Initial Plenary Report from MFE Physics Working Groups

Based on contributions from members of the Working Groups P(n) and especially their coordinators:

P1: Wave-particle interactions (Don Batchelor, Miklos Porkolab)
P2: Energetic particles (Raffi Nazikian, Jim Van Dam)
P3: MHD (Ted Strait, Chris Hegna)
P4: Transport (Ron Waltz, Ed Synakowski)
P5: Boundary (Steve Allen, Gary Porter)

presented by J. W. Van Dam

Acknowledgment: Stewart Prager (MFE Physics Leader)

2002 Fusion Summer Study
Snowmass, CO – July 9, 2002

Broad questions for the Physics working groups

— What limitations will the challenges of *P(n)* physics impose on the ability of a burning plasma (BP) experiment to achieve its full range of scientific goals, and how can these challenges be avoided or ameliorated?

— What new *P(n)* 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 *P(n)* physics to be learned in a burning plasma experiment have on the development of future fusion devices -- both tokamaks and other concepts?

Main objective of this plenary talk

To delineate:
— “Settled” issues
— “Unsettled” issues (**blue**), needing more discussion here at Snowmass

P1: Wave-Particle Interactions

Working group participants:

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E. Tracy – William and Mary

Wave heating and current drive in BP operating scenarios

Roles	IGNITOR	FIRE		ITER-FEAT	
	Non-Ohmic	***Base***	***AT mode***	***Inductive***	***Steady-state***
1. Start-up capability (plasma breakdown, impurity burn-thru)	(OH)	(OH)	(OH)	(OH) ECH	(OH) ECH
2. Plasma heating — to achieve burn — to access H-mode — to supplement alpha heating; for shut-down	 ICRH ICRH	 ICRH ICRH ICRH	 ICRH ICRH ICRH	 ICRH, ECH ICRH, ECH ICRH, ECH	 ICRH, ECH ICRH, ECH ICRH, ECH
3. Non-inductive current drive (for extended duration)			LHCD, FWCD	LHCD, FWCD	LHCD, FWCD
4. Profile control to optimize performance (control magnetic islands, sawteeth, etc.)	ICRH (freeze current profile)		LHCD, ICRH—minority CD	LHCD, ECH, ICRH—minority CD	LHCD, ECH, ICRH—minority CD
Ancillary roles: — Maintain plasma rotation (NBI, ICRH) — Provide wall conditioning (low-freq ECH)					

Typical operational scenarios

ITER

- ***Inductive Operation***: ELMy H-Mode, P_{fusion} = 400 MW, I_P = 15 MA
  - Heating: P_{NB} = 33 MW, P_{ICRF} = 7 MW
  - RF mode: f_{RF} = 56 MHZ = $2\Omega_T$
- ***Steady State Scenario***: "Weak Negative Shear", I_P = 9 MA, I_{CD}/I_P = 0.52, I_{BS}/I_P = 0.48
  - Heating/CD: P_{NB} = 30 MW, P_{LH} = 29 MW
  - RF Mode: off-axis current drive

FIRE

- ***Base Case***: ELMy H-mode, P_{fusion} = 150 MW, I_P = 7.7 MA
  - Heating: P_{ICRF} = 14.5 MW
  - RF mode: f_{RF} = 56 MHZ = $\Omega_{3He} \rightarrow 2\Omega_T$
- ***AT mode***: "Aries-AT", P_{fusion} = 40 MW, I_P = 5.4 MA, I_{BS}/I_P = 0.67
  - Heating/CD: P_{ICRF} = 14.5 MW, P_{LH} = 20 MW
  - RF mode: on-axis CD (ICRF→ 350 KA) and off-axis current drive (LH→ 1.5 MA)

IGNITOR

- "***Non-Ohmic Ignition***": L-mode, P_{fusion} > 20 MW, I_P = 8 MA
  - Heating: P_{ICRF} = 18 - 24 MW
  - RF mode: f_{RF} = 90, 105, 120, MHZ = $\Omega_{3He} \rightarrow 2\Omega_T$ (heat during field ramp)

RF Questions	Conclusions/Issues
*1. **Do proposed RF systems meet device requirements for heating to ignition, current drive, and plasma control?***	• Overall, planned RF base-case operational scenarios are fairly conservative, based on established practice and theory modeling. Physics is well-enough understood to allow projection to burning plasmas. However, dynamic accessibility to proposed scenarios is not yet simulated.
— Are power requirements correct? — Are effects that degrade efficiency (e.g., alpha damping, parasitic losses, antenna directivity, etc.) included? — Are assumed power deposition profiles consistent with RF physics?	• ICRF absorption by alphas/NBI-ions could be an issue: (1) edge wave absorption by α's due to Doppler broadened resonances; (2) parasitic absorption on FWCD; (3) absorption by beryllium impurity. • Both ICRF and LH have launcher technology and edge plasma interaction issues: — ICRF antenna survival; LH reactor-grade wave guide grill. — Maintain adequate loading (ICRF): edge density profile, H-mode operation, ELMs, AT operation, compatibility with divertor operation. — Adequate edge density for coupling (LH). • ECH source is not available for IGNITOR or FIRE. Used on ITER for core heating and NTM control (but top-side port will result in non-optimal localization of damping).
—Are current drive efficiencies and profiles for AT scenarios achievable?	• AT scenarios (on FIRE and ITER) need on-axis seed FWCD. — Experimentally demonstrated and physics is understood, but efficiency is sensitive to details (antenna characteristics, resonance location, alpha/beam ion energy profile): need to optimize. — FWCD and LH simulated on FIRE; ITER simulations underway. — Low-frequency current drive no longer possible in ITER.

