Interaction Between Different Physical Processes Within Integrated Predictive Modeling Simulations

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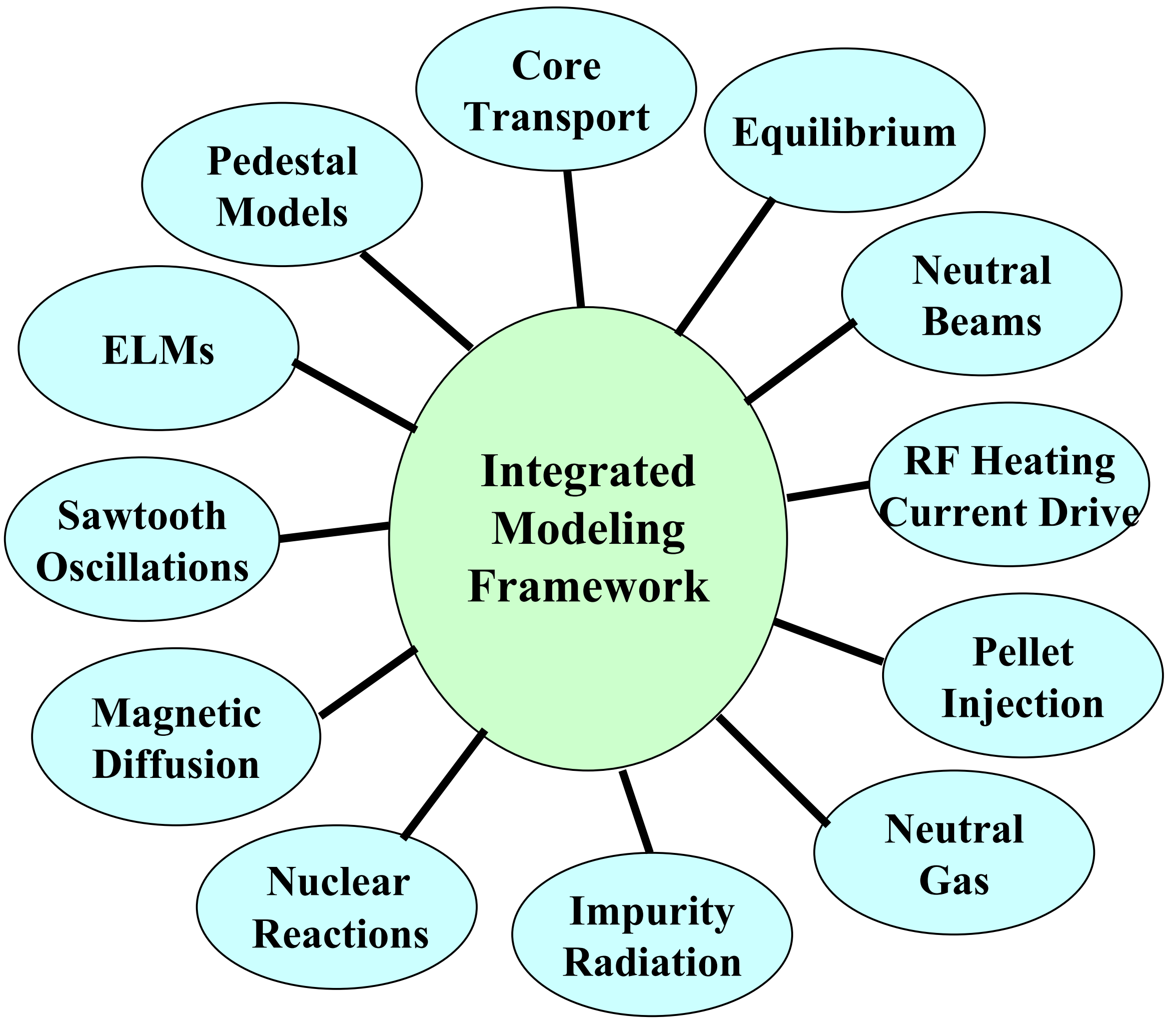
Integrated Predictive Tokamak Modeling



