Grassy ELM regime at low pedestal collisionality in high-power tokamak plasma

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Outline

- 1. Motivation
- 2. Intrinsic grassy ELM regime in DIII-D
- 3. Prediction of access to grassy ELM regime in CFETR
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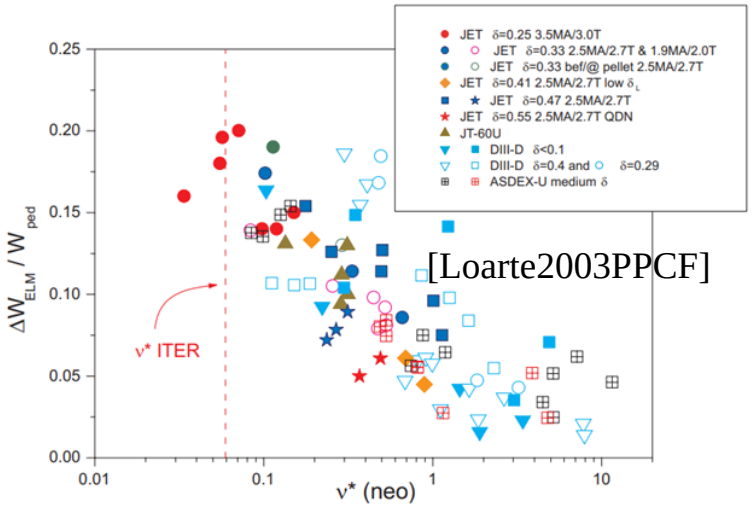
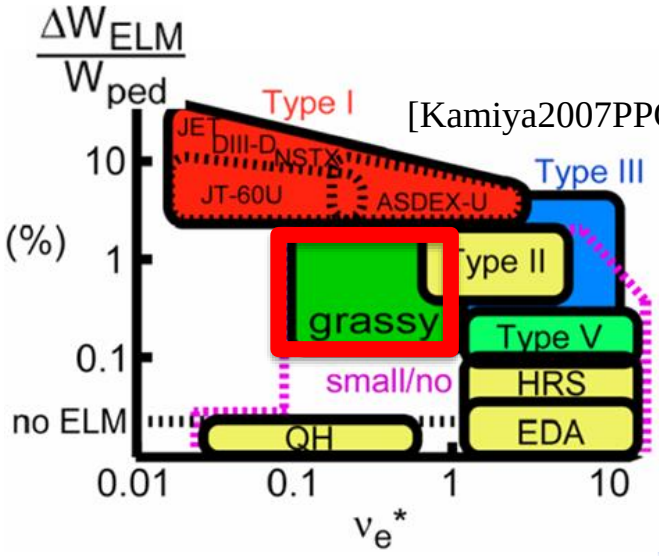
The grassy ELM regime offers a potential candidate for the operation of future fusion reactors

- Large ELMs at low ν* induces intolerable heat load for reactors.
- Grassy ELM regime is potentially accessible at relatively low pedestal collisionality and compatible with high-β_p steady-state operational scenarios ➔ CFETR
- High β_p, high q_{95} and high plasma shaping facilitate access to grassy ELMs.
- Further study is required to understand the physics of the grassy ELM regime.

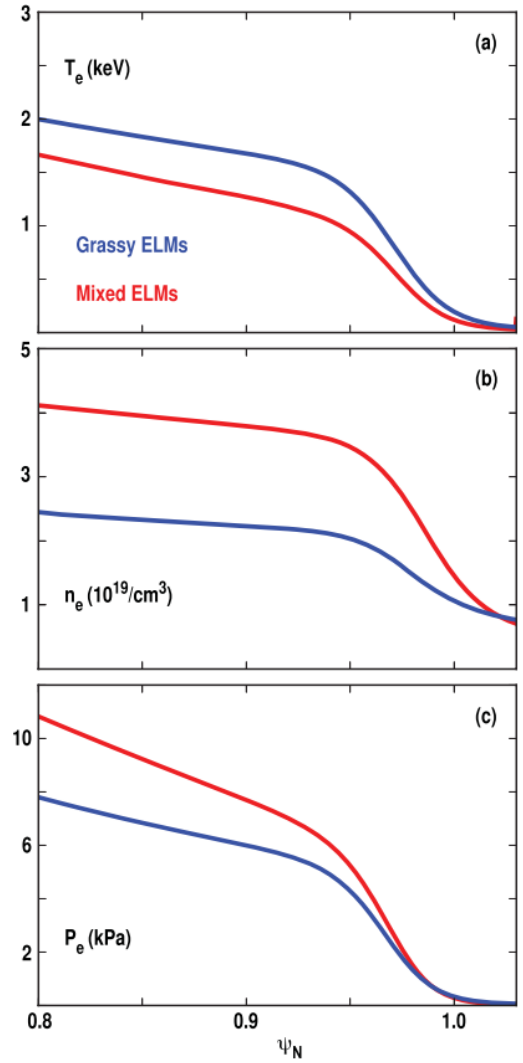


[Loarte2003PPCF]



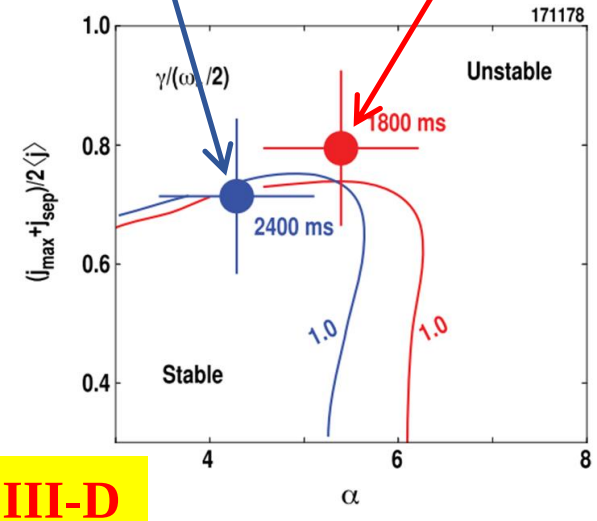
[Kamiya2007PPCF]

The importance of pedestal density profile has been highlighted in recent grassy ELM studies



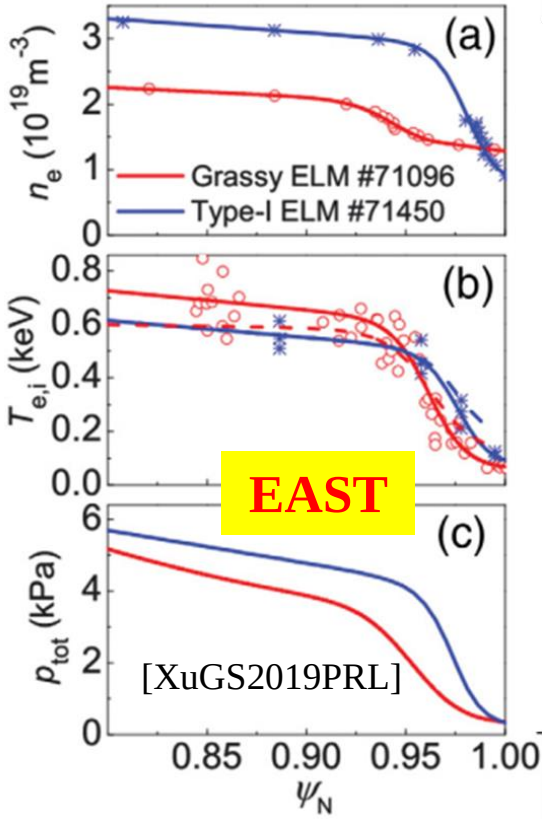
Grassy ELM (w. RMP)

Mixed ELM



DIII-D

[Nazikian2018NF]



- $\nabla n_{e,ped}$ in grassy ELM regime appears to be much smaller than that in large ELM regime.
- For the grassy ELM regime, the operational point is located near the peeling boundary.

