Expanding The Limits For Controlling And Sustaining Fusion Plasmas

How Close To Maximum Performance Can A Fusion Plasma Be Controlled And Maintained For An Unlimited Duration ?

A Proposed Research Thrust For The US Fusion Program

Alan Turnbull (GA)

Dave Humphreys, Mike Walker, Rejean Boivin, (GA)
Randy Wilson, Dave Gates (PPPL)
Tom Weaver, (Boeing)
Eric Hollman, (UCSD)
Steve Wolfe (MIT)

The Key Scientific Issue

What is the highest performance level of a fusion plasma that can be controlled and maintained for an unlimited period of time without unacceptable transients?

- **This requires developing and integrating control solutions, diagnostics, and control actuators to enable operation in close proximity to or beyond passive stability limits**

- **Thrust 5 is focused largely on realizing the maximum performance potential in the Advanced Tokamak and related configurations:**
  - Some issues are applicable still to other concepts

Thrust 5 Is Driven By Compelling Science Needs

- **The Advanced Tokamak requires an unprecedented level of control of the plasma for its ultimate success:**
  - Fusion plasma is a complex nonlinear system with interactions of physical processes on multiple time scales and length scales
  - In an extremely hostile environment

Active control is an essential defining element for the AT

- **The plasma must be controlled through startup and then for an unlimited duration:**
  - Far longer than achieved in current high performance experiments
  - Kept away from operational and controllability limits but as close to optimum performance as possible
  - Maintained at a constant but flexible operating point – either thermally stable or actively controlled
  - Including protection response for off-normal events and faults
- **Control of the power flow to material surfaces is essential for fusion:**
  - Maintained within material limits through control of the plasma
  - With fluctuations controlled from disruptions, ELMs and other events

Control Of The Advanced Tokamak Requires A Systematic Integrated Effort

- **Control must operate on multiple time scales:**
  - MHD time scales for control of plasma instabilities
  - Resistive diffusion and transport scales for control of plasma profiles
  - Long times on the scale of plasma-wall interactions, chemistry, etc
- **Control requires an integrated system of:**
  - Sensors, algorithms, and actuators
  - Historically not treated in an integrated program within fusion
- **High degree of cross community effort and integration required:**
  - Physics, mathematics, engineering, and materials science are essential
- **An appropriate balance needs to be maintained between the sensor, algorithm, and actuator elements:**
  - Define first what needs to be measured and controlled
  - Then decide what techniques can accomplish the goal

The control system cannot function if any one leg of the triad is missing

A two-legged stool cannot stand

Major Elements Of The Control Thrust

- **Steady State control issues:**
  - Steady state global plasma parameters and plasma profiles
  - Startup and shutdown
  - Thermal operating point
  - Power flow of radiation, heat, and particles to material surfaces

Interactions and interdependencies of these imply they must be treated in a comprehensive unified effort

- **Active closed loop control of passively unstable operating points:**
  - Increased performance beyond passive stability limits is enabled by active feedback control
  - Example of a modern fighter:
    - Inherently unstable without active control
    - Operation within passive limits would drastically limit flight performance
- **Intervention in off-normal events:**
  - Plasma induced disruptions
  - Hardware faults

Control that ignores fluctuations and off normal events is not control !

Specific Issues Cover Understanding And Solutions In An Integrated And Consistent Approach

- Active control of steady state global plasma parameters and plasma profiles
- Startup and shutdown
- Thermal stability of the operating point
- Regulation of the power flow distribution to material surfaces
- Robust active stabilization of instabilities and transient fluctuations
- Active prediction, avoidance, detection, and response to off-normal and fault events

Some Essential Elements Are Expected To Be Covered By Other Thrusts

- **Development of actual target scenarios for integrated control:**
  - Scenarios from Thrust 4 and Thrust 8 will be used to guide target choices
- **Novel divertor schemes for power flow control:**
  - Thrust 12
- **Physics understanding of incipient instabilities:**
  - ELMs, Resistive Wall modes, vertical instabilities, Neoclassical tearing modes, sawteeth, Alpha-driven instabilities
  - Thrusts 2, 6 and 12
- **Development of strategies for eliminating, mitigating, and recovering from plasma induced disruptions:**
  - Novel avoidance schemes
  - Thrust 2
- **Thrust 5 will interact with other thrusts and adapt these solutions to the goal of expanding performance limits in a controlled and sustained fusion plasma**

Demonstrate Active Control Of Equilibrium Maintained Close To An Optimum Performance Configuration

How near optimal can the plasma profiles and bulk parameters be robustly maintained in sustained steady state?

