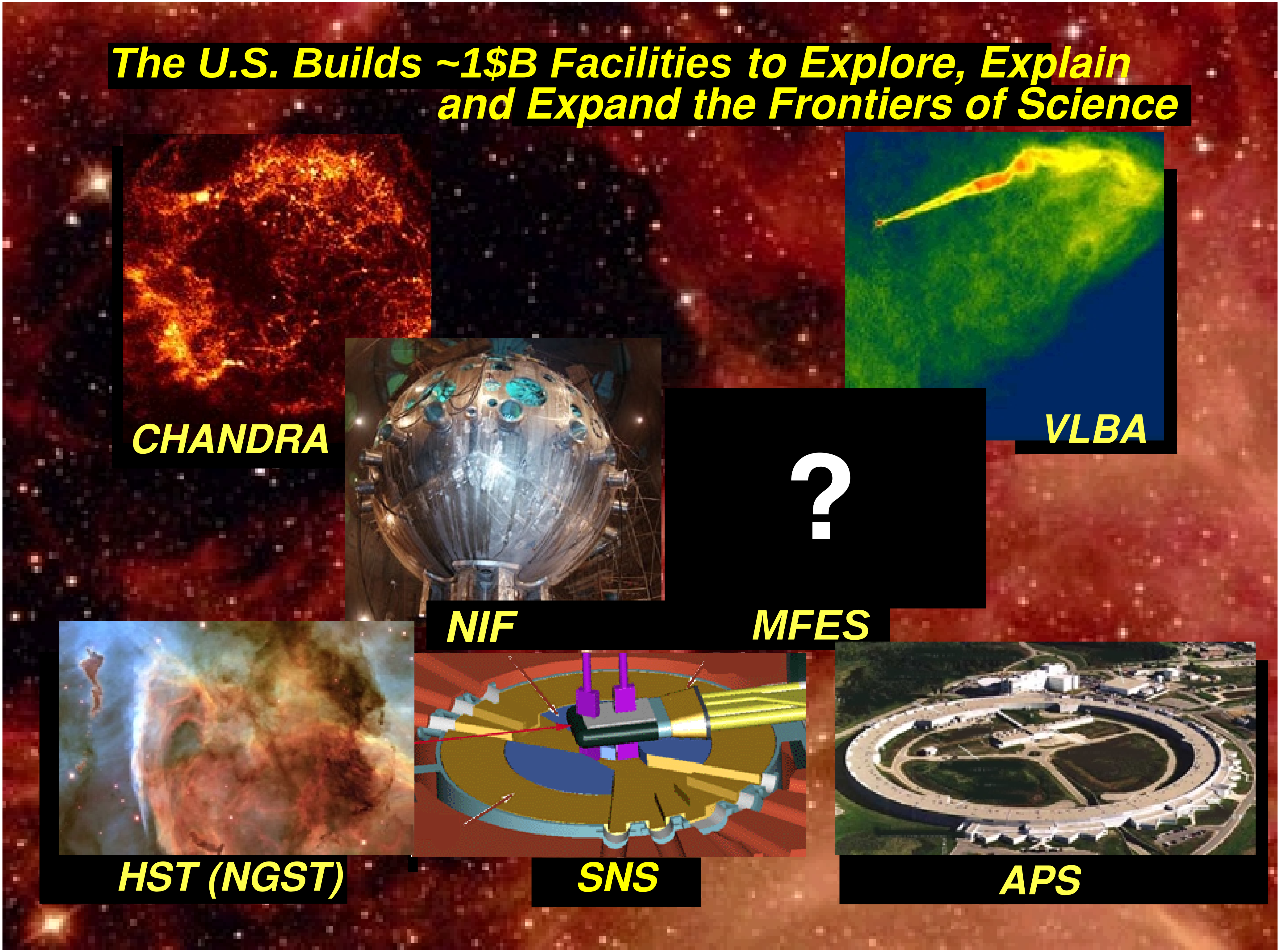

The U.S. Builds ~1$B Facilities to Explore, Explain
and Expand the Frontiers of Science
CHANDRA
VLBA
?
NIF
MFES
HST (NGST)
SNS
APS

Fusion, FIRE and the Future

Dale M. Meade

for the National FIRE Study Team

Discussion at
Naval Research Laboratory
Washington, DC

December 2, 2002

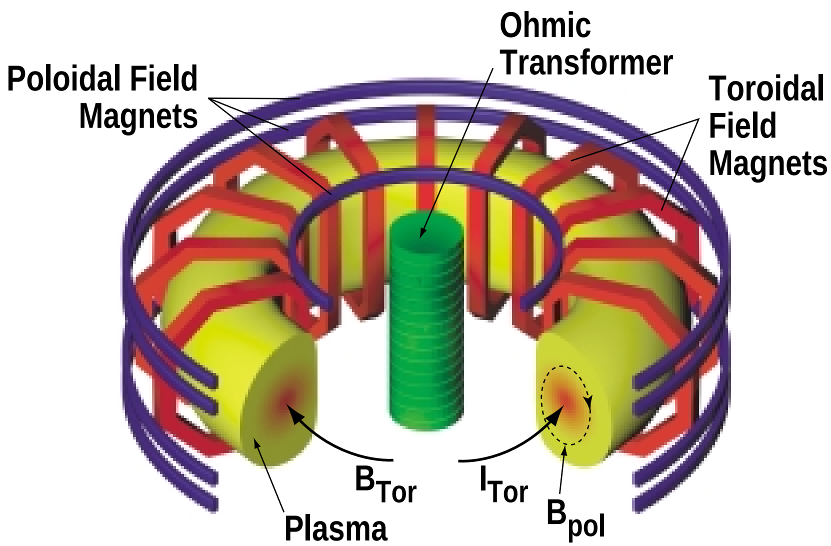
http://fire.pppl.gov

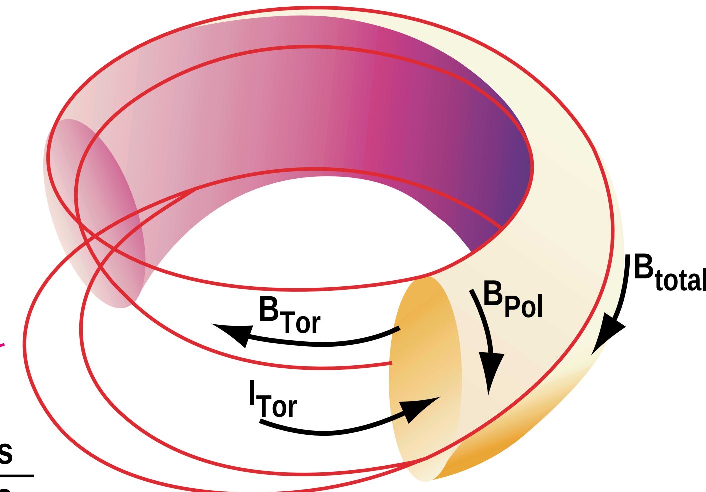
Outline

- Fusion Goals and the Advanced Tokamak
- Critical Issues for Fusion
- Strategy for a Road Map (Development Path)
- FIRE
  - Goals
  - Characteristics
  - Issues/Challenges
- Plans for the Future
- Comparison of Development Paths

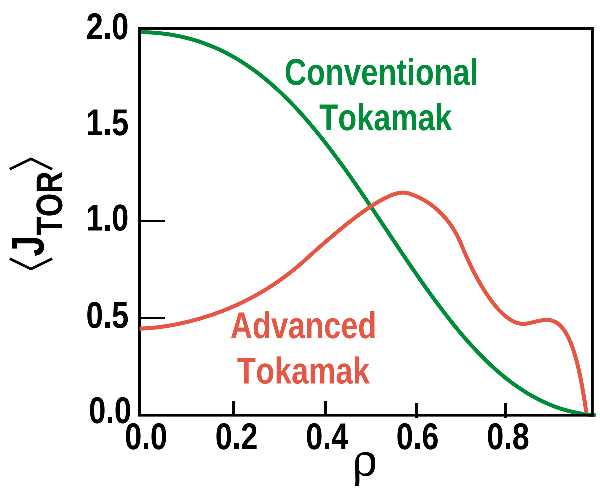
http://fire.pppl.gov

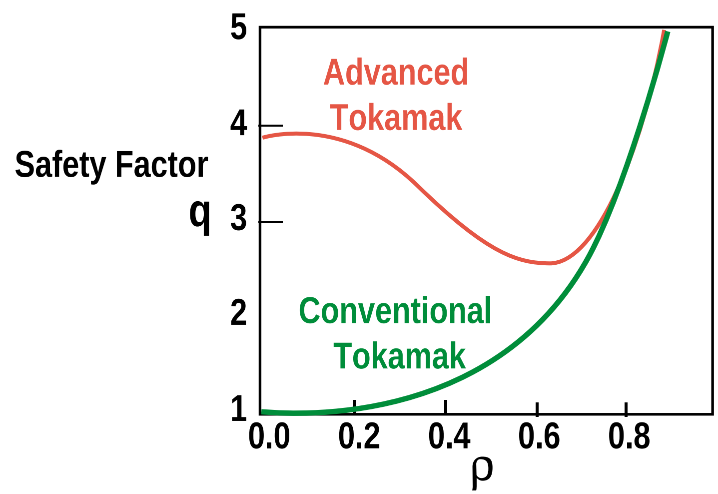
THE CONFINING MAGNETIC FIELD IN A TOKAMAK IS PRODUCED BY CURRENTS IN EXTERNAL COILS PLUS A CURRENT IN THE PLASMA





$$q = \frac{\#\text{Tor Circuits}}{\#\text{Pol Circuits}}$$





THE GOAL OF THE ADVANCED TOKAMAK PROGRAM IS TO OPTIMIZE THE TOKAMAK CONCEPT FOR ATTRACTIVE FUSION ENERGY PRODUCTION

— Discovering the Ultimate Potential of the Tokamak —

Key Elements

- **Steady state**
  - High self-generated bootstrap current
- **Compact (smaller)**
  - Improved confinement (reduced heat loss)

    Fusion Ignition Requirement

    $$3\times10^{21}\ \mathrm{m^{-3}\ keV\ s} < n\,T_i\,\tau \propto (H\,\underbrace{a\,B\,\kappa}_{\text{Size}})^2$$

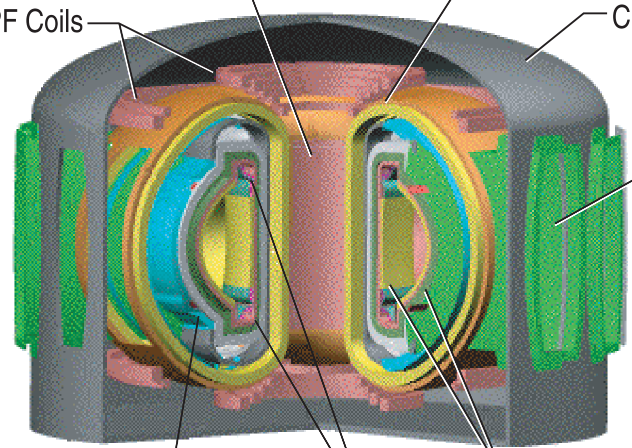
    $$H = \tau_E/\tau_E^{conv}$$
- **High power density**
  - Improved stability

    $$P_{Fus} \propto (n\,T)^2\,\mathrm{Vol} \propto \beta^2 B^4\ \mathrm{Vol}$$

    $$\beta = \frac{2\,\mu_o\,\langle P \rangle}{B^2}$$

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.

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

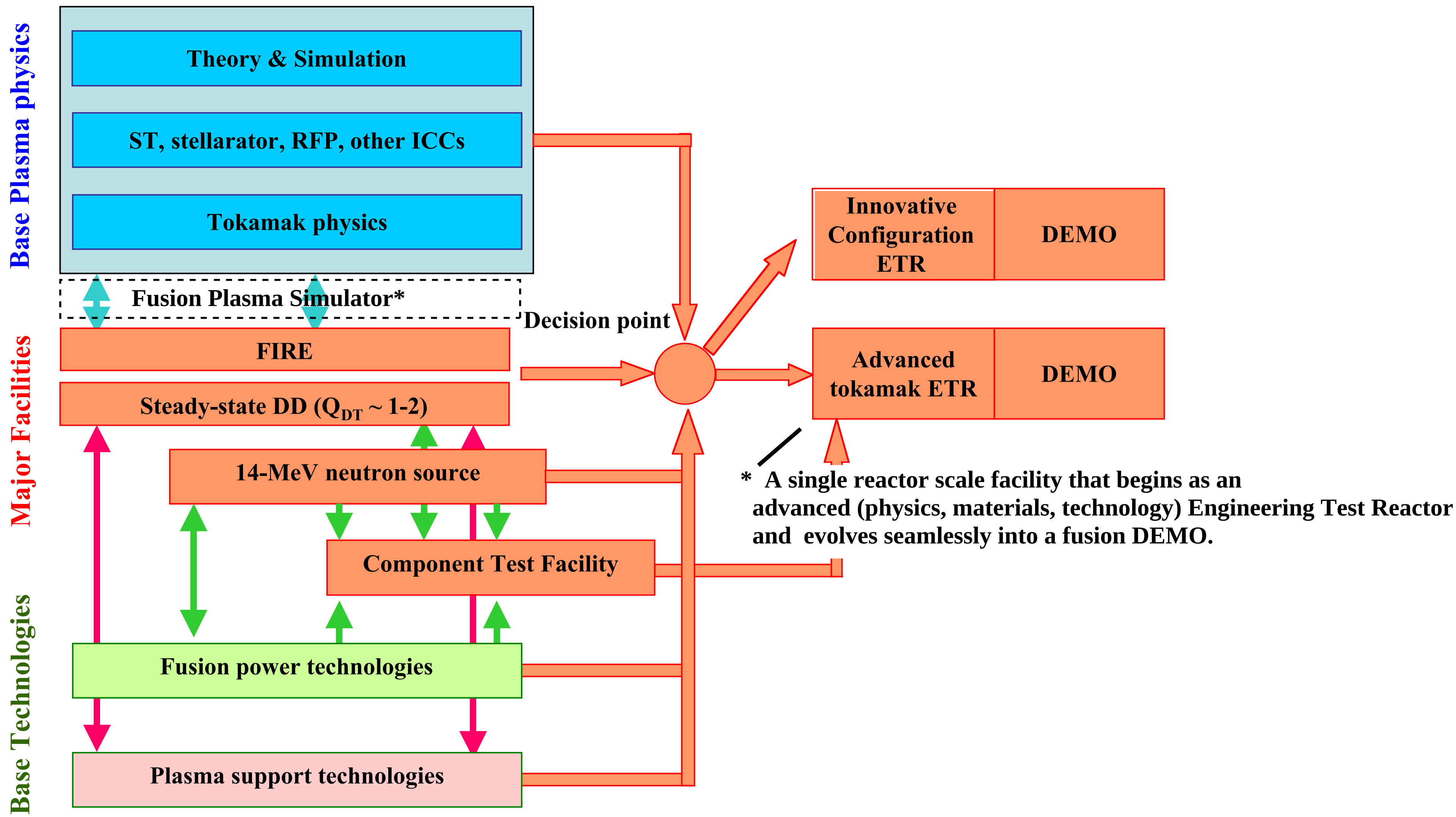
- **Neutron-Resistant Low-Activation Materials**
  - high fluence material testing facility using “point”neutron source
  - high fluence component testing facility using volume neutron source

- 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.

