Exploring ARIES-like

Advanced Burning Plasma Regimes in FIRE

Dale M. Meade

for the National FIRE Study Team

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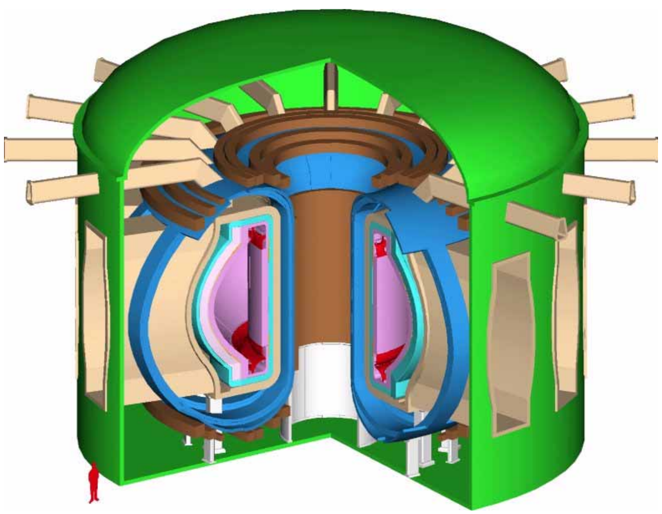
http://fire.pppl.gov

FIRE Lighting the Way to Fusion

VLT

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 m^3

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) (>75%)

- **A burning plasma experiment needs the capability to explore advanced tokamak operation**

High Power Density Needed for Attractive Reactors

- The fusion power density is given by:

$$P_f / V_p \sim n^2 \langle \sigma v \rangle = n^2 T^2 \langle \sigma v \rangle / T^2$$

