Fusion and Plasma Physics are at the Core of Nature's Most Intriguing Self-Driven Systems
Can we Solve the Mystery of Producing a Stationary Self-Sustained Fusion Fire??

Galactic Jet - M87

VLBA

SOHO

Crab Nebula

CHANDRA

Fusion: Power of the Cosmos Brought to Earth
Confining a Fusion Fire

A Grand Challenge for Science and Technology

Dale Meade
Princeton University

Presented at
Columbia University Plasma Physics Colloquium
in the City of New York

Fusion is an Outstanding Physics Challenge and is Connected to Other Outstanding Challenges

Ten Outstanding Physics Challenges

- Quantum gravity presents the ultimate challenge to theorists
- Explaining high-$T_c$ superconductors
- Unstable nuclei reveal the need for a complete theory of the nucleus
- Realizing the potential of fusion energy
- Climate prediction is heavy weather
- Turbulence nears a final answer
- Glass physics: still not transparent
- Solar magnetic field poses problems
- Complexity, catastrophe and physics
- Consciousness: the physicists view

December 1999
Fusion Does Work at Large Size

Why is it so difficult in the lab?
Relevant Reactions for Fusion in the Laboratory

\[
\begin{align*}
D^+ + D^+ & \rightarrow 3\text{He}^{++} \ (0.82 \text{ MeV}) + n^0 \ (2.5 \text{ MeV}) \\
& \rightarrow \ T^+ \ (1 \text{ MeV}) + p^+ \ (3 \text{ MeV}) \\
D^+ + 3\text{He}^{++} & \rightarrow 4\text{He}^{++} \ (3.6 \text{ MeV}) + p^+ \ (14.7 \text{ MeV}) \\
D^+ + T^+ & \rightarrow 4\text{He}^{++} \ (3.5 \text{ MeV}) + n^0 \ (14.1 \text{ MeV}) \\
\text{Li}^6 + n & \rightarrow 4\text{He} \ (2.1 \text{ MeV}) + T \ (2.7 \text{ MeV})
\end{align*}
\]
There are Three Principal Fusion Concepts

**Spherical Inertial**
- gravitational
- transient compression
- drive (laser-D/I, beam)
- radial profile
- time profile
- electrostatic

**Toroidal Magnetic**
- surface of helical B lines
- twist of helix
- twist profile
- plasma profile
- toroidal symmetry

**Reactivity Enhancement**
- muon catalysis
- polarized nuclei
- others?
Burning Plasma Physics is Widely Accepted as the Primary Objective for a Next Step in Fusion Research

• Grunder Panel (98) and Madison Forum endorsed Burning Plasmas as next step.

• NRC Interim Report (99) identified “integrated physics of a self-heated plasma” as one of the critical unresolved fusion science issues.

• The Snowmass Fusion Summer Study (99) endorsed the burning plasma physics objective, and that the tokamak was technically ready for high-gain experiment. A burning plasma experiment should also have advanced tokamak capability.

• SEAB (99) noted that “There is general agreement that the next large machine should, at least, be one that allows the scientific exploration of burning plasmas” and if Japan and Europe do not proceed with ITER “the U. S. should pursue a less ambitious machine that will allow the exploration of the relevant science at lower cost.” ….. “In any event the preliminary planning for such as machine should proceed now so as to allow the prompt pursuit of this option.”

• NRC/FuSAC (00) - “The US scientific community needs to take the lead in articulating the goals of an achievable, cost-effective scientific burning plasma experiment, and to develop flexible strategies to achieve it, including international collaboration.”
Fusion Science Objectives for a Major Next Step Magnetic Fusion Experiment

Explore and understand the strong non-linear coupling that is fundamental to fusion-dominated plasma behavior (self-organization)

- Energy and particle transport (extend confinement predictability)
- Macroscopic stability (β-limit, wall stabilization, NTMs)
- Wave-particle interactions (fast alpha particle driven effects)
- Plasma boundary (density limit, power and particle flow)
- Test/Develop techniques to control and optimize fusion-dominated plasmas.
- Sustain fusion-dominated plasmas - high-power-density exhaust of plasma particles and energy, alpha ash exhaust, study effects of profile evolution due to alpha heating on macro stability, transport barriers and energetic particle modes.
- Explore and understand various advanced operating modes and configurations in fusion-dominated plasmas to provide generic knowledge for fusion and non-fusion plasma science, and to provide a foundation for attractive fusion applications.
Plasma Requirements for a Fusion-Dominated Plasma

Power Balance

\[ P_{\text{aux-heat}} + n^2 <\sigma v> U_{\alpha} V_p/4 - C_B T^{1/2} n_e^2 V_p = 3nkTV_p/\tau_E + d(3nkTV_p)/dt \]

where: \( n_D = n_T = n_e/2 = n/2 \), \( n^2 <\sigma v> U_{\alpha} V_p/4 = P_{\alpha} \) is the alpha heating power, \( C_B T^{1/2} n_e^2 V_p \) is the radiation loss, \( W_p = 3nkTV_p \) and \( \tau_E = W_p/(P_{\text{aux-heat}} - dW_p/dt) \) is the energy confinement time.

