“Multi-machine” Strategy: The Other Path of the FESAC Burning Plasma Strategy

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We Have Two Viable Paths for Developing the Science & Technical Basis for Fusion Energy

- Snowmass: both ITER and FIRE are technically credible choices to study BP physics AND give BP information leading to fusion energy DEMO.
- Moving forward with BP is **essential** so FESAC proposed a dual-track strategy: try ITER first, if no-go by July 2004, proceed with FIRE.
- Goal of my remarks: describe this ‘other’ path and to clarify development path differences between the two options.

My Perspective on the Burning Plasma Step…

- 91 ITER CDA Review Panel
- 95-97 Chair of TFTR PAC
- 97 Member of FESAC/Grunder Panel on ITER involvement.
- 98 Chair of Madison Forum on Major Next-Step Experiments
- 98-99 US Representative of ITER SWG-2 Panel and Member of ITER TAC in 99
- 00 Chair of 1st UFA Burning Plasma Workshop
- 01-02 Co-chaired the Snowmass Fusion Summer Study

A Sound Strategy Requires Several Major Facilities Leading to DEMO

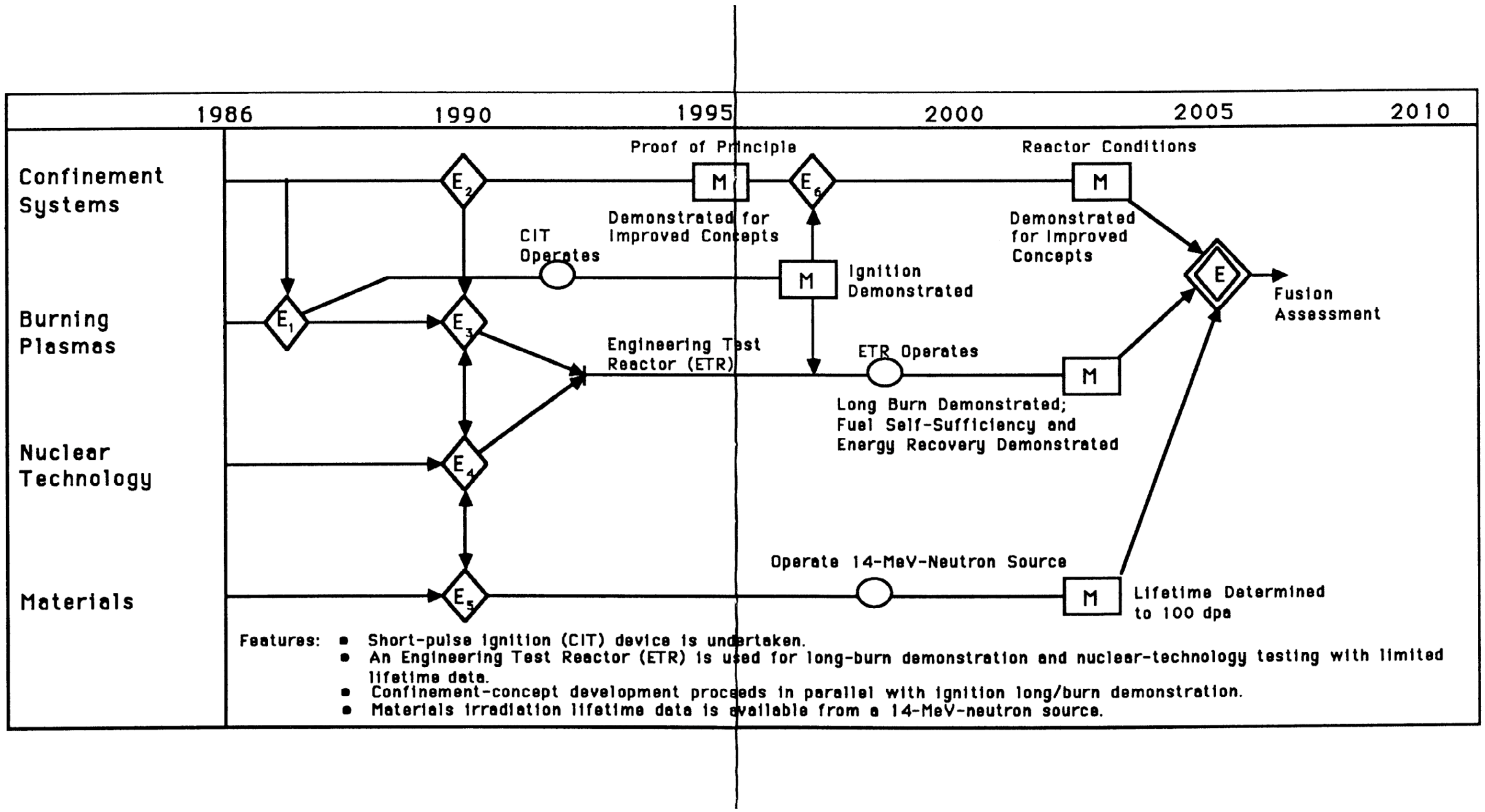
- …must bridge the gap from present knowledge to that required to construct a DEMO.
- Attempting to cover them all in a single device will limit the domain of investigation and lead to unacceptable risk of failure...
- A single Next Step facility (ITER) is a high risk strategy in terms of physics, technology, and management, since it does not provide a sufficiently sound foundation for DEMO.

