ASIPP

Latest advances in active control of H-mode detachment & phys on EAST & DIII-D for ITER/CFETR

L. Wang[1,*], H. Q. Wang[2], Q. P. Yuan[1], D. Eldon[2], K. D. Li[1], K. Wu[1], J. C. Xu[1], J. B. Liu[1], L. Y. Meng[1], Y. M. Duan[1], B. Zhang[1], B. Cao[1], Z. S. Yang[1], F. Ding[1], G. S. Xu[1], B. J. Xiao[1], G.-N. Luo[1], X. Z. Gong[1], H. Y. Guo[2], J. Barr[2], A. W. Leonard[2], A. Hyatt[2], D. Thomas[2], D. Humphreys[2], A. M. Garofalo[2], J. Li[1], B. N. Wan[1]

[1]Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, China
[2]General Atomics, P. O. Box 85608, San Diego, CA 92186, USA

***E-mail: lwang@ipp.ac.cn**

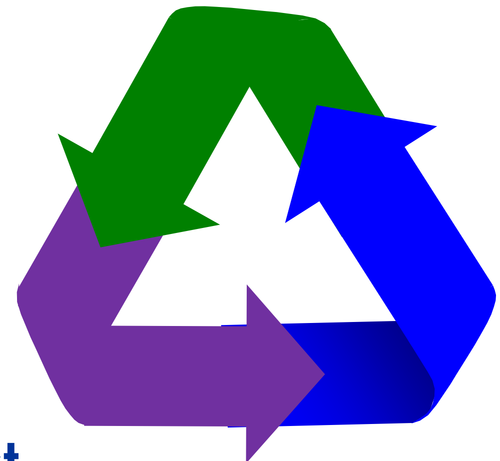
Outline

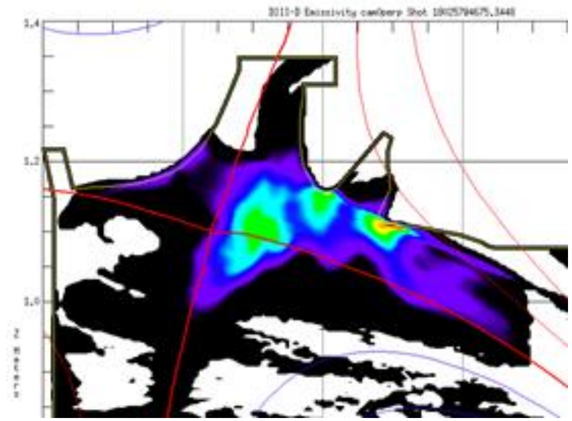
- Introduction
- Active detachment control in EAST H-mode
- Active detachment ctr. in DIII-D high β_p scenario
- Summary & outlook

ASIPP

Key PWI Issues for Long-Pulse High Performance Operations with W divertor

Heat Load on Target Plates





Particle Exhaust & Neutral Recycling

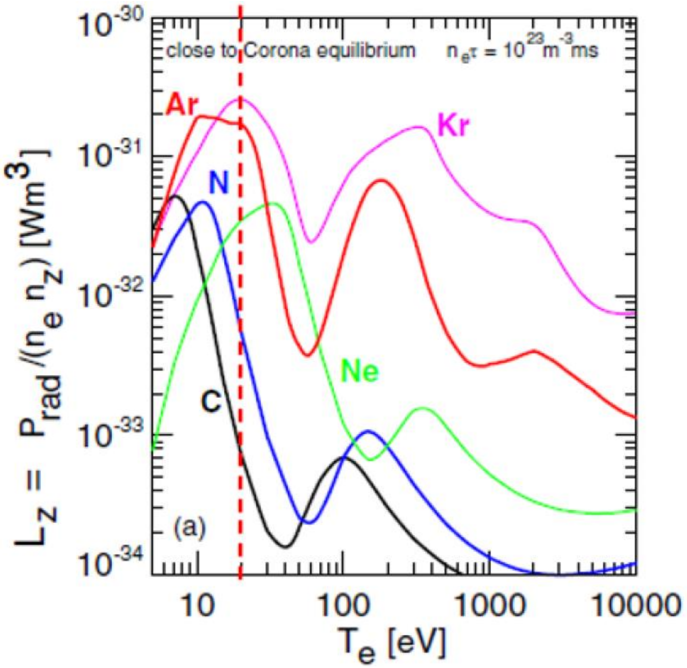
Edge & Core Impurity Control

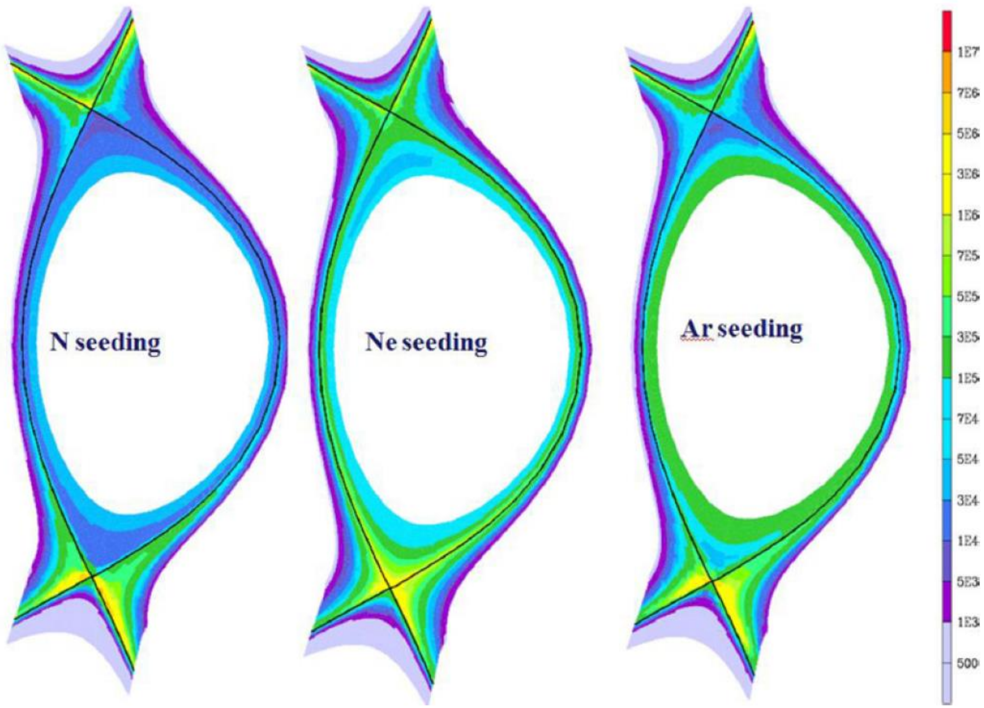
- ☐ Critical challenges for Steady State Operation
- ☐ Radiative divertor induced detachment is acknowledged as the most promising means for steady-state PWI control.

