Some implications of recent technology advances on divertor physics performance requirements of tokamak reactors

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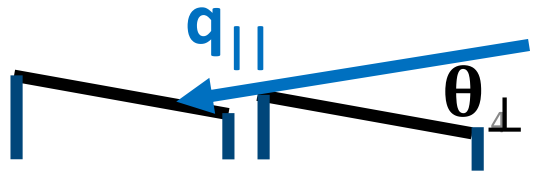
The rapid evolution of several
advanced technologies
being strongly pursued for major non-fusion applications, is
potentially transformative
for the
divertor physics
performance requirements of tokamak reactors:

1. Advanced Manufacture

3D printing etc. will increase power handling of solid divertor targets by increasing the contact area between coolant and solid surfaces, and by increasing turbulent heat transfer rates.

2. Advanced Robotics

- **For non-demountable (not openable) toroidal field coils, e.g. ITER, internal components must be modular.**
- **<u>Problem</u>: larger gaps and misalignments than for a pre-fabricated, vertical-lift monolithic structure.**
- **∴ to shadow-protect *edges*, power-handling *surfaces* have to be tilted. $\theta_{\perp} \sim 4.5^{o}$ in ITER, c.f. $\sim 1^{o}$ in, e.g. DIII-D.**
- **<u>Problem</u>: greatly increased power load on *surfaces*.**
- **Advances in robotics could enable reduction of gaps & misalignments of modular structures.**



3. High temperature superconductor, HTSC magnets

- HTSC magnets: potentially demountable, openable.
- Enables monolithic rather than modular structure.
- The entire, highly-aligned and robust monolithic internal structure, including the divertor, is pre-assembled and lowered in and out of place (vertical-lift), making possible safe use of small $\theta_{\perp}$ i.e. edges not exposed.
- ARC with HTSC magnets and vertical-lift: $\theta_{\perp} \sim 1^{o}$.

Advanced *technologies* → divertor *physics*

- These high tech areas are being pursued for major, rapidly growing non-fusion applications.
- Robotics industry doubles every ~3 years. World-wide expenditures: $B116 (2019) → $B210 (2022, proj.)
- **Reactor design should assume these advances will be exploited.**
- ITER design is now largely fixed, but advances in robotics and additive manufacture will undoubtedly be exploited to upgrade the ITER divertor, which is planned to be replaced.

Advanced *technologies* → divertor *physics*

- Advanced technologies are potentially transformative for divertor physics requirements re the paramount requirement of target survival :

