Thrust #2: Control of Transient Events

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for the
Thrust 2 Working Group,
Off-Normal Events Panel,
and ReNeW Themes I and II

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DIII-D NATIONAL FUSION FACILITY

GENERAL ATOMICS

Sustained operation of a tokamak burning plasma requires avoidance of disruptions and ELMs

- **Transient events may cause loss of operating time due to**

(Disruptions and ELMs)	(Disruptions)
– High transient heat loads	– Electromagnetic forces
– Erosion of plasma-facing surfaces	– Runaway electron beams

- **A coordinated research program is needed to develop the means to reliably control or avoid such events.**

Off-normal Plasma Events:

Understand the underlying physics and control of high-performance magnetically confined plasmas sufficiently so that 'off normal' plasma operation, which could cause catastrophic failure of internal components, can be avoided with high reliability and/or develop approaches that allow the devices to tolerate some number or frequency of these events.

(Because of their implications and importance, these 'off-normal events' are called out separately from the control issues.)

– FESAC Priorities Panel (2007)

Key issues

- **Capability to predict disruptions.** *Can plasma stability be assessed accurately enough to* ***predict the approach to stability limits****?*
  Can other triggering events be reliably detected?
- **Capability to avoid disruptions.** *How can a control system be designed to robustly* ***steer the discharge operating point to a more stable state****?*
  What are causes and frequency of disruptions that cannot be avoided?
- **Means to minimize the impact of disruptions.**
  What is the best means to ***mitigate the effects of disruptions****?*
  Can ***effects of mitigated disruptions*** *be predicted reliably enough to allow design of tokamak systems that will survive mitigated disruptions?*
- **Means of robustly avoiding or suppressing ELMs.** *How do* ***2-D & 3-D magnetic fields*** *alter transport and stability in the plasma edge?*
  Can ***other means of edge modification*** *(e.g. rotation, fueling, recycling control) remove ELMs or sufficiently reduce their amplitude?*

Proposed actions

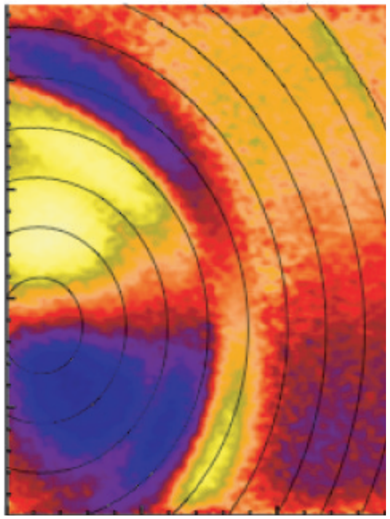
- **Develop plasma stability analysis tools fast enough to operate in real time, and test them on existing tokamak experiments.**
- **Develop control strategies for steering the operating point away from impending instabilities, and for active stabilization.**
  - Develop on existing tokamaks and demonstrate on the emerging generation of superconducting tokamaks.
- **Develop techniques for mitigating disruptions by rapid but benign shutdown of the discharge.**
  - Demonstrate the solutions in medium and large tokamaks.
- **Develop techniques for mitigating ELMs through control of the edge plasma transport and stability.**
  - Demonstrate the solutions in medium and large tokamaks.

Scientific and Technical Research Elements

The research in this area can be organized into four broad elements:

- **Prediction of disruptions**
  - Operating limits, real-time stability assessment, detection of precursors
- **Avoidance of disruptions**
  - Equilibrium control: detect and avoid stability limits
  - Stability control: active suppression of instabilities
- **Mitigation of disruptions**
  - Controlled shutdown
  - Rapid shutdown (e.g. impurity injection)
- **Avoidance or suppression of ELMs**
  - 3-D magnetic fields
  - Pellet pacing
  - Other means of edge profile control

