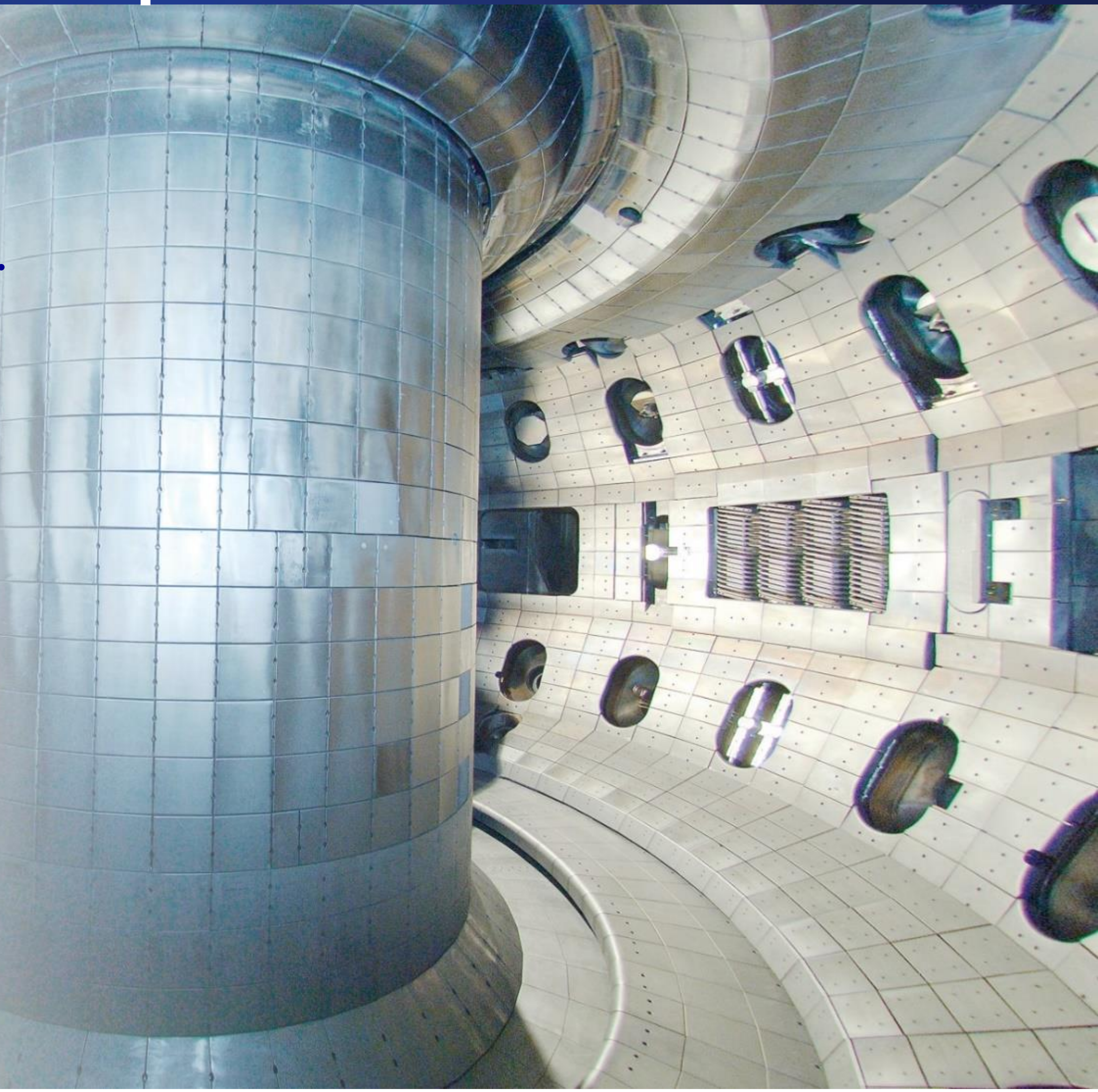
Development of an Integrated Core-Edge Scenario using the Super H-mode



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

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

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

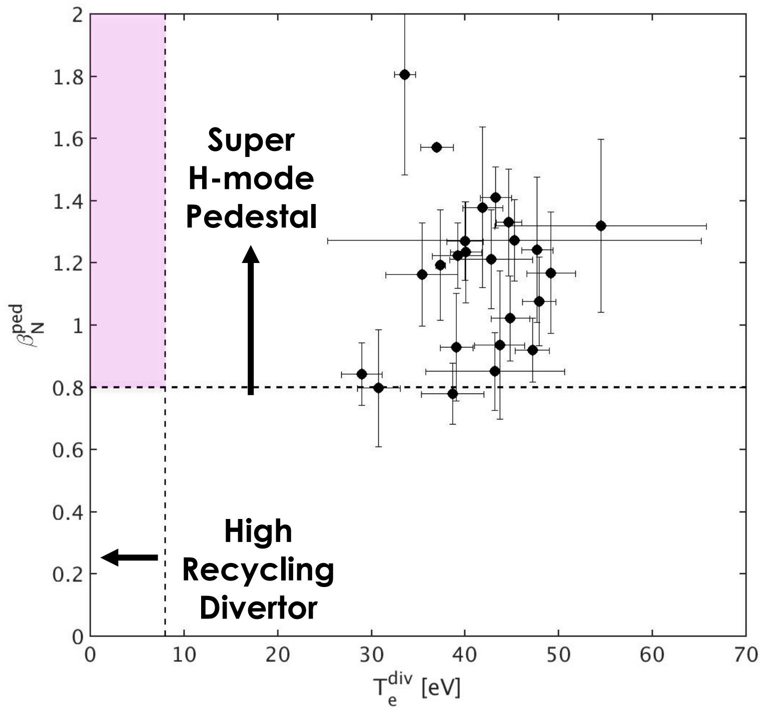
DIII-D NATIONAL FUSION FACILITY

PSFC

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



DIII-D NATIONAL FUSION FACILITY

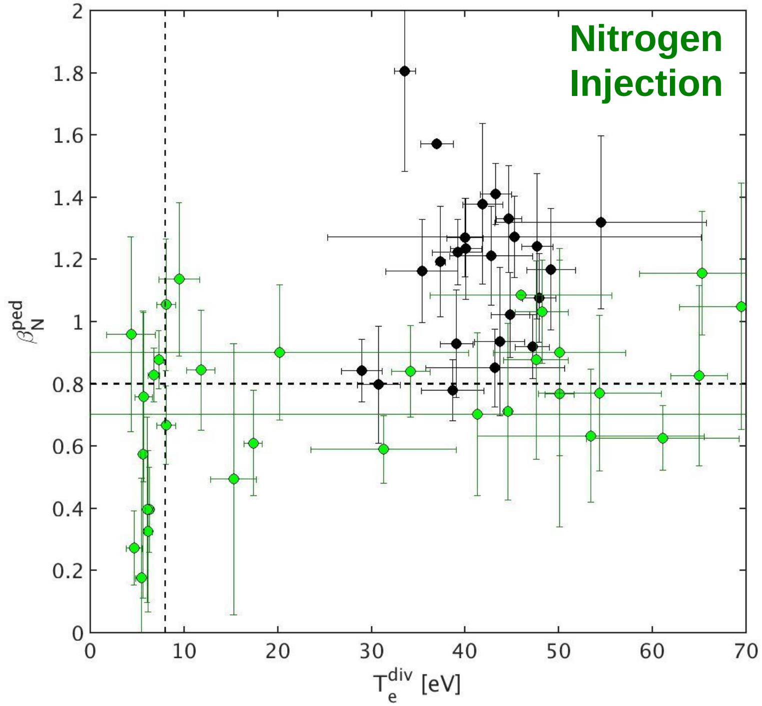
Super H-mode has potential to integrate a high performance core, pedestal and divertor

- 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

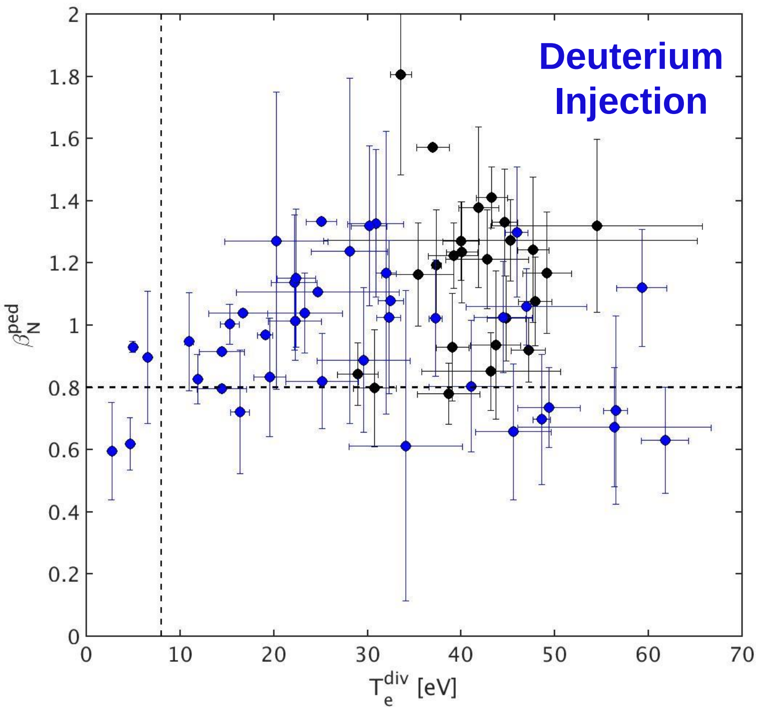


Super H-mode has potential to integrate a high performance core, pedestal and divertor

- 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



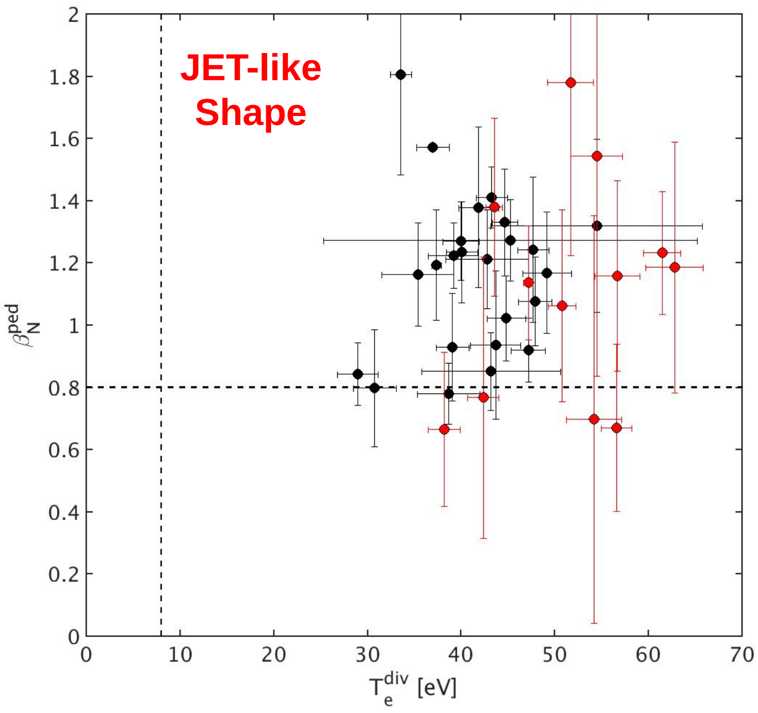
Super H-mode has potential to integrate a high performance core, pedestal and divertor