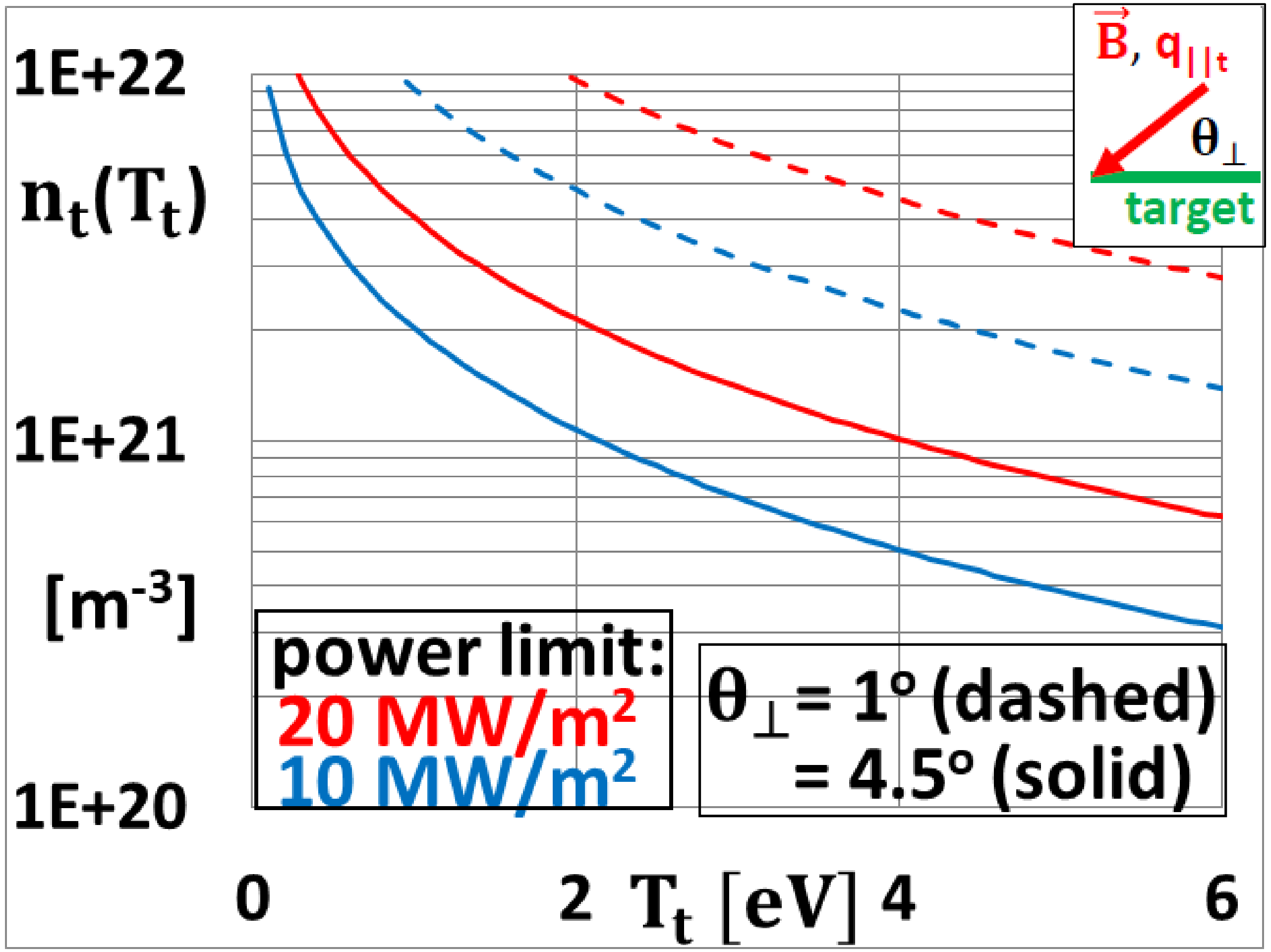
I. Required plasma temperature, density at target,