RF Questions-*cont.*	Conclusions/Issues
2. What new wave-plasma interaction physics can be investigated in a burning plasma?	• Presence of large fast alpha population will modify RF wave physics: — Fusion alphas are isotropic, with larger ε/T, $k_\perp\rho$,… (cf. RF experience in presence of beams and weak alphas) — Affect wave dissipation: damping location and species partitioning will depend on details of alpha profile. — Might affect wave dispersion and mode conversion. — Alpha gradients might cause RF wave growth. • Plasma seen by RF waves different in BP device: — Alpha heating concentrated on electrons and centrally peaked. — $T_e \geq T_i$: increased Landau damping $\Rightarrow$ higher CD efficiencies, hence easier to observe RF effects. — Nonlinear coupling of wave/alpha heating and plasma behavior.
— What are the capabilities of the candidate machines to address basic physics issues? — What can each contribute to the knowledge base for RF applications in future reactor devices (tokamak or other concepts)?	• ITER has more RF sources, hence more flexibility. • Learn how to maintain control of nonlinearly interacting plasma processes (transport, stability, profile evolution, confinement barrier formation,…). • Study advanced applications proposed for RF waves: plasma rotation generation; flow shear and ITB control; instability control (sawteeth, neoclassical tearing, Alfven eigenmodes, fishbones); formation and control of fast particles; wave-induced transport; alpha channeling. • RF physics understanding can be concept-transferable.

P2: Energetic Particles

Working group participants:

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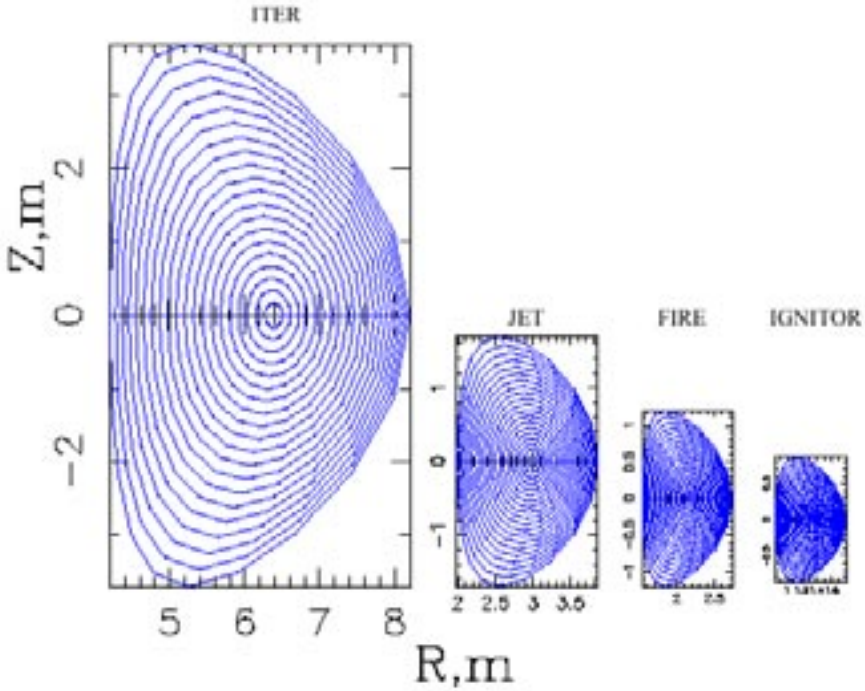
Difficulties in assessing BP alpha stability & confinement

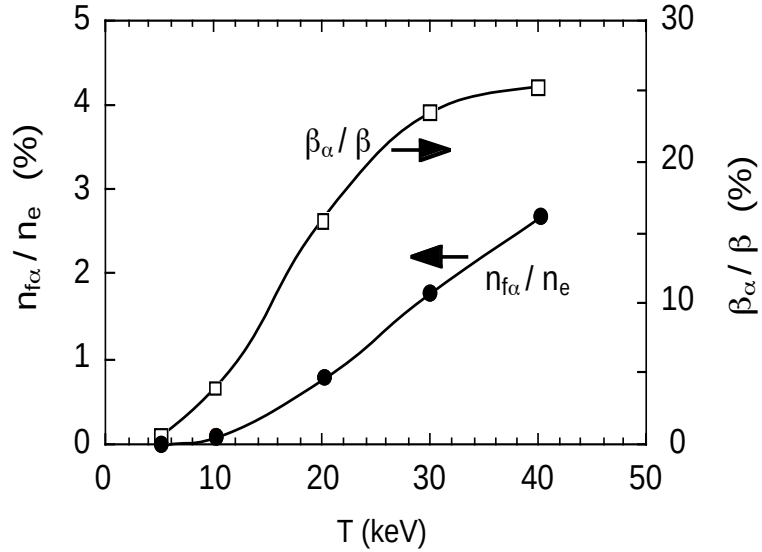
- Key ingredients of fast particle physics will be the same, but features in a BP will be different than in present experiments.
- A plethora of possible instabilities can be excited by alpha particles:
  - Low-frequency MHD modes (sawtooth, NTM, kinetic ballooning)
  - Alfvén frequency modes (TAE, EAE, NAE, BAE, KTAE, CLM)
  - High-frequency modes (CAE, ICE)
  - Energetic Particle Modes (fishbone, r-TAE)
- Frequency predictions are robust, but growth/damping of α-induced instabilities (and, to less extent, mode structure/location) are highly sensitive to equilibrium details.
- Nonlinear theory/codes for anomalous alpha particle transport have had successes, but still being developed and benchmarked.
- Diagnostics for alpha particle spatial/velocity distribution and core mode structure will be challenging in a BP environment.
  - Reflectometry of limited use when plasma temperature > 20 keV.
  - Gamma-ray spectroscopy (used in JET d-t) may be unusable in a BP.

