Burning Plasma Experiment Requirements and FIRE

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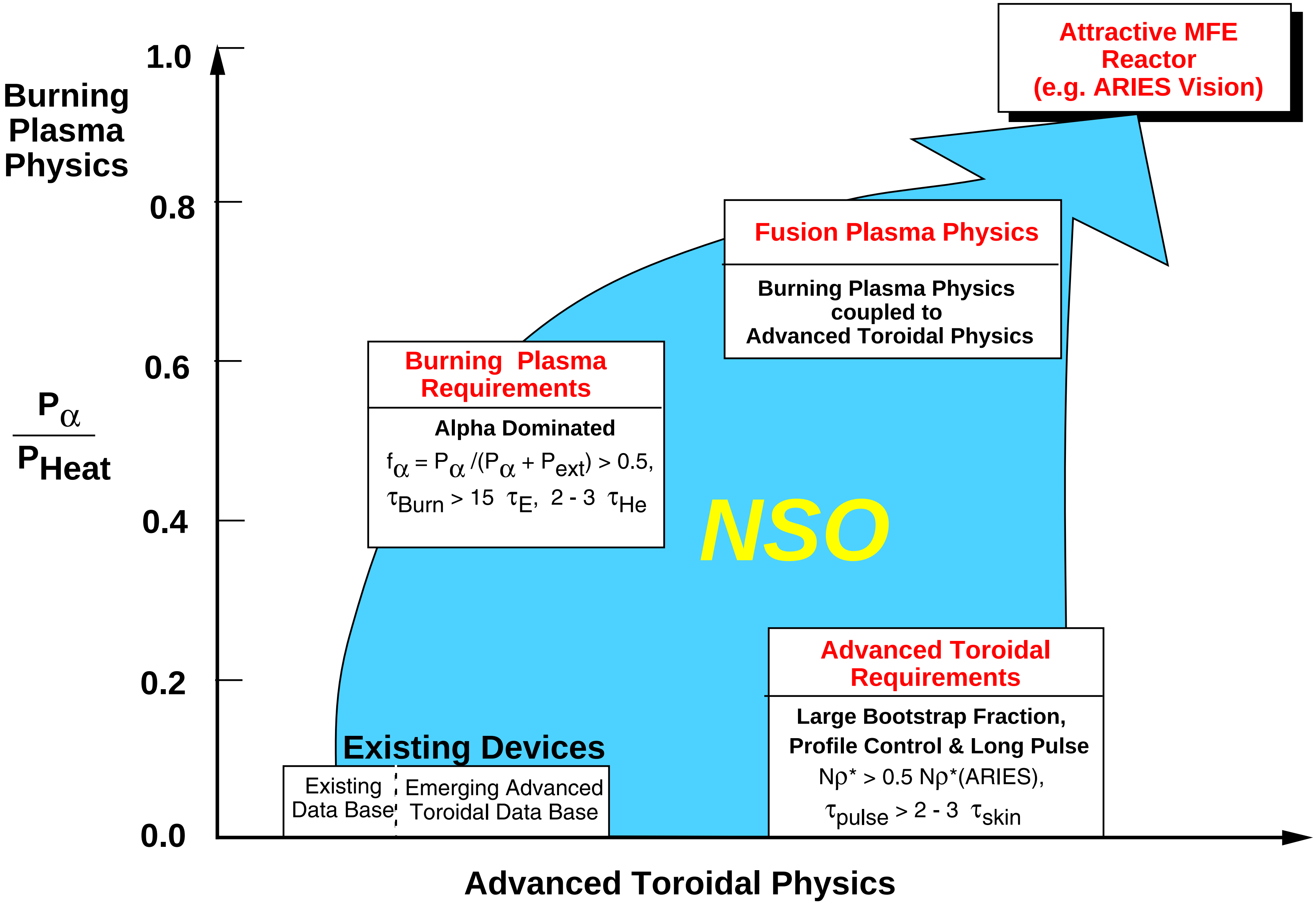
Fusion Science Objectives for a Major Next Step Experiment

- Explore and understand the physics of alpha-dominated fusion plasmas:
  - Energy and particle transport (extend confinement predictability)
  - Macroscopic stability (β-limit, wall stabilization, NTMs)
  - Wave-particle interactions (fast alpha driven effects)
  - Plasma boundary (density limit, power and particle flow)
  - Strong coupling of previous issues due to self-heating(self-organization?)
- Test techniques to control and optimize alpha-dominated plasmas.
- Sustain alpha-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 some advanced operating modes and configurations that have the potential to lead to attractive fusion applications.

