Benchmarking of edge models:

We should do the ReNeW Theme III Thrusts

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ARIES Town Meeting on PMI

UCSD, San Diego, CA

May 20-21, 2010

UT-BATTELLE
Management Contractor for DOE's
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ReNeW report details a series of actionable thrusts to improve Plasma-Material Interface predictability

9. Understanding (decoding) the plasma scrape-off layer
   - Develop predictive capability by adding lots of new diagnostics
   - Test physics innovations, such as novel divertors
10. PMI technology understanding and development
   - Develop new well-controlled and well-diagnosed dedicated facilities
   - Fully utilize and upgrade existing facilities
11. Engineering Innovations to improve power and particle handling
   - New solid and liquid concepts, and new innovative heat sinks
12. Integrated demonstration of PMI performance
   - Integrated test of PFC and IC components + PMI modeling
   - Low activation environment with improved diagnostics
13. Establish the Science and Technology for Fusion Power Extraction and Tritium Sustainability

T9: Unfolding the physics on the boundary layer plasma

- Existing data on the variation of the plasma SOL predict a variation of heat flux width λ_q^{mid} in ITER from 5 to 25 mm
- There are also substantial variations in the predicted power flow to the divertor and the particle flux magnitude and profile
- ITER design is based on the worst case predictions and leads to aggressive PFC designs with little margin for off-normal events
- At least a dozen new facets of edge plasma behavior have been uncovered over the past decade, suggesting that our understanding of the physics is significantly incomplete

➢ We need an aggressive program of new or more complete diagnostics of the plasma edge on a variety of fusion devices coupled with an innovative theory and modeling effort to understand the boundary layer plasma

At least a dozen important new facets of boundary plasma behavior have been uncovered over the past decade, suggesting that our understanding of the physics is significantly incomplete:

- intermittent, filamentary nature of SOL turbulence
- ELM filamentation in SOL
- in/out asymmetry of ELM heat deposition
- substantial plasma recycling from main chamber walls
- large parallel flows in SOL
- transport of C13 to inner divertor and PF regions
- tritium SOL transport including hydrocarbons
- substantial plasma in the private flux region
- impact of RF sheaths on sputtering/boronization
- effect on SOL of magnetized particle drifts/B-field direction
- hydrogen retention in metals
- flux dependence of chemical sputtering of C
- tungsten "fuzz" and implications
- inability to quantitatively model detachment and near-separatrix potential
- dust production and transport
- narrow target power profiles
- evidence of strong kinetic effects in the SOL
- SOL flows set a toroidal rotation 'boundary condition' on the confined plasma
- X-point dependence of SOL flows and the L-H power threshold
- critical gradient dynamics in near SOL and tokamak density limit
- …..

Stangeby, ReNeW UCLA 2009

T9: Unfolding the physics on the boundary layer plasma

- **Develop and deploy new diagnostics in existing devices** for comprehensive boundary layer measurements of plasma flow, density, temperature, electric field, turbulence characteristics, and neutral density in at least 2 dimensions and, as appropriate, 3 dimensions, to provide the data necessary to uncover the controlling physics.
- Increase level-of effort on **validation of individual edge turbulence and transport codes**, then expand this effort to involve more comprehensive boundary layer models.
- **Develop measurements and predictive capability of the plasma fluxes to radio frequency antennas and launchers**; develop models for the self-consistent modification of the boundary layer plasma by the radio frequency wave injection and other internal components.
- **Design and implement innovations of the boundary magnetic geometry** in existing devices to demonstrate optimized plasma heat exhaust that is within material limits, and design/implement such a configuration in a future fusion device.

T10: Decode and advance the science and technology of plasma-surface interactions (in well-diagnosed dedicated facilities)

- Plasma materials interactions vary by many orders of magnitude depending on temperature, particle species, fluence, hydrogen and helium content, material composition, and exposure time
- PMI research has revealed many previously unknown phenomena such as radiation enhance sublimation, chemical erosion, blistering, particle pumping and release, and formation of nano-scale fuzz
  - Many of these have no accurate physical model

➢ We need controlled laboratory experiments under long pulse, fusion relevant conditions, to accurately measure material changes, and plasma reaction to develop first principles models to predict material response for future fusion machines.

