The Diversified International Portfolio for Fusion Based on FIRE

Is this the

The Lowest-Cost Most-Efficient Path to Attractive Fusion Power?

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FESAC Development Path Panel

Orlando, FL

November 15, 2002

Background

- There is an extensive literature describing the Diversified International Portfolio Development Path (Modular Strategy or Multi-Machine Strategy) including:

  1. Technical Planning Activity C. Baker Editor, US ANL Report 1987
  2. P.H. Rebut *et al*, "A Program Toward a Fusion Reactor," Phys. Fluids 6 3(8), (1991).
  3. "The U.S. Program of Fusion Energy Research and Development," Presidents Committee of Advisors on Science and Technology (PCAST) J. Holdren Chair, July 1995
  4. D. Meade, "Modular Fusion Program," Journal of Fusion Energy 2000
  5. C. Baker *et al, "*Possible Pathways for Pursuing Burning Plasma Physics and Fusion Energy Development," Journal of Fusion Energy, V19, Ch 3, Number 1, 2000

  These and other related reports on Development Paths for Fusion are available at http://fire.pppl.gov, http://fire.pppl.gov/fusion_library.html

- The present FIRE Based Development Path was developed at Snowmass and the Cost Analysis and Schedule was presented at a FESAC Burning Plasma Strategy Breakout meeting at Austin on August 7, 2002, and as a poster at the 44th American Physical Society Division of Plasma Physics meeting November 14, 2002.

The FESAC Development Path Activities should be Consistent with the FESAC Burning Plasma Findings

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.

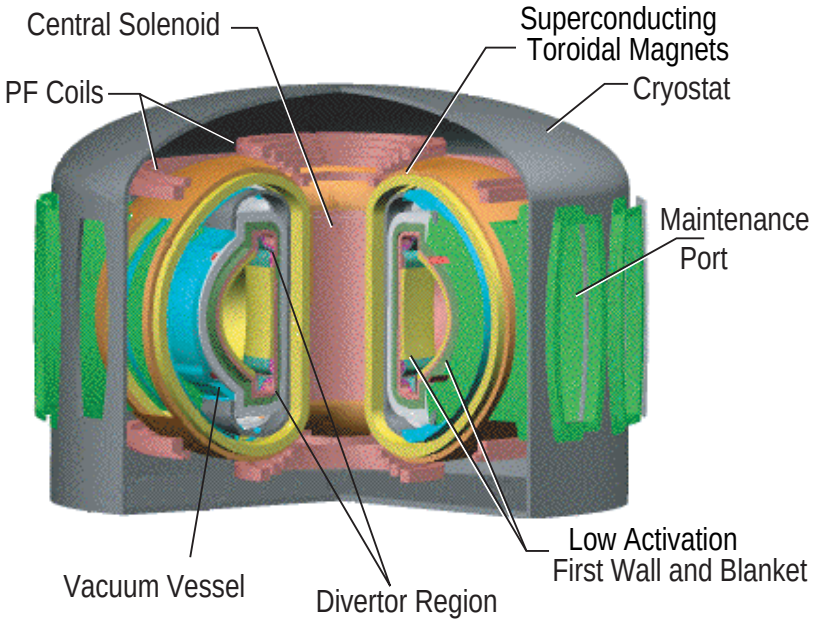
Because additional steps are needed for the approval of construction of ITER or FIRE, a strategy that allows for the possibility of either burning plasma option is appropriate.

The FIRE and ITER Based development paths have different objectives, different strategies, different costs, different schedules and different DEMOs.

The FIRE based path: emphasizes innovation before integration at reactor scale, lowers technical risk using multiple facilities with focused objectives, has lower initial costs, and a simplified management structure. This is likely to produce a better product, at lower cost on a faster time scale. The Modular Strategy for the is the natural way to develop high tech products.

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 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**
- **High Availability** > 80%

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 (includes long pulse)**
  - 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

