How DIII-D Can Access New Plasma Regimes with More ECH to Close Long Pulse Fusion Pilot Plant Knowledge Gaps

C. Holcomb[1], J. Park[2], R. Buttery[3], C. Petty[3], A. Garofalo[3]

[1]Lawrence Livermore National Laboratory
[2]Oak Ridge National Laboratory
[3]General Atomics

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DIII-D Program Aims to Establish the Physics Basis of a Long-Pulse Compact Tokamak Fusion Pilot Plant

	CAT-D
R (m)	4
a (m)	1.29
B_T (T)	7
I_P (MA)	8.1
κ	2
β_N	3.6
β_T %	3.2
f_{BS}	0.9
H_{98y2}	1.51
q_{95}	6.5
Q	17.3
P_{FUS} (MW)	658
P_{NET}(MW)	200

- **Multiple compact FPP design studies exist**
- **CAT-DEMO (Buttery NF '21) is used as a guide here**
- **There are many physics uncertainties, including how to achieve sufficient:**
    1. Core performance (stability, confinement, current drive)
    2. Heat & particle exhaust
    3. Integration of core- and edge- constraints

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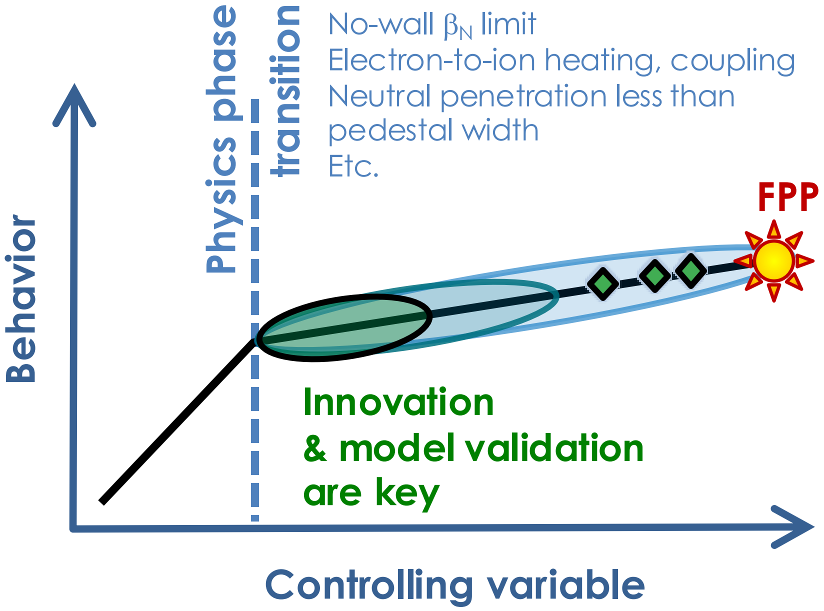
How Far Towards FPP Conditions Must We Go To Sufficiently Reduce Physics Uncertainty?



- **Some physics has "phase transitions where behavior changes**
  - Some known, e.g., β_N>no-wall limit
  - Some uncertain, e.g., turbulence regime vs. rotation
- **Aim to be on the right side of known transitions & have ability to sample large parameter range**
- **Balance maximizing integrated performance vs. wider scans in select parameters**

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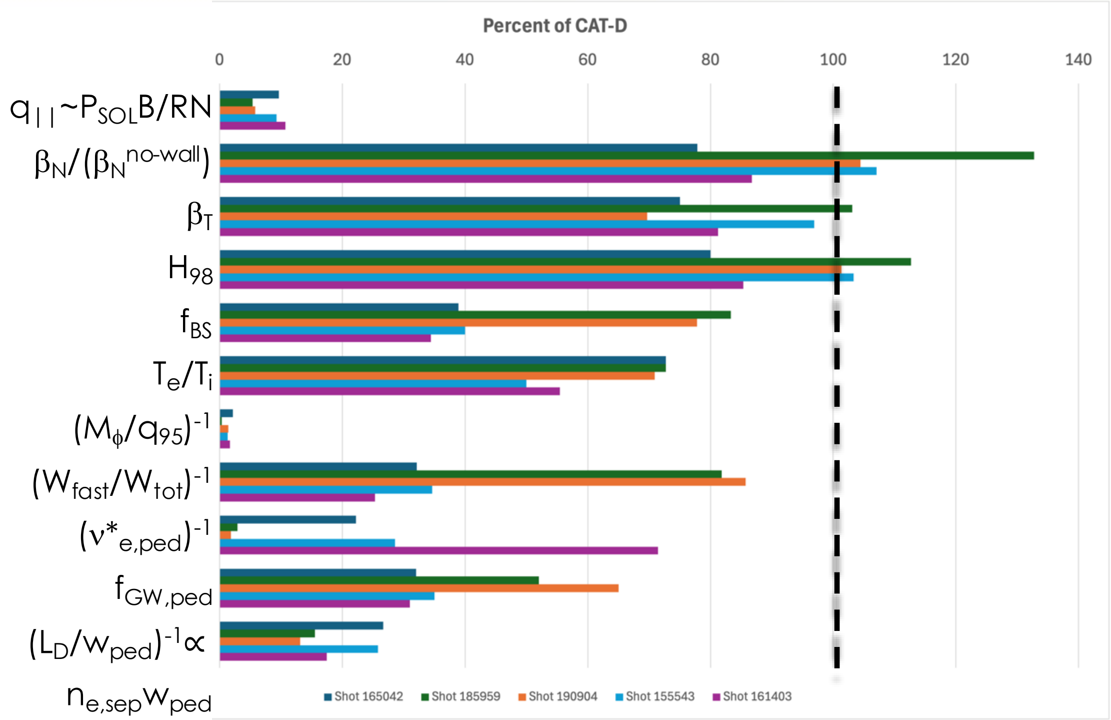
DIII-D Can Improve Confidence in Physics for FPP by Expanding the Ranges of Achievable Parameters



