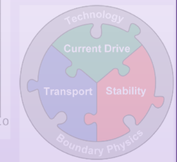


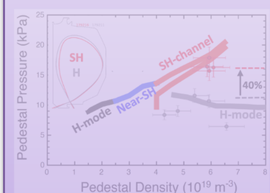




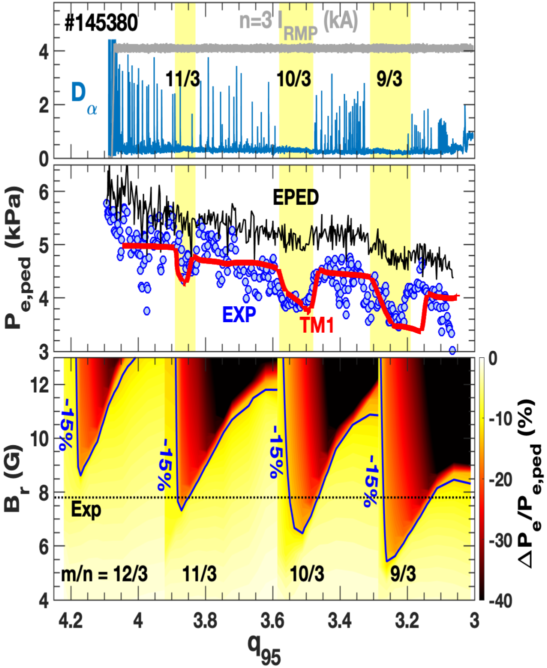
3. Integrated Core-Edge Scenarios



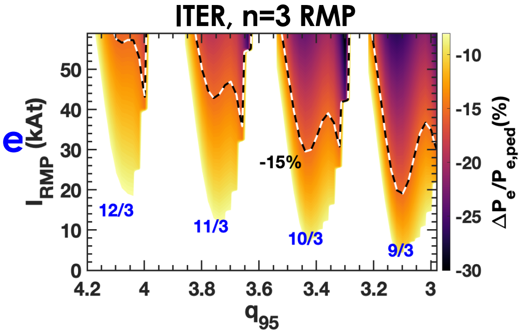


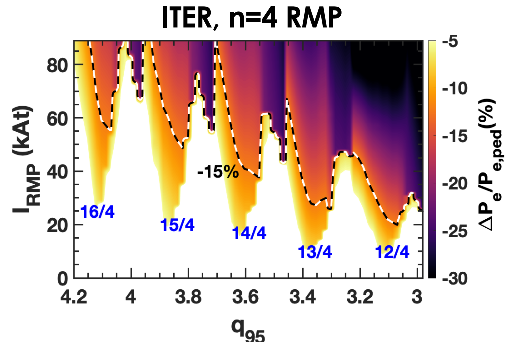


TM1 Non-linear Plasma Response Model Predicts Narrow Isolated q_{95} Windows of RMP ELM Suppression



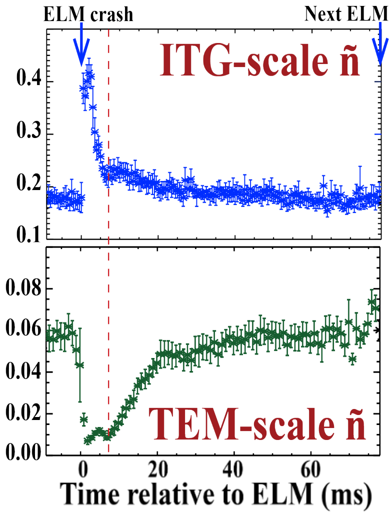
- ELM suppression windows, β_N, and shape dependence predicted by p_e^{ped} reduction
- Developed predictive Br penetration scaling that matches full ITER simulations





