High Fusion Performance in Super H-Mode Experiments on Alcator C-Mod and DIII-D

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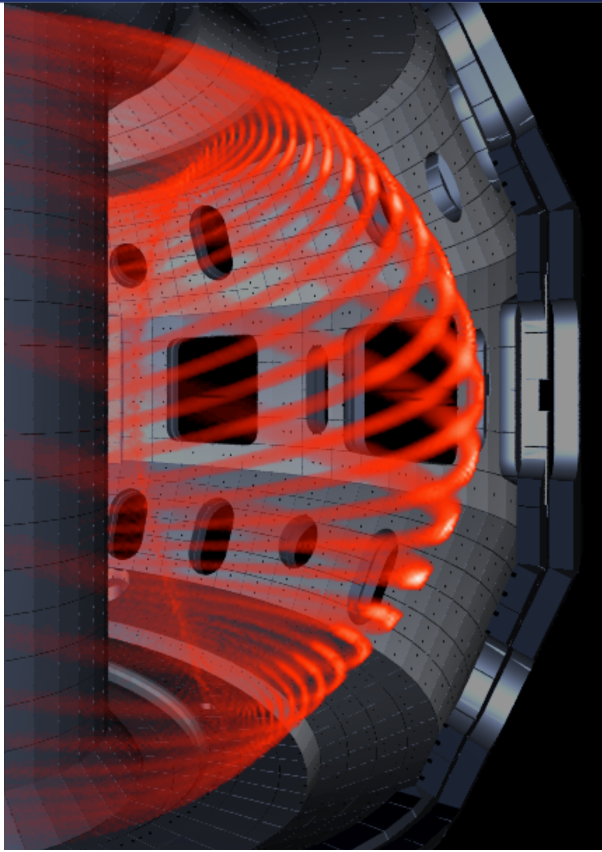

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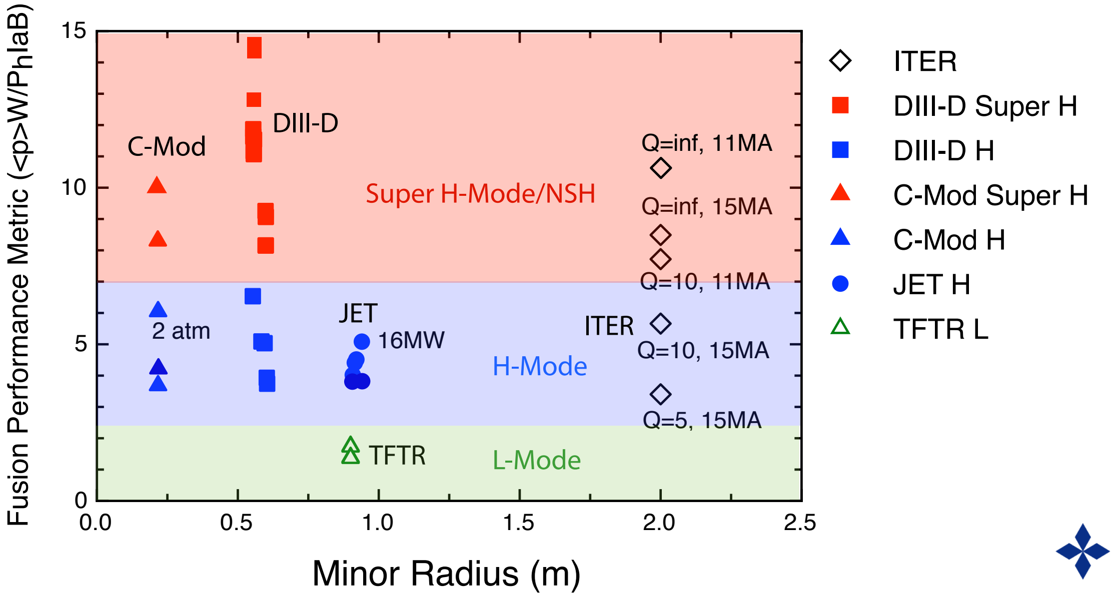
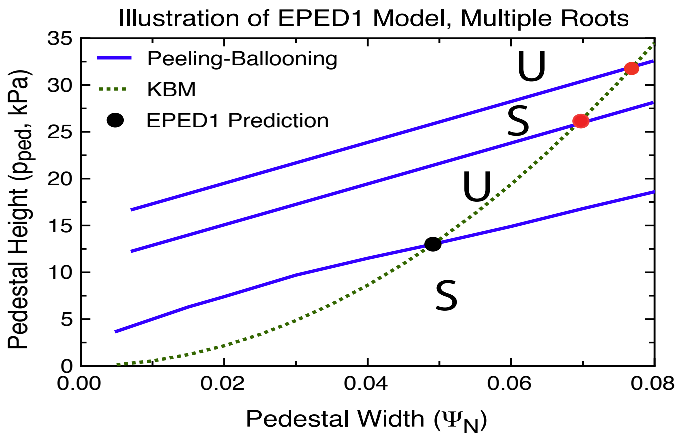
Super H-Mode Experiments on Alcator C-Mod and DIII-D Achieve High Fusion Performance, Record Pedestal Pressure

- **Super H-mode (SH) predicted in strongly shaped plasmas: high p_{ped}, increases with n_e** *[Snyder NF15]*
- ***Record pedestal pressures*** **(~80 kPa) achieved in C-Mod SH experiments** *[Hughes NF18]*
    - Successful tests of EPED model up to ~90% of predicted ITER p_{ped}
- ***Record DIII-D fusion gain*** **($Q_{DT,eq}$~ 0.54). $Q_{DT,eq}$/IaB and $Q_{DT,eq}/(RB)^2$ highest reported on any tokamak**
- **High performance sustained w/ 3D magnetic perturbations to control n_e and impurity accumulation**
- ***Predicted to enable high performance on ITER, and be compatible with high separatrix density for divertor solutions***



EPED Model Predicts a High Pedestal "Super H-Mode" Solution

- **EPED** *(Snyder NF11)* **normally predicts a single pedestal solution**
  - Intersection of calculated peeling-ballooning (PB) and KBM criticality
  - Predicted using sets of realistic model equilibria w/ self-consistent bootstrap current
- **At strong shaping, fixed input parameters (including density), PB mode can go from stable to unstable (pressure driven) and back to stable again with increasing pressure and current: multiple roots for two "equations", PB and KBM**