In Steady-state:

\[ n\tau_E = \frac{3kT}{<\sigma v> U_{\alpha} (Q+5)/4Q - C_B T^{1/2}} \]

where \( Q = P_{\text{fusion}}/ P_{\text{aux-heat}} \) \( \text{Palpha}/(\text{Palpha} + \text{Paux-heat}) = Q / (Q + 5) \)

\( Q = 1 \) is Plasma Breakeven, \( Q = \infty \) is Plasma Ignition
Status of Laboratory Fusion Experiments

Central Ion Temperature, $T_i$ (0) (keV)

Lawson Parameter, $n_i e$ ($10^{20} m^{-3} s$)

Legend:
- D-T
- D-D
- Laser D-T
International Thermonuclear Experimental Reactor (ITER)

**Parties**
- US (left in 1998)
- Japan
- Europe
- Russia

**$P_{fusion}$** \(~1,500 \text{ MW}\) for 1,000 seconds

**Cost** \(~$10 \text{ B}\)

Japan, Europe and Russia are continuing to work on a reduced size version with a goal of reducing the cost to \(~$5 \text{ B}\).

**Demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes.**
NSO/FIRE Community Discussions

A Proactive NSO/FIRE Outreach Program has been undertaken to solicit comments and suggestions from the community on the next step in magnetic fusion.

- Presentations have been made and comments received from:

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
<th>Location 1</th>
<th>Date</th>
<th>Location 2</th>
<th>Date</th>
<th>Location 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOFT/France</td>
<td>Sep 98</td>
<td>IAEA/Japan</td>
<td>Oct 98</td>
<td>APS-DPP</td>
<td>Nov 98</td>
<td></td>
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<tr>
<td>FPA</td>
<td>Jan 99</td>
<td>APEX/UCLA</td>
<td>Feb 99</td>
<td>APS Cent</td>
<td>Mar 99</td>
<td></td>
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<td>IGNITOR Wkshp</td>
<td>May 99</td>
<td>NRC/NAS</td>
<td>May 99</td>
<td>GAT</td>
<td>May 99</td>
<td></td>
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<td>LLNL</td>
<td>May 99</td>
<td>VLT-PAC</td>
<td>Jun 99</td>
<td>MIT PSFC</td>
<td>Jul 99</td>
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<td>Snowmass</td>
<td>Jul 99</td>
<td>PPPL/SFG</td>
<td>Aug 99</td>
<td>VLT-PAC</td>
<td>Jun 99</td>
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<tr>
<td>NYU</td>
<td>Oct 99</td>
<td>PPPL/SFG</td>
<td>Aug 99</td>
<td>U. Wis</td>
<td>Oct 99</td>
<td></td>
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<tr>
<td>U. Maryland</td>
<td>Dec 99</td>
<td>DOE/OFES</td>
<td>Dec 99</td>
<td>VLT PAC</td>
<td>Dec 99</td>
<td></td>
</tr>
<tr>
<td>Dartmouth</td>
<td>Jan 00</td>
<td>Harvey Mudd</td>
<td>Jan 00</td>
<td>FESAC</td>
<td>Feb 00</td>
<td></td>
</tr>
<tr>
<td>ORNL</td>
<td>Feb 00</td>
<td>Northwest’n</td>
<td>Feb 00</td>
<td>U. Hawaii</td>
<td>Feb 00</td>
<td></td>
</tr>
<tr>
<td>Geo Tech</td>
<td>Mar 00</td>
<td>U. Georgia</td>
<td>Mar 00</td>
<td>PPPL</td>
<td>Mar 00</td>
<td></td>
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<tr>
<td>Naval Postgrad S</td>
<td>Mar 00</td>
<td>U. Wis</td>
<td>Mar 00/Apr 00</td>
<td>EPS/Budapest</td>
<td>Jun 00</td>
<td></td>
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<tr>
<td>IPP/Garching</td>
<td>Jun 00</td>
<td>CEA/Cadarae</td>
<td>Jun 00</td>
<td>JET-EFDA</td>
<td>Jun 00</td>
<td></td>
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<tr>
<td>NSO-PAC</td>
<td>Jul 00</td>
<td>SOFT/Spain</td>
<td>Sep 00</td>
<td>IAEA/Italy</td>
<td>Oct 00</td>
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<td>Int’l DB/Frascati</td>
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<td>CRPP/Lausanne</td>
<td>Oct 00</td>
<td>ANS/TOFE</td>
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<tr>
<td>APS/DPP-ICPP</td>
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<td>VLT-PAC</td>
<td>Dec 00</td>
<td>UFA BP Wkp</td>
<td>Dec 00</td>
<td></td>
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<tr>
<td>NSO-PAC2</td>
<td>Jan 01</td>
<td>MIT IAP</td>
<td>Jan 01</td>
<td>Columbia U.</td>
<td>Jan 01</td>
<td></td>
</tr>
</tbody>
</table>