Note: $\langle \sigma v \rangle / T^2 \approx$ constant from 10 to 20 keV

Define $\beta = \langle p \rangle / B^2$

Then

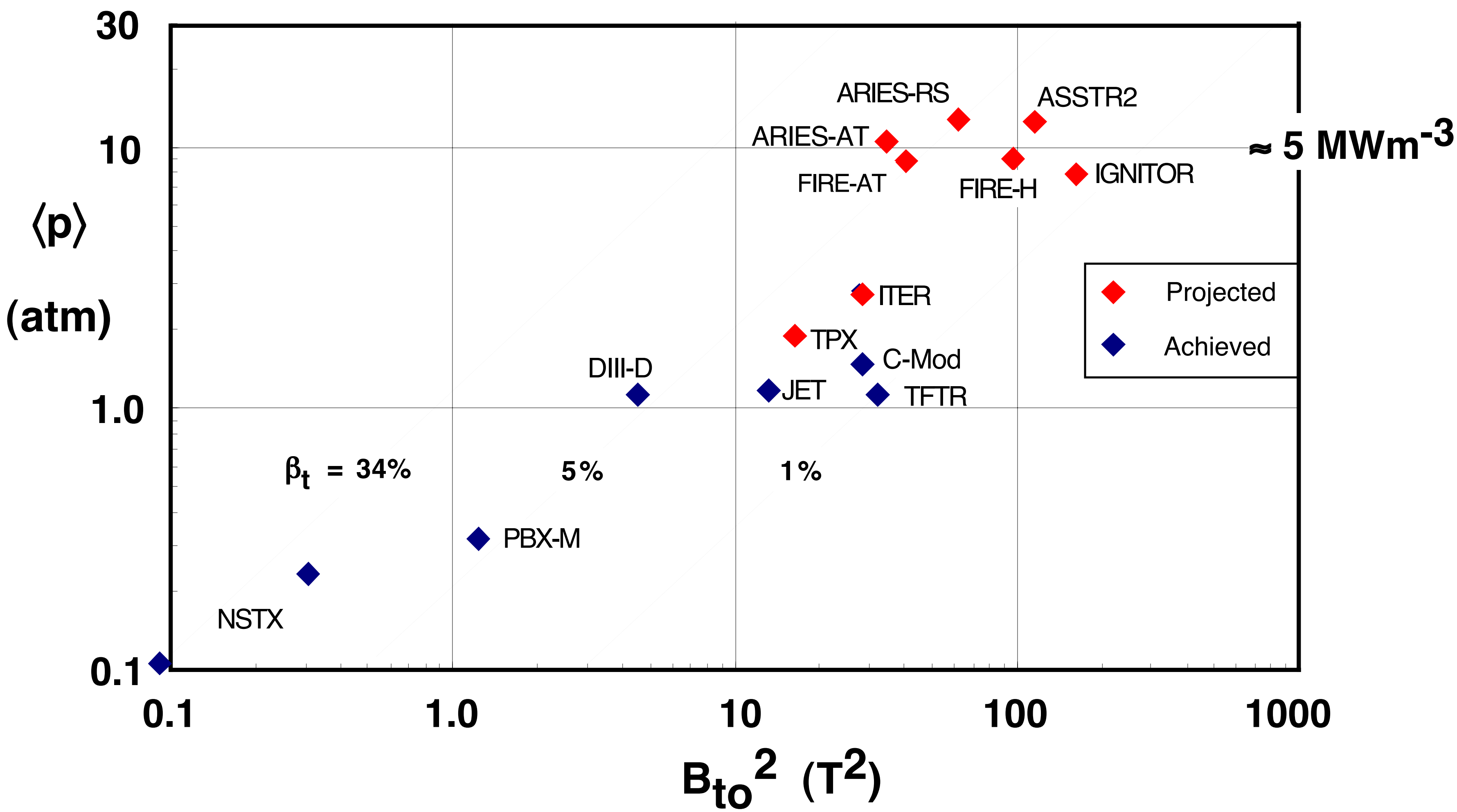
$$P_f / V_p \sim \beta^2 B^4$$

or (a) $P_f / V_p \sim \boldsymbol{\beta_t^2 B_{to}^4}$ where $\mathbf{B_{to}}$ is the field at the magnetic axis

or (b) $P_f / V_p \sim \boldsymbol{\beta_t^2 (B_{to} / B_{coil})^4 B_{coil}^4}$

Physics limit (β_t^2) — Geometry ($(B_{to}/B_{coil})^4$) — Engineering limit (B_{coil}^4)

Fusion Will Require Plasma Pressures of 10 to 15 Atm.



- "Attractive" fusion systems require power densities of ~ 5 MWm^{-3}
- Plasma pressure must be increased by a factor of 10 while maintaining $\beta \sim 5\%$

Guidelines for Estimating H-Mode Performance (0-D)

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 - Based on today's tokamak data base