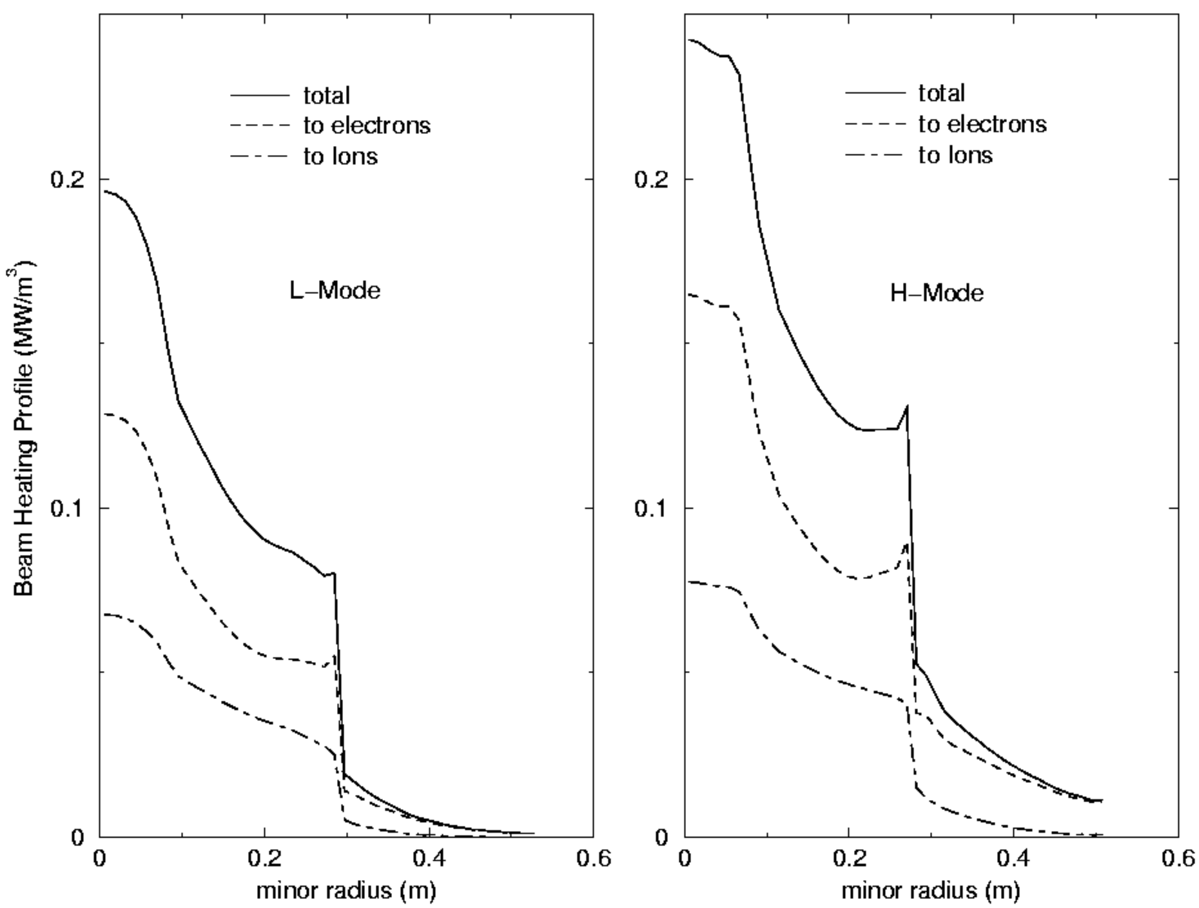
Interactions between many different kinds of physical processes are computed for:

- Sources
- Sinks
- Transport
- Equilibrium shape
- Large-scale instabilities
- Boundary conditions

