FIRE,

A Test Bed for ARIES-RS/AT Advanced Physics and Plasma Technology

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FIRE Collaboration *http://fire.pppl.gov*

AES, ANL, Boeing, Columbia U., CTD, GA, GIT, LLNL, INEEL, MIT, ORNL, PPPL, SNL, SRS, UCLA, UCSD, UIIC, UWisc

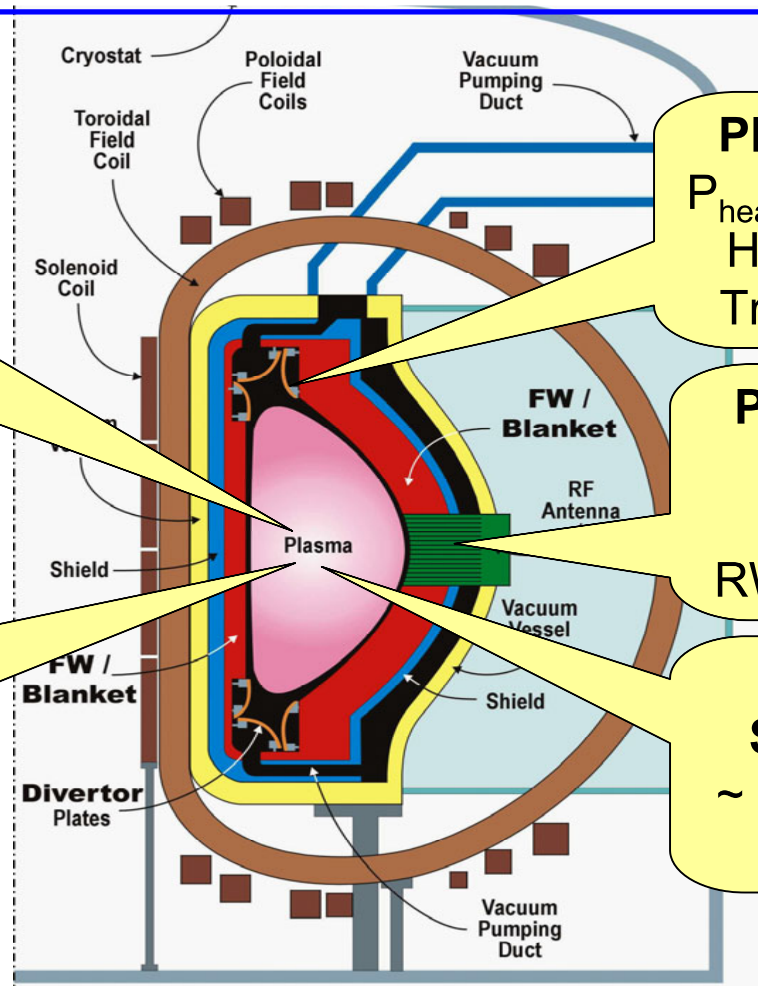
Topics to be Discussed

- Vision for Magnetic Fusion Power Plant
- Critical Issues for Magnetic Fusion
- Status of FIRE- Progress since Snowmass/FESAC 2002
- Comparison of FIRE/ITER/ARIES
- Issues Needing R&D
- Plans
- Concluding Remarks

ARIES Economic Studies have Defined the Plasma Requirements for an Attractive Fusion Power Plant

High Gain
$Q \sim 25 - 50$
$n\tau_E T \sim 6\times10^{21}\ m^{-3}skeV$
$P_\alpha/P_{heat} = f_\alpha \approx 90\%$

High Power Density
$P_f/V \sim 6\ MW^{-3}$
~10 atm
$\Gamma_n \approx 4\ MWm^{-2}$



Plasma Exhaust
$P_{heat}/R_x \sim 100MW/m$
Helium Pumping
Tritium Retention

Plasma Control
Fueling
Current Drive
RWM Stabilization

Steady-State
~ 90% Bootstrap

Significant advances are needed in each area.
High gain, high power density and steady-state are the critical issues.

General Goals for FIRE*

Address Key Burning Plasma Issues in an Advanced Configuration

Address Critical Plasma Technology Issues

Minimize Technological risks and costs

(Use ARIES-RS/AT studies as a guide)

* From Madison Forum April 1998 - this room

FIRE Physics Objectives

Burning Plasma Physics (Conventional Inductively Driven H-Mode)

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

Advanced Toroidal Physics (100% Non-inductively Driven AT-Mode)

Q	~ 5 as target, higher Q not precluded
$f_{bs} = I_{bs}/I_p$	~ 80% as target, ARIES-RS/AT≈90%
β_N	~ 4.0, n = 1 wall stabilized, RWM feedback

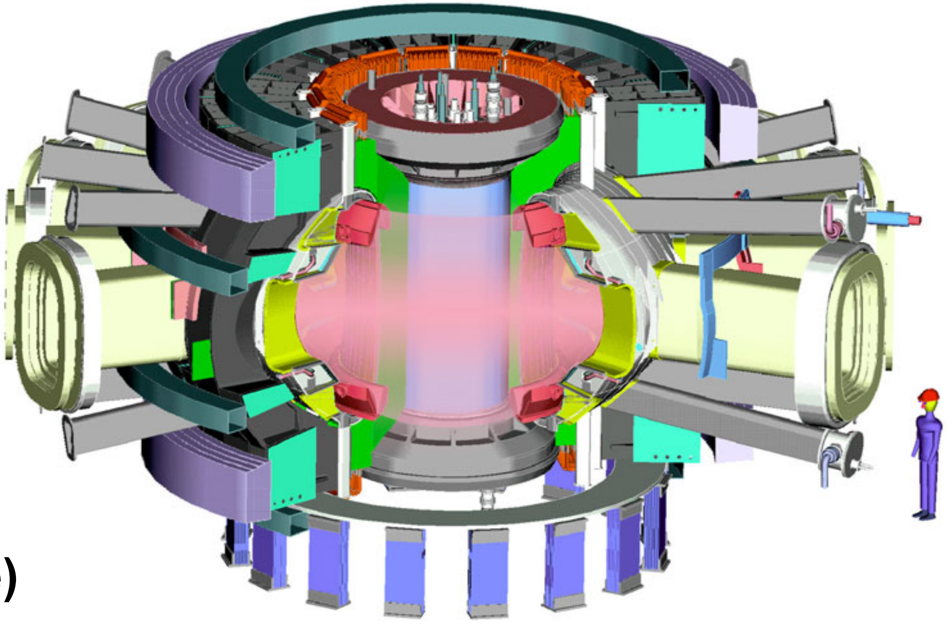
Quasi-Stationary Burn Duration (use plasma time scales)