- The FIRE web site has been developed to make information on FIRE and fusion science accessible and up to date. Over 14,000 visitors from around the world have logged on to the FIRE web site since the site was initiated in July, 1999.
Stepping Stones for Resolving the Critical Fusion Plasma Science Issues for an Attractive MFE Reactor

The “Old Paradigm” required three separate devices, the “New Paradigm” could utilize one facility operating in three modes or phases.
## Dimensionless Parameters Required for Fusion Plasma Physics Experiment

<table>
<thead>
<tr>
<th></th>
<th>Core*</th>
<th>Edge</th>
<th>Alpha</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$BR^{5/4}$</td>
<td>$P_\alpha/P_{\text{heat}}$</td>
<td>$\tau/\tau_{\alpha S}$</td>
<td>$\tau/\tau_E$</td>
</tr>
<tr>
<td><strong>Explore and Understand Fusion Plasmas</strong></td>
<td>&gt;0.5</td>
<td>&gt;0.5</td>
<td>&gt;3</td>
<td>&gt;5</td>
</tr>
<tr>
<td>Energy and Particle Transport</td>
<td>&gt;0.5</td>
<td>0.4 to 0.6</td>
<td>10</td>
<td>&gt;3</td>
</tr>
<tr>
<td>Wave Particle (alpha heating, fast alpha)</td>
<td>&gt;0.5</td>
<td>0.4 to 0.6</td>
<td>10</td>
<td>&gt;3</td>
</tr>
<tr>
<td>Plasma Boundary</td>
<td>&gt;0.5</td>
<td>0.5 to 0.8</td>
<td>10</td>
<td>&gt;3</td>
</tr>
<tr>
<td><strong>Sustain Fusion-Dominated Plasmas</strong></td>
<td>&gt;0.5</td>
<td>0.5 to 0.8</td>
<td>&gt;10</td>
<td>5</td>
</tr>
<tr>
<td>Exhaust of power, particles and ash</td>
<td>&gt;0.5</td>
<td>0.9</td>
<td>&gt;10</td>
<td>&gt;10</td>
</tr>
<tr>
<td>Profile evolution impact on $\tau_E$, MHD</td>
<td>&gt;0.5</td>
<td>0.5 to 0.8</td>
<td>&gt;10</td>
<td>&gt;10</td>
</tr>
<tr>
<td><strong>Explore and Understand Some AT Modes</strong></td>
<td>&gt;0.5</td>
<td>0.4 to 0.6</td>
<td>10</td>
<td>&gt;3</td>
</tr>
<tr>
<td>ARIES-AT</td>
<td>1</td>
<td>0.9</td>
<td>&gt;10</td>
<td>&gt;10</td>
</tr>
<tr>
<td>FIRE Goals</td>
<td>0.6</td>
<td>0.5 to 0.8</td>
<td>&gt;10</td>
<td>&gt;10</td>
</tr>
<tr>
<td>JET/TFTR D-T Experiments</td>
<td>0.3</td>
<td>0.04</td>
<td>~3</td>
<td>10</td>
</tr>
</tbody>
</table>

* Core parameters are normalized to ARIES-AT $BR^{5/4}$
Fusion Ignition Research Experiment (FIRE)

Design Goals

- $R = 2.0 \text{ m, } a = 0.525 \text{ m}$
- $B = 10 \text{ T, } (12 \text{T})*$
- $W_{\text{mag}} = 3.8 \text{ GJ, } (5.5 \text{T})*$
- $I_p = 6.5 \text{ MA, } (7.7 \text{ MA})*$
- $P_{\text{alpha}} > P_{\text{aux}}, P_{\text{fusion}} < 200 \text{ MW}$
- Burn Time $\approx 18.5 \text{s} \ (\approx 12 \text{s})*$
- Tokamak Cost $\leq $0.3B
- Base Project Cost $\leq $1B

* Higher Field Mode

Attain, explore, understand and optimize fusion-dominated plasmas that will provide knowledge for attractive MFE systems.
Contributors to the FIRE Design Study

FIRE is a design study for a major Next Step Option in magnetic fusion and is carried out through the Virtual Laboratory for Technology. FIRE has benefited from the prior design and R&D activities on BPX, TPX and ITER.