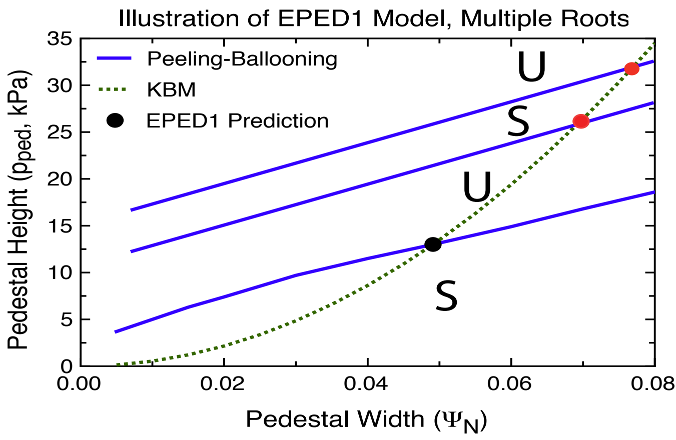
EPED Model Predicts a High Pedestal "Super H Mode" Solution

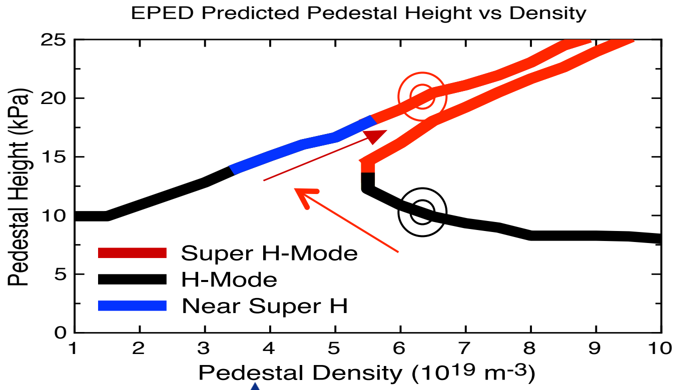
- **Expect only lowest solution to be accessible for these parameters. However, can move in third dimension (eg density) to access higher roots (Super H)**

- **SH predicted by theory** *[Snyder12,15]*, **discovered and explored in counter I_p campaigns on DIII-D** *[Solomon14, Snyder15, Garofalo15, Solomon16]*

2016 C-Mod: L-I-H transition to explore Super H regime access

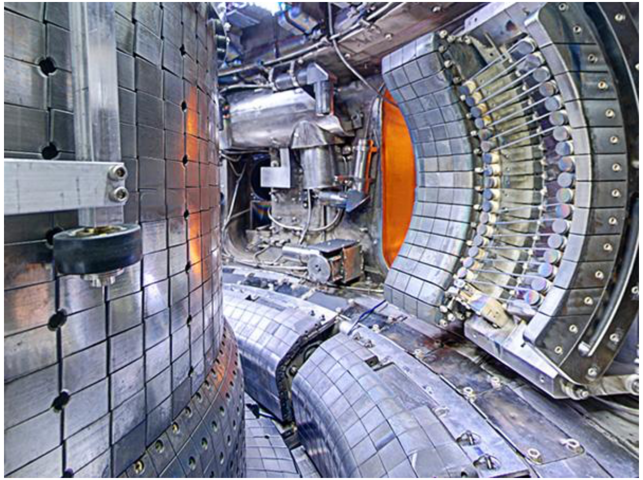
2017-18: DIII-D: co-I_p SH expts explore performance and core-edge

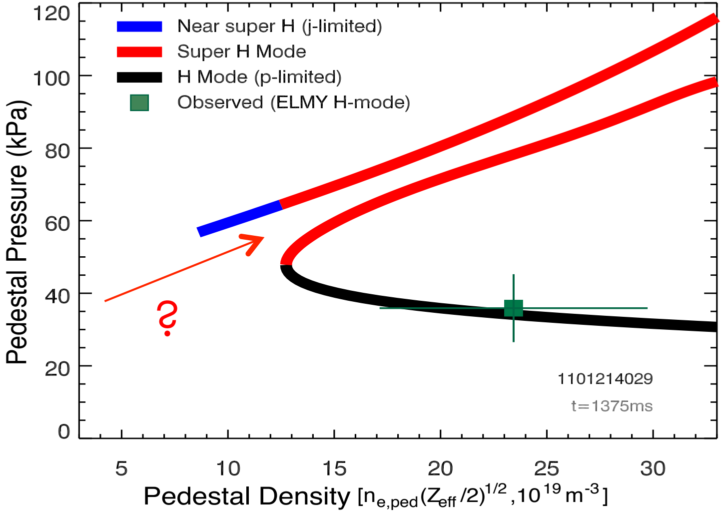




High peak performance in Super H-Mode experiments

Very High Super H Mode Pressure Predicted for C-Mod



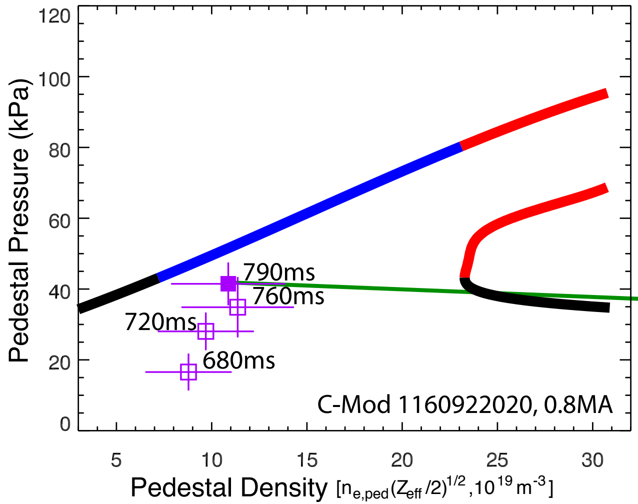


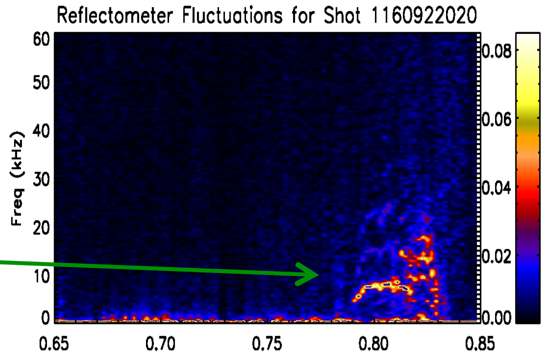
Alcator C-Mod

- **Alcator C-Mod is a compact, high field device (here B_t~5.3T), capable of high δ**
  - After discovery of Super H-Mode on DIII-D, predictions were made for C-Mod (right)
    - *Test SH theory at high B_t & B_p, zero injected torque (RF), high Z metal wall*
  - Following the right parametric trajectory should enable very high pressure
    - *Need to reach densities much lower than typical for C-Mod H-mode to access Super H*
    - *Challenging to do on a high-Z metal wall device like C-Mod*