Different features of alpha physics in a BP experiment

Issue	Present fast particle experiments	BP experiment
Alpha energy distribution ⇒ growth rate, energy transfer	Anisotropic NBI/RF fast ions (isotropic alphas, albeit weak)	Isotropic
Unstable Alfven eigenmodes	Low- to moderate-n; few modes	High n; broad spectrum with many modes
Wave-particle resonant loss	Immediate/marginally diffusive	Diffusive, via multiple over-lapping resonances; may redistribute without loss
Particle orbit size (ρ_α*)	Small (<1)	Very small (<<1)
Alpha pressure ⇒ instability drive	$\beta_{fast} / \beta_T < 1$	$\beta_\alpha / \beta_T \leq 1$
Damping of alpha-induced instabilities	Radiative damping larger than direct wave damping on thermal ions and electrons	Radiative damping scales as ρ_α*; Landau damping independent of machine size
External control of excitation and damping	Beam damping on α-induced instabilities; profile control	"Self-organized"

TAE stability trends carry over to other Alfvén modes





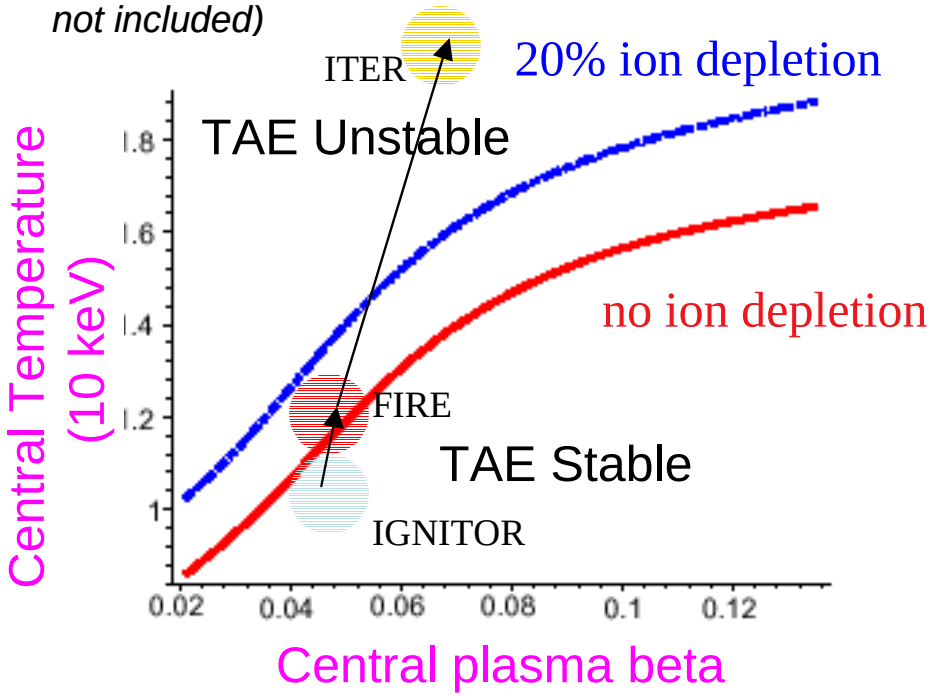
Alpha particle pressure is determined by plasma temperature (independent of machine size)

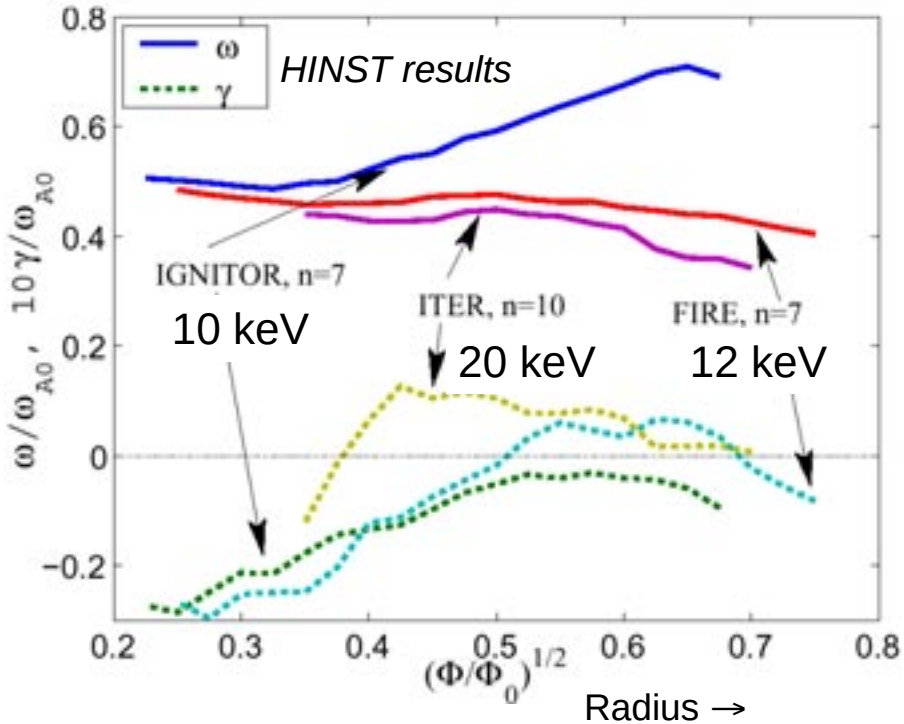
TAE stability parameters #	ITER	JET	FIRE	IGNITOR
Resonance $v_\alpha/v_A > 1$	1.8	2.5	1.6	2.0
Alpha particle beta $\beta_\alpha(0)$	0.8%	0.4%	0.3%	0.2%
Alpha instability drive $R\nabla\beta_\alpha$	4.0	2.3	1.5	0.8
Normalized inverse alpha gyroradius $1/\rho_\alpha$*	39	13	22	23

From R. Budny, web.gat.com/snowmass/working/mfe/physics/p2/ft_2.pdf

TAE stability depends critically on temperature, for given magnetic configuration

(radiation damping not included)





Local analysis: ITER unstable, FIRE marginal, IGNITOR stable

- Temperature variability is needed for probing the stability boundary.
- q-profile/magnetic shear is also a key ingredient for TAE stability.