Advanced Energy Systems
Argonne National Laboratory
DAD Associates
General Atomics Technology
Georgia Institute of Technology
Idaho National Engineering Laboratory
Lawrence Livermore National Laboratory
Massachusetts Institute of Technology
Oak Ridge National Laboratory
Princeton Plasma Physics Laboratory
Sandia National Laboratory
Stone and Webster
The Boeing Company
University of Illinois
University of Wisconsin
### Basic Parameters and Features of FIRE Reference Baseline

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value/Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>R, major radius</td>
<td>2.0 m</td>
</tr>
<tr>
<td>a, minor radius</td>
<td>0.525 m</td>
</tr>
<tr>
<td>κ(_{95}), elongation at 95% flux surface</td>
<td>~1.8</td>
</tr>
<tr>
<td>δ(_{95}), triangularity at 95% flux surface</td>
<td>~0.4</td>
</tr>
<tr>
<td>q(_{95}), safety factor at 95% flux surface</td>
<td>&gt;3</td>
</tr>
<tr>
<td>B(_{t}), toroidal magnetic field</td>
<td>10 T with 16 coils, 0.34% ripple @ Outer MP</td>
</tr>
<tr>
<td>Toroidal magnet energy</td>
<td>3.7 GJ</td>
</tr>
<tr>
<td>Ip, plasma current</td>
<td>~6.5 MA (7.7 MA at 12 T)</td>
</tr>
<tr>
<td>Magnetic field flat top, burn time</td>
<td>26 s at 10 T in dd, 18.5 s @ Pdt ~ 200 MW</td>
</tr>
<tr>
<td>Pulse repetition time</td>
<td>~3hr @ full field and full pulse length</td>
</tr>
<tr>
<td>ICRF heating power, maximum</td>
<td>30 MW, 100MHz for 2Ω(_{t}), 4 mid-plane ports</td>
</tr>
<tr>
<td>Neutral beam heating</td>
<td>None, may have diagnostic neutral beam</td>
</tr>
<tr>
<td>Lower Hybrid Current Drive</td>
<td>None in baseline, upgrade for AT phase</td>
</tr>
<tr>
<td>Plasma fueling</td>
<td>Pellet injection (≥2.5km/s vertical launch inside mag axis, possible guided slower speed pellets)</td>
</tr>
<tr>
<td>First wall materials</td>
<td>Be tiles, no carbon</td>
</tr>
<tr>
<td>First wall cooling</td>
<td>Conduction cooled to water cooled Cu plates</td>
</tr>
<tr>
<td>Divertor configuration</td>
<td>Double null, fixed X point, detached mode</td>
</tr>
<tr>
<td>Divertor plate</td>
<td>W rods on Cu backing plate (ITER R&amp;D)</td>
</tr>
<tr>
<td>Divertor plate cooling</td>
<td>Inner plate-conduction, outer plate/baffle- water</td>
</tr>
<tr>
<td>Fusion Power/ Fusion Power Density</td>
<td>200 MW, ~10 MW m-3 in plasma</td>
</tr>
<tr>
<td>Neutron wall loading</td>
<td>~3 MW m-2</td>
</tr>
<tr>
<td>Lifetime Fusion Production</td>
<td>5 TJ (BPX had 6.5 TJ)</td>
</tr>
<tr>
<td>Total pulses at full field/power</td>
<td>3,000 (same as BPX), 30,000 at 2/3 Bt and Ip</td>
</tr>
<tr>
<td>Tritium site inventory</td>
<td>Goal &lt; 30 g, Category 3, Low Hazard Nuclear Facility</td>
</tr>
</tbody>
</table>

**Higher Field Mode** \( B = 12\text{T} \) and \( I_p = 7.7\text{MA} \) with a 12 second flat top has been identified. Also enhanced performance option \( B = 10\text{T}, I_p = 7.7 \text{ MA} \) with 20 s burn with \( R = 2.14\text{m} \)
FIRE would have Access for Diagnostics and Heating

(and Advanced Tokamak Stabilization Systems)

16 mid-plane ports  1.3m x 0.65m
32 divertor ports  0.5m x 0.2m (16 for cryopumps/cooling water
24 vertical ports  0.13m diam
FIRE Status

Physics - NSO PAC review with Action Plan to follow up on Recommendations
  • Mission endorsed (recommend even more excitement)
  • Evaluate FIRE performance on the basis of recent scalings e.g., ITER98(y,2) and recent results with enhanced regimes e.g., pellet fueling
  • Enhanced performance design point being developed with $I_p \sim 7.7$ MA to increase confidence of high gain while maintaining pulse length ($\sim 1.5 \tau_{cr}$)
  • Potential for advanced tokamak modes is being developed

