Creating and Controlling a Burning Plasma in the Laboratory

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for the National FIRE Study Team

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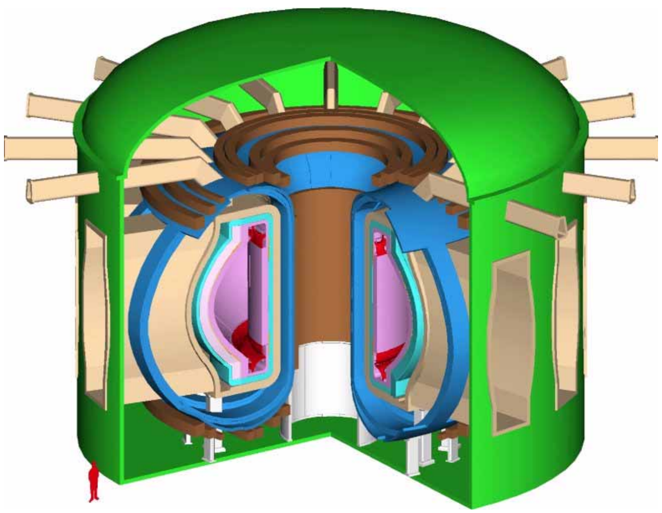
http://fire.pppl.gov

FIRE Lighting the Way to Fusion

VLT

A Decade of Studies has Identified the Requirements for Attractive Fusion Power

Fusion Power Plant ARIES-AT



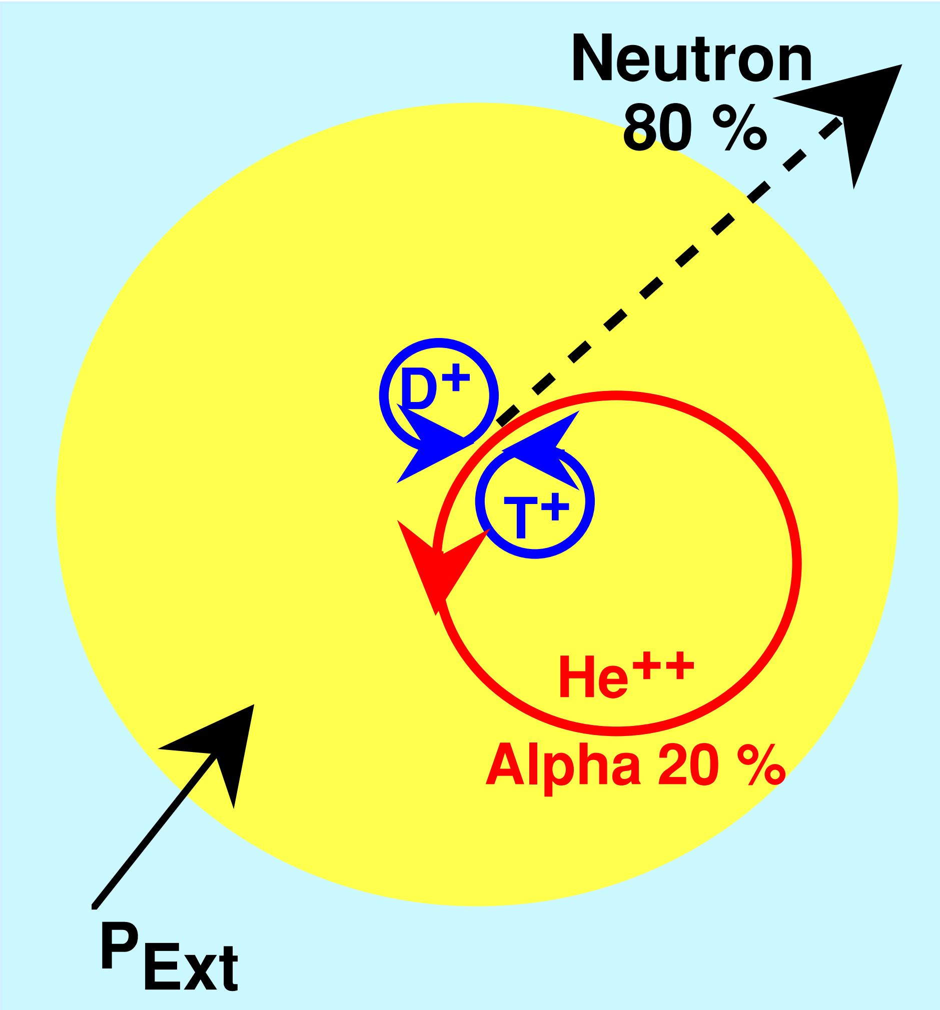
Fusion Power 1,800 MW
Plasma Volume 350 m^3

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) (~90%)