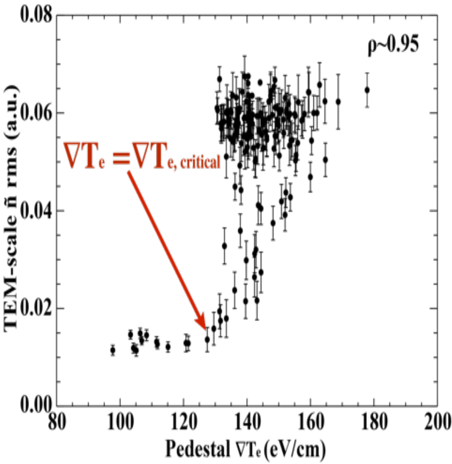
Prediction and optimization of threshold field and Ip range for ELM suppression in ITER

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



For these ν_i*~0.9 plasmas:

- Changes in ITG-scale ñ consistent with transport drive as Q_i decreases from anomalous towards neo-classical
  - ITG-scale ñ increases after ELM, then reduced or suppressed by ExB shear



- TEM-scale ES fluctuations have potential to substantially explain anomalous Q_e
  - TEM-scale ñ 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

J. Chen et al., PoP (2021)
J. Chen et al., PRL (2020)

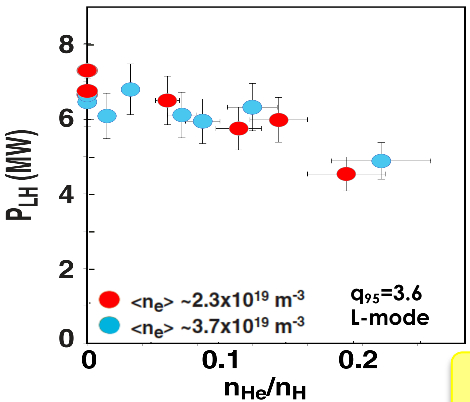
J. Chen (poster), P1, Tues AM

K. Barada (oral), EX/2, Weds PM

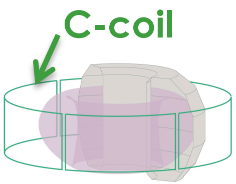
Techniques Identified to Reduce L-H Transition Power Threshold in ITER-Similar-Shape Hydrogen Plasmas