- **Basic control problem requires:**
  - Sufficiently detailed real time diagnosis of the current system state
  - Algorithms capable of:
    - Determining the current state from the diagnostic data
    - Translating the difference between this and the desired state into signals for the available actuators
  - Efficient actuators that can accomplish the required adjustments
  - These elements must operate as a fully integrated system

Specific Challenges:

- **Control of the equilibrium pressure, current, and rotation profiles in a high fluence nuclear environment maintained in steady state**
- **Sensors, algorithms, and actuators need to be capable of responding on multiple time scales:**
  - MHD μsec and msec scales
  - Current diffusion and transport second scales ~ seconds/minutes
  - Wall interaction and atomic and nuclear chemistry scales ~ hours/days

Actuators For Controlling Full Complement Needed For Steady State Are Non-existent Or Not Sufficiently Mature

- **Control of the pressure, current density, and rotation profiles require development and increased understanding:**
  - Limited control of the pressure profile exists in present experiments:
    - Fueling, particle transport, effect of current profile on transport, and heating effects from current drive actuators
    - Control of the pressure profile in the presence of dominant alpha heating will be even more difficult
  - Ability to place RF current drive where required is poorly demonstrated
  - Techniques for rotation control are at rudimentary level of understanding
    - Limited understanding of “intrinsic” rotation
    - Limited understanding of rotation in presence of alpha heating
- **Control of edge gradients is expected to be essential**
- **Diagnostics suitable for a high fluence steady state power producing reactor are in their infancy:**
  - Diagnostics for the first wall conditions and in situ wall conditioning will be needed to maintain control over the immediate external conditions
- **Control system algorithms will need to be capable of:**
  - Optimizing and providing closed loop signals to actuators
  - From necessarily limited diagnostic data supplemented by timely simulations and control level models

Develop And Demonstrate Procedures For Robust Startup To Largely Self-heated, Self-driven Steady State

Does a safe and reliable path exist from low current and low beta to the required highly self-regulated, high performance state envisaged in a burning plasma?

- **Startup and shutdown of tokamak plasmas is prone to heightened possibility of disruption if not done carefully:**
  - Generally, the pressure, current, and plasma shape need to be ramped up to a largely self-sustaining bootstrap current and alpha heated state, and terminated when necessary by a careful rampdown

Specific Challenges:

- **While existing experiments routinely reach bootstrap dominated plasma current states using auxiliary heating methods the alpha – heated state will provide unique challenges:**
  - Achieving the desired current profile with large bootstrap fraction will require optimization of the current drive tools:
    - To meet the current drive requirements (magnitude and location)
    - Within the available power constraints

Demonstrate Operating Point Thermal Stability Control With Sufficient Flexibility To Regulate Total Power output

With what level of dynamic performance and flexibility can thermal stability be provided in a burning plasma?

- **A power-producing reactor will need to:**
  - Operate at a constant total power output determined by the external load and economic considerations
  - With sufficiently flexibilty to vary operating point with external load and
  - Remove Helium ash to avoid quenching the reaction

Specific Challenges:

- **Basic power control is achieved by controlling the temperature dependent fusion cross section and D/T ratio:**
  - Thermally stable operating points exist in which temperature excursions reduce fusion reactivity
  - But passively thermally stable operation is not necessarily most efficient:
    - ⇒ Active feedback control for maintaining density and temperature profiles at passively unstable values is probably necessary
  - Techniques for deep fueling need to be developed along with a deeper understanding of particle transport
- **Methods need to be developed for selective removal of cooled He:**
  - Both diagnostics and actuators are needed

Demonstrate Regulation Of The Power Flow Distribution To Material Surfaces In Presence Of Plasma Fluctuations

What level of power flow regulation can be achieved?

