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:
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**.
- **Problem**: larger **gaps** and **misalignments** than for a pre-fabricated, vertical-lift **monolithic** structure.
- ∴ to shadow-protect **edges**, power-handling **surfaces** have to be **tilted**. $\theta_\perp \sim 4.5^\circ$ in ITER, c.f. $\sim 1^\circ$ in, e.g. DIII-D.
- **Problem**: 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 $\theta_\bot$ i.e. edges not exposed.
- **ARC with HTSC magnets and vertical-lift**: $\theta_\bot \sim 1^\circ$. 
Advanced *technologies* → divertor *physics*

- These high tech areas are being pursued for major, rapidly growing non-fusion applications.
- 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 (→ $\overline{n_e}$).
1. $n_t(T_t)$: divertor plasma $n_{\text{target}}(T_{\text{target}})$ 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 $T_{\text{target}} \rightarrow$ requires less edge radiation, reducing risk of degrading confinement.

All expressions in poster are derived in Stangeby PPCF 60 (2018) 044022.
I. $n_t(T_t)$: divertor plasma $n_{\text{target}}(T_{\text{target}})$ for target survival re both power-load & erosion

Effective physical sputtering yield

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

**ITER**

\[ \theta_\parallel \sim 4.5^\circ \]

outer strike point

\[ q_\parallel \sim 10 \text{ MW/m}^2 \]

Kukushkin

ITER: deeply detached

**FNSF-AT & ST-FNSF**

\[ \theta_\parallel \sim 1^\circ \]

outer strike point

\[ q_\parallel \sim 10 \text{ MW/m}^2 \]

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

<table>
<thead>
<tr>
<th>$q_{\parallel u}$ [GW/m^2]</th>
<th>$\theta_\perp = 1^\circ$</th>
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<td>$q_{\text{target-load}}$ [10 MW/m^2]</td>
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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 \((T_{et}, \theta_\perp, \text{power-limit})\).

\[
n_{eu} \approx \frac{q^{\text{pwr-limit}}}{(7.5 \times 750e^{\sqrt{2e/m_i}}(1 - f_{\text{mom-loss}})T_{et}(1 + 2/T_{et})T_{et}^{1/2}\sin\theta_\perp)}
\]
III. Value of ‘upstream’ SOL plasma density $n_{eu}$ ($\rightarrow \bar{n}_e$)

- However, for the main plasma, ITER needs $n_{eu} \sim 0.6E20$ m$^{-3}$; ARC $\sim 1E20$ m$^{-3}$; FNSF-AT $\sim 0.9E20$ m$^{-3}$.

- If $\theta_\perp = 4.5^\circ$, then $T_{et} \sim 1$ eV, $\therefore$ deep detachment, strong edge rad’n.

- If $\theta_\perp = 1^\circ$, then $T_{et} = \text{several eV}$, $\therefore$ 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.