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

Self-Heating is Critical for a D-T Fusion Reactor

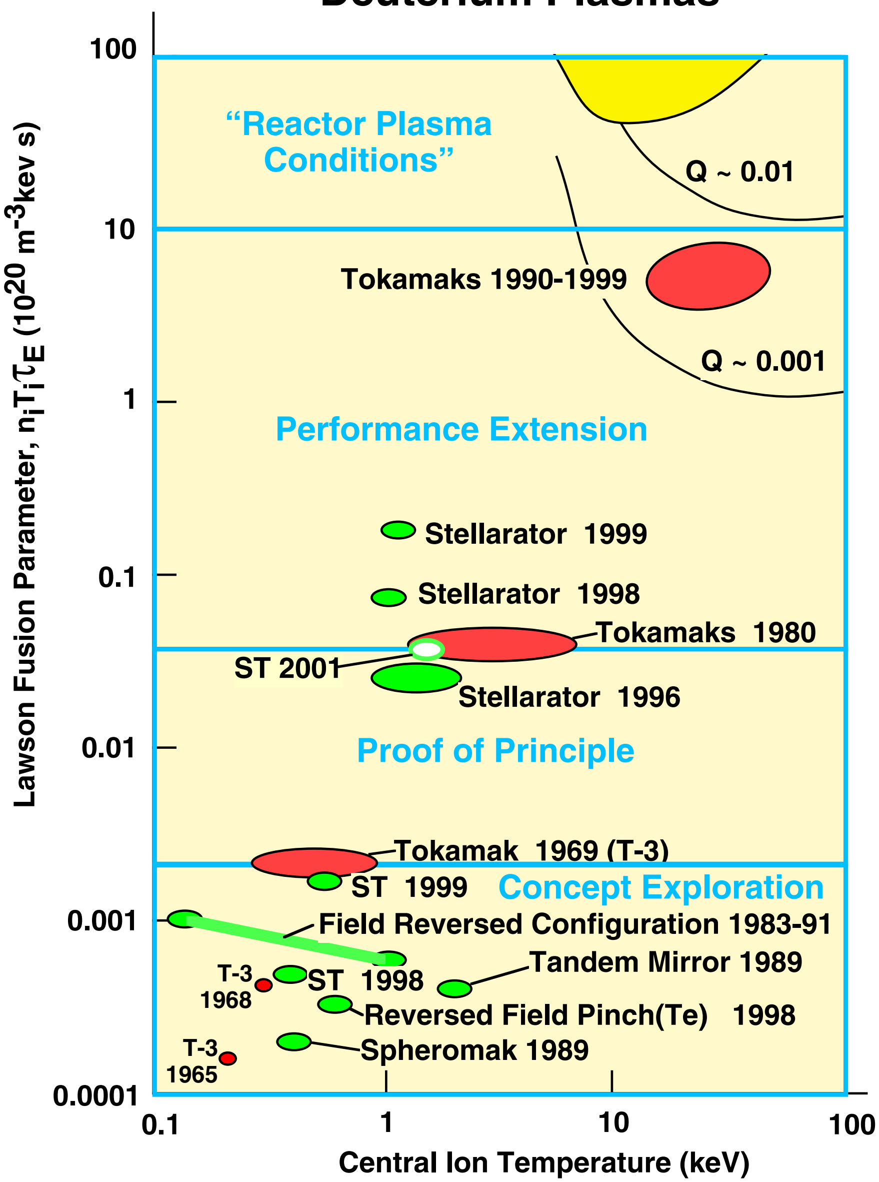


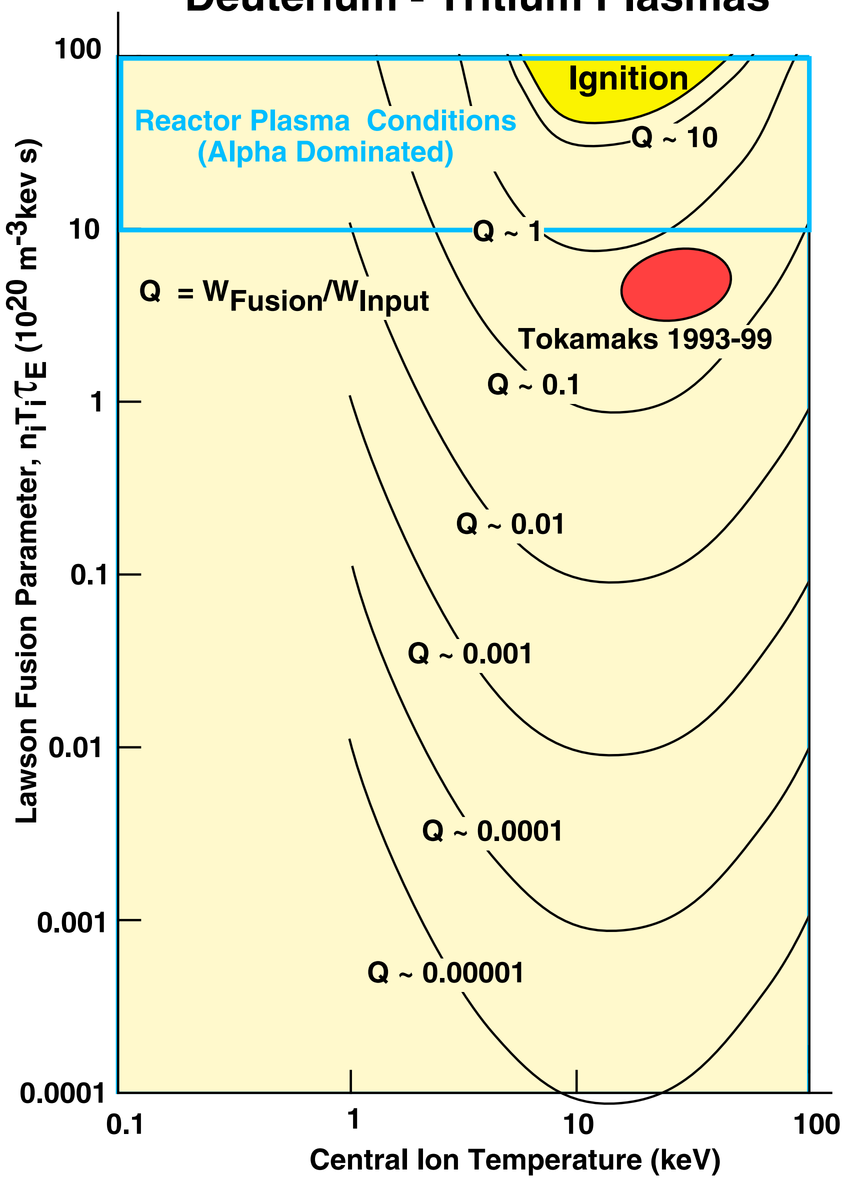
Alpha Physics Issues
• Alpha confinement • Alpha Energy to Plasma from alphas to plasma electrons • Burn Control • Alpha Ash Removal • Alpha Driven Instabilities