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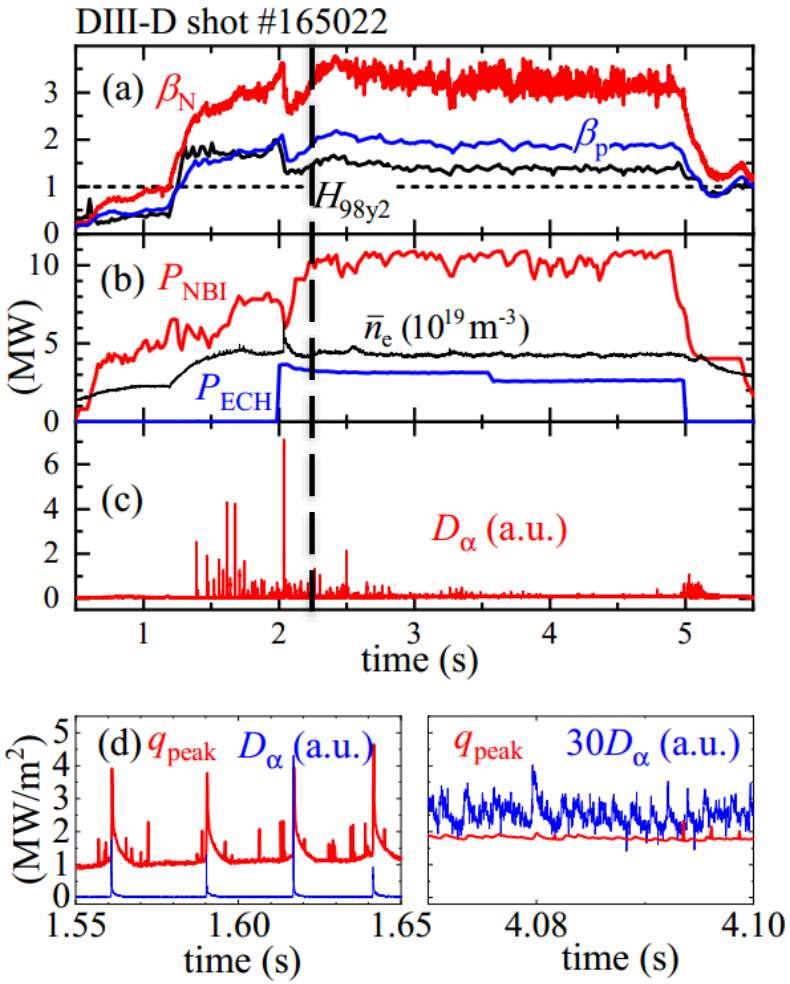
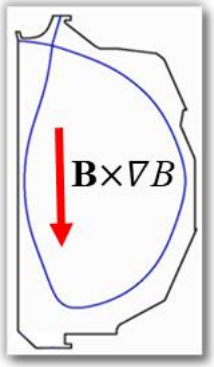
Giant ELMs appear to be spontaneously mitigated and replaced by grassy ELMs as heating power increases

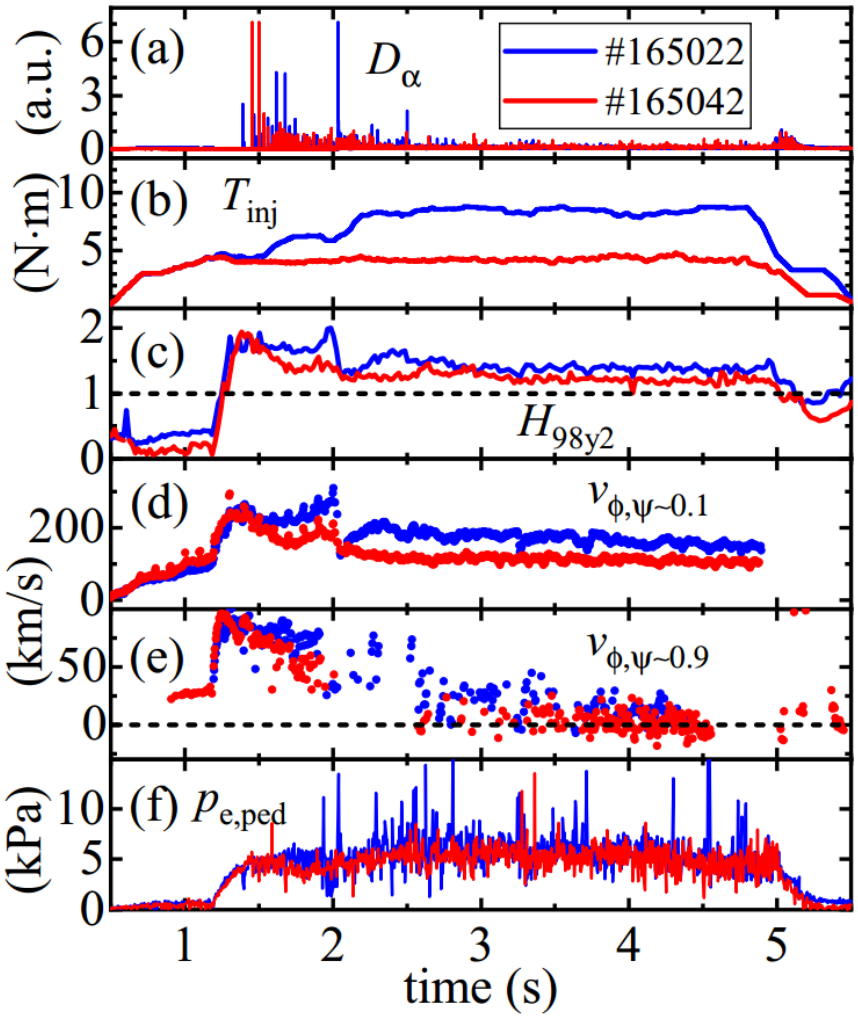


< 1MW/m^2



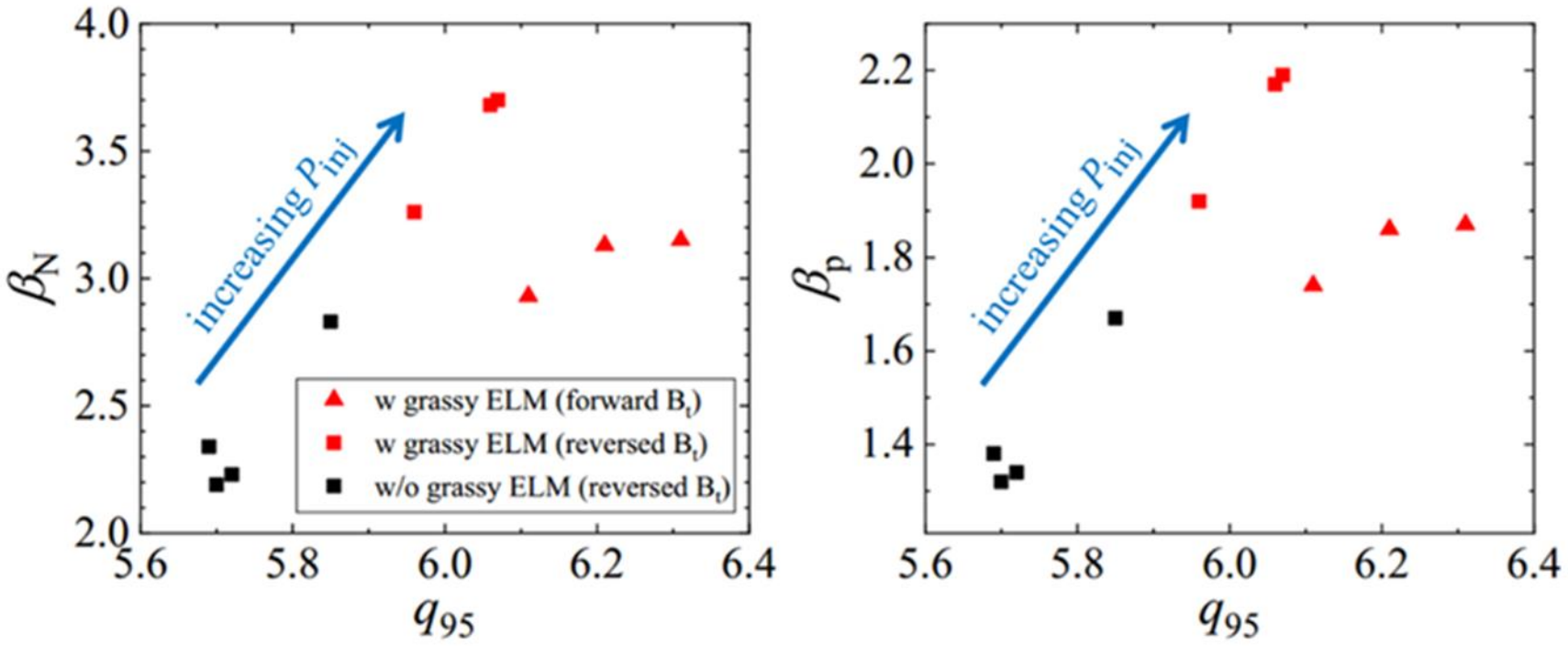
- Giant ELMs are replaced by grassy ELMs.
  - DND configuration with unfavorable B_T
  - q_{95}~6.2, n_e/n_{GW}~0.53, f_{BS}~50%.
  - P_{inj} increases from 6MW to 13MW.
- $q_{peak\text{-}ELM}$ is reduced by >90%.
- No RMP is intentionally applied.
- Good energy confinement: H_{98y2}~1.4, β_p ~1.9, β_N~3.2
- ITER-relevant low $\nu^*_{e,ped}$~0.15 is achieved

