Integration of the High-β_N Hybrid Scenario to a High Performance Pedestal, Stable Zero Torque Operation and a Divertor Solution

by

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PPPL PRINCETON PLASMA PHYSICS LABORATORY

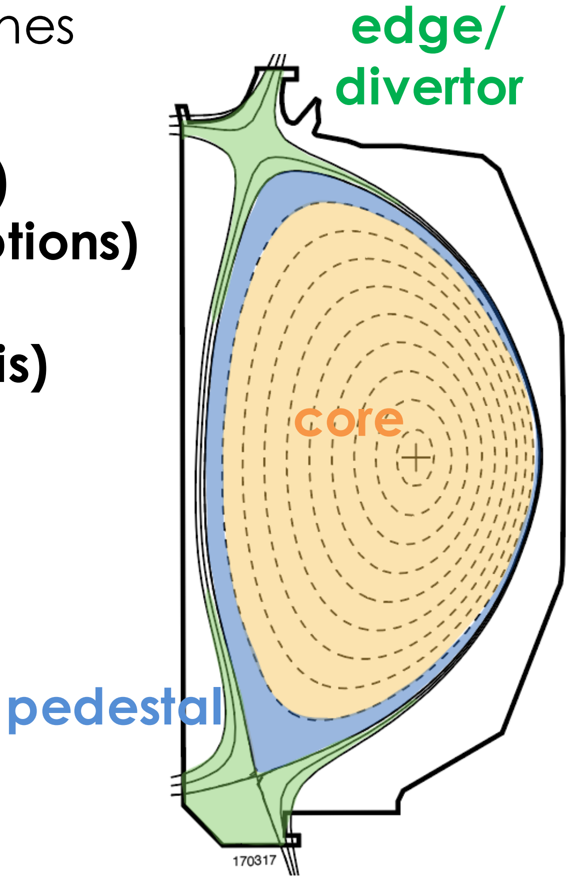
Columbia University

Ingredients for a fusion power plant

Projection to steady-state reactor operation requires integration of core and edge physics in present machines

- Core
  - High fusion power, high gain, f_{NI}~1 (β_T, τ_E, H_{98y2})
  - 2/1 tearing stable (for performance, not disruptions)
  - Low rotation → Low injected torque
  - Compatible with H&CD schemes (on- & off-axis)

- Pedestal and edge/divertor
  - Low heat and particle flux to divertor
  - Low heat to first wall/blanket
  - No ELMs or small-ELM regime



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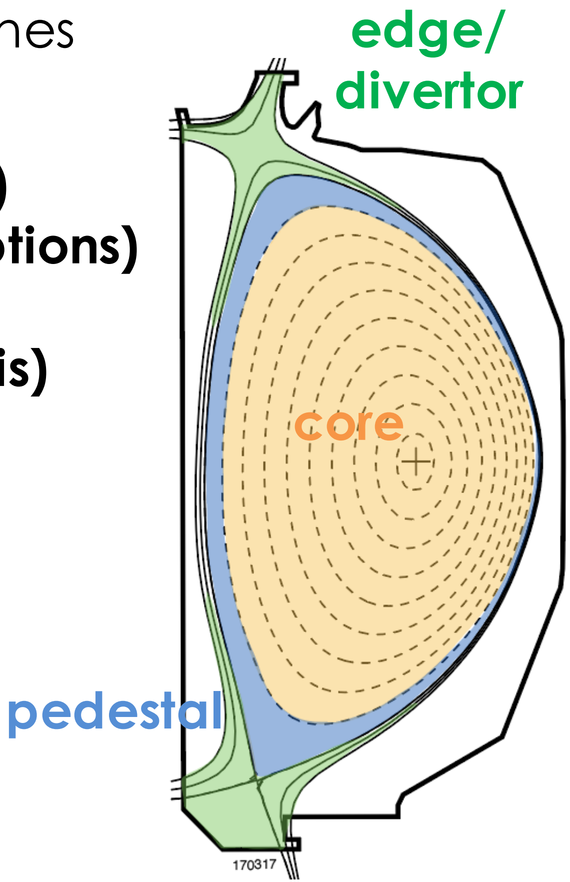
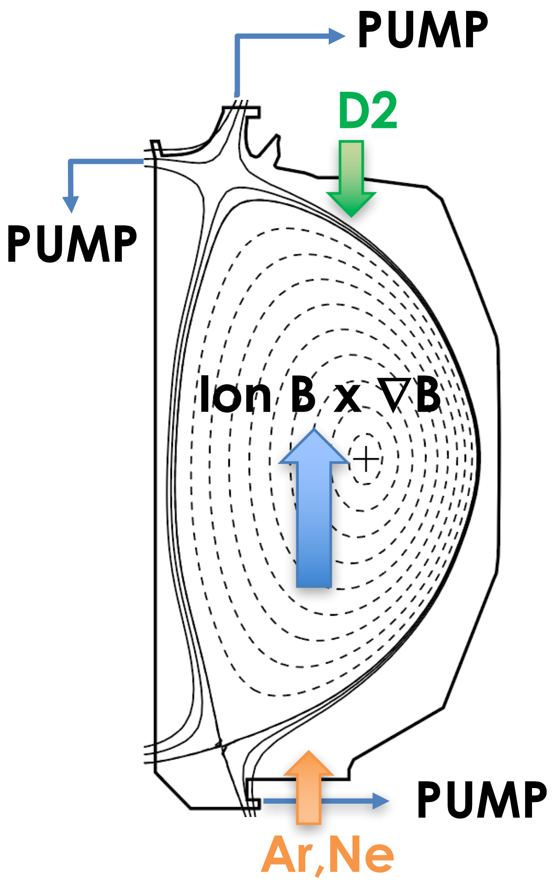


The high-β_N hybrid scenario is an attractive option for steady-state and core-edge integration work

Hybrid scenario = high power, $\beta_N > \beta_{no\text{-}wall}$, no sawteeth, q_{min}~1, ITER $Q_{projection}$~4-5