$$Q = \frac{P_{Fusion}}{P_{Ext}}, \quad f_{\alpha} = \frac{P_{alpha}}{P_{Heat}} = \frac{Q}{Q + 5}$$

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.

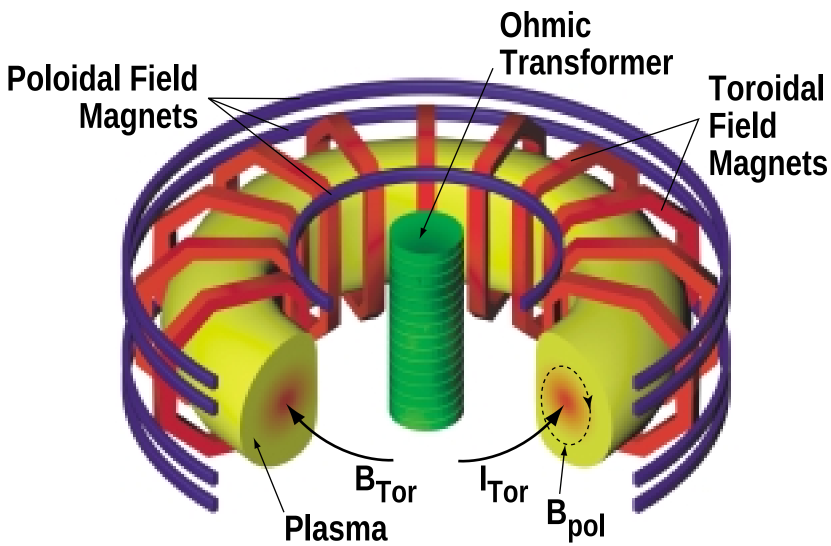
Magnetic Fusion is Technically Ready for a High Gain Burning Exp't

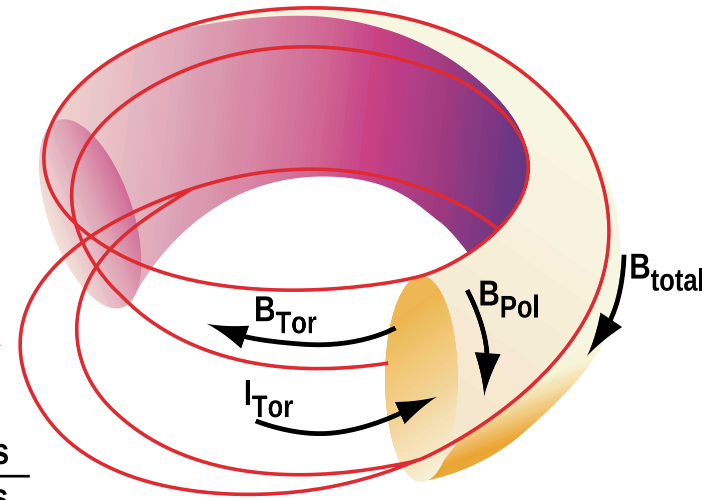




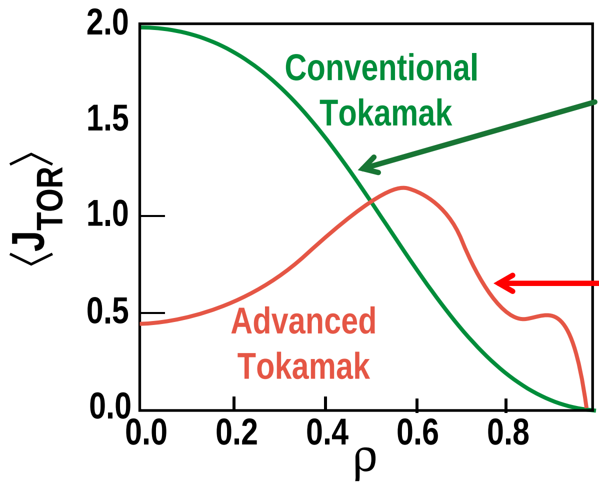
We are ready, but this step is our most challenging step yet.