Even at reduced torque, high confinement and high pedestal are still obtained in the grassy ELM regime



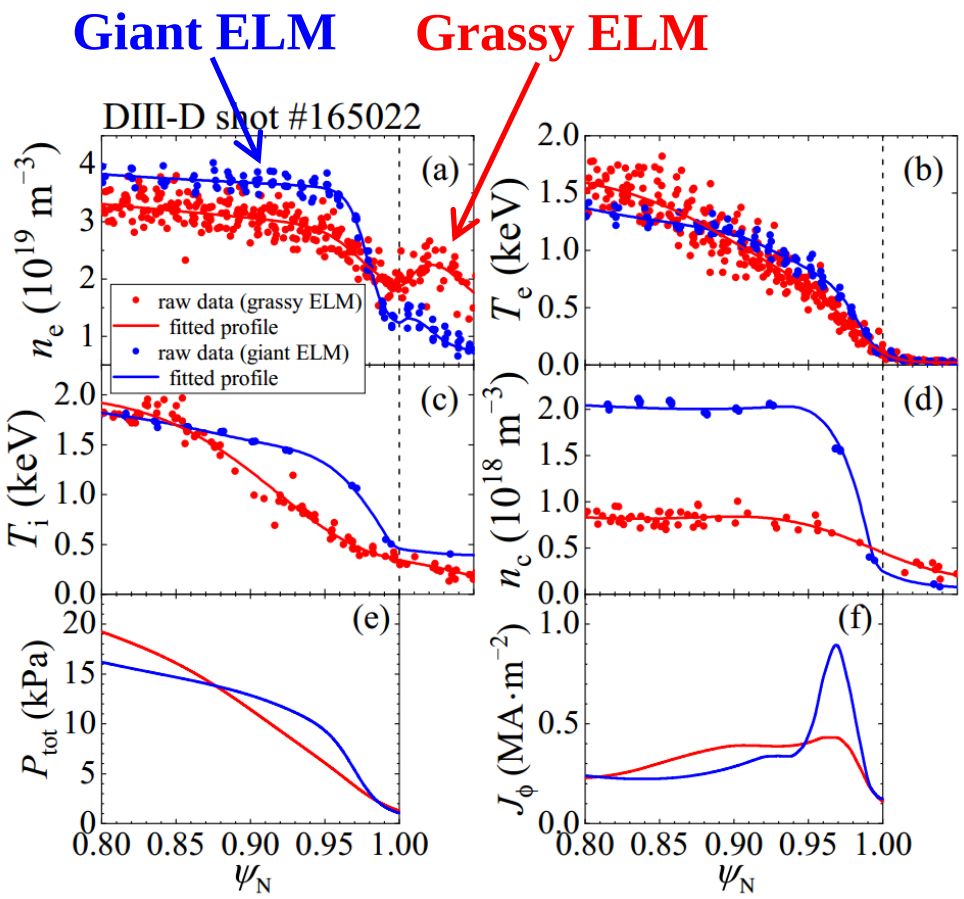
- The grassy ELM regime has been achieved within a certain range of neutral beam torque.
- Similar discharge conditions except T_{NBI} ~8.6/4.4 Nm
- Higher H_{98y2} at higher T_{NBI}
  - Higher core rotation at higher T_{NBI}
  - Small edge rotation change
- Similar pressure pedestal structure

Higher heating power appears to facilitate access to the grassy ELM regime

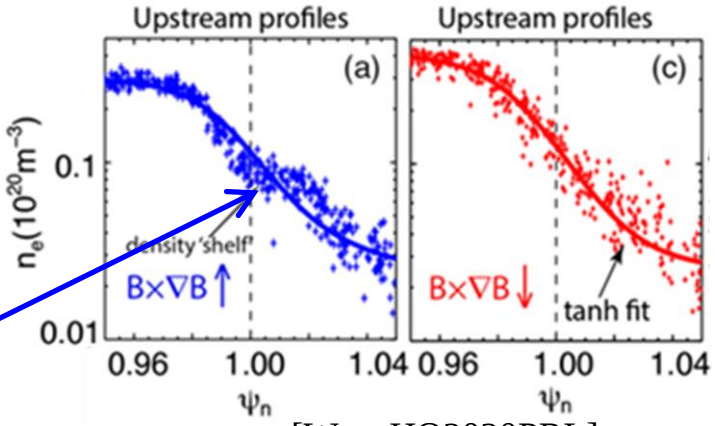


- Compare discharges with similar I_p, B_T (unfav.), n_e and plasma shape
- Divertor geometry effect may be not a dominant factor to enter this regime.

Density pedestal in the grassy ELM regime is characterized by lower density gradient and higher $n_{e,sep}/n_{e,ped}$



- $n_{e,sep}/n_{e,ped}$: 35% vs. 65% (before vs. after raising heating power) with similar line-averaged density
- Both Te and Ti pedestals appear to become wider and flatter.
- The carbon impurity density is significantly reduced.
- Kinetic equilibria are reconstructed.



Density shelf exists under unfavorable B_T

[WangHQ2020PRL]

