FIRE

Exploring Burning Plasma Physics

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for the National FIRE Study Team

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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

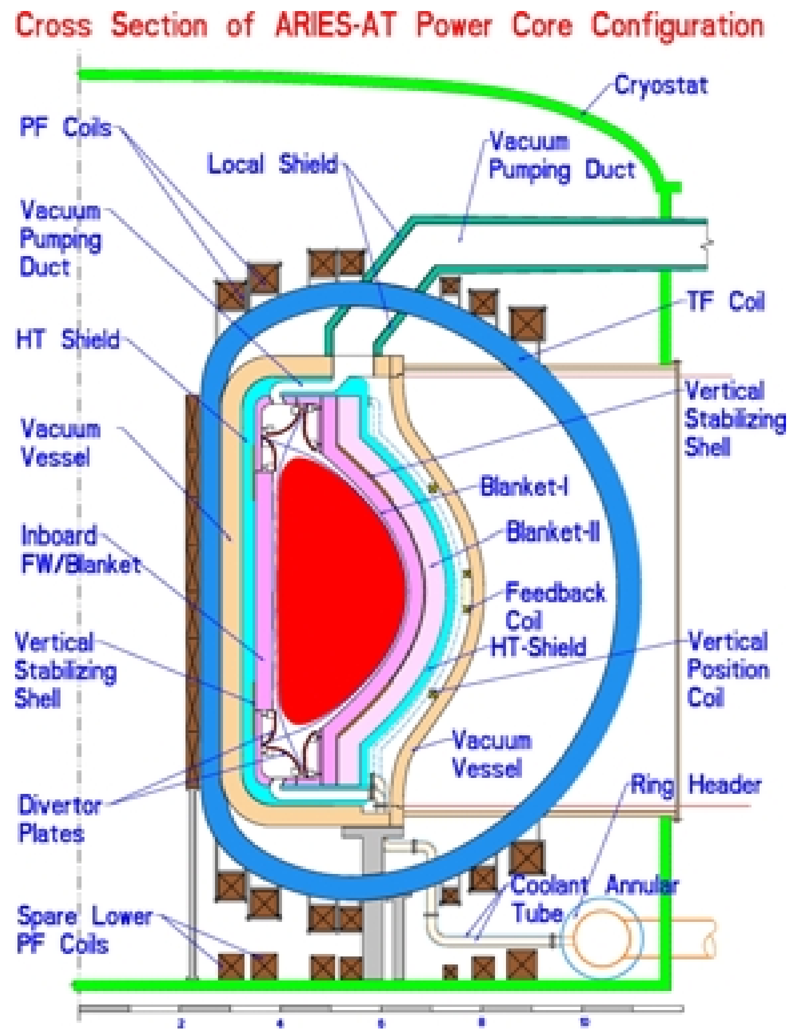
Note: this material is for background. Additional material can be found at:

http://fire.pppl.gov - the general FIRE web page, lots of fusion info

The Key Features for an Attractive Fusion Power Plant have been Identified

Desired Characteristics

- Power Gain Q ≥ 25
  $n\tau_E T_i > 6 \times 10^{21}$ m^{-3} s keV
- Power Density ≥ 6 MWm^{-3}
  high beta = $p_{plasma}/p_{mag} > 5\%$
- Neutron Wall Loading > 3 MW m^{-2}
- Efficient Steady State operation
  self-driven current > 90%
- High Availability
  First Wall Materials > 150 dpa
- Safety and Environment
  low activation materials
  no evacuation



Pfusion = 1.7 GW, Pe = 1 GW

For more information on ARIES Power Plant Studies see http://aries.ucsd.edu/ARIES/DOCS/

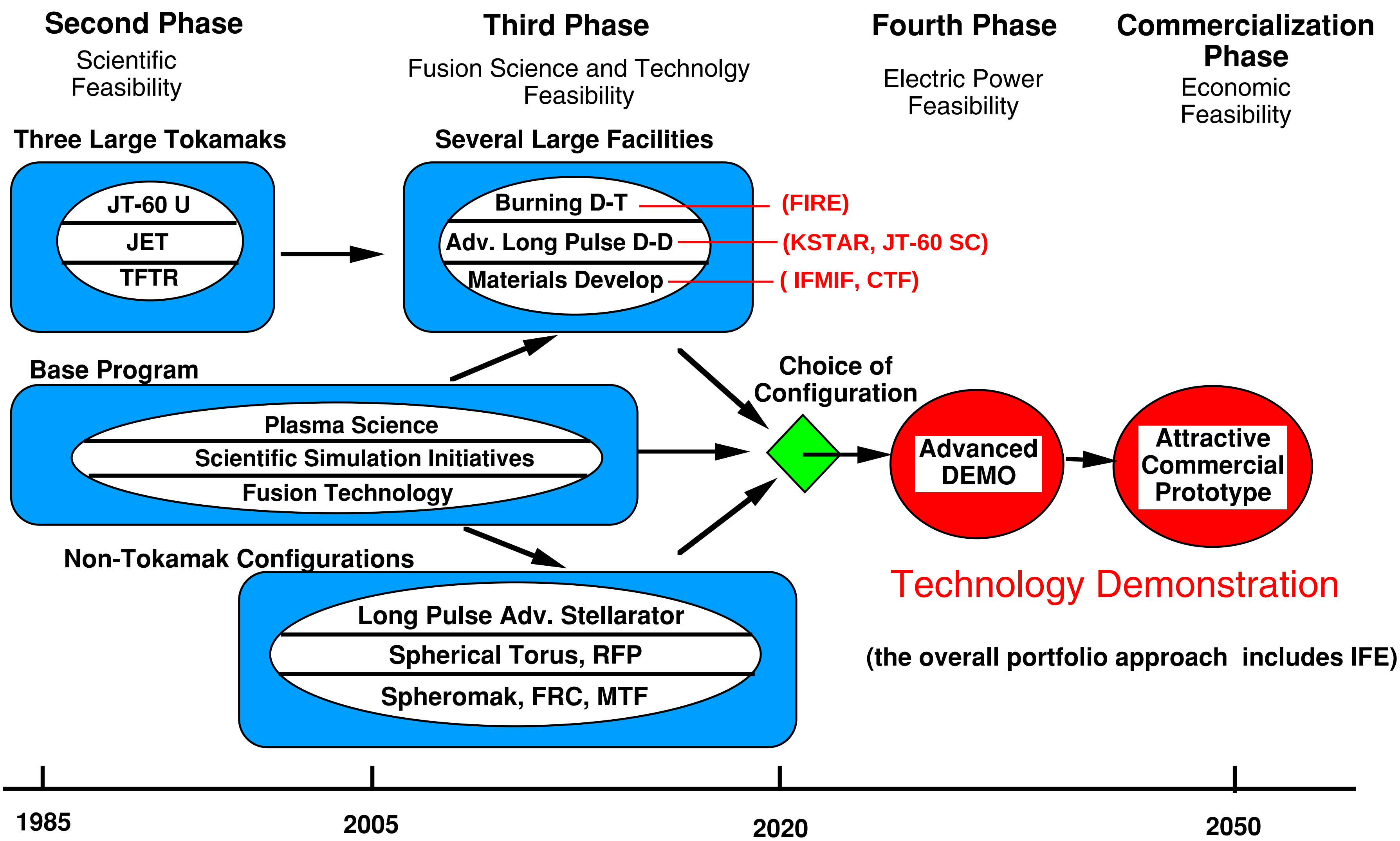
Critical Issues to be Addressed in the Next Stage of Fusion Research

- **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
- **Burning Plasma Physics** (coupled with above)
  - strong nonlinear coupling inherent in a fusion dominated plasma
  - access, explore and understand fusion dominated plasmas
- **Neutron-Resistant Low-Activation Materials**
  - high fluence material testing facility using "point"neutron source
  - high fluence component testing facility using volume neutron source
- Superconducting Coil Technology does not have to be coupled to physics experiments - only if needed for physics objectives

Significant advances in understanding and large extrapolations in performance parameters are required in each of these areas.

Proposed by FIRE advocates at Snowmass

Diversified International Portfolio for Magnetic Fusion



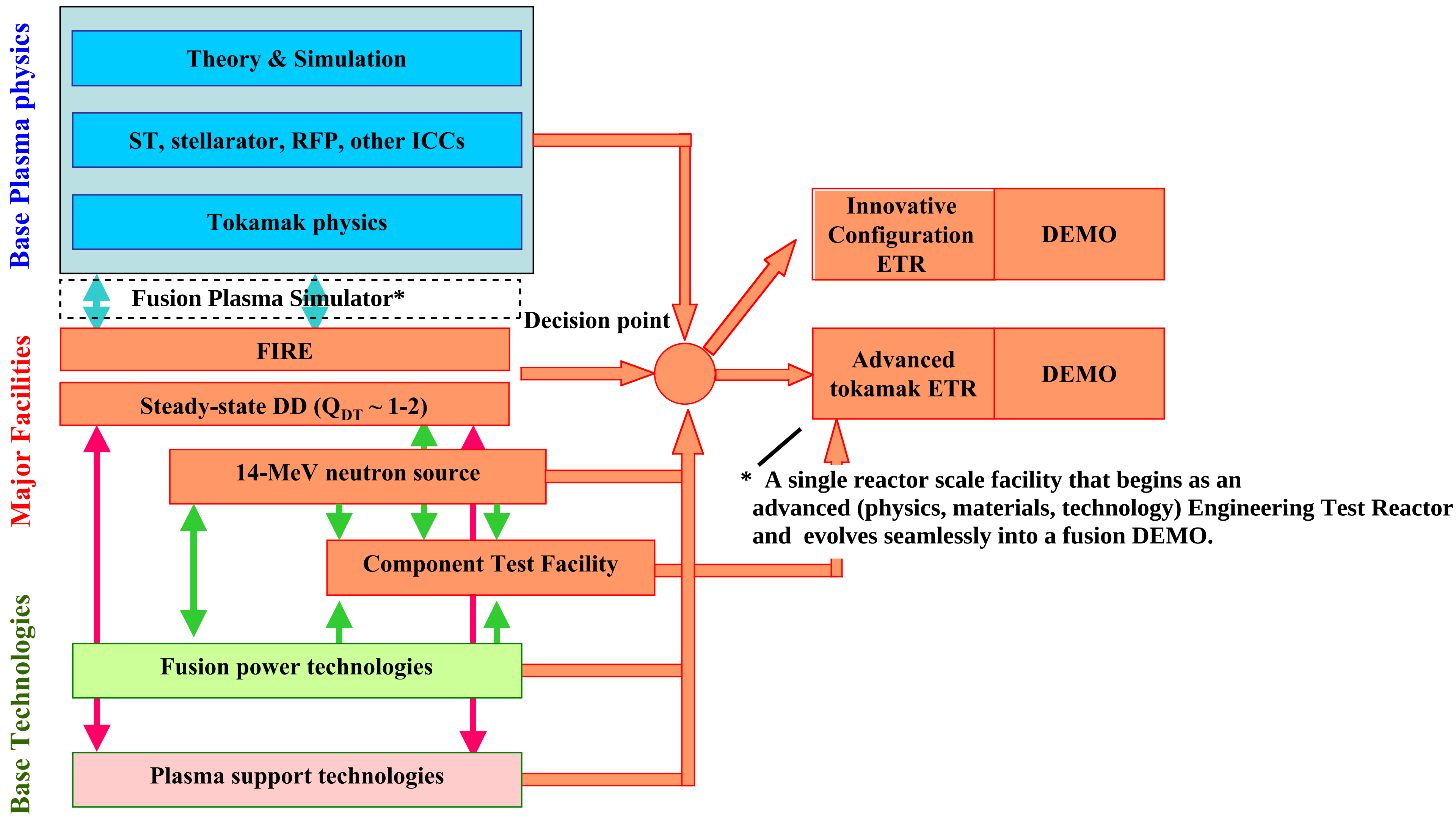
Reduced Technical Risk **Streamlined Management Structure** **Better Product/Lower Overall Cost**

Increased Technical Flexibility **Faster Implementation**

Emphasizes optimization before integration on reactor scale devices.

