FT/2-6

FIRE

Exploring Burning Plasma Physics

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for the National FIRE Study Team

19th IAEA Fusion Energy Conference
Lyon, France

October 17, 2002

http://fire.pppl.gov

Outline

- Fusion Goals
- Critical Issues for Fusion
- Strategy for a Road Map
- FIRE
  - Goals
  - Characteristics
  - Issues/Challenges

- Plans for the Future

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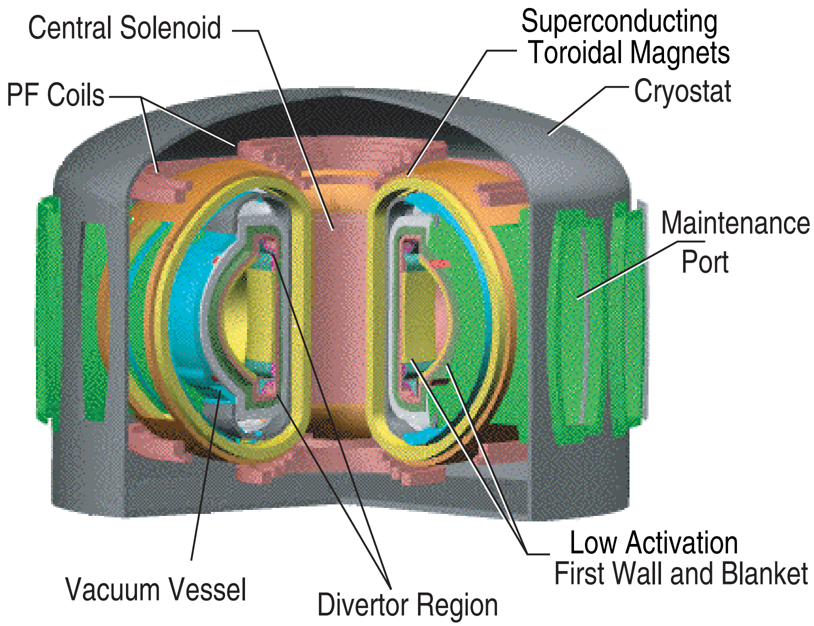
A Decade of Power Plant Studies in the U.S. has led to an Attractive Vision for MFE

The U.S. ARIES — AT system study



Economically Competitive - COE ~ 5¢/kWhr

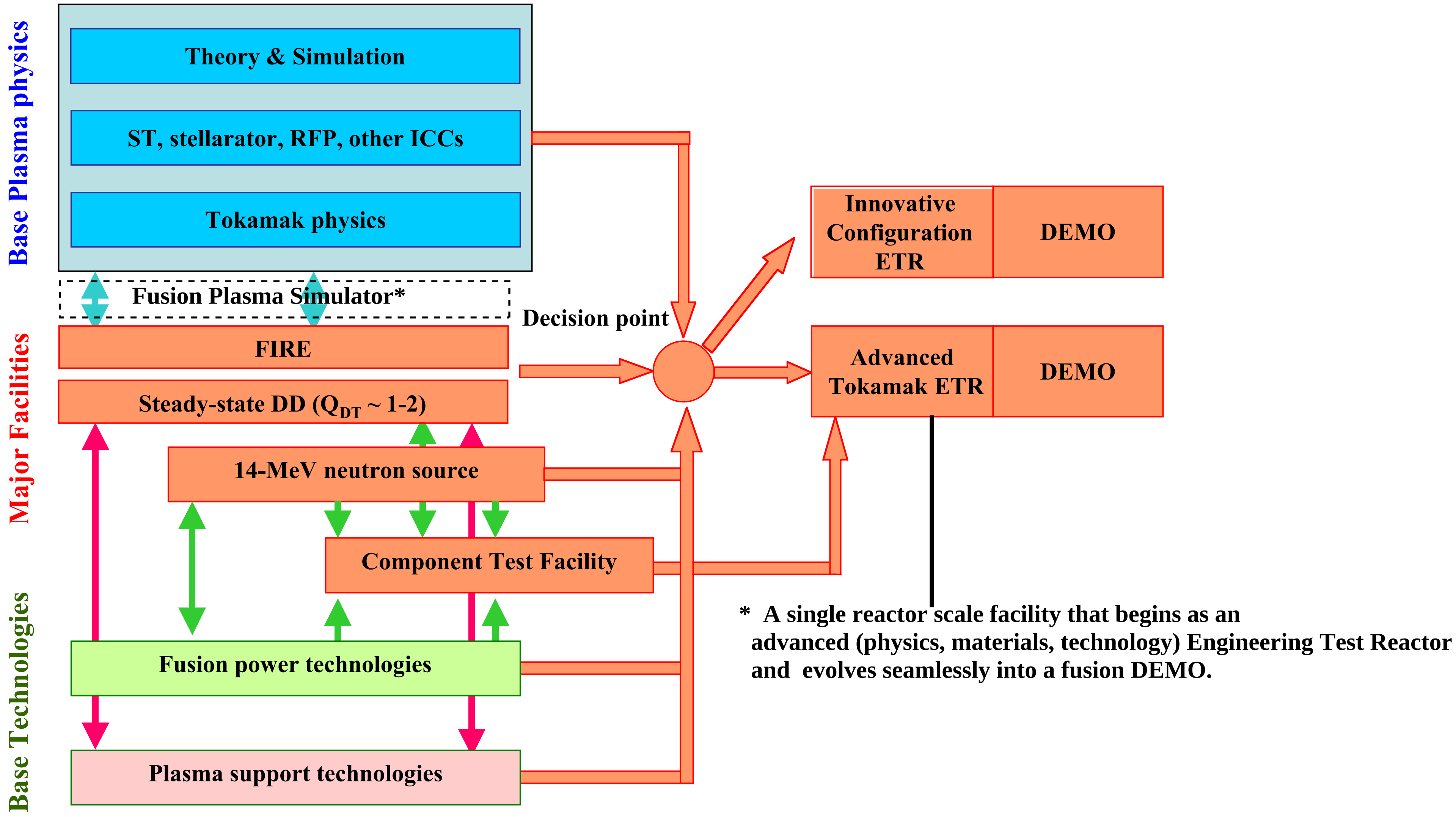
Enviromentally Benign - Low Level Waste

Safety - No evacuation

- **Advanced Tokamak Physics Features**
  - High Power density $\beta_N \sim 5$
  - Steady-State $f_{BS} \sim 90\%$
  - Exhaust Power P/NR ~ 40 MW/m
- **Advanced Technology Features**
  - Hi Tc Superconductors
  - Neutron Resistant >150 dpa
  - Low Activation materials

Major Advances in Physics and Technolgy are needed to achieve this goal.

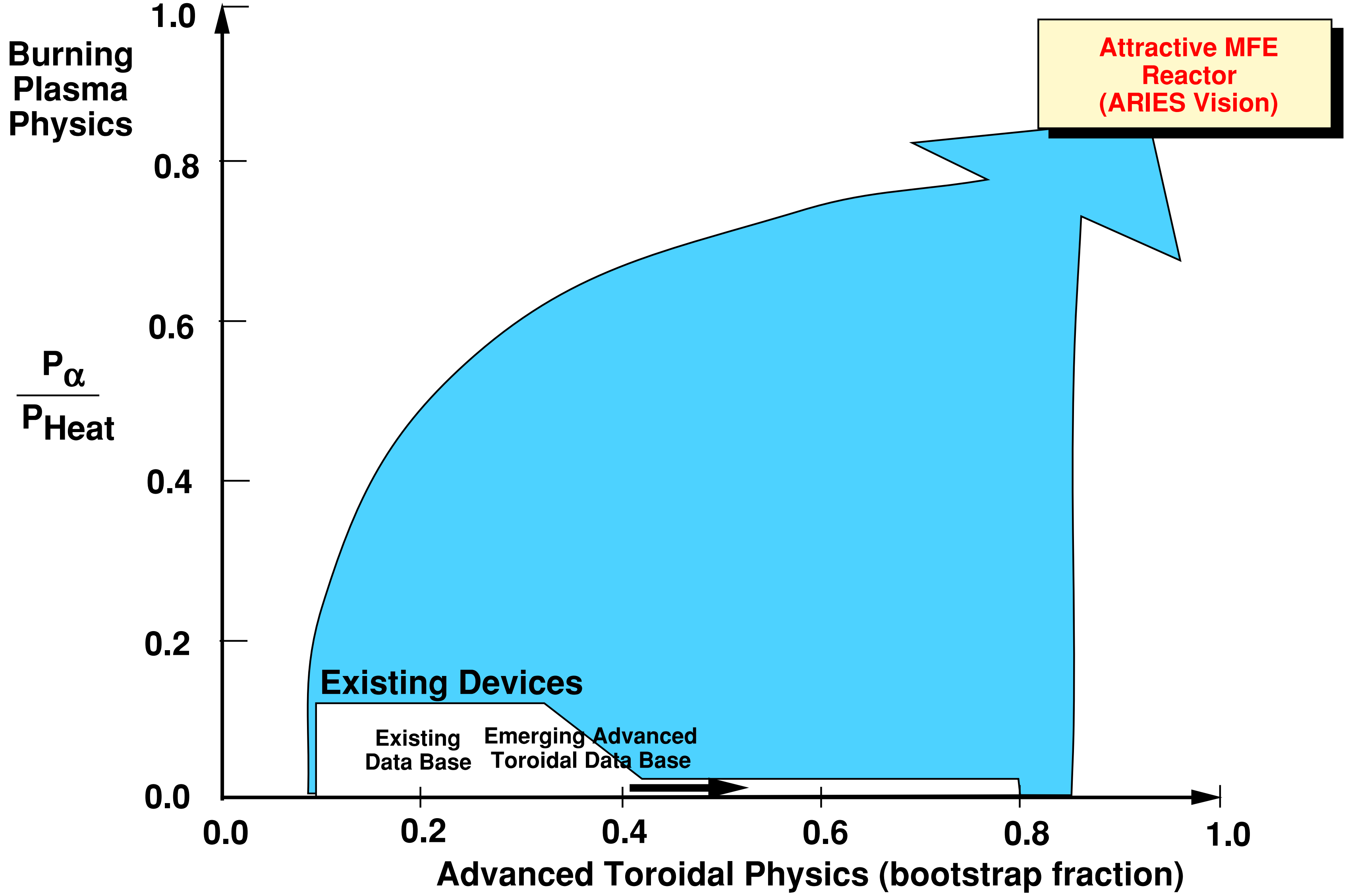
FIRE-Based Development Path (FESAC)