Pressure profile evolution and burn control	~ 20 to 40 τ_E
Alpha ash accumulation/pumping	~ 4 to 8 τ_{He}
Plasma current profile redistribution	~ 2 to 5 τ_{CR}
Divertor pumping and heat removal	~ 15 to 30 $\tau_{divertor}$
First wall heat removal	> 1 $\tau_{first\text{-}wall}$

Fusion Ignition Research Experiment (FIRE)

- $R = 2.14$ m, $a = 0.595$ m
- $B = 10$ T, (~ 6.5 T, AT)
- I_p = 7.7 MA, (~ 5 MA, AT)
- P_{ICRF} = 20 MW
- $P_{LHCD} \leq 30$ MW (Upgrade)
- P_{fusion} ~ 150 MW
- $Q \approx 10$, (5 - 10, AT)
- Burn time ≈ 20s (2 τ_{CR} - Hmode)

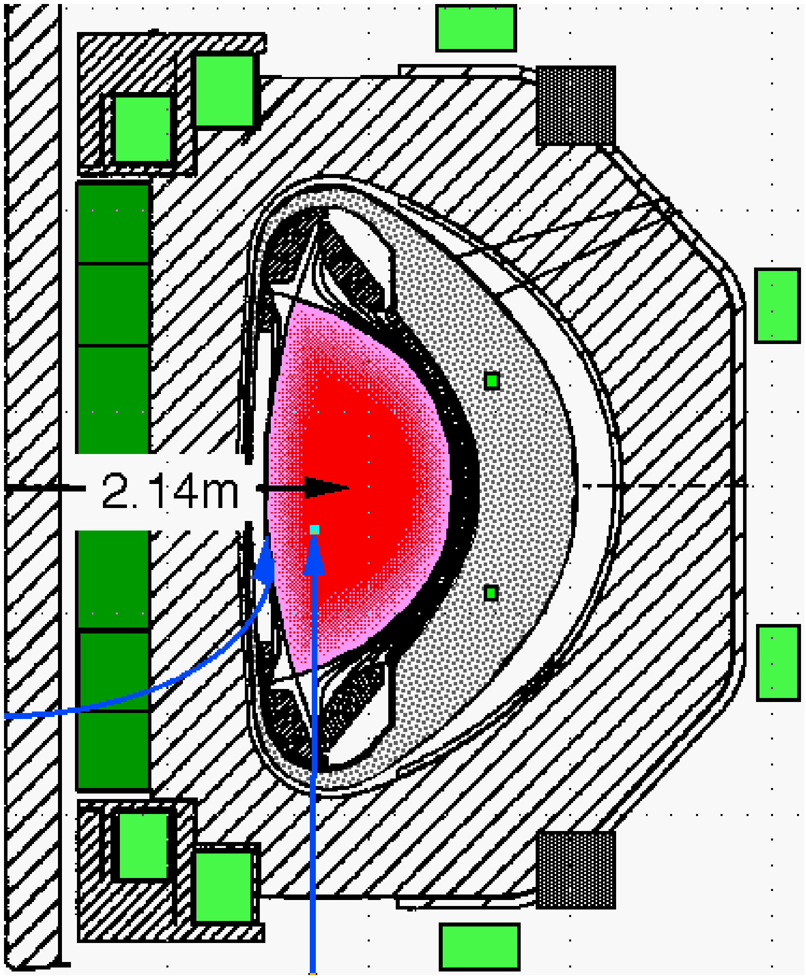
  ≈ 40s (< 5 τ_{CR} - AT)
- Tokamak Cost = $350M (FY02)
- Total Project Cost = $1.2B (FY02)



1,400 tonne
LN cooled coils

Mission: to attain, explore, understand and optimize magnetically-confined fusion-dominated plasmas

FIRE is Based on ARIES-RS Vision



- 40% scale model of ARIES-RS plasma
- ARIES-like all metal PFCs
  - Actively cooled W divertor
  - Be tile FW, cooled between shots
  - Close fitting conducting structure
- ARIES-level toroidal field
  - LN cooled BeCu/OFHC TF
- ARIES-like current drive technology
  - FWCD and LHCD (no NBI/ECCD)
  - No momentum input
- Site needs comparable to previous DT tokamaks (TFTR/JET).
  - T required/pulse ~ TFTR ≤ 0.3g-T

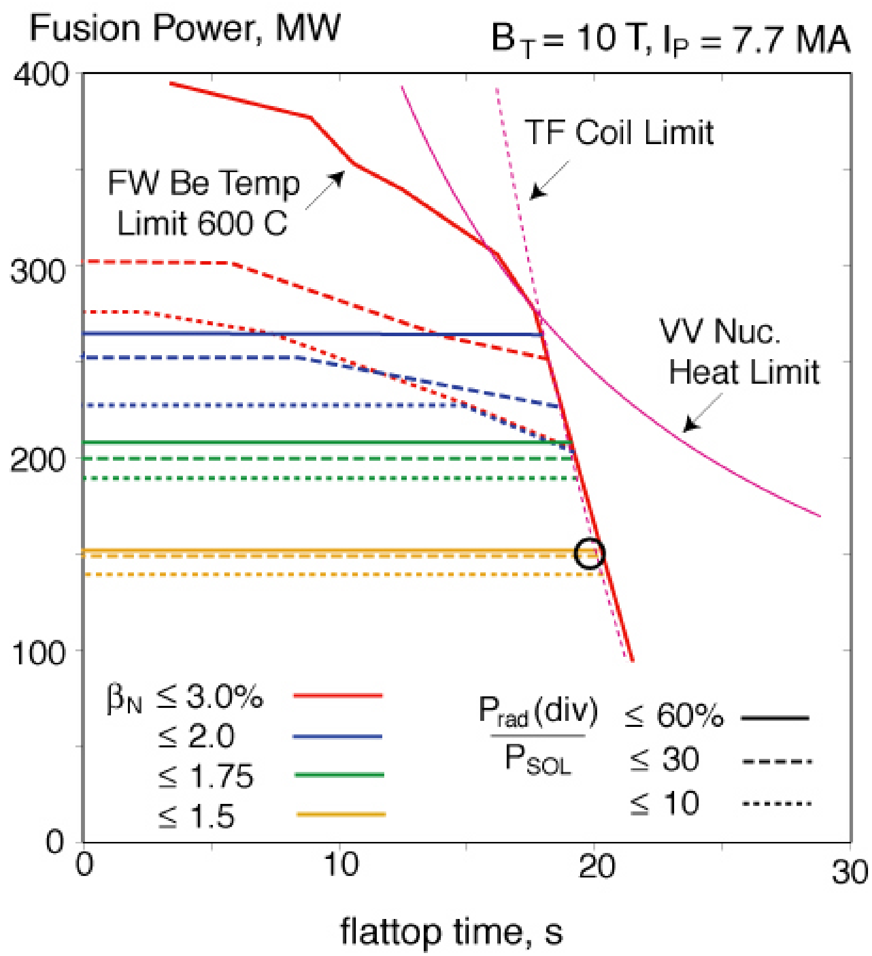
Conventional H-Mode Operating Range Expanded

