A Sustainable High Power Density (SHPD) Tokamak to Enable a Compact Fusion Pilot Plant

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Design parameters, key physics missions and engineering issues are identified for a new high power density tokamak to develop and test predicted sustainable plasma operating scenarios for a low capital cost fusion pilot power plant. Analysis highlights that low cost requires advanced plasma scenarios with high confinement and capable power handling (Fig 1a), ie a “core-edge”solution. Critical phase transitions are identified in the underlying physics; it is important to place the SHPD device on the reactor side of these transitions to find pilot solutions. Key gaps between present devices and the pilot are identified in fusion power density, bootstrap fraction, heat flux, field and particle density (Figs 1b,2a). Self-consistent transport, current drive, pedestal, and equilibrium simulations (Figs 2b,3) show a modest scale SHPD tokamak can meet these challenges, operating with high field, broad current profiles and moderate aspect ratio, A, which, with suitable wall and divertor choices, would pioneer solutions for the fusion pilot.

A low capital cost fusion reactor is reliant on advanced technology and plasma science solutions. Fig. 1a shows an analysis with GA systems code which captures the key known engineering and scientific dependencies in reactor design {1} to project design constraints, scale and cost. Identifying trends about a reference operating point with net electric power of 200MW, confinement quality is the most levering parameter, with a much more expensive and larger device required if high confinement cannot be sustained (major radius, R, rising from <4m to ~6m). High tritium breeding and thermal efficiency are also important, as well as divertor heat flux and neutron handling capacity.

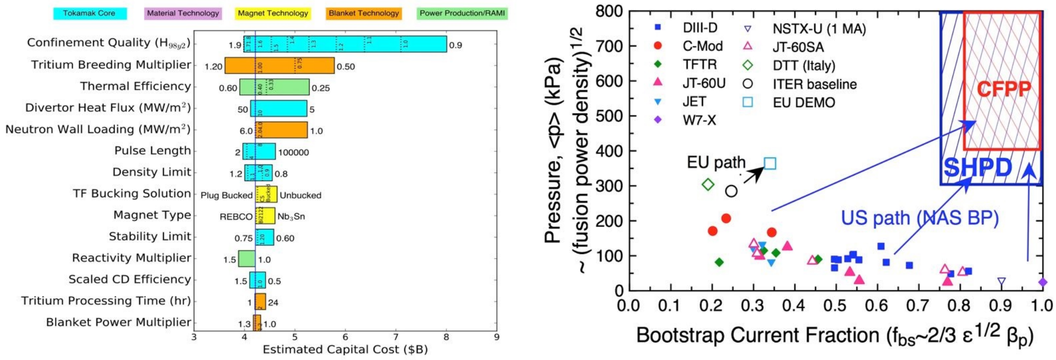

Figure 1: (a) (left): System code analysis identifying the most important parameters governing the capital cost of a fusion pilot plant. (b) (right): Comparison of low capital cost pilot plant (CFPP) with present devices (achieved=solid symbol)

Physics analysis identifies key gaps between present devices and a compact fusion pilot. The plasma must operate at higher pressure ($\langle p\rangle = (2/3)W/V$) and power density ($P_{fus} \sim \langle p\rangle^2$) than ITER, with dominant bootstrap current to reduce recirculating power, enabling sustainable non-inductive net electricity production (Fig. 1b). Techniques to mitigate the plasma exhaust must be developed for high heat flux (Fig. 2a) and opacity regimes with short mean free paths and Lyman alpha trapping. Divertor and wall solutions must be reconciled with an opaque radiative pedestal, which in turn governs optimization of the core solution. Resolving these dynamics requires simultaneously matching dimensional (fluxes, density) and dimensionless (ν_*) parameters to reactor values, and thus higher field, B and pressure.

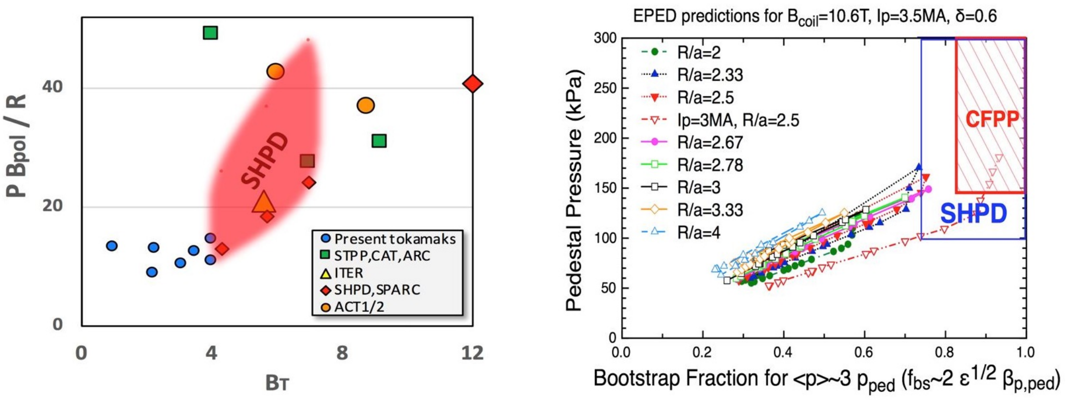

Figure 2: (a) (left): Pilots (green) operate at high field and high heat flux. (b) (right) Pedestal optimization with aspect ratio for SHPD.