→ To provide a solution on integrated Div&PWI control, compatible with core plasma, for EAST → CFETR & ITER

ASIPP

Radiative loss parameters for different seed impurities





A. Kallenbach et al., PPCF (2012), Nucl. Fusion (2013, 2015)

X. J. Liu et al., Phys. Plasmas (2017); Z. S. Yang et al., Phys. Plasmas (2017)

C. F. Sang et al., Phys. Plasmas (2018) ; J. B. Chen et al., Phys. Plasmas (2019)

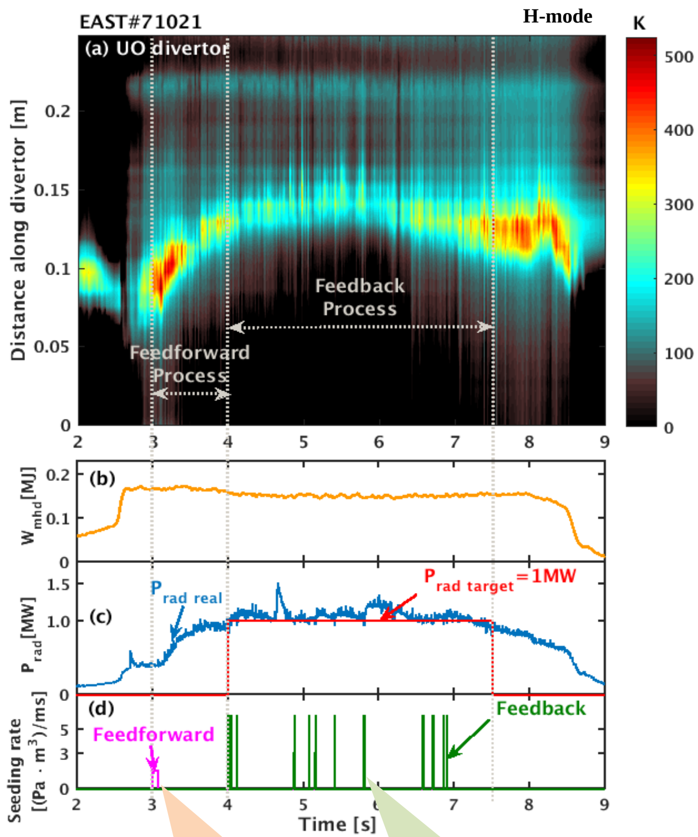
ASIPP

Outline

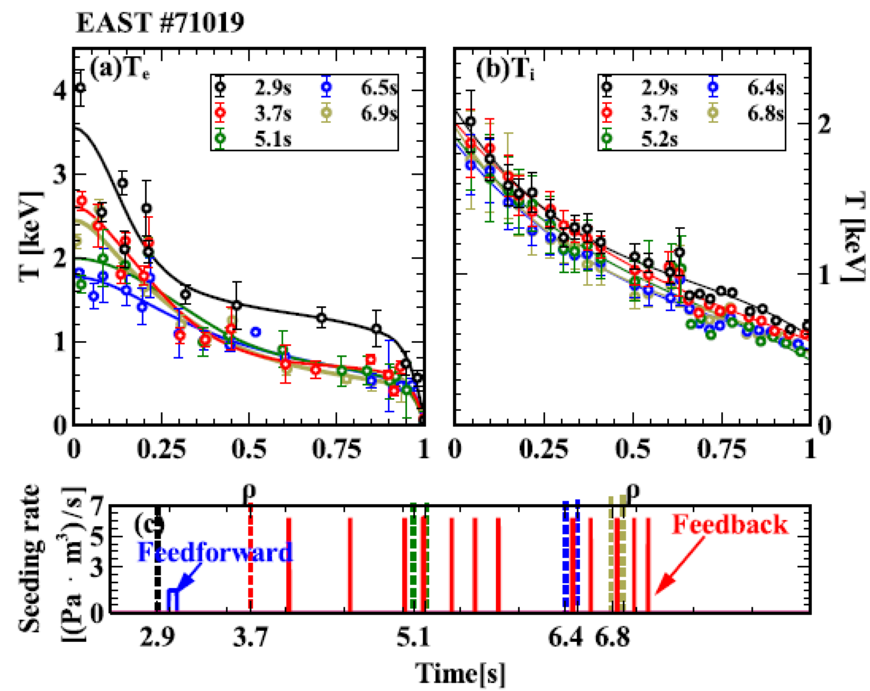
- Introduction
- Active detachment control in EAST H-mode
- Active detachment ctr. in DIII-D high β_p scenario
- Summary & outlook

ASIPP

Success on active feedback control of radiation to reduce heat flux into SOL-Divertor



- **Total radiation power was actively controlled by feedback of LFS neon-SMBI seeding.**
  - **Power/Particle flux** on the divertor clearly decreases.
  - **Slight loss of plasma stored energy: 7 - 11%**



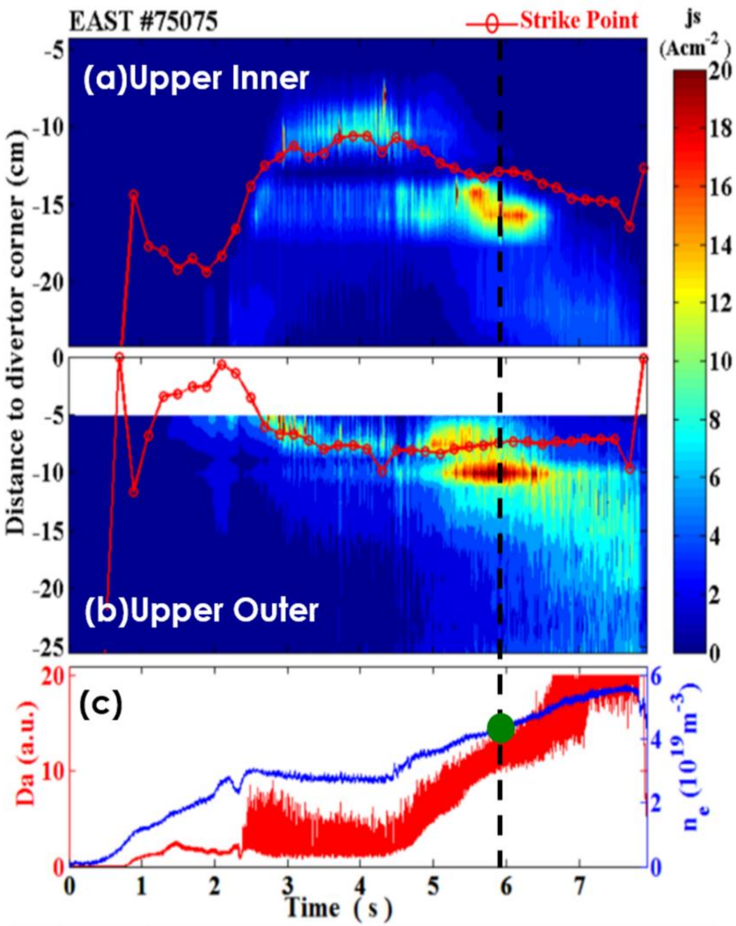
- **Total radiation fraction can be flexibly controlled within 18-36%, in H-mode regime.** ***f_{rad}* extended to 41% in 2018.**

