Radiative Power Exhaust Research at DIII-D – From Divertor Science to Core-Edge Integration of High Performance Plasmas

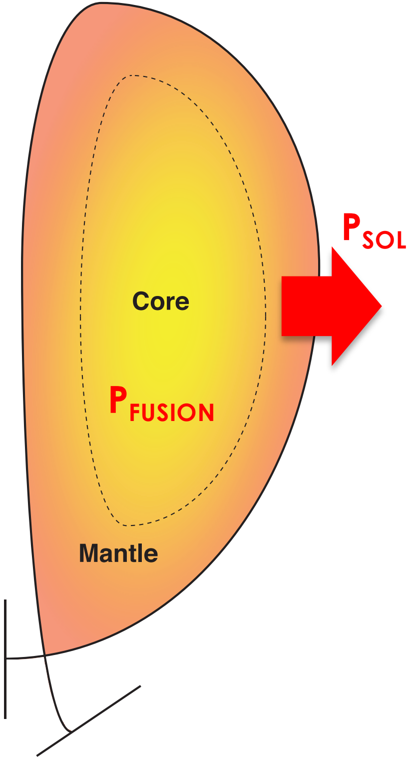
A.E. Jaervinen, B.A. Grierson, A. Garofalo, T.W. Petrie, P.B. Snyder, F. Turco, L. Wang, X. Gong, S.L. Allen, J.M. Canik, D. Eldon, M.E. Fenstermacher, M. Groth, M. Knolker, C. Lasnier, A.W. Leonard, J.D. Lore, A.G. McLean, G.D. Porter, T.D. Rognlien, C.M. Samuell, J.G. Watkins, H. Wang, T.M. Wilks, and the DIII-D and EAST Teams

Third IAEA Technical Meeting on Divertor Concepts
4 – 7 November 2019
IAEA Headquarters, Vienna
Austria

Prepared by LLNL under DE-FC02-04ER54698, DE-AC52-07NA27344, and LLNL LDRD project 17-ERD-020.

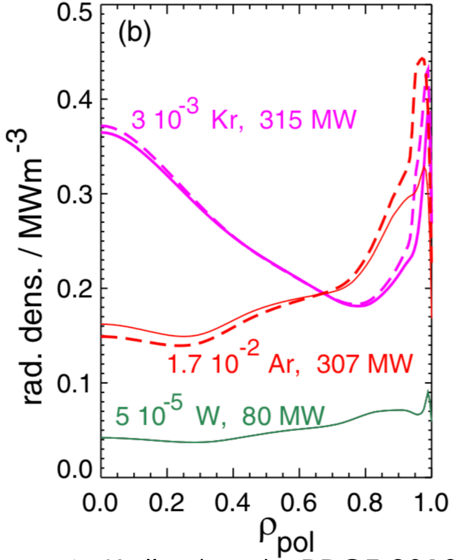
DIII-D NATIONAL FUSION FACILITY

Fusion Reactors Need to Integrate Radiative Mantle with High Plasma Pressure Core and Detached Divertor with Low Collisionality Pedestal



- **$P_{FUSION} \propto \beta_N^2 I_P^2 B^2 R(1+\kappa)$**
  - ➢ High B_T and β_N desired for fusion performance

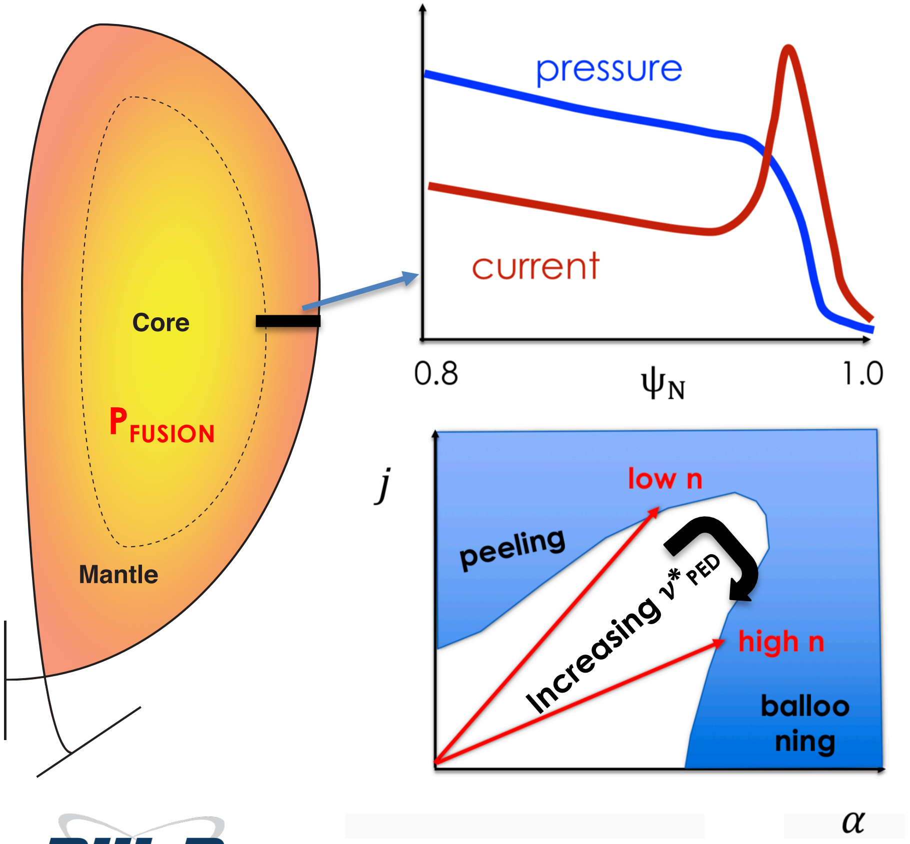
EU-DEMO calculations



A. Kallenbach, PPCF 2013

- **Mantle and core radiation required to reduce P_{SOL} down to manageable level of 1.2 to 3 times P_{LH}**
  - ➢ Impurities needed, but tension with
    - Fuel dilution
    - Profile and P_{RAD} Control
    - Core MHD stability

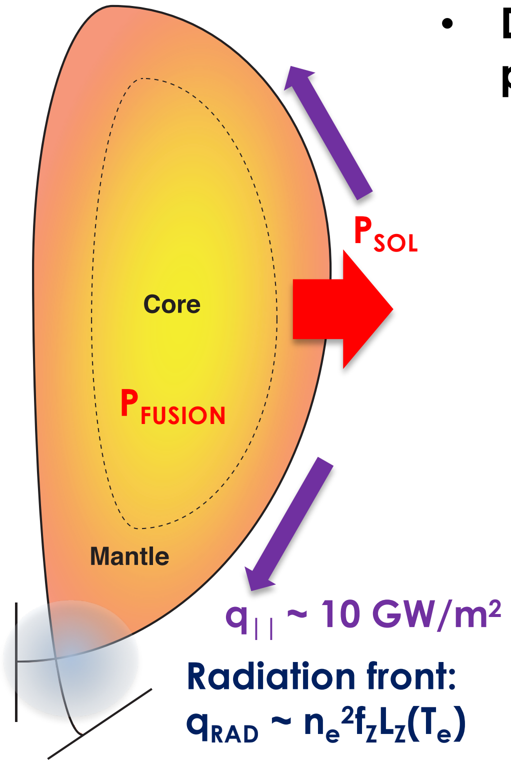
Fusion Reactors Need to Integrate Radiative Mantle with High Plasma Pressure Core and Detached Divertor with Low Collisionality Pedestal