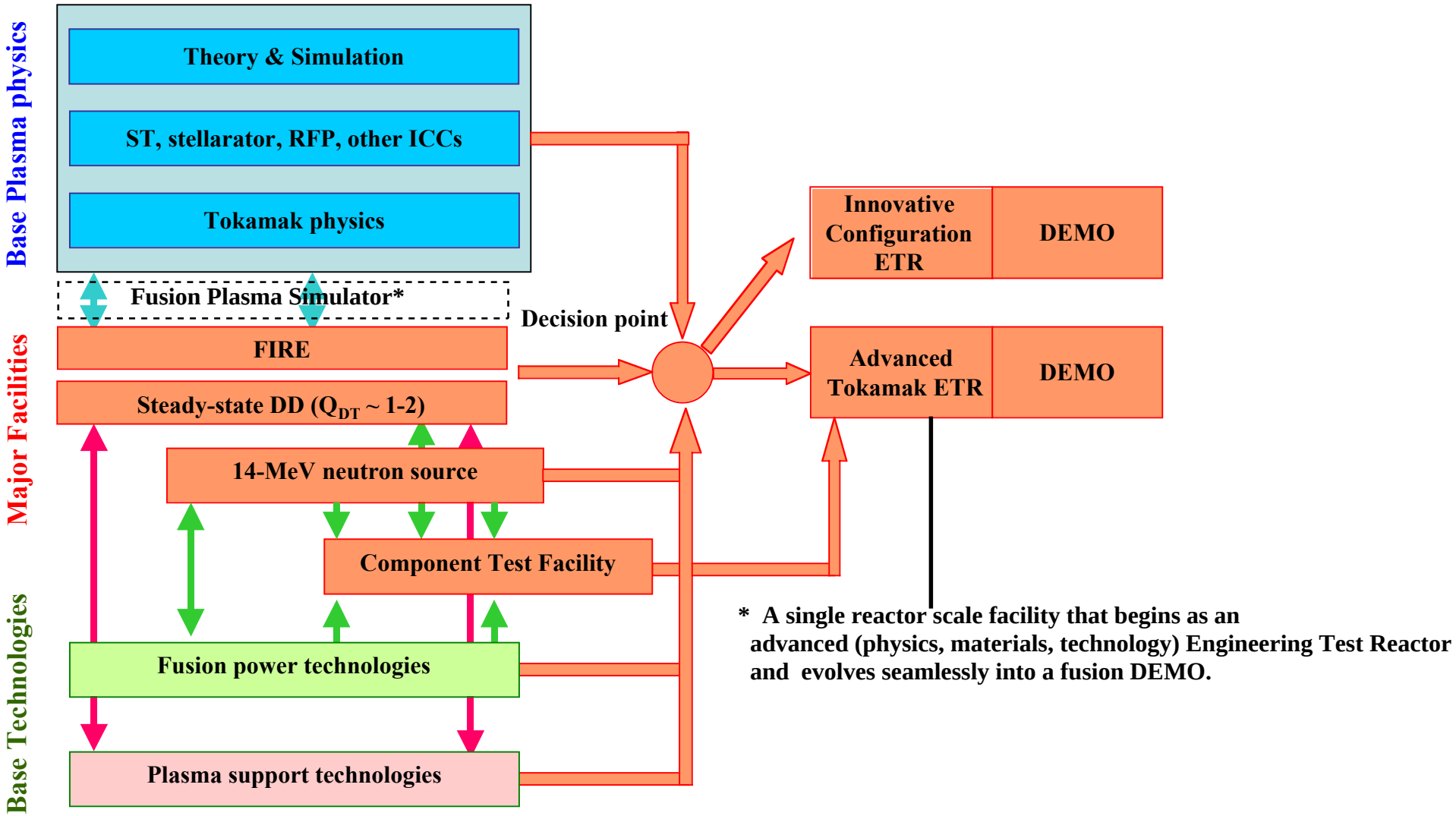
- **Burning Plasma Physics** (coupled with above)
  - strong nonlinear coupling inherent in a fusion dominated plasma
  - access, explore and understand fusion dominated plasmas

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

- **Fusion Technology Component and System Development**
  - blanket testing at high fluence
  - plasma exhaust and PFC development under reactor conditions
  - improve reliability and MTBF to levels required for DEMO

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

FIRE-Based Development Path (FESAC)



Develop and Test Advanced Physics and Technology before Reactor Scale Integration

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	
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																															
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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																													
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	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	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	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															
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	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

