# Establishing the Basis for Sustained Tokamak Fusion Through Stability Control and Disruption Avoidance

E. J. Strait, General Atomics

**Introduction -** The development of tokamak fusion, including the Q=10 mission of ITER and the design of FNSF, requires robustly stable operating scenarios with suitable avoidance and mitigation strategies for disruptions. The causes of disruptions are known and understandable; in general, the immediate cause is an MHD instability or an off-normal event such as a power supply fault. However, the events leading to the instability are not always predictable. Therefore, a multi-layered approach is needed (Fig. 1).

**Proposed United States (US) initiative -** The US fusion energy program is uniquely positioned for an initiative on disruption prediction, avoidance, and mitigation, with the potential for a major impact on worldwide fusion energy development. The US is a world leader in the areas of active stability control and disruption mitigation. Existing US facilities have the high-speed digital control systems, high-resolution diagnostics, control actuators, and numerical modeling capabilities required for such an initiative. Modest size and carbon walls make the existing facilities more tolerant of disruptions than larger, metal-wall devices.

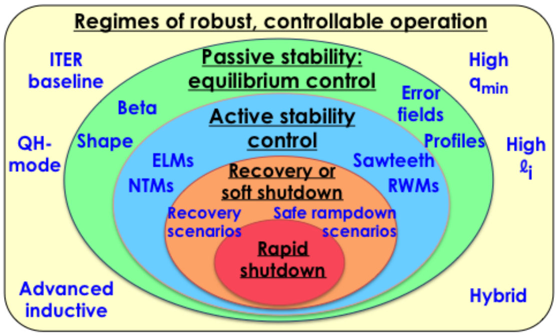

*Fig.1. Multi-layered strategy for disruption avoidance and mitigation*

- **Regimes of Robust Operation -** The most desirable solution is to operate in a regime where disruptions rarely occur. The challenge is to develop robust, passively stable regimes in fusion-relevant conditions (e.g. low input torque) that are at the same time capable of high fusion performance.
- **Passive Stability through Equilibrium Control -** Control of the plasma equilibrium may be required to maintain the desired operating point and to steer it away from stability limits. Actuators include heating and current drive systems, discharge shaping coils, and 3D perturbation coils. The challenge is to develop reliable real-time stability analysis tools that can determine proximity to the limits. These may include real-time stability analysis or direct probing of plasma stability with small perturbations.
- **Active Stability Control -** If a stability limit is crossed, deliberately or due to an off-normal event, active stabilization becomes necessary. Control actuators include local rf heating or current drive, 3D equilibrium fields, and non-axisymmetric coils for direct magnetic stabilization. Challenges include development of control algorithms that can reliably recognize when and how to use these actuators.
- **Recovery or Soft Shutdown -** If active stabilization is not sufficient, a retreat to more stable conditions or a prompt, controlled shutdown may become necessary. Challenges include development of effective control scenarios for recovery of full operation or a stable shutdown.
- **Rapid Shutdown -** In rare instances, a pre-emptive rapid shutdown by injection of radiating impurities may be required. Challenges include prompt and reliable recognition of an imminent disruption, means of rapid delivery of impurities to the plasma core, achievement of sufficient heat load symmetry, reduction of electromagnetic loads, and solutions for suppression or control of runaway electrons.

**Scope of Required Research -** Development of the scientific and engineering basis for real-time prediction and control of tokamak stability will require a focused, multi-year national effort. The primary need is for a significant increase in human resources and operating time on existing facilities. Upgraded control actuators (rf current drive, 3D coils, mass injectors for mitigation) and upgraded diagnostics for model validation will be crucial. Extensive numerical modeling of discharge evolution, stability limits, and active stabilization methods is required, and could be shared among national facilities and universities. Much of the experimental work can and should be done on existing short-pulse tokamak facilities, as described above. Later, the solutions will be tested through collaborations on the newer superconducting facilities in order to demonstrate reliable, long-pulse, disruption-free operation. Achievement of these goals within ~10 years will deliver results near the beginning of ITER's operation.