- **High p_{PED} with high $B_T B_{POL}$**
- **Reduction of natural density with machine size ~ I_P/a^2**
- **Pedestal $\nu^* \propto n_e/T_e^2$ ~ n_e^3/p_e^2 ⇒ high B_T, B_P and strong shaping expected to reduce ped. collisionality**
- **Low ν^* pedestal expected to be peeling mode limited**
  - Peeling ⇒ p_{ped} increases with n_e
  - Ballooning ⇒ p_{ped} reduces with n_e

P.B. Snyder, et al. Nucl. Fusion **51** (2011) 103016
M. Greenwald, Plasma Phys. Cont. Fusion **44** (2002) R27

Fusion Reactors Need to Integrate Radiative Mantle with High Plasma Pressure Core and Detached Divertor with Low Collisionality Pedestal

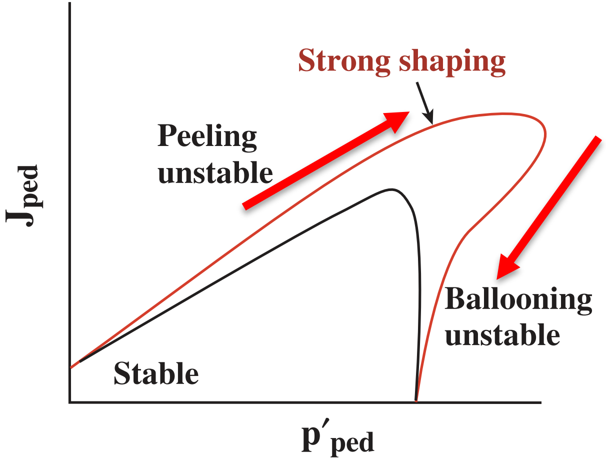


Radiation front:
$q_{RAD} \sim n_e^2 f_Z L_Z(T_e)$

- Divertor detachment is often correlated with pedestal performance reduction in present day tokamaks
  - ➢ Present day small, low B_T facilities operate at high ν^* (ballooning) pedestals in detachment experiments

⇒ Performance reduction with density is expected!

⇒ How to investigate pedestal-divertor integration physics that extrapolate to low ν^* (peeling) pedestals in reactors?



DIII-D NATIONAL FUSION FACILITY

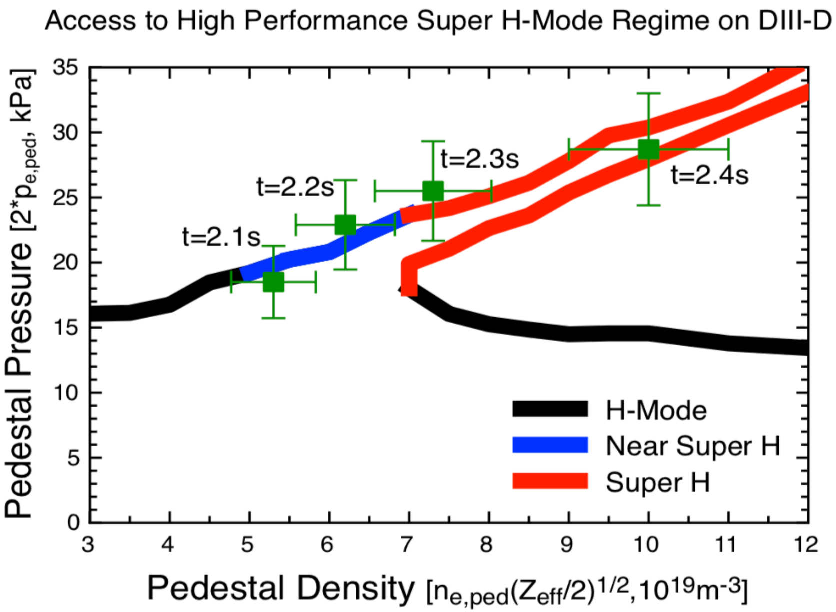
Strong Pedestal and AT Programs of DIII-D Enable Relevant Physics Studies for Pedestal-Divertor Integration and Mantle Radiation

- Strong shaping opens access to peeling limited pedestals at high density, including super H-mode
- AT program enables studies of mantle radiation physics with DEMO or pilot plant relevant normalized core parameters
- Studies of high β_P scenario with an ITB can obtain a feedback controlled detached conditions without core degradation
- New diagnostic tools in DIII-D divertor constrain concentrations of emitting impurities, enabling validation of divertor radiation scalings

Strong Pedestal and AT Programs of DIII-D Enable Relevant Physics Studies for Pedestal-Divertor Integration and Mantle Radiation

- **Strong shaping opens access to peeling limited pedestals at high density, including super H-mode**
- AT program enables studies of mantle radiation physics with DEMO or pilot plant relevant normalized core parameters
- Studies of high β_P scenario with an ITB can obtain a feedback controlled detached conditions without core degradation
- New diagnostic tools in DIII-D divertor constrain concentrations of emitting impurities, enabling validation of divertor radiation scalings

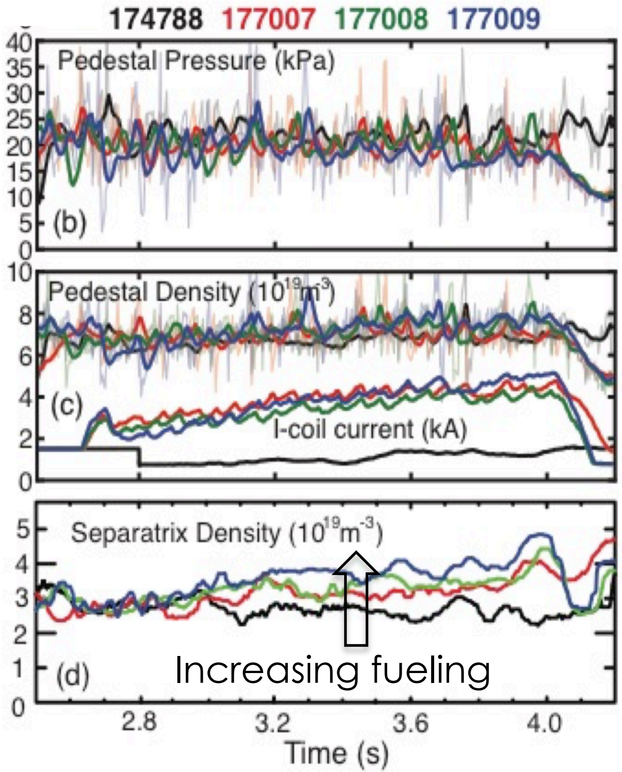
Super H-mode Regime Enables Peeling Limited Pedestal Studies at High Density in DIII-D



- **EPED predicts a bifurcation for highly shaped plasmas**
- **The 2nd branch can be accessed by using a specific density trajectory**
  - Higher $p_{e,PED}$ at the same $n_{e,PED}$
  - Peeling vs. ballooning limited

P.B. Snyder, et al. Nucl. Fusion **55** (2015) 083026
W. Solomon, et al. Phys. Rev. Lett. **113** (2014) 135001
P.B. Snyder, et al. Nucl. Fusion **59** (2019) 086017