Lower torque hybrid (3-4.5s) Thome NF '21

High-β_P "AT" (2.8-3.4s) Huang NF '24

Lower torque high-β_P (4-4.7s) Ding Nature, '24

Steady-state hybrid (2.5-4.5s) Turco NF '15

ITER-shaped, ELM-suppressed steady-state hybrid (3.5-4.5s) Petty NF '17

- **DIII-D steady-state scenario shots approach some, not all FPP values**
- **Stronger shaping & higher NBI power (20 MW) expected to expand ranges**
- ***<u>Goal of this study:</u> predict minimum ECH power to adequately advance parameter ranges towards FPP***

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Consider 6 Experimental Physics Goals

Physics to understand/Solutions to find	Parameter range to aim for
Pedestal structure with high opacity & low collisionality	Advanced Inductive (AI) scenario with $L_D/w_{ped}<0.2$, $\nu^*_{ped}<0.2$, $f_{GW,ped}>0.8$

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Impacts of low v_ϕ, high T_e/T_i on advanced tokamak (AT) core above no-wall limit	$\Delta M_\phi/q_{95}<10^{-3}$, $T_e/T_i>1$, $q_{min}>2$, β_N=4li-6li, $\beta_T>3\%$,

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How to sustain AT high f_{BS} & H_{98} by optimizing $\hat{s}$ & α_{MHD}	$\hat{s}<-0.5$, $\alpha_{MHD}>3$ at $\rho\sim0.6$, $q_{min}>2$, $\beta_N>3$, $\nu^*_{ped}<0.2$

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Interplay between effects in AT core	Simultaneous increase of key core metrics to > ~60% of CAT-D values

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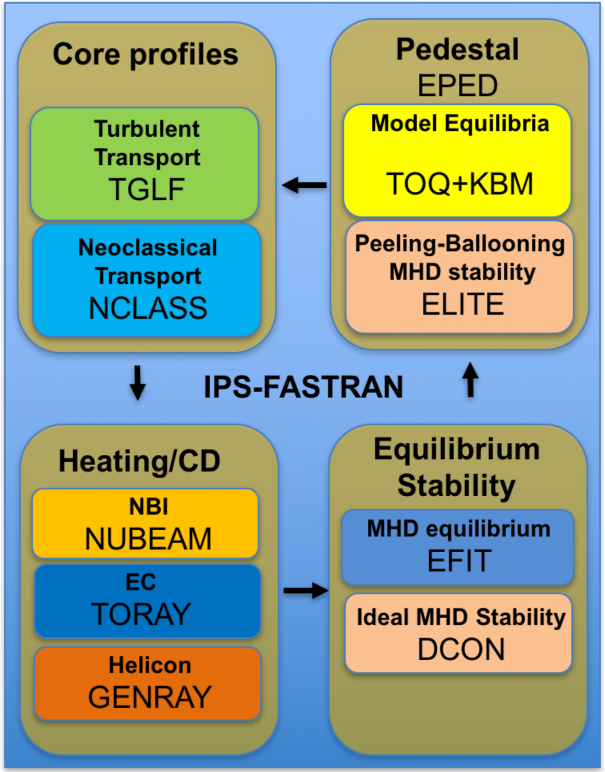
How to sustain AT high f_{BS} & H_{98} by optimizing $\hat{s}$ & α_{MHD}	$\hat{s}$<-0.5, α_{MHD}>3 at ρ~0.6, q_{min}>2, β_N>3, ν^*_{ped}<0.2
Interplay between effects in AT core	Simultaneous increase of key core metrics to > ~60% of CAT-D values
How to manage divertor heat flux	$P_{SOL}B/RN$ significant fraction of unmitigated CAT-D