FIRE-Based Development Path

2002 Fusion Snowmass Executive Summary (p. 9)



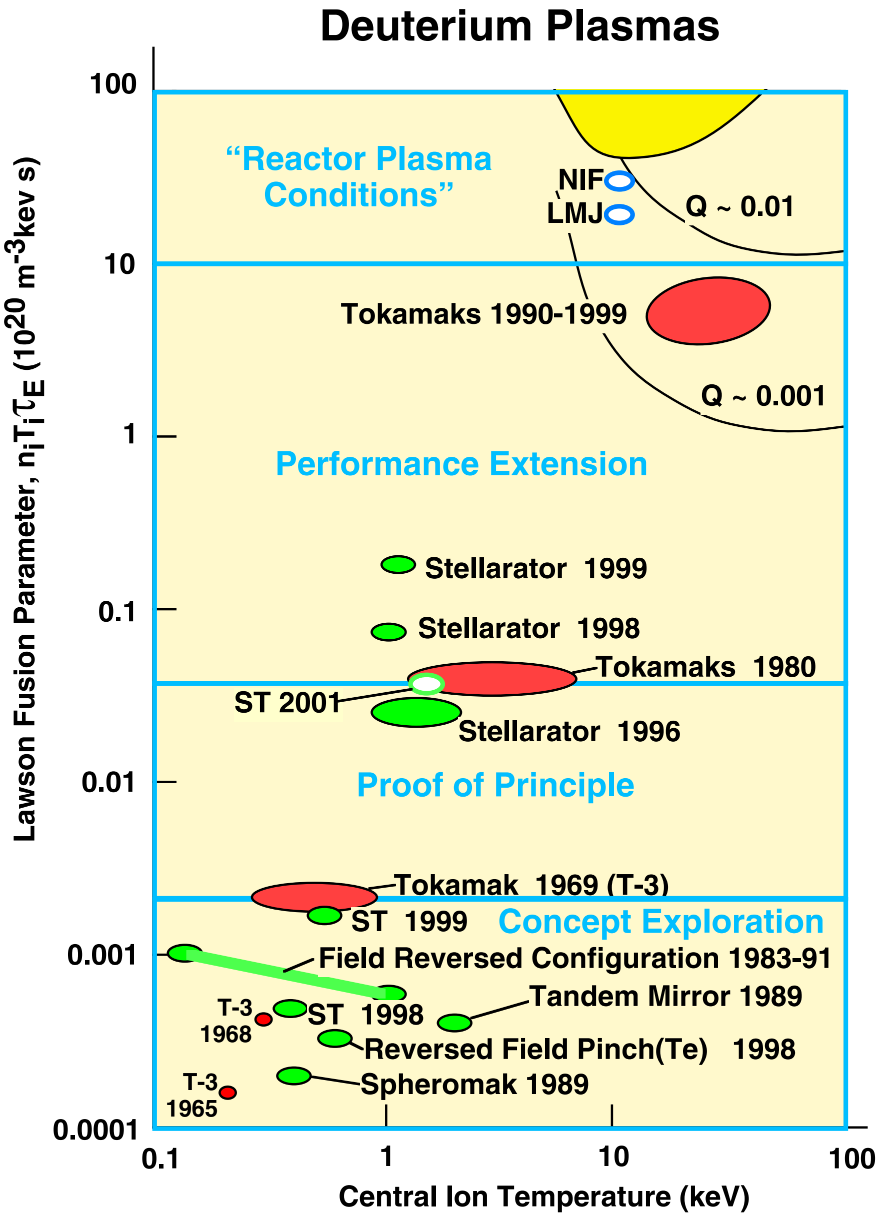
* The Fusion Plasma Simulator would serve as the intellectual integrator of physics phenomena in advanced tokamak configurations, advanced stellarators and tokamak burning plasma experiments.

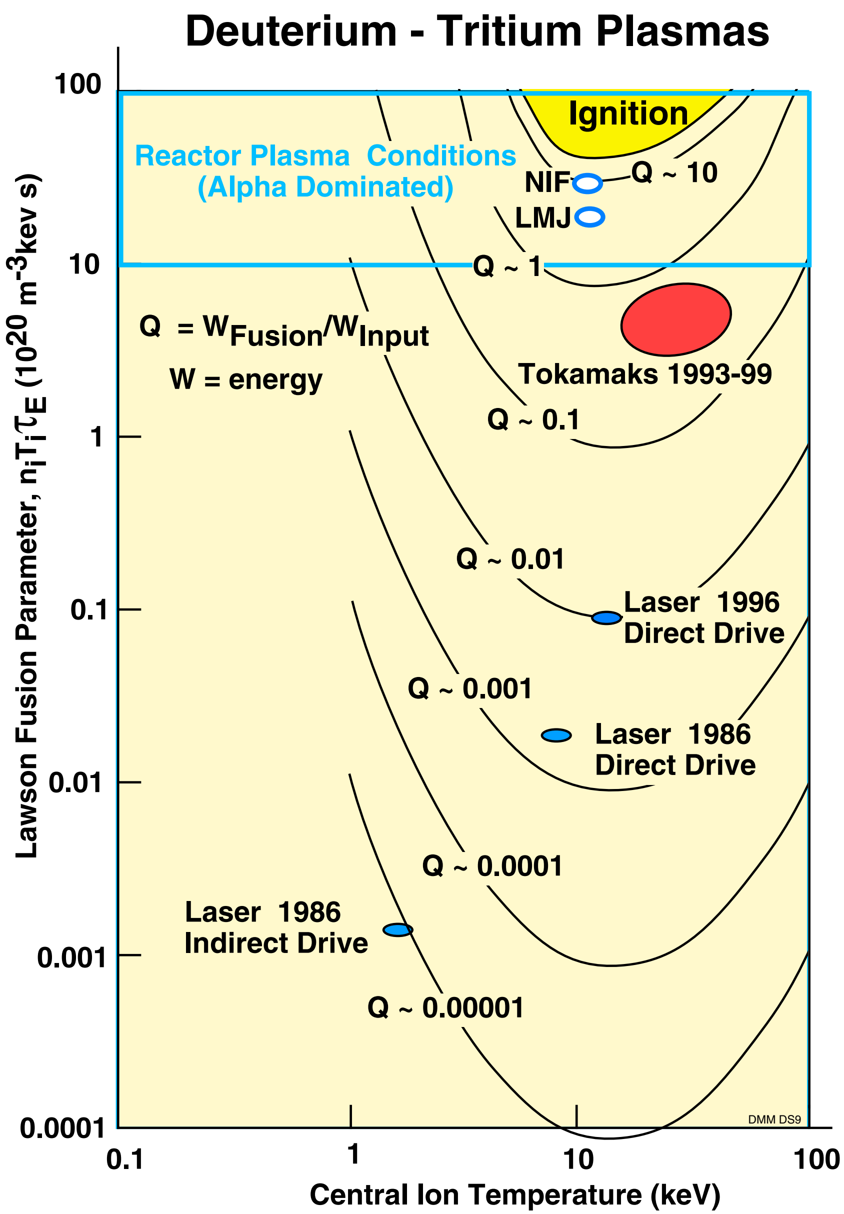
2002 Fusion Snowmass Executive Summary (p. 8)

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.

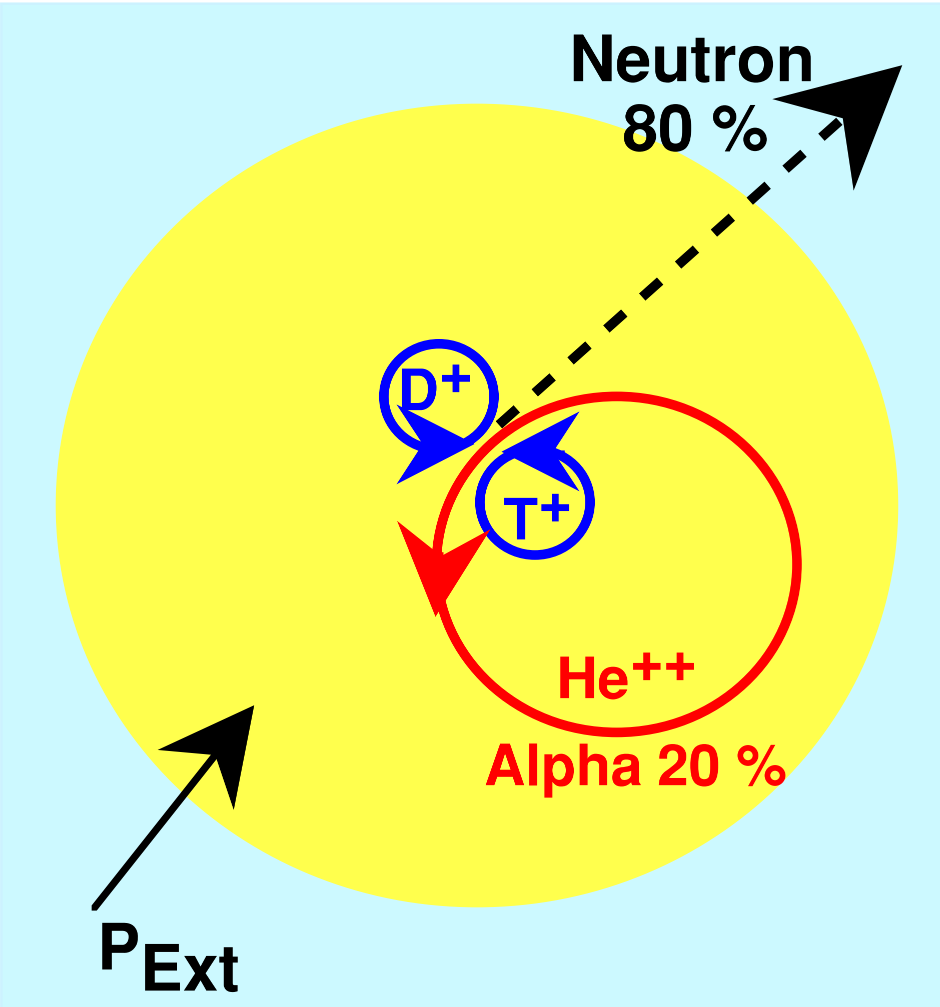
Magnetic Fusion is Technically Ready for a High Gain Burning Exp't





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

Burning Plasma Physics in a D-T Fusion Plasma

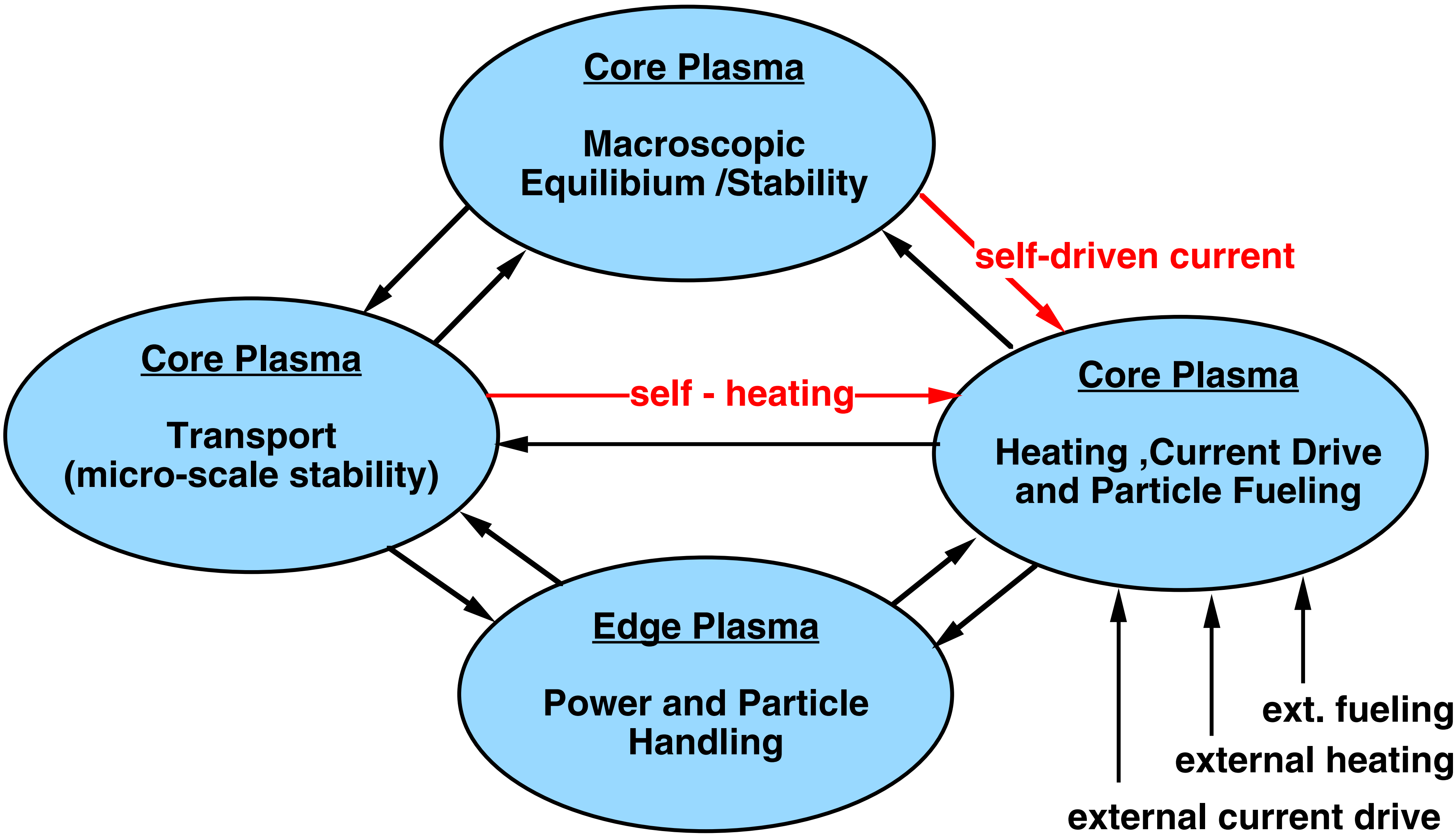


Alpha Physics Issues
• Alpha confinement • Alpha Energy to Plasma from alphas to plasma electrons • Burn Control • Alpha Ash Removal • Alpha Driven Instabilities