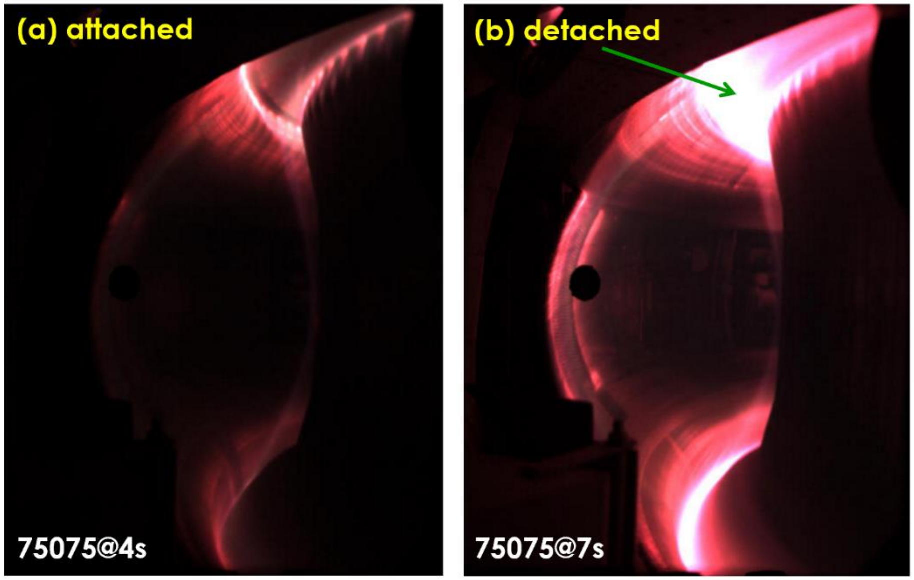
K. Wu, Q. P. Yuan* et al., Nucl. Fusion (2018)

ASIPP

First H-mode detachment with W divertor in EAST

- The particle flux rollover was clearly observed with B×∇B↑, NBI plasma





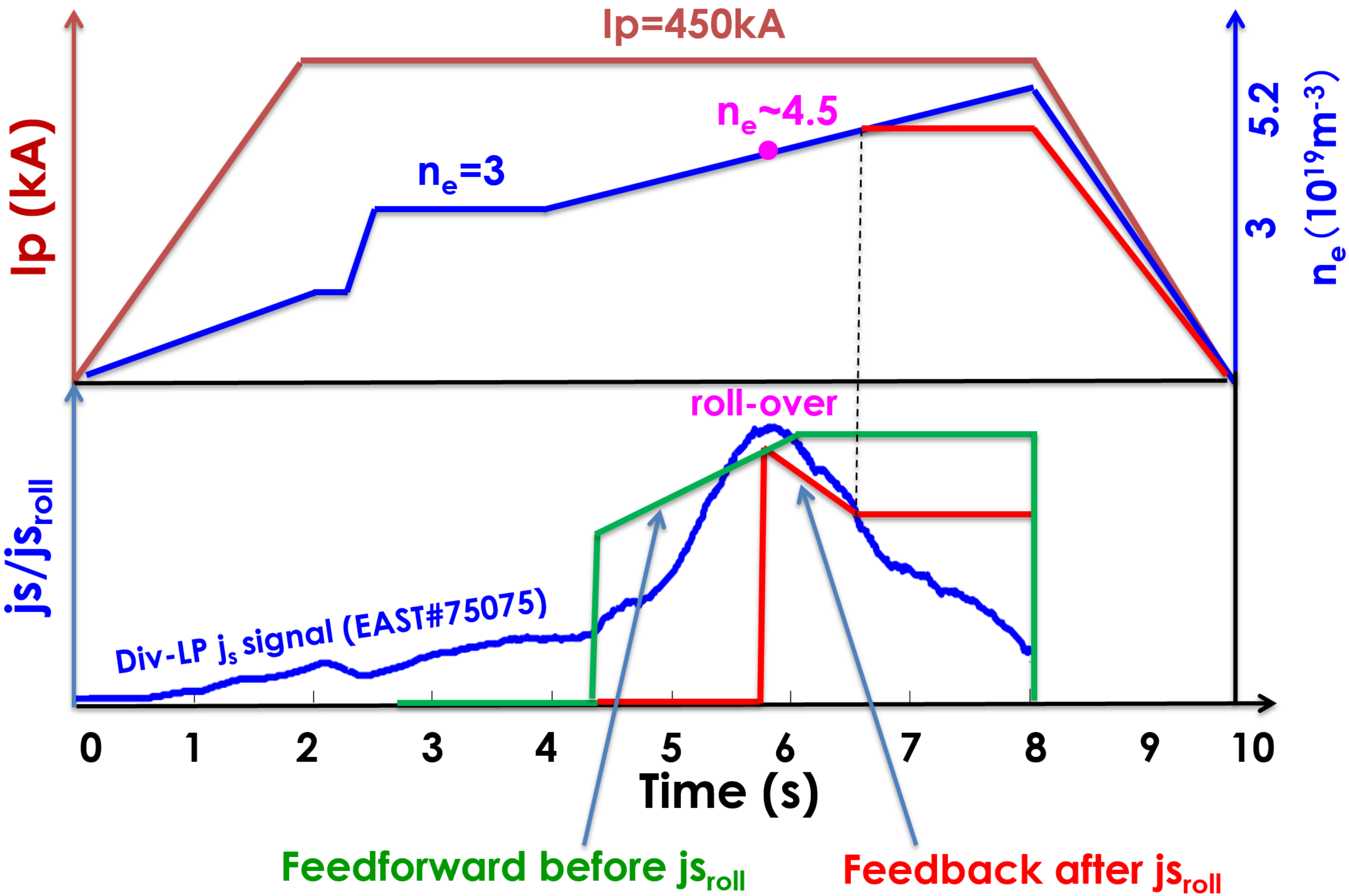
- Neutral density increase during detachment

J. B. Liu et al., Nucl. Fusion 2019

- The H-mode detachment has n_e threshold ($4.5\times10^{19}m^{-3}$, n_e/n_G ~ 0.65, Ip=0.45MA), higher than previous L-mode in EAST.

ASIPP

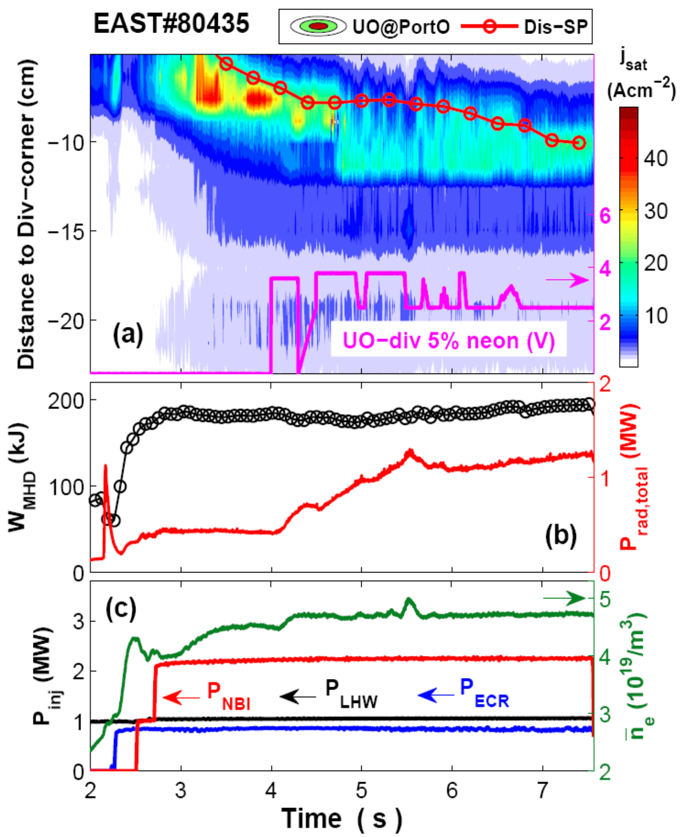
Detachment feedback control module via divertor particle flux

