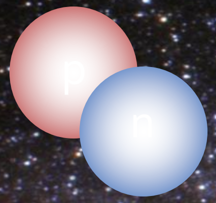
How to fuel a sun?

Saskia Mordijck (W&M)

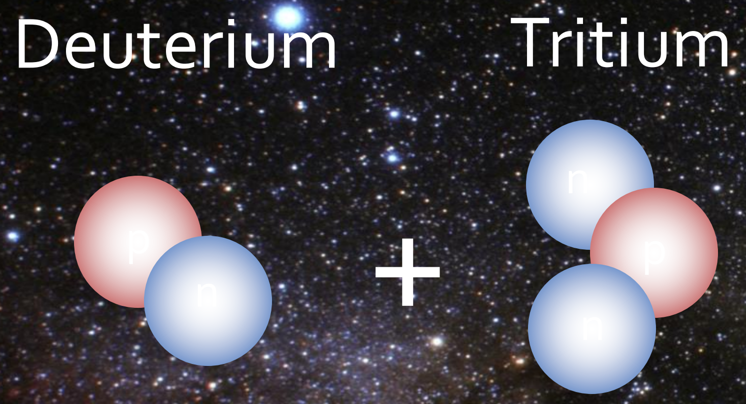
For billions of years fusion has powered the stars

Fusion on earth

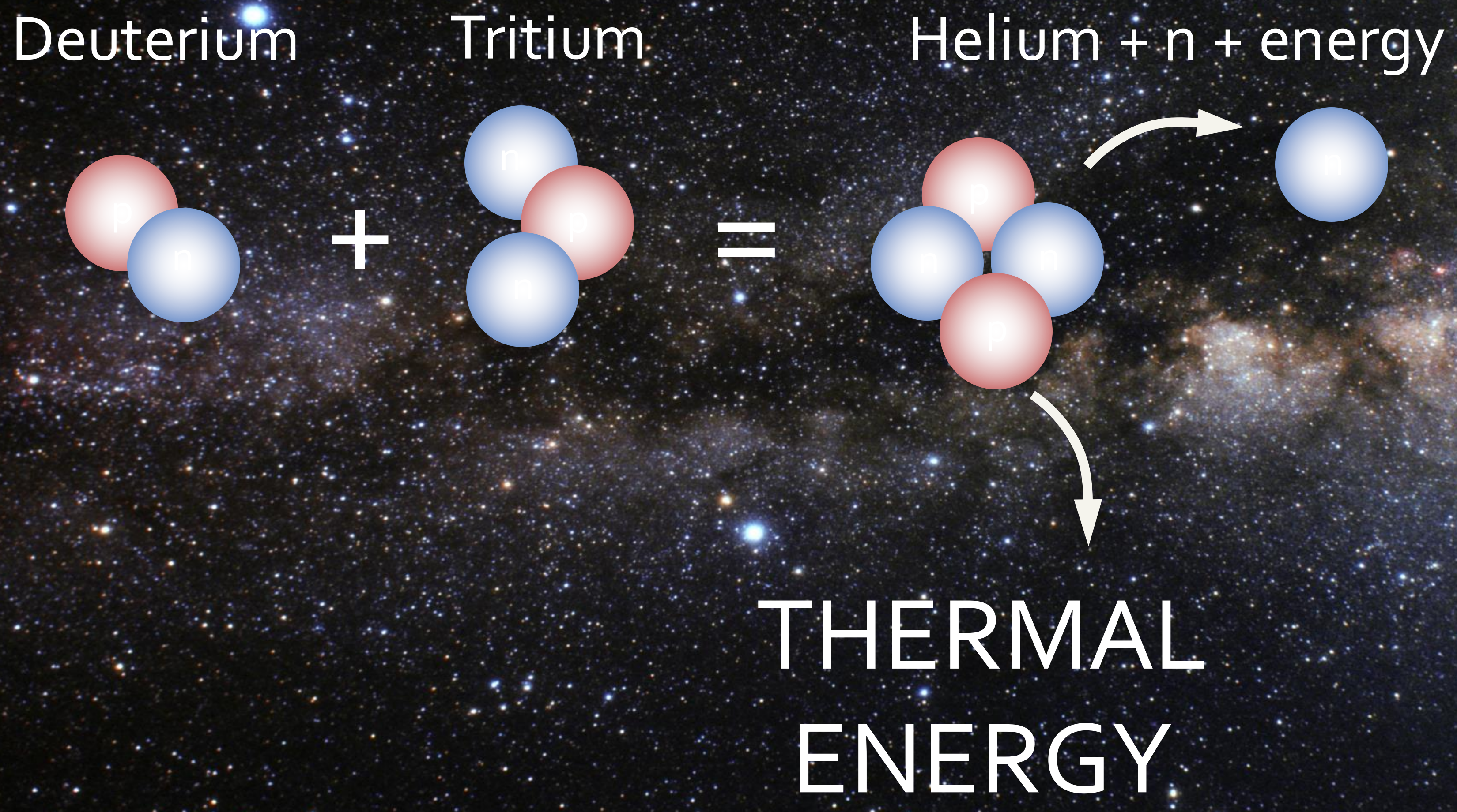
Deuterium



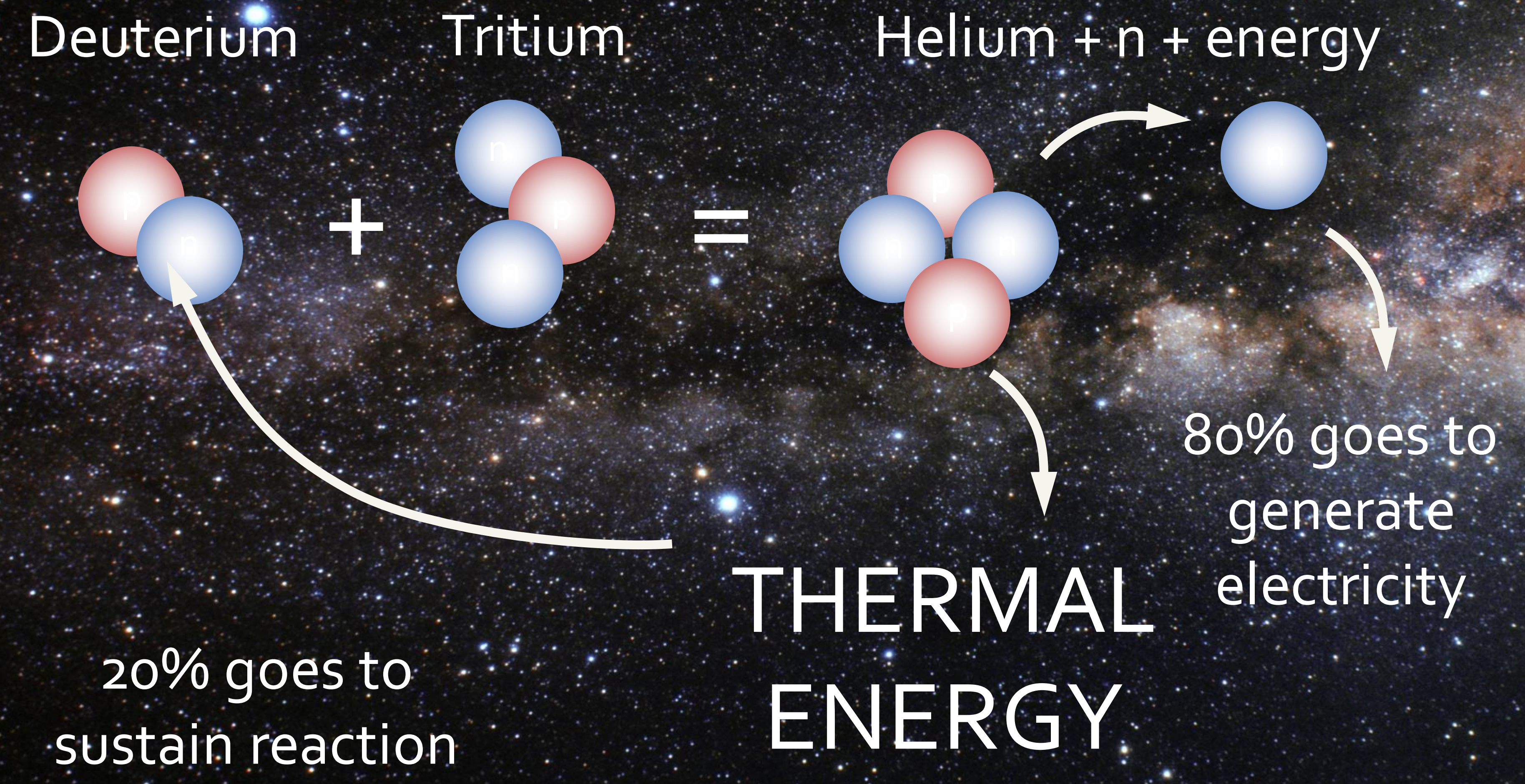
Fusion on earth



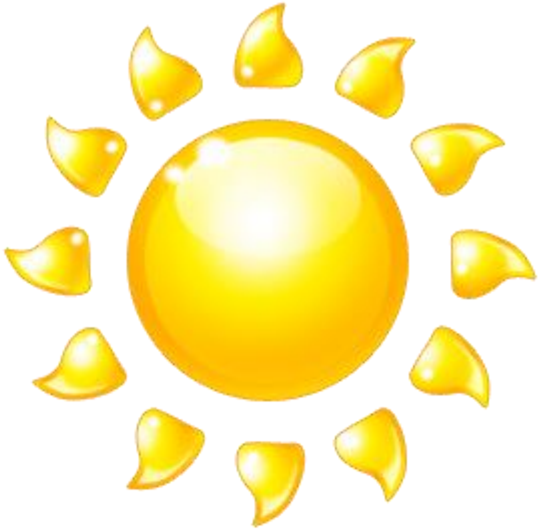
Fusion on earth



Fusion on earth



Bringing a star to earth has its challenges



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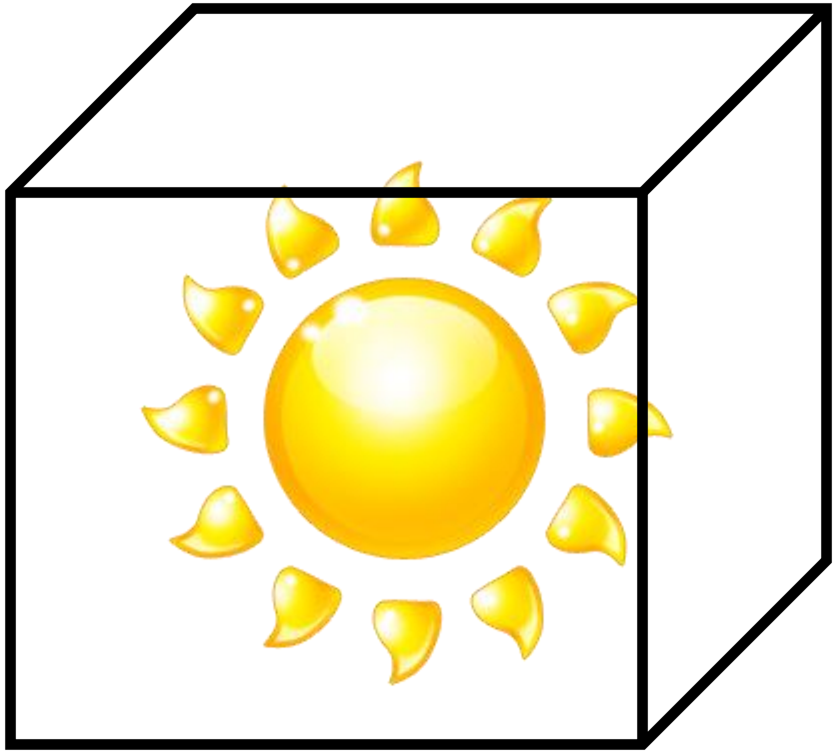

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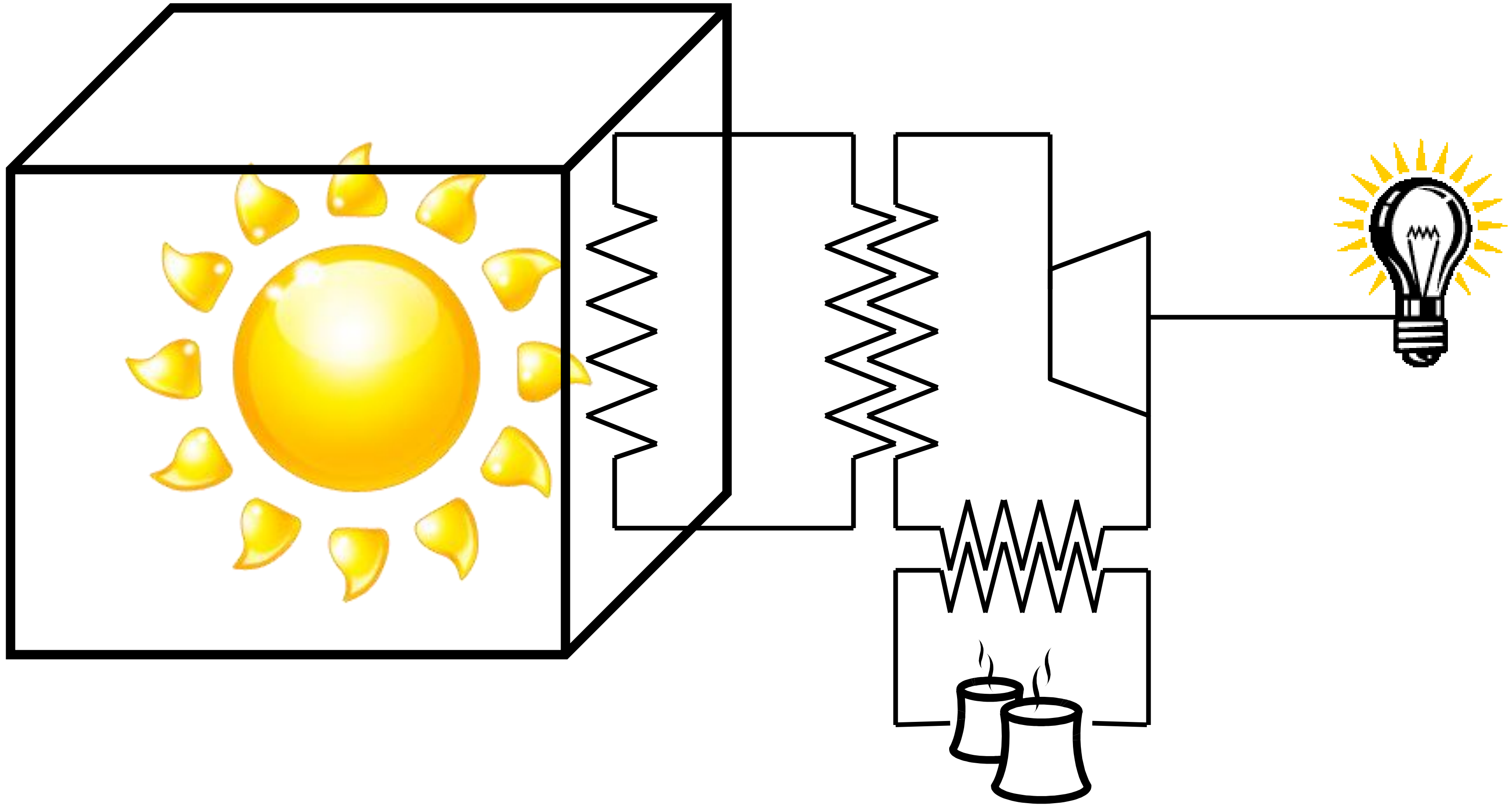

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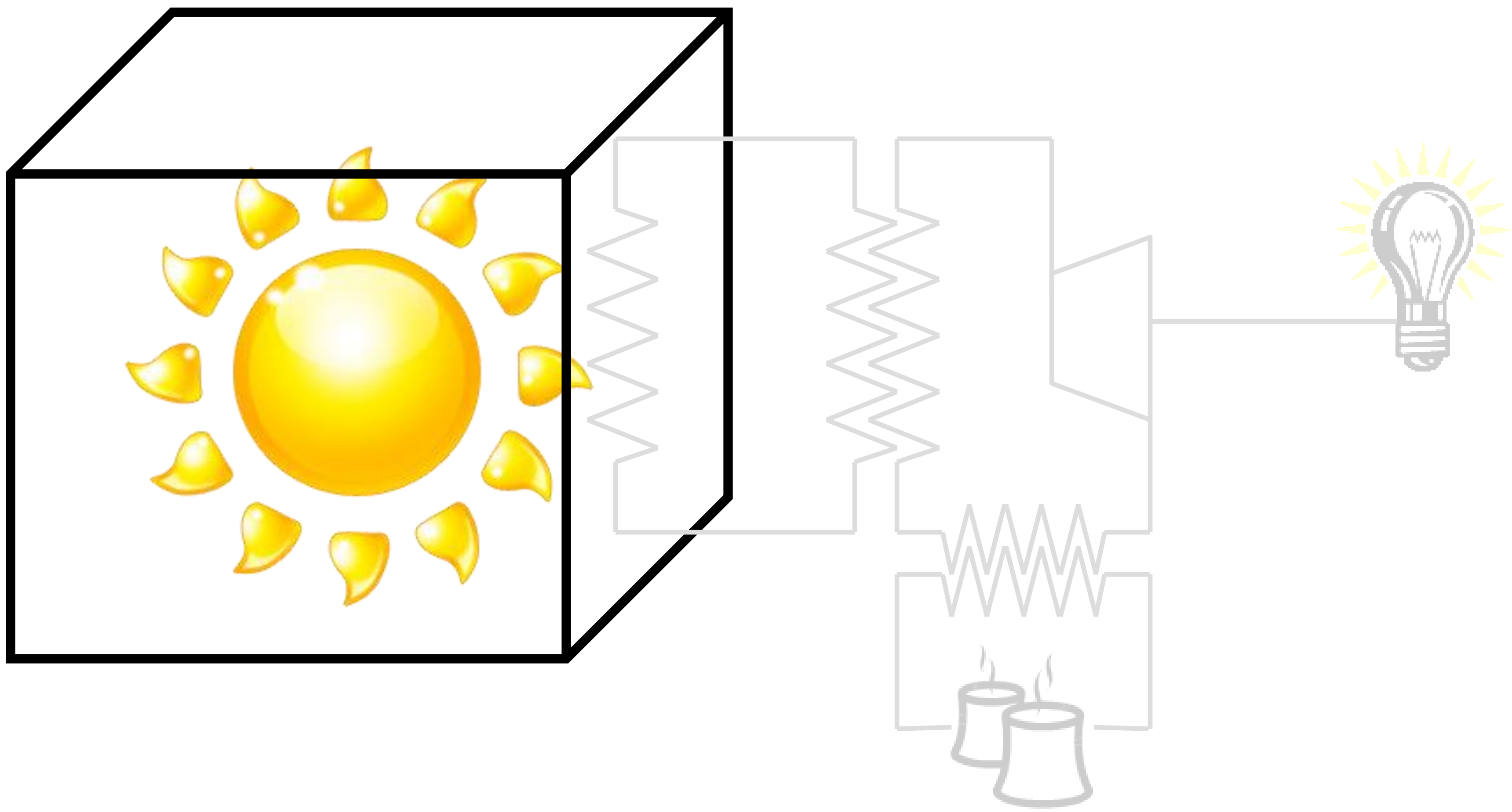
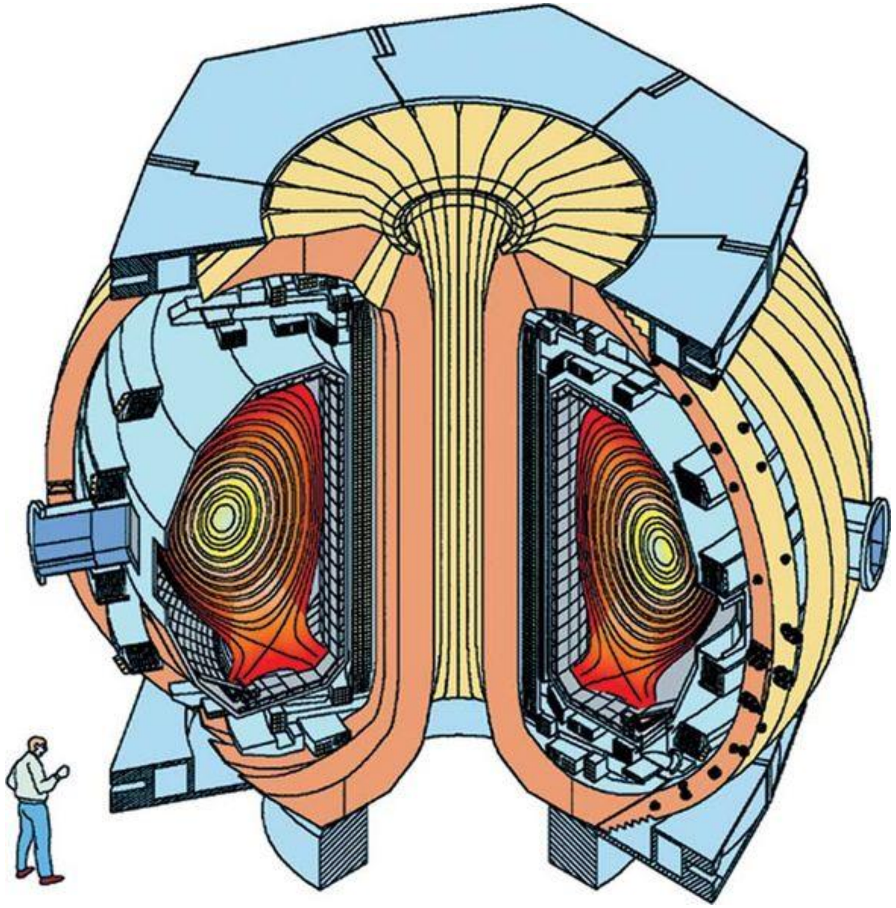


We use **magnetic fields** to confine the plasma in a **Tokamak**



The DIII-D Tokamak
General Atomics

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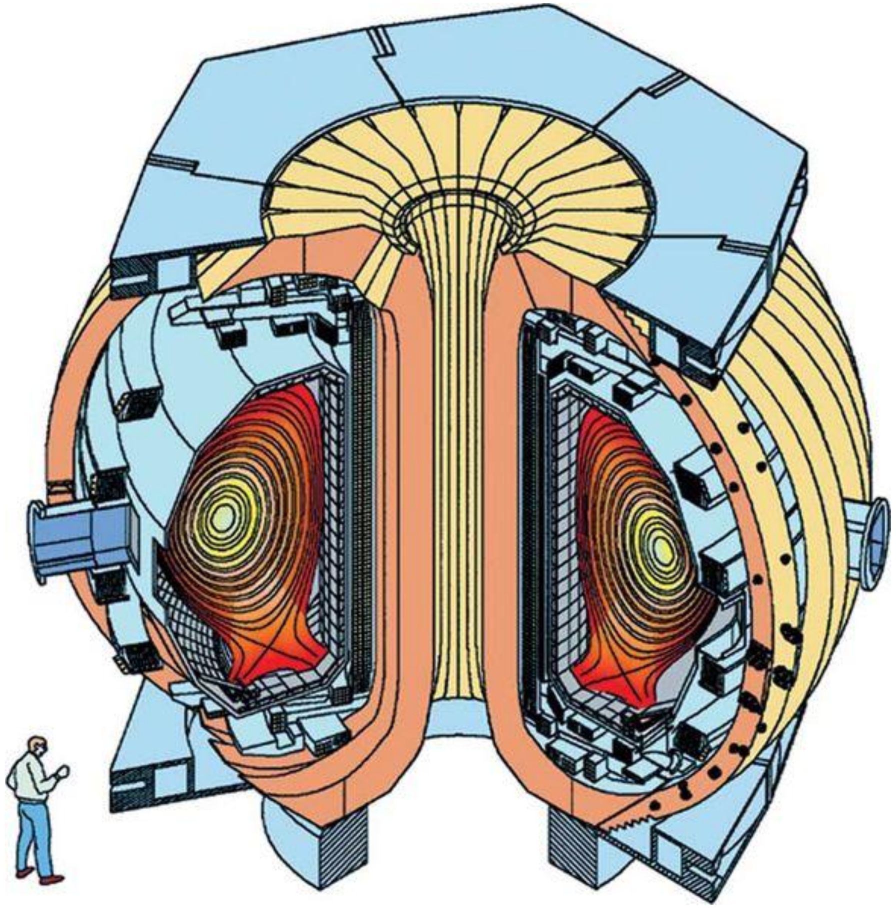
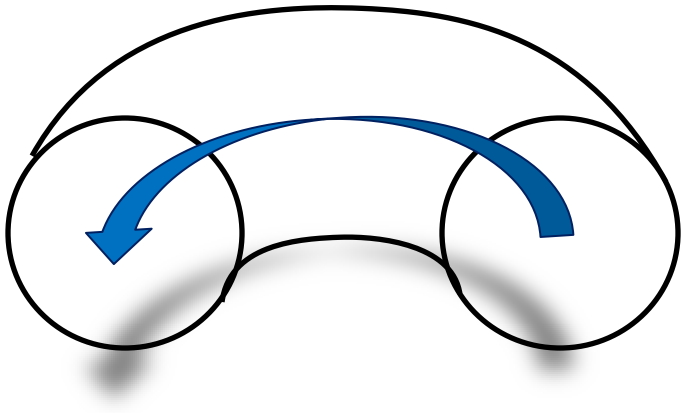


The DIII-D Tokamak
General Atomics

Toroidal B-field



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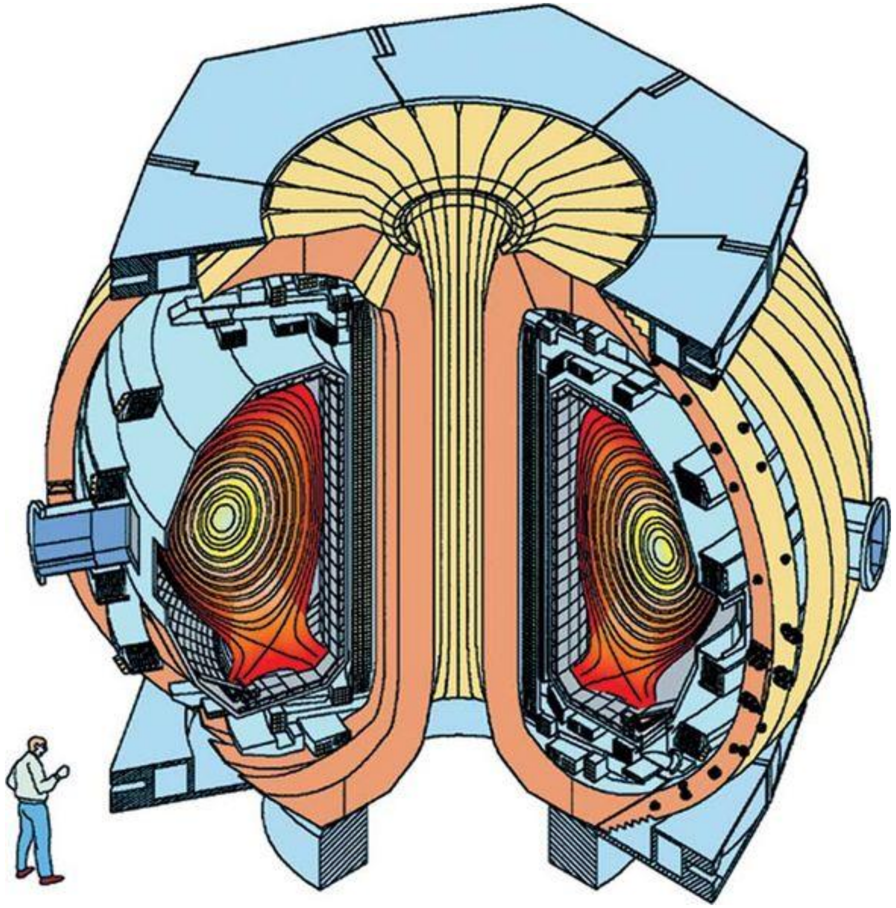