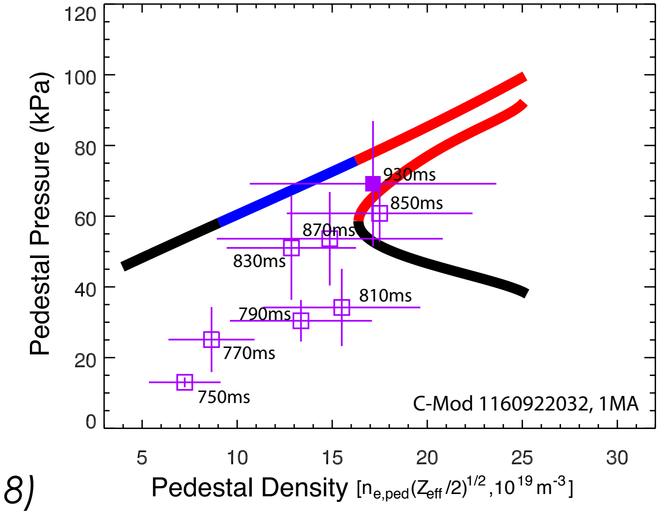
Alcator C-Mod

Access to Super H Mode on C-Mod Achieved via L-I-H Transition





*Hughes et al, NF **58** 112003 (2018)*

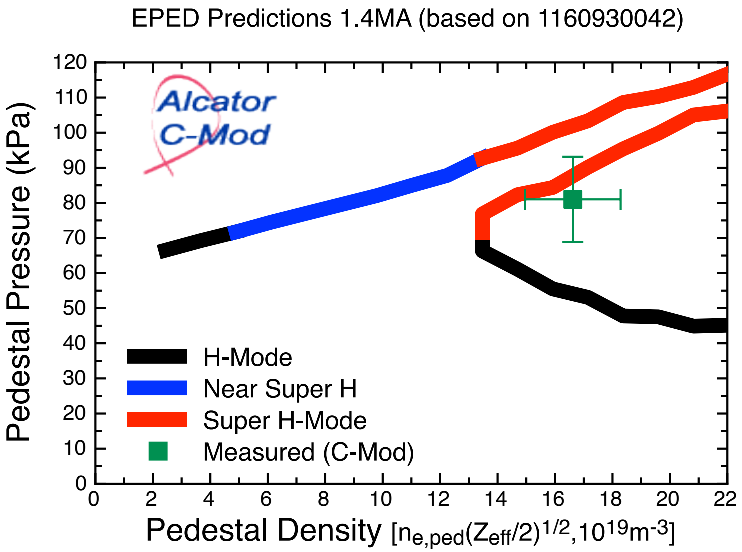


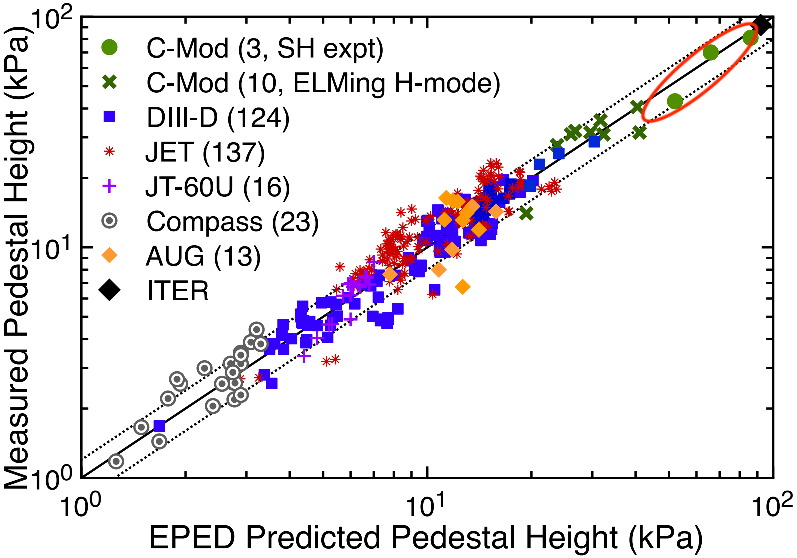
- **Transitioning first to I-mode, then to H-mode leads to a low n_e, low impurity H-mode (left)**
- **As pedestal approaches predicted kink/peeling limit, low n mode observed (center)**
- **Discharges at 1MA, 5.4T reach SH regime, p_{ped}~70 kPa (right)**

Alcator C-Mod

GENERAL ATOMICS

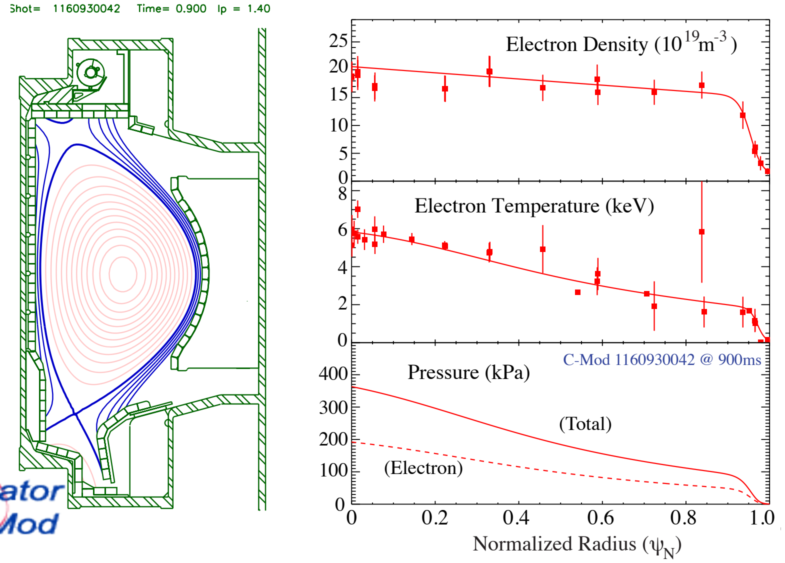
Super H-Mode Experiments on C-Mod Yield ITER-like p_{ped}