* A single reactor scale facility that begins as an advanced (physics, materials, technology) Engineering Test Reactor and evolves seamlessly into a fusion DEMO.

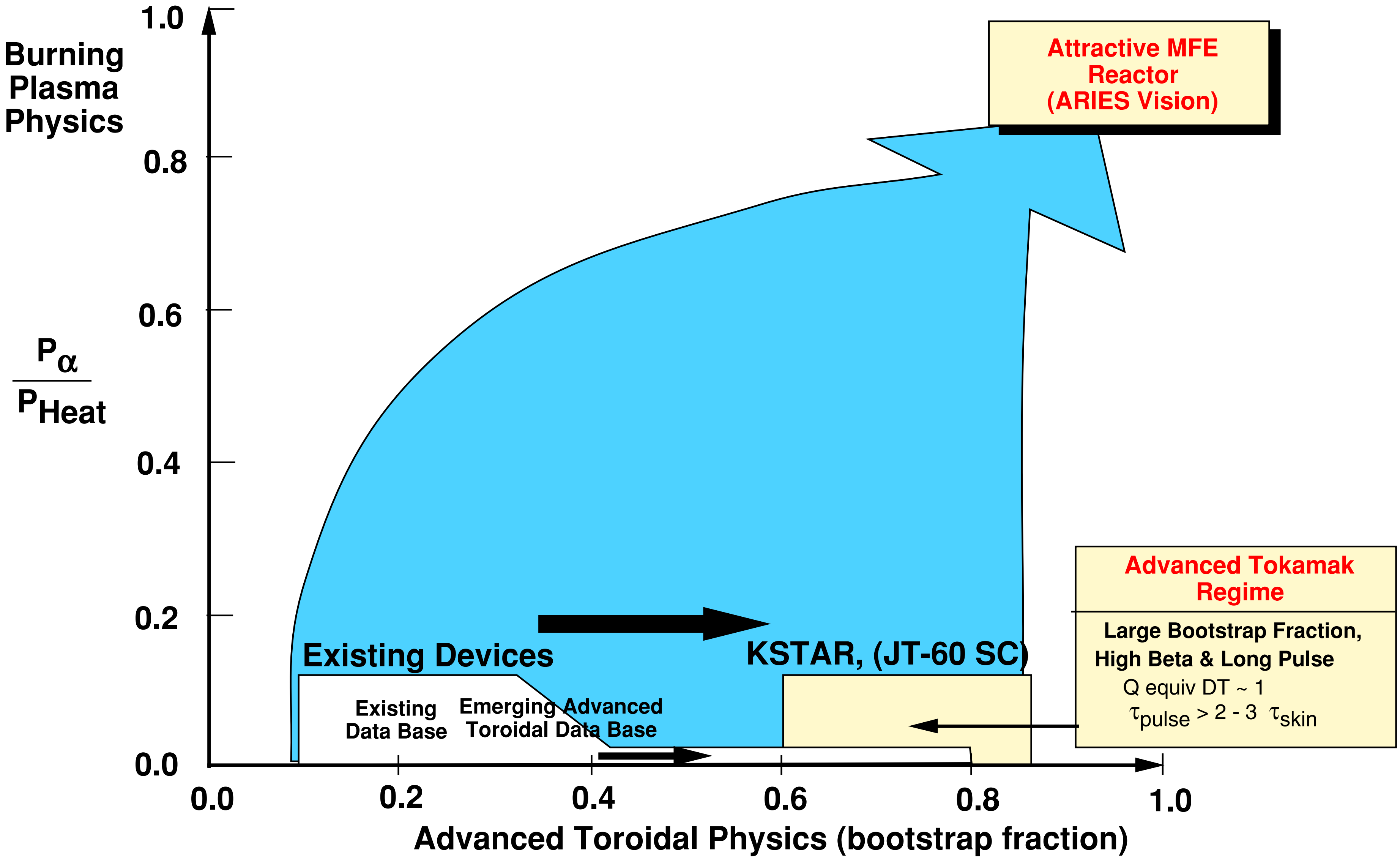
Develop and Test Advanced Physics and Technology before Reactor Scale Integration

Portfolio Approach to Address the Critical Burning Plasma Science Issues for an Attractive MFE Reactor.



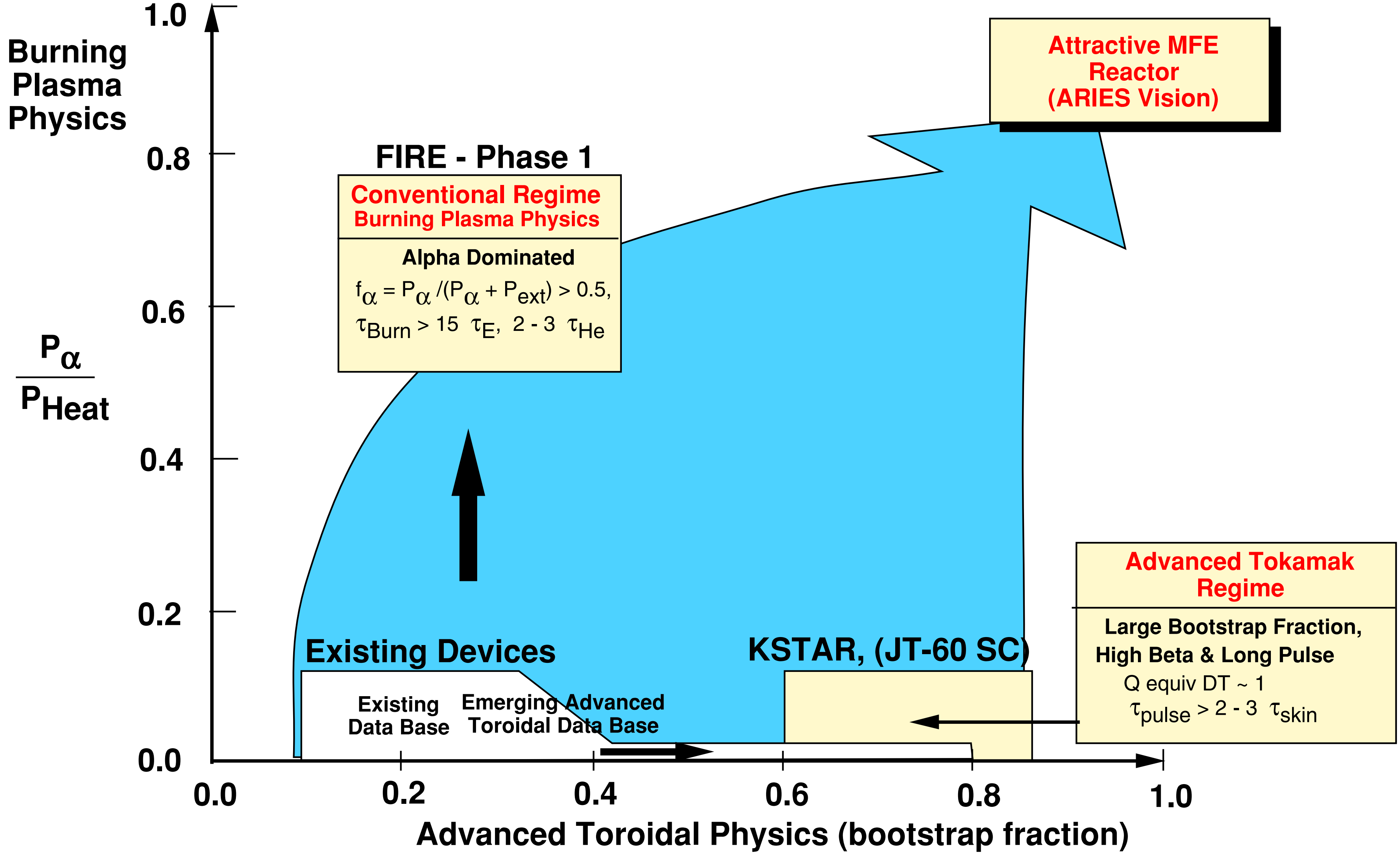
There is a very large gap between the capability of existing advanced tokamaks and the requirements for an attractive reactor.