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General Atomics

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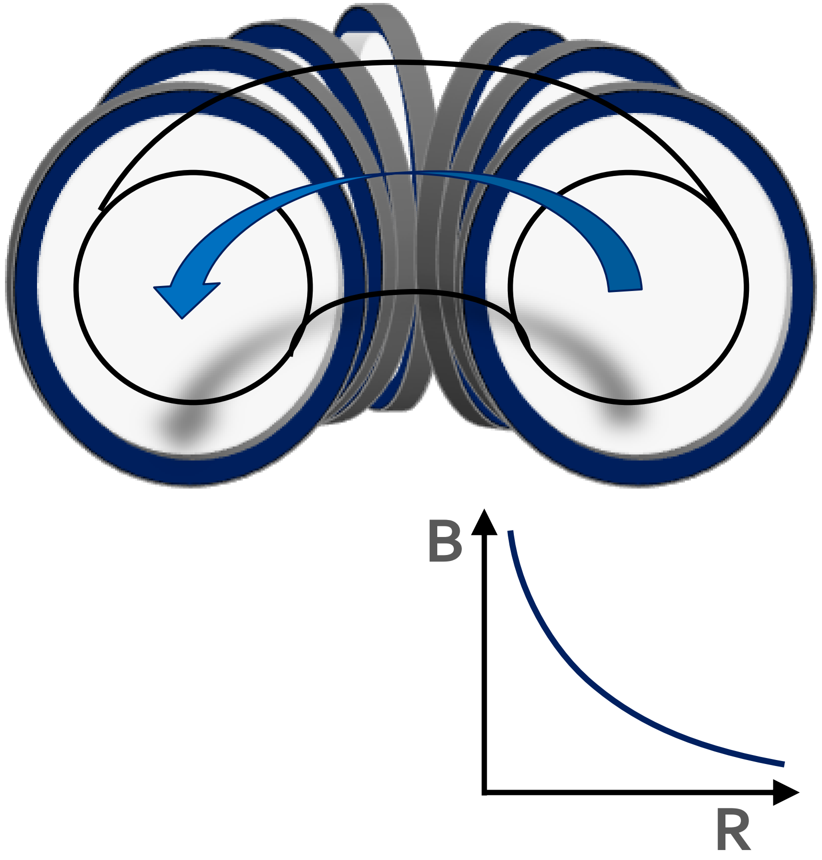

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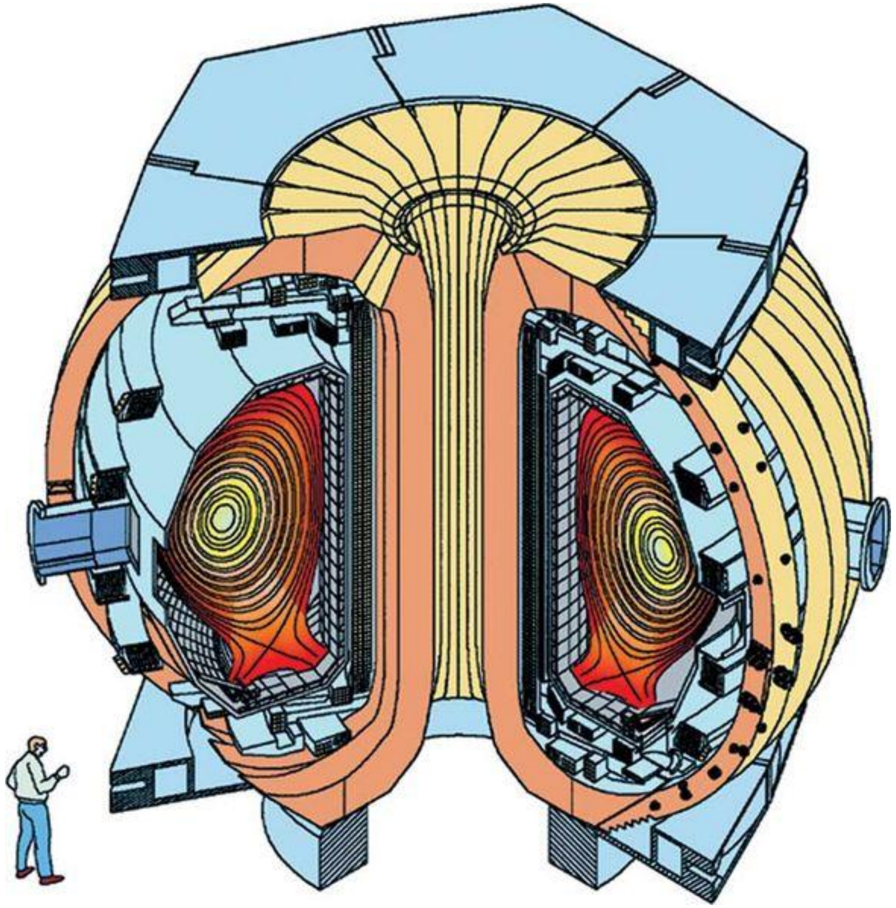
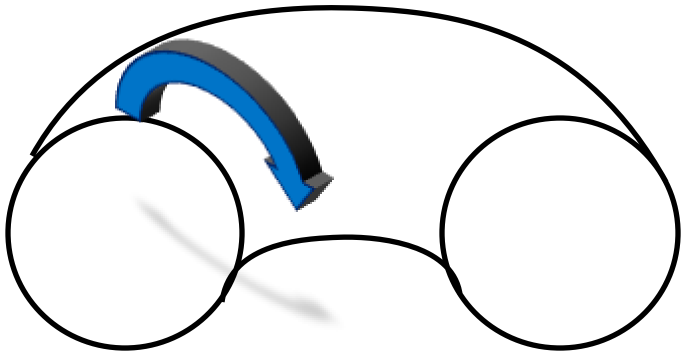


The DIII-D Tokamak
General Atomics

Poloidal B-field



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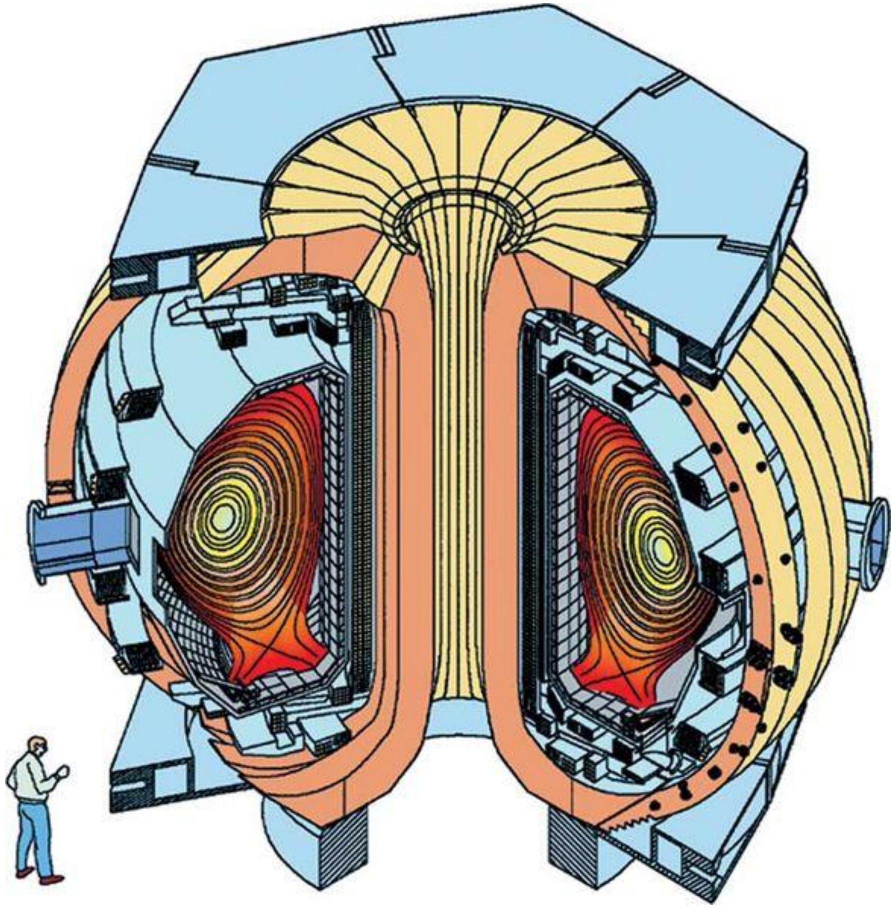
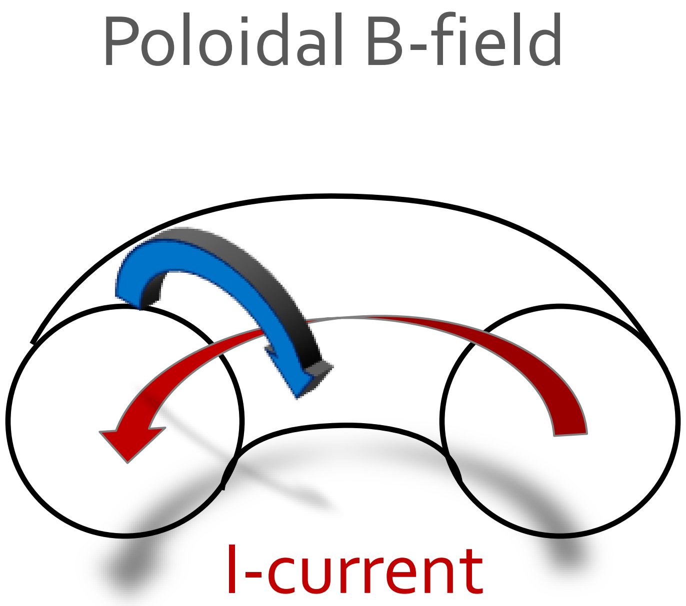


The DIII-D Tokamak
General Atomics



The Tokamak: some pictures of the interior of a tokamak

The DIII-D Tokamak

General Atomics

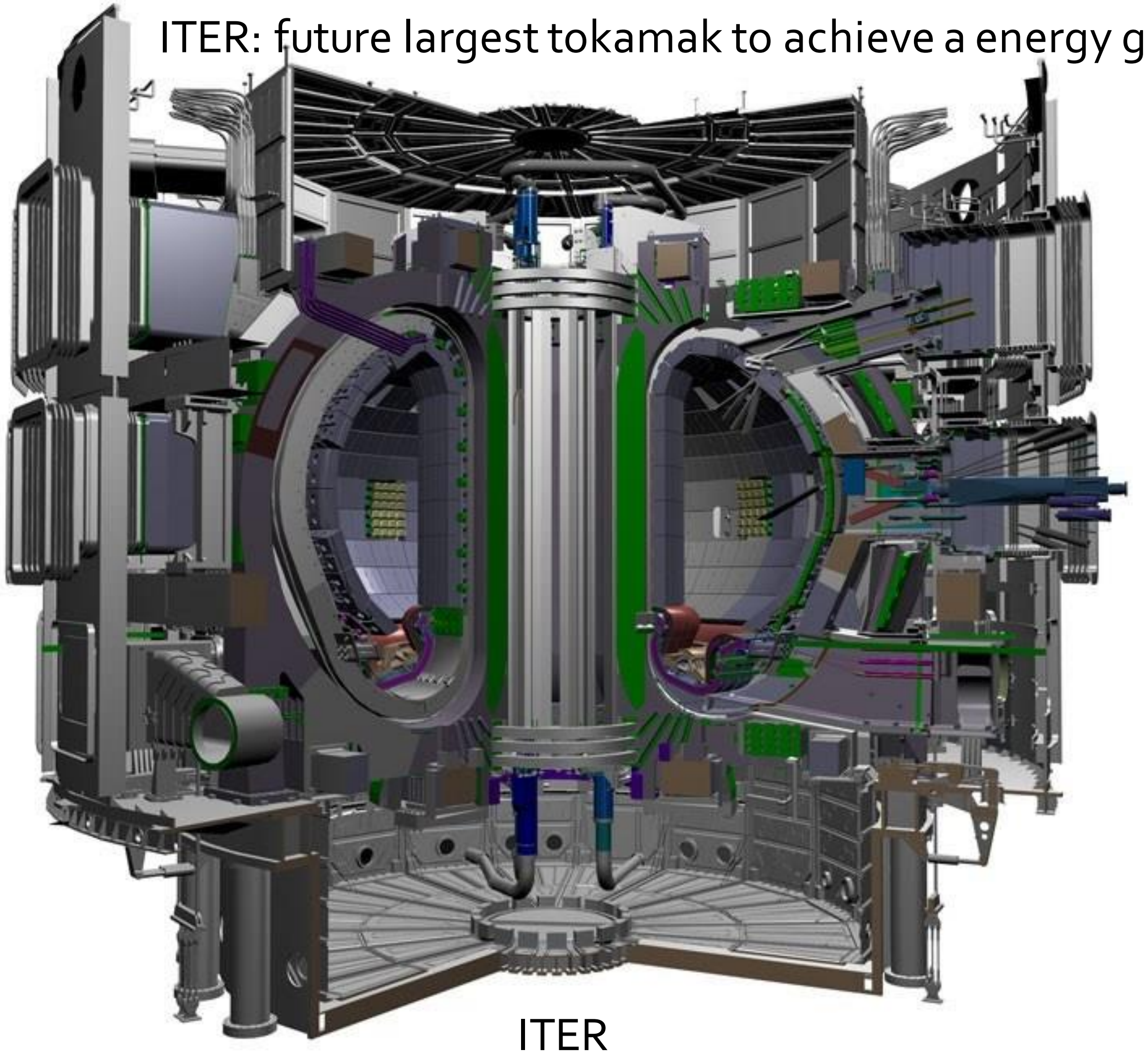
The Tokamak: some pictures of the interior of a tokamak

JET Tokamak: currently the world largest Tokamak

CCFE

The Tokamak: some pictures of the interior of a tokamak

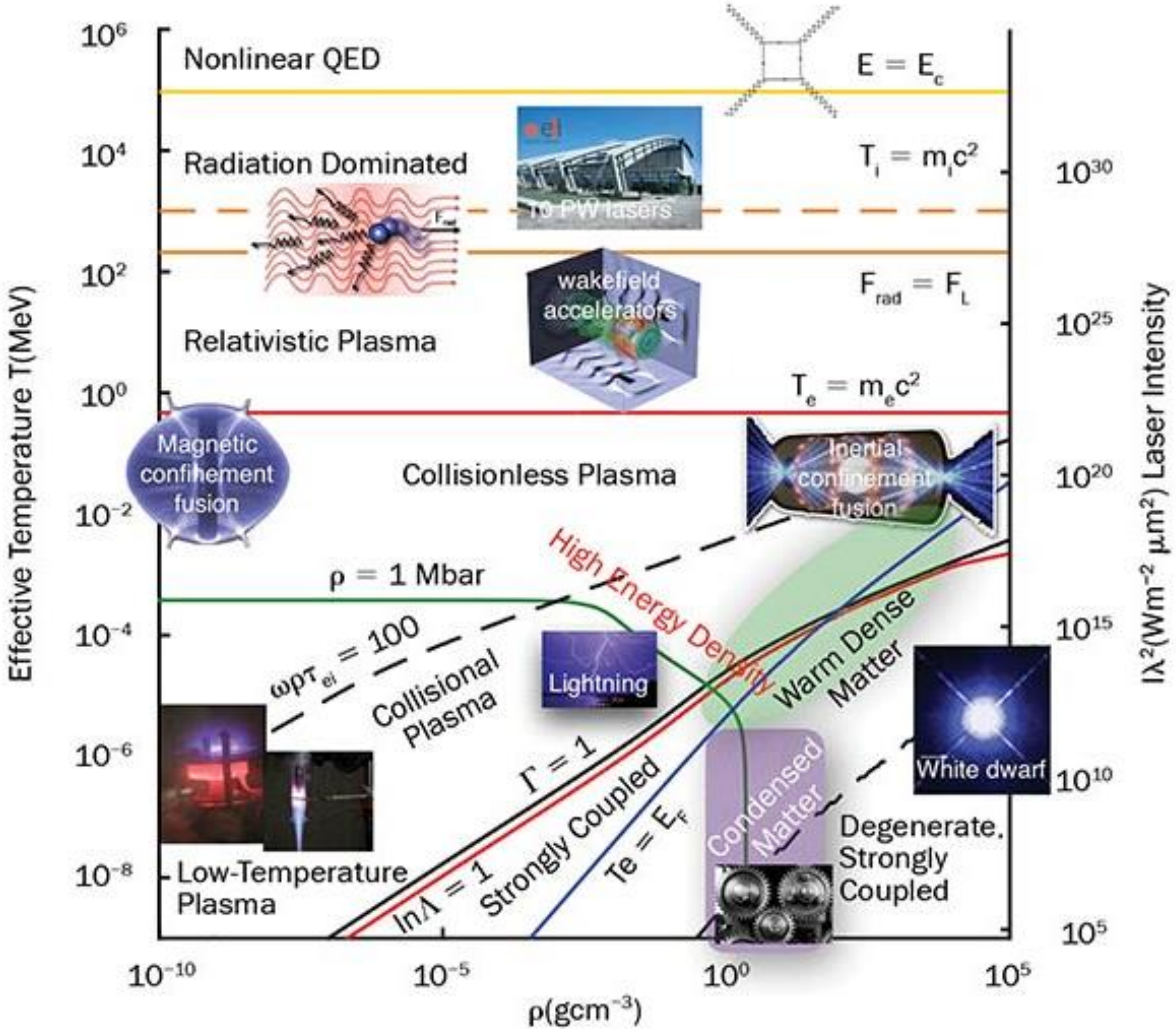
ITER: future largest tokamak to achieve a energy gain of 10



ITER

Courtesy of Dr. Alec Thomas, University of Michigan

99% of all visible matter comes in the form of a plasma



Plasma Physics is required to address some of the fundamental questions that govern our universe

What is the origin of magnetic fields?

Why does the Sun’s magnetic field reverse periodically?

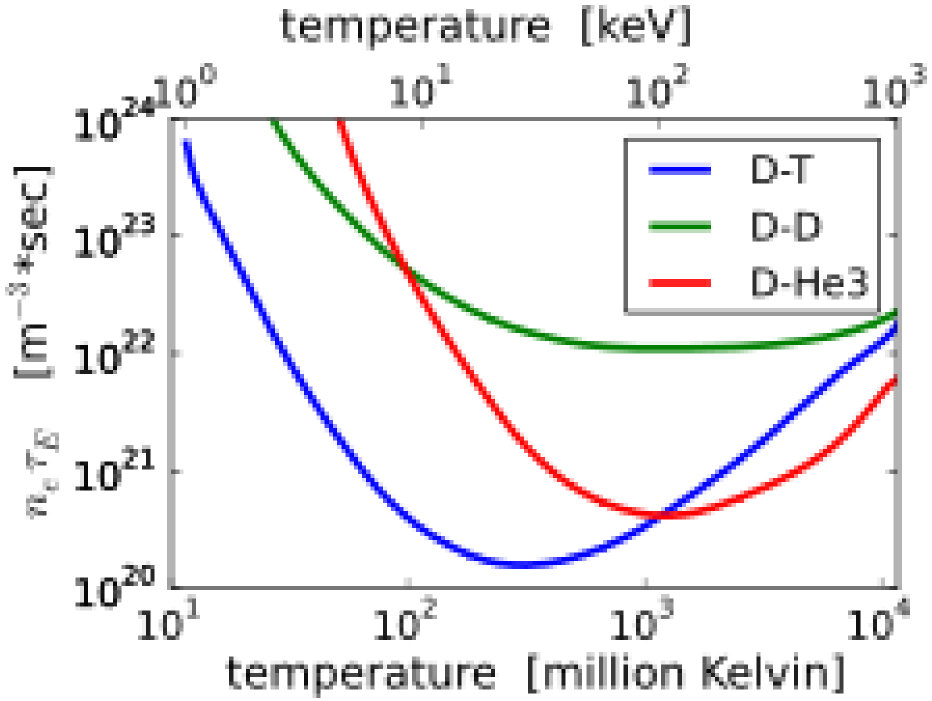
Why is the outer layer of the Sun hotter than its core?

Is the universe at very large scales anisotropic, making the cosmological principle an invalid assumption?

Can we confine a hot and dense enough plasma long enough for fusion power to become a reality?

What is the exact mechanism by which an implosion of a dying star becomes an explosion?

The Lawson criterion determines whether we achieve ‘ignition’



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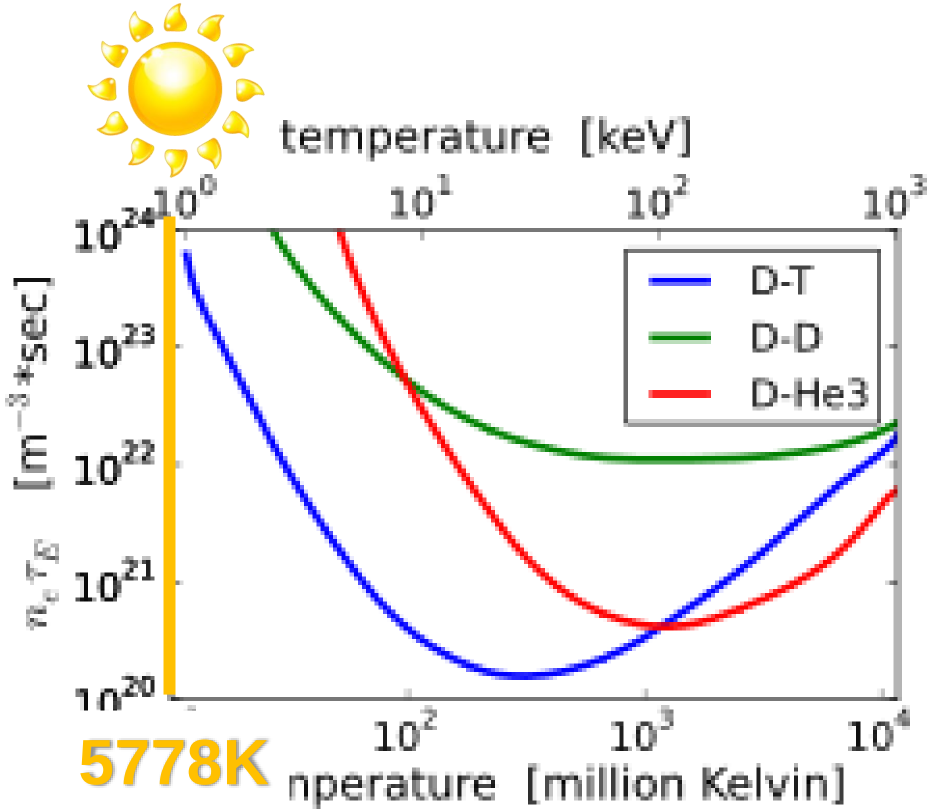

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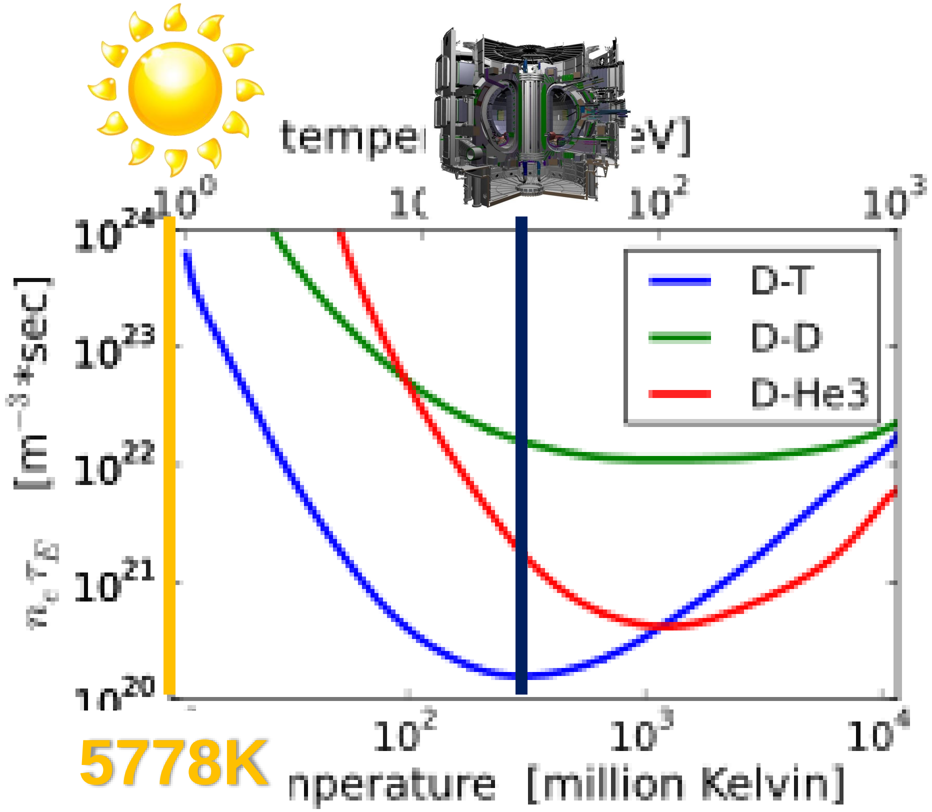

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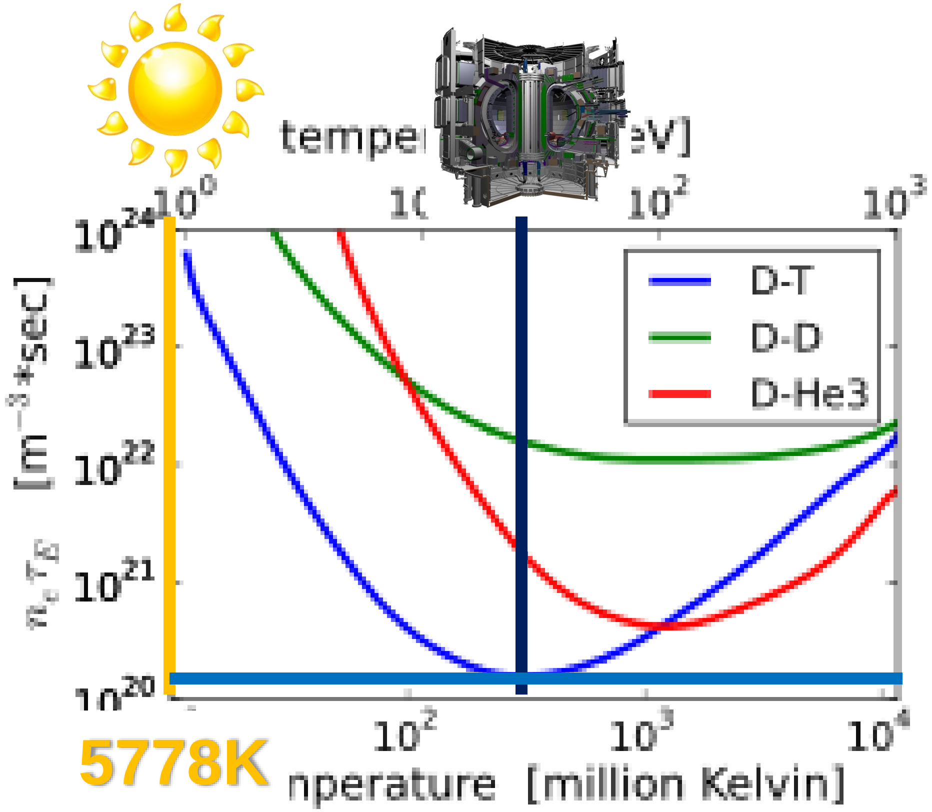

To reach ignition using DT:

τ_e ~ 10^{-1} on DIII-D

n_e ~ 10^{21} on DIII-D

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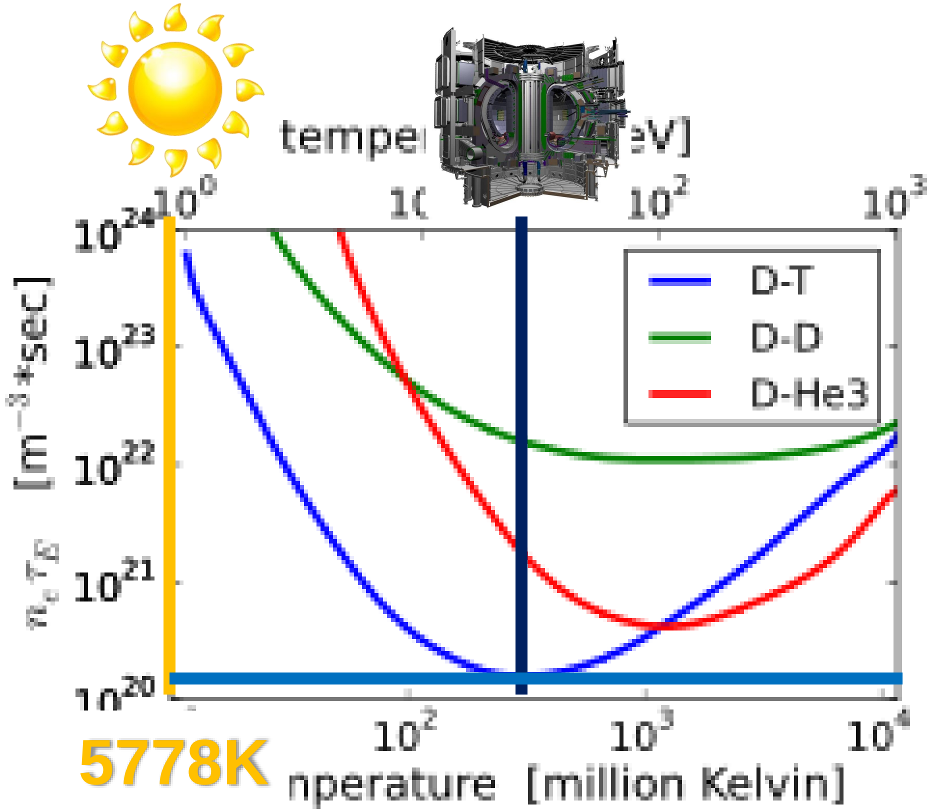