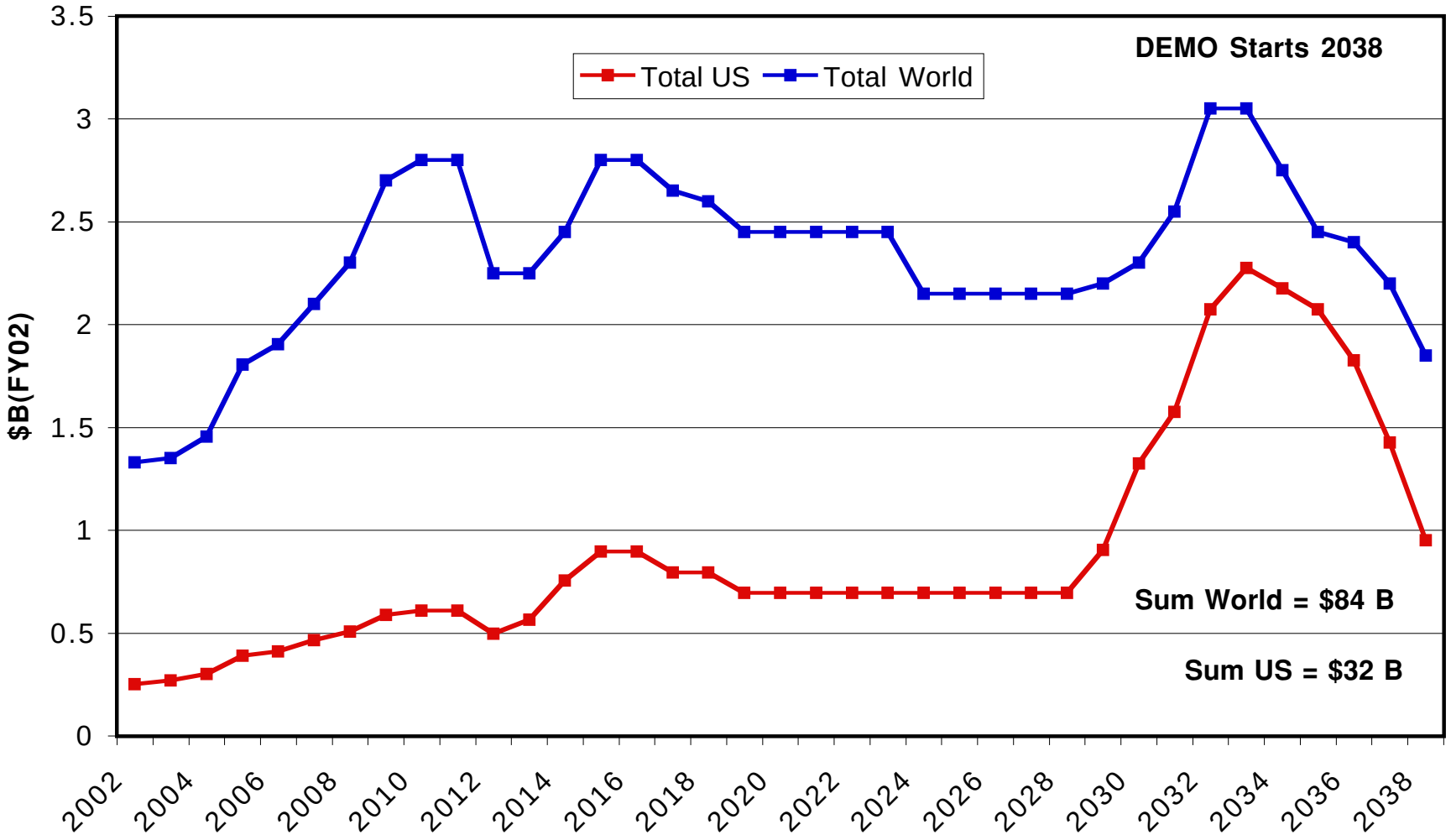
FIRE Plan

	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

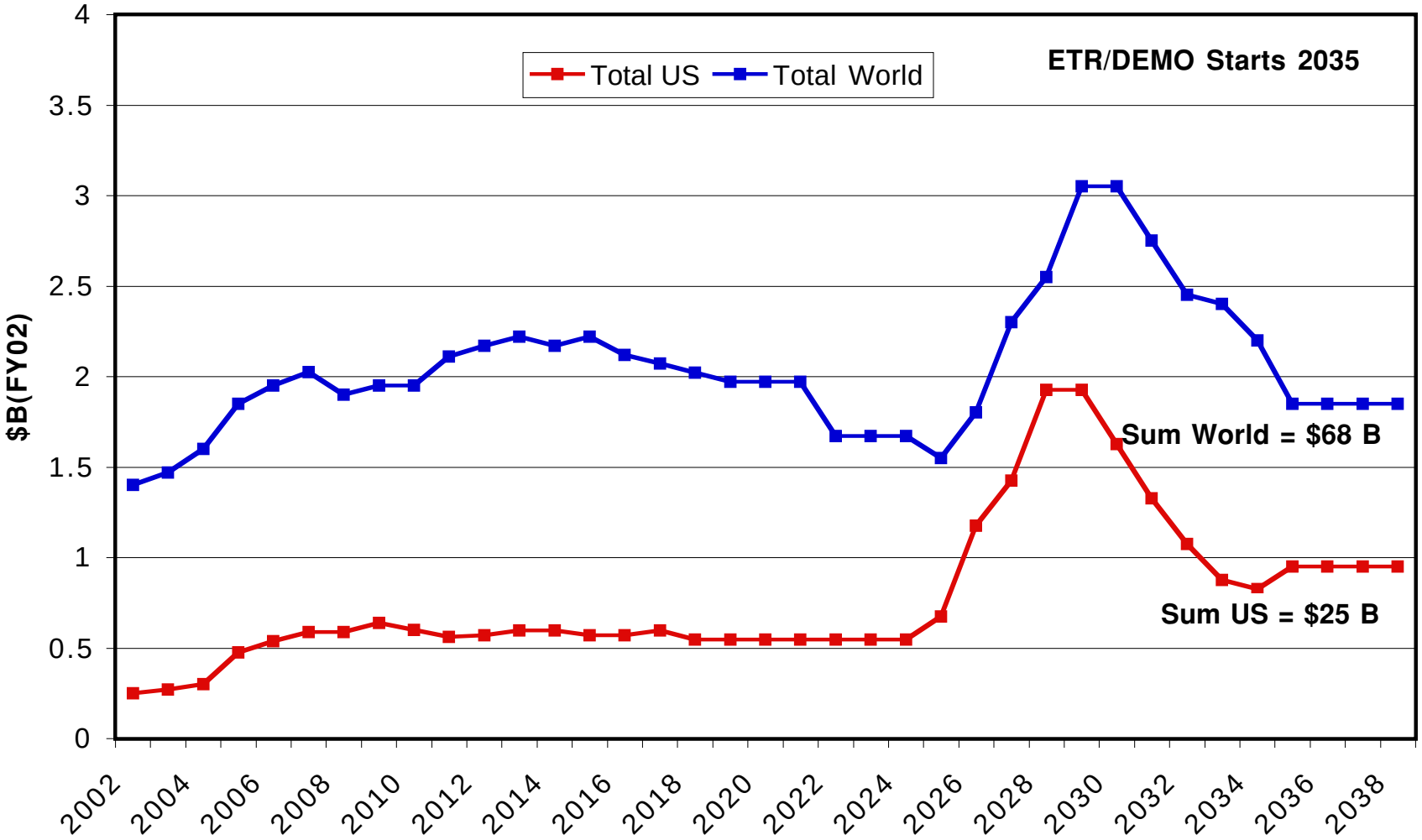
US Funding	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038
Integrate First-ITEF	0.25	0.27	0.3	0.39	0.41	0.465	0.508	0.588	0.608	0.608	0.495	0.565	0.755	0.895	0.895	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