2002 Fusion Snowmass Executive Summary (p. 9)

FIRE-Based Development Path



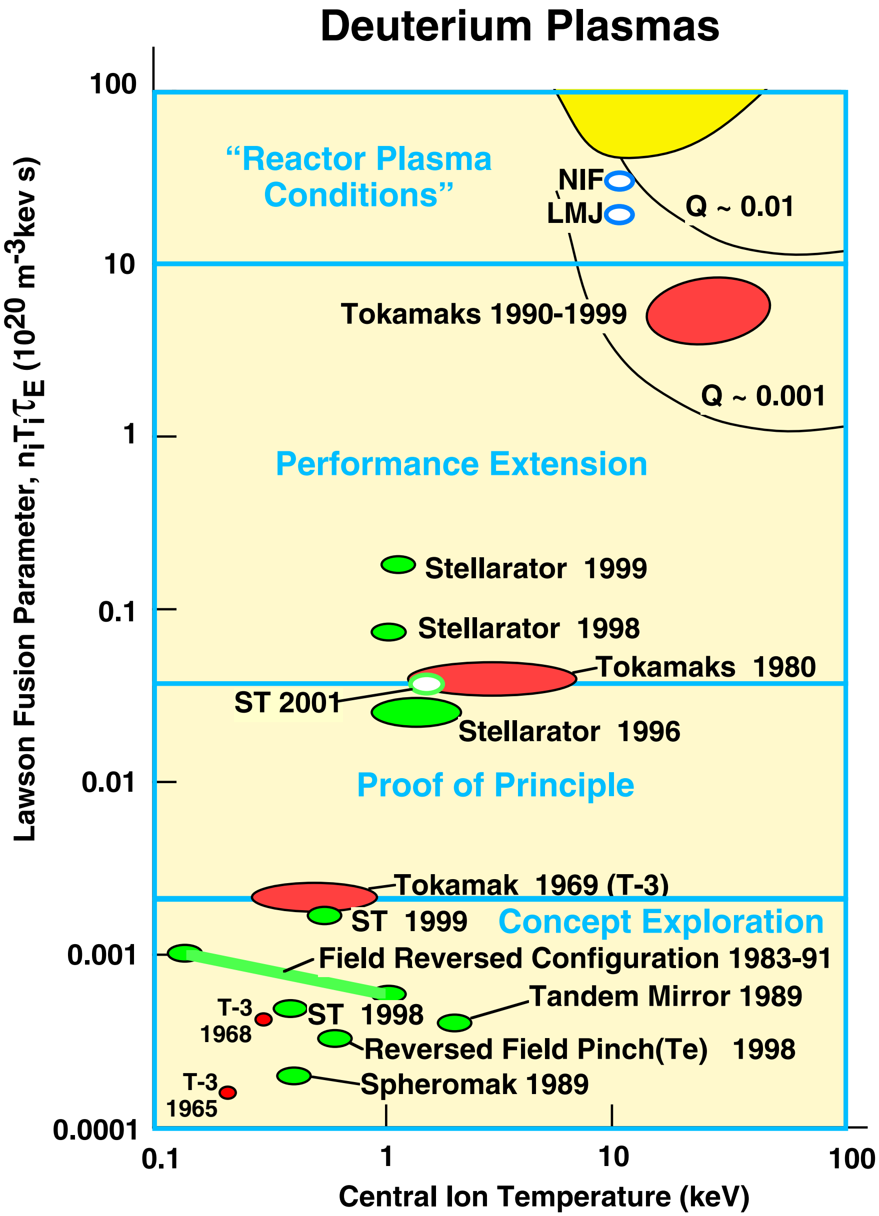
* The Fusion Plasma Simulator would serve as the intellectual integrator of physics phenomena in advanced tokamak configurations, advanced stellarators and tokamak burning plasma experiments.

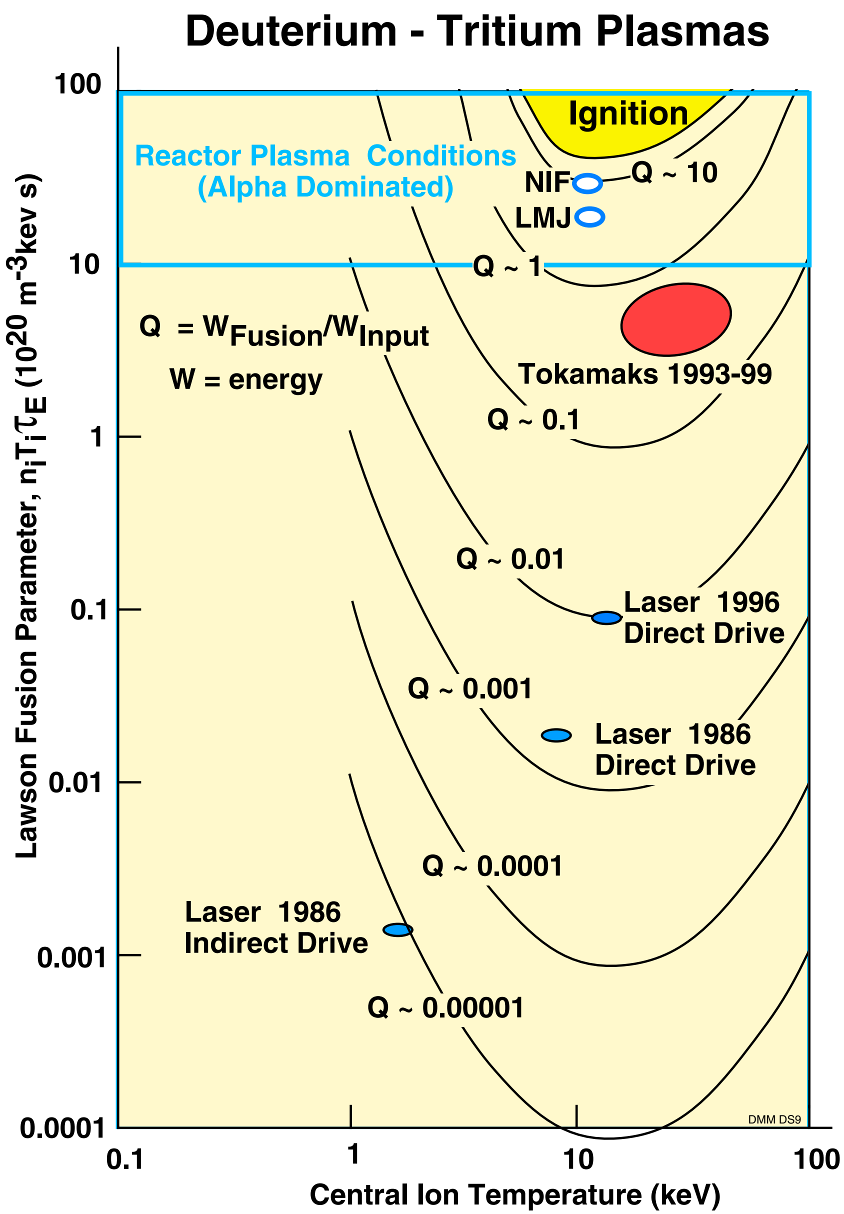
2002 Fusion Snowmass Executive Summary (p. 8)

FIRE-Based Development Path

- FIRE-based development plan reduces initial facility investment costs and allows optimization of experiments for separable missions.
- It is a lower risk option as it requires “smaller” extrapolation in physics and technology basis.
- Assuming successful outcome, a FIRE-based development path provides further optimization before integration steps, allowing a more advanced and/or less costly integration step to follow.

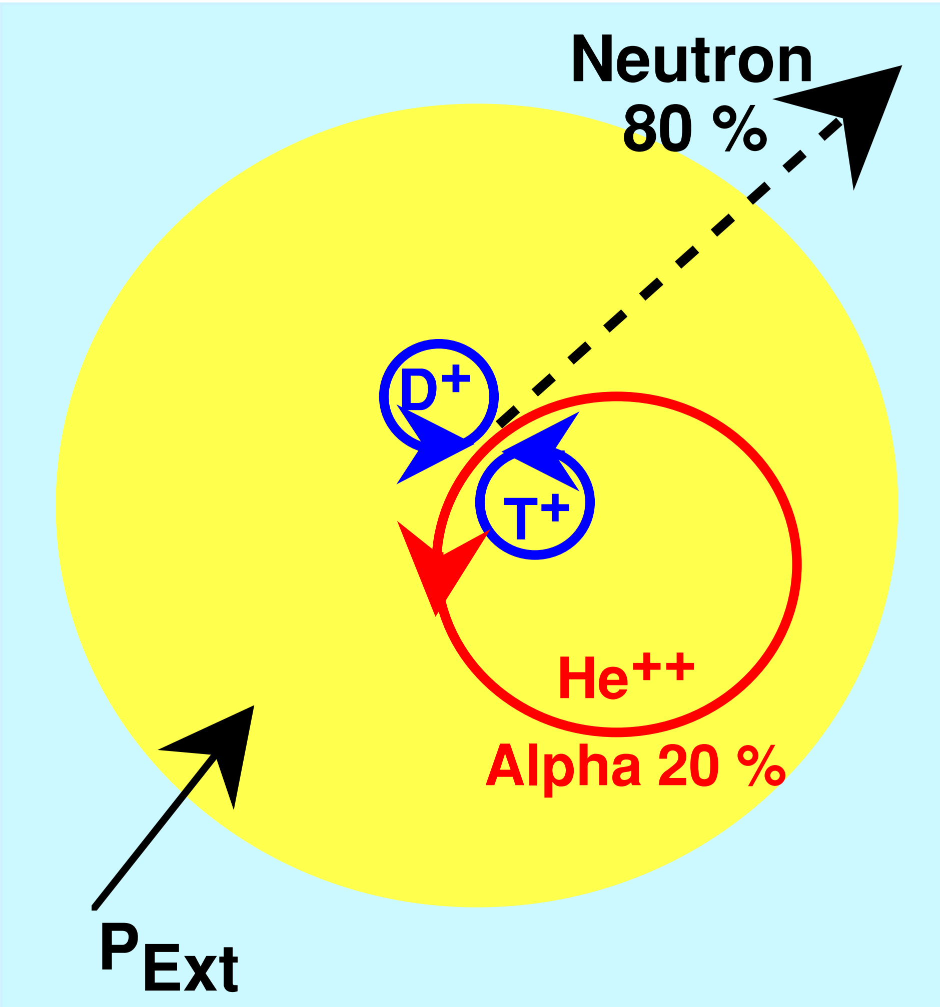
Magnetic Fusion is Technically Ready for a High Gain Burning Exp't





