Open Issues for Integrated Modeling

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Comprehensive integrated modeling codes are used to simulate the interactions among the relevant physical processes in magnetically confined plasmas. First-principles computations together with self-consistent integrated modeling simulations are intended to embody nearly all of the theoretical and experimental understanding of confined thermonuclear plasmas.

Integrated Modeling Requirements: Can we predict plasma startup and performance well enough to design heating, current-drive, fueling, torque production, feedback control and diagnostics in future devices?

- Integrated modeling involves bridging the wide gap between short and long time and space scales
  - Physical phenomena such as turbulence and MHD instabilities develop on μ-second time scales while integrated modeling results are needed over 100's of seconds
    - Bridging time-scale gap is made more difficult by stiffness of transport and episodic nature of large-scale instabilities
  - Physical phenomena such as magnetic reconnection and electron temperature gradient modes involve microscopic spatial scales while whole device modeling is needed over meter radial scales and 10's of meters along field lines
- Physical phenomena are strongly interactive in magnetically confined plasmas requiring whole device rather than single phenomena or single region treatment
  - Core and edge plasmas are strongly coupled in tokamaks
  - Episodic instabilities (sawtooth oscillations or ELMs) involve combined effects of transport and sources as well as large-scale instability trigger and non-linear evolution
    - Sawtooth period, for example, depends strongly on evolution of profiles (*i.e.,* sources and transport) between sawtooth crashes and redistribution of magnetic flux during each crash
  - Theoretical models tend to be so narrowly focused on one part of a problem that they leave awkward gaps that must be filled in with empirical models
    - ELM crash models, for example, have not yet addressed the issue of the redistribution of plasma current density during each ELM crash, which is critically important to compute ELM periods
- Integrated modeling codes require an extraordinarily high level of reliability for each component and for the framework connecting components
  - A failure rate of 1/1000 is not good enough when there are 1000's of time steps

Research requirements associated with missing physics

- Integrated modeling codes use reduced physics models for expediency but more comprehensive and reliable models are needed
  - Improved reduced models are needed for sawtooth crashes, ELM crashes, neoclassical tearing modes, plasma-wall interaction and turbulent transport over a wide range of conditions
    - Sawtooth crash model must predict fraction of magnetic reconnection
    - Sawtooth trigger model must consider details of fast ion distribution
    - ELM crash model must predict removal of plasma current and redistribution of edge profiles as well as heating transients to the divertor plates
    - Neoclassical tearing mode model must consider effects of mode coupling and rotation

    - Transport models must compute transport near magnetic axis and in H-mode edge pedestal
    - 3-D transport models must be developed for plasma near helical magnetic islands
    - Dynamic model is needed for neutrals recycled from plasma-facing components

- Improved numerical techniques must be developed to bridge the wide gap in space and time scales from μ-sec to whole-device modeling on 100's of seconds
    - Projective integration techniques must address the stiffness of transport and the periodic nature of sawtooth and ELM cycles
    - Improved sub-grid and adaptive techniques must be developed to address fine-scaled localized phenomena such as magnetic reconnection in the context of whole-device modeling on the scale of 10's of meters
- Advanced integrated modeling frameworks and advances in applied math computer science are needed
    - Fundamentally 3-D frameworks are needed to deal with magnetic islands and ripple
    - Improved frameworks are needed to facilitate bridging time and space scales
- Additional examples where better physics models are needed
    - Improved L-H and H-L transitions, pedestal properties, MHD events, fast ion interactions, startup and ramp-down temperature and rotation profiles, fueling and impurity transport, ripple, magnetic islands, recycling, improved transport models

Issues Concerning Validation: *How can we establish the validity of predictive models?*

- What constitutes an adequate test of integrated predictive modeling codes?
    - How good does the comparison with experimental data have to be before we have confidence in the models and simulations?
    - How much difference does there have to be with experimental data before we can reject a model?
    - How sophisticated do models have to be before they are accepted by theoreticians?
    - When are models and codes good enough to trust results of fusion reactor simulations?
- It is important that the needs of integrated modelers be considered in planning experiments
- It is important that experimental data be made fully available for validation studies
- Pulse propagation experiments provide one example of the scientific challenges involved in producing more discriminating tests of transport models

Policy Issues Concerning Integrated Modeling

- What is the relative balance needed between investment in first-principles codes and whole-device integrated modeling codes?
- What balance should be struck between expensive shared-memory massively parallel computers and relatively inexpensive cluster computers and workstations?
- How do we find a place for integrated modeling in fusion research, given the pervasive fragmentation
    - Hard to find a proper forum for results that span a wide range of specialized subfields