--P.-H. Rebut, Phys. Fluids B 3, 2209 (1991).

What do we need for DEMO?

- Produce and understand behavior of “self-heated” fusion plasma [Q ~ 10] and demonstrate efficient current drive extrapolating to steady-state.
- Demonstrate steady-state heat removal and particle control at power plant energy density.
- Validate acceptable materials behavior at ~100 dpa damage levels.
- Successfully test meter size scale tritium breeding and heat exchange blanket modules for acceptable lifetime & performance under power plant conditions [5 to 10 MW-yr/m^2].

1987 TPA Burning Plasma Logic

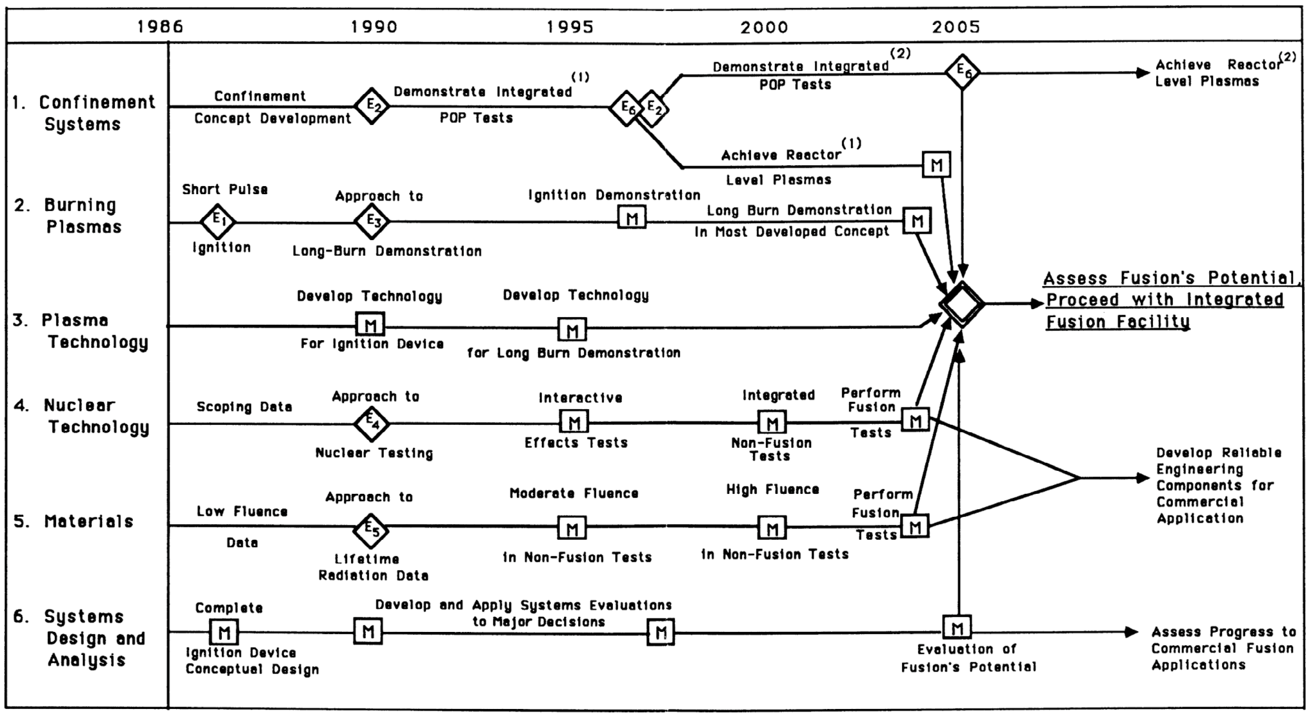


- Employed a Copper BPX, then ETR, followed by DEMO.
- Innovative Concepts provided input for DEMO choice.

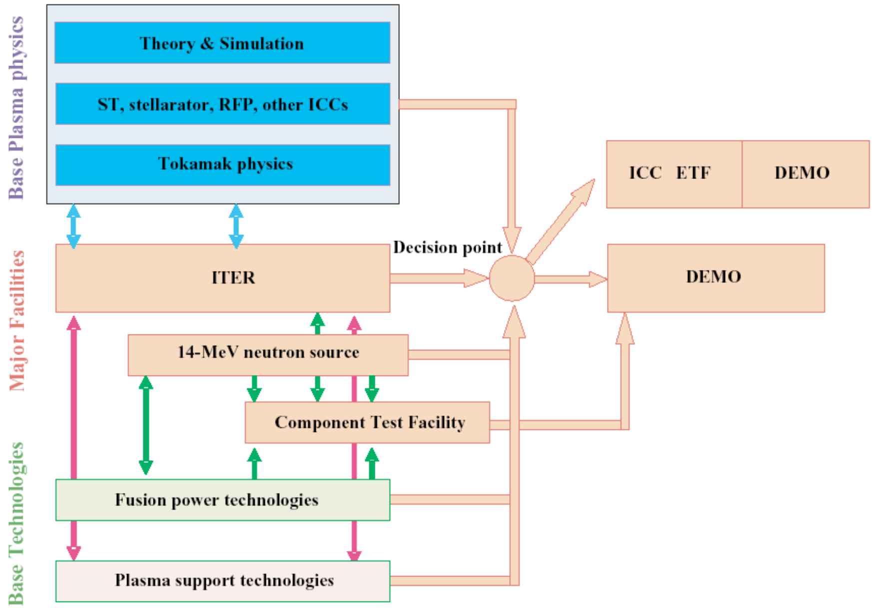
1987 TPA Overall Program Logic

(1) From class of present "moderately-developed" concepts

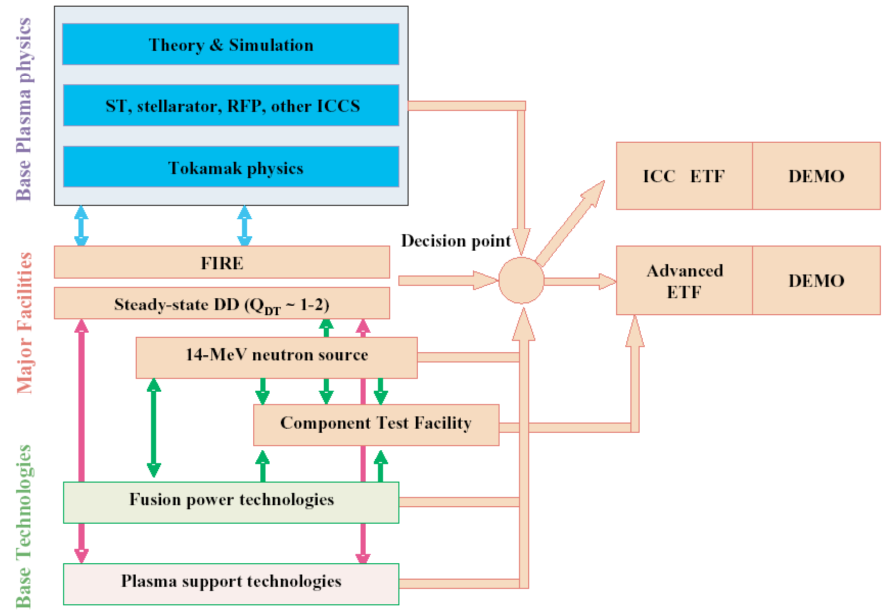
(2) From class of present 'developing' concepts