- 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**

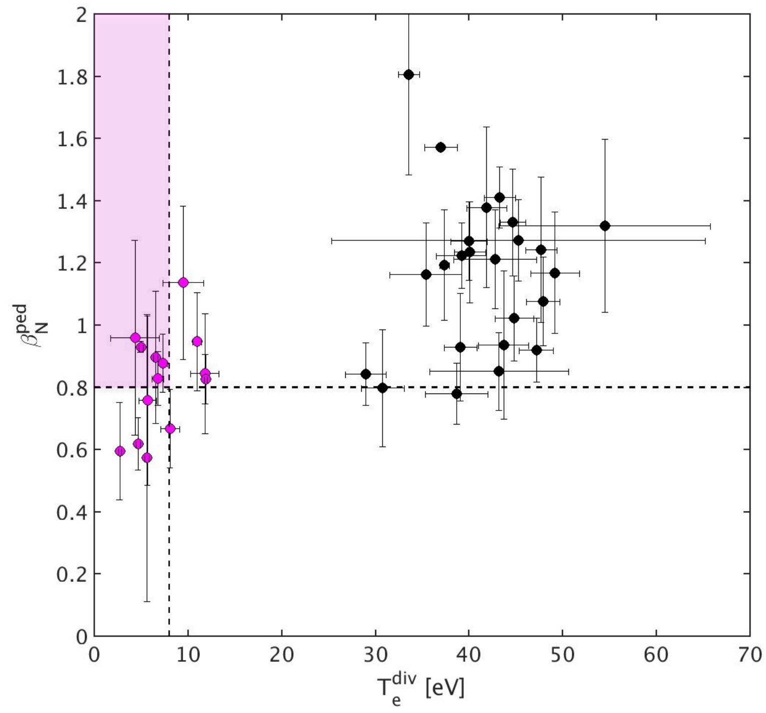
Core Edge Integration on DIII-D



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

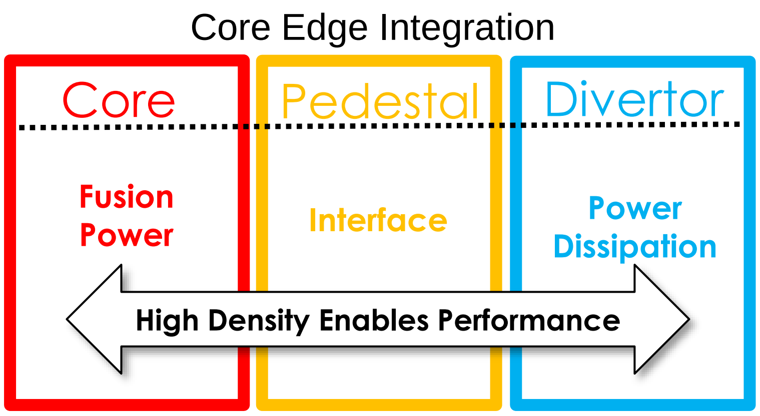


A key challenge for future devices is integration of a high performance core with realistic power exhaust solutions

- 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

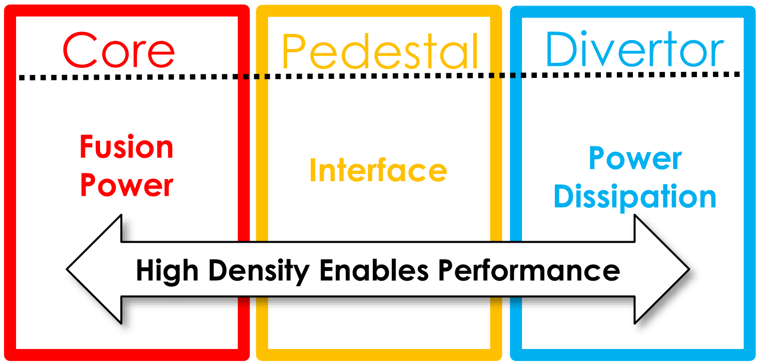
- High density operation enables performance in both core and boundary regions



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



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

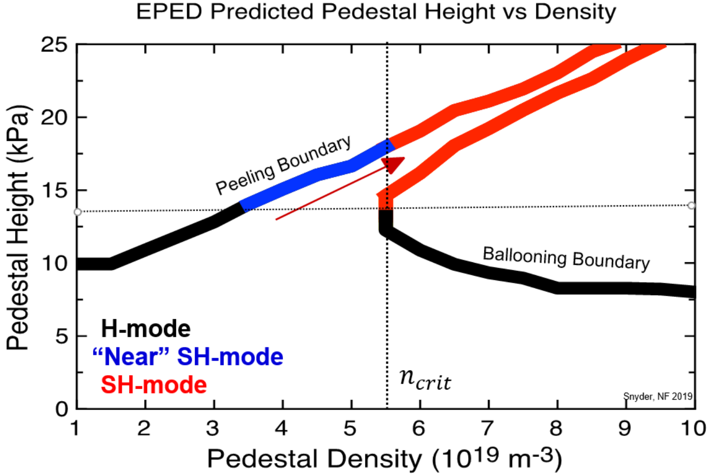
- Increased separatrix density compatible with radiative divertor and detachment
- High separatrix density coupled to high pedestal pressure leads to optimal core-edge integration

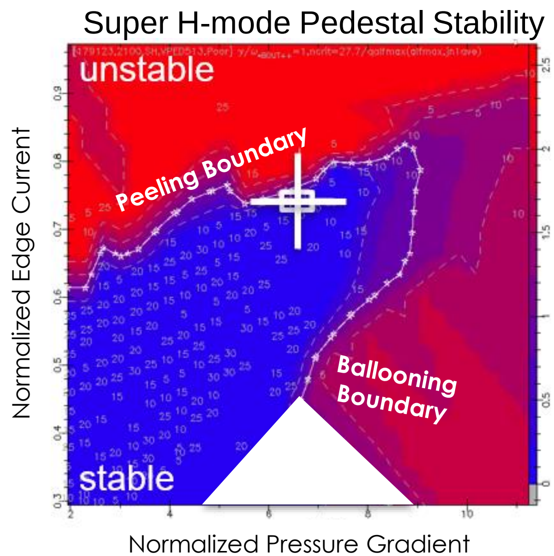
*Hughes, NF 2018

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

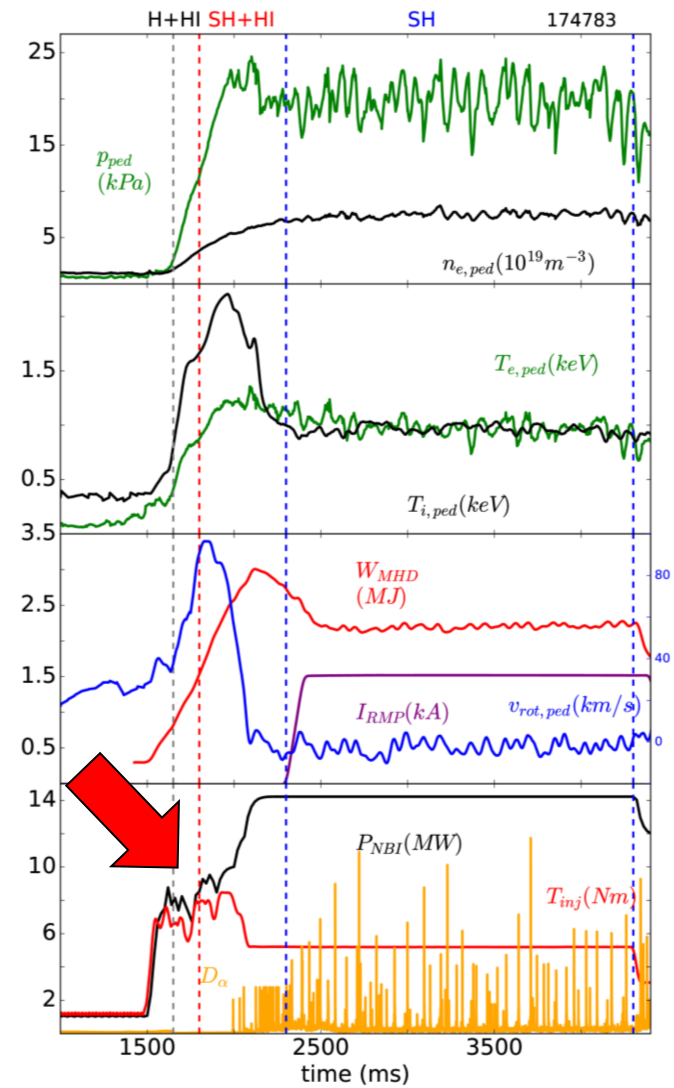




Theoretical framework provides a strategic path towards pedestal optimization and Super H-mode access conditions

Experimental actuators:

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



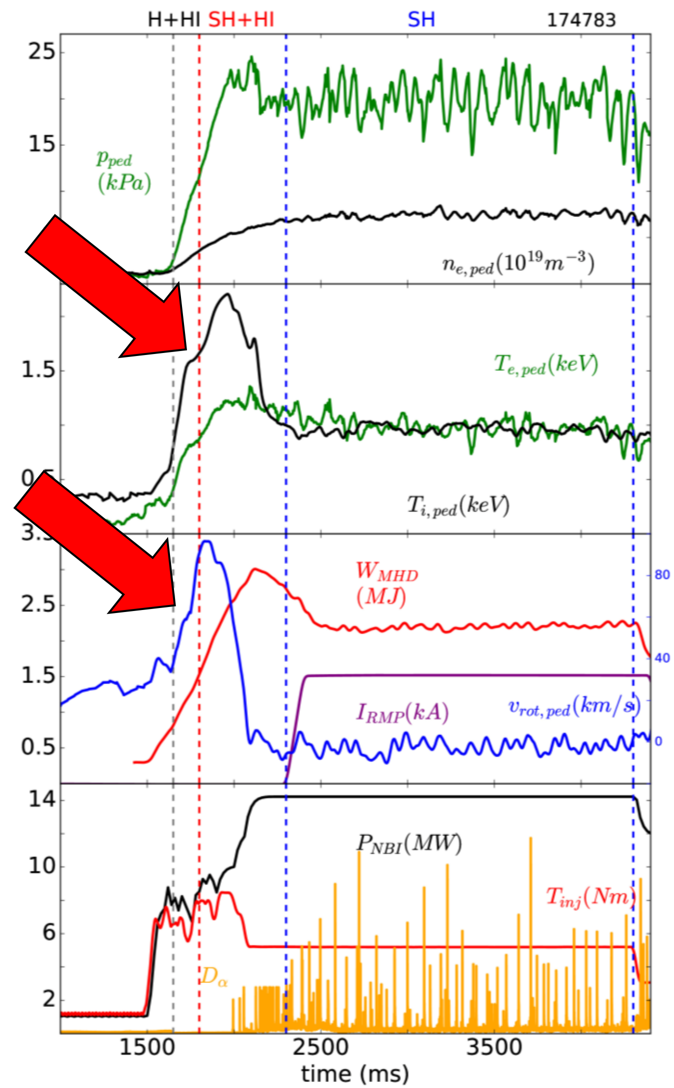
Knolker, PPCF 2021

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

Experimental actuators:
- EPED parameters $(I_p, B_T, R, a, \delta_{avg}, \kappa, n_e^{ped}, \beta_N)$
- Tailored beam program
- Null reversal