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n_e ~ 10^{20} on JET

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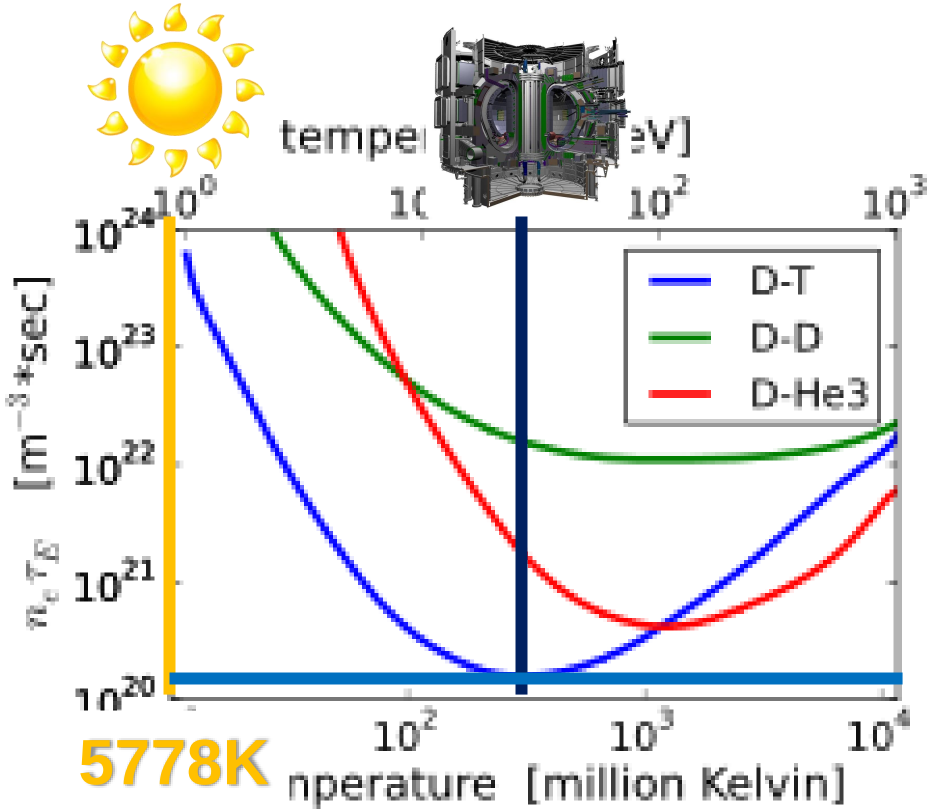

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τ_e ~ $10^{0\text{-}1}$ on ITER

n_e ~ $10^{19\text{-}20}$ on ITER

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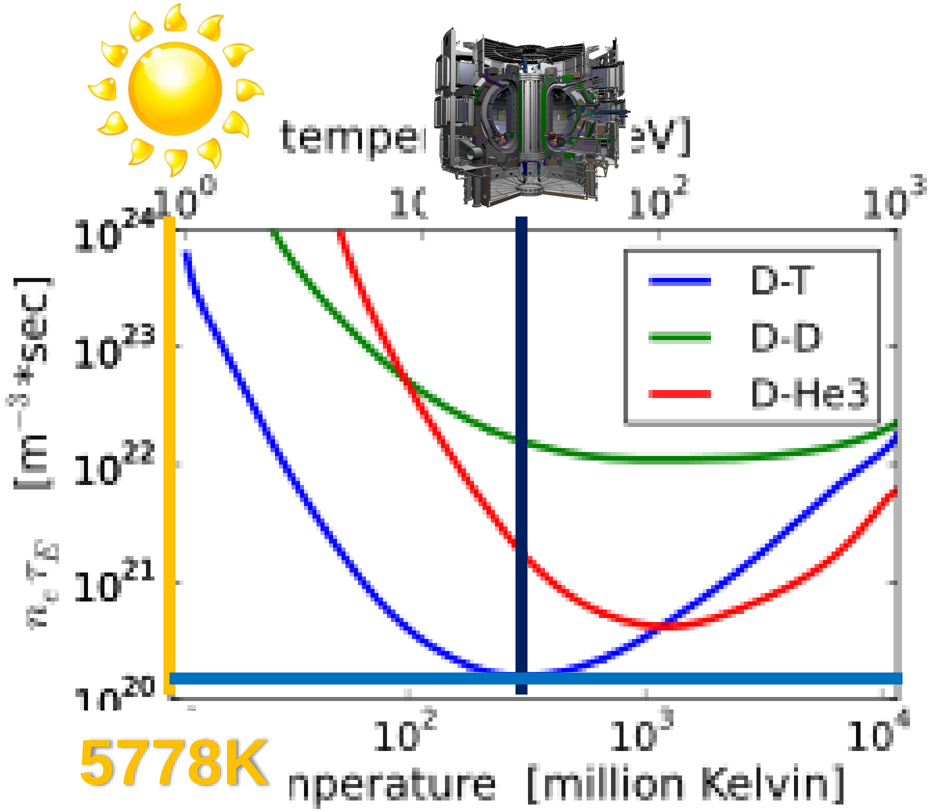

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$n_e \sim 10^{21}$ on DIII-D

$\tau_e \sim 10^{0}$ on JET

$n_e \sim 10^{20}$ on JET

$\tau_e \sim 10^{0\text{-}1}$ on ITER

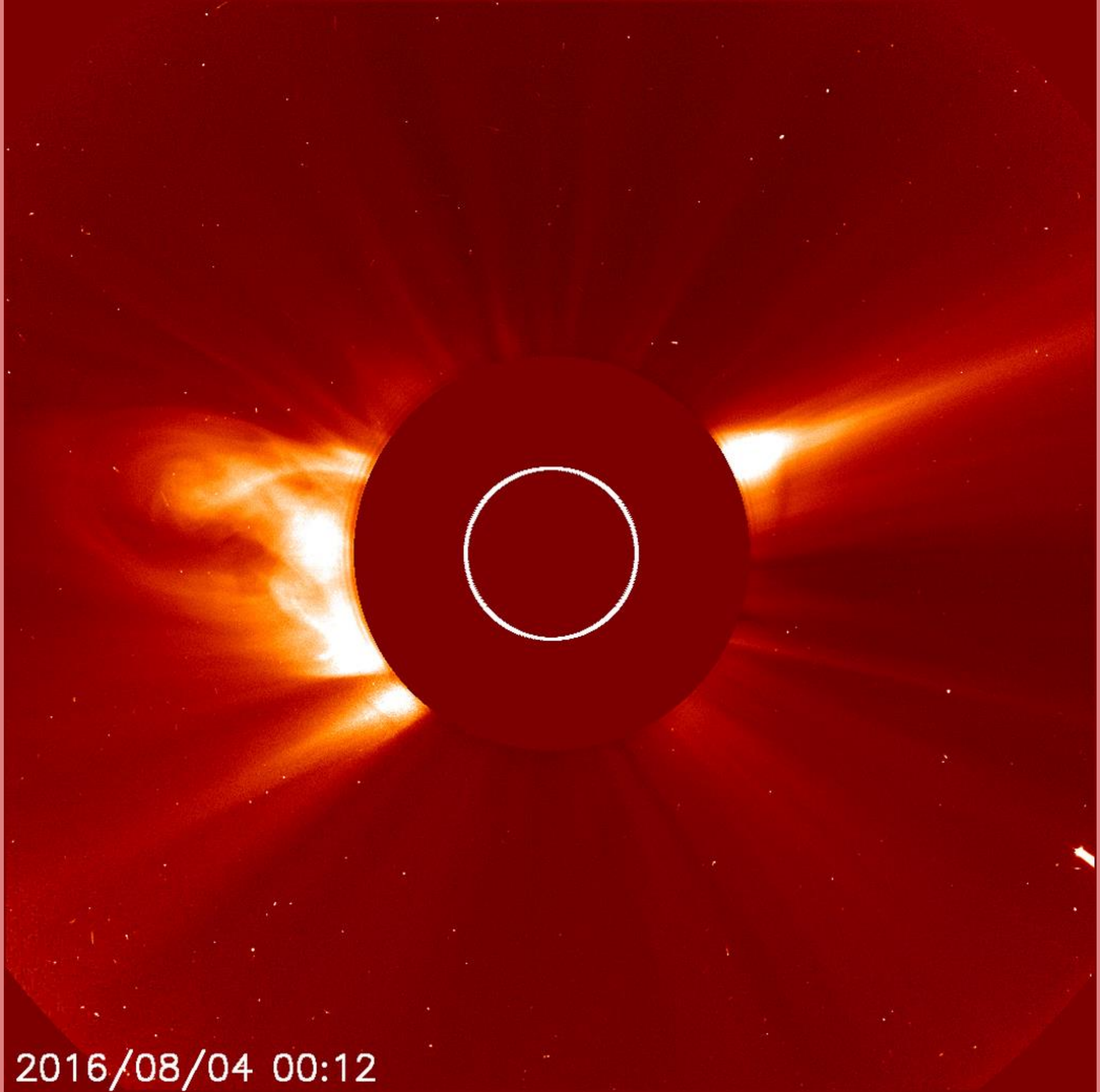
$n_e \sim 10^{19\text{-}20}$ on ITER

DD experiments now:

$\tau_e \sim 0.25$ on DIII-D

$n_e \sim 1\text{x}10^{20}$ on DIII-D

$Q_{DT} \sim 0.6$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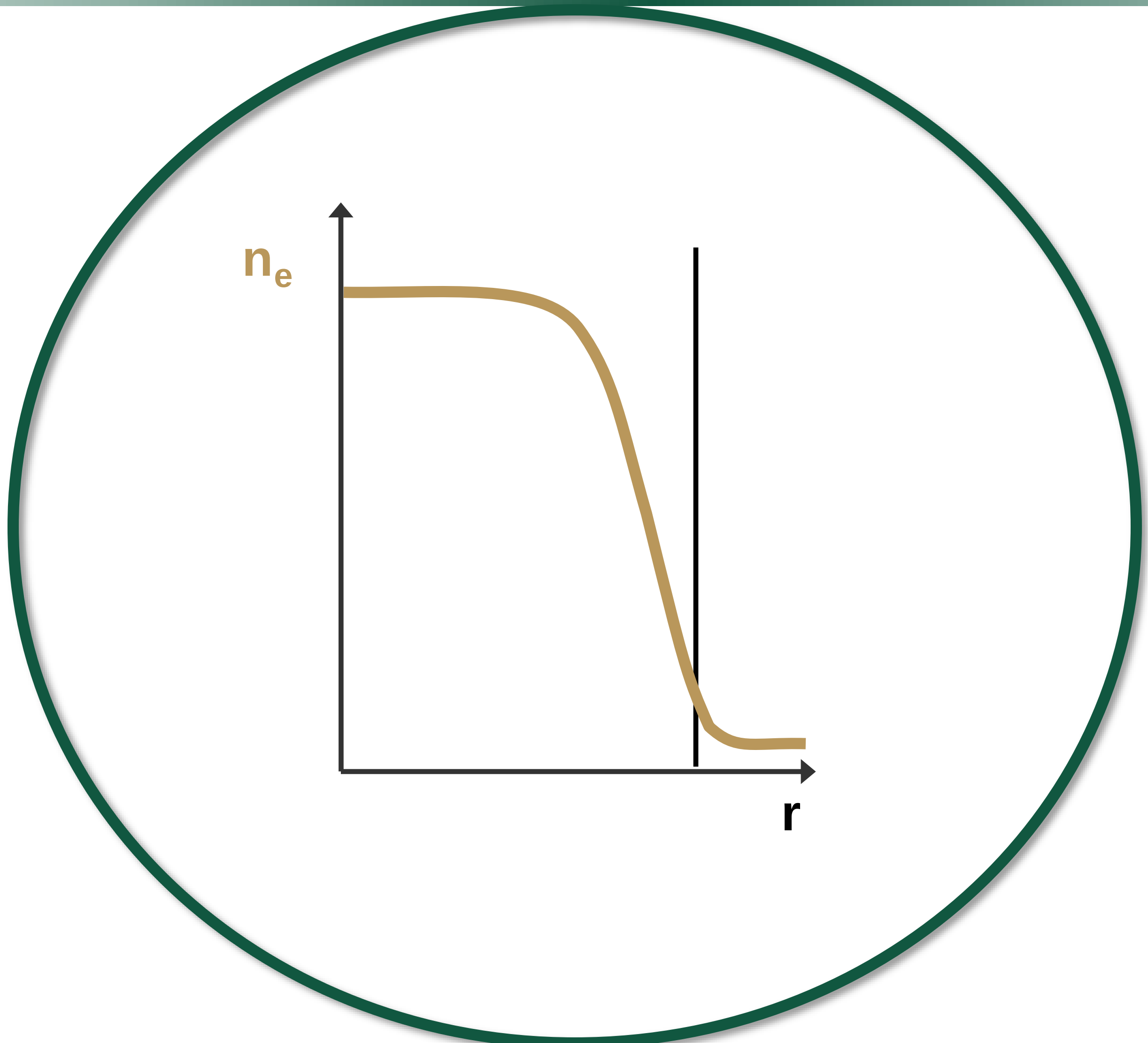
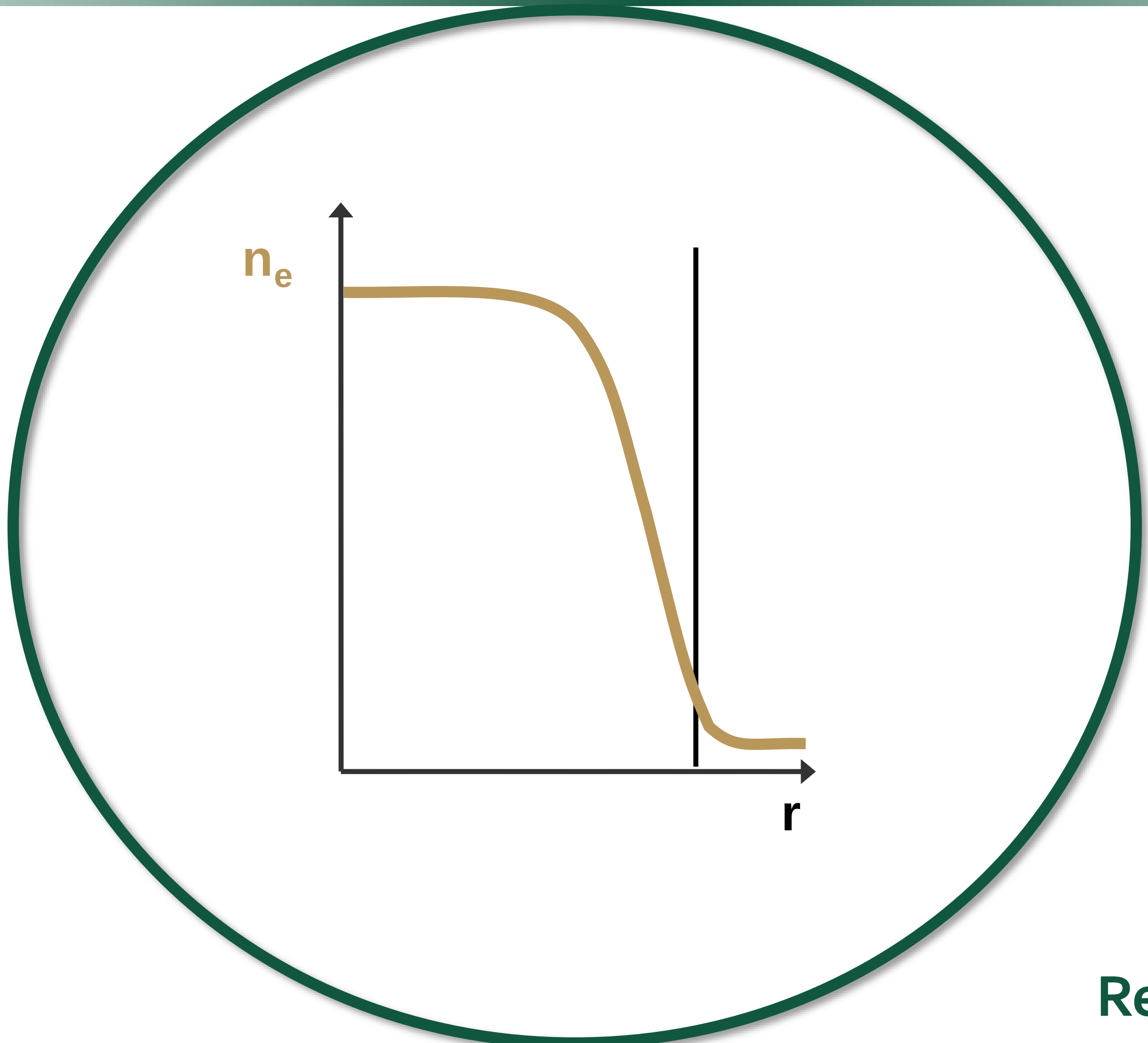
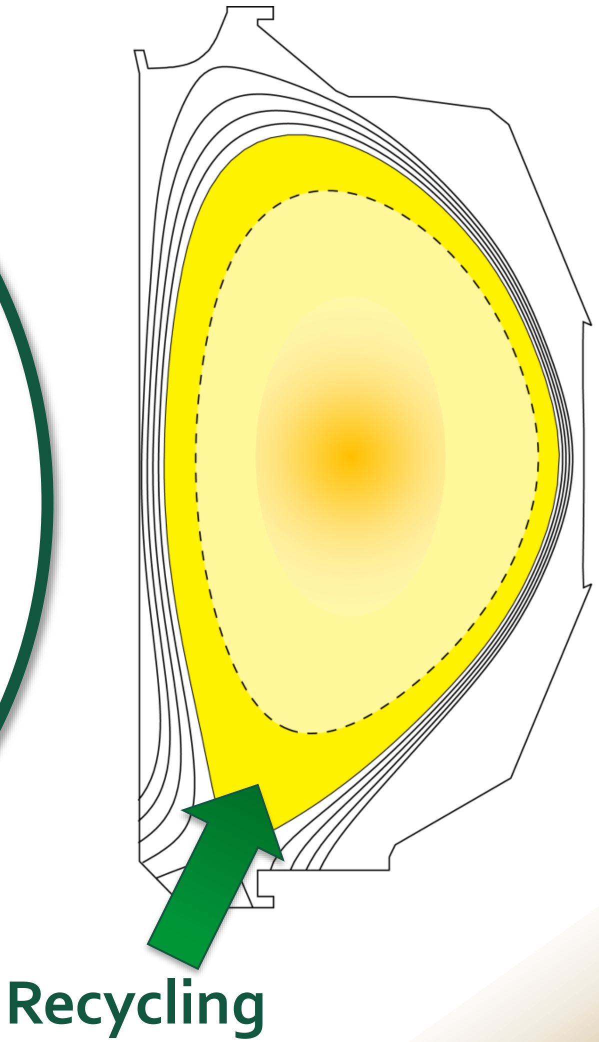
What sets the pedestal density profile?



What sets the pedestal density profile? Role of neutral density and ionization





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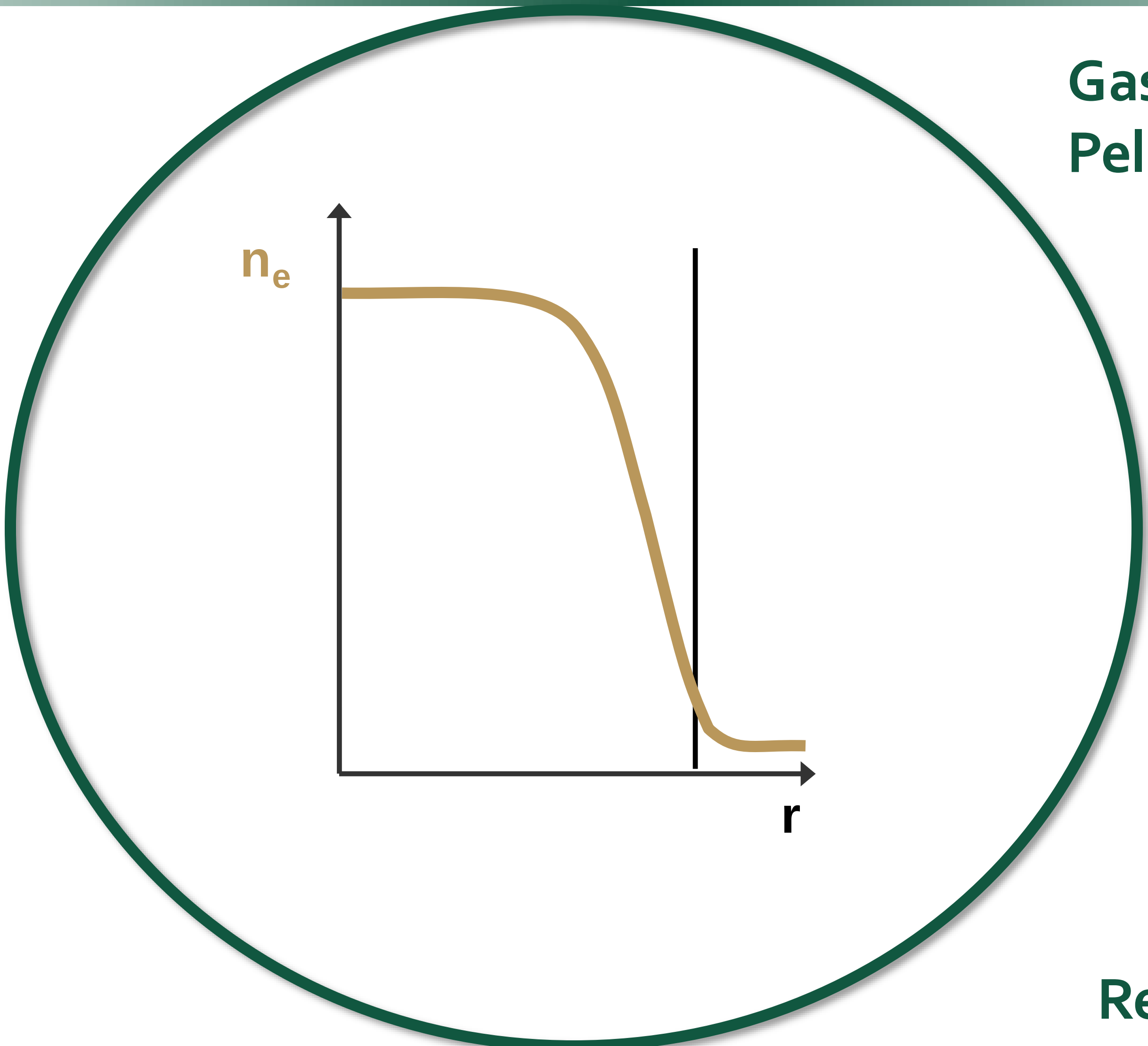

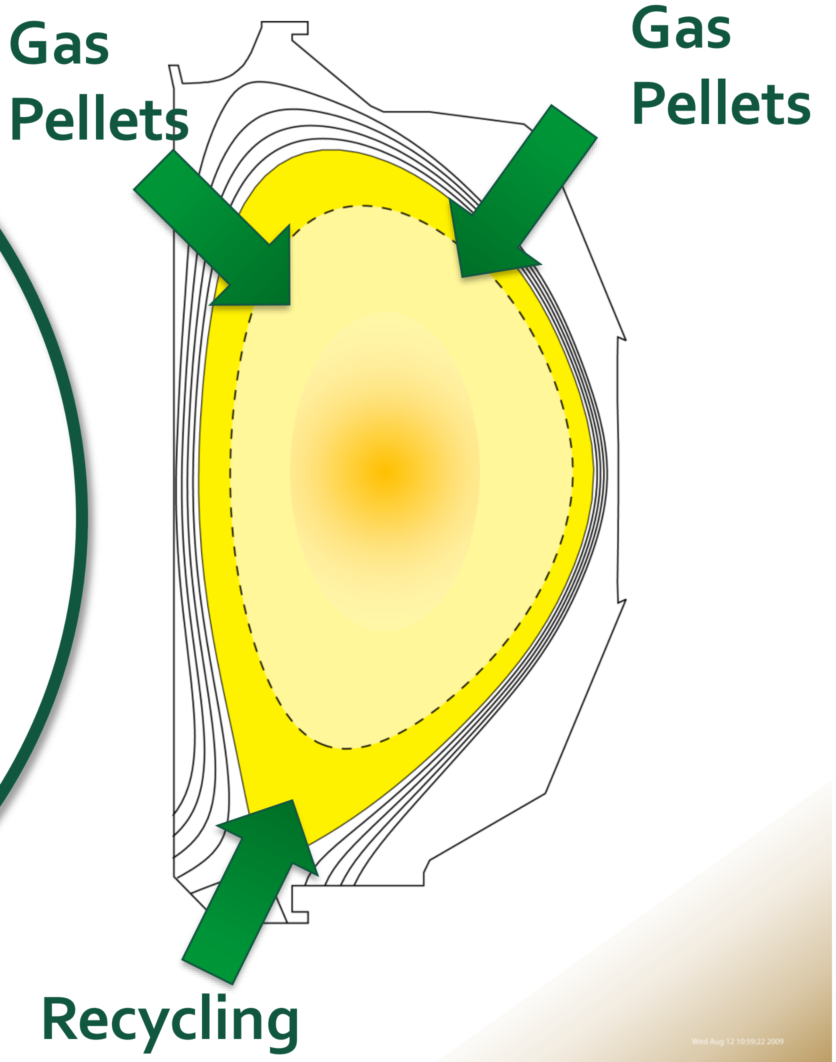

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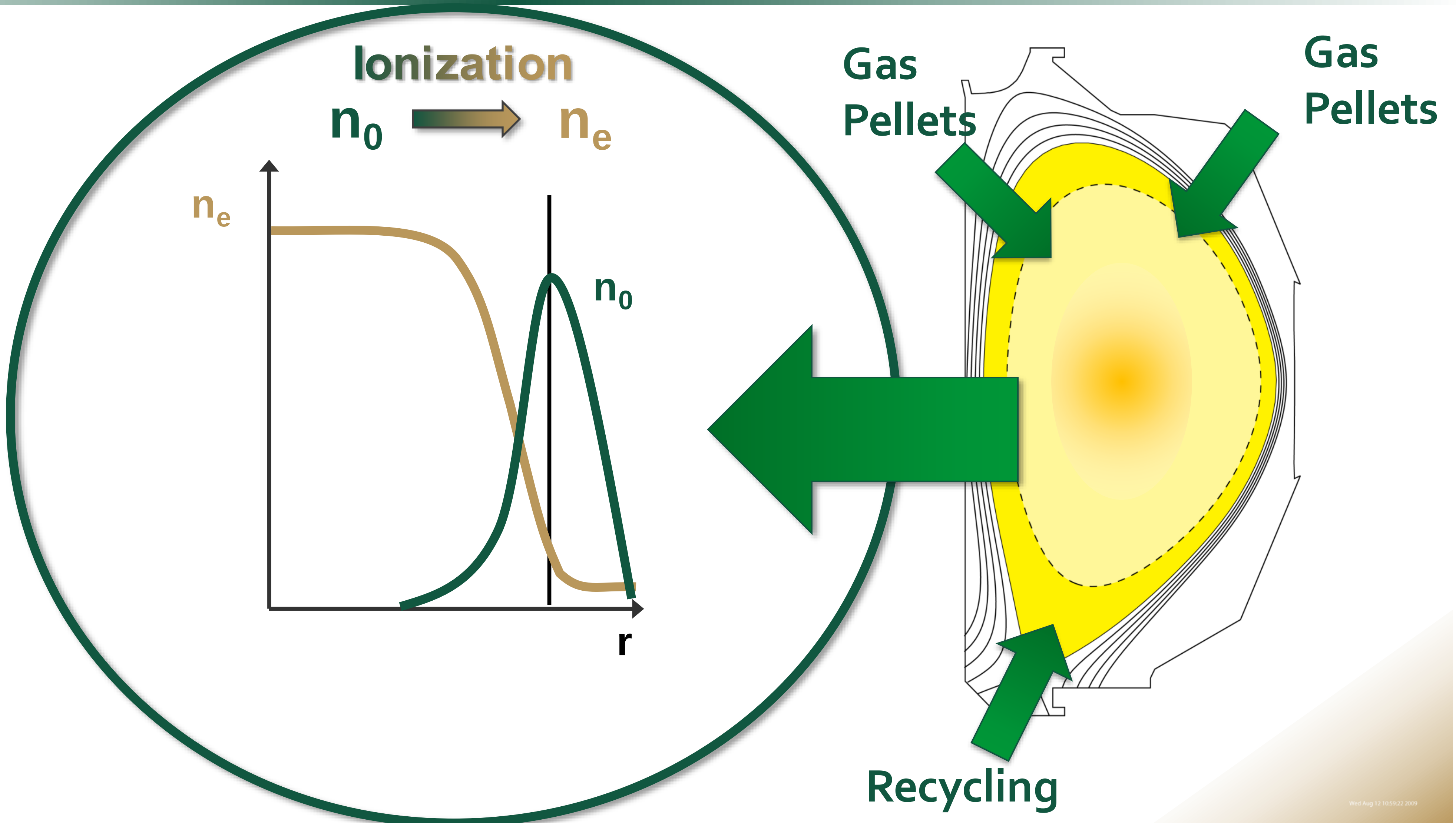