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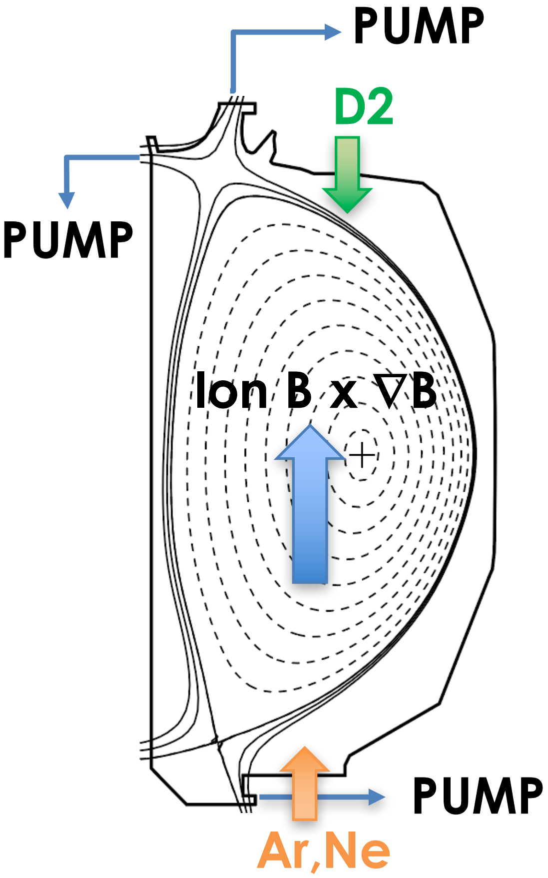
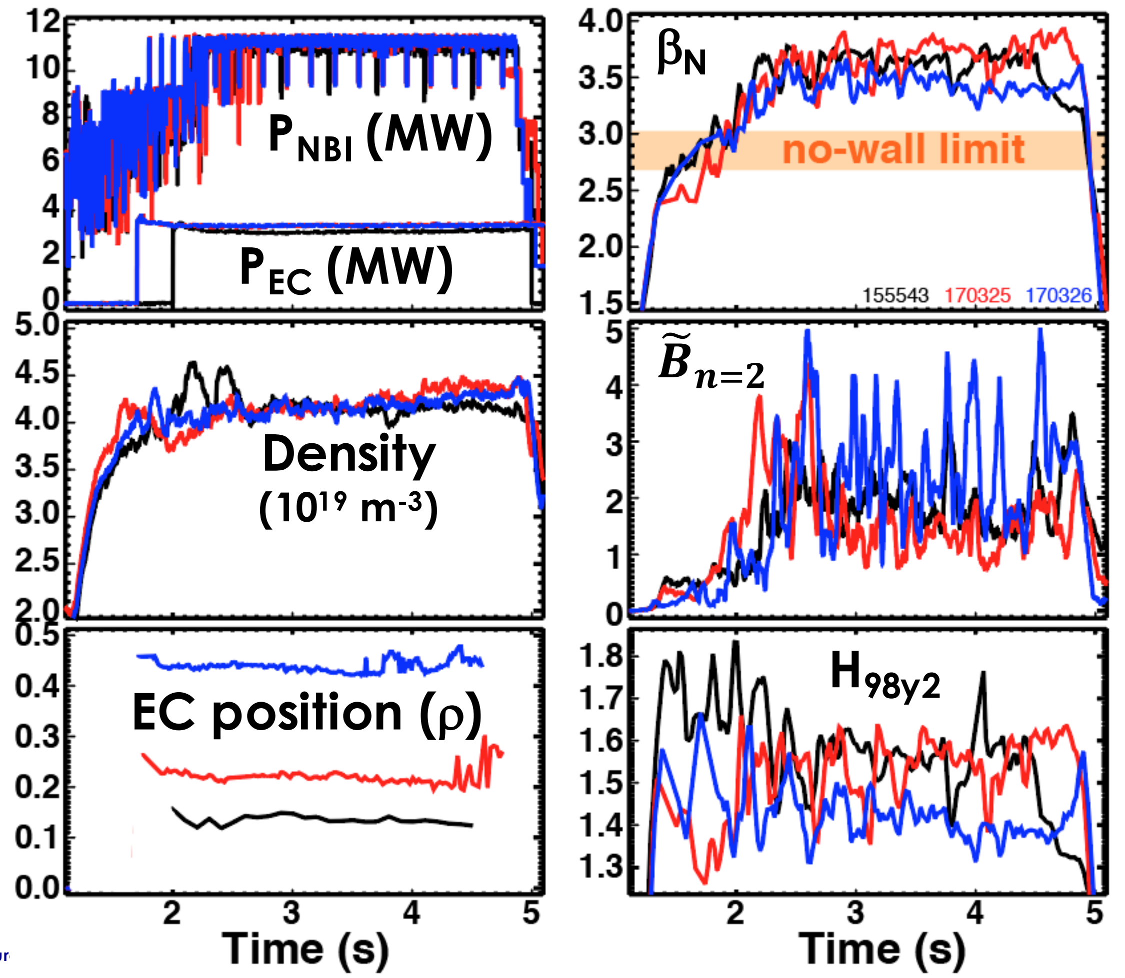
- **ECH: varied deposition and injection angle for CD vs heating and compatibility with high density operation**
- **NBI: mix co- and ctr-I_p injection for low and balanced torque**
- **D_2 puff for radiating divertor operation**
- **Ar and Ne injection for radiating mantle**



Highly reproducible high-β_N hybrid plasmas modified for radiating divertor/mantle solution

- $P_{TOT} = P_{NBI} + P_{EC} = 11.2 + 3.4 = 14.5$ MW
- $\beta_N \sim 3.6 \sim 0.8 \times \beta_{lim}$; $H_{98y2} \sim 1.4\text{-}1.6$

- ρ_{EC} varied from 0.14 to 0.65
- Torque varied from 9 to 0 Nm (at lower input power)



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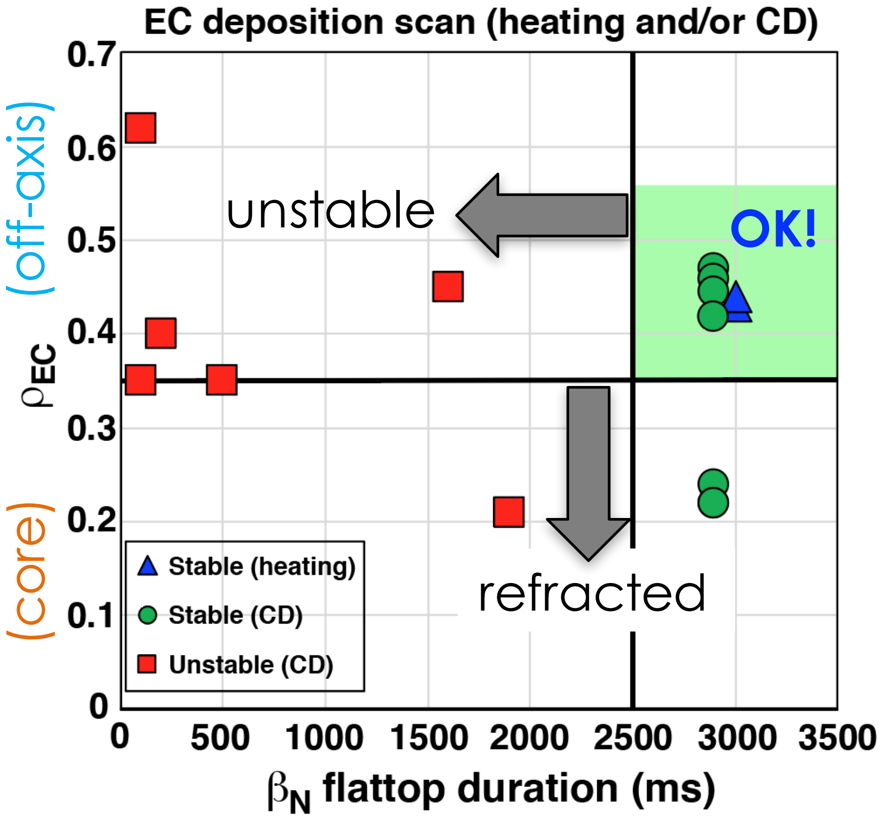
Moving EC power off-axis has consequences on both stability and confinement

- **Off-axis EC is deposited in lower density region → less susceptible to wave refraction**

ρ_{EC}<0.35 → mostly stable, but potentially refracted

ρ_{EC}=0.45 (radial) → more reproducibly stable than current drive (tangential)