Portfolio Approach to Address the Critical Burning Plasma Science Issues for an Attractive MFE Reactor.



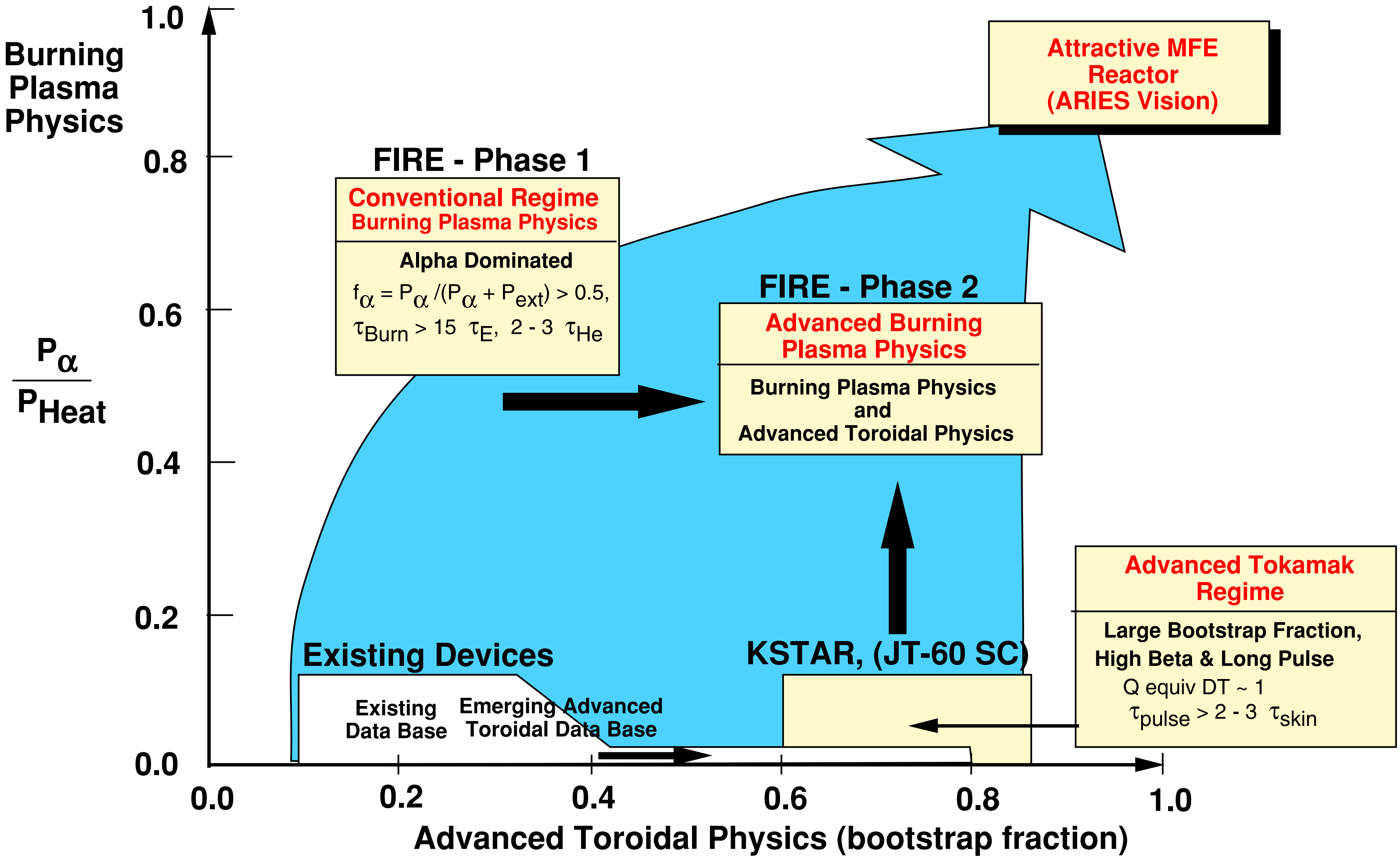
New high-beta “steady-state" tokamaks are needed to the develop and test AT physics in non burning plasmas.

Portfolio Approach to Address the Critical Burning Plasma Science Issues for an Attractive MFE Reactor.



FIRE-Phase 1 would build on the results of existing tokamaks and begin burning plasma studies in the convential regime.

Portfolio Approach to Address the Critical Burning Plasma Science Issues for an Attractive MFE Reactor.



Attractive MFE Reactor (ARIES Vision)

FIRE - Phase 1

Conventional Regime Burning Plasma Physics

Alpha Dominated

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

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

FIRE - Phase 2

Advanced Burning Plasma Physics

Burning Plasma Physics and Advanced Toroidal Physics

Existing Devices

Existing Data Base

Emerging Advanced Toroidal Data Base

KSTAR, (JT-60 SC)

Advanced Tokamak Regime

Large Bootstrap Fraction, High Beta & Long Pulse

Q equiv DT ~ 1

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

FIRE-Phase 2 would integrate results of Non-burning ATs and Conventional burning plasmas to test the compatibility and control of high bootstrap (~ 80%) and high gain (q = 5 to 10) burning plasmas.

Burning Plasma Experiment (FIRE) Requirements

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

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

Fusion Ignition Research Experiment

(FIRE)

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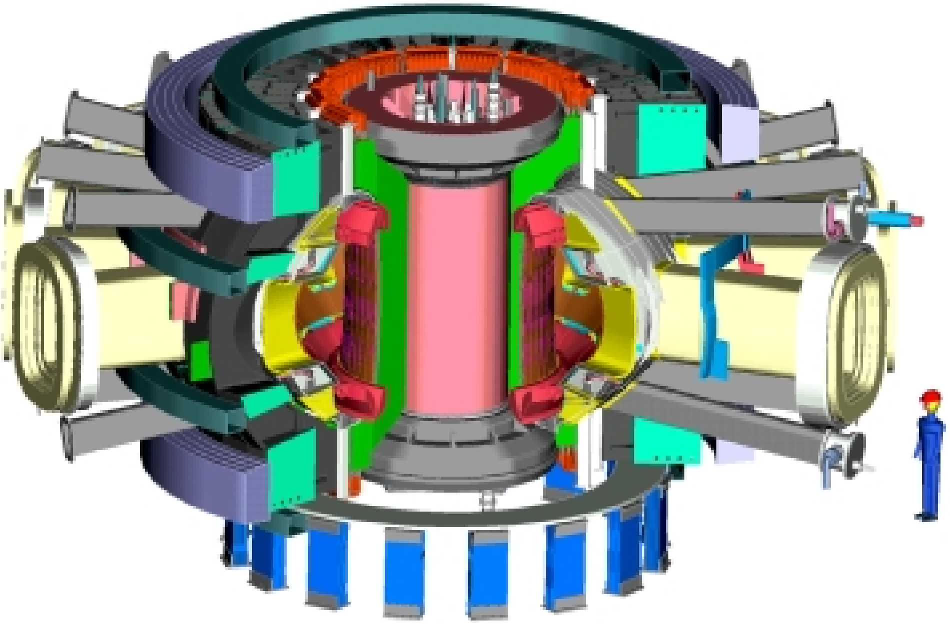


