Core-Pedestal Constraints on Divertor Design

By

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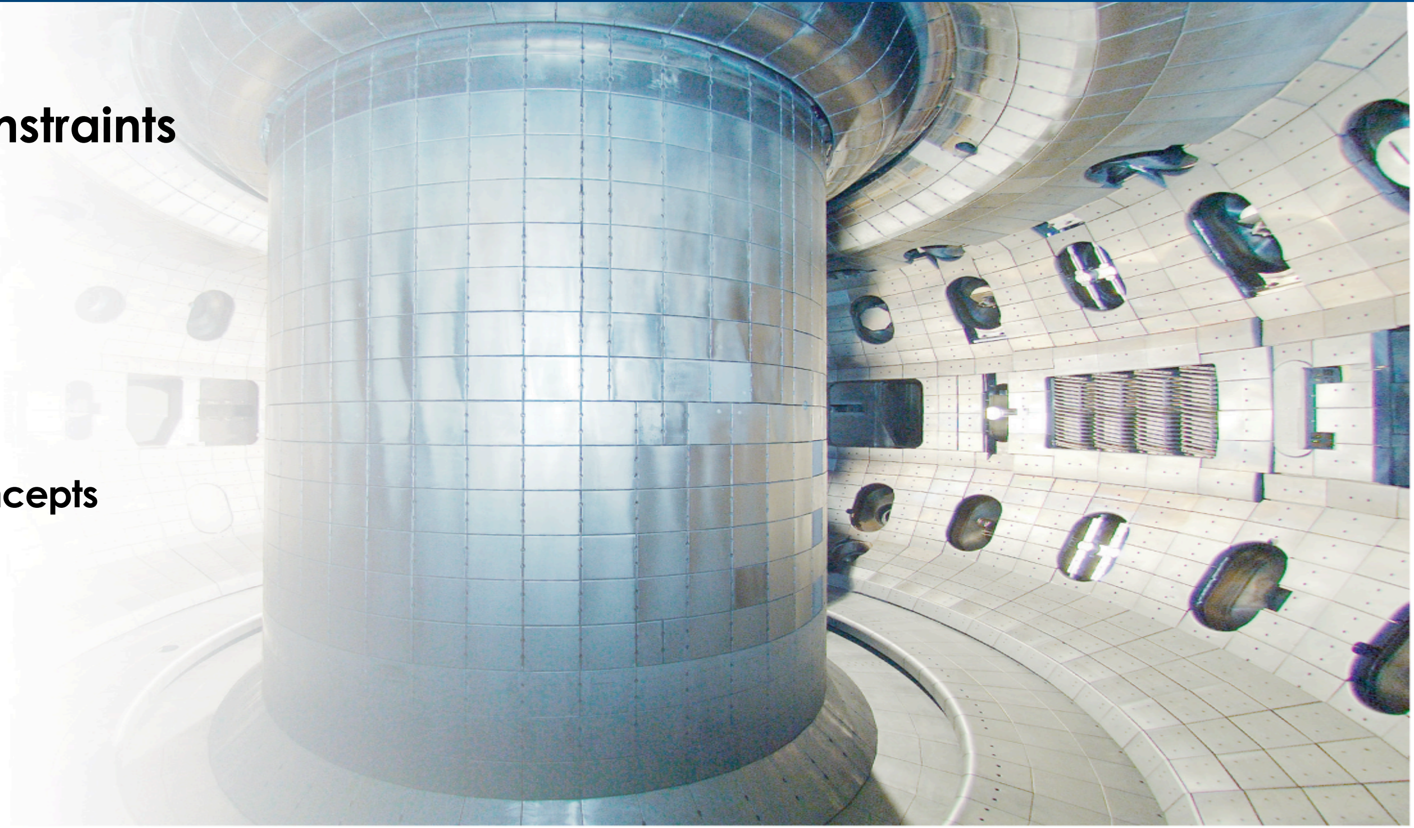

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Upstream (midplane) constraints critical to improved confidence in future divertor design

- **Divertor design must simultaneously accommodate core plasma as well as divertor target constraints**
  - Divertor: $q_{\perp} \leq 10$ MWm^{-3}, $T_e \leq 5$ eV, no transients (ELMs)
  - Core: High confinement, High β, etc.
- **Divertor dissipation nonlinearly dependent on upstream boundary conditions; $q_{||}$, n_{sep}, f_{imp} (radiator)**
  - $T_{div} \propto \frac{q_{\|}^{10/7}}{n_{sep}^2 L_{\|}^{4/7}} \frac{(1-f_{rad})^2}{(1-f_{mom})^2}$, $n_{div} \propto \frac{n_{sep}^3 L_{\|}^{6/7}}{q_{\|}^{8/7}} \frac{(1-f_{mom})^3}{(1-f_{rad})^2}$, $f_{rad} \propto n_{e,div}^2 f_z$
- **Required divertor volume ($L_{\|}$), or even need for an advanced divertor configuration is dependent on prediction of upstream boundary conditions!**
- **For discussion:**
  - What is the status of predictive capability for upstream constraints?
  - What work is most urgent to improve our predictive capability?