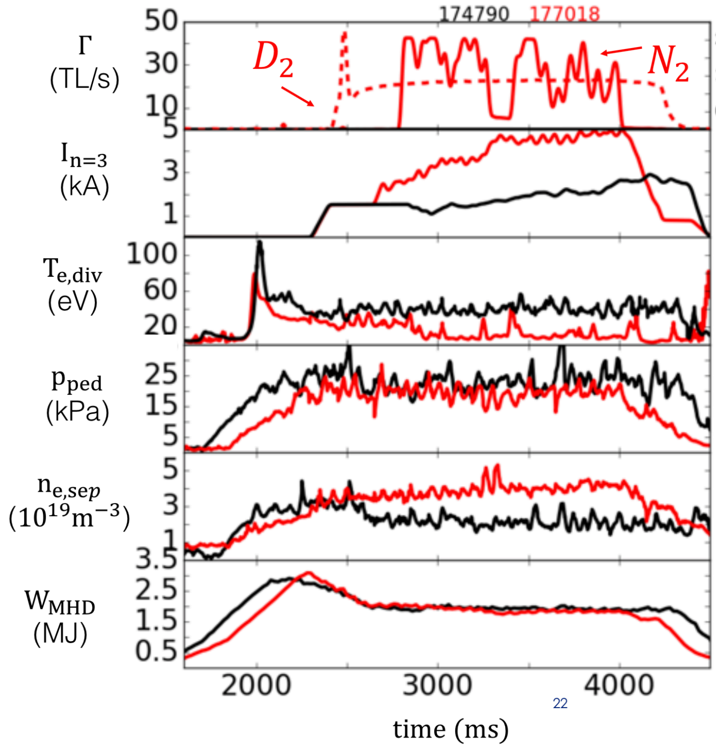
Controlling Pedestal Density with 3D Fields, $n_{e,SEP}$ can be Increased Close to 50% of $n_{e,PED}$ without Compromising $p_{e,PED}$



- Pedestal density is controlled with 3D field feedback to retain near super H-mode in a D_2 gas puff scan
- Pedestal pressures of 20 – 25 kPa maintained while increasing $n_{e,SEP}$ from ~30% of $n_{e,PED}$ to > 50% of $n_{e,PED}$
- Greenwald fraction of these plasmas is fairly low (~50 – 60%) as I_p is high (1.95 MA) and pedestal and core density is controlled with 3D fields

P.B. Snyder, et al. Nucl. Fusion **59** (2019) 086017

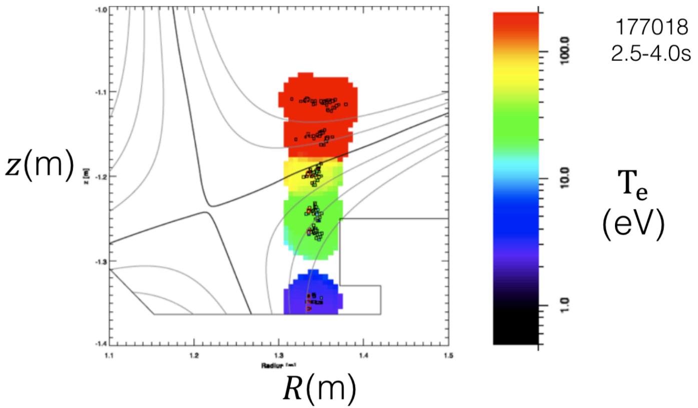
With Nitrogen Seeding, Radiative Divertor with T_e ~ 15 eV can be Obtained without Pedestal Reduction

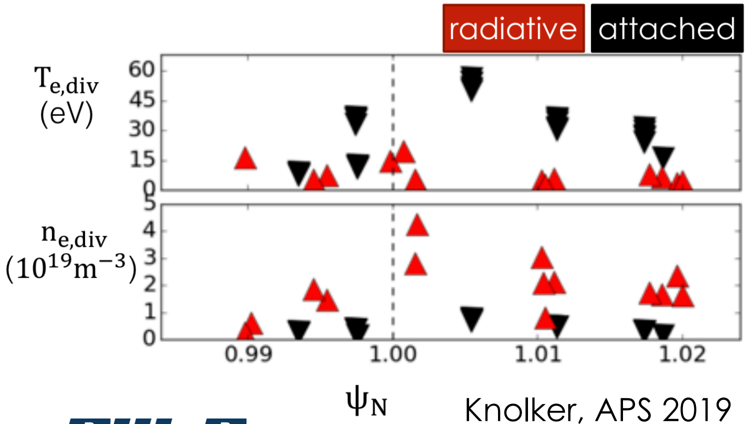


Knolker, APS 2019

- Radiation feedback controlled nitrogen gas puff
- 3D fields feedback control for pedestal density
- Divertor cooling to low temperatures less than 15 eV without reduction of $p_{e,PED}$ or W_{MHD}
- Radiated power fraction increased from 40% to 65%

Divertor Thomson Scattering and Langmuir Probes show Clear Divertor Cooling with the Nitrogen gas Puff

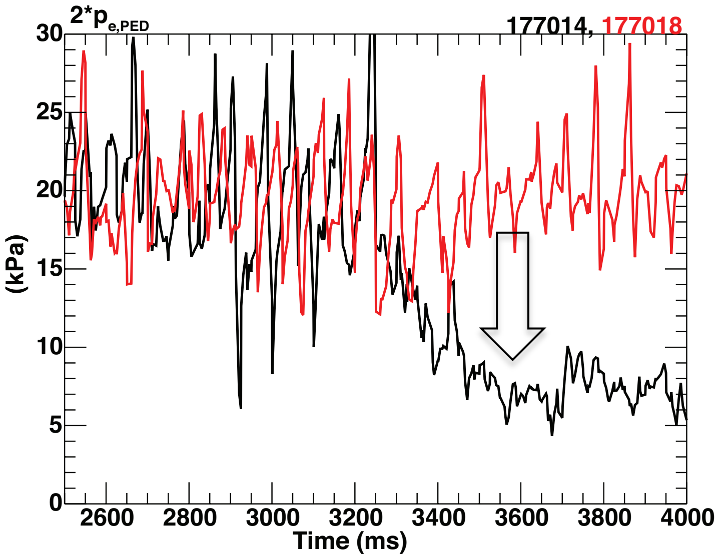


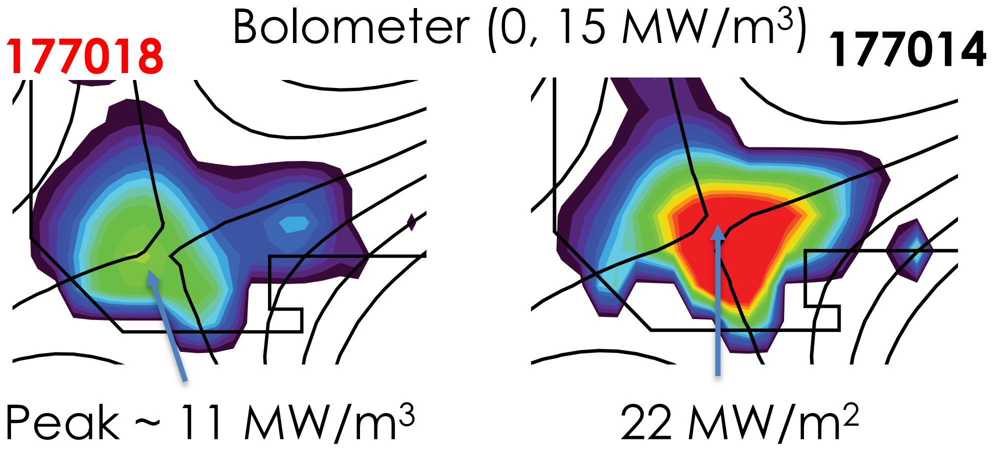


Knolker, APS 2019

- Clear Cooling of Divertor Conditions with the nitrogen gas puff
- High recycling conditions indicated by the DTS and Langmuir probe measurements