1,400 tonne

Design Features

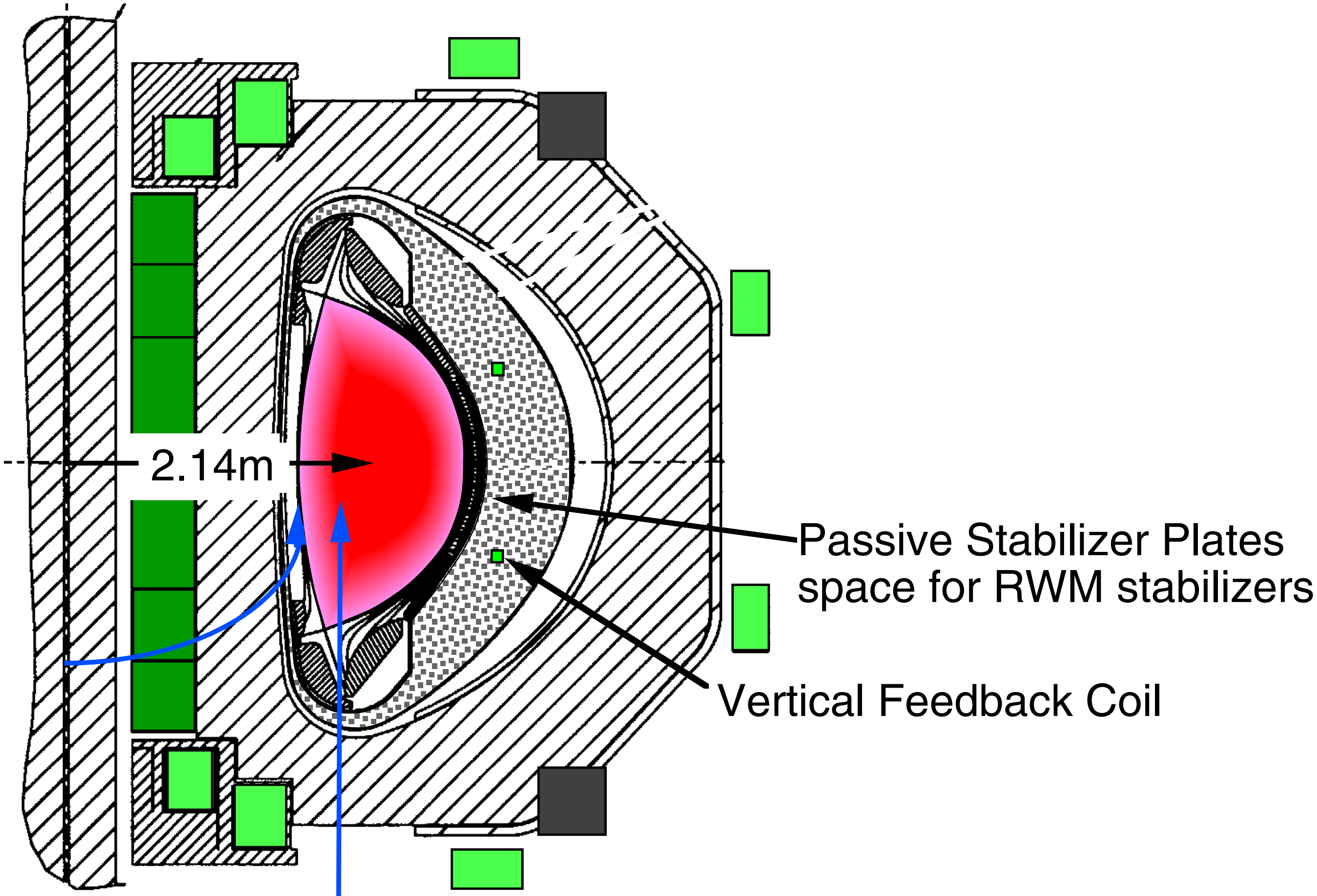
- R = 2.14 m, a = 0.595 m
- B = 10 T (~6.5 T AT)
- W_{mag}= 5.2 GJ
- I_p = 7.7 MA (~5 MA AT)
- $P_{aux} \leq$ 20 MW
- Q $\approx$ 10, P_{fusion} ~ 150 MW
- Burn Time $\approx$ 20 s (~ 40 s AT)
- Tokamak Cost $\approx$ \$350M (FY02)
- Total Project Cost $\approx$ \$1.2B (FY02) at Green Field site.

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

FIRE Incorporates Advanced Tokamak Features (ala ARIES)

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

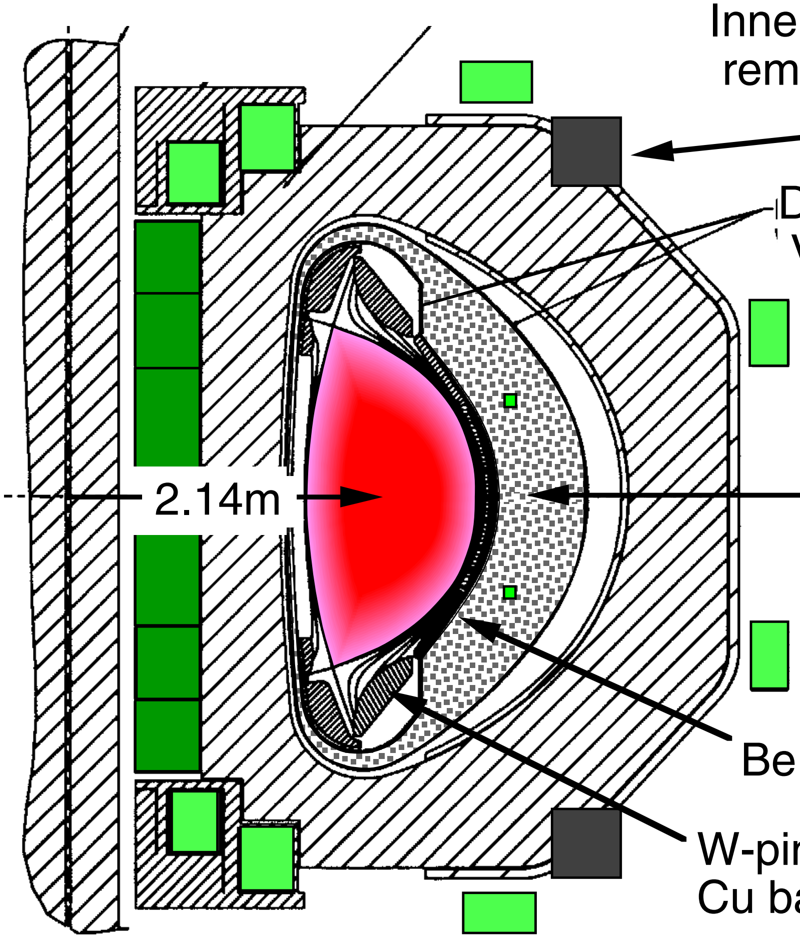


Passive Stabilizer Plates
space for RWM stabilizers

Vertical Feedback Coil

Direct and Guided Inside Pellet Injection

FIRE Engineering Features



Wedged TF Coils (16), 15 plates/coil* pre-cooled to 80 K
Inner Leg BeCu C17510,
remainder OFHC C10200

Compression Ring

Double Wall Vacuum
Vessel (316 S/S)

All PF and CS Coils*, 80K
OFHC C10200

Internal Shielding
(60% steel & 40%water)

Be coated (5 mm) first wall

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

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

FIRE Auxiliary Systems

Plasma Heating.

ICRF Heating: 20 MW, 80 – 120 MHz
Four mid-plane launchers (two strap)

Current Drive

Fast Wave
Lower Hybrid Upgrade: 20 - 30 MW, 4.6 - 5.6 GHz, n = 1.8- 2.2
Electron Cyclotron Upgrade: 170 GHz @ r/a ≈ 0.33 for Adv Tok at 6.6T.