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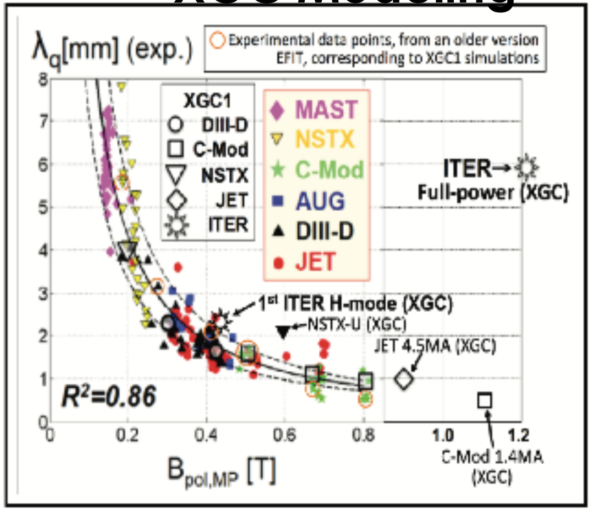
Pedestal physics a critical aspect for prediction of upstream constraints in future tokamaks

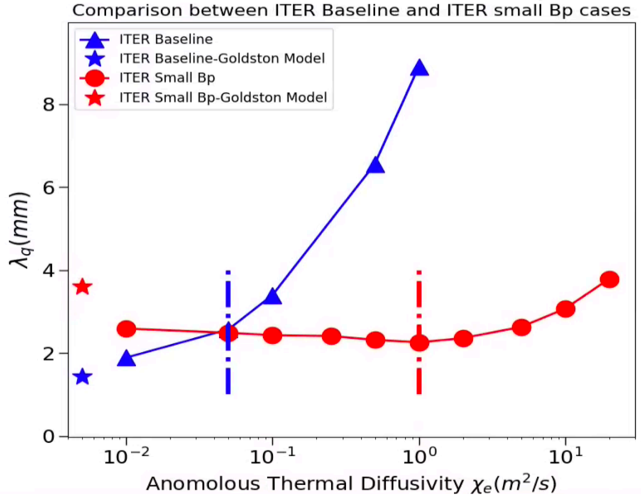
- **$q_{\|}$ at divertor entrance (SOL λ_q)**
  - Will pedestal turbulence expand SOL beyond existing λ_q scaling?
  - Will MHD stability expand SOL λ_q and/or limit upstream density?
- **Accessible values of n_{sep}/n_{ped}**
  - How does the pedestal density gradient respond to a radial ion flux?
  - What will be the core fueling rate setting the radial ion flux?
- **Tolerable upstream seeded (radiating) impurity density, $n_{imp,sep}$**
  - Maximum core n_{imp}; $P_{sep} \geq f P_{LH}$, Core MHD (NTMs), Fuel dilution
  - Accessible $n_{imp,sep}/n_{imp,ped}$ dependent on pedestal density profile
- **Other factors to consider**
  - Divertor detachment control requirements; X-point sensitivity
  - Geometry; Triangularity, Double vs. Single null