Nominal operating point
- Q =10
- P_f = 150 MW, 5.5 MWm^{-3}

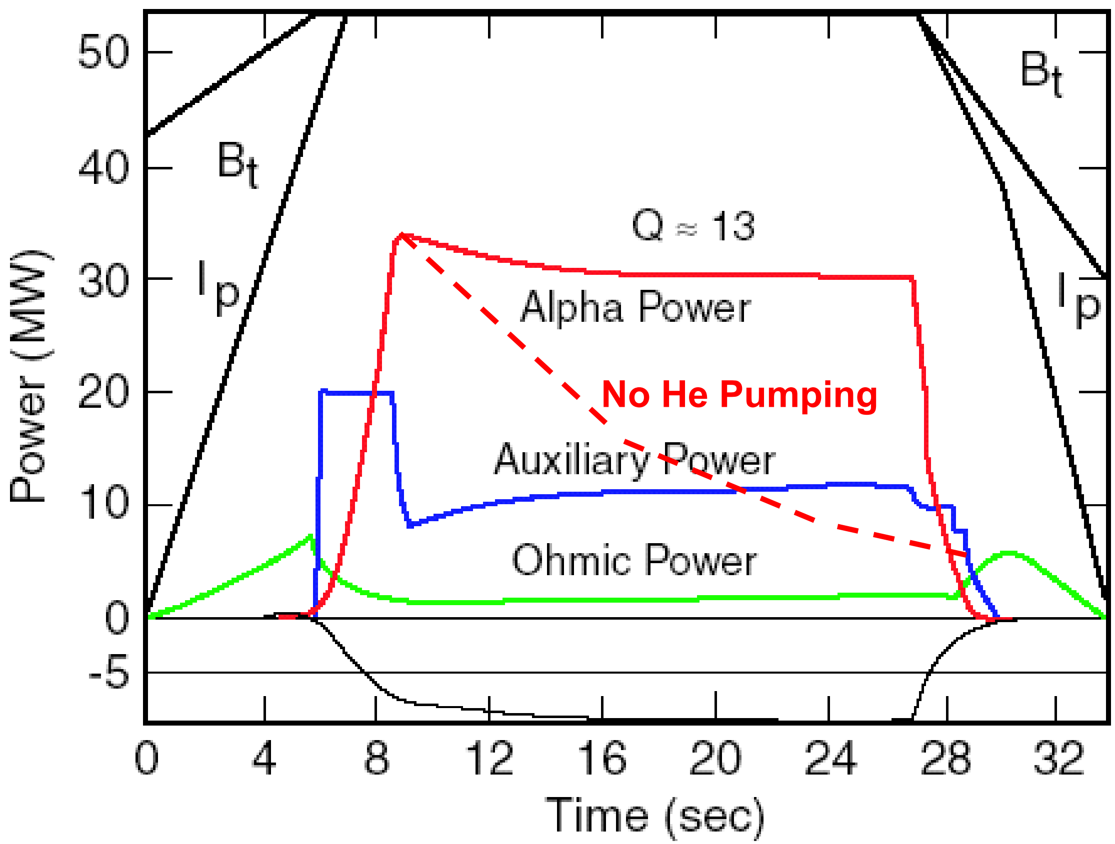
Power handling improved
- P_f ~ 300 MW, 10 MWm^{-3}

Physics basis improved (ITPA)
- DN enhances τ_E, β_N
- DN reduces Elms
- Hybrid mode has Q ~ 20

Engineering Design Improved
- Pulse repetition rate tripled
- divertor & baffle integrated