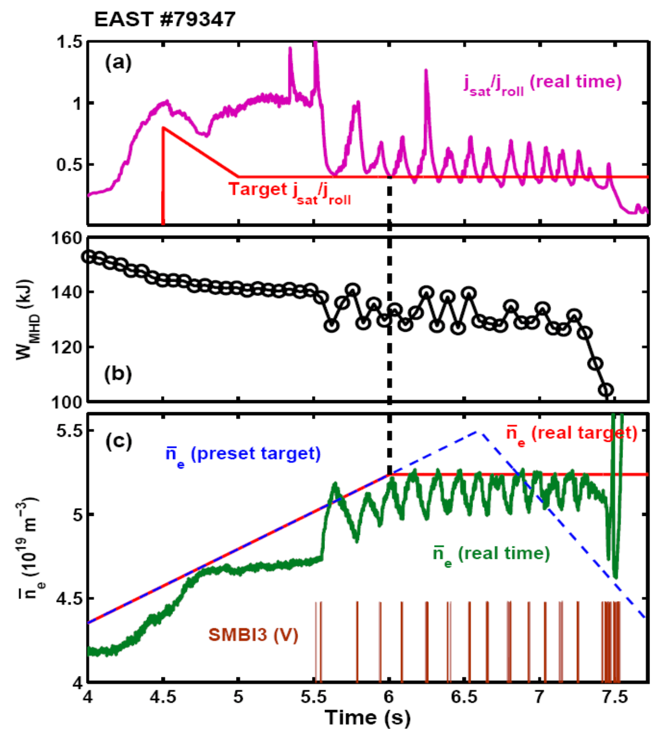


ASIPP

Active feedback control of H-mode detachment via j_{sat}

- **The feedback was achieved with two separate means, $T_{e,div}$ < 5eV**
  - ✓ Divertor neon seeding
  - ✓ LFS SMBI D_2 fueling
- **Excellent compatibility with core plasma performance, $\Delta W_{mhd} < 10\%$**