We must Burn to Learn!!

F. Perkins and N. Sauthoff, FIRE Wkshp

A Next Step Option (NSO) Should Provide the Capability to Explore Burning Plasma Physics, Advanced Toroidal Physics and their Coupling.



Attractive MFE Reactor (e.g. ARIES Vision)

Fusion Plasma Physics

Burning Plasma Physics coupled to Advanced Toroidal Physics

Burning Plasma Requirements

Alpha Dominated

$f_\alpha = P_\alpha/(P_\alpha + P_{ext}) > 0.5$,

$\tau_{Burn} > 15\ \tau_E,\ 2 - 3\ \tau_{He}$

Advanced Toroidal Requirements

Large Bootstrap Fraction, Profile Control & Long Pulse

$N\rho^* > 0.5\ N\rho^*(\text{ARIES})$,

$\tau_{pulse} > 2 - 3\ \tau_{skin}$

Existing Data Base

Emerging Advanced Toroidal Data Base

Dimensionless Parameters Required for Fusion Plasma Physics Experiment

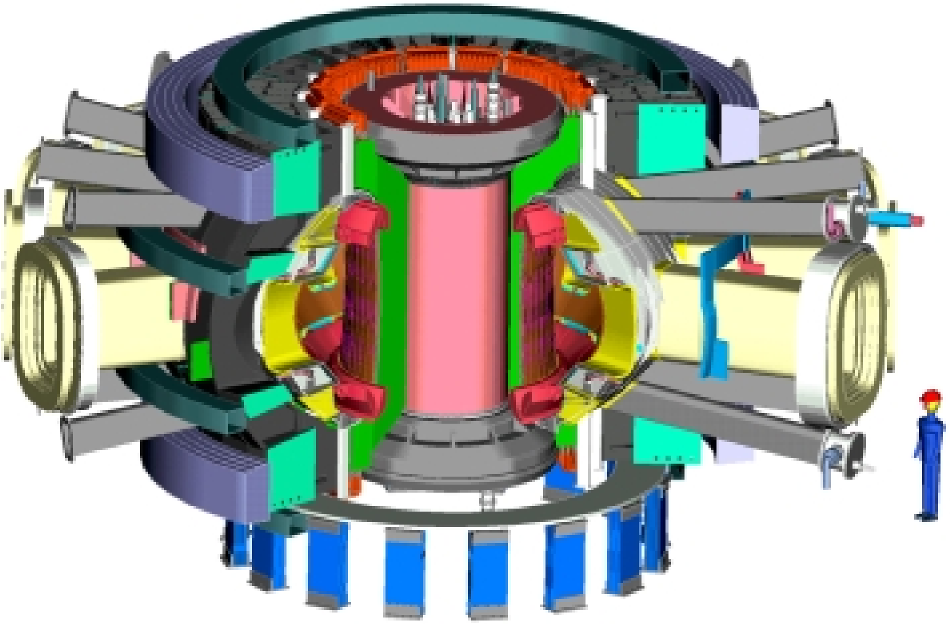
	Core*	**Edge**	**Alpha**	**Duration**			
	$BR^{5/4}$	**?**	**P_α/P_{heat}**	$\tau/\tau_{\alpha s}$	τ/τ_E	τ/τ_{He}	τ/τ_{CR}
<u>Explore and Understand Fusion Plasmas</u>	>0.5		>0.5	>3	>5	>3	>3
Energy and Particle Transport							
Macroscopic Stability							
Wave Particle (alpha heating, fast alpha)			β_α ~ ARIES				
Plasma Boundary		?					
<u>Test Control and Optimization Techniques</u>	>0.5		0.4 to 0.6		10	>3	1
<u>Sustain Alpha Dominated Plasmas</u>	>0.5				10		
Exhaust of power, particles and ash			0.4 to 0.6			3 to 5	
Profile evolution impact on τE, MHD			0.5 to 0.8				1.5 to 3
<u>Explore and Understand Some AT Modes</u>			0.5 to 0.8		>10	5	1.5 to 3
ARIES-AT	**1**		**0.9**	**>10**	**> 10**	**>10**	**> 10**
FIRE Goals	**0.6**		**0.5 to 0.8**	**>10**	**>10**	**>5**	**1.5 to 3**
JET/TFTR D-T Experiments	**0.3**		**0.04**	**~3**	**10**	**~2**	**<0.2**

