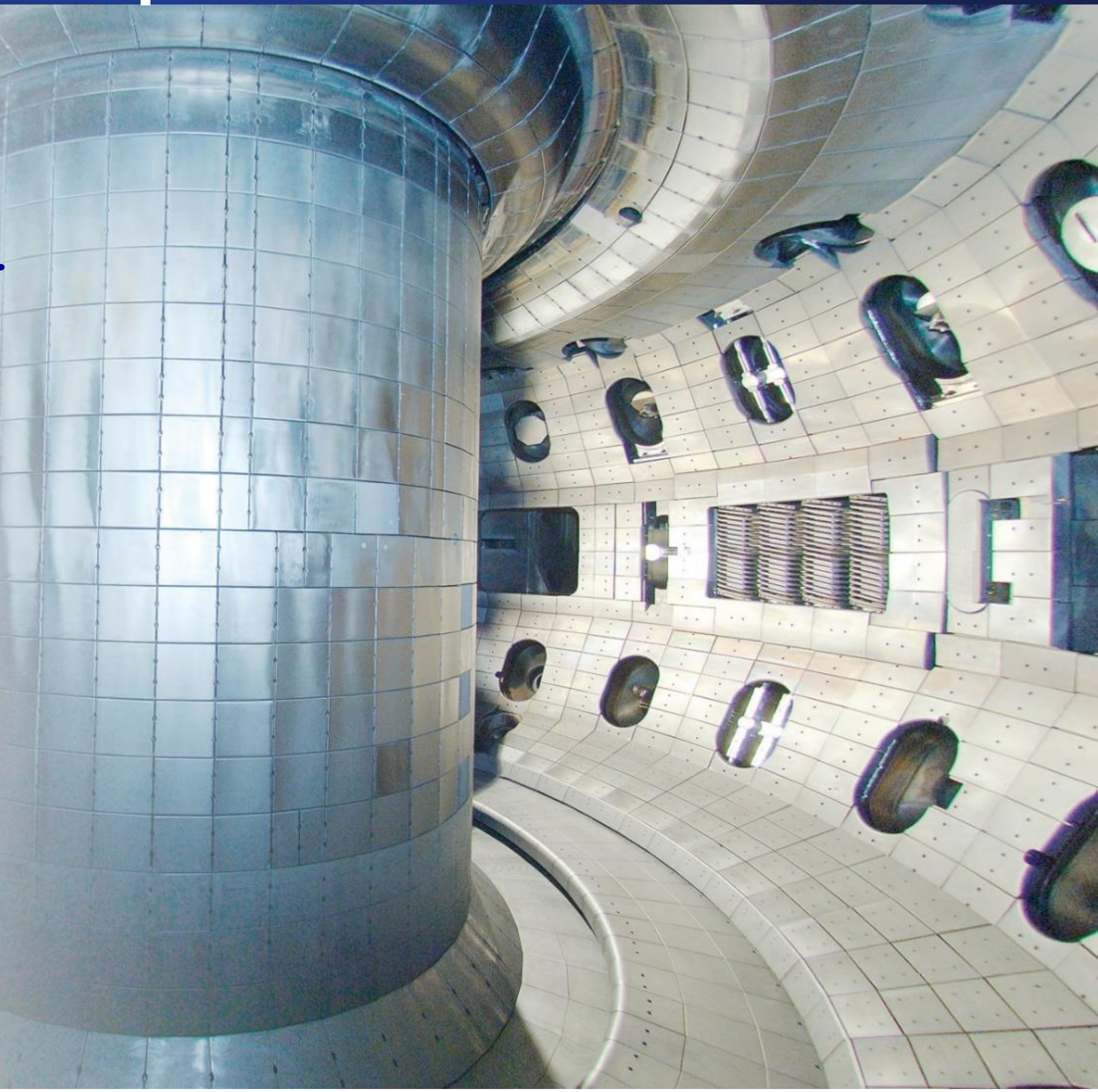
Development of an Integrated Core-Edge Scenario using the Super H-mode



T.M. Wilks[1], P.B. Snyder[2], M. Knolker[2], D. Eldon[2], F. Laggner[3], C. Paz-Soldan[2], T. Osborne[2], A. Bortolon[3], F. Effenberg[3], C. Lasnier[4], A. McLean[4], F. Scotti[4], J. Watkins[5], H. Wang[2], A. Rosenthal[1], L. Casali[2], B. Grierson[3], J.W. Hughes[1] and DIII-D Team

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[2]General Atomics
[3]PPPL
[4]LLNL
[5]SNL

28th IAEA Fusion Energy Conference
Virtual Event
May 10-15, 2021

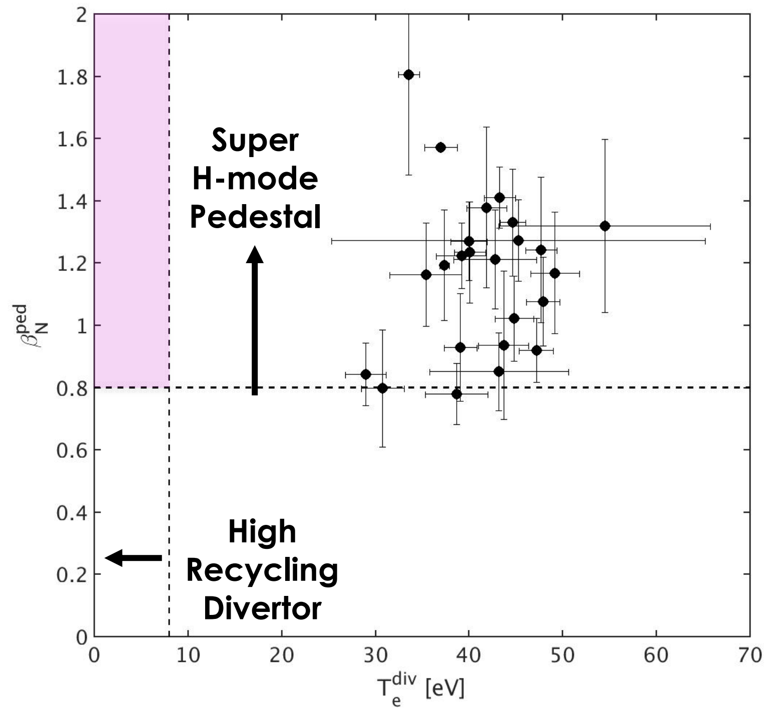
Super H-mode has potential to integrate a high performance core, pedestal, and divertor

- **Motivations, tools, and access to Super H-mode (SH) plasmas**

- **Core edge integration strategies in highly shaped SH plasmas**
  - Compatibility with N_2 seeded radiative divertor
  - Divertor closure studies with D_2 fueling

- **Access to SH in moderate triangularity and applicability to JET and ITER**

Core Edge Integration on DIII-D



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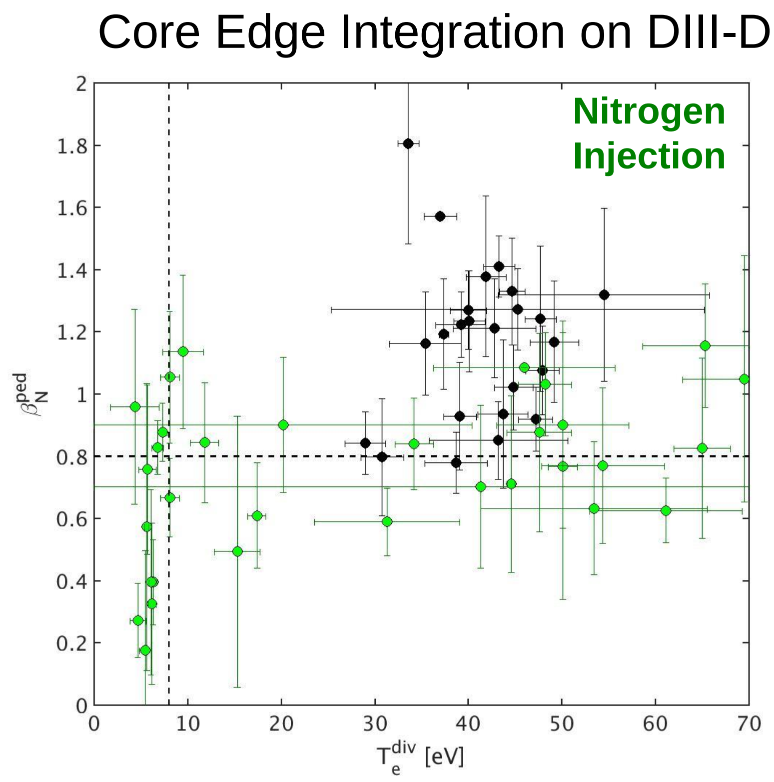

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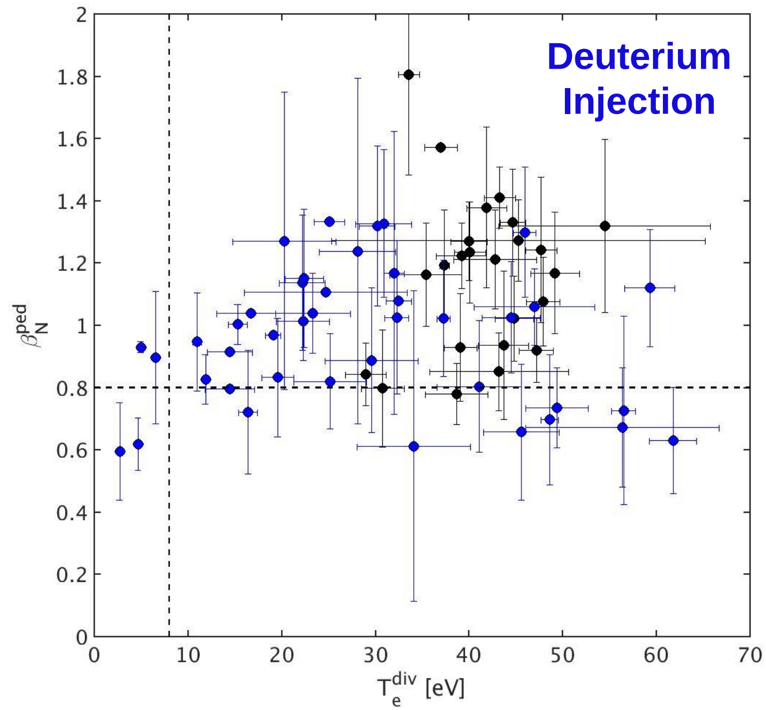

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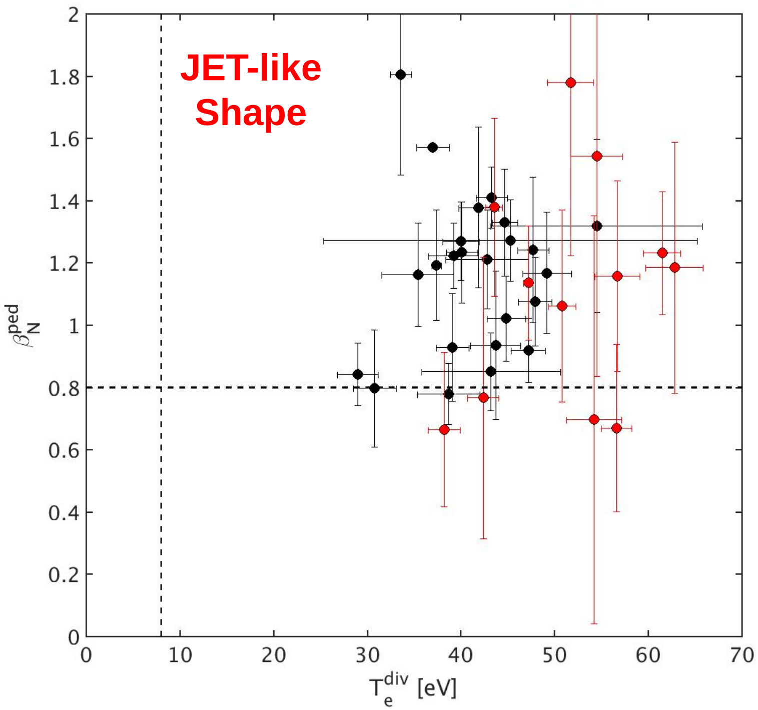