1.5D Simulation of Quasi-Stationary H-Mode in FIRE



B = 10 T

I_p = 7.7 MA

R = 2.14 m

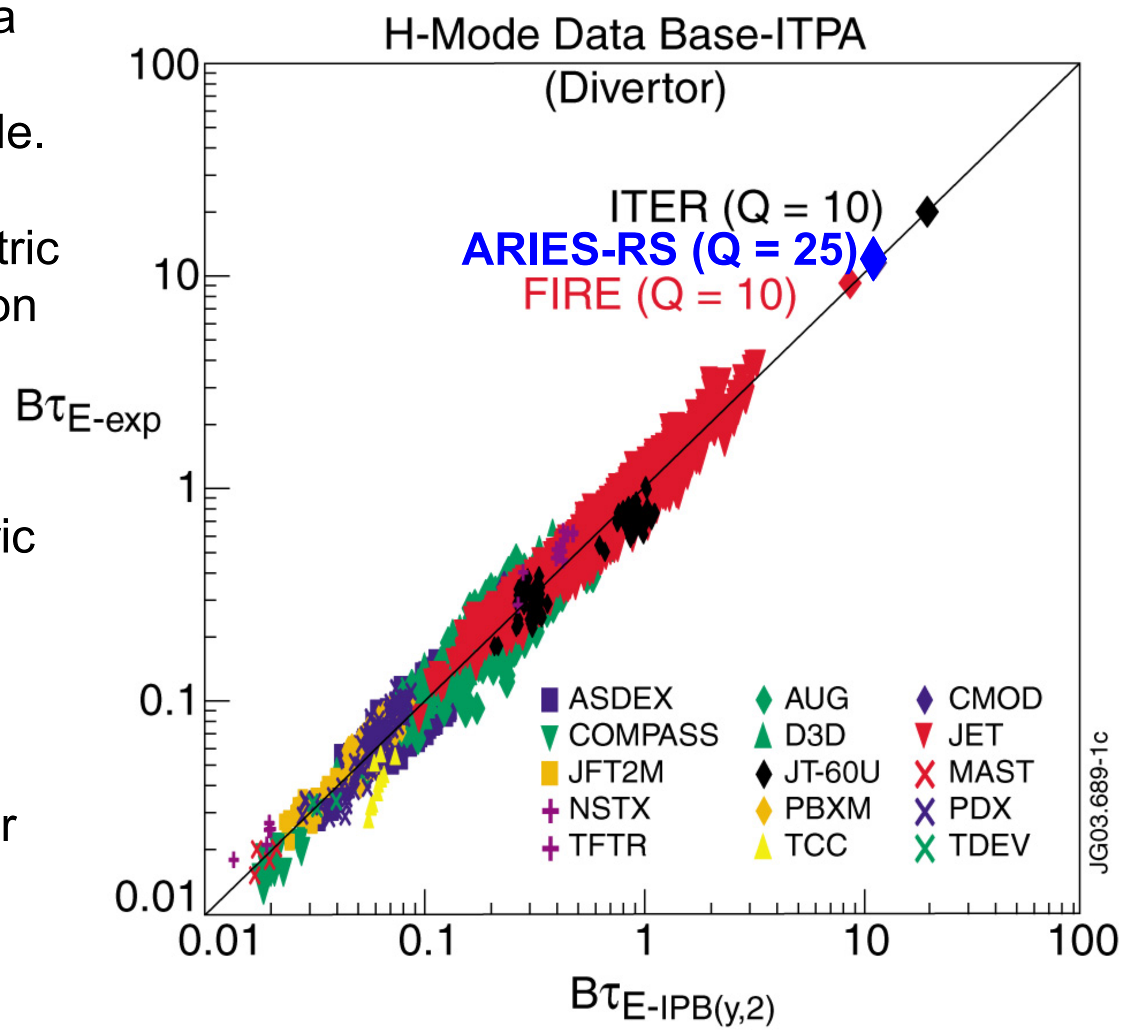
A = 3.6

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

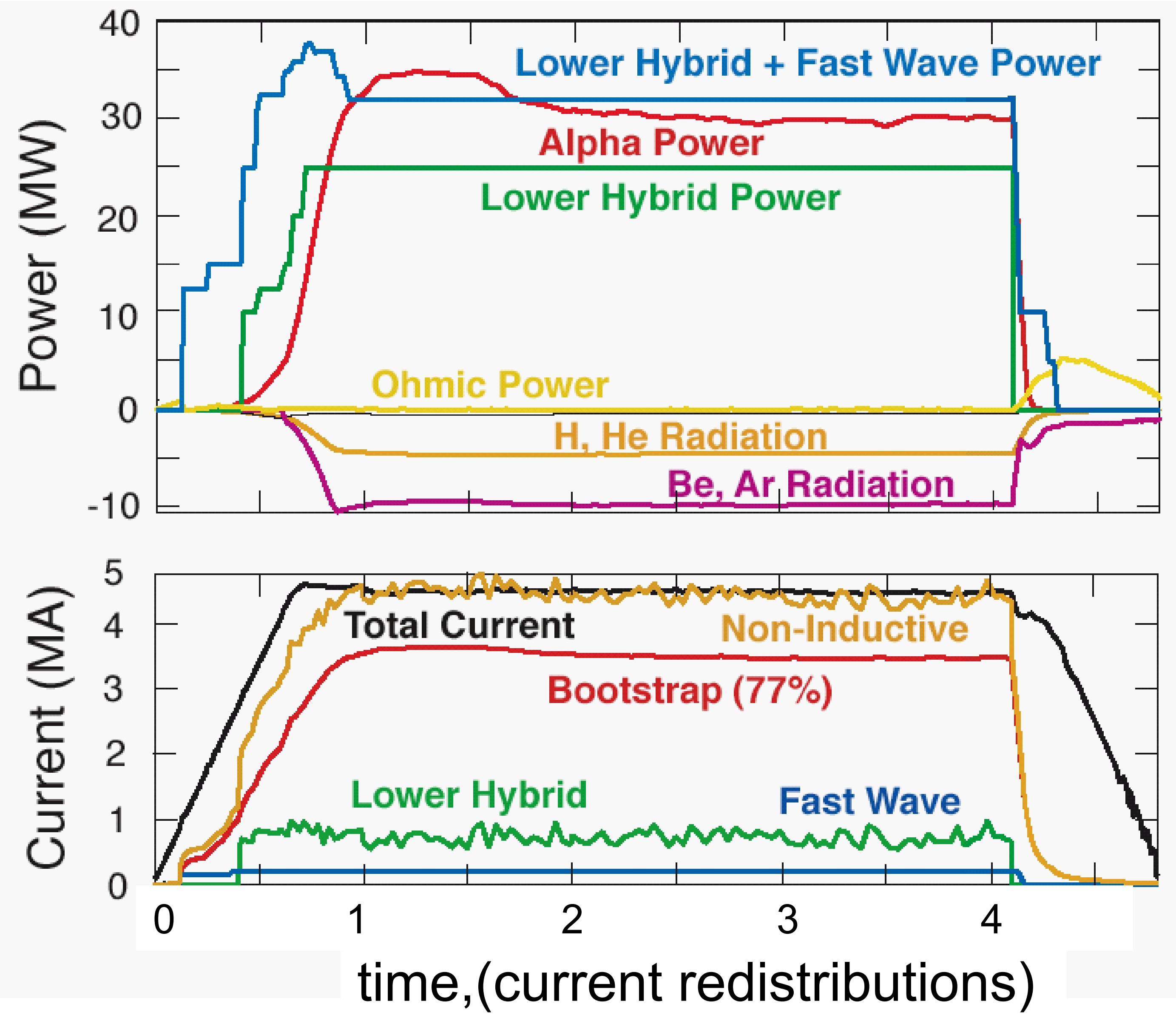
Q = Pfusion/(Paux + Poh)

Critical Issue #1- High Fusion Gain (confinement): FIRE and ITER Require Modest (2.5 to 4.5) Extrapolation

- Tokamaks have established a solid basis for confinement scaling of the diverted H-Mode.
- $B\tau_E$ is the dimensionless metric for confinement time projection
- $n\tau_E T$ is the dimensional metric for fusion
  - $n\tau_E T = \beta B^2\tau_E = \beta B \,.\, B\tau_E$
- ARIES-RS Power Plants require $B\tau_E$ only slightly larger than FIRE due high β and B.