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

Burning Plasma Physics in a D-T Fusion Plasma

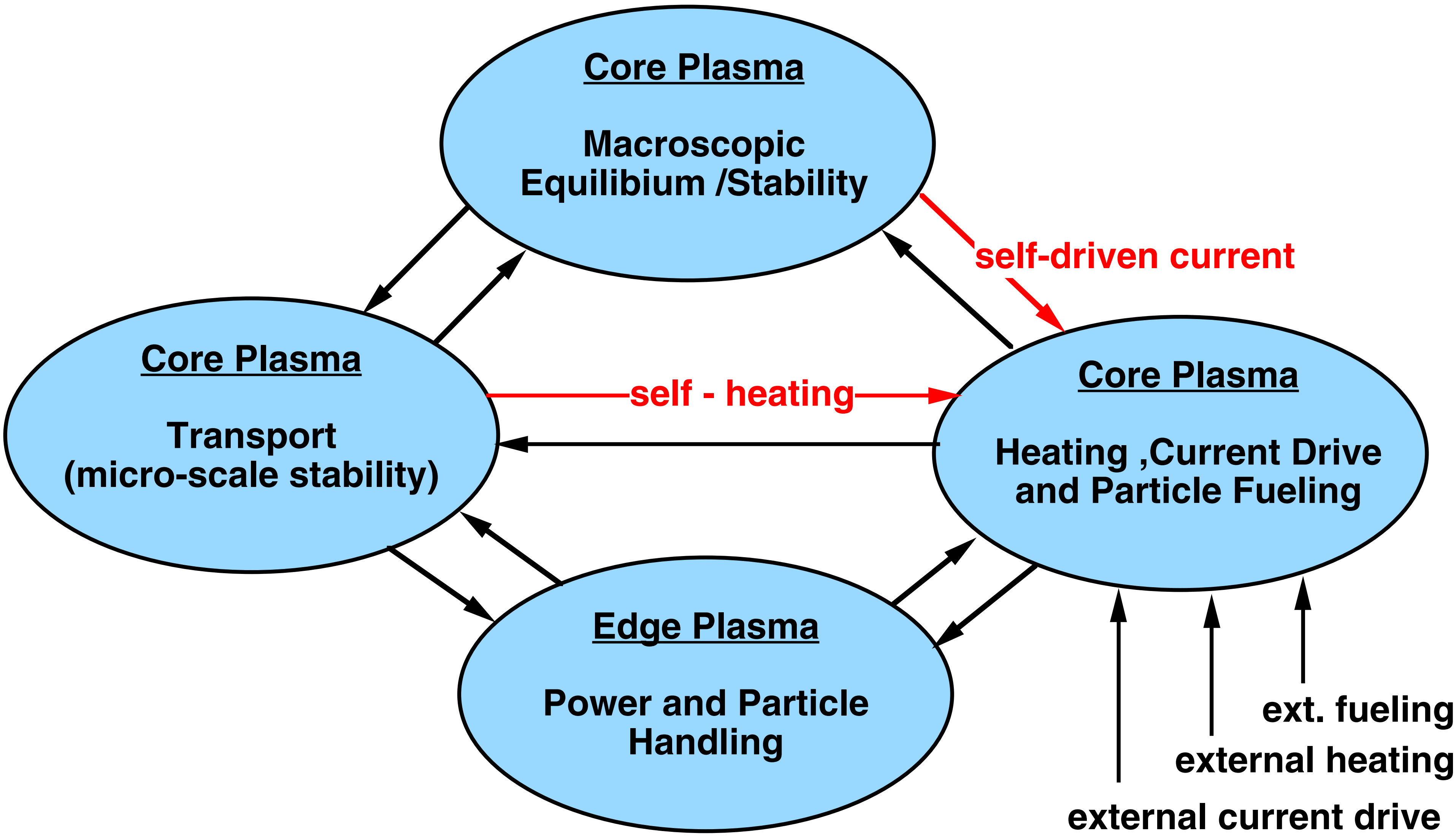


Alpha Physics Issues
• Alpha confinement • Alpha Energy to Plasma from alphas to plasma electrons • Burn Control • Alpha Ash Removal • Alpha Driven Instabilities

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

The alpha particle, which has 20% of the fusion reaction energy, remains trapped in the plasma and heats the plasma.

Fusion Plasmas are Complex Non-Linear Dynamic Systems



Can a fusion-dominated plasma be attained, controlled and sustained in the laboratory?

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.

Tokamak Plasma Operating Regimes

Conventional Tokamak - Edge Transport Barrier (H-Mode)

Suitable for first burning plasma experiments but not for an attractive reactor

Test of dominant alpha heating tests, burn control, energetic alpha particles

Advanced Tokamak - Internal Transport Barrier (e.g., Reversed Shear)

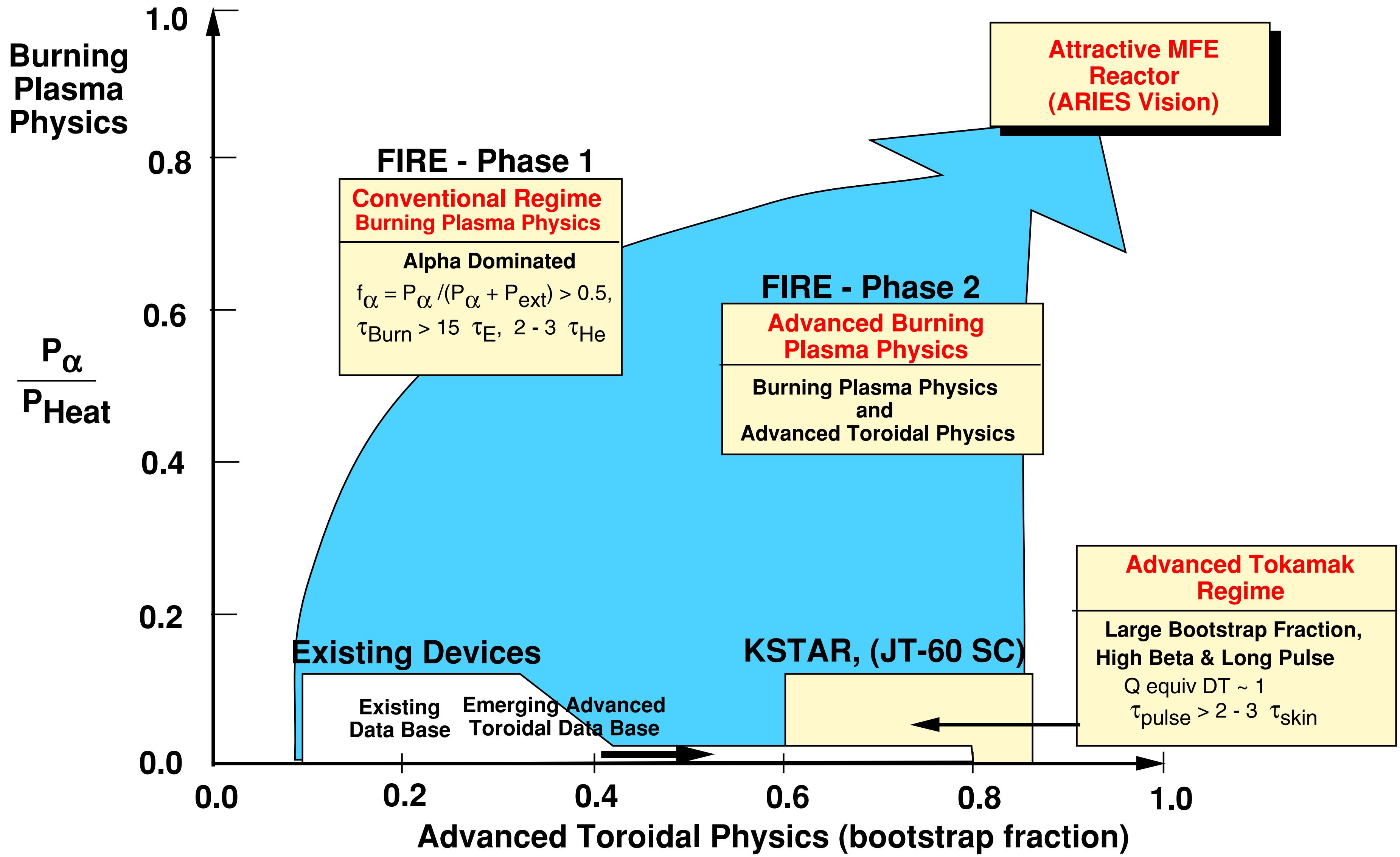
Suitable for an attractive steady state reactor with high power density

Requires specific plasma profiles, that will have to be maintained in the presence of strong alpha heating and self-driven plasma currents

ARIES studies have identified the desired characteristics
high beta $\beta_N \approx 5$, high bootstrap fraction $f_{bs} \approx 90\%$, $Q > 25$

The exploration, understanding and optimization of advanced tokamak modes are priority activities in the tokamak program.

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



Attain a burning plasma with confidence using “todays” physics, but allow the flexibility to explore tomorrow’s advanced physics.

Burning Plasma Experiment (FIRE) Requirements

Burning Plasma Physics

Q	$\geq$ 5, ~ 10 as target, ignition not precluded
$f_\alpha = P_\alpha/P_{heat}$	$\geq$ 50%, ~ 66% as target, up to 83% at Q = 25
TAE/EPM	stable at nominal point, able to access unstable

Advanced Toroidal Physics

$f_{bs} = I_{bs}/I_p$	$\geq$ 50% (first stage) with ~ 75% (goal)
β_N	~ 2.5, no wall ~ 4.2, n = 1 wall stabilized

Quasi-stationary Burn Duration

Pressure profile evolution and burn control	> 10 τ_E
Alpha ash accumulation/pumping	> several τ_{He}
Plasma current profile evolution	1 to 3 τ_{skin}
Divertor pumping and heat removal	several $\tau_{divertor}$

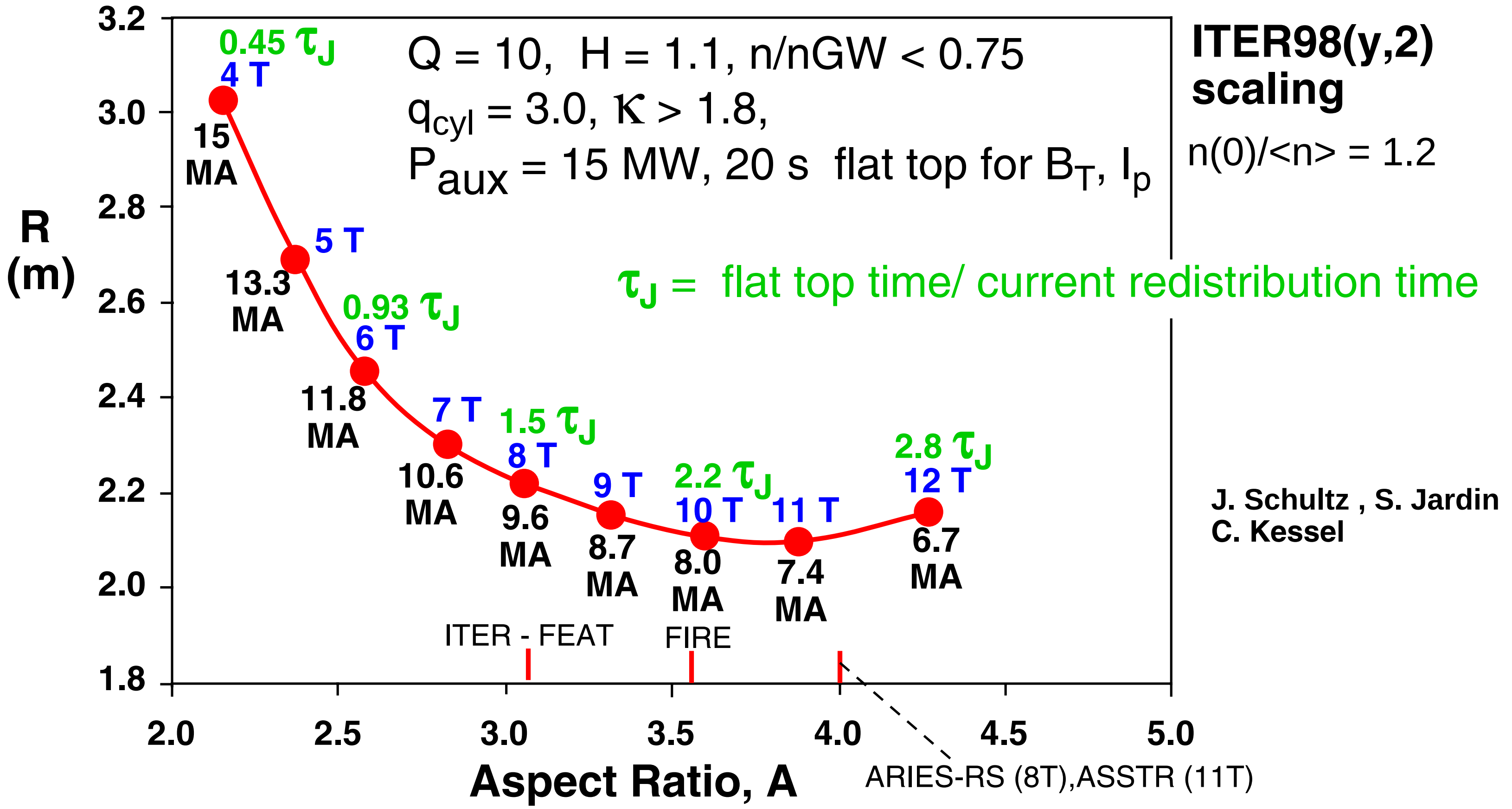
FIRE has Adopted the Advanced Tokamak Physics Features Identified by ARIES Studies

- High toroidal field
- Double null
- Strong shaping
  - $\kappa = 2.0$, $\delta = 0.7$
- Internal vertical position control coils
- Cu wall stabilizers for vertical and kink instabilities
- Very low ripple (0.3%)
- ICRF/FW on-axis CD
- LH off-axis CD
- LHCD stabilization of NTMs
- Tungsten divertor targets
- Feedback coil stabilization for Resistive Wall Modes (RWM)
- Burn times exceeding current diffusion times
- Pumped divertor/pellet fueling/impurity control to optimize plasma edge

Optimization of a Conventional Regime Burning Plasma Experiment

- Consider an inductively driven tokamak with copper alloy TF and PF coils precooled to LN temperature that warm up adiabatically during the pulse.