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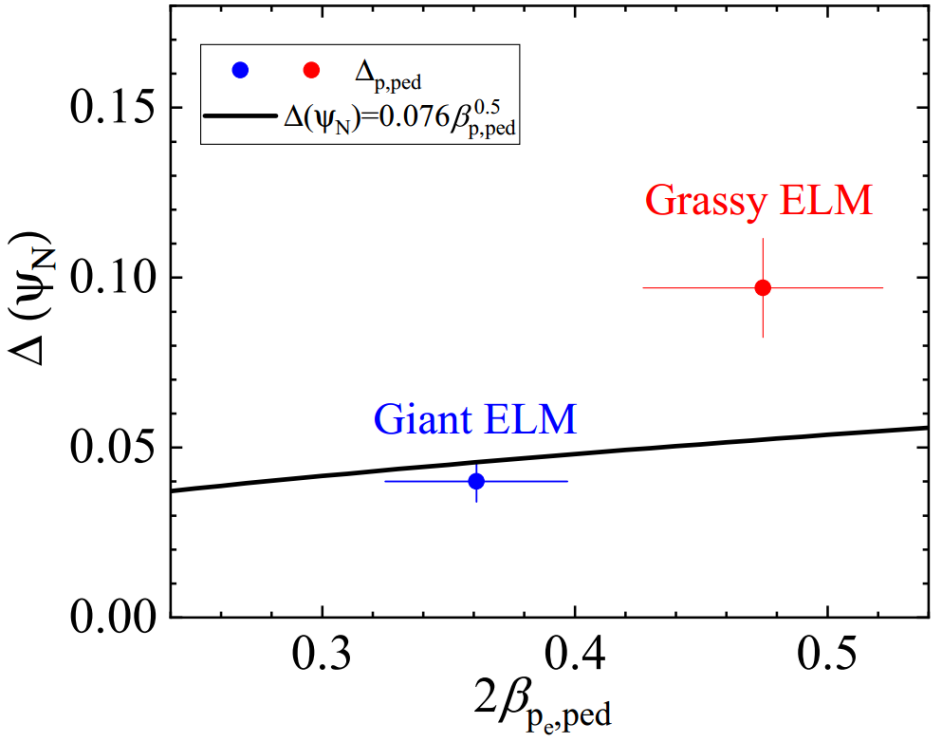
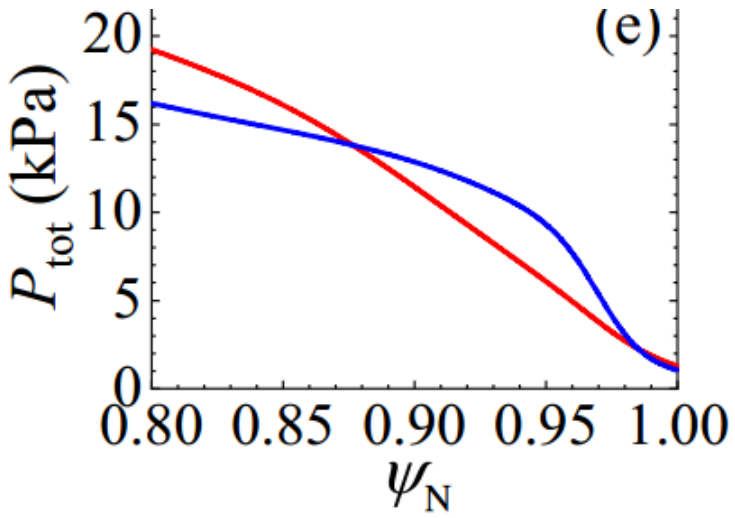
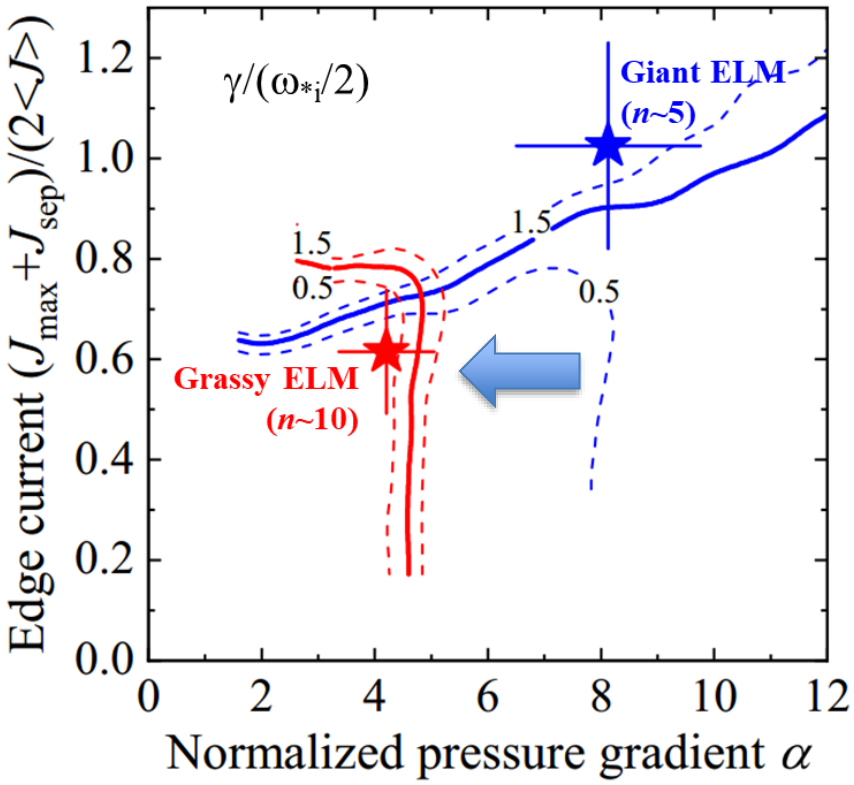
Pedestal width in the grassy ELM regime exceeds the EPED1.0 model prediction by more than 50%





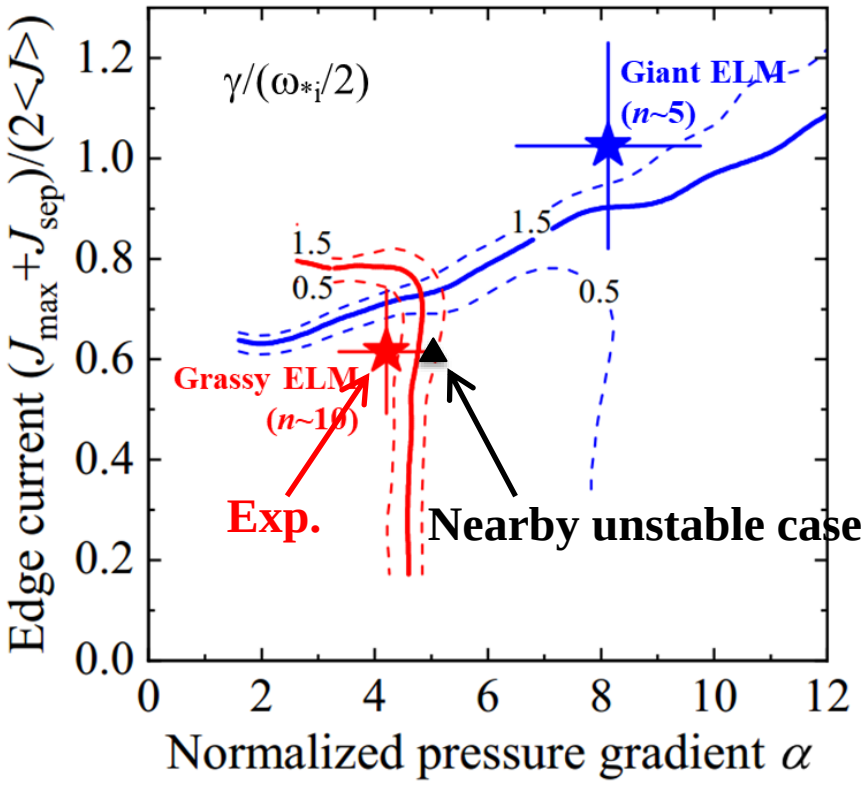
- **Pedestal width in giant ELM regime is consistent with that predicted by the EPED1.0 model.**
- **The wide pedestal in grassy ELM regime leads to a high pressure at the pedestal top even though there is a low pedestal pressure gradient. This explain why good energy confinement is achieved in the grassy ELM regime.**

The operational point in the grassy ELM regime is located near the ballooning boundary



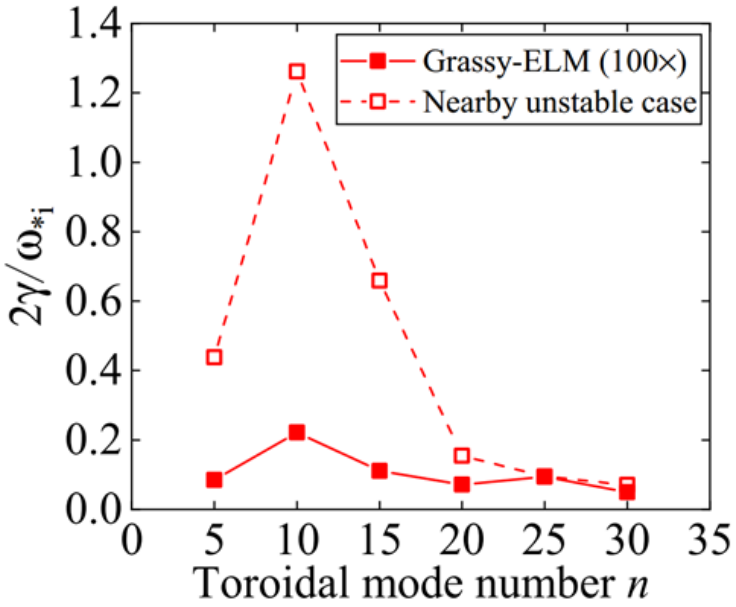
- The values of α and J_N are both smaller in the grassy ELM regime.
- The ballooning boundary retreat significantly in the grassy ELM regime.
- The pedestal stability against low-n kink/peeling modes is improved after access to the grassy ELM regime.