Access to peeling physics

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



Knolker, PPCF 2021

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

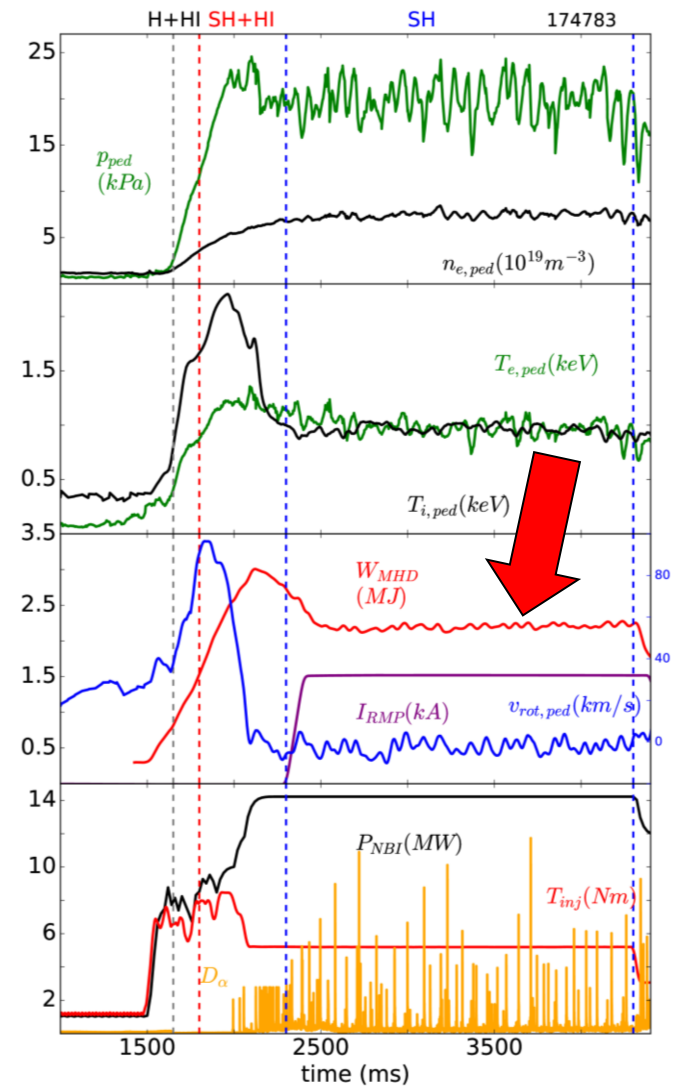
Experimental actuators:
- EPED parameters$(I_p, B_T, R, a, \delta_{avg}, \kappa, n_e^{ped}, \beta_N)$
- Tailored beam program
- Null reversal

Access to peeling physics

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

Increased density;
ion/electron coupling

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



Knolker, PPCF 2021

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

Experimental actuators:
- EPED parameters($I_p, B_T, R, a, \delta_{avg}, \kappa, n_e^{ped}, \beta_N$)
- Tailored beam program
- Null reversal

↓ *Access to peeling physics*

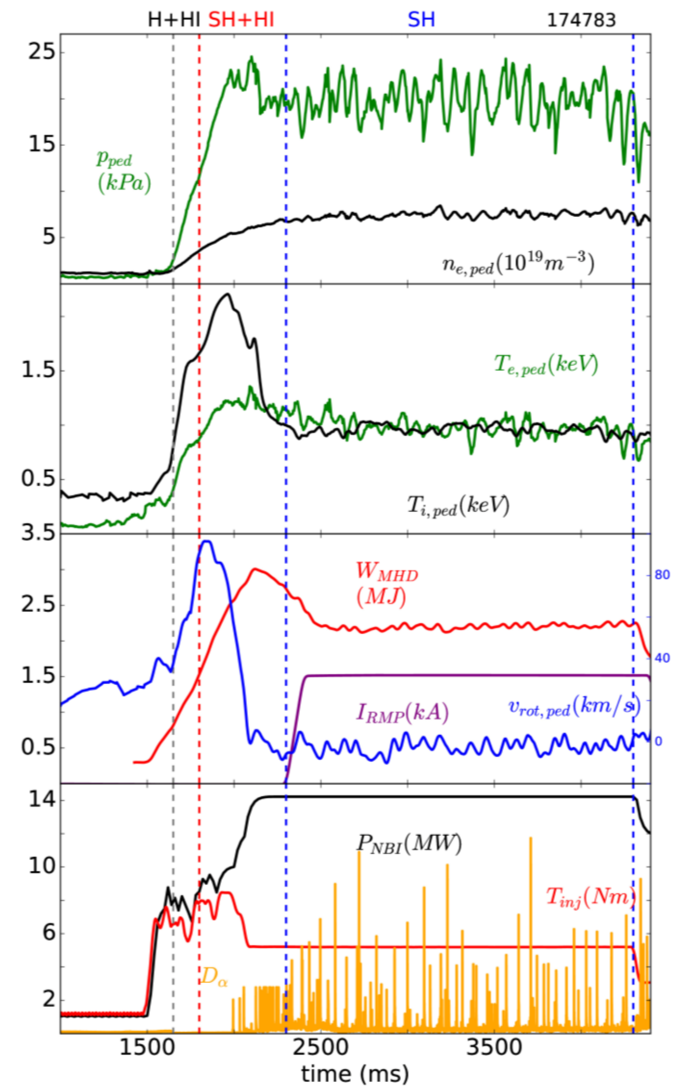
Hot Ion Mode:
- High T_i^{ped}, rotation shear & Shafranov shift
- High core pressure, stored energy, Q

↓ *Increased density; ion/electron coupling*

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

↘ *RMP > 3kA; Large tearing mode coupled to edge*

H-mode:
- Further reduced core pressure
- Core MHD



Knolker, PPCF 2021

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

Experimental actuators:
- EPED parameters($I_p, B_T, R, a, \delta_{avg}, \kappa, n_e^{ped}, \beta_N$)
- Tailored beam program
- Null reversal

Access to peeling physics

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

Increased density; ion/electron coupling

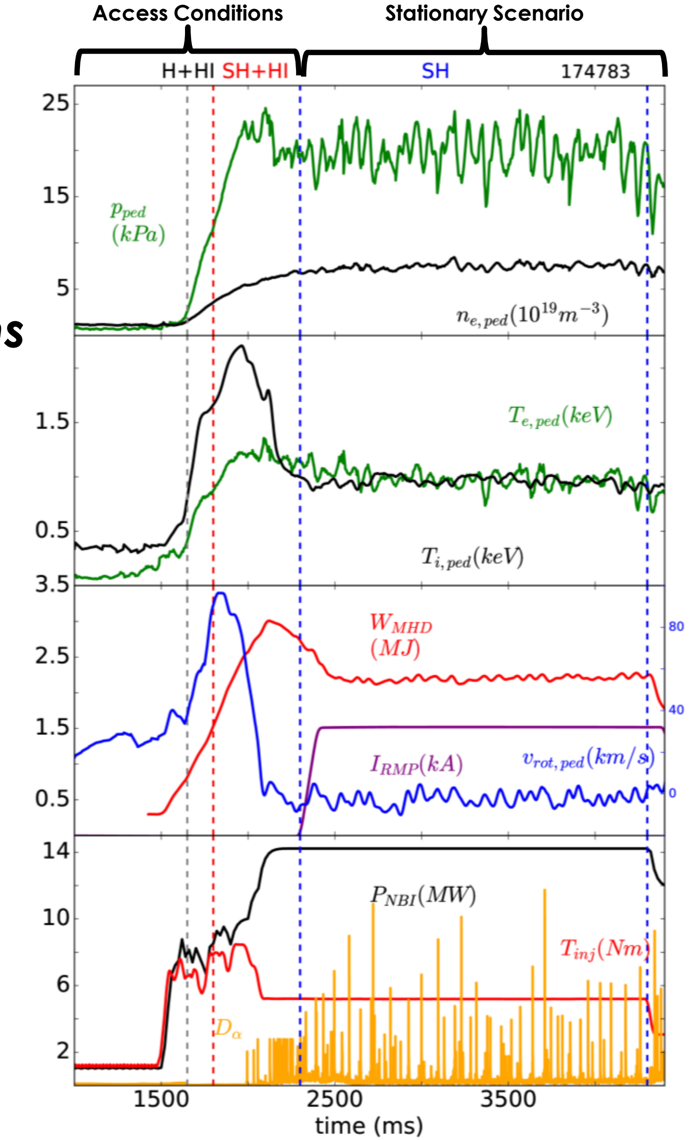
Stationary SH/"Near" Super H-mode:
- Stationary w/ I-coils
- Reduced stored energy

Access Conditions

Stationary State

RMP > 3kA; Large tearing mode coupled to edge

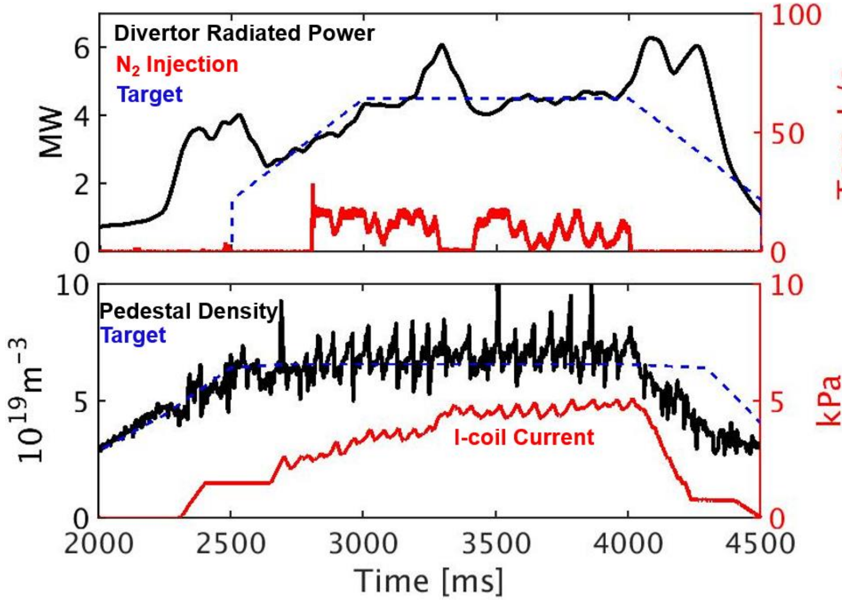
H-mode:
- Further reduced core pressure
- Core MHD