Sweet spot ρ_{EC}=0.45, without CD



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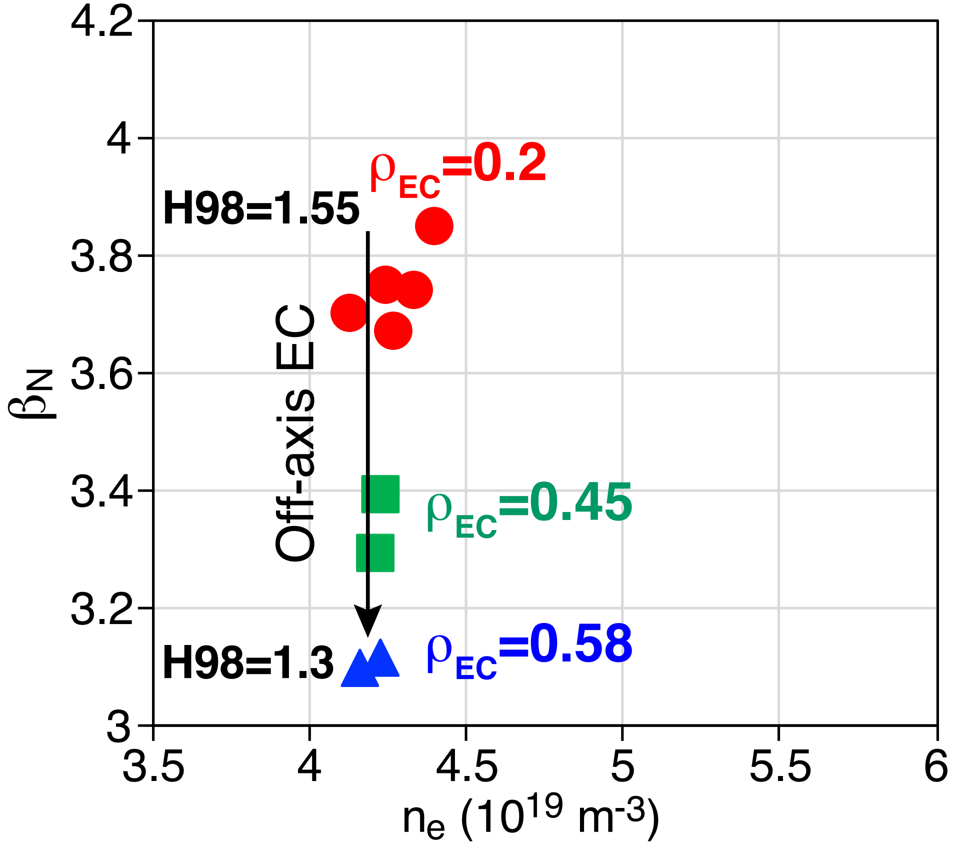
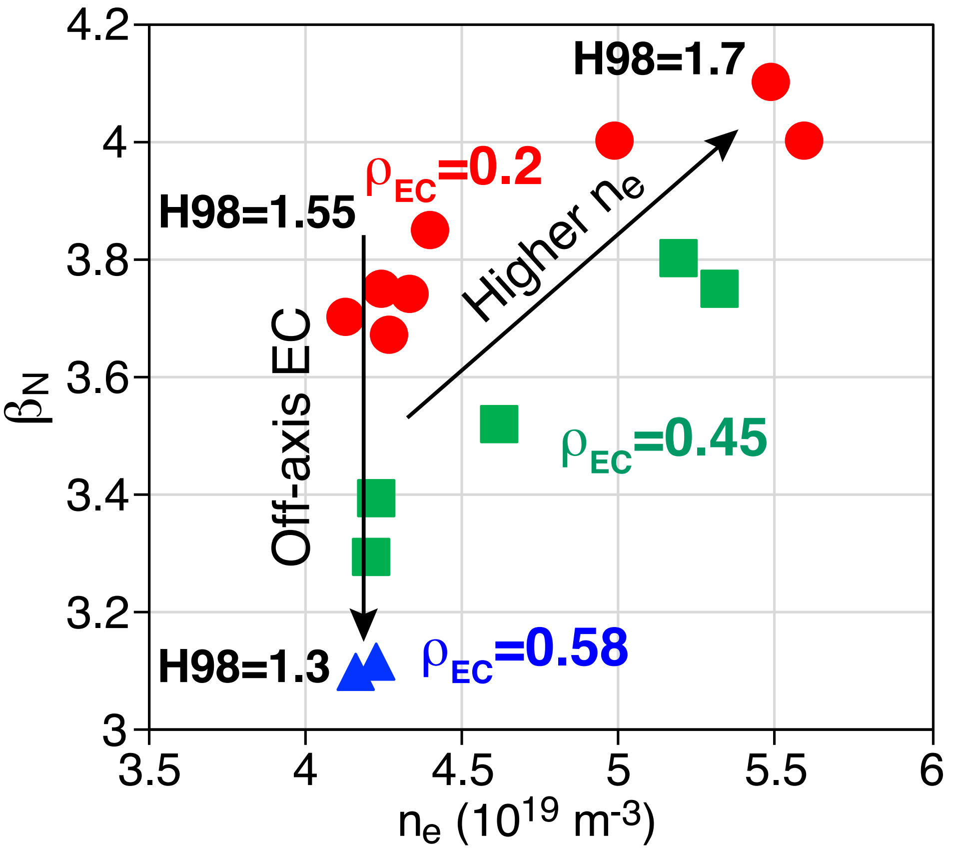
Moving EC power off-axis has consequences on both stability and confinement

- **Off-axis EC deposition, at fixed density → lower heating efficiency → lower β_N, H_{98y2}~1.6→1.3**



Moving EC power off-axis has consequences on both stability and confinement

- Off-axis EC deposition, at fixed density → lower heating efficiency → lower β_N, H_{98y2}~1.6→1.3
- Higher density, at fixed power and ρ_{EC} → recover high confinement (H_{98Y2}~1.7), exceeds β_N=4



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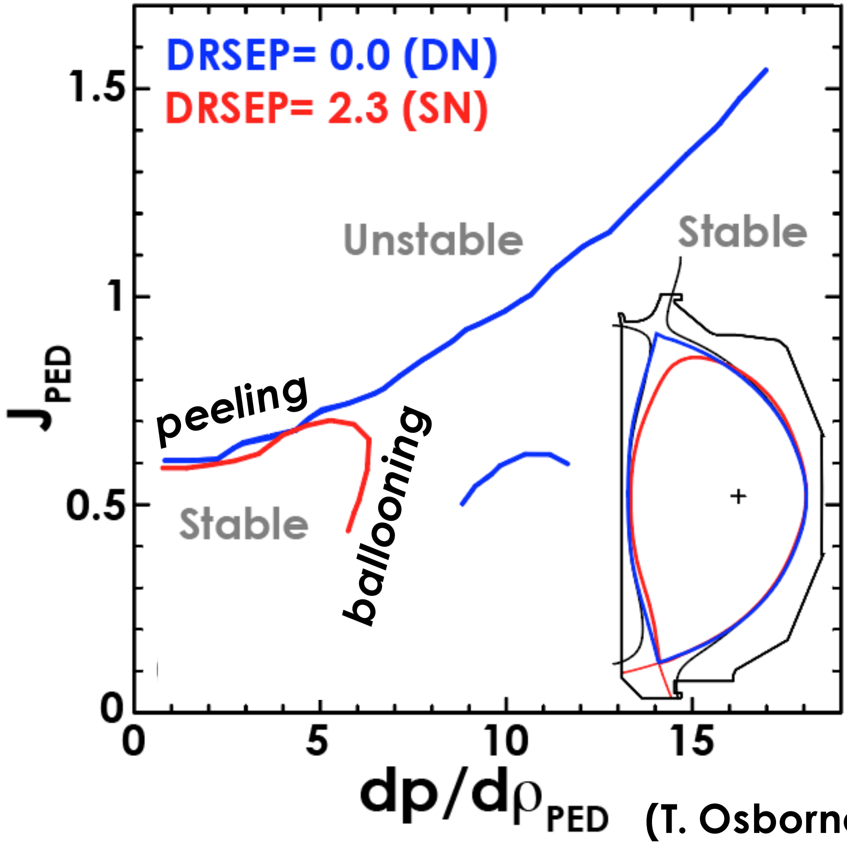
At high power, the pedestal rises with density → leads to enhanced confinement regime

Confinement increases with density because of pedestal changes:

- **Peeling-ballooning branches decouple → critical ∇p increases along the peeling branch → higher pedestal**

- **ELITE (pedestal stability) simulations predict this for q_{95}>5.7, dRsep<1 cm, and high power**



(T. Osborne)

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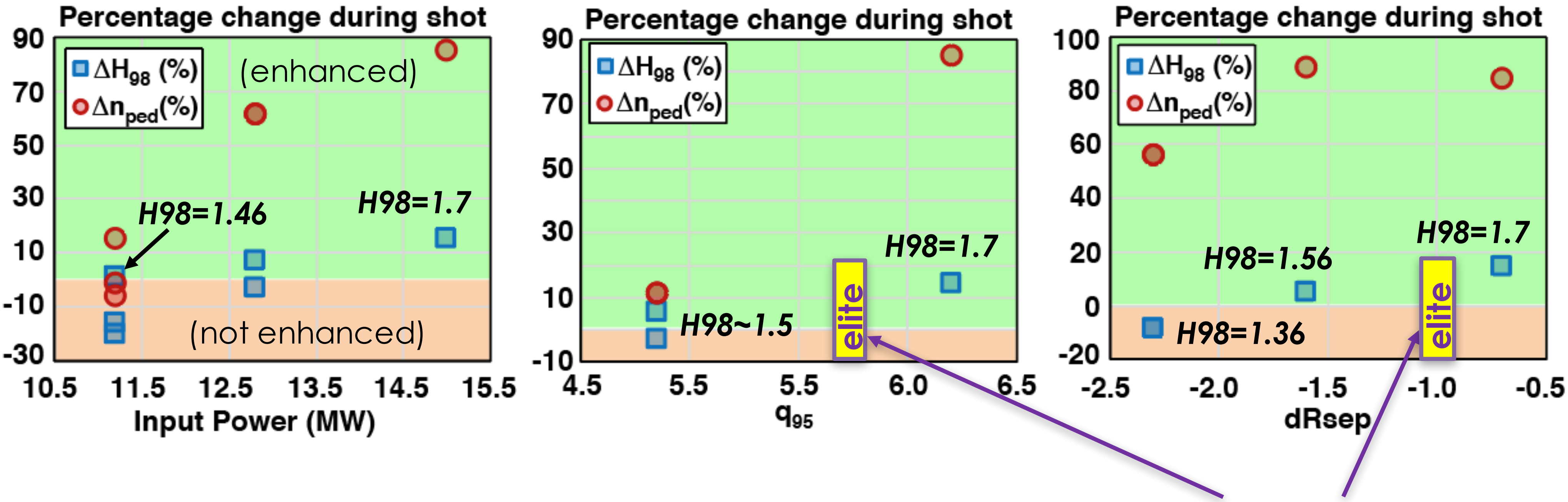
New experiments explored operational space with shaping and power variations