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

P_{LH} reduced up to 35% with He-doping at low/high <n_e>



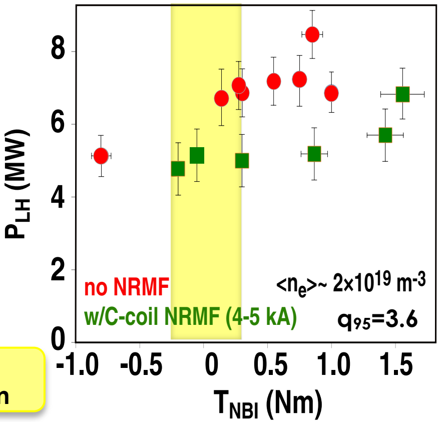
Low torque $T_{NBI} \leq 0.4$ Nm



- P_{LH} reduced due to edge NTV counter-torque

Low torque $T_{NBI} \leq 0.3$ Nm

P_{LH} reduced via applied n=3 NRMF

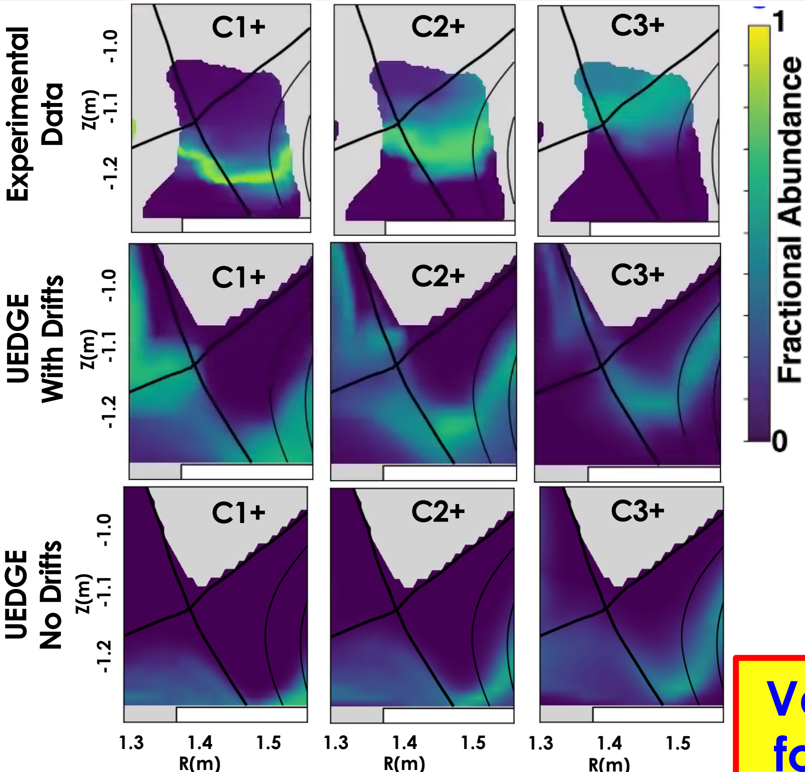


Identifies actuators to reduce P_{L-H} in ITER non-nuclear phase

See Belli, Th/5, Thu AM

L. Schmitz (poster), P/1, Tues AM

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



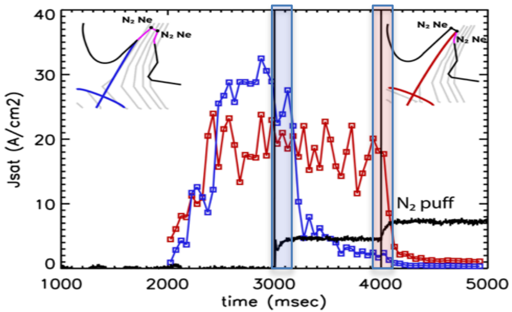
- 2D profiles of impurity charge states from EUV/VUV, Divertor TS and Collisional Radiative model
- Departure from a fixed fraction: Detached 10x lower than attached
- 2D profiles comparable to UEDGE only when drifts and multi-species carbon transport included

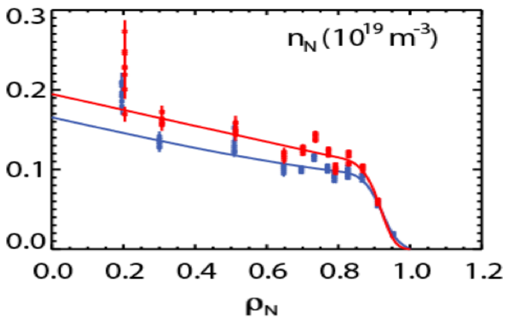
Validated essential models for predicting detachment in ITER and reactors

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

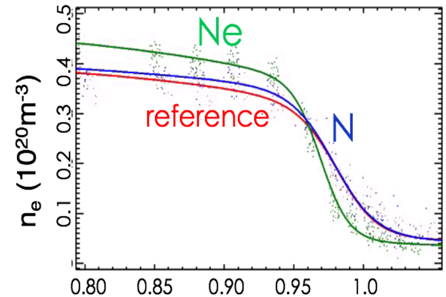
McLean [Samuell] (poster) P1, Tues AM

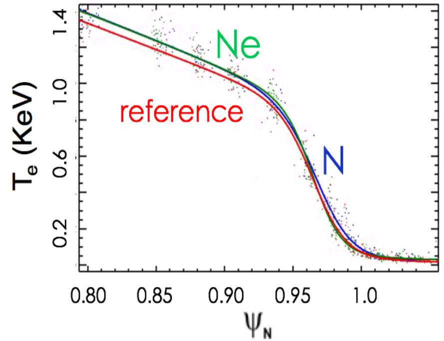
Path to Optimize Detachment and Pedestal by Target Geometry and Impurity Species Demonstrated in SAS Divertor





- Improved performance with OSP on SAS slanted baffle vs corner
  – Jsat rollover with lower N and upstream ne
  – Lower core N
- Modeling with drifts is required: points to main ion flow changes
- Pedestal ne gradient and height increased with Ne radiating mantle



