Burning Plasmas Physics Issues Illustrated by FIRE Simulations

W.A. Houlberg

ORNL

Workshop on Physics Issues for FIRE

1-3 May 2000

Princeton, NJ

Outline

- **WHIST simulations of FIRE**
  - » **Models**
  - » **Illustrations of physics issues in burning plasmas**
    - – **Case 1: 30 MW short square-wave FWCD, H-mode**
    - – **Case 7: 15 MW long programmed FWCD, H-mode**
    - – **Case 3: 30 MW long square-wave FWCD, L-mode**
- **Conclusions**

1-1/2-D Time-Dependent Transport Modeling

- **1-1/2-D time-dependent transport codes are ideal for:**
  - » **Scoping out the dynamics of access to attractive operating regimes**
  - » **Evaluating the capabilities of auxiliary heating, fueling, and CD systems to exploit those scenarios**
  - » **Identifying and avoiding the 'hurdles' of operation (e.g., density limits, tolerance to impurities, L-H transition, etc)**
  - » **Evaluating confinement with consistent profiles**
- **Simulation codes address these issues within the context of given, approximate confinement models:**
  - » **Similar to a real experiment, all devices show a wide range of behavior in simulations within a given transport model**
  - » **There are more 'knobs' available in simulation codes than real experiments - simulations only partially explore the operating space**

☛ **SIMULATIONS ARE NO SUBSTITUTE FOR REAL BURNING PLASMA EXPERIMENTS**

☛ **Designates unresolved 'issue'**

WHIST: Confinement Model for This Study

- **Neoclassical plus anomalous transport**
- **Fixed anomalous conductivity and diffusivity profiles:**
  - » **Normalized to yield global L-mode confinement (ITER-97L):**

$$\tau_E^{97L} = 0.023 I^{0.96} B_T^{0.03} P^{-0.73} n_{19}^{0.40} M^{0.2} R^{1.83} \epsilon^{-0.06} \kappa^{0.64} \quad \text{(s)}$$

    in (MA, T, MW, 10^{19} m^{-3}, AMU, m)
  - » **Profile:** $\chi_i(\rho) = \chi_e(\rho) = \chi(0)[1+4\rho^2]$, $D(\rho) = \chi(\rho)/2$
  - ☞ **Actual transport would show a richer profile variation**
- **Impurities (fixed broad profiles except for He):**
  - » **Be: fixed broad profile**
  - » **W: fixed broad profile**
  - » **He ash: neoclassical + anomalous transport and recycle**
  - ☞ **Actual profiles may be very peaked or very hollow**

WHIST: L-H Transition Model

- **L-H transition power threshold (IPB98-4):**

$$P_{thr} = 0.082 n_{20}^{0.69} B_T^{0.91} S^{0.96} M^{-1} \quad (MW)$$

in (10^{20} m^{-3}, T, m^2, AMU)

- **Suppress edge transport when $P_{sep} > P_{thr}$:**
  - » **By a factor of 5 for 0.95 < ρ < 1.0**
  - » **Extent similar to Parail model for JET (Δ/a ~ 0.1)**
  - » **ELM effects are lumped into the suppression factor**
  - ☛ **Generally this gives an H-factor ~ 2**