Pedestal turbulence may drive SOL width beyond existing scaling

XGC Modeling



BOUT++ Modeling



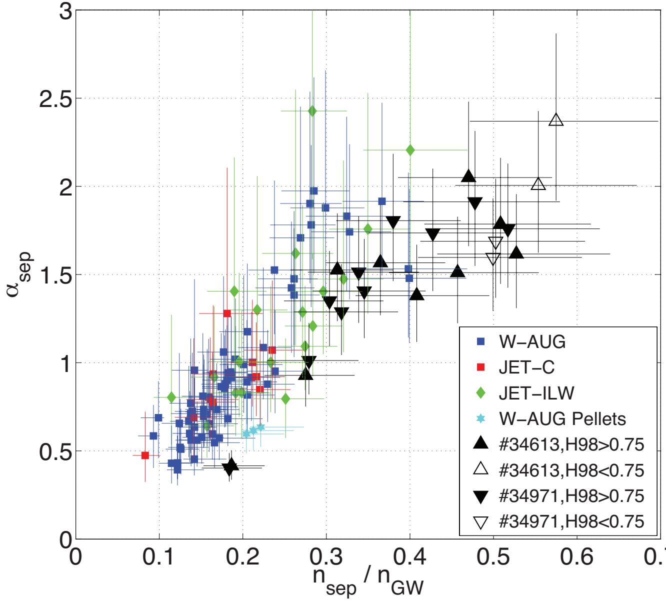
Critical scaling parameter: $B_p(a/\rho_i)$?

- **How do we validate these models in regimes in existing devices where the drift width still dominates?**
  - Scaling of turbulence characteristics?

MHD stability may be a limit for narrow heat flux width during detached conditions

- **MHD stability limit reached for n_{sep} ~$0.5n_{GW}$ derived (Eich NF 2018):**
  - ITPA λ_q scaling
  - λ_{ne}~λ_{Te}
  - α_{crit}~2.5
- **Other observations**
  - Pedestal pressure often degrades for $n_{sep} \geq 0.5\ n_{GW}$
  - SOL width increases with high density and detachment
  - SOL limits may also be correlated with collisionality

JET/AUG ∇p_{sep}

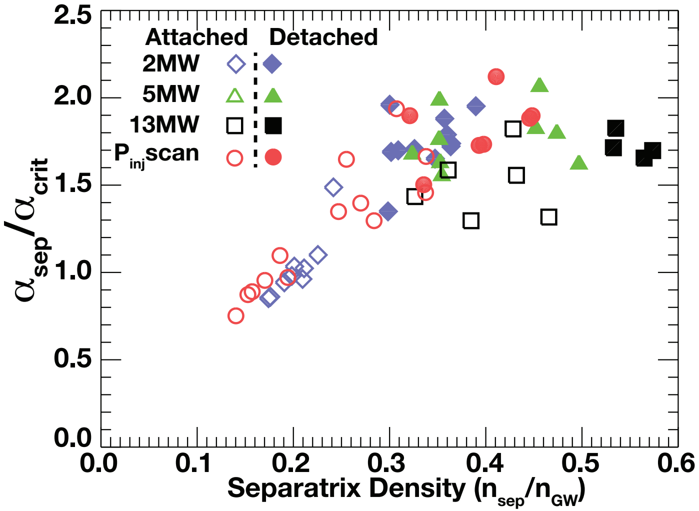


Eich, NF 2018

DIII-D finds similar ∇p_{sep} saturation at high power and high density

- **Separatrix pressure gradient saturates for $n_{sep} \geq 0.4\ n_{GW}$**
- **Normalized pedestal pressure (EPD) does not degrade at high density**
- **High α_{sep} likely due to challenging T_i measurement**
  - T_i from CVI CER compromised by edge effects near separatrix
  - Main ion T_i measurements becoming available

Normalized Separatrix Pressure Gradient
$\nabla p_{e,sep} + \nabla p_{i,sep}$



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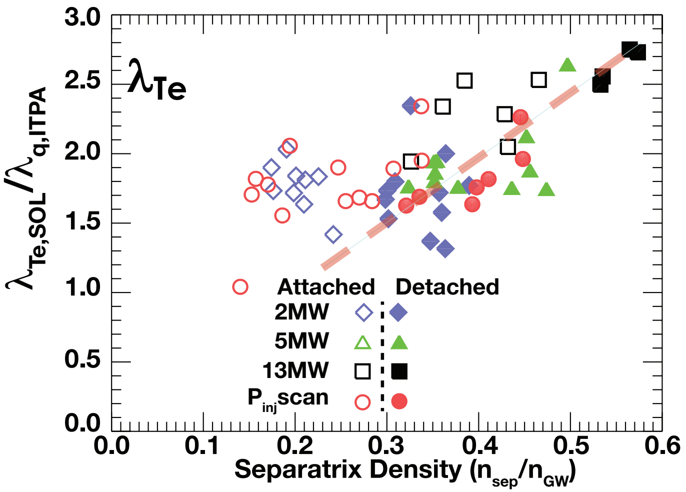
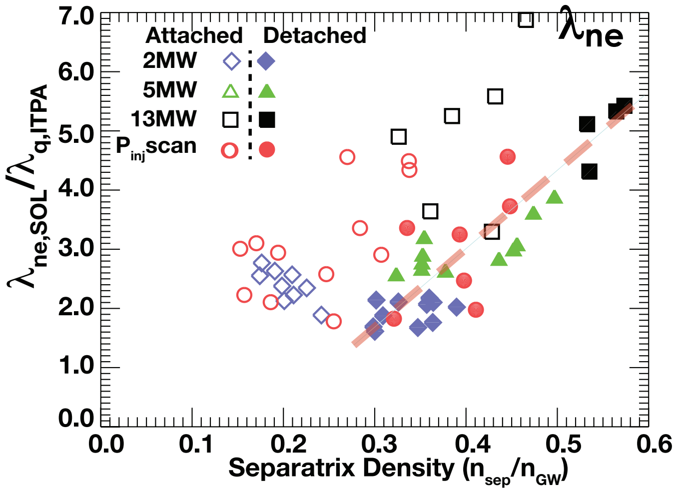
SOL λ_q expands at high density and high power





