Compatibility of Divertor Detachment with High-performance Core Towards Steady-State Fusion

by

H. Q. Wang,

L. Wang[a], S. Ding[a], A. M. Garofalo, X. Z. Gong[a], D. Eldon, H. Y. Guo, A. W. Leonard, A. Hyatt, J. P. Qian[a], D. Weisberg, J. McClenaghan, M. E. Fenstermacher[b], T. H. Osborne, C. Lasnier[b], J. G. Watkins[c], M.W. Shafer[d], B. Grierson[e], X. Jian[f], G. S. Xu[a], J. Huang[a], R. J. Buttery, D. Humphreys, D. M. Thomas, B. Zhang[a], J. B. Liu[a]

General Atomics, PO Box 85608, San Diego, CA 92186-5608, USA
[a]Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, China
[b]Lawrence Livermore National Laboratory, Livermore, California 94550, USA
[c]Sandia National Laboratories, PO Box 969, Livermore, CA 94551, USA
[d]Oak Ridge National Laboratory, PO Box 2008 Oak Ridge, TN 37831, USA
[e]Princeton Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08543, USA
[f]University of California, San Diego, La Jolla, California 92093-0417, USA

Presented at the
US-PRC workshop

March 2021

Outline

- Motivation
- Full detached divertor with high β_p high-confinement core
- The synergy between the ITB+ETB
- Summary

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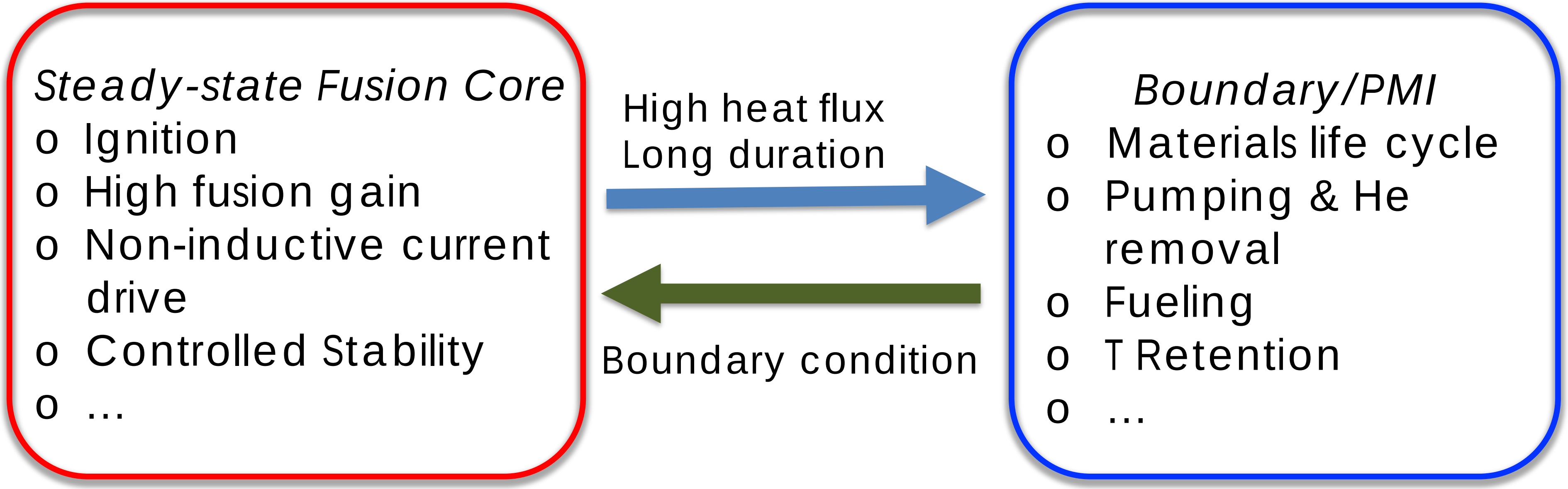
Motivation: Core-edge integration is a critical issue for steady-state fusion operation

- A steady-state tokamak fusion reactor: sustain fusion energy output for sufficiently long duration operation

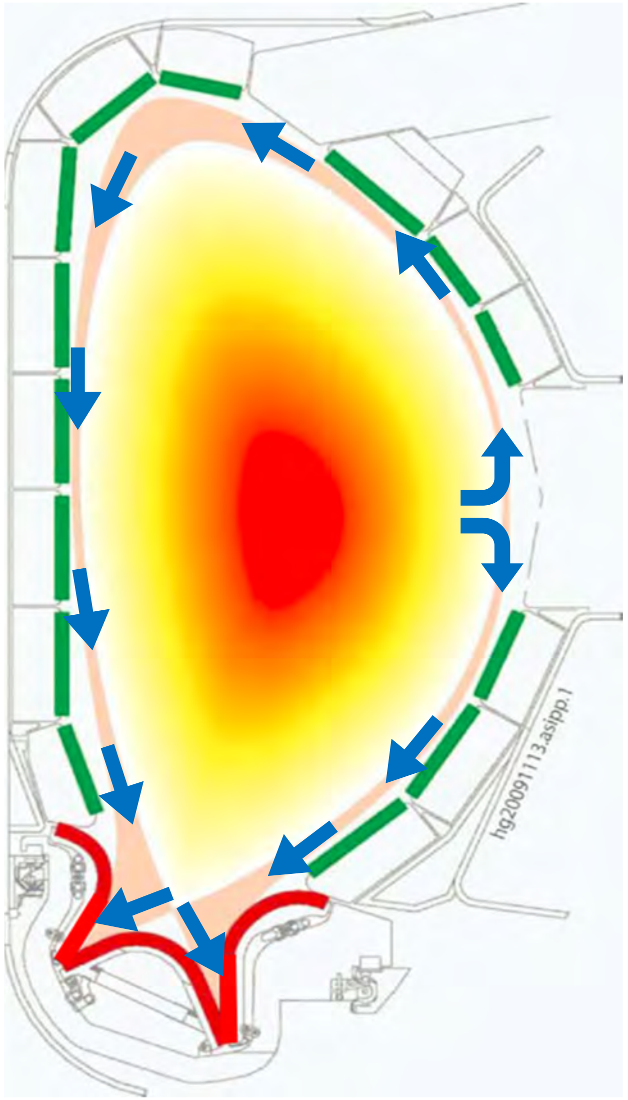


Steady-state Fusion Core
- o Ignition
- o High fusion gain
- o Non-inductive current drive
- o Controlled Stability
- o …

High heat flux
Long duration

Boundary condition

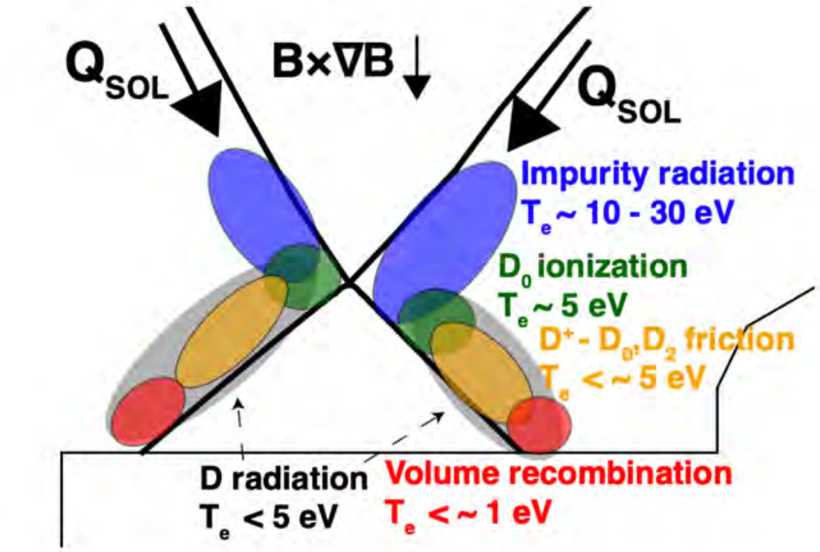
Boundary/PMI
- o Materials life cycle
- o Pumping & He removal
- o Fueling
- o T Retention
- o …



Gormezano, NF 2007

Motivation: Cold boundary/divertor solution is highly required for steady-state fusion

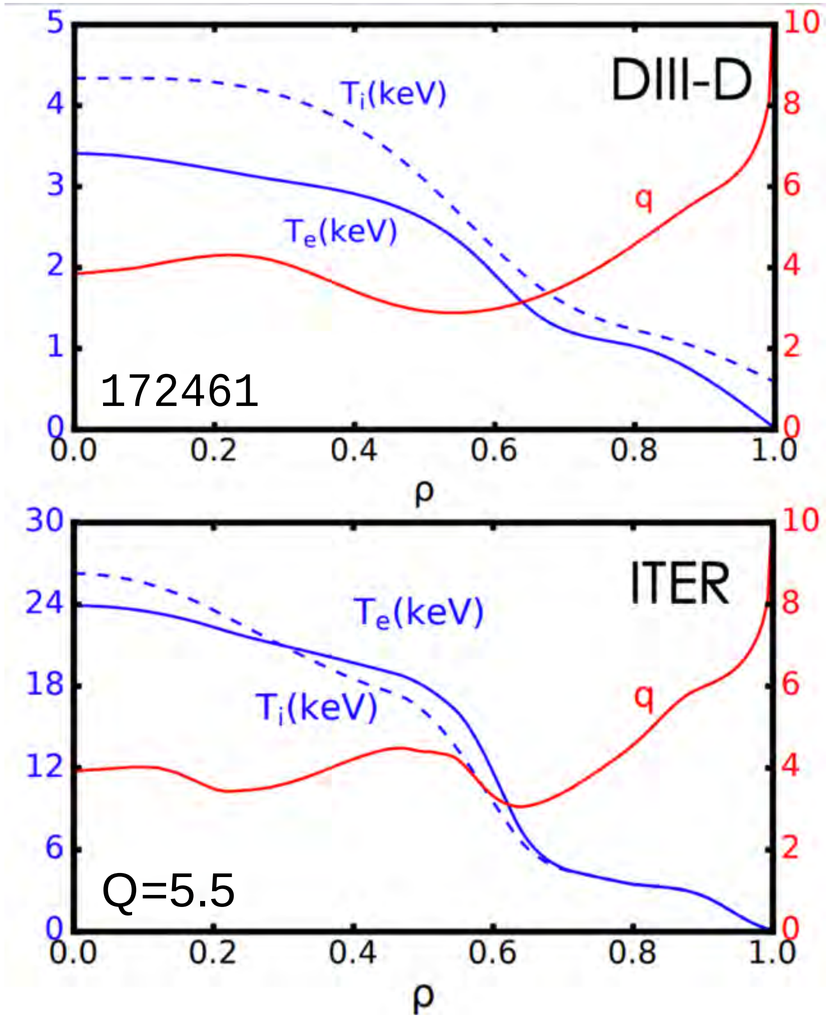
- Divertor Detachment
  - Low temperature T_e <10eV → suppress physical erosion: detach.
  - Low particle flux across entire divertor → suppress chemical erosion: full detachment
  - Low heat flux acceptable by materials $q<10MW/m^2$
- Compatible with high-performance core
- Controllable intermittent events (ELMs) and disruptions
- Pumping, fueling & Helium removal…



Jaervinen, PSI 2018
Pitts, NME 2019
Loarte, NF 2017
Guo, NF 2019
Stangeby, PPCF 2018

Motivation: High β_p is a promising candidate scenario for steady-state fusion core

- High β_p with high q_{95} → lower disruption risk (due to core MHD) even at high β_N
- High β_p → high $f_{bs} \propto \sqrt{\epsilon}\beta_p$ → Non-inductive current drive for Long-pulse Ops
- High β_p → Strong Shafranov shift → High confinement quality → high fusion gain → reduce cost for a reactor
  - Transport barriers → isolate the hot core vs cold boundary
- Recent self-consistent simulations confirms the possibility of high β_p scenario for ITER reaching steady-state Q=5 goal.
  - Similar q profiles as in DIII-D



McClenaghan, IAEA 2018; Qian APS 2019; Garofalo, AAPPS 2019 and this conference

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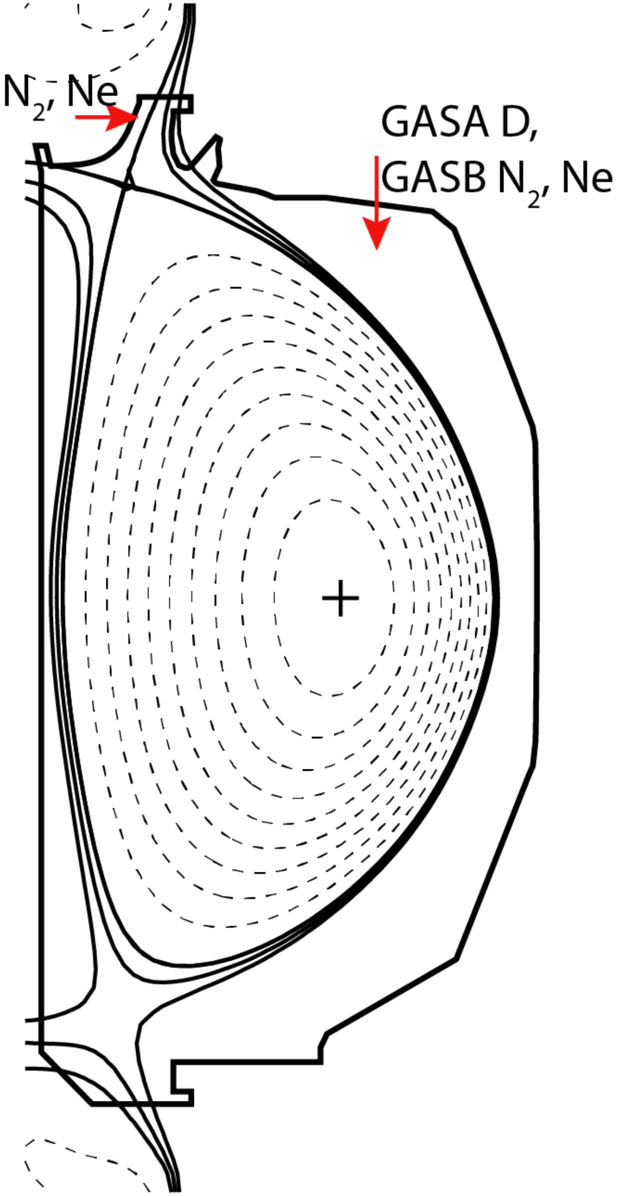
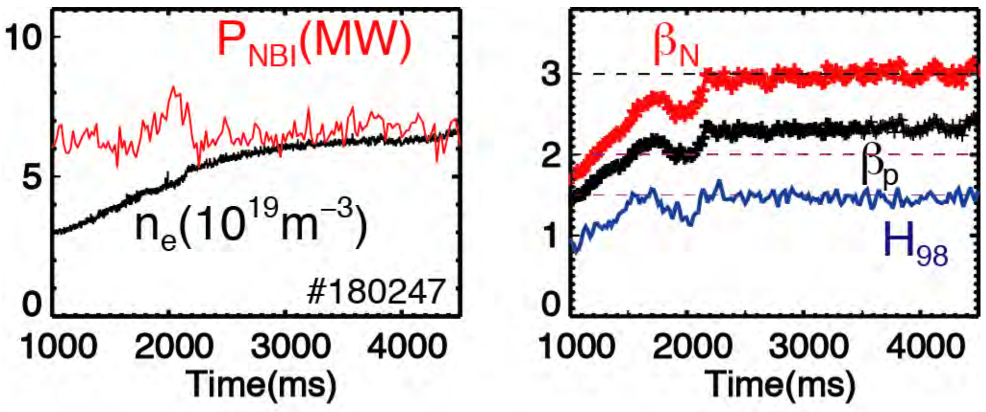
DIII-D experiment was performed under favorable B_T to study the compatibility of high performance core and divertor detachment



- Upwardly Biased Quasi-Double Null with dRsep ~+7mm > $2\lambda_q$
- Ion B-gradB drift towards divertor → favorable B_T
  - Beneficial for full detachment
- Impurity: Nitrogen, Neon; from divertor or main-chamber
- NBI only, No ECH
- Several actively feedback controls
  - ✓ β_n feedback control → adjust the P_{NBI}
  - ✓ n_{eped} feedback control →D gas puffing
- Diagnostics:
  - Divertor: Langmuir probes, Bolometer, IR camera, pressure gauge, Tangential TV, Filterscope, ...
  - Core: TS, CER, SPRED, VB, ...