* Core parameters are normalized to ARIES-AT $BR^{5/4}$

Fusion Ignition Research Experiment

(FIRE)

http://fire.pppl.gov



Design Goals

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

  Base Project Cost ≤ \$1B

* Higher Field Mode

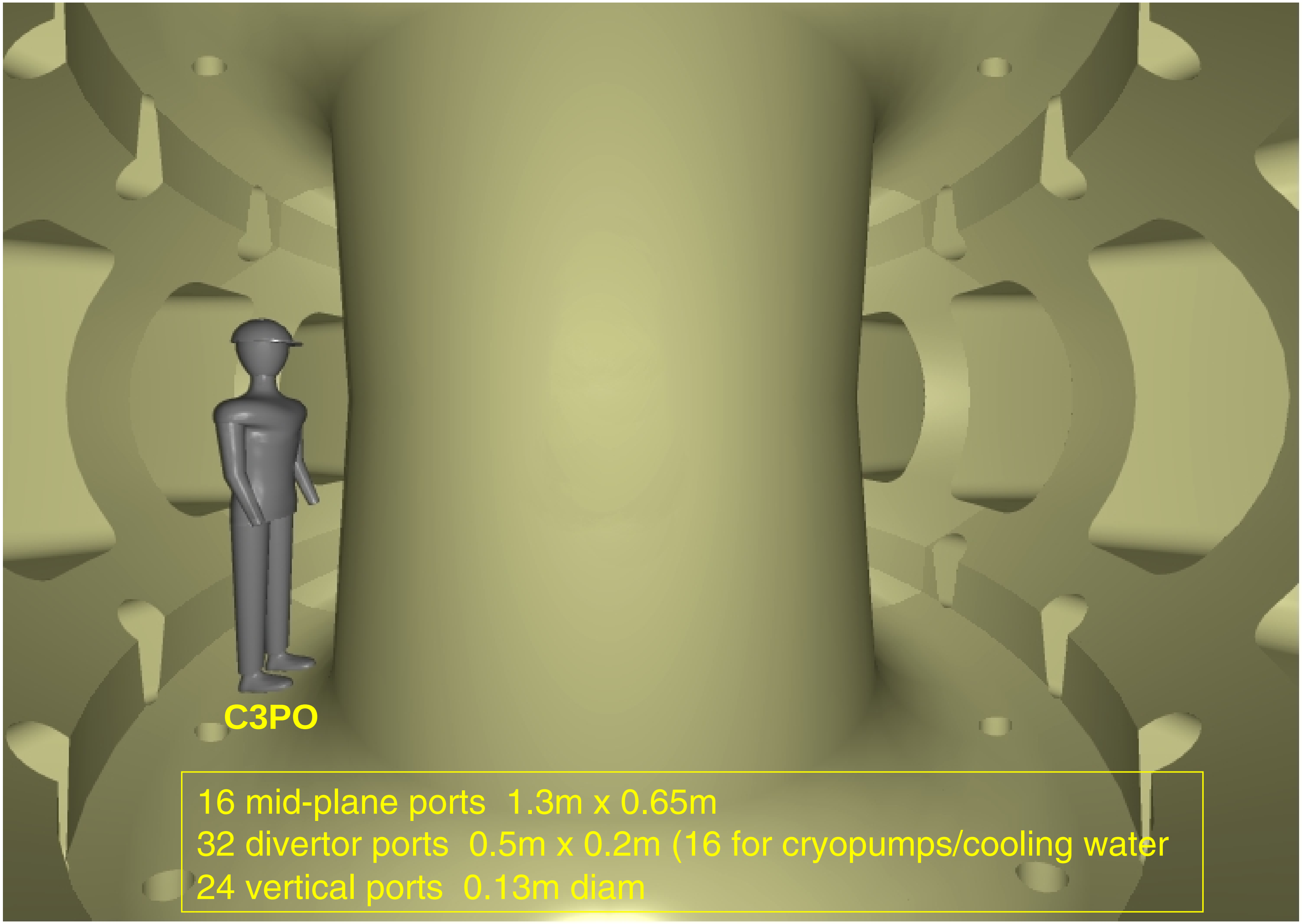
Attain, explore, understand and optimize fusion-dominated plasmas that will provide knowledge for attractive MFE systems.