"Steady-State" High-β Advanced Tokamak Discharge on FIRE



$Q \sim 5$

$B = 6.5$ T

$\beta_N = 4.1$

$f_{bs} = 77\%$

$H_{98} = 1.7$

$n/n_G = 0.85$

$\tau_E = 0.7$s

$\tau_{He} = 3.5$ s

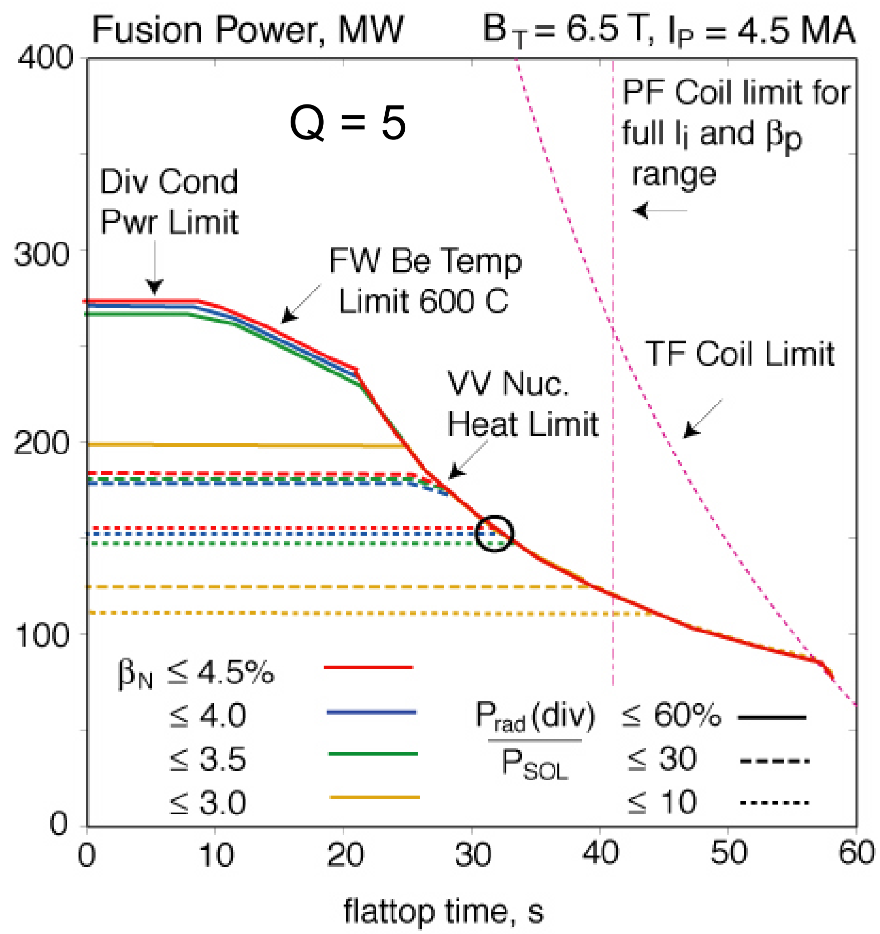
$\tau_{CR} = 9$ s

ARIES-like AT Mode Operating Range Greatly Expanded

Nominal operating point
- Q = 5
- P_f = 150 MW,
- P_f/V_p = 5.5 MWm^{-3} (ARIES)
- ≈ steady-state 4 to 5 τ_{CR}

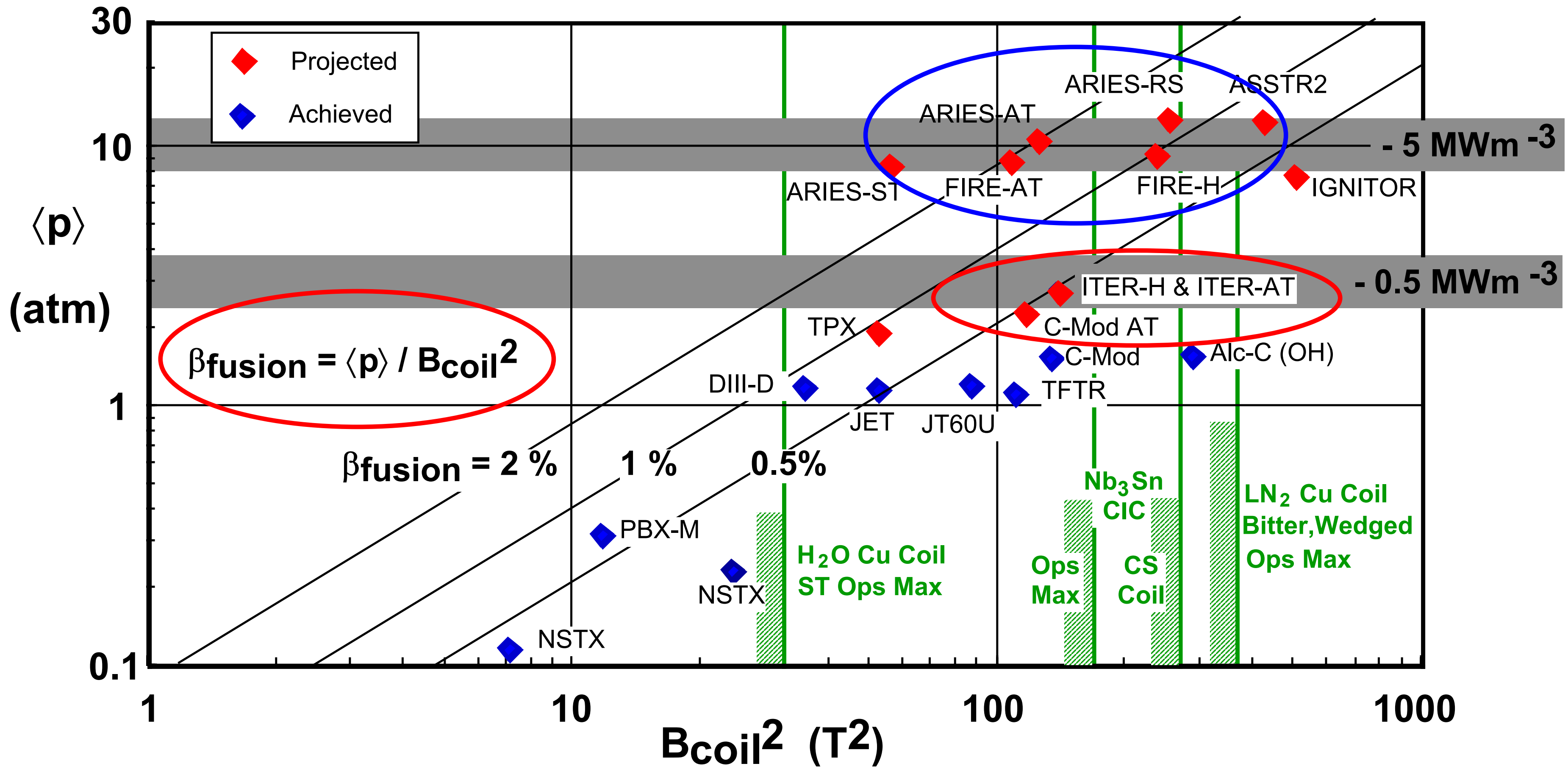
Physics basis improving (ITPA)
- required confinement H factor and β_N attained transiently
- C-Mod LHCD experiments will be very important

First Wall is the main limit
- Improve cooling
- revisit FW design



Lots of opportunity for additional improvement.