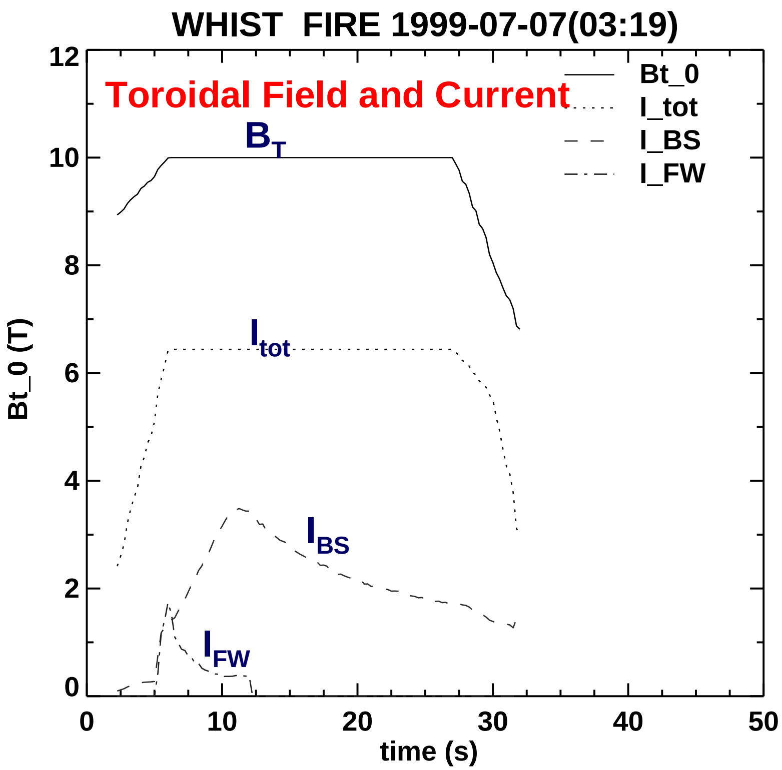
WHIST: Fueling Models

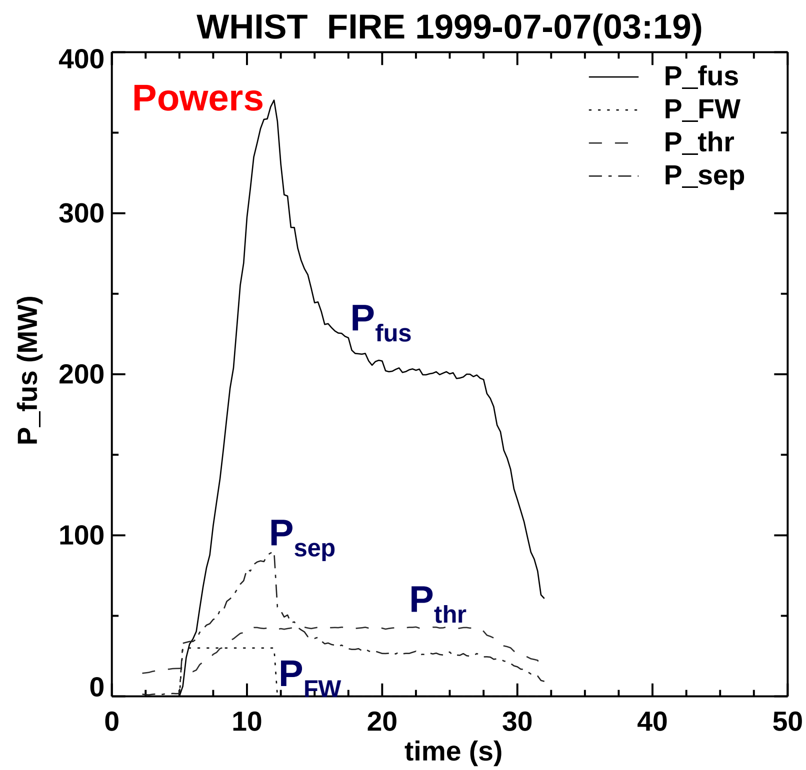
- **Outside pellet launch:**
  - » **Pellet velocity — 1.0 km/s, ~ DIII-D injector**
  - » **Pellet ablation — neutral gas and plasma shielding model agrees with observed pellet penetration**
  - » **Δn profile — assume same as ablation profile**
  - ☞ **Overly optimistic for H-mode cases**
- **Inside pellet launch:**
  - » **Assume uniform Δn profile**
  - ☞ **~ DIII-D observations, more info coming from ASDEX-U, DIII-D, JET**
- **D, T and He recycle:**
  - » **90% of outgoing flux recycled inside separatrix**
  - ☞ **Need coupling to SOL codes for better treatment**

WHIST: Heating and Current Drive Models

- **Fast wave ICRF:**
  - » **Empirical match to strong and weak absorption limits**
  - » **Ehst-Karney current drive**
- **Fusion alphas:**
  - » **Multi-group time-dependent classical thermalization**

FIRE Case 1: H-Mode, P_{FW} = 30 MW Square Wave
☛ Inertial, Startup Control, L-H Transition Hysteresis





- Large I_{BS} with long decay time
- Small I_{FW}
- Long decay time

☛ Inertial effects?

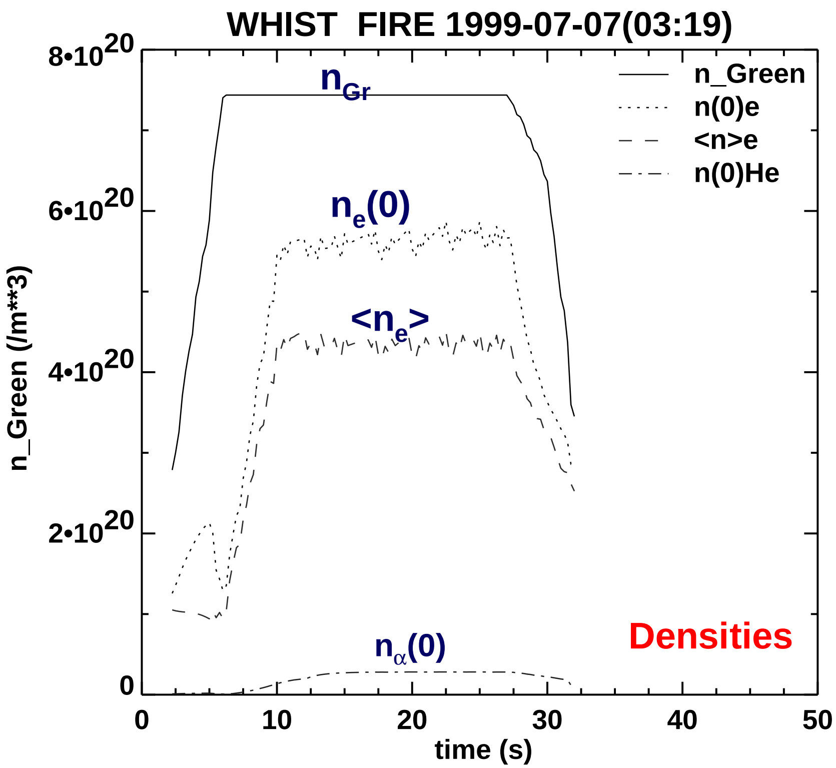
- P_{fus} 'overshoot'