- λ_{Te}:
  - $\lambda_q \sim \frac{2}{7}\lambda_{Te}$ at high collisionality
  - λ_{Te} increases for $n_{sep} \geq 0.3\ n_{GW}$

- λ_{ne}:
  - SOL λ_{ne} broadens twice that of λ_{Te} during detachment
  - Divertor density width increases consistent with midplane λ_{ne}
  - Deteached divertor density increases only modestly with power

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Questions and implications of SOL MHD stability remain

- **Separatrix MHD stability limit could potentially improve divertor performance**
  - Increased SOL λ_q would reduce $q_{||}$ into divertor
  - Could reduce required n_{sep} and/or n_{imp} required for detachment
  - Would result in lower divertor density during detachment

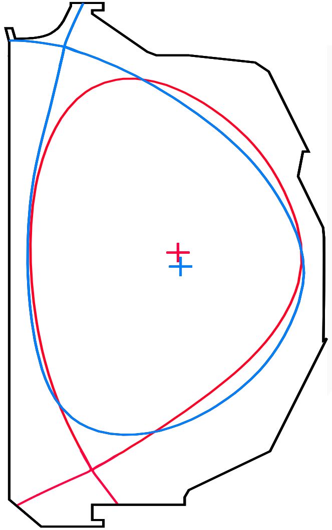
- **Will MHD stability improve divertor performance in DEMO?**
  - Will $n_{sep} \geq 0.5 n_{GW}$ be consistent with DEMO pedestal density?
  - Will enhanced MHD ballooning transport degrade pedestal?

Separatrix density is a key variable for divertor design

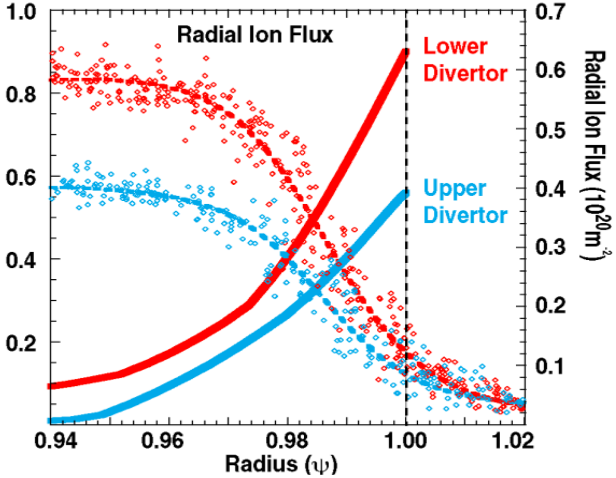
- **Divertor conditions depend nonlinearly on upstream density**
  - $T_{div} \propto \frac{q_{\parallel}^{10/7}}{n_{sep}^2 L_{\parallel}^{4/7}} \frac{(1-f_{rad})^2}{(1-f_{mom})^2}$, $n_{div} \propto \frac{n_{sep}^3 L_{\parallel}^{6/7}}{q_{\parallel}^{8/7}} \frac{(1-f_{mom})^3}{(1-f_{rad})^2}$
  - A small change in separatrix density can make a big difference
- **Core operational scenarios specify (at best) pedestal top density**
  - What fraction of n_{ped} can we assume in divertor design?
  - Existing devices exhibit n_{sep}/n_{ped} ~ 0.3 - 0.7 (Quite a range!)
- **What do divertor designers need from core/pedestal physics?**
  - Specification of core fueling, e.g. pellets for tritium fueling, beam fueling, etc.
  - A model of pedestal density transport; predictive capability for pedestal profile from given core and edge source