Critical Issue #2 - High Power Densities: Requires Significant (x10) Extrapolation in Plasma Pressure

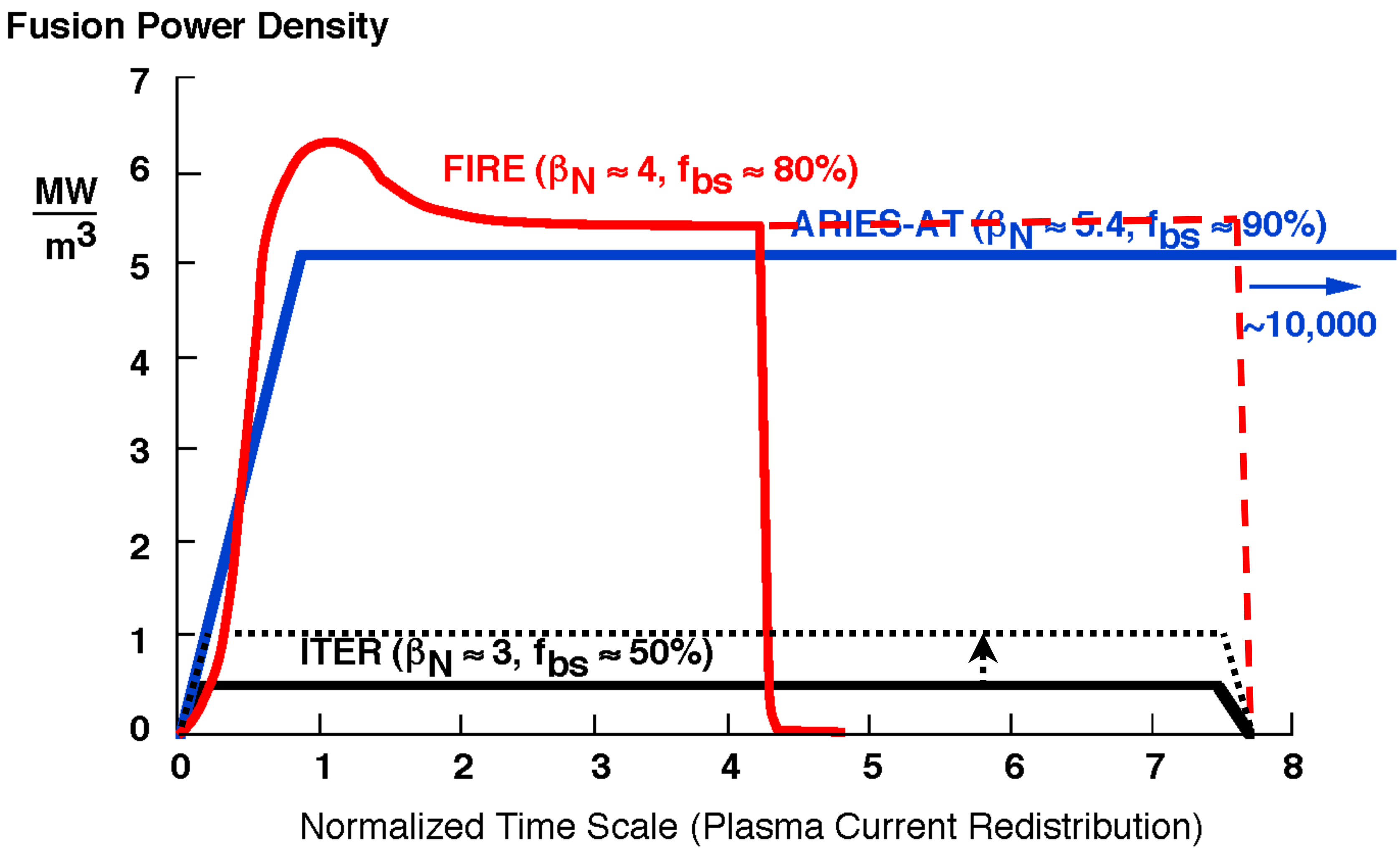


- “Attractive” fusion systems require both high field, high β and efficient utilization.
- Advanced tokamaks offer the best combination of high β and achievable high field.

ITER and FIRE Advanced Tokamak Operating Modes Pose Challenges for Plasma Technology

Technology Items	Existing Toks	ITER-AT	FIRE-AT	ARIES-RS/AT
B(T)	1.5 - 7	5.3	6.5	6 - 8
I_p(MA)	1 - 3	9	5	11
Core Power Density (MWm^{-3})	0.15 - 0.3	0.5	5	5 - 6
FW - Γ_N (MW/m^{-2})	0.1	0.5	2	4
FW - P_{rad} (MWm^{-2})	5	15	15	100
First Wall	C, Be	Be	Be	Mo
Div Target (MWm^{-2})	1	5 - 20	5 - 20	5 - 20
Divertor Target	C, (Mo,W)	C,W?	W	W
Pulse Length(s, τ_{cr})	Typical 5, 2 (max = 5 hrs)	3000, 8	40, 5	months
Cooling Divertor, First Wall	Inertial(SS) inertial	Steady steady	Steady inertial	Steady steady

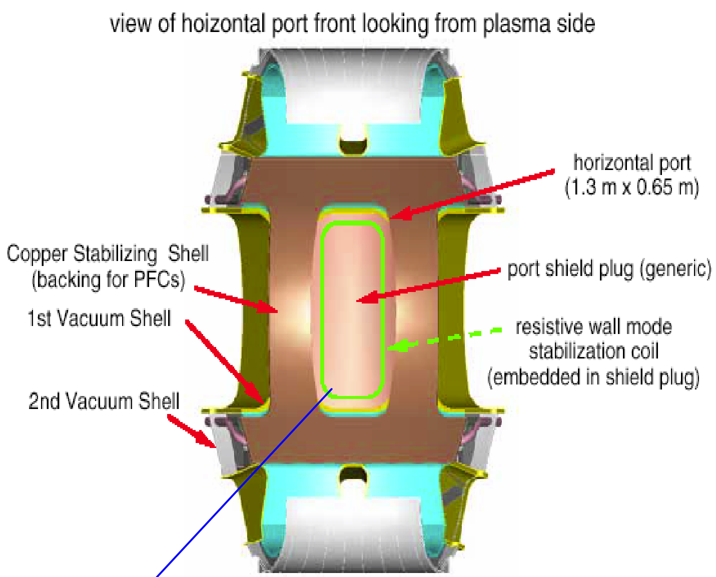
Both ITER and FIRE AT Modes Can be Improved