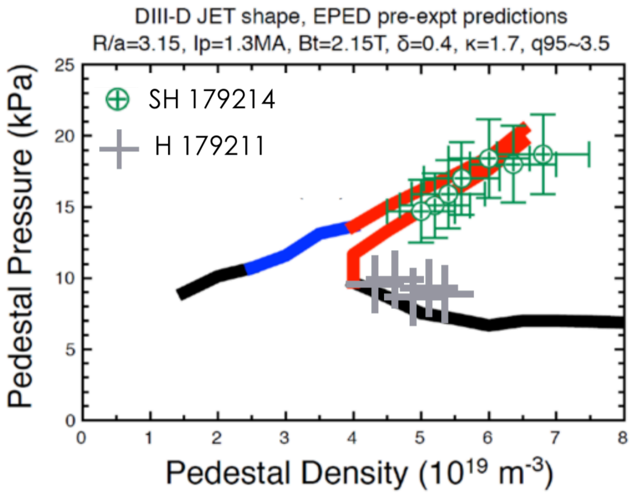
Strong Detachment (f_{RAD} ~ 85%) Leads to the Pedestal Dropping out of Super-H ⇒ p_{PED} Reduced by x2.5



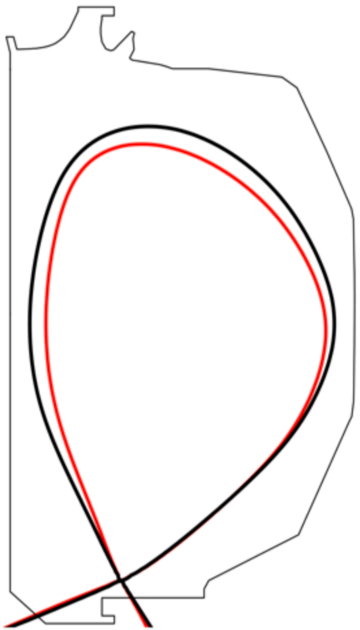


- **Strong detachment with f_{RAD} ~ 85 – 90% observed to lead to radiation front peaking at the X-point and a factor of 2.5 reduction of $p_{e,PED}$**
  - ➢ **Operational space near the pedestal collapse not fully explored yet ⇒ Further studies needed to understand the limits of the high $p_{e,PED}$**

Recent DIII-D Experiments Indicate Access to Super H-mode in JET Shape



Knolker, APS-DPP 2019



JET H
δ~ 0.3
R/a ~2.9

JET SH
δ~ 0.4
R/a~ 3.15

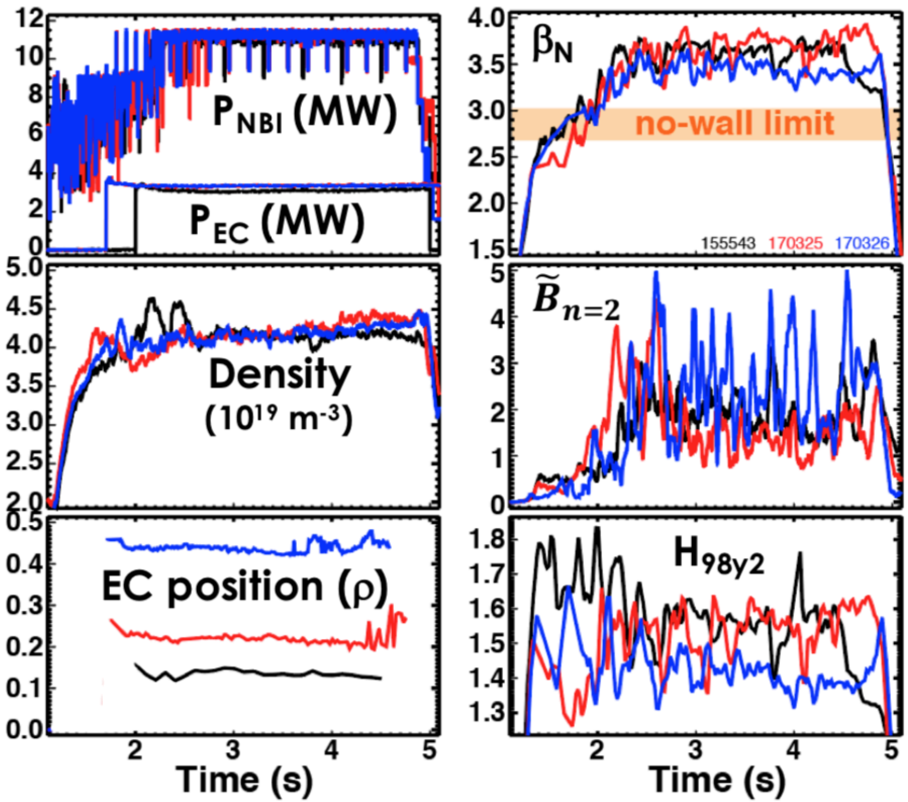
- **The higher triangularity (and aspect ratio) shape predicted to reach Super-H**
- **β_N beam feedback program to tailor trajectory along EPED channel prediction**
- **Large p_{PED} difference confirms deep Super-H access at marginal conditions**

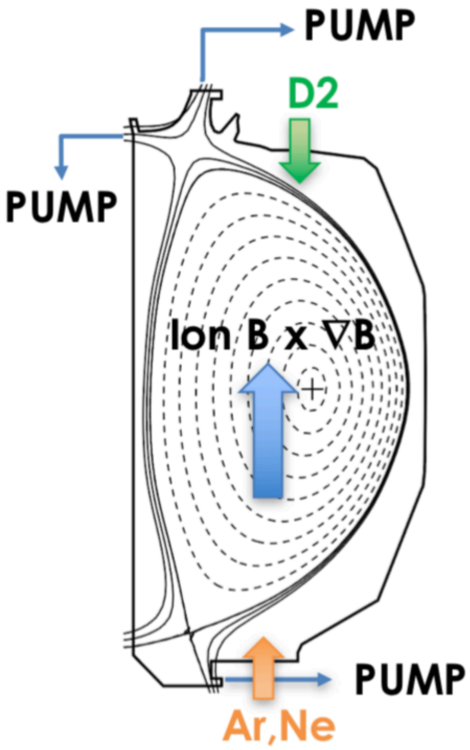
DIII-D NATIONAL FUSION FACILITY

Strong Pedestal and AT Programs of DIII-D Enable Relevant Physics Studies for Pedestal-Divertor Integration and Mantle Radiation