Pedestal density transport was examined in DIII-D through divertor geometry changes

DIII-D



Radial ion flux inferred from OSM modeling



A. Leonard IAEA 2016

- Closed divertor (upper) reduces recycling neutrals from outboard divertor reaching the midplane
- For similar divertor conditions pedestal responds to lower ionization source with lower density gradient

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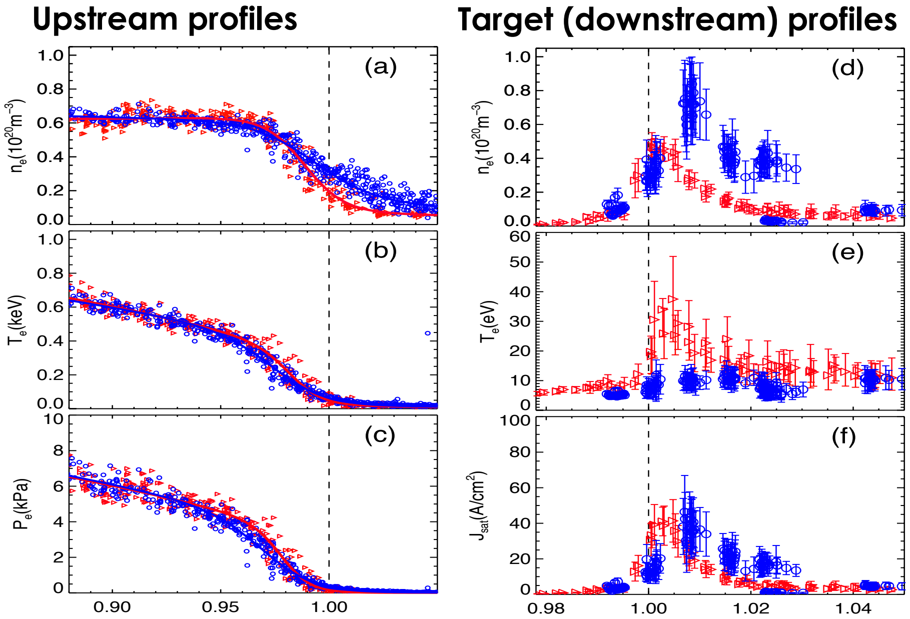
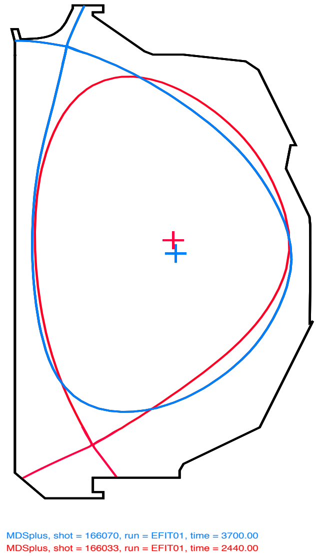
Reduced pedestal fueling allows access to divertor detachment at fixed n_{ped}





Reduced fueling → lower $\nabla n_{e,ped}$ → higher n_{sep}/n_{ped} → detachment

How much higher n_{sep}/n_{ped} can we expect in future tokamaks with reduced edge fueling?

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Pedestal transport model development a critical need for divertor design

- **US has initiated a coordinated effort to address this issue (following talk)**
  - Experimental effort to measure and quantify pedestal transport
  - Theory effort to develop pedestal transport models

- **Can a coordinated international effort be launched?**
- **What are the biggest challenges?**
  - Diagnostics
  - Interpretive modeling of diagnostics
  - Model development

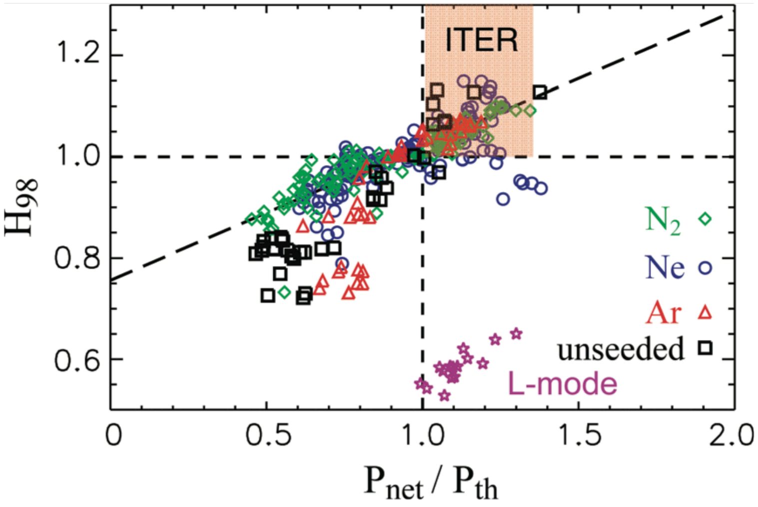
Allowed seeded SOL impurity density is also uncertain