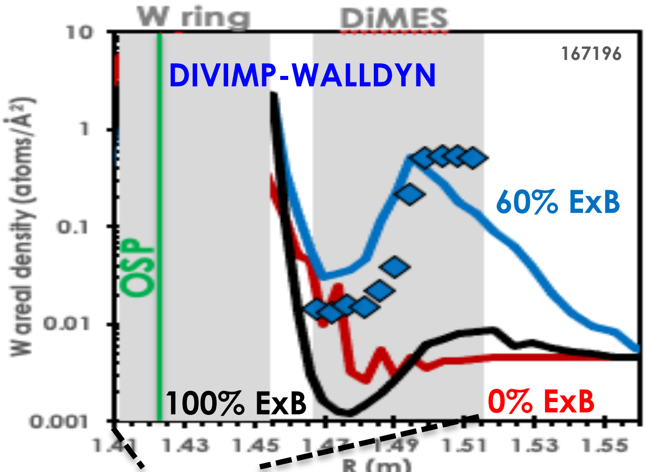


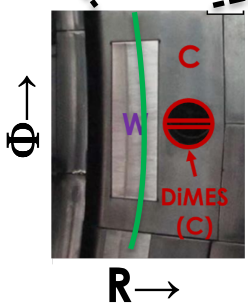
Increased confidence in predictions of divertor detachment optimization by geometry and choice of impurity

L. Casali et al., PoP (2020)

Casali (poster), P/1, Tues AM

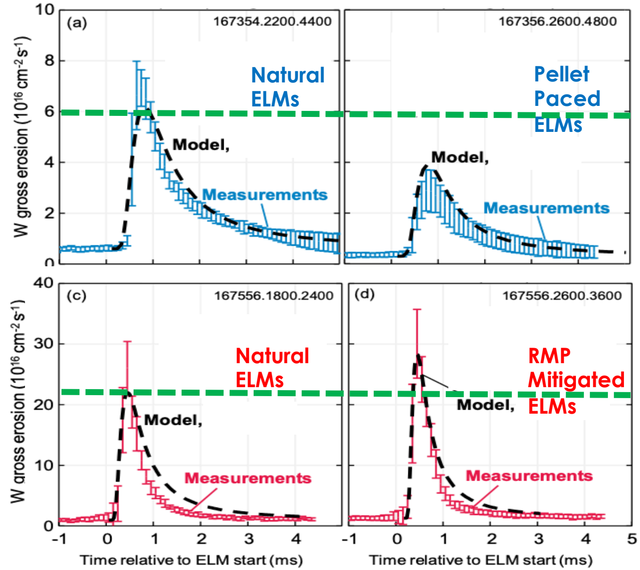
ExB Drifts Important to High-Z Divertor Erosion and Redeposition Both in L-mode and During ELMs





J. Nichols, NF submitted (2021)

- ExB drifts dominate W target multi-step migration



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

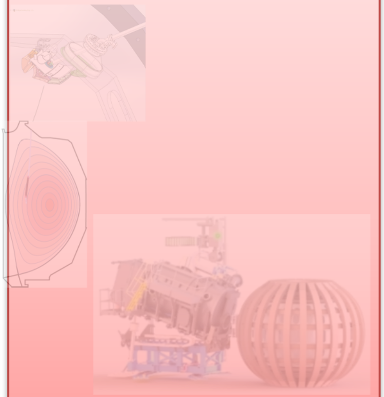
Validated W erosion and redeposition models increase predictability for ITER