II. Required volumetric power dissipation in the edge,

III. Value of 'upstream' SOL plasma density (→ $\bar{n}_e$).

I. n_t (T_t): divertor plasma n_{target} (T_{target}) for target survival re both power-load & erosion

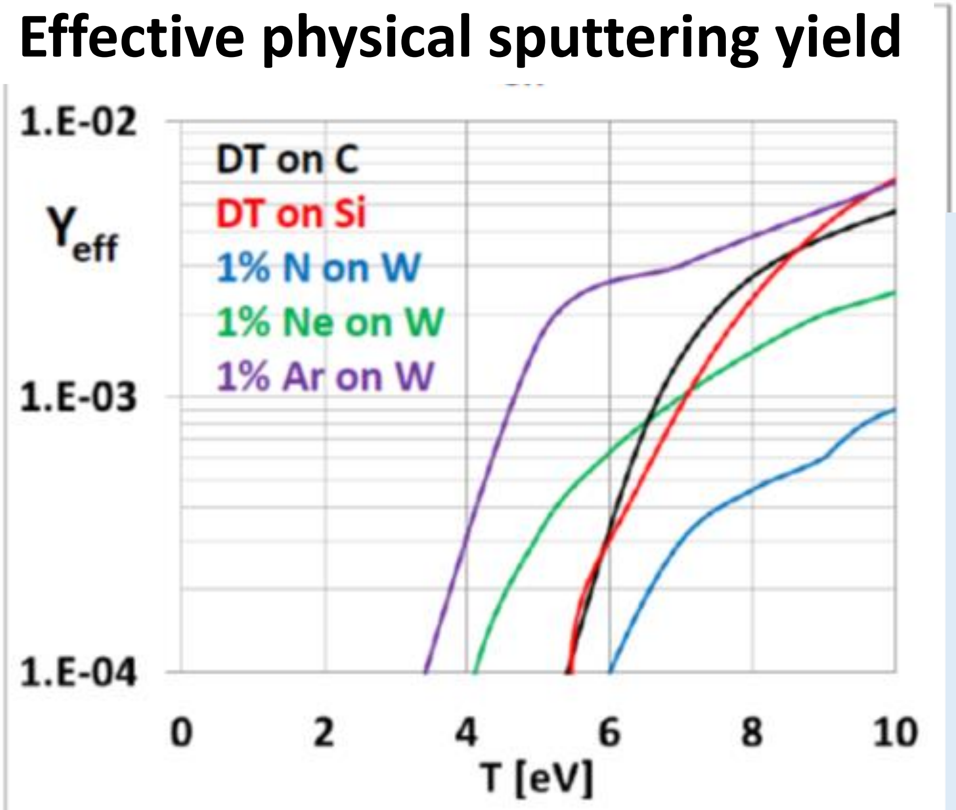
With smaller $\theta_\perp$ and/or higher power handling limits, it isn't necessary to go as deeply into detachment, i.e. to such low T_{target} → requires less edge radiation, reducing risk of degrading confinement.



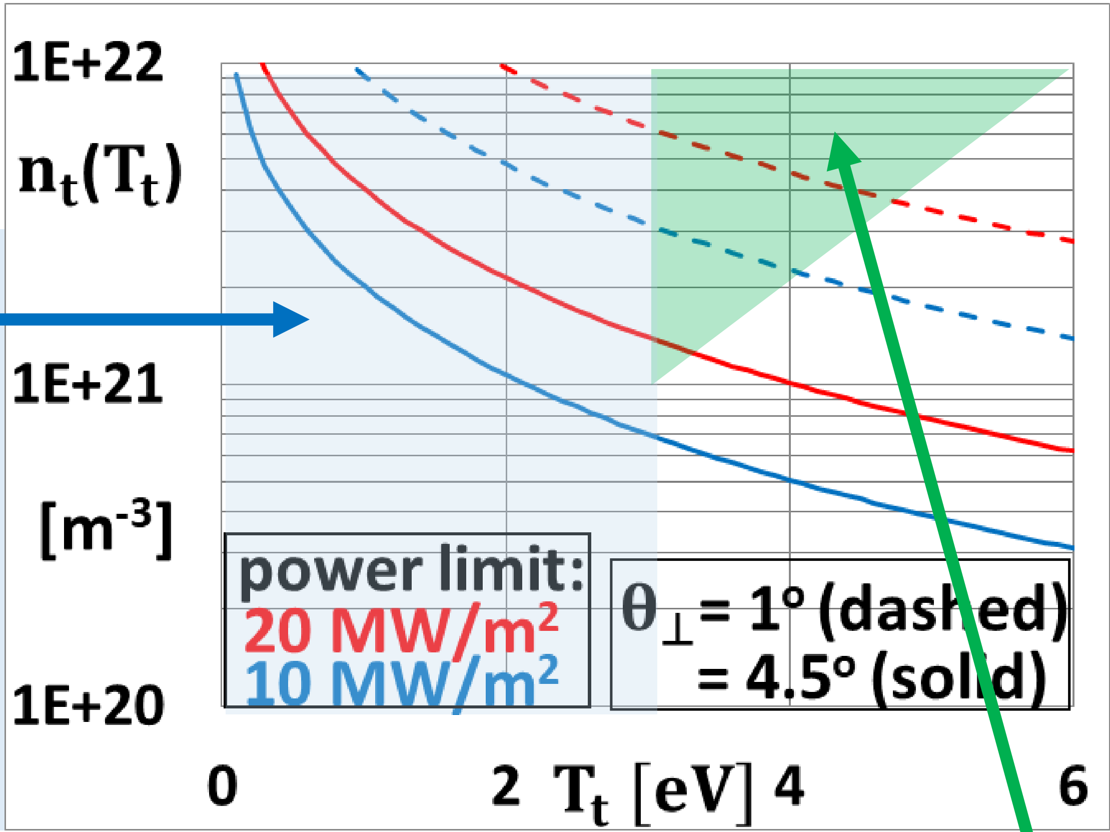
All expressions in poster are derived in Stangeby PPCF 60 (2018) 044022.