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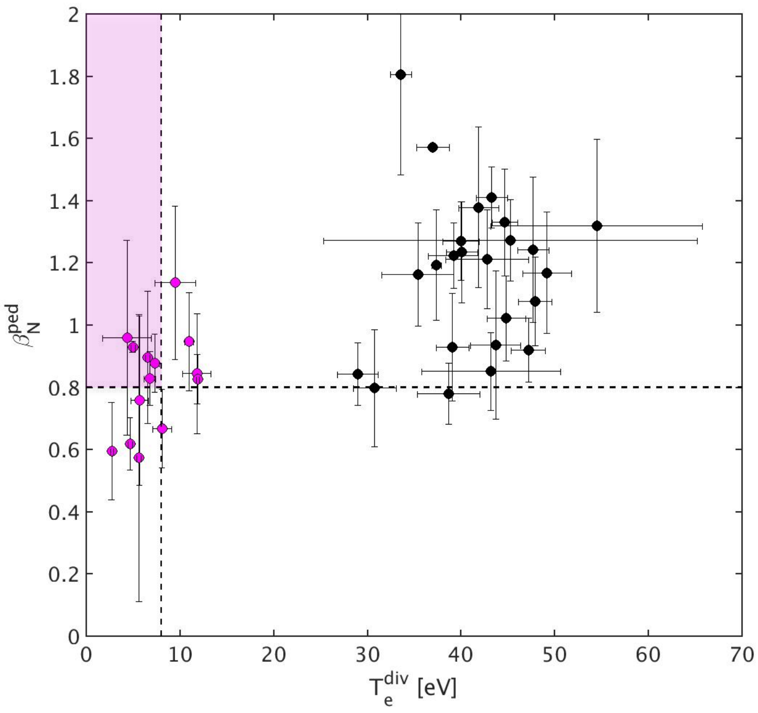


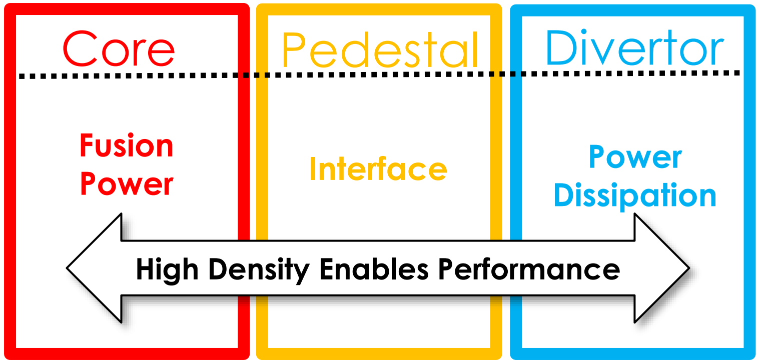
A key challenge for future devices is integration of a high performance core with realistic power exhaust solutions

- Core and boundary governed by different processes → often considered separately in modeling, analysis, and experiments

- Pedestal is critical region where divertor and core physics meet → optimization is important

- High density operation enables performance in both core and boundary regions

Core Edge Integration



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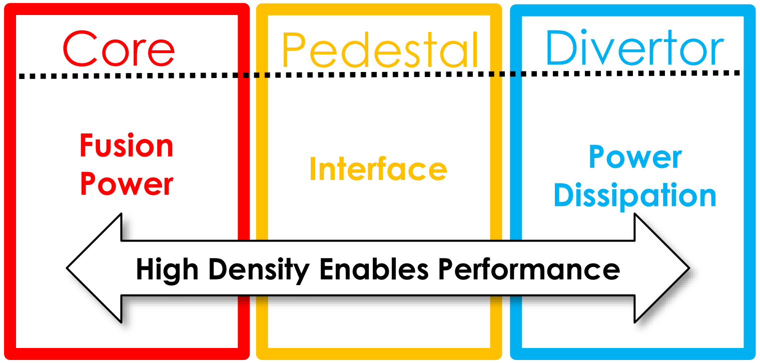


Super H-mode provides a platform for Core-Edge Integration

Core-Pedestal:

Record pedestal pressures and high-performance core plasmas

- World record pedestal pressures on C-Mod* (metal wall)
- Pedestal higher than typical H-modes at the same density

Pedestal-Divertor:

Peeling limited pedestal compatible with high density and high pressure

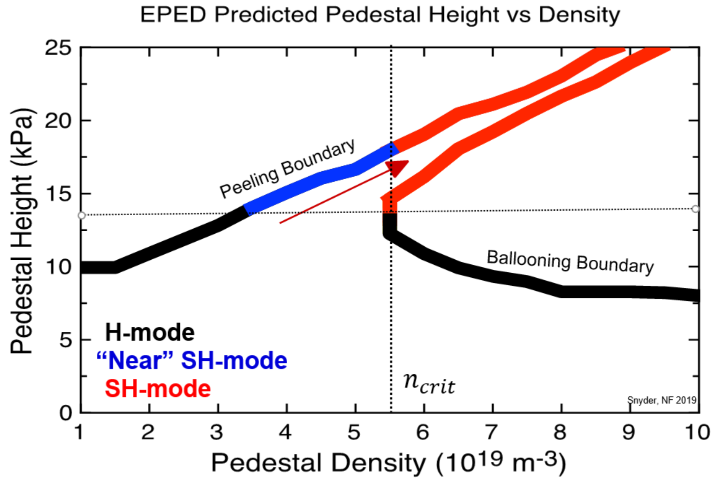
- Increased separatrix density compatible with radiative divertor and detachment
- High separatrix density coupled to high pedestal pressure leads to optimal core-edge integration

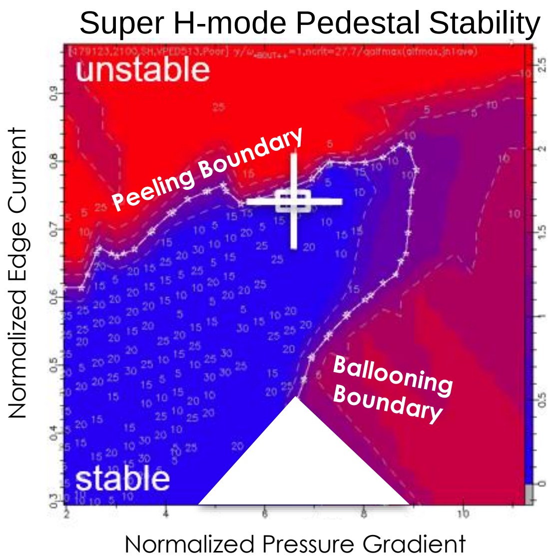
*Hughes, NF 2018

Super H-mode leverages peeling physics to operate at both high density and pressure

- **The Super H-mode defined by EPED predicting multiple solutions for pressure pedestal above critical density**
  - Current gradient driven peeling modes limit pedestal
  - "Near SH" defined by entrance to channel on peeling limited boundary

- **Peeling limited pedestals allow pressure to increase as a function of density**
  - Ballooning limited pedestals are degraded by increasing density (most devices)
  - DIII-D leverages strong shaping to decouple peeling and ballooning modes

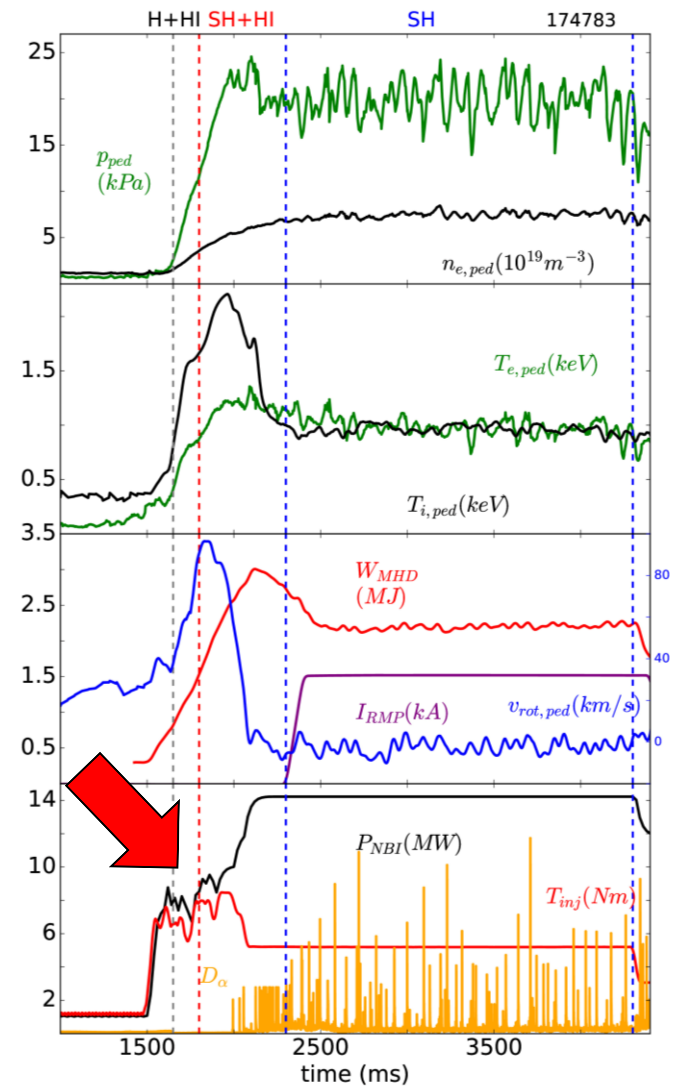




Theoretical framework provides a strategic path towards pedestal optimization and Super H-mode access conditions

Experimental actuators:

- EPED parameters$(\mathrm{I_p}, \mathrm{B}_T, R, a, \delta_{avg}, \kappa, n_e^{ped}, \beta_N)$
- Tailored beam program
- Null reversal