THE MAGNETIC FIELD IN A TOKAMAK IS PRODUCED BY CURRENTS IN EXTERNAL COILS PLUS A CURRENT IN THE PLASMA



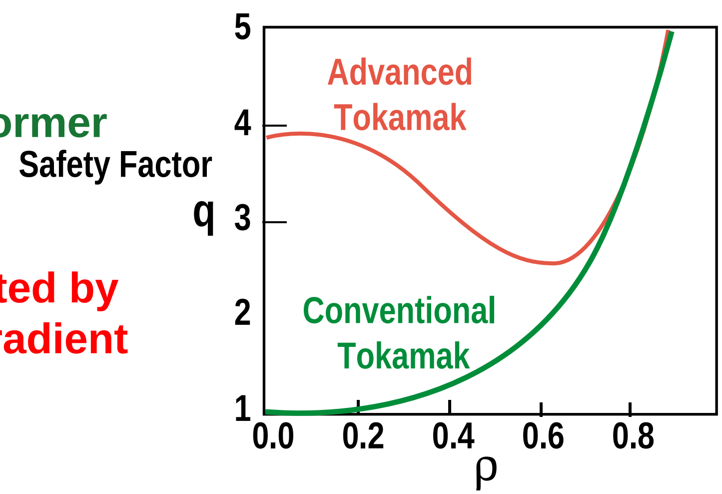


$$q = \frac{\#\text{Tor Circuits}}{\#\text{Pol Circuits}}$$



induced by
ohmic transformer

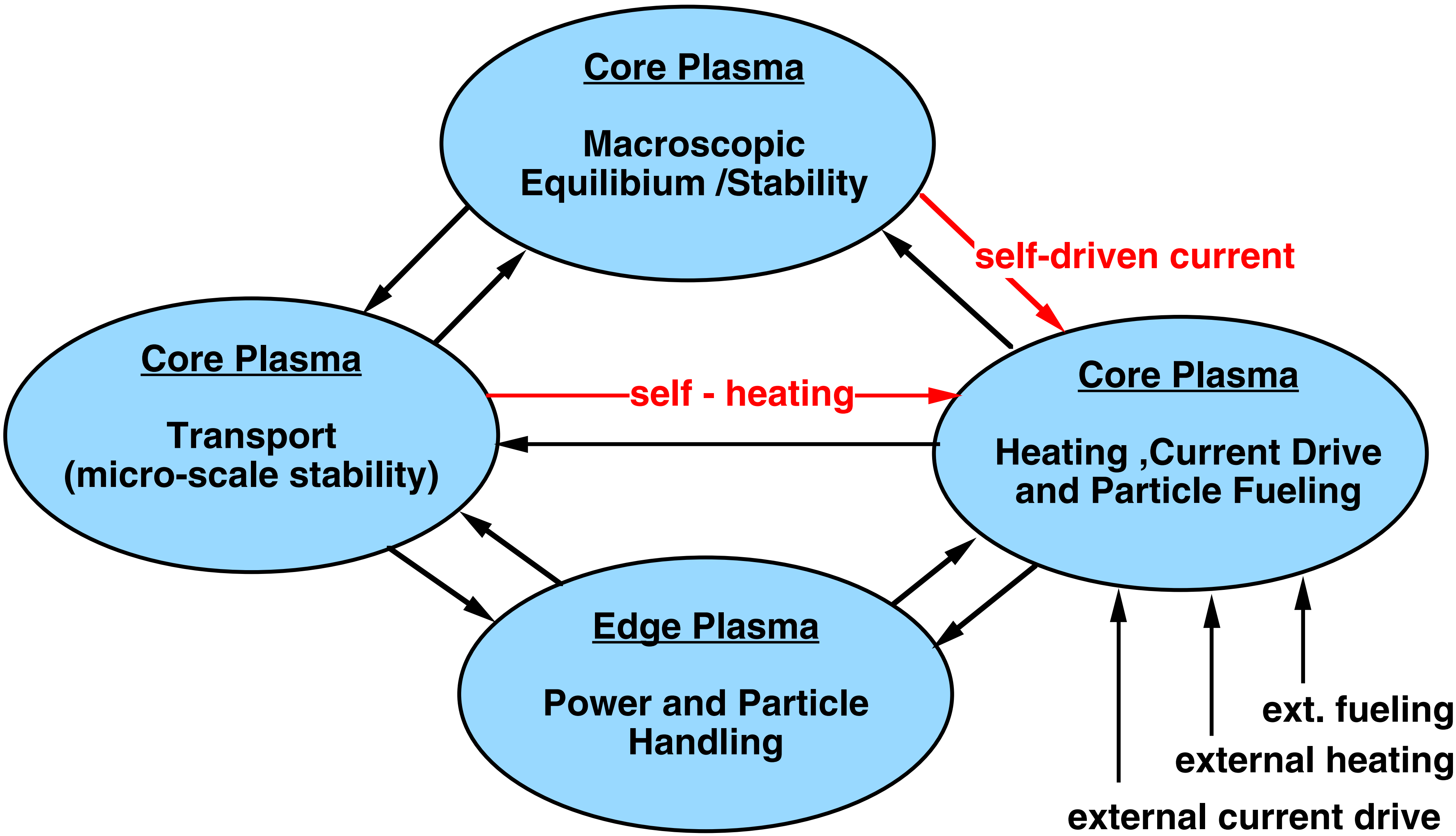
self generated by
pressure gradient



DIII–D
NATIONAL FUSION FACILITY
SAN DIEGO

130–02/TST/wj

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	~ 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