$$n_t \approx q^{pwr-limit} / \left(7.5e\sqrt{2e/m_i}(1 + 2/T_t)T_t^{1.5}\sin\theta_\perp\right)$$

I. n_t (T_t): divertor plasma n_{target} (T_{target}) for target survival re both power-load & erosion



In blue region: T_t is below sputtering thresholds.



In green region: T_t is above sputtering thresholds; however, for high n_t, **net** erosion is suppressed by prompt redeposition.

I. n_t (T_t): divertor plasma n_{target} (T_{target}) for target survival re both power-load & erosion

ITER

$\theta_{\perp}$ ~ 4.5°

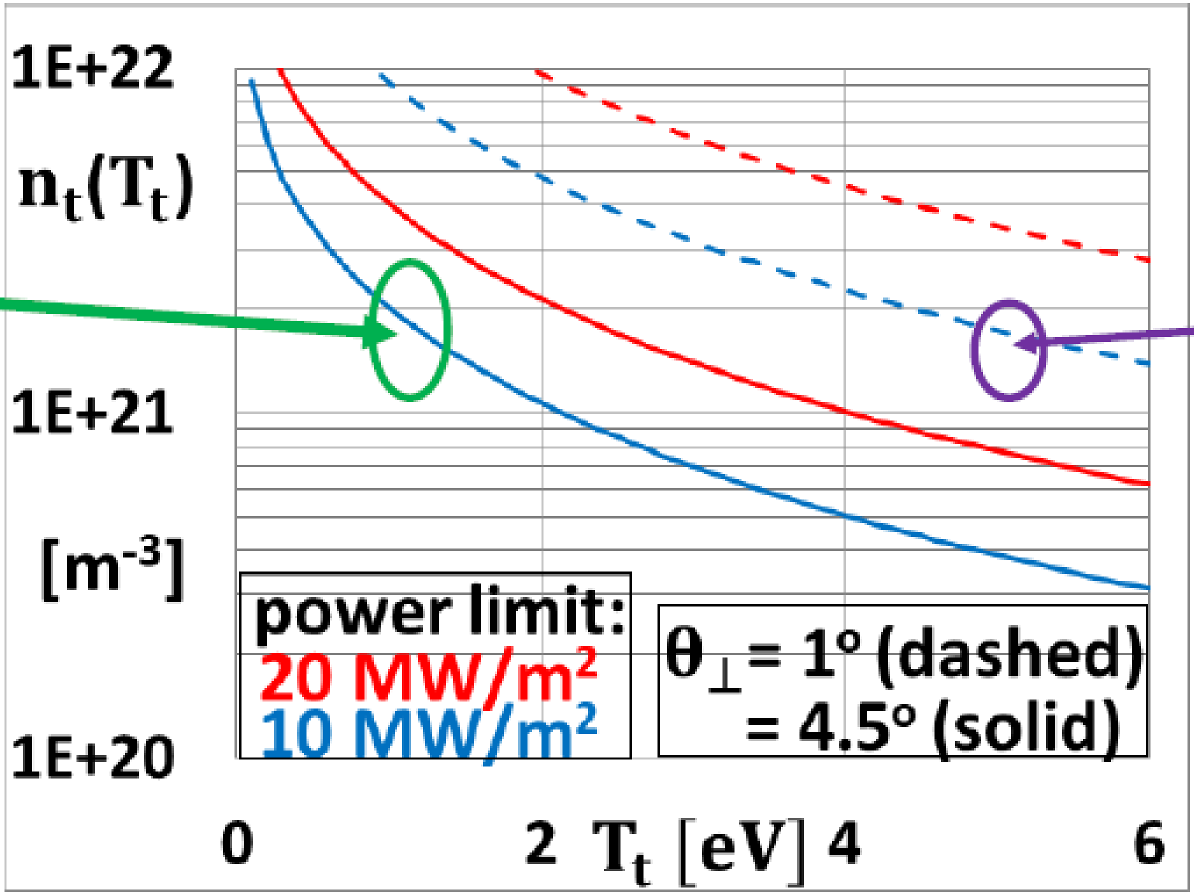
outer strike point

$q_{\perp}^{target}$

~ 10 MW/m²

Kukushkin

ITER: deeply detached



FNSF-AT & ST-FNSF

$\theta_{\perp}$ ~ 1°

outer strike point

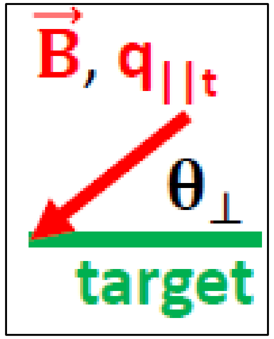