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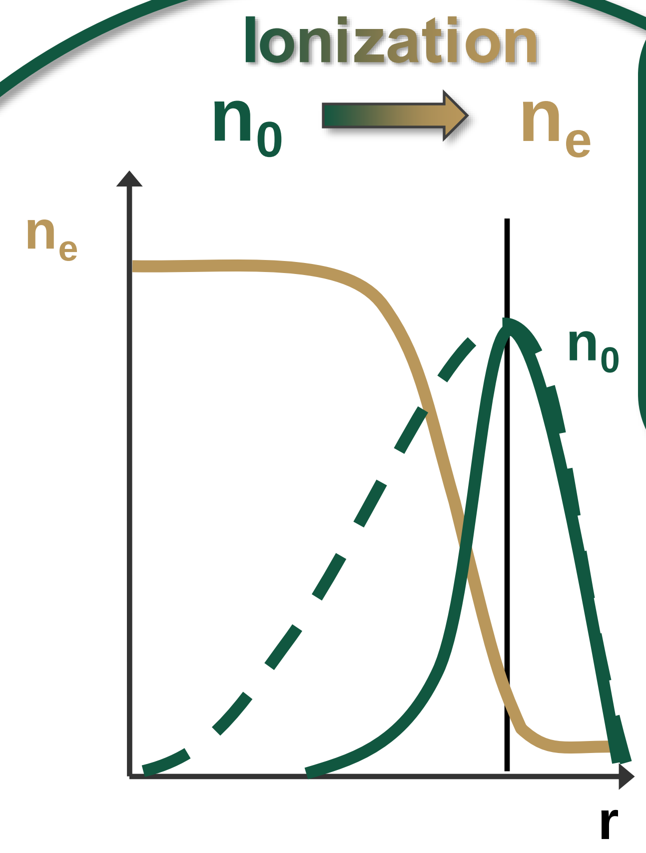

Model 1:

$$\nabla n_e \sim \nabla n_0$$

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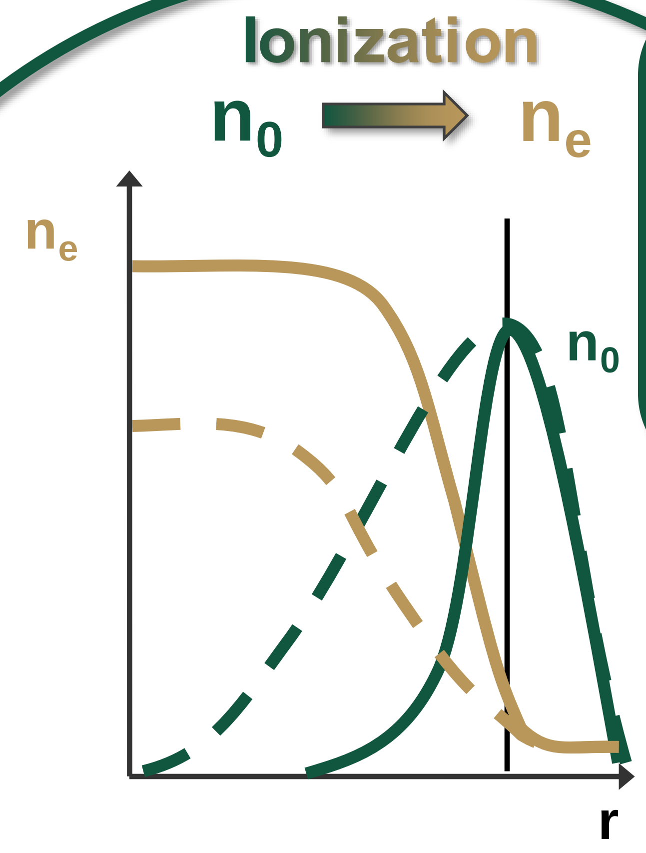

Model 1:

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$$\rightarrow n_{e_{ped}} \sim {}^{1}/_{\Delta n_e}$$

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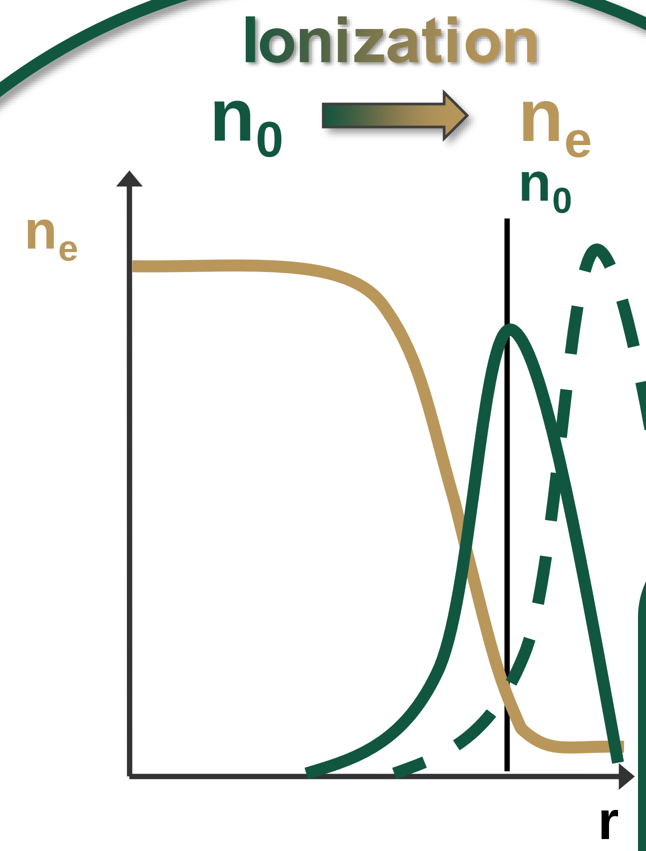

Model 2:

$n_0 \uparrow \Longrightarrow$ shift out in SOL

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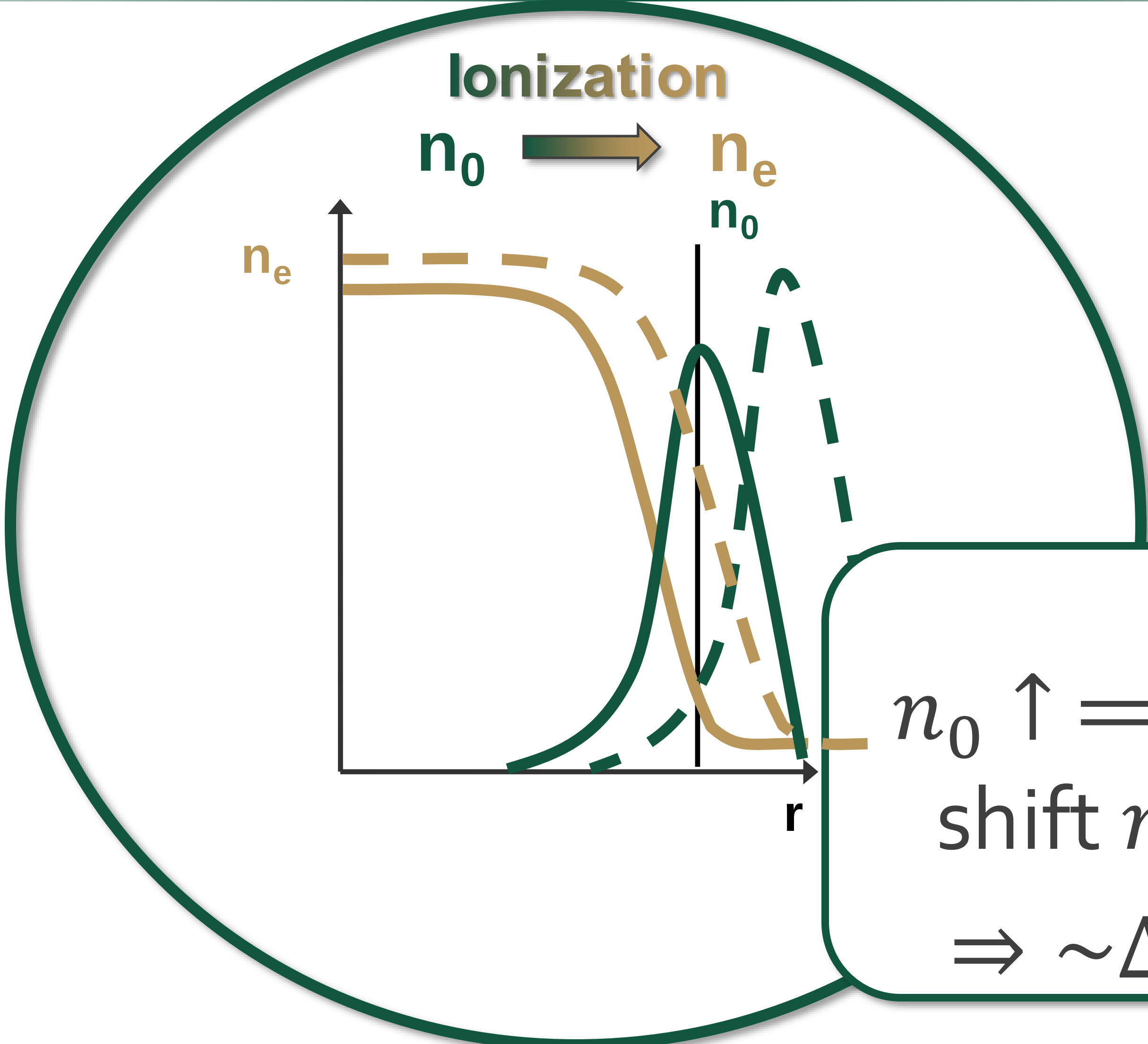

Model 2:

$n_0 \uparrow \Longrightarrow$ shift out in SOL

shift $n_{e_{ped}}$ out in SOL

$\Rightarrow \sim\Delta(n_e - T_e) \neq 0$

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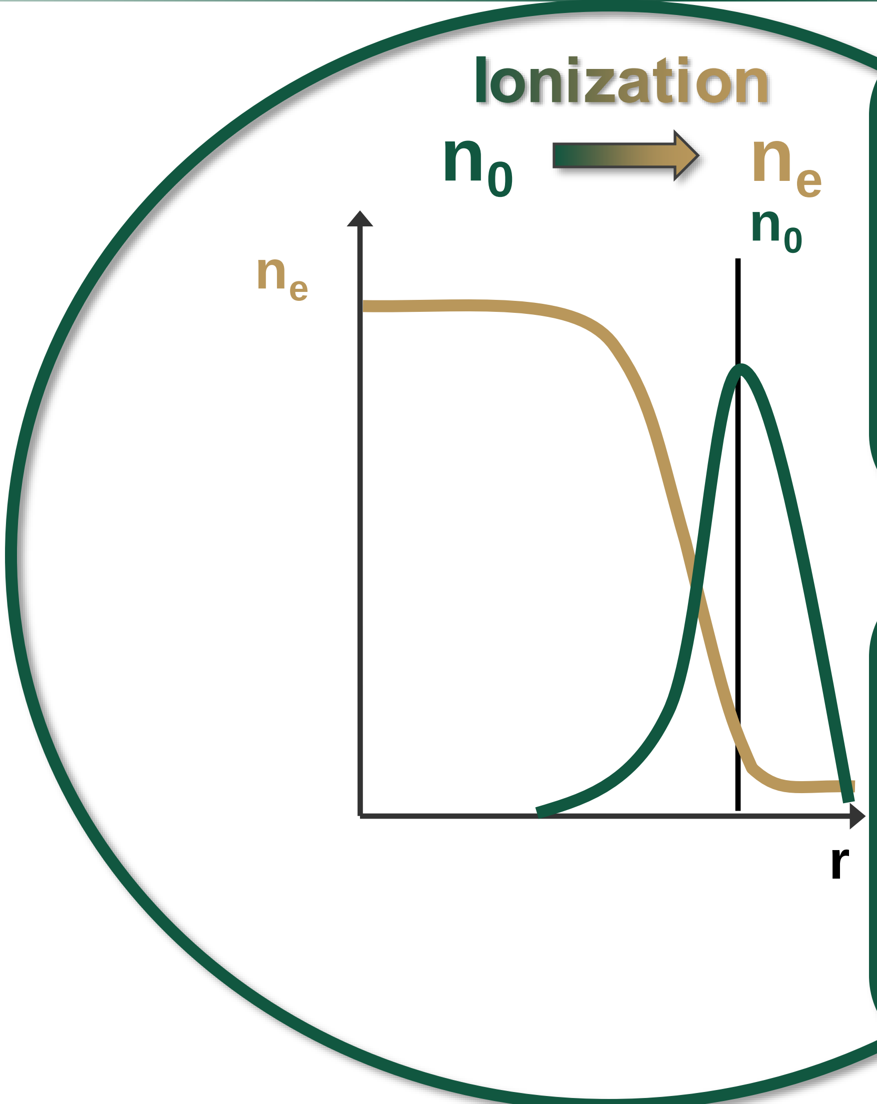

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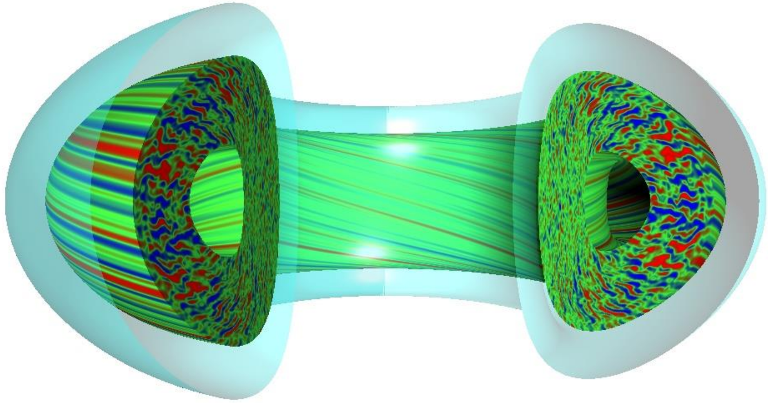
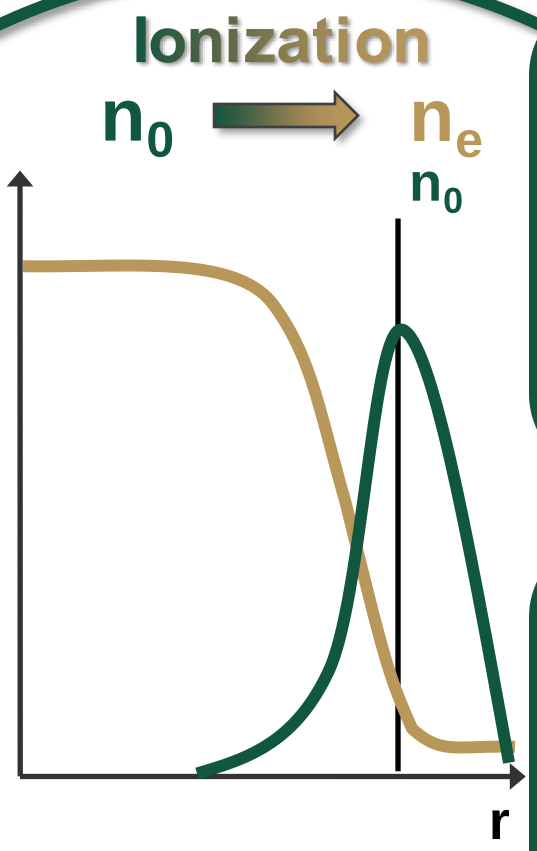


Courtesy GA theory group
General Atomics



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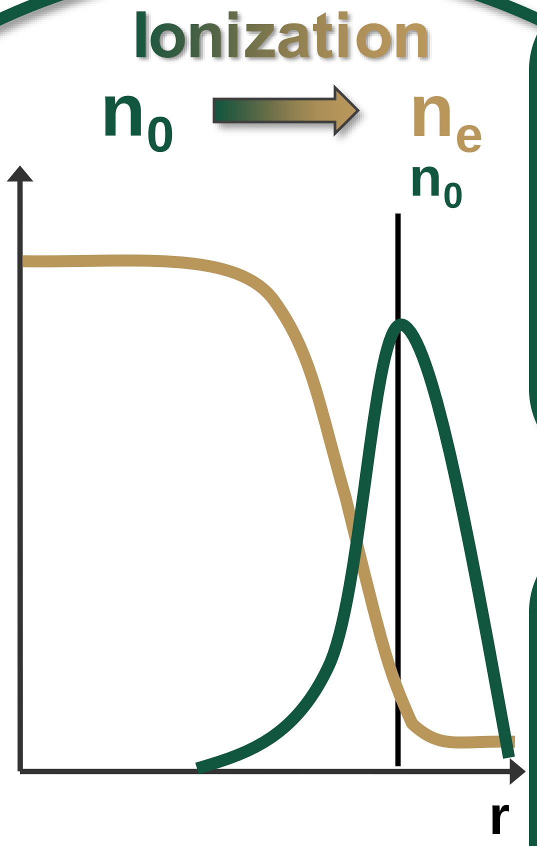
$$\mathrm{T} = -D\nabla n + vn$$



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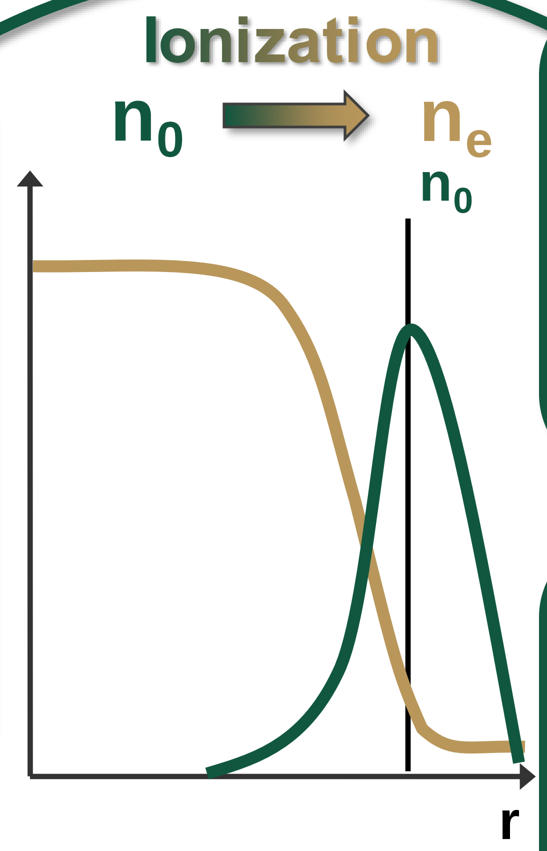

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What sets the pedestal density profile?

In future reactor role of transport becomes dominant

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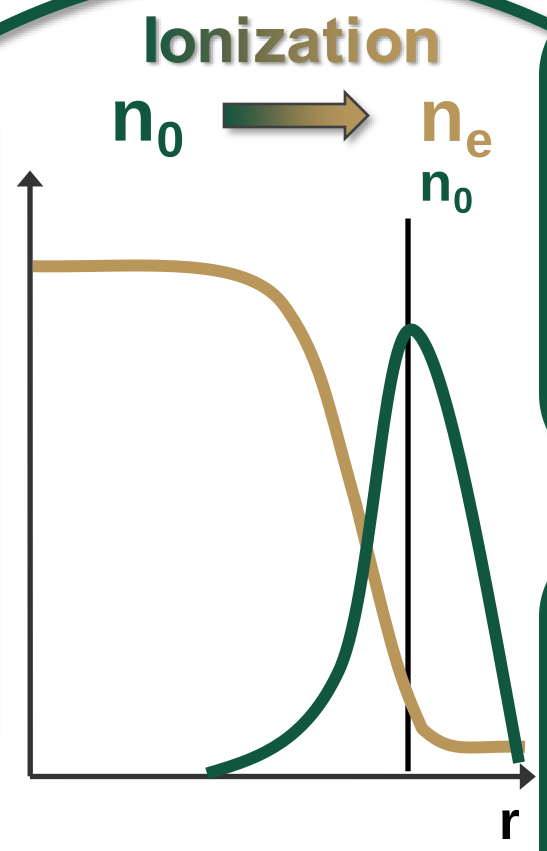

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$\nabla n_e \sim \nabla$

$-$ Δn_e

n_0 ift SOL

e_{ped} out L

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$$\Gamma = -D\nabla n + vn$$

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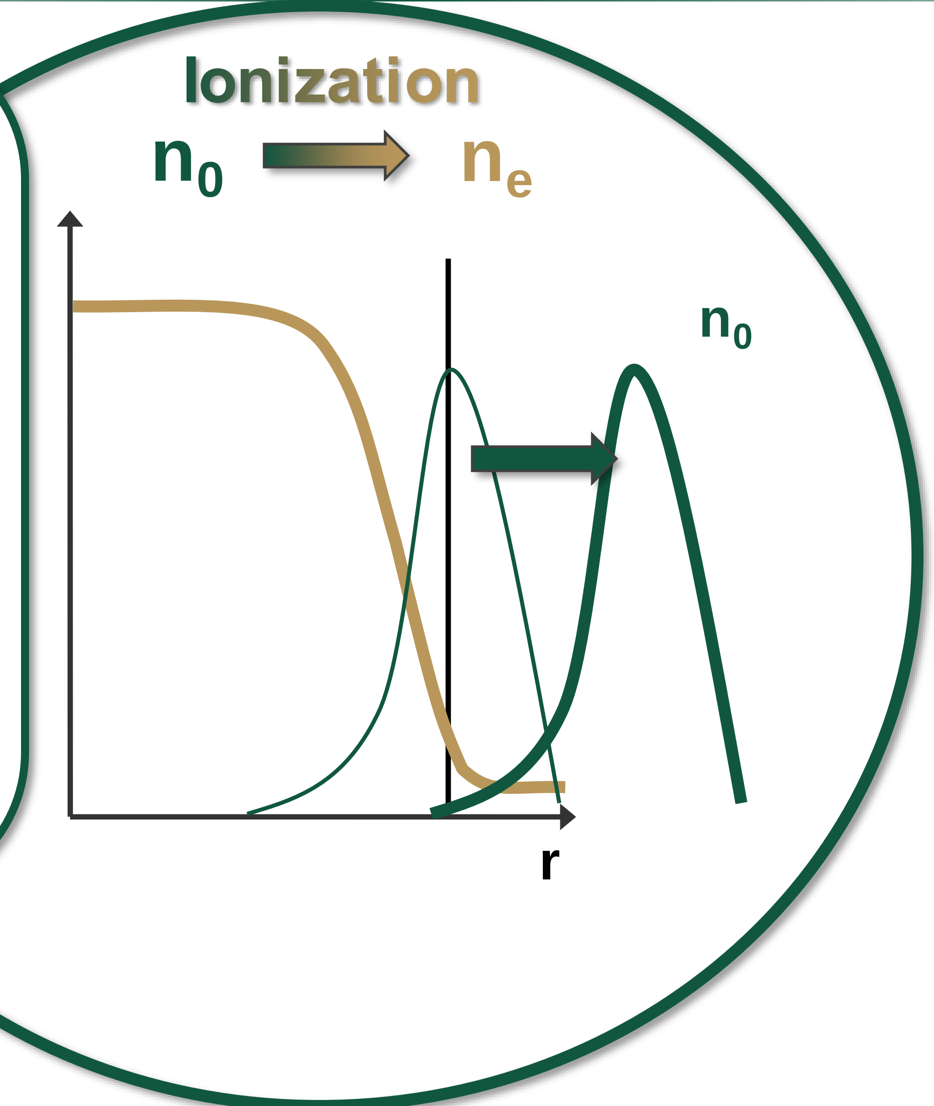

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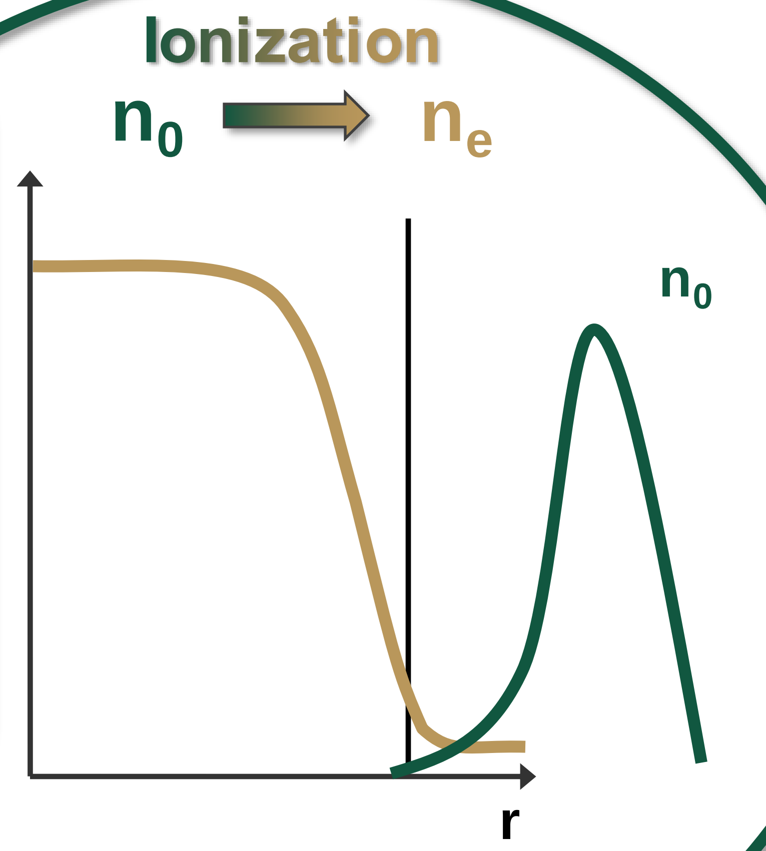