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

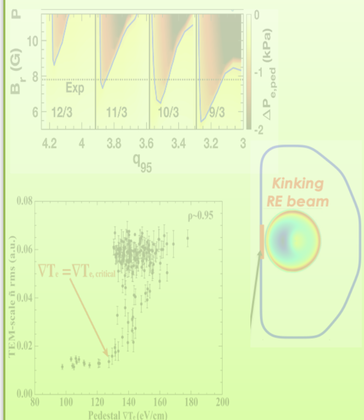
T. Abrams (poster), P1, Tues AM

DIII-D Research Advances the Physics Basis for Optimizing Future Fusion Reactors

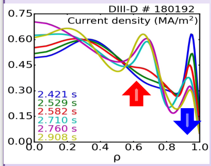
1. New Physics Actuators

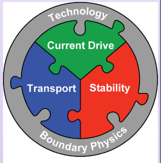


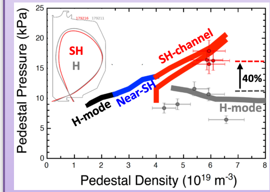
2. Key Physics Understanding



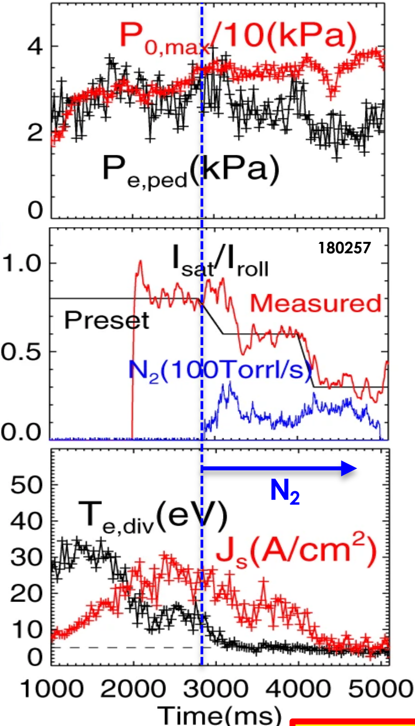
3. Integrated Core-Edge Scenarios



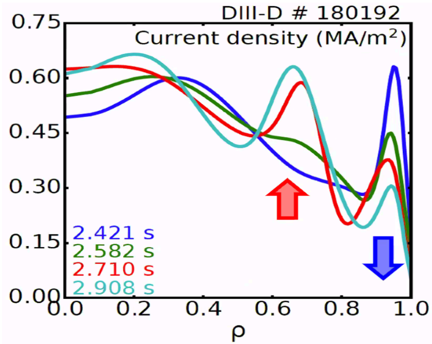




Large Radius ITB in High β_p Scenario Compensates Pedestal Reduction in Detachment for Excellent Core-Edge Integration



- **Sustained high performance core β_N~3, β_p>2, H_{98}~1.5, f_{GW}~0.9, q_{95}~7-8**
- **Nitrogen seeded divertor detachment**
- **Large radius ITB where j(r) peaks**



- **ITER simulation predicts ITB at ρ=0.7, Q=10 at 7.5MA (q_{95}=7.7) and P_{fus}=300MW**

S. Ding et al., NF (2020)

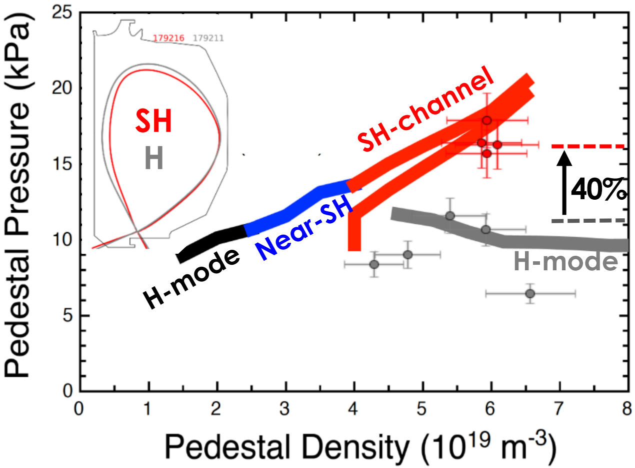
Pedestal height decreases -> Magnetic shear decreases at large radius

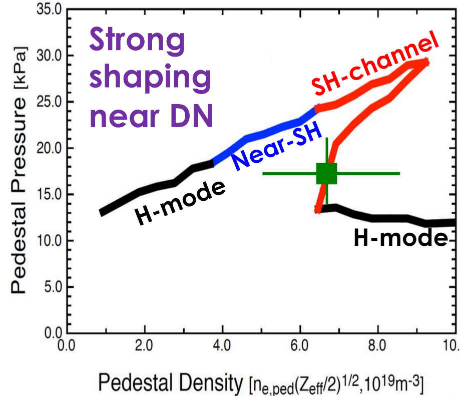
Plasma self-organizes into low transport state at higher core pressure gradient

