A Vision Of An Actively Controlled Advanced Tokamak Reactor

Alan Turnbull
General Atomics

With contributions from:
Dave Humphreys (GA)
Mike Walker, (GA)
Tom Weaver, (Boeing)
Eric Hollman (UCSD)

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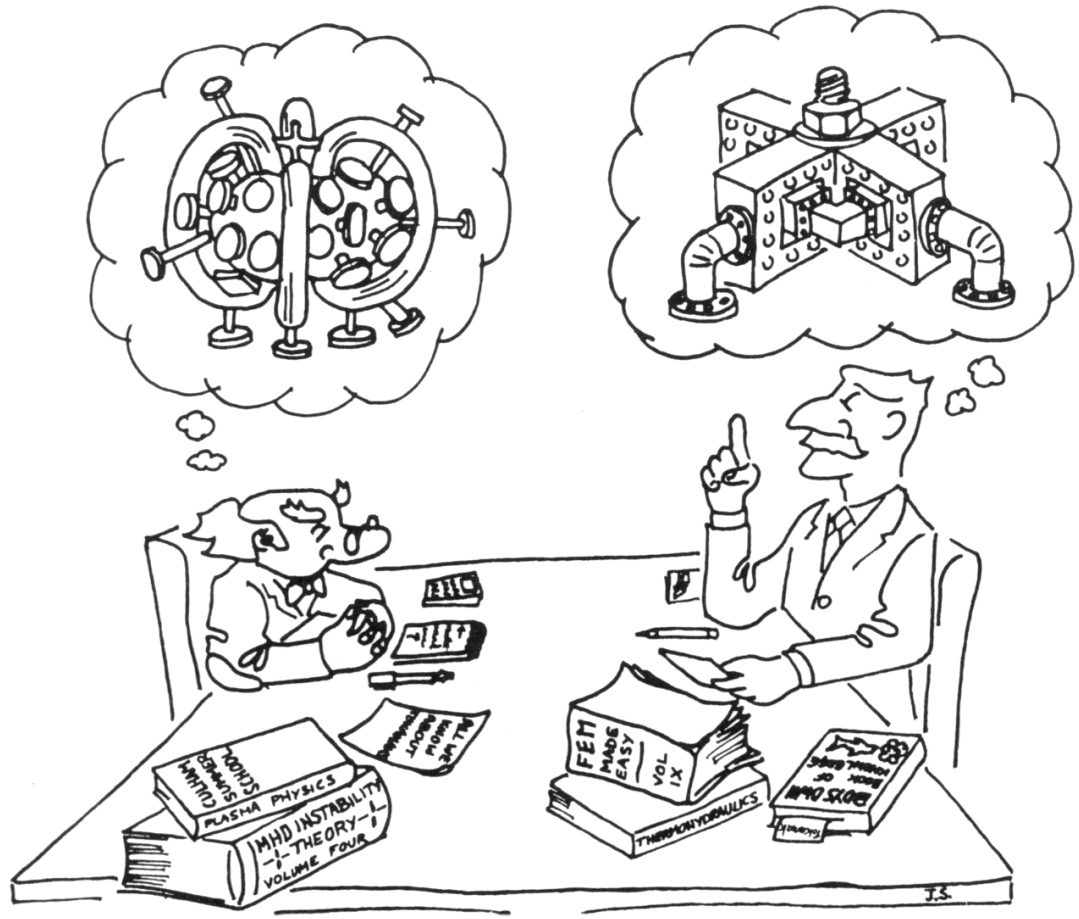
Physics view **Engineering view**



T. Todd, in R. Dendy Plasma Physics p. 448 (1993)

Actively Stabilized Systems Can Offer Large Performance Gains Over Passively Stable Systems

Passive system → Balloons **Active system → Planes**

- **Actively stabilized systems operating in passively unstable regimes offer a range of performance improvements:**
  - Wright brothers biplane:
  - ⇒ Moderate performance gain
  - Modern fighter aircraft:
  - ⇒ Large performance gain

- **Advanced Tokamak seeks to optimize fusion performance through active control:**
  - Conventional tokamak:
  - ⇒ Moderate performance gain
  - Advanced Tokamak:
  - ⇒ Large performance gain

Even The Conventional Tokamak Employs a Significant Level of Active Control

- **Conventional tokamak:**
  - Active control of:
    - ⇒ Total current
    - ⇒ Heating profile
    - ⇒ Vertical instability
    - ⇒ Operating point through fuelling
- **Advanced tokamak:**
  - Additional active control of:
    - ⇒ Current profile
    - ⇒ Pressure profile
    - ⇒ Non-axisymmetric instabilities
    - ⇒ And ….