Good compatibility of detachment and high global performance has been achieved in N_2 seeded high β_p plasmas



- ➢ β_N~3, β_p~2.4, H_{98}~1.5, f_{GW}>0.9,f_{NI}~0.7, V_{loop}~0.1V
  - ➢ Relevant to ITER steady-state operation

- ➢ Feedforward N_2 → facilitate detachment

- ➢ Pedestal reduction: 3kPa → 1.8kPa
- ➢ Core pressure remained constant

- ➢ Radiation dominant the power dissipation:
- ✓ $P_{rad,tot}/P_{nbi}$ ~0.75; $P_{rad,core}/P_{nbi}$ ~0.3

- ➢ IR peak heat flux from 2MW/m² to ~0.3MW/m²

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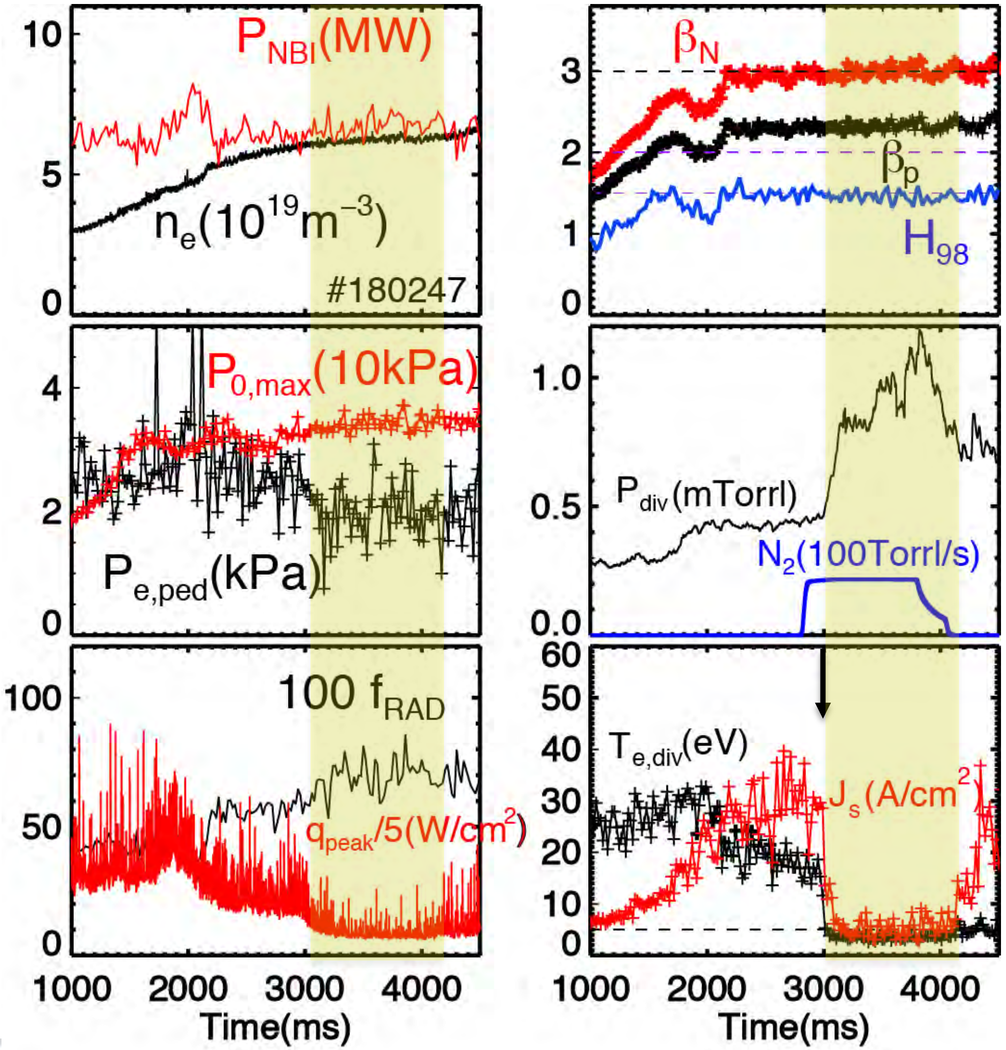

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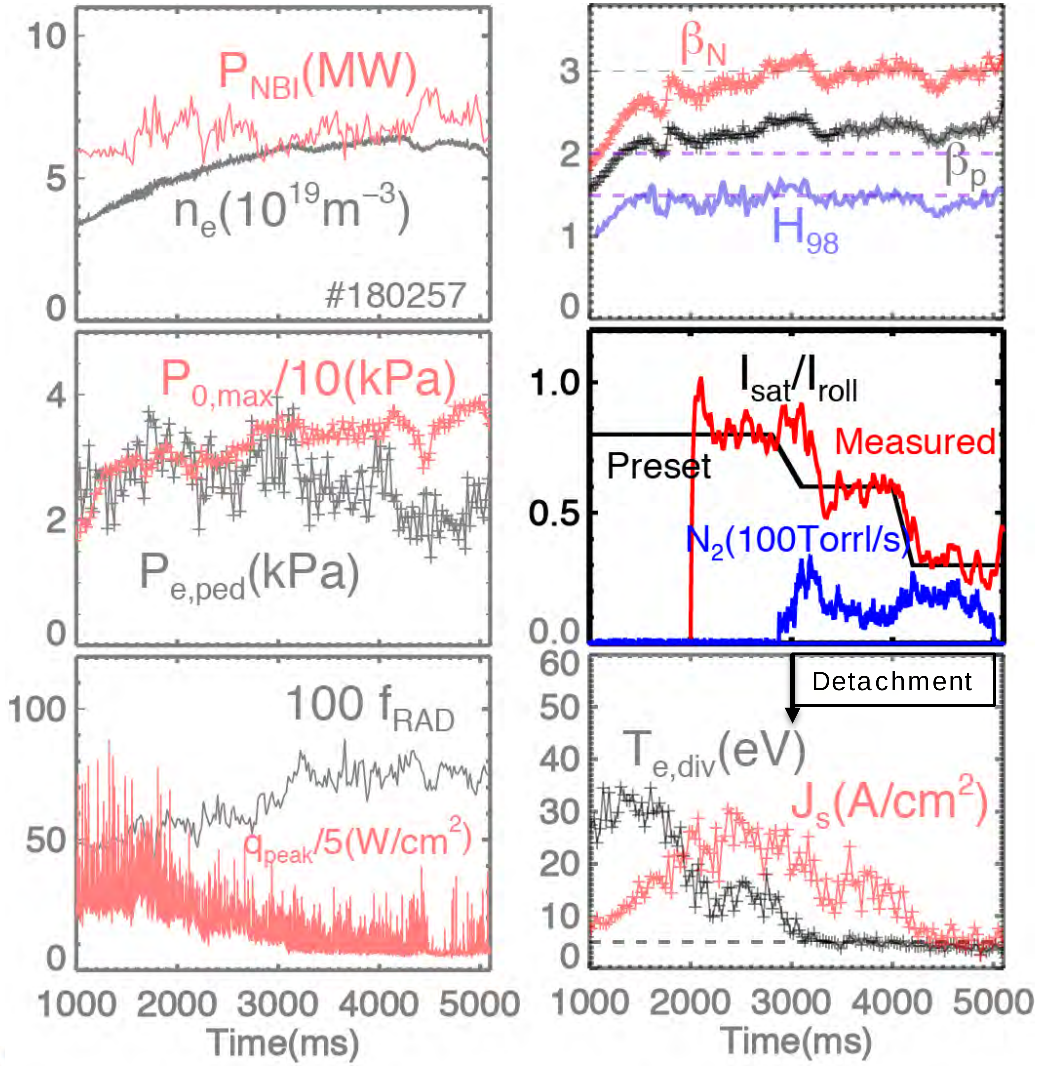
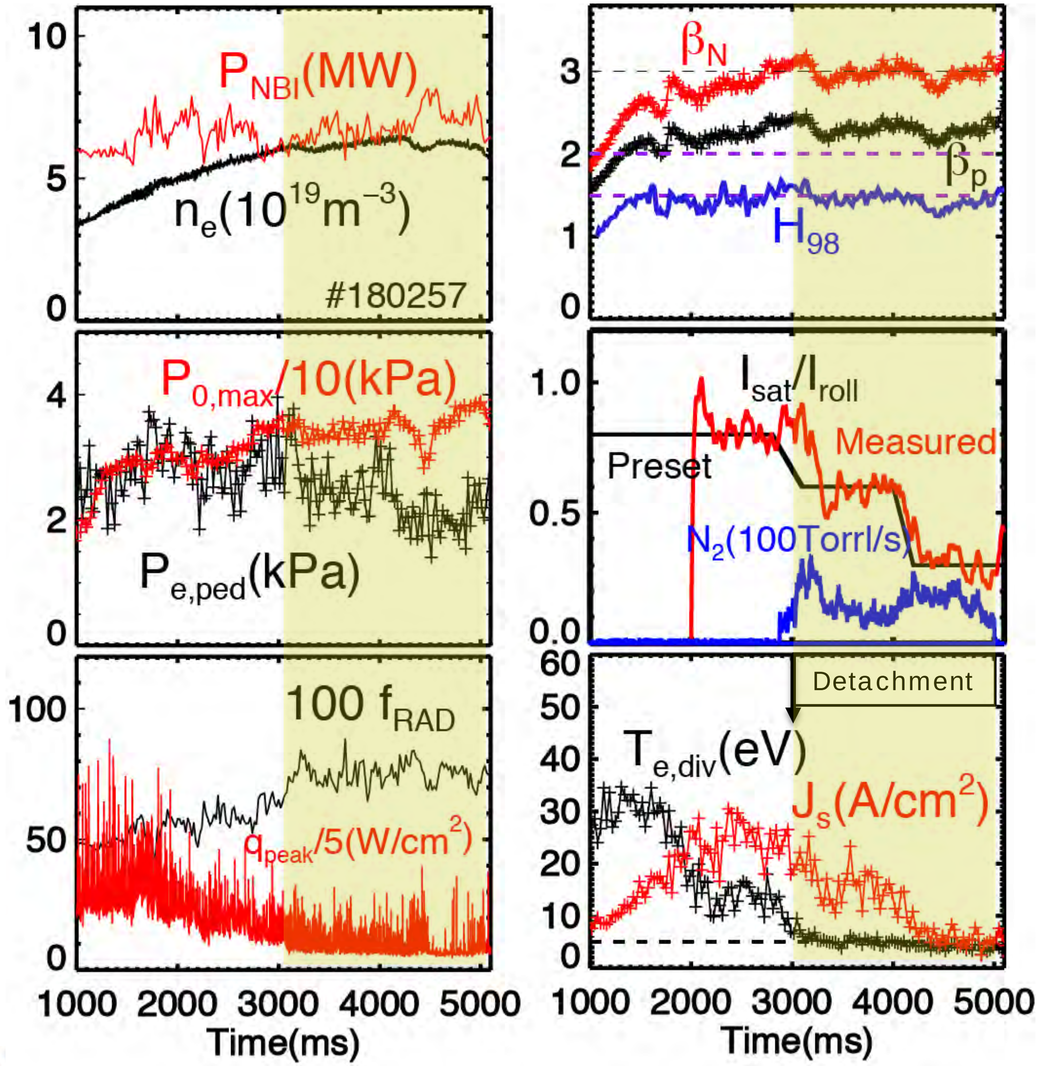
Newly developed detachment feedback control is used to optimized impurity puffing



- ➢ β_N~3, β_p~2.4, H_{98}~1.5, f_{GW}>0.9, f_{NI}~0.7, V_{loop}~0.1V
- ➢ Degree of Detachment feedback control →
  - Adjust impurity puff rates
  - DoD ~ I_{roll}/I_{sat}
  - Divertor Js follows the control preset
- ➢ Actively Controllable Detachment is desired for reactors
- ➢ Less detachment →less pedestal reduction
- ➢ Core pressure remained constant

Newly developed detachment feedback control is used to optimized impurity puffing



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- Degree of Detachment feedback control →
  - Adjust impurity puff rates
  - DoD ~ I_{roll}/I_{sat}
  - Divertor Js follows the control preset
- Actively Controllable Detachment is desirable for reactors
  - Integration of core and edge control systems
- Less detachment →less pedestal reduction
- Core pressure remained constant

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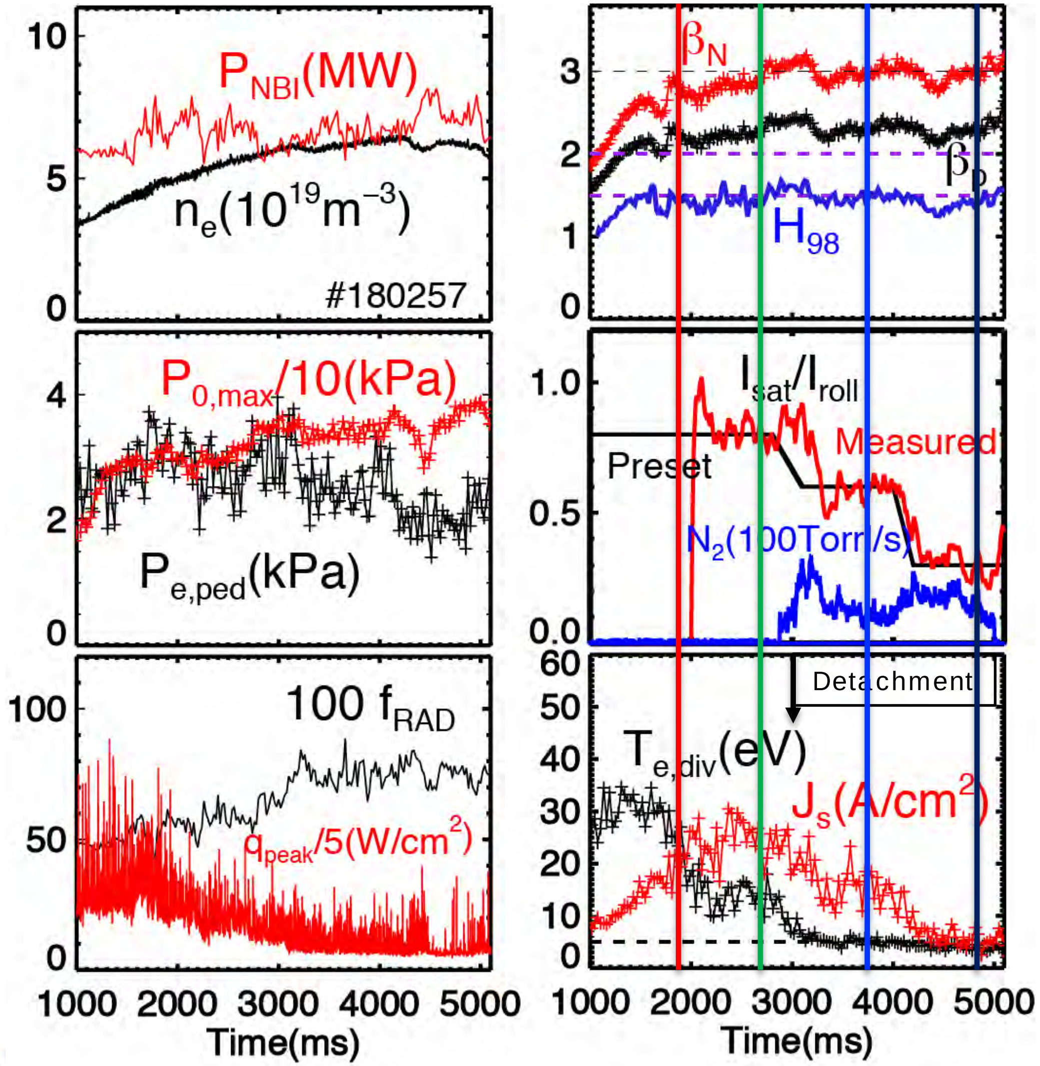
Newly developed detachment feedback control is used to optimized impurity puffing



