Progress report for the
MHD Physics Working Group (P3)

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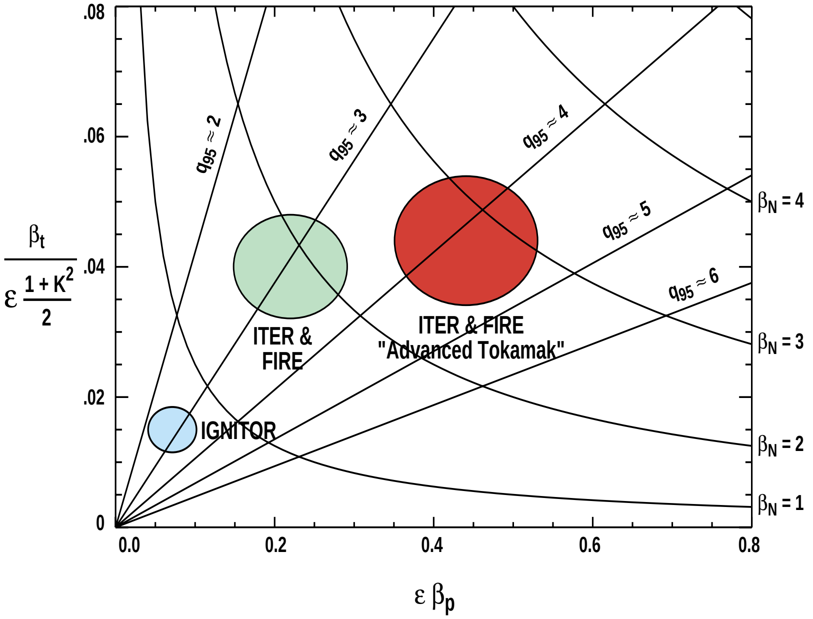
Broad questions for the MHD working group

- What limitations will MHD instabilities impose on the ability of a burning plasma experiment to achieve its full range of scientific goals, and how can these instabilities be avoided or ameliorated?
- What new MHD physics can we learn from a burning plasma, and to what extent will the proposed machines allow us to investigate those physics issues?
- What impact will the MHD physics to be learned in a burning plasma experiment have on the development of future fusion devices - both tokamaks and other concepts?

MHD issues in a burning plasma

- m=1 stability and its impact on fusion performance
- neoclassical tearing mode avoidance or stabilization (FIRE and ITER)
- stability of H-mode edge pedestal, impact on core transport and divertor heat loading (FIRE and ITER)
- critical error field to avoid mode locking during low-beta startup



Ideal MHD stability is well understood

- The base scenarios for all three machines are stable to ideal MHD with one notable exception.
  - m/n = 1/1 ideal internal kink is sensitive to central q value

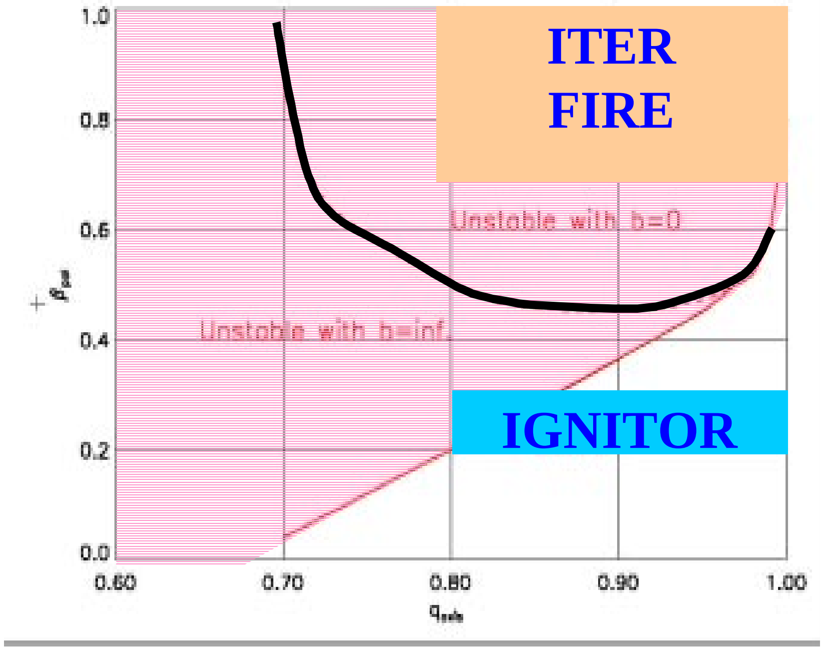
- FIRE and ITER operate in similar parameter regimes with respect to ideal MHD (β_N ~ 1.8).
  Ignitor operates at lower beta (β_N ~ 0.65).