- Seek minimum R while varying A and space allocation for TF/PF coils for a specified plasma performance - Q and pulse length with physics and eng. limits.

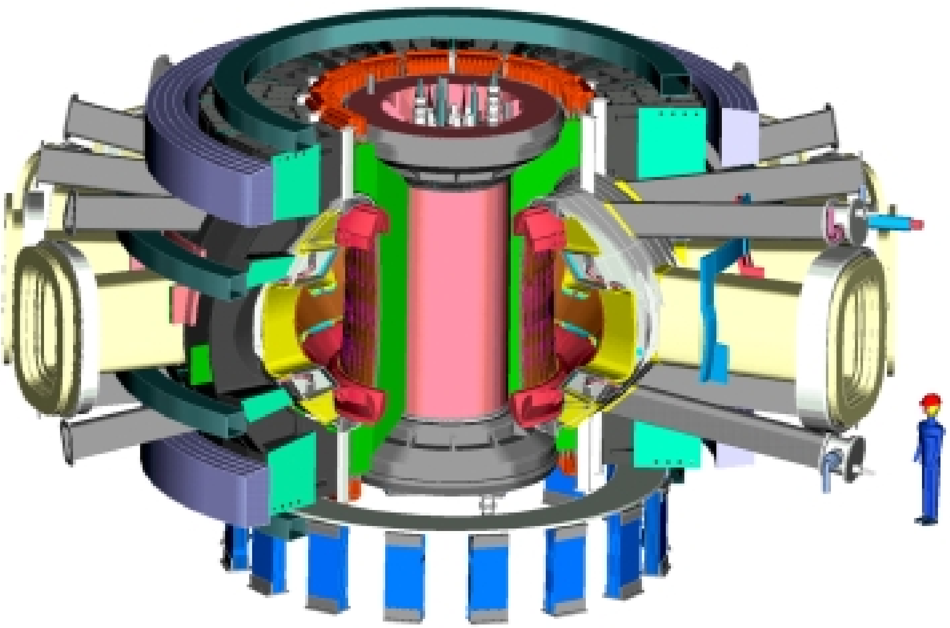


What is the optimum for an Advanced Regime burning plasma experiment?

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
- W_{mag}= 5.2 GJ
- I_p = 7.7 MA
- $P_{aux} \leq$ 20 MW
- Q ≈ 10, P_{fusion} ~ 150 MW
- Burn Time ≈ 20 s (2 tau_cr)
- Tokamak Cost ≈ $351M (FY02)
- Total Project Cost ≈ $1.2B(FY02) at Green Field site.

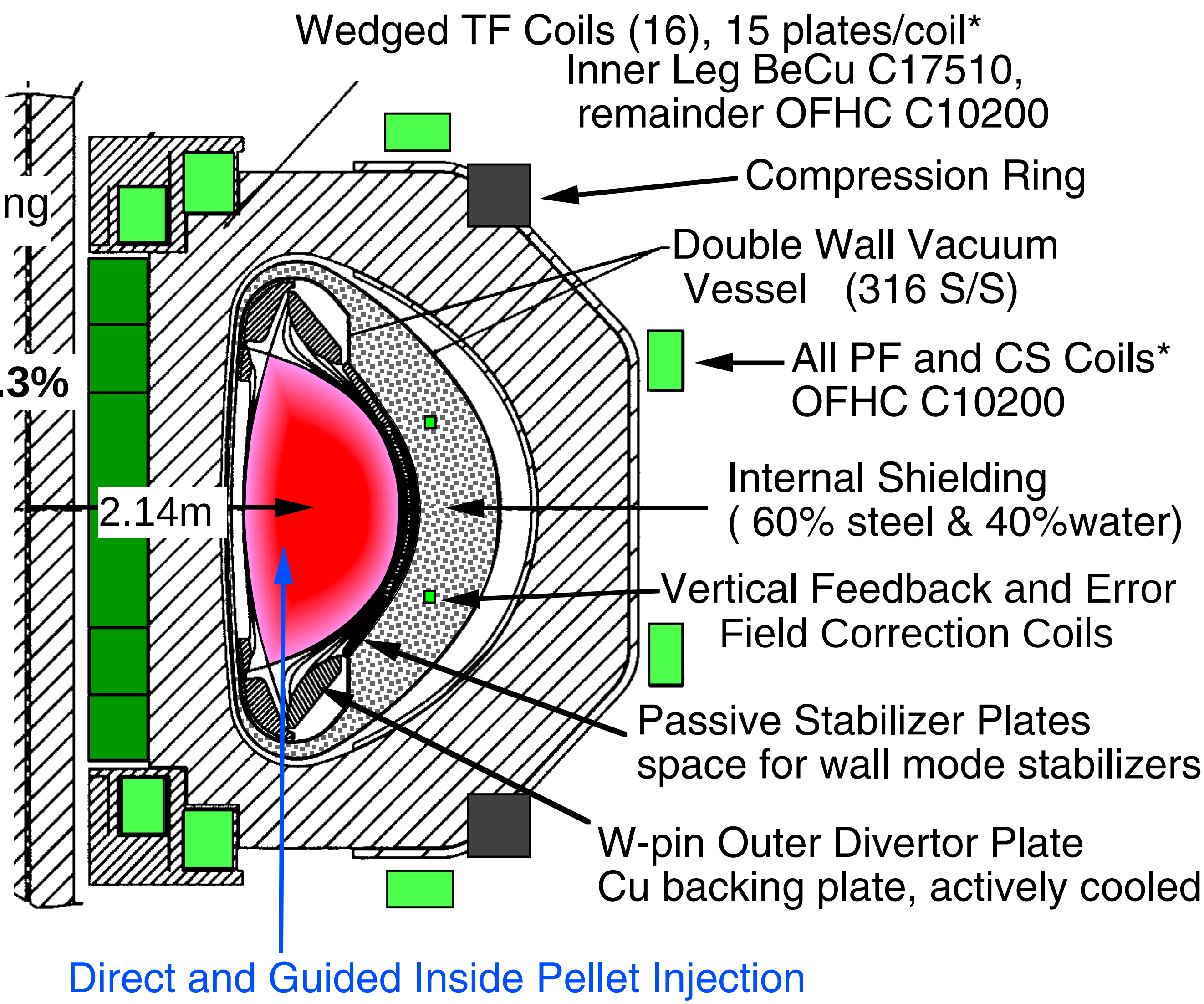
Mission: Attain, explore, understand and optimize magnetically-confined fusion-dominated plasmas.

CIT + TPX = FIRE leading to ARIES

FIRE Incorporates Advanced Tokamak Features (ala ARIES)

AT Features

- DN divertor pumping
- 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.**

*** Neutron shielding of the copper TF coil is not required and the magnetic field can be ~ doubled allowing the size to be reduced by ~ 3 relative to superconducting.**

Basic Parameters and Features of FIRE

R, major radius	2.14 m
a, minor radius	0.595 m
κx, $\kappa 95$	2.0, 1.77
δx, $\delta 95$	0.7, 0.55(AT) - 0.47(conventional)
q95, safety factor at 95% flux surface	>3
Bt, toroidal magnetic field	10 T with 16 coils, 0.3% ripple @ Outer MP
Toroidal magnet energy	5.8 GJ
Ip, plasma current	7.7 MA
Magnetic field flat top, burn time	28 s at 10 T in dd, 20s @ Pdt ~ 150 MW)
Pulse repetition time	~3hr @ full field and full pulse length
ICRF heating power, maximum	20 MW, 100MHz for $2\Omega_T$, 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
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 like TFTR

Plans for Diagnostics on FIRE

- Diagnostic specifications have been established for FIRE and a comprehensive set of diagnostics has been proposed based on experience with D-T experiments on TFTR.

- FIRE has significant access through a large number of relatively large ports. A preliminary port assignment of diagnostics has been made.

- A schedule for diagnostic installation has been established where the diagnostics are installed in a phased manner consistent with the needs of the research program.

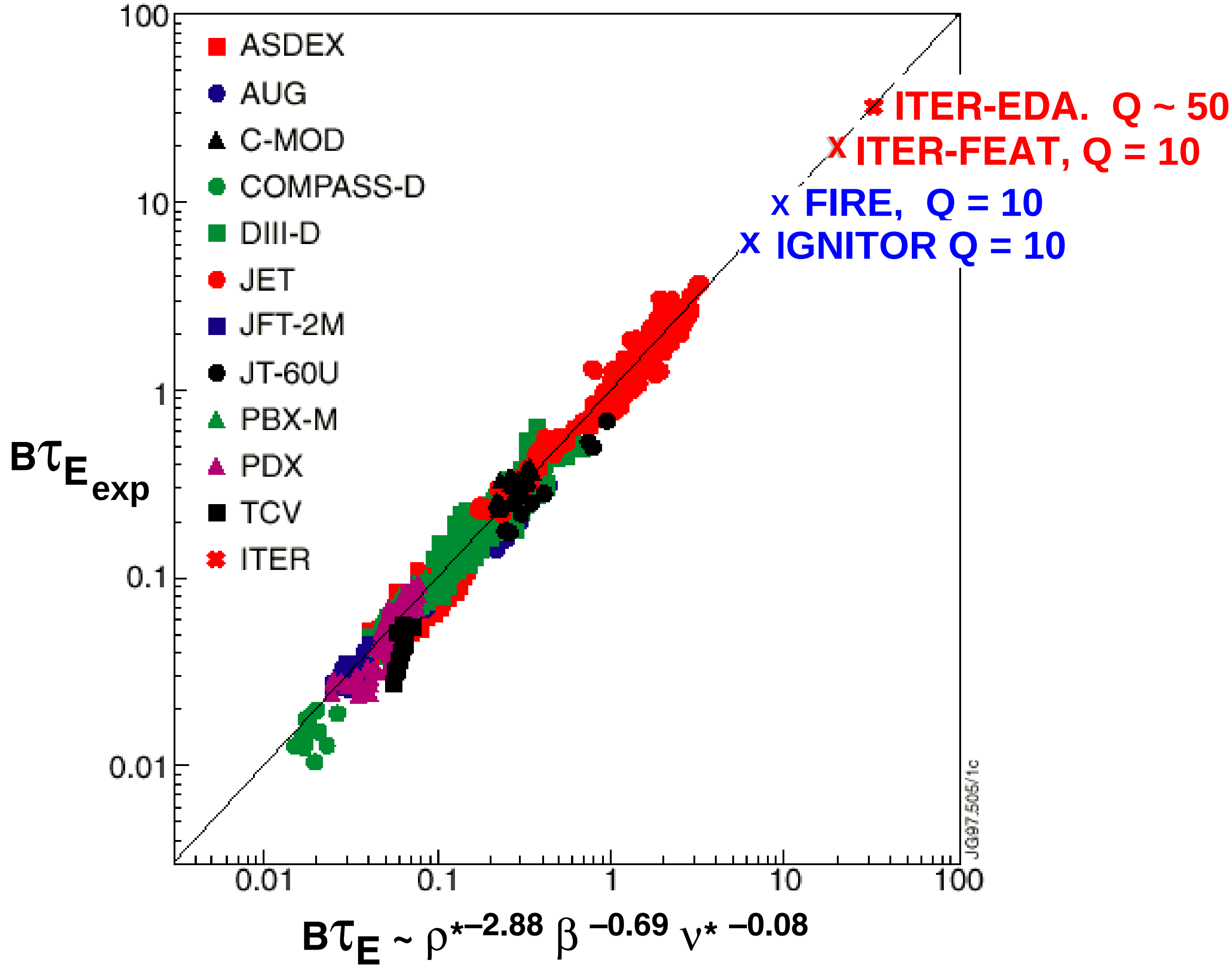
- A draft R&D program has been identified that would address issues in the areas of radiation induced noise, neutral beams for diagnostics and the development of new diagnostics for confined alpha particles, etc.