Plasma Fueling and Pumping

HFS launch: guided slow pellets, high speed vertical inside mag axis
Various impurity seeding injectors for distributing power
Cryopumps (>100 Pa m^3 s^{-1}) in the divertor for exhaust and He pumping

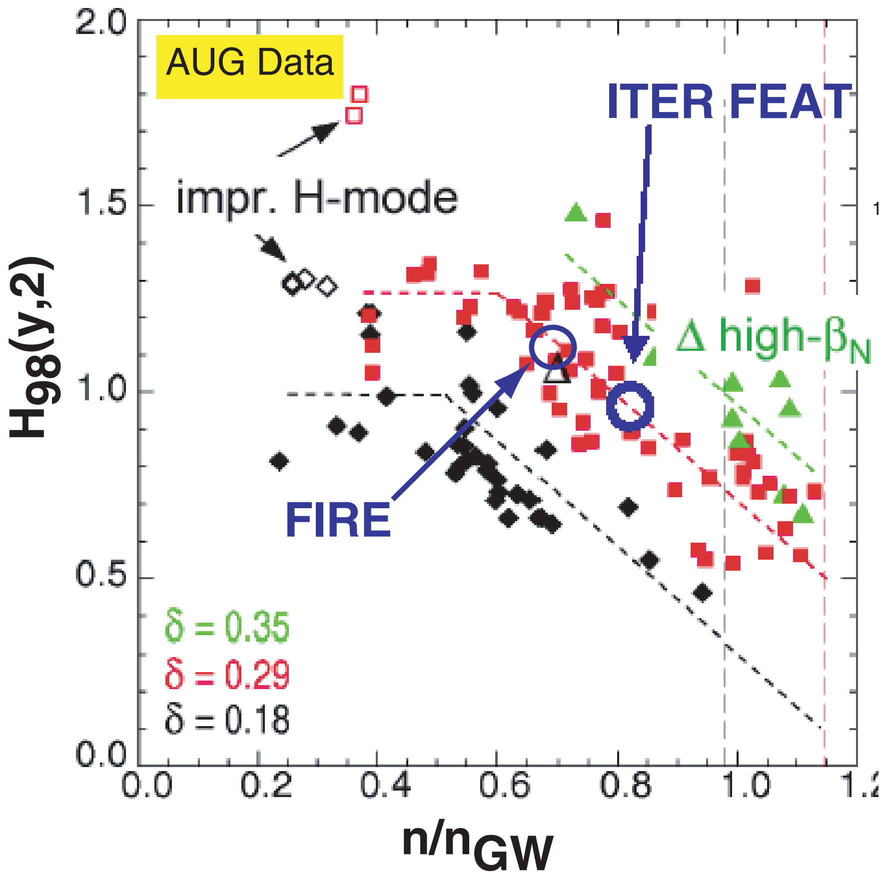
Tritium Inventory (similar to TFTR)

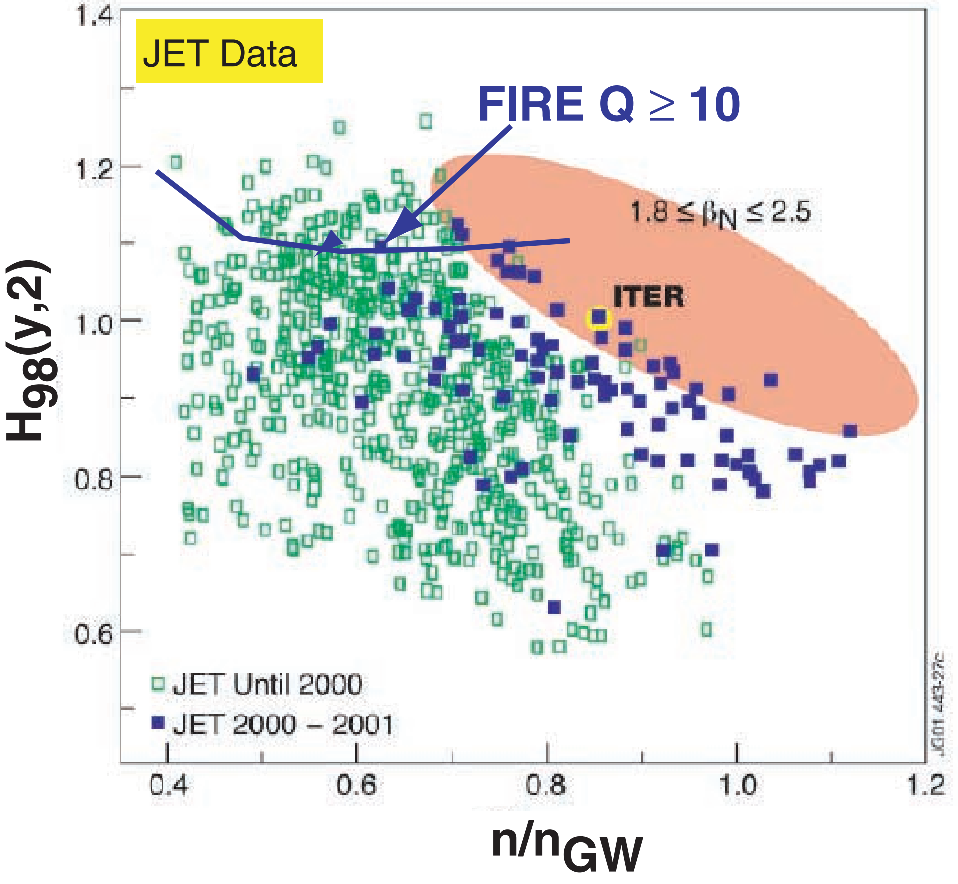
~0.3 g-T/pulse, site inventory
< 30 g-T, Low Hazard Nuclear Facility, Category 3 like TFTR

Operating Sequences

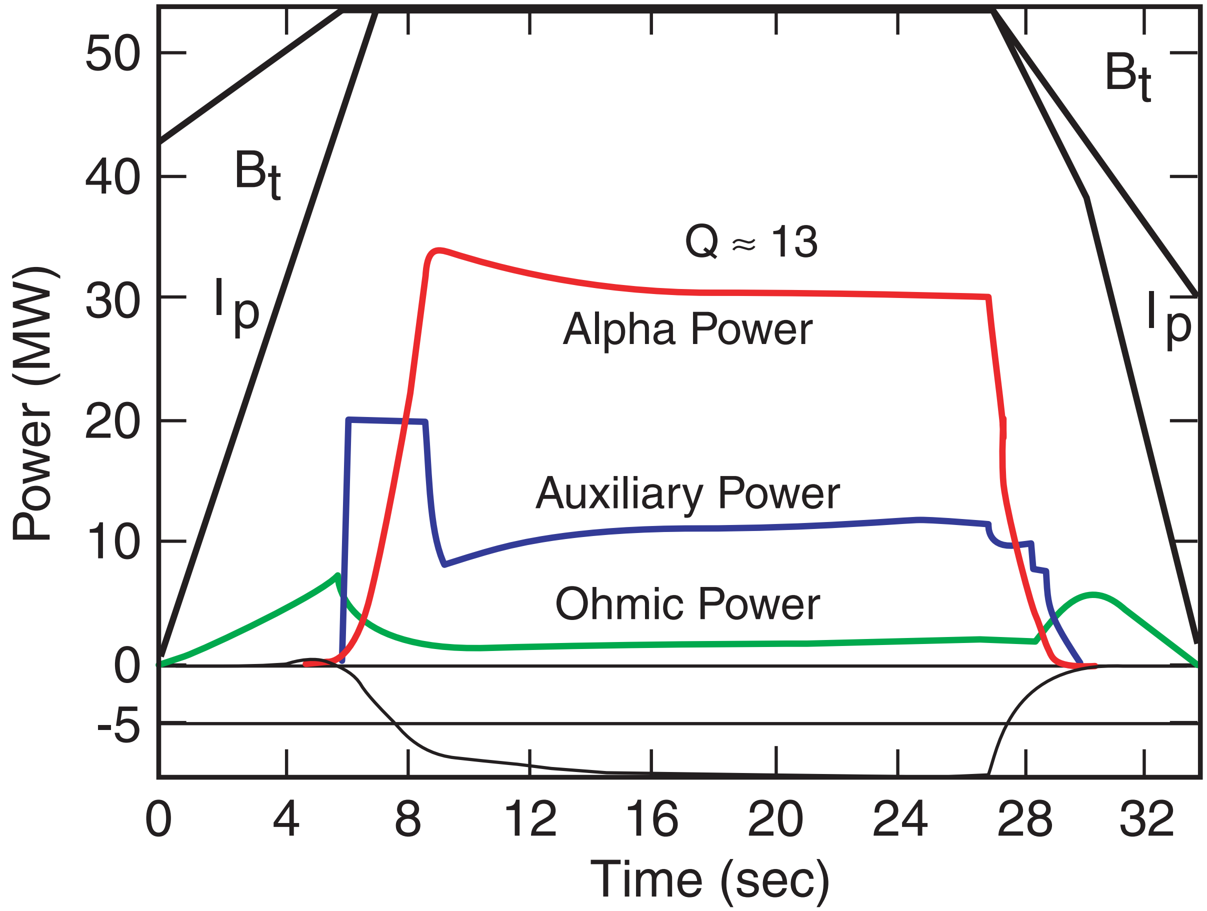
3,000 full field and power, 30,000 pulses at 2/3 field (AT) like BPX
3 hr rep time at full power and pulse length, ~1 hr for AT 10 s pulses
Insulator R&D and improved cooling design to increase pulse and rep rate

