
FIRE Overview

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for the FIRE Team

**Prepared for
Uniform Assessment
Snowmass Fusion Summer Study**

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<http://fire.pppl.gov>

FIRE

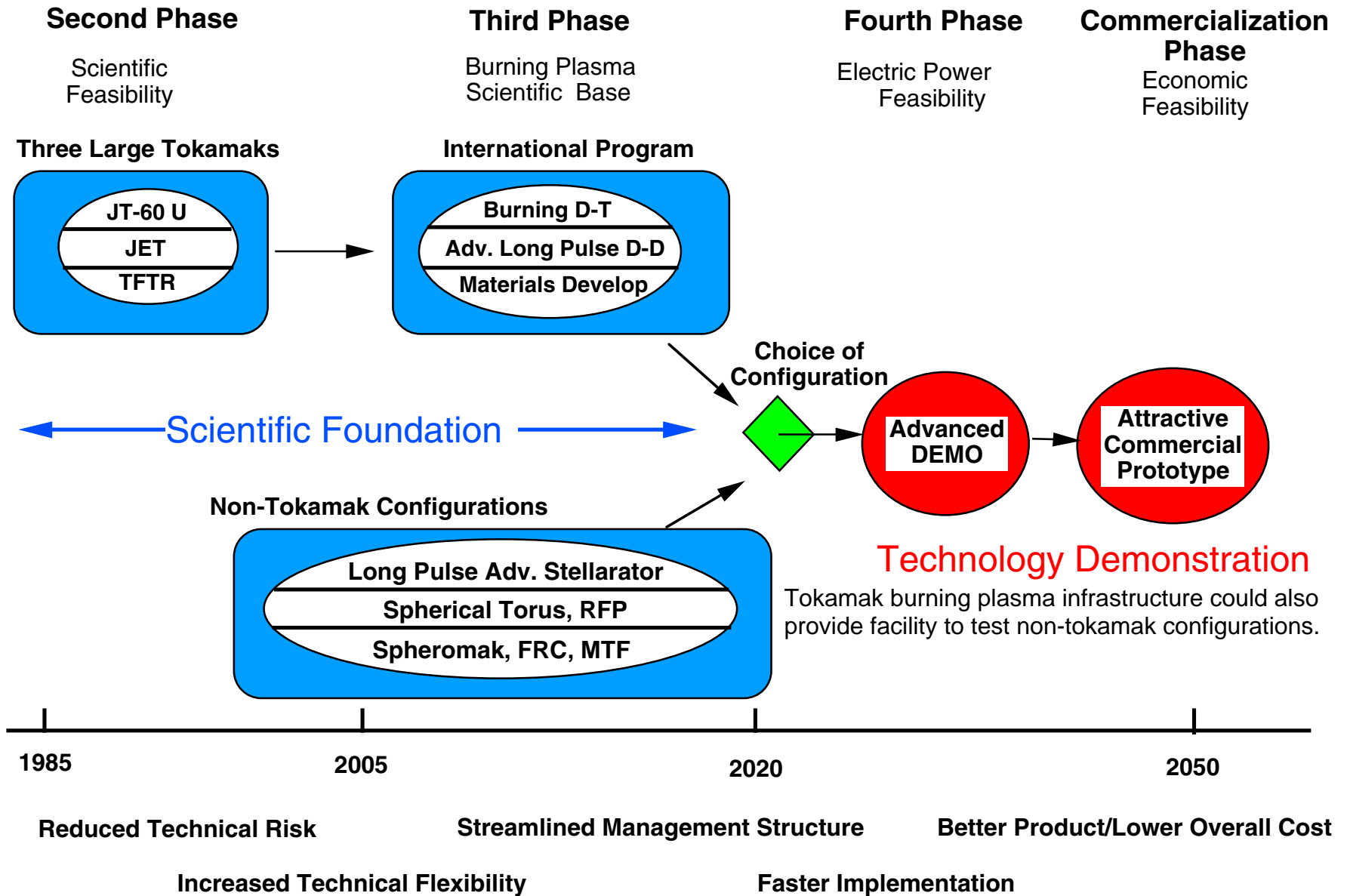
Lighting the Way to Fusion



Critical Issues to be Addressed by the Next Stage of Fusion Research

- **Burning Plasma Physics**
 - strong nonlinear coupling inherent in a fusion dominated plasma
 - access, explore and understand fusion dominated plasmas
 - **Advanced Toroidal Physics**
 - develop and test physics needed for an attractive MFE reactor
 - couple with burning plasma physics
 - **Boundary Physics and Plasma Technology** (coupled with above)
 - high particle and heat flux
 - couple core and divertor
 - fusion plasma - tritium inventory and helium pumping
 - **Neutron Resistant Materials** (separate facility)
 - high fluence testing using “point” neutron source
-
- Superconducting Coil Technology does not have to be coupled to physics experiments - only if needed for physics objectives
 - Nuclear Component Testing should wait for the correct reactor materials