Sawtooth Oscillations $\leftrightarrow$ Fast Ion Heating Profile

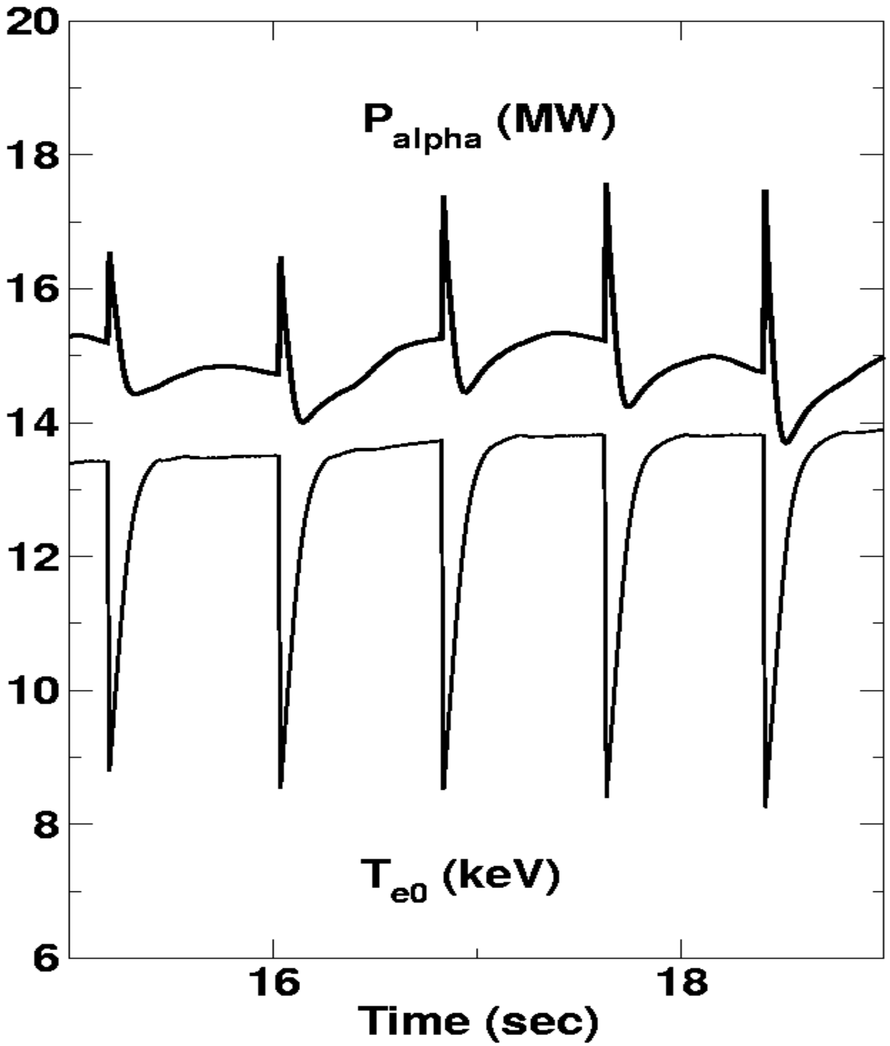
- Fast ions are spread out across the sawtooth mixing region during each sawtooth crash
  - Consequently, fast ion heating of the thermal plasma is spread out over the sawtooth mixing region
  - Fast ions are driven by
    - Neutral Beam Injection (NBI)
    - Fusion reactions (e.g., deuterium-tritium reactions produce fast alpha ions)
    - Ion Cyclotron Resonance Frequency (ICRF) heating
  - Stand-alone codes for NBI, alpha heating, or ICRF generally do not consider this effect

NBI Heating Profile in BALDUR Simulation of MAST



NBI heating profile is spread out over the sawtooth mixing region

Effect of Sawtooth Crashes on Heating by Fast Alpha Particles



- With each sawtooth crash:
  - Central temperatures drop as plasma is spread over the sawtooth mixing region
  - Fast alpha particles slow down more rapidly

  ⇒ There is a faster transfer of power from fast alpha particles to thermal plasma
  - This appears as a transient spike in P_{alpha} after each crash

  ⇒ Thermal electrons and ions reheat rapidly
- As a result, the fusion burn can recover from transient low central temperatures

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Boundary Conditions ↔ Confinement