Knolker, PPCF 2021

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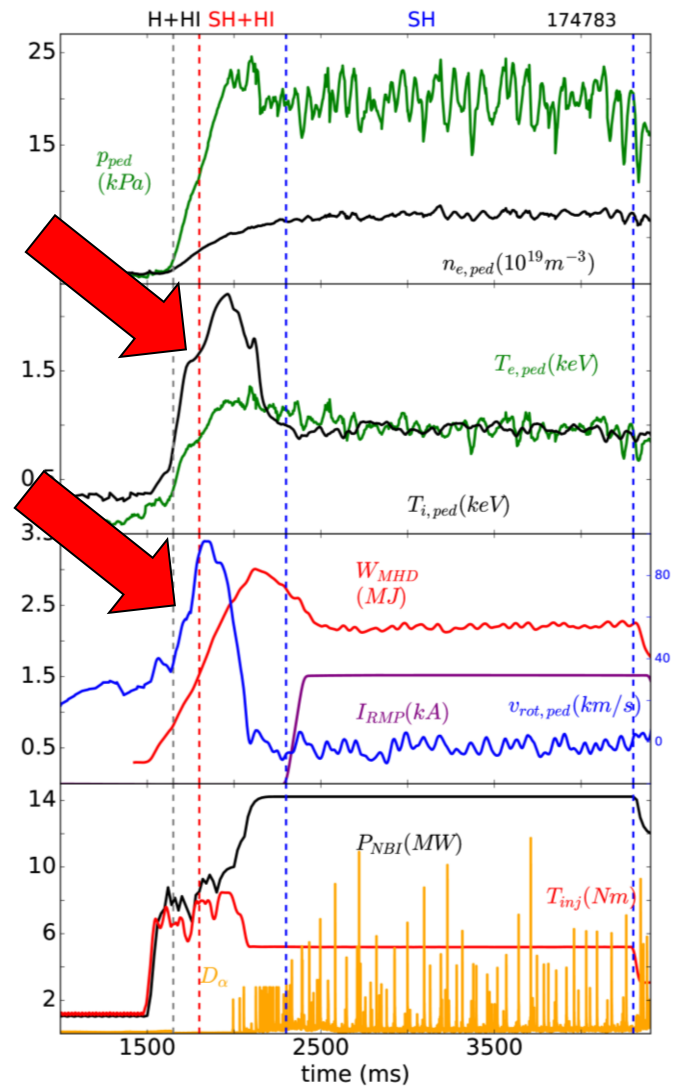
- High T_i^{ped}, rotation shear & Shafranov shift
- High core pressure, stored energy, Q



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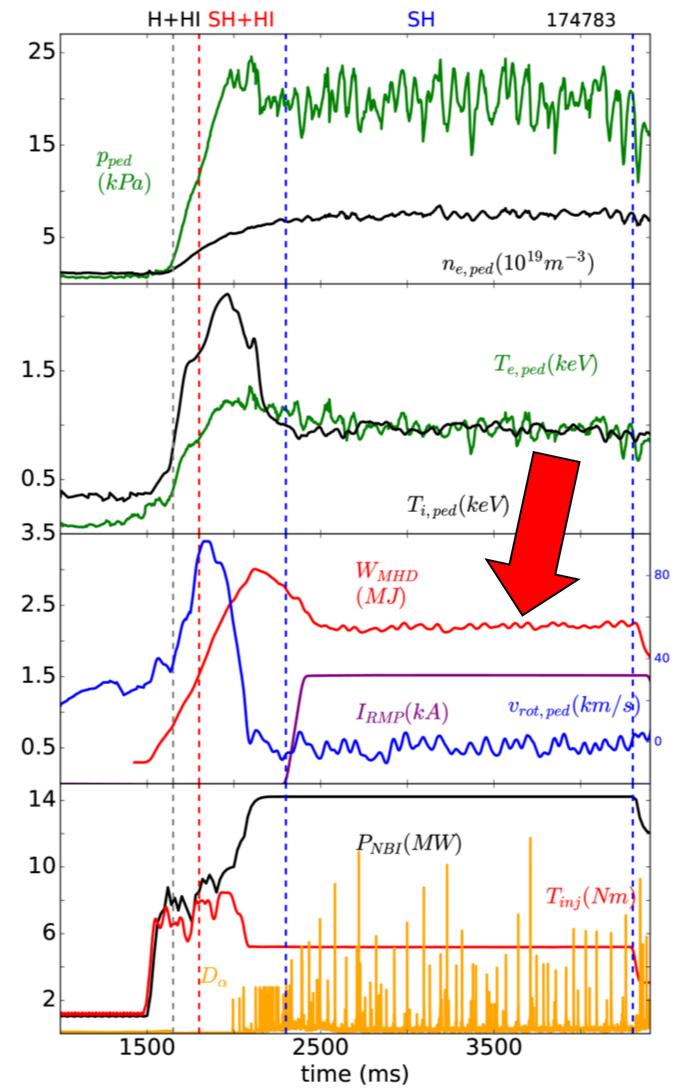
Stationary SH/"Near" Super H-mode:
- Stationary w/ I-coils
- Reduced stored energy



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RMP > 3kA;
Large tearing mode
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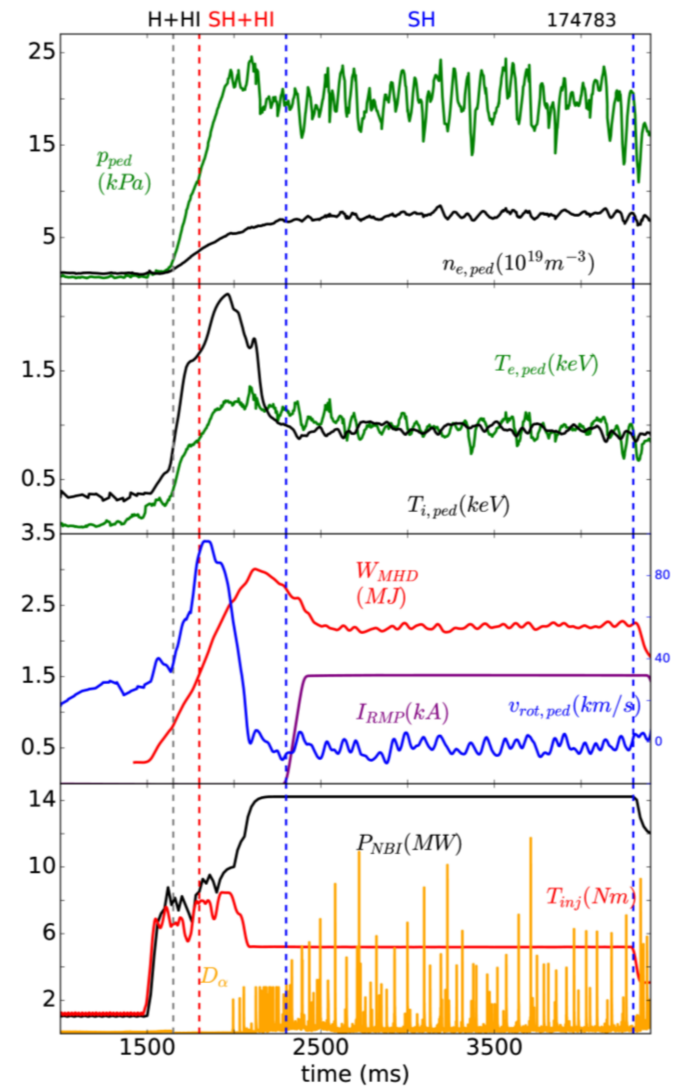
H-mode:
- Further reduced core pressure
- Core MHD



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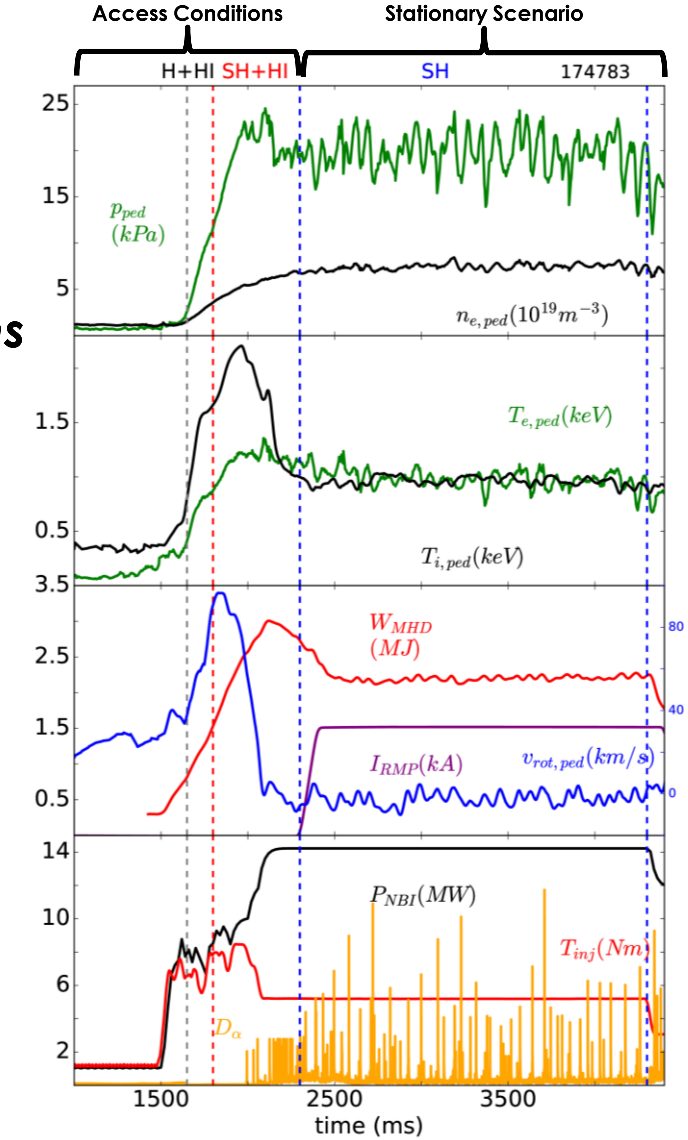
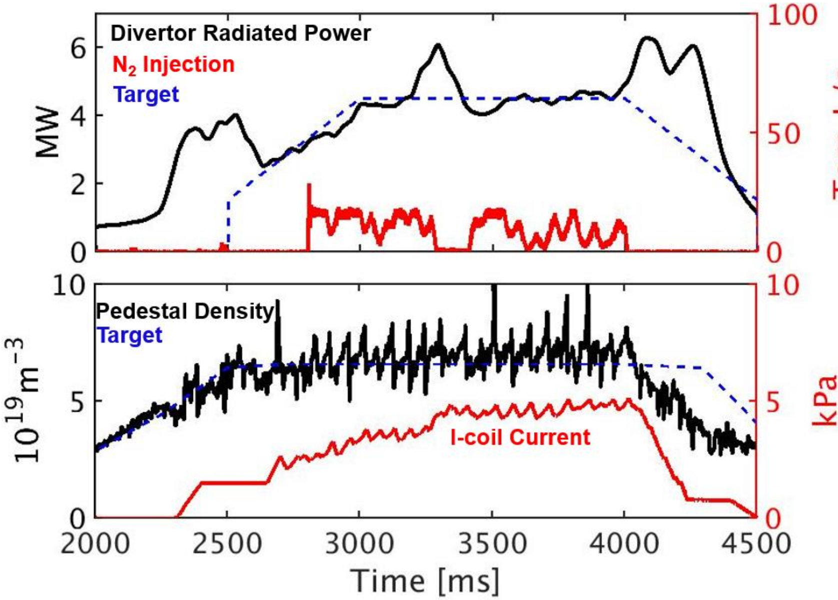


Knolker, PPCF 2021

Advanced control algorithms are employed for pedestal-divertor integration

- **Realtime control used for independent optimization in different spatial regions**
  - Feedback on N_2 for radiative power control in the divertor using bolometer measurements
  - Feedback on I-coil to control pedestal density