Integrated Modeling Predictions Done Using FASTRAN-IPS*



- Integrates physics models for transport, H&CD, pedestal, MHD stability, etc.
- Built a database with random sampling over ranges of density, B_T (1.6-2.2T), P_{NBI} (up to 20MW), P_{ECH} (up to 14MW, 105/138/170GHz)
- Generated a reduced system model from random sampling to predict ECH needs to reach targets

*Park J.M. *et al* 2018 Integrated modeling of high β_N steady state scenario on DIII-D *Phys. Plasmas* **25** 012506

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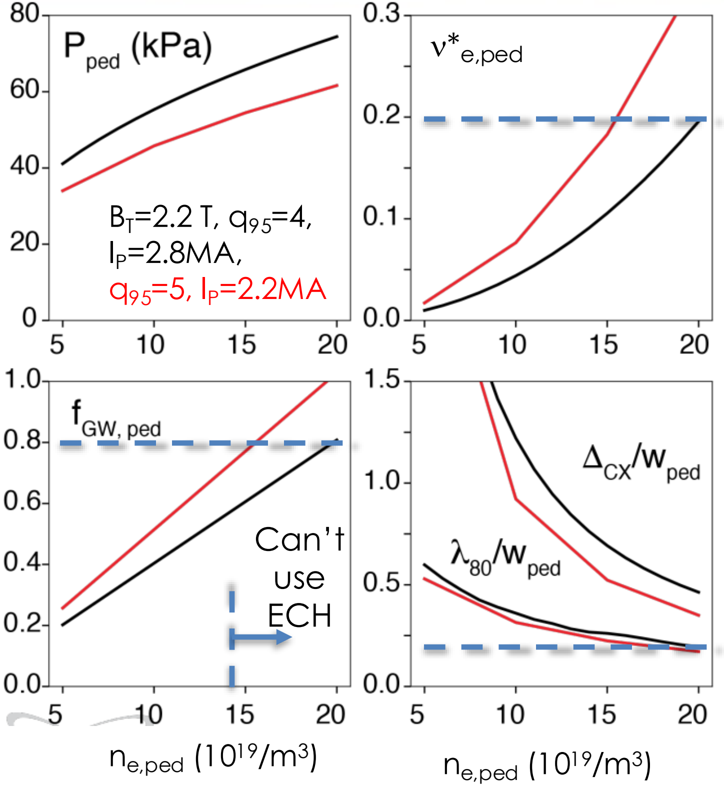
Models Say ECH Does Not Help Obtain Opaque, Low ν* Pedestals in Advanced Inductive/Hybrid Plasmas



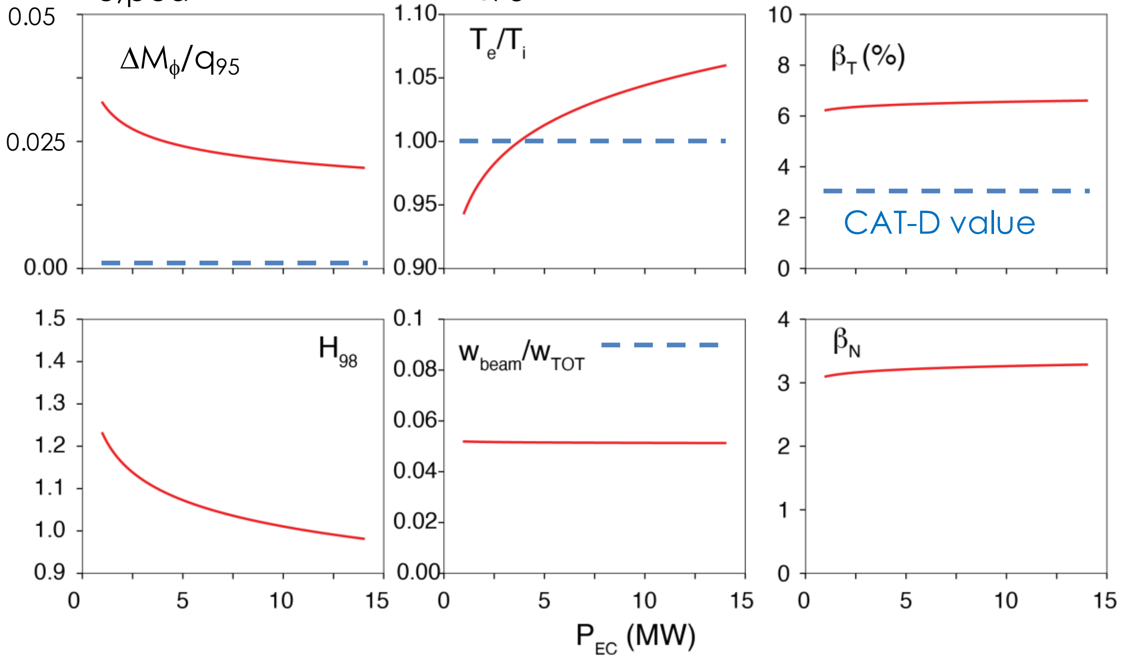
- **FPP-relevant pedestals predicted on DIII-D at $n_{e,ped}$ > ~15x10^{19} m^{-3}**
  - Neutral penetration ~ $w_{ped}/4$
- **ECH use* limited to $n_{e,ped}$< ~14x10^{19} m^{-3}**
- **EPED predicts pedestal parameters are insensitive to large variations in input power (ECH & NBI)**
- ***Caveat: EPED may not be sufficient for predicting impacts of ECH on achieving relevant pedestals (backup slides)***