Prediction of disruptions



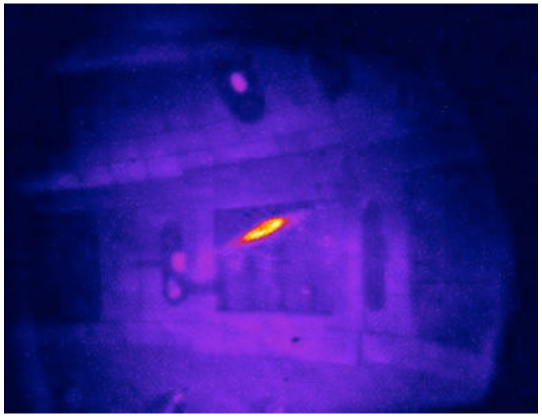
- **Characterization of disruptions in existing data**
  - causes, electromagnetic and thermal loads
- **Time-dependent transport and stability modeling**
  - minimize uncertainty in predicting disruptions
- **Real-time stability calculations**
  - proximity to stability limits
- **Real-time energy balance and transport analysis**
  - early warning of impurity accumulation and other disruption precursors
- **Direct, real-time determination of plasma stability**
  - active MHD spectroscopy: measure MHD damping rates
- **Diagnostics and algorithms for identification of a growing instability**
  - at amplitude well below the threshold for disruption
- **Development and testing of sensors capable of disruption prediction in a long-pulse, nuclear environment.**

Avoidance of disruptions

- **Modeling and benchmarking of control techniques to steer the operating point away from an impending instability**
  - without approaching other operating limits
- **Modeling and experimental benchmarking of control techniques to recover normal operation after an instability or off-normal event**
- **Actuators to modify pressure, current density, and rotation profiles**
  - while minimizing the circulating power
- **Modeling, experimental benchmarking of active stability control**
  - Using localized current drive, non-axisymmetric coils, …
- **High bandwidth coils for MHD spectroscopy and active feedback**
  - suitable for use in a nuclear environment
- **Assess the impact of implementing disruption prediction and avoidance techniques**
  - consistent with ITER and Demo requirements on fusion power

Mitigation of disruptions

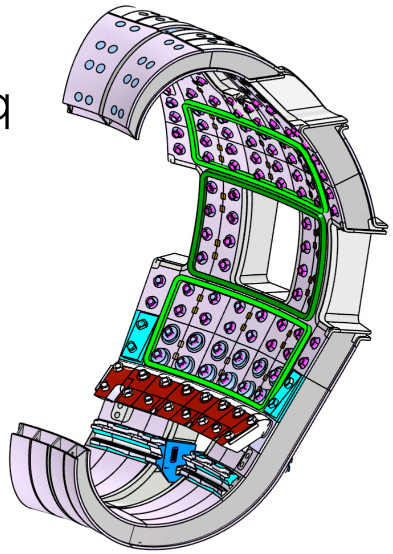
- **Rapid and reliable disruption prediction, enabling a control decision to abandon disruption avoidance and initiate shutdown.**



- **Develop and test gas, liquid, or solid injection systems for collisional suppression of runaways**
- **Develop alternate solutions for runaway electron suppression (e.g. stochastic magnetic fields)**
- **Develop and benchmark 2-D and 3-D models for the entire shutdown process:**
  - impurity delivery and transport to the plasma core
  - thermal energy release
  - discharge termination
  - generation, confinement, and loss of runaway electrons