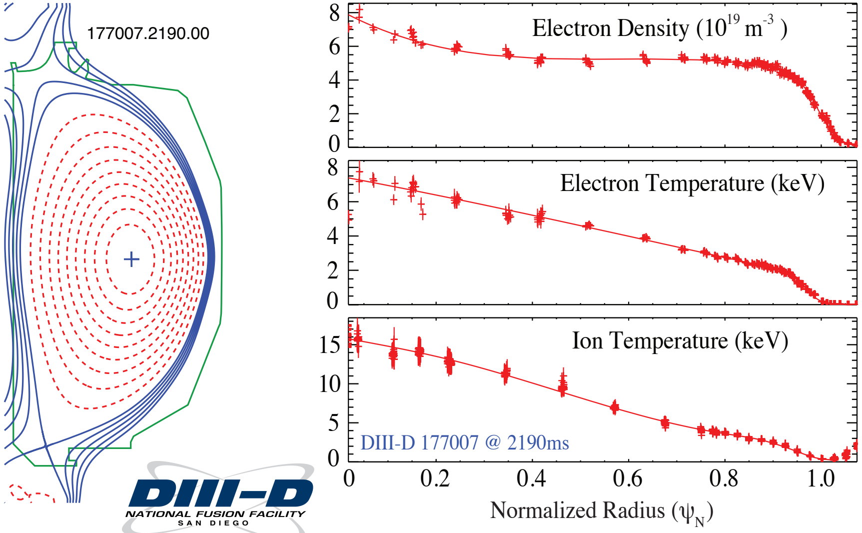




- **Super H-Mode expt at 1.4MA achieved record 81 kPa pedestal pressure on last day of Alcator C-Mod operations, ITER-like pressure at ITER-like field** ***[Hughes NF 2018]***
  - EPED model successfully tested over 2 orders of magnitude in pressure on 6 tokamaks
    - *No indication of significant variation of model accuracy with ρ^* or p_{ped}*

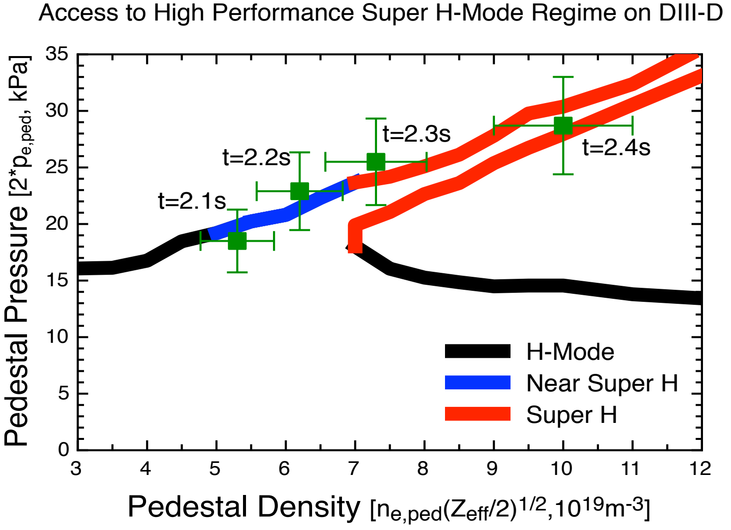
Broad Profiles and High Pressure Obtained in Both C-Mod and DIII-D

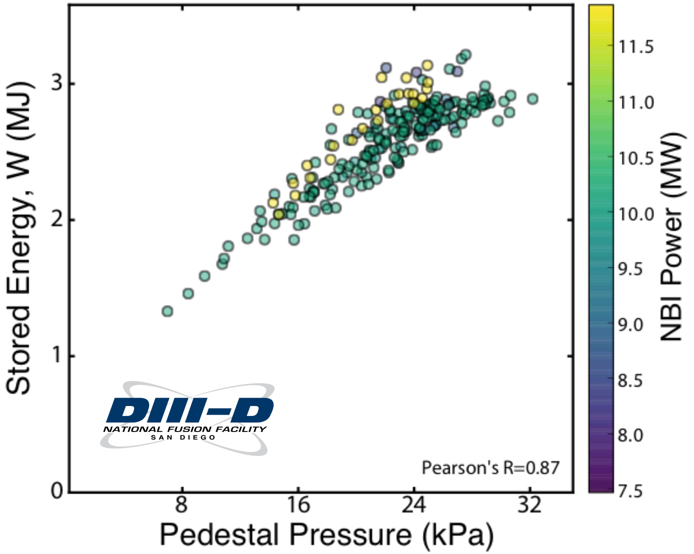




- **High pedestal pressure enables good confinement, high global MHD limits**
  - C-Mod: B_t=5.3-5.8T, I_p=0.8-1.4MA, a=0.19m, R=0.67m, δ ~0.5
    - *<p> ~ 100-170 kPa, p_{ped} ~ 50 - 80 kPa*
  - DIII-D: B_t=2.1-2.2T, I_p=1.6-2.0MA, a=0.6m, R=1.67m, δ ~0.5-0.7
    - *<p> ~ 70 – 110 kPa, p_{ped} ~ 20 – 32 kPa, $T_{i,0}$ ~ 14 -18 keV*