High-n local HINST code:
— TAE modes: ITER unstable, FIRE marginal, IGNITOR stable
— NAE modes: FIRE unstable (for T_e=20 keV)
Global NOVA-K code:
— TAE modes: ITER slightly unstable, FIRE and IGNITOR stable

Working group assessment of issues: current status

Alpha physics issue	IGNITOR	FIRE	ITER
Alpha instabilities — MHD (fishbone, KBM) — Alfvénic modes	Well below TAE and fishbone thresholds.	TAE marginally stable. Below fishbone threshold. Cascade AEs in AT.	TAE unstable. Below fishbone threshold. Cascade AEs in AT.
Alpha loss mechanisms — TF ripple loss — MHD modes (sawteeth, disruptions, NTM) — Anomalous transport	Ripple loss within design limit. Alphas may modify sawtooth period.	Ripple loss within design limit in base case and AT. Alphas may modify sawtooth period.	Ripple loss within design limit; ferritic boards needed in AT (10% loss → 1%). Alphas may modify sawtooth period.

Further potential issues related to alpha particle physics

- How will alpha particle power affect thermal stability of BP operation?
  — Burn control and ash removal are also transport issues.

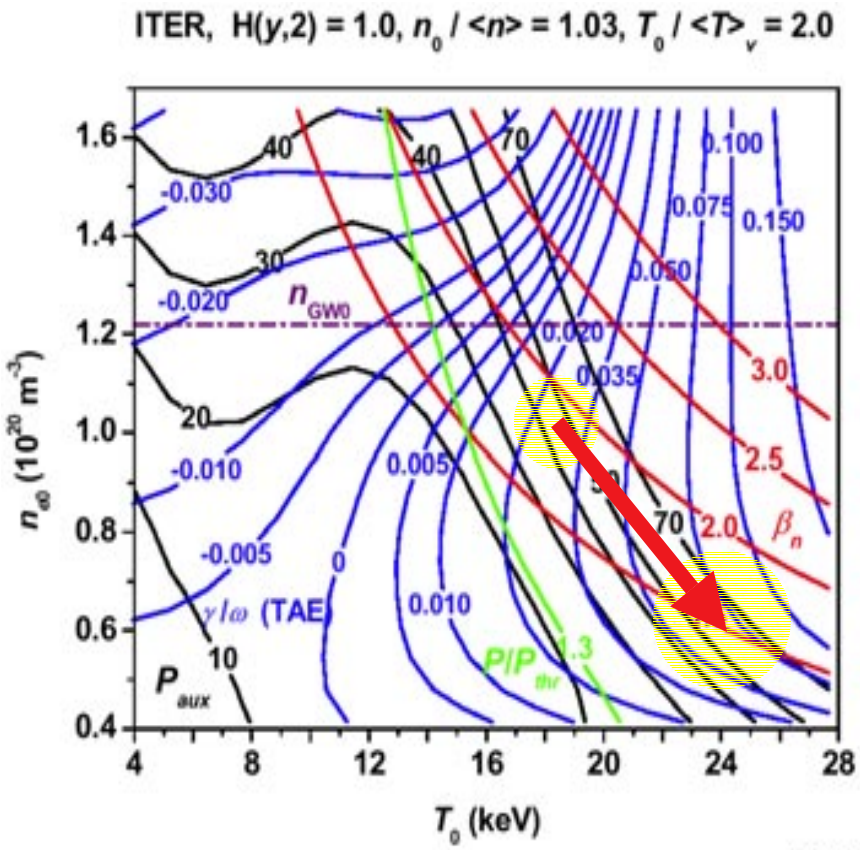
- What fraction of alphas may be lost while still (1) maintaining burn and (2) preventing wall damage? Which of these two possibilities is more critical?

Alpha physics that can be studied in BP experiment

- Excitation and control of alpha-driven collective instabilities:
  — *Base-case operation*: ITER needs modest temperature increase (20%) to explore the stability threshold.
  — *Advanced operation*: All three machines can access shear reversal, but instability requires higher T_e.

- Effects of alpha particles on sawtooth stability ("giants"):
  —Burn time > current redistribution time for all three machines.

- Behavior of multiple-mode diffusive transport ("sea" of resonant Alfvén eigenmodes):
  — "Transport barrier" for alpha loss via beam damping at plasma edge?



Paux = 70 MW
(33 MW NNBI)

Density control and auxiliary heating are essential to probe TAE stability (but not necessarily high Q).

P3: MHD

Working group participants:

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J. Breslau, D. Gates, S. Jardin, C. Kessel, J. Manickam, F. Perkins – PPPL

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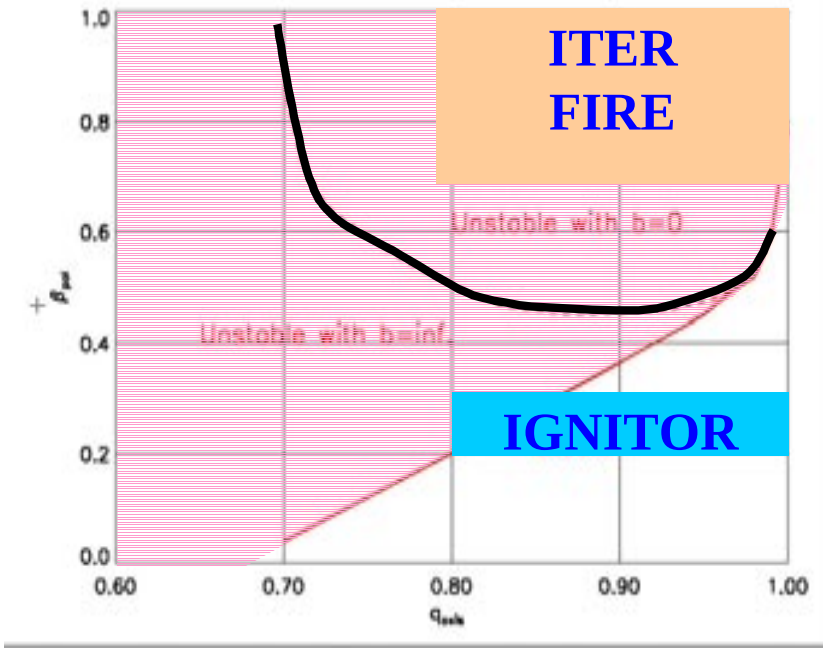
Ideal MHD stability physics is well understood