- Strong shaping opens access to peeling limited pedestals at high density, including super H-mode
- **AT program enables studies of mantle radiation physics with DEMO or pilot plant relevant normalized core parameters**
- Studies of high β_P scenario with an ITB can obtain a feedback controlled detached conditions without core degradation
- New diagnostic tools in DIII-D divertor constrain concentrations of emitting impurities, enabling validation of divertor radiation scalings

Mantle and Divertor Radiation Studied in Highly Reproducible High β_N Hybrid Plasmas





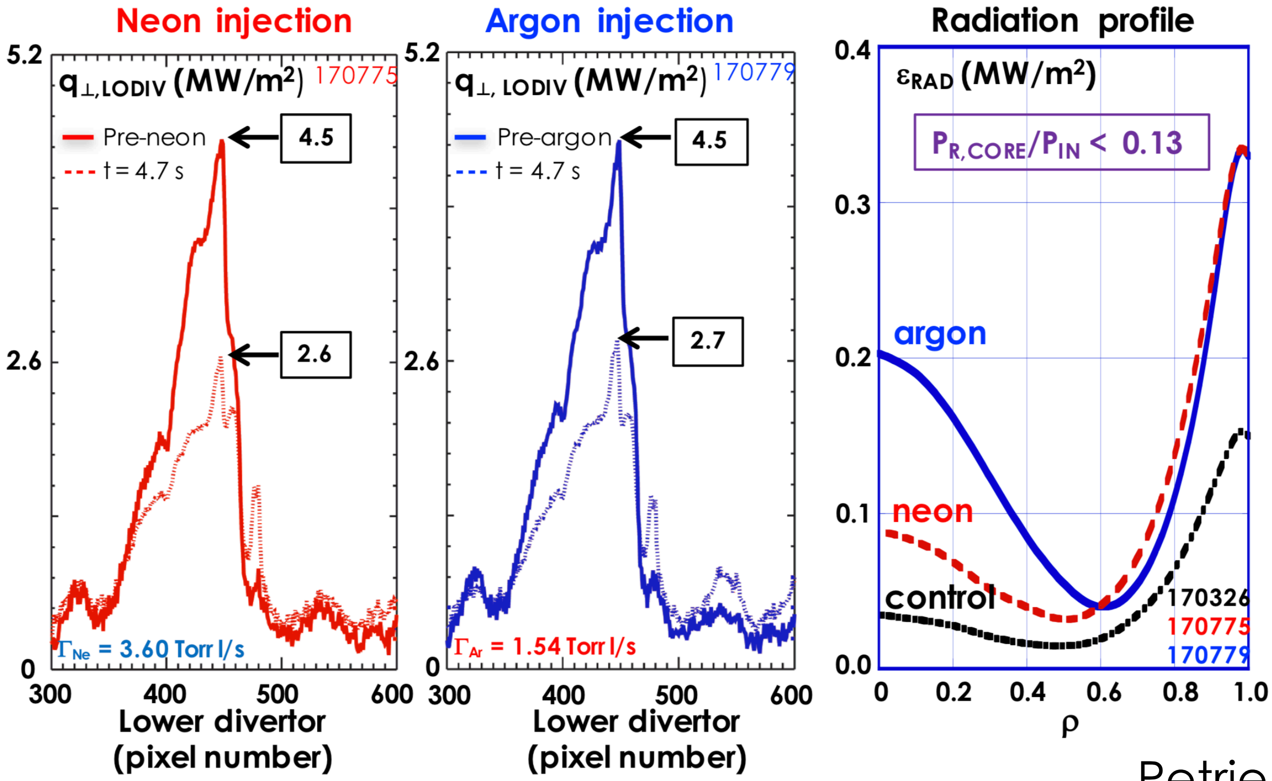
P_{HEAT} ~ 11.5 NBI + 3.5 ECH MW

β_N ~ 3.6

H_{98} ~ 1.5

F. Turco, IAEA FEC 2018

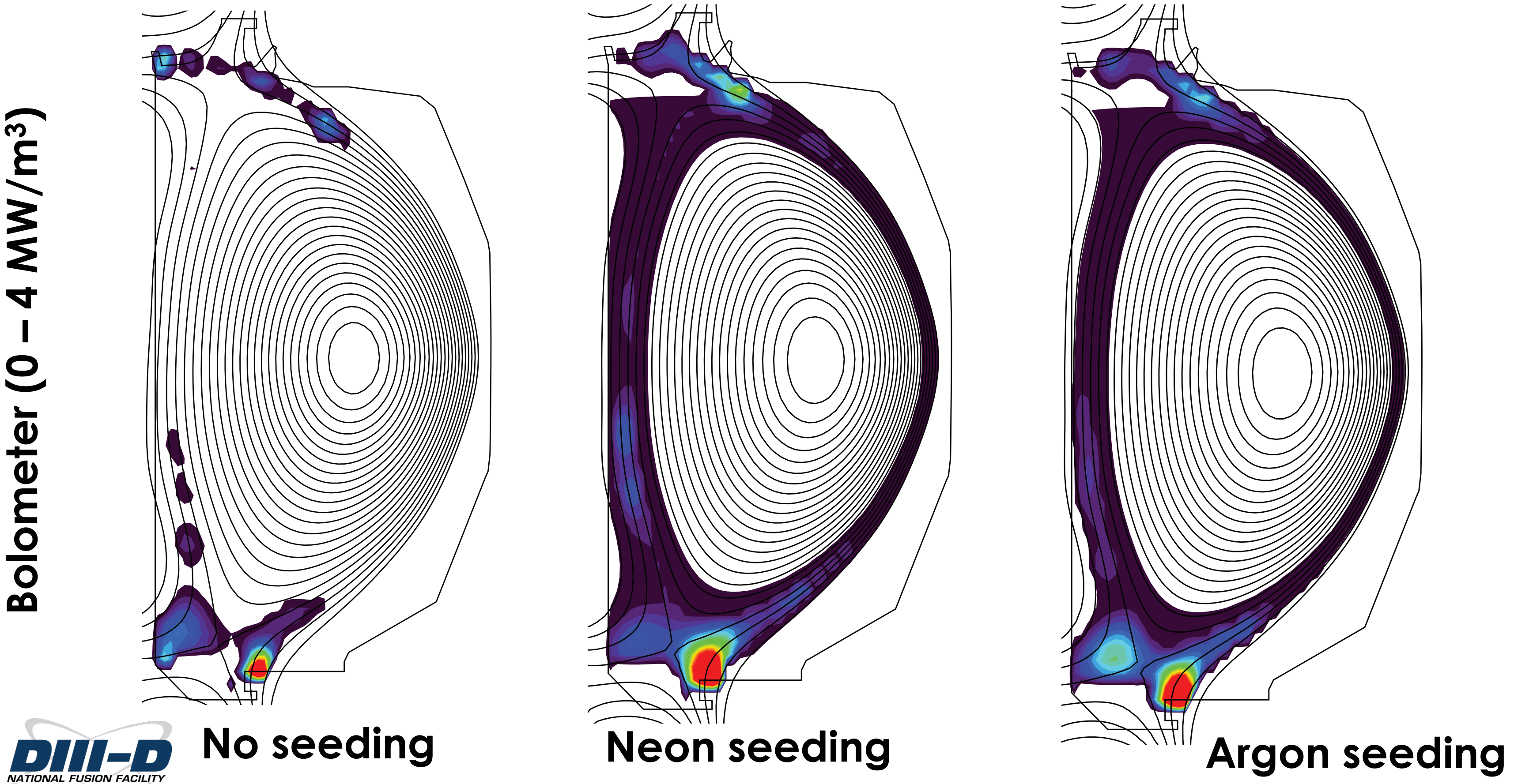
Both Ne and Ar Injection can Reduce Divertor Heat Flux through Mantle and Divertor Radiation