FESAC/Snowmass Plans Similar Structure, BUT With a Significant Strategic Difference



ITER Development Path
'Single Machine Strategy'
'One Step to DEMO'
'Penultimate Step to DEMO'



FIRE Development Path
'Multi-machine Strategy'
Modular Strategy

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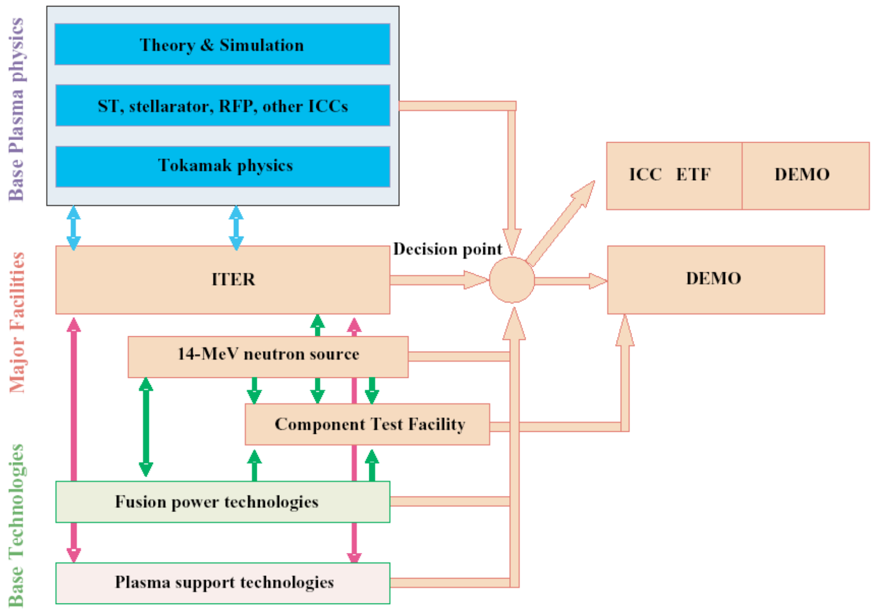


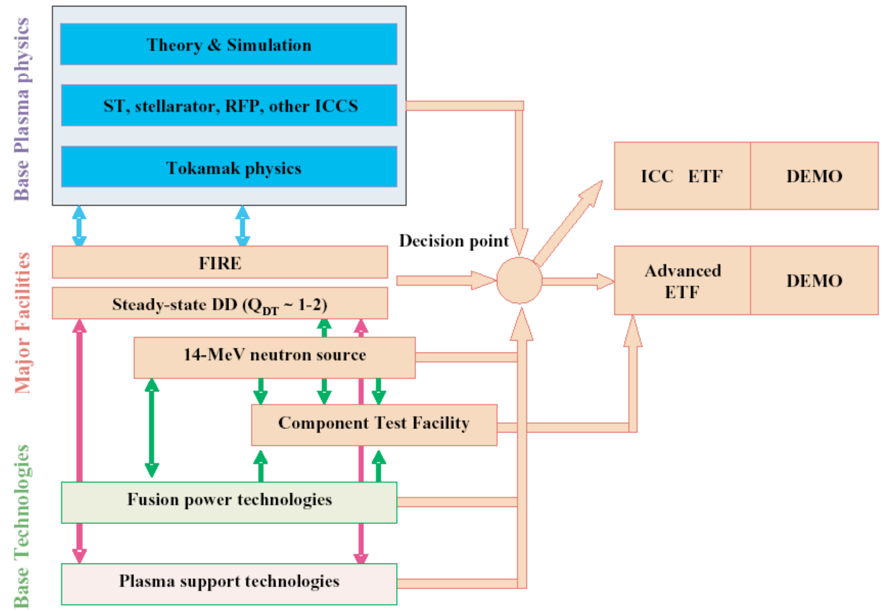
ITER Development Path

‘~~Single Machine Strategy~~’