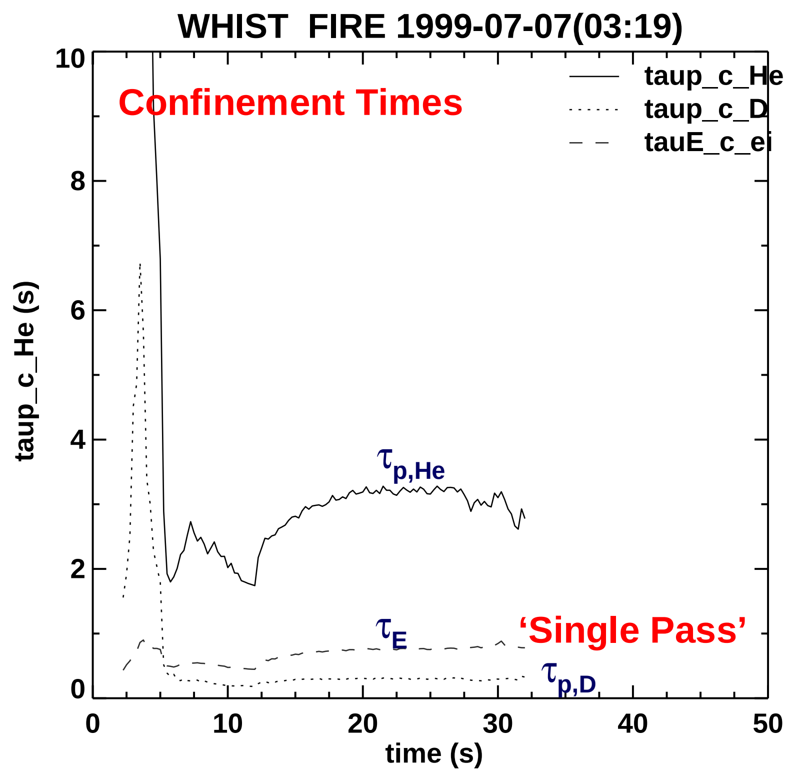
☛ Control startup?

- With $P_{sep} > P_{thr}/2$ stays in H-mode
- $P_{sep} < P_{thr}$

☛ H-mode hysteresis?

FIRE Case 1: H-Mode, P_{FW} = 30 MW Square Wave
☛ Density Limit, He Accumulation and Confinement