Engineering
  • Pre-Conceptual Design Activity has addressed all subsystems. Engineering Report 2000 completed, see http://fire.pppl.gov. CD is available on request
  • Baseline design of 10 T/20 s flat top and 12 T/12 s flat top exceeds original design goals of 10 T/10 s flat top.
  • Actively cooled W outer divertor and baffle with conduction cooled inner W divertor, and Be first wall on Cu substrate satisfy cooling requirements.
  • Cost Estimate of Baseline design gives $1.2B(FY-99)$ for Green Field site with good possibility of < $1B(FY-99)$ at an existing site.
FIRE Incorporates Advanced Tokamak Innovations

AT Features
- DN divertor
- strong shaping
- very low ripple
- internal coils
- space for wall stabilizers
- inside pellet injection
- large access ports

*Coil systems cooled to 77 °K prior to pulse, rising to 373 °K by end of pulse.

FIRE Cross/Persp- 5/25//DOE
Recent Innovations have Markedly Improved the Technical Basis for a Compact High Field Tokamak Burning Plasma Exp't.

Tokamak experiments (1989-1999) have developed enhanced confinement modes that scale (e.g., ITER-98H) 1.3 times higher than the 1989 CIT design assumption.

Alcator C-Mod - the prototype for Compact High Field tokamaks has shown:

- Confinement in excess of 1.4 times the 1989 design guidelines for CIT and ~1.15 times the recent ITER-98H design guidelines.
- Successful ICRF heating at high density in shaped diverted plasmas.
- Successful detached divertor operation at high power density.

VDEs and halo currents have made internal hardware design more difficult.

D-T experiments on TFTR and JET have shown:

- Tritium can be handled safely in a laboratory fusion experiment!!!
- D-T plasmas behaved roughly as predicted with slight improvements in confinement in plasmas with weak alpha-heating.

Engineering Innovations to increase capability and reduce cost

- Improved coil and plasma facing component materials, improved 3-D engineering computer models and design analysis, advanced manufacturing.
FIRE Confinement Projection Activities

Design Guidelines
• Similar to ITER-FEAT
  - Campbell APS paper on FIRE, ITER-FEAT presentation to TAC 7/00
  - Uckan, Wesley ANS paper
  - Meade, IAEA, ANS papers

Confinement Database Meeting (DB4)
• Collection of random vs library of repeatable (eg Barabaschi EPS paper)

FIRE Specific Assumptions
• JET H-mode data base of FIRE-like shots (55)
  \( \kappa \geq 1.7, \beta_N > 1.7, 2.7 < q_{95} < 3.5, Z_{\text{eff}} < 2, 0.3 < n/n_{GW} < 0.8 \)
  
  • \( <H(y,2> = 1.1, \quad <n(0)/<n>_v> = 1.2 \)

  • density peaking \( \approx 1.2 \) consistent with 1-D modeling (e.g., Houlberg-ANS)

• Impurity assumption needs more analysis. Not taking credit for reduction at high density, but must make sure hi-Z ions do not get into core plasma.

Starting interactions with first principles modeling groups.
Guidelines for Estimating Plasma Performance

Confinement (Elmy H-mode) - ITER98(y,2) based on today’s data base

\[ \tau_E = 0.144 I^{0.93} R^{1.39} a^{0.58} n_{20}^{0.41} B^{0.15} A_i^{0.19} \kappa^{0.78} P_{heat}^{-0.69} \ H(y,2) \]

Density Limit - Base on today's tokamak data base

\[ n_{20} \leq 0.75 n_{GW} = 0.75 \frac{I_p}{\pi a^2}, \ H98 \approx 1 \text{ up to } 0.75 n_{GW} \ (JET, 1998) \]

Beta Limit - theory and tokamak data base

\[ \beta \leq \beta_N(I_p/aB), \quad \beta_N \sim 2.5 \text{ conventional, } \beta_N \sim 4 \text{ advanced} \]

H-Mode Power Threshold - Based on today's tokamak data base

\[ P_{th} \geq (2.84/Ai) n_{20}^{0.58} B^{0.82} Ra^{0.81}, \text{ same as ITER-FEAT} \]

Helium Ash Confinement \[ \tau_{He} = 5 \tau_E, \quad \text{impurities} = 3\% \ Be \]

Understanding is mainly empirical. Better understanding is needed from existing experiments with improved simulations, and a benchmark in fusion-dominated plasmas is needed to confirm and extend the science basis.
FIRE is a Modest Extrapolation in Plasma Confinement