- **Power flow from a fusion reactor must be in a useable form:**
  - Comprises radiation, neutrons, heat, and energetic charged particles
  - Spatial and temporal distribution of each needs to be controlled sufficiently to avoid exceeding local material limits
  - While minimizing recirculating power required by the control actuators
- **The different elements have different spatial distributions:**
  - Volumetric sources absorbed by the first wall and shielding
  - Specific target divertor plates by the plasma edge magnetic geometry
  - Highly localized energy fluxes
- **Temporal fluctuations from periodic but transient instabilities:**
  - Notably sawteeth and ELMs but also NTMs, RWMs, etc.
  - ⇒ Needed to balance and maintain the various fluxes at manageable levels in the presence of fluctuations

Specific Challenges:

This is a serious control issue requiring a concerted effort:

- Means is done elsewhere – thrust 12
- Thrust 5 intends to implement solutions obtained

- **Divertor solution that can be scaled does not yet exist:**
  - Little or no margin for fluctuations from ELMs

Develop The Means For And Demonstrate Robust Active Stabilization Of Instabilities And Fluctuations

How close to or how far beyond stability limits can ATs operate with maximum efficiency and negligible probability of control loss using robust active control?

- **Potential performance gains from active control of instabilities (ELMs, sawteeth, Alfven instabilities, RWMs, NTMs, etc…) can be large:**
  - β increased by up to 50% of its passively stable value
  - Fusion power possibly doubled

A precedent exists in modern aerospace designs, which have similarly evolved from passively stable early aircraft with limited maneuverability to modern high performance fighters that operate in an unstable dynamic range but with control maintained by a complex system of integrated sensors, actuators, and complex nonlinear control algorithms

Specific Challenges:

- **Active control is already routine in the case of axisymmetric MHD stability with the passive plasma elongation limits exceeded in most tokamaks but maintained by an active feedback system:**
  - But operation beyond the passive β limits is an ongoing research area

Operation In Passively Unstable Regions Requires A High Confidence And Robust Control System

- **Actuators are envisaged to be RF waves and active nonaxisymmetric field coils:**
  - Coils and magnetic sensors must be close to the plasma to be effective
  - RF systems for locally restabilizing instabilities require precise localization or they generally become destabilizing or require too much power
  - Tracking systems and mirrors are required and need to be shielded Remote steering of ECH has been proposed to solve the in close mirror problem but needs to be demonstrated as a viable technique
- **Effect of nonaxisymmetric fields on ELMs is not understood:**
  - This is expected to be a focus of Thrust 2 and Thrust 12
- **Sawteeth and ELMs may play a positive role in eliminating impurities, including alpha ash, and regulating profiles:**
  - Goal is to provide sufficient control to regulate the amplitudes at low enough levels that they do not degrade overall performance and do not result in intolerable fluctuations for power handling
  - Strongly nonlinearly coupled with RWMs, NTMs and AEs:
  - ⇒ Regulation must be integrated into full active feedback control system
- **Reliable detectors and actuators that can survive in a burning plasma are needed for the major beta limiting instabilities**

Demonstrate Active Prediction, Avoidance, Detection, And Response To Off-normal And Fault Events

Can the probability or occurrence be reduced to levels required for power plant operation, and reliable response algorithms be developed for acceptable device protection?

- **Off normal events will occur in any complex system and means must be in place to:**
  - Detect them early
  - Respond by minimizing and mitigating their effects
  - Recover control and cleanup as needed
- **In addition to possible unanticipated plasma events, off normal events can result from loss of control, failures of sensors or actuators, or other system hardware failures**

Specific Challenges:

This is a serious control issue requiring a concerted effort:

- Means is done elsewhere – thrust 2
- Control thrust intends to implement solutions obtained

- **Limited control and recovery and mitigation options exist that can be reliably scaled to a power producing reactor:**
  - Recovery, cleanup, repair, and reconditioning must be done remotely