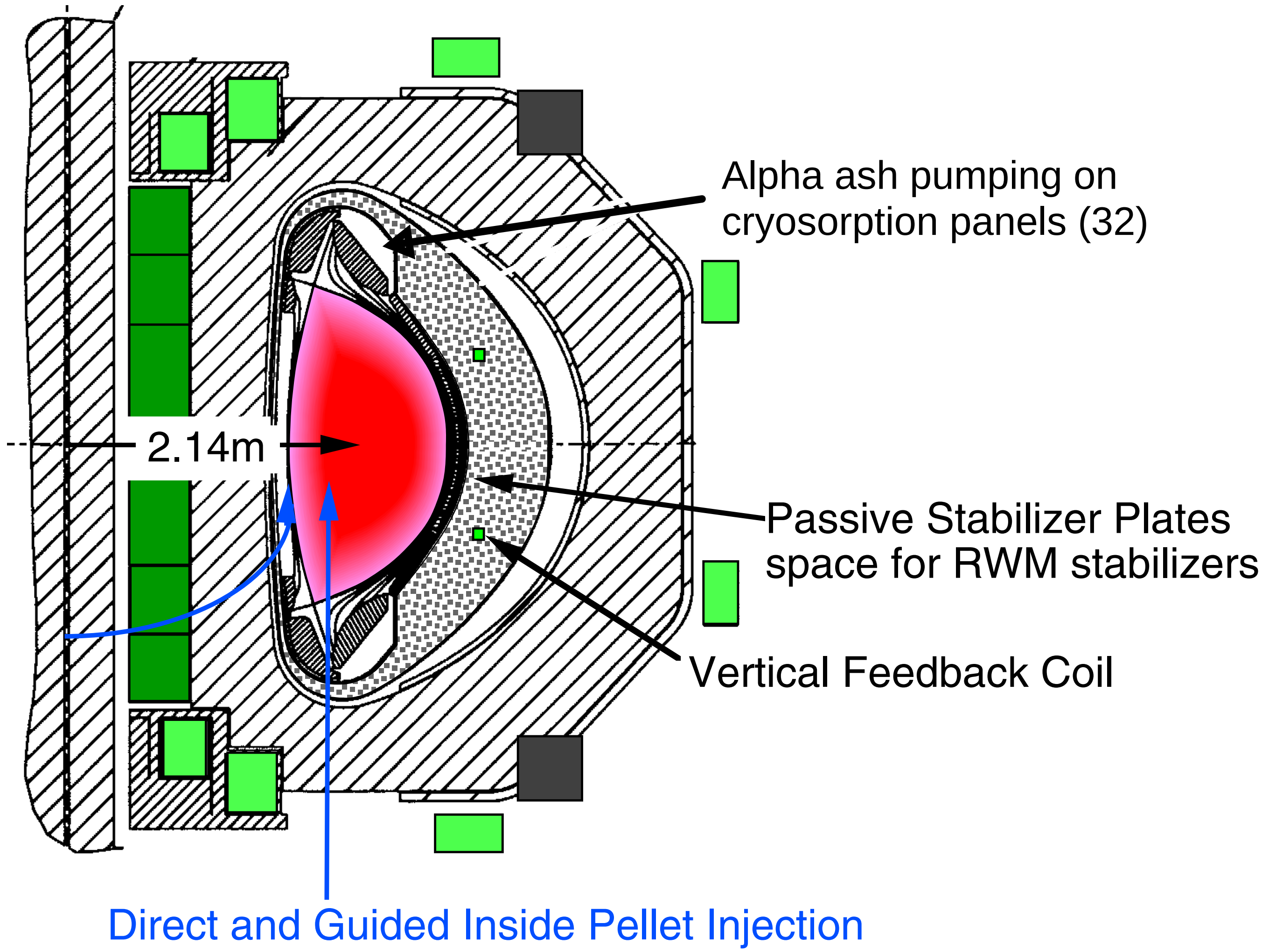
Quasi-stationary Burn Duration (use plasma time scales)