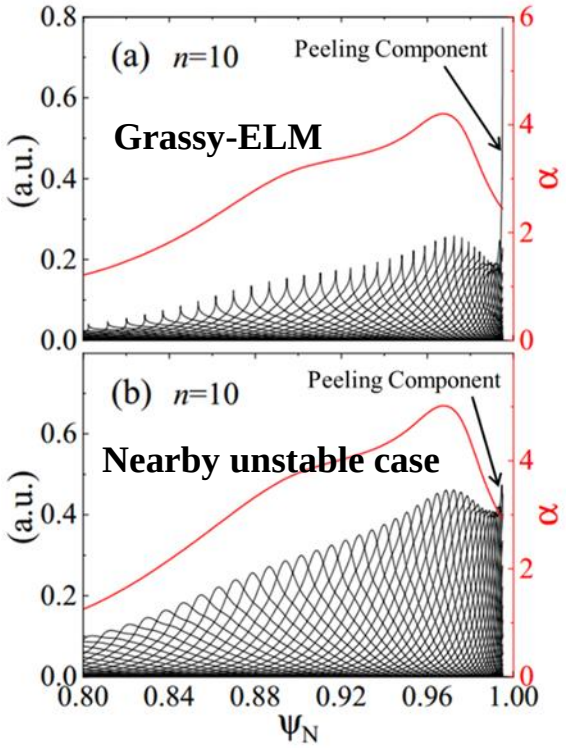
The operational point in the grassy ELM regime is located near the ballooning boundary



- The values of α and J_N are both smaller in the grassy ELM regime.
- The ballooning boundary shrinks significantly in the grassy ELM regime.
- The pedestal stability against low-n kink/peeling modes is improved after access to the grassy ELM regime.

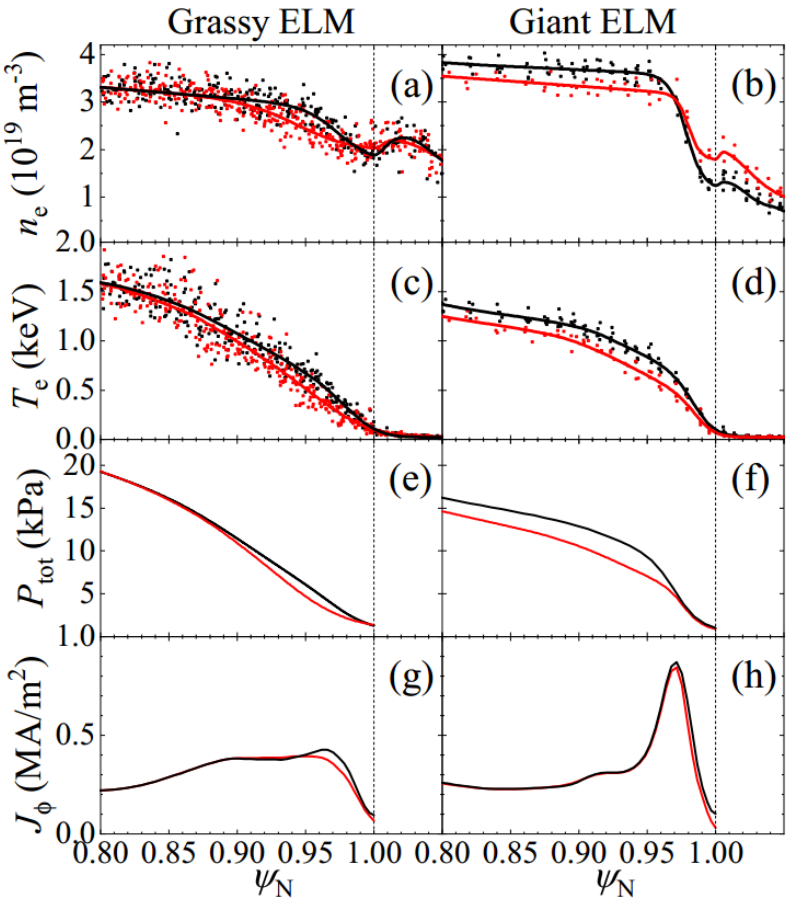
The ballooning component of the most unstable mode structure becomes stronger in the nearby unstable case



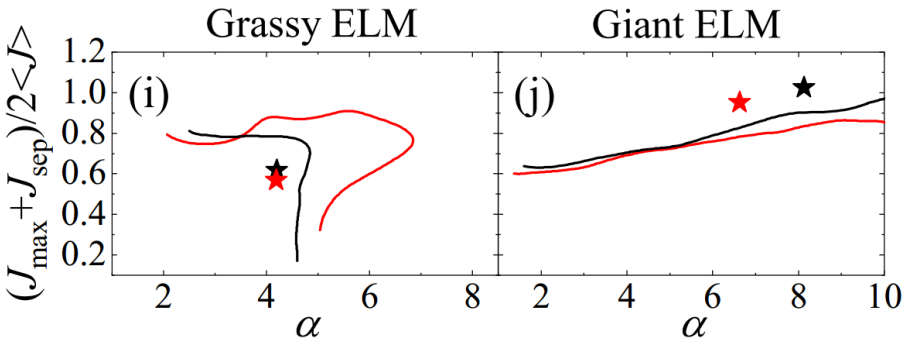


- **The grassy ELMs are most likely triggered by intermediate-n (n~10) PBMs.**
- **The ballooning component of the most unstable mode structure becomes stronger while the peeling component becomes weaker in the nearby unstable case, suggesting the dominant unstable modes are the ballooning modes**

During grassy ELM crash, the ballooning boundary expands and helps to stop further pedestal collapse



- **Comparison of profiles before (black) and after (red) ELM crashes**
- **Giant ELMs induce large crashes**
  - **Move along the peeling boundary**
- **During grassy ELM crashes, the ballooning boundary expands due to an initial radially localized small pedestal collapse.**



G.S. Xu, et al. PRL 122, 255001 (2019)