Basic Parameters and Features of FIRE Reference Baseline

R, major radius	2.0 m
a, minor radius	0.525 m
κ95, elongation at 95% flux surface	~1.8
δ95, triangularity at 95% flux surface	~0.4
q95, safety factor at 95% flux surface	>3
Bt, toroidal magnetic field	10 T with 16 coils, 0.34% ripple @ Outer MP
Toroidal magnet energy	3.7 GJ
Ip, plasma current	~6.5 MA (7.7 MA at 12 T)
Magnetic field flat top, burn time	26 s at 10 T in dd, 18.5s @ Pdt ~ 200 MW)
Pulse repetition time	~3hr @ full field and full pulse length
ICRF heating power, maximum	30 MW, 100MHz for $2\Omega_T$, 4 mid-plane ports
Neutral beam heating	None, may have diagnostic neutral beam
Lower Hybrid Current Drive	None in baseline, upgrade for AT phase
Plasma fueling	Pellet injection (≥2.5km/s vertical launch inside mag axis, possible 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	200 MW, ~10 MW m-3 in plasma
Neutron wall loading	~ 3 MW m-2
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 Bt and Ip
Tritium site inventory	Goal < 30 g, Category 3, Low Hazard Nuclear Facility

Higher Field Mode B = 12T and Ip = 7.7MA with a 12 second flat top has been identified.

FIRE would have Access for Diagnostics and Heating

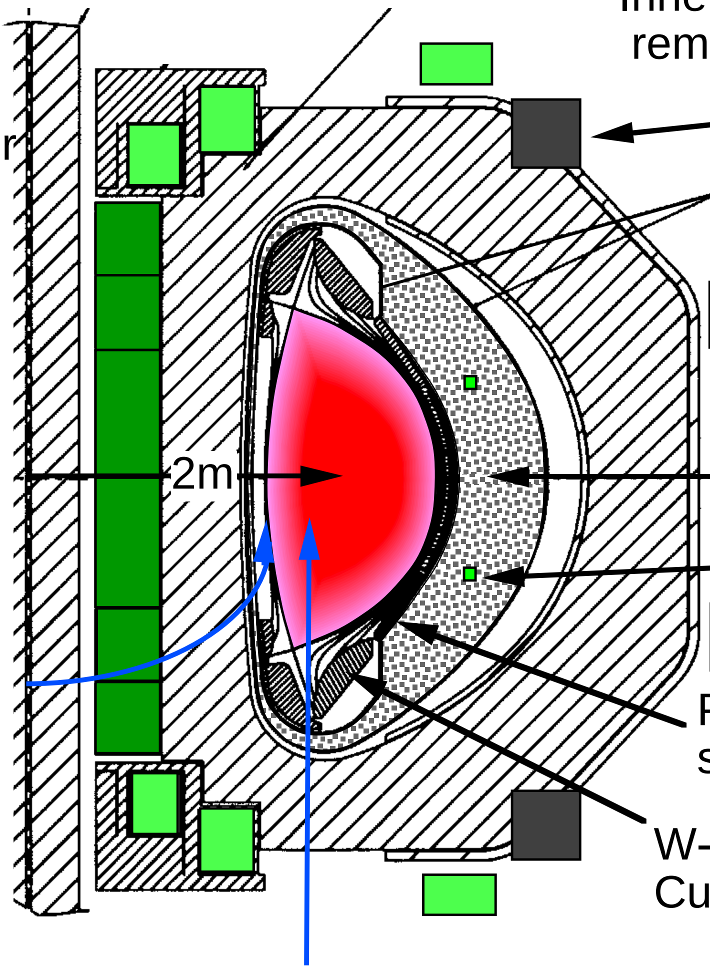


16 mid-plane ports 1.3m x 0.65m
32 divertor ports 0.5m x 0.2m (16 for cryopumps/cooling water
24 vertical ports 0.13m diam

FIRE is Compatible with Advanced Tokamak Features

Features

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



Wedged TF Coils (16), 15 plates/coil*
Inner Leg BeCu C17510,
remainder OFHC C10200