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 $\tau_{divertor}$

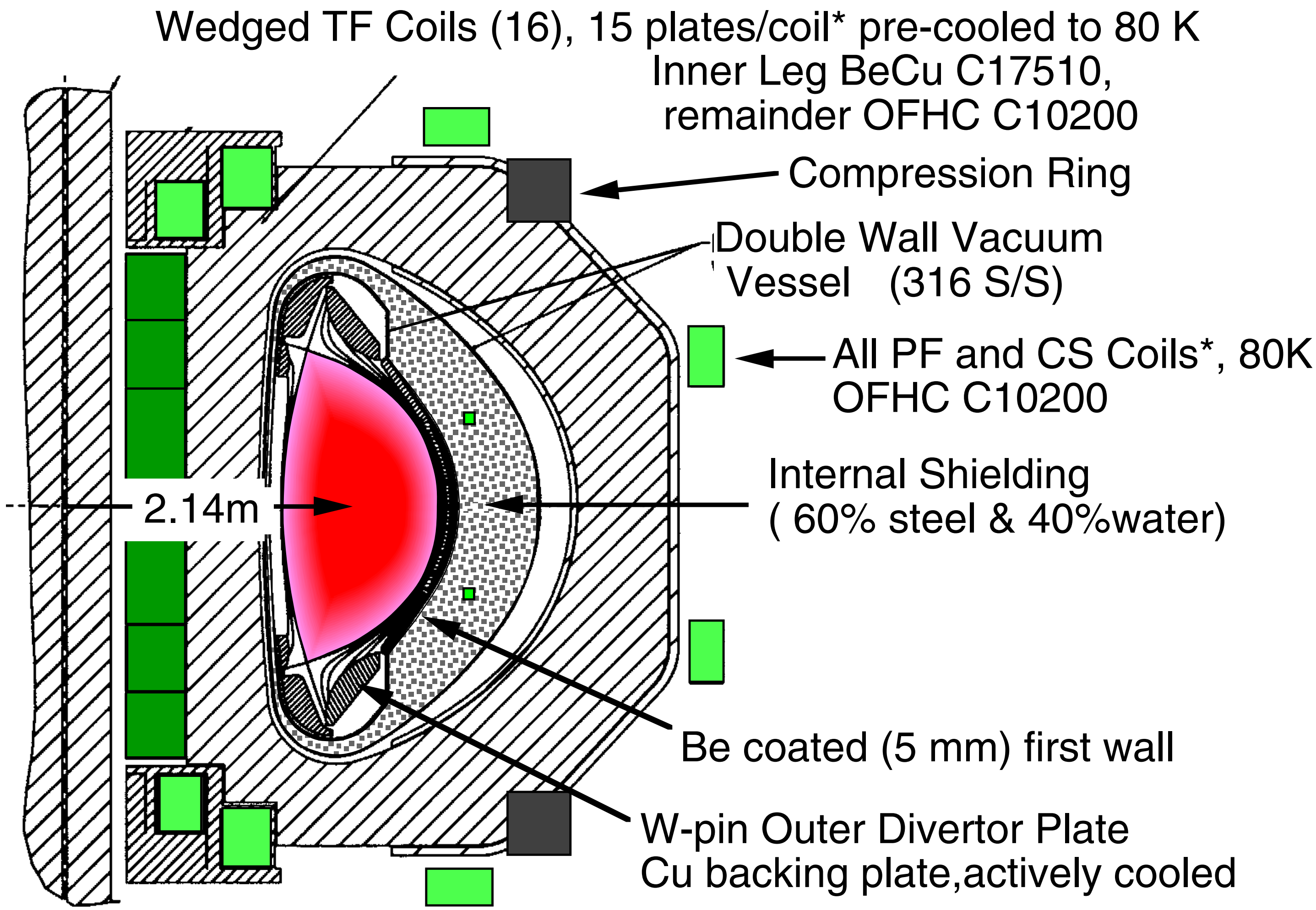
The FIRE Design has Adopted ARIES-RS Plasma Features

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



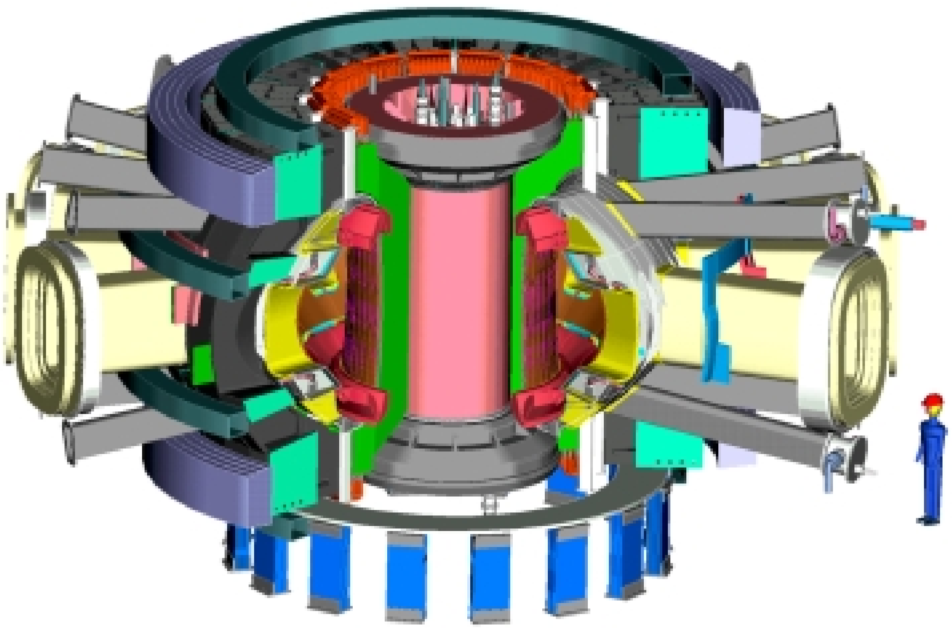
FIRE Engineering Features



FIRE will push plasma facing components for the wall and divertor toward reactor power densities.

Fusion Ignition Research Experiment (FIRE)