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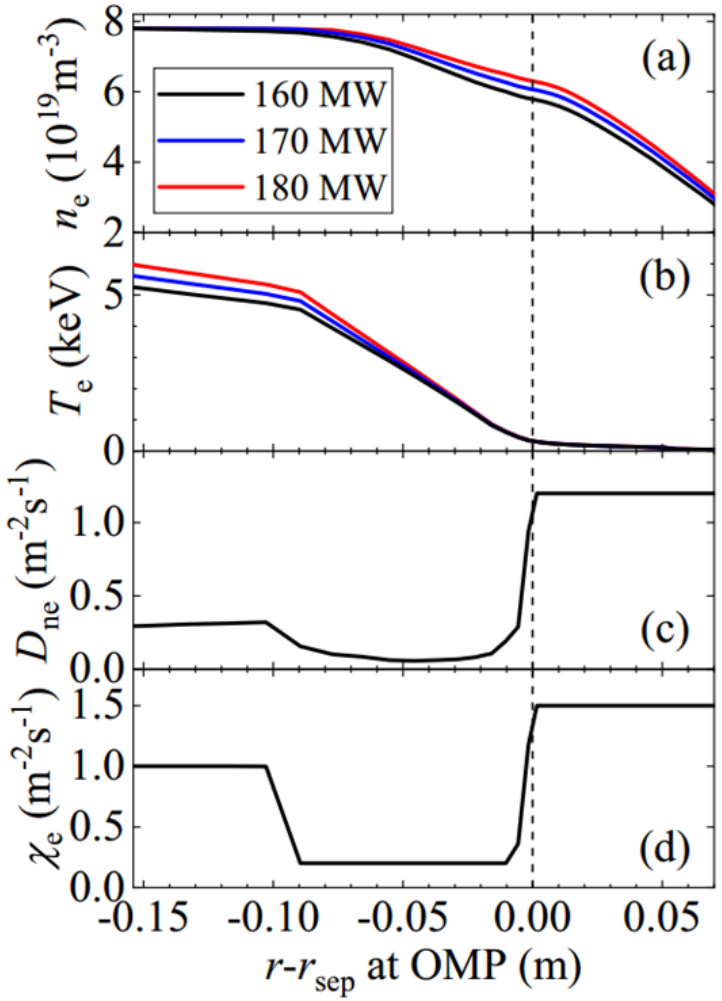
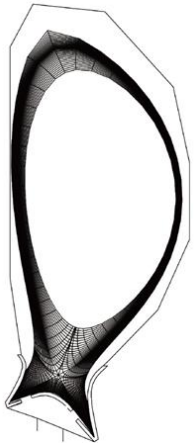
Higher heating power is beneficial to formation of higher separatrix density

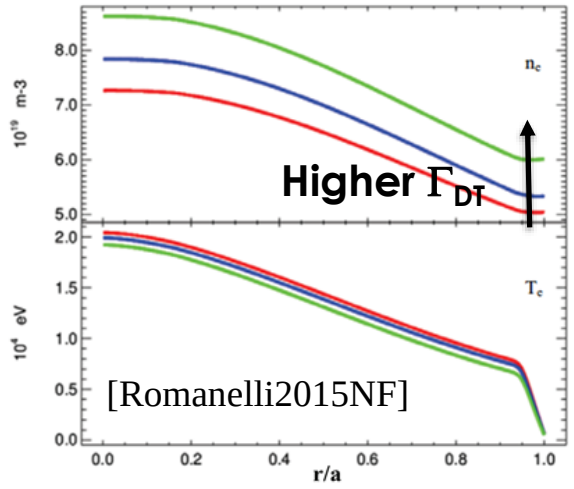
- Scan input power P_{input}



SOLPS-ITER code simulation domain



High $n_{e,sep}$ similar to SOLPS simulations of ITER plasmas →



- The separatrix electron density increases with P_{input}.

$$n_{e,sep} = \frac{1.1\times10^{15} q_{\parallel}^{5/7}}{L_{\parallel}^{2/7} T_{e,div}^{1/2}} \left(\frac{1-f_{rad}}{1-f_{mom}} \right)$$

- The increased P_{input} also enhances the electron temperature at the pedestal top.
- The separatrix electron temperature changes very little.

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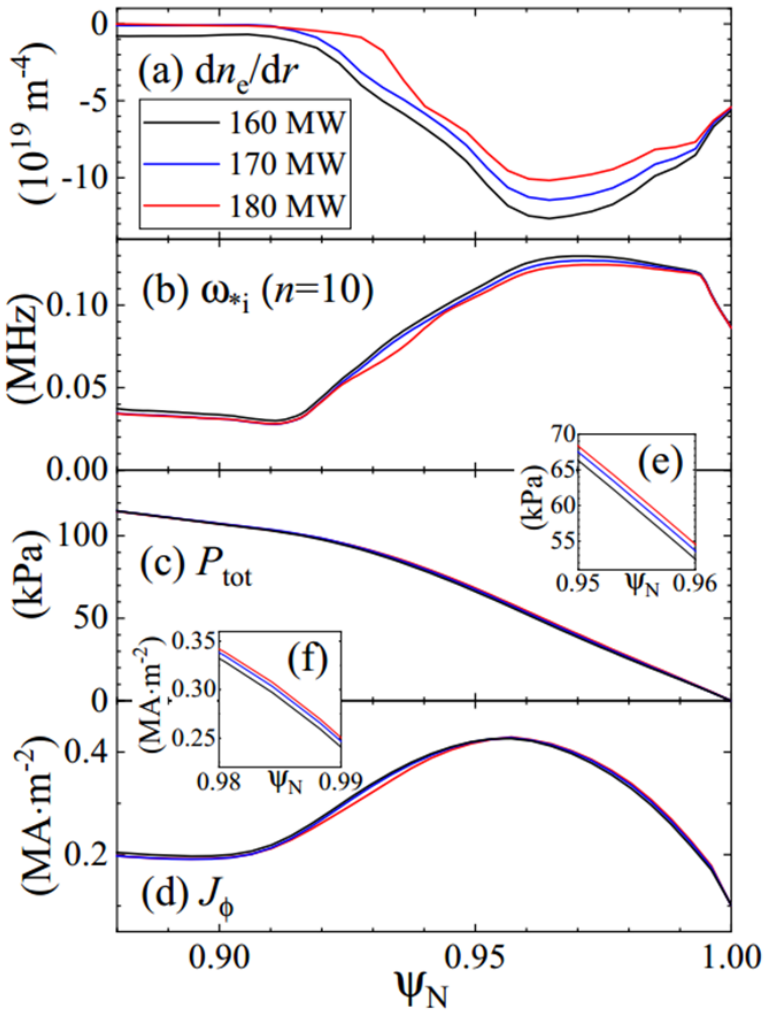
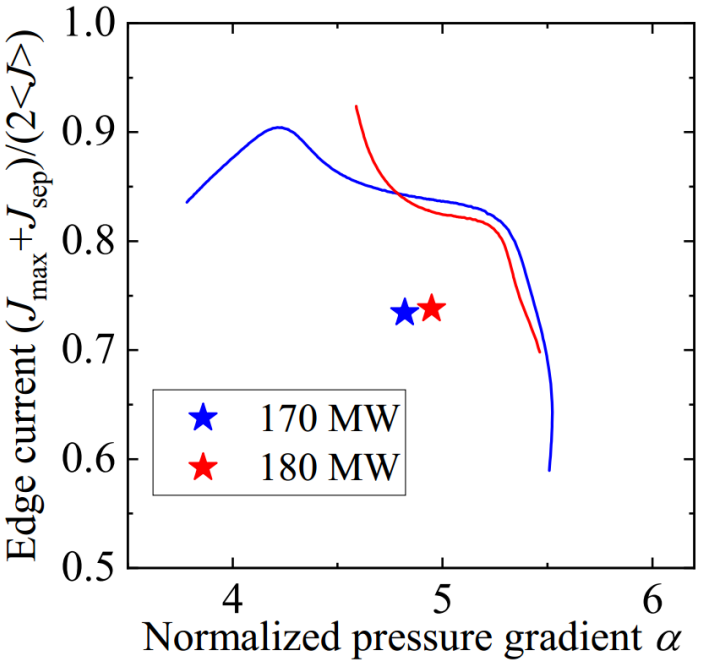
Higher separatrix density would help to destabilize ballooning modes and facilitate the access to the grassy ELM regime