Dimensionless Parameters

- $\omega_c \tau$
- $\rho^* = \rho / a$
- $\nu^* = \nu_c / \nu_b$
- $\beta$

Similarity Parameter

- $B R^{5/4}$

Kadomtsev, 1975

$B \tau_{Eth} \sim \rho^{*-2.88} \beta^{-0.69} \nu^*^{-0.08}$
FIRE can Access Most of the H-Mode Database

FIRE
\[
\frac{n}{n_{GW}} \geq 0.30
\]
ITER-FEAT
\[
\frac{n}{n_{GW}} \geq 0.85
\]

H(y,2)

DB03v5
H-Mode

ITER-FEAT TAC Meeting
June 2000
This approach discussed at IAEA(Sorrento) and at the International Confinement Database meeting (Frascati).
Confinement Enhancement Required to Access Various Q-values Compared with JET H-Mode Data

- $\beta_N > 1.7,$
- $2.7 < q_{95} < 3.5,$
- $\kappa > 1.7,$
- $Z_{\text{eff}} < 2.0$
Percentage of JET FIRE-like Data Points that Project to a Specific Alpha Heating Fraction (Q)

ITER98(y,2)

\[
n(0)/\langle n \rangle = 1.2
\]

Base 10T

FIRE*

Base 12T

\[
Q = 5
\]

\[
Q = 10
\]

\[
Q = 20
\]

\[
Q = 50
\]
Projections of FIRE Compared to Envisioned Reactors

ARIES-AT, Najmabadi,  Q = 50

FIRST “ITER” Reactor
Toschi et al

Base 12T
7.7MA

FIRE*
10T
7.7MA

Base 10T
6.44MA

P_{fusion} = 150 MW
n/n_{GW} = 0.7

n(0)/<n>_V = 1.5
n(0)/<n>_V = 1.2

FIRE*
R = 2.14m, a = 0.595m
A = 3.6

* JET H-Mode Data for
\beta_N > 1.7, 2.7 < q_{95} < 3.5
\kappa > 1.7, n/n_{GW} = 0.5 -0.8,
and Z_{eff} < 2  have

<H98(y,2)> = 1.1
<n(0)/<n>_V> = 1.2
FIRE Projections as Confinement is Enhanced Toward that Required for Attractive Reactors

\[ \text{Alpha Heating Fraction} = \frac{P_\alpha}{(P_\alpha + P_{\text{ext}})} \]

- ARIES-AT
  Najmabadi, IAEA 2000
- FIRST “ITER” Reactor
  Toschi, SOFT 2000

**FIRE Projections**

- Base 12T, \(\alpha_n = 0.5\)
- Base 12T, \(\alpha_n = 0.2\)
- FIRE* 10T, \(\alpha_n = 0.5\)
- FIRE* 10T, \(\alpha_n = 0.2\)
- Base 10T, \(\alpha_n = 0.5\)
- Base 10T, \(\alpha_n = 0.2\)

**Projections of FIRE Performance**

- \(P_{\text{fusion}} = 150\,\text{MW}\)
- \(n/n_{\text{GW}} = 0.7\)
- \(n(0)/<n>_V = 1 + \alpha_n\)

**JET H-Mode Range**

- \(\beta_N > 1.7,\ 2.7 < q_{95} < 3.5\)
- \(\kappa > 1.7,\ Z_{\text{eff}} < 2\)

**Alpha Heating Fraction**

- Alpha heating fraction, the science goal, is less sensitive to confinement uncertainty.
FIRE* 10T, R=2.14m, 7.7 MA, H(y,2) = 1.1, $\alpha_n = 0.2$
1 1/2-D Simulation of Burn Control in FIRE

- ITER98(y, 2) scaling with $H(y,2) = 1.1$, $n(0)/<n> = 1.25$ and $n/n_{GW} = 0.59$

- Pulse Duration $\approx 30 \tau_E$, $6 \tau_{He}$ and $\sim 1.5 \tau_{skin}$

![Graph showing power and time]
FIRE could Access High-Gain Advanced Tokamak Regimes for Long Durations

- The coupling of advanced tokamak modes with strongly burning plasmas is a generic issue for all advanced “toroidal” systems. The VLT PAC, Snowmass Burning Plasma and Energy Subgroup B recommended that a burning plasma experiment should have AT capability.

- FIRE, with strong plasma shaping, flexible double null poloidal divertor, low TF ripple, dual inside launch pellet injectors, and space reserved for the addition of current drive (LHCD) and/or a smart conducting wall, has the capabilities needed to investigate advanced tokamak regimes in a high gain burning plasma.

- The LN inertially cooled TF coil has a pulse length capability ~250 s at 4T for DD plasmas. This long pulse - AT capability rivals that of any existing divertor tokamak or any under construction. The coils are not the limit.

