Closing the Loop: Why Fusion Power Demands a New Diagnostic Blueprint

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Following more than five decades of development, nuclear fusion has reached a point where it transits from pure physics experiments towards fusion power plant demonstrators (FPPs) using an engineering approach and preparing for commercial deployment. However, operating a commercial facility requires a radical departure from historical approaches. In this new paradigm, diagnostic and measurement systems, that are typically key for control, operation and asset protection, need to be much more robust and adhere to industry standards.

They must provide the critical data required to maintain a steady-state burning plasma(for machines like tokamaks) or steady pulsed-mode operation(for pulsed concept machines), optimise fusion power output, and ensure robust asset protection by detecting off-normal behaviours early enough for real-time control systems to take actions.

A new strategy is required that considers the entire diagnostic and machine lifecycle from day one, balancing systemic diversity with fewer overall systems. To ensure reliability, control systems need redundancy through high diagnostic robustness or intelligent control capable of dynamically switching inputs, such as inferring missing data from alternative sensors if a primary one fails. Beyond control, diagnostics will retain a vital physics role, especially for first-of-a-kind machines like STEP, in exploring uncharted burning plasma territory where no experimental data yet exists.

Deploying these systems means confronting a harsh operational environment for a machine-like STEP has not been observed yet, and we only can quantify and estimate it using past(e.g. JET) or current devices(e.g. JT60-SA, ITER). Significant technology and materials gaps remain to be bridged. Consequently, diagnostics can no longer be bespoke laboratory instruments; they must become scalable (e.g. able to be volume manufactured adhering to tight quality standards), largely autonomous, integrated solutions for native real-time operation, align with remote handling protocols during commissioning or maintenance, and match the lifecycle constraints of other parts of the reactor where they sit. Ultimately, FPP diagnostics must deliver years of highly reliable, low-maintenance operation, engineered for remote maintenance from day one. This presentation will outline the essential pillars of this new diagnostic blueprint.

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