"THE NEXT STEP BURNING PLASMA EXPERIMENT SHOULD BE CAPABLE OF ADVANCED TOKAMAK RESEARCH"

(1999 Fusion Summer Study, Development Path Issues Subgroup Report)

- Present vision of an attractive tokamak fusion power plan (demo/prototype)
  - Steady-state
  - Low recirculating power (high self driven bootstrap current)
  - Pulsed is acceptable, but less attractive
    Requires high average power (high duty cycle, long pulse)

- The next step burning plasma experiment should contribute to developing the scientific basis for the "follow on step" towards the vision of a steady state high performance fusion power plant.

- A frontier physics issue in the self heated burning plasma regime is the "strong nonlinear coupling amongst fusion alpha particles, pressure driven current, turbulent transport, MHD stability and boundary plasma behavior."

THREE CLASSES OF ADVANCED SCENARIOS

1. **Transient high performance**
   - Possibility of significantly larger □ power or fusion gain than ELMing H–mode.
   - Platform for testing diagnostics and materials for reactor environment.

2. **Stationary high performance**
   - Active control of MHD allows operation at increased fusion performance.
   - Lower plasma current per unit fusion power □ reduced risks.

3. **Steady-state**
   - 100% noninductive current drive required.
     - Advantage to maximized fraction of well-aligned bootstrap current.

FLEXIBILITY TO EVALUATE ADVANCED TOKAMAK PLASMAS

- FIRE, IGNITOR and ITER all have capabilities to transiently access AT regimes
  - ITER has capability to pursue near steady-state
  - FIRE can pursue longer pulse at reduced toroidal field and current τ_{DUR}/τ_{CR} >~ 1-3.

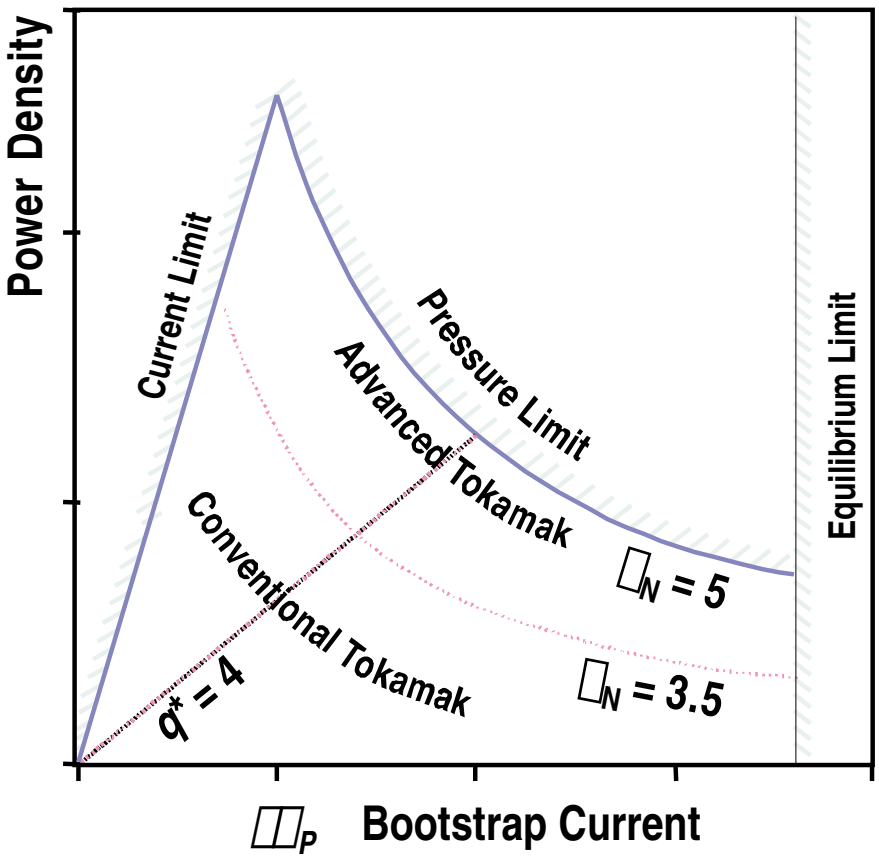
- FIRE, IGNITOR and ITER all have plans for important profile measurements
  - Complete, good resolution measurements are critical to developing the scientific basis (and extrapolation to the future)
  - Developing and assessing advanced regimes in IGNITOR would benefit from measurement of the current profile.