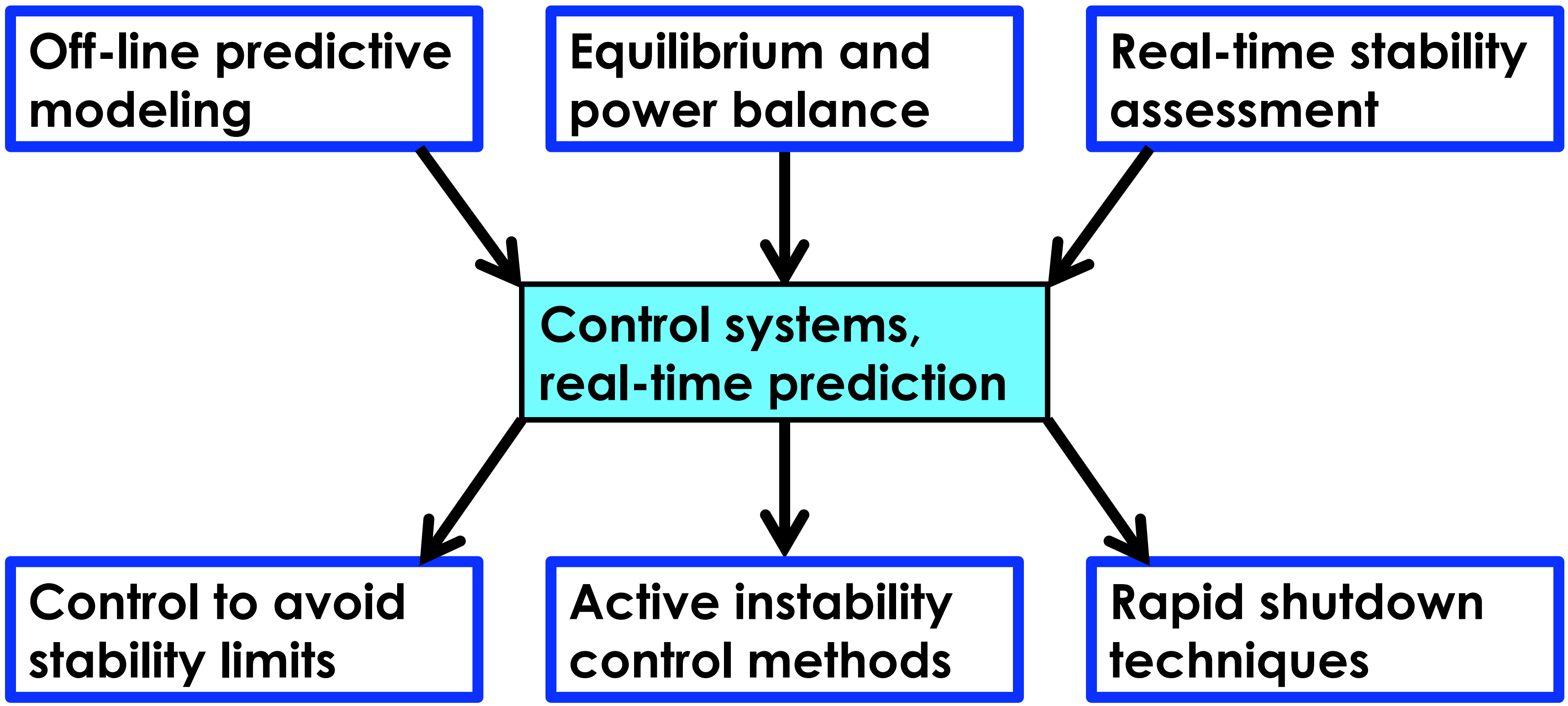
Avoidance or suppression of ELMs

- **Predictive capability for ELM suppression by 3-D magnetic fields**
  - Physics of particle and thermal transport effects
  - Magnetic spectrum for suppression with varying edge q
  - Requirements for avoiding non-resonant fields
  - Effectiveness of fueling and pumping in 3-D fields