$q_{\perp}^{target}$ ~ 10 MW/m²

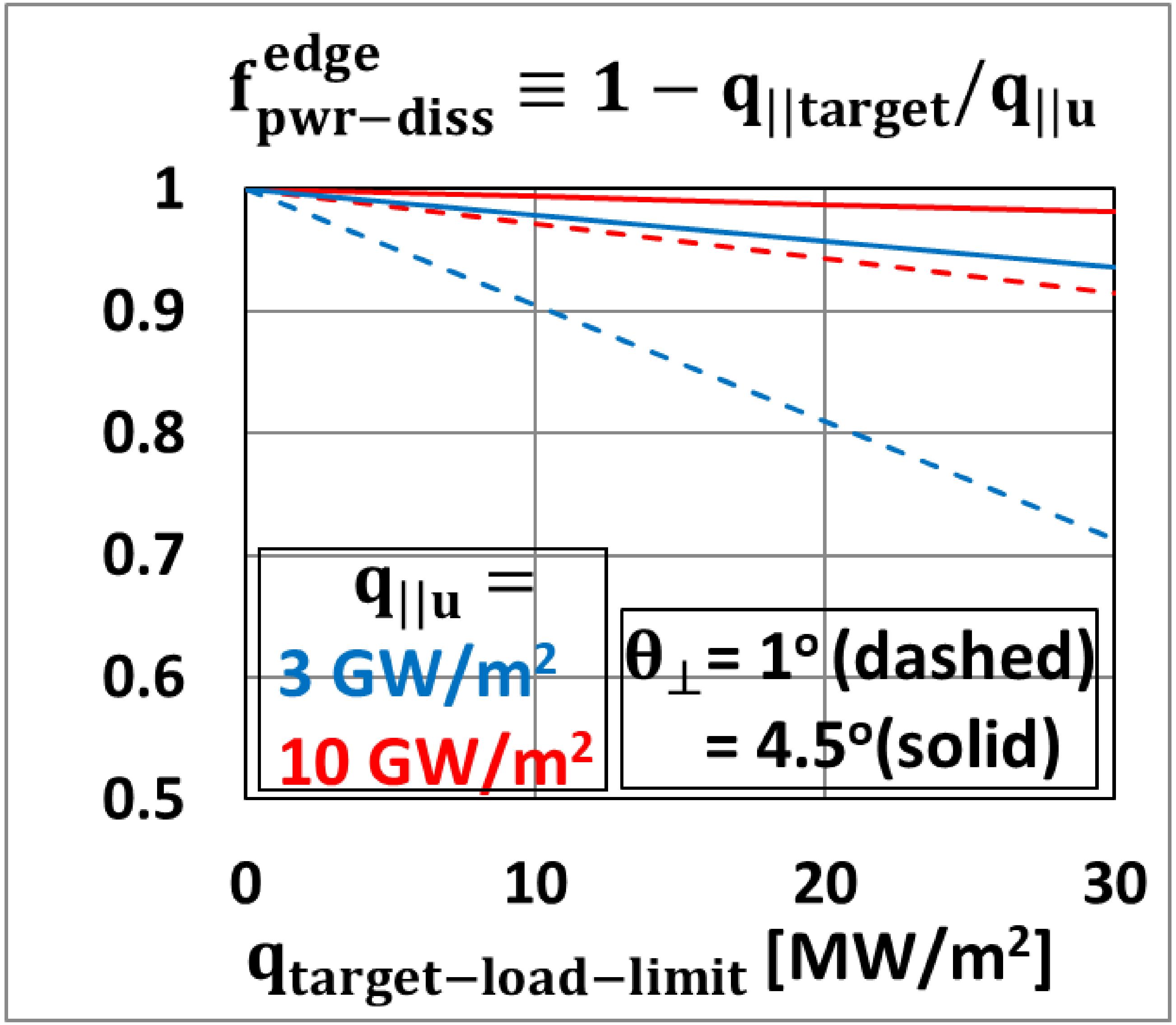
Canik

Not deeply detached

II. Required volumetric power dissipation in the edge

With smaller $\theta_\perp$ and/or higher power handling capability, less edge radiation is required, **reducing risk of degrading confinement.**





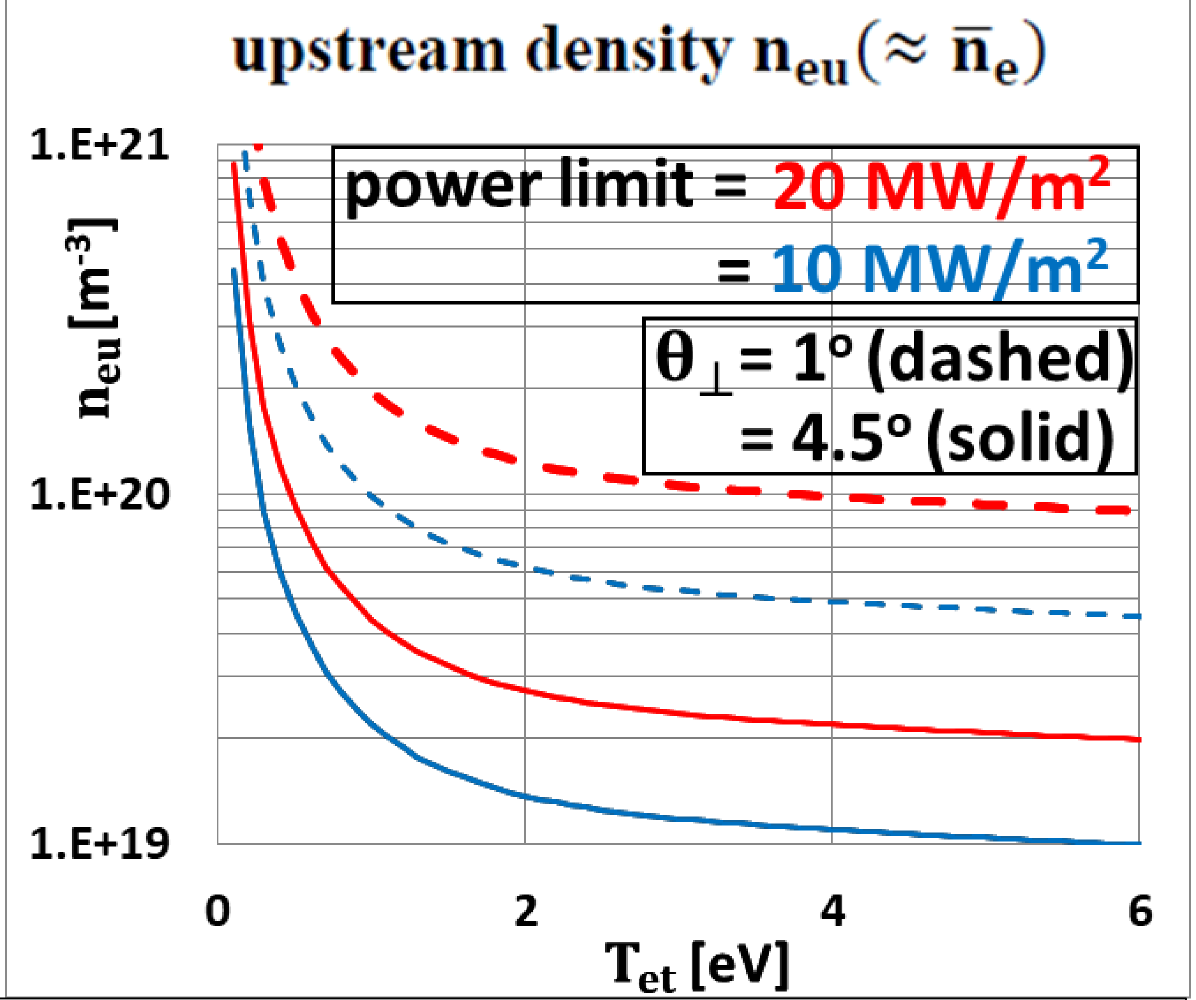
II. Required volumetric power dissipation in the edge