- **Seeded impurity density key parameter for divertor design**
  - Heat dissipation ~ $\propto f_{imp}$
- **Core (pedestal) impurity limits set by a several issues**
  - Fuel dilution
  - Maximum core radiation $P_{sep}>P_{LH}$
  - Changes to current profile, NTMs
- **Ratio of $n_{imp,sep}/n_{imp,ped}$ dependent on pedestal density profile**
  - Neoclassical pinch increases $n_{imp,ped}/n_{imp,sep}$ in existing devices
  - A pedestal density transport model is needed to determine $n_{imp,ped}/n_{imp,sep}$ in future tokamaks

Maximum core impurity level set by several limits

- **Fuel dilution limits maximum tolerable impurity density**
- **Maximum impurity density for heat flux dissipation**
  - $P_{sep} \geq \alpha P_{LH}$
  - Required P_{sep} dependent on core scenario (still uncertain)
- **Core impurities may trigger NTMs due to modified current profile**

Alcator C-mod



$$P_{LH} = 4.9x10^4 n_{e,20}^{0.72} B_t^{0.8} S^{0.94}$$

A. Loarte PoP 2011

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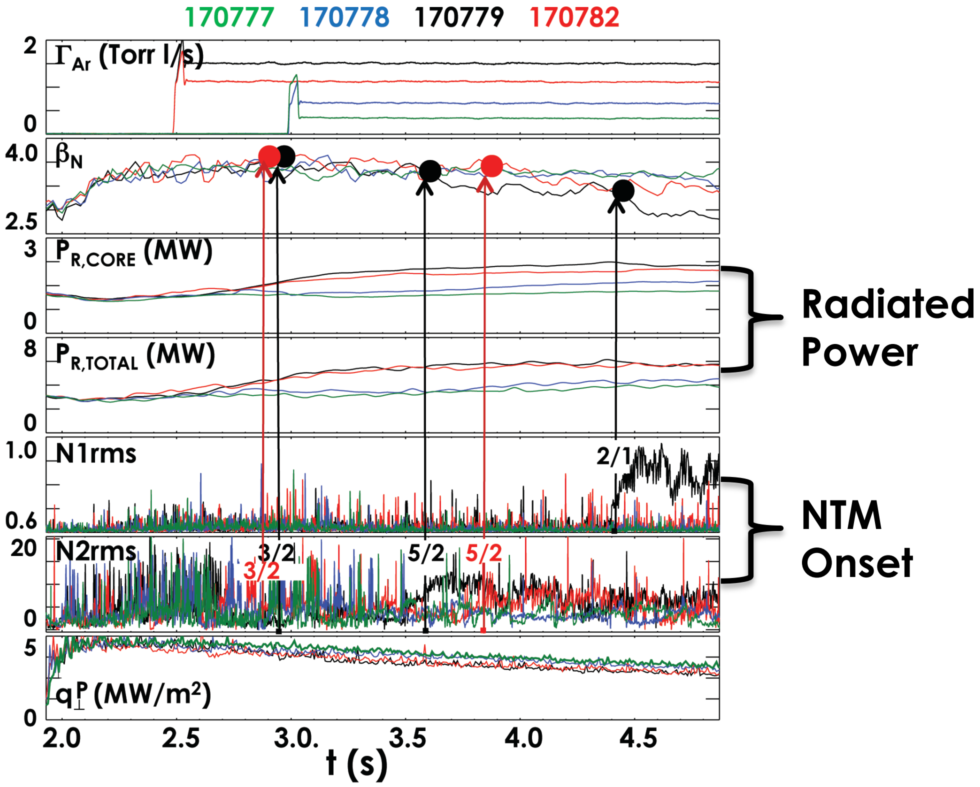
Impurity density may be limited by core MHD stability, below that for $P_{sep} \geq P_{LH}$