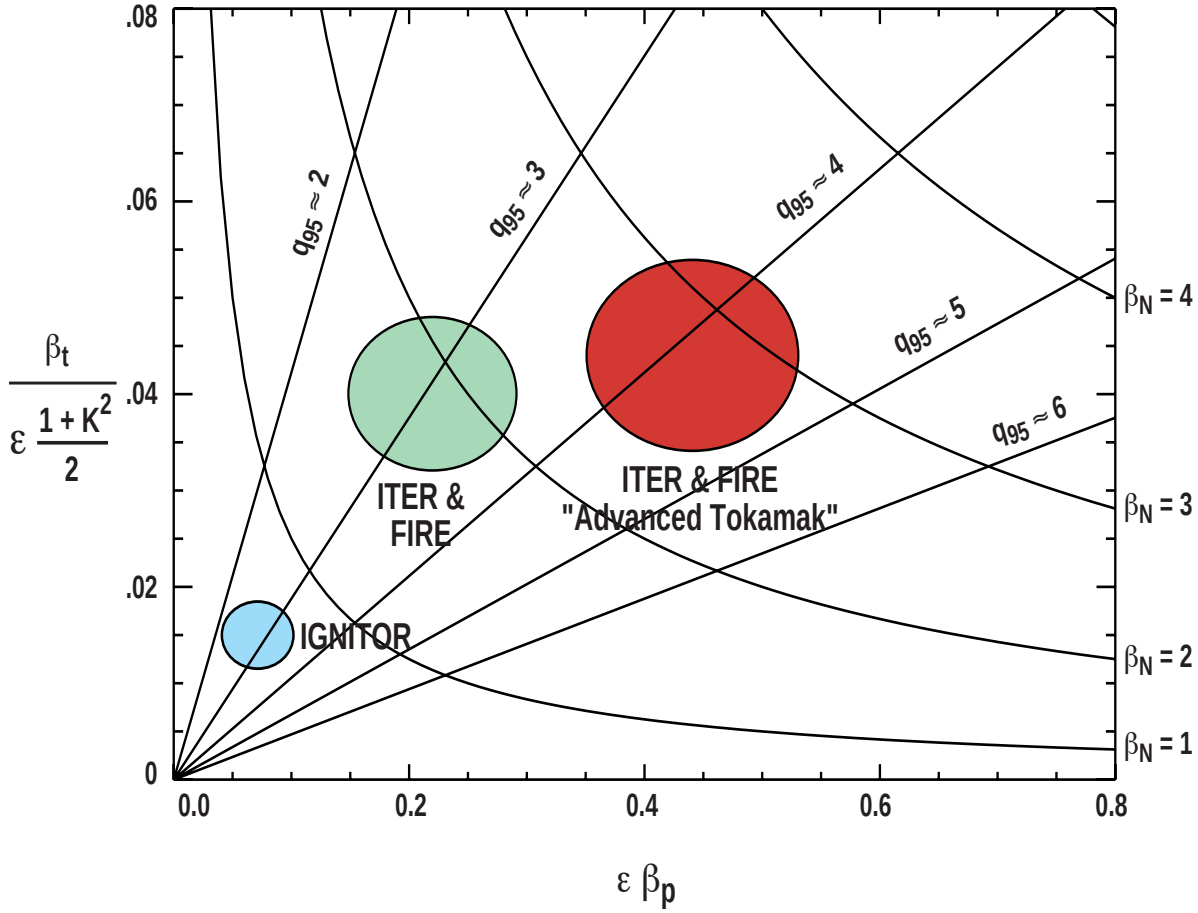
- The base scenarios for all three machines are stable to ideal MHD, with one notable exception.
- In ITER and FIRE, the m/n = 1/1 mode is ideally unstable for typical β_θ with q(0) < 1.
  - Stability window is reduced with larger -dp/dr or smaller dq/dr.
  - m/n = 1/1 ideal internal kink is sensitive to q(0). Due to its unique character, an additional study has been carried out that incorporates non-ideal MHD effects.
- Complete sawtooth modeling requires energetic particles, non-ideal MHD effects, and profile modeling.
- For very low q(0), one might expect giant sawteeth, seeds for NTMs, or disruptions.

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



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
- Resistive wall mode stability



- With respect to ideal MHD, FIRE and ITER operate in similar parameter regimes ($\beta_N \sim 1.8$). IGNITOR operates at lower beta ($\beta_N \sim 0.65$).
- Advanced-tokamak operational scenarios in FIRE and ITER have higher beta ($\beta_N \sim 2.5$–3.5) and lie at or beyond the no-wall stability limit.

MHD Scorecard

Issues	IGNITOR	FIRE	ITER
m/n=1/1 mode stability • Non-ideal MHD effects? • Interaction with isotropic alphas? • Giant sawteeth at low q(0): NTM, disruption?	For typical β_p, ideal stability possible with q(0)<1	Ideally unstable for typical β_p and q(0)<1	Ideally unstable for typical β_p and q(0)<1
Neoclassical tearing • Threshold physics? • Seed island formation? • Unfavorable excitation scaling ($\beta_{crit} \sim \rho^*$)?	Not critical issue	Metastable for typical beta; large saturated islands when excited. Ameliorate with current profile control (method?)	Metastable for typical beta; large saturated islands when excited. Ameliorate with localized ECCD.
Edge stability • Predictive capability for pedestal physics and ELMs at small ρ^*? • Access 2nd stability at edge with high δ and BS current?	N/A since H-mode is not primary regime	Pedestal height in range needed for good performance (if width is similar to present experiments)	Pedestal height in range needed for good performance (if width is similar to present experiments)

MHD Scorecard - *continued*

Issues	IGNITOR	FIRE	ITER
Error fields (mode locking) • Error field penetration with low rotation? • RF-driven rotation?	$B_r(2,1)/B_T < 9\times10^{-5}$ Achievable with correction coils.	$B_r(2,1)/B_T < 9\times10^{-5}$ Achievable with correction coils. AT needs rotation drive (NBI?)	$B_r(2,1)/B_T < 3\times10^{-5}$ Achievable with correction coils. AT needs rotation drive (NBI?)
Resistive wall mode stability for AT operation (n=1 ideal kink) • RWM stability at low rotation? • Feedback control with non-axisymmetric coils?	? N/A	Wall-stabilized if $\Omega_{rot}\,\tau_A \geq 0.015$ at q=3. Use NBI?	Wall-stabilized if $\Omega_{rot}\,\tau_A \geq 0.01$ at q=3. Use NBI?