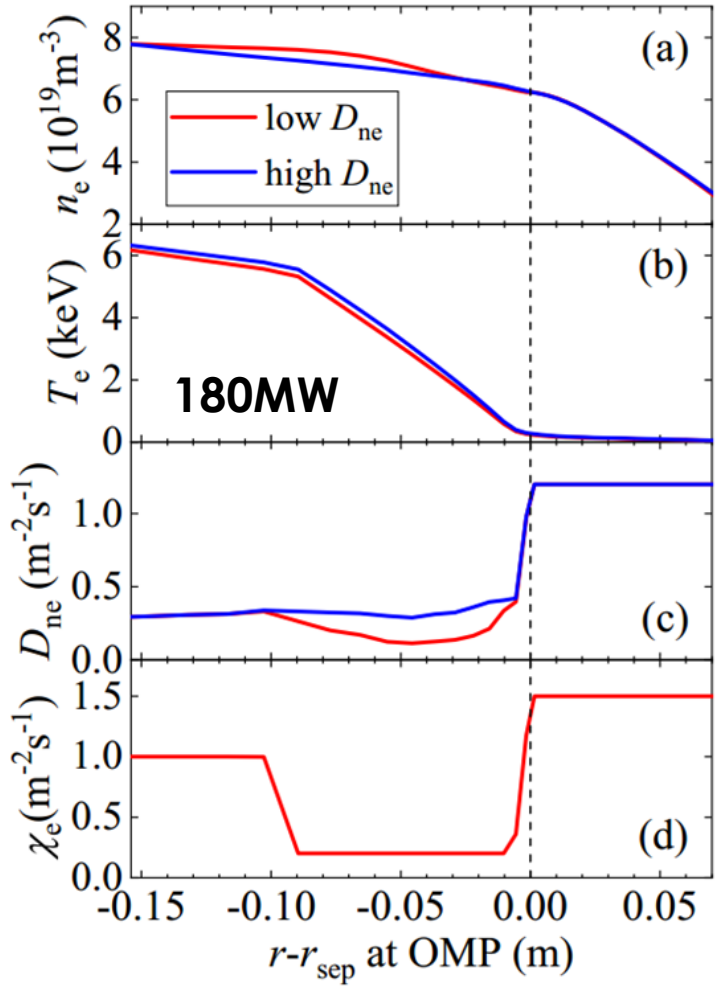




- **Pedestal stability analysis with n_e profiles produced in SOLPS simulations**
- **With higher heating power and thus higher separatrix density, the operational point moves closer to the ballooning boundary.**

Separatrix density might be insensitive to the pedestal electron diffusivity

- Modify pedestal electron diffusivity D_{ne}



- The electron density and temperature at the pedestal top slightly change.
- The electron density and temperature at the pedestal foot and in the SOL changes very little.
- Suggest that the separatrix density and temperature is insensitive to the pedestal diffusivity and they are mainly determined by the divertor and SOL physics.
- Confirm our argument that this kind of density profile very likely appear in future fusion reactors.

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Summary

- **A naturally spontaneous grassy ELM regime has been achieved in high-power (P_{inj}>13MW) hybrid scenario in DIII-D.**
  - ν^*_{ped}~0.15, H_{98y2}~1.4, β_N~3.2, low ELM peak heat flux < 1MW/m^2

- **The low pedestal density gradient and high $n_{e,sep}/n_{e,ped}$ help stabilize the peeling-ballooning modes and destabilize ballooning modes.**
  - The operation point locates near the ballooning boundary.

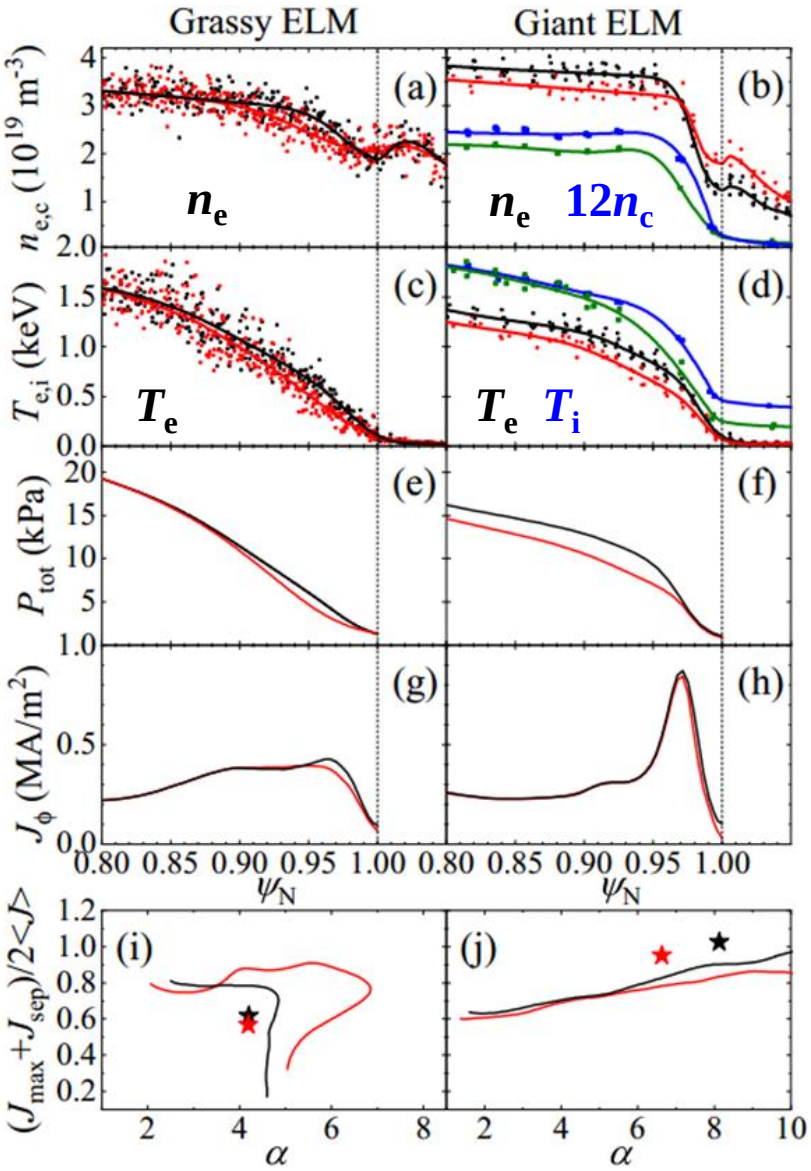
- **SOLPS simulation of CFETR plasmas suggests that the density pedestal could be very flat with high $n_{e,sep}$, especially at high heating power, which is considered to facilitate the access to the grassy ELM regime.**
  - The grassy ELM regime is potentially more easily accessible in ITER, CFETR and other future large fusion devices.

Thank you!