Knolker, PPCF 2021

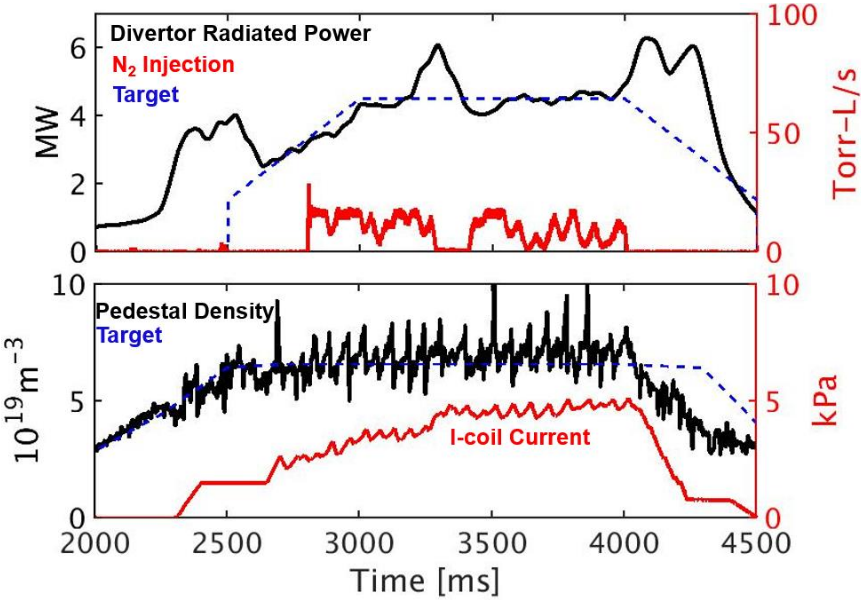
Advanced control algorithms are employed for pedestal-divertor integration

- **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

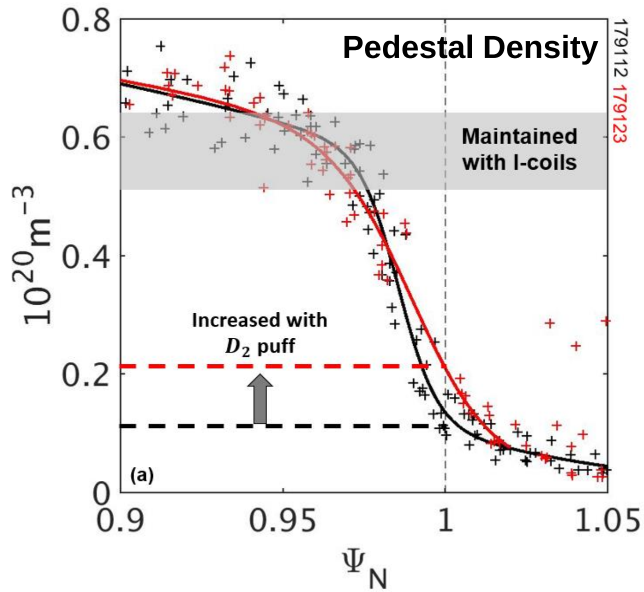


Advanced control algorithms are employed for pedestal-divertor integration

- **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



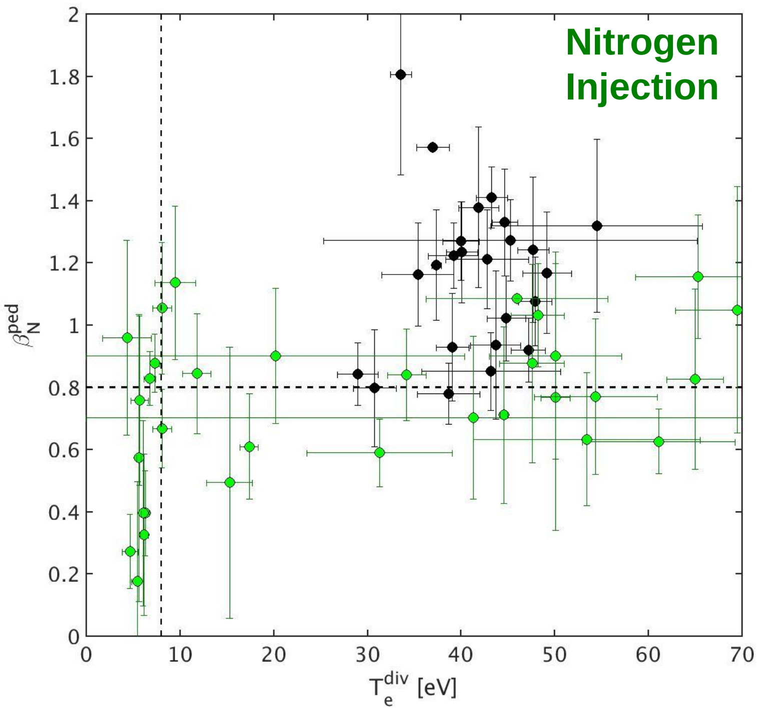
- **Peeling physics leveraged to decouple pedestal and separatrix response to gas injection**
  - Separatrix density increases with fueling
  - Pedestal density held approximately fixed (does not degrade)



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



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

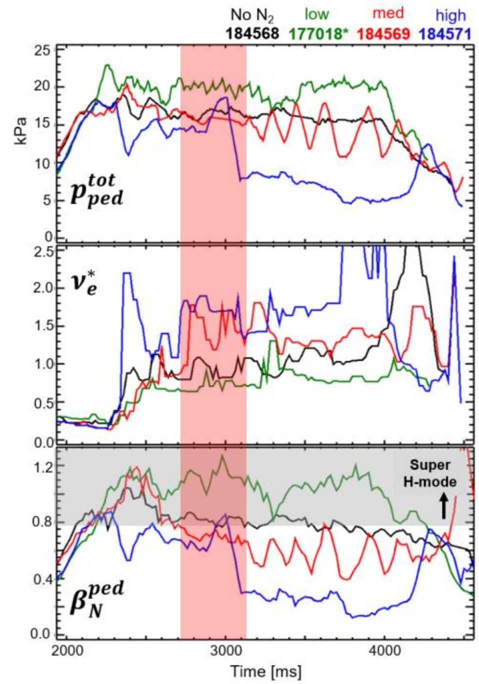
	Core			Pedestal			Divertor		
	Prad Target (shot)	W_{MHD} (MJ)	β_N	T_i^{ped} (eV)	T_e^{ped} (eV)	ELMs	T_e^{div} (eV)	q_{div} (W/cm²)	Divertor Condition
No Seeding	0.0MW (184568)	2.1	2.5	1100	825	Regular Type I	60	480	Attached
Low Seeding	4.5MW (177018*)	1.7	2.1	750	900	Regular Type I	15	300	Attached
Medium 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

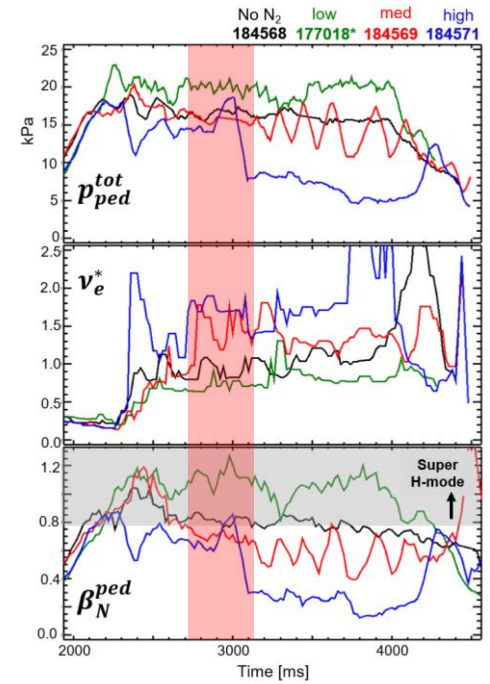
- **Increasing radiative power targets (low→med→high) quantitatively map trade offs between core and edge metrics**
  - $\beta_N^{ped} \geq 0.8,\ 15kPa < p_{ped}^{tot} < 20kPa,\ \ \nu_e^* < 1$

- **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



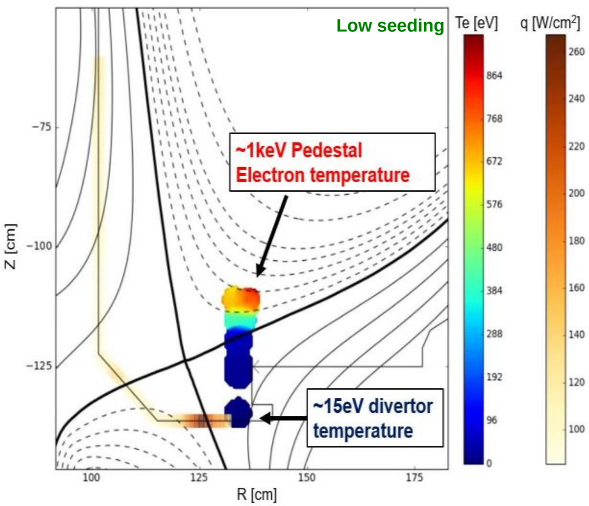
DIII-D experiments show Super H-mode scenario can operate with high pedestal temperature and low divertor temperature

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

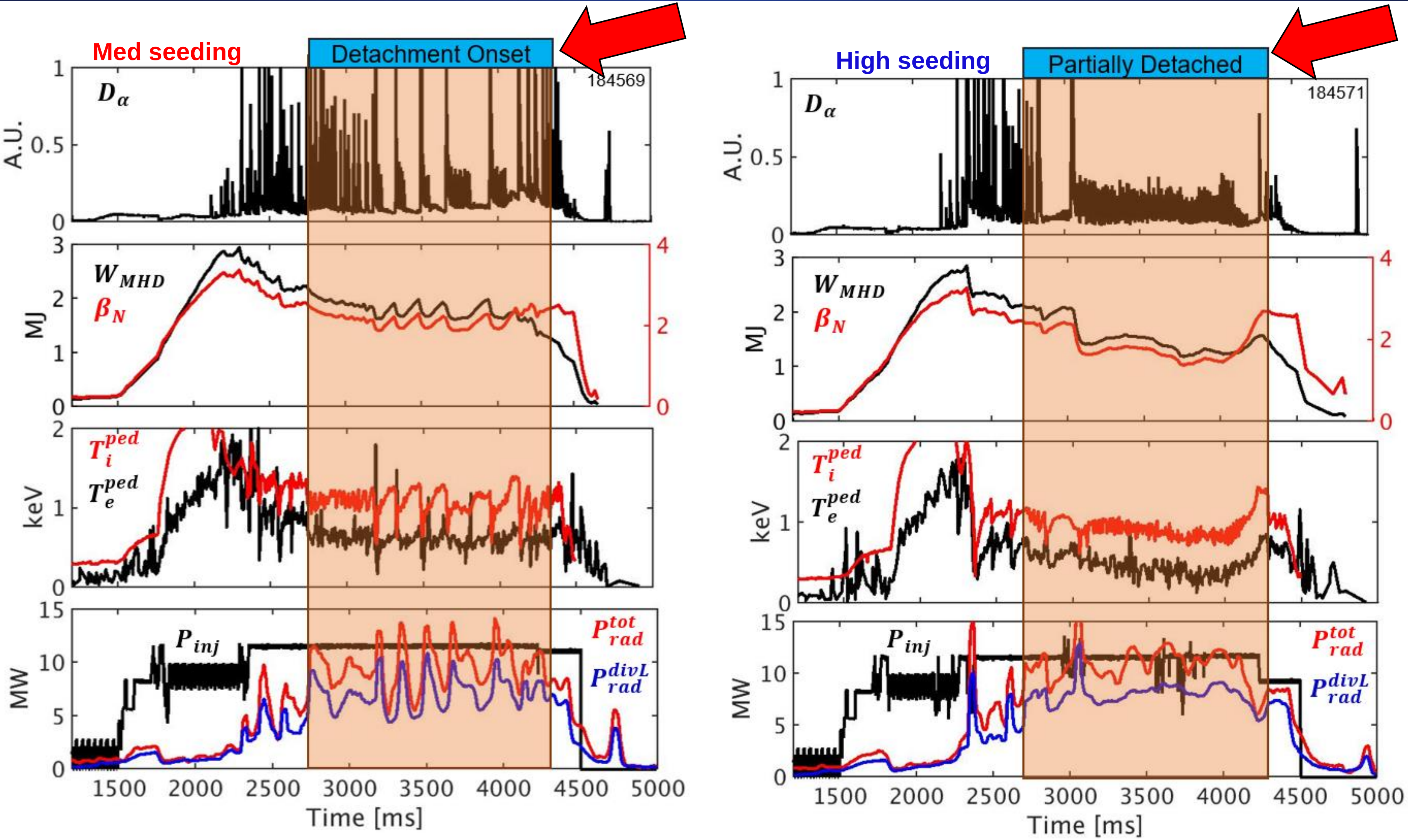


- **Balanced core edge integration combines detachment onset and SH access**
  - Both pressure and density rise in between large ELMs, indicating peeling boundary
  - More stationary state in early flattop represents a promising operating point