- Recent AT regimes on DIII-D (Shot 98977) sustained for ~ 16 \( \tau_E \) serve as demonstration discharges for initial AT experiments on FIRE. Need to develop self-consistent scenarios with profile control on FIRE with durations ~ 3 \( \tau_{\text{skin}} \).
FIRE could Access “Long Pulse” Advanced Tokamak Mode Studies at Reduced Toroidal Field.

Note: FIRE is ≈ the same physical size as TPX and KSTAR.
At Q = 10 parameters, typical skin time in FIRE is 13 s and is 200 s in ITER-FEAT.

The combination of JET-U, JT-60 Mod, KSTAR and FIRE could cover the range from steady-state non-burning advanced-tokamak modes to “quasi-equilibrium” burning plasmas in advanced tokamak modes.
FIRE can Access MHD Regimes of Interest from Today's Data Base to those Envisioned for ARIES-RS

\[ \frac{\beta}{(S\varepsilon)} \]

- **ARIES-RS**
  - \( q^* = 2 \)
  - \( q^* = 3 \)
  - \( q^* = 4 \)

- **FIRE-RS**
  - \( q(0) = 2.9 \), \( q_{\text{min}} = 2.6 \), \( q_{95} = 4.6 \)

- **FIRE-I**
  - \( n=1 \) RWM
  - \( \beta_N = 5 \)
  - \( \beta_N = 4 \)
  - \( \beta_N = 3 \)
  - \( \beta_N = 2 \)

- **FIRE**
  - \( n>1 \) RWM
  - \( \beta_N = 1 \)

- **ITER**
  - \( \beta_N = 1 \)

- **SSTR**
  - \( \beta_N = 1 \)

- **Neoclassical tearing**
  - \( \beta_N = 1 \)
Potential for Resistive Wall Mode Stabilization System

view of horizontal port front looking from plasma side

Copper Stabilizing Shell (backing for PFCs)
1st Vacuum Shell
2nd Vacuum Shell

horizontal port (1.3 m x 0.65 m)
port shield plug (generic)
resistive wall mode stabilization coil (embedded in shield plug)

Concept under development by J. Bialek, G. Navratil, C. Kessel et al
## Potential Next Step Burning Plasma Experiments and Demonstrations in MFE

### Parameters

<table>
<thead>
<tr>
<th>Cost Drivers</th>
<th>ARIES-ST</th>
<th>ITER-FEAT</th>
<th>ARIES-RS</th>
<th>JET</th>
<th>FIRE</th>
<th>IGNITOR</th>
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<tr>
<td>Plasma Volume (m$^3$)</td>
<td>810</td>
<td>837</td>
<td>350</td>
<td>95</td>
<td>18</td>
<td>11</td>
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<tr>
<td>Plasma Surface (m$^2$)</td>
<td>580</td>
<td>678</td>
<td>440</td>
<td>150</td>
<td>60</td>
<td>36</td>
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<td>Plasma Current (MA)</td>
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<td>15</td>
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<td>4</td>
<td>6.5</td>
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<tr>
<td>Magnet Energy (GJ)</td>
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<td>50</td>
<td>85</td>
<td>2</td>
<td>5</td>
<td>5</td>
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<tr>
<td>Fusion Power (MW)</td>
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<td>500</td>
<td>2200</td>
<td>16</td>
<td>200</td>
<td>100</td>
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<tr>
<td>Burn Time (s), inductive</td>
<td>steady</td>
<td>300</td>
<td>steady*</td>
<td>1</td>
<td>20</td>
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* assumes non-inductive current drive
## FIRE Power Requirements for BeCu or CuTF Coils

<table>
<thead>
<tr>
<th></th>
<th>10T  (20s flattop)</th>
<th>12T  (12s flattop)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Peak Power (MW)</td>
<td>Peak Energy (GJ)</td>
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<tr>
<td><strong>BeCu</strong></td>
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<tr>
<td>TF</td>
<td>490</td>
<td>11.5</td>
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<tr>
<td>PF</td>
<td>250</td>
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<tr>
<td>RF</td>
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<tr>
<td>Σ</td>
<td>800</td>
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<tr>
<td>Grid</td>
<td>550 (TF&amp;RF)</td>
<td>12.5</td>
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<tr>
<td>MG</td>
<td>250 (PF)</td>
<td>2.2</td>
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<table>
<thead>
<tr>
<th></th>
<th>10T  (45s flattop)</th>
<th>12T  (25s flattop)</th>
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<tr>
<td></td>
<td>Peak Power (MW)</td>
<td>Peak Energy (GJ)</td>
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<tr>
<td><strong>Cu</strong></td>
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<tr>
<td>TF</td>
<td>267</td>
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<tr>
<td>PF</td>
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<tr>
<td>RF</td>
<td>60</td>
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<tr>
<td>Σ</td>
<td>577</td>
<td>19.9</td>
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<tr>
<td>Grid</td>
<td>577 (All Systems)</td>
<td>19.9</td>
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<tr>
<td>MG</td>
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### Preliminary FIRE Cost Estimate (FY99 US$M)