The Modular Strategy for MFE



(the overall Modular Strategy includes IFE)

Fusion Science Objectives for a Major Next Step Burning Plasma 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.

Need to develop an integrated burning plasma simulation with good visualization output - useful for design phase, experimental phase and to provide the transfer to other configurations and “DEMO”.

Advanced Burning Plasma Exp't Requirements

Burning Plasma Physics

$Q \geq 5$, ~ 10 as target, ignition not precluded

$f_\alpha = P_\alpha/P_{\text{heat}} \geq 50\%$, $\sim 66\%$ as target, up to 83% at $Q = 25$

TAE/EPM stable at nominal point, able to access unstable

Advanced Toroidal Physics

$f_{\text{bs}} = I_{\text{bs}}/I_p$ ($\sim 25\%$ in H-Mode) $\geq 50\%$ as target AT up to 75% allowed

$\beta_N \sim 2.5$, no wall ~ 3.6 , $n = 1$ wall stabilized

Quasi-stationary

Pressure profile evolution and burn control $> 10 \tau_E$

Alpha ash accumulation/pumping $> \text{several } \tau_{\text{He}}$

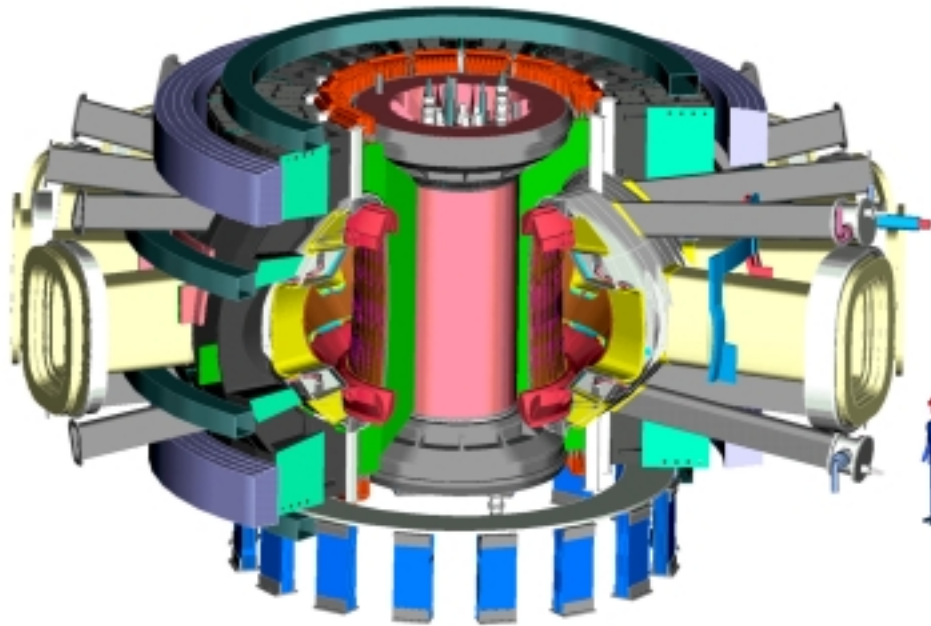
Plasma current profile evolution $1 \text{ to } 3 \tau_{\text{skin}}$

Divertor pumping and heat removal $\text{several } \tau_{\text{divertor}}, \tau_{\text{first wall}}$

Fusion Ignition Research Experiment

(FIRE)

<http://fire.pppl.gov>



Design Features

- $R = 2.14 \text{ m}$, $a = 0.595 \text{ m}$
- $B = 10 \text{ T}$
- $W_{\text{mag}} = 5.2 \text{ GJ}$
- $I_p = 7.7 \text{ MA}$
- $P_{\text{aux}} \leq 20 \text{ MW}$
- $Q \approx 10$, $P_{\text{fusion}} \sim 150 \text{ MW}$
- Burn Time $\approx 20 \text{ s}$
- Tokamak Cost $\approx \$375\text{M}$ (FY99)
- Total Project Cost $\approx \$1.2\text{B}$ at Green Field site.