λ_{80} from FRANTIC code

*Heating only with 140GHz O2 + 170GHz X3

~5 MW ECH is Sufficient For Access to Relevant Core Transport Regime in an Advanced Inductive Scenario

5 MW co- + 10 MW balanced-NBI, $n_{e,ped}$=9x$10^{19}m^{-3}$, q_{95}=4



- **Most curves level off above P_{ECH}~5 MW**
- **5 MW:**
  - Achieves T_e/T_i>1
  - Surpasses W_f/W_{tot}, β_T, ν^*_{ped} targets
  - Rotation shear still too high, but much closer
- Lower $n_{e,ped}$ moves most parameters in the wrong directions, higher $n_{e,ped}$ doesn't help much

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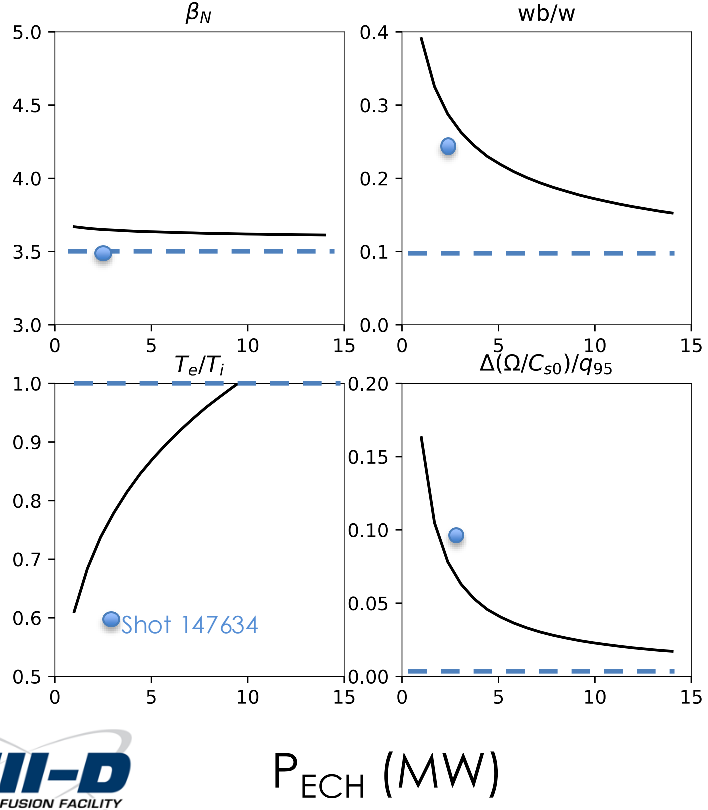
Heating only with 140GHz O2 + 170GHz X3

Testing Impacts of Rotation, T_e/T_i, W_f/W_{tot} on AT Core Above No-Wall Limit Requires ~10 MW ECH

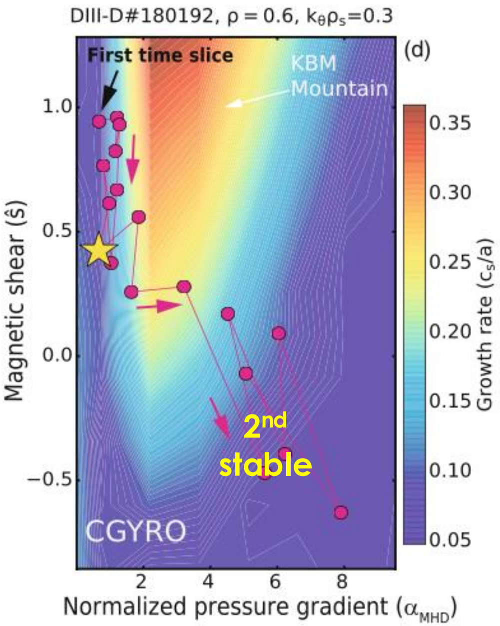
B_T=2.2 T, q_{95}=7, co-NBI



- **Use 140GHz X2 off-axis CD + 170GHz O3 or X3 on-axis**
  - max n_{eped}=7×10^{19}m^{-3}
- **10 MW hits T_e/T_i=1 when f_{NI} is relaxed to 0.85**
- **Approach low rotation even with co-NBI in this case**
- **β_N is above no-wall limit & CAT-D β_N**
- **Will explore RWM stability & transport**