- NTMs arise in high β plasmas with higher Z impurity seeding
- Core plasma MHD stability at high β very sensitive to current profile

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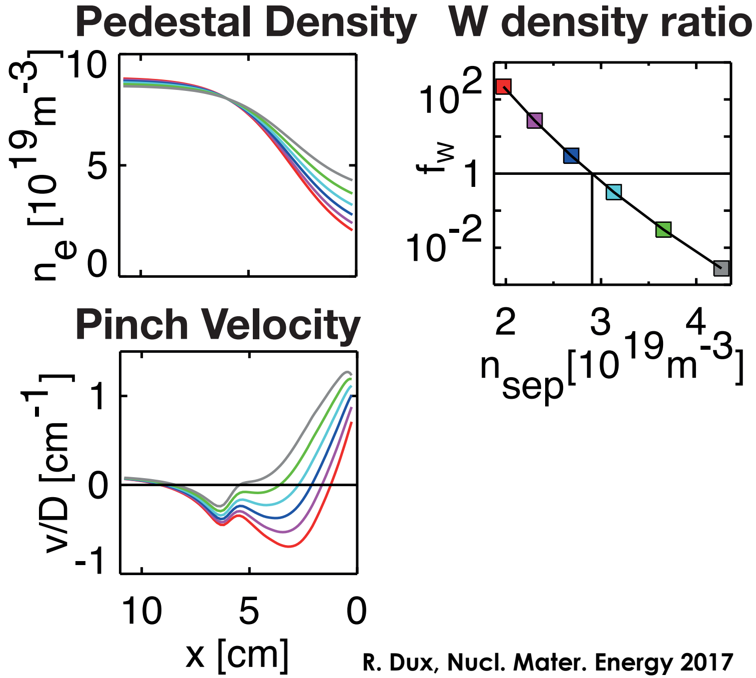
Neo-classical transport across pedestal in future tokamaks increase SOL impurity density limit

ITER Simulation

I_p=15 MA, B_t= 5.3 T, T_{ped}=4.5 keV



R. Dux, Nucl. Mater. Energy 2017

- **Pedestal neoclassical pinch dependent on ratio of density to temperature gradient**

$$\left(\frac{v}{D}\right)_{neo} \propto Z\left(d\ln\left(n_i\right)/dr - Hd\ln\left(T_i\right)/dr\right)$$

- **Shallower pedestal density gradient allows for higher $n_{imp,SOL}/n_{imp,ped}$**
- **The neoclassical effect for lower Z seeded impurities is smaller but still likely important**

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Sensitivity of X-point to cooling, neutral flux, etc. also a factor in divertor design

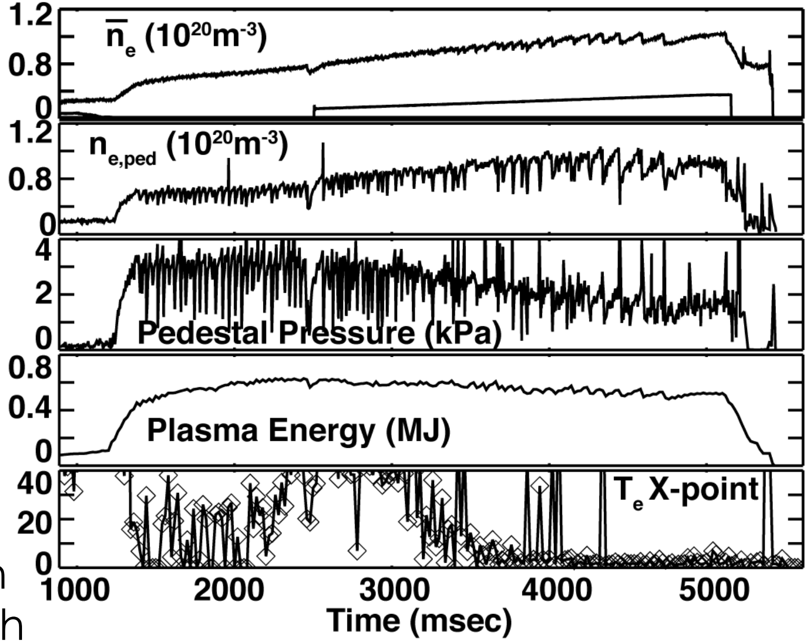
Pedestal Degradation

	Pre D_2	Early	Late
WMHD (MJ)	**0.62**	**0.59**	**0.52**
$p_{e,ped}$(kPa)	**3.4**	**2.7**	**1.9**
$n_{e,ped}$($10^{20}m^{-3}$)	**6.9**	**9.6**	**11.4**
$T_{e,ped}$(eV)	**330**	**190**	**120**