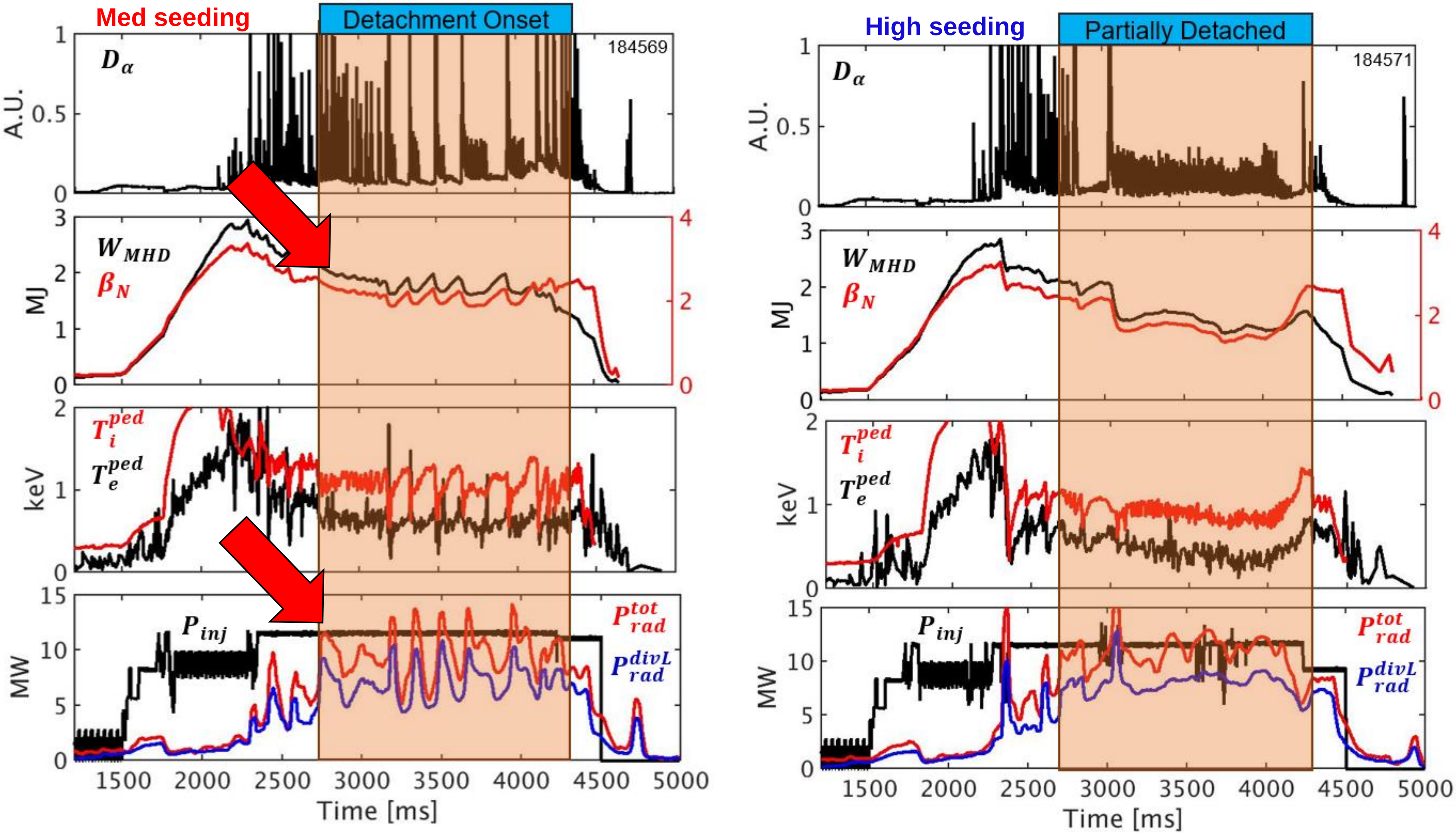
- **Attached Super H-mode has 1 keV pedestal in combination with <15eV divertor temperature**
  - Divertor temperature ~4x higher without N_2 seeding
  - High recycling; attached



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

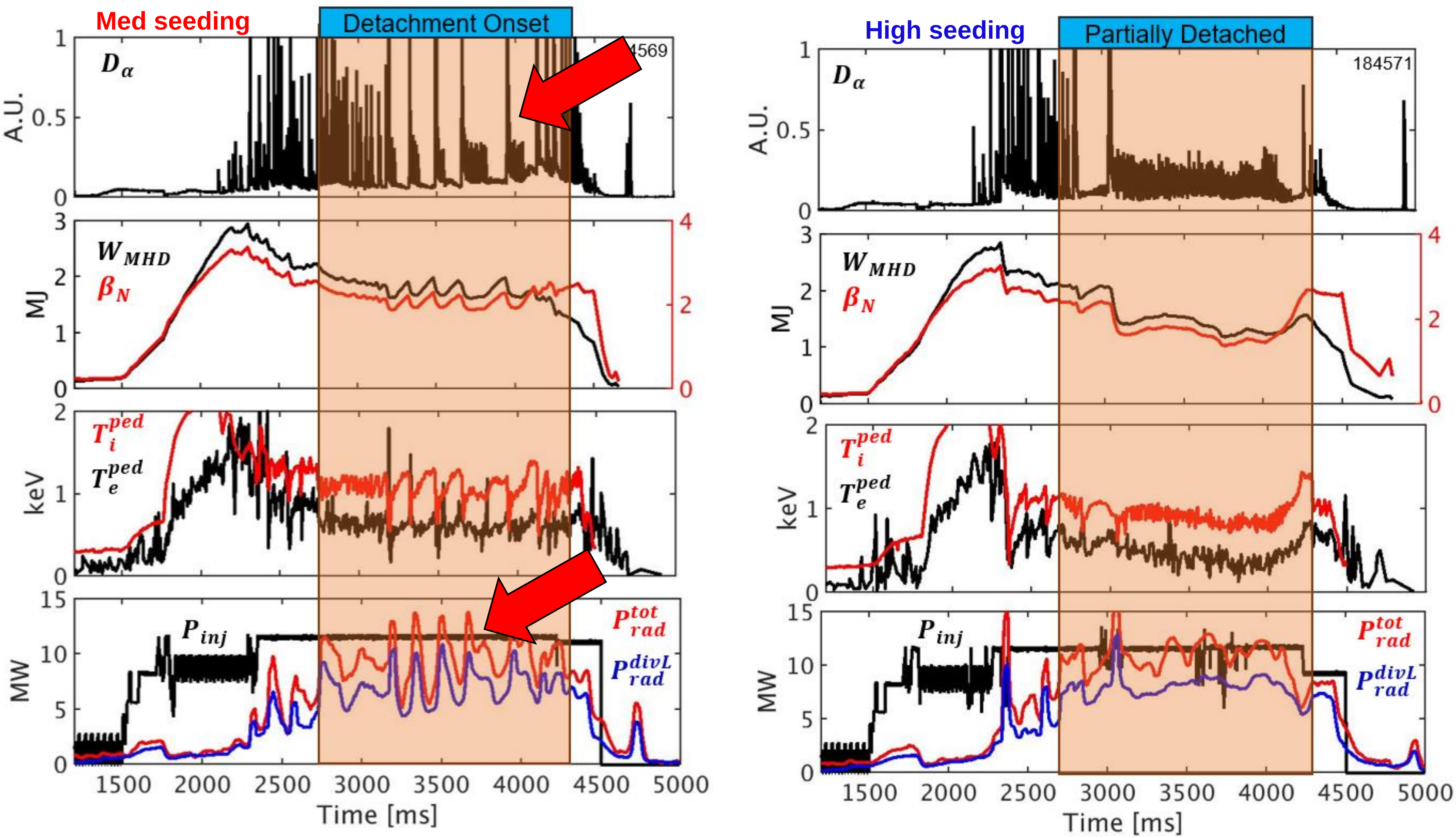


Time histories show Super H-mode passes through an optimal phase for future feedback targets