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, ITER).
- Interaction of m=1 mode with an isotropic population of energetic alpha particles.
- NTM threshold and stabilization physics in plasmas with small $\rho^*=\rho_i/a$ and large S (FIRE, ITER).
- Scaling of H-mode pedestal width and stability properties to plasmas with small ρ^* (FIRE, ITER).
- Rotation damping and error field penetration physics in plasmas with low natural rotation.
- Stability of resistive wall modes in plasmas with low rotation (FIRE, ITER).

P4: Transport

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G. Bateman, J. Kinsey – Lehigh

D. Newman – Alaska

P. Terry – Wisconsin

Overall goals for Transport working group

- Provide a uniform technical assessment of the projected confinement performance ($Q=P_{fus}/P_{aux}$) of the three proposed BP experiments.
  - Empirical scaling laws and theory-based transport models benchmarked to existing plasma discharges will provide the rules for this assessment.
  - Assessing the performance is straightforward, but assessing the assessment (i.e., the rules) is not.

- Identify the transport physics issues that could emerge in a burning plasma, in which turbulence, transport, and self-heating are strongly coupled.

- Evaluate the flexibility required to achieve a desired range of Q values and to allow study of the transport physics issues.
  - Flexibility also includes operational control in advanced regimes.
  - BP transport results can feed *into* ICC research and *forward* to NSO.

Difficulties in assessing BP confinement performance

- Predicting Q from empirical scaling laws for H-mode power threshold, H-mode global energy confinement time τ_E, and density limit n_G requires plasma profiles, which are either assumed or calculated from models.

- Some theory-based core transport models have successfully calculated core H-mode profiles and energy confinement time τ_E (with RMSE <10%), but only if *given* the pedestal height parameters (temperature and density).

- There is yet no experimentally validated theory model for predicting the H-mode power threshold or pedestal heights.

- Since core transport models are "stiff," the calculated profiles, τ_E, and Q are strongly dependent on pedestal heights—for which there are only empirical scaling laws, with sizeable statistical error (e.g., RMSE >25% for β_{ped}).

- Q is a very sensitive function of $\langle nT \rangle \tau_E$ for Q>5 (50% self-heating).
  - Q goes from 5 to ∞ as $\langle nT \rangle \tau_E$ doubles. (The RMSE on $\langle nT \rangle \tau_E$ is ≥ 30%.)

Figure-of-merit Q for H-modes

Given the difficulty of precisely predicting confinement performance, devise a simple H-mode figure of merit for Q, with which to compare the proposed devices:

— Take the stiff-models scaling $Q \sim [Vol / P_{aux}] (\beta_{N\text{-}ped})^2 [B^2 (I/aB)]^2$

— Use the empirical $P_{L\rightarrow H}$ scaling for full P_{aux}, and the MHD scaling for $\beta_{N\text{-}ped}$

Device	n_{ped}/n_G	P_{aux} **(MW)**	$P_{L\rightarrow H}$ **(MW)**	$\beta_{N\text{-}ped}$	Q_{FOM} **(arbitrary scale)**
ITER-FEAT	0.85	40	51	0.42	5.1
FIRE	0.70	20	26	0.58	5.7
IGNITOR	0.50	10	23	0.75	24 #

Comments:

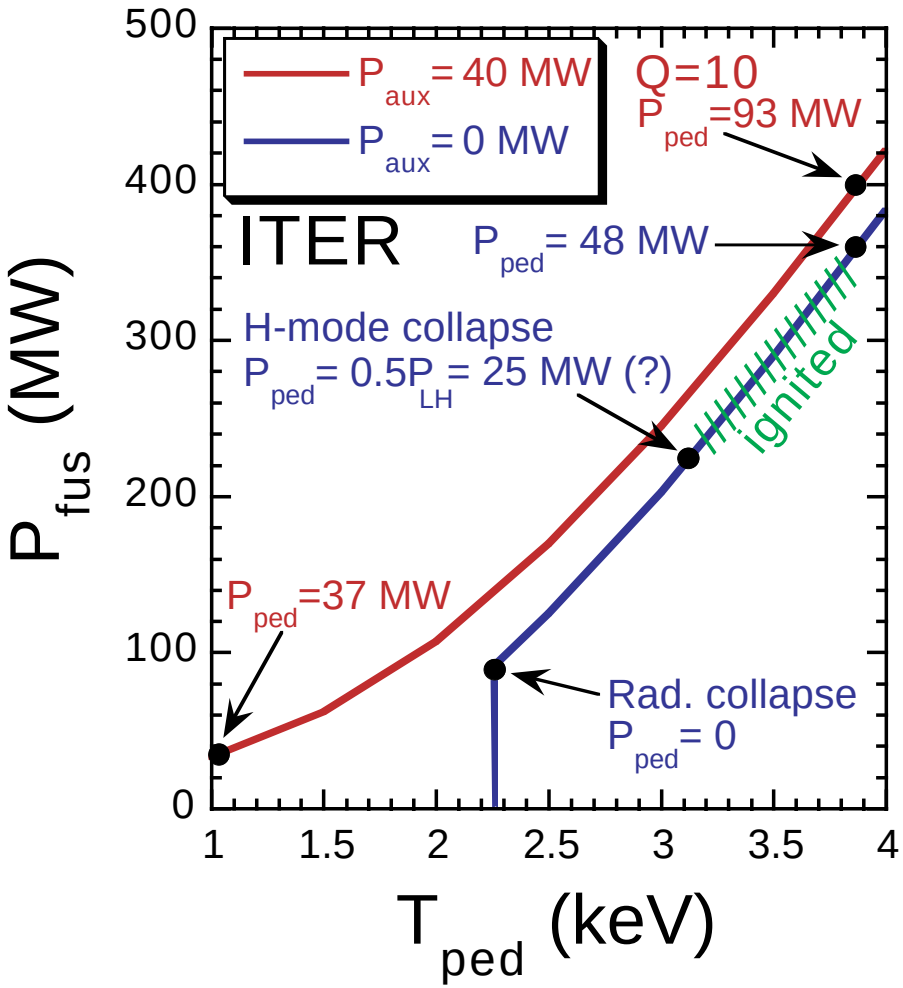
1. Statistical uncertainty implies that $Q_{calc} = 10$ could correspond to $5 < Q < 16$.
2. This estimate indicates that ITER-FEAT and FIRE are equally likely to attain their Q performance goals.
3. The IGNITOR estimate (#) assumed H-mode scaling rules, for the sake of "uniform" technical assessment. An X-point on the wall is possible at reduced current, but L-mode operation is likely in the absence of a divertor. L-mode global empirical scaling rules suggest that high-Q operation may be problematic.