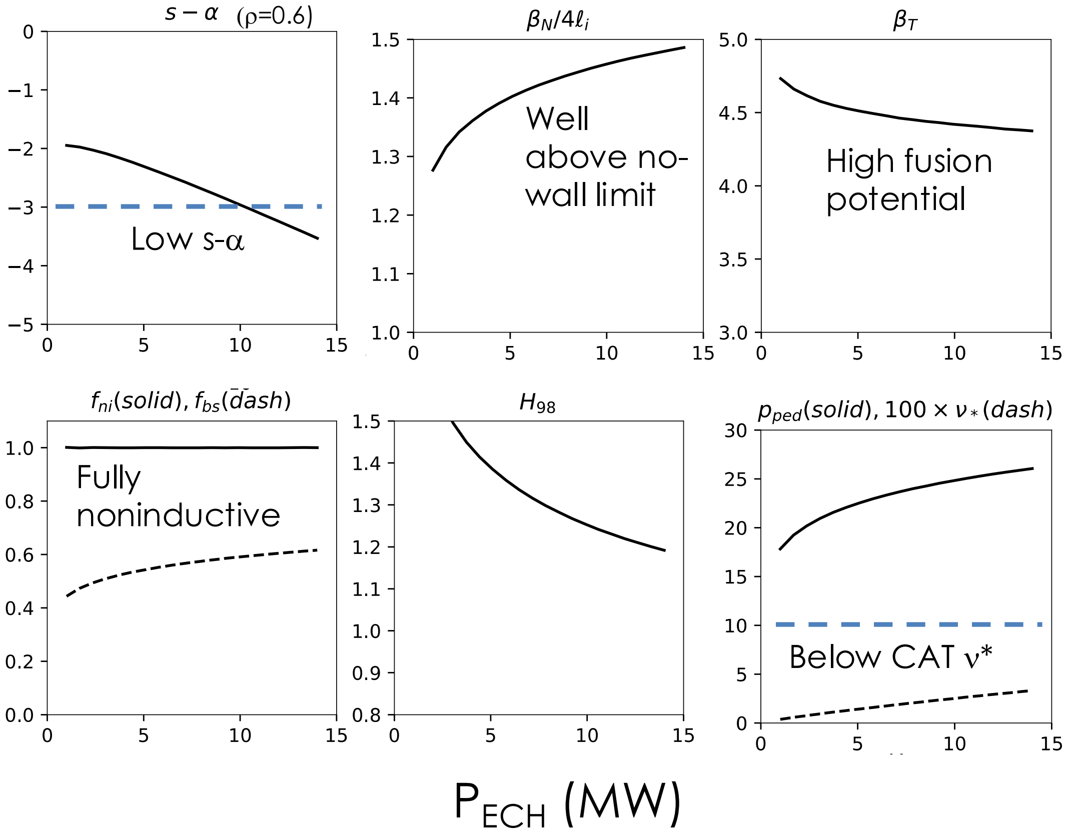
10 MW ECH Accesses Sustained Low $\hat{s}$ & High α_{MHD} at ρ~0.6 to Explore AT Core Operation in 2nd Stable Regime