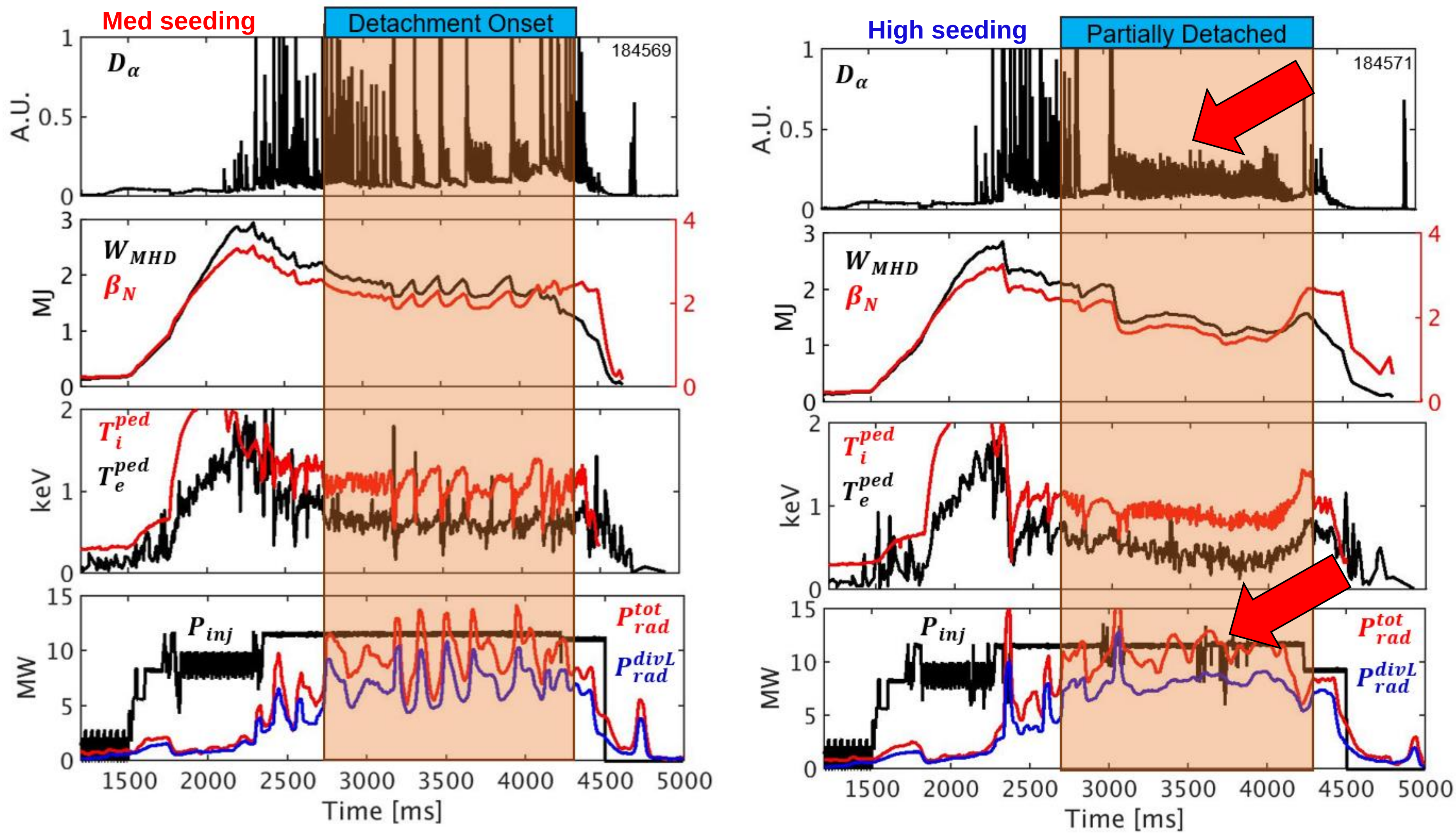


DIII-D NATIONAL FUSION FACILITY

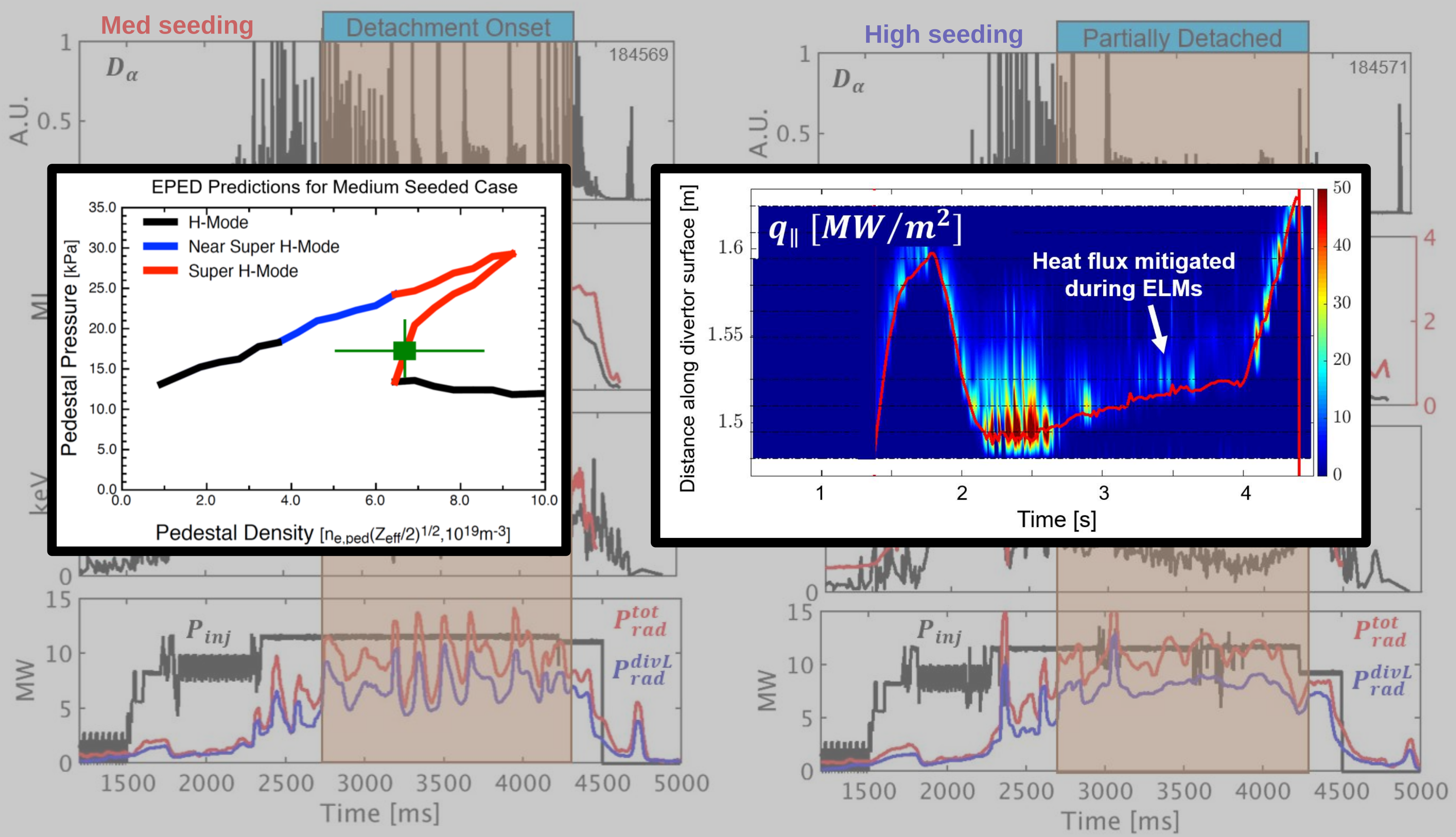
Time histories show Super H-mode passes through an optimal phase for future feedback targets



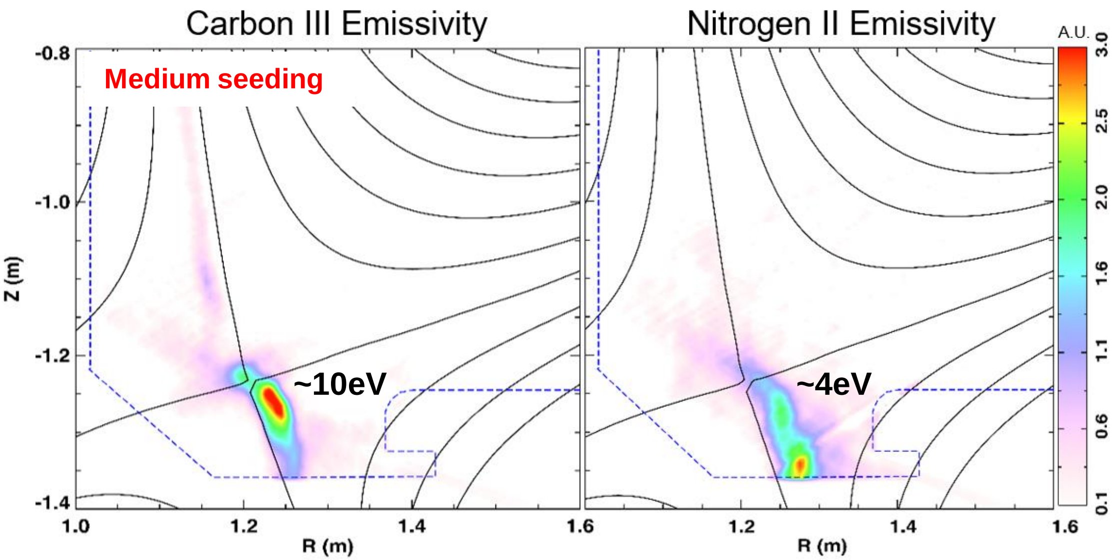
Time histories show Super H-mode passes through an optimal phase for future feedback targets