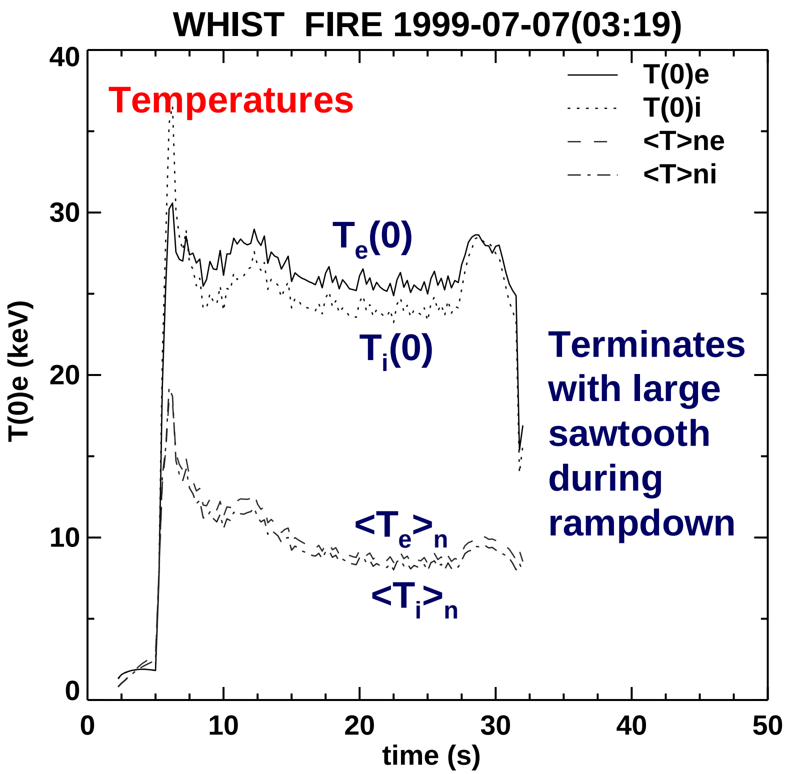


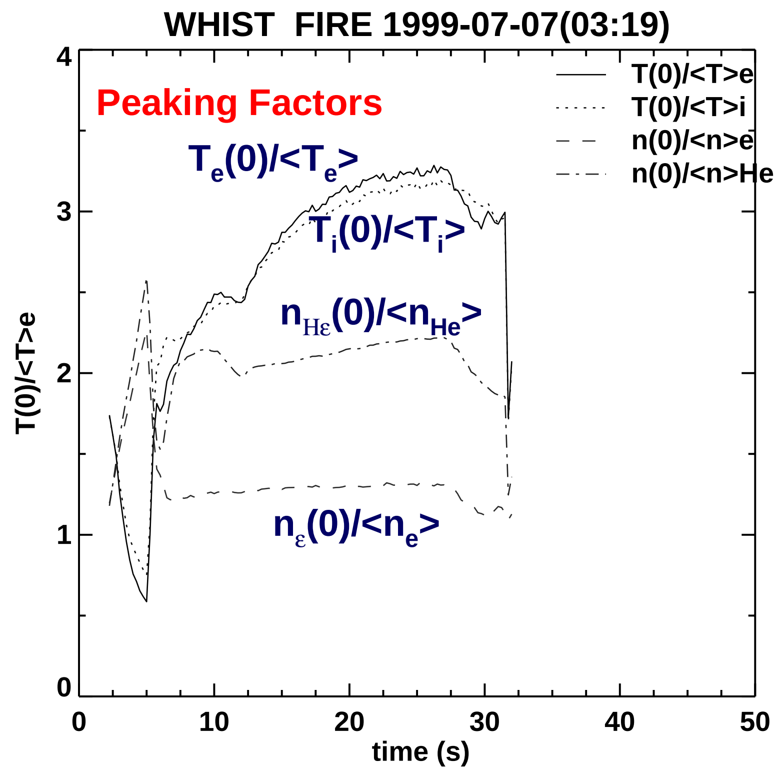


- Moderate density peaking
- ☛ Far enough below n_{Gr}?
- Low helium density
- ☛ Sufficient pumping and recycle?

- $\tau_{p,He} >> \tau_E > \tau_{p,D}$
- ☛ $\tau_{p,He}$ dominated by central source?
- ☛ $\tau_{p,D}$ dominated by edge recycle?

FIRE Case 1: H-Mode, P_{FW} = 30 MW Square Wave
☛ Sawteeth, Rampdown, T(ρ) Sensitivity to q





- T(0)~constant, <T> decays
- Termination by giant sawtooth

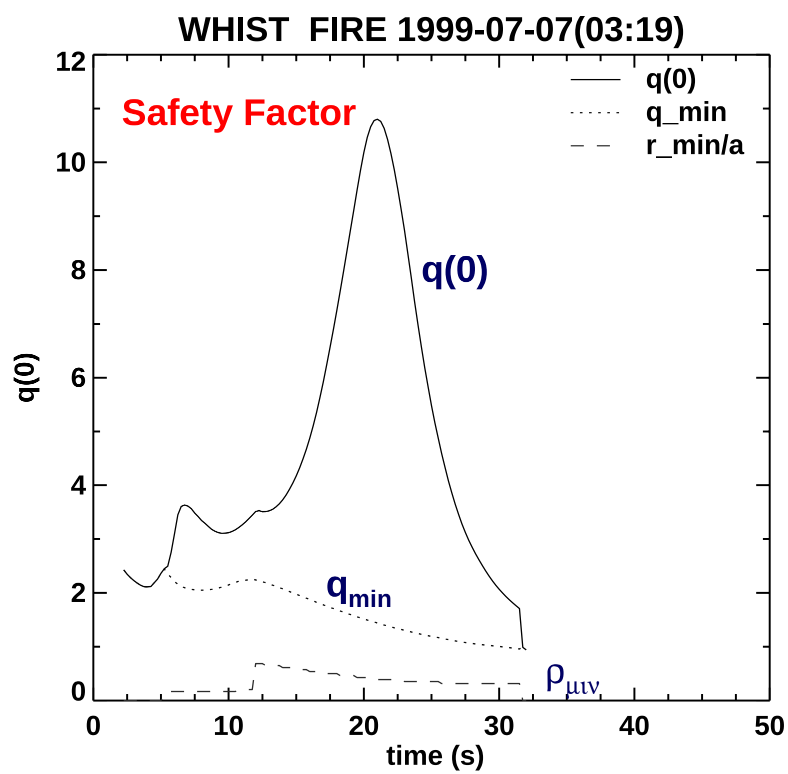
☛ Control rampdown?