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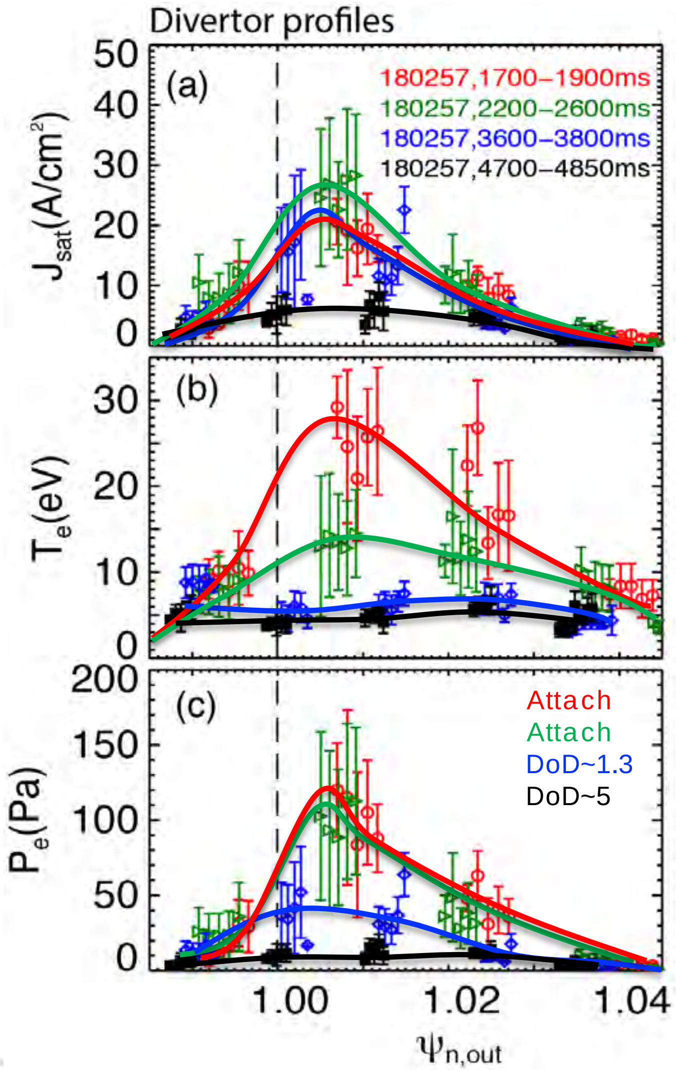
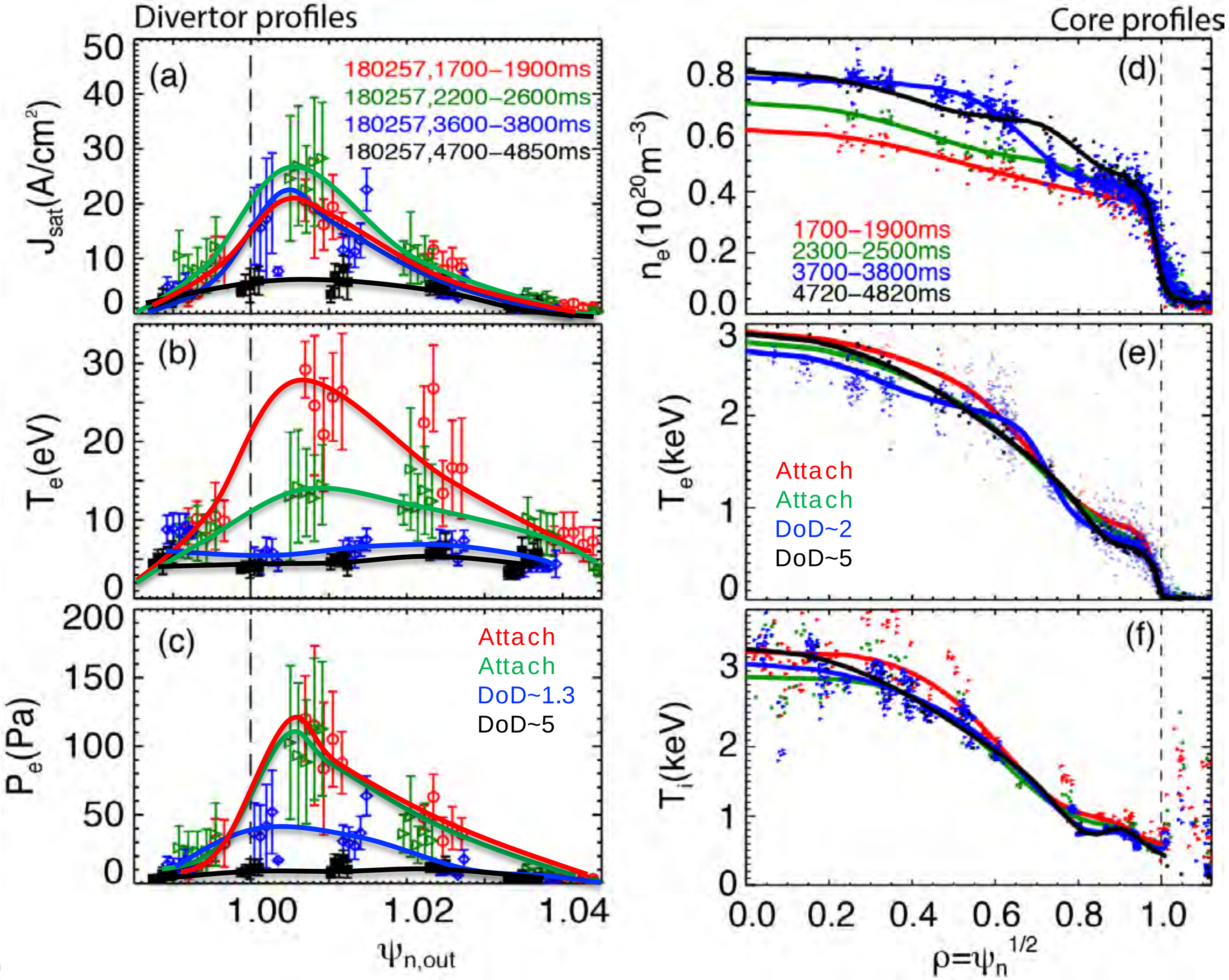
Full divertor detachment and sustained ITB+ETB are simultaneously achieved



- Detachment across entire target plates
  - >90% divertor pressure loss
  - DoD >5 with strong J_s reduction
  - Low T_e across entire divertor targets
  - High neutral pressure → exhaust

Full divertor detachment and sustained ITB+ETB are simultaneously achieved

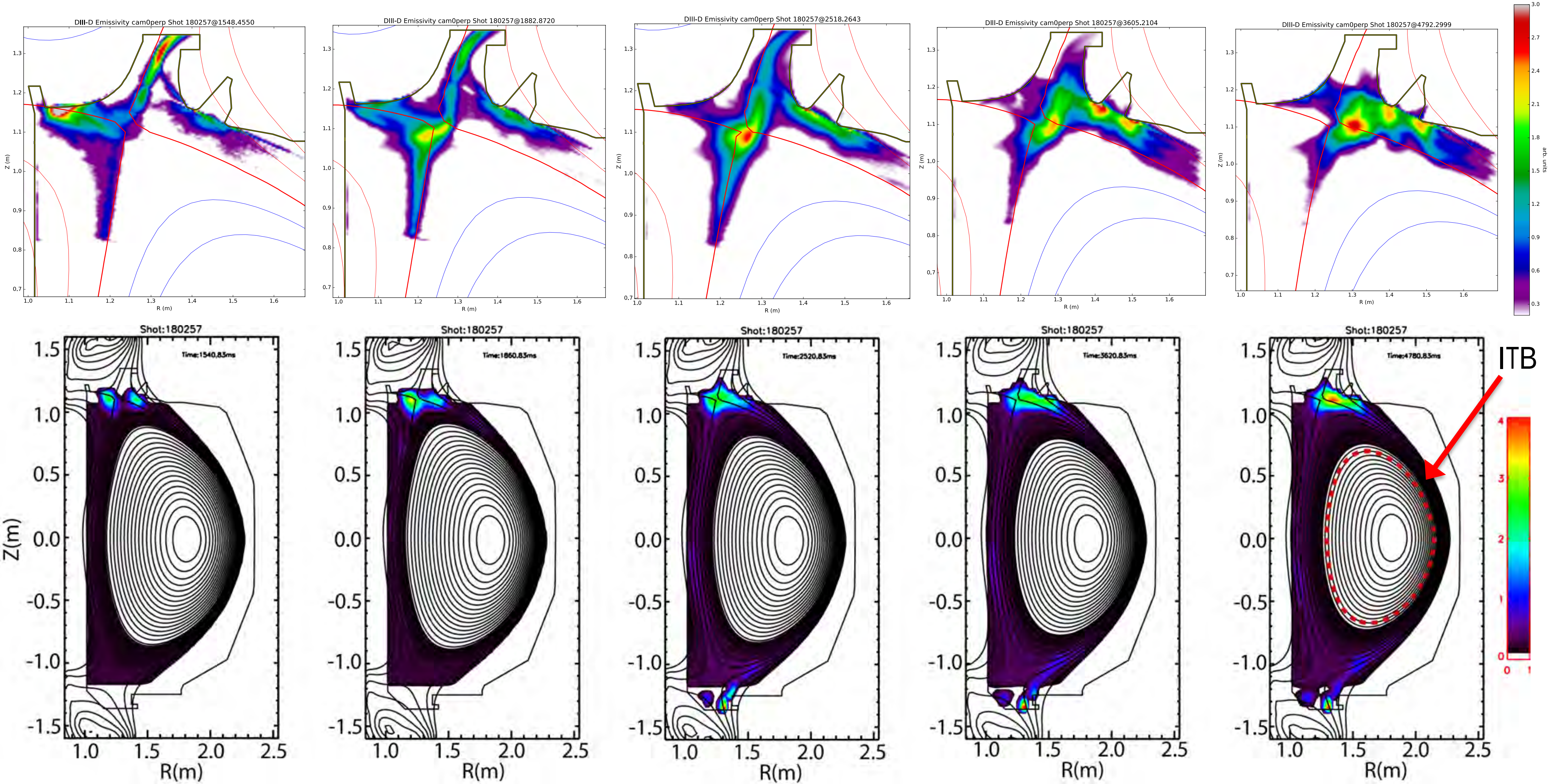


- ➢ Detachment across entire target plates
  - >90% divertor pressure loss
  - DoD >5 with strong J_s reduction
  - Low T_e across entire divertor targets
  - High neutral pressure → exhaust
- ➢ ITB grows during detachment
  - ITB at a large radius
  - n_e and T_e ITB grows and expand
- ➢ Pedestal reduction and narrower due to divertor detachment
  - n_e pedestal increases slightly
  - T_e pedestal reduced by 50%

2D imagings show the peak radiation near X-point during divertor detachment

CIII Tangential TV

Radiation Bolometer



Both attachment

D puff

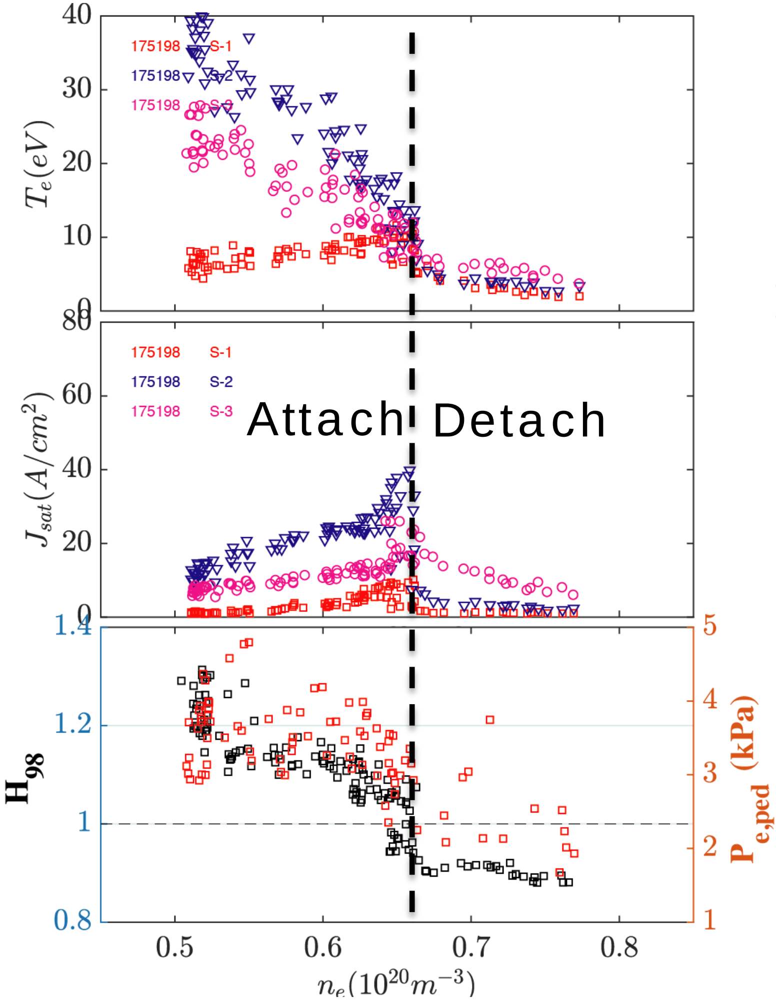
Pre N puff

N detachment

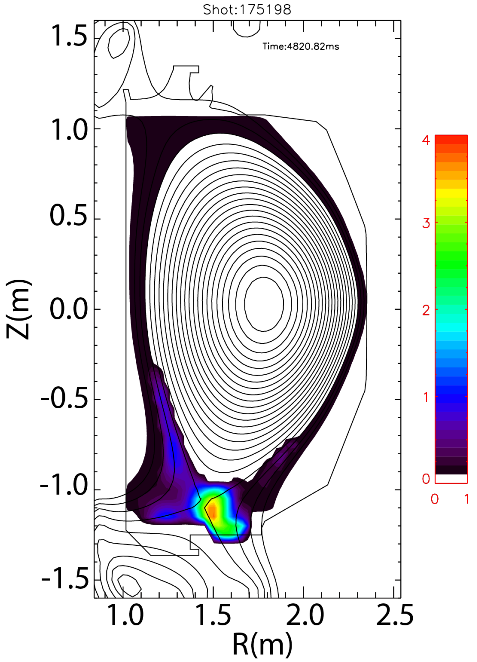
Full detachment

Divertor detachment degrades global performance in standard H-mode plasmas without ITB