Compression Ring

Double Wall Vacuum
Vessel (316 S/S)

All PF and CS Coils*
OFHC C10200

Internal Shielding
(60% steel & 40%water)

Vertical Feedback Coil

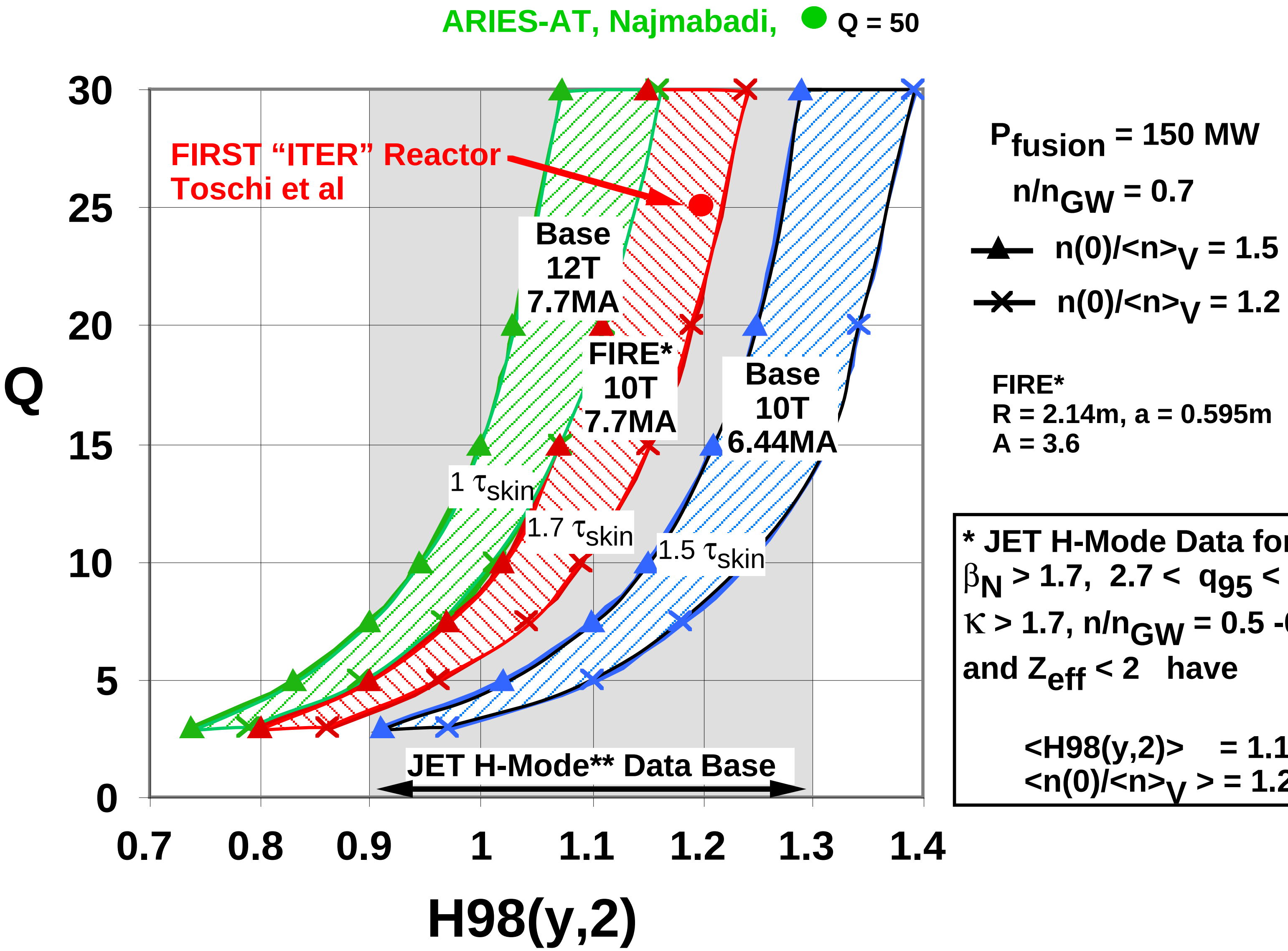
Passive Stabilizer Plates
space for wall mode stabilizers