    Snowmass Assessment on Need for Diagnostics R&D:
    In all cases (i.e., ITER, FIRE and IGNITOR), an aggressive and dedicated R&D program is required for full implementation of the necessary measurements in the three options, building on the extensive ITER R&D effort.

FIRE is a Modest Extrapolation in Plasma Confinement

Dimensionless Parameters
$\omega_c \tau = B\ \tau$
$\rho^* = \rho / a$
$\nu^* = \nu_c / \nu_b$
β

Similarity Parameter
$B\ R^{5/4}$



Kadomtsev, 1975

Guidelines for Estimating Plasma Performance (0-D)

Confinement (Elmy H-mode) - ITER98(y,2) based on today's data base

$$\tau_E = 0.144\, I^{0.93}\, R^{1.39} a^{0.58}\, n_{20}^{0.41} B^{0.15} A_i^{0.19} \kappa^{0.78}\, P_{heat}^{-0.69}\;\; H(y,2)$$

Density Limit - Based on today's tokamak data base

$$n_{20} \leq 0.8\, n_{GW} = 0.8\, I_p/\pi a^2,$$

Beta Limit - theory and tokamak data base

$$\beta \leq \beta_N(I_p/aB), \quad \beta_N < 2.5 \text{ conventional}, \ \beta_N \sim 4 \text{ advanced}$$

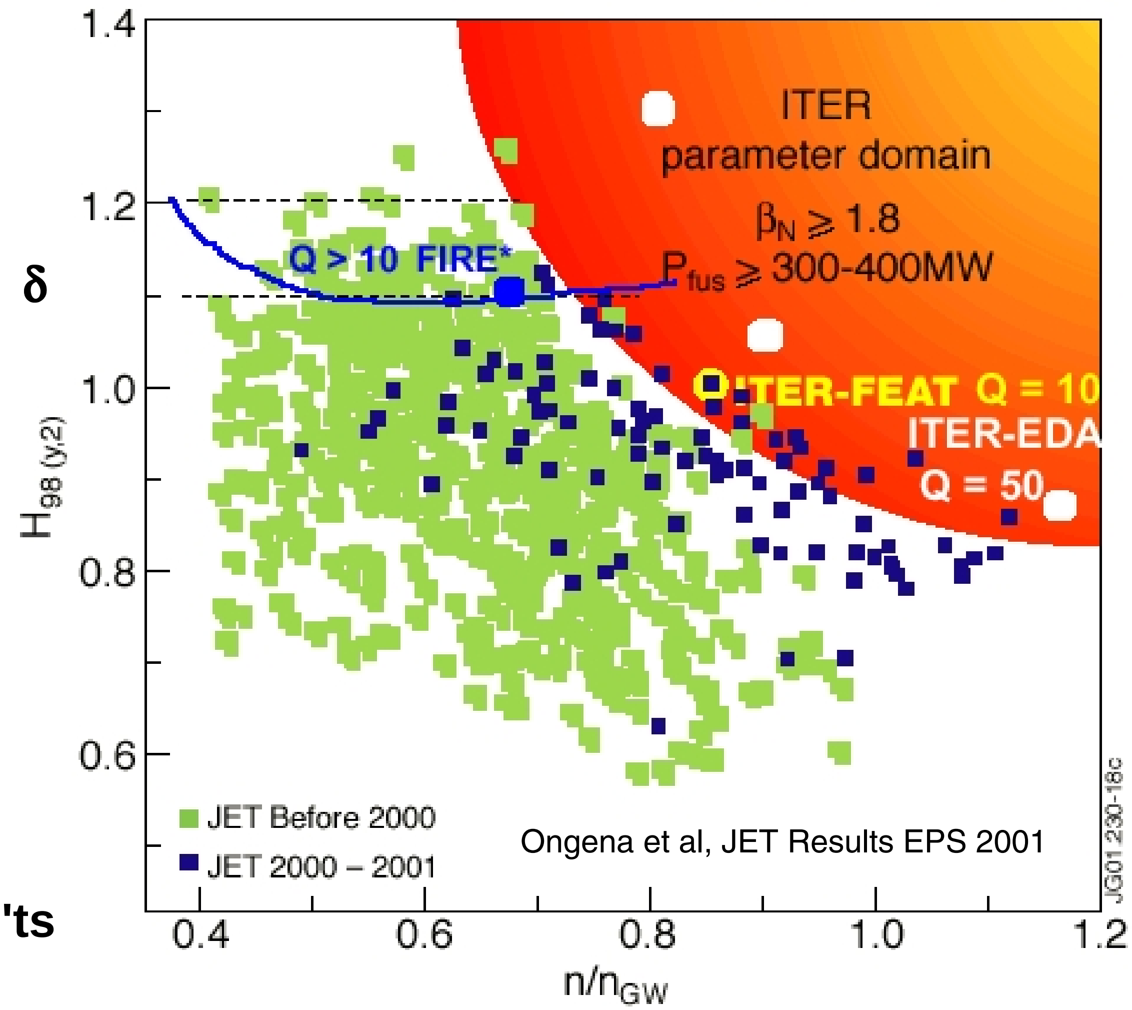
H-Mode Power Threshold - Based on today's tokamak data base

$$Pth \geq (2.84/Ai)\, n_{20}^{0.58} B^{0.82} Ra^{0.81}$$, same as ITER-FEAT

Helium Ash Confinement $\tau_{He} = 5\,\tau_E$, impurities = 3% Be, 0% W

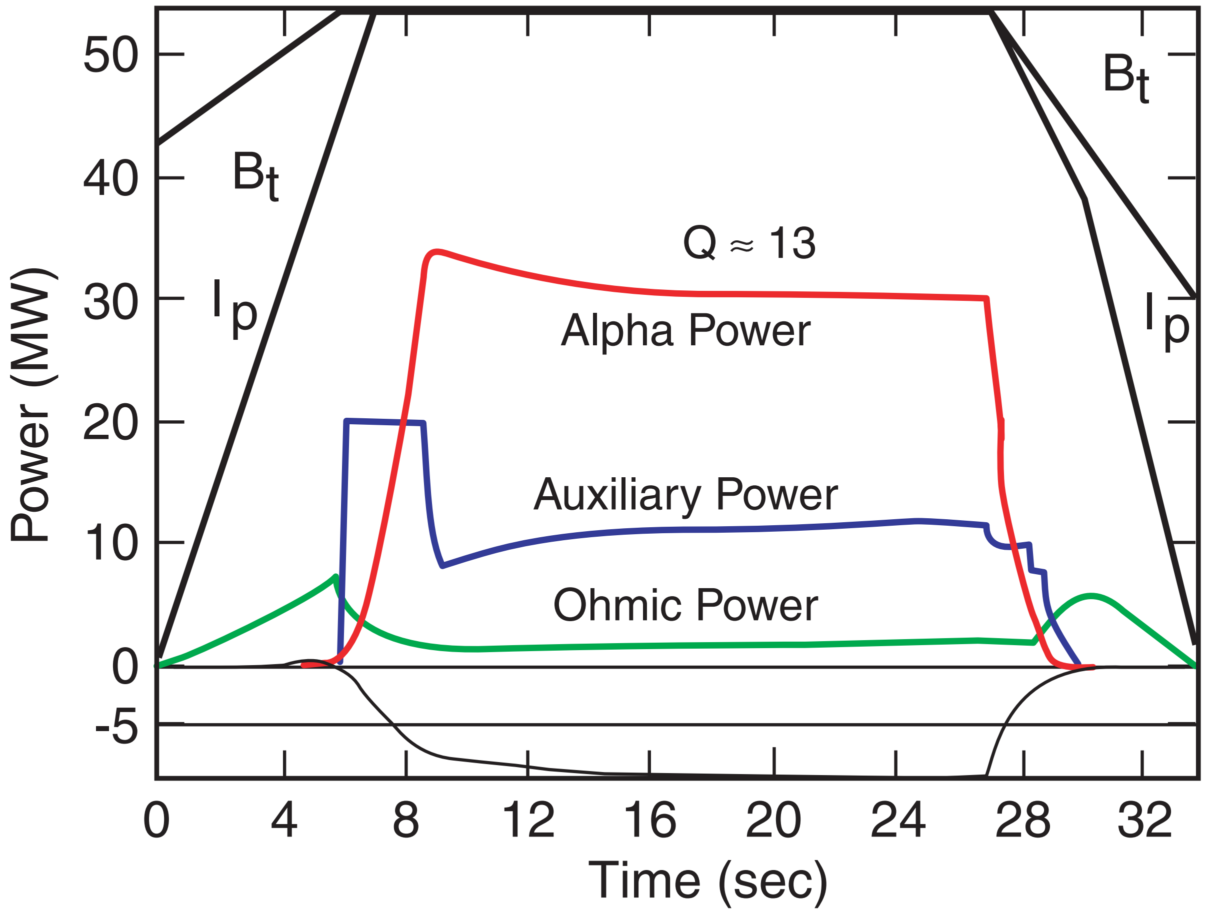
FIRE's Operating Density and Plasma Cross-section Triangularity are Near the Optimum for the Elmy H-Mode

- **The optimum density for the H-Mode is $n/n_{GW} \approx 0.6 - 0.7$**
- **H-mode confinement increases with triangularity - δ**
  - **$\delta \approx 0.7$ FIRE**
  - **$\delta \approx 0.5$ ITER-FEAT**
- **Elm size is reduced for $\delta > 0.5$**
- **Z_{eff} decreases with density (Mathews/ITER scaling)**
- **DN versus SN ? C- Mod Exp'ts**



Cordey et al, H = function (δ, n/n_{GW}, n(0)/<n>) EPS 2001

Simulation of Burning Plasma 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 $\approx 21\tau_E \approx 4\tau_{He} \approx 2\tau_{CR}$

Q = Pfusion/(Paux + Poh)