- In FIRE and ITER, advanced tokamak cases have higher beta (β_N ~ 2.5-3.5) and lie at or beyond the no-wall stability limit.

Ideal MHD theory predicts instability to the m/n = 1/1 mode at high β_θ with q(0) < 1

- ITER and FIRE are ideal MHD unstable for typical β_θ, if q(0)<1. Ignitor is stable to lower q(0)
- Fast alphas are expected to stabilize m=1 to lower q(0) and larger q=1 radius, leading to giant sawteeth
- Possible impact of sawteeth on central temperature and fusion power
- Large q=1 radius may lead to global mode, strong coupling to NTMs and other MHD modes

- m/n = 1/1 stability boundaries generated from generic profiles



m=1 stability and the effect of sawteeth remain an area of disagreement

- DT experiments in JET show little direct impact of sawteeth on time-average stored energy or fusion power
  - Major issue is triggering of NTMs by sawtooth crash
- Simulations with Porcelli model indicate sawteeth have little impact on time-average stored energy or fusion power
  - Possibly greater impact in Ignitor due to peaked profiles, lower T_0
- However, there are uncertainties in quantitative predictions
  - Form of ideal δW_{MHD} (and non-ideal effects?)
  - Reconnection physics at sawtooth crash
  - Transport model for profile evolution between crashes
  - Period determined by transport or current diffusion?

Physics opportunity: sawteeth at high S, effects of isotropic population of energetic alpha particles

Susceptibility to Neoclassical Tearing Modes is expected in burning plasma scenarios

- Critical scaling ($\beta_{crit} \sim \rho^*$) is not favorable for large tokamaks.
- Significant issue for ITER and FIRE: low threshold β and large saturated islands (w/a~0.2)
  - not likely to be a major issue for Ignitor
- Control techniques are essential
  - localized ECCD: well established but may need modulation (ITER)
  - Continuous LHCD for Δ' control: used in COMPASS (FIRE)
  - Modulated LHCD in island (FIRE)
    - Untested, may be difficult to localize sufficiently
  - Sawtooth control by ECCD, FWCD, or LHCD: tested in JET

Physics opportunity: threshold island size and seed island coupling at low ρ^* and high S

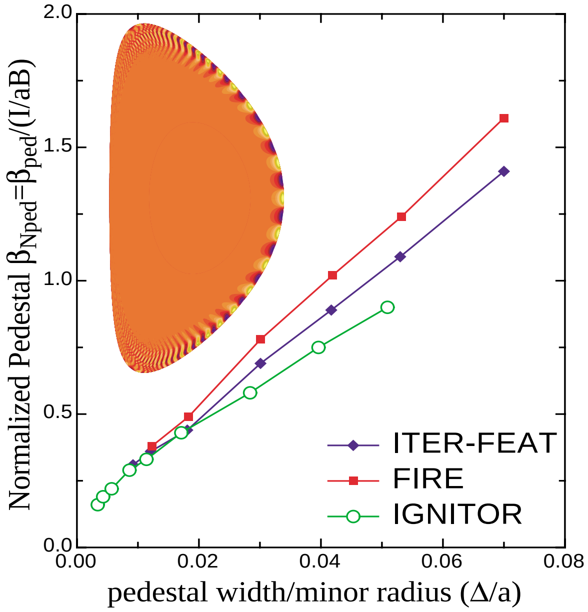
Large ELMs can limit H-mode performance through impact on global confinement and transient heat load on divertor

- MHD stability limits pressure gradient ⇒ pedestal height
  - – Pedestal physics not fully understood (transport physics?)
- ELM heat load is a critical issue for ITER and FIRE
  - – Not an issue for Ignitor base case
- ITER and FIRE could explore tradeoffs between higher pedestal pressure, smaller ELMs
  - – Collisionality
  - – Shaping
  - – second regime access with high triangularity and j_{bs}

Physics opportunity: pedestal width and stability at small $\rho^*=\rho_i/a$

- Pedestal height is in the range needed for good performance
  - – If width similar to present experiments (Δ/a~0.03)