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

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)

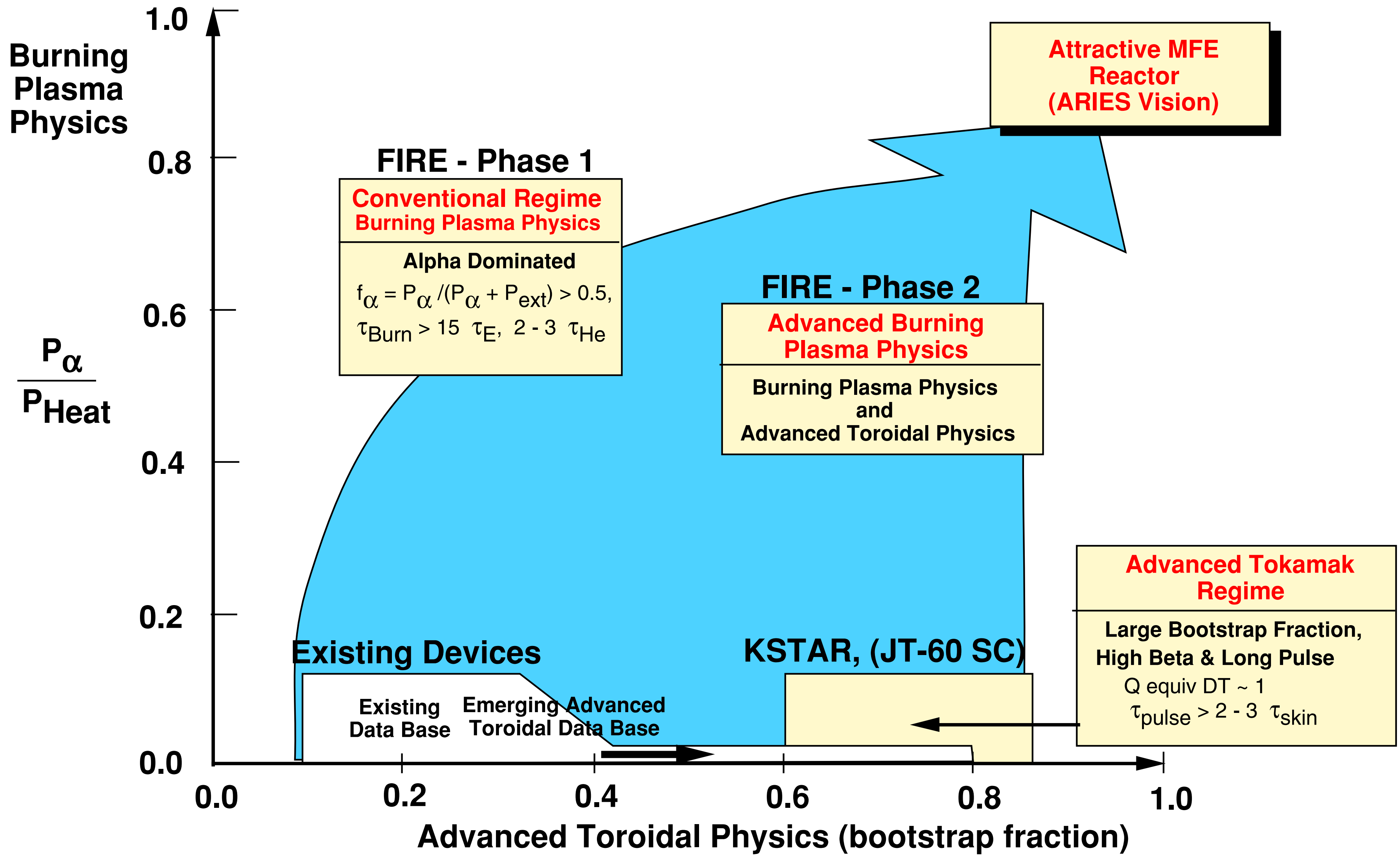
Suitable for an attractive steady state reactor with high power density

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	~ 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

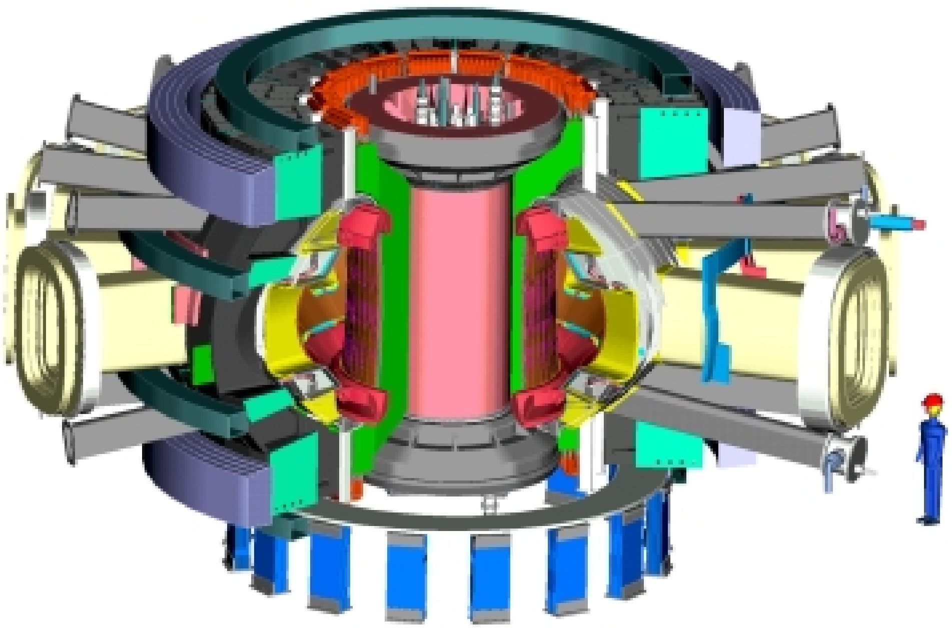
$f_{bs} = I_{bs}/I_p$	~ 80% (goal)
β_N	~ 4.0, n = 1 wall stabilized

Quasi-stationary Burn Duration

Pressure profile evolution and burn control	> 10 τ_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)

http://fire.pppl.gov



1,400 tonne

Design Features

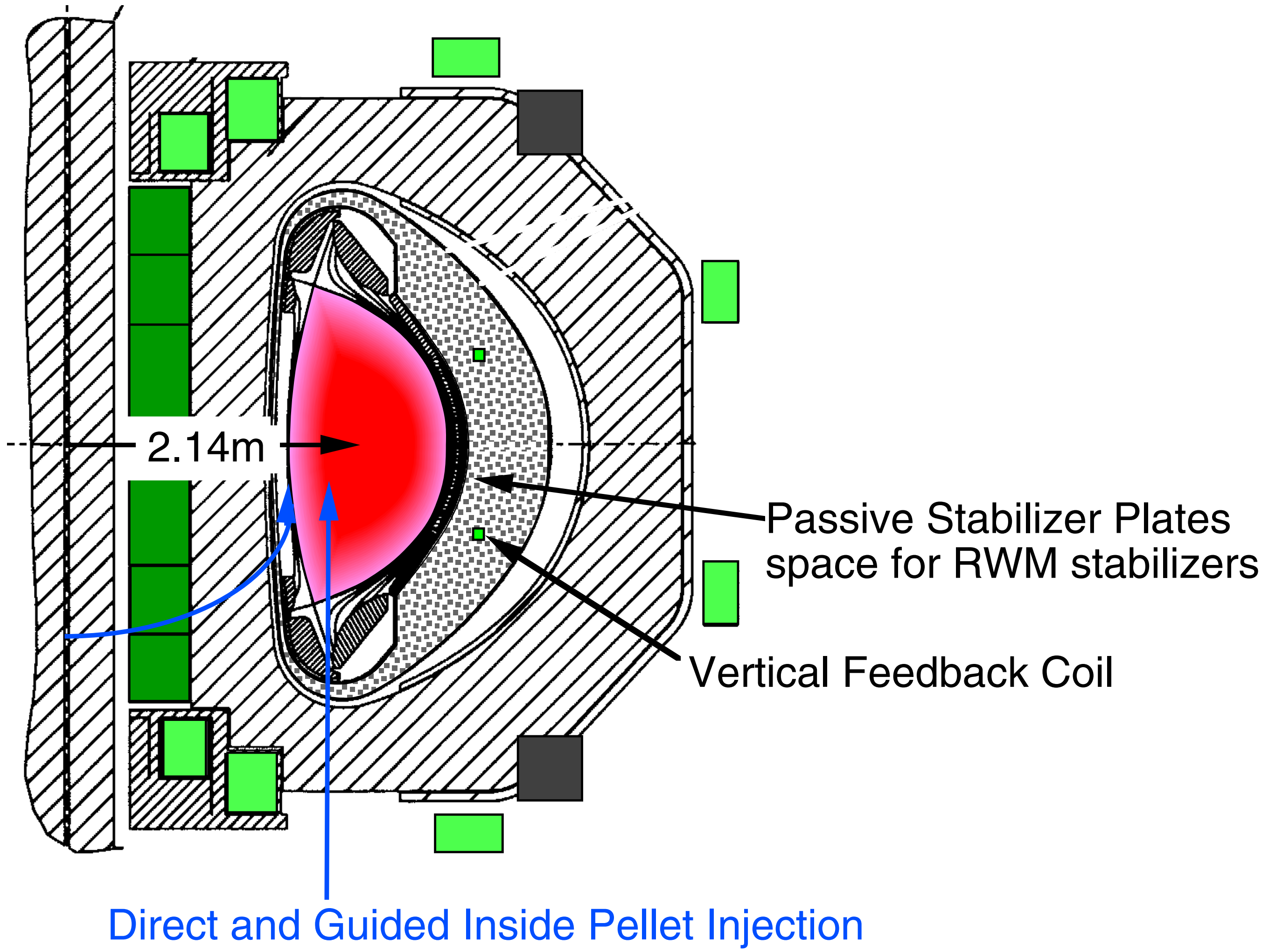
- R = 2.14 m, a = 0.595 m
- B = 10 T (~6.5 T AT)
- W_{mag}= 5.2 GJ
- I_p = 7.7 MA (~5 MA AT)
- $P_{aux} \leq$ 20 MW
- Q ≈ 10, P_{fusion} ~ 150 MW
- Burn Time ≈ 20 s (~ 40 s AT)
- Tokamak Cost ≈ $350M (FY02)
- Total Project Cost ≈ $1.2B (FY02) at Green Field site.

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

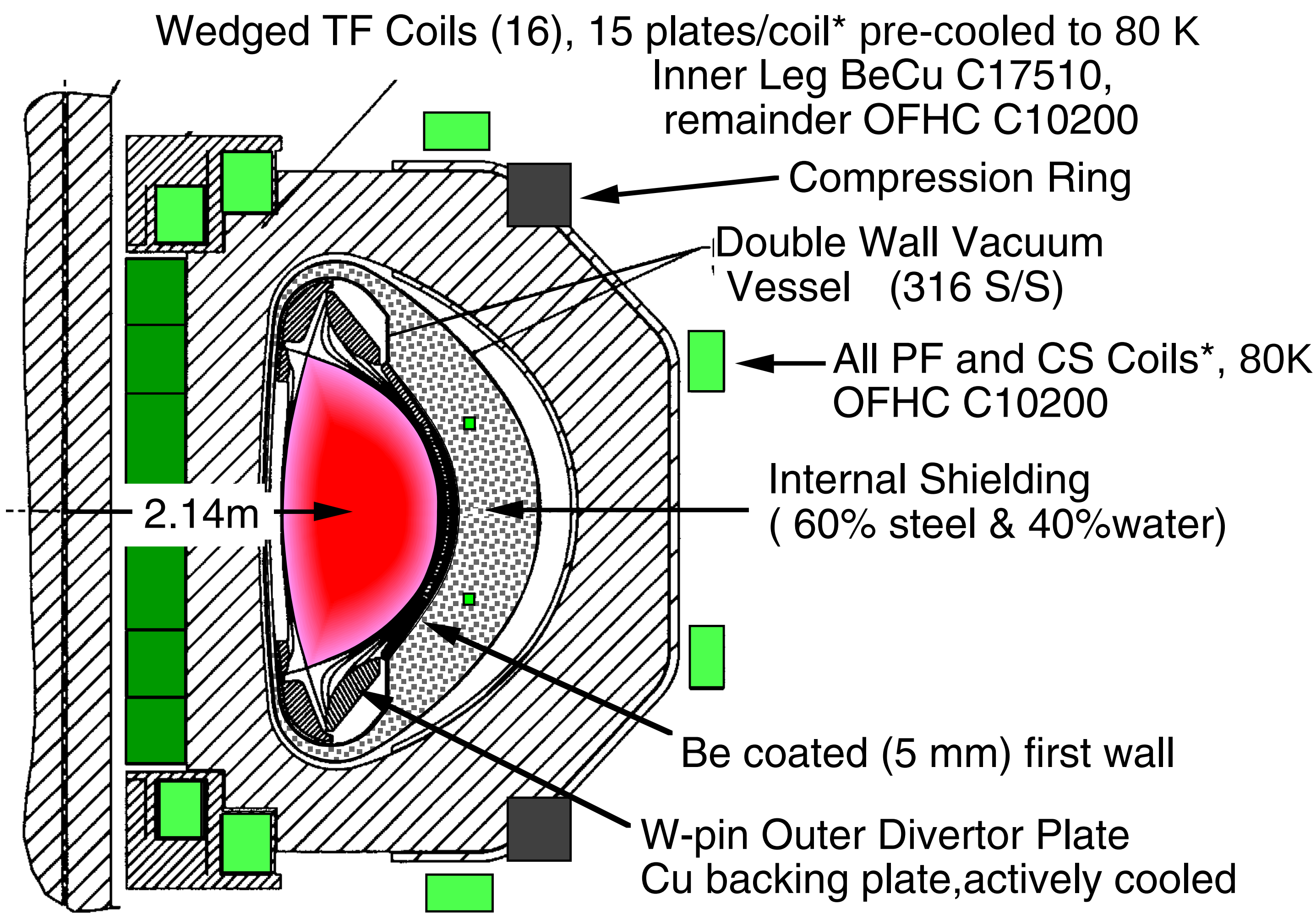
FIRE Incorporates Advanced Tokamak Features (ala ARIES)

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



FIRE Engineering Features



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

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.