- **Active control is an essential defining element for the AT**

- **Ultimate vision of Advanced Tokamak reactor is an actively controlled system with highly optimized performance**

Question is how far should we trade off performance for the added complexity

Vision Of Actively Controlled Highly Optimized System Is Akin To Modern Aerospace Engineering Systems

- **Modern military fighter planes:**
  - Inherently unstable without active control
  - Operation within passive limits would drastically limit flight performance
- **Similar performance gains:**
  - Order of magnitude potential gains in performance
- **Similar challenges:**
  - A control system capable of safely and reliably maintaining operation routinely and robustly
  - 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

Comparison With Aerospace Engineering of a High Performance Modern Fighter Aircraft is Apt

- **Flexible mode instability suppression in aircraft requires:**
  - Accelerometers placed at specific locations to sense induced oscillation
  - Control surfaces modulated to suppress natural modes
  - Feedback control to optimize sensor, actuation and system performance and minimize oscillatory dynamics
  - (cf Suppression of electromagnetic modes)
- **Pitch and yaw control in tailless aircraft requires:**
  - Gyros and accelerometers measure aircraft rates and accelerations
  - Augmentation of baseline control system to stabilize unstable aircraft
  - Control algorithms
  - (cf Bootstrap and current drive for steady state)
- **Aircraft spin recovery requires:**
  - Stall detection and yawing sensing, etc.
  - Rudder, throttle, pitch, and aileron control and recovery chute
  - Early detection spin avoidance and recovery technology
  - (cf Disruption mitigation)

(Thanks to J.A. Ramsey and T. Weaver – Boeing)

The Fusion Issues Are Even More Challenging Than The Aerospace Issues

- Fusion plasma is a complex nonlinear system with interactions of physical processes on multiple time scales and length scales
- Limited access to the core plasma
- The environment is hostile to an unprecedented degree

Control Of The Advanced Tokamak Requires A Systematic Integrated System

- **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
- **Cross community effort and integration required:**
  - Physics, mathematics, engineering, and materials science are essential
- **Vision of plasma control in the Advanced Tokamak is a fully integrated system**

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

A two-legged stool cannot stand

An Advanced Control System Requires Three Main Components

- **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

- **Active closed loop control of passively unstable operating points:**
  - Increased performance beyond passive stability limits is enabled by active feedback control

- **Intervention in off-normal events:**
  - Plasma induced disruptions
  - Hardware faults

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

Control Elements Can Be Conveniently Divided Into Two Categories

- **Control aspects that can be developed on non burning plasmas:**

  Essentially Steady State control aspects

  – Research on current experiments, the Asian steady state tokamaks, and in Phase II of ITER

- **Aspects specific to the high fluence burning plasma regime:**

  This category will require additional facilities

  – 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

The diagnostic problem in a high fluence burning plasma is a serious one that needs focused effort

The Advanced Tokamak Requires An Unprecedented Level Of Control Of The Plasma For Its Ultimate Success

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

1. **The plasma must be controlled for an unlimited duration:**
   - Far longer than achieved in current high performance experiments
   - Kept away from operational limits but as close to optimum performance as possible
2. **The plasma must be controlled through startup and shutdown:**
   - Avoiding instabilities from changing conditions
3. **The plasma must be maintained at a constant but flexible operating point:**
   - Either thermally stable or actively controlled
   - Active energy and particle input (ECCD, pellets, etc)

In Addition To Steady State Control The Advanced Tokamak Control System Must Also Provide:

4. **Regulation of the power flow distribution to material surfaces:**
   - Maintained within material limits
   - With fluctuations controlled from disruptions, ELMs and other events
5. **Monitoring and robust active control of fluctuations and incipient instabilities:**
   - Sensors and coils for detection and active stabilization of:
     - ELMs
     - Resistive Wall modes
     - Vertical instabilities
     - Neoclassical tearing modes
     - Sawteeth (conventional and hybrid scenarios)
     - Alpha-driven instabilities
6. **And strategies for active prediction, avoidance, detection, and response to off-normal and fault events:**
   - Protection response for off-normal events and faults
   - Recovery of control
   - Mitigation schemes
   - Cleanup strategies

Defining Element of Advanced Tokamak: Active Control To Maintain Equilibrium At Optimum Performance

1. *Performance gain from optimization is demonstrably large:* $P_F \propto \beta^2 B^4$