- **Enhanced confinement regime occurs with P≥12 MW, q_{95}>5.5, dRsep<|1.5| cm**



- Experimental dRsep range is slightly wider than **ELITE predictions**

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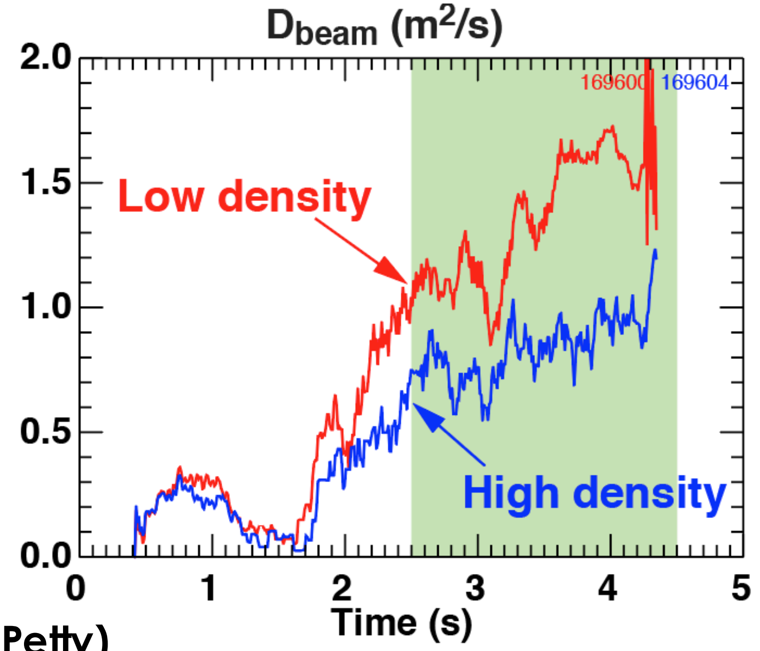
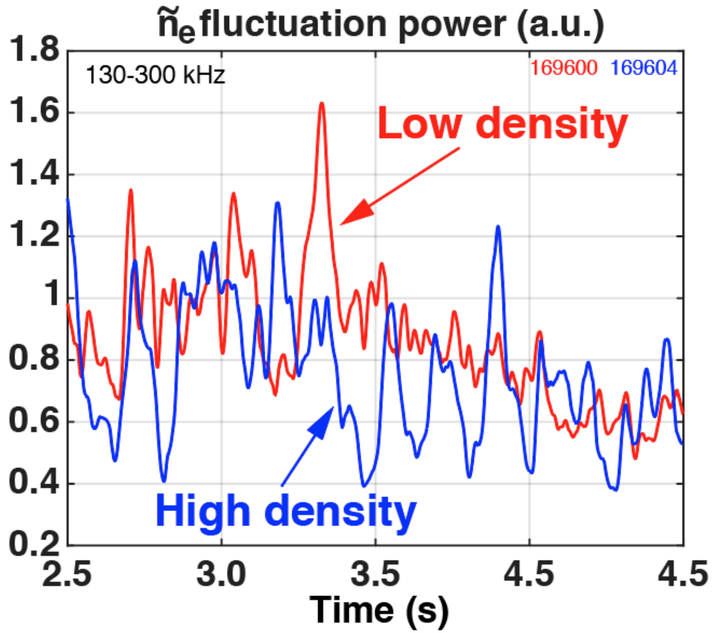
Higher fast-ion losses from the core contribute to decreased confinement at lower density

Anomalous fast-ion diffusion coefficient inferred by reproducing neutron rate



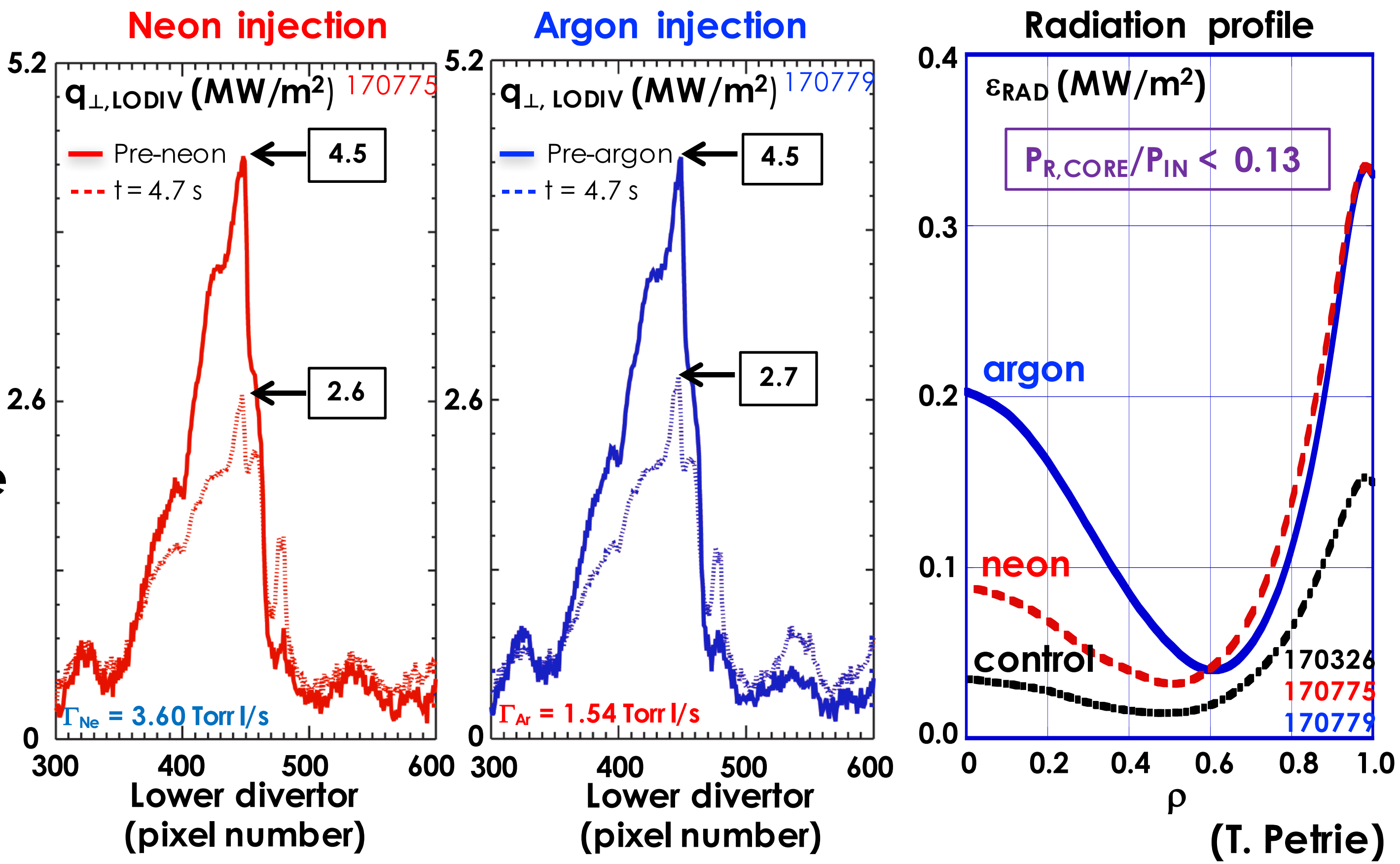
(C. Petty)