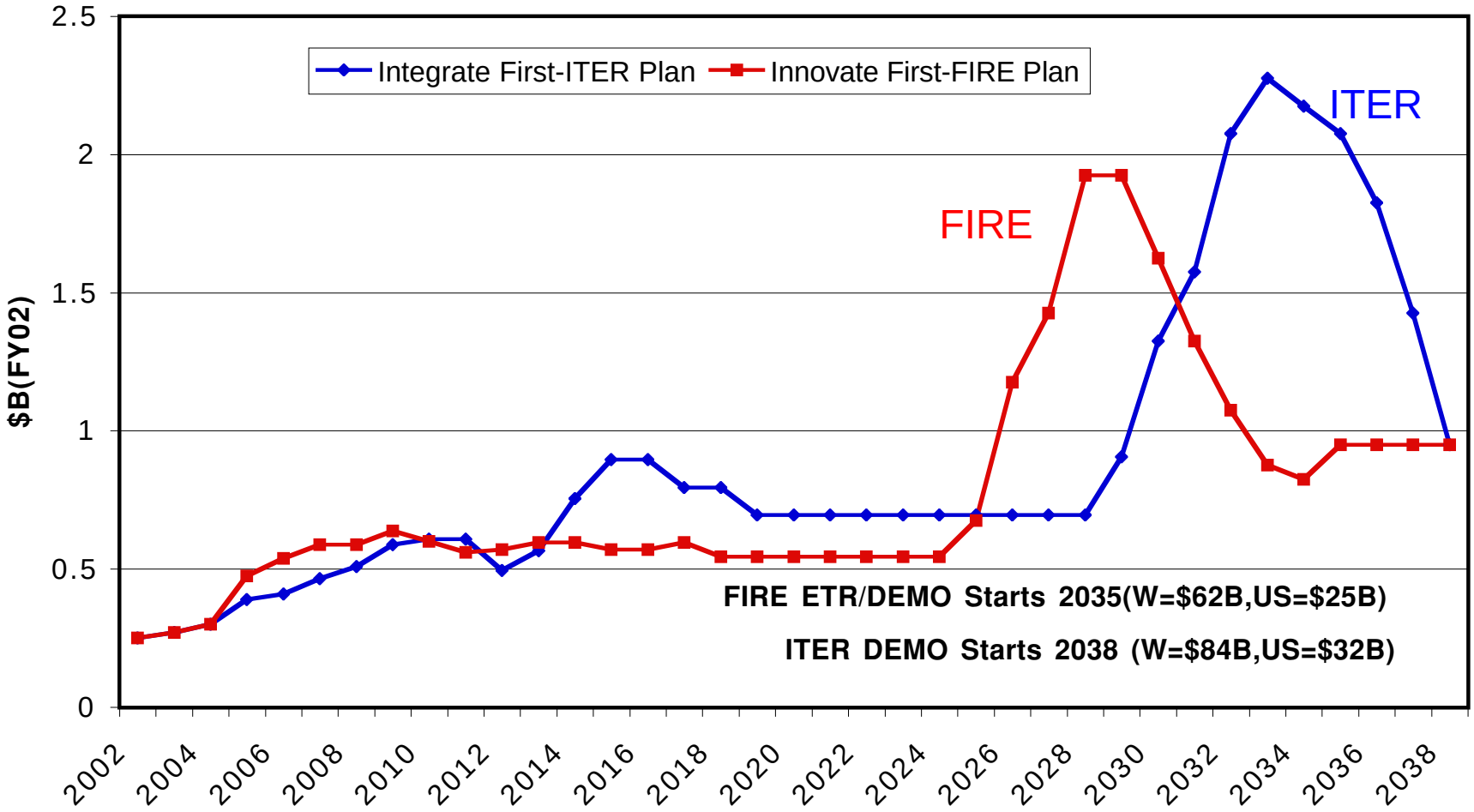
Integrate First Development Plan (ITER Based)