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

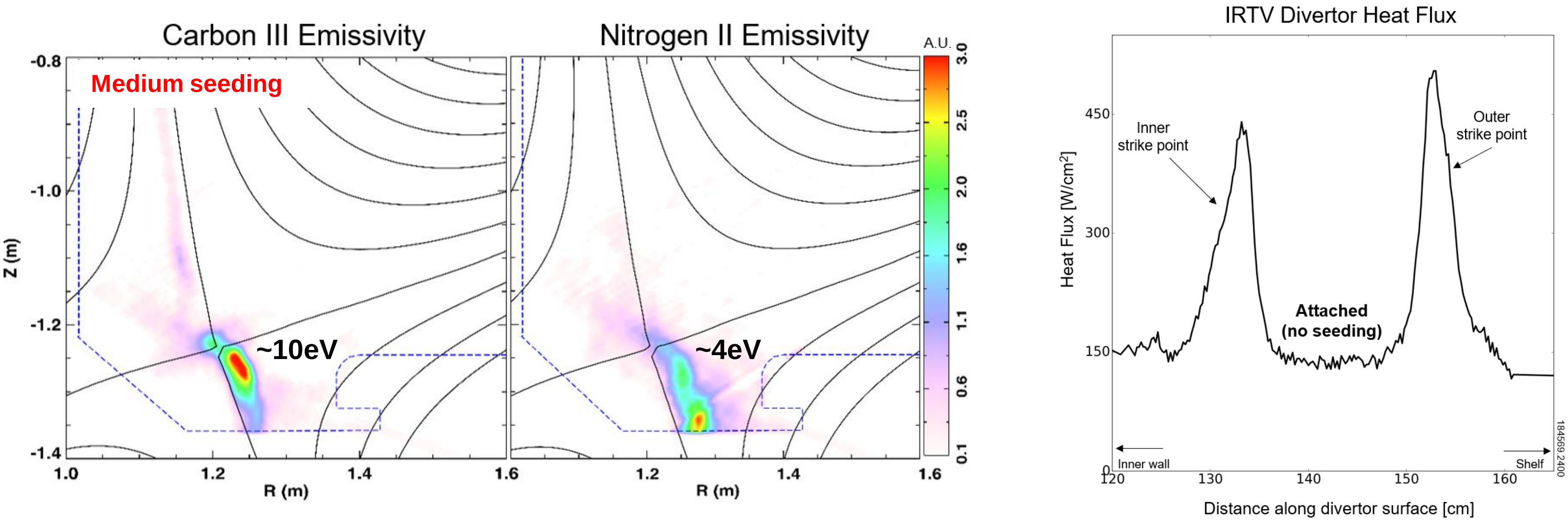


Divertor plate is cooled and heat flux mitigated with detachment onset



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

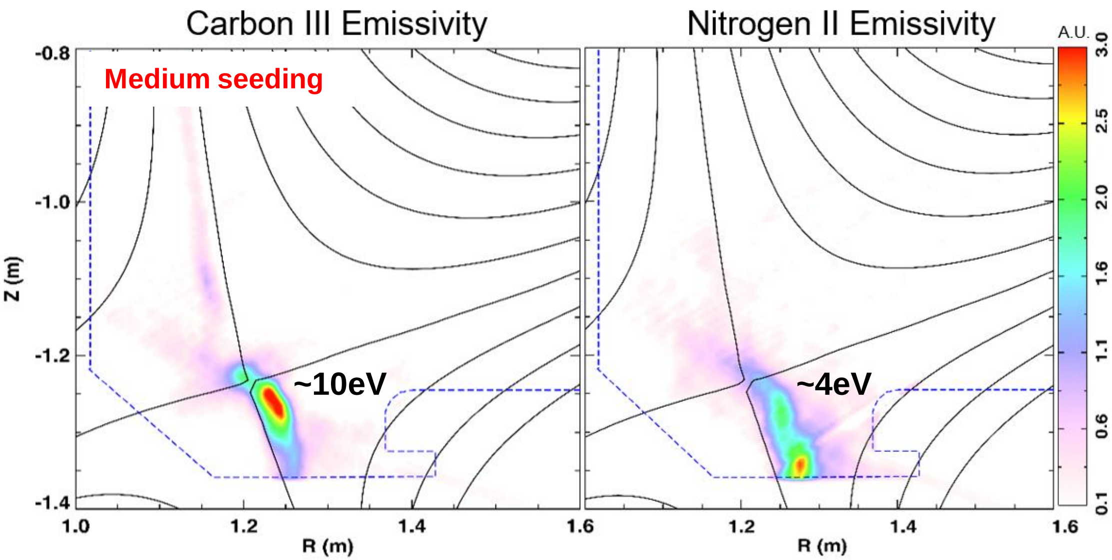
Divertor plate is cooled and heat flux mitigated with detachment onset

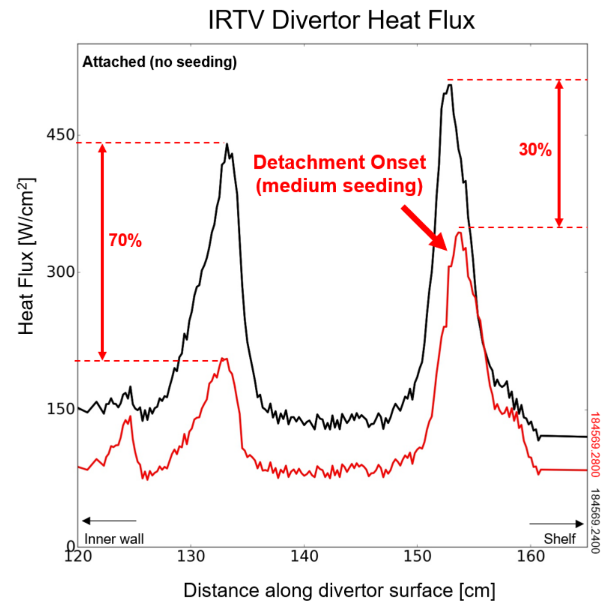


- Detachment onset shown by carbon radiation front moving away from strike point towards the x-point

- Heat flux at the divertor plate reduces approaching detachment

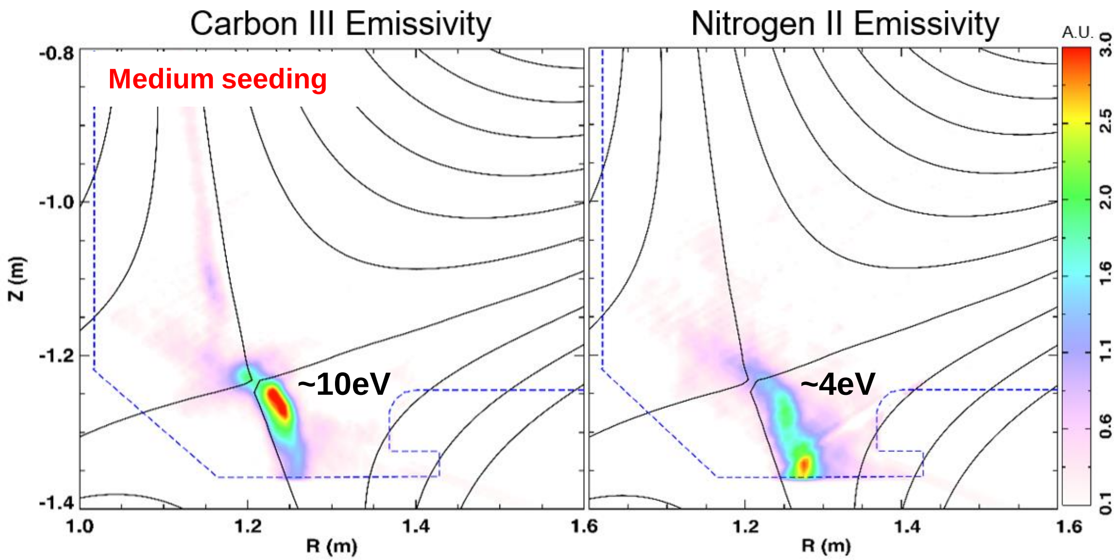
Divertor plate is cooled and heat flux mitigated with detachment onset

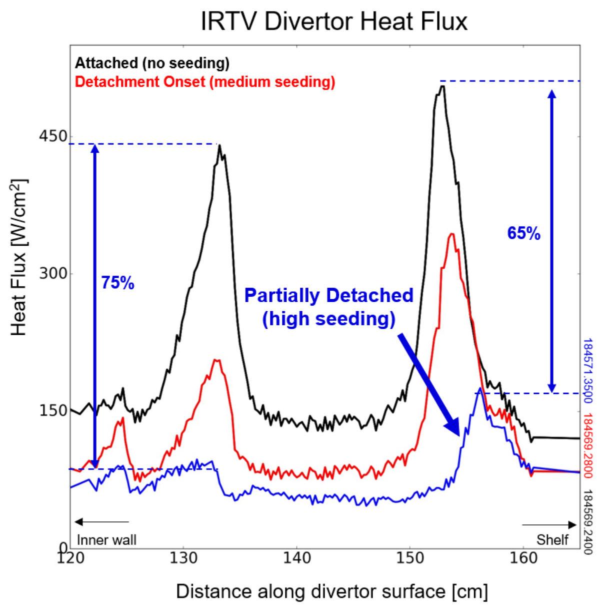




- **Detachment onset shown by carbon radiation front moving away from strike point towards the x-point**
- **Heat flux at the divertor plate reduces approaching detachment**

Divertor plate is cooled and heat flux mitigated with detachment onset



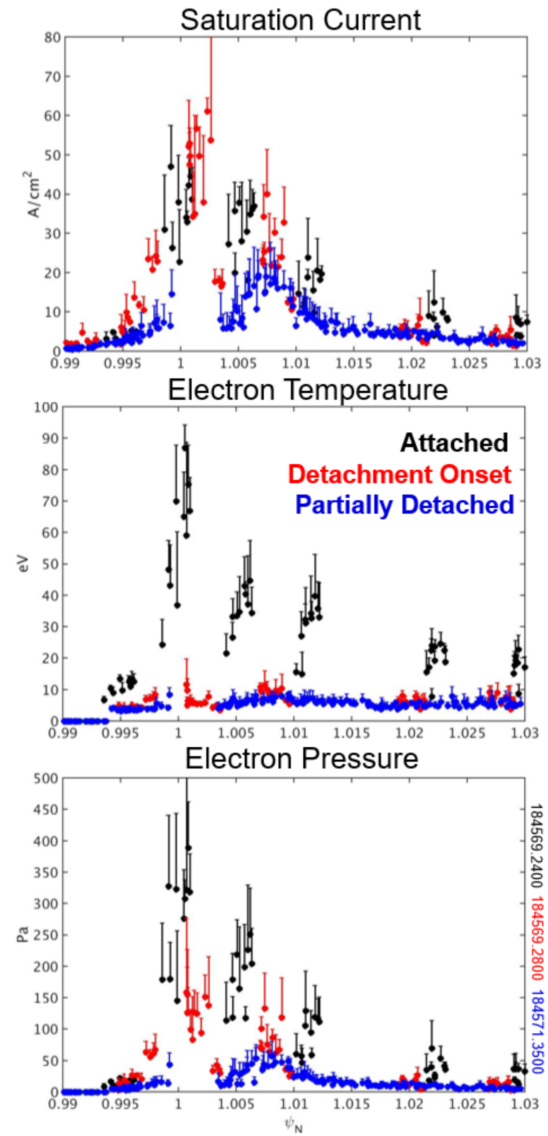


- **Detachment onset shown by carbon radiation front moving away from strike point towards the x-point**

- **Heat flux at the divertor plate reduces approaching detachment**

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**



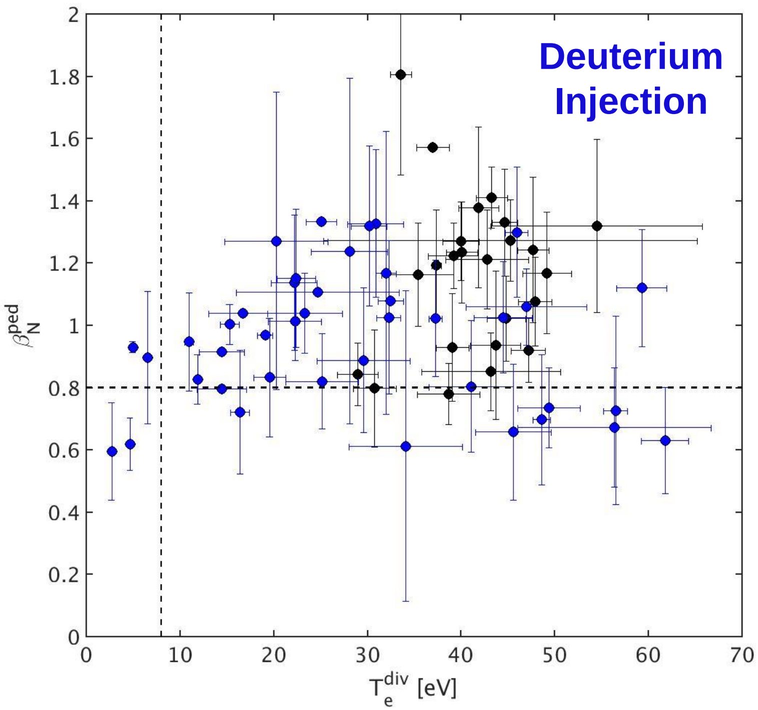
Super H-mode has potential to integrate a high performance core, pedestal and divertor