Consistent with density fluctuation measurements in the f_{TAE} range



Ne and Ar injection for radiating mantle → 40% divertor heat flux reduction achieved

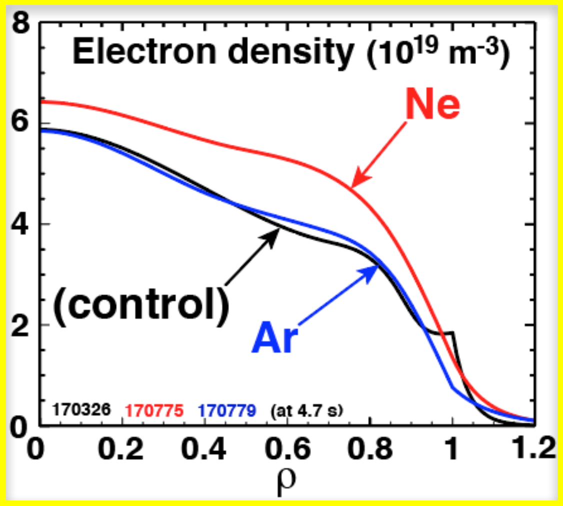
- Main chamber injection
- Similar results with PFR injection
- Core power balance is not a problem ($P_{rad,core}$~13%)



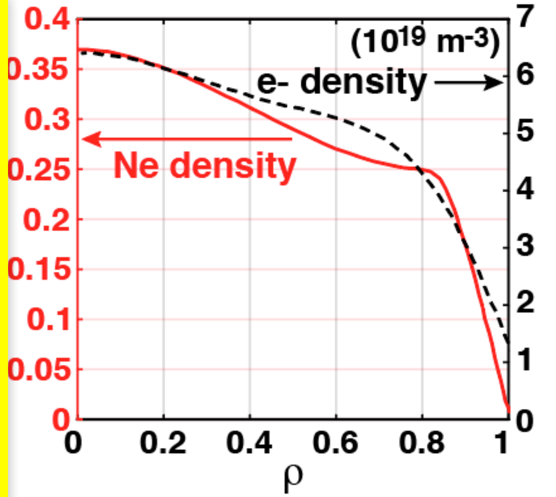
(T. Petrie)

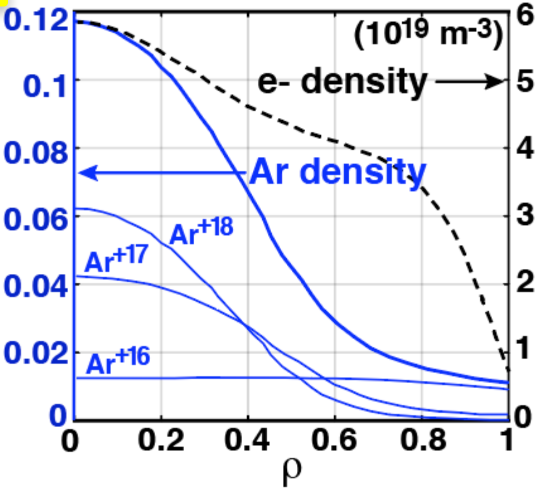
Choice of impurity leads to different core density and profile peaking factor

- **Ne** is fully stripped → **2.3x larger flow for same heat flux reduction** → **higher core electron density**



(B. Grierson and T. Petrie)





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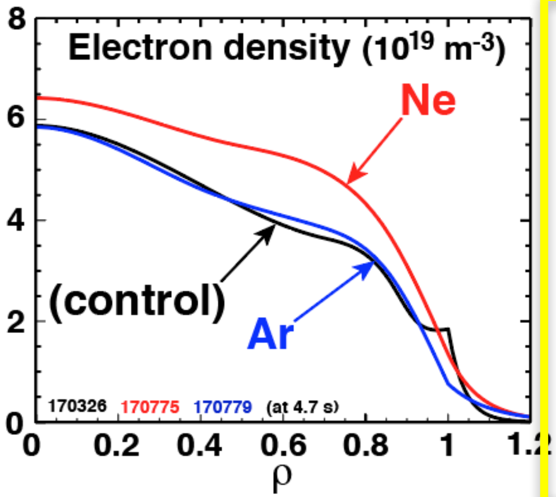
- **At high density and Ne flow,** **Ne profile is as flat as e^- profile**



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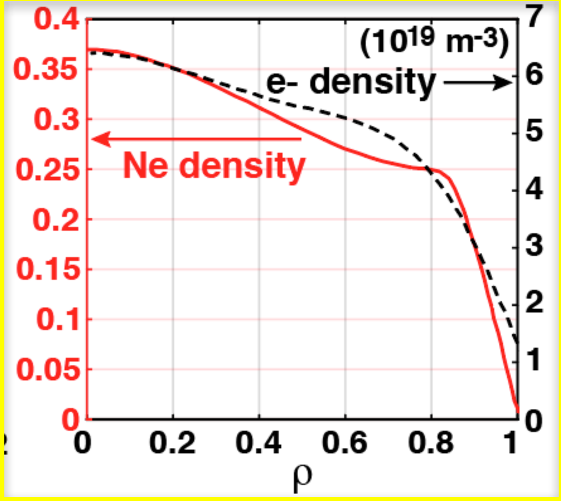
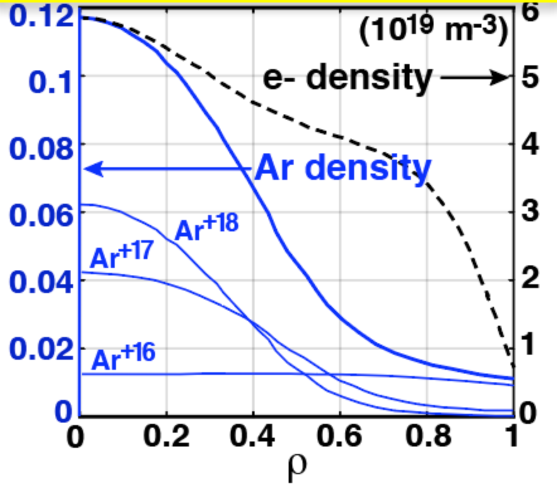
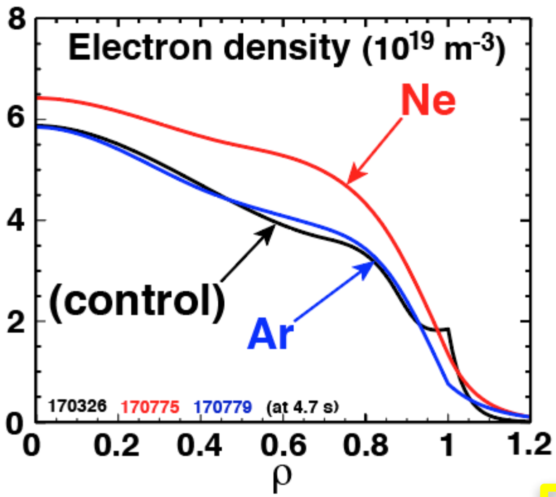
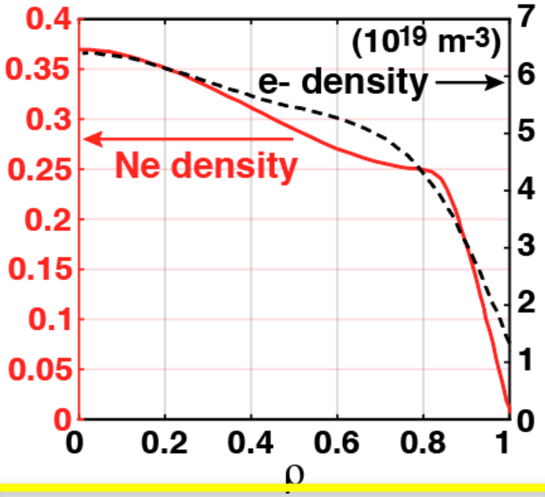




Choice of impurity leads to different core density and profile peaking factor

- Ne is fully stripped → 2.3x larger flow for same heat flux reduction → higher core electron density
- At high density and Ne flow, Ne profile is as flat as e^- profile
- **Ar profile is much more peaked** **(lower n_e, Ar flow)**





