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

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Abstract. A compact fusion pilot plant lies in physics regimes where plasma behavior can be different from present devices. It requires integrating innovative and improved solutions to tokamak physics problems that go beyond presently developed implementations. A well-developed physics basis with validated models is required to project solutions to the pilot. This motivates new research capabilities with considerable flexibility to pioneer and project the necessary solutions, operating at higher pressure, power and particle densities than present facilities. Options to address this need include a new 'built from scratch' facility and upgrades to existing devices in collaboration with planned facilities.

1. INTRODUCTION – THE CHALLENGE OF A COMPACT FUSION PILOT

A low capital cost Compact Fusion Pilot Plant (CFPP) places particular challenges in its plasma physics to sustain the higher power densities required for sufficient fusion performance (Fig. 1). Systems analysis [1] highlights that low capital cost requires advanced plasma scenarios with high energy confinement and capable power handling (Fig. 2). The required parameters [2] place the plasma in different physics regimes compared to those accessed in present devices; these need investigation to develop the improved solutions necessary, and the scientific foundations to project behavior. In this short paper, we summarize studies undertaken as part of a recent U.S. community planning process to address this issue [3]. In section 2, we discuss the changes in physics at the CFPP scale, and the consequent research mission. In section 3, we consider a possible approach to meet the mission with a new device. Finally, section 4 discusses the key questions and trade-offs between the various approaches possible.

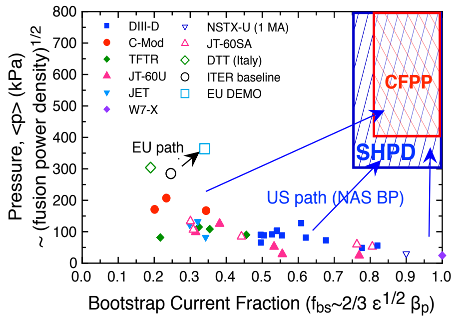

Fig 1: Comparison of pilot with present devices (achieved=filled symbols).

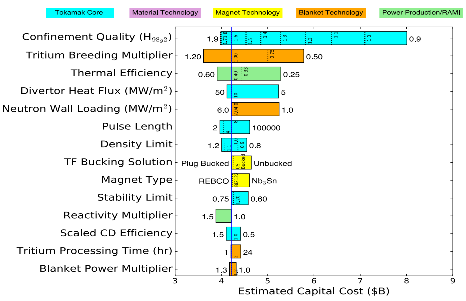

Fig 2: System analysis identifies the most important parameters governing capital cost of a 4m radius 200MWe fusion pilot.

2. PLASMA PHYSICS RESEARCH MISSION FOR A PILOT PLANT

A CFPP poses exacting plasma physics and technology challenges to develop the innovative solutions necessary to resolve a viable device concept. To discover these requires (i) access to relevant physics regimes, (ii) flexibility to pioneer new approaches, and (iii) to integrate the required techniques. On the first point, the key concept is to place research capabilities on the right side of phase transitions in the physics that can alter behavior and projections. In the divertor this means accessing regimes such as divertor detachment with short neutral and photon path lengths relative to divertor dimensions, with relevant recombination rates, and at heat fluxes where turbulence broadening in the SOL can be assessed. In the pedestal, reactor plasmas will be opaque to neutrals, and so profiles and impurity distributions will be defined by transport and pinch processes, rather than by the ionization profile. This is particularly important to assess as radiative mantle impurities are needed to mitigate the divertor challenge. In the core, electrons and ions are coupled, while rotational turbulence stabilization, induced by neutral beams in present devices will depend on self-generated rotational shears. Fast ion fractions will be lower than many neutral beam heated devices, influencing Alfvénic modes, for which it is desirable to study super Alfvénic ions. These effects, and high β and q_{min} requirements, also impact stability and transport.

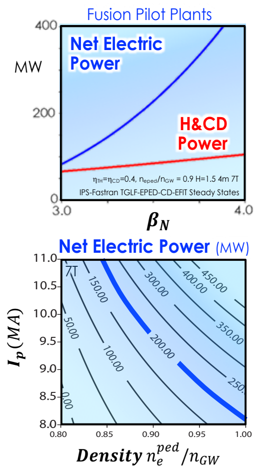

Fig 3: Integrated physics simulations of steady state CFPP existence points at 4m radius & 7T [2].

Plasma scenario solutions must be pioneered in these regimes. A central question is how to reach robust, stable, high performance? Is this best attained in high β_N advanced tokamak (AT) regimes with high safety factor and broad current profiles increasing stability and normalized confinement to achieve noninductively sustained steady state? Or through higher current inductively pulsed regimes, where low-order instability resonances are more prevalent, but confinement is high. There is a clear benefit to higher pressure and density operation (Fig. 3); these limits must be scoped. High density is particularly important because it reduces recycling current drive power (through higher bootstrap current), and also increases radiative dissipation and lowers required current, easing the divertor challenge; scope to raise density through advanced pedestal or confinement regimes is highly desirable. For steady state solutions, efficient reactor-compatible current drive is also key, while for inductive approaches, the means to avoid and mitigate more prevalent and severe disruptions is vital.

However, the divertor is perhaps the most critical area, where continuous or high duty cycle CFPP operation requires a non-eroding power handling solution. Studies need to explore how advanced magnetic geometries and closure can make a solid divertor possible, or whether liquid techniques that offer transformative potential can be harnessed. Innovative regimes such as negative triangularity that may lower SOL heat fluxes should also be tested. Potential solutions must be proven compatible with relevant wall materials. Also, projectable control techniques for instabilities, ELMs and disruption mitigation must be rigorously developed as these events become intolerable in a CFPP.