W-pin Outer Divertor Plate
Cu backing plate, actively cooled

Direct and Guided Inside Pellet Injection

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

Projections of FIRE Compared to Envisioned Reactors

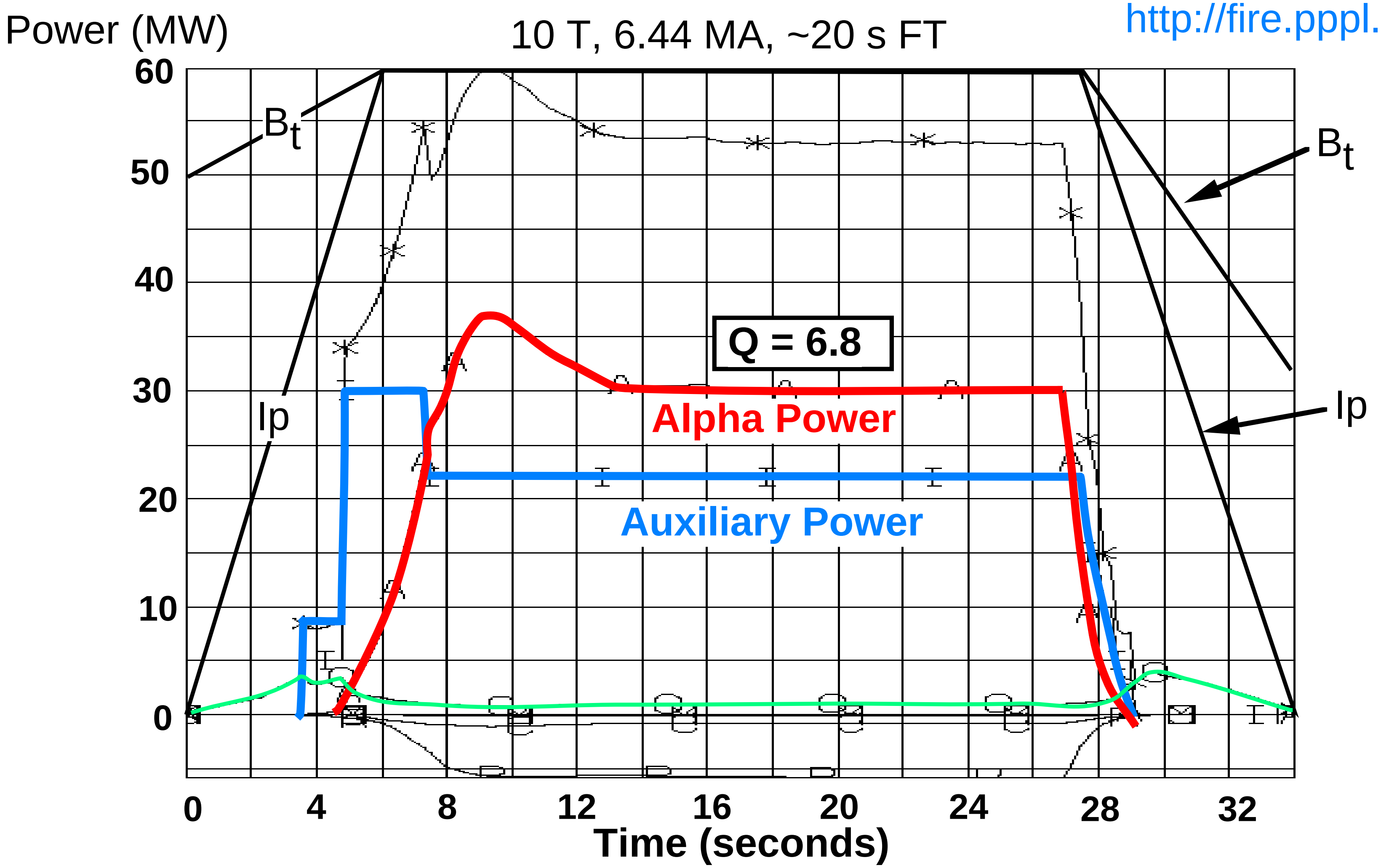


* JET H-Mode Data for $\beta_N > 1.7$, $2.7 < q_{95} < 3.5$
$\kappa > 1.7$, $n/n_{GW} = 0.5 - 0.8$,
and $Z_{eff} < 2$ have

