Theme II: Creating predictable, high performance, steady state plasmas — *Thrusts*

Blame	Credit
Amanda Hubbard Chuck Greenfield Mark Foster	Dave Anderson, Max Austin, Larry Baylor, Lee Berry, Ted Biewer, Réjean Boivin, Paul Bonoli, Allen Boozer, Leslie Bromberg, David Brower, Bob Budny, Troy Carter, Tom Casper, C.S. Chang, Daniel Den Hartog, Bill Dorland, John Ferron, Eric Fredrickson, Andrea Garofalo, David Gates, John Goetz, Mike Gouge, Bob Granetz, Martin Greenwald, Larry Grisham, Rich Hawryluk, Dave Humphreys, Val Izzo, David Johnson, Chuck Kessel, Steve Knowlton, Arnold Kritz, Rob La Haye, David Larbalestier, Bruce Lipschultz, George McKee, Dale Meade, Jon Menard, Joseph Minervini, Masanori Murakami, Farrokh Najmabadi, Brad Nelson, Tom Petrie, Peter Politzer, Miklos Porkolab, Ron Prater, Roger Raman, Gian Luca Sabbi, Joel Schultz, Phil Snyder, Ted Strait, Dan Stutman, Ed Synakowski, Bill Tang, Rick Temkin, Jim Terry, Dick Thome, Alan Turnbull, George Tynan, Thomas Weaver, John Wesley, Dennis Whyte, Randy Wilson, Steve Wolfe, John Wright, and a cast of thousands

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Thank you!

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Overall Scope and Goal of Theme II

- **Derived directly from "Theme A" of the 2007 FESAC panel report:** ***"Creating predictable, high performance, steady state plasmas: The state of knowledge must be sufficient for the construction, with high confidence, of a device that permits the creation of sustained plasmas that meet simultaneously, all the conditions required for practical production of fusion energy"***
- **As with ReNeW in general, the deliverable of our research is the scientific knowledge base to enable development of fusion energy.**
- **ITER will be an enormous and necessary step toward this goal, allowing us to learn about burning plasmas – and how to achieve them. However, it is not a prototype for "practical production of fusion energy". A demonstration reactor, generically referred to as DEMO, leading to economic energy production would need other features, including:**
    - Truly steady-state operation, with high reliability, using modest auxiliary heating and current drive (for efficient use of generated power)
    - Higher fusion power density (to reduce needed size)
    - Many other needed system features, such as tritium breeding, are covered in Theme IV.

Scope of Theme II (con't)

- The issues covered in this Theme are extremely broad, covering a wide spectrum of plasma physics and engineering science (often within a single panel) but major progress on all of them is essential to reach the Theme II goal.
- A key difference of ReNeW from the Greenwald report is that FESAC presumed success of ITER and the current program, and examined gaps to DEMO. Our research needs to start NOW, and presume little.
- Theme I focuses primarily on the needs of ITER. Theme II looks more broadly at needs for higher performance, steady state, self-sustained burning plasmas. Clearly, issues overlap, hence several joint panels.

Theme II = Greenwald Theme A. Creating predictable high-performance steady-state plasmas
Each issue corresponds to a panel

1. **Measurement:**
   Make advances in sensor hardware, procedures and algorithms for measurements of all necessary plasma quantities with sufficient coverage and accuracy needed for the scientific mission, especially plasma control.
2. **Integration of high-performance, steady-state, burning plasmas:**
   Create and conduct research, on a routine basis, of high performance core, edge and SOL plasmas in steady-state with the combined performance characteristics required for Demo.
3. **Validated Theory and Predictive Modeling:**
   Through developments in theory and modeling and careful comparison with experiments, develop a set of computational models which are capable of predicting all important plasma behavior in the regimes and geometries relevant for practical fusion energy.
4. **Control:**
   Investigate and establish schemes for maintaining high-performance, burning plasmas at a desired, multivariate operating point with a specified accuracy for long periods without disruption or other major excursions.
5. **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 tolerate some number or frequency of these events.
6. **Plasma Modification by Auxiliary Systems:**
   Establish the physics and engineering science of auxiliary systems which can provide power, particles, current and rotation at the appropriate locations in the plasma at the appropriate intensity.
7. **Magnets:**
   Understand the engineering and materials science needed to provide economic, robust, reliable, maintainable magnets for plasma confinement, stability and control.