- Boundary conditions affect confinement in many different kinds of tokamak discharges:
  - H-mode discharges:
    - A sharply defined pedestal forms at the edge of the plasma
    - Confinement is enhanced by the pedestal
      - Especially since core transport models are stiff
    - Sufficiently good confinement is required to form the pedestal during the L to H-mode transition
    - Combinations of pedestal and core models are required for integrated predictive transport simulations
  - “Supershot” discharges
    - Wall conditioning was used to minimize recycling in order to prepare for hot-ion “supershot” discharges in TFTR

Transport $\leftrightarrow$ Current Profile

- There is the following non-linear feedback loop in tokamaks:

Current profile $\rightarrow$ transport $\rightarrow$ pressure gradient $\rightarrow$ bootstrap current $\rightarrow$ current profile

- Usually, the current profile evolves on a slower time scale than the transport
  - Magnetic diffusion is slower than thermal transport
  - Sawtooth oscillations, current drive, and edge phenomena also affect the current profile
- Reversed magnetic shear (*ie,* low central current) can produce Internal Transport Barriers

This slide was suggested by Irina Voitsekhovitch

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Transport ↔ Lower Hybrid Heating

- **Radio-frequency power absorption depends on plasma parameters which, in turn, depend on sources, sinks, boundary, and transport**
  - In a low temperature plasma, there is weak, off-axis multi-pass heating
  - As the temperature increases, there is a transition from weak multi-pass to strong single-pass heating
  - Single pass heating deposition scales like $T^{-1/2}$
- **Lower hybrid can also be used to drive current**
  - Driving current off-axis can produce reversed magnetic shear, which can produce an Internal Transport Barrier

This slide was suggested by Irina Voitsekhovitch

Sawtooth Oscillations $\leftrightarrow$ Transport $\leftrightarrow$ Edge Localized Modes (ELMs)

- Heat pulses are produced by sawtooth oscillations and (cold pulses) by ELMs
  - Sawtooth crashes and ELMs are periodic abrupt redistributions of the plasma profiles
  - Heat pulses are observed to propagate much faster than the background heat transport
  - Ion particle and ion momentum pulses also propagate through the plasma
  - Stiff, non-linear transport models are used to model the observed pulse propagation
    - This is one way to discriminate between different models
  - Large sawteeth and ELMs can degrade confinement

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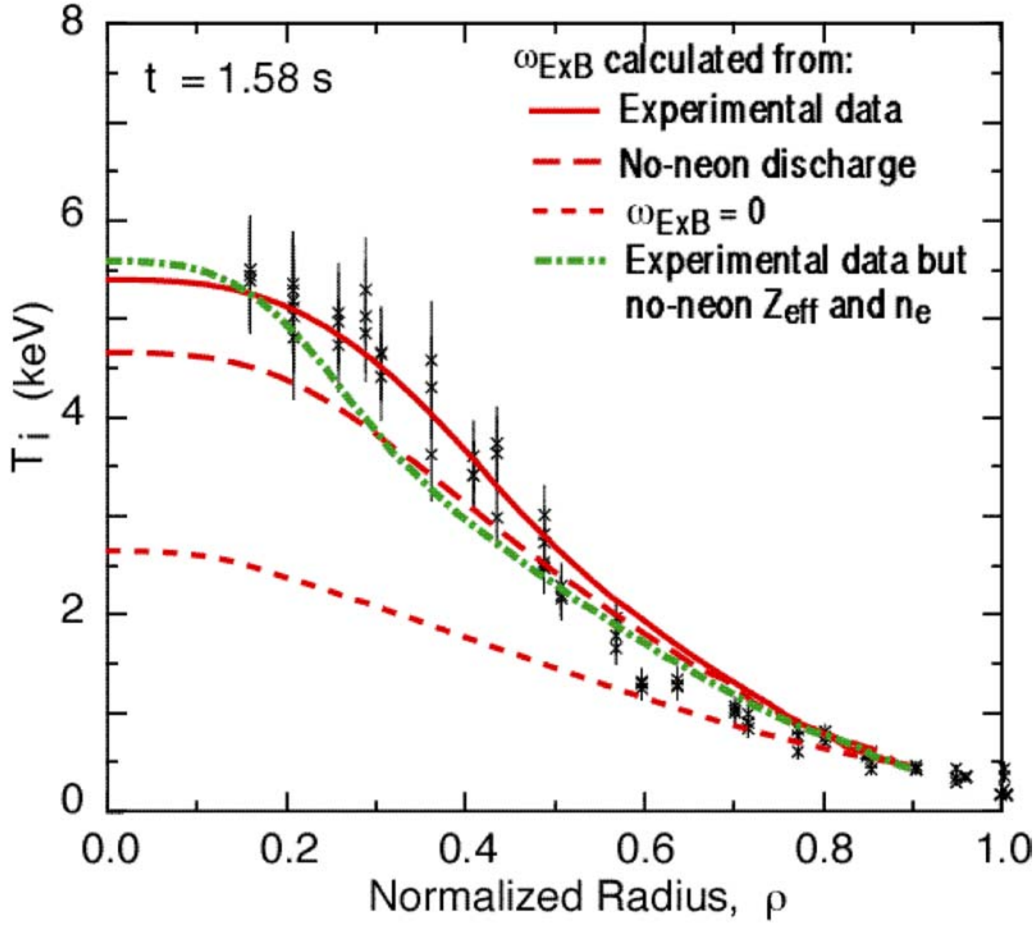
Impurity Influx $\rightarrow$ Enhanced Confinement