$$n_{20} \leq 0.8\ n_{GW} = 0.8\ I_p/\pi a^2,$$

Beta Limit - theory and tokamak data base

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

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

$$Pth \geq (2.84/Ai)\ n_{20}^{0.58}\ B^{0.82}\ Ra^{0.81}$$, same as ITER-FEAT

Helium Ash Confinement $\tau_{He} = 5\ \tau_E$, **impurities = 3% Be, 0% W**

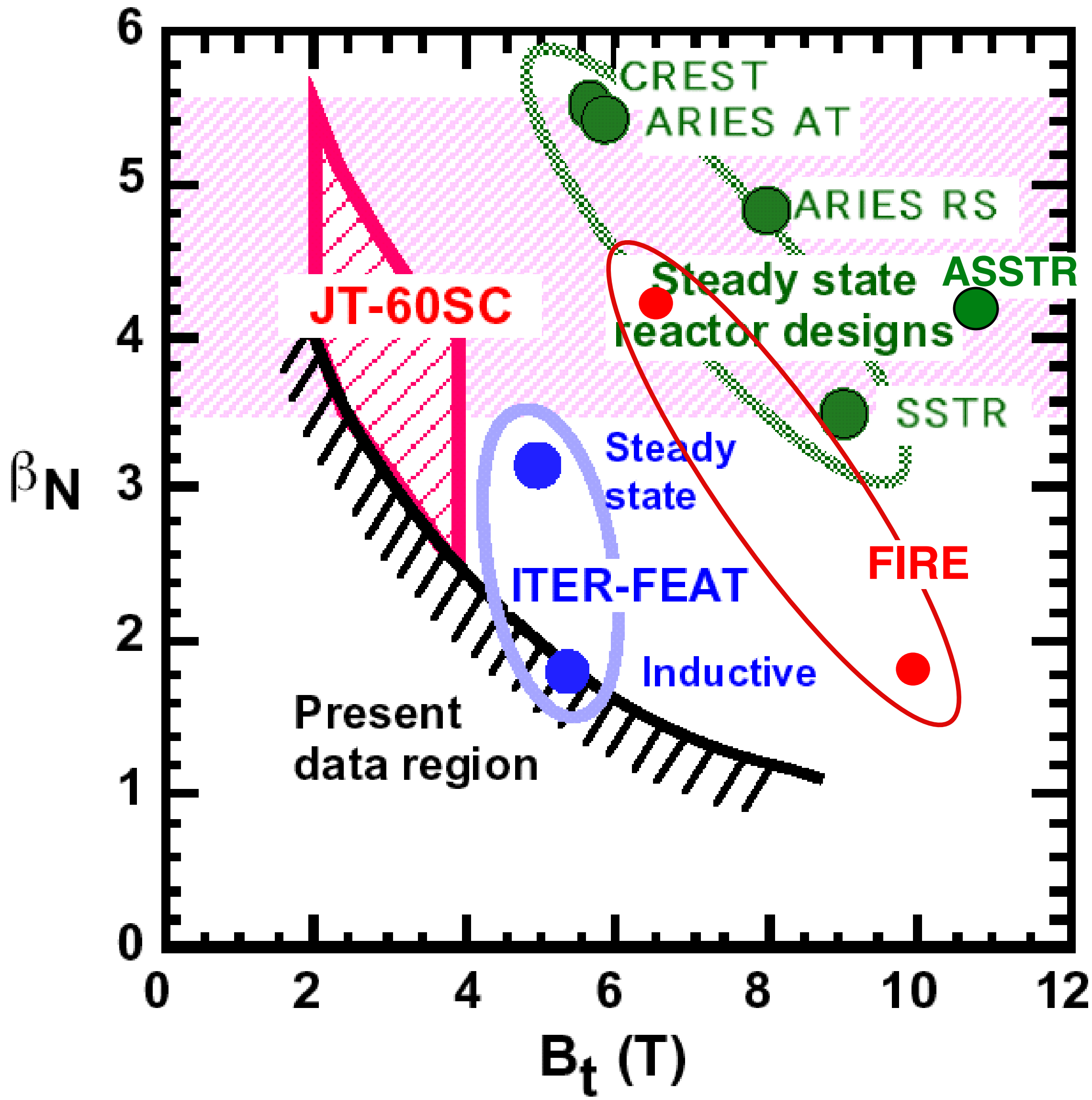
FIRE can Access Regimes of Interest to Advanced Reactors

- Reactor studies ARIES in the US and CREST/SSTR in Japan have determined the requirements for an attractive fusion reactor.

- Present tokamak results are far from the attractive reactor regime.

- The present ITER-FEAT design **does not** access the attractive reactor regime.

- The present FIRE design **does** access the attractive reactor regime.