With smaller $\theta_\perp$ and/or higher power handling capability, less edge radiation is required, reducing risk of degrading confinement.

	$\theta_\perp = 1^o$	$\theta_\perp = 1^o$	$\theta_\perp = 4.5^o$	$\theta_\perp = 4.5^o$
	$q_{target-load}$ [10 MW/m²]	$q_{target-load}$ [20 MW/m²]	$q_{target-load}$ [10 MW/m²]	$q_{target-load}$ [20 MW/m²]
$q_{\|\|u}$ [GW/m²]	$f^{edge}_{pwr-diss}$ =	$f^{edge}_{pwr-diss}$ =	$f^{edge}_{pwr-diss}$ =	$f^{edge}_{pwr-diss}$ =
0.25			0.745	0.490
0.5	0.427		0.873	0.745
0.75	0.618	0.236	0.915	0.830
1	0.714	0.427	0.936	0.873
1.5	0.809	0.618	0.958	0.915
3	0.905	0.809	0.979	0.958
5	0.943	0.885	0.987	0.975
10	0.943	0.943	0.994	0.987
20	0.986	0.971	0.997	0.994

III. Value of 'upstream' SOL plasma density n_{eu} ($\rightarrow \bar{n}_e$)

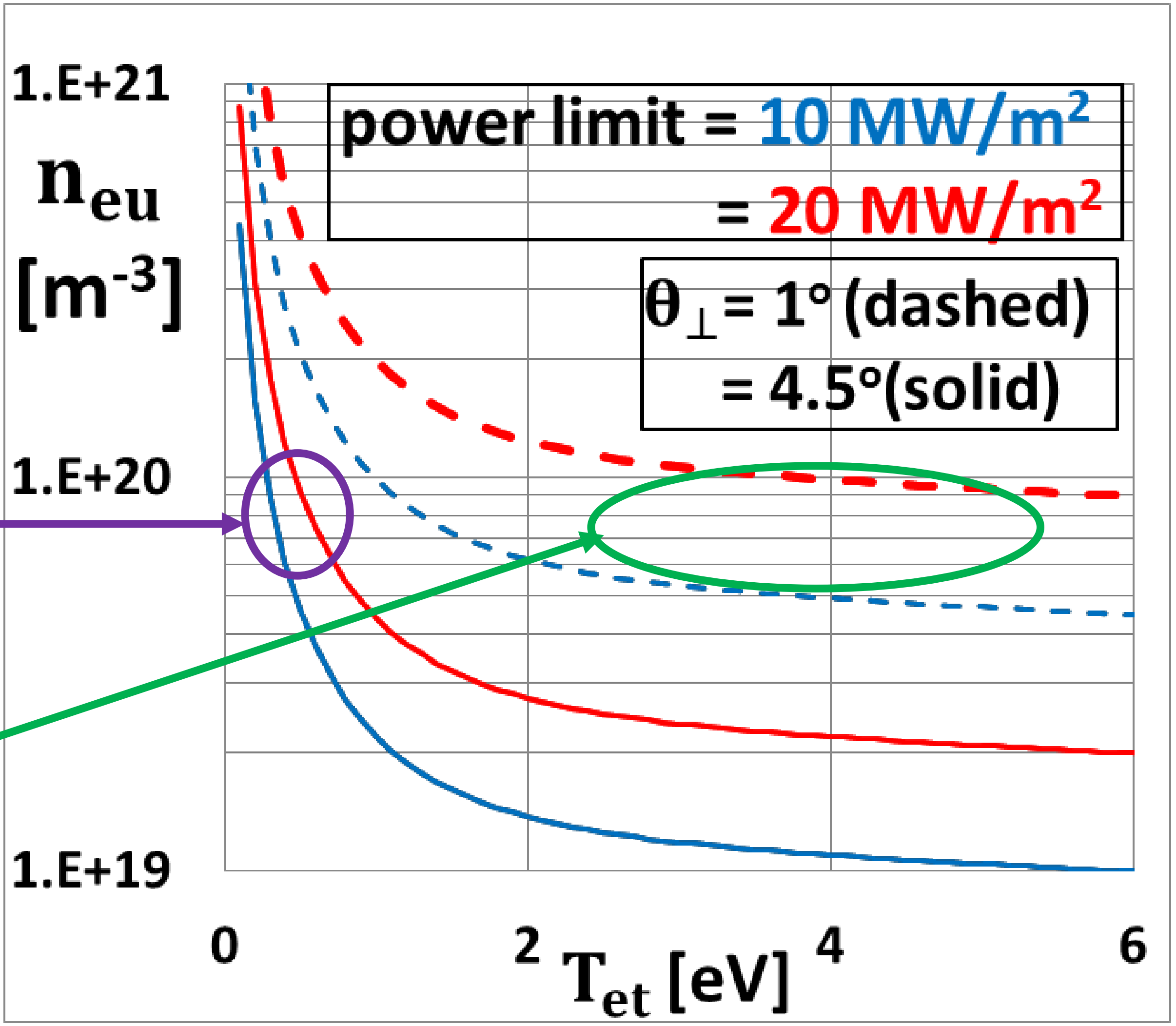
- Traditionally target quantities (n_t, T_t) are considered to depend on the specified upstream ones (n_{eu}, $q_{||u}$).