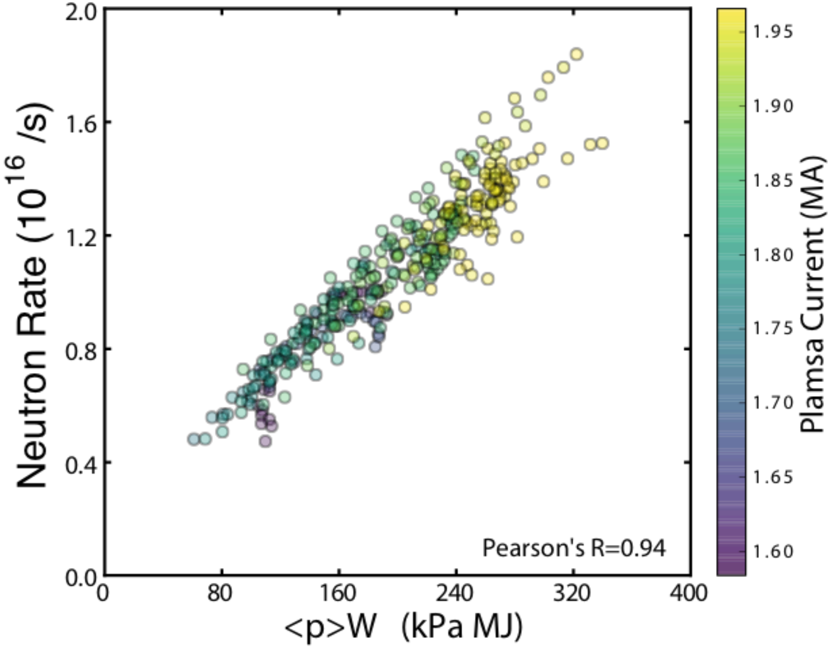
Very High Pedestal Pressure, Stored Energy, and Confinement Time in Recent co-I_p Super H-Mode Experiments on DIII-D

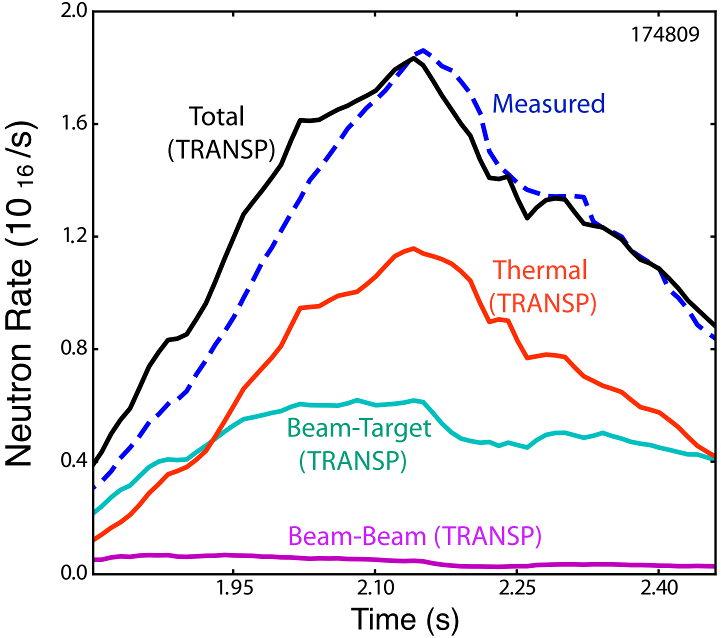




- **Deep access into Super-H regime, good agreement with EPED predictions**
  - B_t=2.17T, I_p=1.6-2.0MA, a=0.6m, δ ~0.5-0.7
  - p_{ped}~30kPa, W~2 - 3.2 MJ (highest in present DIII-D config.) at modest P_{nbi} ~ 8-12 MW
  - Peak τ ~0.4-0.7s, H_{98}~2.2-2.9, <p> τ_E ~ 30-67 kPa s, nT τ ~ 4 - 8 10^{20} keV m^{-3} s

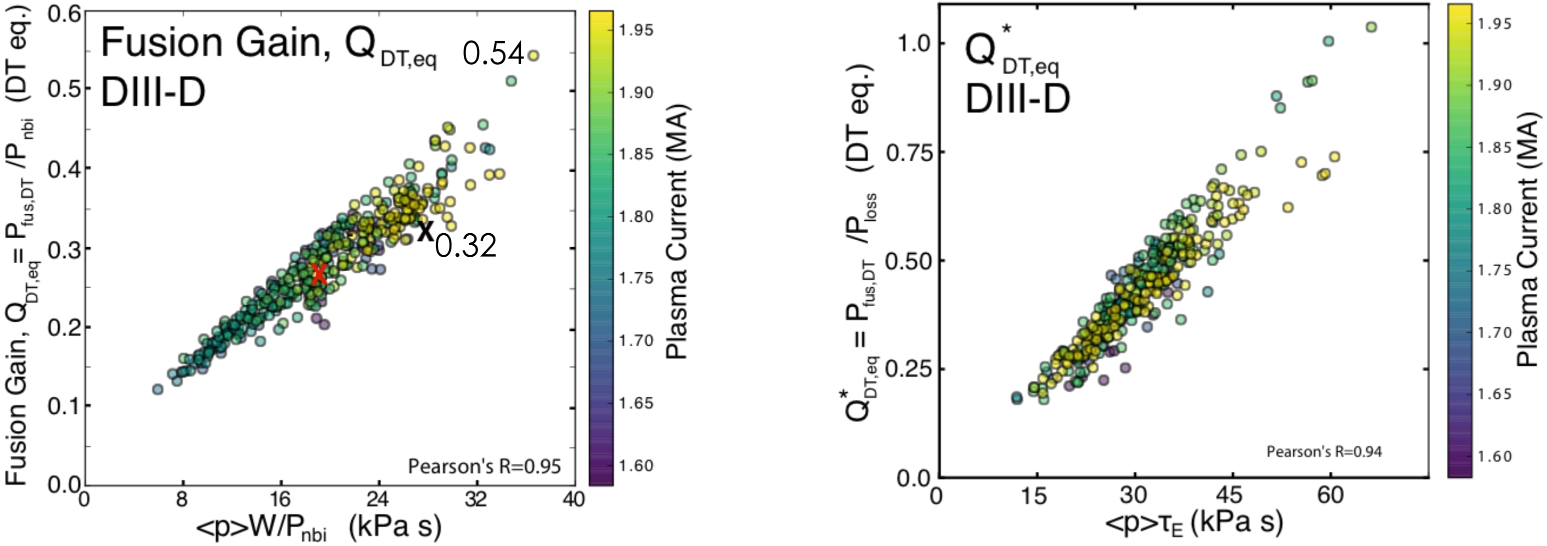
High Pedestal Pressure and T_i Enable High Peak Fusion Performance on DIII-D