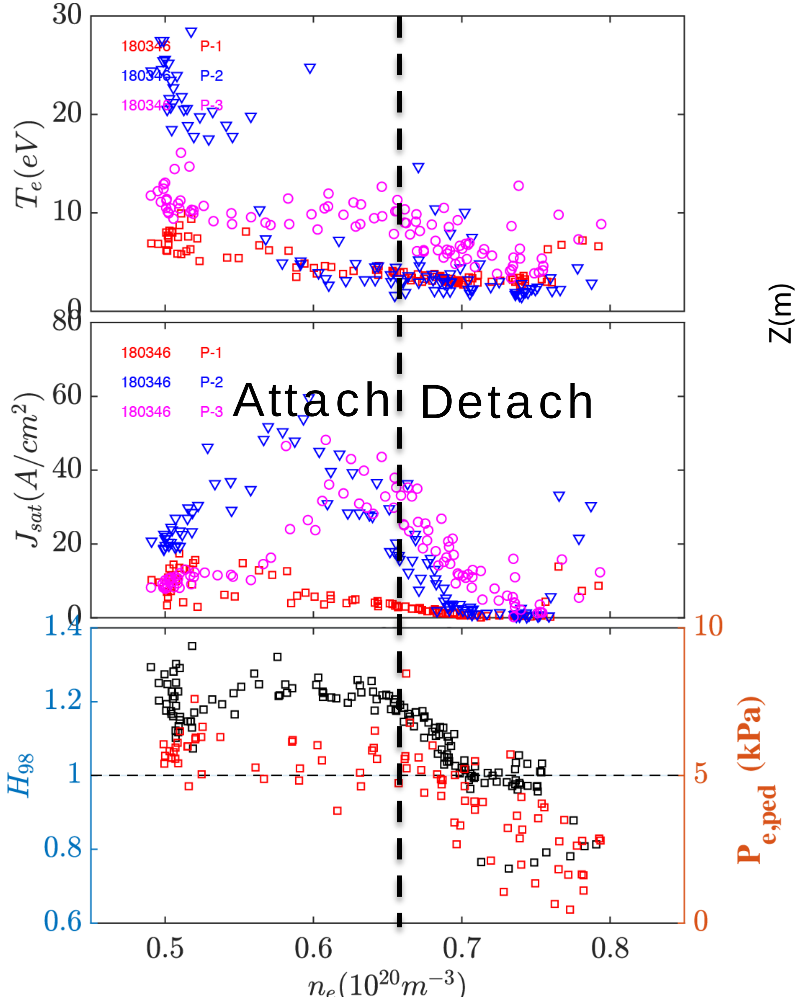
Open divertor

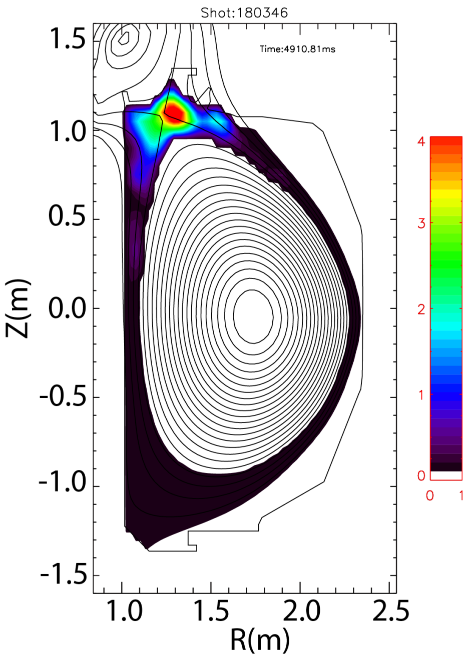


Standard H-mode and no ITB



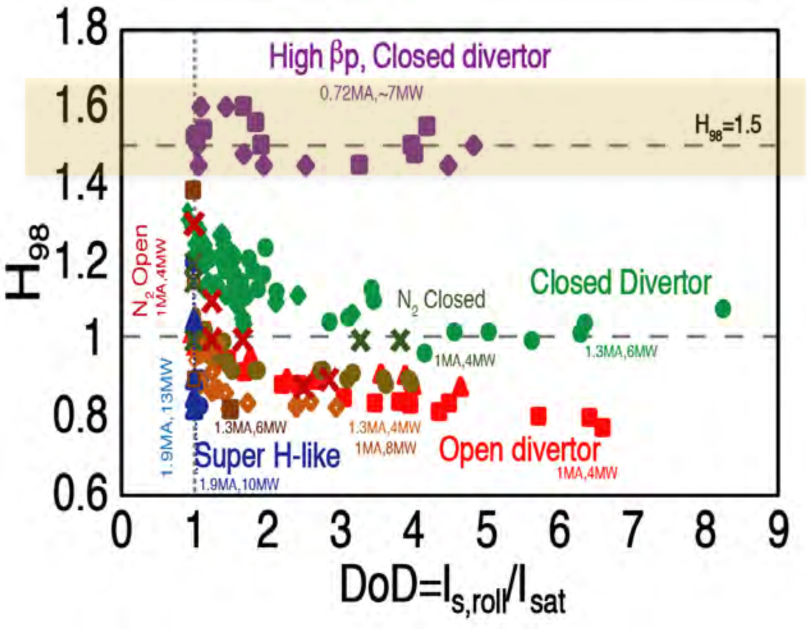
Closed divertor





- D or impurity detachment →1. high X-point radiation, 2. narrow pedestal, 3. high collisionality→ degrade pedestal → core stiffness→ degrade global confinement

Compared to other scenario plasmas, the high β_p plasmas exhibit advantages on core-edge integration



- With core stiffness, small window between detachment and high performance core
  - Open divertor, H_{98} <1.0 at DoD >1.5
  - Closed divertor, H_{98} remains 1.0 with deep detachment

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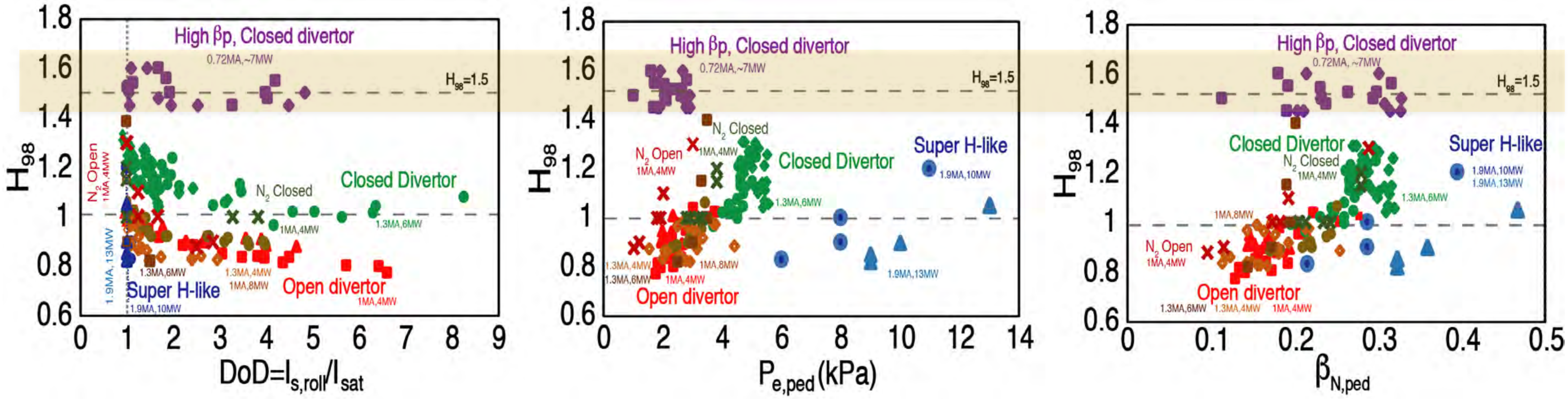

- ➢ With core stiffness, small window between detachment and high performance core
  - Open divertor, H_{98} <1.0 at DoD >1.5
  - Closed divertor, H_{98} remains 1.0 with deep detachment
- ➢ With core stiffness, higher pedestal leads to high H_{98}
  - $\beta_{N,ped} = \frac{p_{e,ped}}{B^2/2\mu_0}\frac{aB_T}{I_p}$ matches among different scenarios during attached divertor
- ➢ In high β_p plasmas, the ITB breaks the core stiffness and improves the core-edge integration

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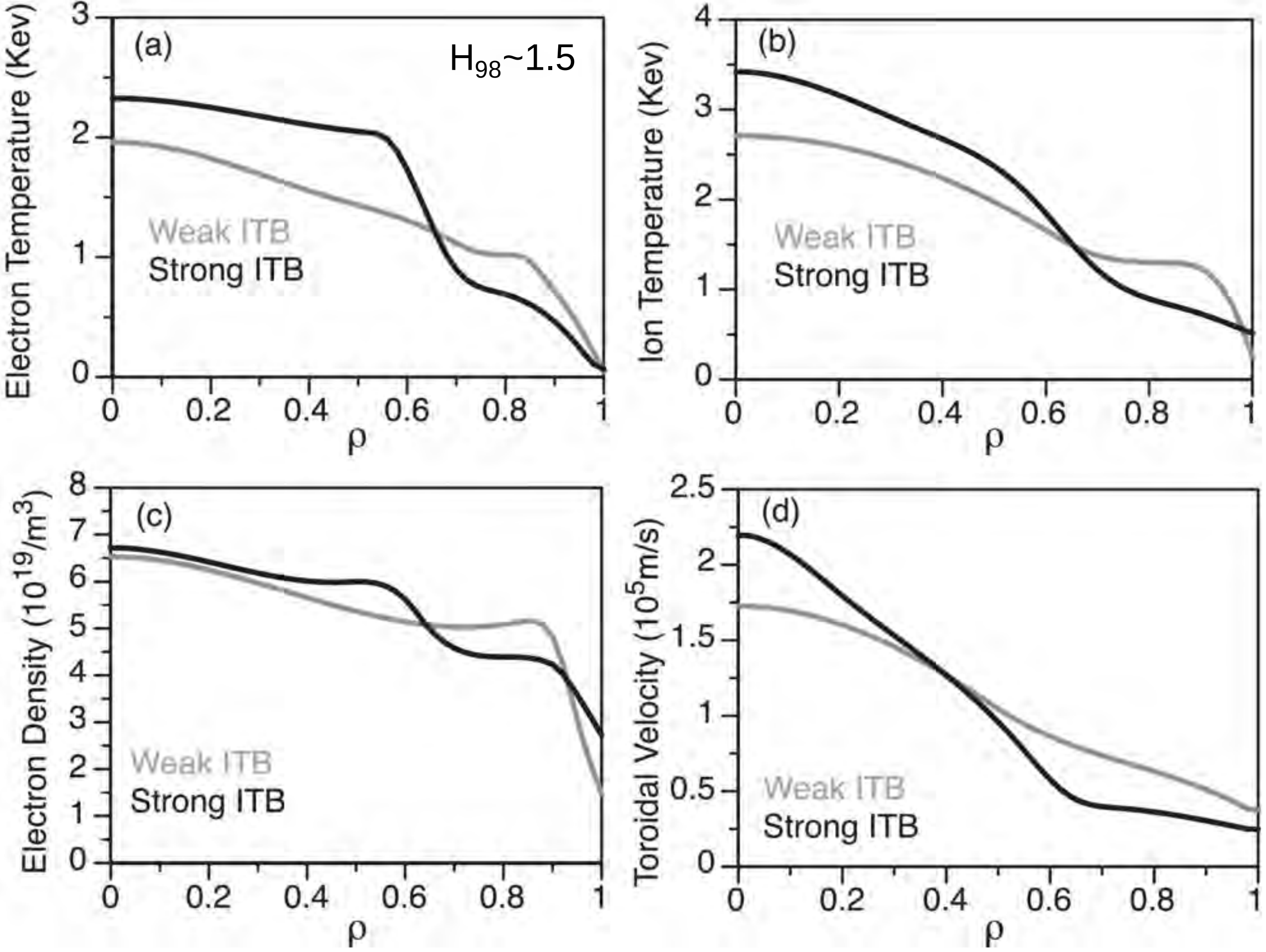
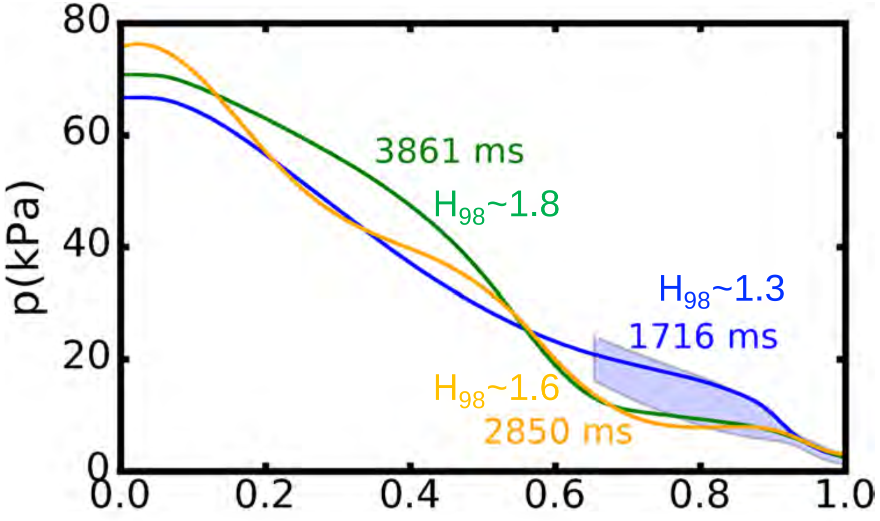
In high β_p plasmas, a low pedestal is even beneficial for the formation of large radius ITB

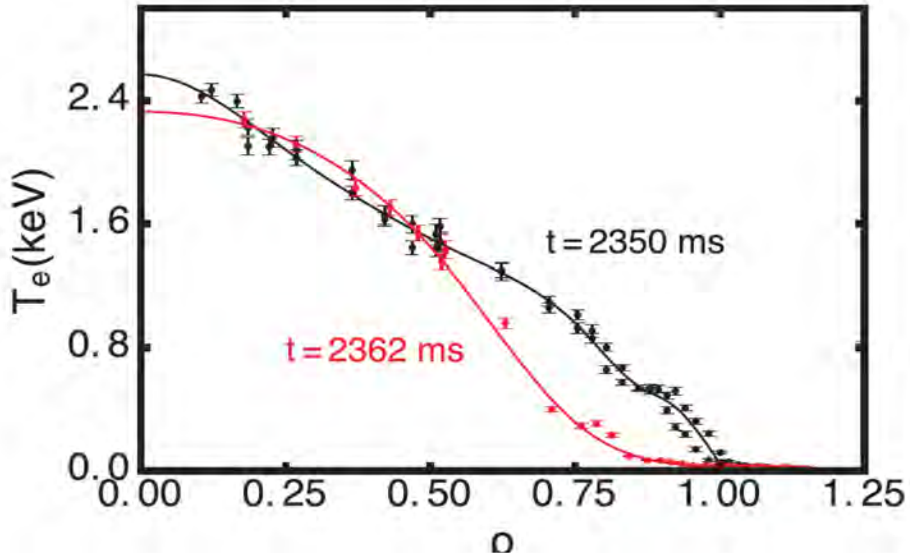
D_2 Only



Staebler, PoP 2018; NF 2018;