- FIRE and ITER both have current profile control capability and active MHD control capability.

- FIRE is a high triangularity double null divertor which is calculated to be favorable for high beta, high bootstrap fraction plasmas.

HIGH PERFORMANCE REQUIRES THE CAPABILITY TO OPERATE AT HIGH BETA

- Advanced tokamaks combine:
  - High fusion power density □ high β_T.
  - Large bootstrap fraction □ high β_P to minimize current drive requirements.
- Beta limits can be maximized by:
  - Strong shaping (high □ and □).
  - Broad pressure profile □ pressure profile control.
- Where conventional limits are exceeded, MHD instabilities can be mitigated via feedback control.
  - Neoclassical tearing mode suppression via ECCD(demonstrated in ASDEX-U, DIII–D, etc.).
    - LHCD demonstrated in Compass.
  - Resistive wall mode suppression via internal (preferred, in process in DIII–D) or external coils (demonstrated in DIII–D).

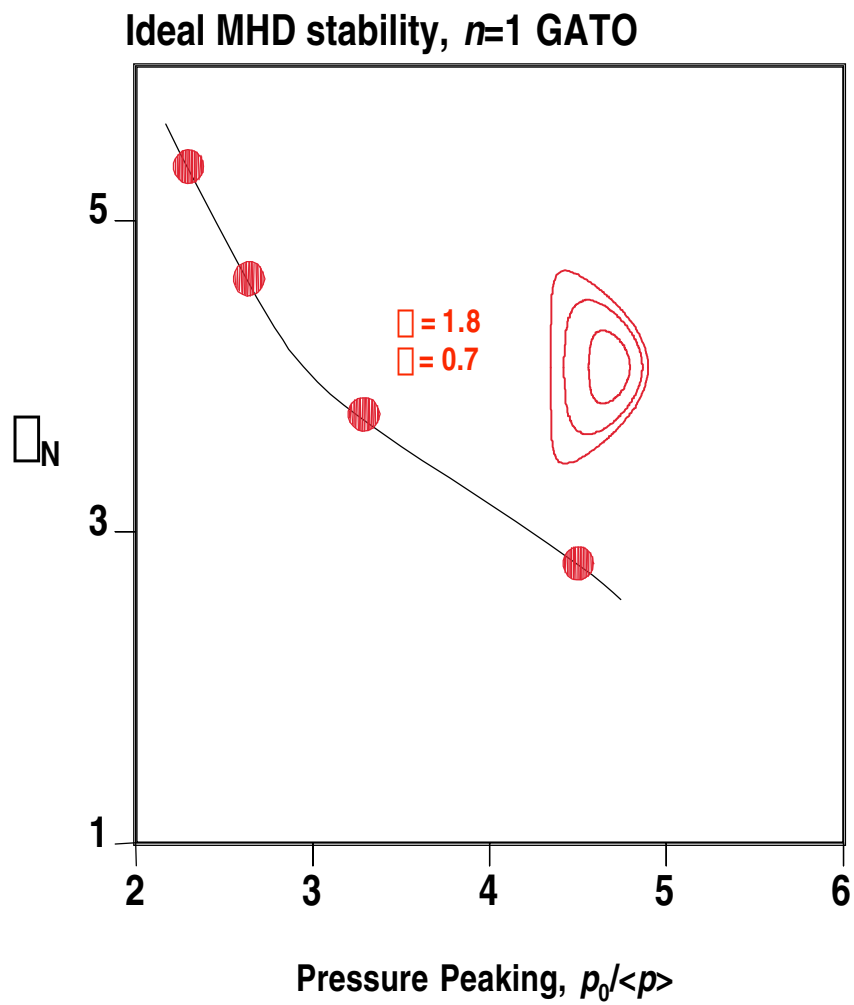


TOOLS FOR CONTROLLING MHD STABILITY

Tool	Mechanism	ITER	FIRE	IGNITOR	ARIES-RS
Shaping capabilities	Access to high β typically better with higher elongation and triangularity.	$\kappa \leq 2.1$, $\delta \leq 0.55$ (possible triangularity change via divertor mods) SN Divertor	κ_x=2-2.1, δ_x=0.65-0.85 DN Divertor	κ=1.83, δ=0.43 Limiter, possibility of SN or DN operation	κ=0.7 DN Divertor
		6 segment center stack + 6 PF coils	6 segment center stack + 8 PF coils	12 segment center stack + 16 PF coils	segmented