- **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

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Specific Challenges:

- **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

- **Steady state control of the equilibrium pressure, current, and rotation profiles in a high fluence nuclear environment**
- **Control of the pressure, current density, and rotation profiles require development and increased understanding:**
  - Limited control of the pressure profile exists in present experiments:
  - Techniques for rotation control are at rudimentary level of understanding
- **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

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

2. *Pressure, current, and plasma shape must be ramped up to a largely self-sustaining bootstrap current and alpha heated state, and terminated when necessary by a careful rampdown*

- **Startup and shutdown of tokamak plasmas is prone to heightened possibility of disruption if not done carefully**

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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
    - Within the available power constraints

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

3. Control of thermal operating point in a burning plasma is needed which may or may not be optimized at thermally stable points

- **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

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Specific Challenges:

- **Basic power control is achieved by controlling the temperature dependent fusion cross section and D/T ratio:**
  - 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

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

4. Power flow from a fusion reactor must be in a useable form

- **Power flow 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:**
  - Sawteeth ELMs NTMs, RWMs, etc.

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Specific Challenges:

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

This is a serious control issue requiring a concerted effort

Robust Active Stabilization Of Instabilities And Fluctuations

5. Advanced Tokamaks are envisioned to operate beyond stability limits and active control system meeds to operate with maximum efficiency and negligible probability of control loss

- **Potential performance gains from active control of instabilities can be large:**
  - β increased by up to 50% of its passively stable value
  - Fusion power possibly doubled

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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
- **Sawteeth and ELMs may play a positive role in eliminating impurities, including alpha ash, and regulating profiles:**
  - Require possible active regulation of the amplitudes

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
- **Reliable detectors and actuators that can survive in a burning plasma are needed for the major beta limiting instabilities**

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

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

6. *Off normal events will occur in any complex system*

- **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**
- **Means must be in place to:**
  - Detect off-normal events early
  - Respond by minimizing and mitigating their effects
  - Recover control and cleanup as needed

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Specific Challenges:

- **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

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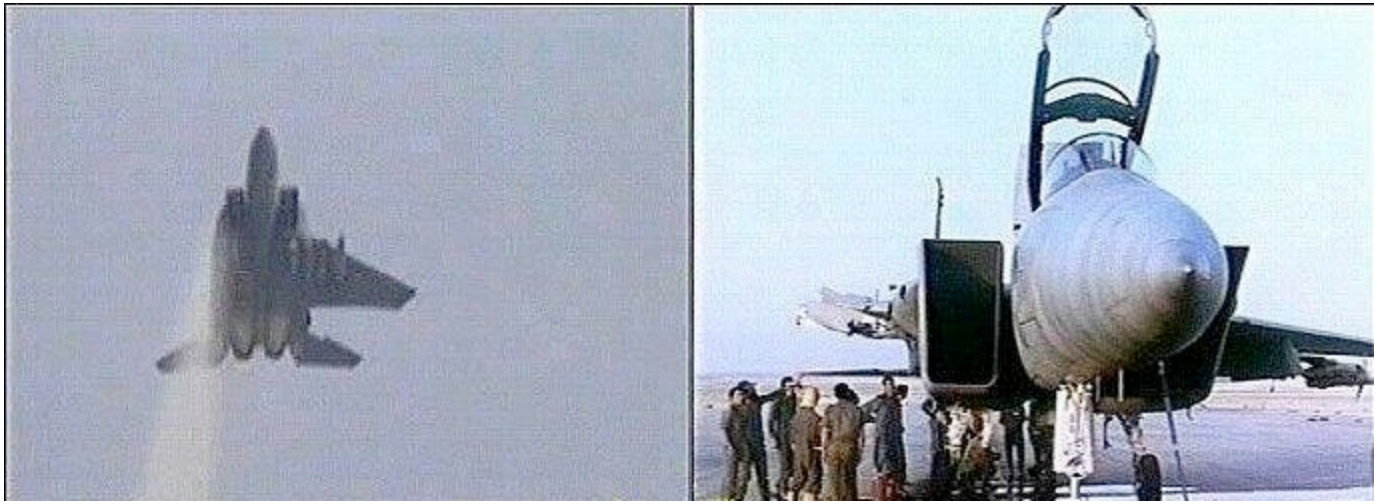
A Full Unmitigated Event In A Reactor Will Dump Huge Energies On Surrounding Structures

- **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

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 ?

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⇒ We physicists have complete confidence in the engineers !