Theme II thrust mappings

1. **Measurement:**
   Thrust 1: Develop Capable and Reliable Measurement Techniques for Understanding and Controlling Burning Plasmas
2. **Integration of high-performance, steady-state, burning plasmas:**
   Thrust 8: Understand the highly integrated dynamics of dominantly self-heated and self-sustained burning plasmas
   Thrust 12: Demonstrate an integrated solution for plasma-material interfaces compatible with sustainment and control of an attractive core plasma
3. **Validated Theory and Predictive Modeling:**
   Thrust 5: Expanding the Limits For Controlling and Sustaining Fusion Plasmas
   Thrust 6: Develop Predictive Models for Fusion Plasmas, Supported by Theory and Challenged with Detailed Experimental Measurements
   Many others
4. **Control:**
   Thrust 5: Expanding the Limits For Controlling and Sustaining Fusion Plasmas
5. **Off-normal Plasma Events:**
   Thrust 2: Control transient events in burning plasmas
   Thrust 5: Expanding the Limits For Controlling and Sustaining Fusion Plasmas
6. **Plasma Modification by Auxiliary Systems:**
   Thrust 4: Develop and qualify operational scenarios and the supporting physics basis for achieving a wide range of burning plasma regimes in ITER
   Thrust 5: Expanding the Limits For Controlling and Sustaining Fusion Plasmas
7. **Magnets:**
   Thrust 7: Develop high temperature superconductors and other magnet innovations to advance fusion research

***Joint panel with Theme 1**

Thrust 5: Expanding the Limits For Controlling and Sustaining Fusion Plasmas

- **To make fusion power economically viable and attractive, a reactor plasma likely will require a robust steady-state operating scenario with pressures at or above conventional stability limits…**
  …this requires an unprecedented level of active control
- **Key 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?**
- **Significant advancements and related R&D required in three areas:**
  - Sensors: *Diagnostic techniques*… capable of operating robustly in a sustained-duration burning plasma nuclear environment
  - Actuators: Means of efficiently affecting the plasma, through flexible high power heating, current drive and fuelling systems
  - Algorithms: Mathematical solutions enabling determination of actuator commands from measurements, *based on control-level reduced models*, and providing robust and quantifiable assurance of sustained operation

Thrust 5: Expanding the Limits For Controlling and Sustaining Fusion Plasmas (PROPOSED ACTIONS)

- **<u>Short term</u>: Initiate development of**
  - Nuclear-robust control-specific diagnostics
  - High performance actuators
  - Reduced models,
  - Robust control algorithms

  …With appropriate enhancement and exploitation of presently operating devices
- **<u>Medium term</u>:**
  - Utilize new experiments to demonstrate required solutions with extended pulse duration, seeking international collaboration
- **<u>Longer term</u>:**
  - Use ITER and new DT devices being proposed to develop and demonstrate integrated control solutions required for DEMO

Thrust 6: Develop Predictive Models for Fusion Plasmas, Supported by Theory and Challenged with Detailed Experimental Measurements

Developing tested computational models needed for fusion plasmas will require coordinated effort substantially beyond the current level of activities and an unprecedented degree of cooperation among program elements

- **This thrust**
  - Builds on remarkable progress, scientific achievement and discovery
  - Plays to US strengths: Most advanced first-principles codes, best diagnosed experiments
  - Leverages developments in numerical techniques and software engineering to exploit newest generations of powerful parallel processing computers
  - Develops and demonstrates required physical understanding
  - ☞ Enables maximum exploitation of experiments, in particular ITER, and facilitates more reliable design of new experiments or facilities, critical for progress toward a DEMO
- **Key Issues**
  - How well can complex, multi-scale phenomena of fusion plasmas be understood through first-principles models?
  - What are appropriate methods for integrating multi-physics and multi-scale effects needed to increase fidelity of practical computer models?
  - How can reliable, reduced, integrated models be constructed that allow for rapid exploration of operating scenarios on experiments?
  - What innovations in measurement techniques or experiments should be pursued to facilitate comprehensive tests of these models?