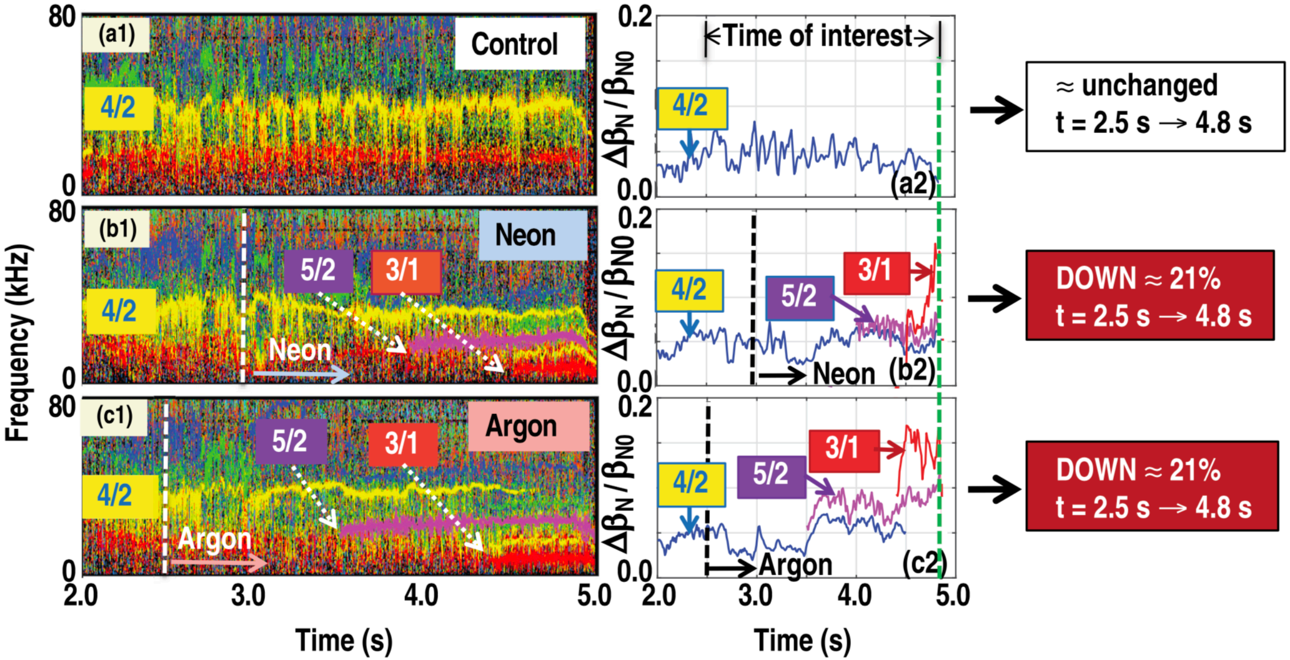
- P_{HEAT} ~ 11.5 NBI + 3.5 ECH MW
- $P_{RAD,\ CORE}$ 1.4 ⇒ 2.8 MW
- $P_{RAD,TOT}$ 3.5 ⇒ 6.8 MW

Petrie

Both Ne and Ar Injection can Reduce Divertor Heat Flux through Mantle and Divertor Radiation



Tearing Mode Activity Followed by the Mantle Formation Compromises the Scenario at High β_N

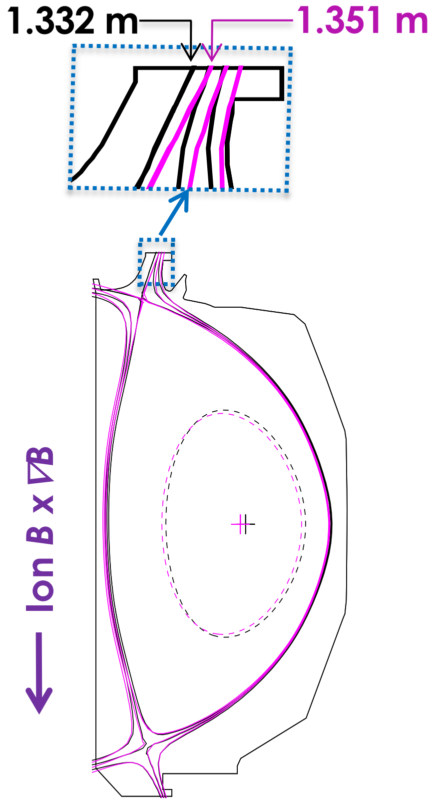


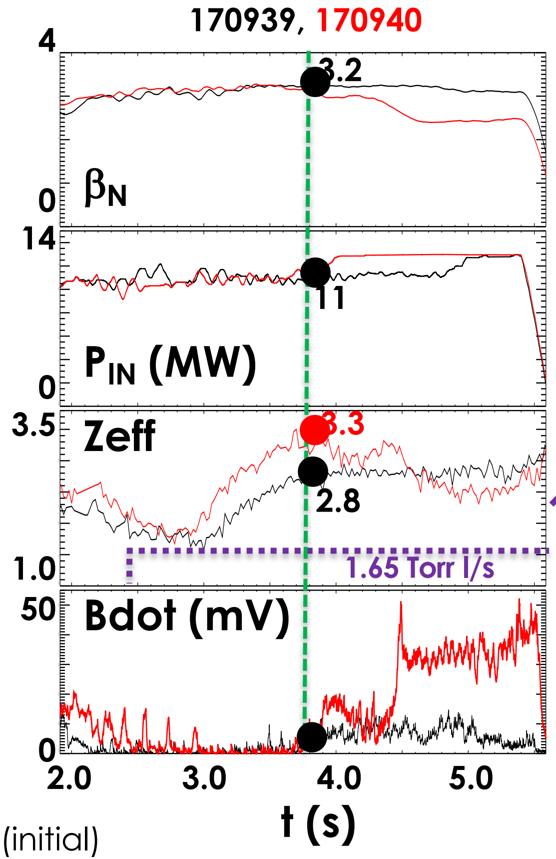
- Tearing modes reduce confinement and β_N
  - ➢ Not observed in lower β_N scenarios