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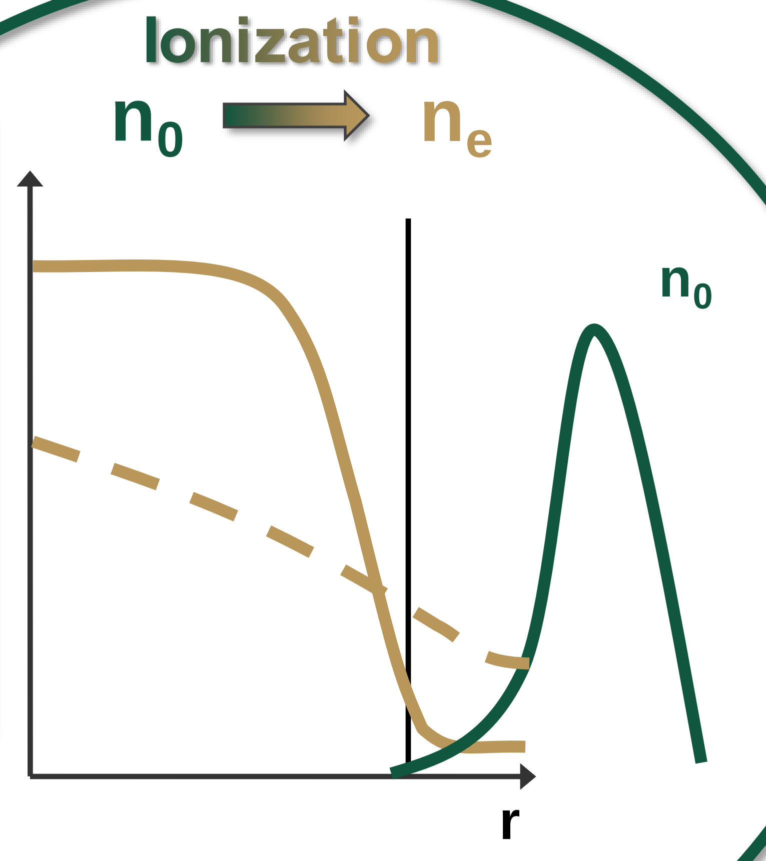

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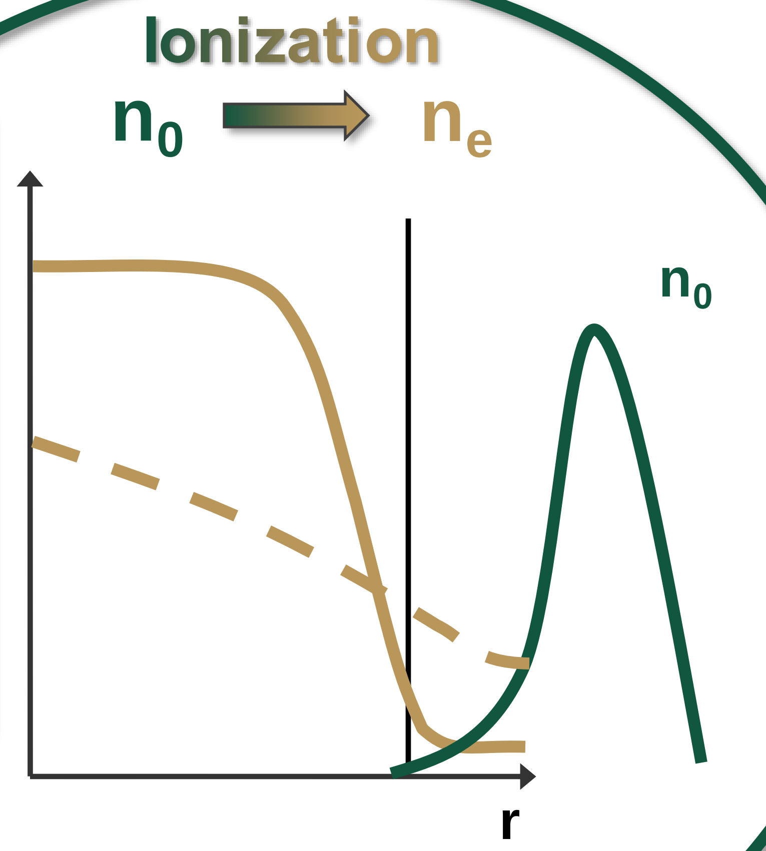

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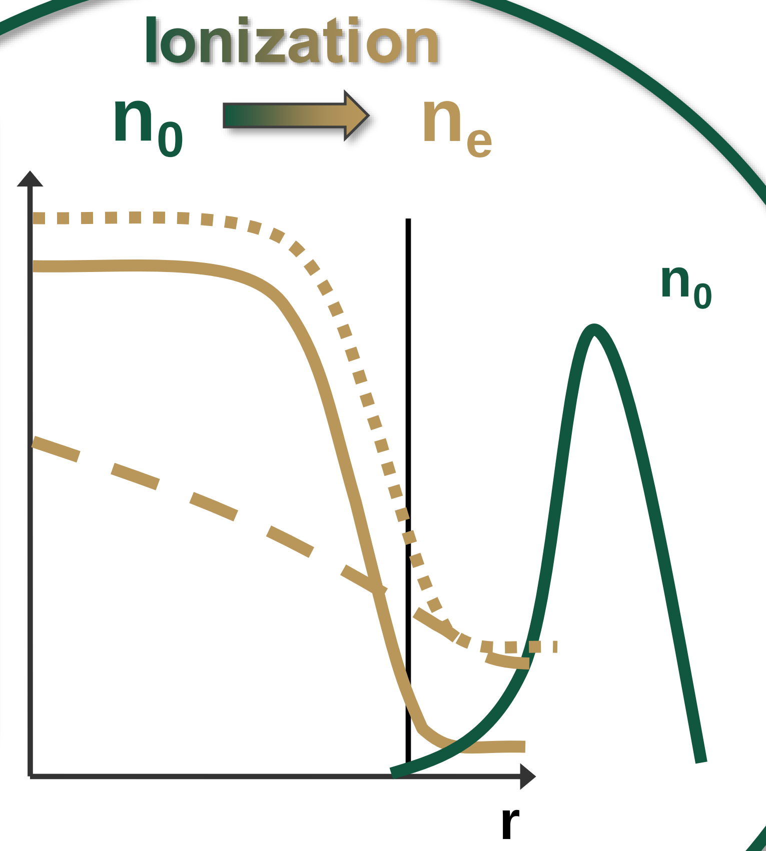
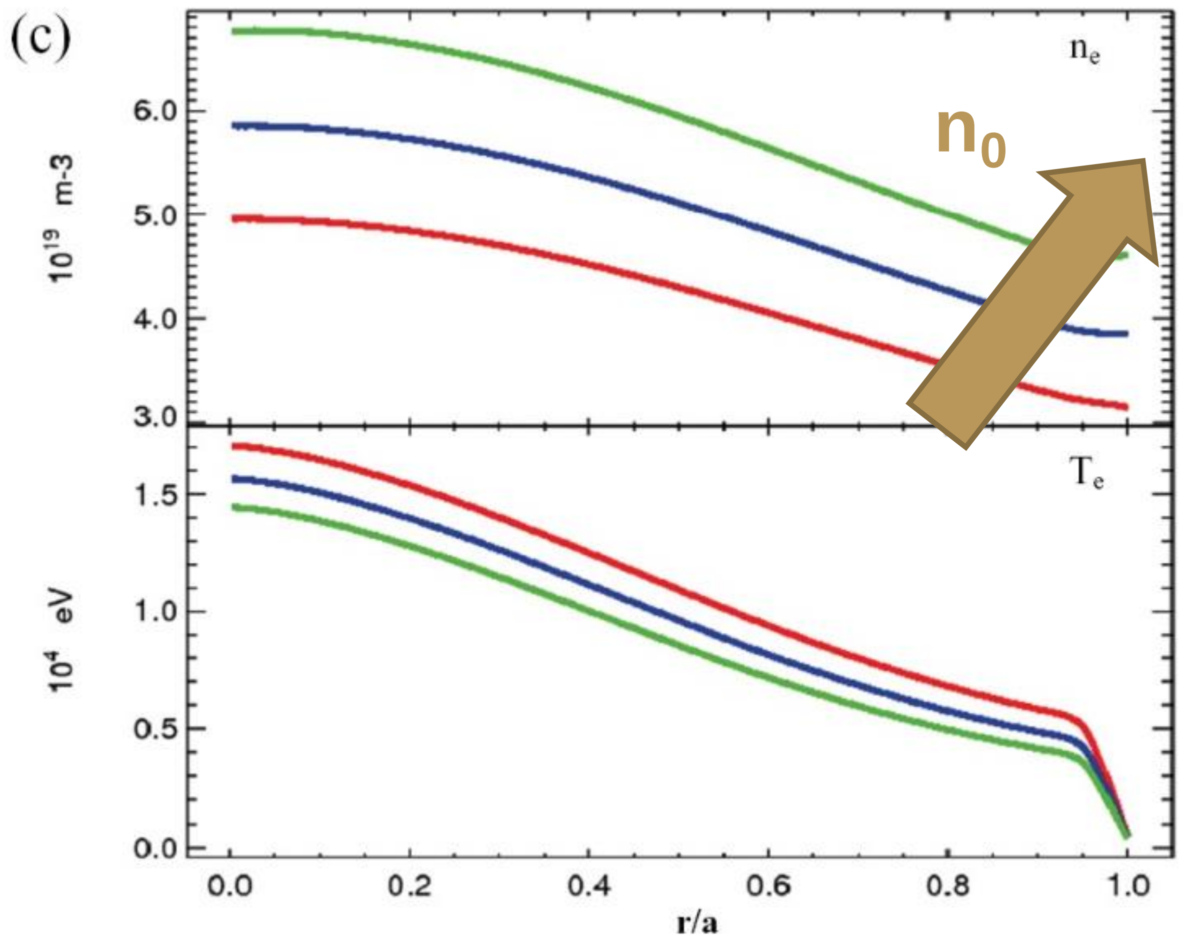


Integrated predictive modeling for ITER based on understanding of current devices result in disappearance of density pedestal structure

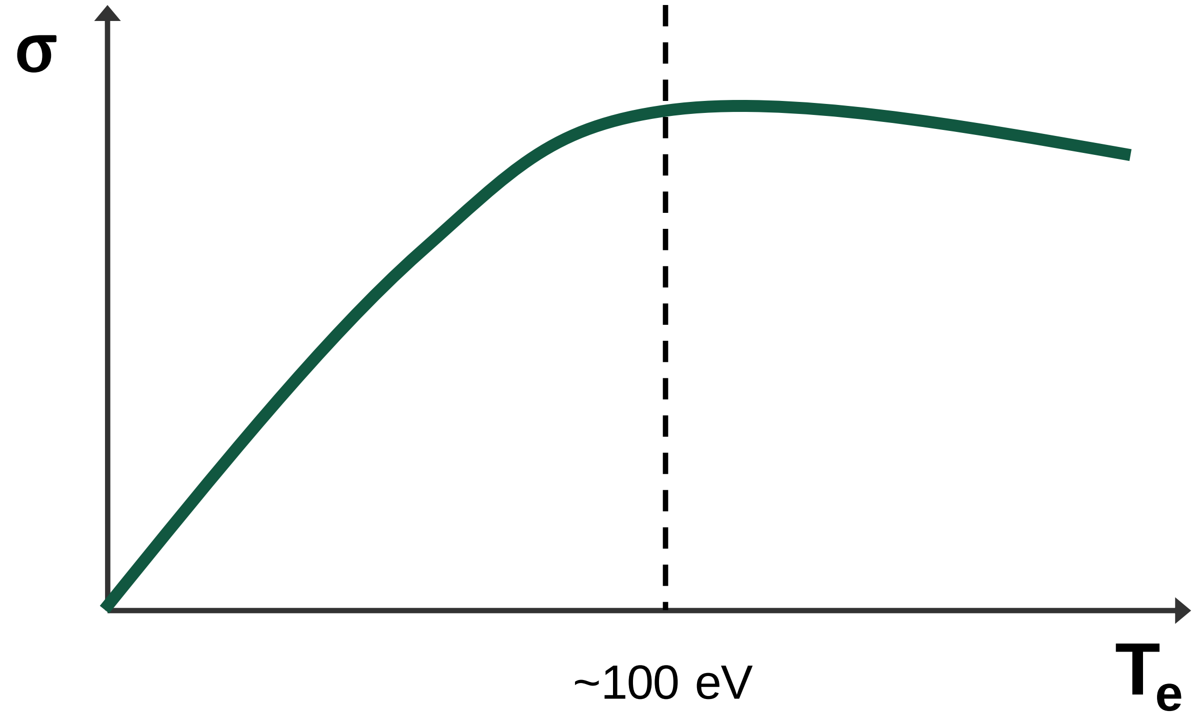
- Integrated modeling using JINTRAC & SOLPS to predict ITER profiles
- The model relies for transport on a diffusion coefficient
- Increases in fueling does not result in a shift, nor an increase of the density gradient
- Need to perform experiments to investigate the role of opacity



M. Romanelli *et al* 2015 *Nucl. Fusion* **55** 093008

How do pedestals change when the SOL becomes more opaque?

Low opacity → **High opacity**



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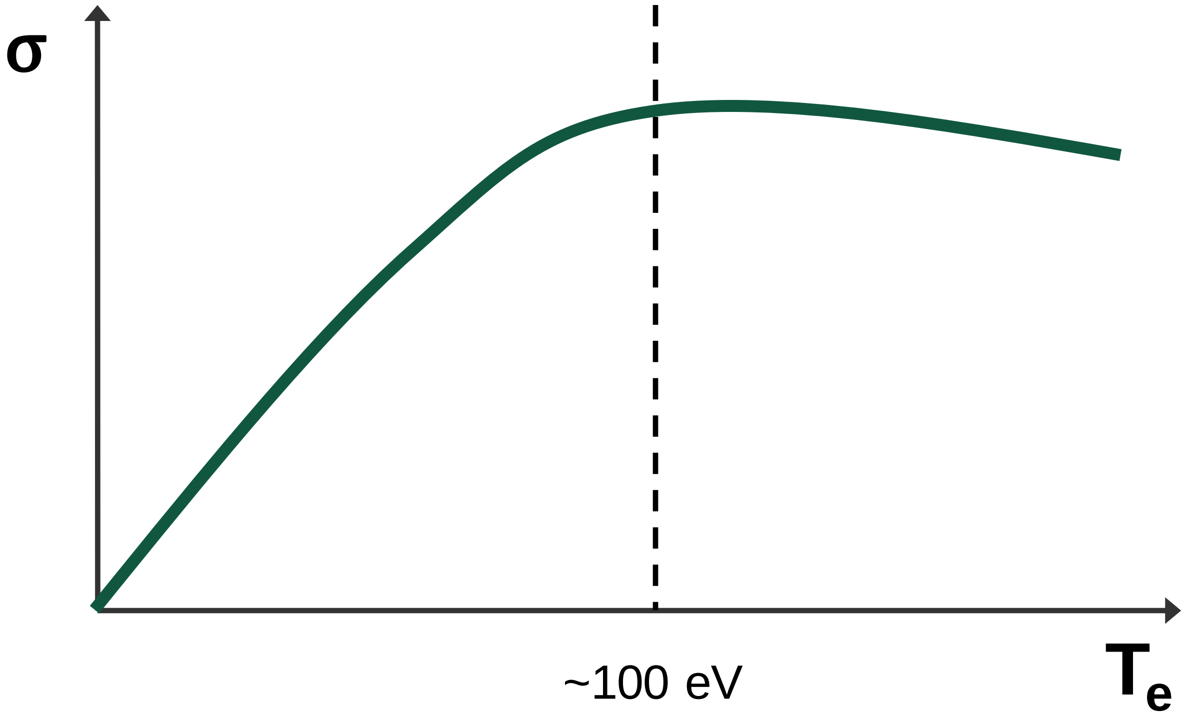
Low opacity | **High opacity**

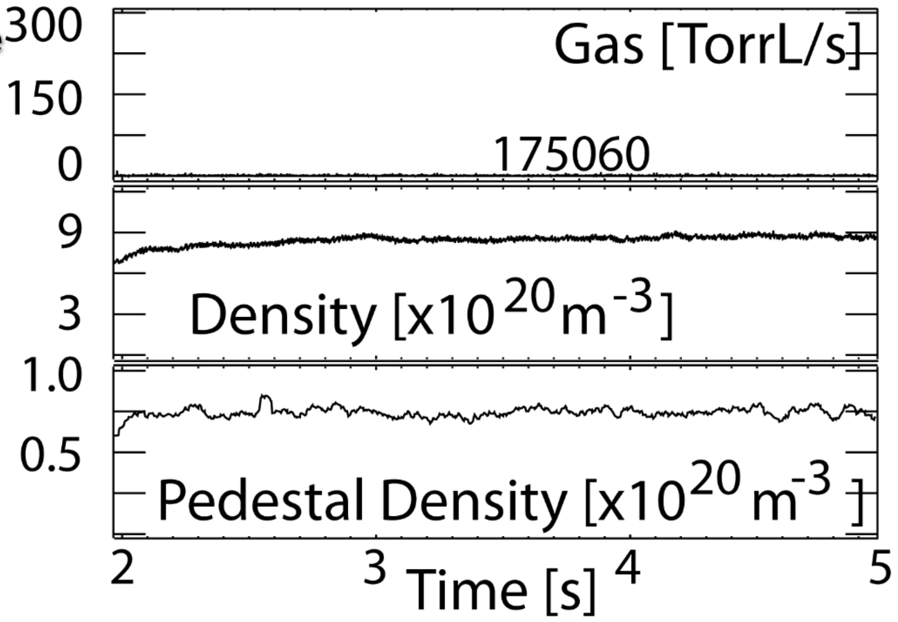
Lower n_e | **Higher n_e**

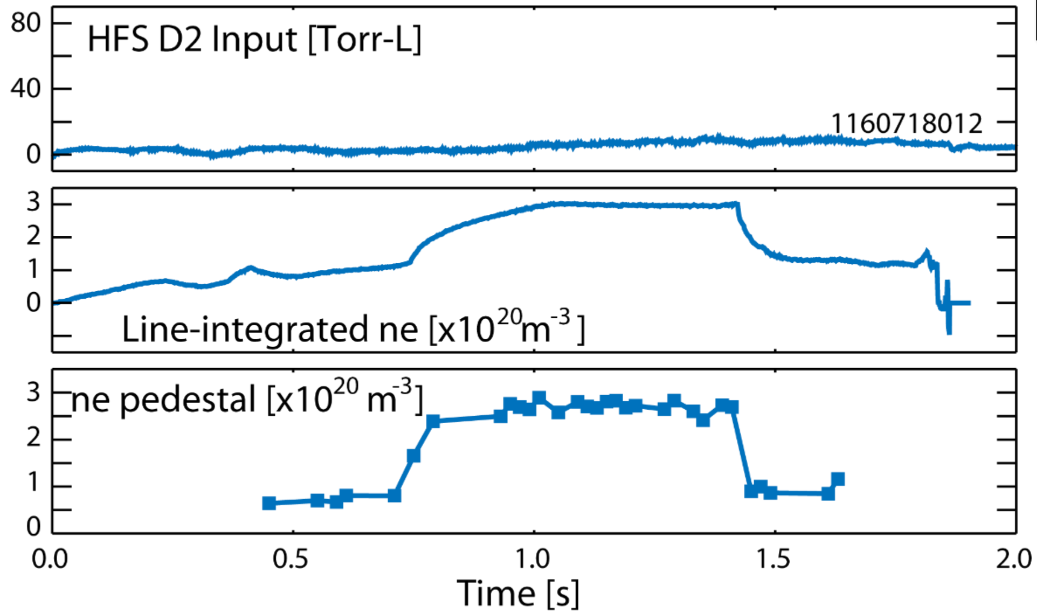


Experiments on DIII-D and C-Mod were performed to scan a variety of level of opacity using changes in Ip and gas fueling

Low opacity **High opacity**

Lower n_e



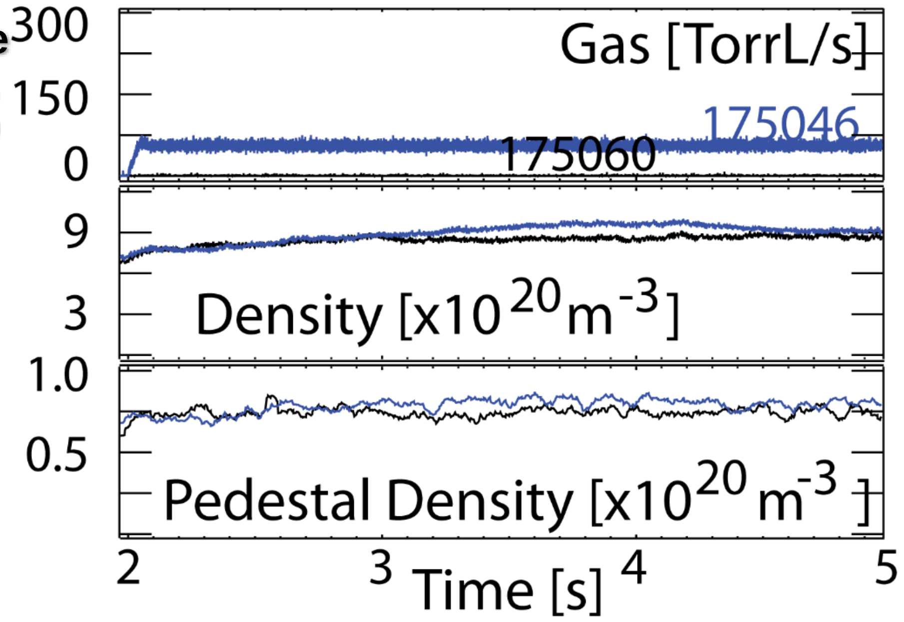


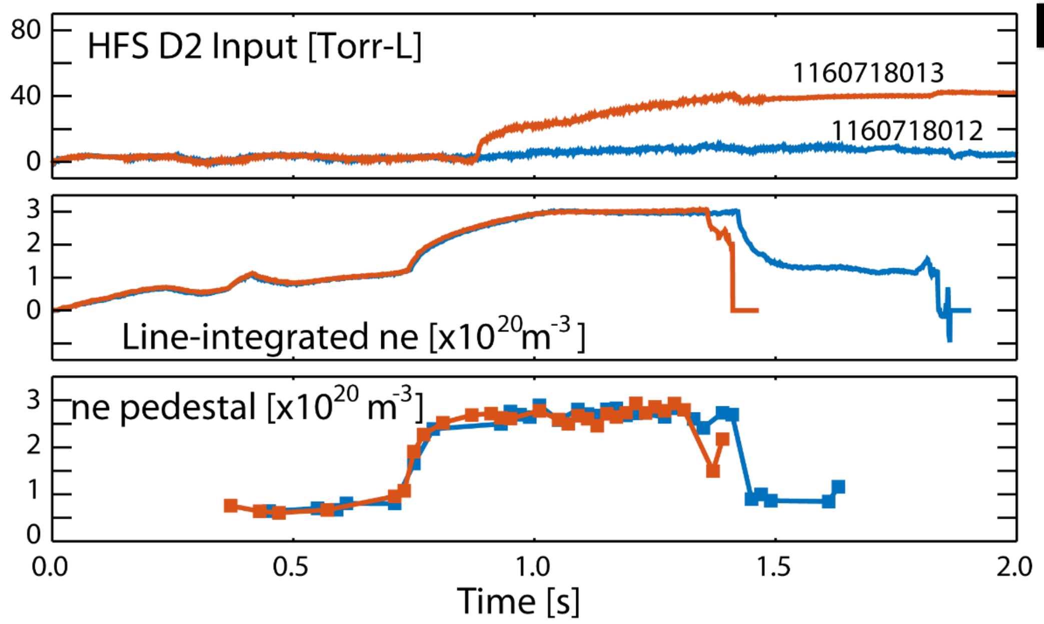
Higher n_e

Experiments on DIII-D and C-Mod were performed to scan a variety of level of opacity using changes in Ip and gas fueling

Low opacity → **High opacity**

Lower n_e → **Higher n_e**





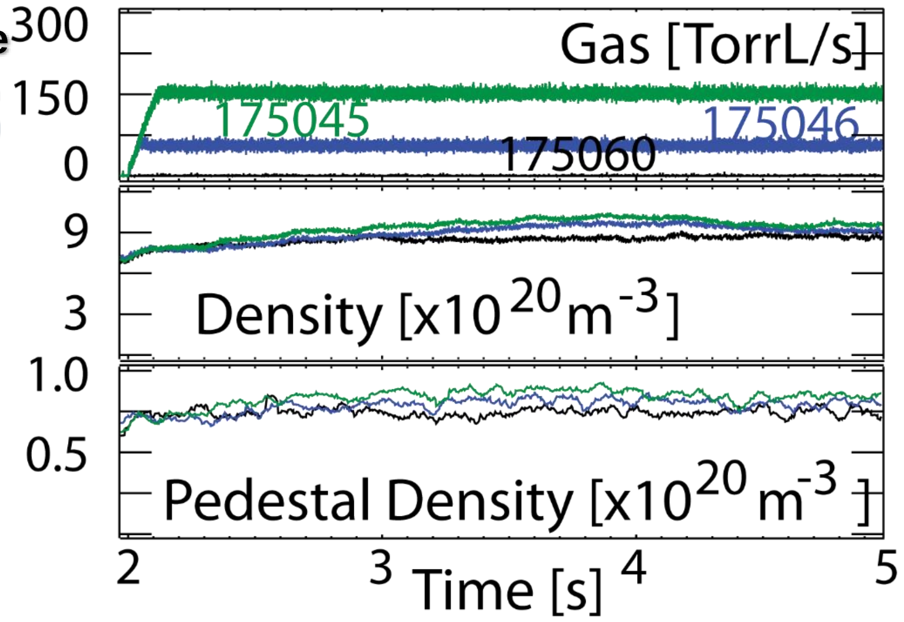
DIII-D NATIONAL FUSION FACILITY

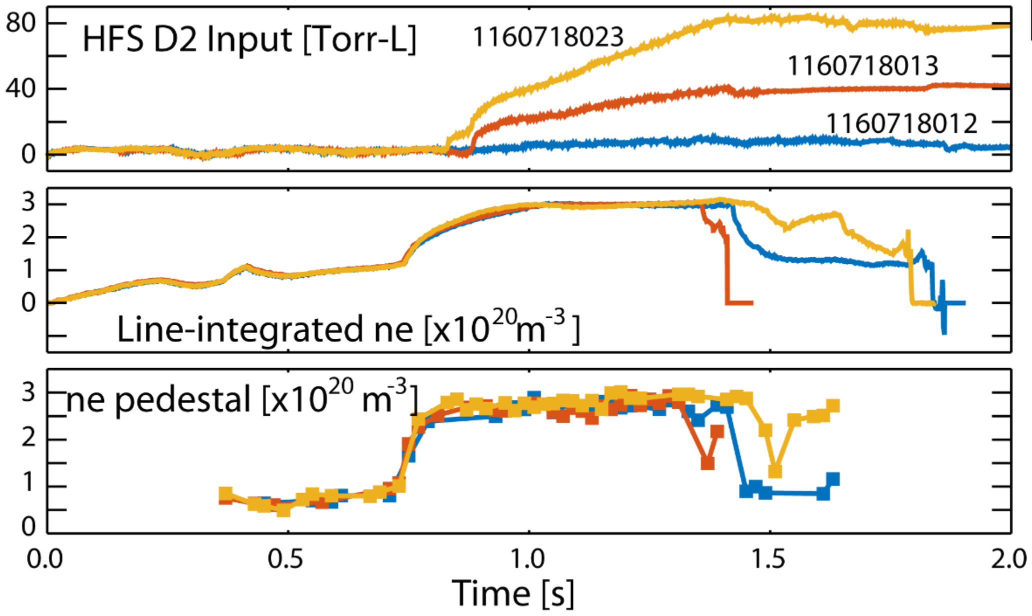
Alcator C-Mod

Experiments on DIII-D and C-Mod were performed to scan a variety of level of opacity using changes in Ip and gas fueling

Low opacity **High opacity**

Lower n_e **Higher n_e**





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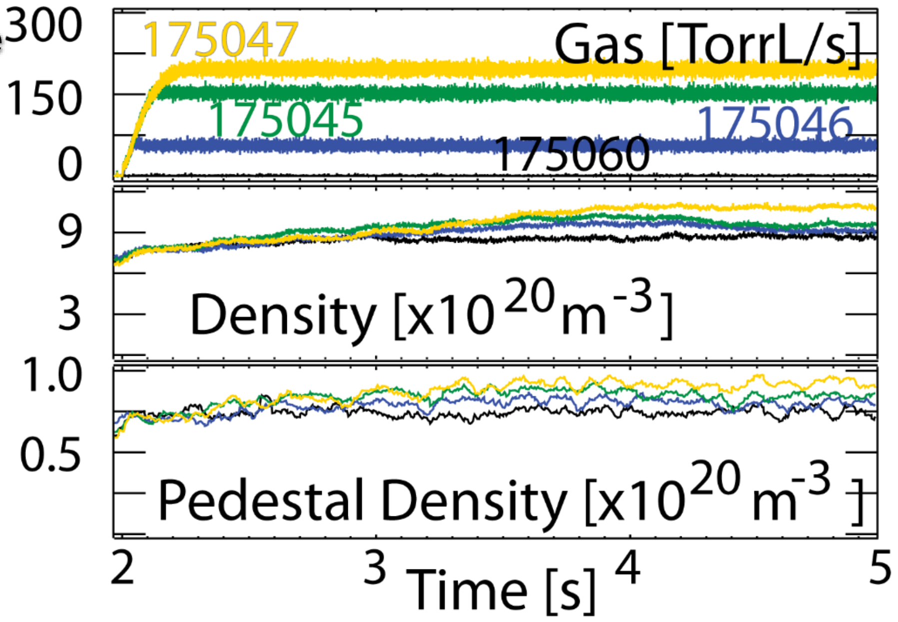