Thrust 6: Develop Predictive Models for Fusion Plasmas, Supported by Theory and Challenged with Detailed Experimental Measurements (PROPOSED ACTIONS)

- **Conduct rigorous set of validation activities to assess critical elements of physical models through careful comparison with experiments**
  - Would help to guide research in theory and computation by identifying important gaps in current models
- **Resources required**
  - Strong basic theory program ⟹ addresses areas where current physical models are inadequate or incomplete
  - Spectrum of powerful, robust, well-verified computer models shared by large user community (could include FSP)
  - Diagnostic innovation to enable measurements critical for validation
  - Adequate run time on a spectrum of facilities spanning a range of device sizes and confinement configurations
  - Analysts to independently compare models and experiments
  - Substantial computer time for code verification and model validation

Thrust 7: Develop high temperature superconductors and other magnet innovations to advance fusion research

This thrust proposes a targeted effort on advanced magnet R&D, focusing primarily on new opportunities enabled by High Temperature Superconductors (HTS), with enormous potential to expand for future MFE research experiments.

- **Key issues:**
  - Development of practical conductors and cables – *Can present fragile HTS tape geometry be made into high current cables? Round wires?*
  - Integration of HTS cables into practical magnet systems for fusion experiments
- **Potential applications which would greatly benefit several other thrusts, include:**
  - High field magnets for steady state facilities with demountable joints
  - HTS tapes integrated into coils with complex shapes for 3-D and other configurations
- **Summary of proposed actions**
  - Fabrication and integration of HTS wires and tapes into high current density cables
    - Requires coordinated program of R&D, including university, national laboratory and industry
  - Development of magnet components, including improved structural and insulating elements, and assessment of performance for fusion applications
  - The most promising applications would be tested in prototypes, and ultimately incorporated into new OFES research facilities.

Thrust 8: Understand the highly integrated dynamics of dominantly self-heated and self-sustained burning plasmas

This thrust aims to explore challenging DEMO core plasma regime where

- **Self-heating dominates over external heating sources (Q ≥ 20, i.e. $P_{alpha} \geq 4\ P_{input}$)**
- **Self-generated current dominates over external current drive sources**
- **Plasma pressure is high**
- **Plasma radiates significant fraction of its power**

Transport of energy, particles, momentum, rotation, and current, and MHD processes are strongly coupled in this regime ⟹ self-organized state. This raises several new questions requiring experiments to develop understanding:

- ***What is the plasma configuration that emerges from these self-consistent internal physics processes?***
- ***What maximum stability properties will the plasma access?***
- ***Can such strongly coupled burning plasmas be established and sustained with much less external power and current drive than in present experiments?***
- ***What is the most attractive core burning plasma regime that can be achieved?***
- ***What is the self-consistent plasma core / scrape-off layer / divertor plasma state?***

Thrust 8: Understand the highly integrated dynamics of dominantly self-heated and self-sustained burning plasmas (PROPOSED ACTIONS)

- **U.S. researchers, together with international colleagues, should assess potential operating plasma scenarios and upgrades on ITER, which could enhance the performance of non-inductively sustained burning plasma demonstrations**
- **In parallel, examine design options for construction of a U.S. facility, to supplement the ITER mission, focused on high P_{alpha}/P_{input}, pressure, density, self-driven current fraction, DT plasmas for durations of several current profile re-distribution times**
- ***Based on the assessments above, proceed with either ITER enhancements or a US DT facility, or both.***

Carrying out these thrusts would make possible significant advancement of our ability to conceive and construct a DEMO

5 **Expanding the Limits For Controlling and Sustaining Fusion Plasmas**
  - Develop needed tools and experimental basis for reliably sustaining a high performance plasma near operational limits with minimal actuators
    - Includes/requires diagnostic development (sensors), heating, current drive, etc. (actuators), and algorithms including reduced physical models
  - *Provides necessary tools to demonstrate Thrust 8's scenarios*

8 **Understand the highly integrated dynamics of dominantly self-heated and self-sustained burning plasmas**
  - Design and achieve advanced DT scenarios with desirable characteristics for DEMO
  - Operation in this challenging regime will require tools developed by Thrust 5

6 **Develop Predictive Models for Fusion Plasmas, Supported by Theory and Challenged with Detailed Experimental Measurements**
  - Verified and validated predictive capability needed for scenario design and projection to new devices (e.g. DEMO)
    - Supports both Thrusts 5 and 8

7 **Develop high temperature superconductors and other magnet innovations to advance fusion research**
  - Opens up possibilities for easier and cheaper construction of new SC facilities