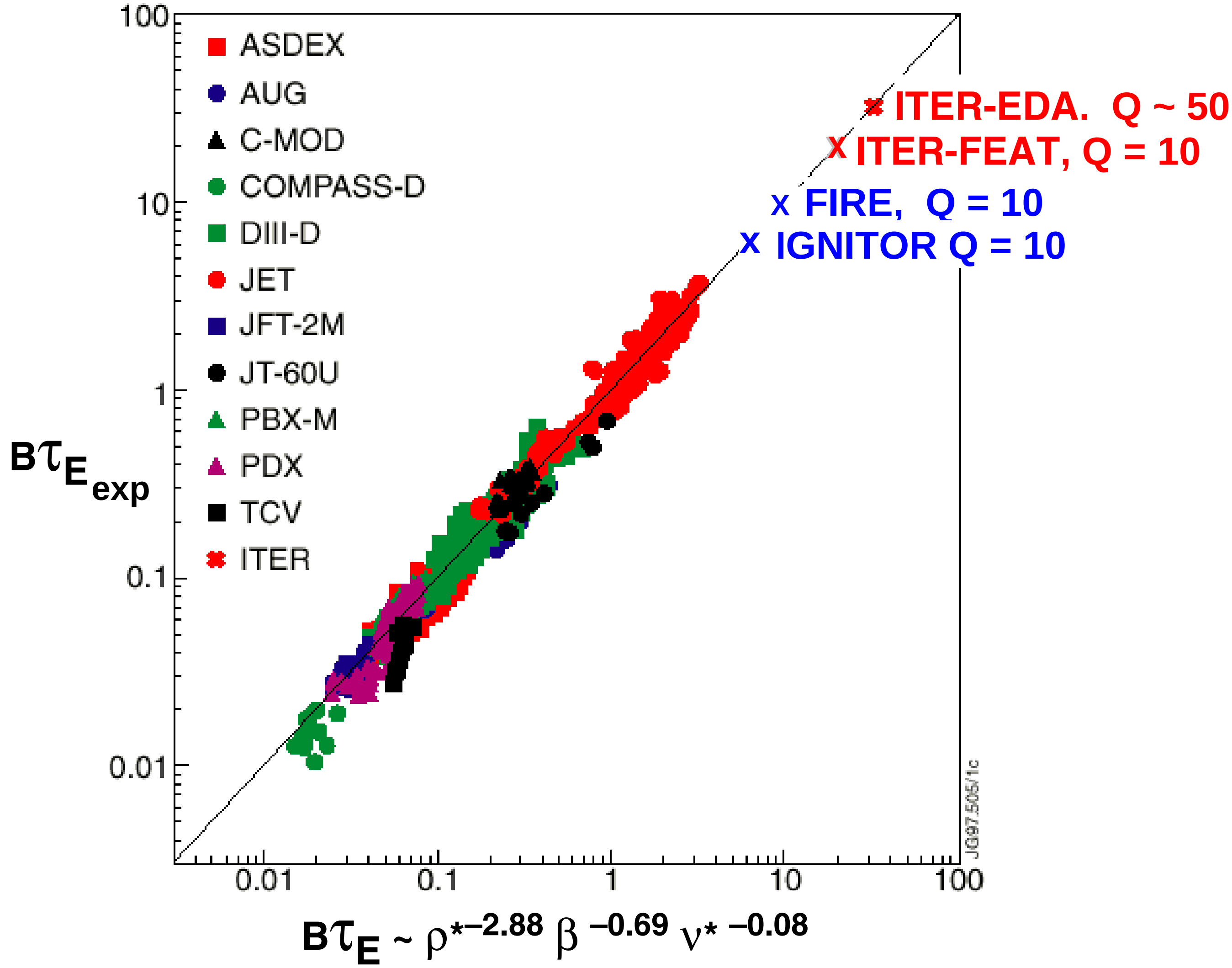
  Snowmass Assessment on Need for Diagnostics R&D:
  In all cases (i.e., ITER, FIRE and IGNITOR), an aggressive and dedicated R&D program is required for full implementation of the necessary measurements in the three options, building on the extensive ITER R&D effort.

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



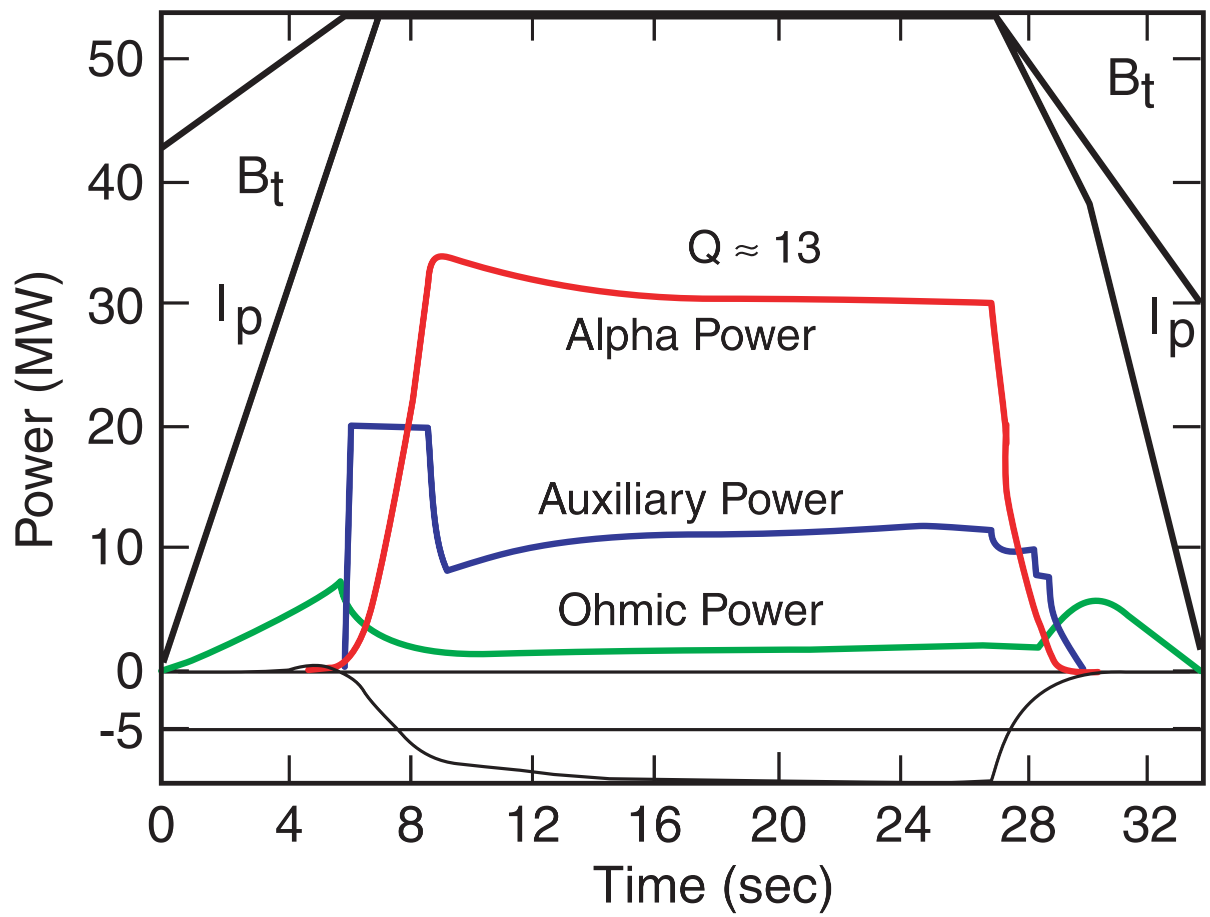
Snowmass Conclusions on Confinement Projections for FIRE

- 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

Simulation of Burning Plasma in FIRE



B = 10 T

I_p = 7.7 MA

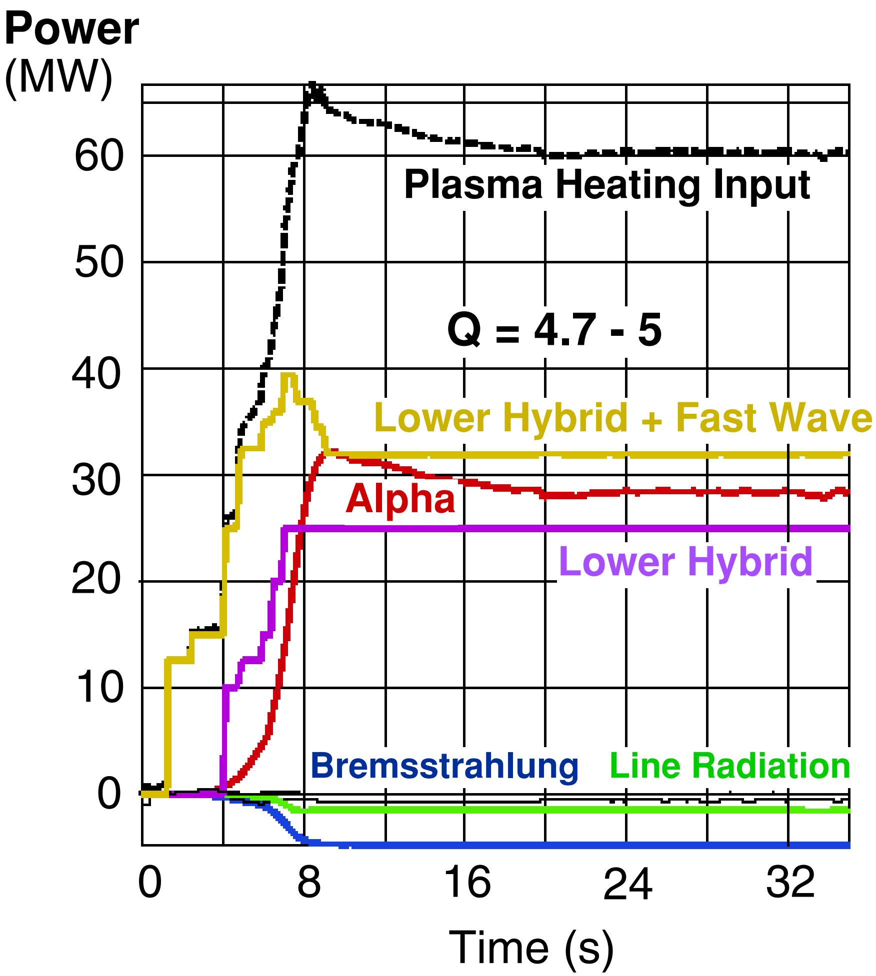
R = 2.14 m

A = 3.6

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

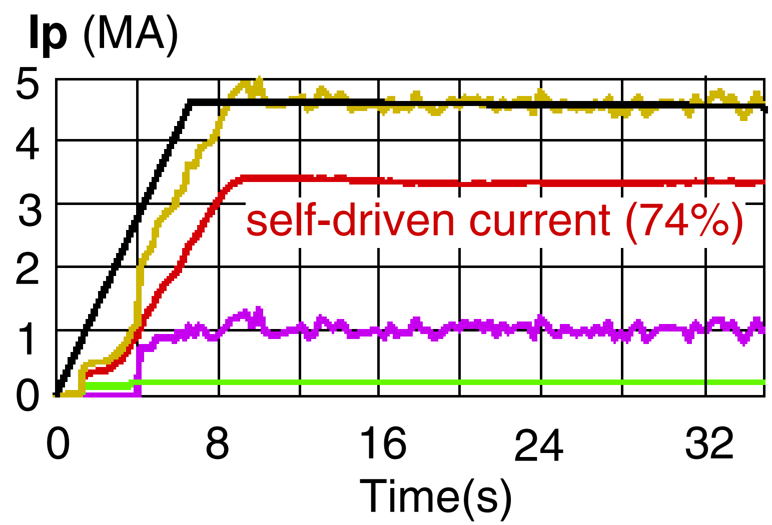
Q = Pfusion/(Paux + Poh)

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 $\Rightarrow$ 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

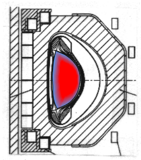
Solutions to these issues would be a major output from a next step experiment.