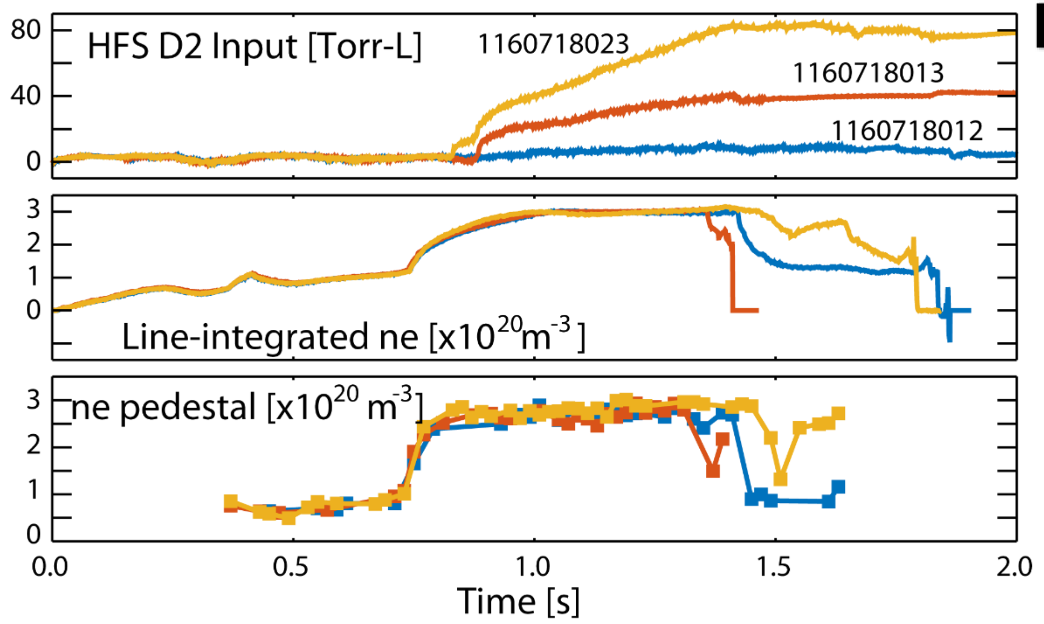

Higher n_e

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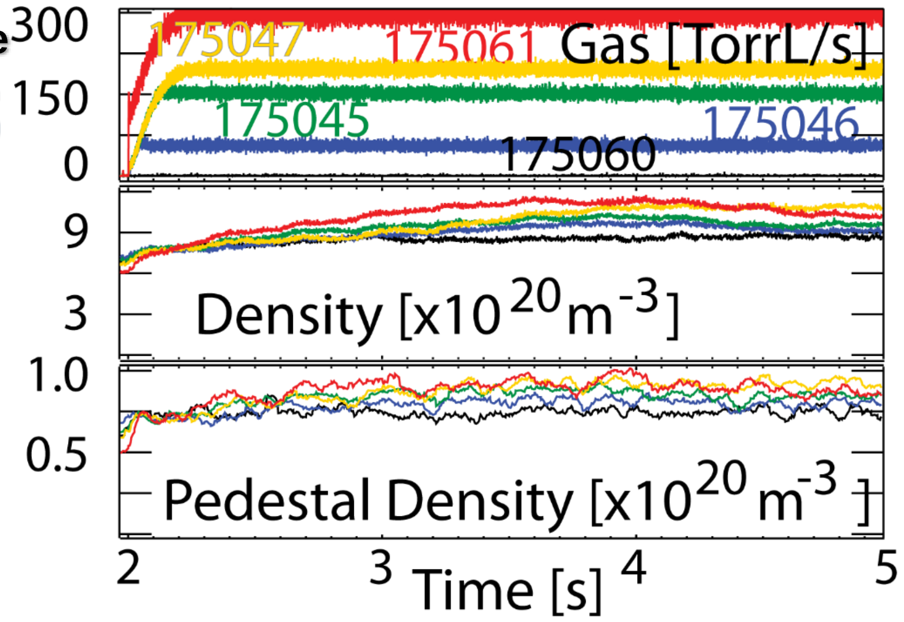
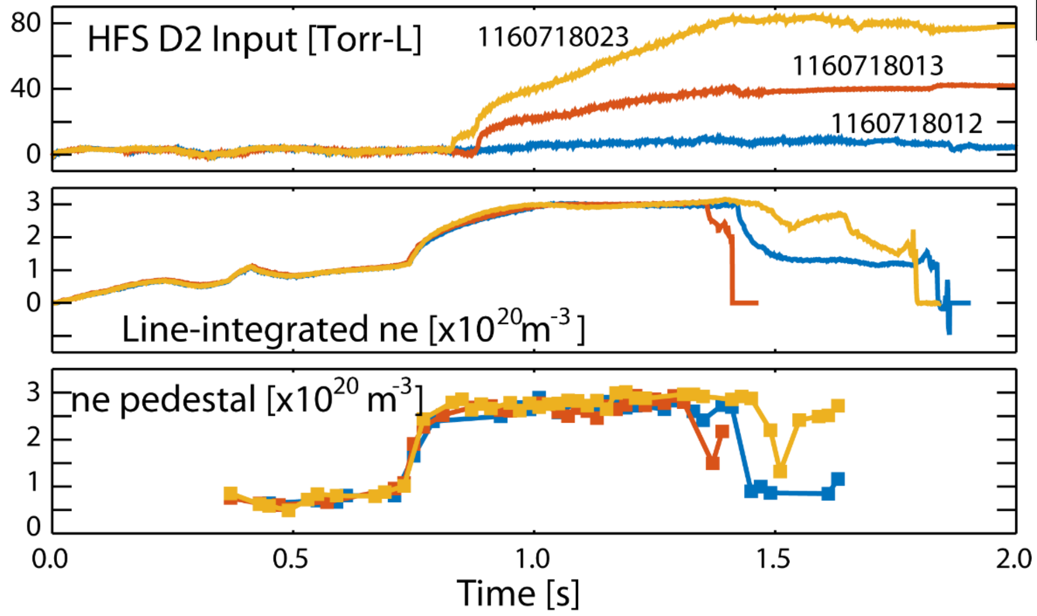
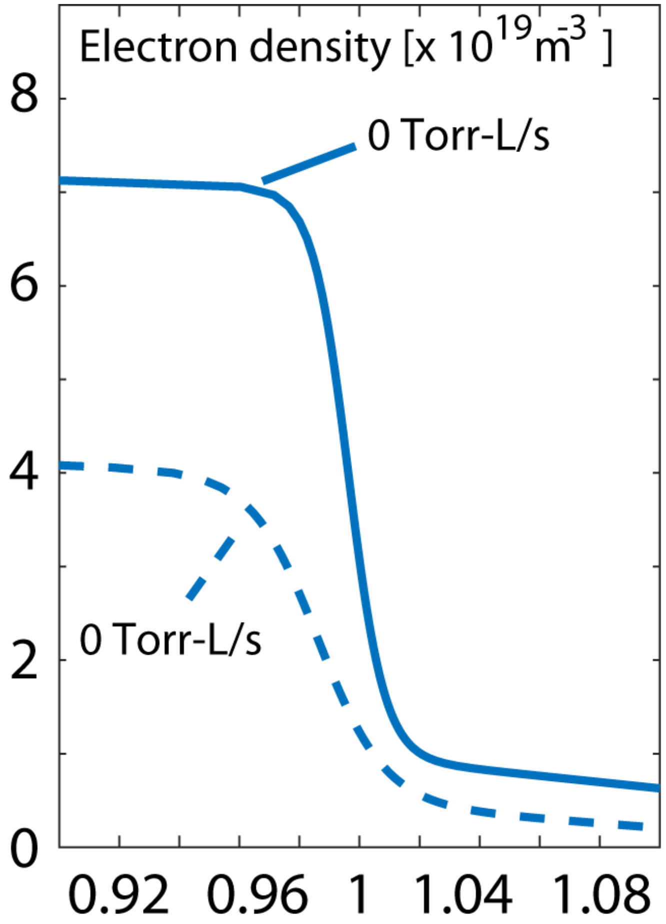


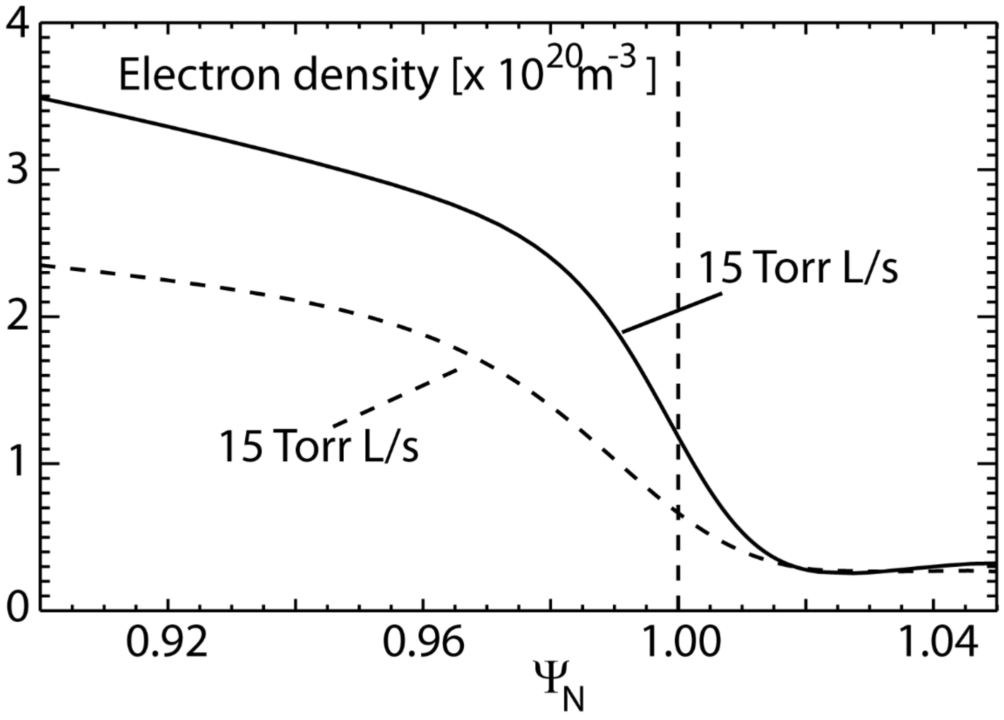


How does the pedestal structure change with increasing opacity and what is the effect of additional fueling?

Low opacity

Lower n_e





High opacity

Higher n_e

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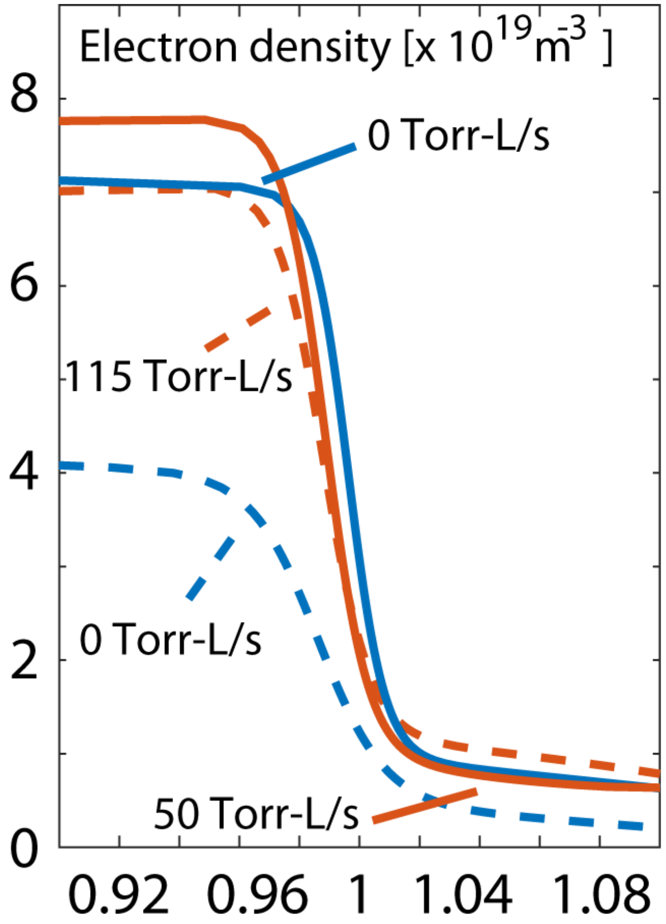
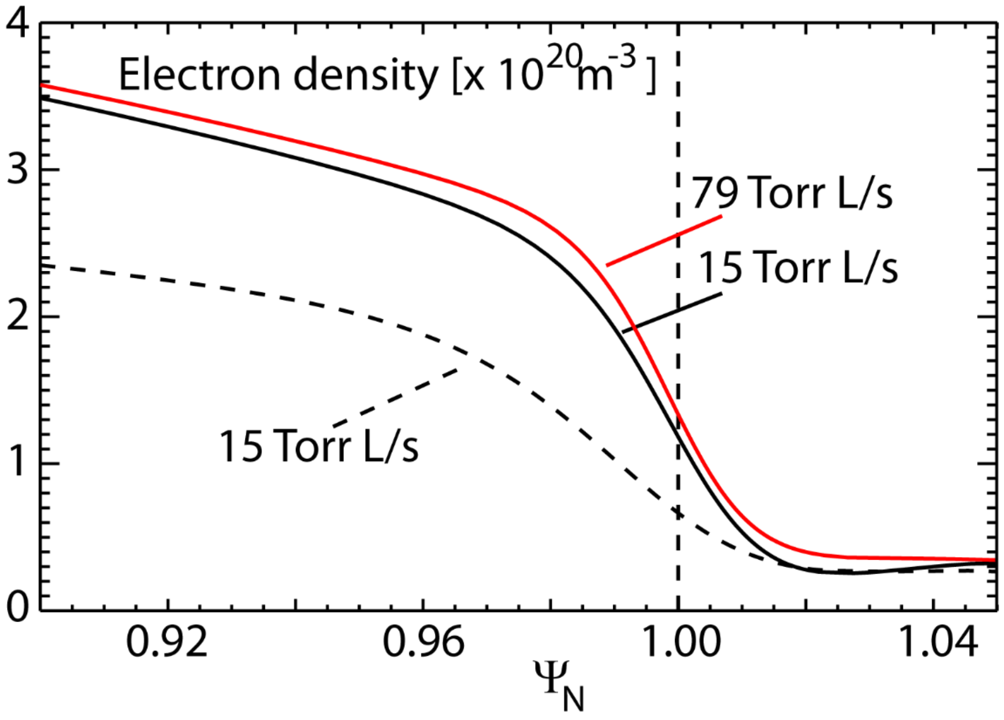


High opacity

Higher n_e



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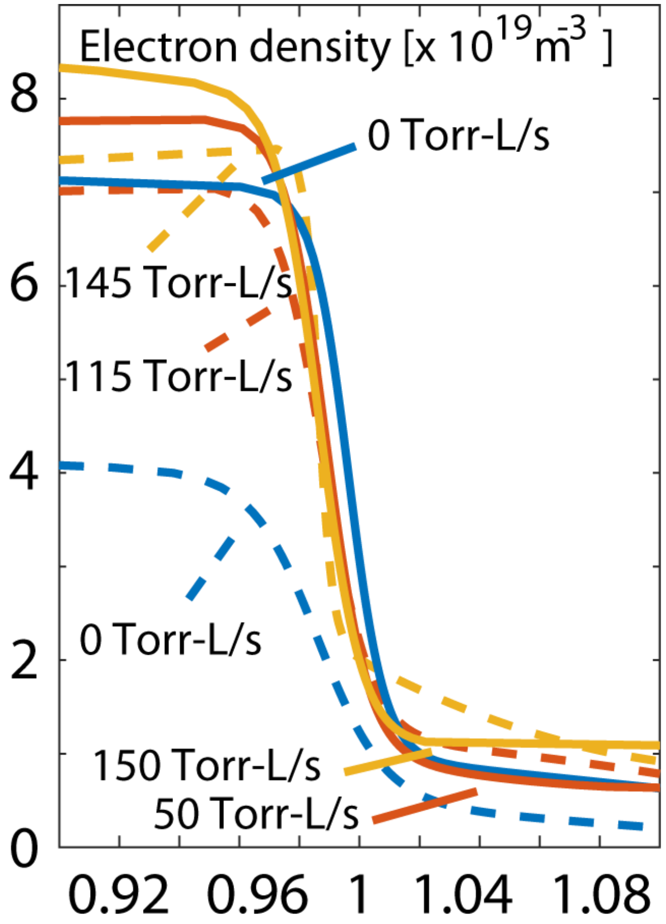

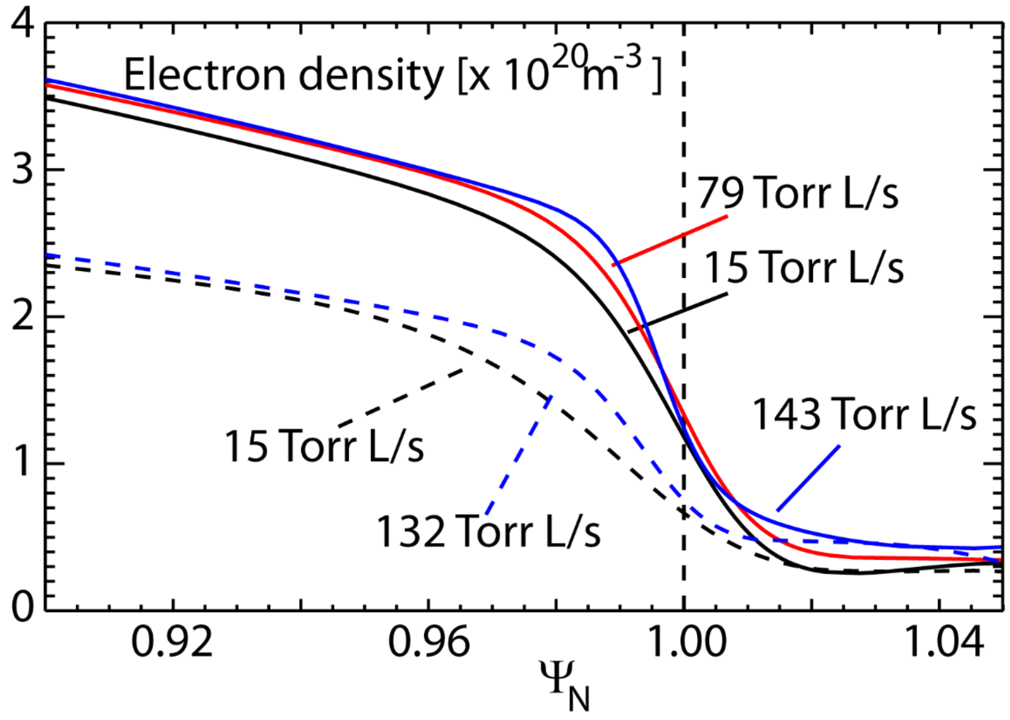

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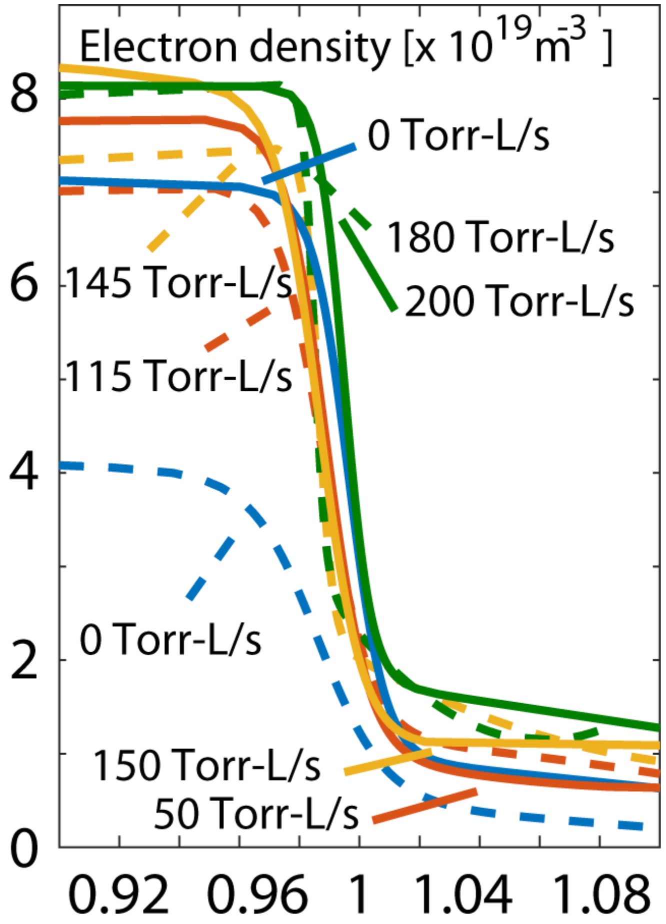

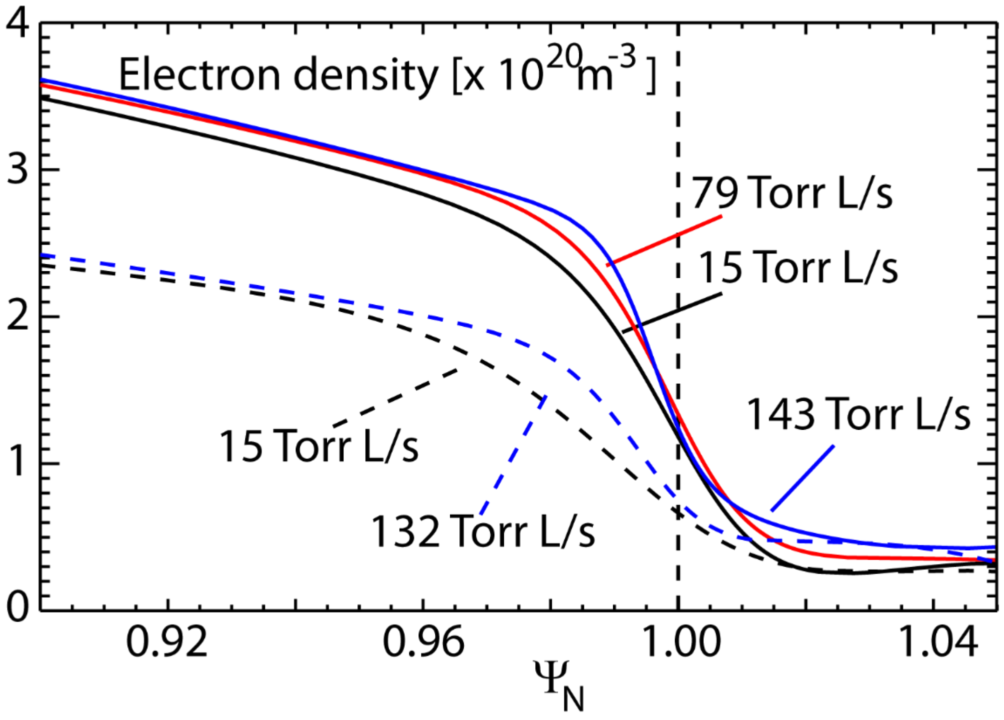

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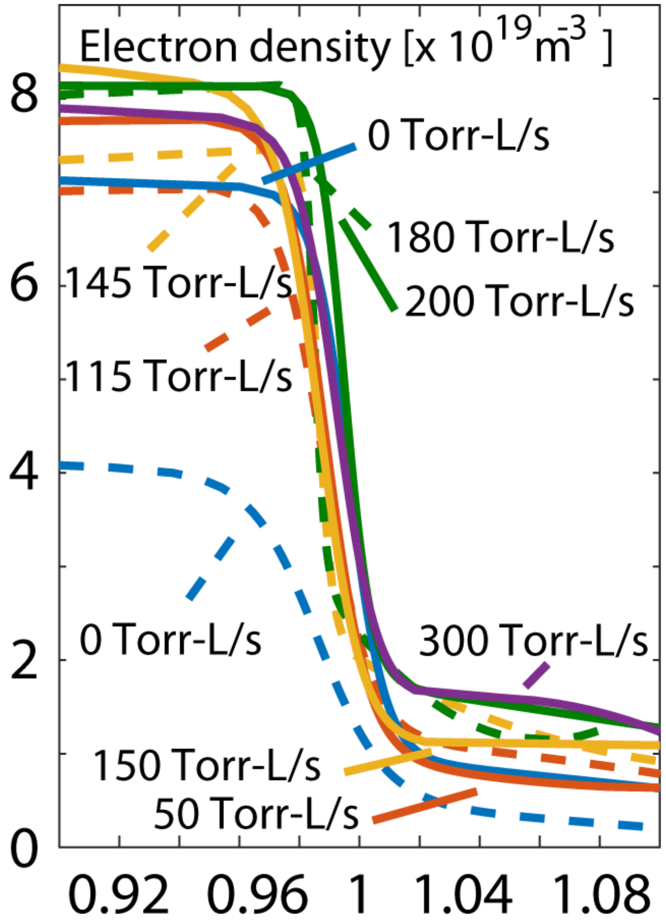

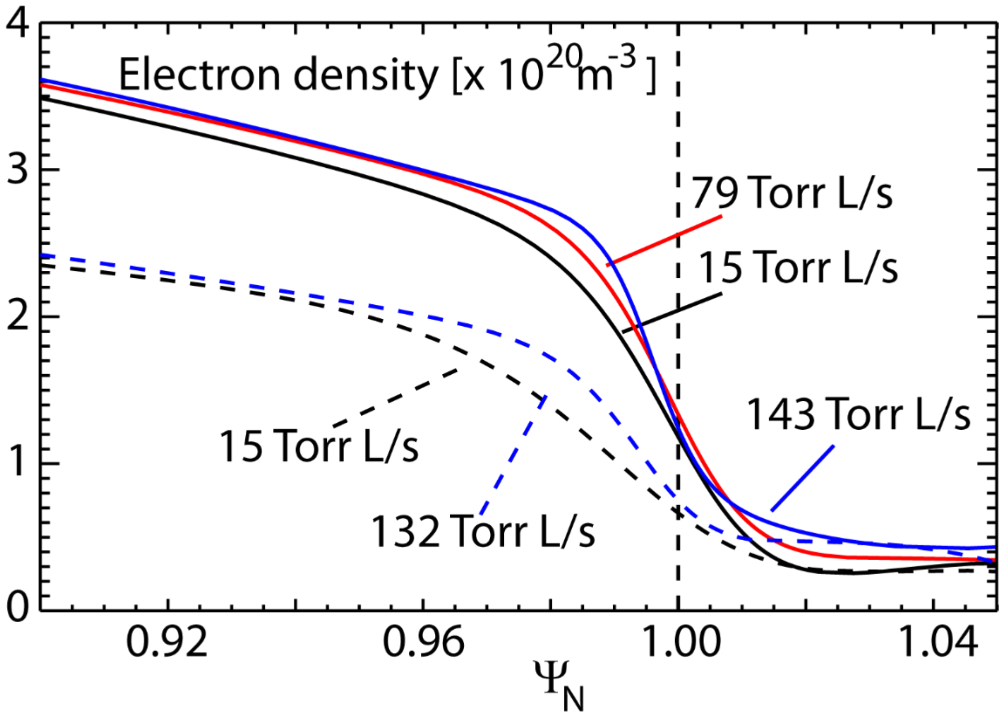

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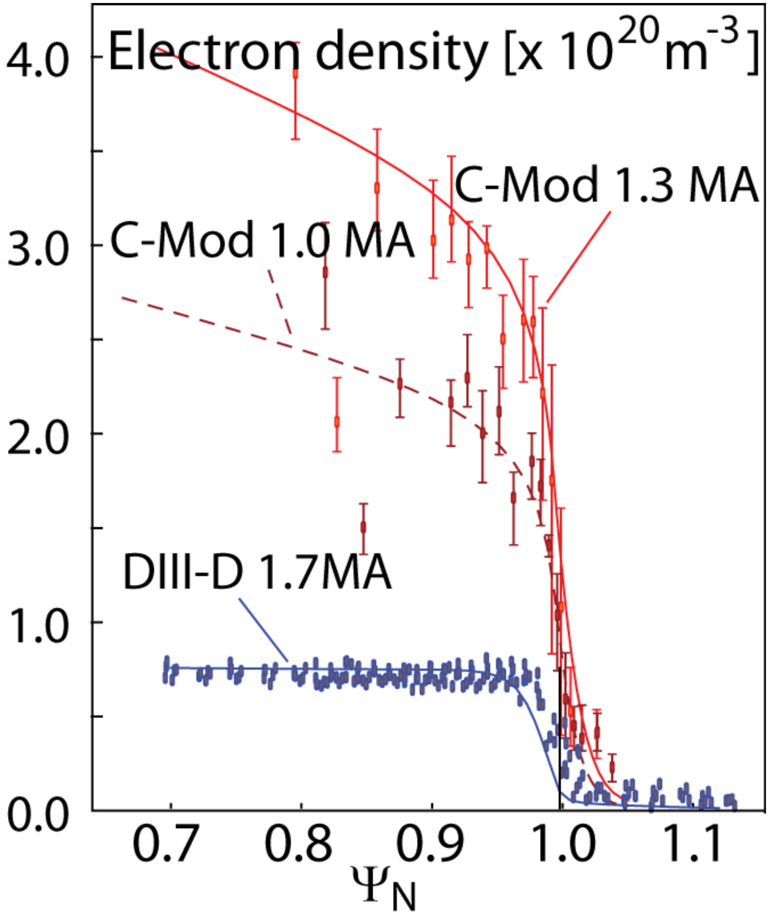