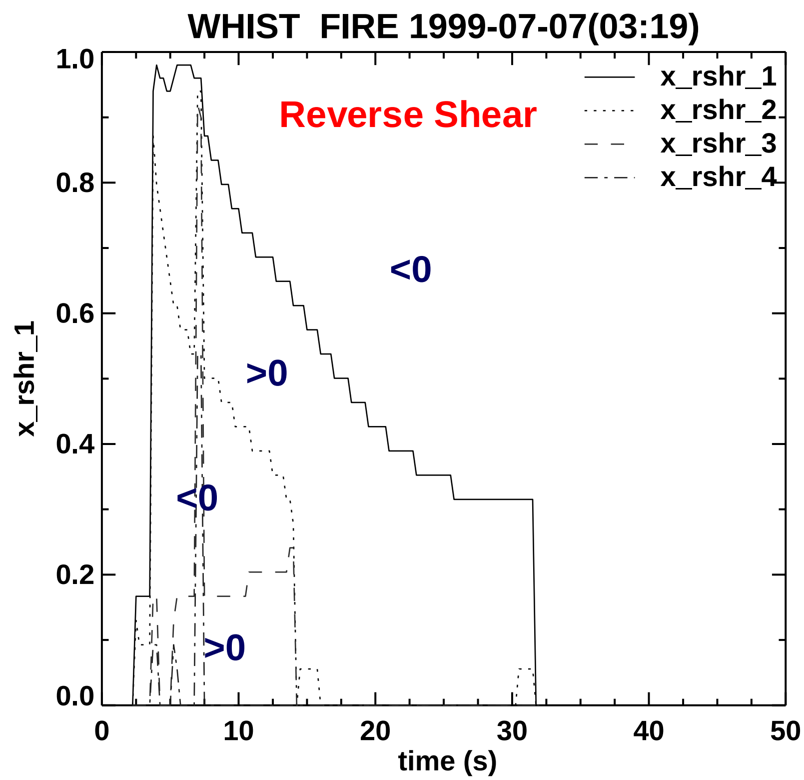
☛ Sawteeth?

- Deep pellet penetration during rise peaks n, hollows T (~PEP mode)
- T peaks from reducing χ_i^{NC} (~$0.3\chi_i^{an}$)

☛ Sensitivity to q?

FIRE Case 1: H-Mode, P_{FW} = 30 MW Square Wave
☛ Reverse Shear Control, Influence on MHD and τ





- $q(0)$ rises and falls with bootstrap
- q_{min} decays through burn

☛ Influence of q(ρ) on MHD?

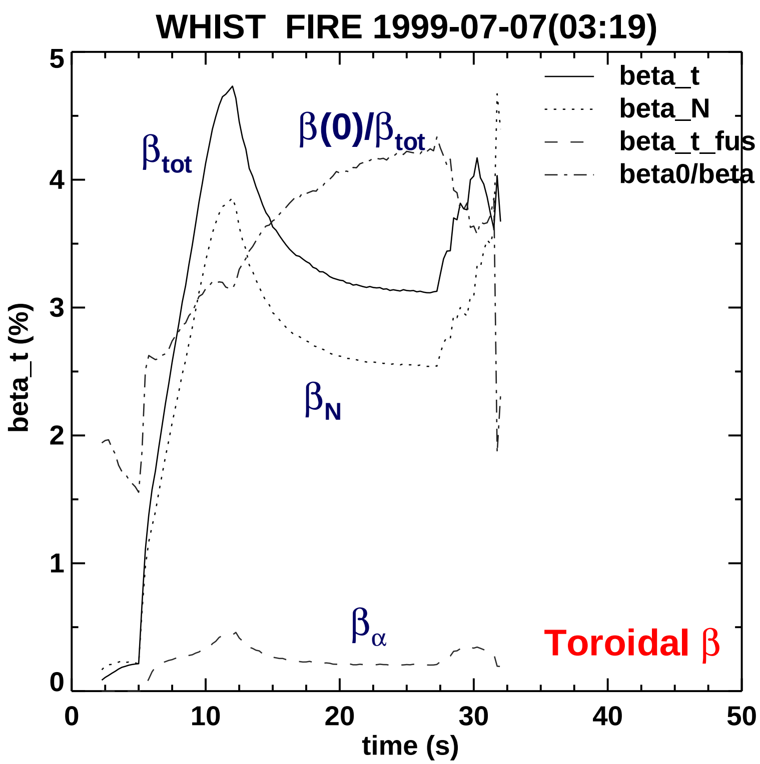
- Multiple reverse shear regions merge and collapse toward axis

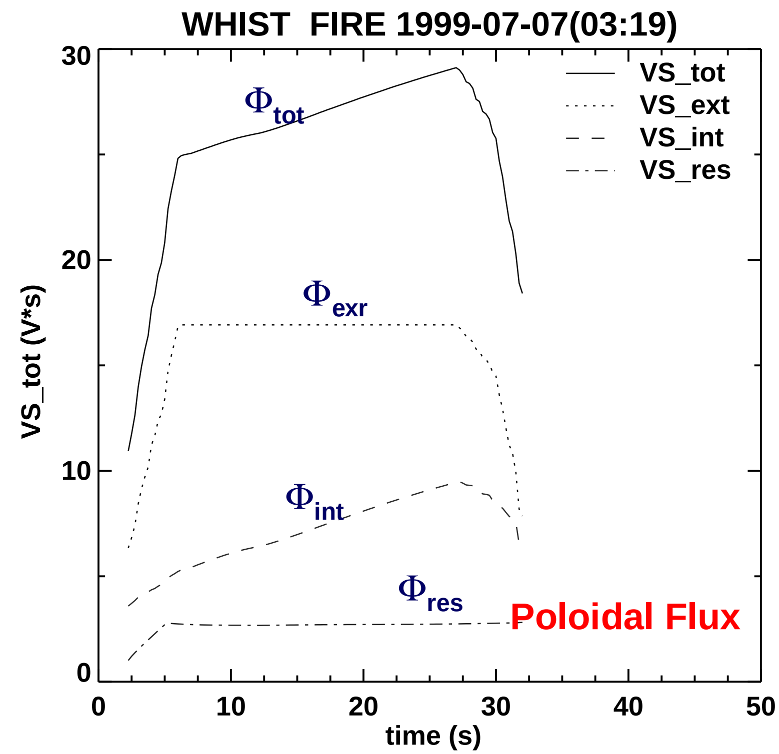
☛ Influence of reverse shear on χ?