NTM control	RF current drive in magnetic island	ECCD	LHCD		NTM stable
RWM control	Magnetic feedback control of instability	External coils, Rotation (NBI)	Internal coils		Internal coils
Neutral beams (co/counter)	Provides rotation for control of RWM, control shape of pressure profiles	33 MW at 1 MeV, D^- (steerable).	Possible upgrade, 8MW at 120 keV D^+.		

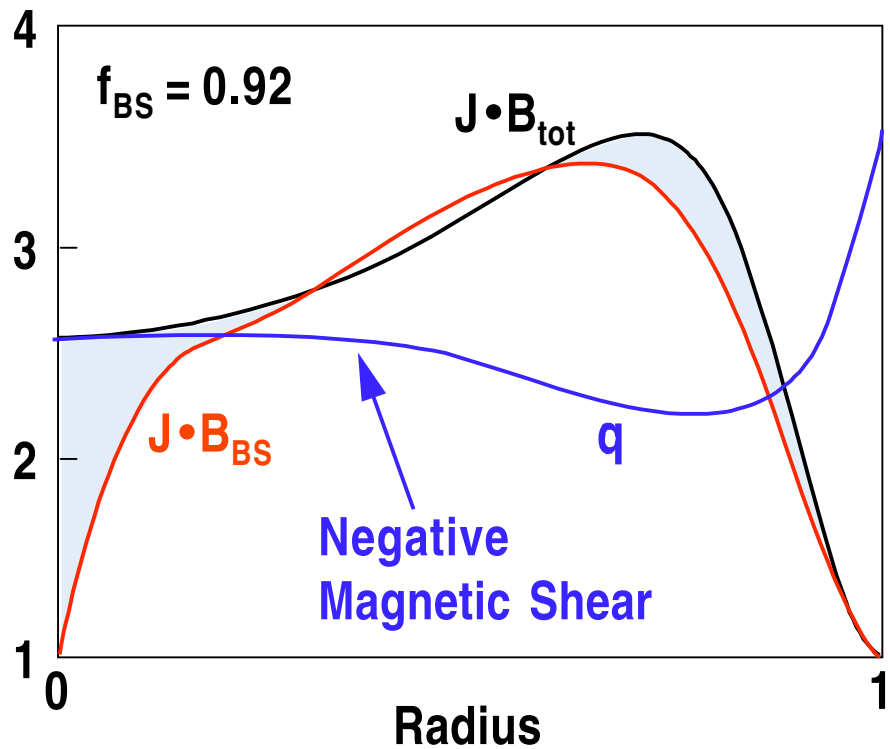
PRESSURE PROFILE CONTROL IS ESSENTIAL FOR ACCESS TO HIGH β

- MHD stability favors broad pressure profile.
- Pressure profile control is needed to:
  - Maximize beta limit
  - Approach beta limit with minimum power
- This motivates the need to:
  - Establish a firm understanding of transport.
  - Develop profile control tools.



WHERE DOES THE 100% NONINDUCTIVE CURRENT COME FROM?

- External current drive tools can be prohibitively expensive if they need to drive most of the current.
  - Conventional tokamak: f_{BS} ~ 25%.
  - "Free" bootstrap current should provide most of the current in an *AT* with properly tailored profiles.
- Both f_{BS} and BS alignment to desired current profile are critical issues.
  - Proportional to gradients in kinetic profiles ⇒ requires profile control.
- External current profile control must be available to provide the remainder of the current to achieve steady-state.
  - A variety of tools is needed since current may be needed both on- and off-axis.