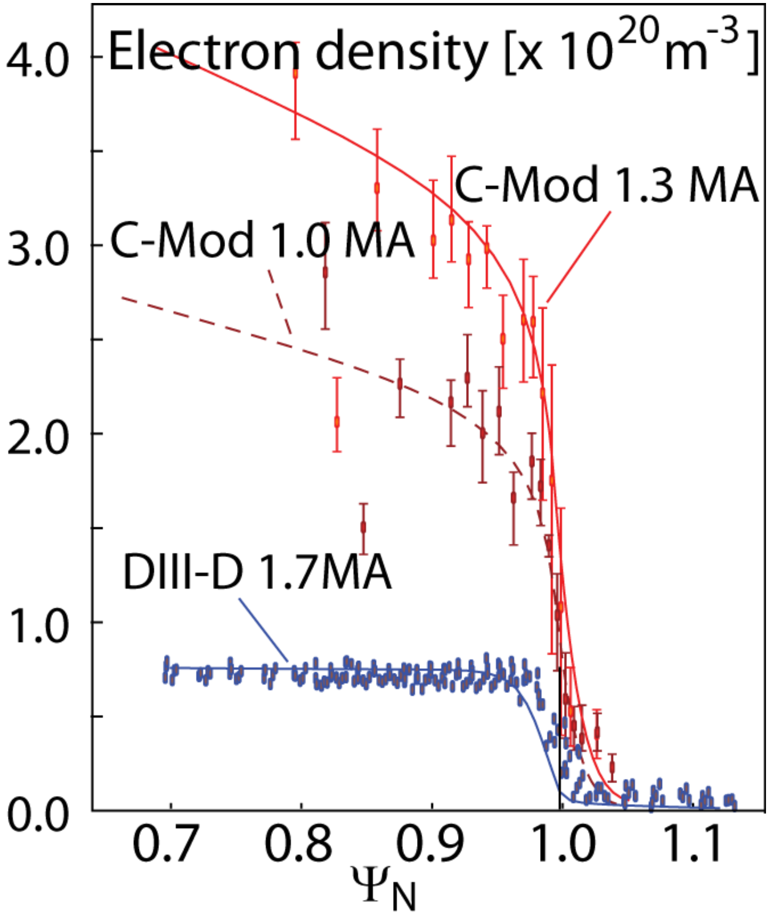
Normalized increases in gas fueling result in an increase in the SOL density independent of opacity levels

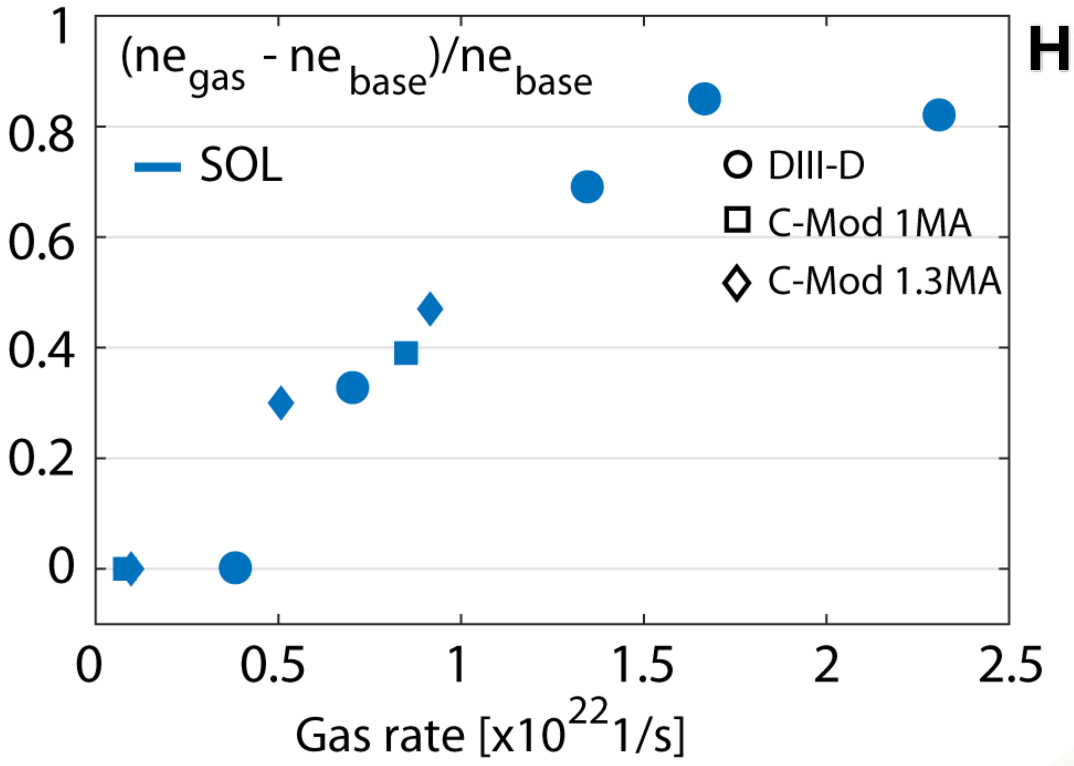
Low opacity

Lower n_e

High opacity

Higher n_e





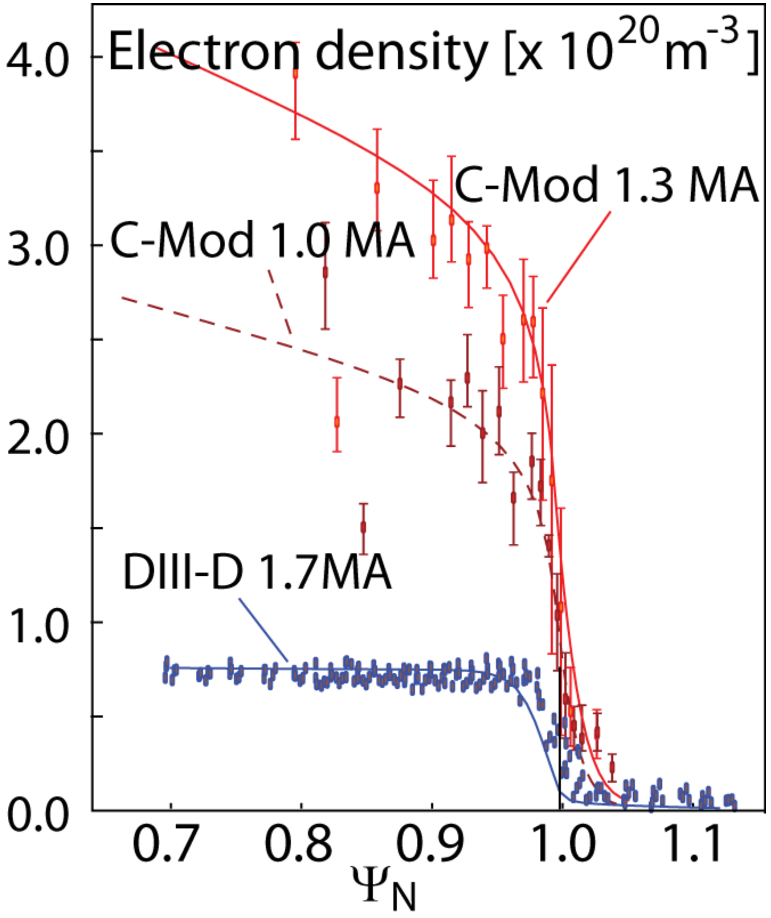
Normalized increases in gas fueling result in a much more modest increase of the separatrix density

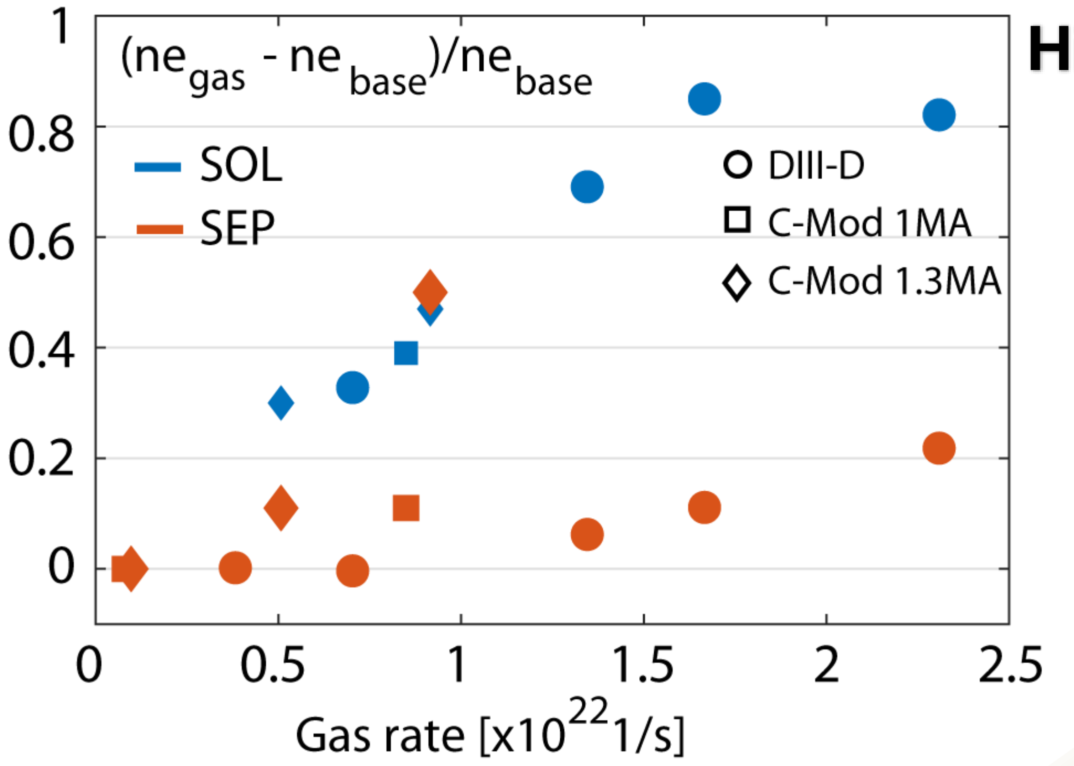
Low opacity

Lower n_e

High opacity

Higher n_e

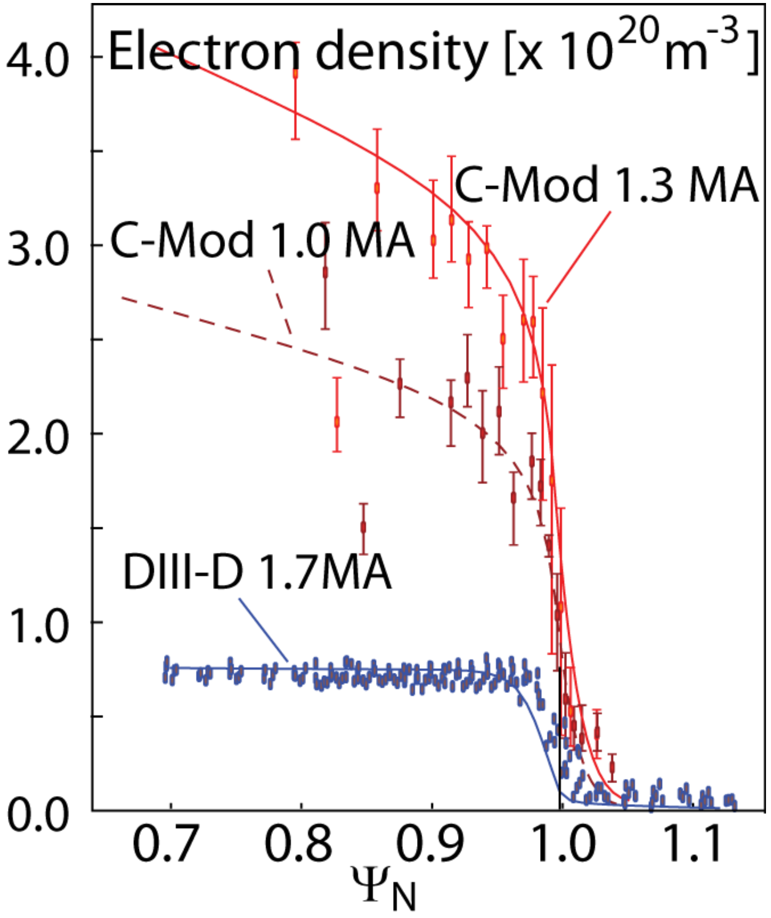


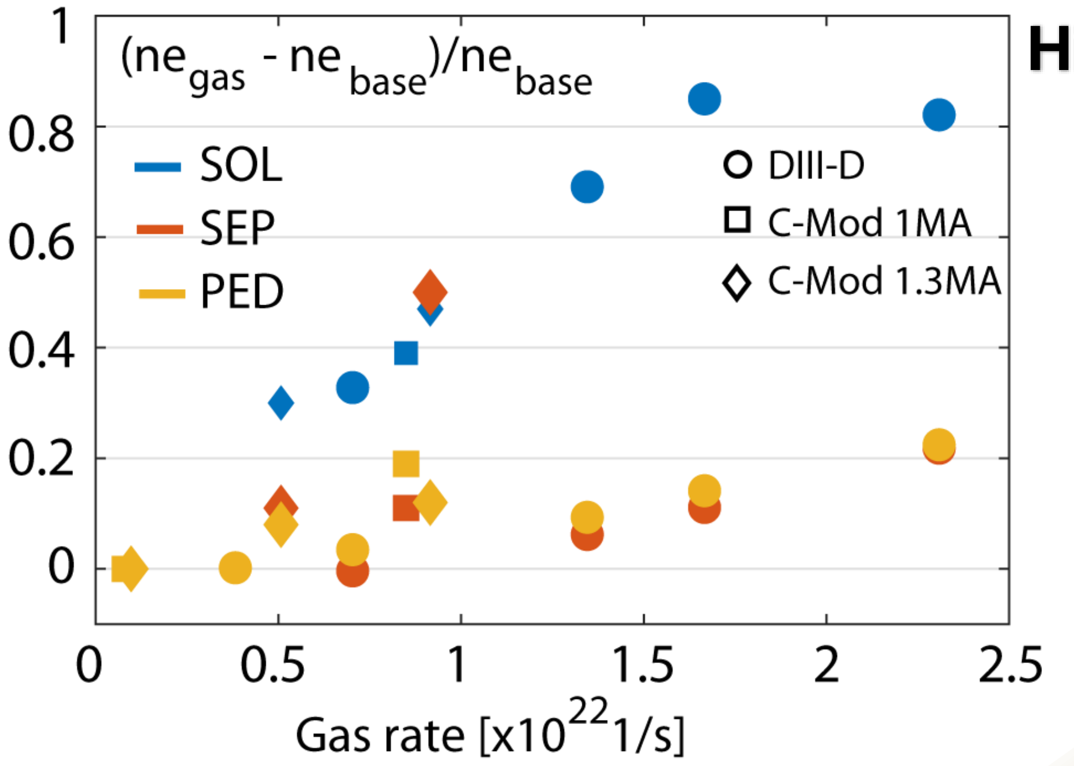


Normalized increases in gas fueling are similar for the pedestal as well as the separatrix

Low opacity **High opacity**

Lower n_e **Higher n_e**

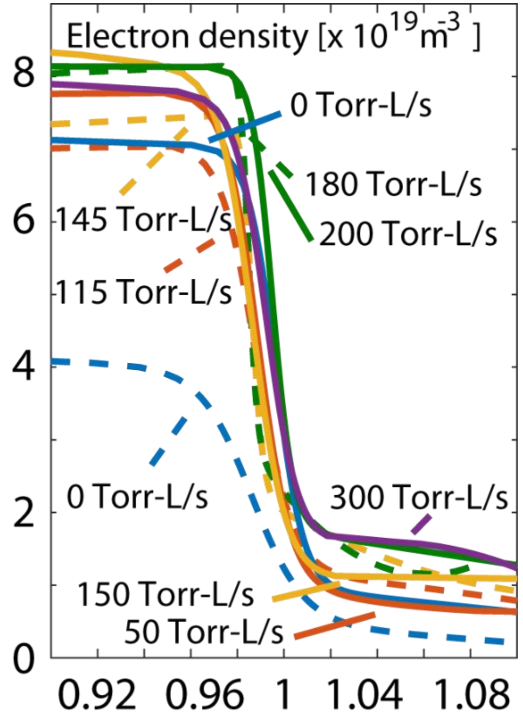




How does the pedestal structure change with increasing opacity and what is the effect of additional fueling?

Low opacity

Lower n_e



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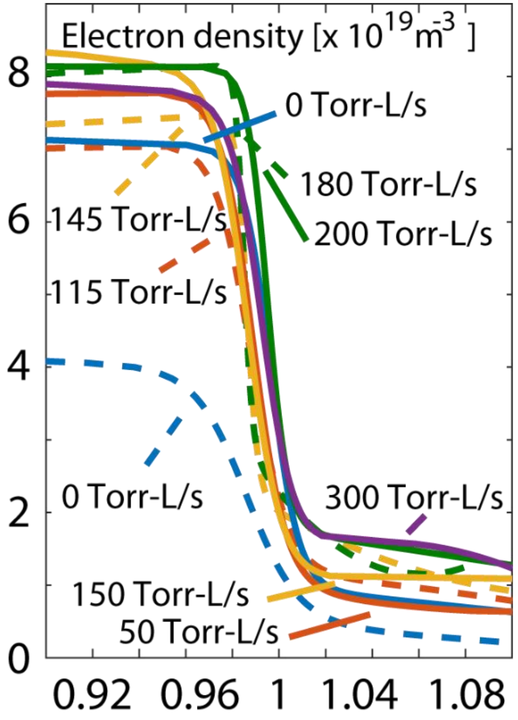

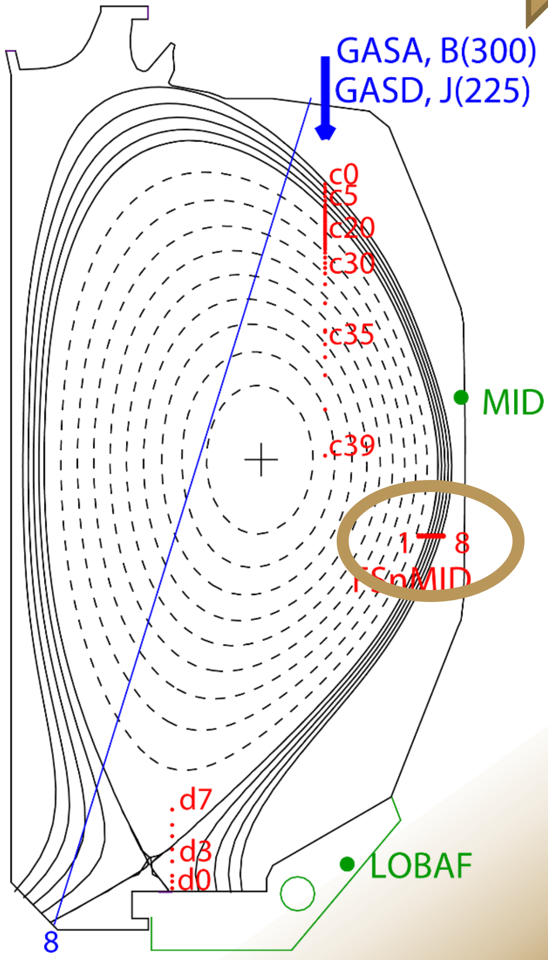

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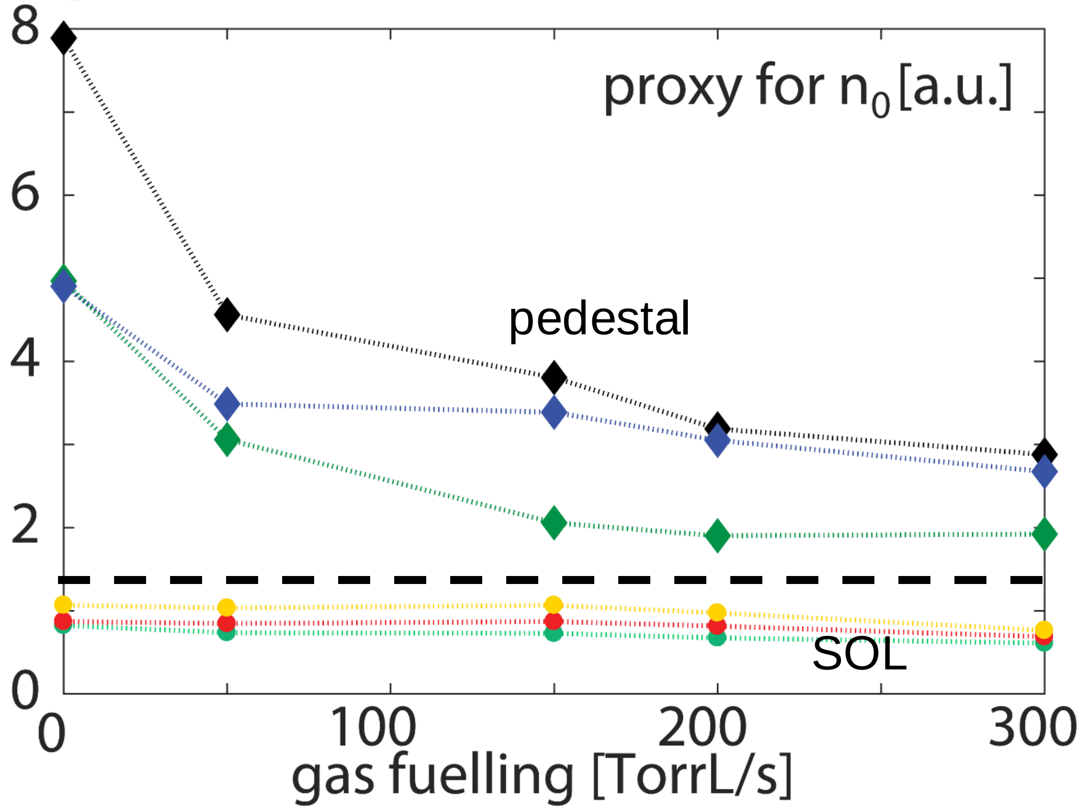

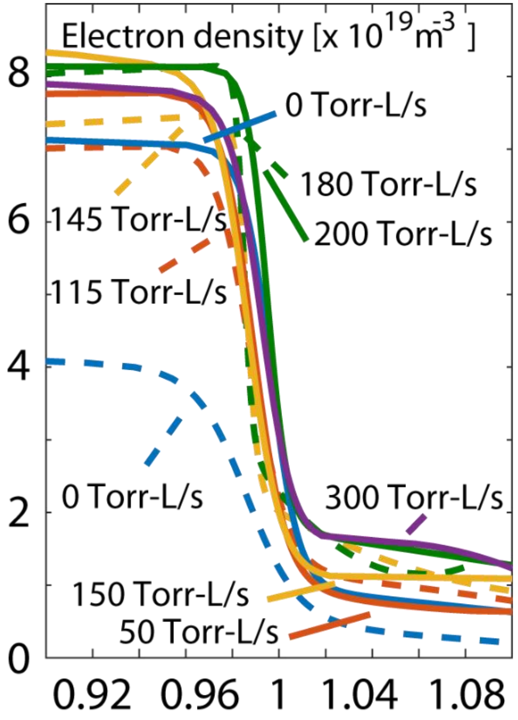

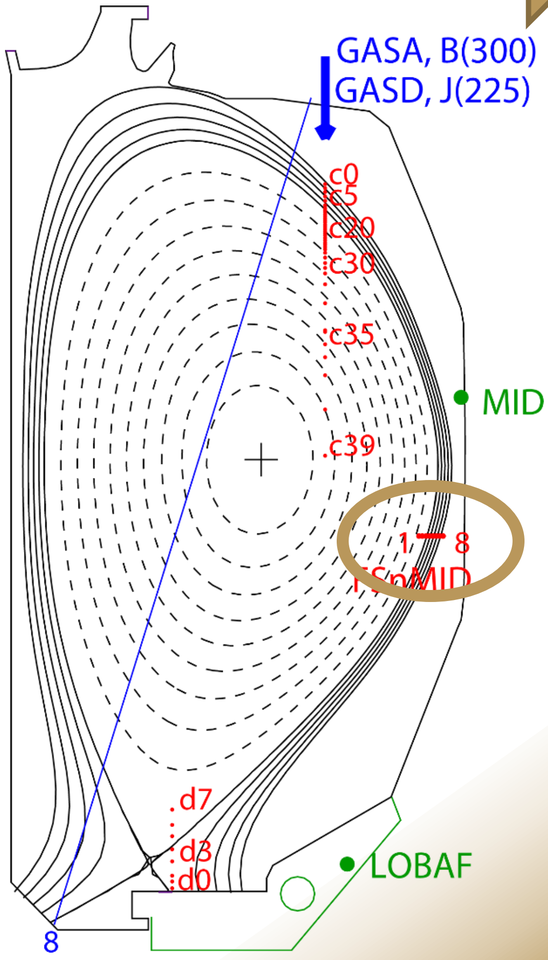

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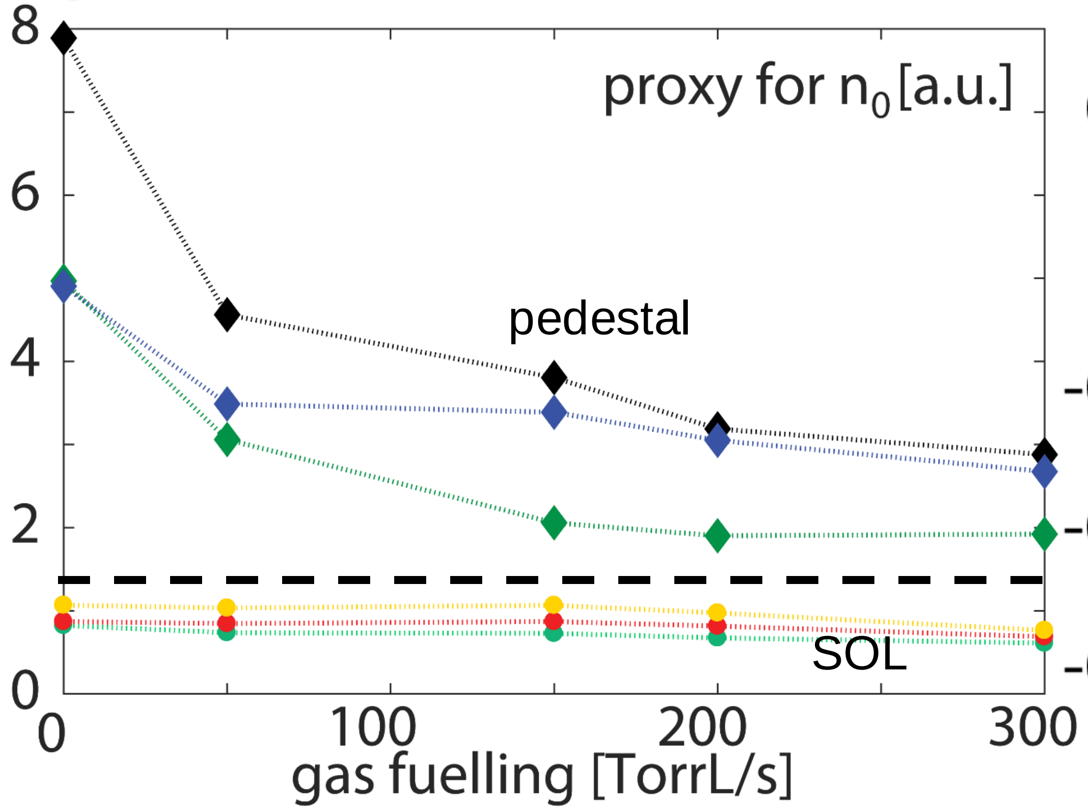