- ELM lowering the pedestal can trigger ITB

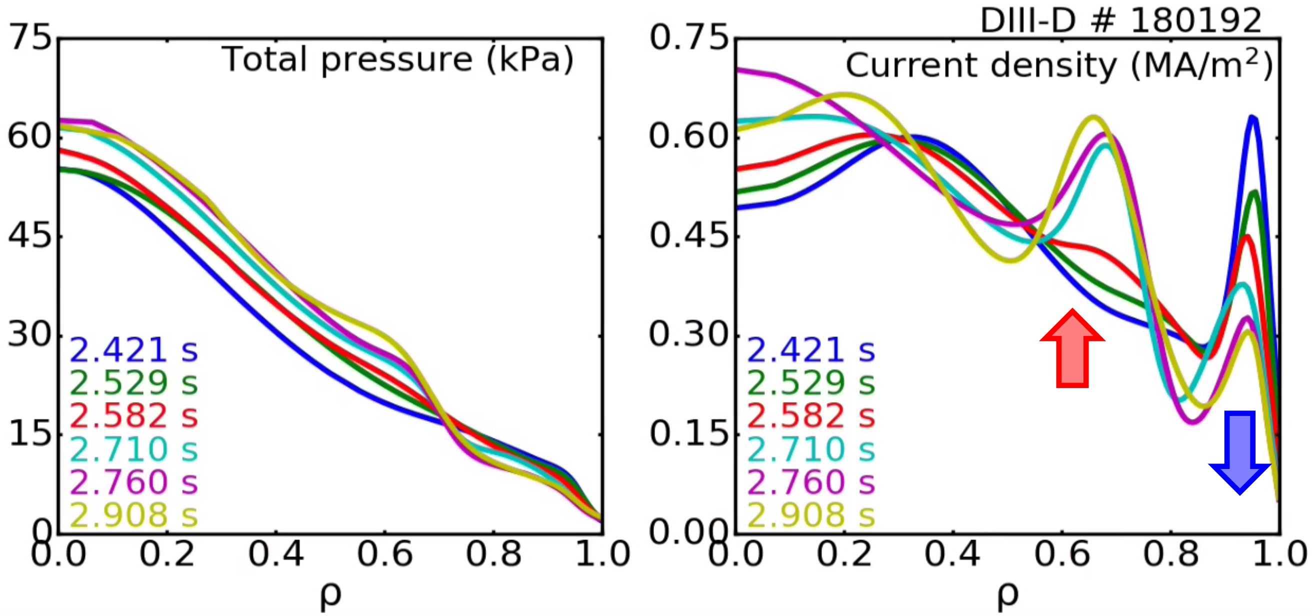


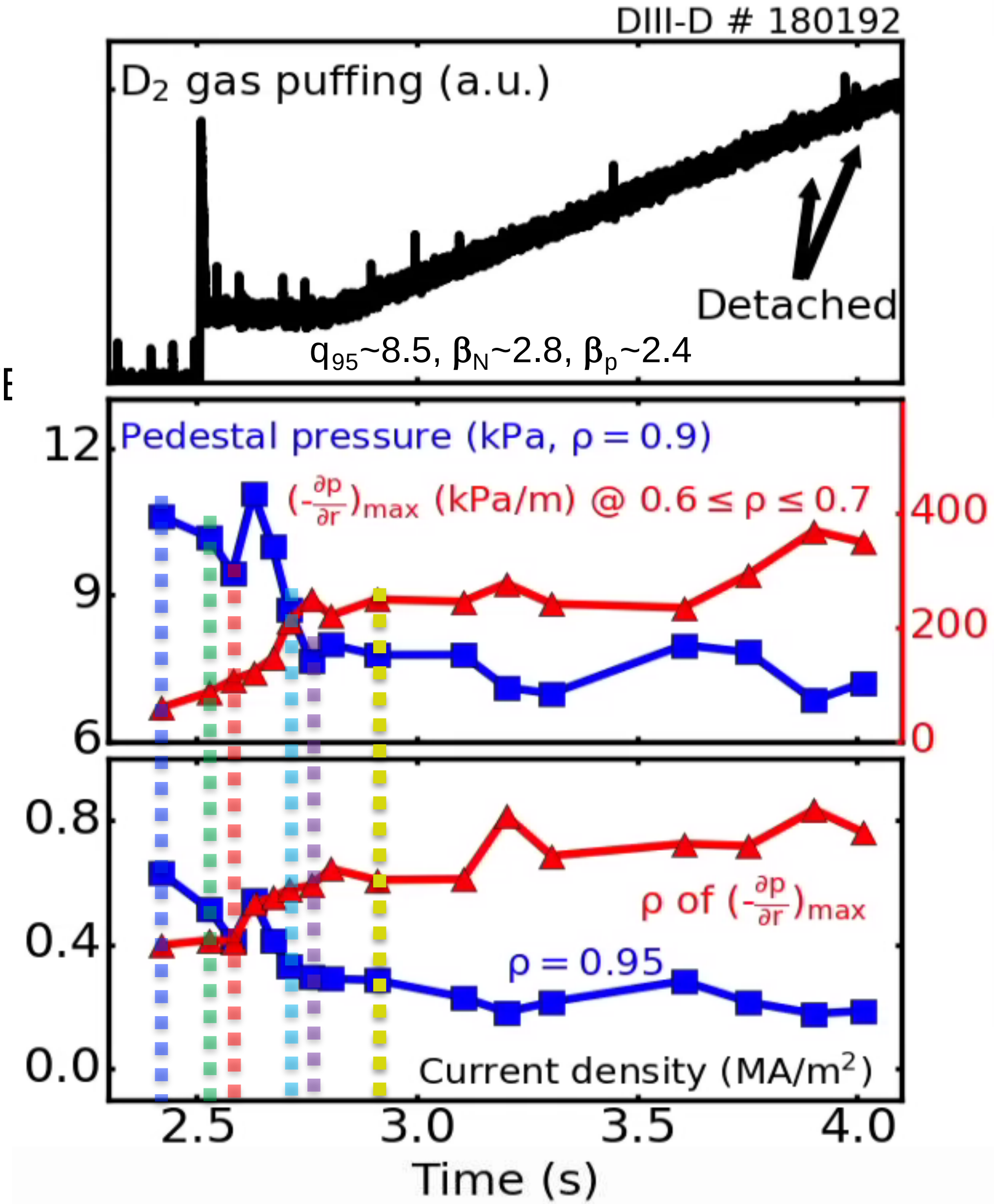


McClenaghan, NF 2019;

Current Density Increases at Large Radius due to Reduced Pressure Pedestal Height

- Gas puffing lowers pressure pedestal height
- Edge current density decreases → current density increases at large radius
  - Total plasma current at large radius is constant
  - Equivalent to an inward movement of current peak
  - Decreasing of magnetic shear around rho~0.7 triggers IT
  - Given high Shafranov shift and high q_{min}





Formation of Large Radius ITB due to Reduced Pressure Pedestal Height

- s-α contour plot is produced by **CGYRO** scan based on exp. data
  - ρ=0.6, $k_\theta\rho_s$=0.3, EM

Pedestal reduction

↓

Large-radius current density increases

↓

Local magnetic shear decreases

↓

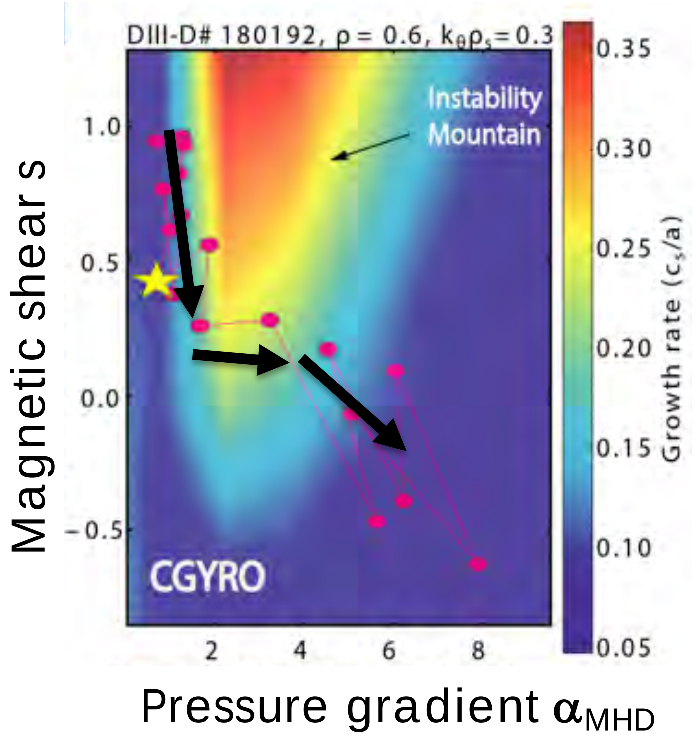
plasma leaves high growth rate region

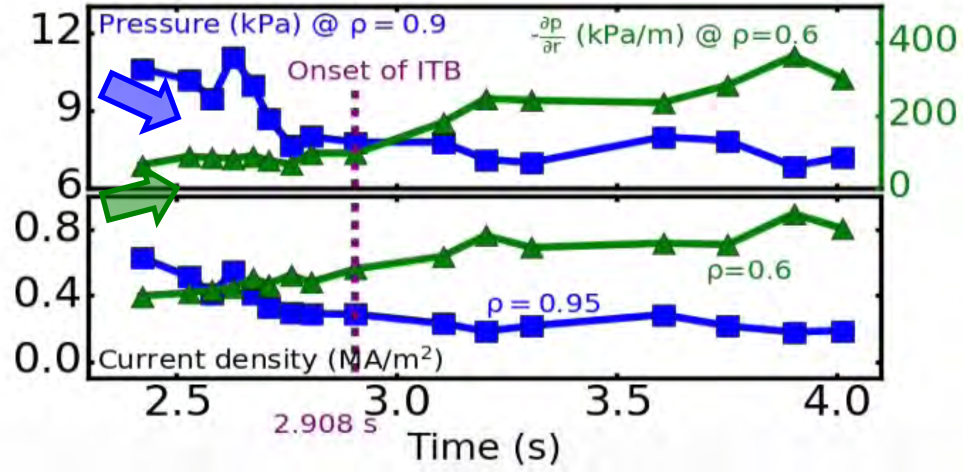
↓

pressure gradient build up

↓

plasma moves into second stability regime





Staebler, POP 2018
McClenaghan, NF 2019

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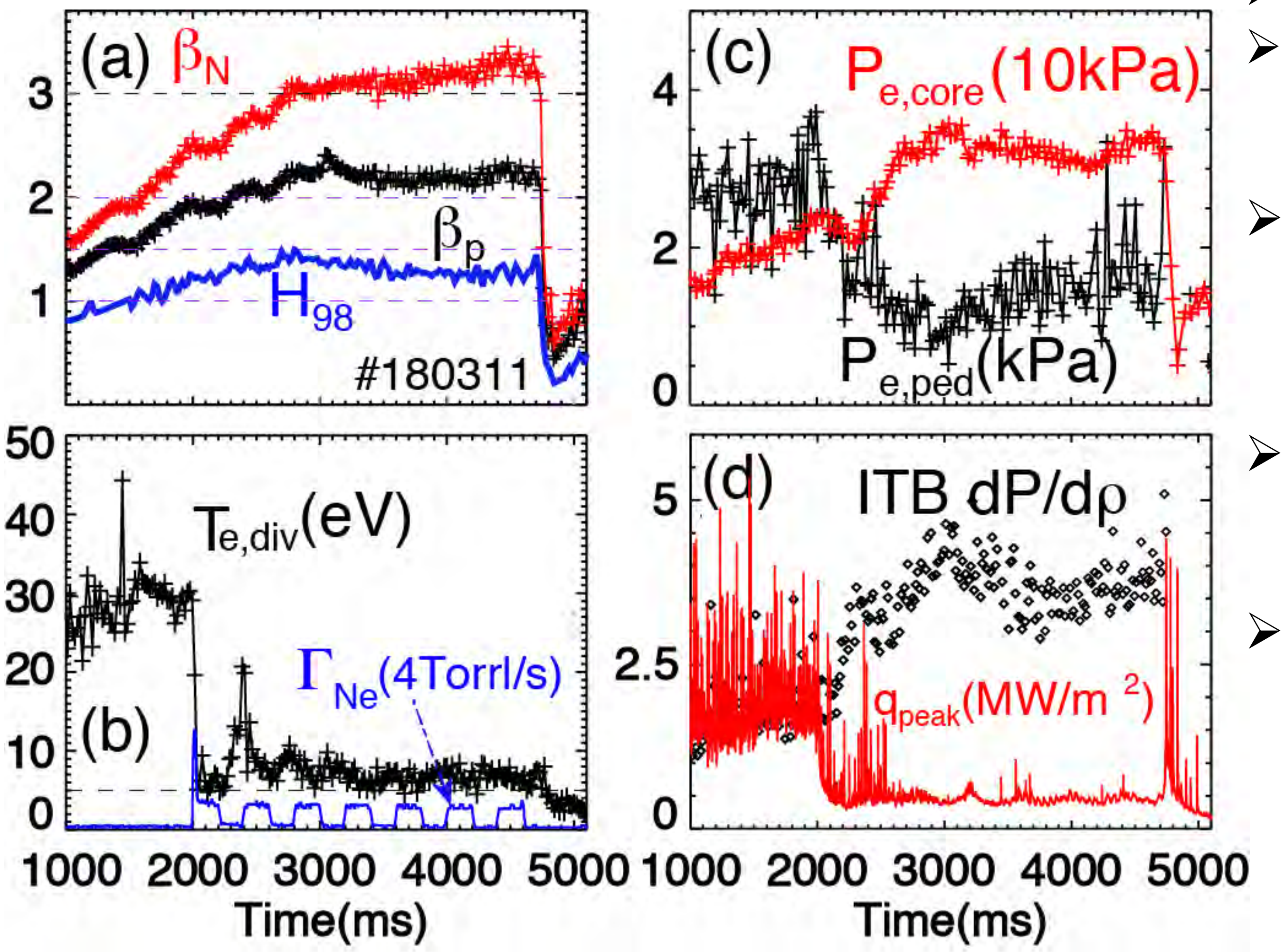
Neon seeded detachment: Detachment+ELM suppression+ high performance core



- β_N>3, β_p~2.3, H_{98}~1.4, f_{GW}>1.1
- Partially detached → less radiation in divertor, strong core radiation

- Neon reduces the pedestal even more compared to N_2 cases
  - Lower pedestal, higher ITB