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T10: Decode and advance the science and technology of plasma-surface interactions (in well-diagnosed dedicated facilities)

- **Upgrade existing laboratory facilities and test stands, and build new facilities** capable of extending plasma-surface interaction parameters closer to conditions expected in fusion reactors, including the capability to handle tritium, liquid metals, and irradiated materials
- **Build large-size test stands** where full-scale internal component tests and design validations can occur
- **Develop and improve first principle models** of the material and plasma coupling for future fusion machines by validating against new experimental data
- Invest in **surface material diagnostics** to quantify material behavior and evolution
- Develop and test **new surface materials** to improve performance margins

T11: Improved power handling through engineering innovations

- ITER will have carbon, tungsten or beryllium joined to water cooled copper heat sinks
  - Most present day devices have inertially cooled systems (no SS)
- Preferred PFC structures for future devices are helium cooled refractory structures
  - This option will require near term research to develop new materials compatible and tolerant with the fusion environment, including fabrication and joining techniques that will yield robust components

➢ It will be necessary to provide thermal fatigue testing of innovative solid surface and components (before and after irradiation) to verify performance, including modeling to verify compatibility with future fusion devices. New concepts for improved power and particle control may be required.

T11: Improved power handling through engineering innovations

- **Design, fabricate and test refractory heat sinks** with advanced cooling techniques for high temperature operation (>600C) and deploy liquid metal PFC experiments in plasma devices
- **Develop fabrication processes and better joining techniques** using reduced activation refractory alloys for both PFCs and internal components, e.g. RF launchers
- **Construct/upgrade new lab facilities for synergistic testing** including cyclic high-heat-flux, irradiation/permeation, and liquid metal performance; and improve models of thermal performance, irradiation damage and tritium transport in PFCs
- **Provide improved PFCs** for qualification on existing or new confinement experiments
- **Develop more robust PFCs for transient events** with higher design margins and improved reliability and maintainability. Include engineering diagnostics to monitor PFC performance and provide data for lifetime prediction models.

T12: Demonstrate an integrated solution for plasma-material interfaces compatible with an optimized core plasma

- Components must be designed, fabricated, and demonstrated in (a) working fusion device(s), in a long pulse, hot wall system, probably in a low activation environment for diagnostic access
  - The operation of the device(s) will provide the validation of the modeling and laboratory qualification , and will validate the predictions of plasma edge conditions, heat flux margins, and robustness for off-normal events
  - could be a new long-pulse tokamak, an upgraded tokamak, or a combination
  - linear devices with heated surfaces would contribute
  - details of the facilities will need to be worked out

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T12: Demonstrate an integrated solution for plasma-material interfaces compatible with an optimized core plasma

- **Develop design options** for a new moderate-scale facility with a DEMO-relevant boundary, to assess core-edge interaction issues and solutions. Key desired features include **high power density, sufficient pulse length and duty cycle, elevated wall temperature, as well as steady-state control of an optimized core plasma**. Design for a hydrogen and deuterium fuel environment, to assure flexibility in changing boundary components as well as access for comprehensive measurements to fully characterize the boundary plasma and plasma-facing surfaces. The balance and sequencing of hydrogen and deuterium operation should be part of the design optimization. **Develop an accurate cost and schedule for this facility, and construct it.**
- Extend and validate transient heat flux control from Thrust 2, plasma control and sustainment from Thrust 5, boundary plasma models from Thrust 9, plasma-material interaction science from Thrust 10 and plasma-facing component technology from Thrust 11 with the new research from this facility, thereby demonstrating a viable solution to the very challenging core-edge integration problem for DEMO.

T13: **Establish the Science and Technology for Fusion Power Extraction and Tritium Sustainability**

- How can fusion power be extracted from the complex structures surrounding the burning plasma? Can these structures be engineered to operate reliably in this extreme environment?
- How do we contain and efficiently process the tritium fuel in a practical system? Can this unprecedented amount of mobile tritium be accounted for accurately?
- How should lithium-bearing materials be integrated into power extraction components to generate tritium fuel to replace that burned in the plasma? Can simultaneous power extraction and fuel sustainability be achieved?

T13: **Establish the Science and Technology for Fusion Power Extraction and Tritium Sustainability**

- Perform **fundamental research** to establish the scientific parameters necessary to address the issues. An example activity is the exploration of tritium chemistry, heat transfer, and magnetic field interactions in lithium-bearing liquid metal coolants.
- Perform **multiple-effect studies** to understand the combined impact of the operating conditions and component complexity typical of a fusion environment. An example activity is utilizing ITER burning plasma as a test environment to perform tritium breeding and power extraction experiments with relevant materials, instrumentation, component designs, and operating temperatures.
- Perform integrated experiments to characterize the complete effect of fusion conditions and facility performance. **An example would be construction and operation of a fusion nuclear science facility (FNSF)** to perform testing that resolves the remaining gaps stemming from the effects of significant neutron irradiation over a long period of time in concert with all other fusion conditions.
- Develop the accompanying **theory and predictive models** necessary to understand and apply the experimental results, and collect reliability and safety data at all stages.