- **DD neutron rates up to 1.85 10^{16}/s**
  – ~2/3 thermal, $P_{fus,DD}$ ~ 22 kW, $P_{fus,DT,eq}$ ~ 4.8 MW (at P_{nbi} ~ 9 MW)

High Pedestal Pressure and T_i Enable High Peak Fusion Performance on DIII-D, Record Fusion Gain



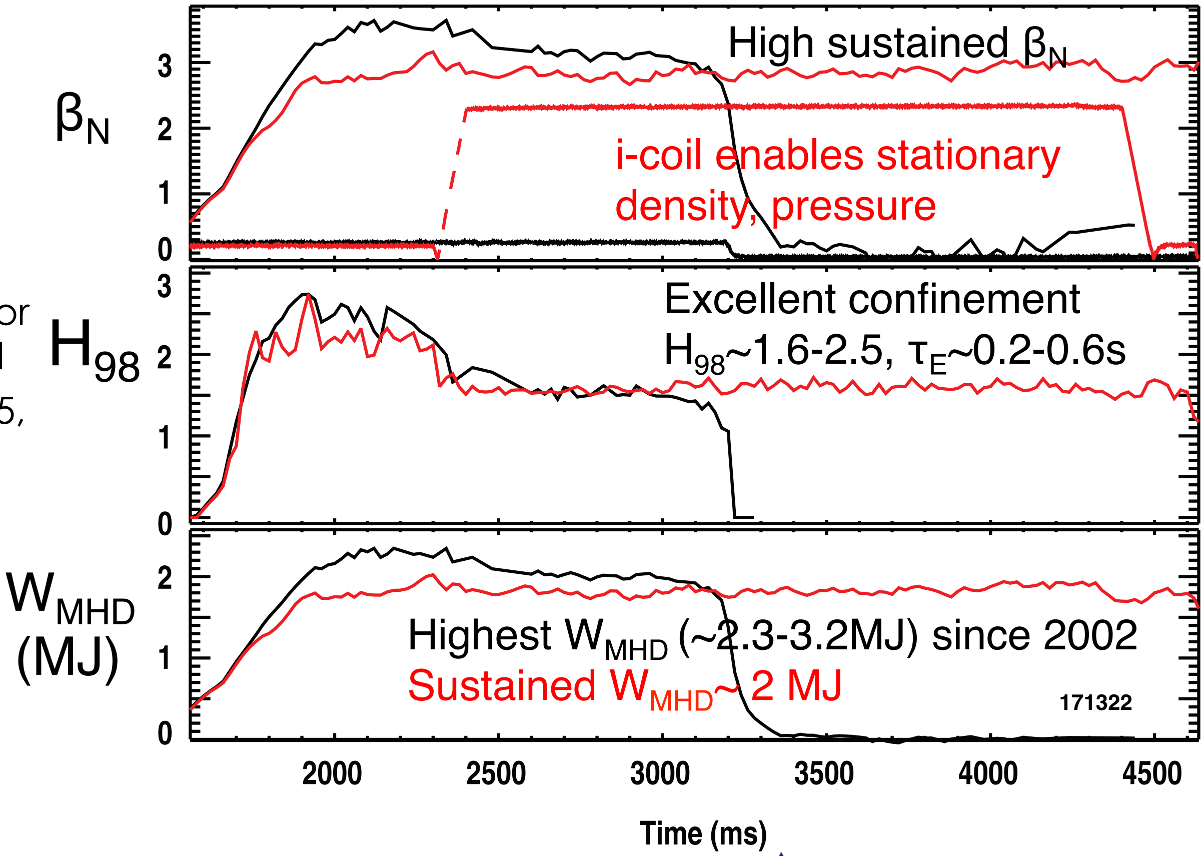
- **Equivalent $Q_{DT,eq} = P_{fus,DTeq}/P_{nbi} \sim 0.54$. $Q^*_{DT,eq} = P_{fus,DTeq}/(P_{nbi} - dW/dt) \sim 1$**
  - *Previous DIII-D record Q = 0.32, Lazarus96 in negative central shear discharges with 2.2MA, 22m^3*
  - Achieved at modest B = 2.17T, I_p=2MA, V=20 m^3. DT_{eq} Fusion power density ~0.2 MW/m^3

Appears to be highest $Q_{DT,eq}$ and <p> τ on any medium size (R<2m) tokamak, and highest $Q_{DT,eq}$/IaB or $Q_{DT,eq}/R^2B^2$ on any MFE device

Sustainment and Core-Edge Compatibility of Super H-Mode Regime

Super H-Mode Sustained Using 3D Magnetic Perturbations to Control Density and Impurity Accumulation

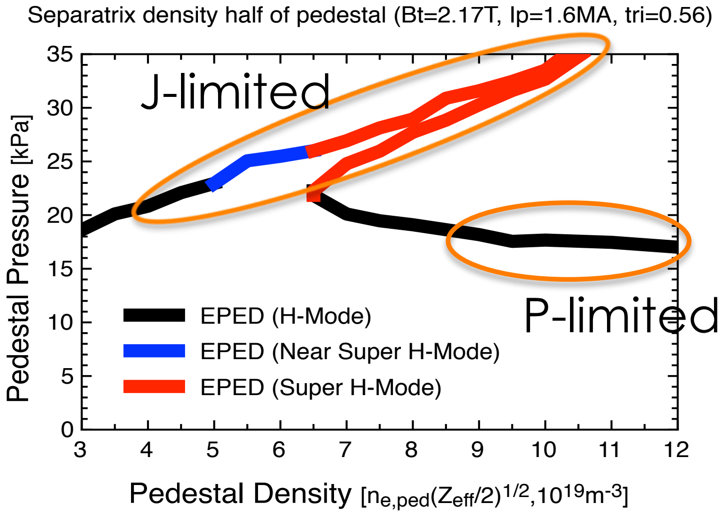
- **High performance condition sustained by applying 3D magnetic perturbation**
  - Controls density and impurity accumulation
  - Feedback control of pedestal or average density demonstrated
  - Sustained W~1.9MJ, $Q_{DT,eq}$~ 0.15, τ ~0.2s, H98~1.6, β_N ~ 2.9
  - ~2s sustainment (hardware limited)