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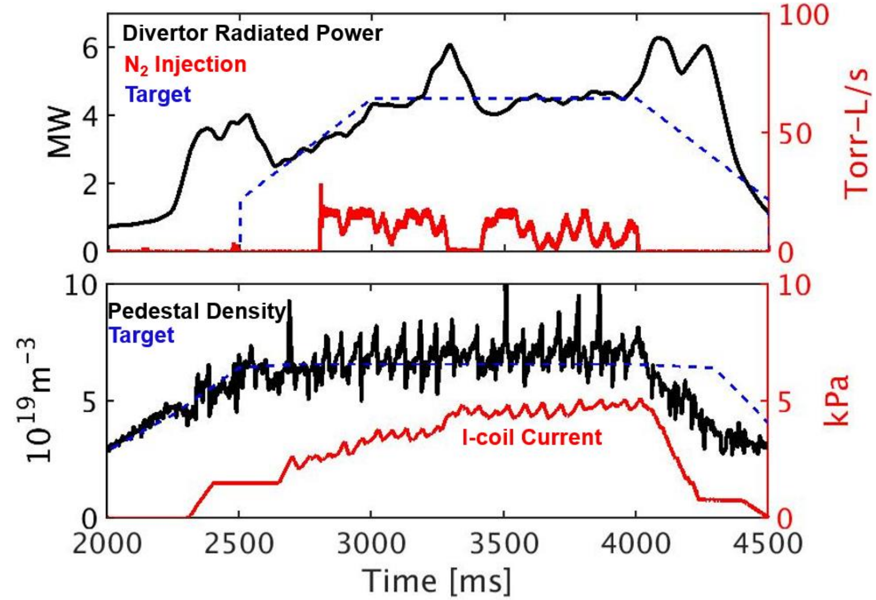
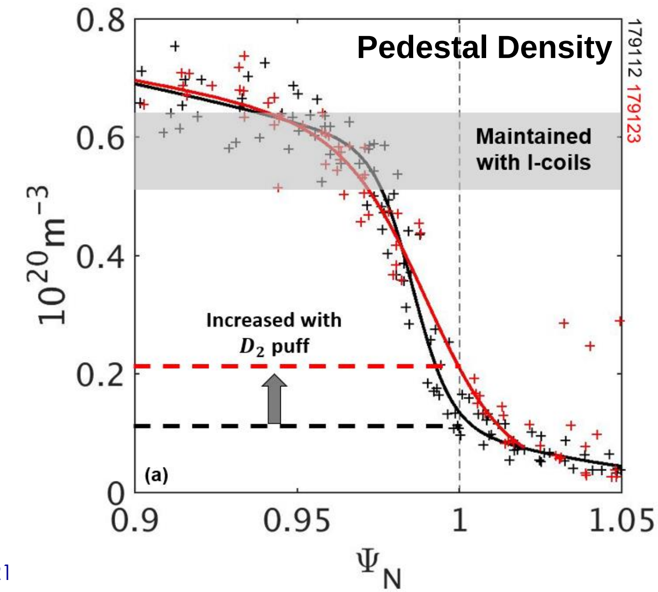
  - Feedback on I-coil to control pedestal density
- **Peeling physics leveraged to decouple pedestal and separatrix response to gas injection**
  - Separatrix density increases with fueling
  - Pedestal density held approximately fixed (does not degrade)





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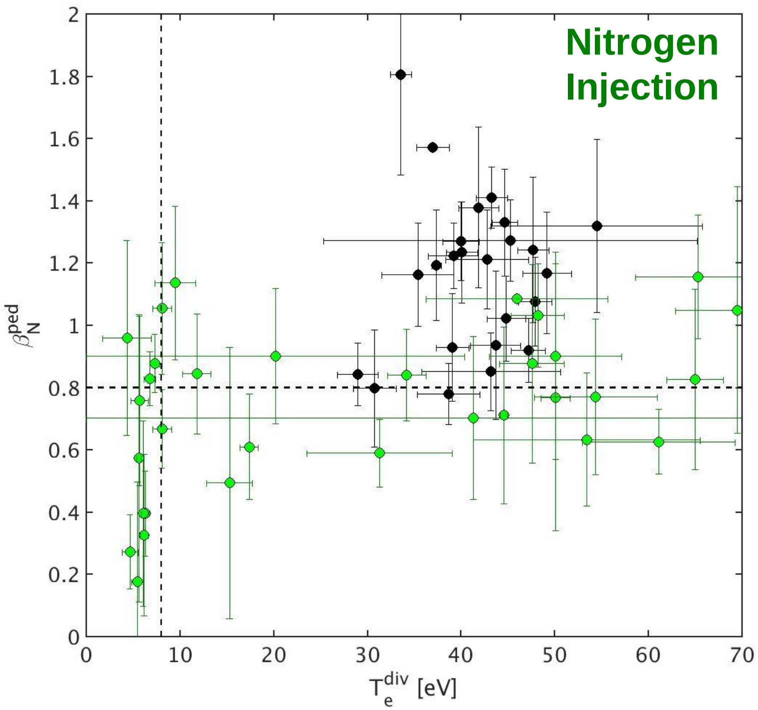


DIII-D Super H-mode experiments outline a phase space for several core-edge integration scenarios

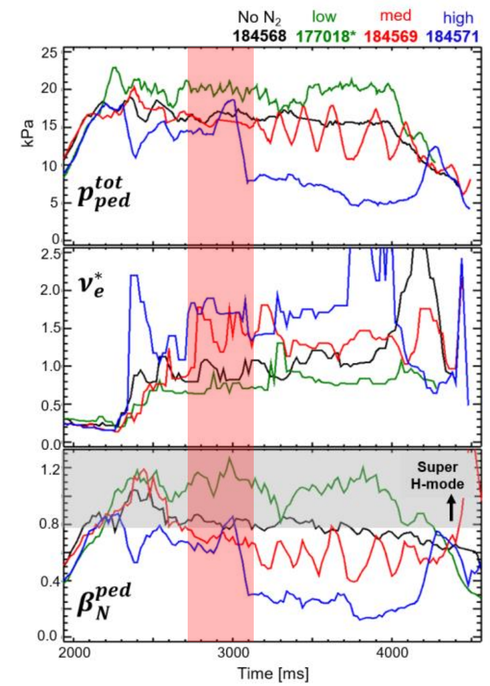
	Core			Pedestal			Divertor		
	Prad Target (shot)	W_{MHD} (MJ)	β_N	T_i^{ped} (eV)	T_e^{ped} (eV)	ELMs	T_e^{div} (eV)	q_{div} (W/cm²)	Divertor Condition
No Seeding	0.0MW (184568)	2.1	2.5	1100	825	Regular Type I	60	480	Attached
Low Seeding	4.5MW (177018*)	1.7	2.1	750	900	Regular Type I	15	300	Attached
Medium Seeding	7.5MW (184569)	2.1	2.4	1000	620	Irregular Type I	<5	350	Detachment Onset
High Seeding	8.5MW (184571)	1.5	1.8	900	450	Grassy	<5	160	Partially Detached (reduced momentum)

I_p = 2MA, B_T = 2.1T
*Different experimental day; Ip = 1.95MA

DIII-D experiments show Super H-mode scenario can operate with high pedestal temperature and low divertor temperature

- **Increasing radiative power targets (low→med→high) quantitatively map trade offs between core and edge metrics**
  - $\beta_N^{ped} \geq 0.8,\ 15kPa < p_{ped}^{tot} < 20kPa,\ \ \nu_e^* < 1$

- **Balanced core edge integration combines detachment onset and SH access**
  - Both pressure and density rise in between large ELMs, indicating peeling boundary
  - More stationary state in early flattop a promising operating point



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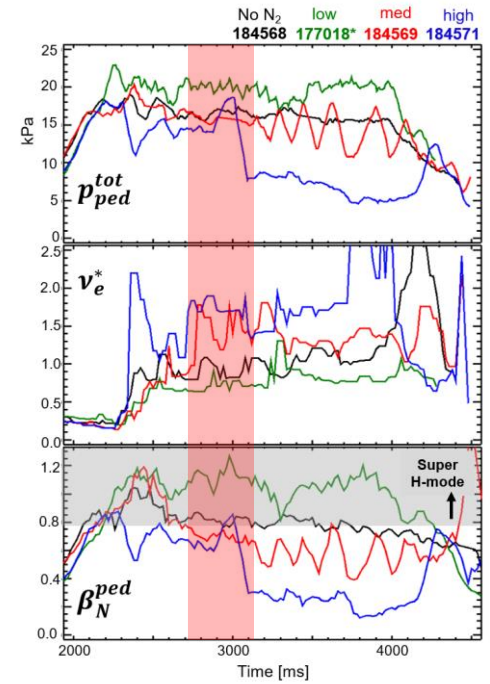
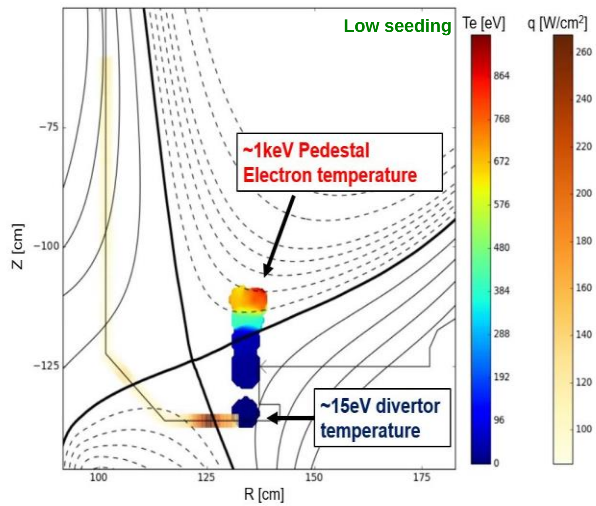
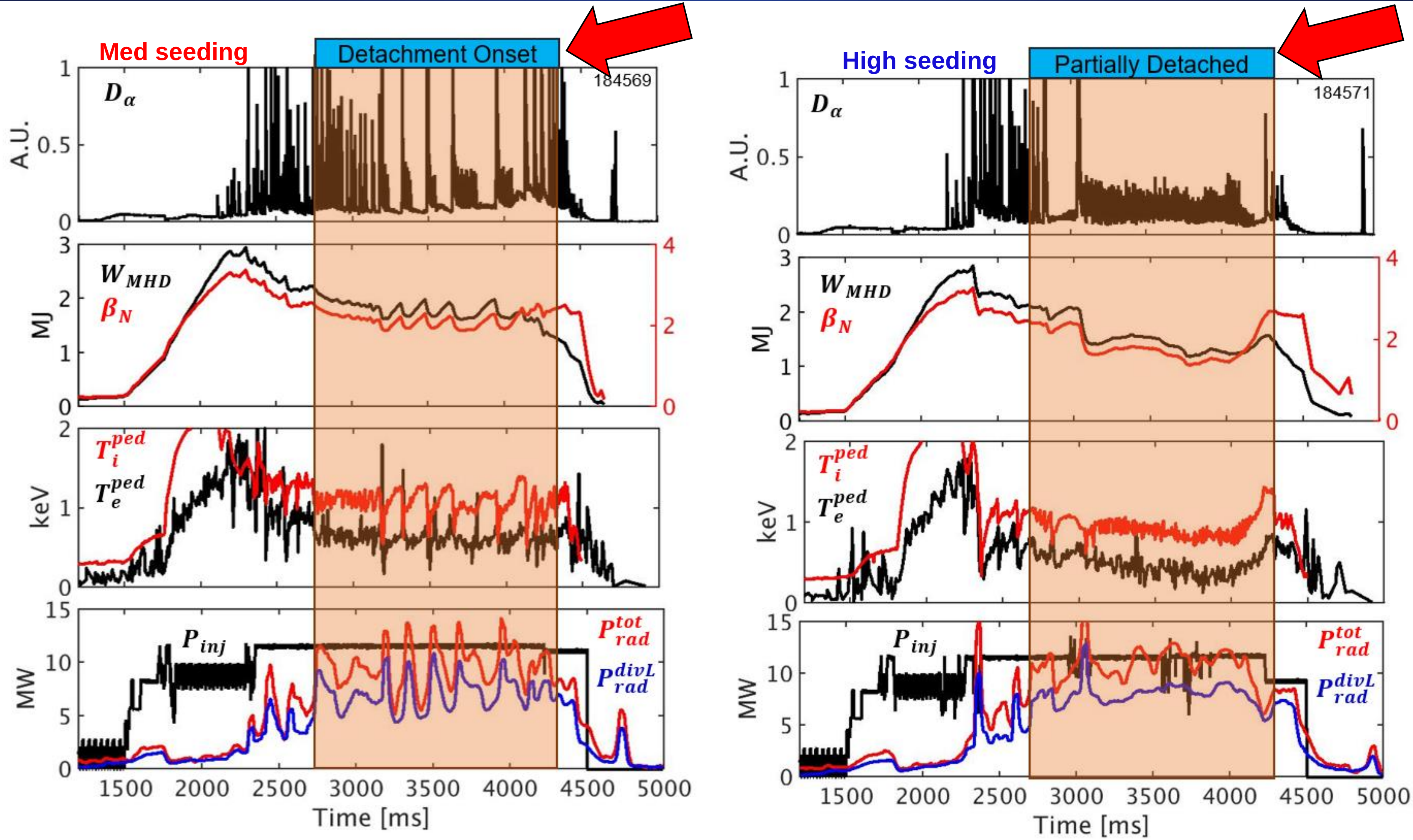
- **Attached Super H-mode has 1 keV pedestal in combination with <15eV divertor temperature**
  - Divertor temperature ~4x higher without N_2 seeding
  - High recycling; attached