Simulations of performance Q-value

Core theoretical transport model simulations (Multi-Mode and GLF23renorm), combined with MHD (power-independent) pedestal height empirical scaling models and H-mode global empirical scaling rules (e.g., $H98_{y2}$), give the following predictions:

- *GLF23renorm*
  - Q > 5 at full power in ITER and FIRE, and Q > 10 at half power.
  - With the use of H-mode rules, IGNITOR appears to have very high Q (i.e., ignition)—but low Q<<5 with L-mode empirical global scaling rules (e.g., L97).
- *Multi-Mode*
  - Q=11 (full power) and Q=17 (half power) for ITER.
  - Q=5 (full power) and Q=6 (half power) for FIRE.
  - Q=7 for IGNITOR.

Stiff models suggest that Q>5 at full auxiliary power could lead to ignition as power is withdrawn



(similar figure for FIRE)

$$P_{ped} = 0.2\, P_{fus} + P_{aux} - P_{brem} + P_{OH}$$

Q=5 corresponds to P_{fus}=200 on the P_{aux}=40 MW curve.

Fall out of H-mode when P_{ped} goes below about half of $P_{L\rightarrow H}$.

Radiation collapse when $P_{\alpha} = P_{brem}$.

⇒ The value of Q is "slippery."

Device flexibility is critical to tackle confinement issues

1. Access to advanced operation
Current profile control and long pulse capability • All devices capable of reversed shear operation: ITER-FEAT has LHCD, NBI-CD, ECCD, ICRF fast wave. FIRE has LHCD, ICRF fast wave. IGNITOR will rely on transient inductive operation.
Density control • All devices have pellet fueling capability. (ITER has high-field launch capability.) • Pumping planned on FIRE and ITER-FEAT. Is a limiter pump possible on IGNITOR?
Sheared plasma rotation • ITER-FEAT has 1 MeV beams: Can applied torque be varied? Impact on CD? • NBI possible on FIRE: Tangential access difficult without reducing number of TF coils. • NBI not planned on IGNITOR. • Can new schemes for inducing flow shear (e.g., IBW or CT injection) be developed and deployed to modify the nonlinear pressure profile?
Shaping variability *(also for pedestal and ELM studies)* • Elongation and triangularity constrained (cf. to present AT's) in ITER-FEAT and FIRE, due to closed divertor geometry. • IGNITOR shape not constrained by divertor requirements, but unclear how limiter BP will inform pedestal and ELM physics base for these ρ^*. Divertor-less H modes are possible, but do not have high pedestals; also, pulse length for inertially cooled wall-separatrix is short.

Device flexibility for confinement issues - *continued*

2. Transport science knowledge base
Perturbative heating of ions and electrons *(to test new electron/particle/momentum transport models)* • Localized heating capability in all devices. ITER-FEAT has the most options (ECRH, LH, ICRH, 1 MeV beams) and longest transport time scales.
Transport diagnostics *(profile)* • Extended period of low-neutron-fluence operation useful for developing diagnostics and control tools: ITER (first 10 years); FIRE (2 years of D-D only operation); IGNITOR (lowest total neutron fluence due to short pulse lengths). • Could access be an issue for a small-size, high-field device?
Turbulence diagnostics *(fluctuations)* • Challenging because usual techniques harder to apply in a BP experiment: — BES (on FIRE and ITER) problematic in core (beam attenuation, collisional saturation). — Reflectometry (all 3 devices) good for edge density fluctuation measurements, but utility in the core without wavefront imaging needs to be assessed. — ECE emission (all 3 devices) to measure temperature fluctuations. • No plans for short-wavelength fluctuation measurements, related to critical topic of electron thermal transport.