Connecting a High Performance Super H Pedestal & Core to a High Density, Radiative Divertor & SOL

- **Super H (J-limited) solution predicted not to show degradation of pedestal pressure w/ $n_{e,sep}$**
  - P-limited solution degrades with increasing $n_{e,ped}$ and $n_{e,sep}$ (eg high gas puff in JET ILW)

- **Scan D_2 gas rate, and introduce radiative impurities (N_2) into the Div/SOL to test predictions on DIII-D**
  - Use 3D magnetic perturbations (i-coil) to control particle and impurity accumulation in core
  - Use i-coil feedback to maintain ~constant density in pedestal & core as separatrix, divertor and SOL density are increased
    - *Test EPED predictions of sensitivity of pedestal to separatrix conditions*

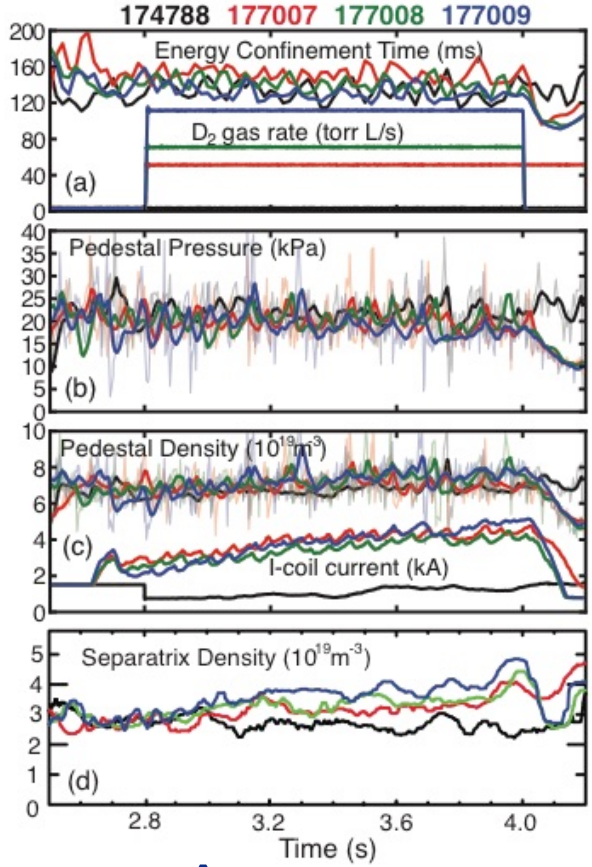


D_2 gas Scan Increases Separatrix and Divertor Density while Pedestal Pressure and Confinement Remain High

- **D_2 gas scan in Super H mode experiment at I_p=2MA, B_t=2.1T. Gas rate varied ~30x**
  - Pedestal pressure and τ_E remain ~fixed, high
  - i-coil feedback control of $n_{e,ped}$ ~ 7-8 10^{19} m^{-3} successful up to~110 torrL/s of D_2 gas
  - Separatrix density rises from ~2.5 – 4 10^{19} m^{-3}
  - Strike point density rises from ~2.5 – 7 10^{19} m^{-3}

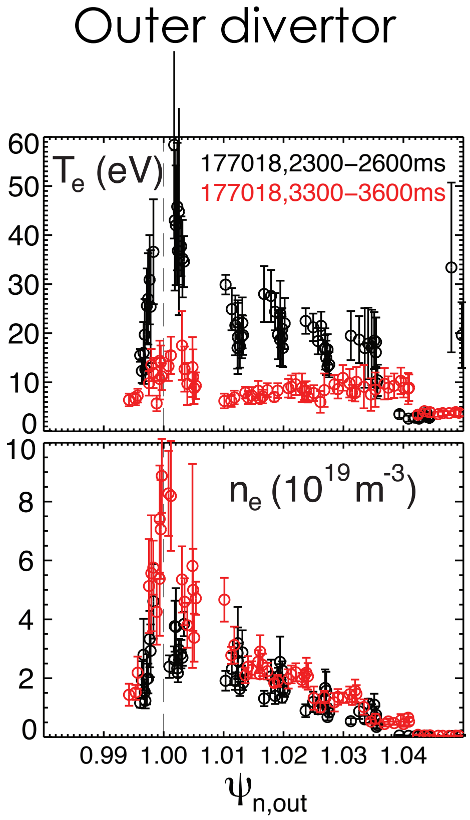
Both pedestal and separatrix density reach ITER values while maintaining high confinement and p_{ped}

Super H-mode compatible with both high fusion performance and high separatrix density for divertor solutions.



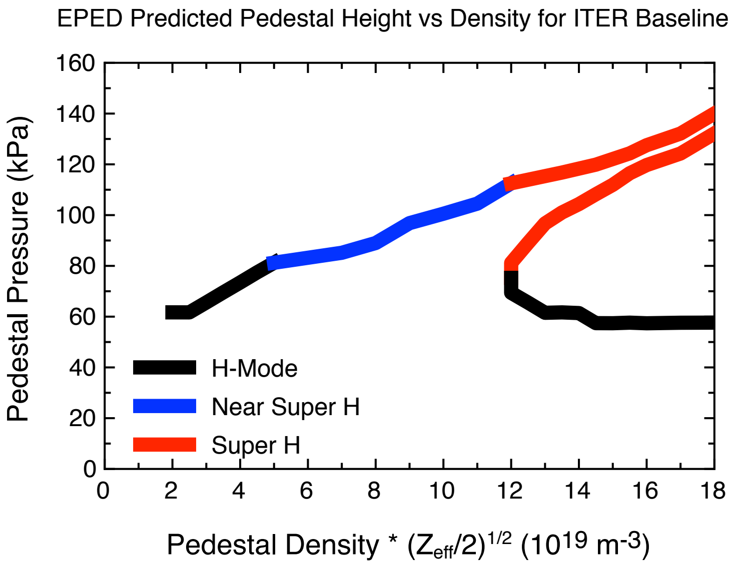
N_2 Injection Effective for Cooling Divertor while Maintaining High Performance Core & Pedestal

