R-7: thinking outside the box: New integrated approaches are needed to solve divertor, main chamber and steady state sustainment challenges for fusion

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The tokamak concept is the most advanced magnetic confinement approach for fusion. But before it can be considered viable for a steady-state, electricity producing power plant, robust solutions for plasma-material interaction (PMI) challenges must be found: (1) power exhaust – order of magnitude improvements in steady state divertor power density handling are needed; (2) divertor target lifetime – target plate erosion must be almost completely suppressed; (3) main-chamber component lifetime – wall components must survive the PMI onslaught for sufficient time, including current drive and heating actuators, which must also attain high overall system efficiency and availability.

In order to meet these challenges – and also satisfy constraints imposed by the DT fusion environment (tritium breeding, magnet shielding/lifetime) – integrated tokamak reactor designs are needed that can fully implement promising advanced divertor approaches and also exploit key attributes of divertor and scrape-off (SOL) plasma physics:

- **Employ double-null topology.** Take advantage of the tendency for heat/particles to exhaust near the outer midplane, preferentially sending fluxes to outer divertor legs.
- **Employ advanced outer divertor legs.** Locate target plates at large major radii (e.g., super-X and X-point target divertor ideas) to decrease target plate heat flux density and provide detachment front stability/control; employ X-points as virtual targets in the divertor volume to intercept peak heat fluxes and increase field line lengths; employ tight neutral baffling for gas-dynamic control; employ liquid metal target concepts.
- **Take advantage of ‘quiescent’ high-field side (HFS) SOL.** Exploit excellent impurity screening properties and profile narrowness (facilitated by double-null) of HFS SOL – locate all close-fitting wall surfaces and RF actuators to the HFS for reduced PMI, reduced impurity sources and core contamination, and highly favorable RF wave physics.

While some of these requirements may appear inconsistent with reactor designs that use current technologies, one should keep in mind that significant advances can occur over a 10-20 year time frame. For example, since the ITER EDA, high temperature superconductors (HTS) and 3D printing of structural materials are now commercially available. Demountable, HTS toroidal field magnetics may be possible. This may allow the entire vacuum vessel/divertor of a compact reactor to be replaced as a single unit, as considered in the ARC pilot reactor concept [1]. Such a design might employ: (a) frequent (~1.5 year) replacement of the first wall and actuator components, as well as internal poloidal field coils (perhaps non-superconducting) needed to produce advanced magnetic divertor topologies; (b) use of a full immersion blanket design for enhanced tritium breeding and effective neutron shielding.

Thus, near-term fusion research should focus on exploring/developing/demonstrating physics solutions for divertor and main chamber challenges, without being overly concerned about technology constraints. At the same time, innovative reactor designs using the latest technologies should be investigated.

Finally, to expedite fusion development, a strategy of first targeting a high-field, compact, tokamak that demonstrates net electricity production, even for just a short period of time, may be most effective. This would ‘ignite’ the world’s interest and marshal resources needed to take fusion to the next step – the scale up to a demonstration power plant.