Time histories show Super H-mode passes through an optimal phase for future feedback targets



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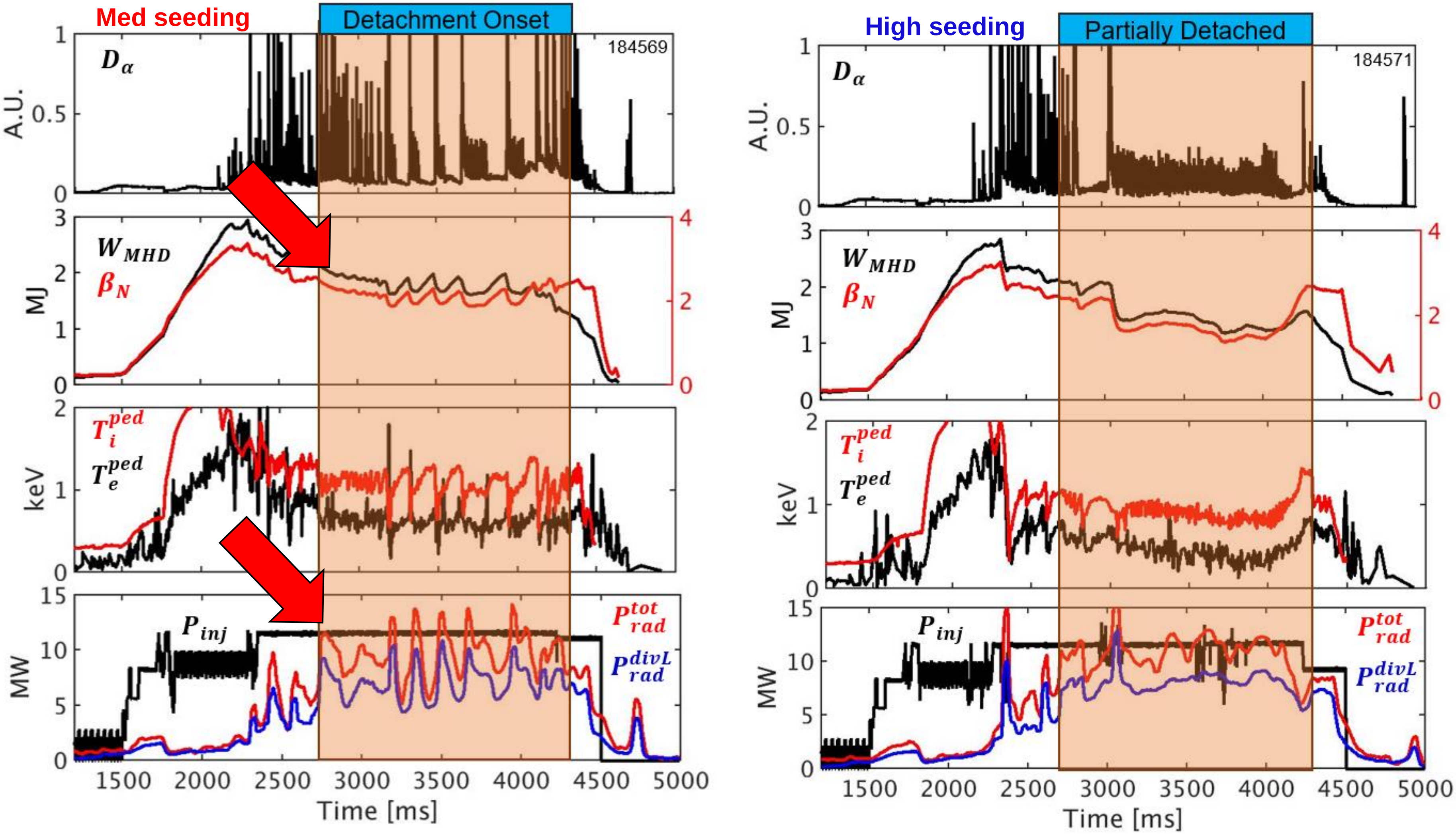

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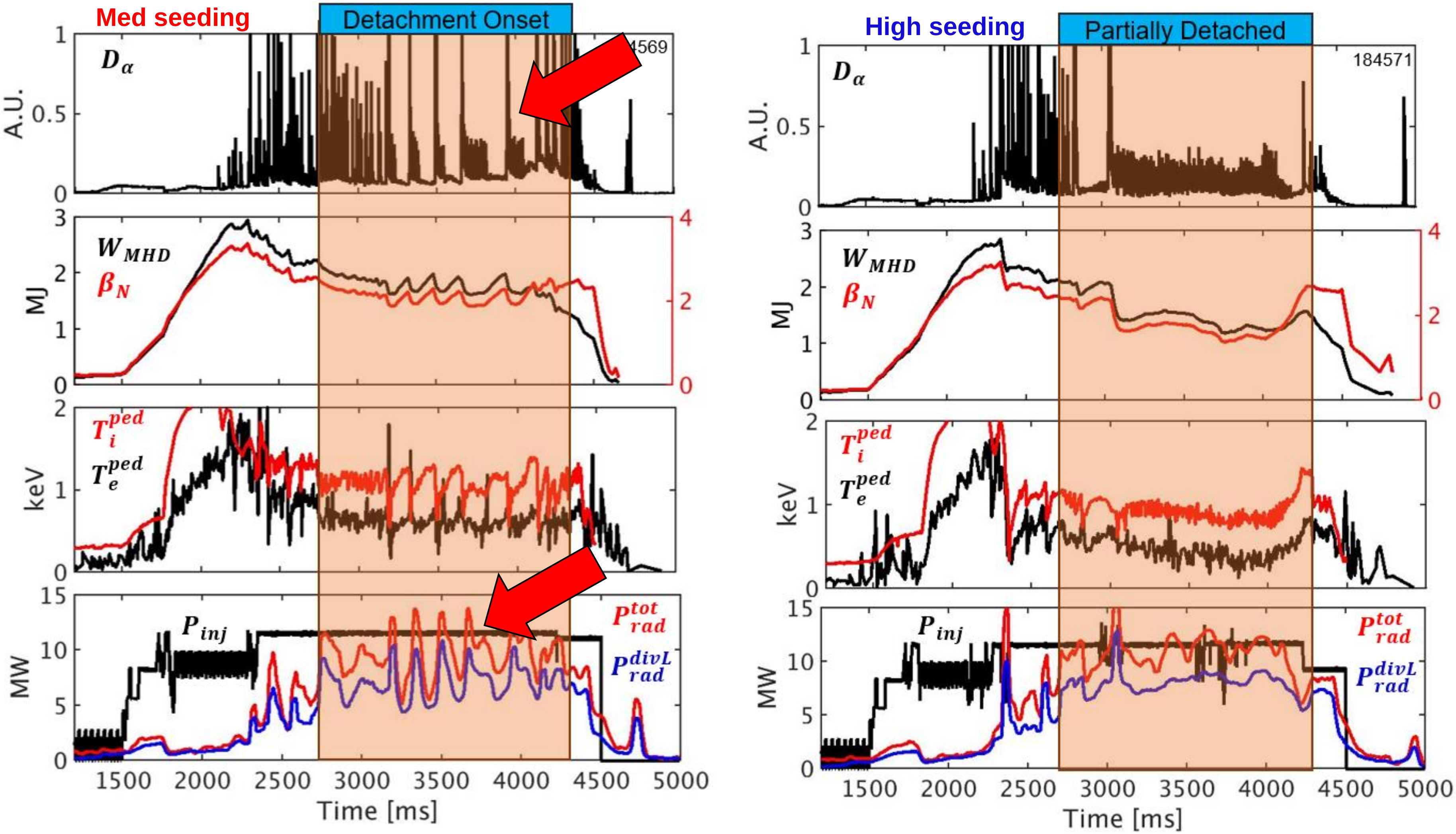

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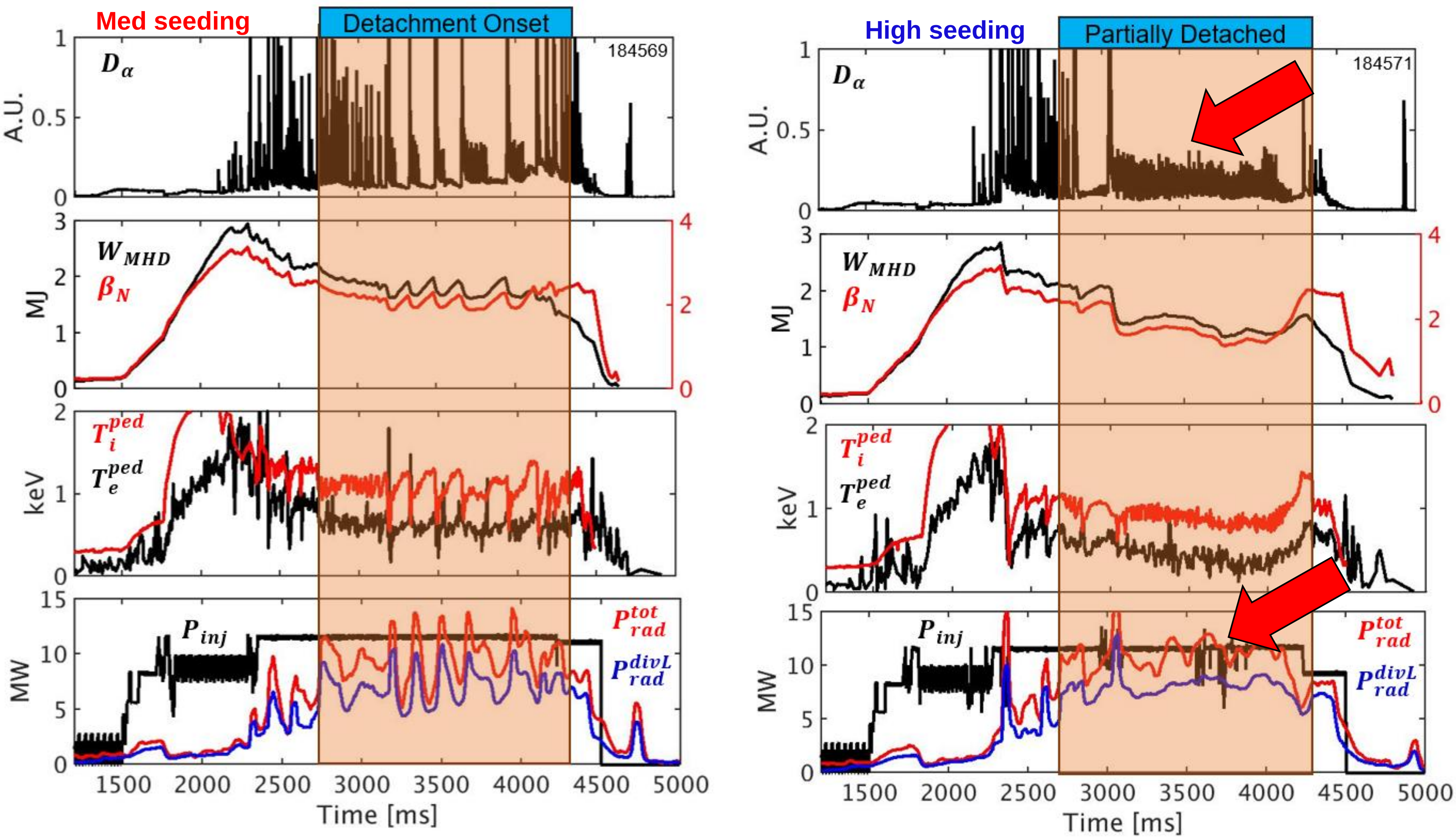