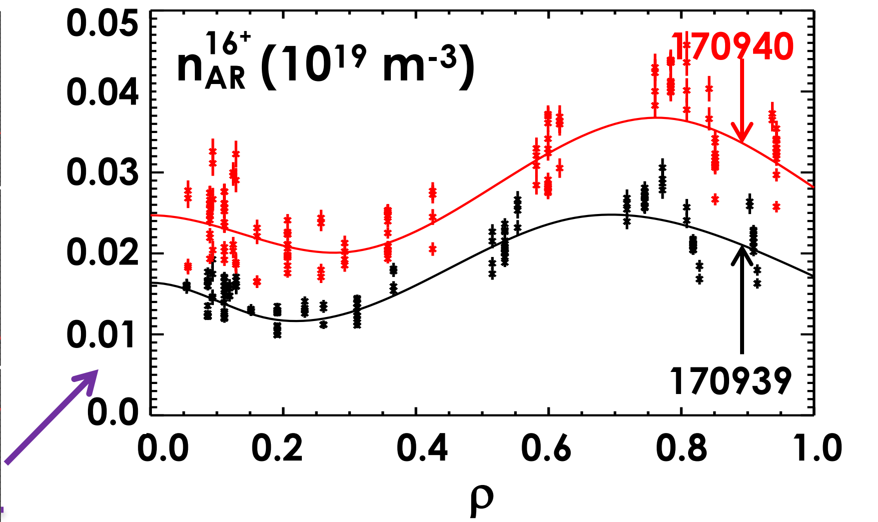
- Future studies will explore more central ECH heating for profile control and higher main plasma densities

T.W. Petrie, et al. Nucl. Fusion **59** (2019) 086053
T.W. Petrie, et al. J. Nucl. Mat. **363-365** (2007) 416-420

For a Closed Divertor, A Modest Change in R_{OSP} Inside the Slot Increased Argon Leakage Out of the Divertor







- Background density and temperature profiles were similar for both R_{OSP} cases
- The higher Zeff in the R_{OSP} = 1.351 m case resulted entirely from higher argon accumulation in the core

$H_{98} \approx 1.5$ (initial)

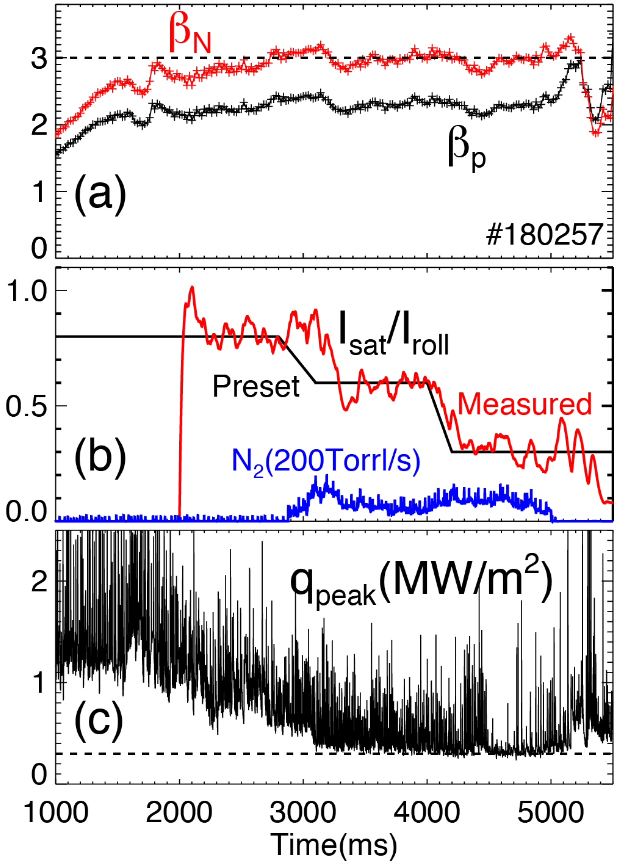
dRsep = +3 mm

Petrie, IAEA FEC 2018

Strong Pedestal and AT Programs of DIII-D Enable Relevant Physics Studies for Pedestal-Divertor Integration and Mantle Radiation

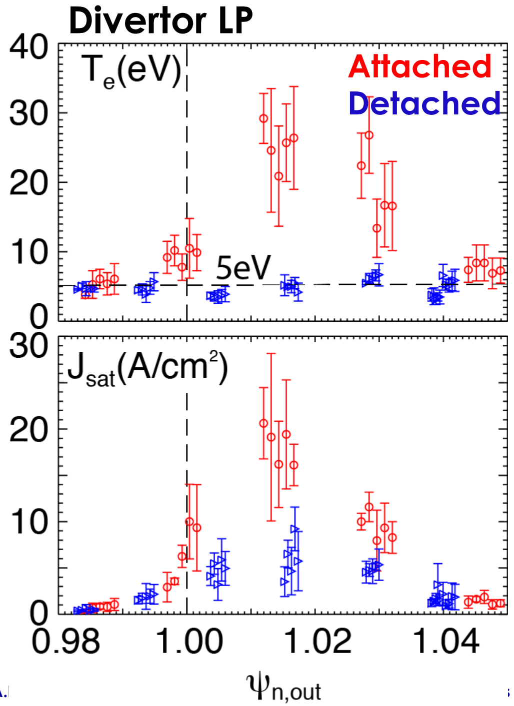
- Strong shaping opens access to peeling limited pedestals at high density, including super H-mode
- AT program enables studies of mantle radiation physics with DEMO or pilot plant relevant normalized core parameters
- **Studies of high β_P scenario with an ITB can obtain a feedback controlled detached conditions without core degradation**
- New diagnostic tools in DIII-D divertor constrain concentrations of emitting impurities, enabling validation of divertor radiation scalings

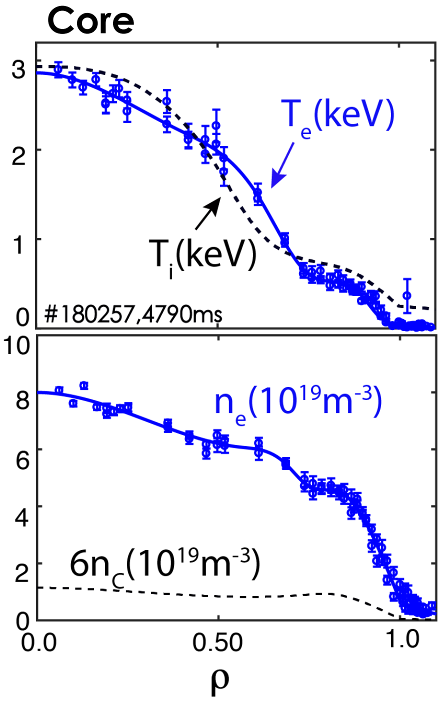
High-β_p Scenario with an Internal Transport Barrier can Obtain Feedback Controlled Detached Conditions without Reducing Core Performance



- β_n~3, β_p>2, H_{98}~1.5, q_{95}~8

See L. Wang (Monday 12.50)





Strong Pedestal and AT Programs of DIII-D Enable Relevant Physics Studies for Pedestal-Divertor Integration and Mantle Radiation

- Strong shaping opens access to peeling limited pedestals at high density, including super H-mode
- AT program enables studies of mantle radiation physics with DEMO or pilot plant relevant normalized core parameters
- Studies of high β_P scenario with an ITB can obtain a feedback controlled detached conditions without core degradation
- **New diagnostic tools in DIII-D divertor constrain concentrations of emitting impurities, enabling validation of divertor radiation scalings**

Radiative Divertor Scaling based on Simple SOL Models Predict High SOL Impurity Concentrations for Reactor Scale Devices

	C-Mod	ASDEX-U	JET	ITER	FNSF ($A = 4$)	EU Demo1
P_{sep}	3.83	10.7	14	100	96	154.7
B_{t}	5.47	2.5	2.5	5.3	7.0	5.7
R_0	0.7	1.6	2.9	6.2	4.5	9.1
P_{sep}/R	5.5	6.7	4.8	16.1	21.3	17.0
$P_{\text{sep}}B_{\text{t}}/R$	29.9	16.7	12.1	85.5	149.3	96.9
I_{p}	0.82	1.2	2.5	15	7.5	20
a	0.22	0.52	0.90	2.00	1.13	2.94
κ_{95}	1.51	1.63	1.73	1.80	2.10	1.70
$\langle B_{\text{p}} \rangle$	0.58	0.34	0.39	1.03	0.81	0.98
q_{cyl}	3.78	3.16	2.79	2.42	3.55	2.62
n_{GW}	5.39E + 20	1.44E + 20	9.82E + 19	1.19E + 20	1.89E + 20	7.39E + 19
Projected c_{N} for detachment	1.0%	4.0%	4.1%	10.1%	8.6%	18.8%

R.J. Goldston, *et al. Plasma Phys. Cont. Fusion* **59** (2017) 055015

Compatibility challenge with pedestal and core!