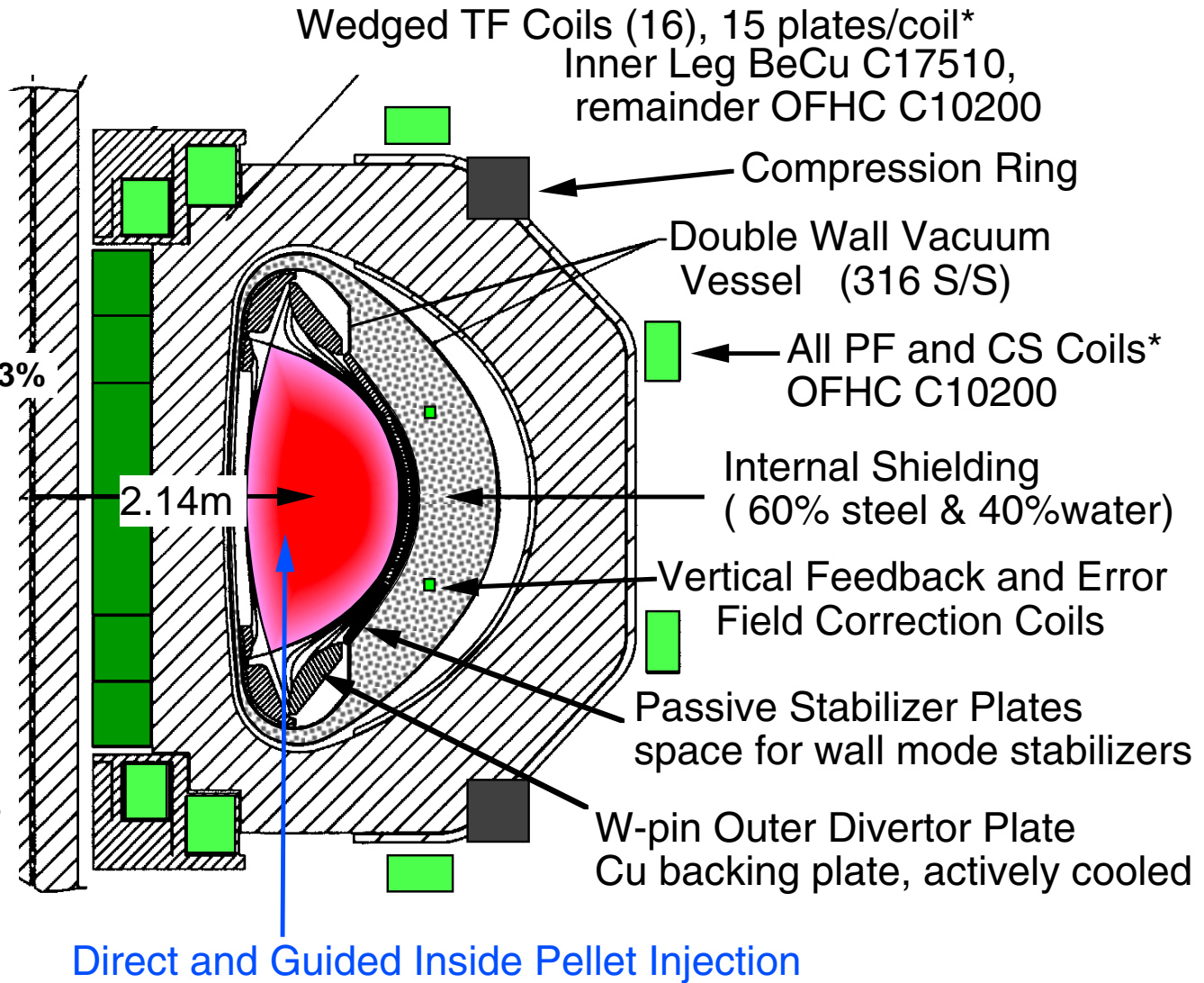
Mission:

Attain, explore, understand and optimize magnetically confined fusion-dominated plasmas.