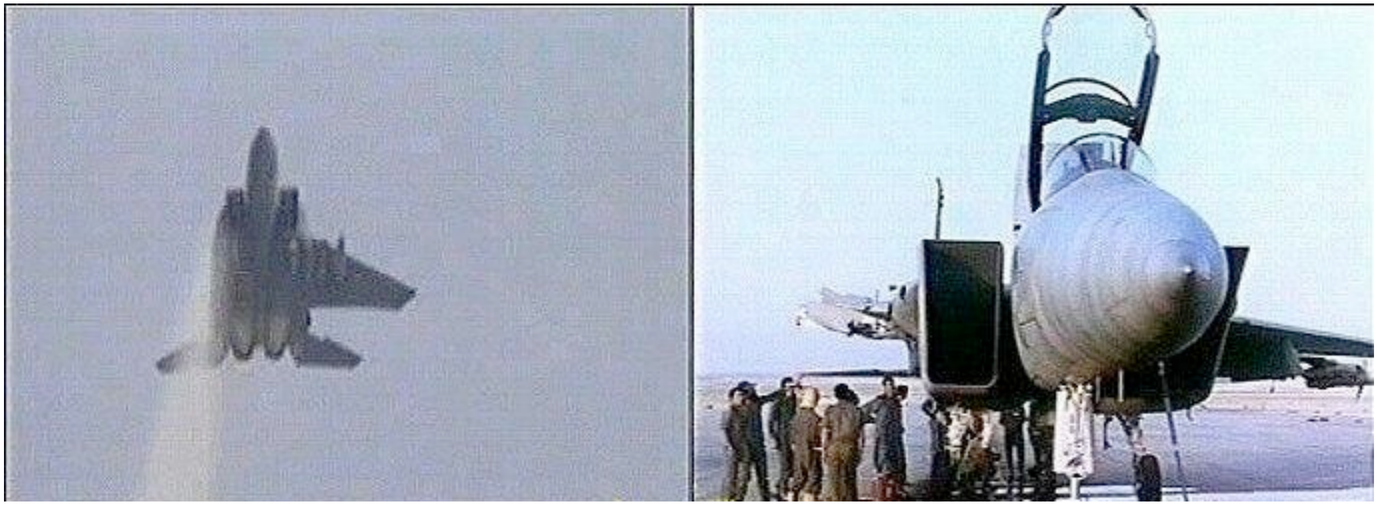
⇒ This is also a control issue in the case of fusion

A Full Unmitigated Event In A Reactor Will Dump Huge Energies On Surrounding Structures

- **Handling of these events needs to be an integral part of the complete control system:**
  - ⇒ Good control makes failures rare
  - ⇒ Sophisticated control level automated decision software for determining the best course of action
  - ⇒ Additional facilities for mitigation, recovery, and cleanup

The vision:

- **Israeli F-15 lost its wing but managed to stay airborne:**



  - – Pilot re-connected the electric control to the control surfaces, and slowly regained control
  - – Wing was replaced and plane is flying again !

Mitigation and Recovery

Cleanup

Research Plan For The Control Thrust Will Require New Emphases And Collaboration

- **Near Term :**
  - Research on current experiments to integrate diagnostics, algorithms, and actuators into a control system capable of maintaining near optimum performance over a few current diffusion times
  - Will require:
    - More experimental time than typically devoted – for example, a push to determine how reliably and under what conditions disruptions can be avoided and ELMs controlled (Thrust 2 and 12)
    - Probable facility upgrades for increased performance
    - Expanded mathematical control research
  - Implement new ideas for control and avoiding off-normal events
- **Medium Term :**
  - Research on the Asian steady state tokamaks to demonstrate control can be maintained over longer time scales in a high performance non-burning environment

Research Plan For The Control Thrust Will Require Possible New Facilities

- **Medium Term:**
  - Possible new domestic experiment capable of long pulse or steady state
- **ITER:**
  - Research on burning plasmas, including ITER, to start to address the major additional challenges of self-heating
- **Long Term:**
  - Control aspects specific to a high fluence burning plasma:
    - Control of a largely alpha-heated, self-regulated burning plasma with limited direct control over the heating profile
    - Survivable diagnostics suitable for a high fluence nuclear environment for long times

⇒ A new burning plasma facility with minimum requirements:

- High fluence and alpha heating dominant
- Pressure and associated bootstrap current produced largely from alpha heating
- At least moderate, but preferably long or steady state

to demonstrate the control solutions required for a power-producing reactor

Benefits to MFE Expected From A Control Thrust

- **Usual motherhood, apple pie, etc:**
  - Fusion cannot do without this
  - It will keep us employed until retirement (it's late in the day !!!)
- **Thrust 5 has responsibility for making the Advanced Tokamak viable:**
  - Requires resources to accomplish this that maintain the balance between components
- **This thrust has potential for a considerable number of spin-offs outside fusion:**
  - Algorithms for coupling actuators and sensors in a highly nonlinear, near marginal system with multiple time and length scales
  - Robust diagnostic techniques capable of surviving an intense nuclear environment over periods of weeks and months or more
  - Possible new actuators needed for controlling the self-heated, self-organized plasma indirectly

The Final Vision Of A Fusion Reactor Control System

- **A control system capable of safely and reliably maintaining operation of a self-heated burning plasma beyond the normal passive stability limits using active control to maintain stability, with:**
  - Sufficient flexibility to adjust power output in response to external conditions, and
  - The full complement of detection, plus avoidance, mitigation, and recovery needed to handle plasma system fluctuations and off normal events

The vision would be akin to that of modern high performance aerospace engineering systems that also operate routinely and robustly beyond passive stability limits

- **The specific challenge in a fusion reactor is that the fusion environment is inherently much more hostile to sensors and actuators and the system is more fully self-driven**

Impossible ?