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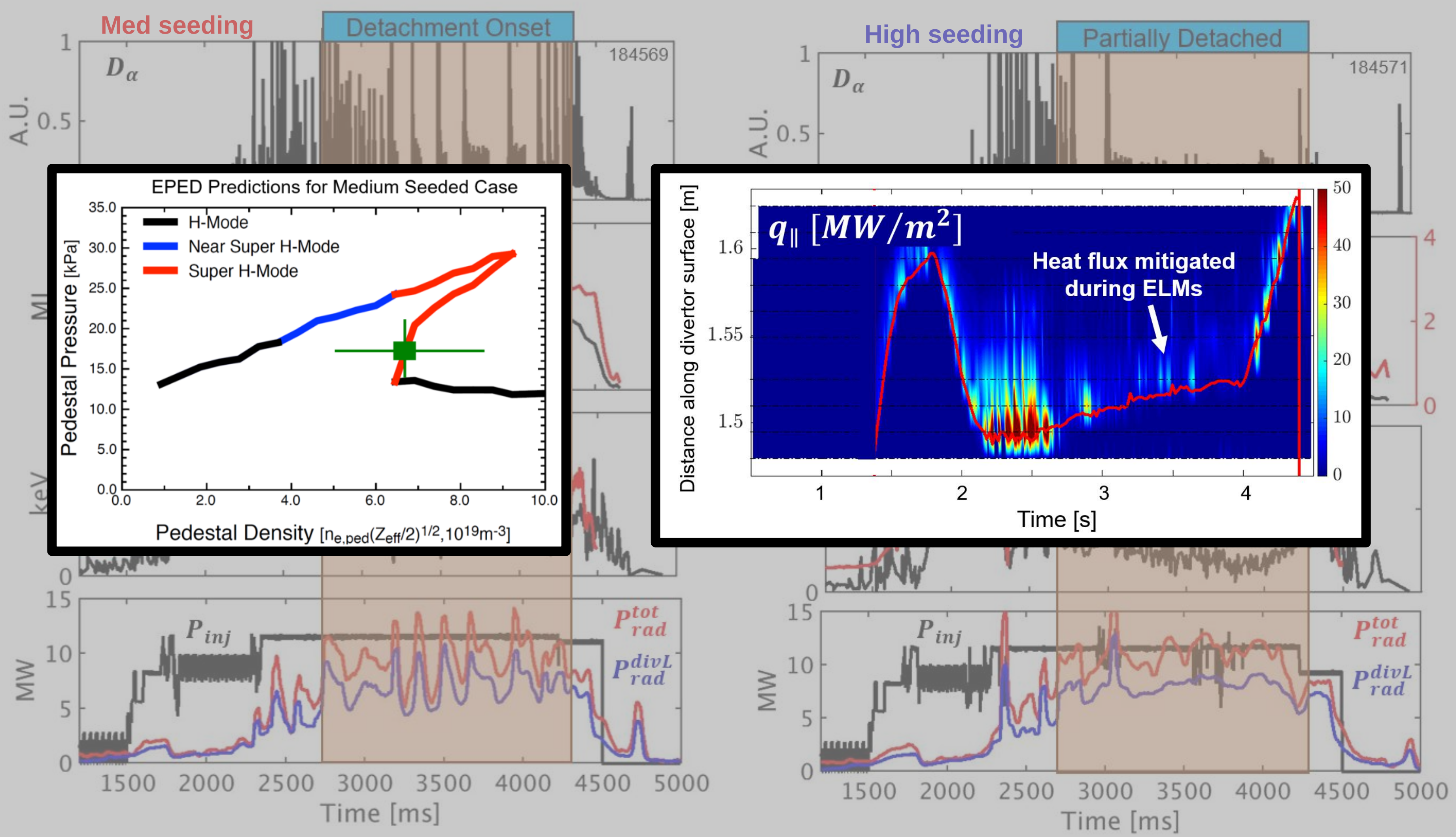
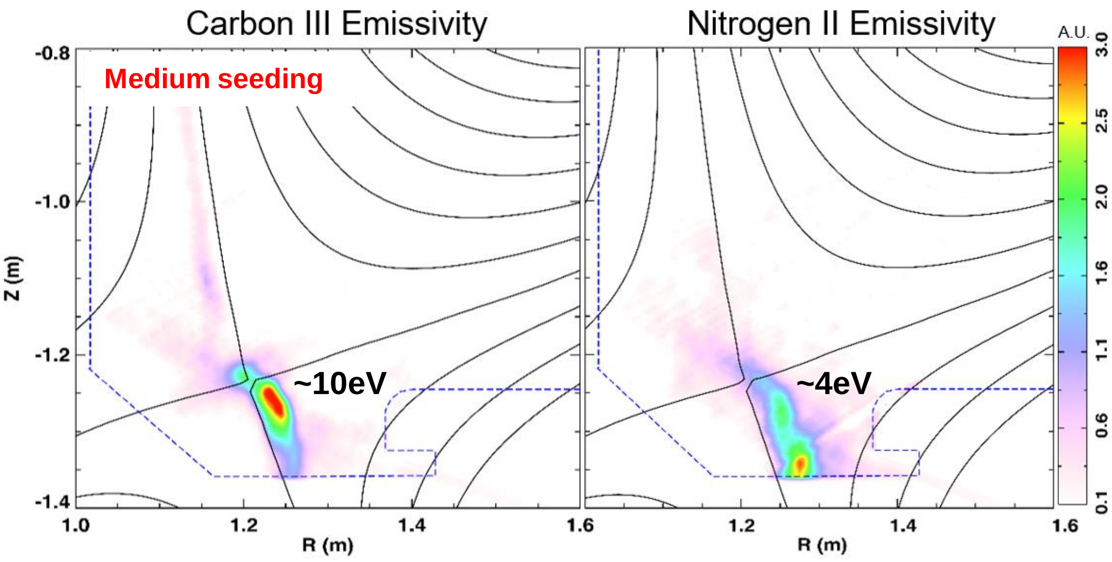
Optimized core-edge integration operation described by detachment onset and SH channel access



Divertor plate is cooled and heat flux mitigated with detachment onset



- **Detachment onset shown by carbon radiation front moving away from strike point towards the x-point**

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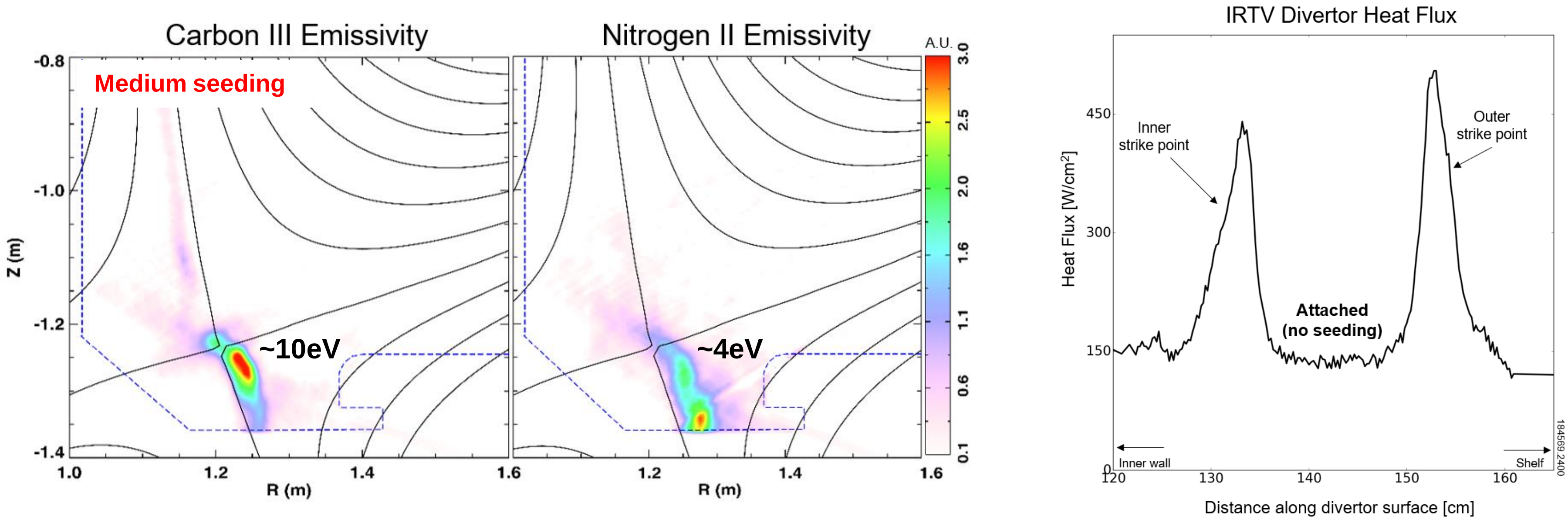

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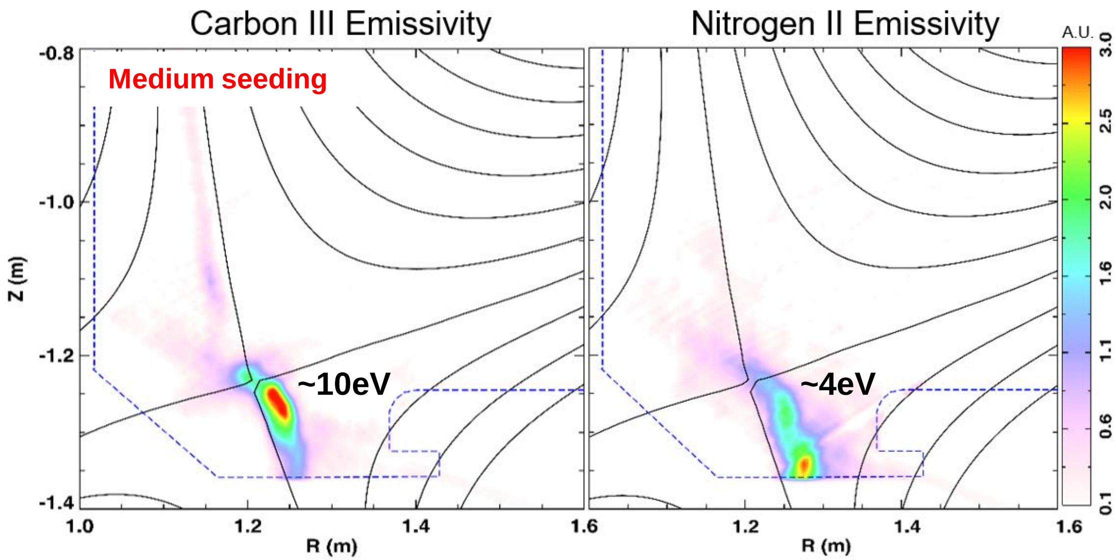