☛ Control shear with CD?

FIRE Case 1: H-Mode, P_{FW} = 30 MW Square Wave

☛ Influence of β, β_α and Peaking on Stability

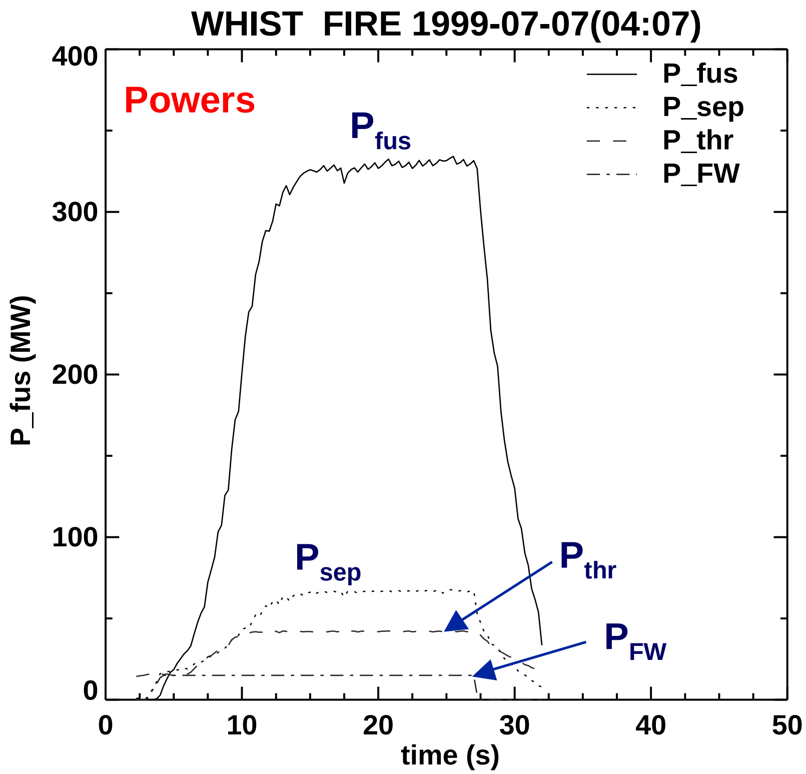


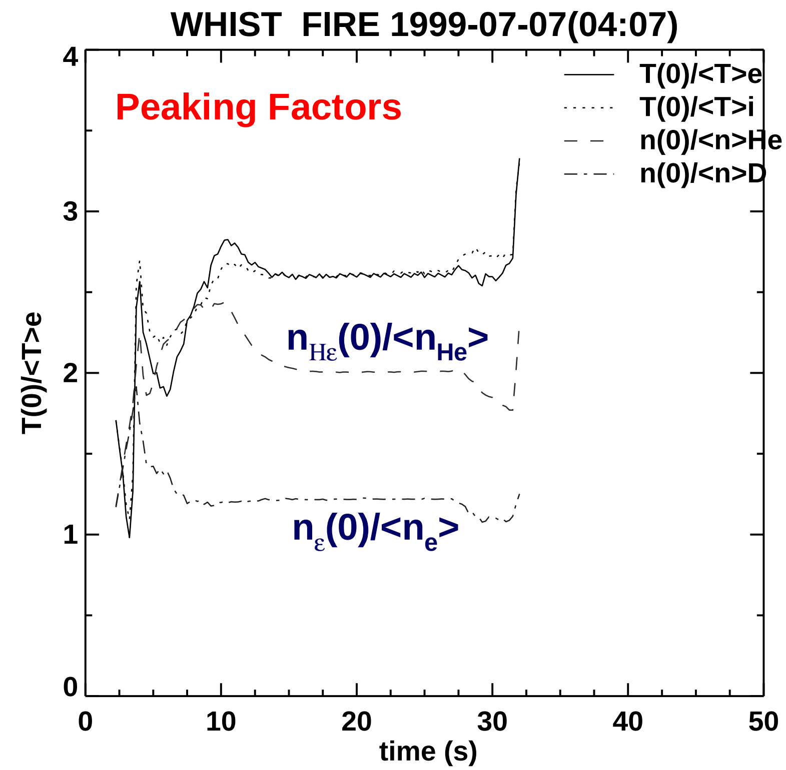


- β peaking increases through burn
- ☛ Influence of β peaking on MHD?
- ☛ β_N overshoot MHD unstable?
- ☛ β_α influence on instabilities