Goals: 2X ITER power level to 1000 MW and 2X FIRE Pulse Length

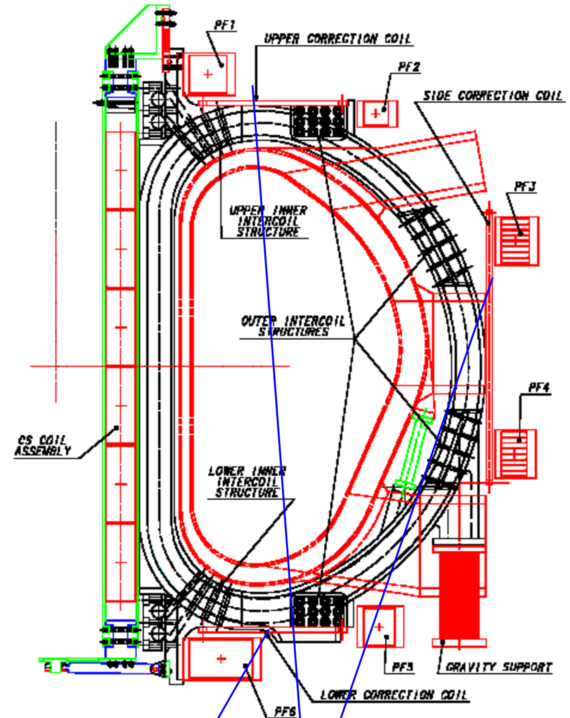
The Realization of AT modes in a Power Plant will require Conducting Walls and Stabilization Coils near the Plasma.

FIRE



RWM coils integrated with first wall of port plug

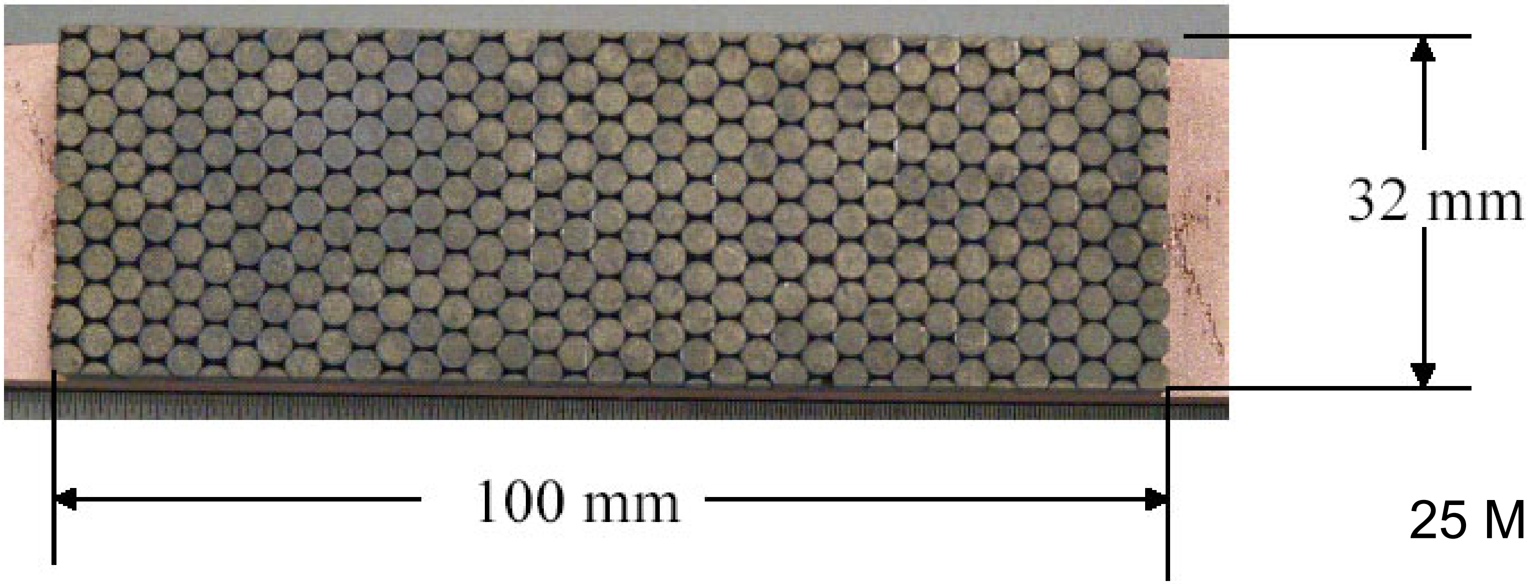
ITER



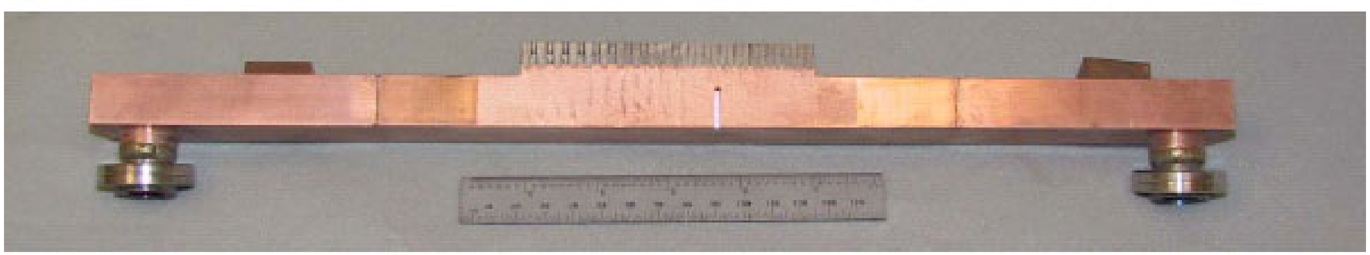
RWM coils located outside TF coils

The FIRE and ITER cases span the extremes. US AT/BP activity is analyzing intermediate ITER cases, and the engineering feasibility of the FIRE integrated approach.