- However, if **target survival** is made **paramount** then (n_t, T_t) get **specified** and therefore **n_{eu} becomes a function of (T_{et}, $\theta_\perp$, power-limit)**.



$$n_{eu} \approx q^{pwr-limit} / \left(7.5 \times 750 e \sqrt{2e/m_i}(1 - f_{mom-loss})_{T_{et}} (1 + 2/T_{et}) T_{et}^{1/2} \sin\theta_\perp \right)$$

III. Value of 'upstream' SOL plasma density n_{eu} ($\rightarrow \bar{n}_e$)

- However, for the main plasma, ITER needs n_{eu}~0.6E20 m^{-3}; ARC ~1E20 m^{-3}; FNSF-AT ~0.9E20 m^{-3}.
- If $\theta_{\perp}$= 4.5°, then T_{et} ~1 eV, ∴ deep detachment, strong edge rad'n.
- If $\theta_{\perp}$= 1°, then T_{et} = several eV, ∴ less deep detachment, less strong edge radiation, less risk to confinement.



Conclusion

- **The rapid evolution of several advanced technologies being strongly pursued for major non-fusion applications, is potentially transformative for the divertor physics performance requirements of tokamak reactors.**
- **They can ensure target survival for less-strong detachment/edge radiation, reducing risk of degrading fusion performance.**