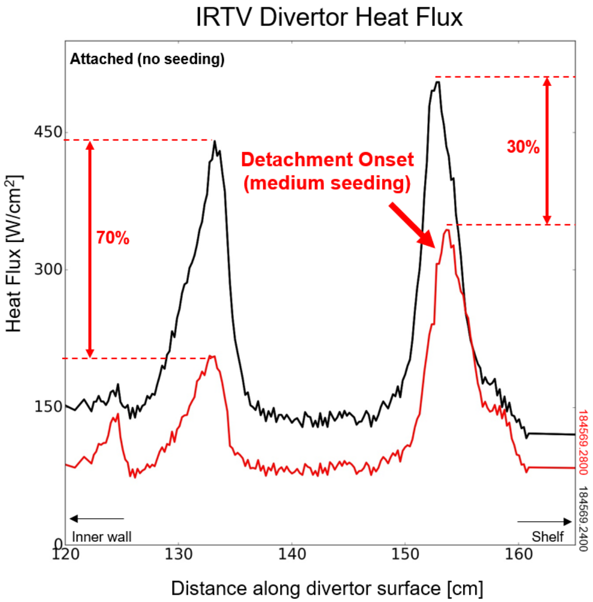

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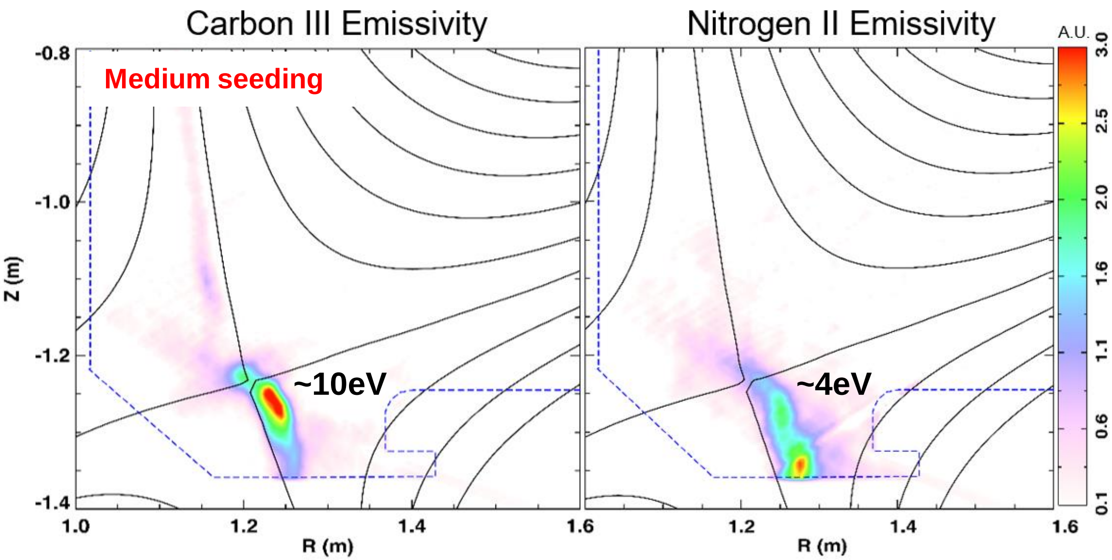

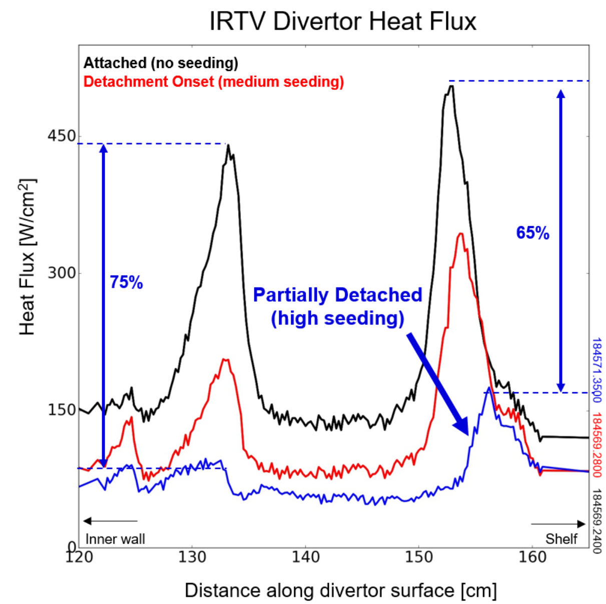

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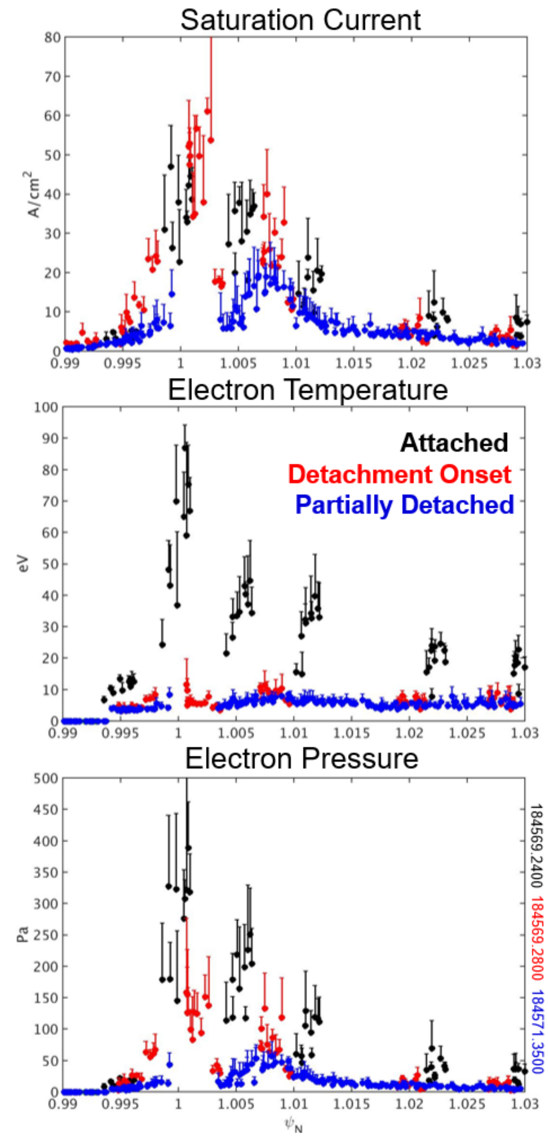
Detachment onset shown by reduced saturation current and electron temperature, pressure

- **Langmuir probes indicate detachment onset**
- **Electron temperature ~ 5eV, allowing charge exchange physics along with conduction (Consistent with NII radiation measurements)**
- **Electron pressure reduced by 3x consistent with momentum loss from CX, still plasma at the plate with some conduction**



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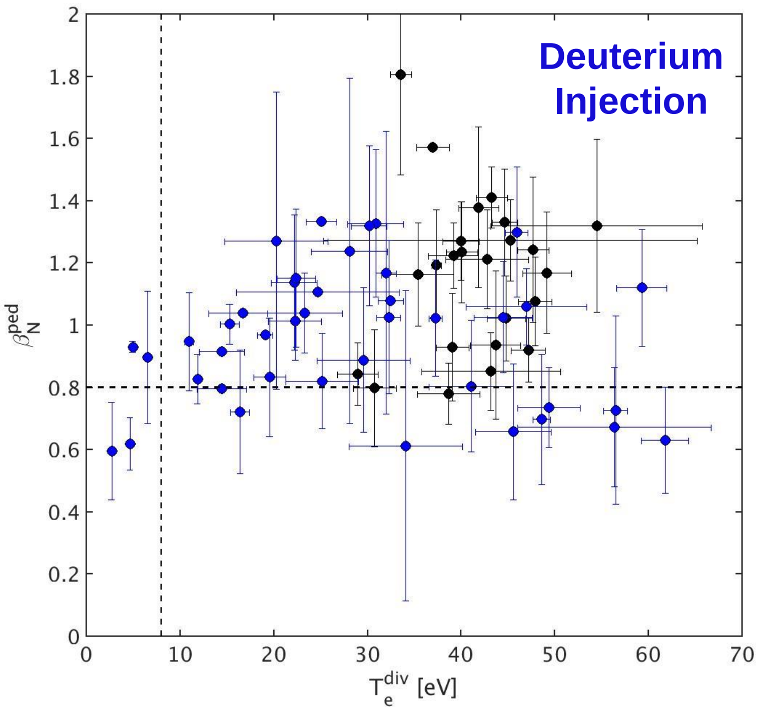
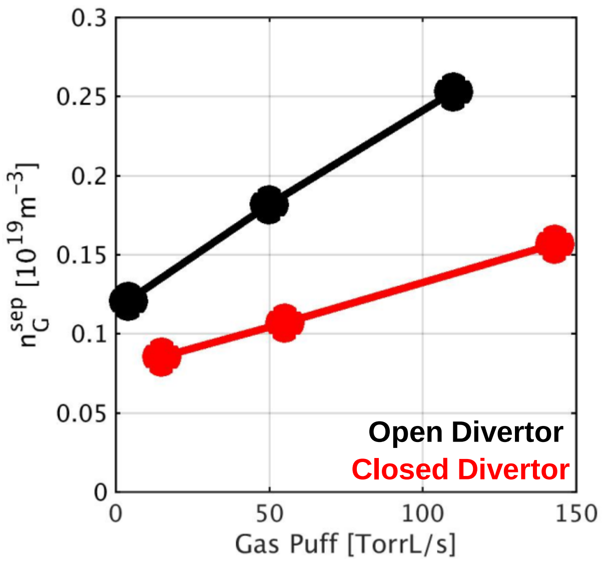
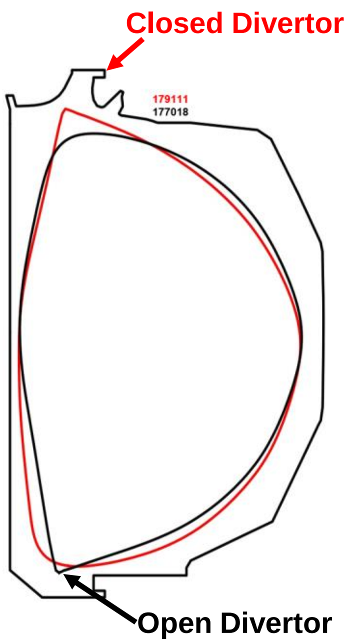
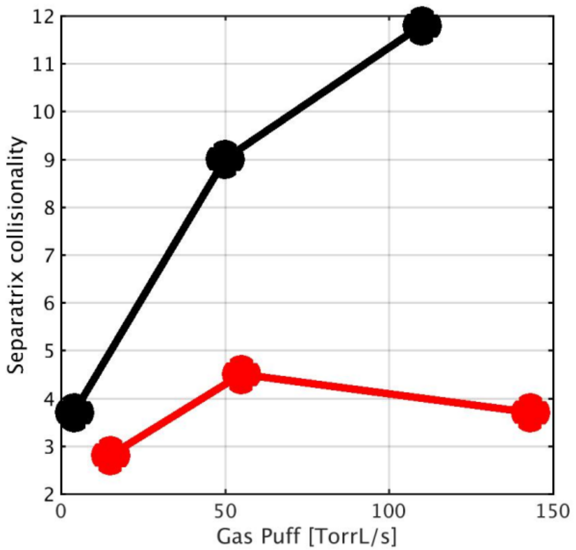