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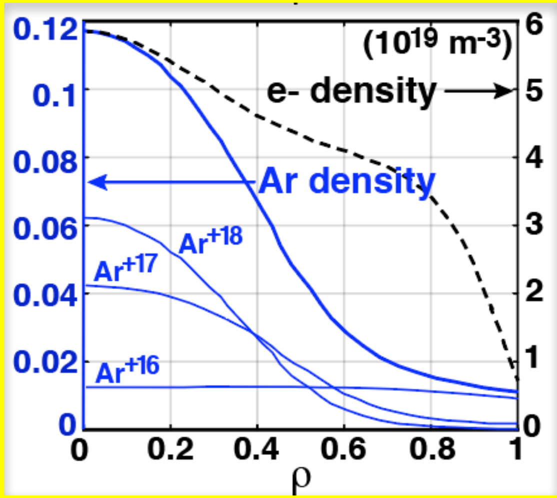

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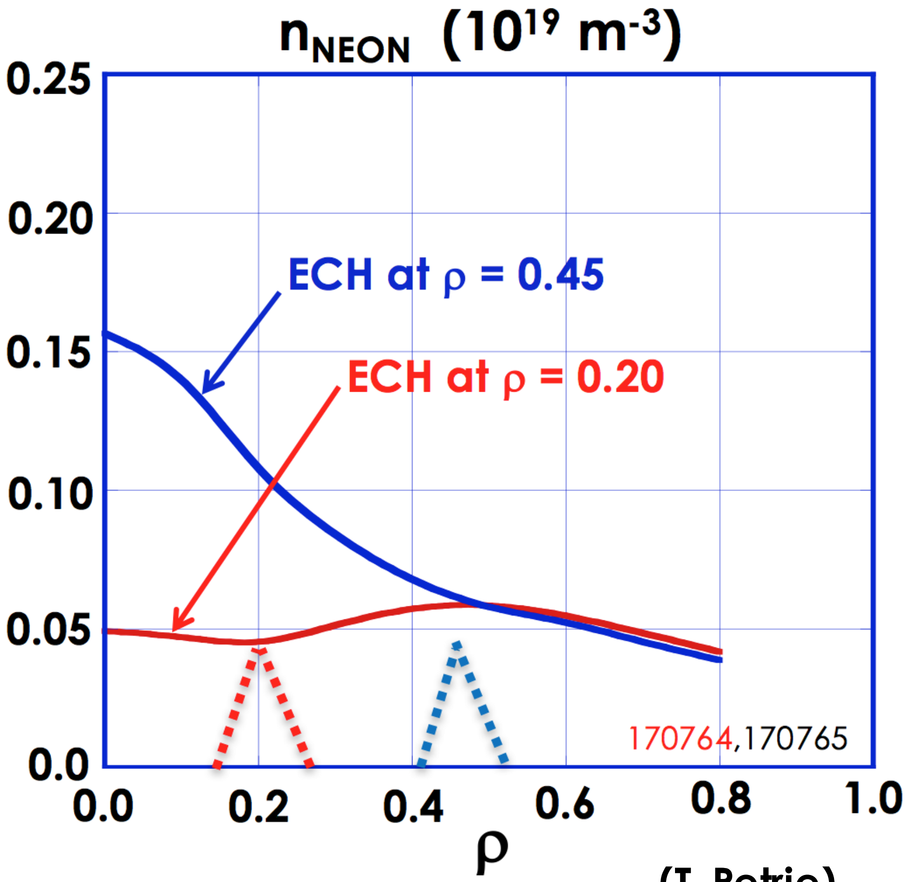
At lower density, off-axis EC leads to core impurity accumulation

- Off-axis EC leads to core accumulation for impurities and C alike
  - ➢ Core dilution becomes a problem

- On-axis EC injection avoids the core accumulation

- Expands DIII-D tungsten ring campaign and AUG results to high β_N, high power

- Similar results with PFR or main chamber injection



(T. Petrie)

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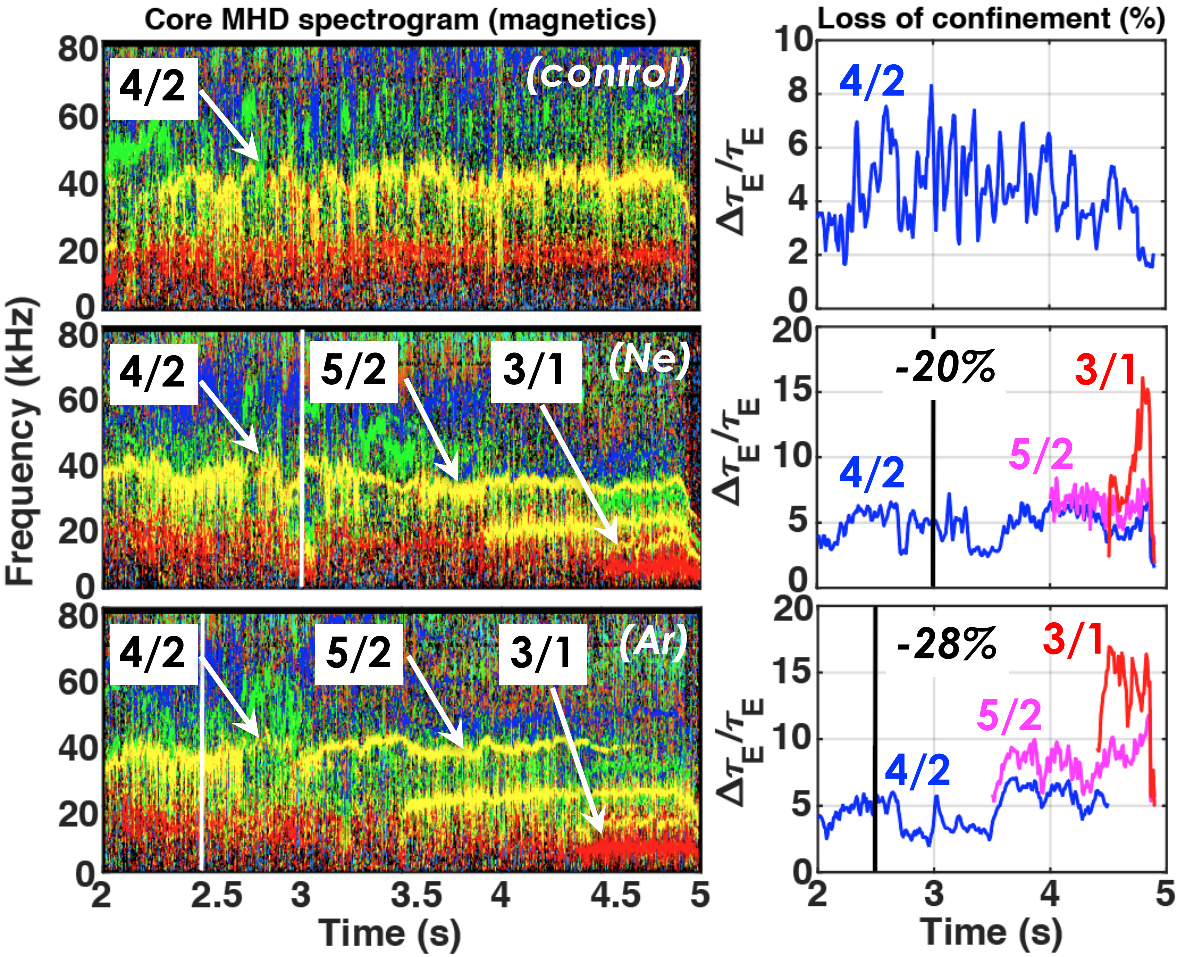
Impurity core accumulation is associated with deleterious tearing modes

- Series of n=2 and n=1 core instabilities appear with larger injection rates (Ar, Ne)
- Same effect with C from dome tiles → divertor leakage can be an issue



