Creating and Controlling a Burning Plasma in the Laboratory

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http://fire.pppl.gov
A Decade of Studies has Identified the Requirements for Attractive Fusion Power

**Fusion Power Plant ARIES-AT**

- Fusion Power: 1,800 MW
- Plasma Volume: 350 m³

**Advanced Tokamak Features**

- Self heated by fusion products (~90%)
- Smaller size
  - Improved confinement (reduced turbulence)
- High fusion power density for economics
  - \( \sim p^2 \sim \beta^2 B^4 \) \((\beta_N > 4)\)
- Efficient steady-state operation
  - Self generated confinement magnetic field (bootstrap current) (~90%)

- A burning plasma experiment needs the capability to explore advanced tokamak operation
Self-Heating is Critical for a D-T Fusion Reactor

The self-heating rate is $\sim (nT)^2 \sim p^2$ for $T$ between 10 - 25 keV

The pressure profile depends on heating rate and transport profile.

**Alpha Physics Issues**

- Alpha confinement
- Alpha Energy to Plasma from alphas to plasma electrons
- Burn Control
- Alpha Ash Removal
- Alpha Driven Instabilities

$$Q = \frac{P_{\text{Fusion}}}{P_{\text{Ext}}}, \quad f_\alpha = \frac{P_{\text{alpha}}}{P_{\text{Heat}}} = \frac{Q}{Q + 5}$$
Magnetic Fusion is Technically Ready for a High Gain Burning Exp't

Deuterium Plasmas

Central Ion Temperature (keV)

We are ready, but this step is our most challenging step yet.
THE MAGNETIC FIELD IN A TOKAMAK IS PRODUCED BY CURRENTS IN EXTERNAL COILS PLUS A CURRENT IN THE PLASMA.

\[ B_{\text{total}} = B_{\text{Tor}} + B_{\text{Pol}} \]

Induced by ohmic transformer

Self generated by pressure gradient

\[ q = \frac{\# \text{Tor Circuits}}{\# \text{Pol Circuits}} \]
Fusion Plasmas are Complex Non-Linear Dynamic Systems

Can a fusion dominated plasma be created and controlled in the laboratory?
FIRE will Emphasize Advanced Tokamak Goals

**Burning Plasma Physics**

- \( Q \sim 10 \) as target, ignition not precluded
- \( f_\alpha = \frac{P_\alpha}{P_{\text{heat}}} \sim 66\% \) as target, up to 83\% at \( Q = 25 \)
- TAE/EPM stable at nominal point, able to access unstable

**Advanced Toroidal Physics**

- \( f_{bs} = \frac{I_{bs}}{I_p} \sim 80\% \) (goal)
- \( \beta_N \sim 4.0, n = 1 \) wall stabilized

**Quasi-stationary Burn Duration (use plasma time scales)**

- Pressure profile evolution and burn control \( > 10 \tau_E \)
- Alpha ash accumulation/pumping \( > \) several \( \tau_{\text{He}} \)
- Plasma current profile evolution \( 2 \) to \( 5 \tau_{\text{skin}} \)
- Divertor pumping and heat removal several \( \tau_{\text{divertor}} \)
The FIRE Design has Adopted ARIES-RS Plasma Features

**AT Features**

- **Strong shaping**
  \[ \kappa_x, \kappa_a = 2.0, 1.85 \]
  \[ \delta_x, \delta_{95} = 0.7, 0.55 \]
- **Segmented central solenoid**
- **Double null double divertor pumped**
- **Low ripple** (<0.3%)
- **Internal control coils**
- **Space for RWM stabilizers**
- **Inside pellet injection**

![Diagram of FIRE Design features](image-url)
FIRE will push plasma facing components for the wall and divertor toward reactor power densities.
**Fusion Ignition Research Experiment (FIRE)**

**Design Features**

- \( R = 2.14 \, \text{m} \), \( a = 0.595 \, \text{m} \)
- \( B = 10 \, \text{T} \) (~6.5 T AT)
- \( W_{\text{mag}} = 5.2 \, \text{GJ} \)
- \( I_p = 7.7 \, \text{MA} \) (~5 MA AT)
- \( P_{\text{aux}} \leq 20 \, \text{MW} \)
- \( Q \approx 10, \; P_{\text{fusion}} \sim 150 \, \text{MW} \)
- Burn Time \( \approx 20 \, \text{s} \) (~40 s AT)
- Tokamak Cost \( \approx $350M \) (FY02)
- Total Project Cost \( \approx $1.2B \) (FY02) at Green Field site.

**Mission:** Attain, explore, understand and optimize magnetically-confined fusion-dominated plasmas.
Simulation of Conventional H-Mode in FIRE

- ITER98(y, 2) with $H(y, 2) = 1.1$, $n(0)/\langle n \rangle = 1.2$, and $n/ n_{GW} = 0.67$
- Burn Time $\approx 20 \text{s} \approx 21\tau_E \approx 4\tau_{He} \approx 2\tau_{CR}$
- $Q = \frac{P_{fusion}}{(P_{aux} + P_{oh})}$

- $B = 10 \text{T}$
- $I_p = 7.7 \text{ MA}$
- $R = 2.14 \text{ m}$
- $A = 3.6$
FIRE Simulation Project

- realistic geometry
- 2-D magnetics
- 1-D transport
- time evolution

Conventional Mode

~ 70% self heating
~20% self generated confining magnetic field

5.5 MW/m³ Fusion Power density (reactor level)
FIRE would be part of an International Multi-Machine Program to develop attractive fusion power.
ITER and FIRE are Each Attractive Options (FESAC)

Primary Burning Plasma Experiments (same scale)

FIRE ($1.2B - 1.4 ktonne)

Conventional Operation

\[ Q \sim 10 \quad @ \quad 86\% \quad J(r) \quad \text{equilibration} \]

(FIRE and ITER)

Advanced Operation

\[ Q \sim 5, \quad f_{\text{bs}} \sim 80\%, \quad \beta_N \sim 4 \quad @ \quad 98\% \quad \text{equil.} \]

(FIRE)

\[ Q \sim 5, \quad f_{\text{bs}} \sim 50\%, \quad \beta_N \sim 3 \quad @ \quad 99.9\% \quad \text{equil.} \]

(ITER)

ITER ($5B - 19 ktonne$)

A strategy that allows for the possibility of either burning plasma option is appropriate. (FESAC)