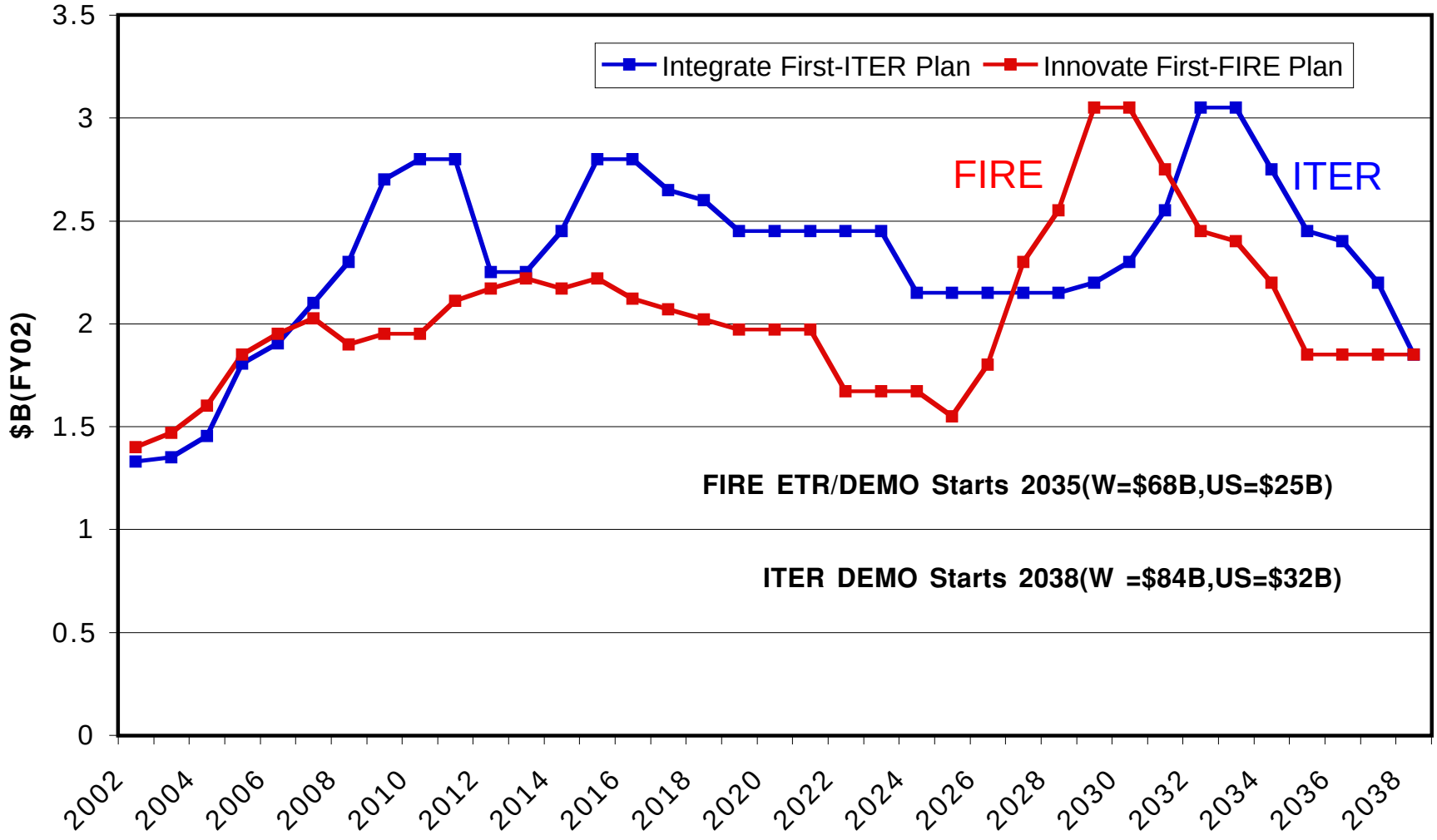
Innovate First Development Path (FIRE Based)