$\langle H98(y,2) \rangle = 1.1$
$\langle n(0)/\langle n \rangle_V \rangle = 1.2$

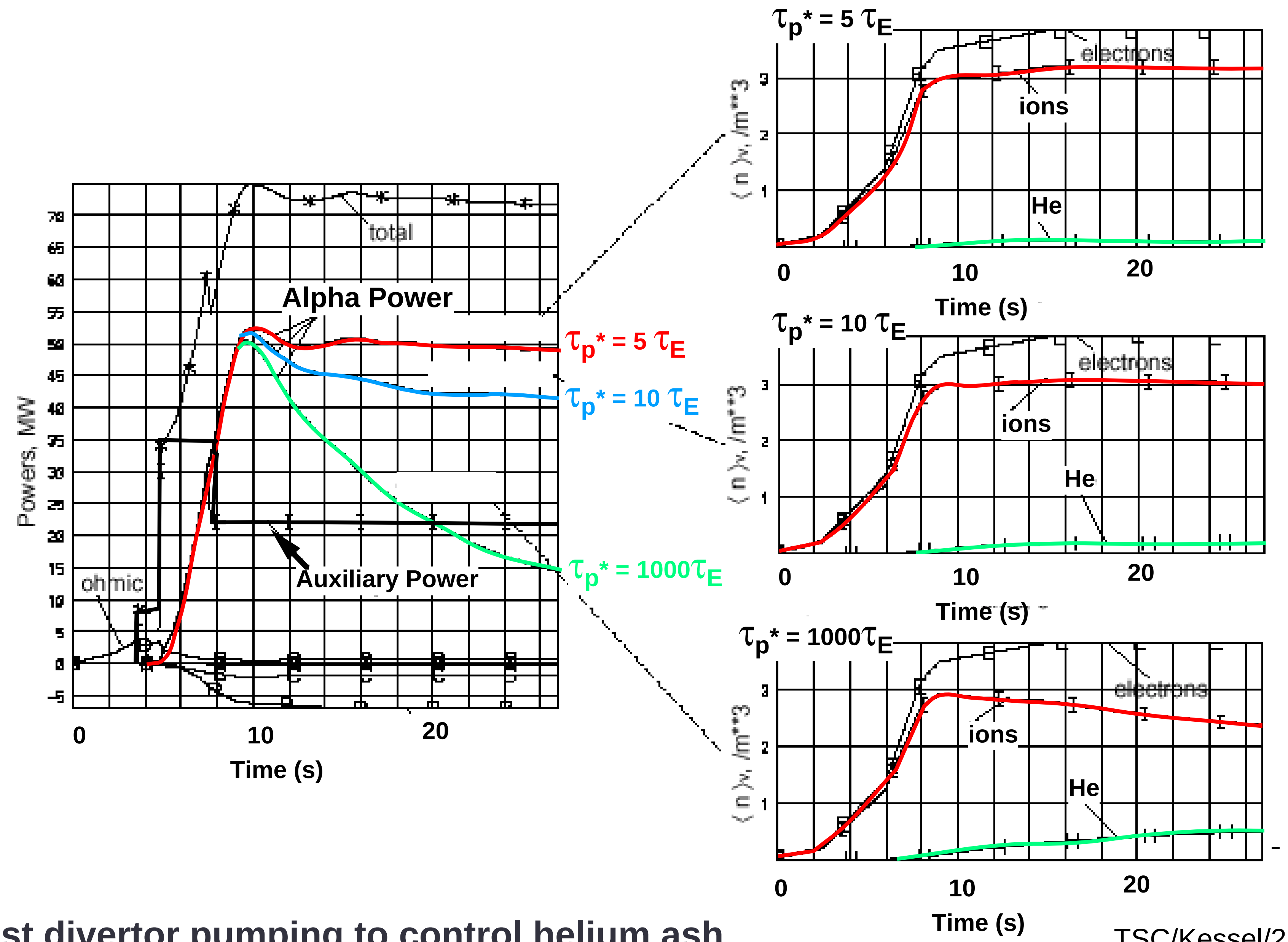
1 1/2-D Simulation of Burn Control in FIRE

http://fire.pppl.gov



- ITER98(y, 2) scaling with H(y,2) = 1.1, n(0)/<n> = 1.25 and $n/n_{GW} = 0.59$
  - Pulse Duration ≈ 30 τ_E, 6 τ_{He} and ~1.5 τ_{skin}