TOOLS FOR CONTROLLING CURRENT AND PRESSURE PROFILES

Tool	Comment	ITER	FIRE	IGNITOR	ARIES-RS
Neutral beams (co/counter)	Provides energy and particle source. Electron/ion balance not directly controlled. Can also drive current.	33 MW at 1 MeV, D^- (steerable).	Possible upgrade, 8 MW at 120 keV D^+. Negligible CD due to geometry.		
Pellet injection	Particle fueling. May be central with high field side (HFS) launch at midplane.	HFS	Vertical and HFS	LFS Vertical	HFS
Particle pumping	Density control	SN	DN	Pumped limiter under consideration	DN
Impurity injection	Modifies turbulence growth rates	Ar, Ne, He	Ar, Ne, He	Ar, Ne, He	
ECH/ECCD	Spatially localized source of energy to electrons. Can also drive current.	20 MW at 170 GHz	Under consideration		
LH	Heats electrons. Can also drive current.	Upgrade to 20 MW at 5 GHz	Upgrade to 30MW at 4.6-5.6 Ghz.		34 MW
Fast wave and/or ICRF	Heats electrons or ions (minority ICRF). Can also drive current.	ICRF: 20 MW at 50 MHz	ICRF/FW: 20-30 MW at 80-120 Mhz.	ICRF 18-24 MW at 70-140 MHz	ICRF: 5 MW HHFW: 48 MW

Does not include flow control:

- **NBI (ITER)**
  - **FIRE NBI small tangency radius… small but finite torque.**
- **IBW**
  - **Difficult to couple.**
  - **Under consideration for FIRE.**

GENERIC AT ISSUES

- An improved set of flow control tools would benefit all AT scenarios.
  - MHD stabilization
  - E□B shear for pressure profile control

- Transport models used in calculating AT scenarios have same caveats as conventional regimes.

- Due to profile control power and high performance, the power flows to the first wall (divertor) can be larger in an AT.
  - Limit loss power
    or
  - Improve power handling capabilities
    or
  - Develop radiative divertor solutions

ITER SHOULD BE ABLE TO CARRY OUT A COMPREHENSIVE STUDY OF AT REGIMES

- Baseline AT regimes with $\beta_N \approx 3$, $f_{BS} \approx 50\%$, $f_{NI} \approx 100\%$ and $Q = 6$ appear possible in near steady-state.
  - Weak negative or positive shear.

- Flexibility included to explore the AT operating space and test new regimes.
  - Supported by on and off-axis heating and current drive tools.
  - MHD control via ECCD (NTM) and error field correction coil (RWM).
  - Near steady-state accessible (up to 700 MW for 3000 s with facility upgrades).

- Room for improvement:
  - More shaping might improve the prospects.
  - Study the addition of internal coils for more effective RWM control.

FIRE SHOULD BE ABLE TO STUDY HIGH β AT REGIMES FOR 1-3 CURRENT RECONNECTION TIMES

- Baseline AT regimes with $\beta_N \approx 3.7$, $f_{BS} \approx 75\%$, $f_{NI} \approx 100\%$ and $Q \approx 5$ appear possible in near steady-state.
  - Takes advantage of strong shaping and internal coils to operate above no-wall beta limit.

- Flexibility included to explore the AT operating space and test new regimes.
  - Supported by on and off-axis heating and current drive tools.
  - MHD control via LHCD (NTM) and error field correction coil (RWM).
    - ECCD under consideration for use at low field.

- Issues for further study:
  - Can LHCD mitigate NTMs?
  - Pulse length of $\tau_{DUR}/\tau_{CR} = 1 - 3$ may limit studies of steady-state regimes.

IGNITOR CAN STUDY DYNAMIC ADVANCED PERFORMANCE REGIMES

- Lack of provisions for current profile control and particle removal prevents stationary AT operation.
  - This is not part of Ignitor's mission!

- Advanced performance scenarios may transiently improve *Q*.
  - Several scenarios using current ramp and intense heating to form internal transport barriers well known and reliable in present-day machines.

- Issue for further study:
  - MHD stability and current diffusion may limit duration of ITB scenarios.