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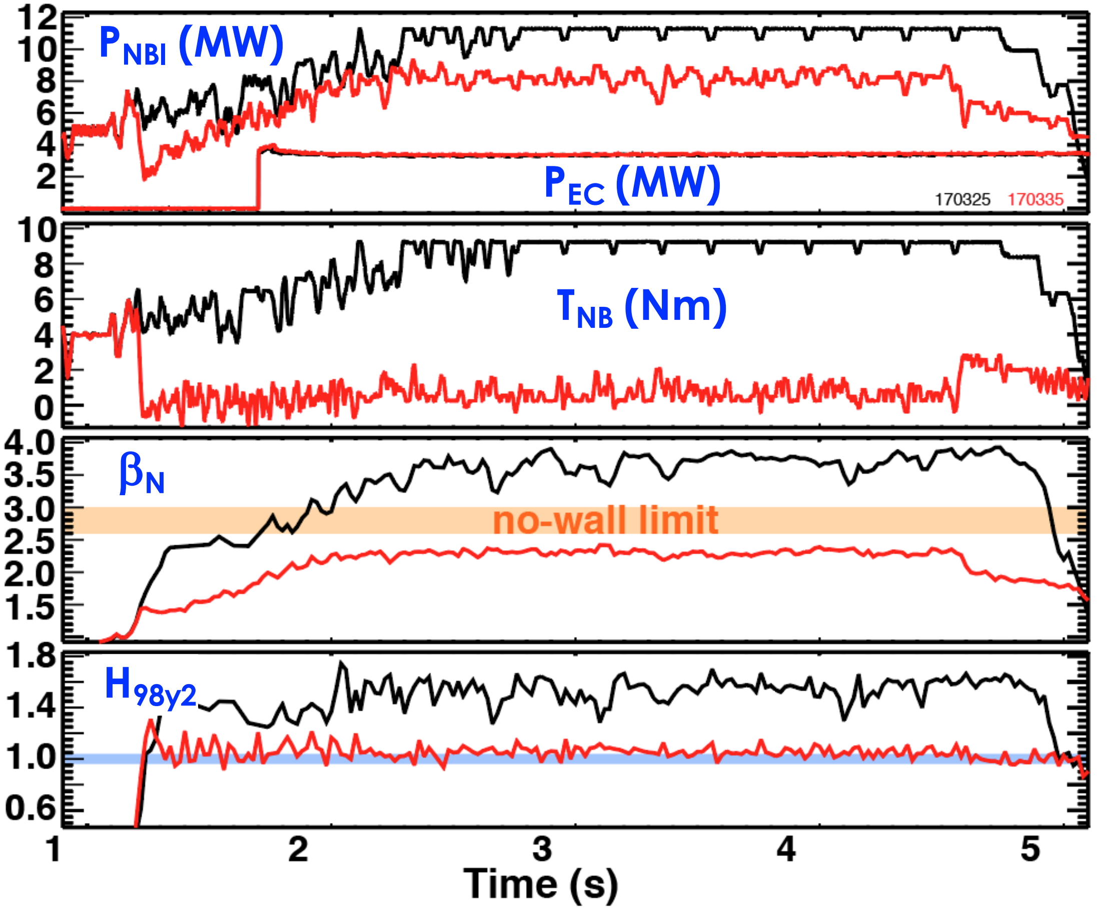
Stable hybrid plasmas obtained at zero injected torque

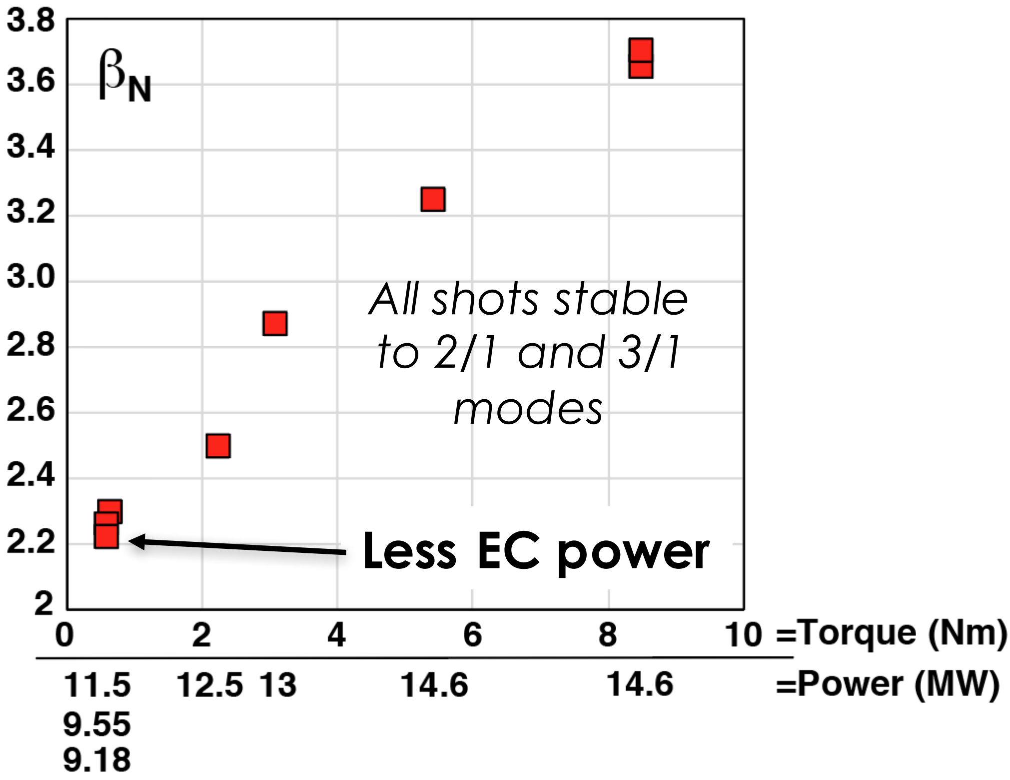
- Torque=0 Nm uses P_{ctr}~4 MW + P_{co}~4 MW → lower β_N achieved
- All shots stable to deleterious 2/1 or 3/1 modes
- ECCD at ρ_{EC}~0.22



Passively stable hybrid plasmas obtained, without EC stabilization

- Zero torque plasmas remain stable when P_{EC} is reduced to ~0.5 MW
- No need for ECCD stabilization because of higher MHD limits:

→ Higher q_{95}~5.7-6 → higher ideal and resistive MHD limits than q_{95}~4, β_N~2.5 AI plasmas [Solomon2013]



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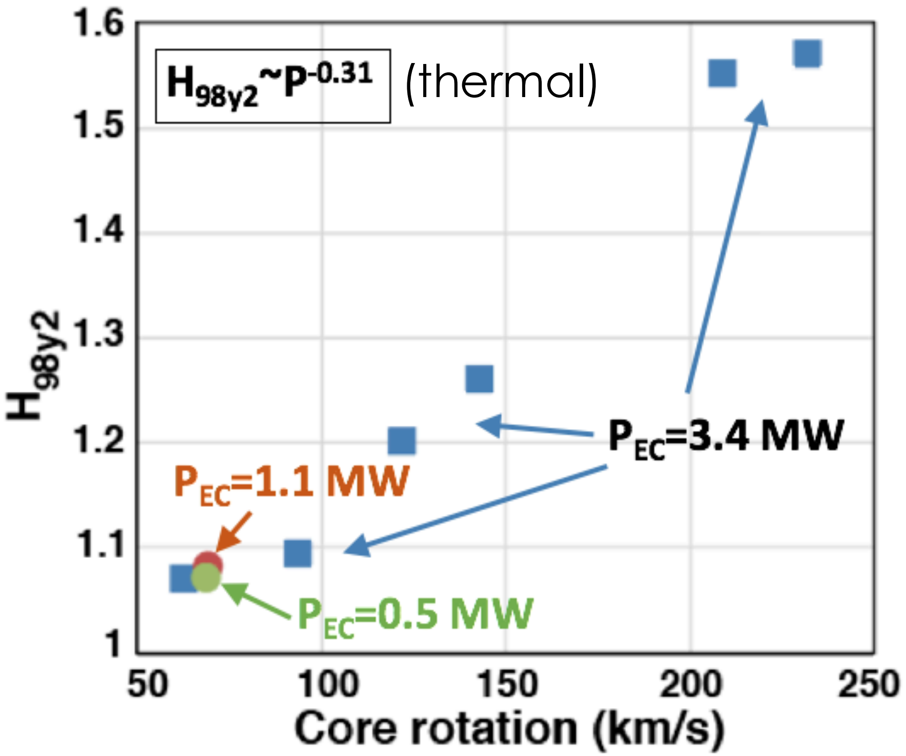
H_{98y2} decreases with lower core rotation – stays above normal H-mode confinement