P5: Boundary Physics

Working group participants:

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J. Boedo, D. Rudakov – UCSD

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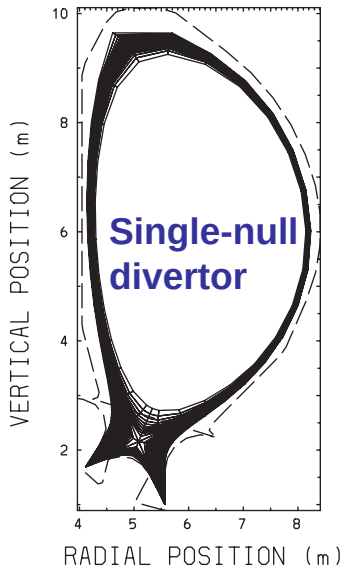
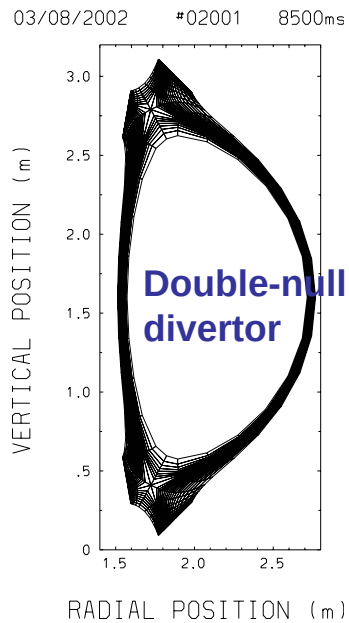
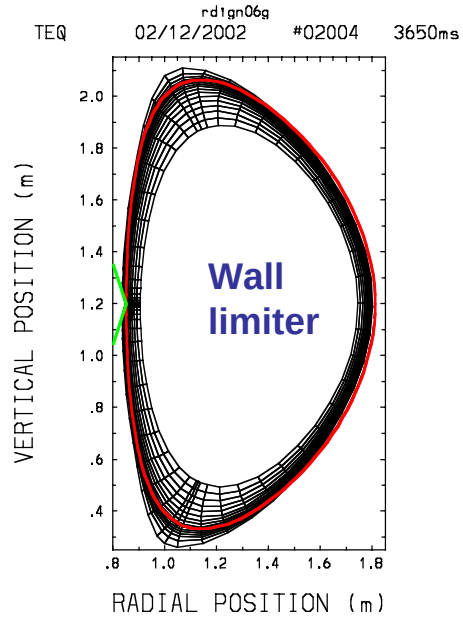
P. Stangeby – Toronto



ITER-FEAT



FIRE



IGNITOR

Boundary configuration and parameters are different for the three devices

(Not shown to scale)

Parameter / Device	ITER-FEAT	FIRE	IGNITOR
P_{SOL}[MW]	100	30	22[1]
$n_{ped}[10^{20}m^{-3}]$	0.6	1.5-3.0	2.0
Confinement mode	H	H	L
Boundary configuration	Single-null divertor	Double-null divertor	Limiter
material	C[2]	W	Mo

[1] $P_{SOL}=P_{\alpha}+P_{OH}-P_{Brem}$

[2] Divertor region only, W and Be first walls

Boundary physics issues

1. Power and particle exhaust

— PFC protection
— High divertor pressure, low chamber pressure
— Helium exhaust
— Fuel pumping for density control
— Induced flow to divertor for impurity screening
— Edge compatibility with current drive

2. Transient events & localized heating

— ELMs for particle and power flux
— Disruptions
— Fast particles: current drive, orbit losses to wall

3. Impurity production & transport

— Tritium retention: carbon or metal?
— Helium & impurity transport in core
— Impurity production and screening in divertor and main chamber

4. Pedestal and SOL

— Turbulent transport scaling

Working Group focused on the power exhaust question.

— 2D fluid code UEDGE was main tool.
— Impurity radiation was estimated with simple model; some full impurity transport modeling has been performed. High-Z impurity transport was studied with Monte Carlo DIVIMP code.
— Edge transport was examined with 3D Braginskii-fluid code BOUT.

Peak heat loads are within the three machine designs

ITER-FEAT	FIRE	IGNITOR
SN configuration has peak **divertor heat load** ~10MW/m^2 (consistent with design) — Uncertainty in heat diffusivity (if $\chi\downarrow$, then P$\uparrow$): ameliorated by impurity injection in divertor region	**DN** configuration has peak **divertor heat load** ~16MW/m^2 (for standard transport assumptions), consistent with 25 MW/m^2 design maximum — Uncertainty in heat diffusivity (if $\chi\downarrow$, then P$\uparrow$) — Reduce to 10 MW/m^2 with neon injection (caveat marfes) — Should include cross-field drifts to calculate divertor heat load up/down asymmetry	Peak **limiter heat load** ~2 MW/m^2, with 30% impurity radiation — Consistent with design, which assumes 70% power radiation with low-Z intrinsic impurities — Power exhaust evenly split between limiter and outer wall — Alignment of wall and flux surfaces is critical
Large **particle throughput** (ion flux across ψ_{95}) is consistent with pumping design capability — Implies large fueling source for core, which could limit T_{ped} below the value for good H-mode confinement	Large **particle throughput** (ion flux across ψ_{95}) is consistent with pumping design capability	

Important remaining boundary issues

- **Peak heat flux is sensitive to edge transport–hence, need:**
  — Guidance from 3D turbulence simulations
  — Consistency with H-mode pedestal height/width from ballooning-peeling analysis

- **Helium pumping simulations**

- **Particle fueling and pumping assessment**

- **More complete impurity simulations**

- **Better assessment of effect of ELMs**
  — ELM energy release is above ablation threshold for divertor erosion in ITER-FEAT; might become tolerable if operate close to density limit ($n/n_G > 80\%$).
  — ELM heat flux is less severe for compact devices.
  — High triangularity/low collisionality regimes could be explored for reduced ELMs.

- **Tritium retention/metal walls**
  — Tritium retention problem is not well understood with carbon walls.
  — Inadequate database for use of metal walls in high-power devices.
  — Enhanced sputtering of metal walls by low-Z impurities is a concern.

Physics and Machine Joint Sessions

FIRST WEEK

ITER ***(Tuesday PM)***
- m=1 modes
- Neoclassical tearing modes
- Edge stability
- Rotation/error fields
- Power flux
- Confinement
- Alpha instabilities
- Wave-particle

FIRE ***(Wednesday PM)***
- Rotation/error fields
- m=1 modes
- Neoclassical tearing modes
- ELMs
- Power flux
- Alpha instabilities
- Wave-particle

IGNITOR ***(Thursday PM)***
- Error fields
- m=1 modes
- Power flux
- Alpha instabilities
- L- and H-mode features
- Wave-particle

SECOND WEEK *(Monday PM)*

Pedestal session
ELM session