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

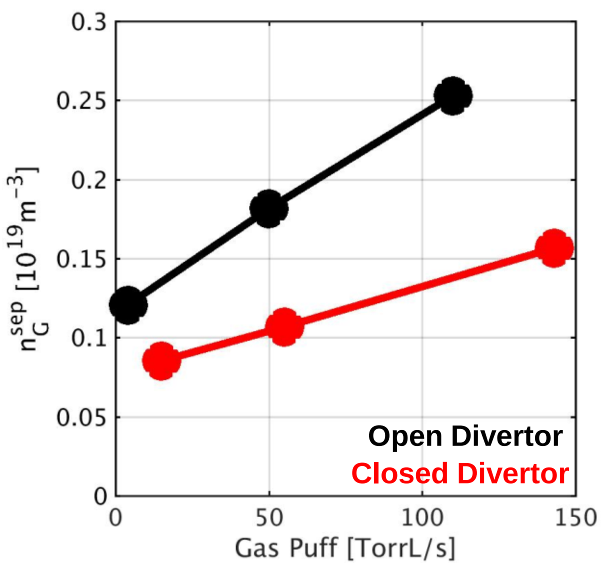
- **Core edge integration strategies in highly shaped SH plasmas**
  - Compatibility with N_2 seeded radiative divertor
  - Divertor closure studies with D_2 fueling

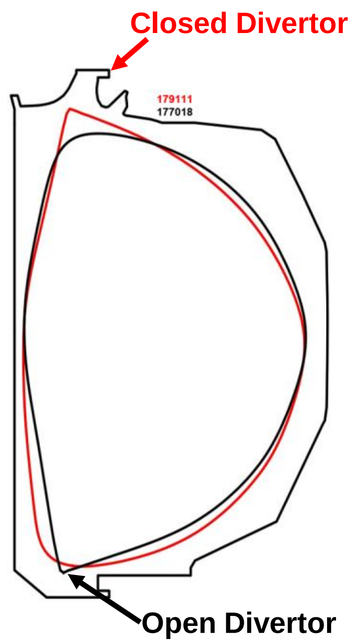
- Access to SH in moderate triangularity and applicability to JET and ITER

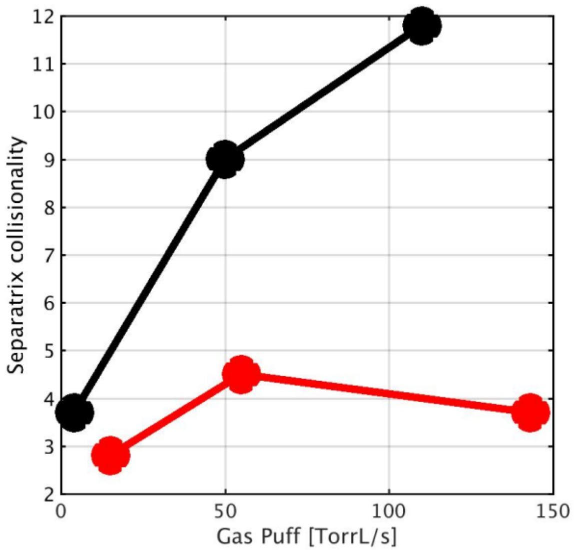
Core Edge Integration on DIII-D



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





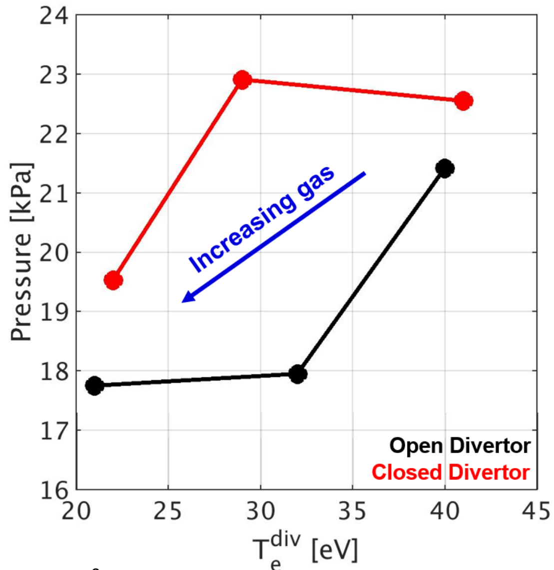


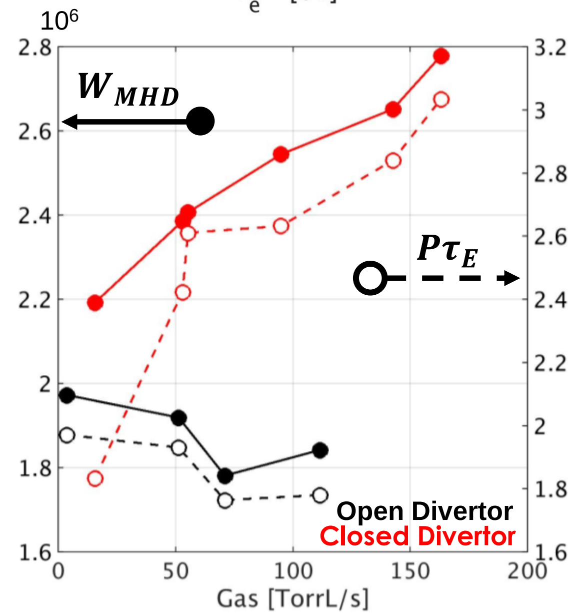
- Upper single null (USN) has a more closed divertor on DIII-D
- Separatrix density and collisionality increase more with gas puff in open divertor than closed due to decreased pumping

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**

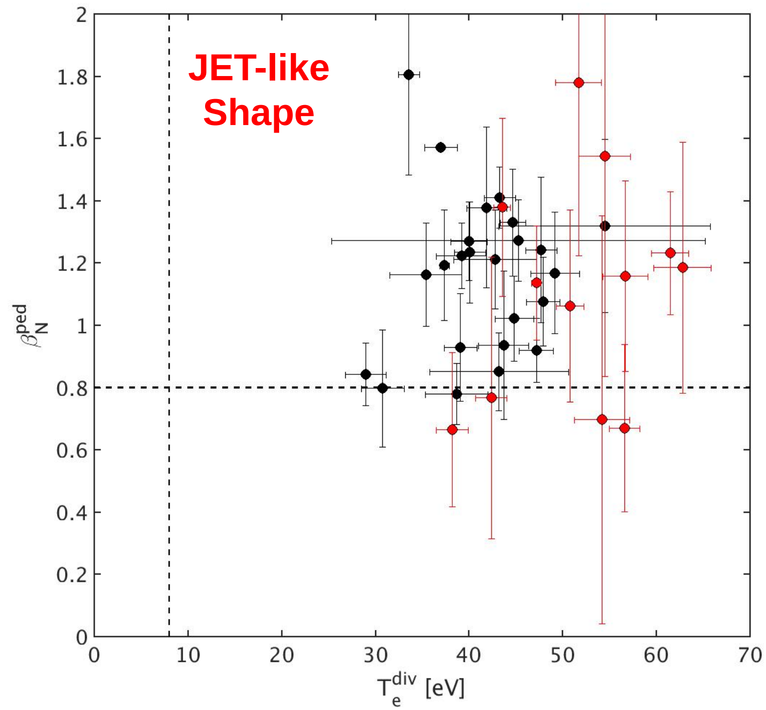




Super H-mode has potential to integrate a high performance core, pedestal and divertor

- 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**

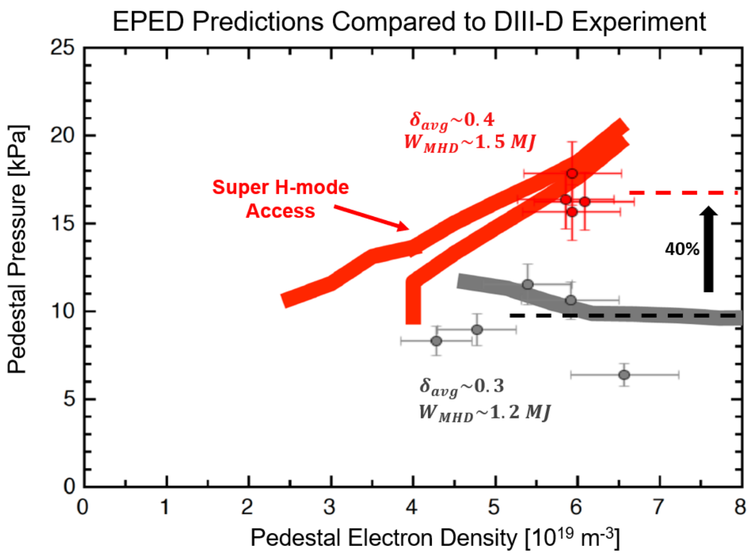
Core Edge Integration on DIII-D

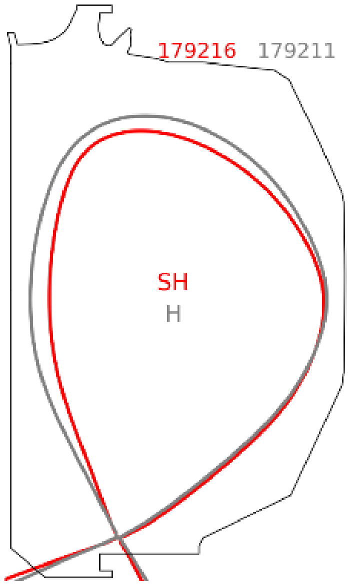


DIII-D NATIONAL FUSION FACILITY

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**





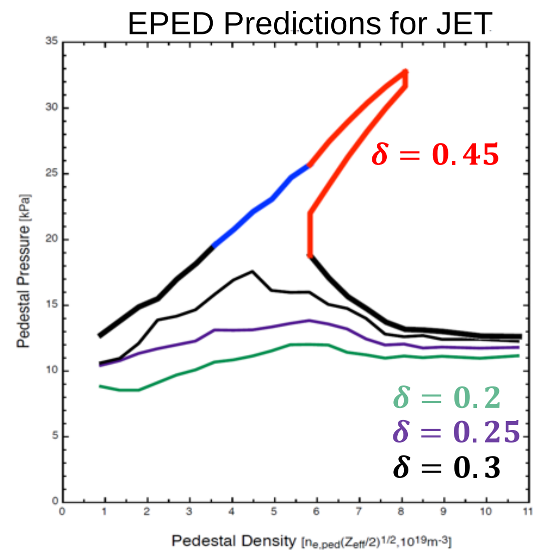
DIII-D NATIONAL FUSION FACILITY

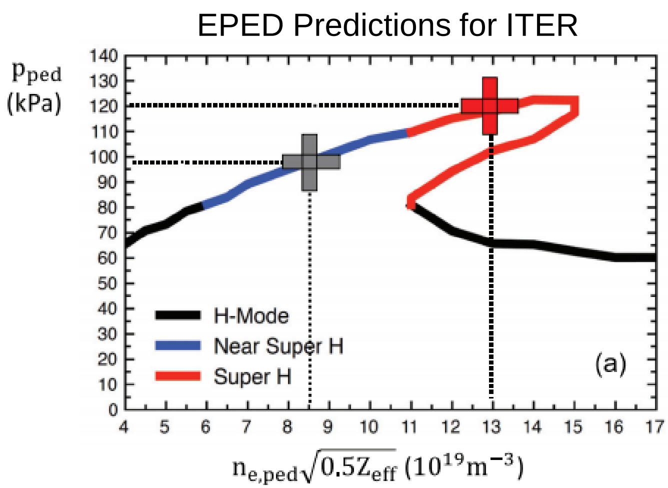
EPED predictions for JET and ITER show broad and deep Super H-mode channel access

- **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**