http://fire.pppl.gov



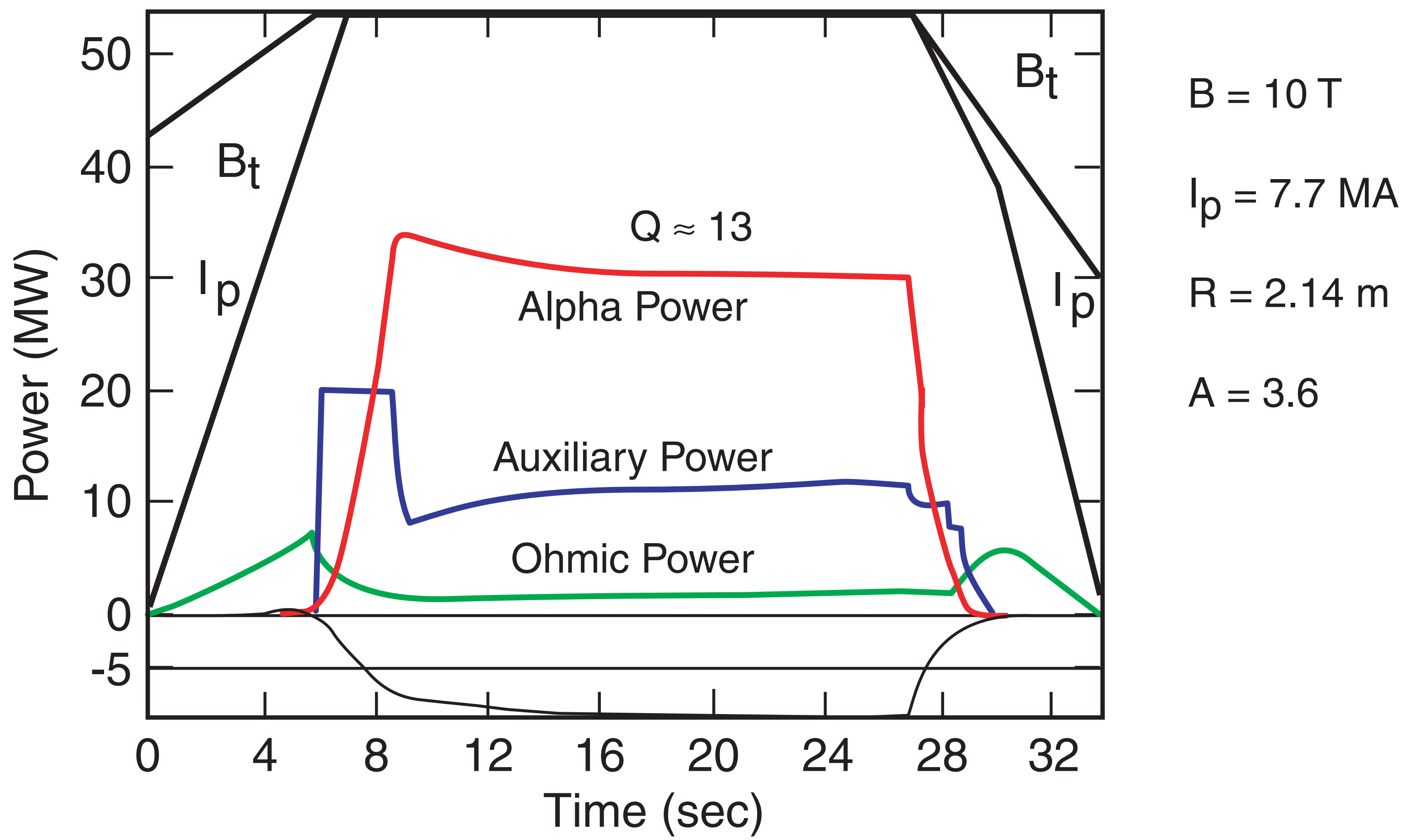
1,400 tonne

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
- $Q \approx 10$, $P_{fusion} \sim 150$ 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



- 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 s $\approx 21\tau_E \approx 4\tau_{He} \approx 2\tau_{CR}$

Q = Pfusion/(Paux + Poh)