US Fusion Budget Requirements

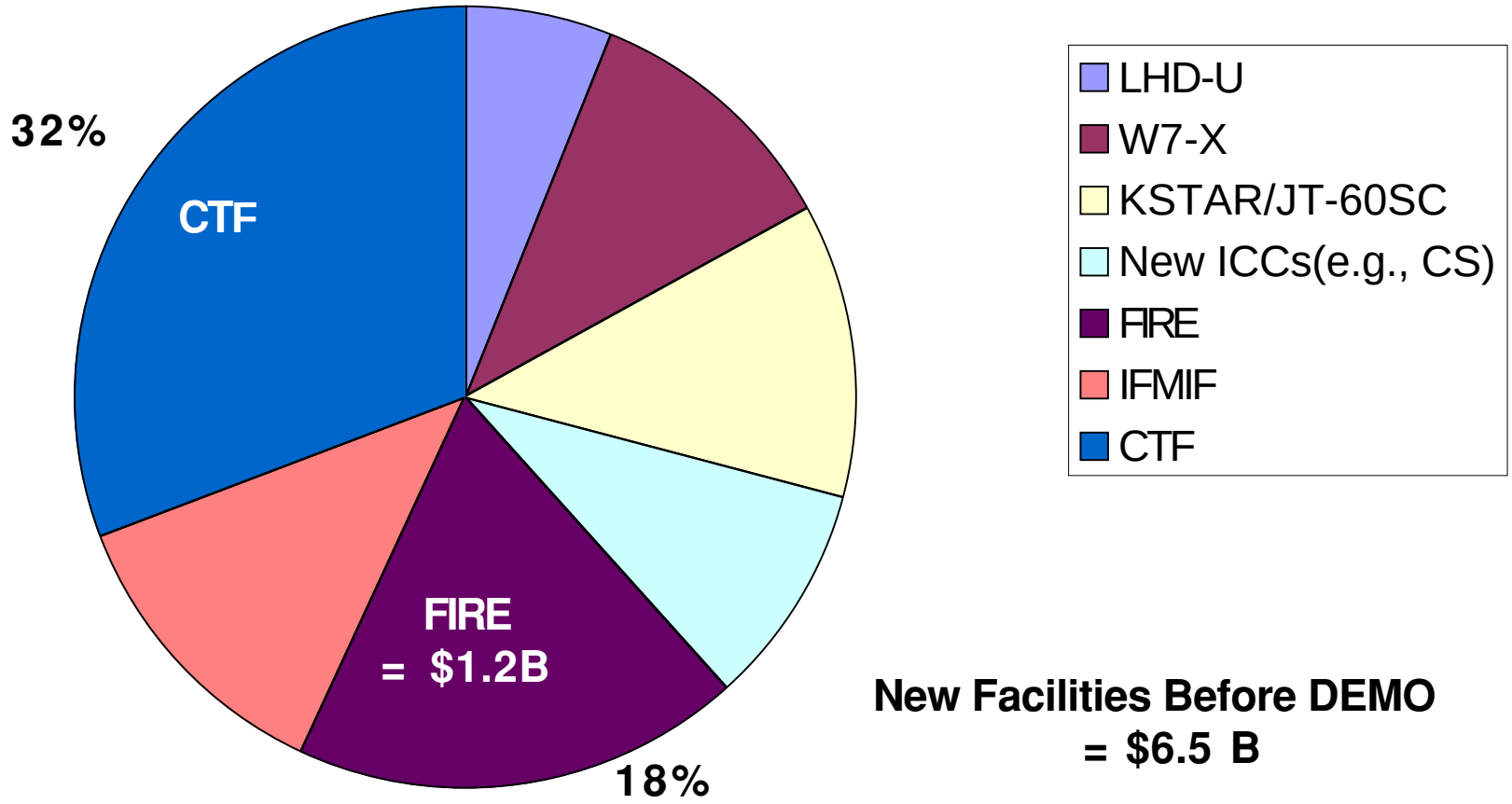


World Fusion Budget Requirements



FIRE Based Path to DEMO

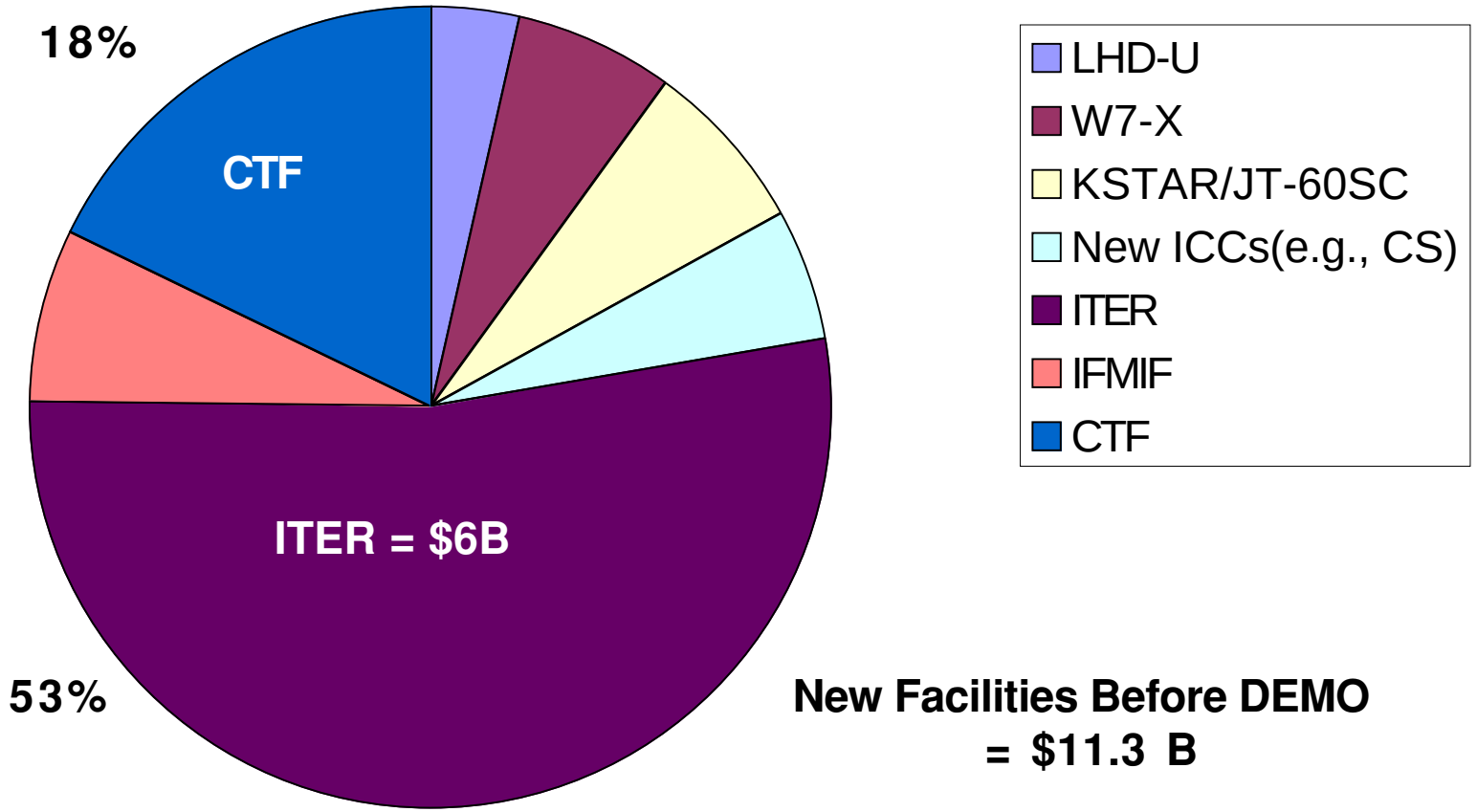
Diversified International Portfolio



New Facilities Before DEMO
= $6.5 B

ITER Based Path to DEMO

Success Oriented Portfolio

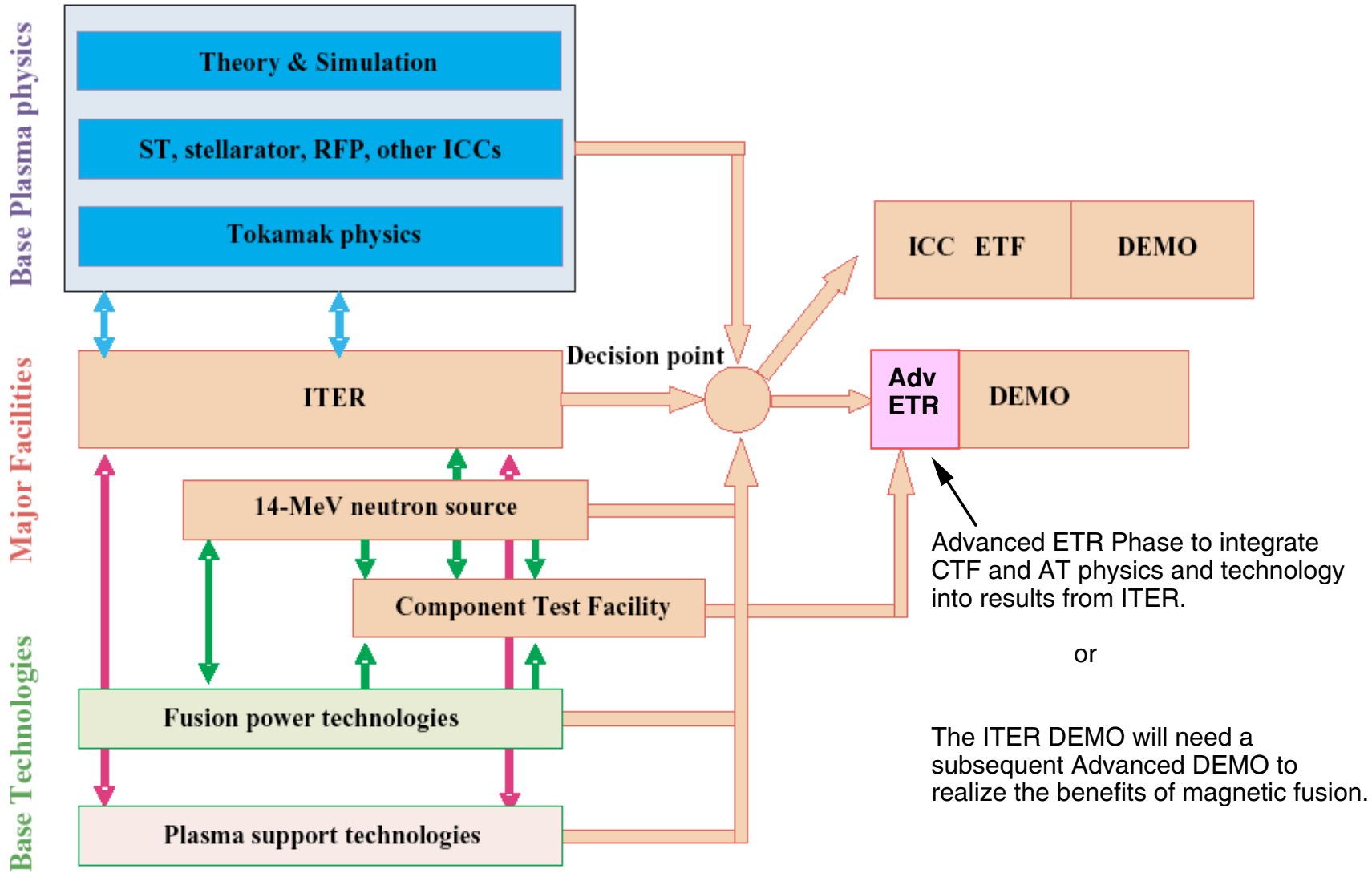


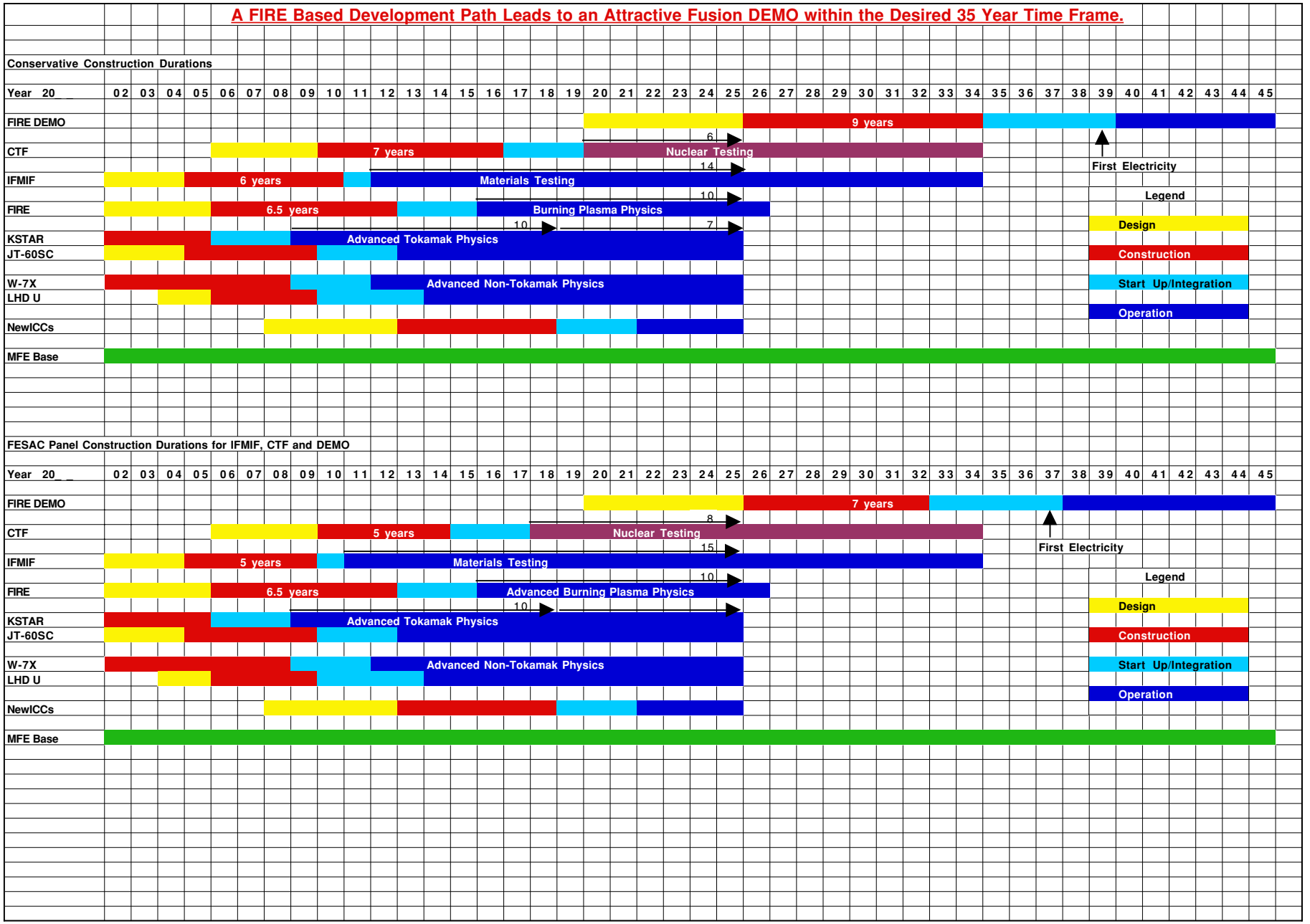
New Facilities Before DEMO = $11.3 B

The FIRE-Based and ITER-Based Development Paths Lead to Different DEMOs

- The FIRE-Based Development Path aims to provide the technical basis for an ARIES-like AT DEMO ($\beta_N \approx 4$, $f_{bs} > 80\%$, R ≈ 5.5m, Ip ≈ 12 MA) with advanced first wall materials and other advanced technologies.
  - KSTAR goals: $\beta_N \approx 4$, $f_{bs} > 80\%$ with many τ_{skin} is under construction
  - JT-60SC goals: $\beta_N \approx 4$, $f_{bs} > 80\%$ with many τ_{skin} at $Q_{dt\ equiv} \sim 1\text{-}2$, and low activation first wall is under detailed design
  - FIRE goals: $\beta_N \approx 4$, $f_{bs} > 80\%$ with ~ 5 τ_{skin} at Q ≈ 5 (2 τ_{skin} at Q ≈ 10)
  - The first phase of the FIRE-Based Advanced Tokamak Engineering Test Reactor (ETR) will integrate the AT+LP+ CTF data and evolve seamlessly into an Advanced DEMO.