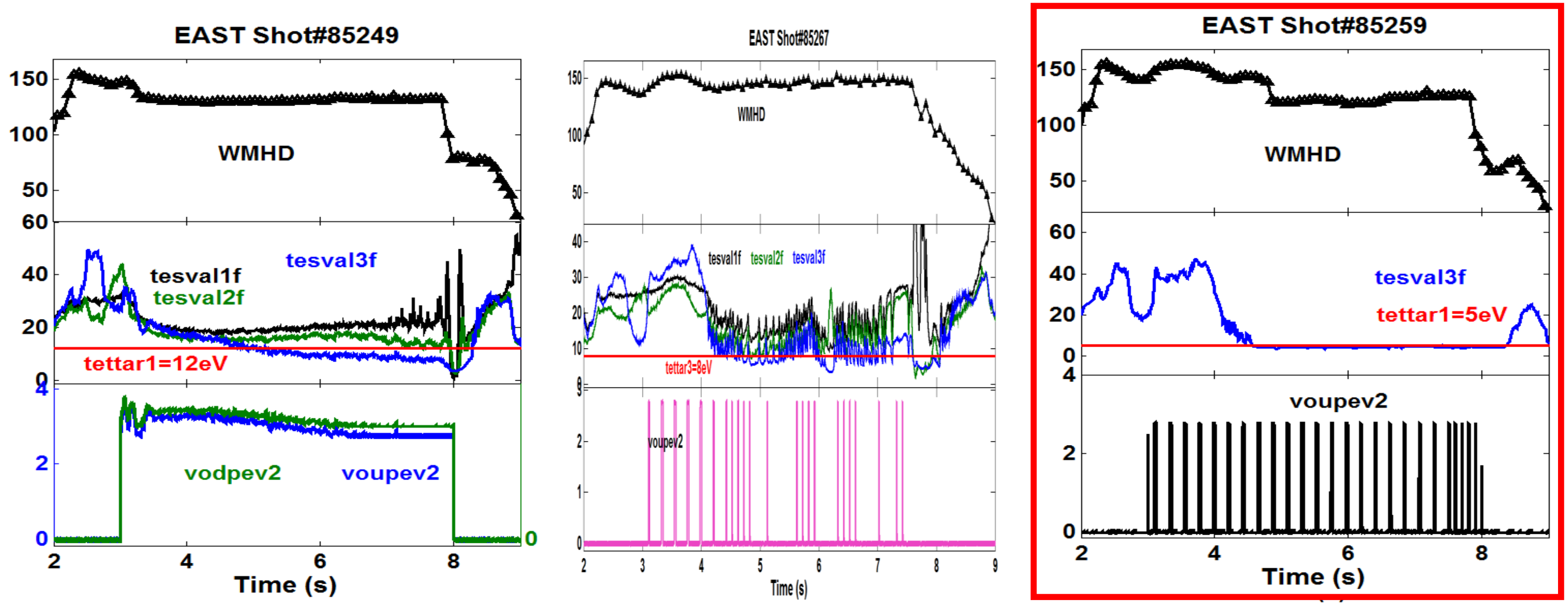


L. Wang et al., Nucl. Fusion (2019)
X. J. Liu et al., Phys. Plasmas (2019)

- **Demonstrated in DIII-D high β_p scenario with H_{98} ~ 1.5, Sep. 2019**

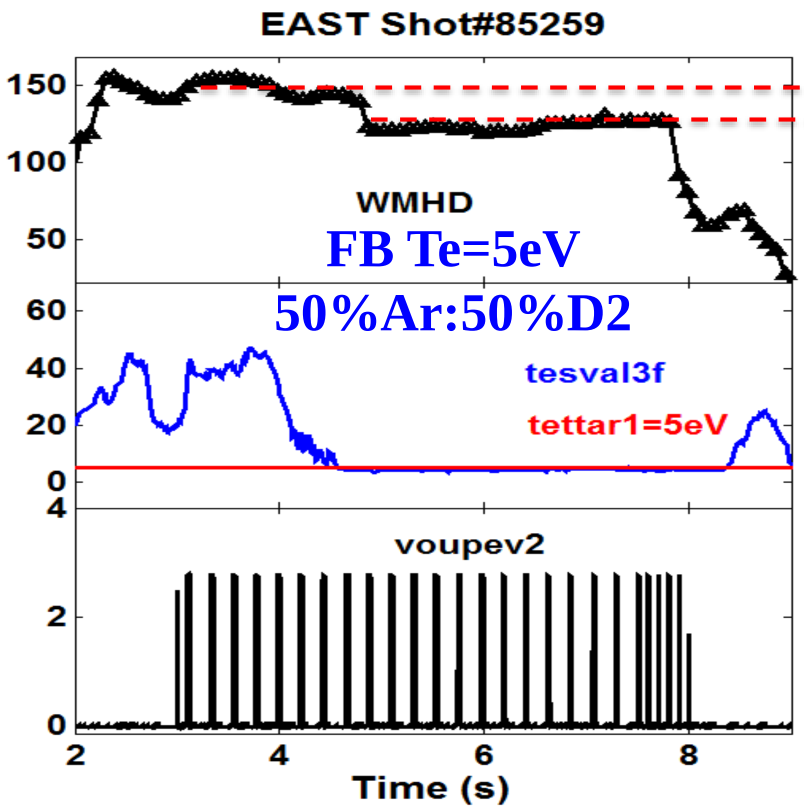
ASIPP

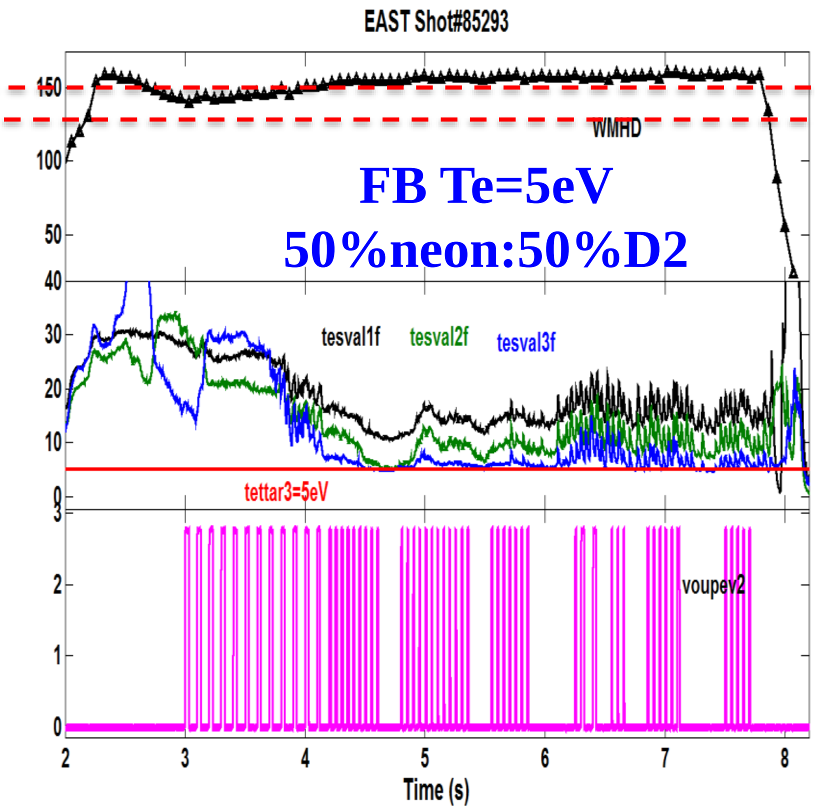
Demonstration of detachment control via $T_{e,div}$



- **Achievements of FB control of Te =12, 10, 8, 5 eV, respectively**
- **Feedback control of Te=8eV is most promising**
  - ✓ Detached-attached dithering facilitating long pulse operation
  - ✓ Excellent divertor-core integration w/o performance loss
- **Te dithering disappears once Te<5eV**

Detachment-Te FB control with Argon VS neon in EAST

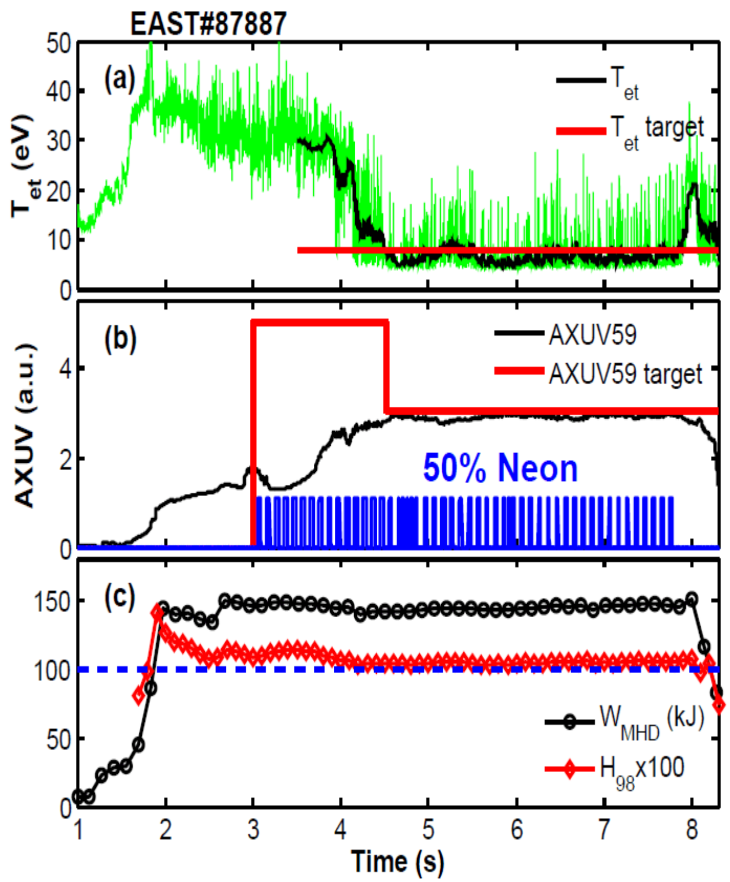


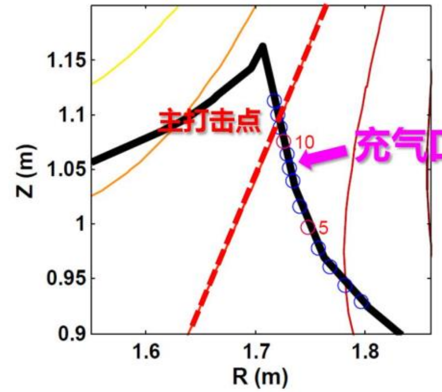


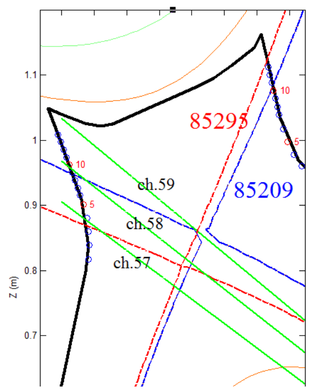
- For $T_{e,div}$ =5eV, neon is more compatible with core plasma, H_{98} >1
- For ITER&CFETR, Ar seeding also performed, more easily to access detachment than Neon, while slight performance loss in EAST
- Neon case needs much more particles than Ar for cooling Te