FIRE Simulation Project

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

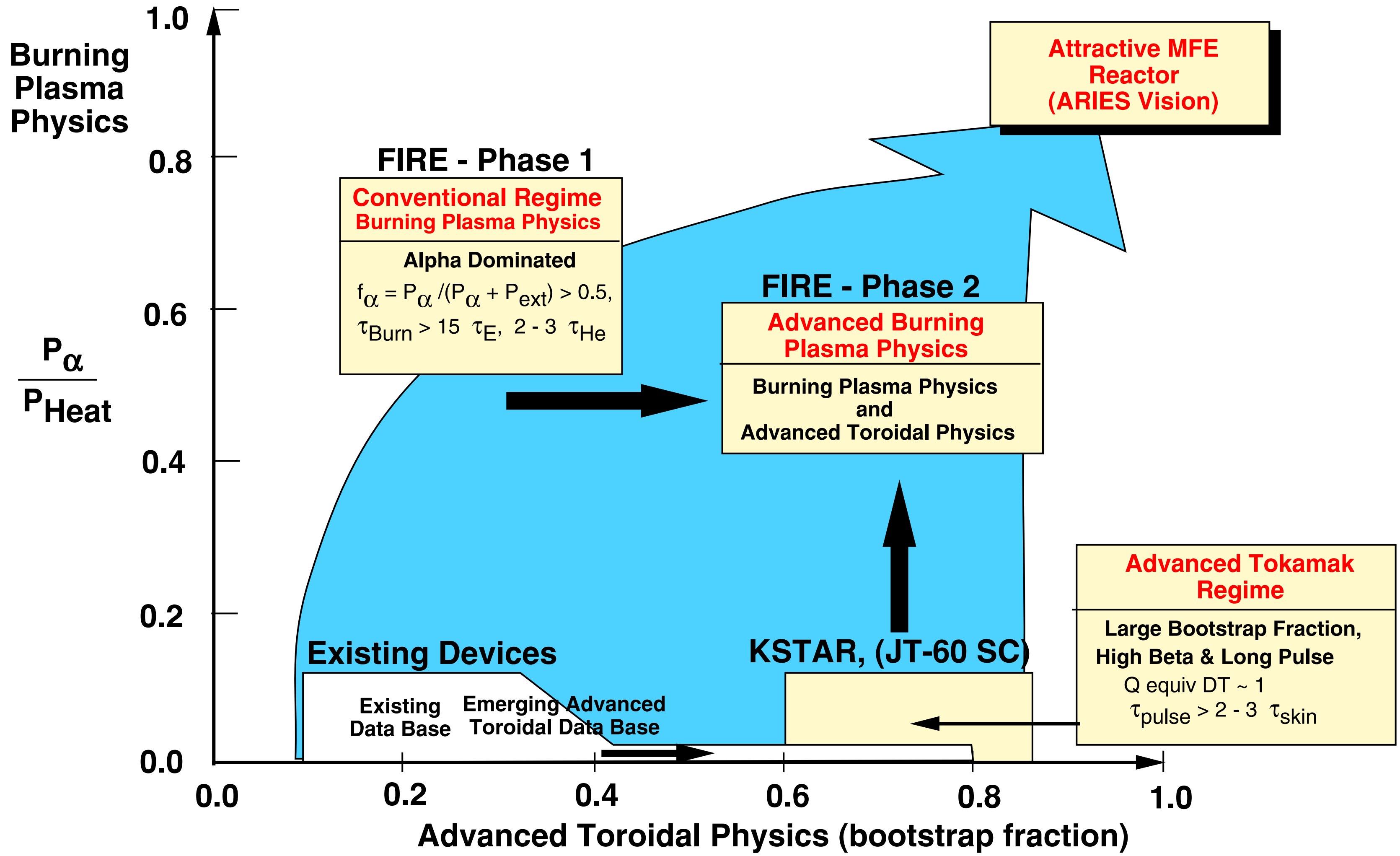
Conventional Mode

~ 70% self heating

~20% self generated confining magnetic field

5.5 MW/m3
Fusion Power density
(reactor level)

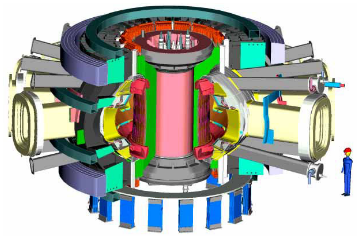
Staged Approach to Burning Plasma Operation
Conventional Mode then Advanced Mode.



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)

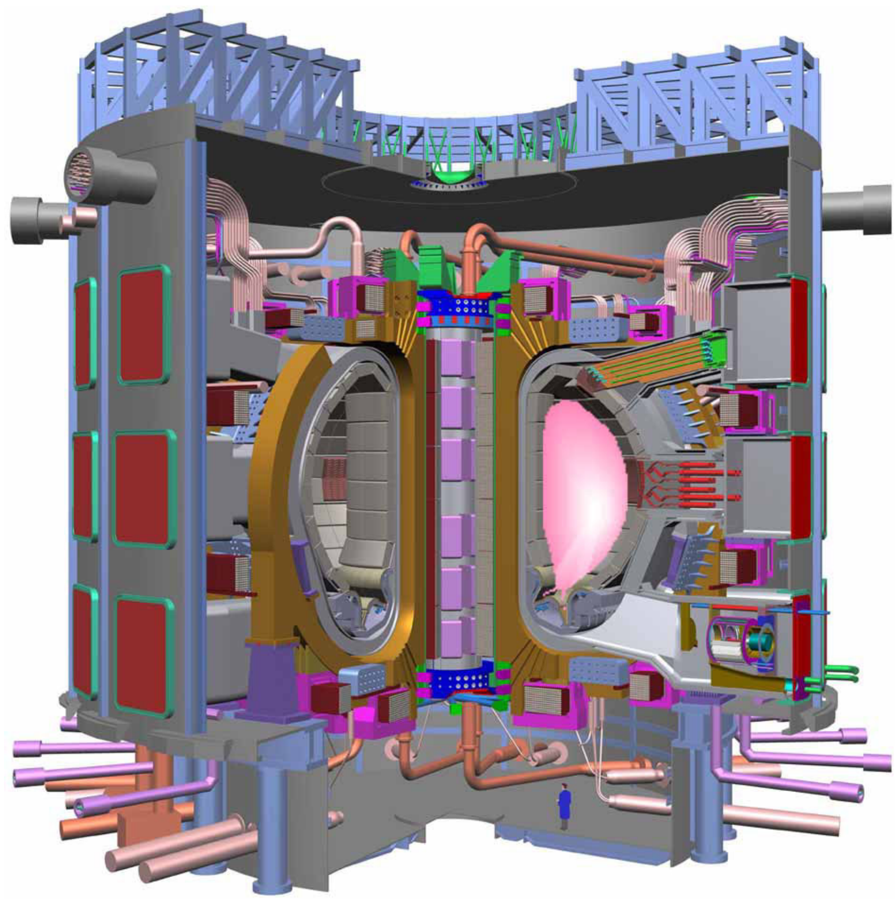
Conventional Operation

Q ~ 10 @ 86% J(r) equilibration
(FIRE and ITER)

Advanced Operation

Q ~ 5, f_{bs} ~ 80%, β_N ~ 4 @ 98% equil.
(FIRE)

Q ~ 5, f_{bs} ~ 50%, β_N ~ 3 @ 99.9% equil.
(ITER)



ITER ($ 5B - 19 ktonne)

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