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<th>Category</th>
<th>Estimated Cost</th>
<th>Contingency</th>
<th>Total with Contingency</th>
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<tr>
<td><strong>1.0 Tokamak Core</strong></td>
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<td>1.1 Plasma Facing Components</td>
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<td>17.0</td>
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<td>1.2 Vacuum Vessel/In-Vessel Structures</td>
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<td>1.3 TF Magnets /Structure</td>
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<td>37.2</td>
<td>151.0</td>
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<tr>
<td>1.4 PF Magnets/Structure</td>
<td>28.4</td>
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<tr>
<td>1.5 Cryostat</td>
<td>1.8</td>
<td>0.5</td>
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<td>1.6 Support Structure</td>
<td>7.5</td>
<td>2.2</td>
<td>9.7</td>
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<td><strong>2.0 Auxiliary Systems</strong></td>
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<td>39.3</td>
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<td>2.1 Gas and Pellet Injection</td>
<td>7.1</td>
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<tr>
<td>2.2 Vacuum Pumping System</td>
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<tr>
<td>2.3 Fuel Recovery/Processing</td>
<td>7.0</td>
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<td>2.4 ICRF Heating</td>
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<td><strong>3.0 Diagnostics (Startup)</strong></td>
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<td><strong>6.0 Site and Facilities</strong></td>
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<td><strong>8.0 Project Support and Oversight</strong></td>
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<td><strong>Preconceptual Cost Estimate (FY99 US$M)</strong></td>
<td><strong>960.9</strong></td>
<td><strong>236.9</strong></td>
<td><strong>1193.5</strong></td>
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</table>

Assumes a Green Field Site with **No** site credits or significant equipment reuse.

This estimate is work in progress and will be reviewed in the winter 2000.
• Even with ITER, the MFE program will be unable to address the alpha-dominated burning plasma issues for \( \geq 15 \) years.

• Compact High-Field Tokamak Burning Plasma Experiment(s) would be a natural extension of the ongoing “advanced” tokamak program and could begin alpha-dominated experiments by \( \sim 10 \) years.

• More than one high gain burning plasma facility is needed in the world program.

• The information “exists now” to make a technical assessment, and decision on MFE burning plasma experiments for the next decade.
## Timetable for a Major Next Step in MFE

<table>
<thead>
<tr>
<th>FY</th>
<th>2000</th>
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<th>2002</th>
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<tr>
<td></td>
<td>• EU Airaghi Report</td>
<td>• ITER-EDA Extension Complete</td>
<td>• JA Decision ITER/JT-60 SC</td>
<td>• EU Response to Airaghi Report</td>
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<td>• FuSAC Report</td>
<td>• EU FP 6 Start</td>
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<td><strong>NSO/FIRE Activities</strong></td>
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<td><strong>Snow</strong></td>
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<td>APS</td>
<td>WkShp</td>
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<td><strong>Preconceptual Design</strong></td>
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<tr>
<td><strong>Conceptual Design</strong></td>
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</table>

- Establish Mission and Provisional Parameters
  - Initial Report
  - Mid-Term Report
  - Preconceptual Design Report

- Resolve Technical Issues
  - Divertor and PFCs, Disruptions
  - Vac Vessel Nuclear Heating, Remote Handling

- Incorporate AT Capability
  - Physics Scenarios: $\beta_N$, $f_{\text{BS}}$, wall stabilization
  - ripple, pulse length, current drive

- Physics R&D

- Enabling Technology R&D
Major Conclusions of the FIRE Design Study

- Exploration, understanding and optimization of fusion-dominated (high-gain) burning plasmas are critical issues for all approaches to fusion.

- The tokamak is a cost-effective vehicle to investigate fusion-dominated plasma physics and its coupling to advanced toroidal physics for MFE. The tokamak is technically ready for a next step to explore fusion plasma physics.

- The FIRE compact high field tokamak can address the important fusion-dominated plasma issues, many of the long pulse advanced tokamak issues and begin the coupling of fusion-dominated plasmas with advanced toroidal physics in a $1B class facility.

- The FIRE design point has been chosen to be a “stepping stone” between the physics accessible with present experiments and the physics required for the ARIES vision of magnetic fusion energy.

- A plan is being developed for an Advanced Tokamak Next Step that will address physics, engineering and cost issues in FY 2000-2 with the goal of being ready to begin a Conceptual Design in 2003.

http://fire.pppl.gov
Laboratories are Needed to Explore, Explain and Expand the Frontiers of Science