- It is observed on DIII-D and other tokamaks that a sudden impurity influx produces enhanced confinement
  - Strong flow shear is produced by the impurity influx
- Integrated modeling simulations using the National Transport Code Collaboration
  - Showed that flow shear reduced the transport to neoclassical values
  - Were able to predict the experimentally observed temperature profiles

INCREASE IN ExB SHEARING RATE IS A NECESSARY CONDITION FOR CONFINEMENT IMPROVEMENT



Simulations are used to test:

- Effects of ExB shearing from experimental ω_{ExB} to 0
- Effects of changing Z_{eff} ($3.2 \rightarrow 1.4$) and $n_e(\rho)$ after the improved state is established

$\Rightarrow$ Neon injection may be used as a trigger

Density Limit in Tokamaks

- Several effects are believed to play a role in determining the density limit in tokamaks:
  - Gas puffing at high density produces a steep density gradient near the edge of the plasma
  - The steep density gradient enhances transport near the edge of the plasma
  - Impurities radiate most of the power at high density
    - This produces a "radiative collapse" of the plasma
  - As the edge of the plasma cools, the plasma current cannel shrinks
  - As the current channel shrinks, the current gradient drives MHD instabilities that lead to disruption

Integrated Modeling Issues - 1

- Which models are correct?
  - There are several different models for
    - Core transport
    - H-mode pedestal
    - Large scale instabilities (such as sawtooth oscillations)
  - Simulations using these different models match experimental data about equally well
    - RMS deviations are in the 10% to 20% range
  - The different models predict different performance when extrapolated to fusion reactor designs
    - For example, the IFS/PPPL model predicted poor performance for ITER-EDA while the Multi-Mode model predicted ignition
  - We need the predictions to converge together

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Integrated Modeling Issues - 2

- Specialized computer codes have gotten way ahead of integrated modeling codes
  - Specialized codes to compute plasma turbulence and large-scale instabilities are way ahead of the models used within integrated modeling codes
  - Scrape-off-layer codes (such as UEDGE) have not yet been combined with most core modeling codes
- Some issues are neglected
  - For example, predicting the impurity concentration in tokamak plasmas
    - The performance of fusion reactors is predicted to be sensitive to high levels of impurity concentration

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Integrated Modeling Issues - 3

- What constitutes an adequate test of integrated predictive modeling simulations?
  - 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, before we can reject a model?
  - How sophisticated do the models have to be, before they are accepted by theoreticians?
  - When are the models and codes good enough to trust the results of fusion reactor simulations?

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