Comparison of Normalized Pedestal Stability Limits



Error field tolerance decreases with machine size and beta

- Primarily an issue for low density ohmic startup and AT regimes
- Torque balance requires low error field to avoid rotation locking in low density ohmic plasma (n_e=0.2 n_G, rotation at ω^*_e)
  - $B_r(2,1)/B_t < 9 \times 10^{-5}$ (Ignitor & FIRE), 3×10^{-5} (ITER)
- Required symmetry should be achievable with correction coils
  - ITER and FIRE designs include correction coils
  - Ignitor may avoid locking with higher density, good coil alignment
- Error field tolerance is lower at high beta, due to greater torque near n=1 stability limit (“error field amplification”)
- Advanced Tokamak cases need rotation significantly greater than ω^*_e to avoid locking even at $B_r(2,1)/B_t \sim 3 \times 10^{-5}$

Physics opportunity: error field penetration with low plasma rotation

Resistive wall mode stabilization by plasma rotation is problematic

- Advanced tokamak cases in ITER and FIRE need wall stabilization of the n=1 kink mode
  - MARS modeling shows stability with $\Omega_{rot}\tau_A$ ~ 0.5-1.5 % at rational surfaces
  - Sensitive to profiles (p, q, Ω, ...)
- Predicted rotation with planned neutral beam power is marginal to sub-marginal ($\Omega_{rot}\tau_A$ ~ 0.5-1 %) in ITER and FIRE
  - Sensitive to model for momentum transport
  - RF-driven rotation is too poorly understood to assess

Physics opportunity: resistive wall mode stability with low plasma rotation frequency, rotation of self-heated plasma

Resistive wall mode stabilization by feedback control improves stability of AT scenarios

- Advanced tokamak cases in ITER and FIRE need wall stabilization of the n=1 kink mode
- Time constants of passive stabilizer (τ_W) and conducting structures near control coils (τ_C) differ in FIRE and ITER
  - Conducting structures can slow the feedback system response
- RWM stabilization should be possible in FIRE and ITER
  - ITER ($\tau_C > \tau_W$): slow feedback coils gives modest gain in β_N (~30% of ideal wall), NBI-driven rotation should improve stability further
  - FIRE ($\tau_C < \tau_W$): faster response gives up to 70% of ideal-wall gain, proposed coils in midplane ports may perform even better

Physics opportunity: feedback stabilization of a low-rotation, self-heated plasma

Opportunities for MHD science in a burning plasma

- MHD stability of self-heated plasmas (Ignitor, FIRE, ITER) with largely self-generated current density profile (FIRE and ITER)
- m=1 mode stability at high S, interaction with an isotropic population of energetic alpha particles (Ignitor, FIRE, ITER)
- NTM threshold and stabilization physics in plasmas with small $\rho^*=\rho_i/a$ and large S (FIRE and ITER)
- physics of H-mode pedestal width and stability properties in plasmas with small ρ^* (FIRE and ITER)
- rotation damping and error field penetration physics in plasmas with low natural rotation (Ignitor, FIRE, ITER)
- stability of resistive wall modes in plasmas with low rotation (FIRE and ITER)

Conclusions . . . *so far*

- MHD stability limits do not present a fundamental obstacle to the burning-plasma missions of the three proposed machines
  - Ignitor operates farther from stability limits
- Flexible control methods are crucial (especially FIRE and ITER)
  - Current drive (sawtooth control, NTM stability)
  - Shaping (edge stability)
- Advanced tokamak scenarios require additional control
  - Plasma rotation
  - Feedback control of MHD modes
- ITER and FIRE will be able to address the relevant MHD stability physics for future fusion devices
  - Ignitor's lower beta restricts the range of accessible stability physics
- MHD stability physics learned in a burning tokamak plasma should be applicable to a broad range of confinement concepts

m=1 stability and the effect of sawteeth need further discussion

- DT experiments in JET show little direct impact of sawteeth on time-average stored energy or fusion power
  - Relevant to future burning plasmas?
- Simulations with Porcelli model indicate sawteeth have little impact on time-average stored energy or fusion power
  - Applicability of Porcelli model?
- There are uncertainties in quantitative predictions
  - Form of ideal δW_{MHD} (and non-ideal effects?)
  - Reconnection physics at sawtooth crash?
  - Transport model for profile evolution between crashes?
  - Period determined by transport or current diffusion?