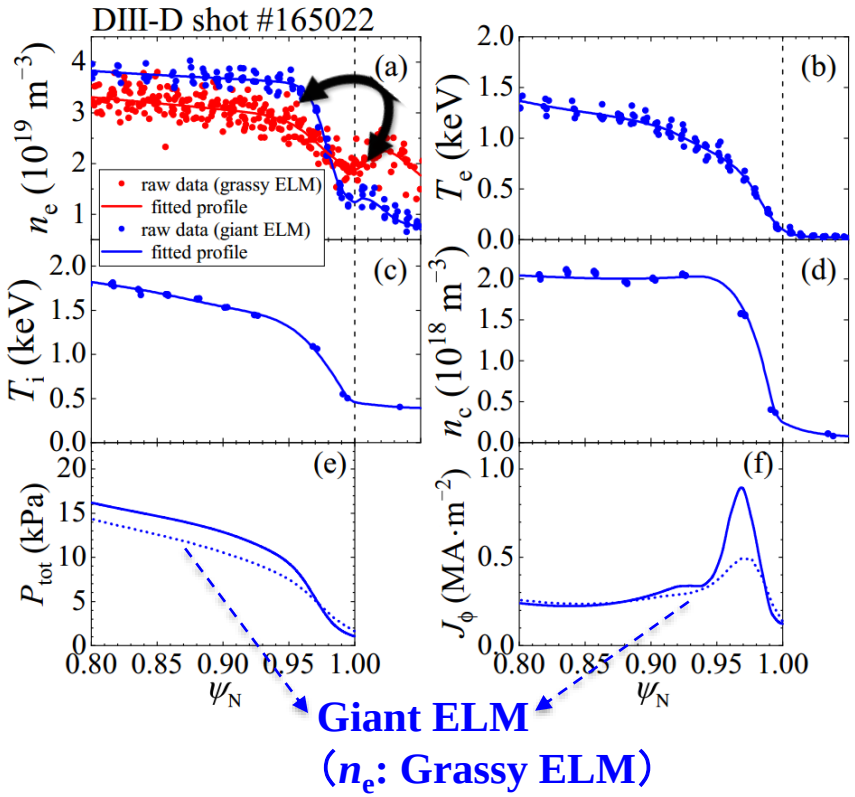
Backup

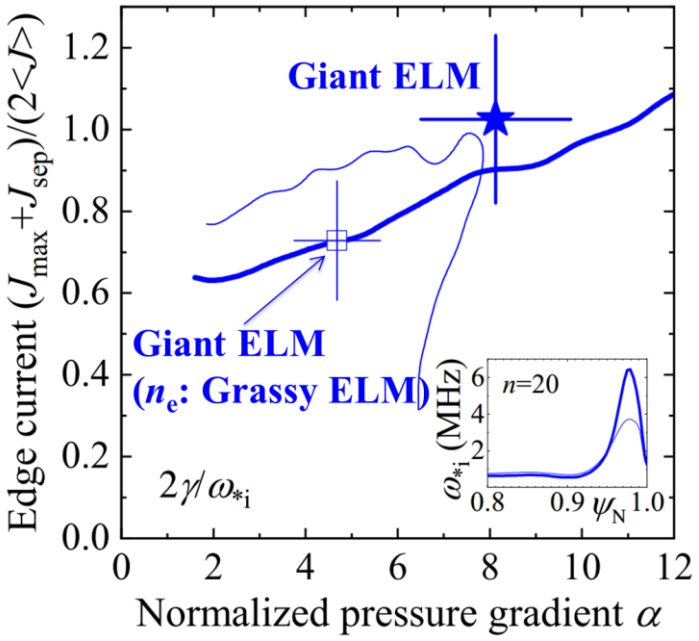
Table 1. The shot numbers involved are listed as well as basic discharge parameters obtained by taking 500 ms average of corresponding signals on the β_N flattop phase of each shot. The plasma current I_p is 0.98 MA in all shots. The plasmas are all in in the near-double null divertor (DND) configuration with unfavorable toroidal magnetic field B_t direction (Negative/positive represents reversed/forward B_t).

shot	B_t /T	q_{95}	β_p	l_i	$\bar{n}_e$ / 10^{19} m^{-3}	P_{inj} /MW	T_{inj} /N·m	H_{98y2}	w or w/o grassy ELM
165022	-1.98	6.21	1.86	0.80	4.26	13.0	8.58	1.38	w
165024	-1.98	6.31	1.87	0.80	4.27	13.7	8.45	1.36	w
165042	-1.98	6.11	1.74	0.82	4.24	14.3	4.37	1.19	w
170272	1.97	5.96	1.92	0.84	3.83	14.6	5.49	1.24	w
170317	1.97	6.07	2.19	0.81	4.29	14.6	9.15	1.55	w
170325	1.97	6.06	2.17	0.82	4.30	14.6	9.15	1.52	w
170333	1.97	5.85	1.67	0.87	3.93	13.0	3.12	1.19	w/o
170335	1.97	5.69	1.38	0.94	4.30	11.5	0.66	1.05	w/o
170336	1.97	5.72	1.34	0.90	4.26	9.6	0.78	1.06	w/o
170340	1.97	5.70	1.32	0.90	4.32	9.2	2.19	1.03	w/o


Grassy ELM
Giant ELM
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
n_e
n_e $12n_c$
T_e
T_e T_i
$n_{e,c}$ (10^{19} m^{-3})
$T_{e,i}$ (keV)
P_{tot} (kPa)
J_ϕ (MA/m^2)
ψ_N
$(J_{max}+J_{sep})/2<J>$
α

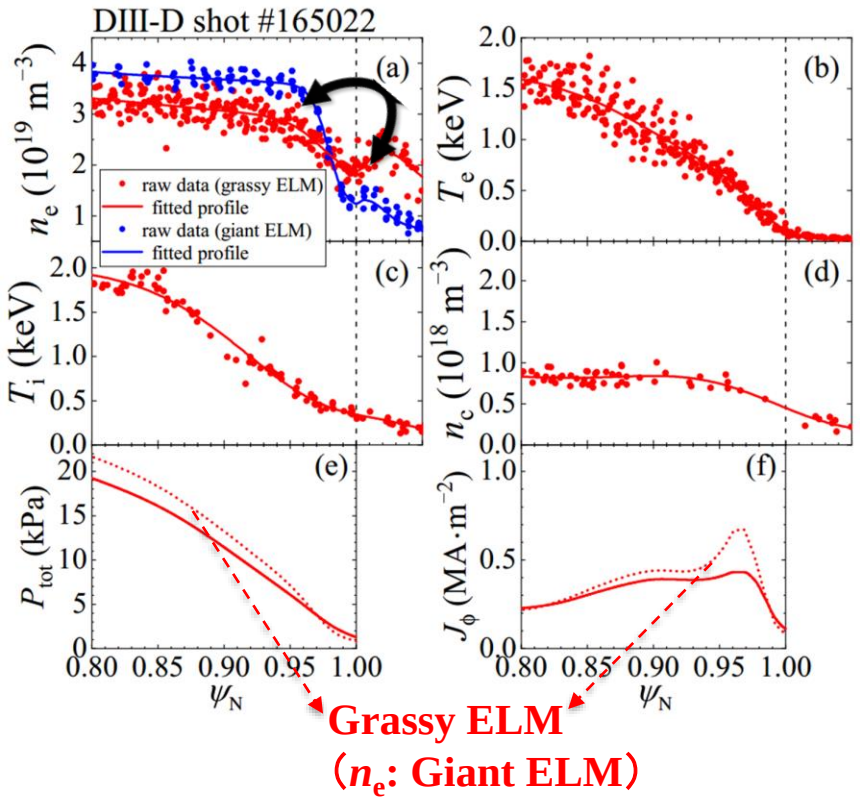
The narrowing of the ballooning boundary mainly attributes to lower ω_{*i} in the pedestal region

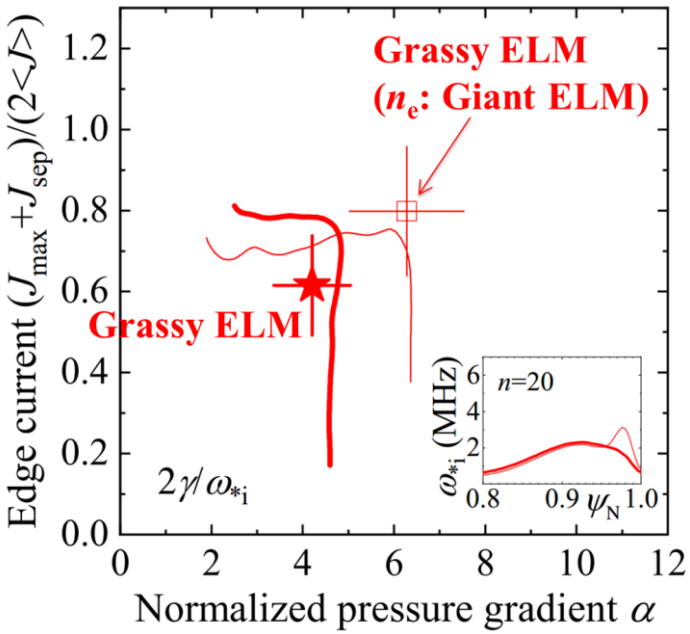




- The n_e profiles are exchanged numerically in the both cases.
- With n_e from the grassy ELM case, α and J_N of the operational point both decrease and the ballooning boundary narrows because of lower ω_{*i}.
  - ion diamagnetic frequency $\omega_{*i} \sim \nabla p_e/n_e$

The low density gradient and high $n_{e,sep}/n_{e,ped}$ help stabilize the peeling-ballooning modes and narrow ballooning boundary





- With n_e from the giant ELM case, α and J_N of the operational point both increase and the ballooning boundary expands.
- The n_e pedestal in the grassy ELM regime helps to stabilize PBMs with lower pressure pedestal gradient and narrow ballooning boundary with lower ω_{*i}.