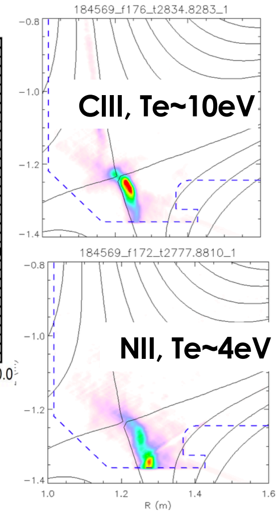
H. Wang et al., PoP 2021
L. Wang, Nature Comm 2021

Demonstrates viable core-edge integration in high β_p scenario may be accessible to ITER

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







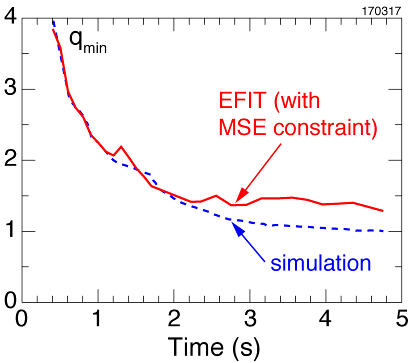
- Stationary Super H achieved in a JET-compatible ITER-like shape
- Predict 50% p_e^{ped} increase for ITER
- Divertor OSP at detachment onset using N_2 with peeling limited pedestal at SH channel entrance

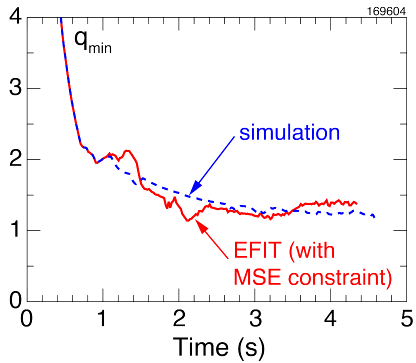
Integrated core-edge solution with a Super H pedestal and dissipative divertor may be possible for ITER

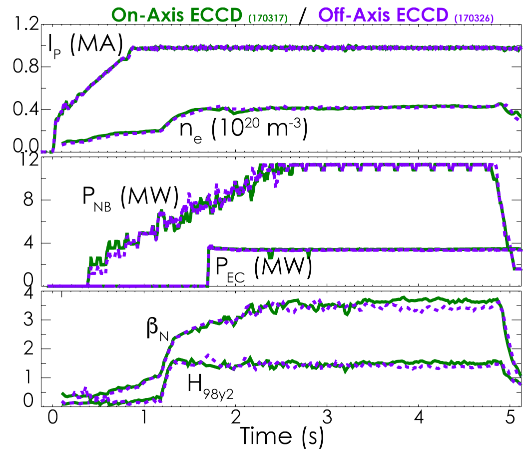
18

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 sawteeth-free, high-β, high-H_{98} performance**



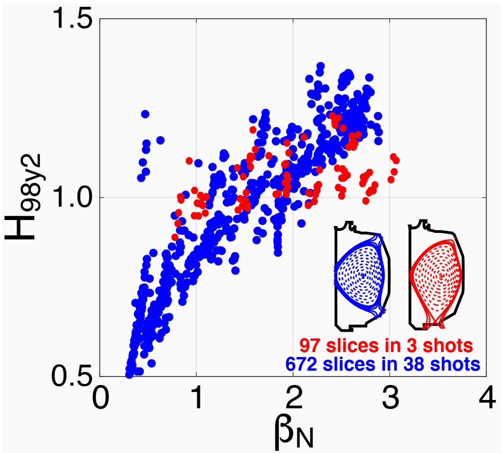




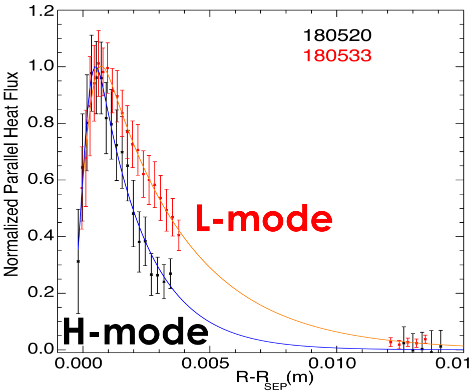
No sawteeth in either case

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 ($H_{98y2} \lesssim 1.2$, $\beta_N \lesssim 3.0$) but no ELMs (L-mode edge) up to 5x $P_{L\text{-}H}$**
  - **Ballooning modes close access to 2nd stability and prevent pedestal growth[1]**
- **Stored energy increase stronger with P_{inj} than L-mode**