⇒ Will just take a little longer…

But we ought to get started !

Research Plan: Active Control In Steady State

Short term:

Complete open loop control of equilibrium state and demonstrate closed loop on existing experiments.

Medium term:

Demonstrate fully functioning integrated control methods in steady state DD plasmas and test new actuators, and new diagnostics scalable to high fluence environments.

Long term:

Demonstrate fully functioning integrated control methods and develop and test new actuators and diagnostics in ITER DT plasmas.

After ITER:

Test and demonstrate successful fully functioning integrated control methods in high fluence DT, strongly alpha heated burning plasma environment.

Research Plan: Startup And Shutdown

Short term:

Explore more fully from current experimental databases and additional experiments the dependence of disruptivity on startup rates across multiple machines for developing control-level models and continue bootstrap current startup experiments and other novel Ohmic-free startup scenarios in existing experiments.

Medium term:

Test options for startup scenarios to full non-inductive current and high beta in steady state DD plasmas.

Long term:

Test startup scenarios to full steady state in ITER DT advanced scenarios with significant alpha heating and corresponding bootstrap current.

After ITER:

Test startup scenarios to full steady state in alpha dominated heating environment and corresponding bootstrap current.

Research Plan: Thermal Stability

Short term:

Develop control systems and control level models in current experiments based on simulations and fusion reactivity calculations for identifying and controlling the operating point, and develop diagnostics and actuators for controlling alpha ash.

Medium term:

Test and further optimize in a long pulse DD device the control models for maintaining and varying passively stable operating points, and test diagnostics for measuring the alpha particle ash profile and novel ash removal techniques.

Long term:

Test integrated system and control models for maintaining and varying passively stable and unstable operating points in ITER and test diagnostics for measuring the alpha particle ash profile and novel ash removal techniques in a DT environment.

After ITER:

Test integrated system and control models for maintaining and varying passively stable and unstable operating points and test diagnostics for measuring the alpha particle ash profile and novel ash removal techniques in a in a high fluence DT, strongly alpha heated burning plasma environment.

Research Plan: Regulation Of The Power Flow

Short term:

Develop the control required for implementing a working divertor solution in existing experiments that can scale to a high fluence DT, strongly alpha heated burning plasma reactor with the required control over transient fluctuations.

Medium term:

Test elements of the control system for regulating power flow in a steady state DD environment with divertor control and fluctuation detection and response.

Long term:

Test elements of the control system for regulating power flow in a DT environment in ITER, with divertor control and fluctuation detection and response.

After ITER:

Test the complete integrated power flow regulation system, including a working divertor solution and control of fluctuations within the tolerable levels, in an environment dominated by alpha particle heating at the several MW power flow levels expected in or near those in a commercial reactor.

Research Plan: Active Stabilization Of Instabilities

Short term:

Continue development and optimization of RF actuators and sensors for detecting early onset and control of fluctuations resulting from instabilities in existing experiments and initiate efforts into new methods that can scale to a reactor.

Medium term:

Test and optimize integrated control system options for controlling all the key instabilities in DD plasmas for long pulses above the passive beta limits.

Long term:

Test integrated control system options for controlling all the key instabilities in DT plasmas for long pulses above the passive beta limits in ITER.

After ITER:

Test integrated control system options for controlling all the key instabilities in high fluence alpha dominated DT plasmas for medium and preferably long pulses above the passive beta limits.

Research Plan: Avoidance And Control Of Off-normal Events

Short term:

Continue development of current and new ideas for early detection and mitigation techniques of the complete range of possible off-normal events that can be reliably scaled while avoiding additional consequences in existing experiments.

Medium term:

Test and optimize, a fully integrated comprehensive early detection, and recovery control options of the complete range of possible off-normal events, including plasma induced events and external hardware system failures in long pulse DD plasmas.

Long term:

Test optimized, fully integrated comprehensive early detection, and recovery control options in moderate pulse DT plasmas in ITER.

After ITER:

Test the comprehensive integrated control scheme for the full range of possible outcomes, including early detection, recovery without shutdown, mitigation, recovery with controlled shutdown, cleanup, repair, and reconditioning options in dominantly alpha heated DT plasmas.