Evolving High-β_P Shot



Ding Rev Mod Phys. '23

IPS-FASTRAN Simulations: B_T=2.2 T, q_{95}=7, co-NBI



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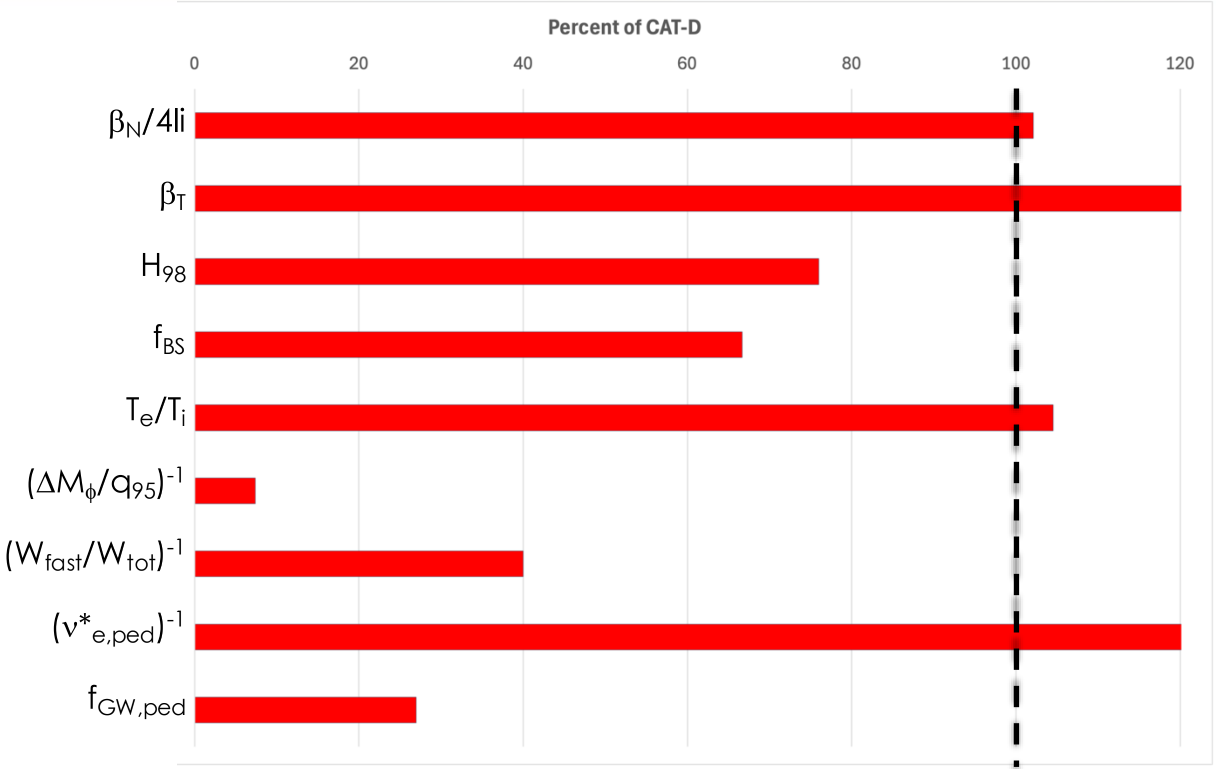
14 MW ECH Helps Explore Interactions of Multiple Effects in AT Core But Plasmas Would Still Fall Short in Some Metrics



- 14 MW ECH, 10 MW balanced NBI + 4 MW co-NBI, B=2.2 T, q_{95}=7.5, $n_{eped}=3.5\times10^{19}m^{-3}$
- **Achieve > 60% of CAT values for several core metrics**
- **Fall short in rotation**
  - But $H_{98}/H_{98,noExB}$ is within ~20% of CAT value
- **ECH use limits $n_{eped} \leq 7\times10^{19}m^{-3} \rightarrow f_{GW,ped}$ < ~50% without lowering lowering I_P**

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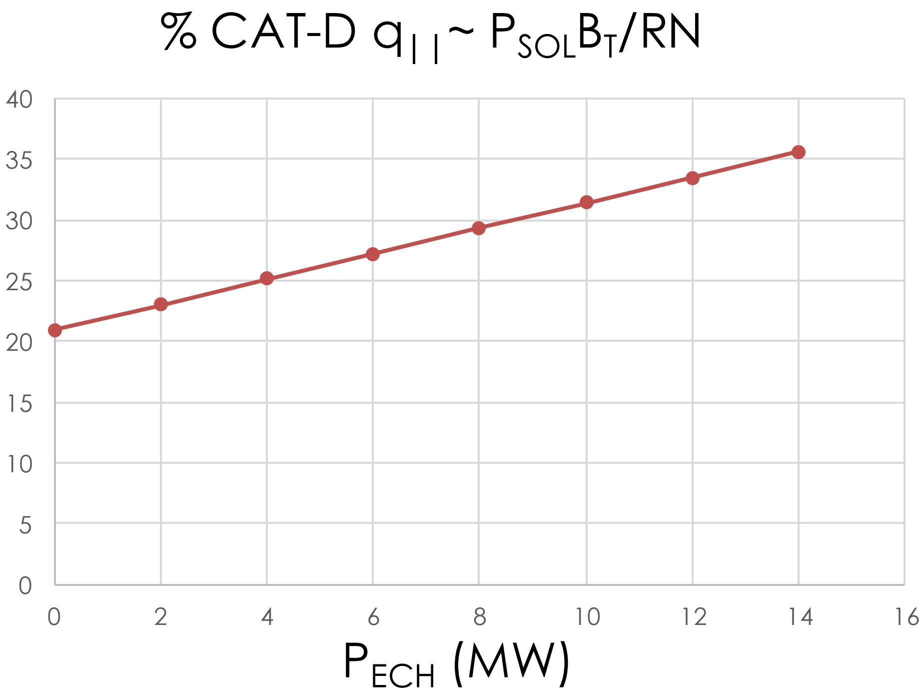
14 MW ECH Would Pose a Divertor Heat Flux Mitigation Challenge ~35% That of CAT-D