- **Promising for core-edge integration with 30-50% broader λ_q, low Zeff~1.5 and impurity τ_p/τ_E~1**

Points to possible transformational characteristics of negative triangularity shapes for reactors

1. Saarelma PPCF submitted

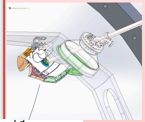
A. Marinoni et al., PoP 2019
M. Austin et al, PRL 2019

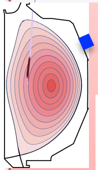
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

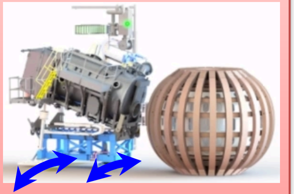
A. Marinoni (oral), EX/6, Fri PM

DIII-D Research Advances the Physics Basis for Optimizing Future Fusion Reactors

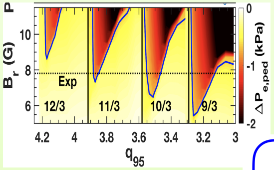
1. New Physics Actuators

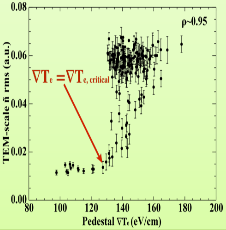


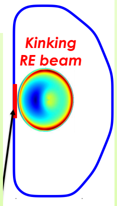




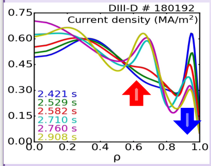
2. Key Physics Understanding

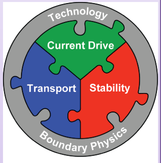


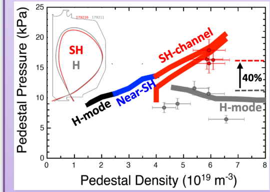




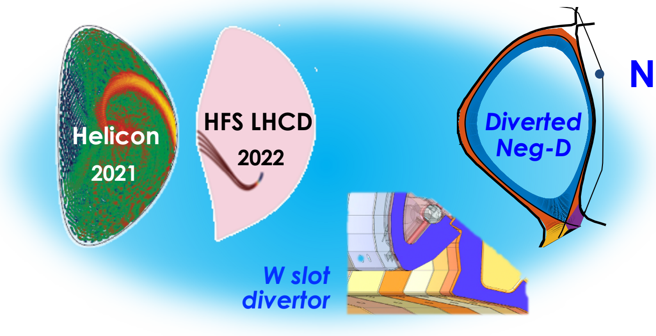
3. Integrated Core-Edge Scenarios



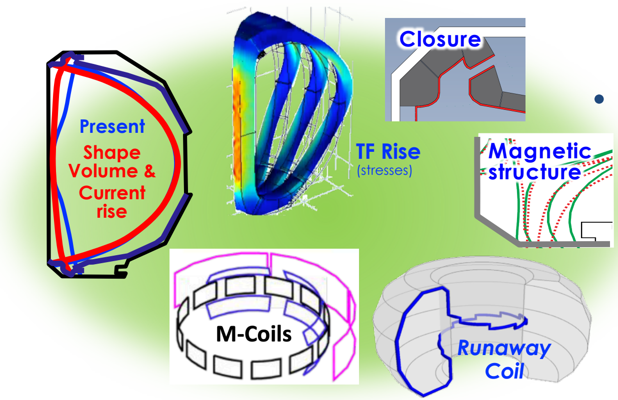




Future Plans Target Integrated Core-Edge Solutions for ITER and a Fusion Pilot Plant



- **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