- Correlation between the pedestal reduction and ITB

- Steady ELM suppression +divertor detachment+ high performance core

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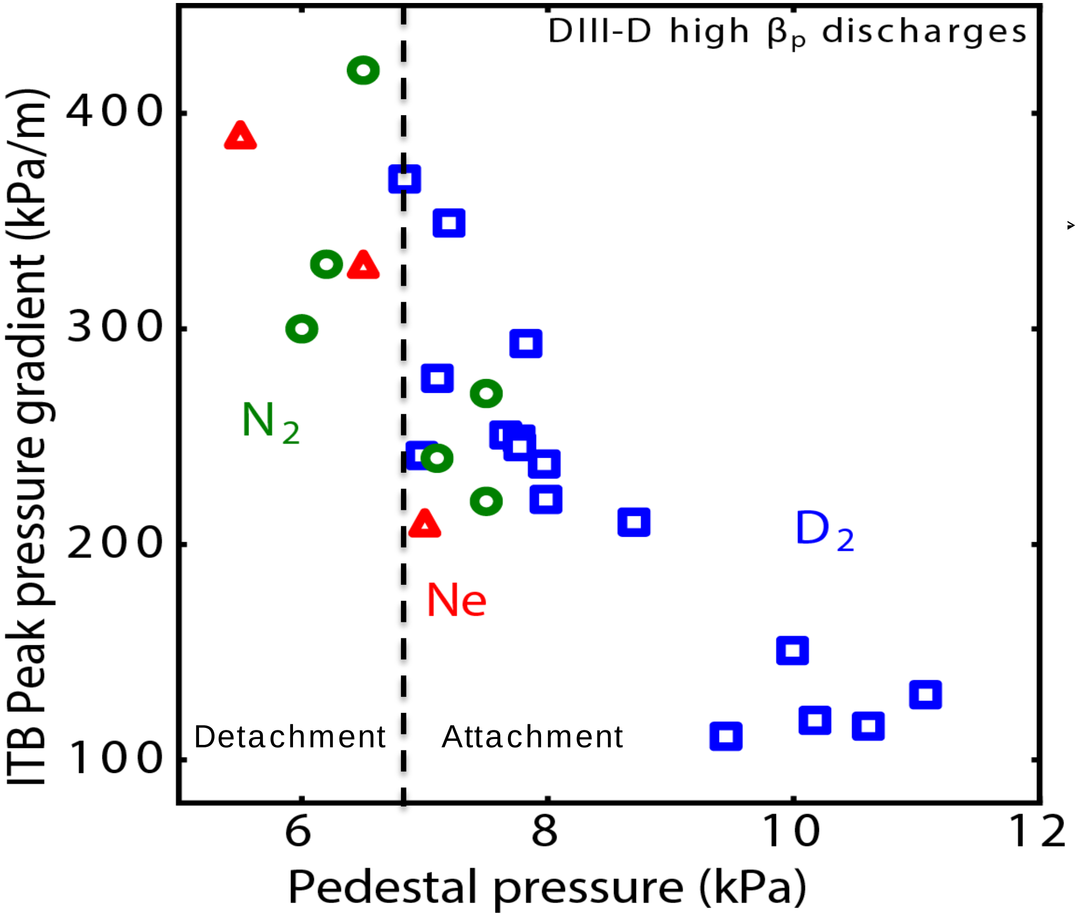
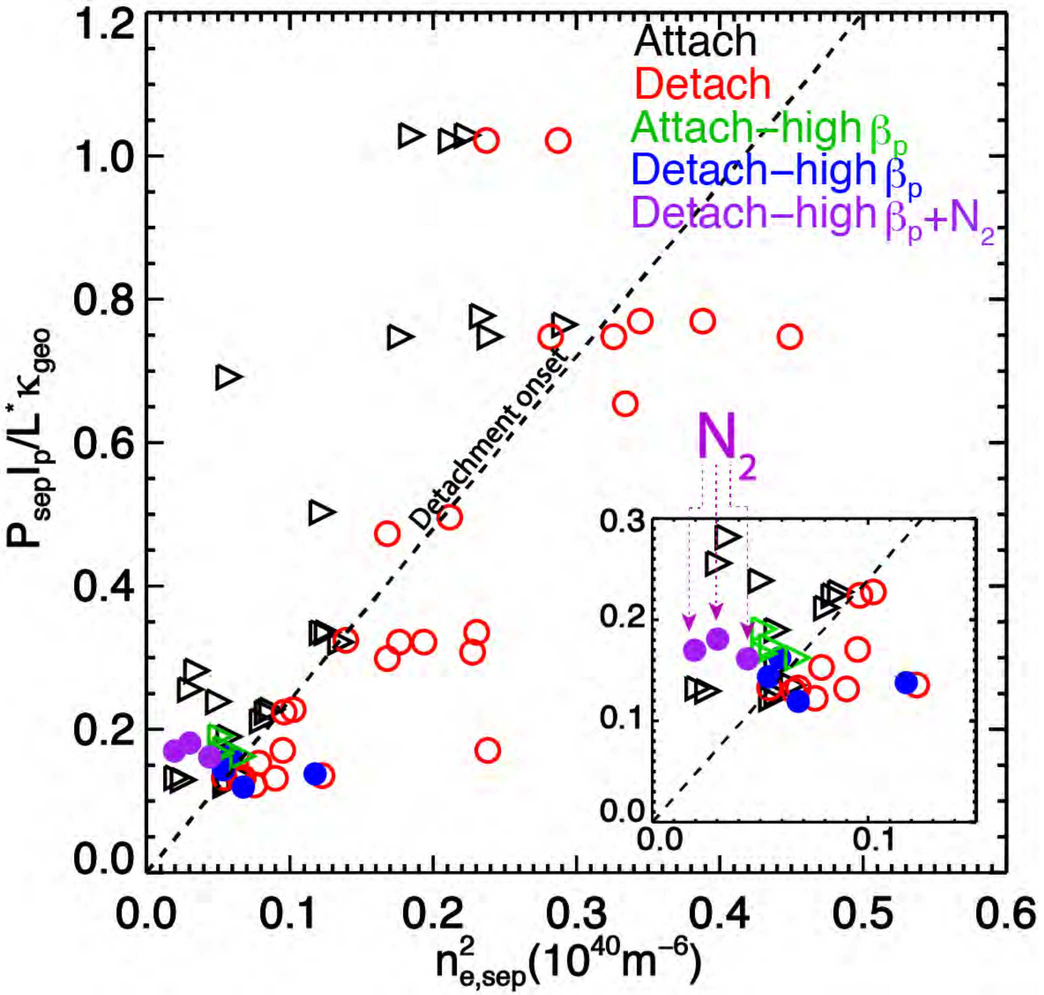
Special Core-edge integration in high β_p plasma: synergy between ITB and ETB

ITB gradient v.s. Pedestal top pressure



- Both Impurity and non-impurity cases show the synergy between ITB and ETB
  - Not due to impurity–induced turbulence stabilization effect
- Extra bonus for core-edge integration
  - Weaker ETB → small ELMs→ less intermittent events
  - Strong ITB → high confinement → reduced heating power for feedback control
  - High β_p → beneficial for small/grassy ELMs
  - High β_p → wide pedestal → larger space between radiation cooling and pedestal top

High β_p with high edge q and reduced power, combined with impurity seeding, facilitate the achievement of full detachment



- ➢ The easy access to detachment is qualitatively consistent with empirical detachment scaling
- ➢ Detachment onset density: $n_{sep,GW}^2 \propto P_{sol}I_p/f_z$

R. Goldston PPCF 2017

- ➢ Impurity seeding → increasing c_z → decreasing detachment onset density
- ➢ High β_p, lower current → longer parallel length → larger radiation area → lower detachment onset density
- ➢ Utilizing closed divertor to reduce detachment onset density and improve core-edge integration

- ➢ $T_{et} \propto \frac{q_{\parallel,u}^2}{p_u^2}\left[\frac{(1-f_{rad})^2}{(1-f_{mom,loss})^2}\right]$
- ➢ $\Gamma_{et} \propto \frac{p_u^2}{q_{\parallel,u}}\left[\frac{(1-f_{mom,loss})^2}{1-f_{rad}}\right] \propto (1-f_{rad})/\frac{(1-f_{rad})^2}{(1-f_{mom,loss})^2}$

- ➢ High radiation → low flux → full detachment

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- Excellent compatibility of full divertor detachment with the high β_p high-confinement core associating with ITB+ETB has been achieved in DIII-D.

- The synergy between the ITB+ETB improves the core-edge integration.
  - Pedestal degradation due to detachment in turn drives strong ITB at large radius
  - ITB breaks the core stiffness and help maintain the good confinement
  - Weak ETB → less intermittent heat flux issue in high β_p plasmas

- Impurity seeding facilitates the achievement of full detachment
- Neon injection leads to the no-ELM +detachment+high performance core

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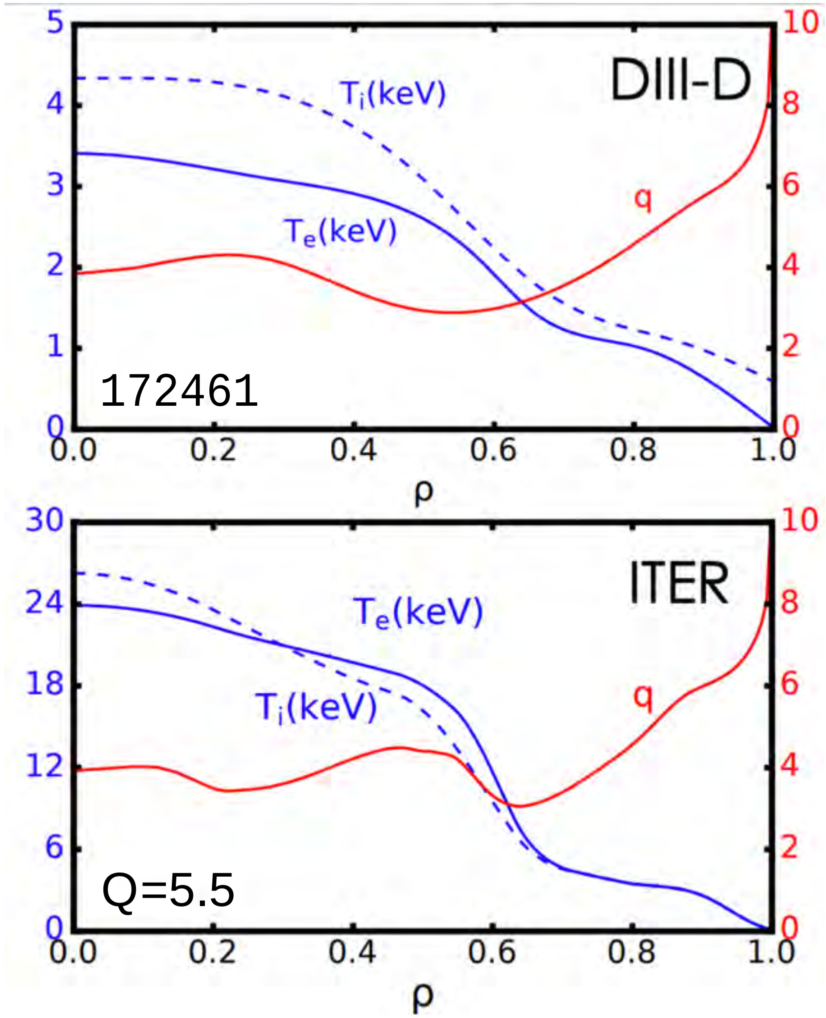
Future work and outlook

- Extrapolate to higher current, higher confinement plasmas
  - Turbulence behavior during the onset of ITB, experiment and modeling
  - Impurity transport with ITB and divertor detachment
  - Neon+N_2 on the no-ELM+full detachment+high confinement core
  - ITER-like Single-Null shape

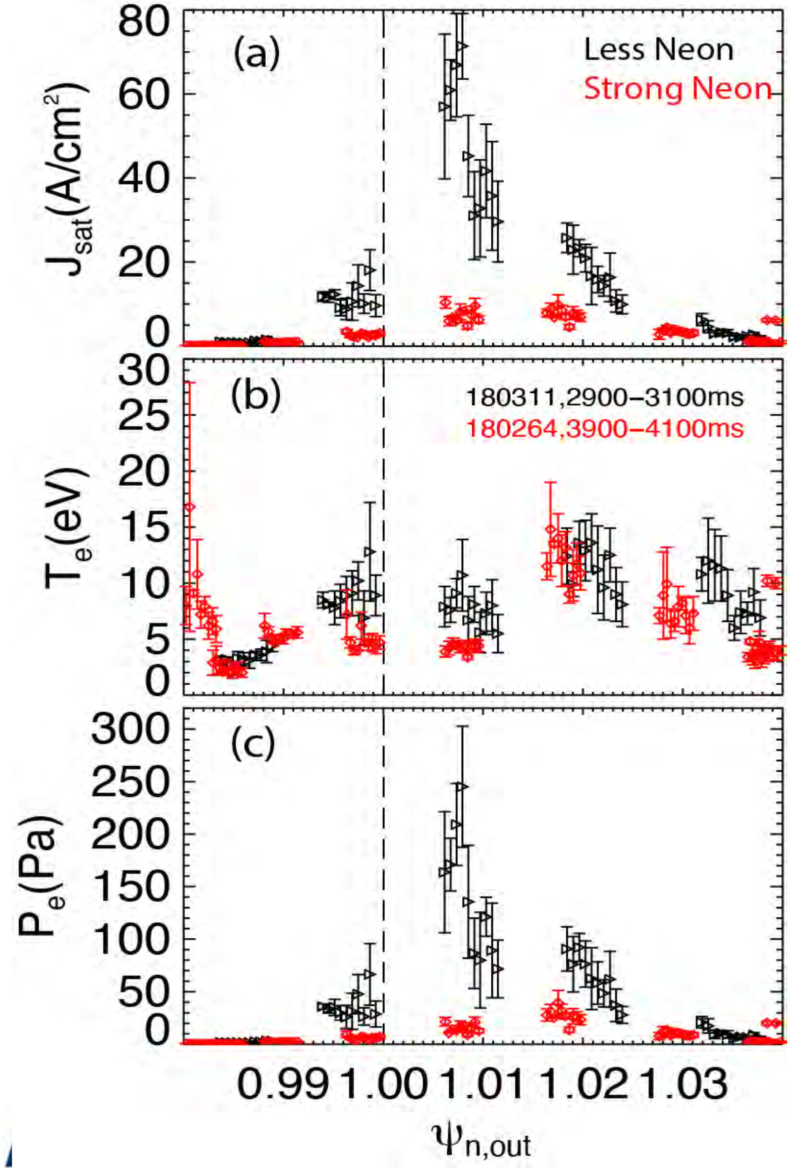
- Core-edge integration to demonstrate ITER or reactor's steady-state operational regime



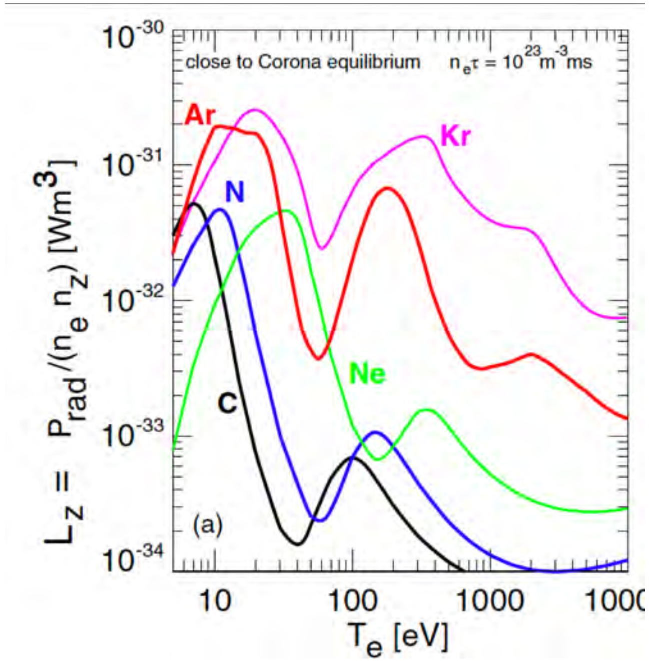
McClenaghan, IAEA 2018; Qian APS 2019; Garofalo, AAPPS 2019 and this conference

Backup

Neon facilitates partial detachment, but not full detachment



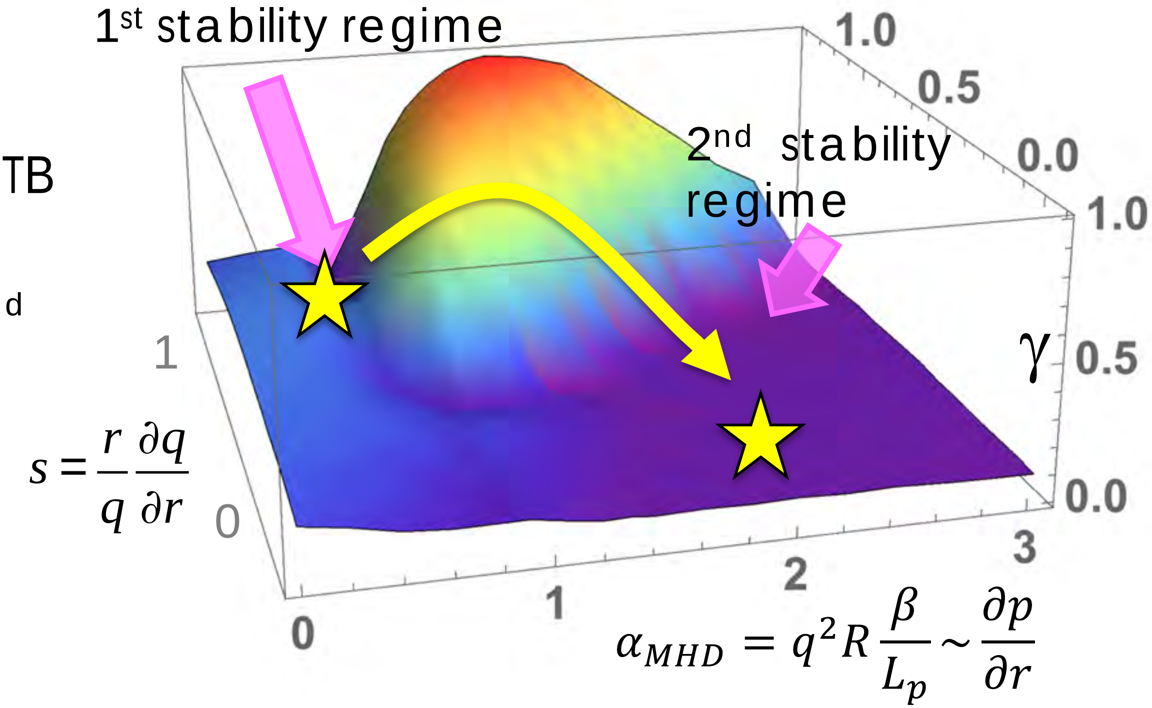
- Neon could lead to strong detachment near the OSP with strong puff
- In the SOL, Te remains >10eV, attached divertor conditions
  - Different from Nitrogen
- Neon radiates significantly in the core → low Psol towards divertor
  - Neon radiates at higher Te and less efficient at low Te
- N radiates at lower temperature
  →mainly in the divertor and wide extent
  → effective detachment in the SOL
- N also facilitates the particle flux reduction via HN recombination