High Triangularity and Modest Density Relative to Greenwald Facilitate H-Mode Operation





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



$B = 10$ T

$I_p = 7.7$ MA

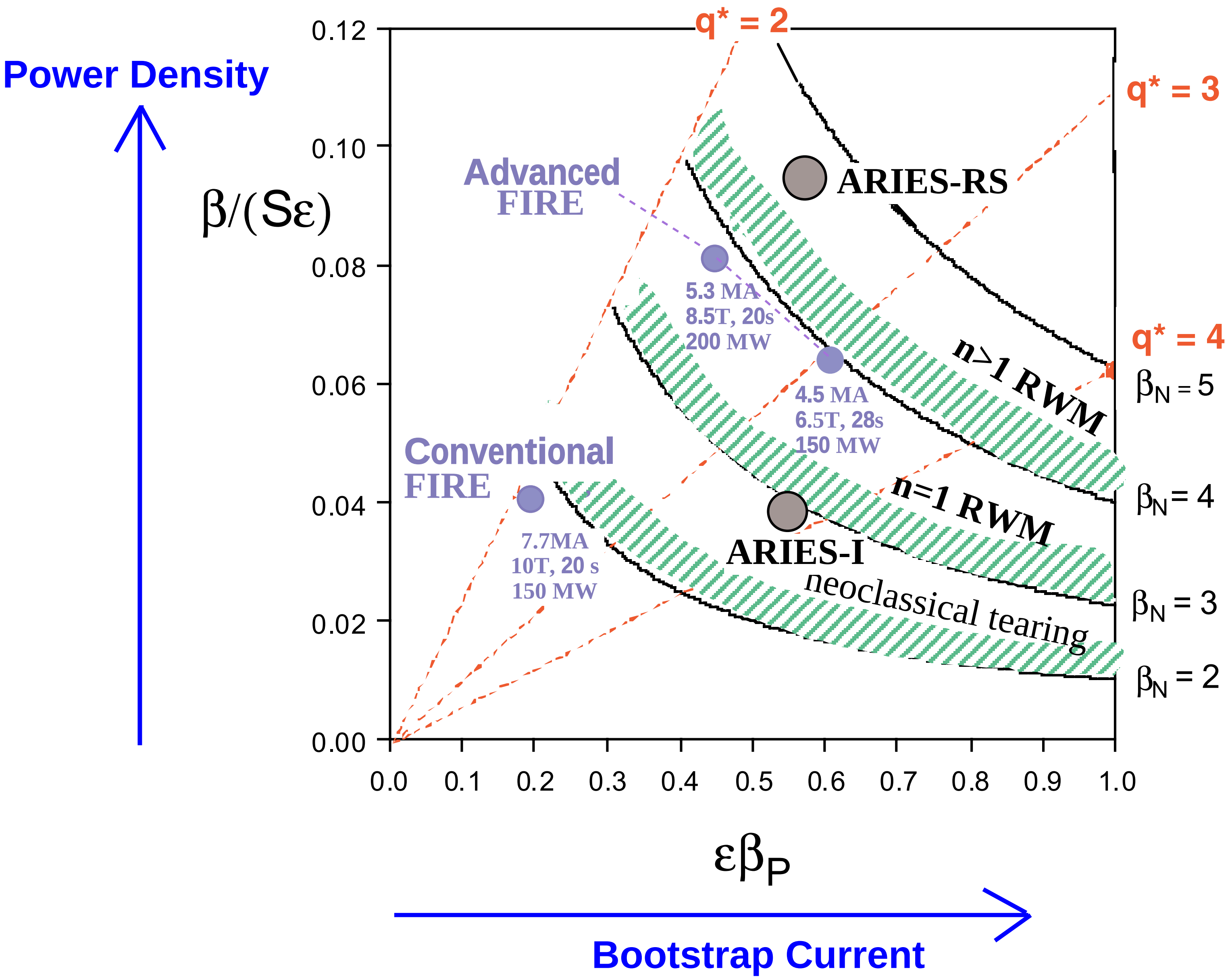
$R = 2.14$ m

$A = 3.6$

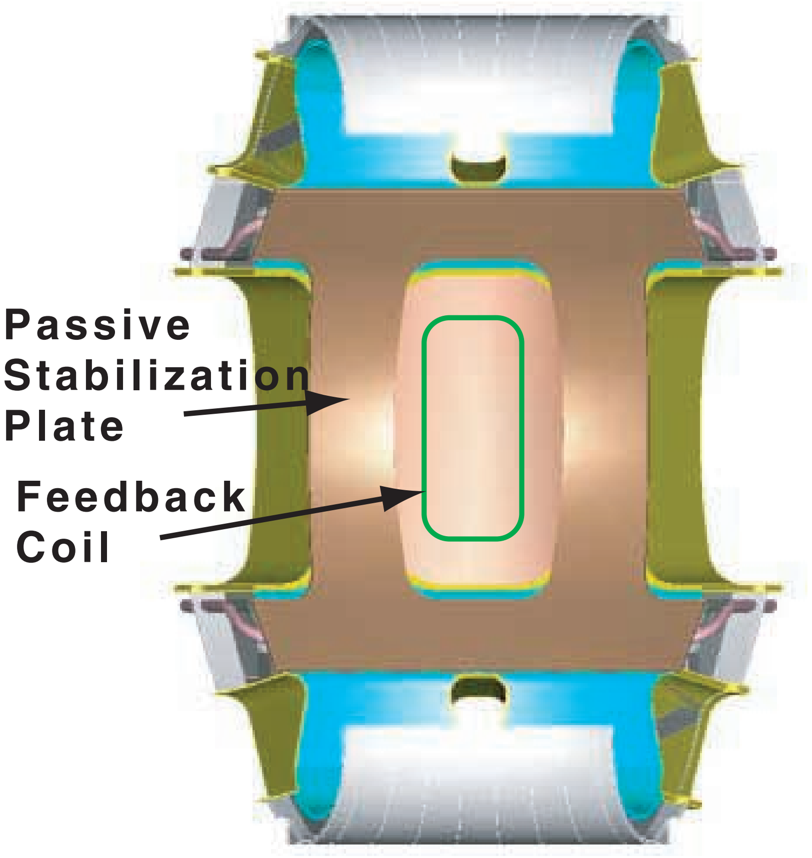
- ITER98(y, 2) with H(y, 2) = 1.1, $n(0)/\langle n \rangle = 1.2$, and $n/ n_{GW} = 0.67$
- Burn Time ≈ 20 s $\approx 21\tau_E \approx 4\tau_{He} \approx 2\tau_{CR}$

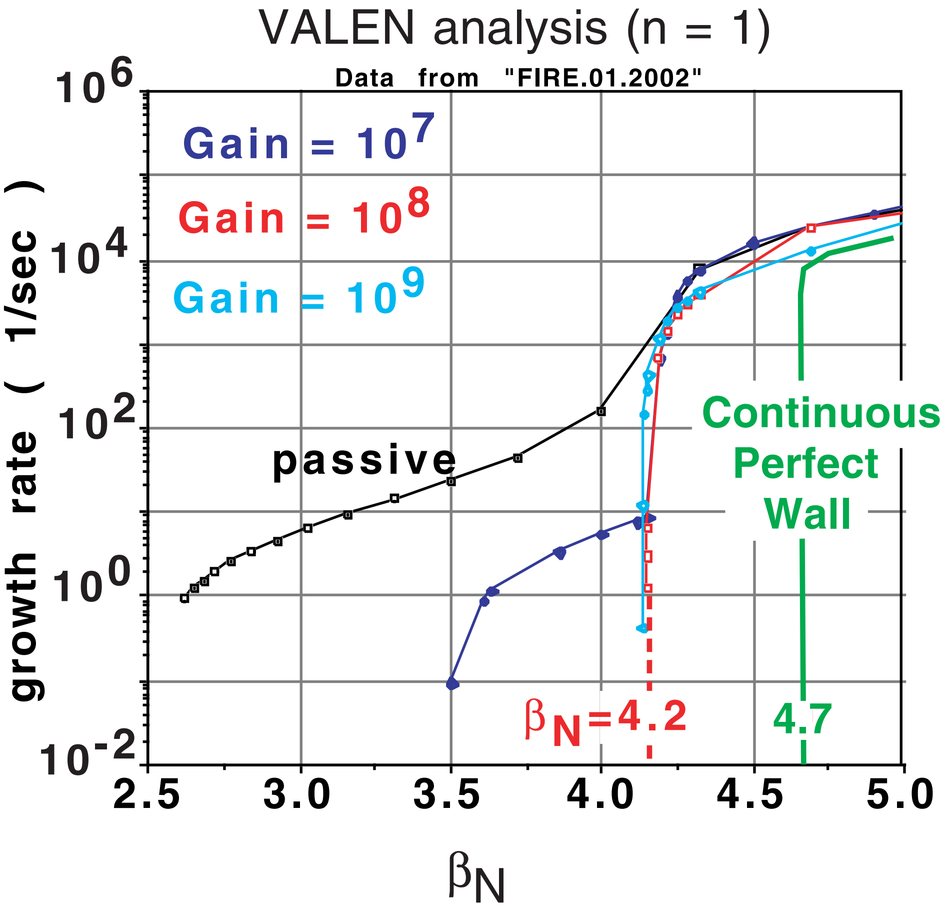
Q = Pfusion/(Paux + Poh)

Advanced Tokamak Modes with $\beta_N > 4$ must be Developed for an Attractive Reactor



FIRE Accesses β_N ~ 4 with RWM Control





- **Control Coils Located in 8 of 16 ports (4 n=1 coil pairs).**
- **Stable β_N for n = 1 reaches 4.2, 90% of continuous wall limit.**
- **Effects of n = 2 are being examined.**

Columbia University

The Range of Energetically Accessible Non-Inductive AT Modes has been Determined using a 0-D Systems Analysis.