- The ITER-Based Development path aims to provide the technical basis for a less advanced DEMO ($\beta_N \approx 3$, $f_{bs} \approx 50\%$) based on a modest extra-polation from ITER. This would lead to an unattractive power plant with R ≈ 9 m and 30 MA. **If the ITER DEMO is to incorporate advanced features, it must also have an Advanced Tokamak Engineering Test Reactor (ETR) phase to integrate AT + CTF data, or an additional generation of advanced DEMO at reactor scale.**

The ITER DEMO will also have an intial Advanced ETR Phase




A FIRE Based Development Path Leads to an Attractive Fusion DEMO within the Desired 35 Year Time Frame.
Conservative Construction Durations
Year 20__
02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45
FIRE DEMO
9 years
6
CTF
7 years
Nuclear Testing
First Electricity
14
IFMIF
6 years
Materials Testing
Legend
10
FIRE
6.5 years
Burning Plasma Physics
Design
10
7
KSTAR
Advanced Tokamak Physics
JT-60SC
Construction
W-7X
Advanced Non-Tokamak Physics
Start Up/Integration
LHD U
Operation
NewICCs
MFE Base
FESAC Panel Construction Durations for IFMIF, CTF and DEMO
Year 20__
02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45
FIRE DEMO
7 years
8
CTF
5 years
Nuclear Testing
First Electricity
15
IFMIF
5 years
Materials Testing
Legend
10
FIRE
6.5 years
Advanced Burning Plasma Physics
Design
10
KSTAR
Advanced Tokamak Physics
JT-60SC
Construction
W-7X
Advanced Non-Tokamak Physics
Start Up/Integration
LHD U
Operation
NewICCs
MFE Base

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 Development Path Panel Plan Nov 11, 2002.
- The FIRE Based Development Plan, described here, has significant advantages and leads to a more advanced fusion DEMO at an earlier time with lower cumulative cost than the ITER Based Development Path. The first fusion DEMO must demonstrate the attractive characteristics of fusion, or it will be a counter demonstration.
- 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 Dev Paths, the whole story needs to be told. (Marburger to SLAC, October 2, 2002)
- The FIRE and ITER Development Paths have different costs, schedules and DEMOs. Don't put FIRE on the ITER Path as "(FIRE)" then deride it as not steady state. Similarly don't put ITER on the FIRE Path and deride it as not advanced. They have different development paths.