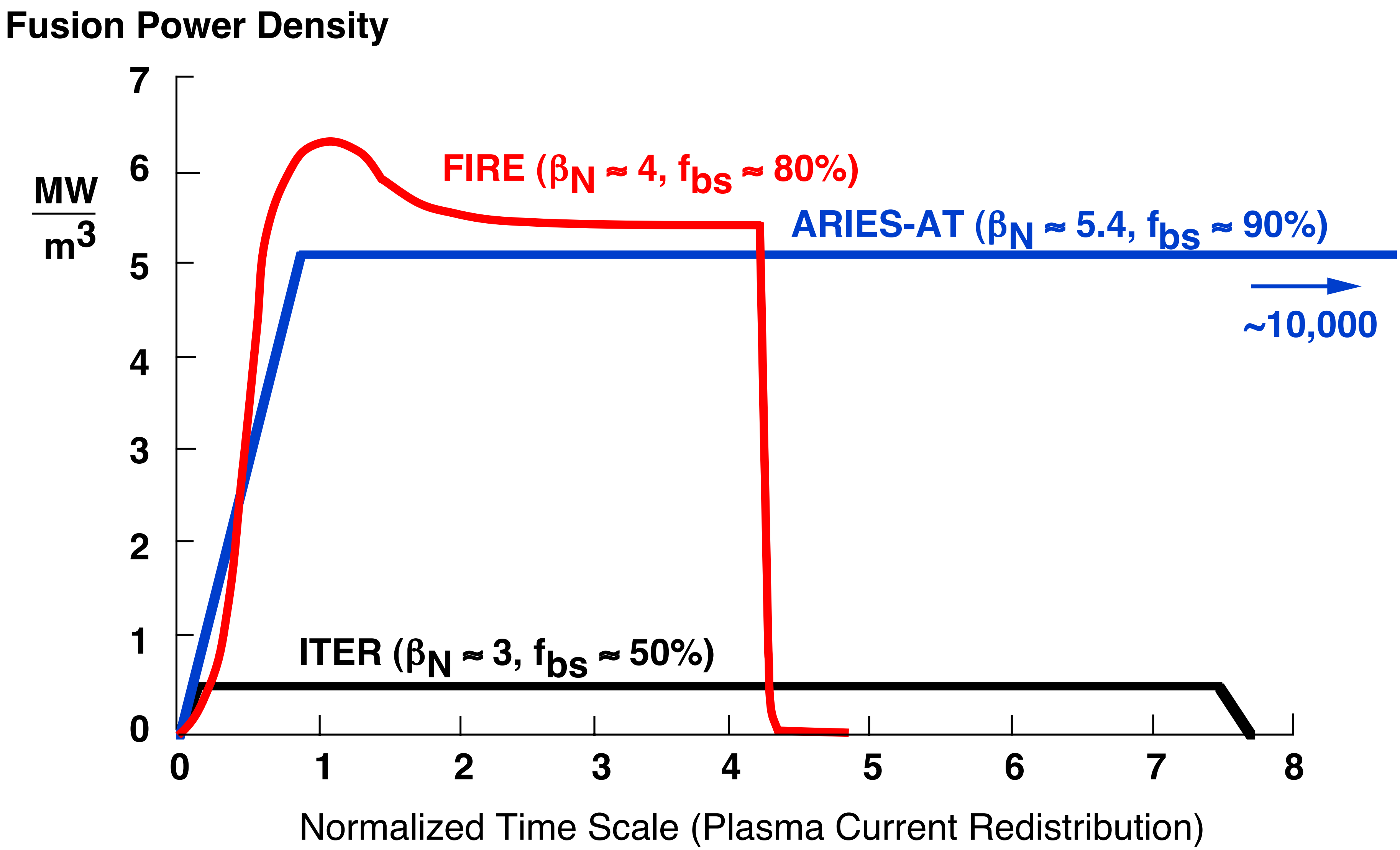


FIRE_JT60SC_at_range

FIRE/ITER Would Test Advanced Physics for ARIES-RS

	ITER	FIRE	ARIES-RS
κ_x plasma elongation	1.85	2.0	2.0
δ_x plasma triangularity	0.49	0.7	0.7
Divertor Configuration	SN	DN	DN
β_N, normalized beta, AT	~3	~4	4.8
Bootstrap fraction, AT	50	80	88
B (T)	5.3	10(6.5)	8
R (m)	6.2	2.14	5.5
Fusion Core Mass, tonne	19,000	1,400	13,000
Plasma Volume, m^2	840	27	350
P_{fusion}(MW)	400	150	2170
P_{fusion}/Vol (MW/m^3)	0.5	5.6	6.2
Neut Wall loading (MW/m^2)	0.57	2.7	4
P_{loss}/R_x	20	20	100
Divertor Target material	C(W?)	W	W
$Q = P_{fus}/P_{ext}$ Conventional	10	10	n.a.
$Q = P_{fus}/P_{ext}$ Advanced Tok	5	5	27
Burn Time			
seconds	400 - 3,000	20 - 40	20,000,000
Current Profile Equilb,%	86 – 99.99	86 - 98	100