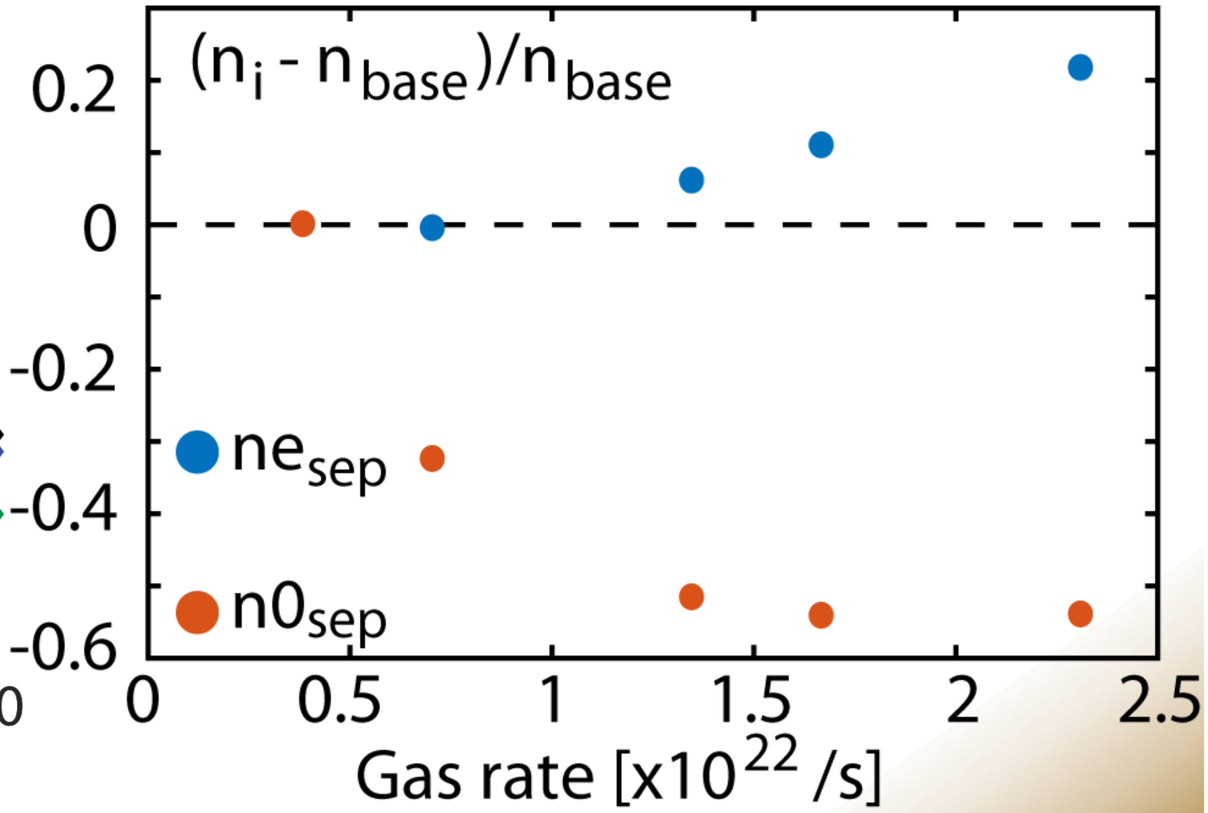

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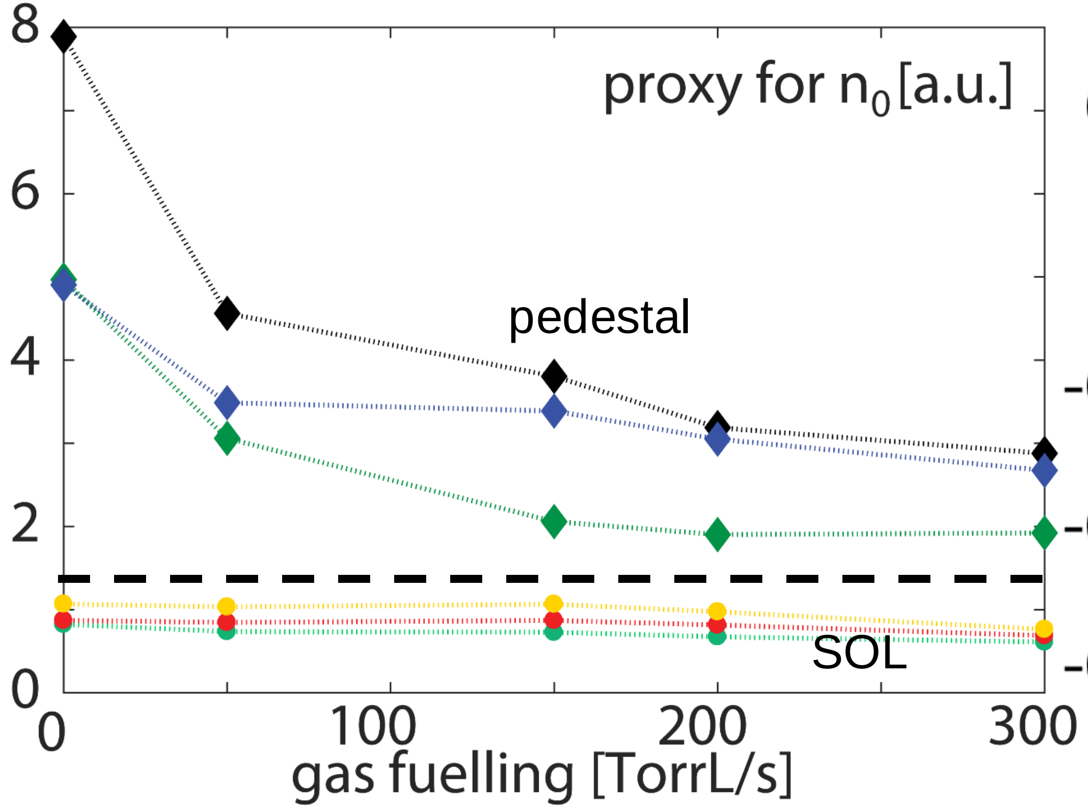
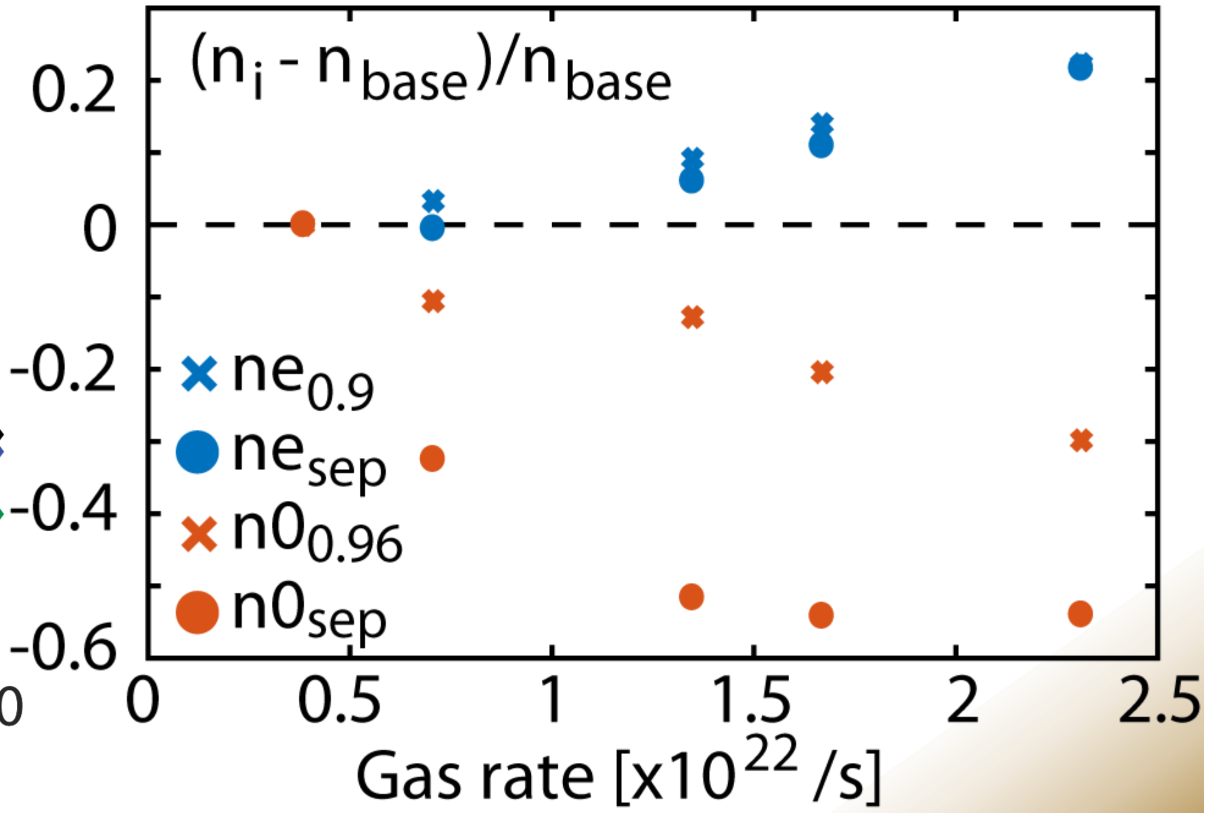
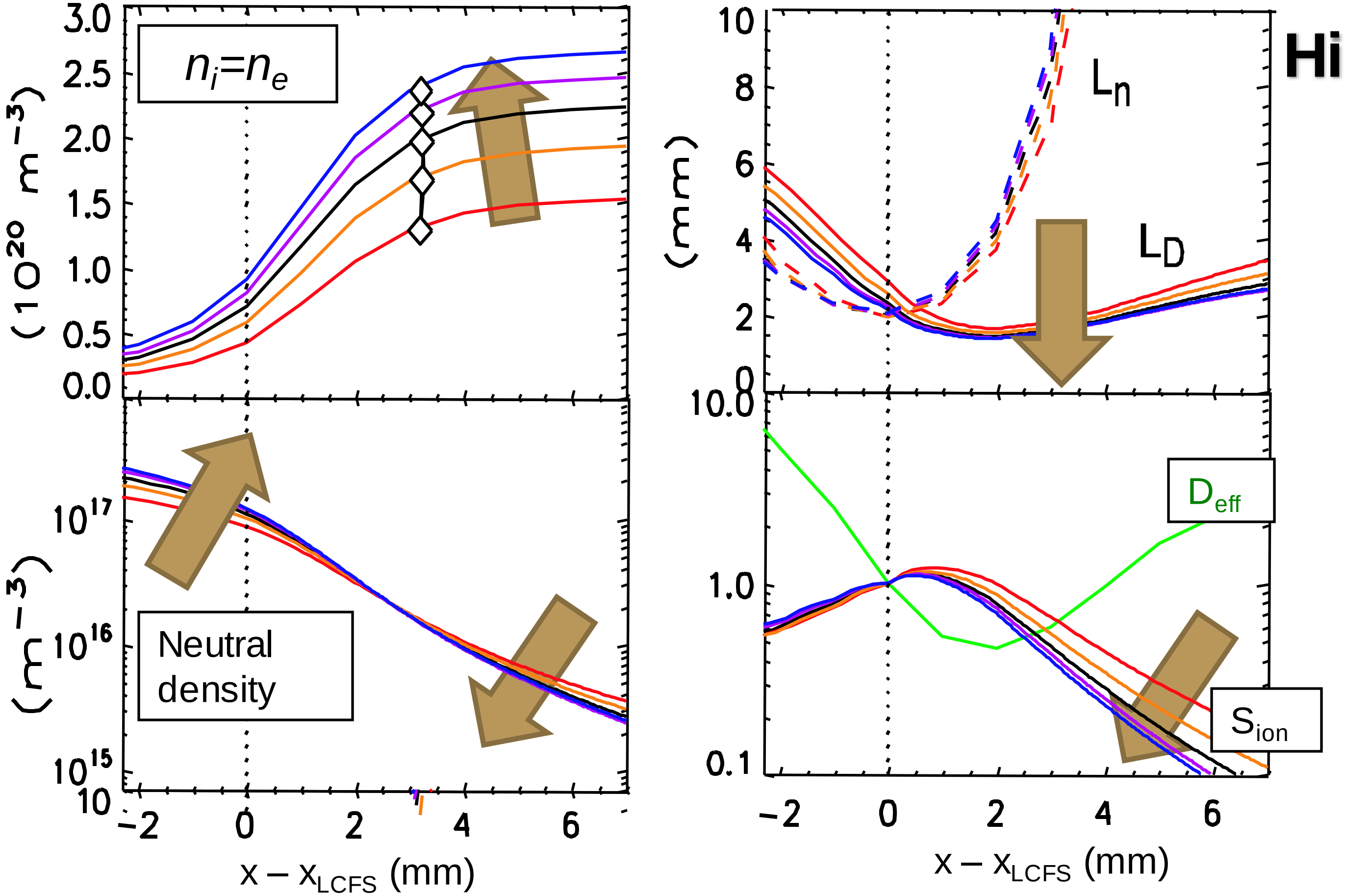




These experiments confirm prior results and modeling from C-Mod: Neutral penetration decreases with increasing $n_{e,PED}$

J.W. Hughes, et al. *PoP* **13** (2006) 056103

- $n_{e,PED}$ scales roughly as $N^{0.5}$
- L_n varies little, indicating stiff n_i profiles



Alcator C-Mod

Changing the modeling for C-Mod like conditions to DIII-D like conditions, we observe similar trends as shown experimentally

J.W. Hughes, et al. *PoP* **13** (2006) 056103

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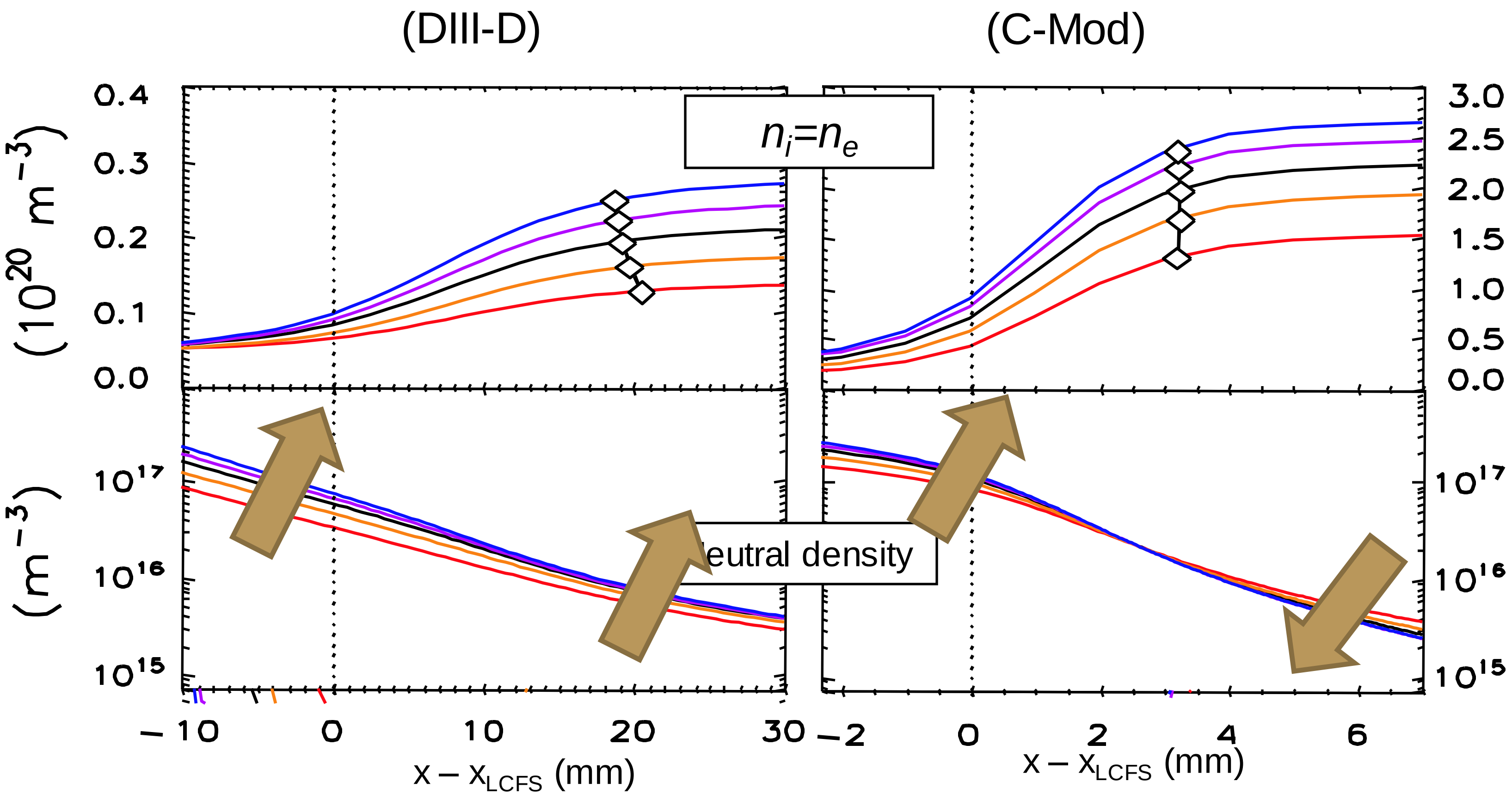

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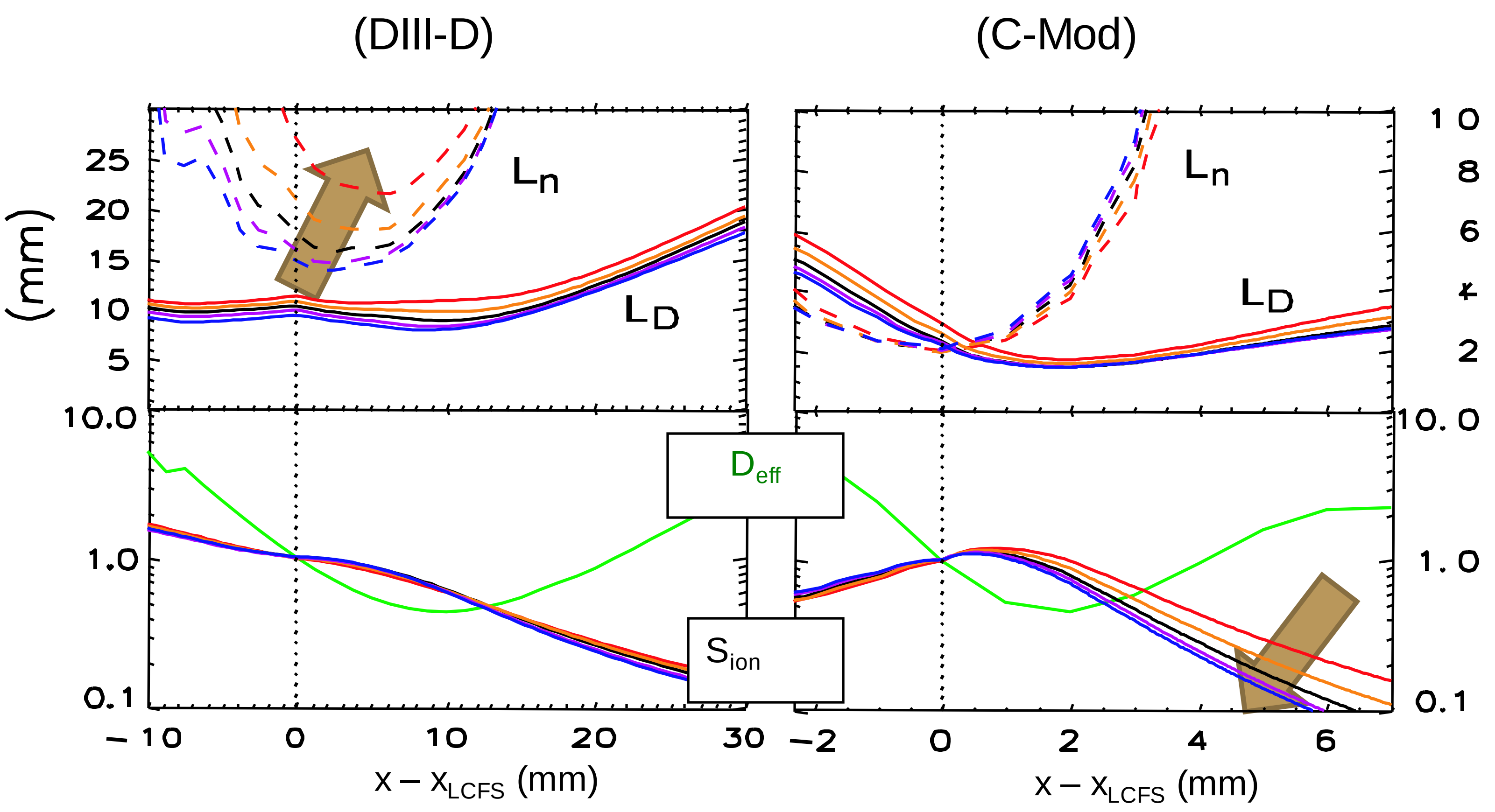
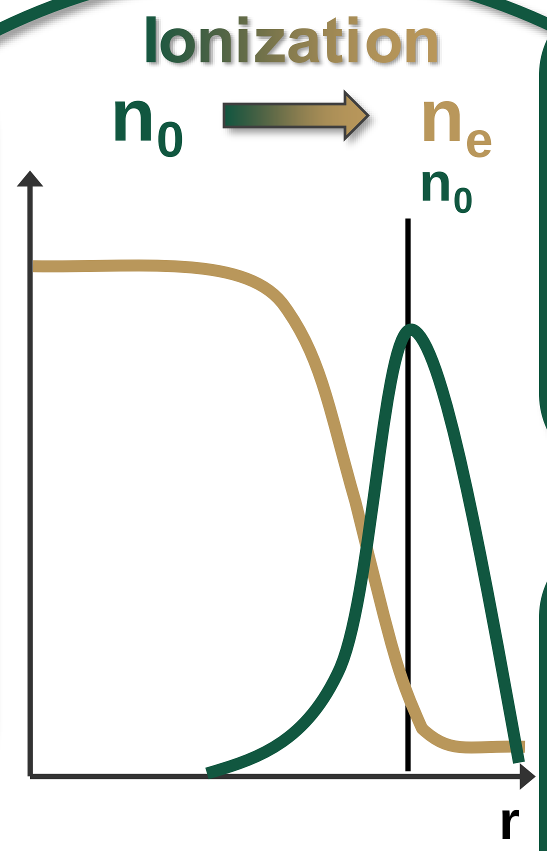


So what will the pedestal profile be like? A need to measure and validate neutral source, to study transport

Transport:

$$\mathrm{T} = -D\nabla n + vn$$

?



Model 1:

$$\nabla n_e \sim \nabla n_0$$

$$\rightarrow n_{e_{ped}} \sim {}^{1}/_{\Delta n_e}$$

Model 2:

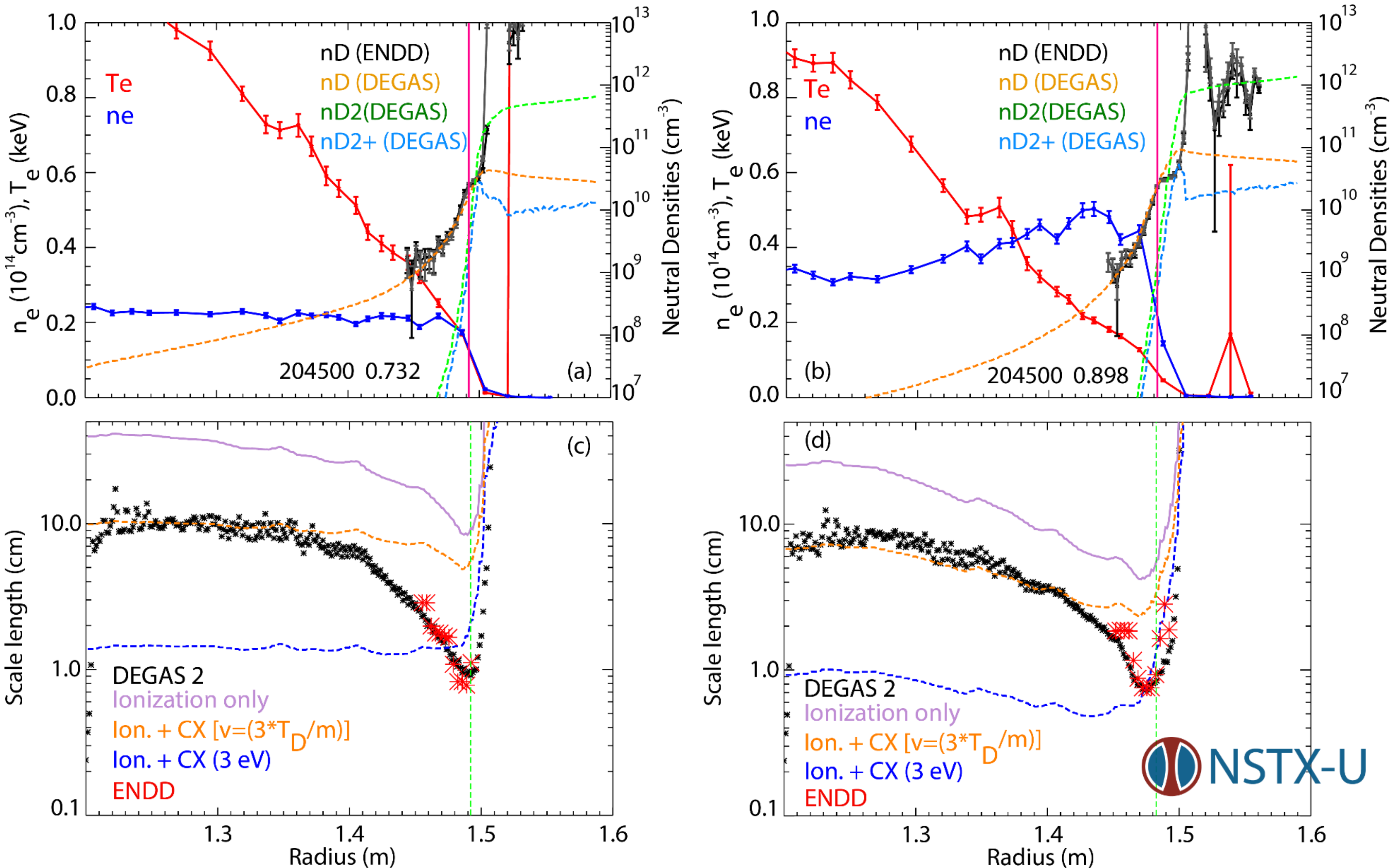
$n_0 \uparrow \Longrightarrow$ shift out in SOL

shift $n_{e_{ped}}$ out in SOL

$$\Rightarrow \sim\Delta(n_e - T_e) \neq 0$$

ENDD diagnostic measurements on NSTX-U have been compared to DEGAS modeling of the neutral sources

- ENDD diagnostic measures D_α
- Direct comparisons of DEGAS to measurements show good agreement
- DEGAS results are very sensitive to electron density and temperature in the far SOL



Conclusions

- Density pedestal currently influenced by neutral penetration
- However density pedestal structure cannot be solely determined by fueling
- Opaque SOL conditions indicate that ‘peaked’ pedestal profiles are possible

→ **Good news for ITER**

- However: we need to identify the role of various transport contribution to the particle flux, which means measure neutrals and validate edge codes