Puff and pump experiments in open and closed divertors in SH-mode show separatrix density and collisionality increase with fueling



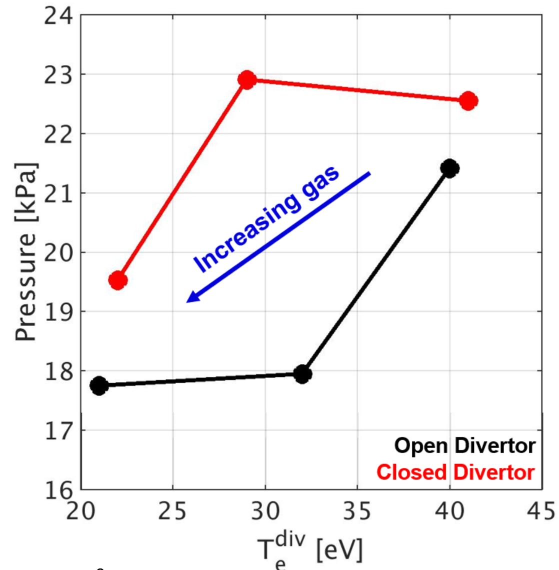




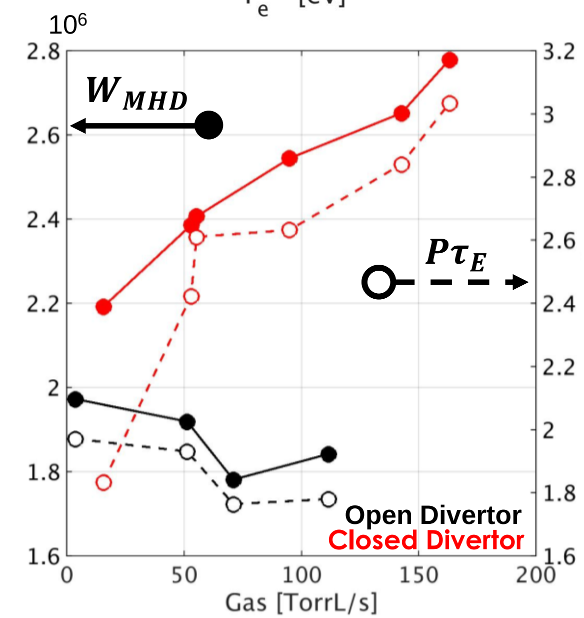
- **Upper single null (USN) has a more closed divertor on DIII-D**
- **Separatrix density and collisionality increase more with gas puff in open divertor than closed due to decreased pumping**

Closed divertor has more robust pedestal to fueling and increases in core performance

- **Pedestal pressure is inversely correlated with divertor temperature measured from LPs**
  - Closed divertor tolerates increased fueling to decrease T_e^{div}, while maintaining high pedestal pressure



- **Core performance metrics of $\beta_N, P\tau_E$ increase more significantly with gas puff for the closed divertor**



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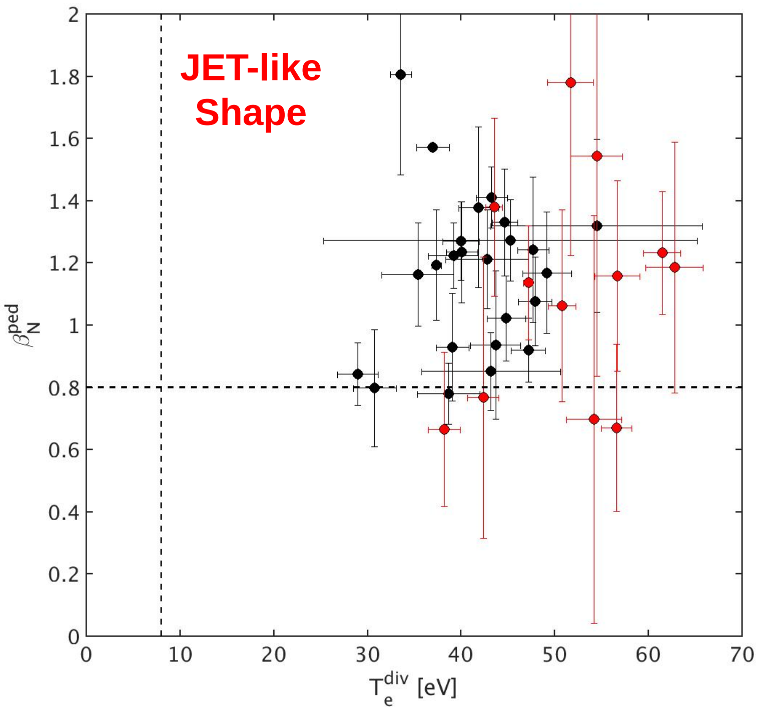
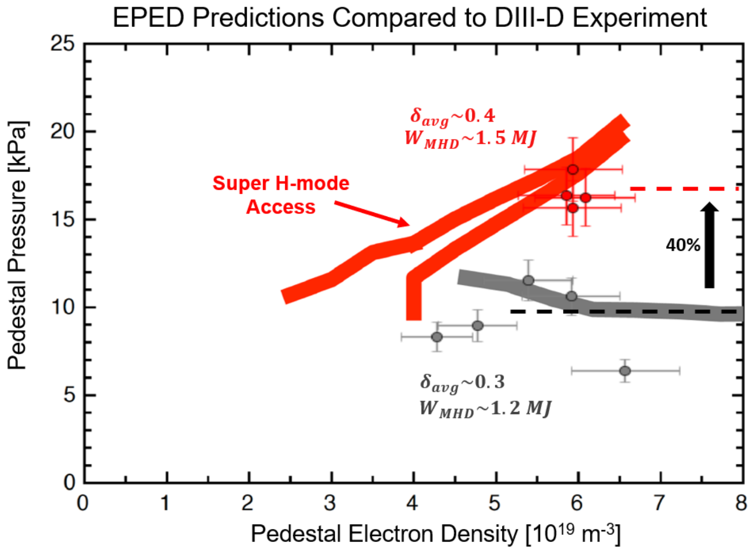
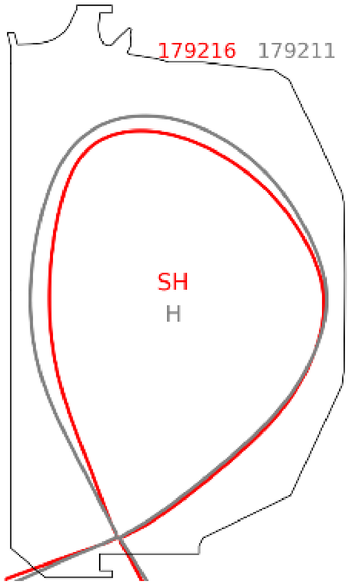


DIII-D experiments show a marginal increase in triangularity leads to SH channel access for JET similar shapes

- **Plasma shape is a key parameter impacting access to SH pedestals**
- **Earlier SH experiments on DIII-D and C-Mod at very high triangularity (δ~0.5-0.7)**
  - Recent DIII-D experiments illustrate robust access to SH with moderately shaped equilibria compatible with JET
- **For JET similar shapes, increased stored energy, triple product, and pedestal pressure enabled by SH channel access**



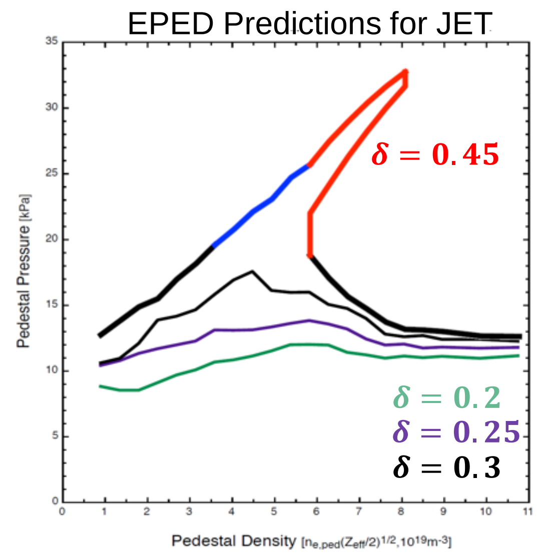


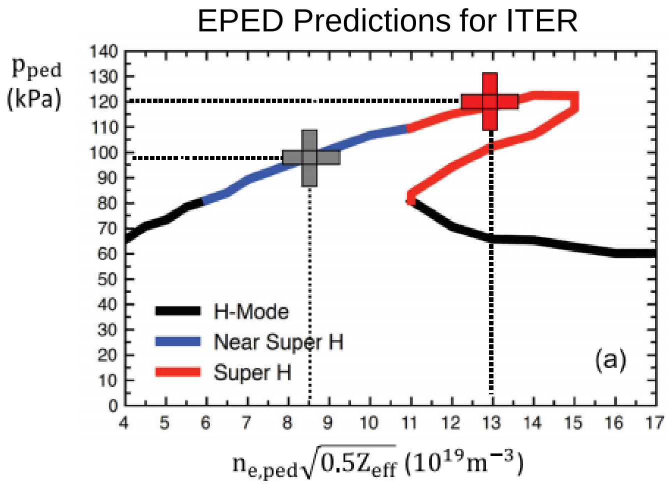
EPED predictions for JET and ITER show broad and deep Super H-mode channel access

- **EPED simulations for JET high Ip scenario ($I_p = 2.7MA, B_T = 2.8T$) at varied triangularity**
  - No SH access for $\delta_{avg} \leq 0.3$
  - Robust SH channel access for $\delta_{avg} \geq 0.4$ at same engineering parameters
  - Small change in triangularity has potential to increase pressure by factor of 2x

- **EPED simulations show robust SH channel prediction for ITER baseline scenario**
  - High separatrix density operation ($4 \times 10^{19}\ m^{-3}$), increased pressure by 20%
  - IBS operating point of 80kPa, SH access leads to ~50% improvement

- **Ongoing research and experiments for SH**
  - Continued detachment and ELM suppression experiments on DIII-D
  - Possible experiments in future JET D-D campaign





Progress in using the Super H-mode in integrating a high performance core, pedestal, and divertor

- **The Super H-mode provides a high performance platform for understanding and optimizing core-edge integration**
  - Advanced control of density (via I-coil) and radiated power are enabling tools
- **Partially detached, high current, peeling limited pedestals achieve core-edge goals**
  - Reduced heat flux to the divertor enabled by nitrogen seeding in feedback control of divertor radiated power
- **Closed divertor Super H-mode experiments provide a promising pathway with little degradation to core plasma**
- **Robust access to Super H-mode channel at moderate triangularity shown both in DIII-D experiments and EPED simulations**

Core Edge Integration on DIII-D