Integration poses perhaps the greatest challenge, as a high-performance core and dissipative power handling solution place competing demands on each other. The former is at low collisionality, ν^*, while the latter requires high density. Thus, resolution and understanding of an integrated solution requires high pressure (noting $\nu^* \sim n_e^3/P^2$) in order to place both regions, and the pedestal/SOL zone where they interact, in relevant regimes. With these issues addressed, it is then possible to develop candidate solutions for a CFPP and crucially, the physics basis to project and integrate them in the pilot plant.

3. A NEW SHPD D-D RESEARCH FACILITY?

To minimize extrapolation to a CFPP, integrated physics simulations [4] were used to identify candidate device parameters and capabilities. A compact scale and short pulse length were adopted to reach reactor-relevant power densities and physics metrics while also ensuring low activation, to provide a flexible, personnel access facility to address the research mission. Shape and aspect ratio were optimized to maximize pedestal performance (δ=0.7, κ=2.1, *R*/*a*~2.5) [5]. The resulting design matches CFPP heat fluxes at high field, while approaching fully bootstrap driven AT scenarios with q_{min}>2 at lower fields (Fig. 4). This is obtained at high pedestal density (fraction of Greenwald, f_{pedGW}~90%) with ν^*~0.3. At f_{pedGW} ~50%, the device matches reactor collisionalities, though with lower bootstrap fraction and opacity regimes. Steady state pressures up to 450kPA exceed ITER values enabling exploration of core-edge integration physics. Higher currents raise pressure further toward reactor values (650kPA at 4.4MA), but reduce bootstrap fraction, becoming inductive above 3MA, and requiring more auxiliary power. 20cm shielding reduces neutron loading and activation to tolerable levels for manned access and site boundaries, with 10s pulse lengths providing 2-3 current redistribution timescales. Thus, one arrives at a flexible facility that can narrow physics parameter gaps to the CFPP, individually matching key metrics to explore relevant techniques in each region, while also being able to explore interaction between regions that are simultaneously in relevant regimes. Nevertheless, further work is needed to quantitatively determine physics capabilities in some key areas such as the divertor.

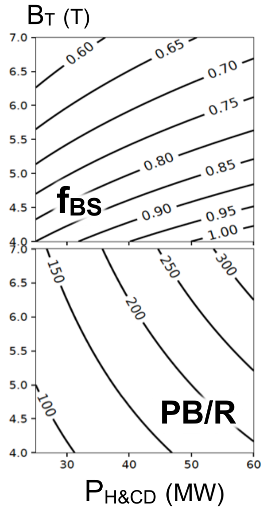

Figure 4: SHPD solutions with H_{98}~1.5 R=1.25m, R/a=2.5, I_P=2-3MA, q_{95}=8 and f_{pedGW}=0.9.

4. DISCUSSION – OPTIONS AND TRADE-OFFS IN THE SHPD MISSION

Careful assessment is needed to resolve the critical question of how far one needs to go, and with what facility capabilities, to sufficiently resolve the path to a CFPP. The answer must come from a balance between risk reduction and opportunity cost. A small, short pulse, high field D-D device will reduce risk for a pilot plant, accessing high power densities and steady state configurations to develop core-edge solutions that can be better extrapolated to a CFPP, with good physics models and incorporating data from long pulse and burning plasma devices. Ideally, this would utilize high temperature superconductors, to enable the higher field and also a more compact scale (heating being an issue for a compact device if copper is used), potentially also demonstrating joint technologies. A long pulse version, would go further to address wall issues and slag build up, although the facility would then become activated (if D-D), providing the opportunity to demonstrate remote handling, but limiting access and flexibility. The introduction of tritium would go further still and may make sense in addition to long pulse, to explore the dynamic and confinement of fusion alphas in integrated core-edge-wall solutions. These latter two options would likely imply limited hands-on access to the device

Alternatively, with significant upgrades, existing facilities would be able to access the relevant physical regimes of the CFPP and could rapidly pioneer key techniques and develop physics-based projection capability. However, their lower field and power densities leave a larger extrapolation gap for model-based projections, and partnership with higher field facilities (ITER, SPARC, iDTT, BEST) would become more important to help narrow these gaps.

Key questions for any path is how much risk it retires for the CFPP, and whether this can eliminate check-out and adjustment phases (e.g. the divertor) that may be needed in the CFPP itself? Additional capabilities of a 'build from scratch' new facility should also be tensioned against the additional timescales, and financial and opportunity costs incurred, where recent studies indicate a ~$1Bn cost for a replacement low field short pulse facility, consistent with recent U.S. facility developments. A report unanimously endorsed by the U.S.'s Fusion Energy Science Advisory Committee, confirmed the need to address the 'Integrated Tokamak Exhaust and Performance' gap, judging construction of a new high field facility as the optimal solution, but stating design, costing and integrated modeling were needed to confirm mission and scope, to be compared to alternative approaches such as enhanced collaborations and upgrades.

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[3] R. J Buttery et al., "Possible Mission and Viability of a Sustained High Power Density Facility" (2019, APS-DPP CPP): https://drive.google.com/file/d/1NKwgcpkcZGA2mbit0HZkcAgQQQwvK4z8/view.
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