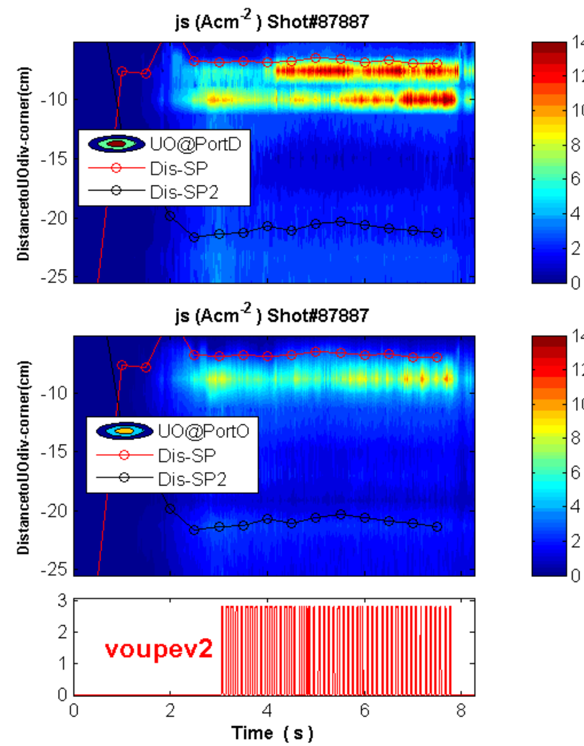
ASIPP

Demonstration of detachment control via Te+P_{rad}









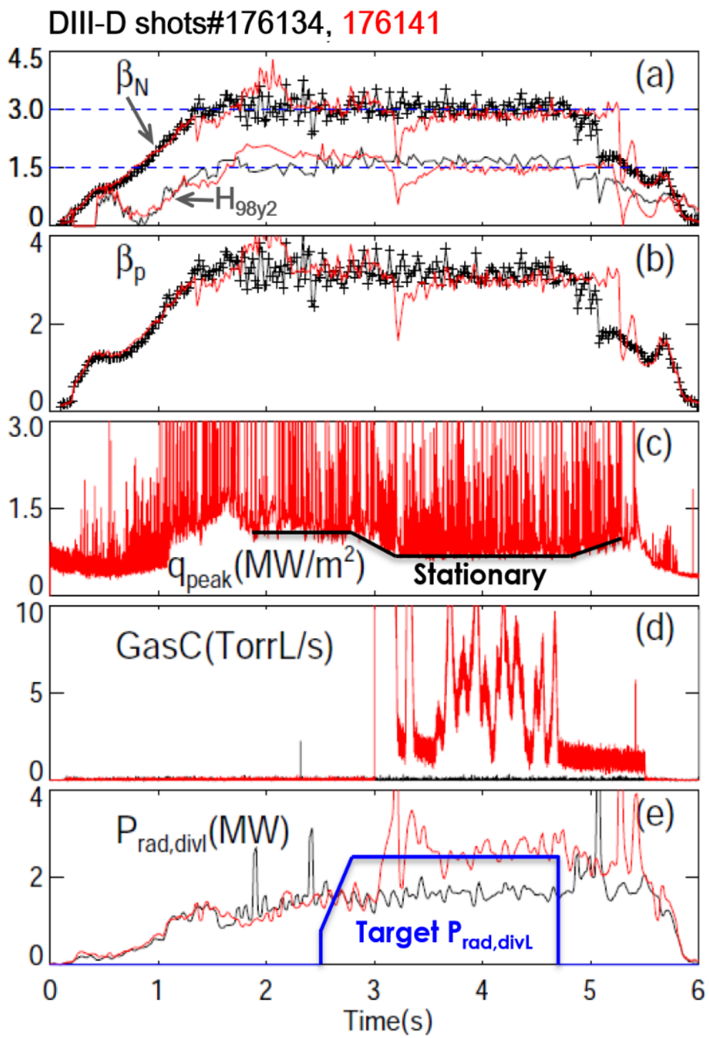
ASIPP

Outline

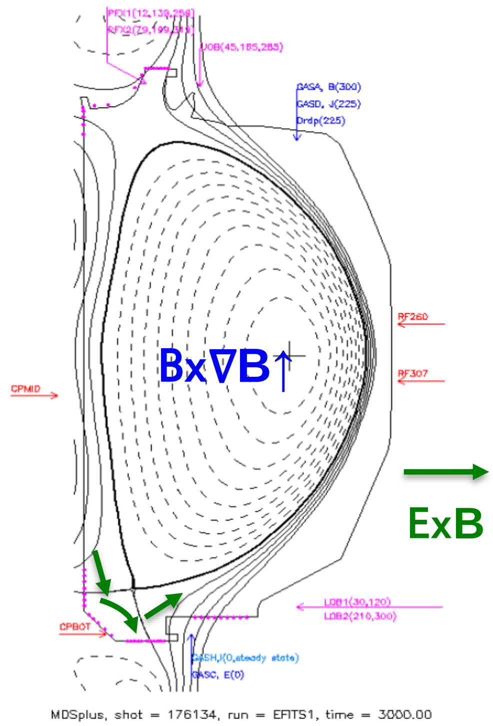
- Introduction
- Active detachment control in EAST H-mode
- Active detachment ctr. in DIII-D high β_p scenario
- Summary & outlook

ASIPP

Active feedback control of divertor radiation in DIII-D



- Feedback control of β & divertor radiation simultaneously.



- High β_p>3 is stable
- SS heat flux ↓ 50%
- $P_{rad,divL}$ follows the target line accurately
- f_{rad} ~ 0.62
- H_{98}~1.5 with stable ITB

- Still attached with $T_{e,div}$ ~ 10 eV at the target

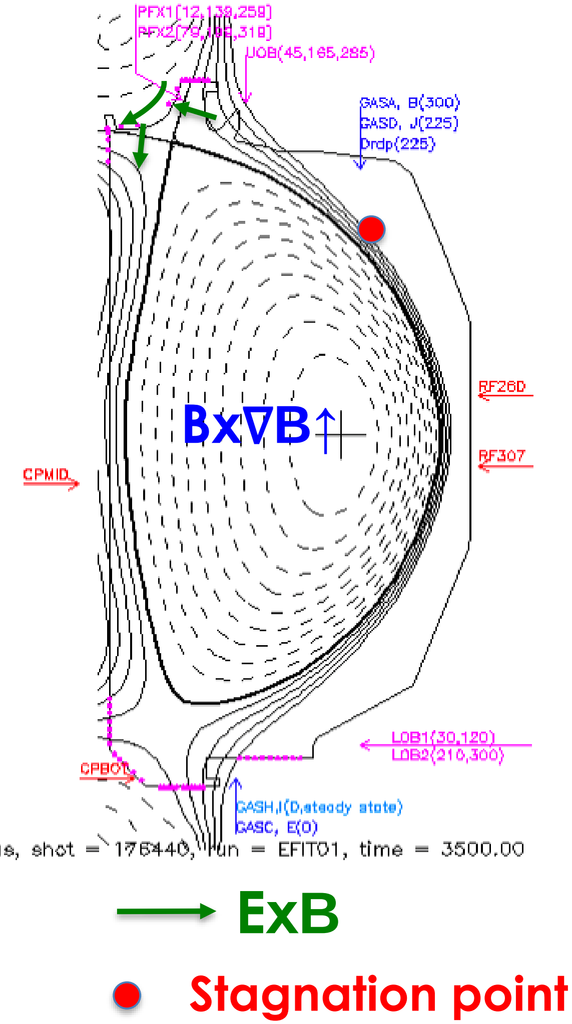
D. Eldon et al., Nucl. Mater. Energy (2019)