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

Pfusion
= ~ 150 MW

Volume
= 27 m^3

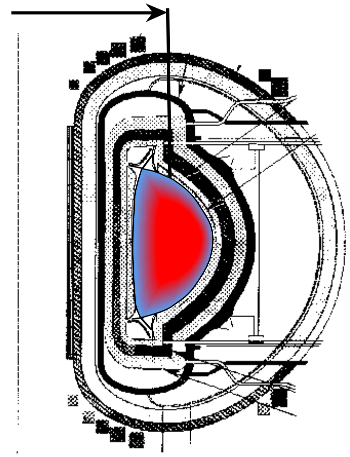
B = 10 T
R = 2.14 m



FIRE

~ 2.5X

B = 8 T
R = 5.5 m



ARIES-RS The "Goal"

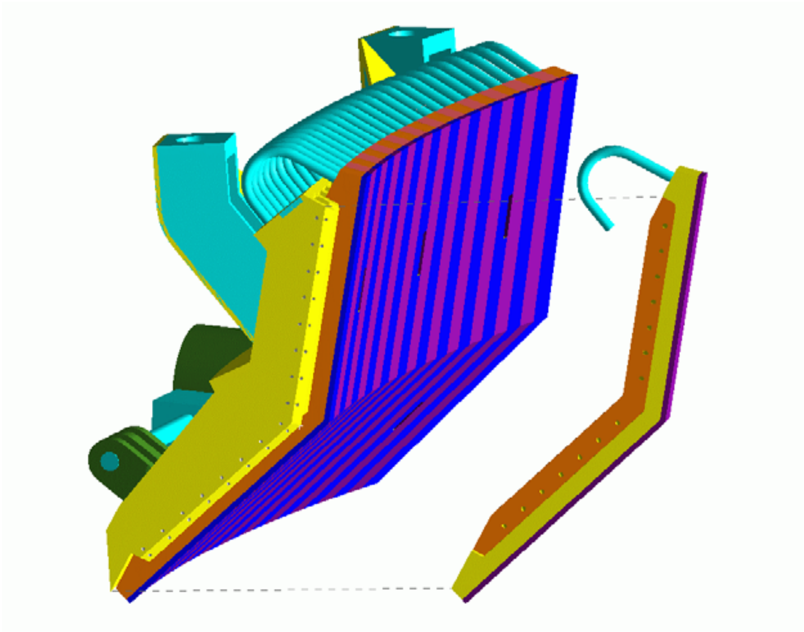
Pfusion
= 2170 MW

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	~5
Burn Duration (s)	4	20	steady

Divertor Module Components for FIRE

Sandia

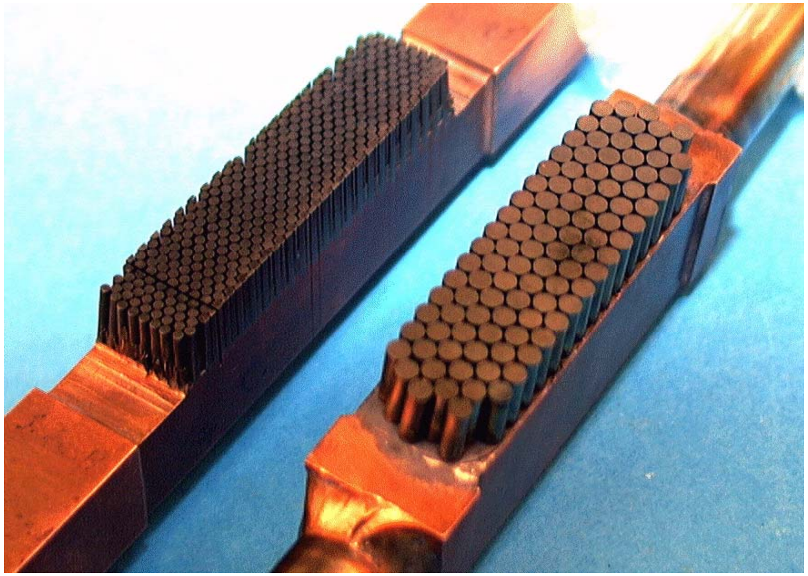


Finger Plate for

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.

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

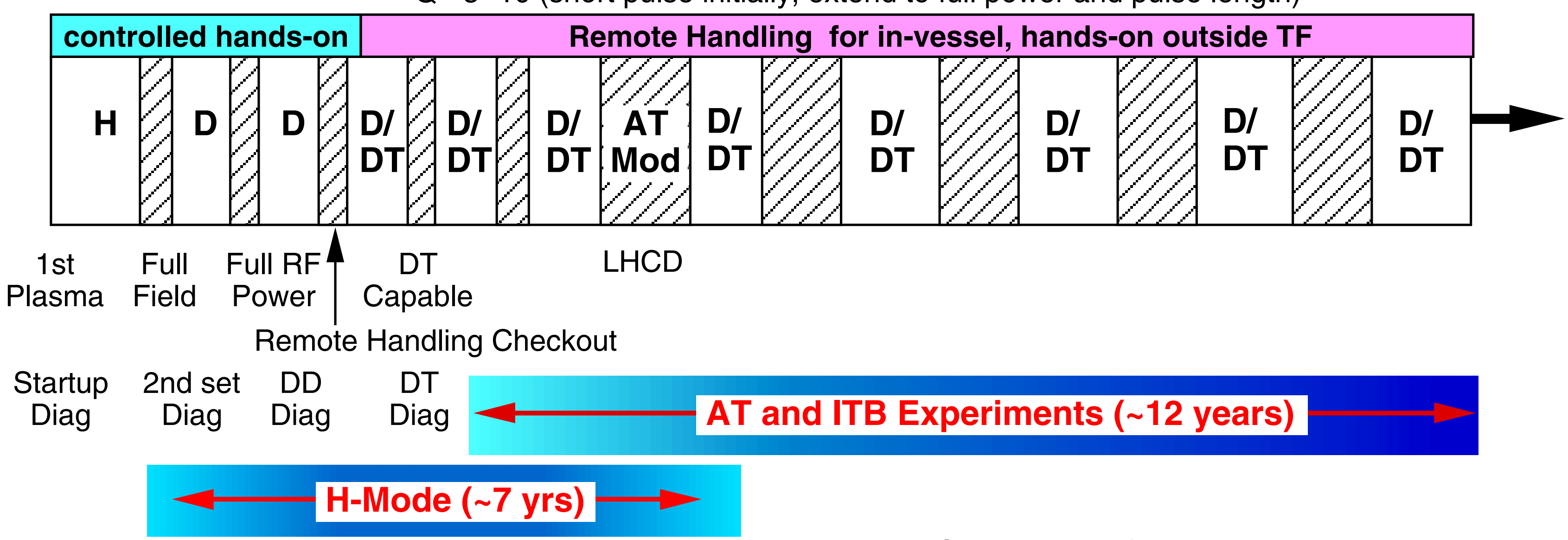
    - Carry the knowledge forward to the following tokamak step or to burning plasmas in other configurations.

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

FIRE Experimental Plan

Years from 1st plasma	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

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

FESAC Recommendations and U.S. 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:

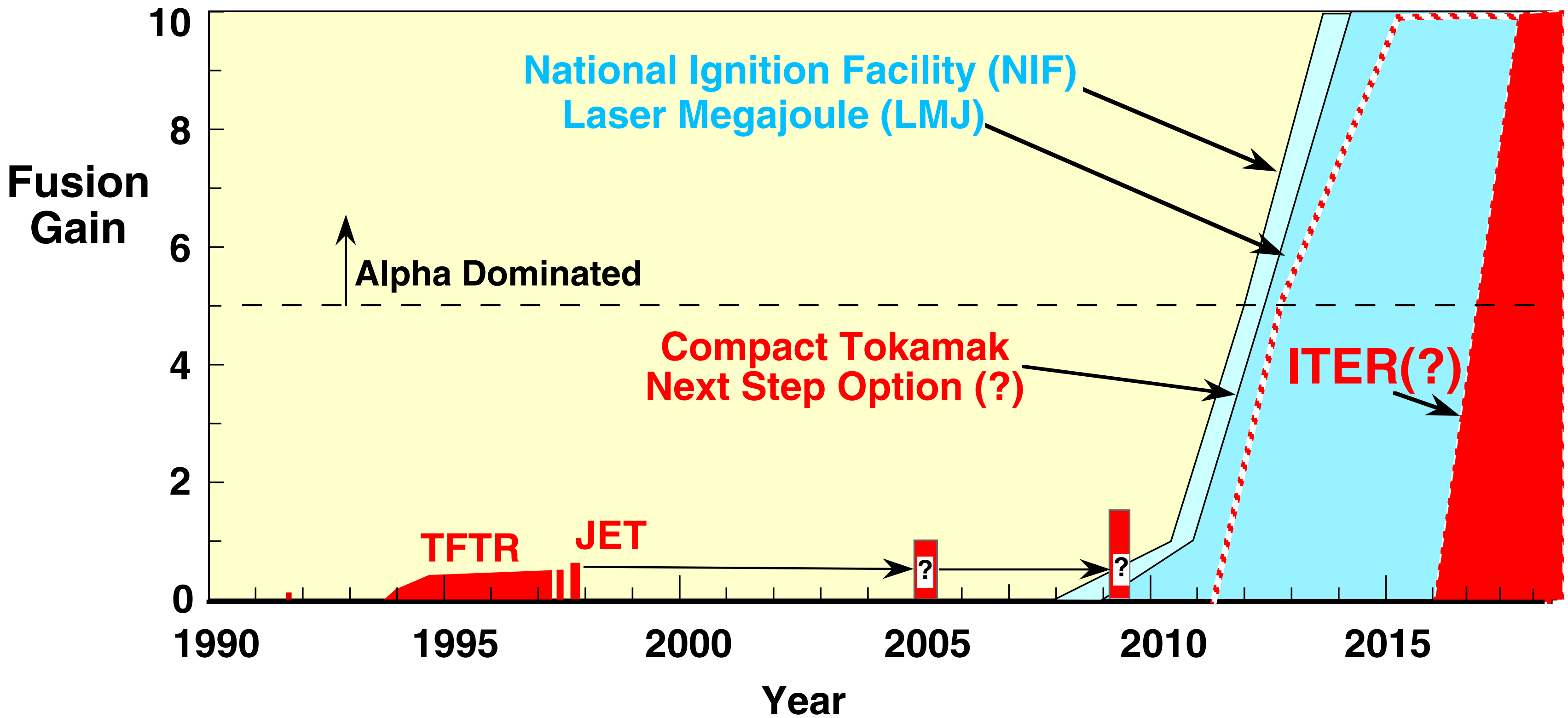
1. that the US should seek to join ITER negotiations as a full participant
    - US should do analysis of cost to join ITER and ITER project cost.
    - negotiations and construction decision are to be concluded by July 2004.

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.

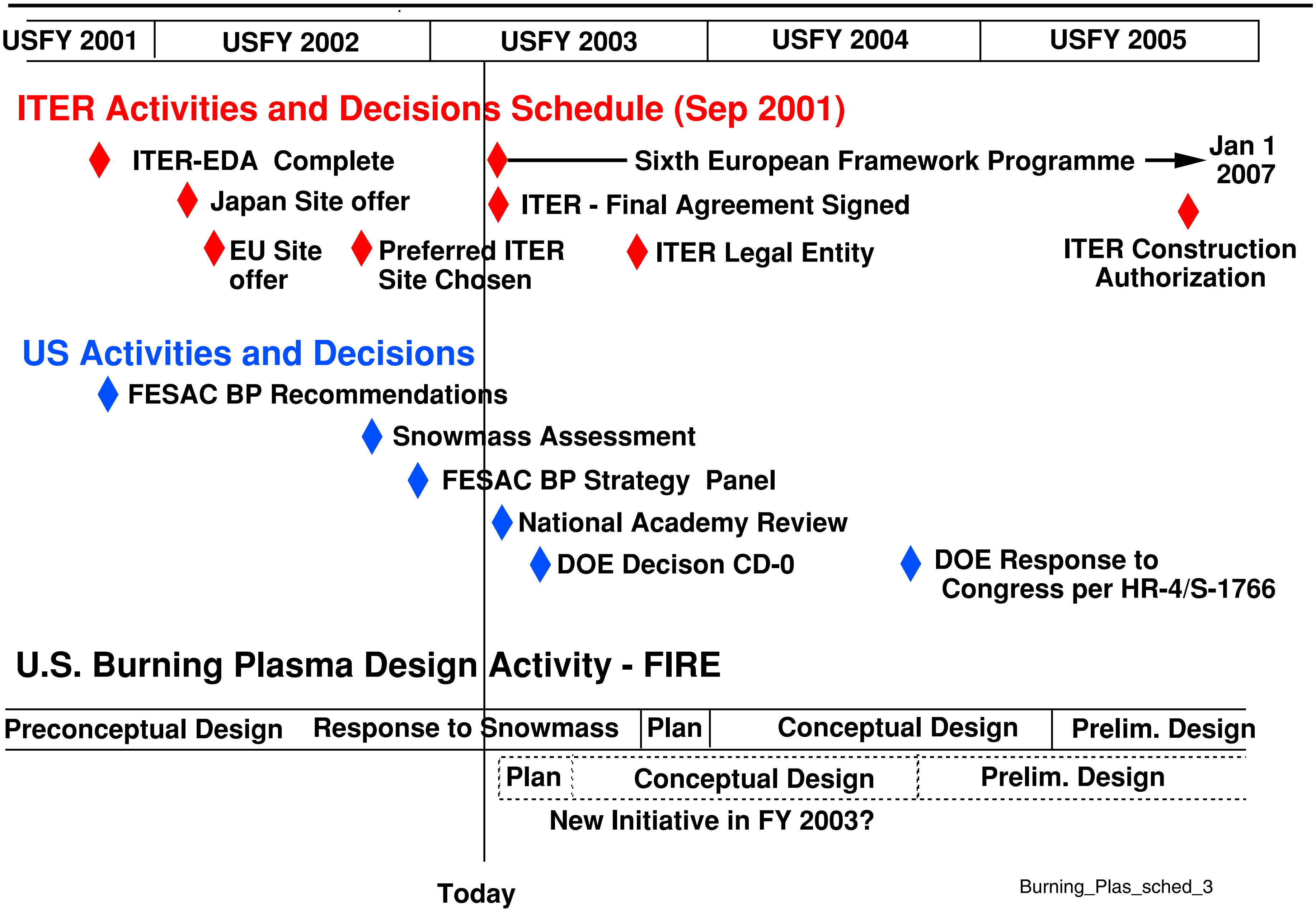
Energy Policy Bill now in the Congress calls for DOE to submit a Plan for the construction of a US Burning Plasma Experiment by 2004.

Timetable for “Burn to Learn” Phase of Fusion



- Even with ITER, the MFE program will be unable to address the alpha-dominated burning plasma issues for ≥ 15 years.
- Compact High-Field Tokamak Burning Plasma Experiment(s) would be a natural extension of the ongoing “advanced” tokamak program and could begin alpha-dominated experiments by ~ 10 years.
- More than one high gain burning plasma facility is needed in the world program.
- The information “exists now” to make a technical assessment, and decision on MFE burning plasma experiments for the next decade.

Timetable for Investment Decisions in Magnetic Fusion



Burning_Plas_sched_3

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.