Radiative Divertor Scaling based on Simple SOL Models Predict High SOL Impurity Concentrations for Reactor Scale Devices

	C-Mod	ASDEX-U	JET	ITER	FNSF ($A = 4$)	EU Demo1
P_{sep}	3.83	10.7	14	100	96	154.7
B_t						5.7
R_0						9.1
P_{sep}/R						7.0
$P_{sep}B_t/R$						6.9
I_p						20
a						2.94
κ_{95}						1.70
$\langle B_p \rangle$						0.98
q_{cyl}						2.62
n_{GW}						E + 19
Projected c_N for						8.8%

But these predictions are based on Lengyel integral, simple SOL model.

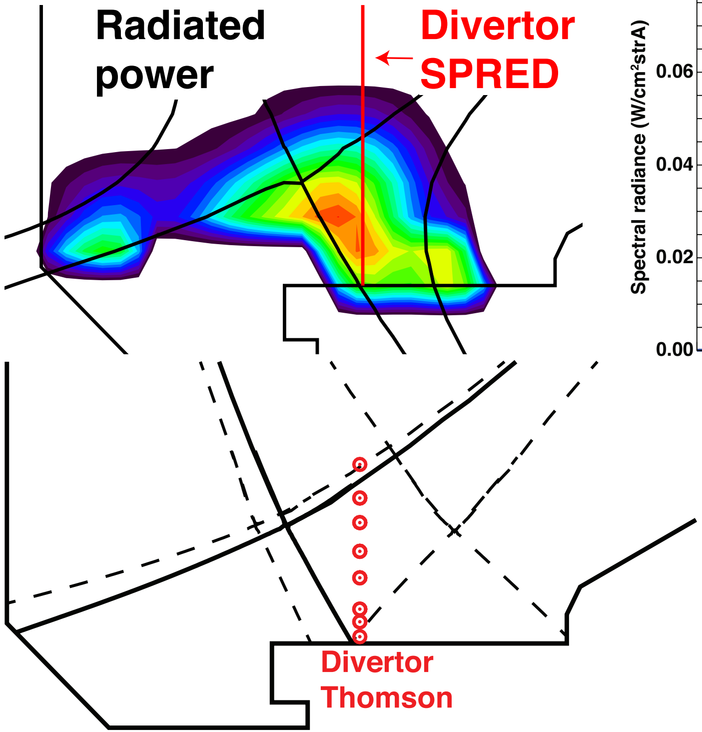
To validate impurity concentration scalings in radiative divertor, we need capability to measure the impurity concentration in the relevant location (radiation front)

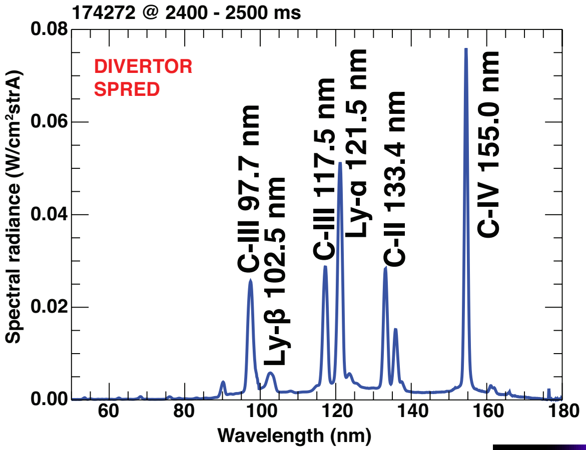
See S.S. Henderson, et al. Nucl. Mat. Ene. **18** (2019) 147-152 (and NEXT TALK)

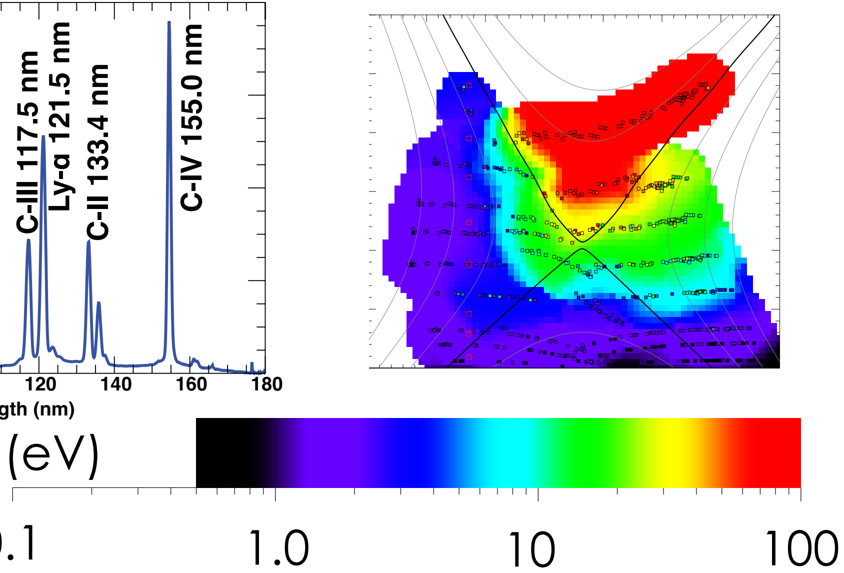
055015

Compatibility challenge with pedestal and core!

Divertor Thomson Scattering and SPRED enable Measurement of Concentrations of the Dominant Emitting Species in the Radiative Front







- **Scaling of divertor impurity concentration required for detachment at various P_{INJ} and n_e levels to be investigated**
  - A.G. McLean, ITPA DivSOL January 2020 and PSI 2020

Strong Pedestal and AT Programs of DIII-D Enable Relevant Physics Studies for Pedestal-Divertor Integration and Mantle Radiation

- **Strong shaping opens access to peeling limited pedestals at high density, including super H-mode**
  - Promising resilience of the super-H pedestal to divertor cooling
- **AT program enables studies of mantle radiation physics with DEMO or pilot plant relevant normalized core parameters**
  - P_{SOL} can be controlled by mantle radiation, but core tearing modes emerge at high β_N
- **Studies of high β_P scenario with an ITB can obtain a feedback controlled detached conditions without core degradation**
  - If the scenario does not depend on a strong pedestal, detaching the divertor is not as challenging for the integration
- **New diagnostic tools in DIII-D divertor constrain concentrations of emitting impurities, enabling validation of divertor radiation scalings**