‘~~One Step to DEMO~~’

‘~~Penultimate Step to DEMO~~’

Integration Now



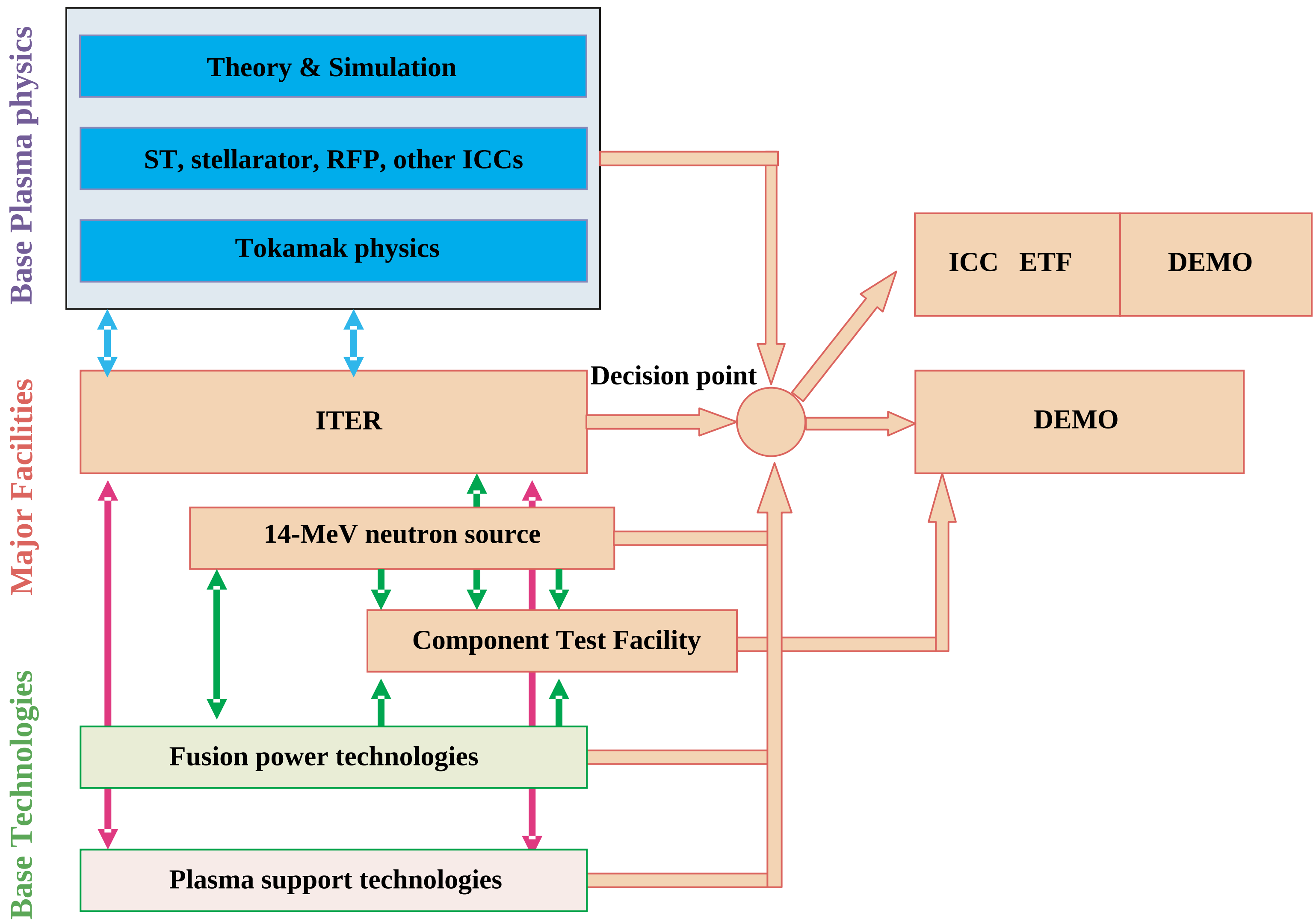
FIRE Development Path

‘~~Multi-machine Strategy~~’