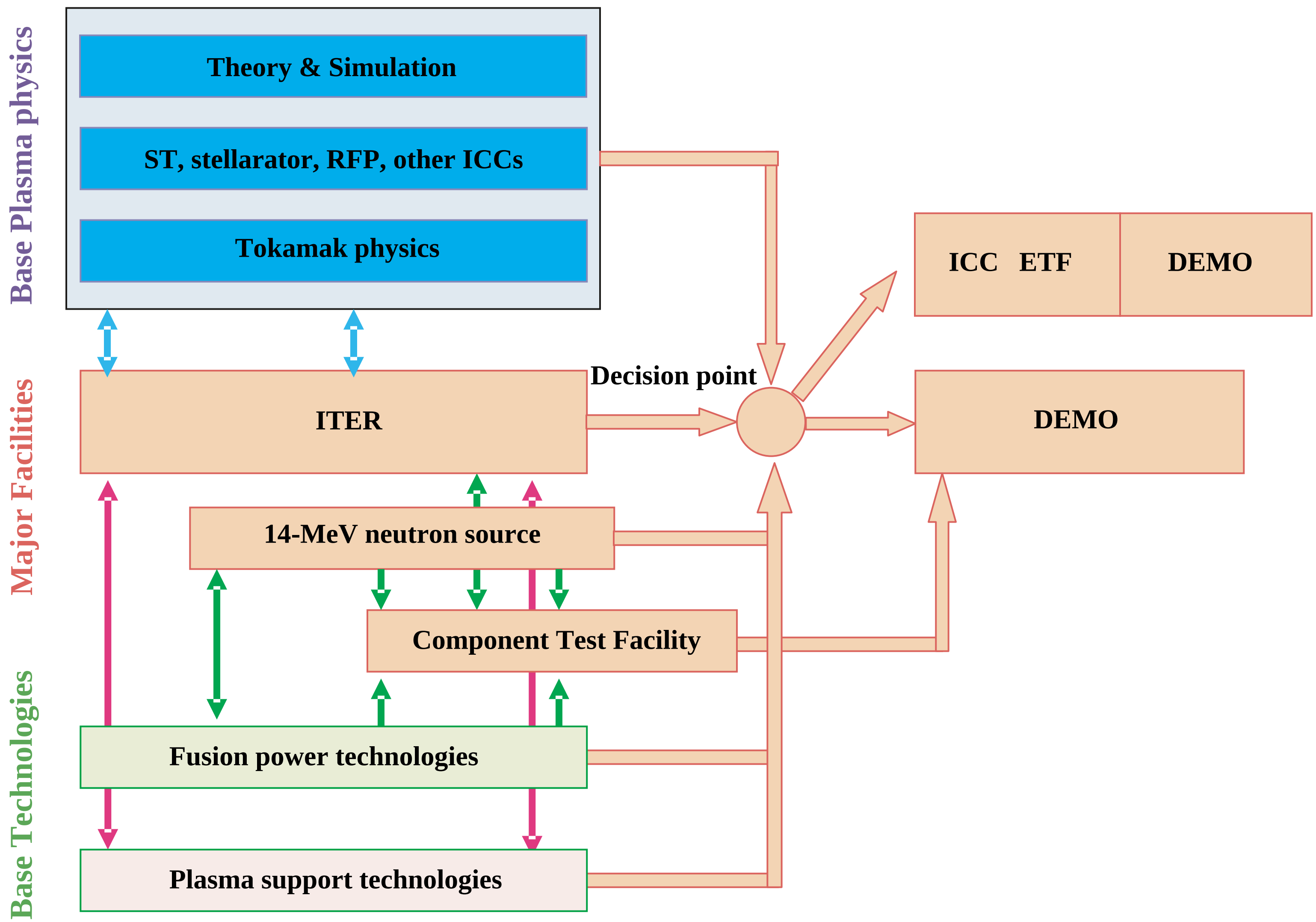
- Some areas that need additional work to realize this potential include:

  - 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.

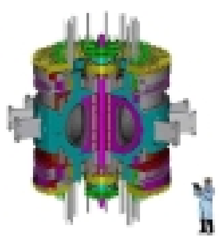
http://fire.pppl.gov

Figure 1 — ITER-Based Development Path



Three Options for a Major Next Step in Magnetic Fusion

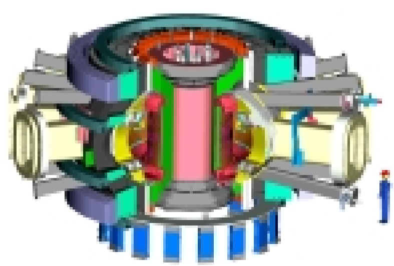
(same scale)



IGNITOR

Italian Based
Int'l Collaboration

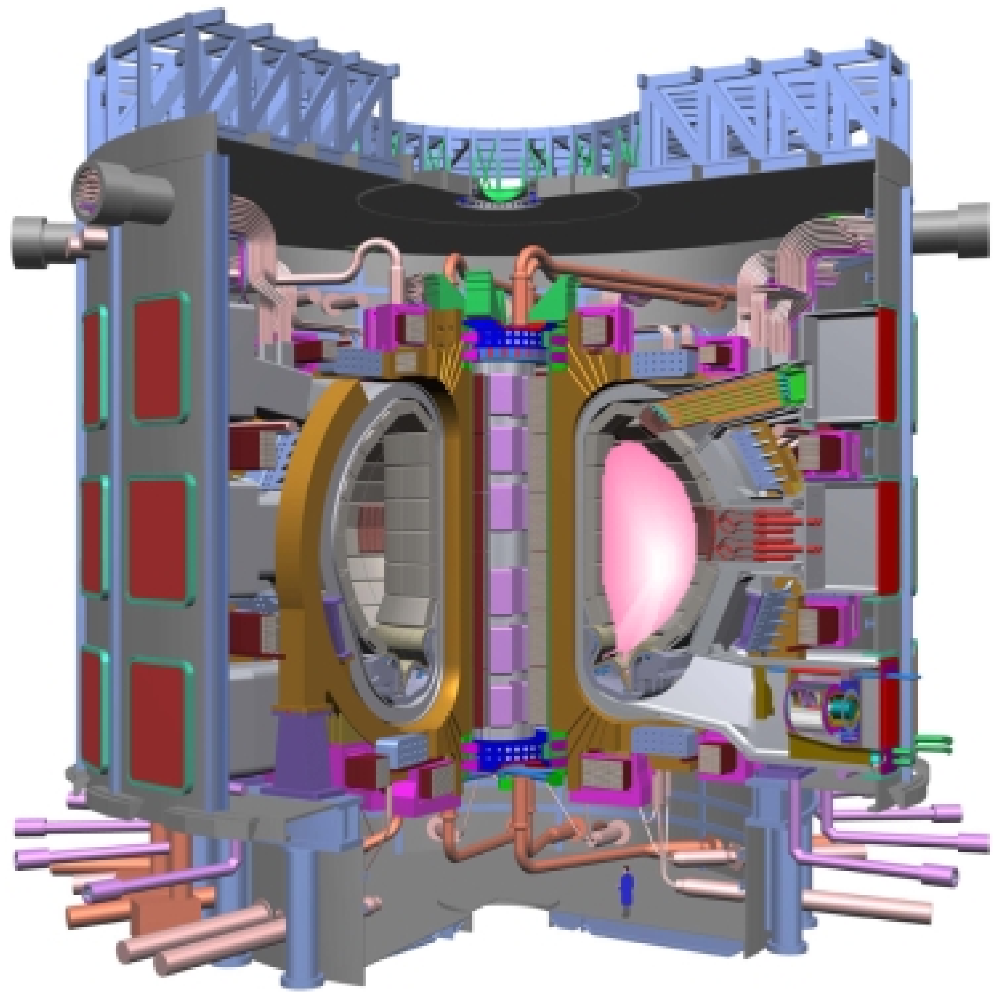
500 tonne



FIRE

US Based
International Portfolio

1,400 tonne



ITER

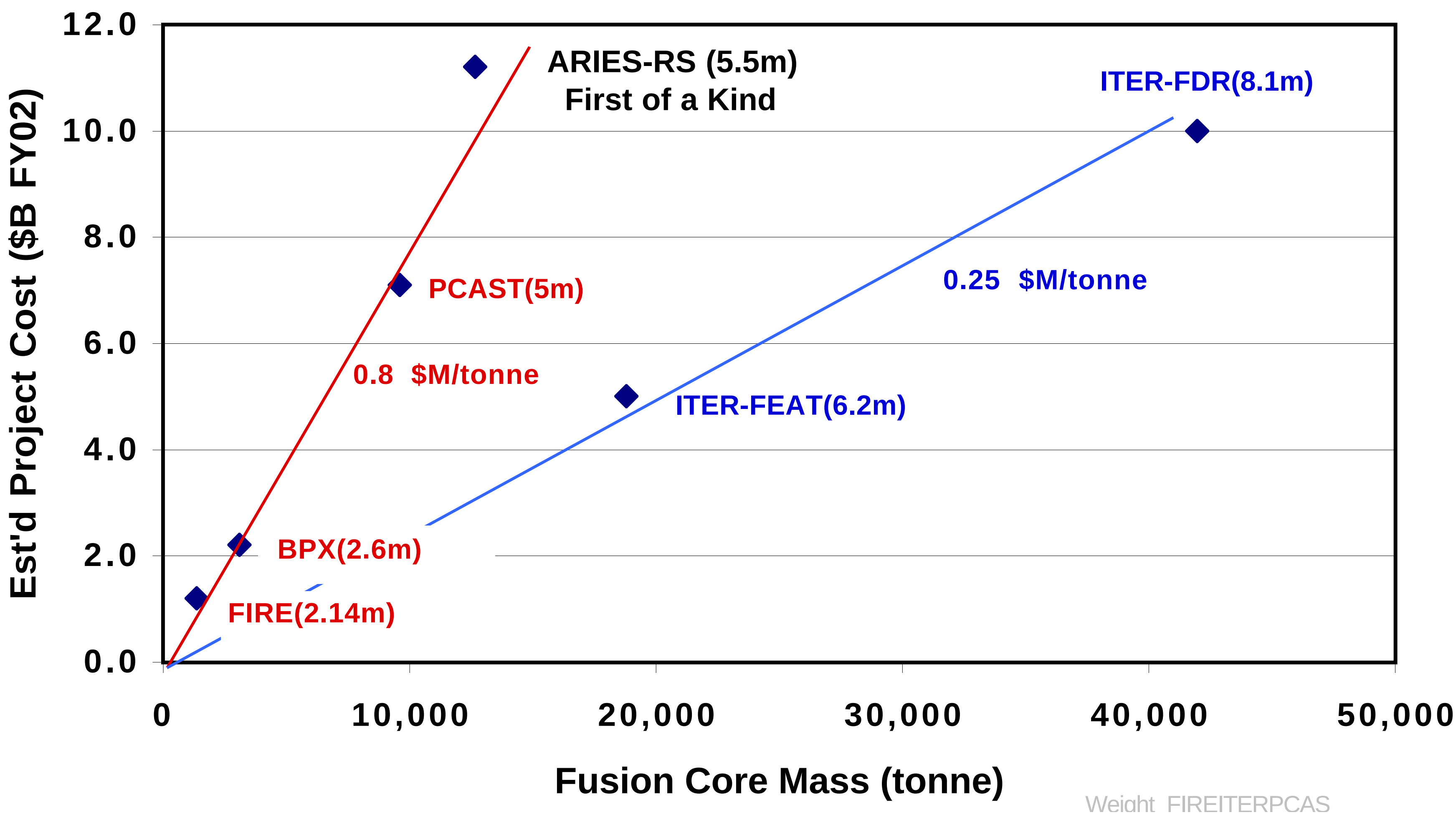
EU, JA or CA Based
International Partnership

19,000 tonne

FIRE Parameters and Design Goals

	FIRE	ITER-FEAT	ARIES-RS
κ_x/κ_{95}	2.0/1.77	1.85/1.7	2/1.7
δ_x/δ_{95}	0.7/0.4-0.55	0.49/0.33	0.7/0.5
Divertor	DN	SN	DN
R (m)	2.14	6.2	5.5
A = R/a	3.6	3.1	4.0
B (T)	10	5.3	8
I_p (MA)	7.7	15	11.3
$Q = P_{fus}/(P_{oh} + P_{aux})$	10	10	27
Burn Time (inductive) (s)	20	400	steady
Current Redistributions	~2	~2	infinite
P_{fusion}(MW)	150	400	2170
P_{fusion}/Vol (MW/m^3)	5.6	0.5	6.2
Neutron Wall loading (MW/m^2)	2.3	0.5	4
First Wall Thermal Equilib.	no	yes	yes
Divertor Target material	W	C(W?)	W
$P_{fusion} - P_{bremm} / N2\pi R_x$ (MW/m)	1.5	1.4(0.7)	8.1
Div. Target Thermal Equilib.	yes	yes	yes

Correlation of Estimated Total Project Cost and Fusion Core Mass



International Portfolio Assumptions

1. Cost Sharing

- If an item on the development path proposed by the US is not on the accepted JA and EU development paths, then the US must pay 100%, therefore US pays 100% of FIRE and CTF construction and ops costs.
- US is a full partner in ITER, US pays 20% of construction and ops costs
- US is a full partner in IFMIF and pays 25% of construction and ops costs
- US pays 100% of the DEMO costs in this analysis.

2. Facility Costs

$B(FY02)	Integrate First – ITER Plan	Innovation First – FIRE Plan
LHD-U	0.4	0.4
W7-X	0.7	0.7
New ICCs(eg., CS)	0.6	0.6
KSTAR and JT-60SC	0.8	0.8
ITER or FIRE	6.0	1.2
IFMIF	0.8	0.8
CTF	2.0	2.0
DEMO	8.0	8.0
Total Facilities Cost	19.3	14.5

3.0 Construction Schedules

DMM: FIRE: 6.5 years, ITER: 9.5 years, IFMIF: 6 years, CTF: 7 years, DEMO: 9 years
(FESAC DP Plan: ITER: 8.5 years, IFMIF: 5 years, CTF: 5 years, DEMO: 7 years) **= -5 yrs**

ITER Based	Const start (FESAC Plan)	Const end	
ITER	10/1/2005-FY06 (2006)	12/31/2014	
IFMIF	2007 (2013)	12/31/2012	
CTF	2013 (2018)	12/31/2019	
DEMO	2029 (2030)	12/31/2037	2038 DEMO Starts
Opn to Demo Constr			
ITER	14 yrs (16 yrs)		
IFMIF	16 yrs (12 yrs) (		
CTF	9 yrs (7 yrs)		

FIRE Based	Const start)	Const end	
FIRE	10/1/2005-FY06	4/1/2012	
IFMIF	1/1/2005	12/31/2010	
CTF	1/1/2010	12/31/2016	What determines start?
DEMO	1/1/2026	12/31/2034	2034 ETR/DEMO Starts
Opn to ETR/Demo C			
FIRE	14 yrs		
IFMIF	15 yrs		
CTF	9 yrs		

- Large ITER funding requirements will constrain the start of other initiatives like IFMIF.
- Greater availability of funding in FIRE based case could allow higher operating budgets for IFMIF and CTF, etc more run weeks per year, this has been partially incorporated.
- What determines the start of CTF – technical results or availability of funding?