The challenges for SHPD illustrated in Figs 1,2a are daunting, but improving physics understanding embodied in sets of self-consistent core-edge predictions indicate it is possible to achieve attractive operating points via optimization of plasma shape, aspect ratio, and field. Pedestal calculations (Fig. 2b) with EPED (recently validated at pedestal pressures up to 80 kPa) {3} identify optimal performance with strong shaping and $A \sim 2.3 - 2.7$, aligning with systems studies that also include engineering considerations {2}. $A \sim 2.5, \kappa = 2.1, \delta = 0.7$ was chosen for self-consistent core-edge predictions with TGLF + EPED {3-5} (Fig. 3). A large parameter exploration identified a reference point with $B = 4 - 7T$ and 30-60MW of heating and current drive (beams and EC) at $R \sim 1.25m$ deliver up to 100% bootstrap fraction and PB/R values approaching those of a pilot. This enables study of radiative mantle pedestal optimization integrated with dissipative detached divertor solutions. Importantly, the pedestal remains low ν_*, peeling limited and opaque with good H-mode access margins. Absolute divertor densities and PB/R are similar to the pilot, permitting exploration of advanced divertor concepts {6} and their pedestal compatibility. Lower density operation (~50% Greenwald) can reach reactor ν_*, though with less bootstrap. High confinement (corresponding to $H_{98y2} \sim 1.3 - 1.5$) arising from broad current profiles at high β is self-consistently predicted by the models, with further optimization possible. Core pressures exceed ITER, and with coupled electron-ion turbulence, permit study of burning plasma relevant behavior in steady state regimes, with high q and q_{min} favorable for tearing and ideal MHD stability, disruption avoidance and mitigation.

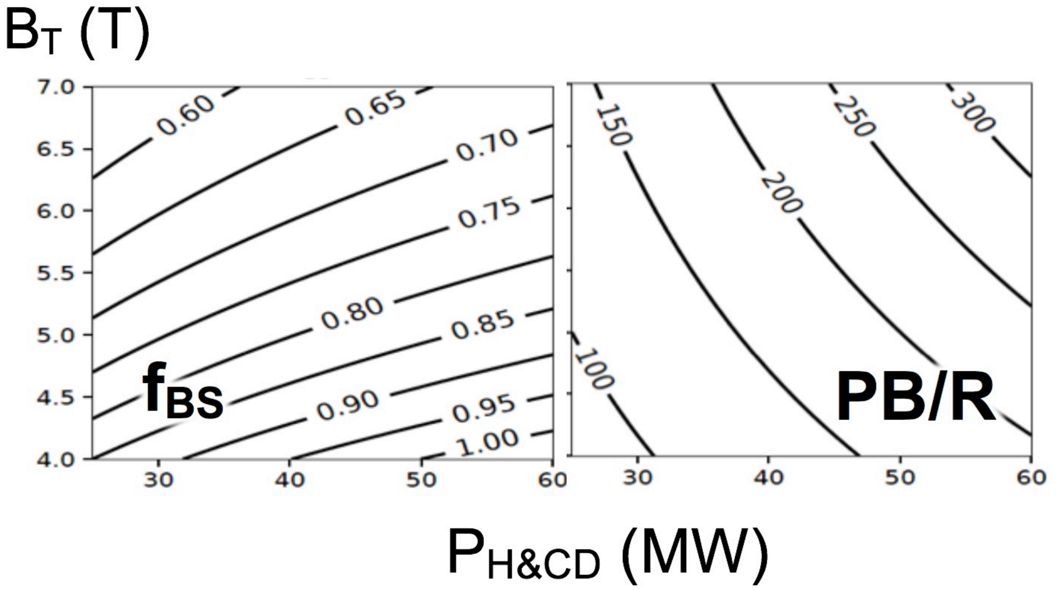

Figure 3: Bootstrap fraction and PB/R for SHPD with $R = 1.25m$, $A = 2.5$, $q_{95} = 8$ and pedestal at 90% of Greenwald density.

With a resistive current diffusion time, $\tau_R \sim 2-3s$, a 10s pulse length will enable exploration of steady-state plasma solutions. Longer pulse lengths would further enable studies of PMI and slag, with tradeoffs against issues of timescale, activation and cost. Wall-core compatibility and impurity dynamics will be key aspects to test, even with short pulses. HTS or improved LTS coils are advantageous in optimizing performance, pulse lengths and compactness. Advanced current drive schemes would also be tested at reactor-like fields, densities, temperatures and SOL properties in this device.

A compact SHPD tokamak would address key issues and validate physics understanding for a low capital cost fusion pilot plant, developing the techniques to design and optimize the pilot plant with confidence, and the expertise and experience to pursue its construction.

{1} R.D. Stambaugh et al., Fus. Sci. Tech. 59 (2011) 279.
{2} J. Menard et al., this conference.
{3} P.B. Snyder et al, NF 59 (2019) 086017.
{4} G.M. Staebler et al, NF 57 (2017) 066046.
{5} J.M. Park et al., Comput. Phys. Com. 214 (2017) 1.
{6} M. Kotschenreuther, PoP 20 (2013) 102507.

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