FIRE Could Explore Advanced Tokamak Regimes Close to ARIES-AT Parameters



FIRE will Emphasize Advanced Tokamak Goals

Burning Plasma Physics

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

Advanced Toroidal Physics

$f_{bs} = I_{bs}/I_p$	~ 80% (goal)
β_N	~ 4.0, n = 1 wall stabilized

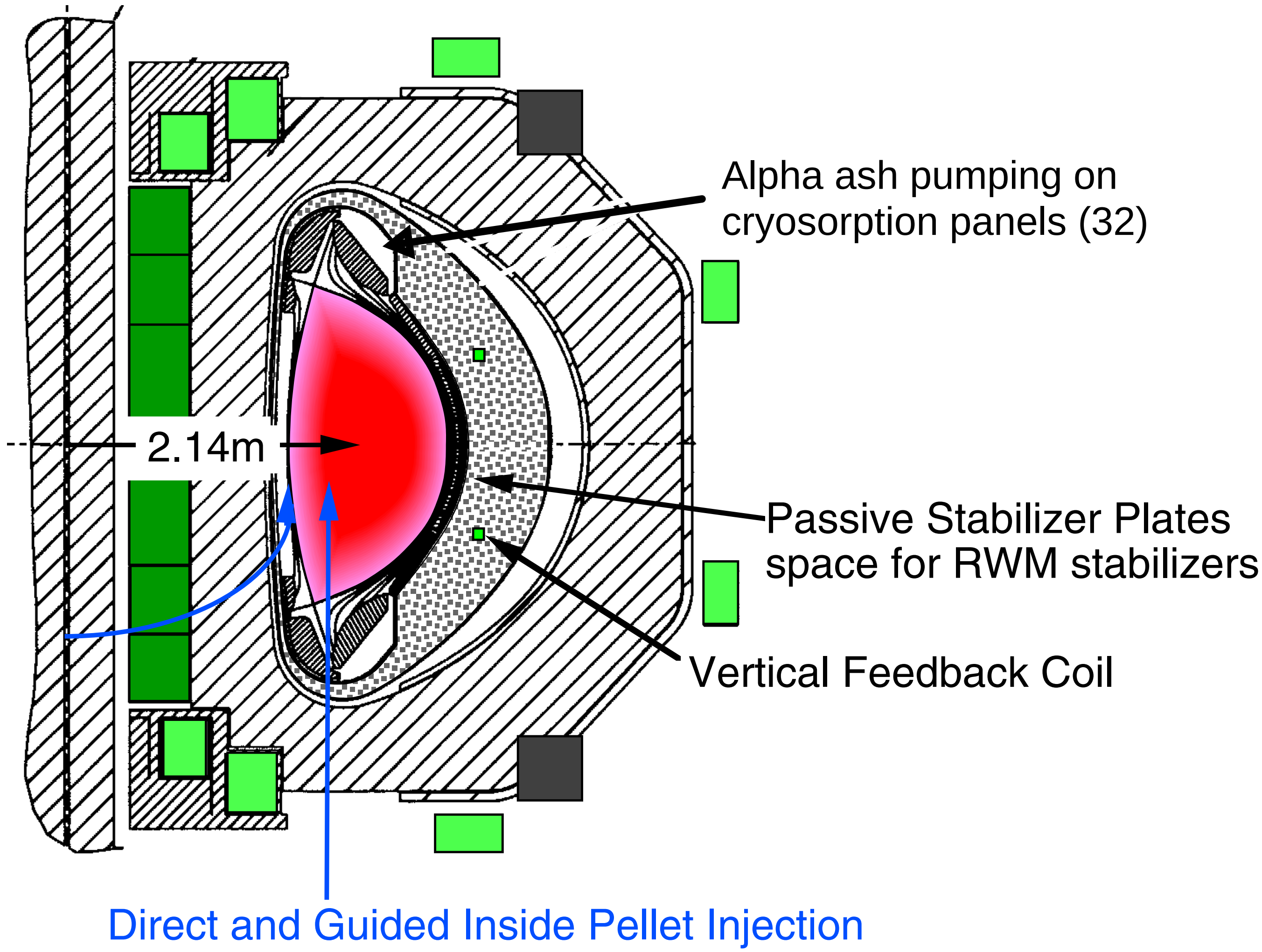
Quasi-stationary Burn Duration (use plasma time scales)