Budget Profies for Development Paths Based on Integration First (ITER) and Innovation First (FIRE)

			2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038
LHD-U	0.4	LHD-U			0.025	0.075	0.075	0.075	0.075	0.075																													
W7-X	0.73	W7-X	0.13	0.13	0.13	0.13	0.13	0.075																															
KSTAR/JT-60SC	0.8	KSTAR/JT-60SC	0.05	0.05	0.1	0.15	0.15	0.1	0.1	0.1																											
New ICCs(e.g., CS)	0.6													0.05	0.1	0.15	0.15	0.1	0.05																				
ITER	6	ITER				0.2	0.3	0.45	0.6	1	1.1	1.1	0.6	0.45	0.2																								
IFMIF	0.8	IFMIF						0.1	0.15	0.15	0.15	0.15	0.1																										
CTF	2	VNS												0.1	0.3	0.4	0.4	0.3	0.3	0.2																			
DEMO	8	DEMO																												0.25	0.75	1	1.5	1.5	1.2	0.9	0.65	0.25	
	19.3																																						
Adv Stell Ops									0.075	0.075	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15															
Adv Tok ops								0.05	0.05	0.05	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15															
ITER ops															0.2	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.4									
IFMIF Ops														0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	
CTF ops																					0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	
DEMO ops																																					0.2	0.4	0.6
Total New + Ops			0.18	0.18	0.255	0.555	0.655	0.85	1.05	1.45	1.55	1.55	1	1	1.2	1.55	1.55	1.4	1.35	1.2	1.2	1.2	1.2	1.2	0.9	0.9	0.9	0.9	0.9	0.95	1.05	1.3	1.8	1.8	1.5	1.2	1.15	0.95	0.6
US Base			0.25	0.27	0.3	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Eu Base			0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Ja Base			0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Total World			1.33	1.35	1.455	1.805	1.905	2.1	2.3	2.7	2.8	2.8	2.25	2.25	2.45	2.8	2.8	2.65	2.6	2.45	2.45	2.45	2.45	2.45	2.15	2.15	2.15	2.15	2.15	2.2	2.3	2.55	3.05	3.05	2.75	2.45	2.4	2.2	1.85
Total US			0.25	0.27	0.3	0.39	0.41	0.465	0.508	0.588	0.608	0.608	0.495	0.565	0.755	0.895	0.895	0.795	0.795	0.695	0.695	0.695	0.695	0.695	0.695	0.695	0.695	0.695	0.695	0.905	1.325	1.575	2.075	2.275	2.175	2.075	1.825	1.425	0.95

FIRE Case			2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038
LHD-U	0.4	LHD-U			0.1	0.1	0.1	0.1																															
W7-X	0.7	W7-X	0.15	0.15	0.15	0.15	0.1																																
KSTAR/JT-60SC	0.8	KSTAR/JT-60SC	0.1	0.15	0.15	0.15	0.15	0.1																															
New ICCs(e.g., CS)	0.6													0.05	0.1	0.15	0.15	0.1	0.05																				
FIRE	1.2	FIRE				0.1	0.15	0.2	0.2	0.25	0.2	0.1																											
IFMIF	0.8	IFMIF				0.1	0.15	0.15	0.15	0.15	0.1																												
CTF	2	VNS									0.1	0.3	0.4	0.4	0.3	0.3	0.2																						
DEMO	8	DEMO																									0.25	0.75	1	1.5	1.5	1.2	0.9	0.65	0.25				
	14.5																																						
Adv Stell Ops								0.075	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15																	
Adv Tok ops							0.05	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15																	
FIRE ops												0.06	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12														
IFMIF Ops												0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1				
CTF ops																		0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2				
DEMO ops																																		0.2	0.4	0.6	0.6	0.6	0.6
Total New + Ops			0.25	0.3	0.4	0.6	0.7	0.775	0.65	0.7	0.7	0.86	0.92	0.97	0.92	0.97	0.87	0.82	0.77	0.72	0.72	0.72	0.42	0.42	0.42	0.3	0.55	1.05	1.3	1.8	1.8	1.5	1.2	1.15	0.95	0.6	0.6	0.6	0.6
US Base			0.25	0.27	0.3	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Eu Base			0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Ja Base			0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Total World			1.4	1.47	1.6	1.85	1.95	2.025	1.9	1.95	1.95	2.11	2.17	2.22	2.17	2.22	2.12	2.07	2.02	1.97	1.97	1.97	1.67	1.67	1.67	1.55	1.8	2.3	2.55	3.05	3.05	2.75	2.45	2.4	2.2	1.85	1.85	1.85	1.85
Total US			0.25	0.27	0.3	0.475	0.538	0.588	0.588	0.638	0.6	0.56	0.57	0.595	0.595	0.57	0.57	0.595	0.545	0.545	0.545	0.545	0.545	0.545	0.545	0.675	1.175	1.425	1.925	1.925	1.625	1.325	1.075	0.875	0.825	0.95	0.95	0.95	0.95

ITER Plan

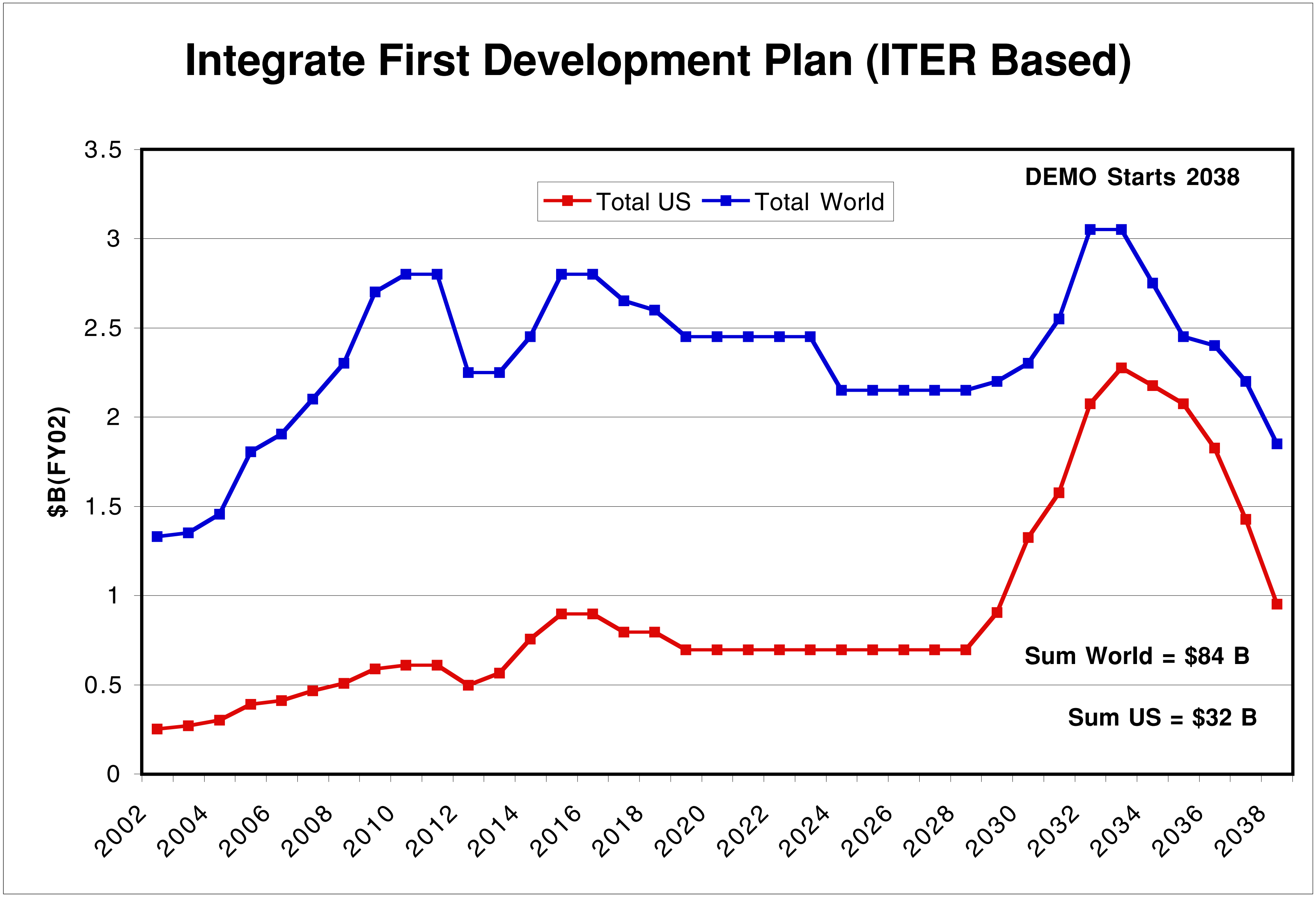
	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038
Total US	0.25	0.27	0.3	0.39	0.41	0.465	0.508	0.588	0.608	0.608	0.495	0.565	0.755	0.895	0.895	0.795	0.795	0.695	0.695	0.695	0.695	0.695	0.695	0.695	0.695	0.695	0.695	0.905	1.325	1.575	2.075	2.275	2.175	2.075	1.825	1.425	0.95
Total World	1.33	1.35	1.455	1.805	1.905	2.1	2.3	2.7	2.8	2.8	2.25	2.25	2.45	2.8	2.8	2.65	2.6	2.45	2.45	2.45	2.45	2.45	2.15	2.15	2.15	2.15	2.15	2.2	2.3	2.55	3.05	3.05	2.75	2.45	2.4	2.2	1.85