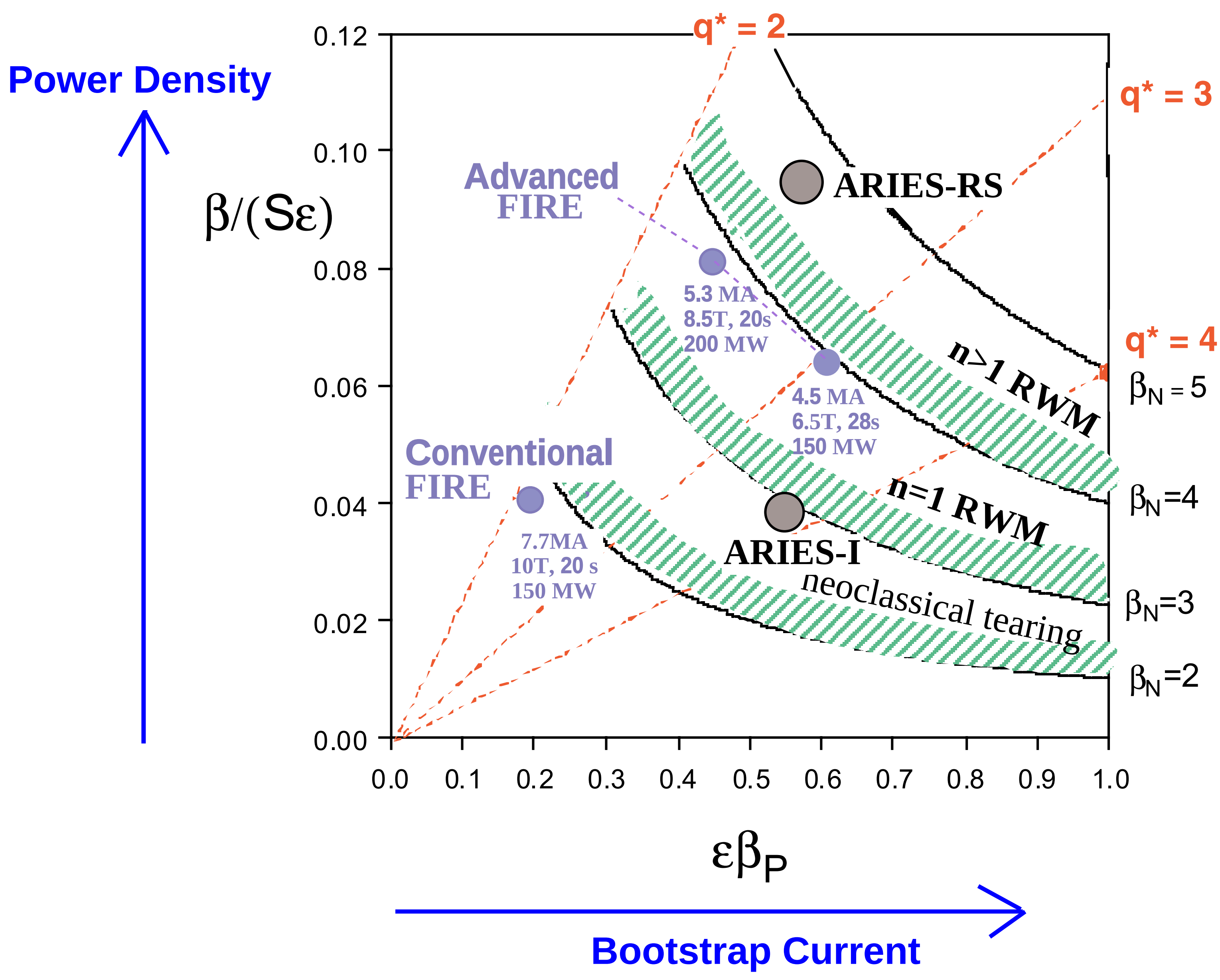
Snowmass Conclusions on Confinement Projections for FIRE

- Based on 0D and 1.5D modeling, all three devices (ITER, FIRE and IGNITOR) have baseline scenarios which appear capable of reaching Q = 5 – 15 with the advocates' assumptions. ITER and FIRE scenarios are based on standard ELMing H–mode and are reasonable extrapolations from the existing database.

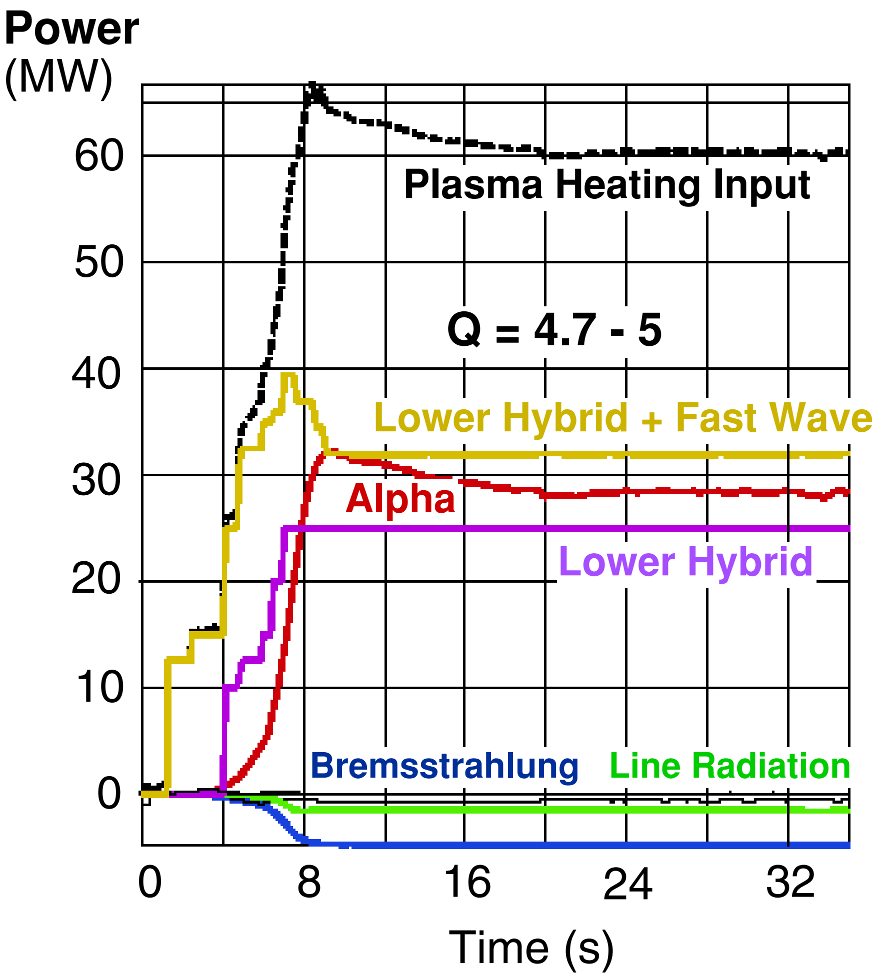
- More accurate prediction of fusion performance of the three devices is not currently possible due to known uncertainties in the transport models. An ongoing effort within the base fusion science program is underway to improve the projections through increased understanding of transport.

Note: part of the purpose of a next step burning plasma experiment is to extend our understanding of confinement into the burning plasma regime

FIRE could Test a Sequence of Advanced Tokamak Modes

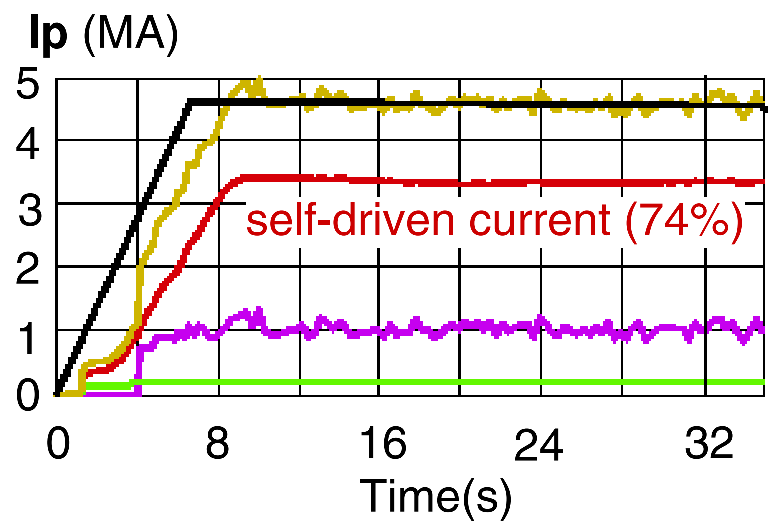


Burning Plasma Physics Could be Explored in Advanced Tokamak Operating Regimes using FIRE



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 τ_{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.

Edge Physics and PFC Technology: Critical Issue for Fusion

Plasma Power and particle Handling under relevant conditions
    Normal Operation / Off Normal events

Tritium Inventory Control
    must maintain low T inventory in the vessel ⇒ all metal PFCs

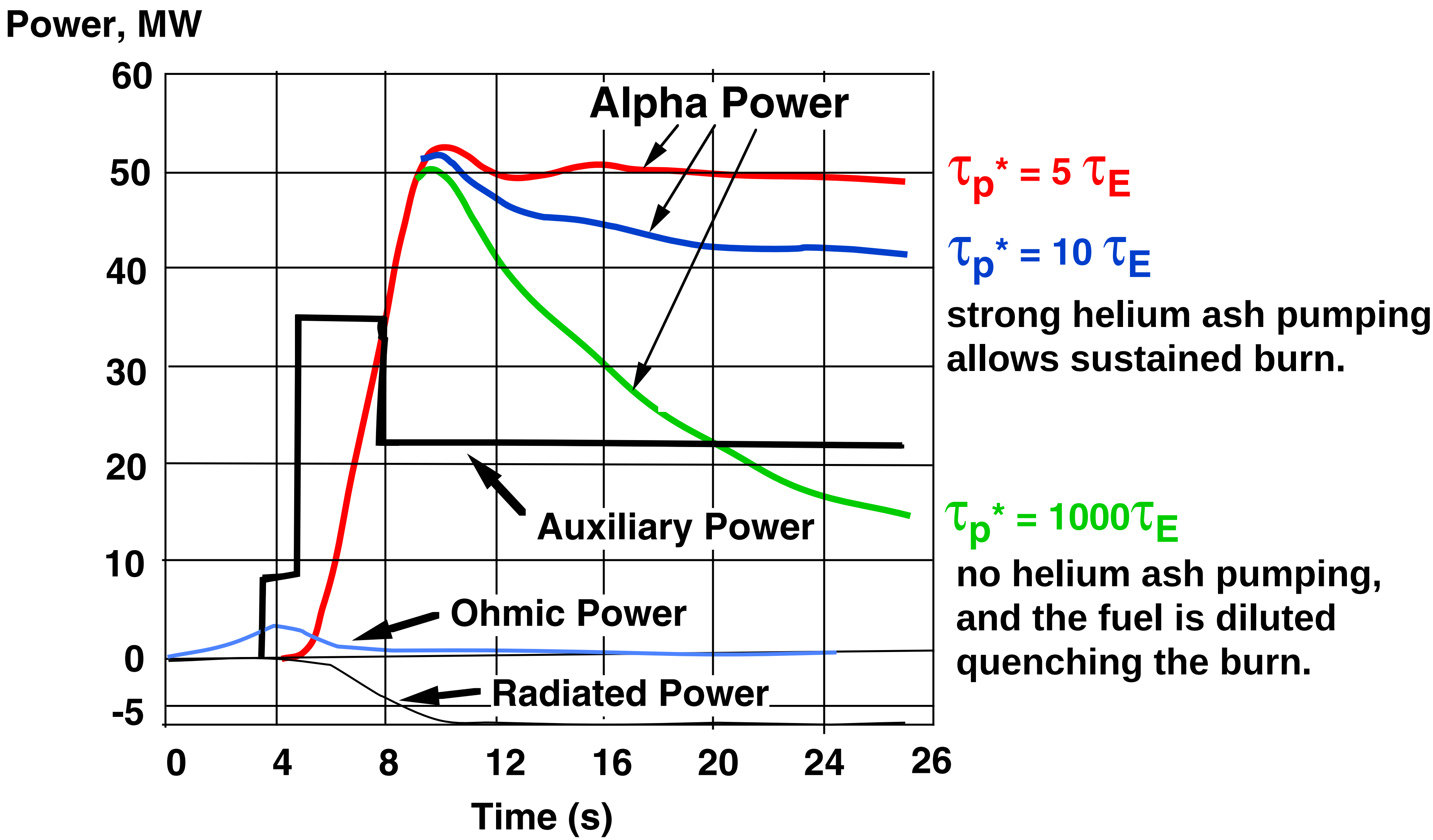
Efficient particle Fueling
    pellet injection needed for deep and tritium efficient fueling

Helium Ash Removal
    need close coupled He pumping

Non-linear Coupling with Core plasma Performance
    nearly every advancement in confinement can be traced to the edge
    Edge Pedestal models first introduced in ~ 1992 first step in understanding
    Core plasma (low n_{edge}) and divertor (high n_{edge}) requirements conflict

Solutions to these issues would be a major output from a next step experiment.