- Plasma Heating and Current Drive provided by LHCD and FWCD with $\eta \approx 0.24$ A/W-m^2 and bootstrap $f_{BS} \approx \beta_N q_{cly} (R/a)^{1/2} C_{bs} n(0)/<n>$

- Confinement assumed to scale as a multiplier on ITER98(y,2)

- Exhaust power distribution optimized by adding impurities in both the core (Be, Ar) plasma and divertor (Ne) subject to:

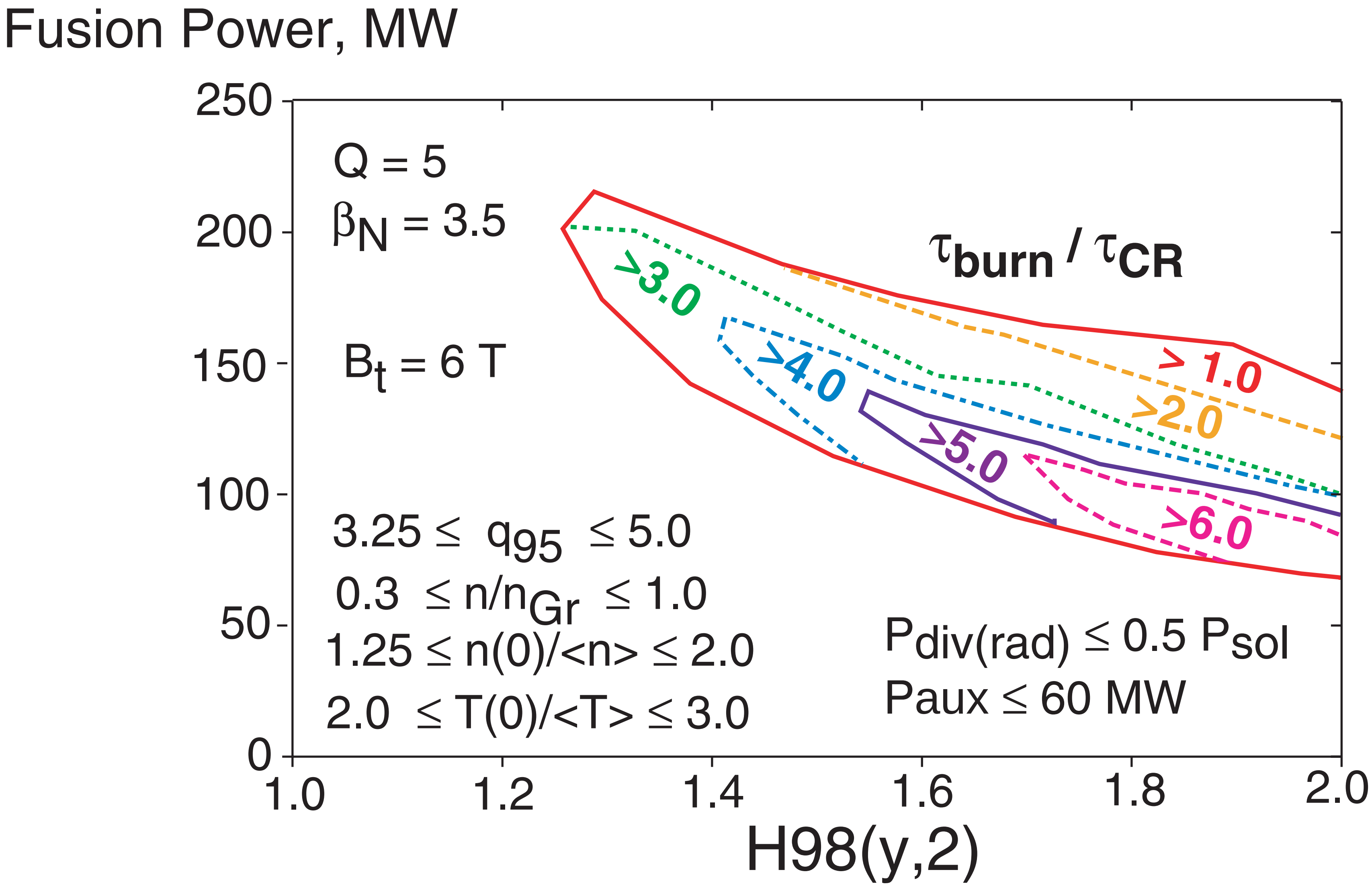
  P_{FW} (rad)$\leq$ 1 MWm^{-2}, including a peaking factor of 2
  P_{div}(part) < 28 MW, P_{div} (rad)< 0.5-0.7 P_{sol}, P_{div} (rad)< 8MWm^2

- Resistive and Nuclear Heating of the TF coils/Nuclear heat of Vac Vess limit

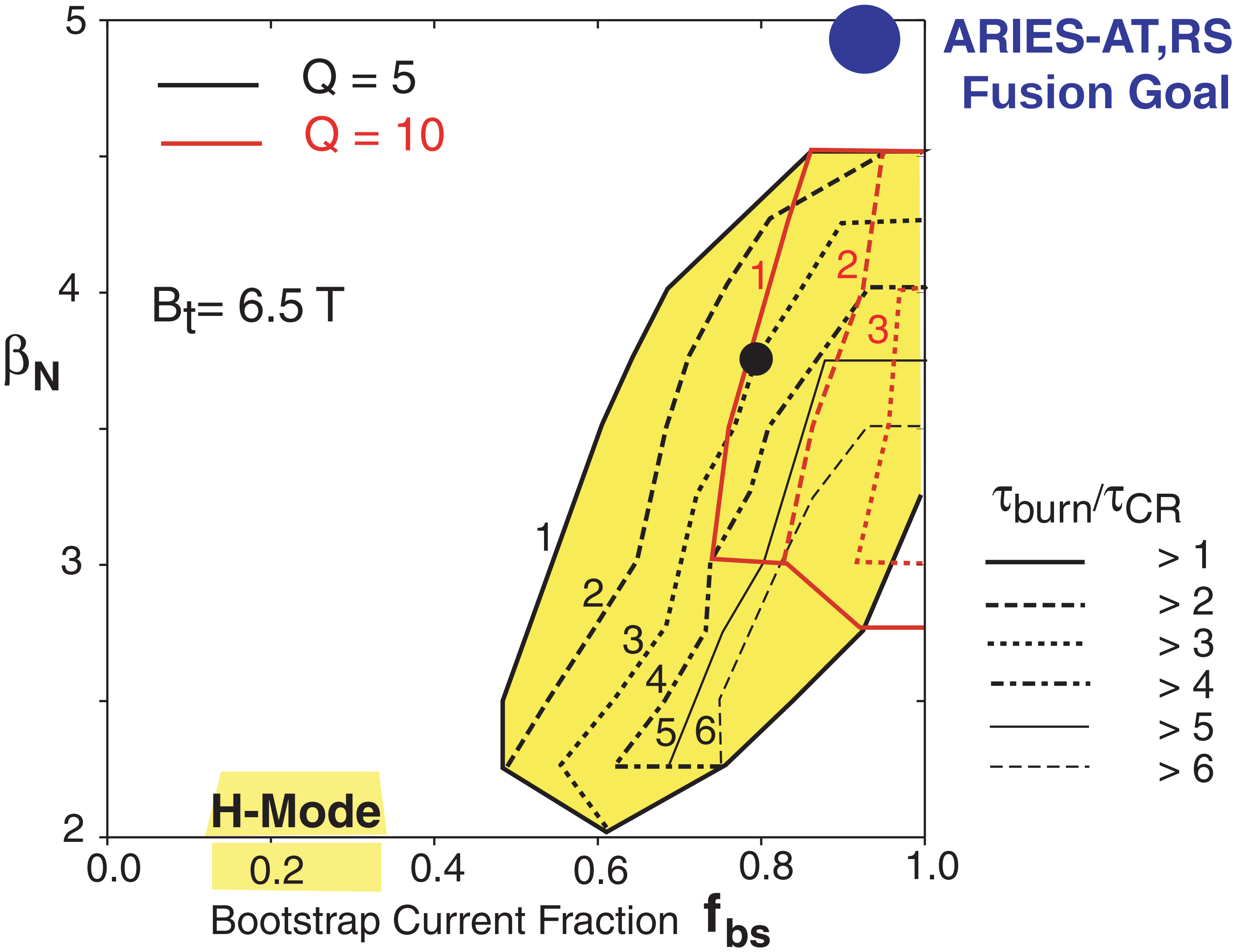
  P_{fusion} x Burn duration $\leq$ 4 GJ/pulse