Kallenbach PPCF 2013

Leading model of Large Radius ITB formation in high β_p scenario is the “KBM Mountain” Picture

- High pedestal weak ITB state: low core α_{MHD} and pressure gradient in 1st stability regime
- High ITB weak pedestal state: high α_{MHD} in 2nd stability regime
- Path from high pedestal state to high ITB state
  - Giant ELMs trigger jump from 1st to 2nd



Staebler, POP 2018
McClenaghan, NF 2019

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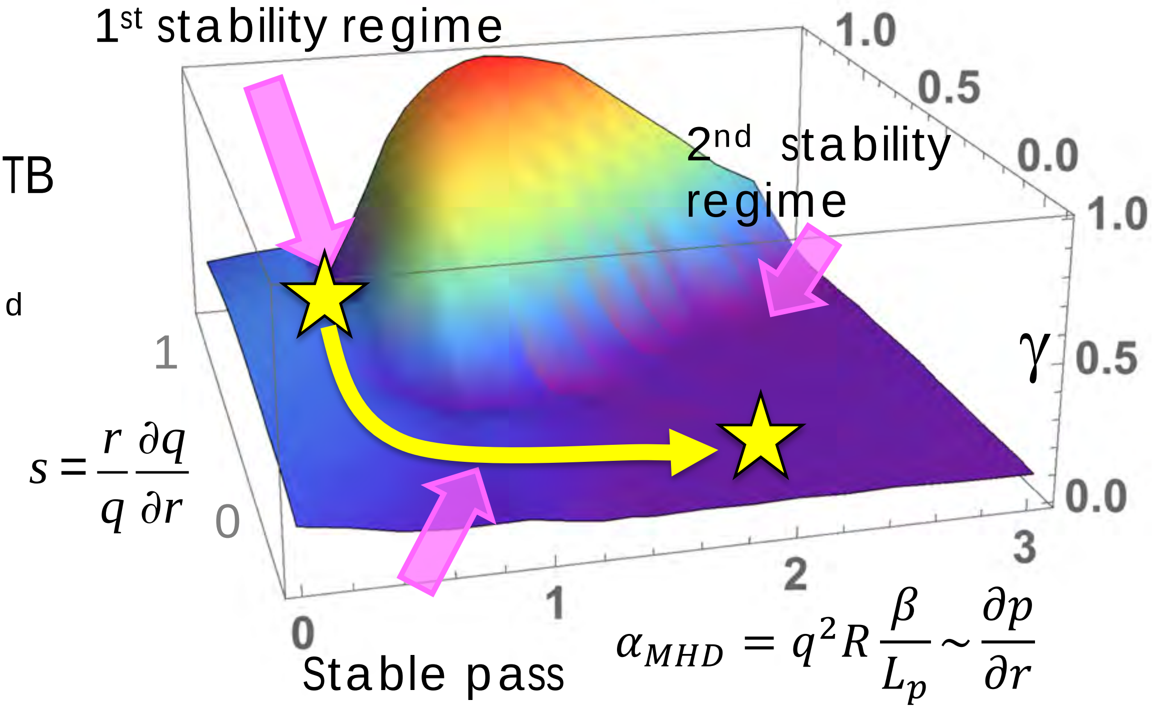
- High ITB weak pedestal state: high α_{MHD} in 2nd stability regime

- Path from high pedestal state to high ITB state
  - Giant ELMs trigger jump from 1st to 2nd
  - Go via the stable pass

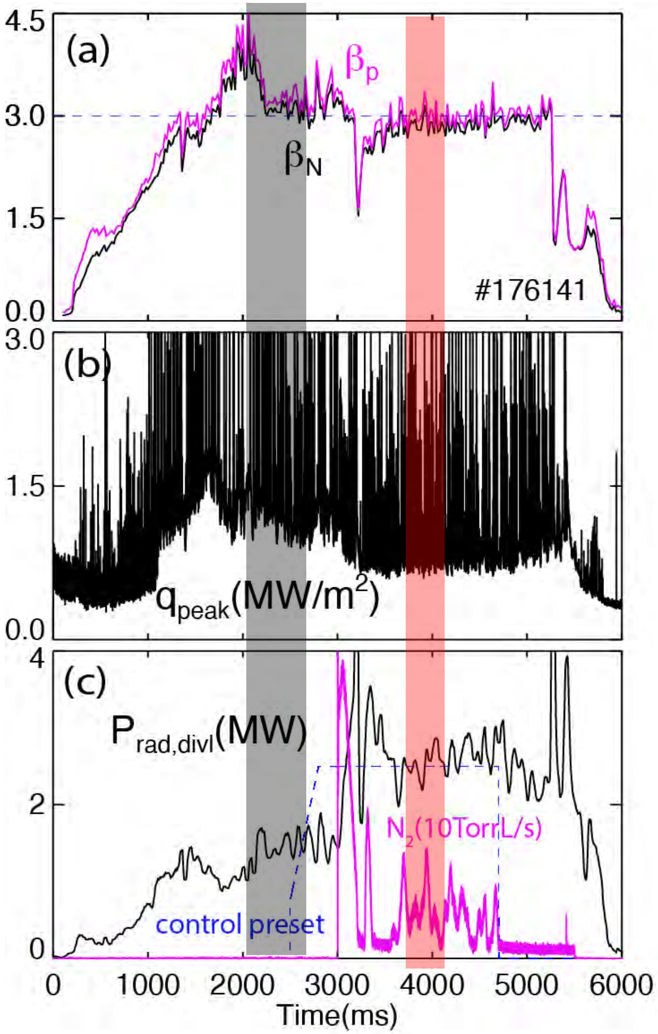
- This result is produced by scans from a "standard case"
- Results from experimental equilibria will be shown in the next few slides

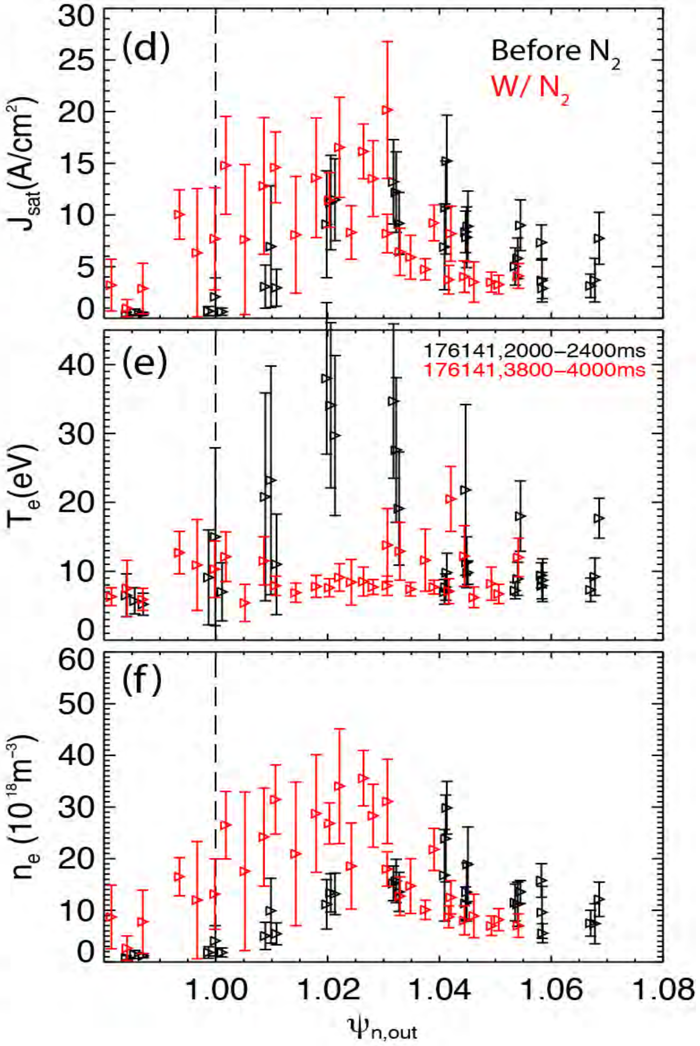
Standard case:
k_y=0.2, a/L_n=1, a/L_T=3.0, q=2, T_i=T_e, n_e=n_i, r/a=0.6, R/a=3.0, Miller circle



Staebler, POP 2018
McClenaghan, NF 2019

With unfavorable B_T, high β_p plasmas exhibit good compatibility between radiative divertor and high confinement core

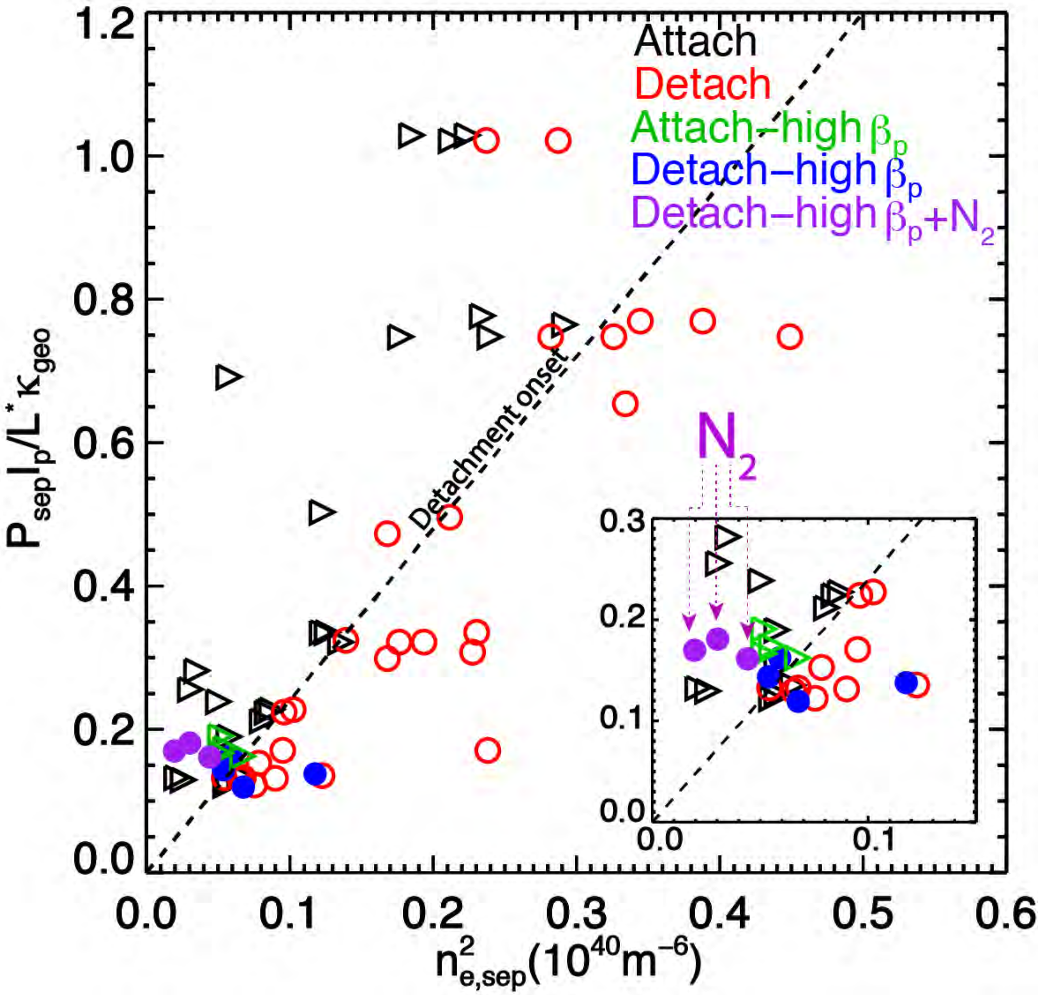




- High β_p is also beneficial for core-edge integration
  - $F_z\, n^2_{sep,det} \propto P_{sep} I_p$
- Past Exp. have shown the compatibility of 50% heat flux reduction and high confinement core
- However, only medium heat flux and particle flux were achieved
  - due to unfavorable B_T

L Wang, NF 2019

High β_p with high edge q and reduced power, combined with impurity seeding, facilitate the achievement of full detachment



- The easy access to detachment is qualitatively consistent with empirical detachment scaling
- Detachment onset density: $n^2_{sep,GW} \propto P_{sol}I_p/f_z$

R. Goldston PPCF 2017

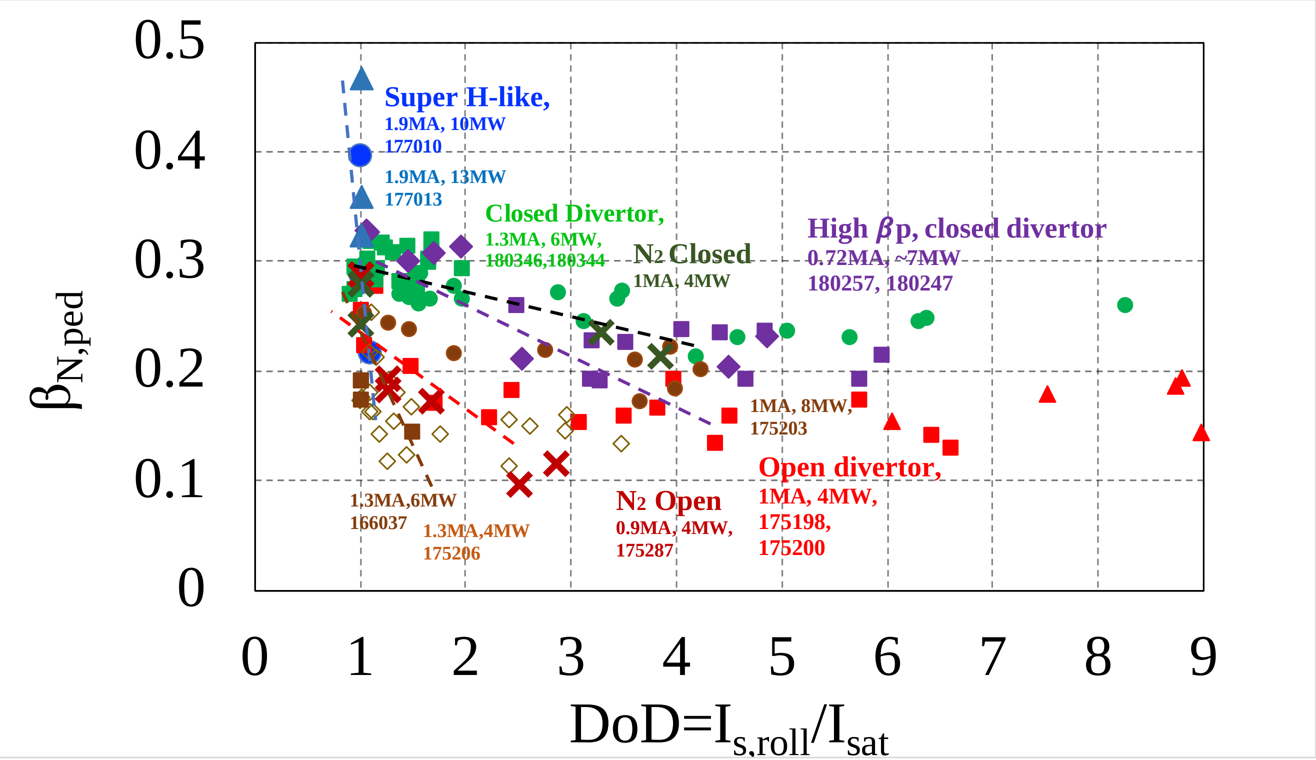
- Impurity seeding → increasing c_z → decreasing detachment onset density
- High β_p, lower current → longer parallel length → larger radiation area → lower detachment onset density
- Utilizing closed divertor to reduce detachment onset density and improve core-edge integration