FIRE Baseline for Snowmass Assessment

AT Features

- DN divertor
- strong shaping
- very low ripple $< 0.3\%$
- 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.

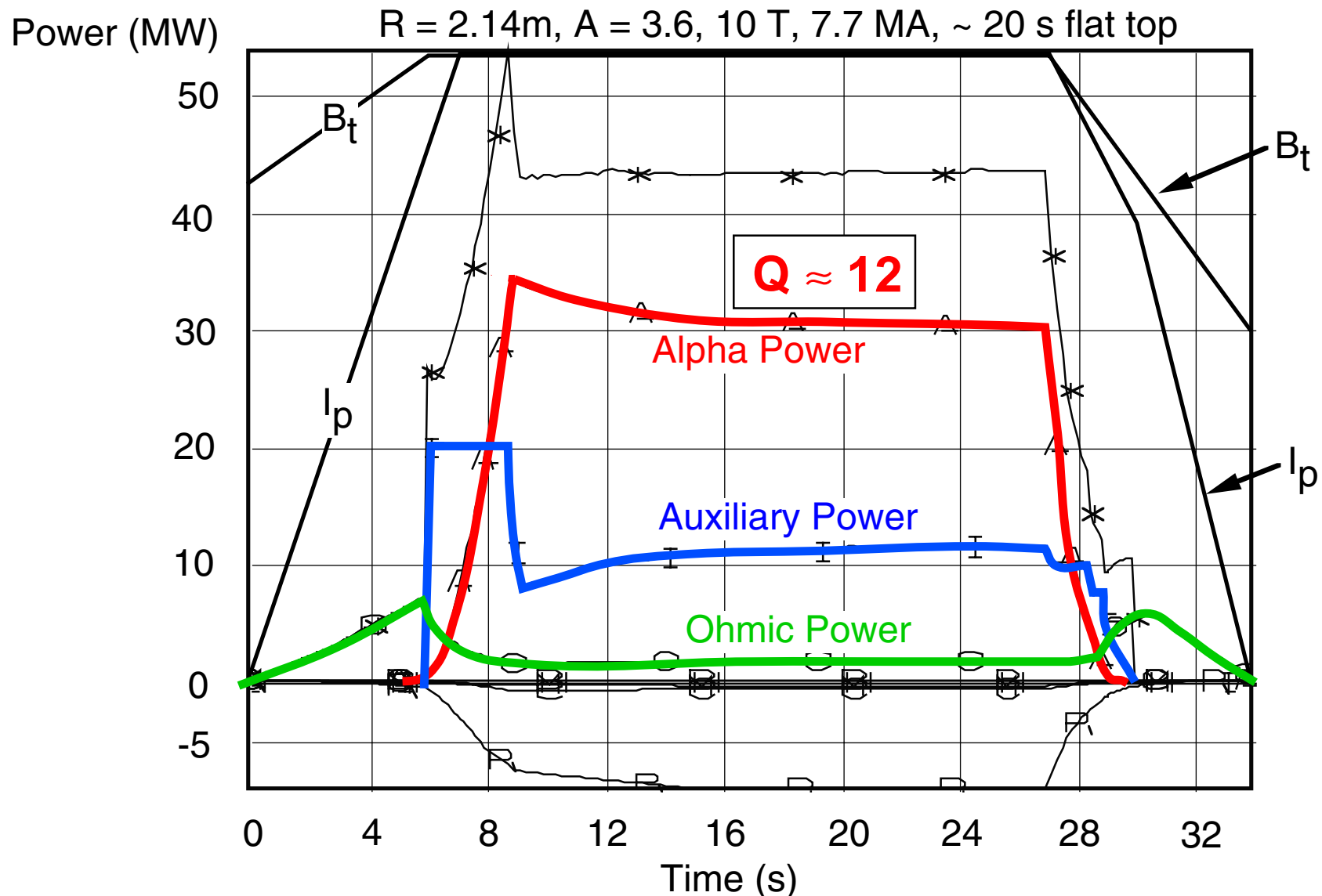
Basic Parameters and Features of FIRE

R, major radius	2.14 m
a, minor radius	0.595 m
κ_x, κ_{95}	2.0, 1.77
δ_x, δ_{95}	0.7, 0.55(AT) - 0.4(OH)
q ₉₅ , safety factor at 95% flux surface	>3
B _t , toroidal magnetic field	10 T with 16 coils, 0.3% ripple @ Outer MP
Toroidal magnet energy	5.8 GJ
I _p , plasma current	7.7 MA
Magnetic field flat top, burn time	28 s at 10 T in dd, 20s @ P _{dt} ~ 150 MW)
Pulse repetition time	~3hr @ full field and full pulse length
ICRF heating power, maximum	20 MW, 100MHz for 2Ω _T , 4 mid-plane ports
Neutral beam heating	Upgrade for edge rotation, CD - 120 keV PNBI?
Lower Hybrid Current Drive	Upgrade for AT-CD phase, ~20 MW, 5.6 GHz
Plasma fueling	Pellet injection (≥2.5km/s vertical launch inside mag axis, guided slower speed pellets)
First wall materials	Be tiles, no carbon
First wall cooling	Conduction cooled to water cooled Cu plates
Divertor configuration	Double null, fixed X point, detached mode
Divertor plate	W rods on Cu backing plate (ITER R&D)
Divertor plate cooling	Inner plate-conduction, outer plate/baffle- water
Fusion Power/ Fusion Power Density	150 - 200 MW, ~6 -8 MW m ⁻³ in plasma
Neutron wall loading	~ 2.3 MW m ⁻² Limits pulse length in some AT modes
Lifetime Fusion Production	5 TJ (BPX had 6.5 TJ)
Total pulses at full field/power	3,000 (same as BPX), 30,000 at 2/3 B _t and I _p
Tritium site inventory	Goal < 30 g, Category 3, Low Hazard Nuclear Facility