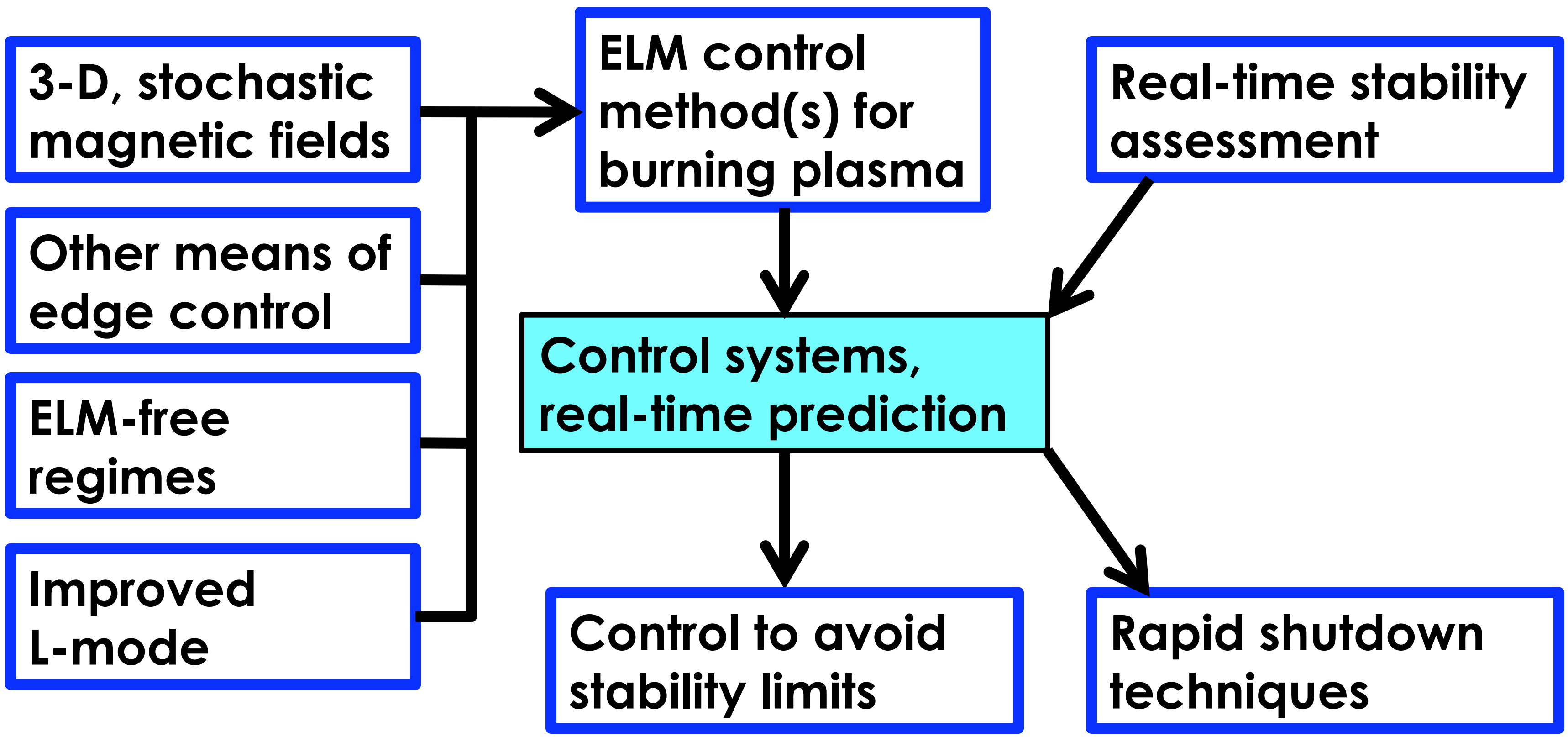


- **Identify mechanisms that modify edge transport and stability in ELM-free regimes**
  - QH mode, EDA H-mode
- **Identify and test other means of edge profile control, such as**
  - shallow pellet injection
  - recycling control (e.g. Li wall)
  - RF-based methods
  - rotation shear modification
- **Assess compatibility of improved L-mode confinement regimes with the required high confinement and global stability limits**

Integration of research elements: Disruptions



Integration of research elements: ELMs



Connections to other thrusts

Thrust #	Title	Connection
5	Science and technology for controlling and sustaining fusion plasmas	"Customer" for avoidance and mitigation strategies
6	Develop predictive models for fusion plasmas	Use models to predict disruptions, ELMs, and avoidance strategies
1	Measurements for burning plasmas	Prediction & avoidance require good diagnostics
4	Operational scenarios for ITER burning plasma	Scenarios must be compatible with avoidance of transients
8	Integrated dynamics of self-sustained plasmas	Sets constraints on control and shutdown strategies
9-12	Boundary and plasma-material interaction topics	Advances in PFC ➔ requirements for control of transient events
17	Optimize toroidal confinement using 3-D magnetic shaping	Physics of transport and stability in 3-D magnetic fields

Scale of effort

Existing short-pulse facilities
- Tolerance for transients
- Flexibility of modification
- Extensive diagnostics