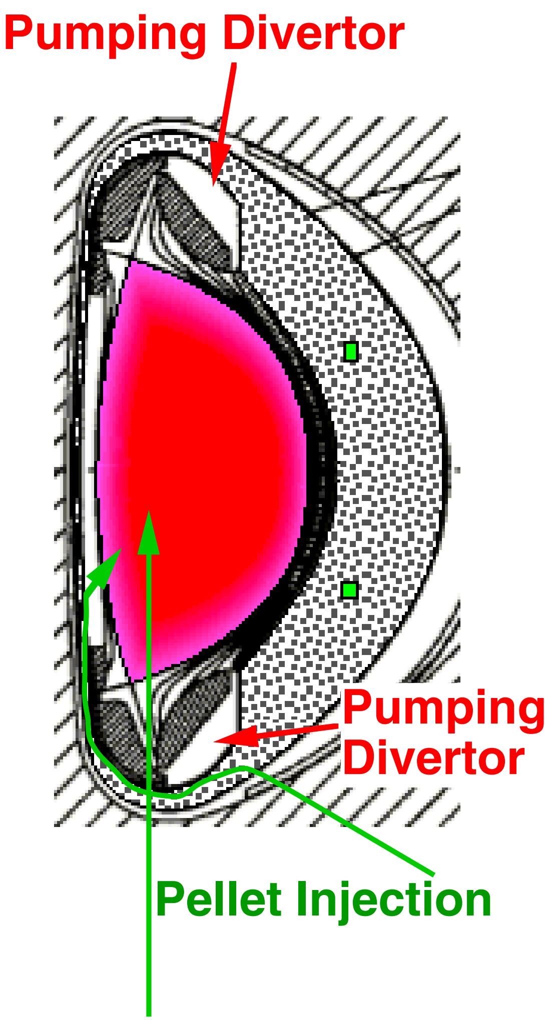
Helium Ash Removal Techniques Required for a Reactor can be Studied on FIRE

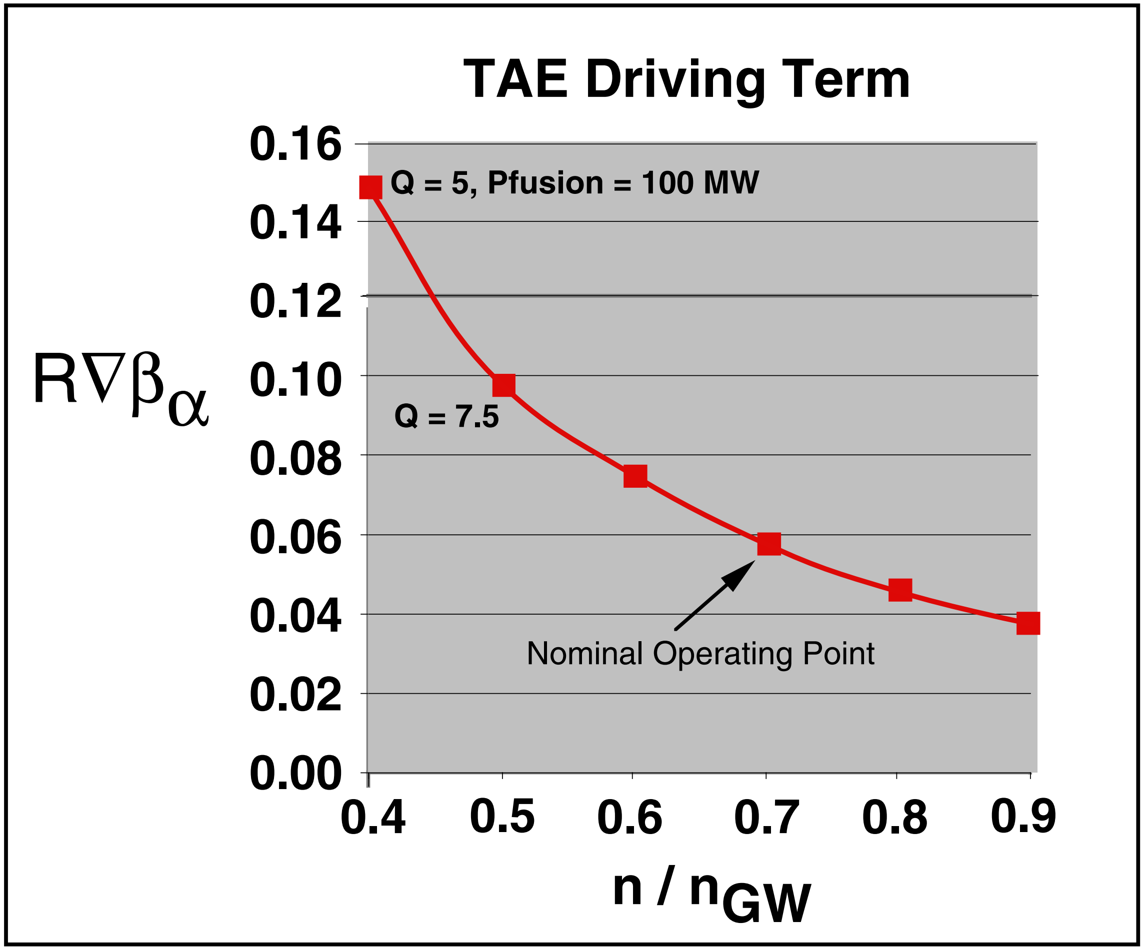


Fusion power can not be sustained without helium ash pumping.

TSC/Kessel/21-q.ps

Energetic Particle Drive can be Varied in FIRE Using Divertor Pumping and Pellet Injection





FIRE: H(y,2) = 1.1, α_n = 0.2, α_T = 1.75,
Q = 10 , P_{fusion} = 150 MW except where noted

The energetic alpha particles could drive toroidal Alfven eigen (TAE) modes unstable causing the alpha particles to be ejected reducing alpha heating and causing damage to the vacuum vessel.

Burning Plasma Simulation Initiative

- A more comprehensive simulation capability is needed to address the strong non-linear coupling inherent in a burning plasma.

- A comprehensive simulation could help:

  - better understand and communicate the important BP issues,

  - refine the design and expectations for BP experiments,

  - understand the experimental results and provide a tool for better utilization of the experimental run time, and

  - Carry the knowledge forward to the following tokamak step or to burning plasmas in other configurations.

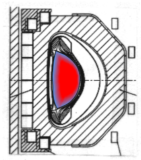
- This is something we should be doing to support any of the future possibilities

FIRE would Test the High Power Density In-Vessel Technologies Needed for ARIES-RS

Pfusion
= ~ 150 MW

Volume
= 27 m^3

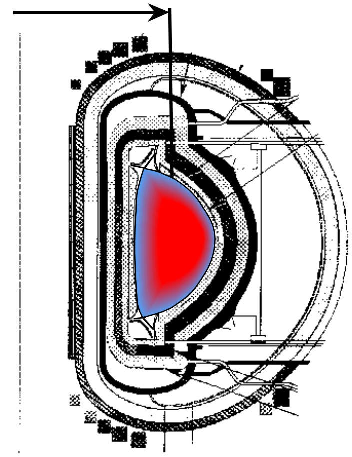
B = 10 T
R = 2.14 m
→



FIRE

~ 2.5X

B = 8 T
R = 5.5 m



ARIES-RS The “Goal”

Pfusion
= 2170 MW

Volume
= 350 m^3

	JET	FIRE	ARIES-RS
Fusion Power Density (MW/m^3)	0.2	5.5	6
Neutron Wall Loading (MW/m^2)	0.2	2.3	4
Divertor Challenge (Pheat/NR)	~5	~10	~35
Power Density on Div Plate (MW/m^2)	3	~15-19 → 6	~5
Burn Duration (s)	4	20	steady

Tritium Considerations for FIRE and BP Experiments

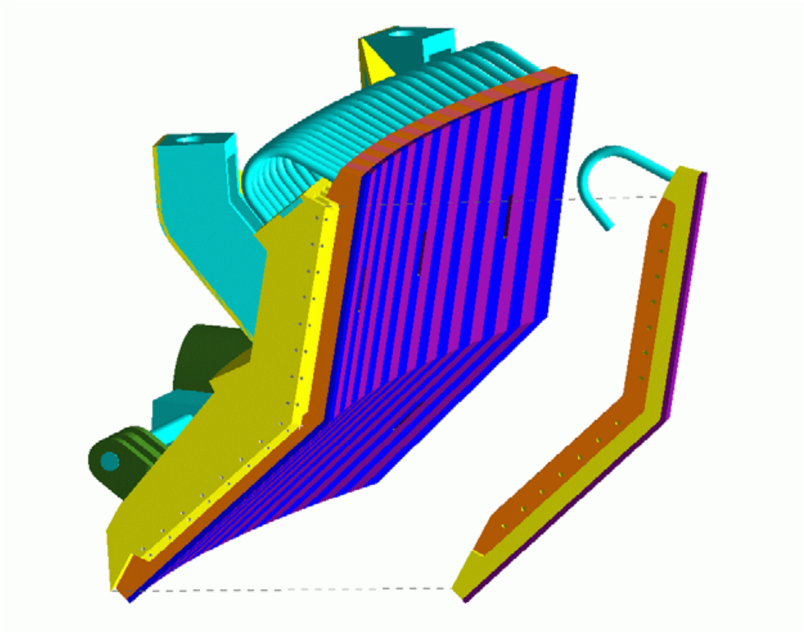
- The tritium injected per shot in FIRE would be same as TFTR ≈ 0.2 g
- Retention fractions as high as JET and TFTR (~15%) would adversely impact operations.
- Tritium retention < 0.2% was measured (Wampler, Sandia) in the all metal system of C- Mod after DD operation.
    - **Carbon divertor targets are ruled out for FIRE, and W was chosen as a reactor relevant solution.**
- The Site Inventory Requirement for FIRE would be similar to TFTR (5g-T) which was Classified as DOE Category III, Low Hazard Facility (< 30g-T).

  Site Limit of < 30g-T presently proposed with

  ≤ 10 g-T in a single system
- Annual burn up of ~ few g-T, only small shipments of fuel and waste required.