- **Existing DIII-D discharges are 5-10% of CAT**

- **20 MW NBI + P_{ECH}**
- **2.2 T**
- **R=1.67 m**
- **N=1 divertor**

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Summary:

- **Physics uncertainty for long-pulse operation can be reduced by going to more relevant regimes in DIII-D with upgrades**

- **Integrated physics model simulations were deployed to estimate the minimum required ECH power to achieve targeted parameters**

- **Initial findings:**
  - **Opaque, low ν^* pedestal studies may not require any ECH**
  - **Pushing AI/Hybrid core to relevant parameters: 5 MW ECH**
  - **Pushing some metrics to relevant values in AT core: at least 10 MW ECH**
  - **Push all AT core metrics to better than ~60% of FPP values, & produce significantly greater heat flux challenge: at least 14 MW ECH**

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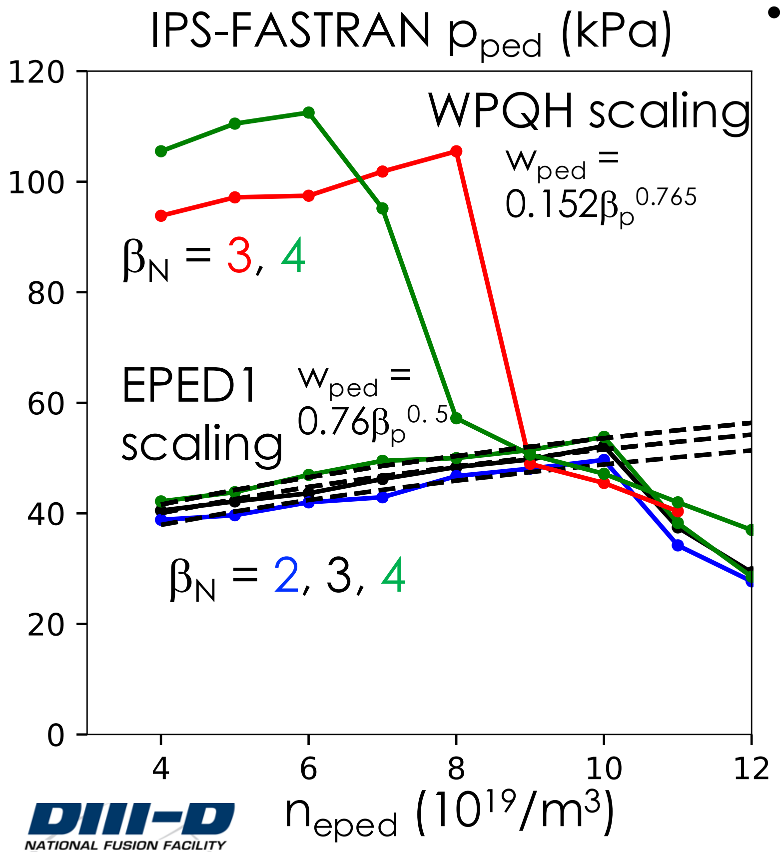
Caveat: EPED May Not Be Sufficient For Predicting Impacts of ECH on Achieving FPP-Relevant Pedestals



- **No reliable physics models for pedestal scenarios with ∇P limited by transport below KBM limit, e.g., WPQH-mode**

Caveat: EPED May Not Be Sufficient For Predicting Impacts of ECH on Achieving FPP-Relevant Pedestals

Groebner, 2013 NF

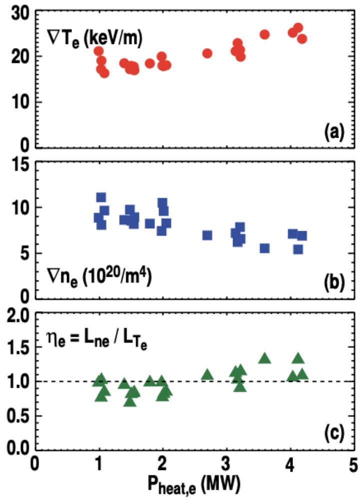


Figure 17. Variations of pedestal (*a*) ∇T_e, (*b*) ∇n_e and (*c*) η_e with electron power flow into the pedestal in the power scan in DIII-D. Heating power is a combination of beam power into the electrons and ECH power, deposited on top of the pedestal.