L. Wang et al., Nucl. Fusion (2019)

DIII-D NATIONAL FUSION FACILITY

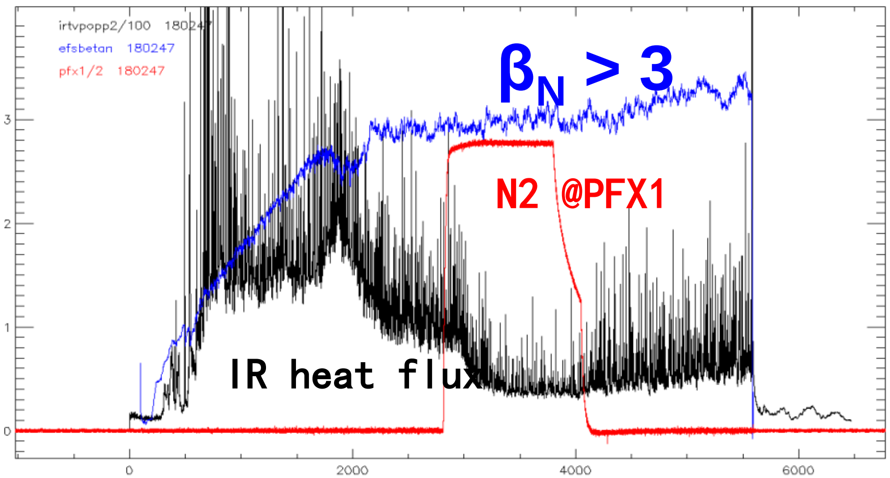
Latest experimental progress in USN (September, 2019)

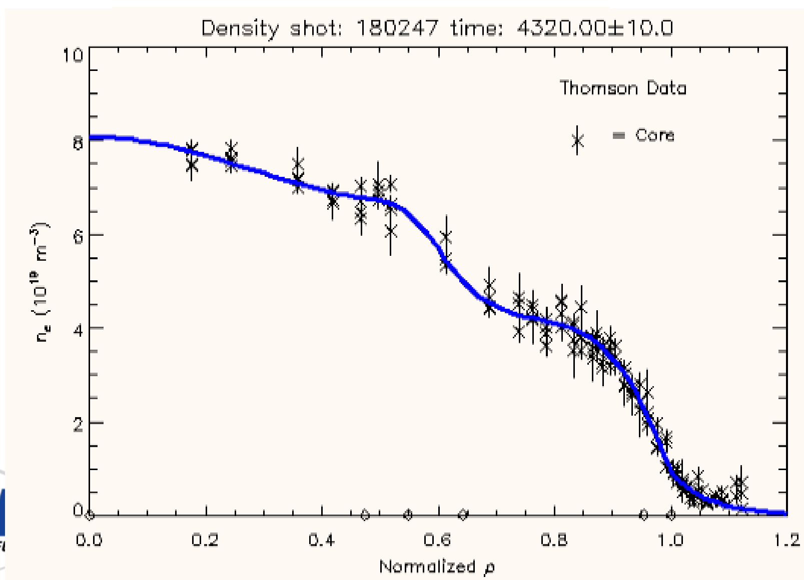
- Detachment feedback control algorithm
- More closed USN configuration
  - Constant Ip~0.72 MA & Bt w/o ramping
  - Increase β_N ~ 3 & dRsep to > 5mm
- Feedforward N2 seeding → $T_{e,div}$ < 5eV
  - N2 seeding through PFX1
- Feedback detachment control with N2 seeding, GASB/PFX1
  - Target j_sat/j_roll =0.3 (T_et < = 5eV)
  - Target j_sat/j_roll = 0.6, 0.3 in one shot
- Neon seeding for USN detachment access, & feedforward control

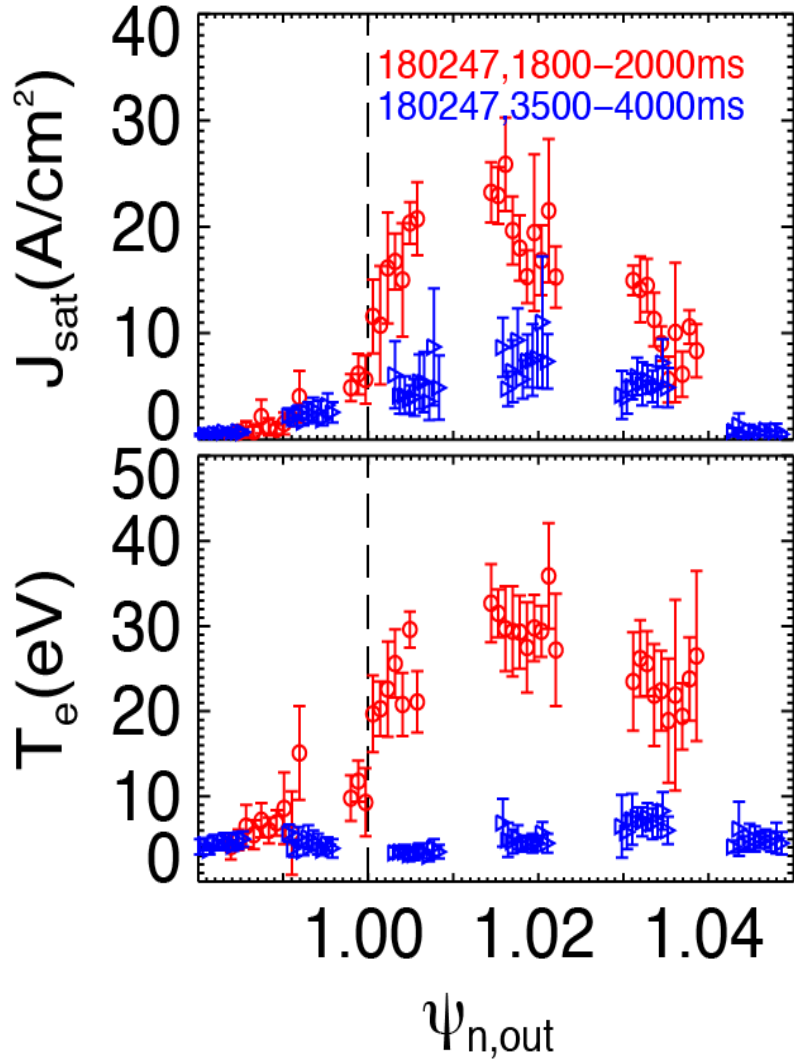


Demonstrated the excellent compatibility of complete detachment with high β_p scenario with sustained ITB+ETB