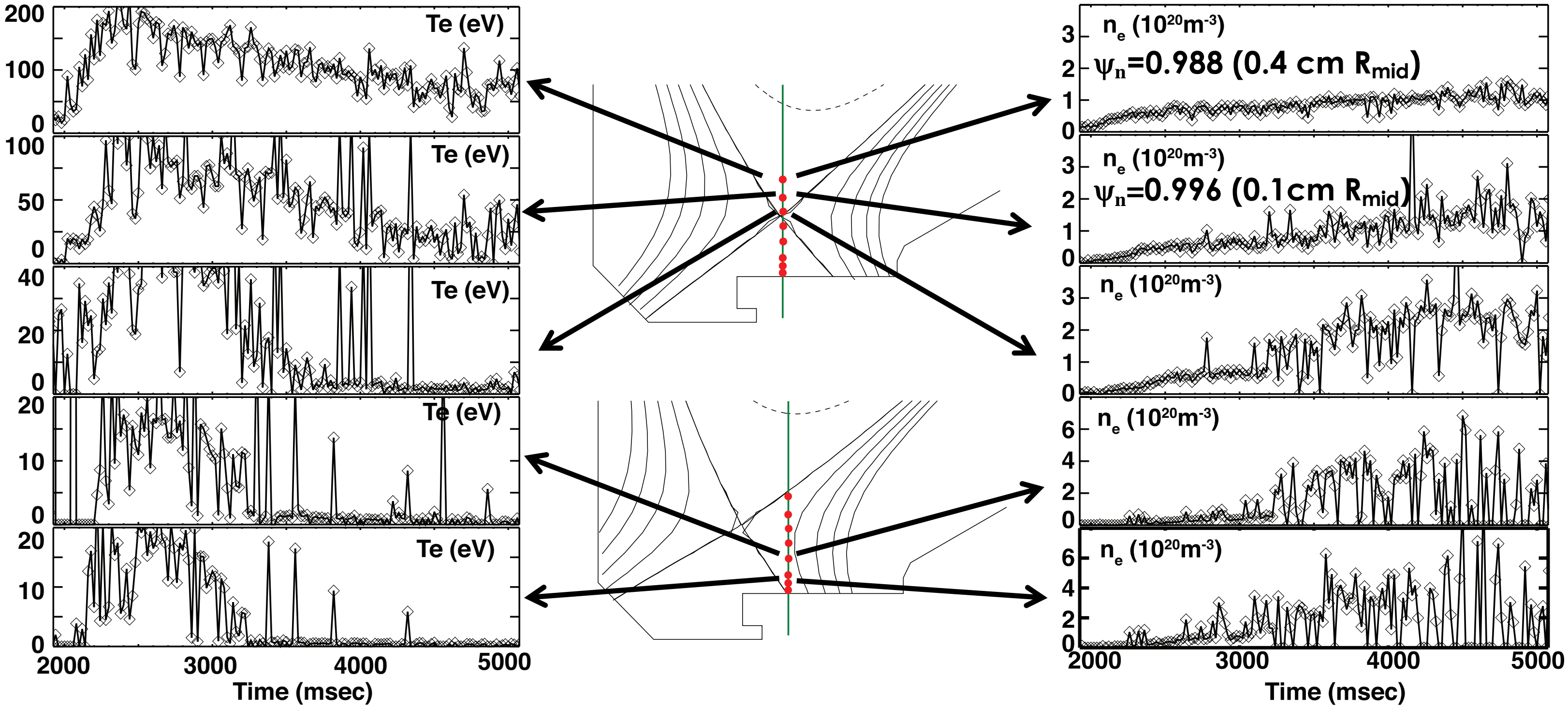
Steady degradation in $p_{e,ped}$ with increasing D_2 should be expected at these parameters

- Pedestal MHD stability is on ballooning branch
- Will peeling limited pedestals also degrade with detachment?

Standard H-mode in DIII-D



X-point along with divertor conditions to be correlated with pedestal profile evolution



Other core-edge issues are also important

- **X-point sensitivity to cooling, neutral flux, etc.**
  - Requirements for divertor detachment control
  - Not adequately studied in core scenario development
- **Transients**
  - What transients from core must divertor design handle?
- **Shaping**
  - Triangularity and Double-null are two features which can significantly affect divertor design
- **Others?**