- Φ consumption during burn dominated by internal flux
- Resistive loss small due to high q(0)

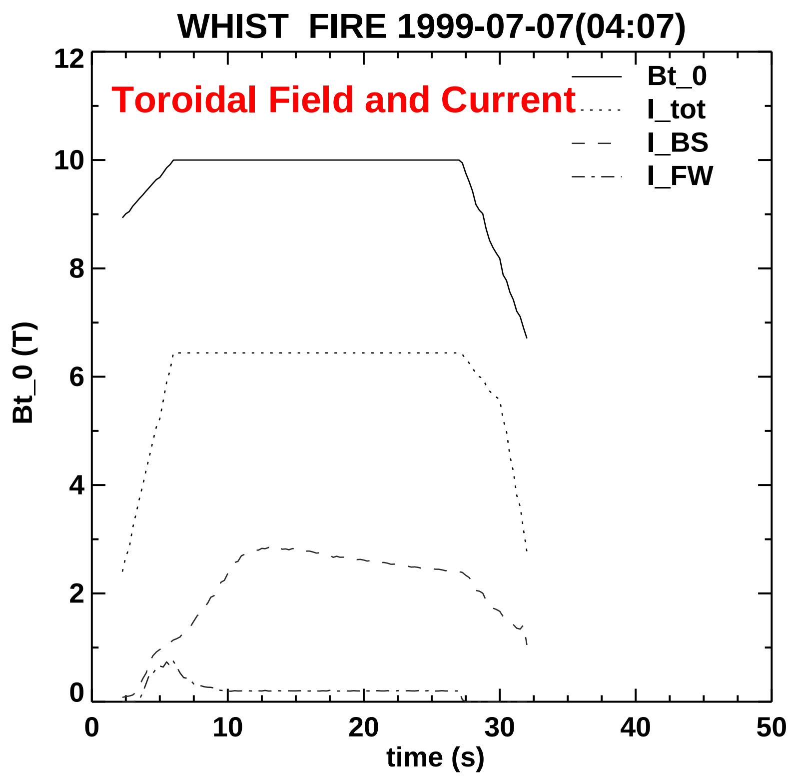
FIRE Case 7: H-Mode, P_{FW} = 15MW Driven Burn
☛ Control Startup and Burn with P_{fw} Waveform

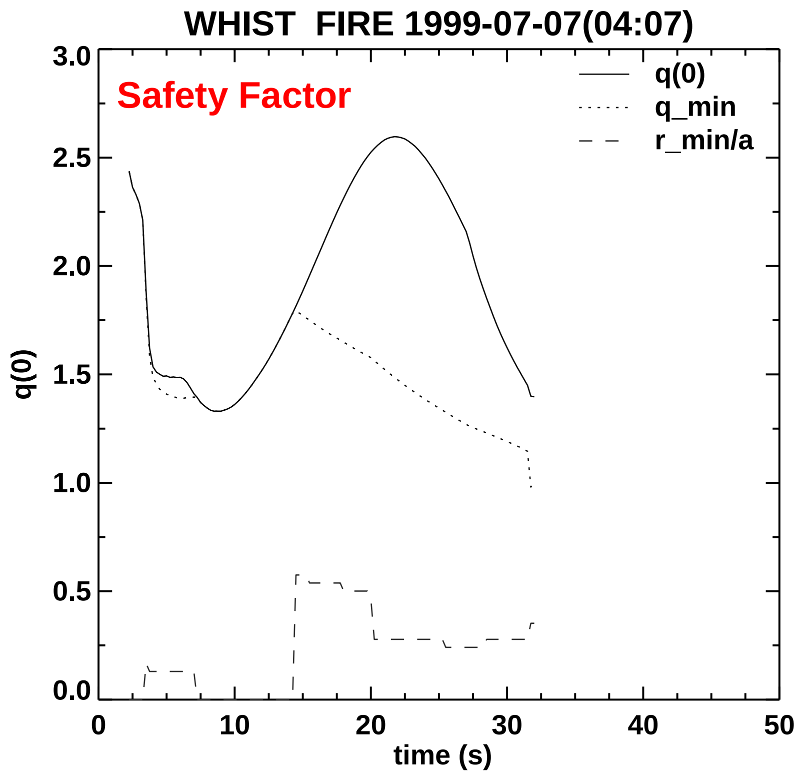




- P_{sep} just above P_{thr} during rise and well above durning burn
- P_{fus} well controlled
- Peaking factors have long flattop

FIRE Case 7: H-Mode, P_{FW} = 15MW Driven Burn
☛ Reverse Shear Appears to be Predominant Feature