Pressure profile evolution and burn control	> 10 τ_E
Alpha ash accumulation/pumping	> several τ_{He}
Plasma current profile evolution	2 to 5 τ_{skin}
Divertor pumping and heat removal	several $\tau_{divertor}$

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



Fusion **I**gnition **R**esearch **E**xperiment

(FIRE)

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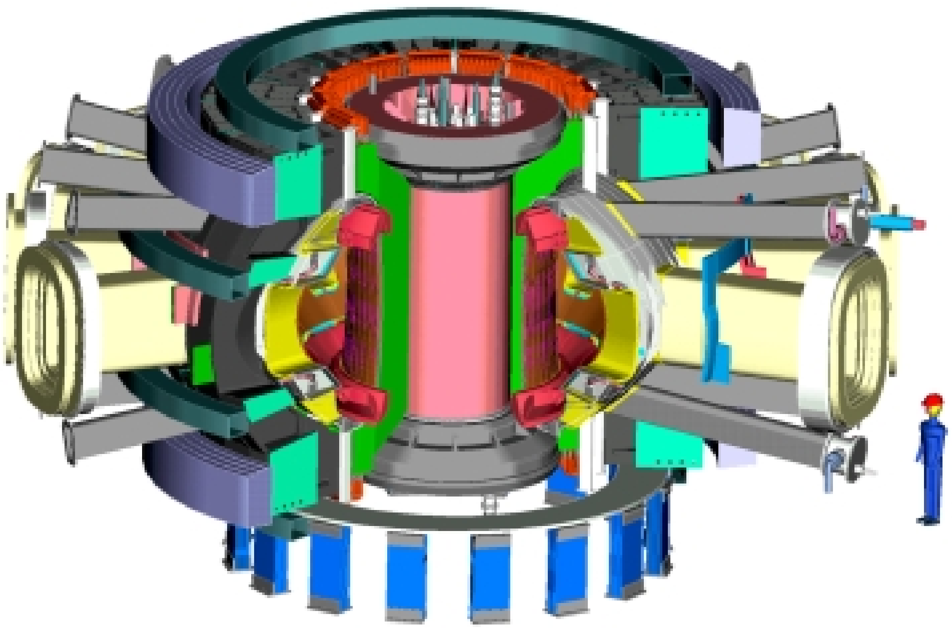