FIRE Tungsten Rod Divertor Target Design

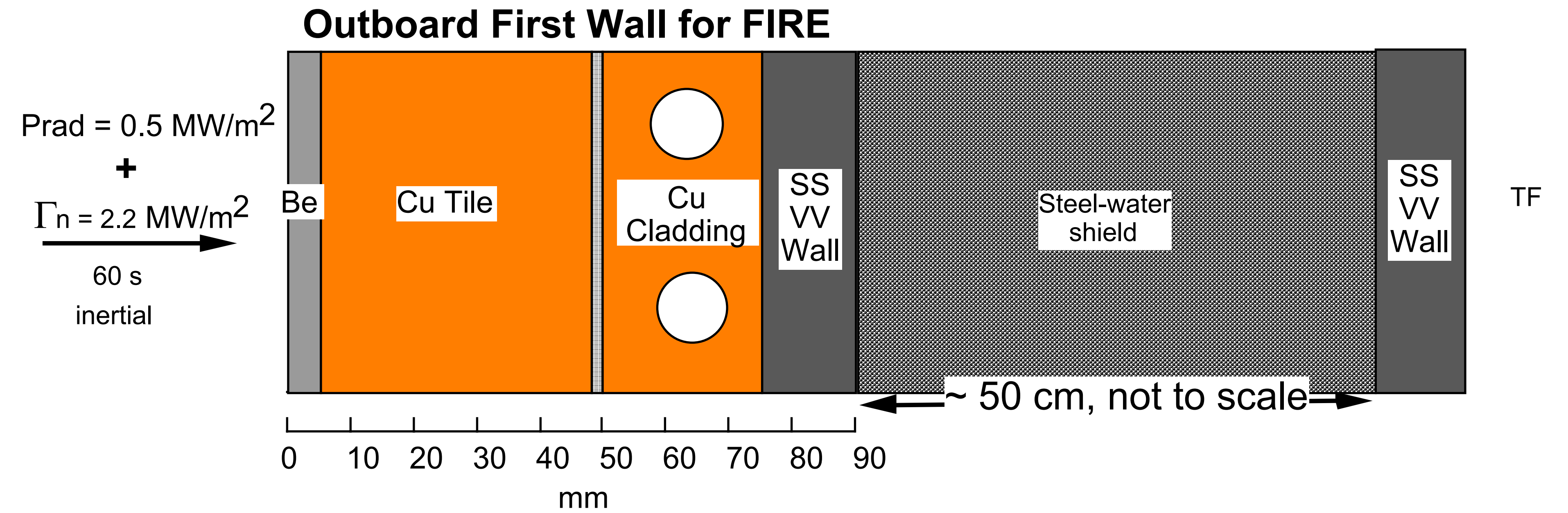


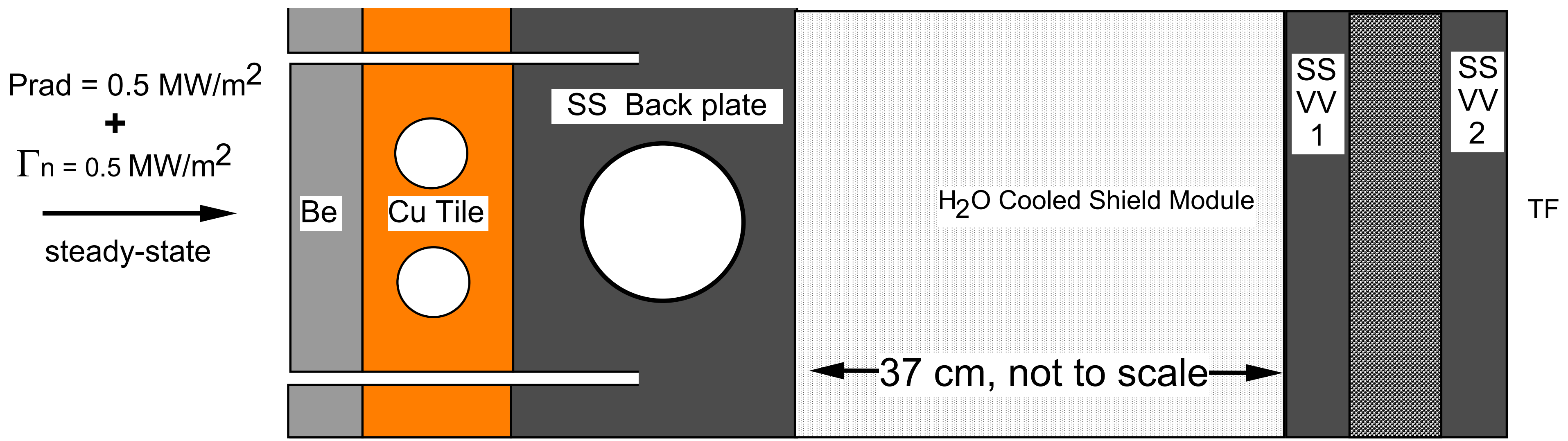
25 MW/m^2



Rods 7 mm long

FIRE and ITER First Wall Design Concepts are Similar





ITER First Wall Panel

FESAC Recommended a Robust Strategy for Burning Plasmas (Sep. 2002)

Based on the community consensus at Snowmass, FESAC found that:

"ITER and FIRE are each attractive options for the study of burning plasma science. Each could serve as the primary burning plasma facility, although they lead to different fusion energy development paths.

Because additional steps are needed for the approval of construction of ITER or FIRE, a strategy that allows for the possibility of either burning plasma option is appropriate."

FESAC recommended a robust strategy:

1. that the US should seek to join ITER negotiations as a full participant
   - US should do analysis of cost to join ITER and ITER project cost.
   - negotiations and construction decision are to be concluded by July 2004.

2. that the FIRE activities continue toward a Physics Validation as planned and be prepared to start Conceptual Design at the time of the ITER Decision.

3. If ITER does not move forward, then FIRE should be advanced as a U.S.-based burning plasma experiment.

Status and Plans for NSO/FIRE

- FIRE has made significant progress in increasing physics and engineering capability since the Snowmass/FESAC recommendations of 2002.

- FIRE successfully passed the DOE Physics Validation Review (PVR) in March 04.
  "The FIRE team is on track for completing the pre-conceptual design within FY 04. They will then be ready to launch the conceptual design. The product of their work, and their contributions to and leadership within the overall burning plasma effort, is stellar. " - PVR Panel

- Most of the NSO resources were transferred to US - ITER activities in late FY 2003. The resources remaining FY 2005 will focus on development of advanced capabilities for ITER - e.g., integrated AT modes, high power PFCs.

- The present US plan assumes that a decision to construct ITER is imminent. If an agreement on ITER is not attained, FIRE is ready, to be put forward as recommended by FESAC.

"I want you to put some FIRE into this program."