➢ Excellent core-edge-divertor integration

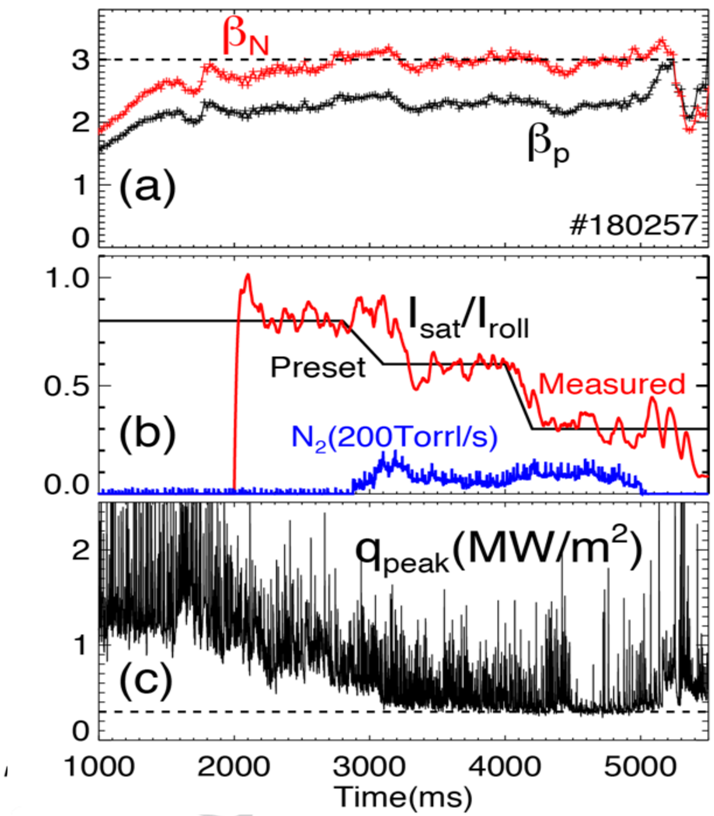


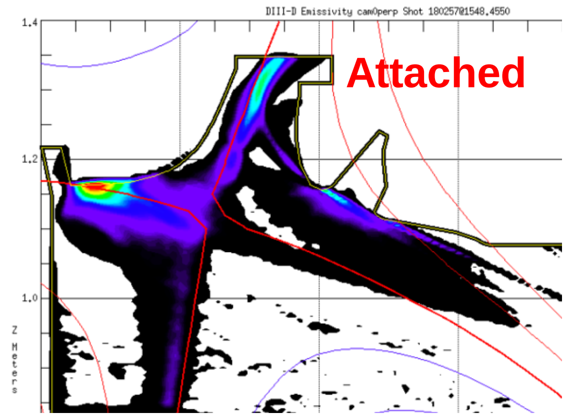


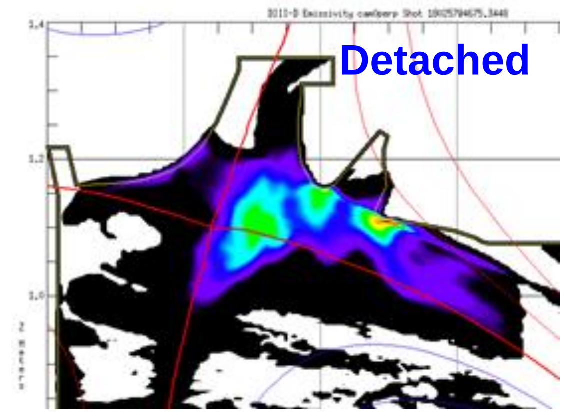


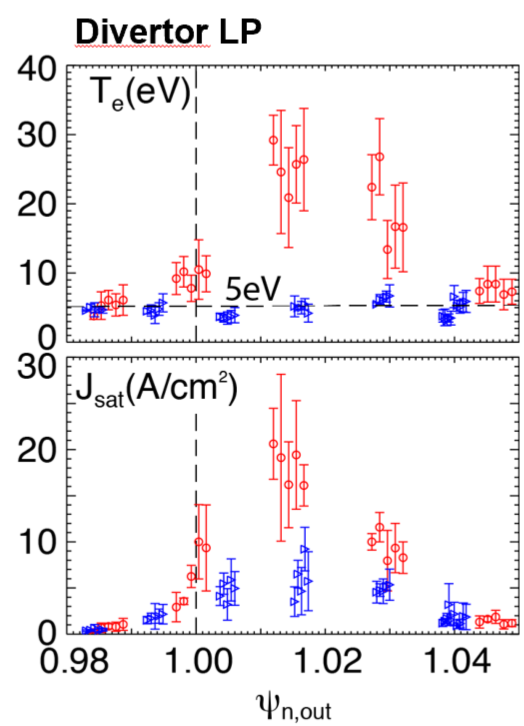
Achieved feedback control of detachment in high β_p scenario successfully, excellent core-edge integration

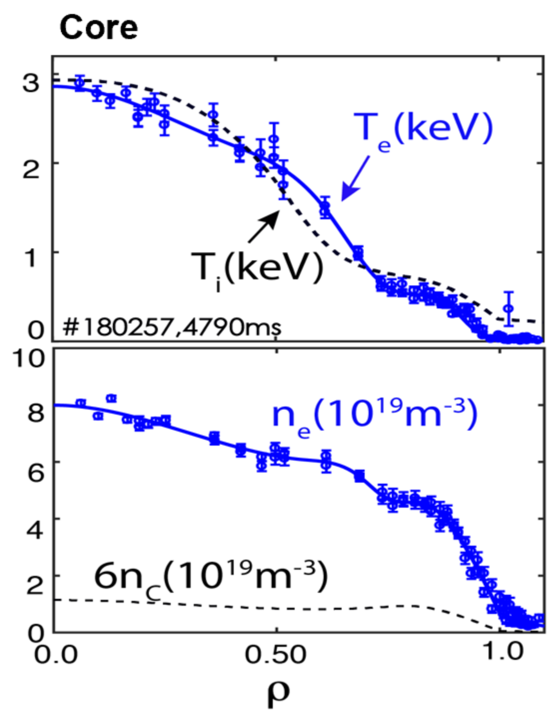
- β_N~3, β_p>2, H_{98}~1.5, q_{95}~8, V_{loop}< 100mV: ITER-SS relevant scenario
  - ITB & ETB
- DoD>3, Div-LP $T_{e, div} \leq$ 5eV











Outline

- Introduction
- Active detachment control in EAST H-mode
- Active detachment ctr. in DIII-D high β_p scenario
- Summary & outlook

Summary & outlook

- **EAST:** Active feedback control of H-mode detachment/radiation
  - P_{rad} (2017), Particle flux (2018), $T_{e,div}$ (2019), $T_{e,div}$+P_{rad} (2019)
  - Excellent compatibility with core performance: $H_{98} > 1$
- **DIII-D:** Demonstration of detachment feedback control for the first time in DIII-D on Sep. 13, 2019
  - $T_{et,div}$ ~ 5eV, H_{98} ~ 1.5: excellent core-edge integration
  - Degree of detachment (DoD) can be controlled actively

Next step → In support of CFETR & ITER

- Demonstration of stable H-mode detachment control > 1 minute
  → Integrated Div&PWI control means compatible with core plasma
- EAST bottom divertor upgrade for enhanced heat/particle exhaust compatible with high-performance
  - More advanced & reliable divertor diagnostics

  → Long pulse H-mode ≥ 400 s w/ H_{98}>1, f_{bs} > 50%

  → High power injection ≥ 1GJ (10MW X 100s)
- Joint physics experiments on more tokamaks

ASIPP

Thank you for your attention