4x $P_{heat,e}$ → 50% increase in ∇T_e & 30% drop in ∇n_e

- **No reliable physics models for pedestal scenarios with ∇P limited by transport below KBM limit, e.g., WPQH-mode**
- **Experiments show ECH near pedestal can perturb gradients → could more power trigger transport bifurcation ?**

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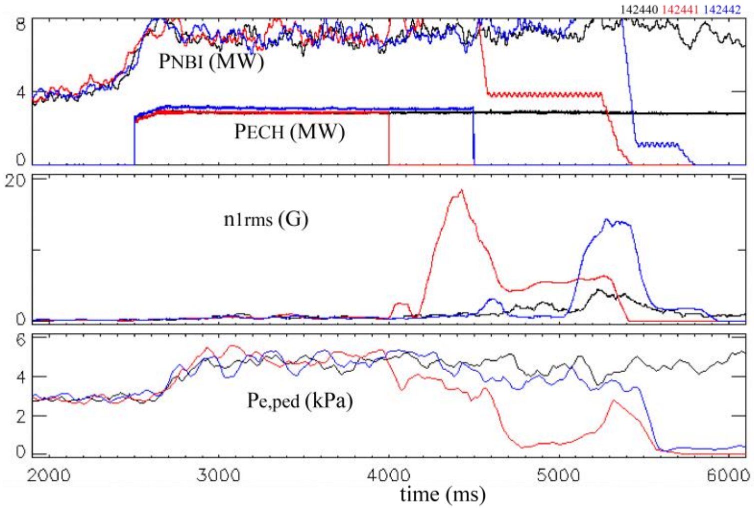

- No reliable physics models for pedestal scenarios with ∇P limited by transport below KBM limit, e.g., WPQH-mode
- Experiments show ECH near pedestal can perturb gradients → could more power trigger transport bifurcation ?
- Experiments also show core-ECH can make profiles more MHD-stable (not direct NTM stabilization) to better sustain high pedestals

➢ ECH likely has benefits for pedestal studies not captured by models

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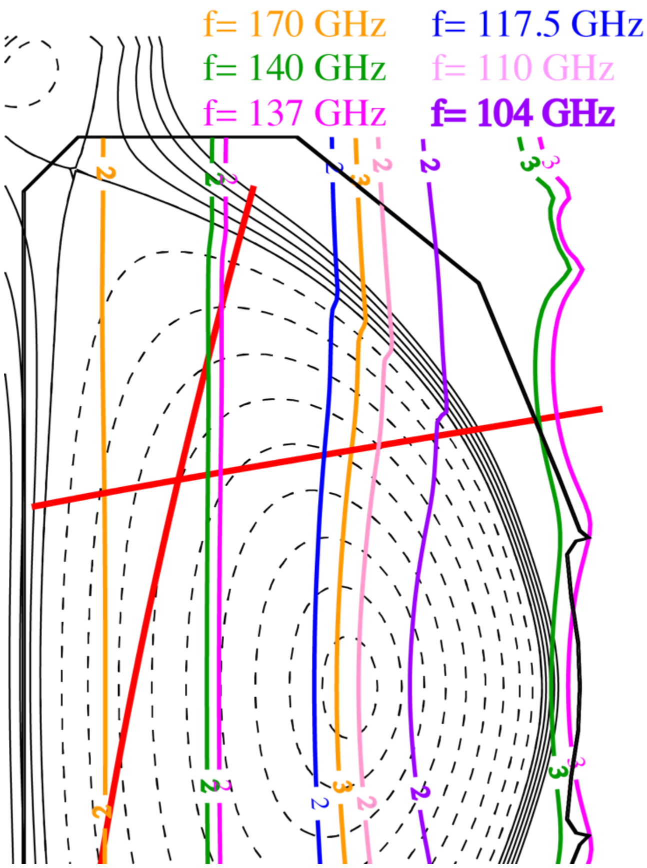
We Focus on Several Key Parameters That Are Relevant For Physics Gaps

Metric	Significance
$q_{\|\|} \sim P_{SOL}B/R$	Divertor heat flux challenge
$\beta_N/4li$	RWM stability above no-wall limit
β_T	Adequate fusion performance
H_{98y2}	Energy confinement quality
f_{BS}	Steady-state or long-pulse
T_e/T_i	Turbulent transport regimes
$\Delta M_\phi/q_{95}$	Effectiveness of rotational suppression of turbulence
W_{fast}/W_{tot}	Energetic particle mode drive/damp
$\nu^*_{e,ped}$	Collisionless hot core
$f_{GW,ped}$	Operate close to density limit
L_D/w_{ped}	Pedestal opaque to neutrals, structure set by transport, not fueling

ECH at 2.2 T



Flexible Multi-Frequency (110/137/170 GHz) Gyrotrons Would Cover Whole Range of B_T in a DIII-D Upgrade