- Parameter space scanned for power balance over:
  $3.5 \leq q_{95} \leq 5$, $0.3 \leq n/n_{Gr} \leq 1.0$, $1.25 \leq n(0)/<n> \leq 2.0$, $2.0 \leq T(0)/<T> \leq 3$
  $1\% \leq f_{Be} \leq 3\%$, $0\% \leq f_{Ar} < 0.4\%$, $2.5 \leq \beta_N < 4.5$, for Q = 5, 10
  to determine the required H(y,2) and allowed τ_{burn}/τ_{CR}

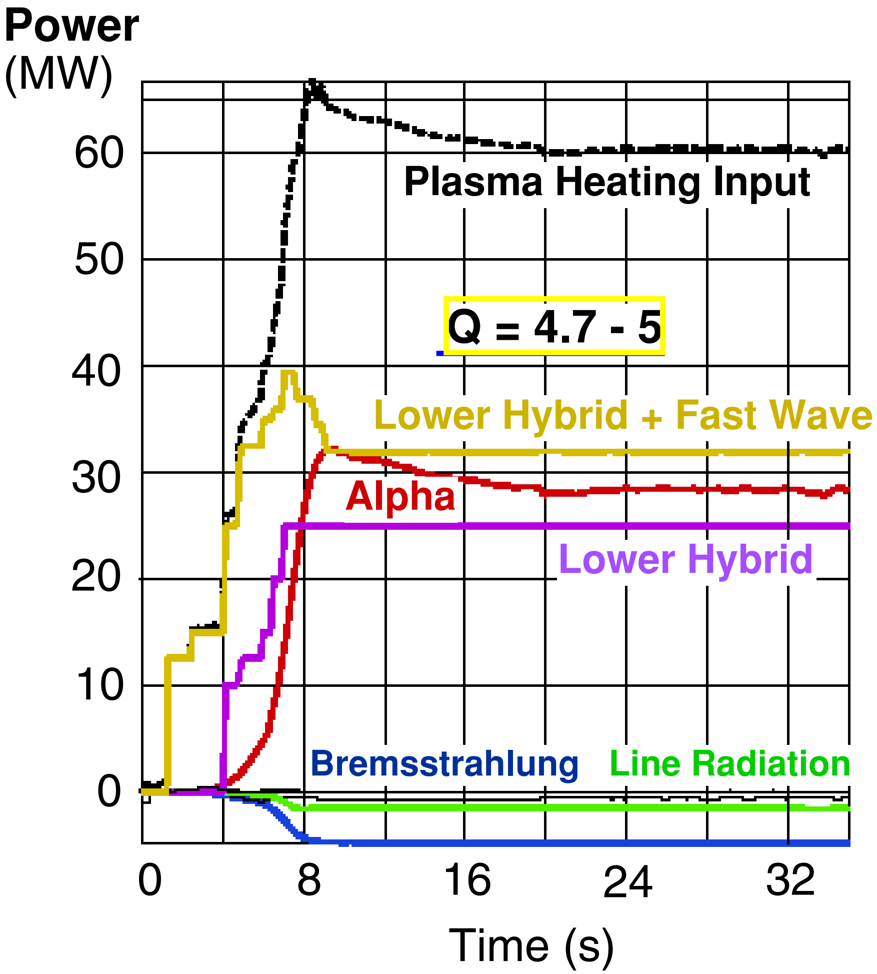
FIRE can Access High-β AT Modes under Quasi-Steady-State Conditions



AT Modes with $\beta_N \approx 4$, $f_{bs} \approx 85\%$ Sustained for 2 - 4 τ_{CR} are Energetically Accessible in FIRE

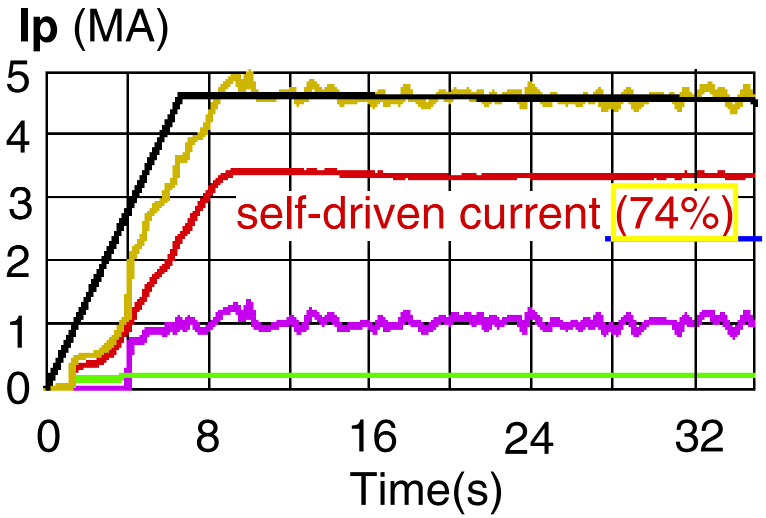


1.5 D Simulation of 100% Non-Inductive High-β Quasi-Stationary AT modes are in Agreement with 0-D Analysis



ARIES-like AT Regime
(Reversed Shear/Negative Central Shear) with q(0) =3.8, q_{95} = 3.5 and q_{min} = 2.7 @ r/a = 0.8, B_t = 6.5 T

Fully Non-Inductively Driven for $3.2\ \tau_{CR}$
(quasi-stationary approaching steady-state)



Tokamak Simulation Code (TSC) results for β_N = 4.3, H(y,2) = 1.7, would require n = 1 stabilization consistent with proposed feedback stabilization system.

Major Issues Under Investigation.

- Disruptions
  - Started with ITER design assumptions, completing analysis
  - Effect of neutral stability due to double null
    - Reduced frequency of VDEs?
    - Can fast radial field feedback “prevent” VDEs?
  - Mitigation techniques (gas jets)

- Type I Elms (5% Wp, 0.1 ms) would erode (surface melt) W divertor targets
  - Can Type II Elms be accessed by high triangularity/double null at q $\approx$3?

- NTM stabilization or avoidance needed.
  - Modify Δ’ with LHCD
  - ECCD for AT modes near 6.5 T?

- Diagnostic Integration and Development
  - Magnetic diagnostics exposed to high flux (induced emf)
  - Generic design of diagnostic port shield plug needed
  - Development of diagnostic beams

Background and Plans

Based on the Snowmass Assessment, 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 dual path 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.

Now being reviewed by the National Academy of Science.

Energy Policy Bill now in the Congress calls for DOE to submit a Plan for the construction of a US Burning Plasma Experiment by 2004.

Summary

- A Window of Opportunity may be opening for U.S. Energy R&D. We should be ready. The Diversified International Portfolio has advantages for addressing the science and technolgy issues of fusion.

- FIRE with a construction cost ~ $1.2B, has the potential to :
  - address the important burning plasma issues, performance ~ ITER
  - investigate the strong non-linear coupling between BP and AT,
  - stimulate the development of reactor relevant PFC technology, and
  - provide generic BP science and possibly BP infrastructure for non-tokamak BP experiments in the U. S.

- Some areas that need additional work to realize this potential include:
  - Apply recent enhanced confinement and advanced modes to FIRE
  - Understand conditions for enhanced confinement regimes-triangularity
  - Compare DN relative to SN - confinement, stability, divertor, etc
  - Complete disruption analysis, develop better disruption control/mitigation.

- If a postive decision is made in this year, FIRE is ready to begin Conceptual Design in FY2004 with target of first plasmas ~ 2011.

http://fire.pppl.gov