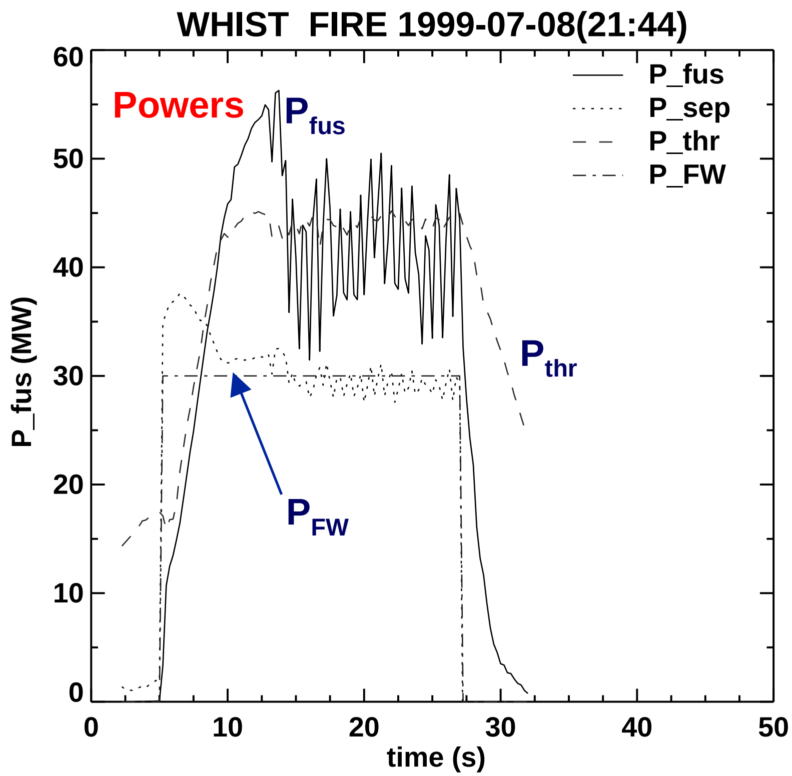


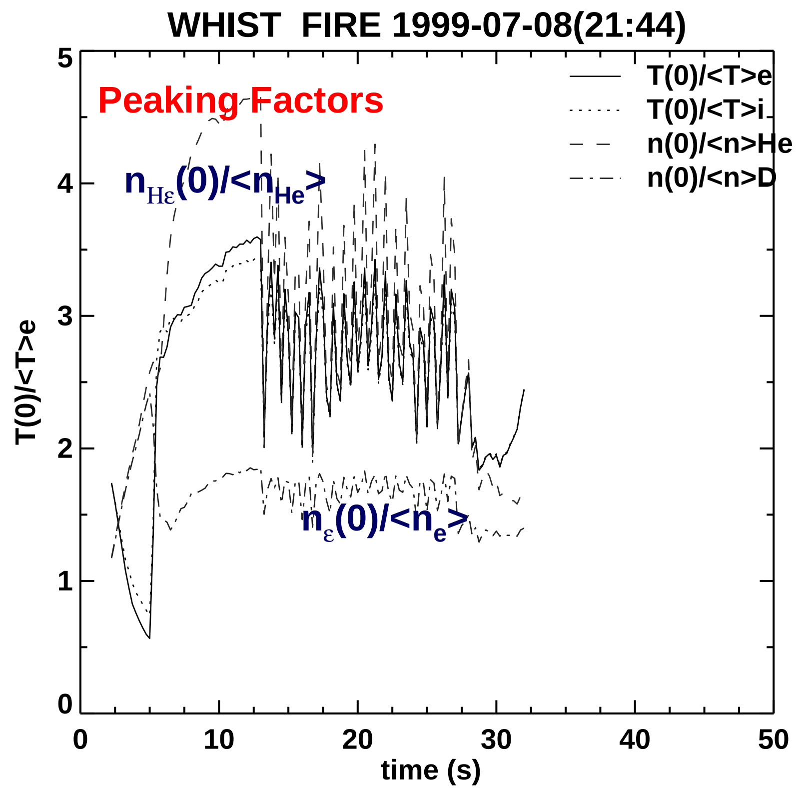
- Small bootstrap current overshoot

- Weaker reverse shear
- q_{min} > 1 for entire burn

ornl

FIRE Case 3: L-Mode, P_{FW} = 30MW Driven Burn
☛ Validation of Sawtooth Model/Effects





- Very large sawteeth
- $P_{sep} > P_{thr}$ only during startup

☛ Sawtooth model?

☛ Low-n L-H transition necessary?

- Significant peaking even with sawtooth activity
- Density more peaked than H-mode

☛ MHD, kinetic instabilities?

Conclusions

- There are many burning plasma physics issues to resolve:
  - » Transport modeling can illustrate them but not resolve them
- Inertial effects during startup can persist for very long times, making steady-state irrelevant in most cases
- Generation of transient, but persistent reverse shear conditions appears to be relatively easy:
  - » Understanding AT physics may be relevant even for scenarios not designed for AT operation
- Inside launch pellets may help to moderately peak the density profile
  - » Stronger effect is expected in L-mode than H-mode, but the models are still highly uncertain
- Only the dynamics and a few attendant issues have been identified here
- None of the cases have attempted to optimize the performance within the context of the assumed models