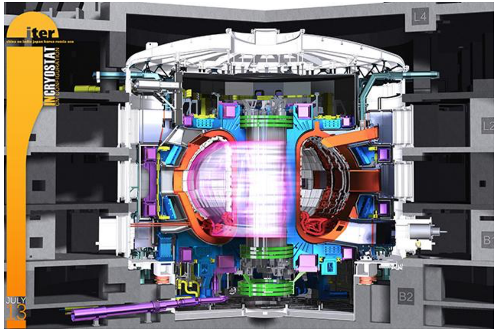
- **Significant cooling with ~5MW of divertor radiated power using feedback on N_2**
  - Peak T_e near strike point drops more than 3x
  - Pedestal pressure and confinement remain ~constant
  - Future experiments needed to explore full detachment and impact of closed divertor



Predictions for ITER, Implications for Compact, High Performance Fusion

Super H/NSH Regime Access is Predicted for ITER: DIII-D has Achieved Needed $\beta_{N,ped}$, $n_{e,sep}$, $n_{e,ped}$ Consistently

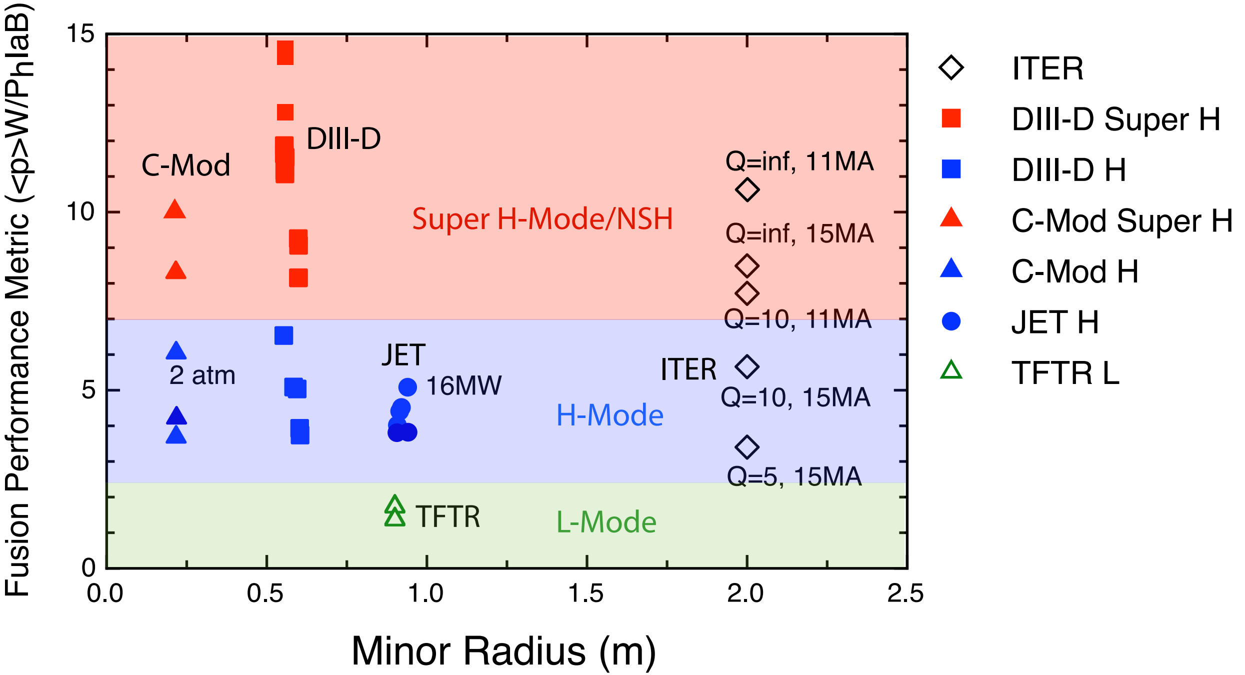




<u>Open issue</u>: Physics of the Greenwald density limit which constrains degree of Super H access and predicted performance for ITER and DEMO concepts

- **Core-pedestal simulations find ITER high performance (Q>10) at high n_e *[Meneghini16]***
- **DIII-D SH experiments reproduce many characteristics of the predicted ITER regime, including $\beta_{N,ped}$~0.8, $n_{e,sep}$~3-4, $n_{e,ped}$~7-10. C-Mod produces p_{ped}~80 kPa**
  - Potential for substantial improvements in ITER performance, consistent with $n_{e,sep}$

Super H and Near Super H Operation Enables Very High Fusion Performance per $I_p a B_t$



Open issues: Challenges for Super H-mode operation include sustainment, impurity control, and ELM control. For JET and ITER, compatibility of strong shaping and nearby metal walls

- **Simple metric of fusion performance (Q or <p>W/P) per $I_p a B_t$**
  - Colored points are observations (<p> > 50 kPa), red points are SH/NSH experiments
  - High Q/IaB enables ITER success, and compact, cost attractive pilot plant

High Fusion Performance and Promising Core/Edge Solutions Developed via Super H Theory & Experiment

- **Theoretical prediction of Super H Mode has guided successful expts on C-Mod and DIII-D**
  - Entering new era where theory can enable predictable, higher MFE performance
- ***Record pedestal pressures*** **(~80 kPa) achieved in C-Mod SH experiments** *[Hughes NF18]*
  - Successful tests of EPED model up to ~90% of predicted ITER p_{ped}
- ***Record DIII-D fusion gain*** **($Q_{DT,eq}$~ 0.54, $Q^{*}_{DT,eq}$~ 1). $Q_{DT,eq}$/IaB ~ 0.21 and $Q_{DT,eq}/(RB)^2$ ~ 0.04**
  - Projects (theoretically & empirically) to excellent ITER performance, compact attractive pilot plant
- **High performance sustained w/ 3D magnetic perturbations to control n_e and impurity accumulation (DIII-D: W~1.9MJ, $Q_{DT,eq}$~ 0.15, τ ~0.2s, H_{98}~1.6, β_N ~ 2.9)**
- **High performance maintained with strong D_2 gas puffing and N_2 injection**
  - Separatrix density reaches ITER values, divertor T reduced by ~3x

Super H-mode compatible with both high fusion performance and high separatrix density for divertor solutions. Projects to excellent ITER performance and compact, attractive pilot plant