FIRE Plasma Parameters (Elmy H-Mode, Q = 10)

R_plasma/ a_plasma	2.14 / 0.595
A	3.6
κ_a	1.81
δ_{95}	0.4
$\langle n_e \rangle$, $10^{20} / m^3$	4.55
Paux (MW)	14.5
Pheat (MW) = Ploss	34
Bt(T) / Ip(MA)	10 / 7.7
Ion Mass	2.5
H(y,2)-ITER98	1.11
H-ITER 89P	2.61
alpha_n / alpha_T	0.2 / 1.0
li(3)	0.8
$\tau_{up}^*(He)/\tau_{uE}$	5
Cbs	0.7
f_bs	0.27
v^*	0.058
$1/\rho^*(uses To)$	352
β (thermal only), %	2.24
q95	3.05
$\langle n \rangle / greenwald$	0.70
P_fusion (MW)	150.7
Pheat/P(L->H)	1.29
Q_DT* = Pfusion/Paux	10.39
Q_DT = Pf/(Pext + Poh)	10.01
fraction_alpha heating	0.67
τ_{uE}	1.04
$n_i(0)\tau_{ETi}(0)$	52.27
skin time	12.23
W(MJ), thermal / W alpha (MJ)	35.3 / 2.3
beta_alpha, %	0.15
Rgradbeta_alpha	0.04
v_{α}/v_{alfven}	2.01
beta_total, %	2.38
beta_N	1.84
eps*betap	0.20
$\langle T \rangle_n / To$	6.47 / 11.04
Zeff	1.41
Be concentration, %	3.00
Ar concentration, %	0.00
He concentration, %	2.30
Ploss/ $2\pi R_x / n_{div}$ (MW/m)	1.48

1 1/2-D Simulation of Elmy H-Mode in FIRE (TSC)



- ITER98(y,2) scaling with $H(y,2) = 1.1$, $n(0)/\langle n \rangle = 1.2$, and $n/n_{GW} = 0.67$

- Burn Time $\approx 20 \text{ s} \approx 21 \tau_E \approx 4 \tau_{He} \approx 2 \tau_{skin}$

$$Q = P_{fusion} / (P_{aux} + P_{oh})$$

1 1/2 D Simulation of a Burning (Self-Drive > 50%) Plasma in FIRE

- $\chi(r)$ matching exp't data, $H(y, 2) = 1.6$, other models available (eg. GLF23)
- $\beta_N = 3.0$, $f_{BS} = 64\%$, reversed shear, $q_{min} \approx 2.7$ at $r/a \approx 0.8$, 3/2,5/2 NTM stable

partial wall for $n=1$

60 % self-heated

64% self-current drive