- **Same β_N~2.3, H_{98y2}~1.07 without EC power**



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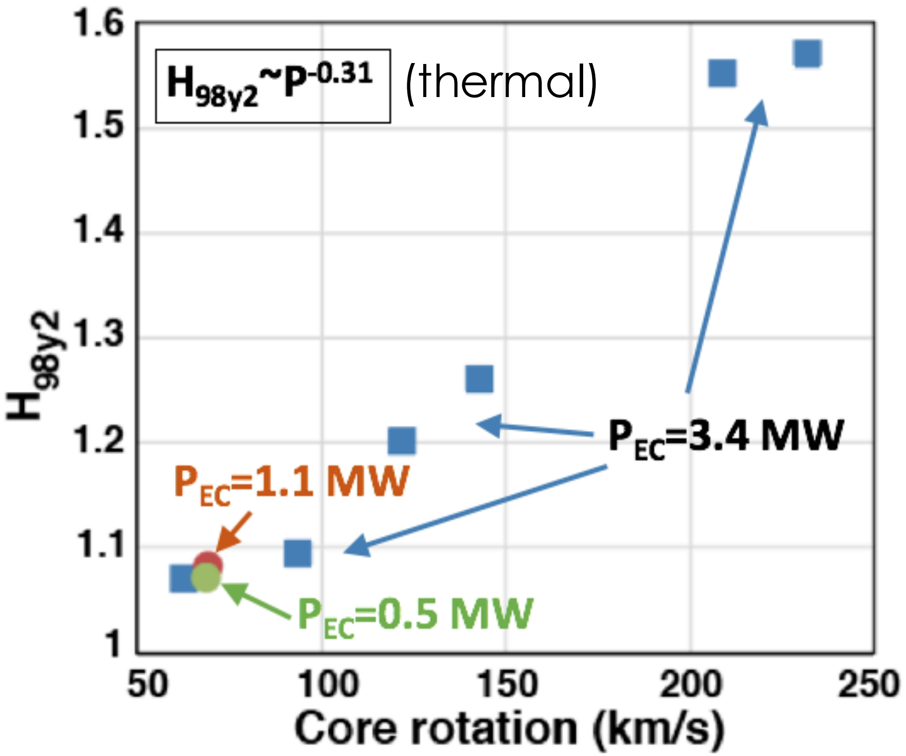
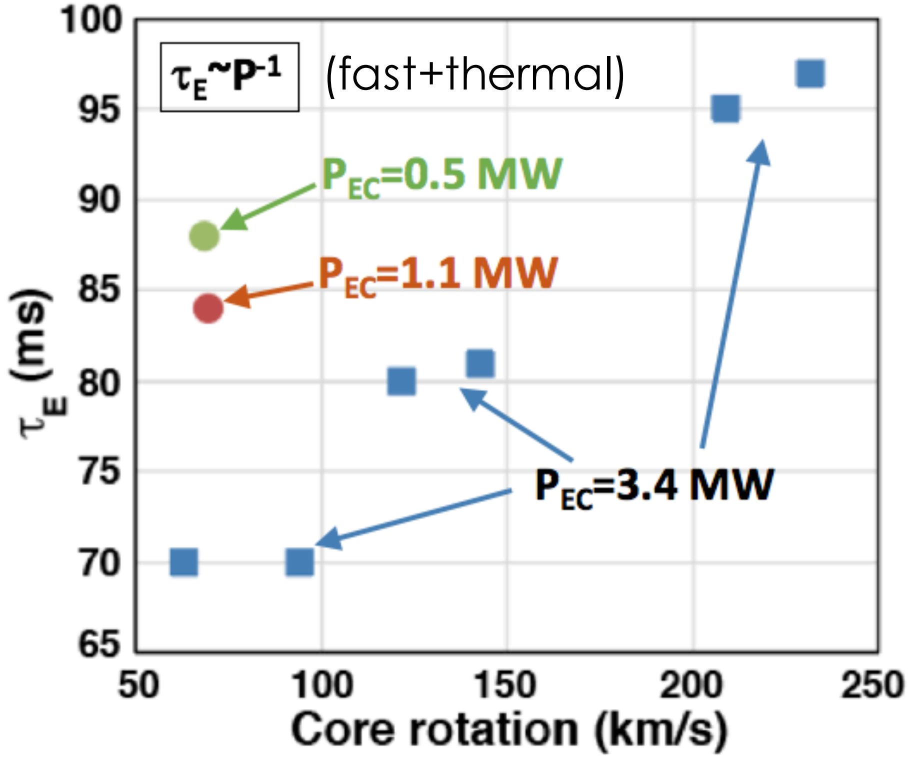


- τ_E recovers 90% of the high Ω confinement without EC power



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Summary and lessons learned

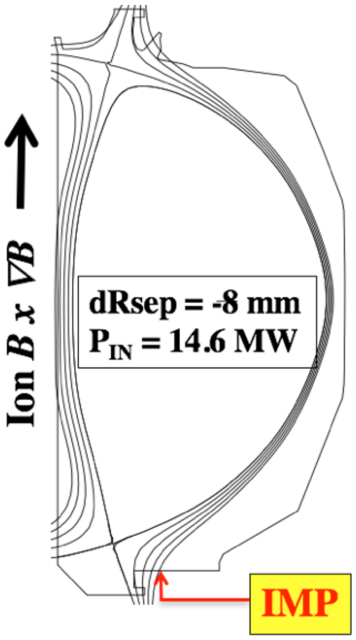
- **Achieved H_{98y2}=1.5-1.7, β_N=3.7-4.2, P_{inj}=15 MW**
  - At high-β_N, low-Z impurity accumulation can become a serious issue
- **Achieved passively stable zero torque hybrid plasmas at β_N~2.3**
  - Confinement decreases at low rotation, but remains > normal H-mode
- **Enhanced pedestal increases confinement at high power (H_{98}~1.7, β_N~4)**
  - Highly shaped, balanced DN equilibria are an attractive option for radiating divertor high-power operation
- **Ar, Ne injection reduce the divertor heat flux by ~40%, with costs for the core performance**
  - Central ECH with O-mode, higher MHD limits with shape optimization

Thank you for your attention

The secondary divertor plays a non negligible role in impurity distribution

- Ne pumped from both divertors, Ar mostly from upper (secondary) divertor

- Ar ionization mean free path is 1/10 of Ne
→ ionized on flux surfaces directly connecting to the upper divertor



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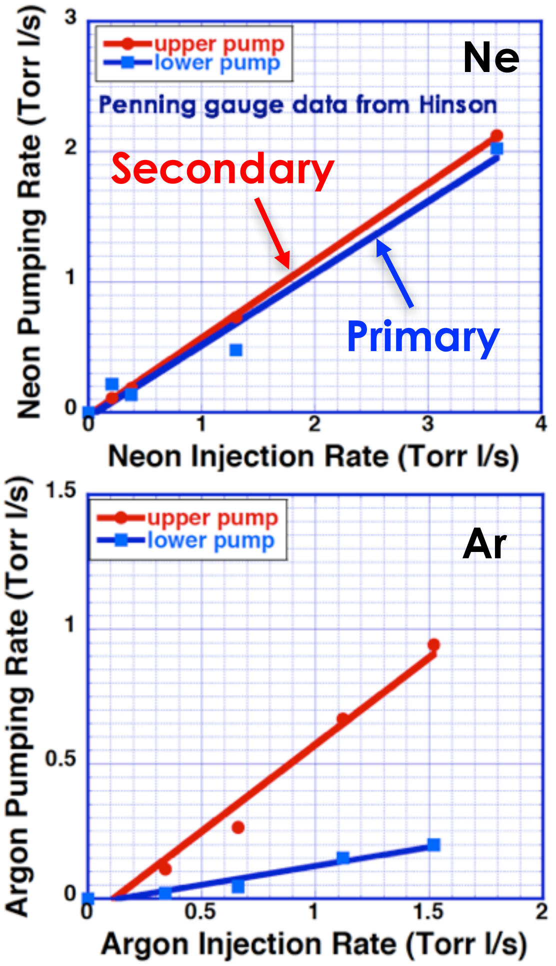

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