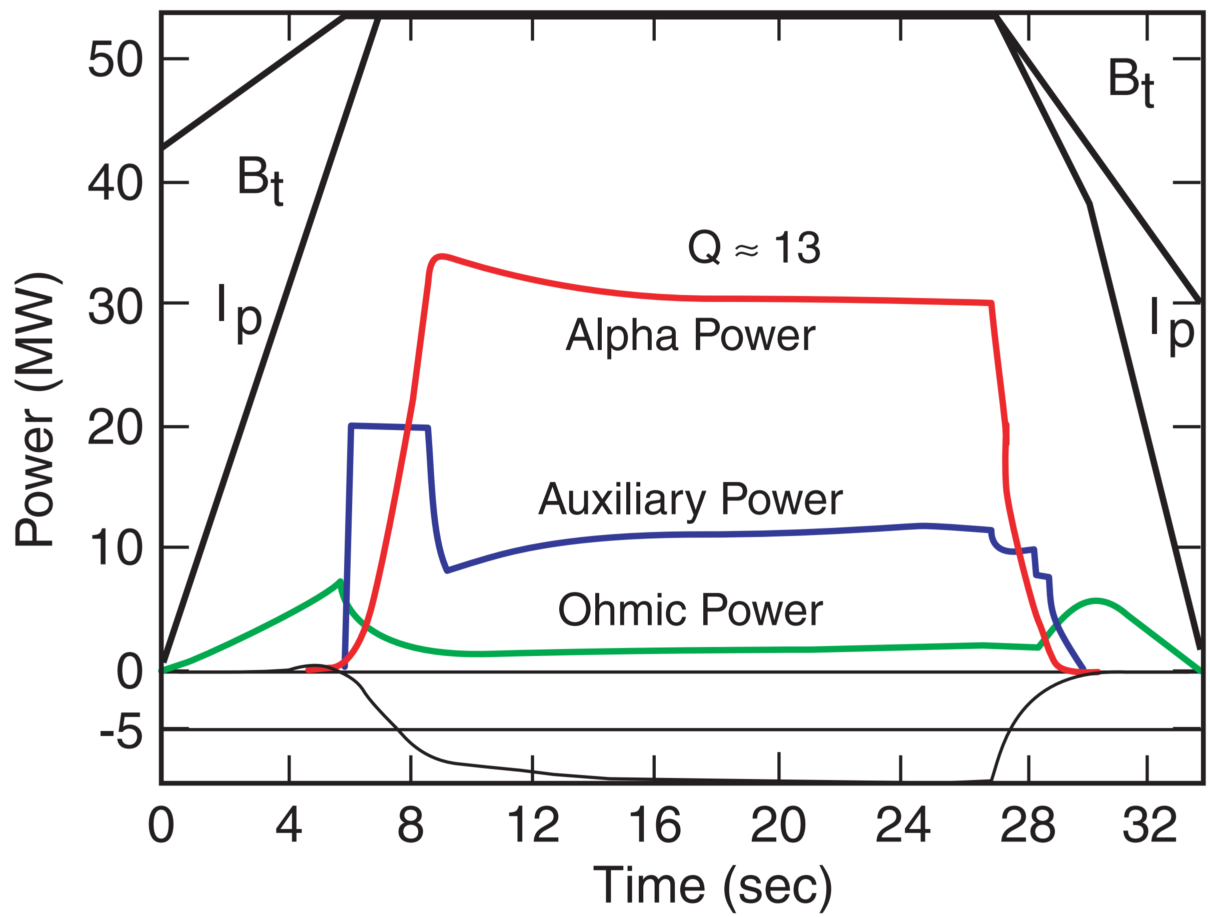
1,400 tonne

Design Features

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



B = 10 T

I_p = 7.7 MA

R = 2.14 m

A = 3.6

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

Q = Pfusion/(Paux + Poh)

Burning Plasma Initiatives or Task Forces

- Advanced Tokamak (U. S. Plan to achieve required capability-ARIES as guide) (κ, δ, A, SN/DN, β_N, f_{bs}, ……)
  - PFCs (high heat flux, tritium retention)
  - RWM Stabilization What is required and what is feasible?
  - Integrated Divertor and AT
- Plasma Control (heating, current-drive, fueling, fast position control)
- Integrated Simulation of Burning Plasmas
- Diagnostic Development, a long term program is needed.
- Plasma Facing Components for BPs and reactor.

Areas of Synergy and Possible Joint Work (FIRE, ITER)

- Plasma Facing Components (Divertor and First Wall)
  - high power density
  - long pulse capability
  - low tritium retention
  - elm erosion and disruption survivability
  - maintainability
- Vacuum Vessel (blanket modules and shielding port plugs)
  - low activation ?
  - nuclear heating ---- blanket module test assemblies
  - disruptions
  - integrate with closely coupled control/stabilization coils and diagnostics
- Plasma Heating, Current Drive and Fueling
  - development/design of ICRF, LHCD systems for BP scenarios
  - interface with fusion environment (esp. launchers)
- Diagnostics Development and Design Integration
  - new diagnostics for J(r), E(r), fluctuations, alpha particles
  - integration with fusion environment(e.g., radiation induced conductivity)
- Advanced tokamak modes approaching ARIES-RS/AT