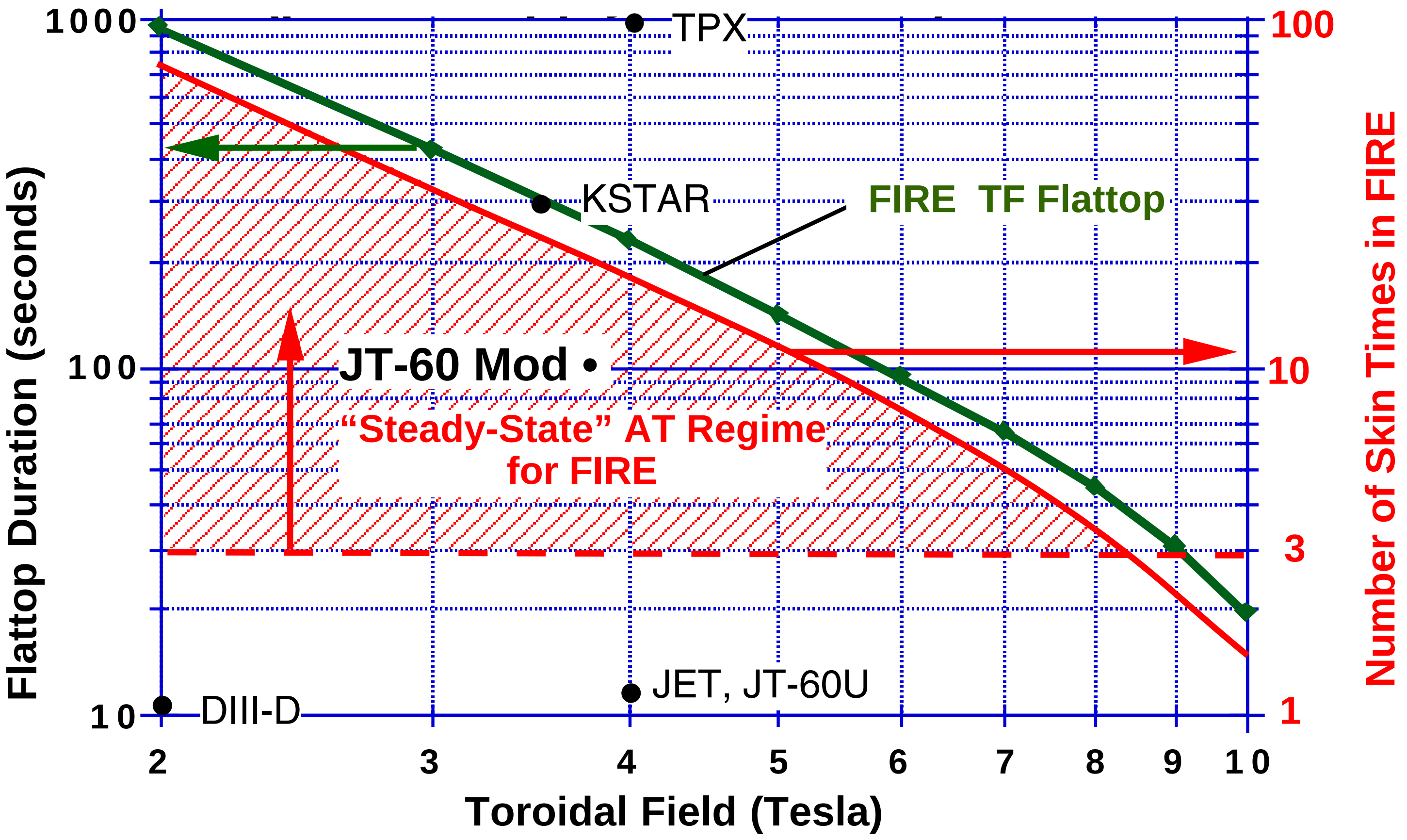
Helium Ash Accumulation could be Explored on FIRE



Adjust divertor pumping to control helium ash

TSC/Kessel/21-q.ps

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 fromsteady-state non-burning advanced-tokamak modes to "quasi-equilibrium" burning plasmas in advanced tokamak modes.

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 ~ 7.7 MA to increase confidence of high gain while maintaining pulse length (~ 1.5 τ_{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.