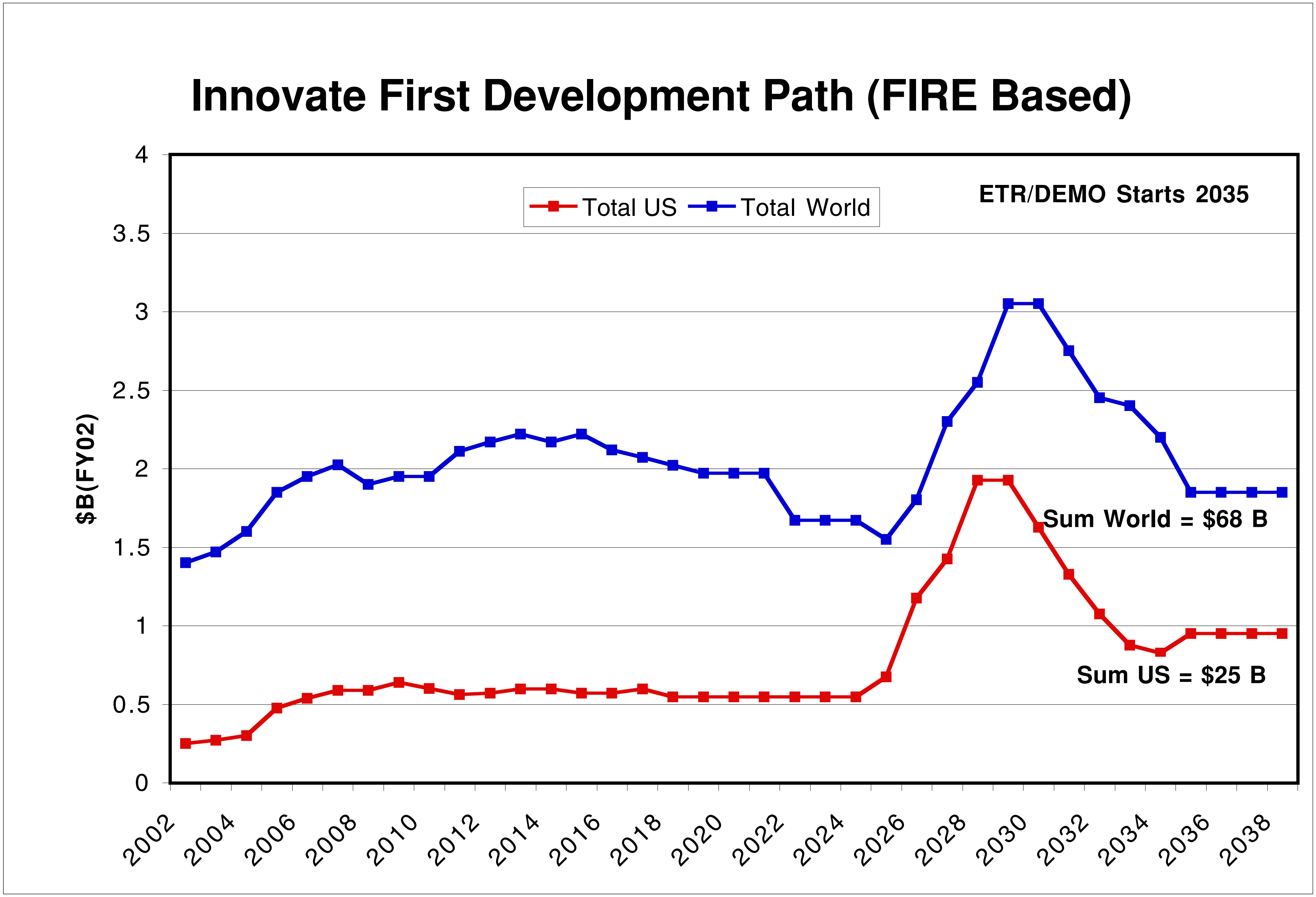
FIRE Plan

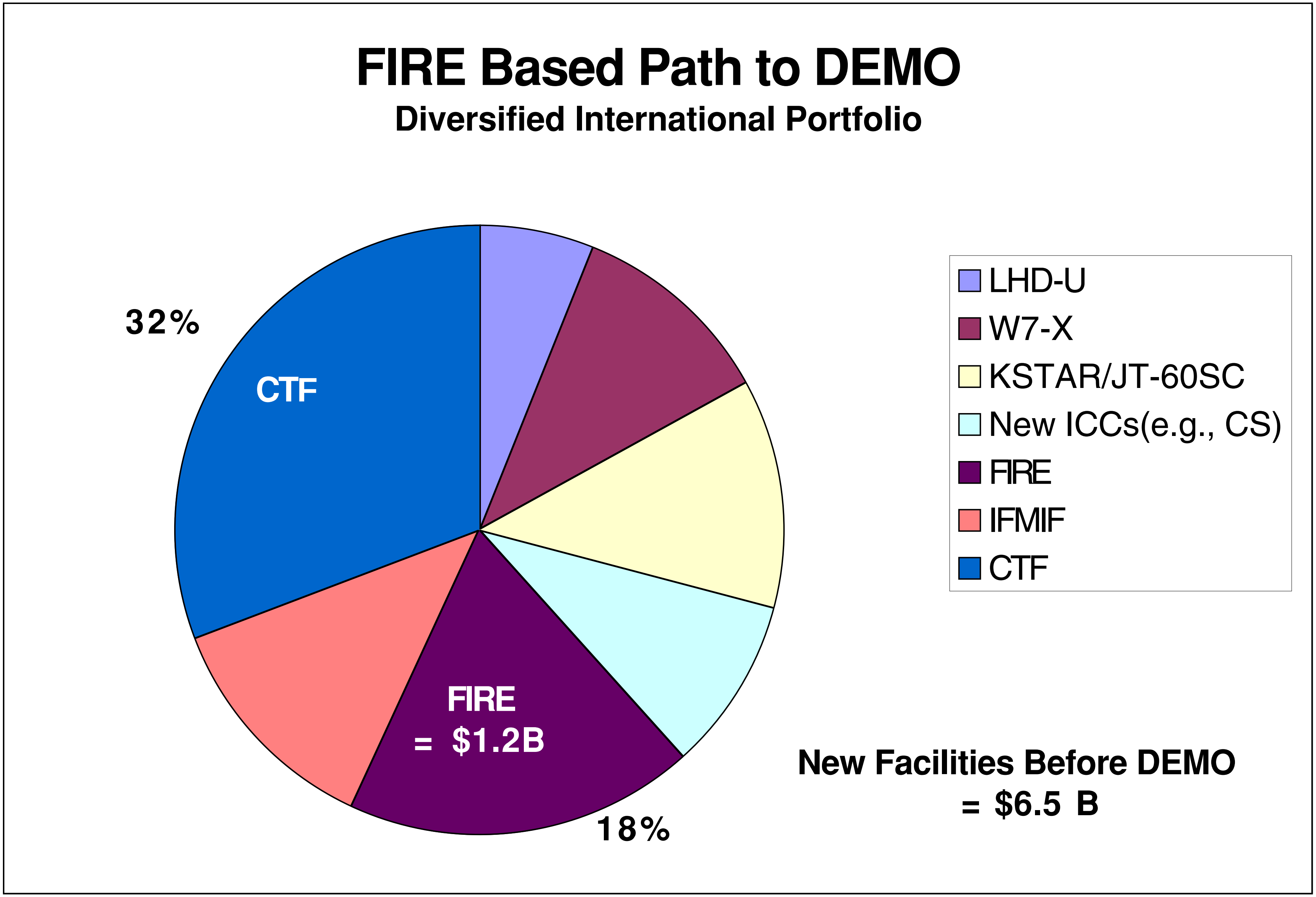
	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038
Total US	0.25	0.27	0.3	0.475	0.538	0.588	0.588	0.638	0.6	0.56	0.57	0.595	0.595	0.57	0.57	0.595	0.545	0.545	0.545	0.545	0.545	0.545	0.545	0.675	1.175	1.425	1.925	1.925	1.625	1.325	1.075	0.875	0.825	0.95	0.95	0.95	0.95
Total World	1.4	1.47	1.6	1.85	1.95	2.025	1.9	1.95	1.95	2.11	2.17	2.22	2.17	2.22	2.12	2.07	2.02	1.97	1.97	1.97	1.67	1.67	1.67	1.55	1.8	2.3	2.55	3.05	3.05	2.75	2.45	2.4	2.2	1.85	1.85	1.85	1.85

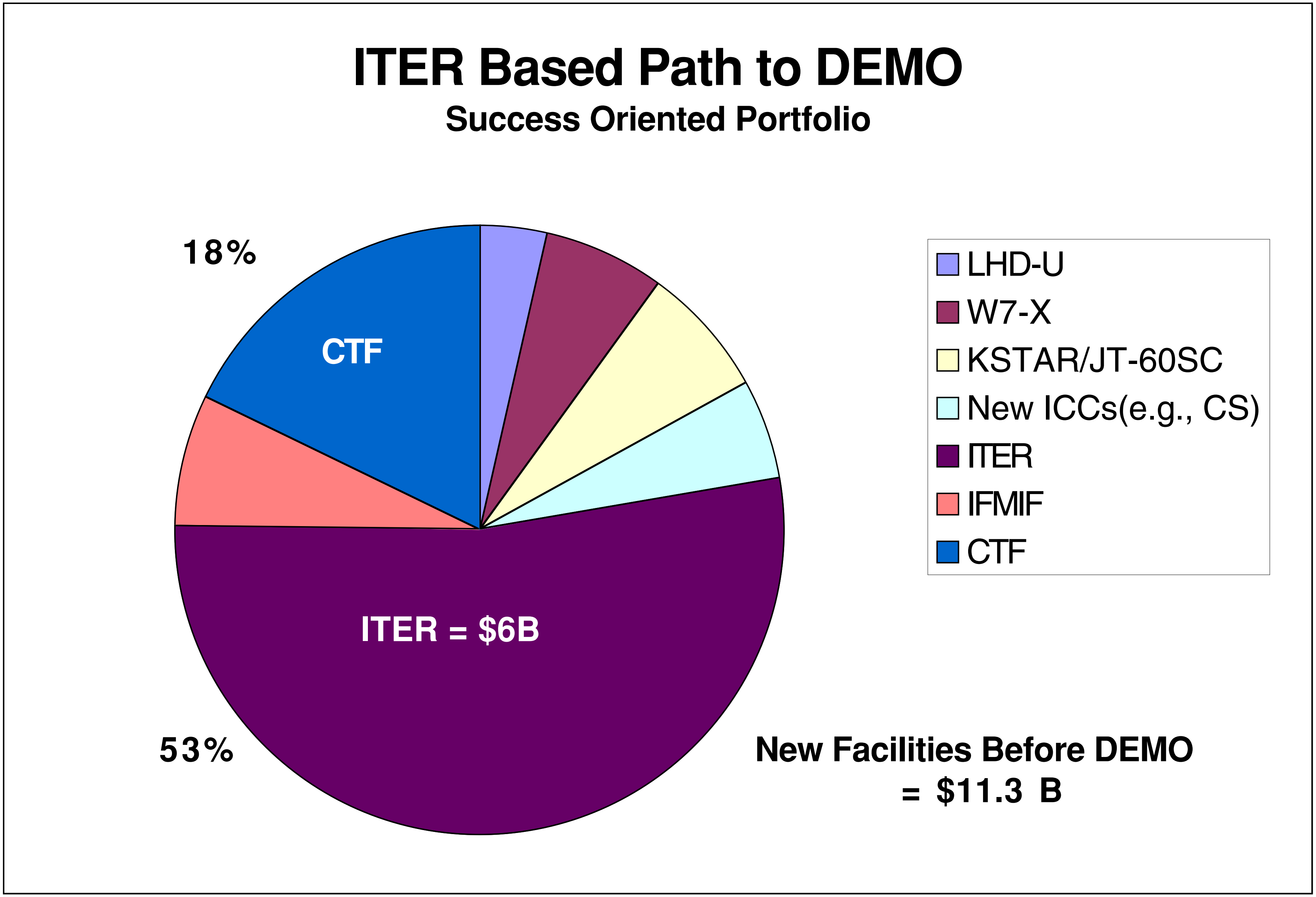
US Funding		2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038
	Integrate First-ITEF	0.25	0.27	0.3	0.39	0.41	0.465	0.508	0.588	0.608	0.608	0.495	0.565	0.755	0.895	0.895	0.795	0.795	0.695	0.695	0.695	0.695	0.695	0.695	0.695	0.695	0.695	0.695	0.905	1.325	1.575	2.075	2.275	2.175	2.075	1.825	1.425	0.95
	Innovate First-FIRE	0.25	0.27	0.3	0.475	0.538	0.588	0.588	0.638	0.6	0.56	0.57	0.595	0.595	0.57	0.57	0.595	0.545	0.545	0.545	0.545	0.545	0.545	0.545	0.675	1.175	1.425	1.925	1.925	1.625	1.325	1.075	0.875	0.825	0.95	0.95	0.95	0.95

World Funding		2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038
	Integrate First-ITEF	1.33	1.35	1.455	1.805	1.905	2.1	2.3	2.7	2.8	2.8	2.25	2.25	2.45	2.8	2.8	2.65	2.6	2.45	2.45	2.45	2.45	2.45	2.15	2.15	2.15	2.15	2.15	2.2	2.3	2.55	3.05	3.05	2.75	2.45	2.4	2.2	1.85
	Innovate First-FIRE	1.4	1.47	1.6	1.85	1.95	2.025	1.9	1.95	1.95	2.11	2.17	2.22	2.17	2.22	2.12	2.07	2.02	1.97	1.97	1.97	1.67	1.67	1.67	1.55	1.8	2.3	2.55	3.05	3.05	2.75	2.45	2.4	2.2	1.85	1.85	1.85	1.85

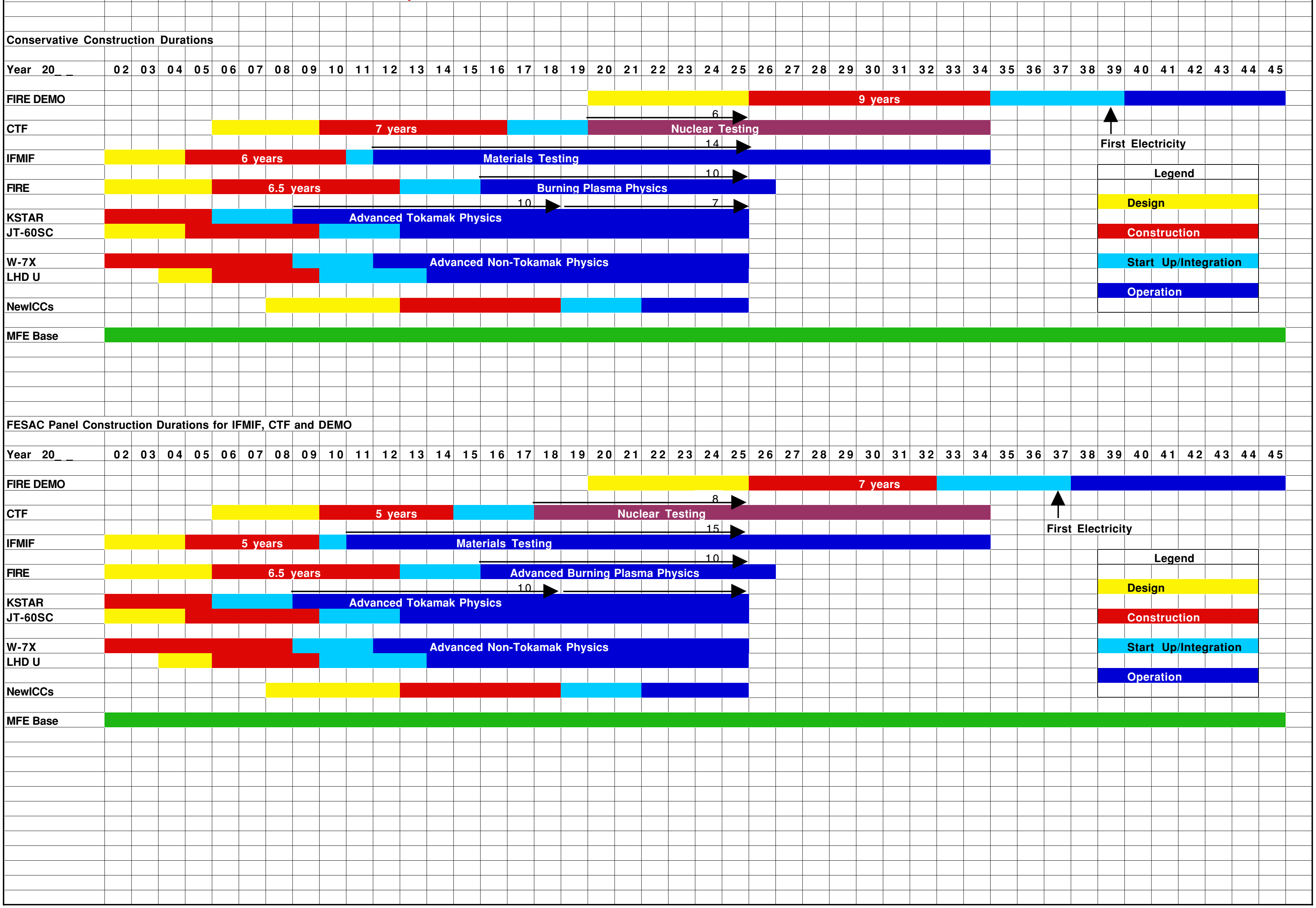

Integrate First Development Plan (ITER Based)
DEMO Starts 2038
Total US
Total World
Sum World = $84 B
Sum US = $32 B
$B(FY02)
3.5
3
2.5
2
1.5
1
0.5
0
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020
2022
2024
2026
2028
2030
2032
2034
2036
2038


Innovate First Development Path (FIRE Based)
Total US
Total World
ETR/DEMO Starts 2035
Sum World = $68 B
Sum US = $25 B
$B(FY02)
4
3.5
3
2.5
2
1.5
1
0.5
0
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020
2022
2024
2026
2028
2030
2032
2034
2036
2038


FIRE Based Path to DEMO
Diversified International Portfolio
32%
CTF
FIRE
= $1.2B
18%
LHD-U
W7-X
KSTAR/JT-60SC
New ICCs(e.g., CS)
FIRE
IFMIF
CTF
New Facilities Before DEMO
= $6.5 B


ITER Based Path to DEMO
Success Oriented Portfolio
18%
CTF
ITER = $6B
53%
New Facilities Before DEMO
= $11.3 B
LHD-U
W7-X
KSTAR/JT-60SC
New ICCs(e.g., CS)
ITER
IFMIF
CTF

A FIRE Based Development Path Leads to an Attractive Fusion DEMO within the Desired 35 Year Time Frame.



Concluding Remarks

- **The FIRE Based Development path leads to an attractive fusion DEMO within the desired time frame of 35 years.** This is based on a detailed analysis of schedules and costs with more conservative assumptions than the "draft illustrative" ITER based FESAC Dev Path Panel Report of Nov 20, 2002.

- In accordance with the Snowmass Consensus, and the FESAC Recommendations the FIRE Based Development Path must be included in the FESAC Development Path Interim Report. Since the decision will be made on the basis of the Interim Report of FESAC Development Path, this is particularly important.

- **Significant Issues that Deserve Immediate Attention:** It is essential that the FIRE design and R&D activities be moved forward in FY 2004 so that the US domestic burning plasma activity can be implemented expeditiously, if the ITER negotiations do not meet the US goals. This requires near term action to include a FY 2004 Budget request for a Burning Plasma Initiative to carry these Dual Path activities forward as recommended by FESAC.