Divertor Module Components for FIRE

Sandia

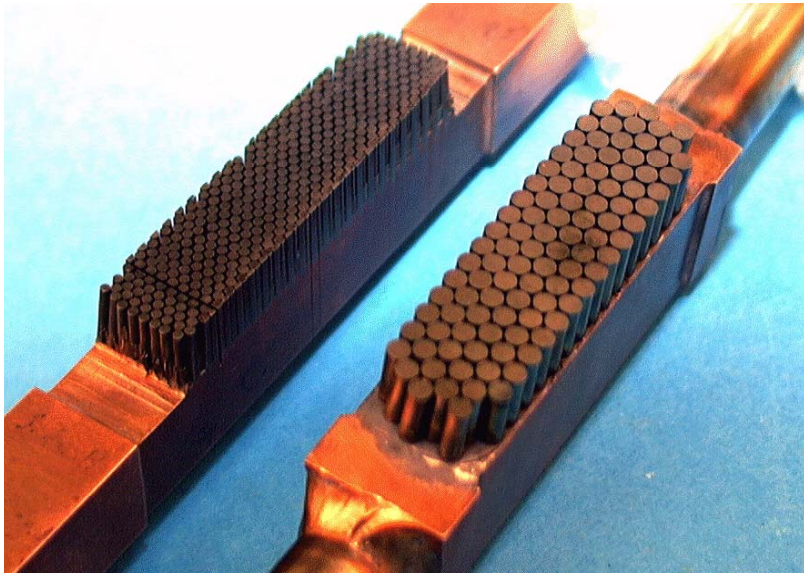


Finger Plate for

Outer Divertor Module

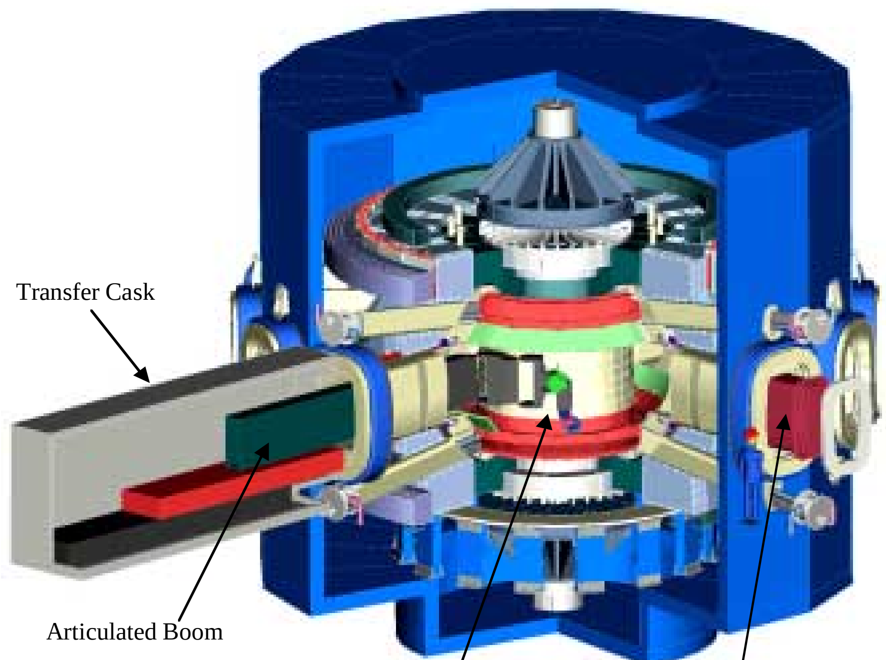
Two W Brush Armor Configurations

Tested at 25 MW/m^2



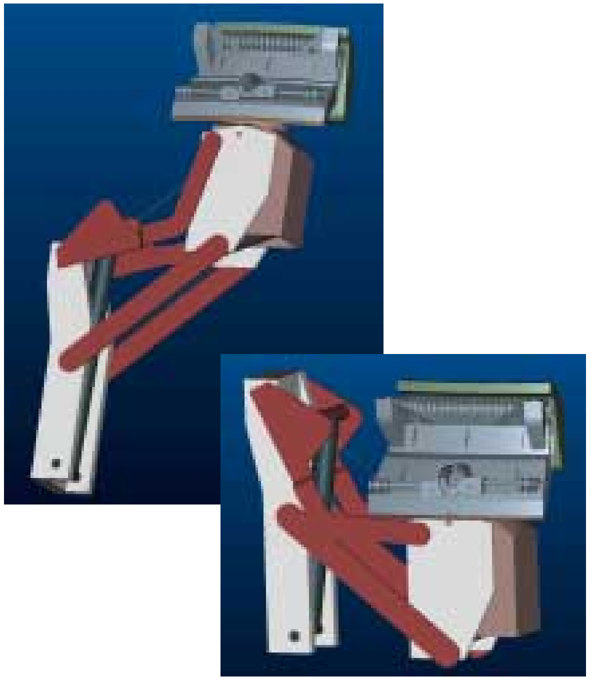
Carbon targets used in most experiments today are not compatible with tritiun inventory requirements of fusion reactors.

FIRE In-Vessel Remote Handling System



In-vessel transporter

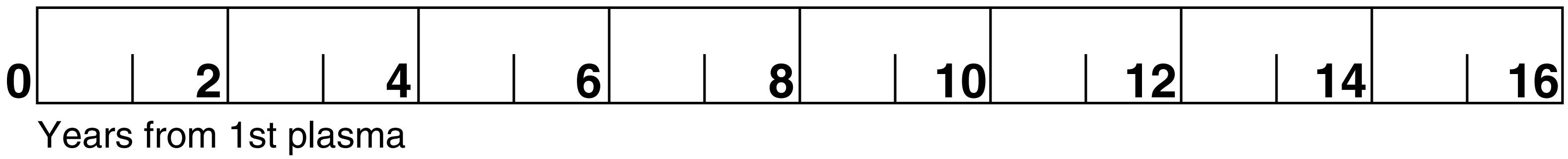
- Articulated boom deployed from sealed cask
- Complete in-vessel coverage from 4 midplane ports
- Fitted with different end-effector depending on component to be handled
- First wall module end-effector shown



Divertor end-effector

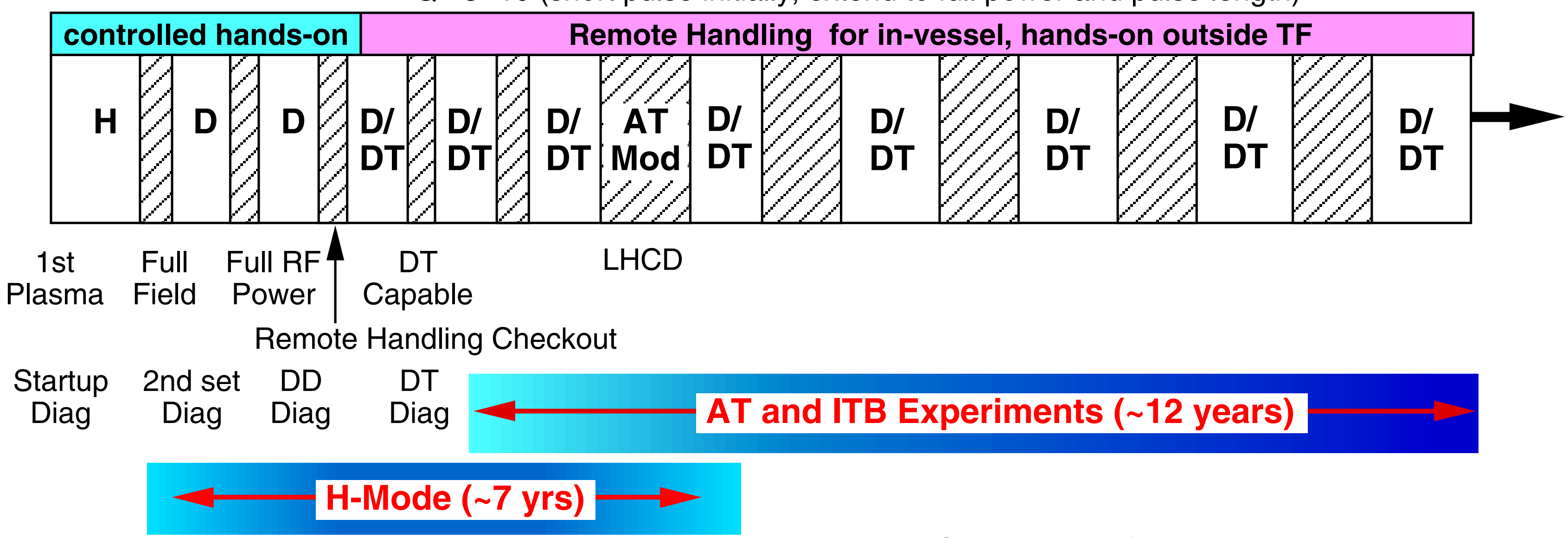
- High capacity (module wt. ~ 800 kg)
- Four positioning degrees of freedom
- Positioning accuracy of millimeters required

FIRE Experimental Plan



	2	4	6	8	10	12	14	16	Original* Limits
Shots/ 2yr	4000	4000	4000	4000	3500	3500	3500	3500	**30,000**
Full B Shots/ 2yr	250	500	600	500	300	300	300	300	**3,000**
DT Energy(GJ)/ 2yr			1000	1000	1000	1000	1500	1000	**6,500**
Tritium Burnup(g)/2yr			2	2	2	2	3	2	

Q~ 5 -10 (short pulse initially, extend to full power and pulse length)



- Control
- Cleanup
- Fueling
- Diagnostics
- Operations
- RF tests

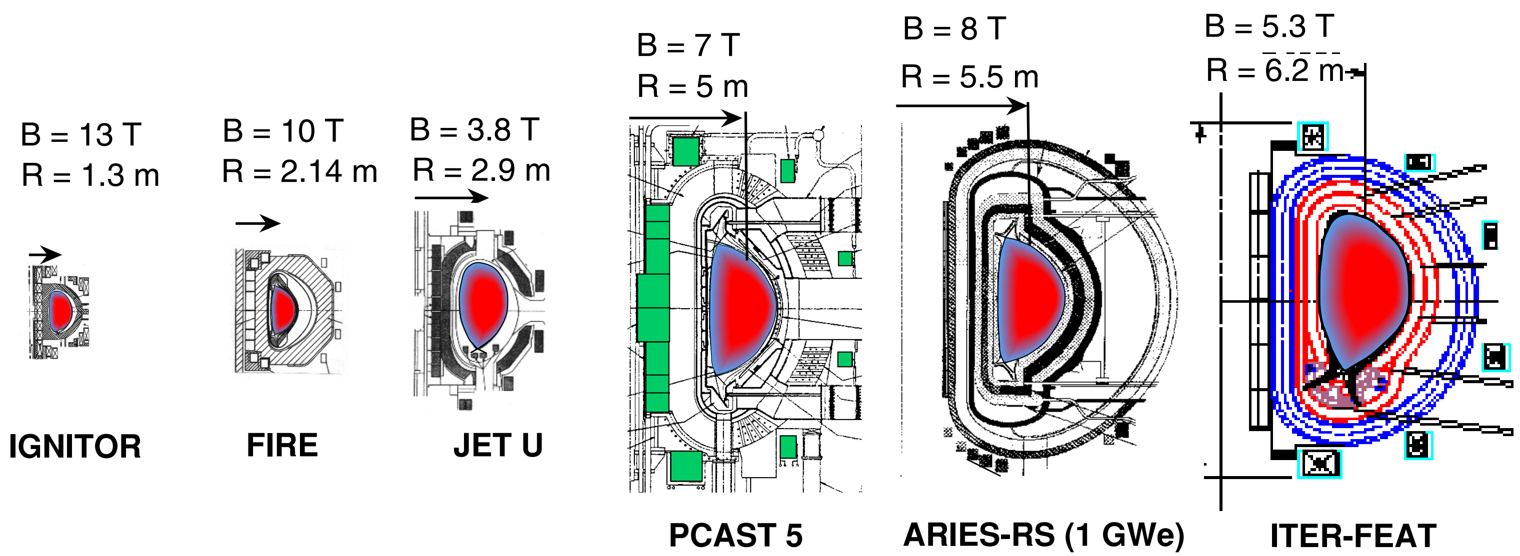
- InitialRF Heating
- Plasma Power Handling
- Initial Physics studies

- Alpha heating
- Energy transport
- Fast particle
- Particle and ash removal

- Global Burn control
- Transient Profile control
- Transient Adv Tok

- Optimization of AT modes
- Non Inductive Profile control
- Improve Divertor and FW power handling
- Extend pulse length

Potential Next Step Burning Plasma Experiments



Cost Drivers	IGNITOR	FIRE	JET U	PCAST	ARIES-RS	ITER-FEAT
Plasma Volume (m^3)	11	27	108	390	350	828
Plasma Surface (m^2)	36	60	160	420	420	610
Plasma Current (MA)	12	7.7	6	15	11.3	15
Magnet Energy (GJ)	1.3	5	1.6	40	85	41
Fusion Power (MW)	100	150	30	400	2170	400
Burn Duration (s), inductive	~1	20	10	120	steady	400
τ Burn Flat-top/ τ CR		~2	0.6	1	steady	2
Cost Estimate ($B-2000$) -proposers		1.2	~0.6	7.1	11.2*	5.0
Fusion Core Mass (kilo tonnes)		1.4		10	13	19

* first , $5.6 B for 10th of a kind

AR RS/ITERs/PCAST/FIRE/IGN

Next Steps for FIRE

- Listen and respond to critiques and suggestions at Snowmass.
- Update design goals and physics basis, review with Community, NSO PAC and DOE.
- Produce a Physics Description Document, and carry out a Physics Validation Review.
- Initiate Project Activities (in 2003-4) consistent with FESAC Strategy

  Form National Project Structure

  Begin Conceptual Design

  Initiate R&D Activities

  Begin Site Evaluations

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 ~ $1B, 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

The U.S. Builds ~1$B Facilities to Explore, Explain and Expand the Frontiers of Science