→ **Develop physics and control techniques for avoidance of transients**

New superconducting tokamaks
- High performance plasmas
- Very long pulses

→ **Demonstrate control and avoidance of transients for very long pulses**

ITER, other burning plasmas
- Self-heating
- Larger size
- Greater energy density

→ **Develop and demonstrate robust control in a fusion environment**

Demo
- Continuous operation
- Very large energy density
- Little tolerance for transients

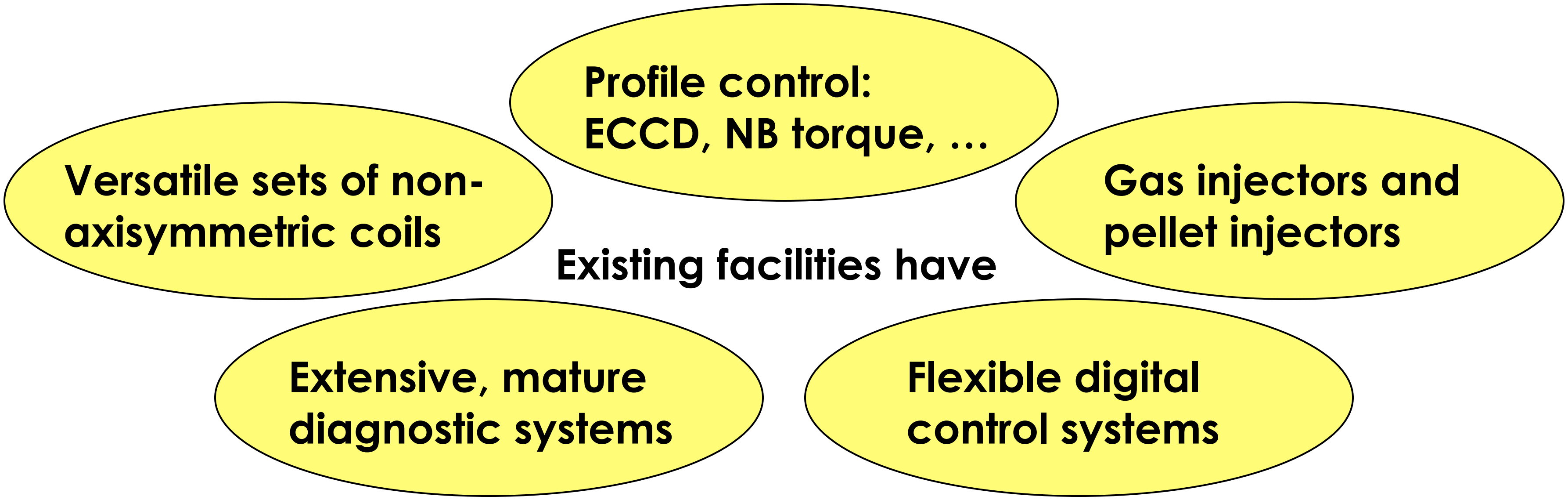
→ **Apply limited control power for sustained fusion power production**

Much of the work can and should be done with existing facilities

To make a major contribution on time scale for ITER will require a substantial increase in the allocation of resources

- **Modest upgrades to existing facilities:**
  - Diagnostics, e.g. for runaway electrons and 3-D field effects
  - Actuators: current drive, impurity injection, non-axisymmetric coils
  - Digital control systems
- **Significant increase in operating time for:**
  - Developing and testing elements of instability avoidance and control
  - Demonstration of integrated stability control
- **Significant increase in human resources for:**
  - Analysis and modeling for prediction of disruptions and ELMs
  - Modeling and experimental tests of avoidance and mitigation strategies
  - Validation of models suitable to design control of transients in ITER
  - Testing of systems to predict, avoid and mitigate disruptions on ITER

Readiness: A research thrust on control of transient events is very well suited to the U.S. fusion program



- **Many avoidance/mitigation techniques pioneered by the U.S.**
  - Massive gas injection for disruption mitigation
  - Active feedback control of error fields and RWM
  - ELM suppression by resonant magnetic perturbations
- **The elements exist for further rapid progress**