- $T_{et} \propto \frac{q^2_{\parallel,u}}{p^2_u}\left[\frac{(1-f_{rad})^2}{(1-f_{mom,loss})^2}\right]$
- $\Gamma_{et} \propto \frac{p^2_u}{q_{\parallel,u}}\left[\frac{(1-f_{mom,loss})^2}{1-f_{rad}}\right] \propto (1-f_{rad})/\frac{(1-f_{rad})^2}{(1-f_{mom,loss})^2}$

- High radiation → low flux → full detachment

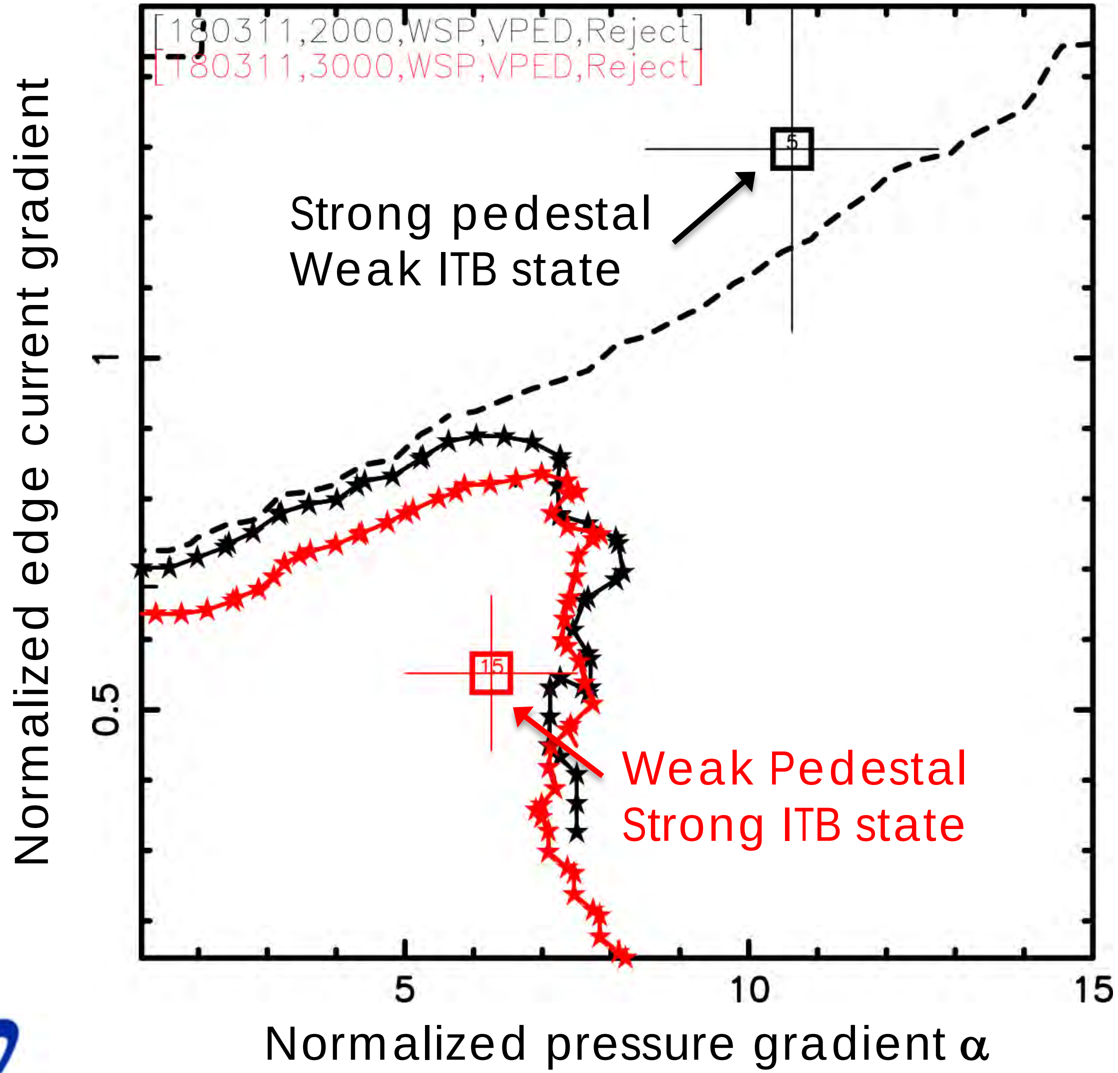
H. Du NME 2019

Pedestal vs DoD



- ➢ High DoD → lower pedestal
- ➢ High current, narrower window for pedestal reduction
- ➢ Closed divertor → less reduction

Decreasing pedestal moves the instability from Peeling/PB to Ballooning unstable boundary

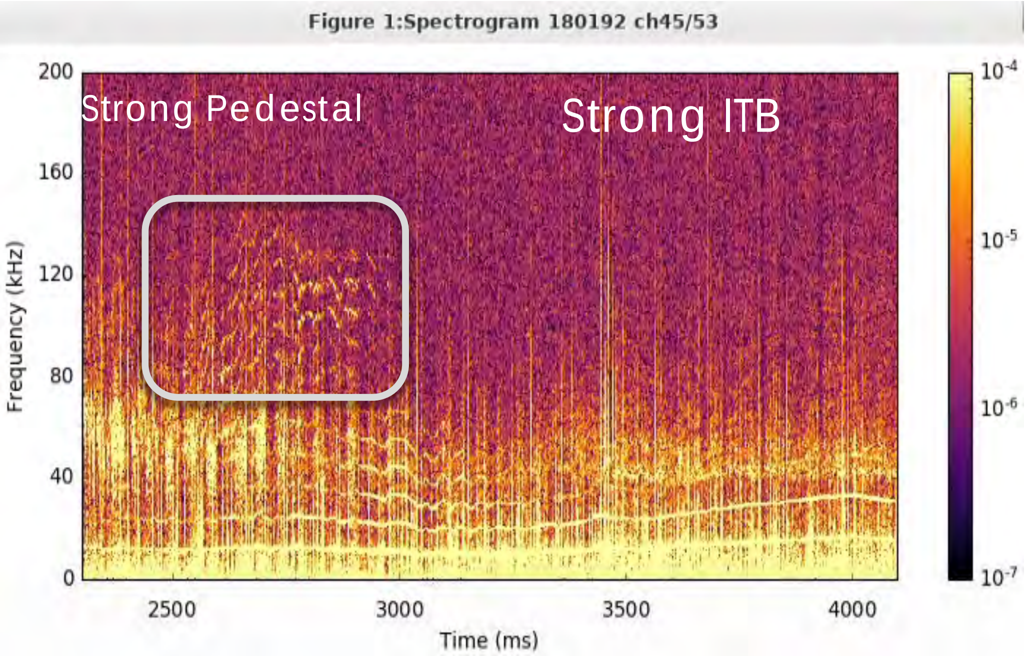


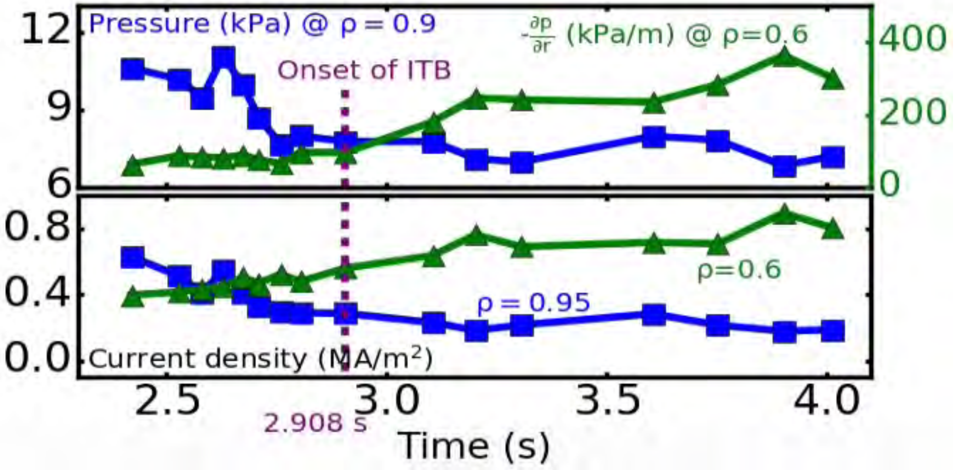
Strong pedestal
Weak ITB state

Weak Pedestal
Strong ITB state

BES measured fluctuations around the ITB region support the CGYRO calculations

- The dynamics of mid-frequency fluctuations agrees with CGYRO predicted KBM behaviors
  - 80-130kHz fluctuations
  - It appears during the transition from strong pedestal state to strong ITB state
  - It gradually disappears as the ITB grows





Special thanks to Z. Yan and G. Mckee for BES

BES measured fluctuations around the ITB region support the CGYRO calculations

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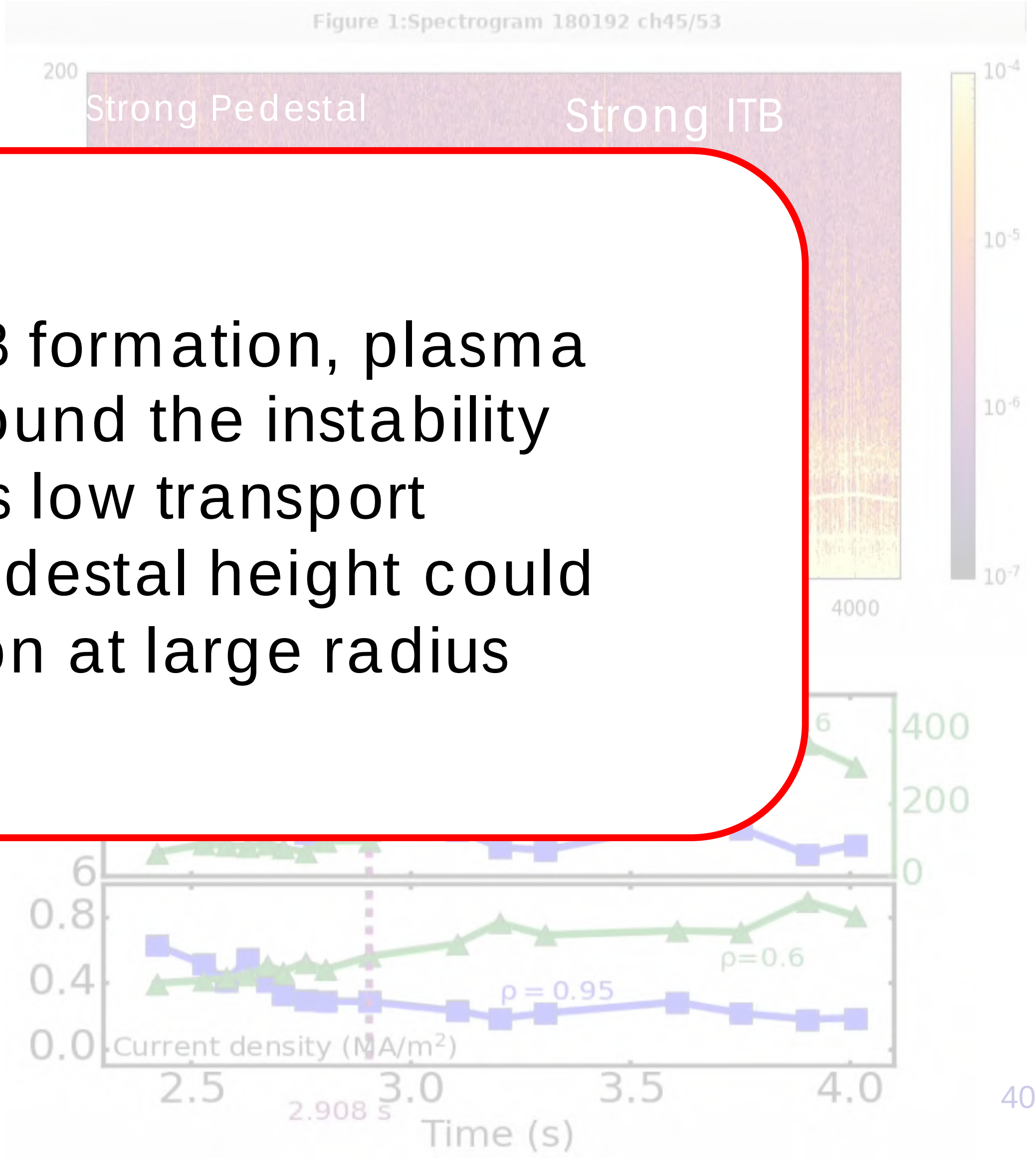
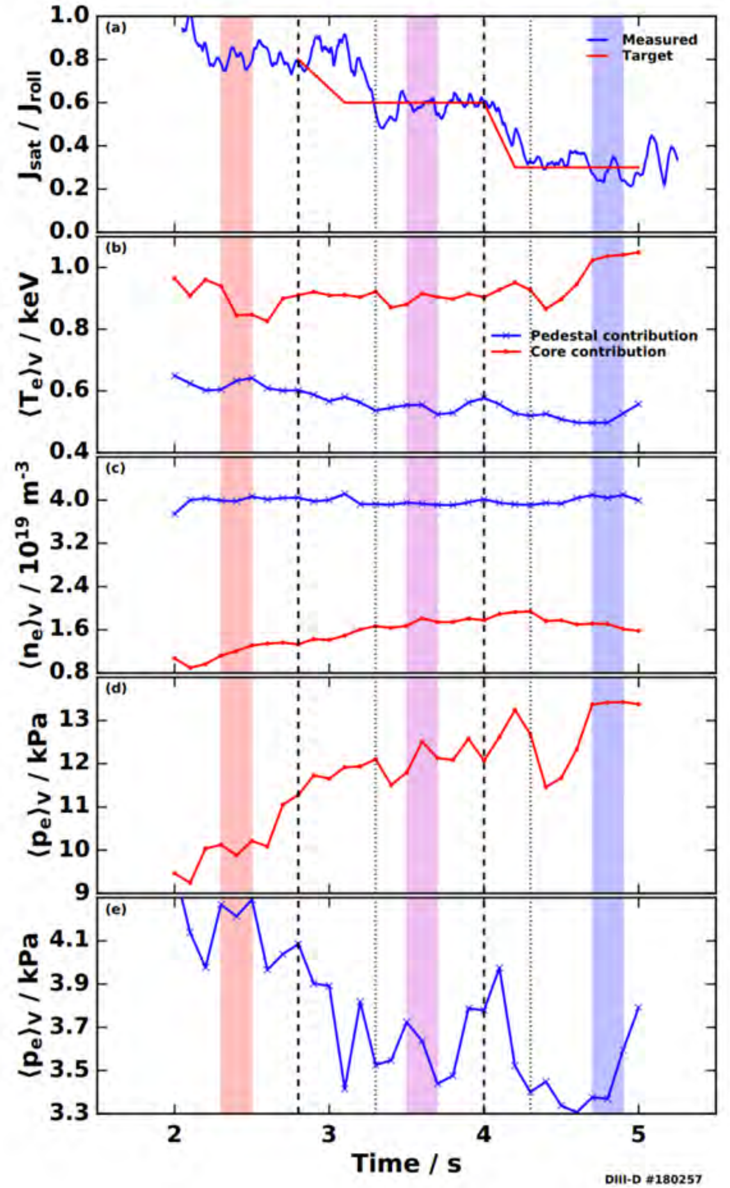


- In the process of ITB formation, plasma makes a detour around the instability mountain to access low transport
- The decrease of pedestal height could drive of ITB formation at large radius

Decreased edge Pe*V is compensated by increased core Pe*V → maintained high confinement

- Decreased edge Pe*V is compensated by increased core Pe*V
- Edge temperature goes down
- Core density increases



Divertor puffing is beneficial for controlling the core impurity concentration

- Divertor puffing is beneficial for divertor detachment
  - similar puffing rate for [3-3.2s]
- Core Zeff is >30% higher with Main Chamber puffing compared with Divertor puffing
  - Identical divertor profiles: full divertor detachment
- Core Impurity accumulation much longer than detachment timescale <0.1s
  - Zeff 1.8 → 2.4, while divertor conditions remains same