~~Modular Strategy~~

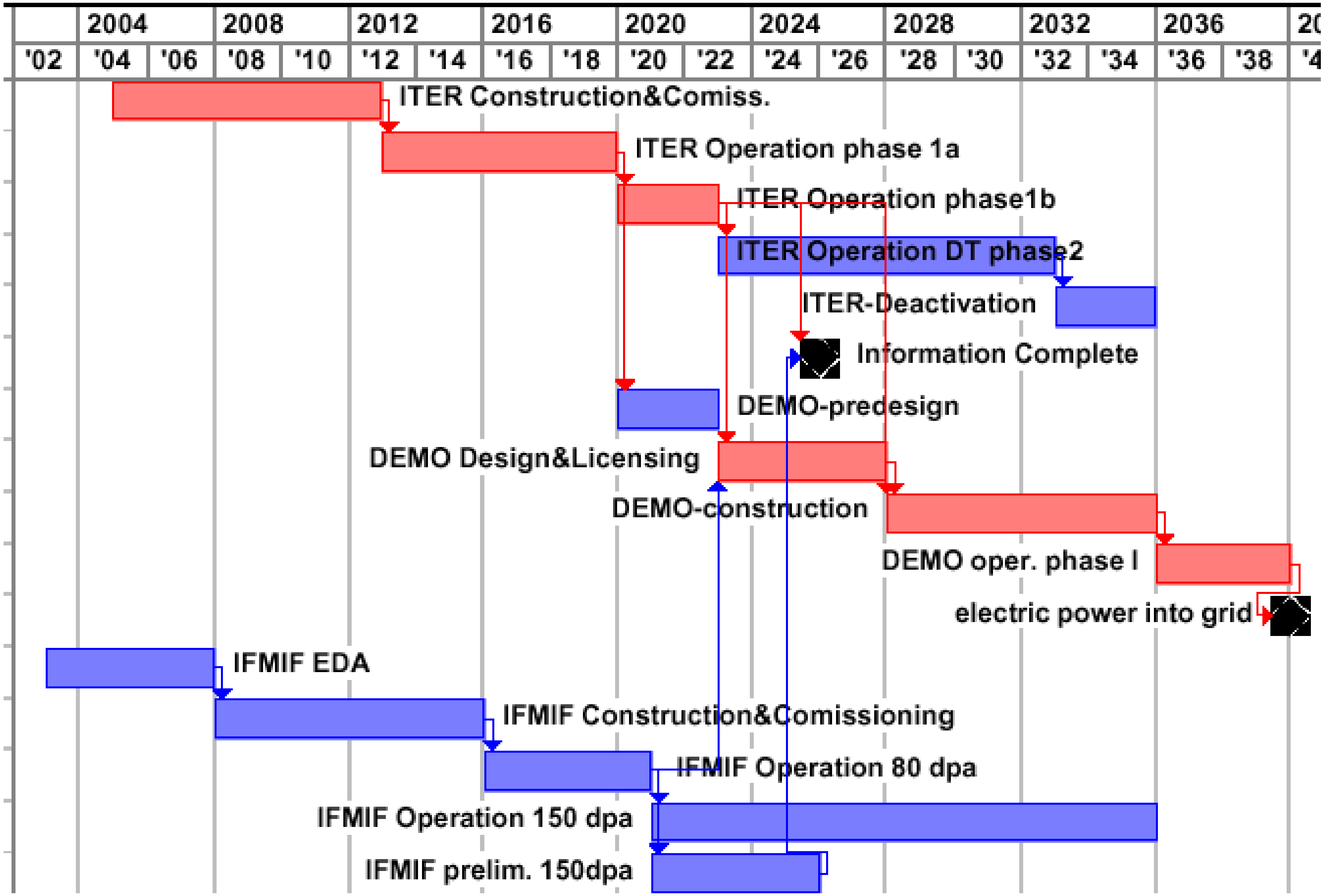
Deferred Integration

FESAC/Snowmass Report: ITER-Based Development Path

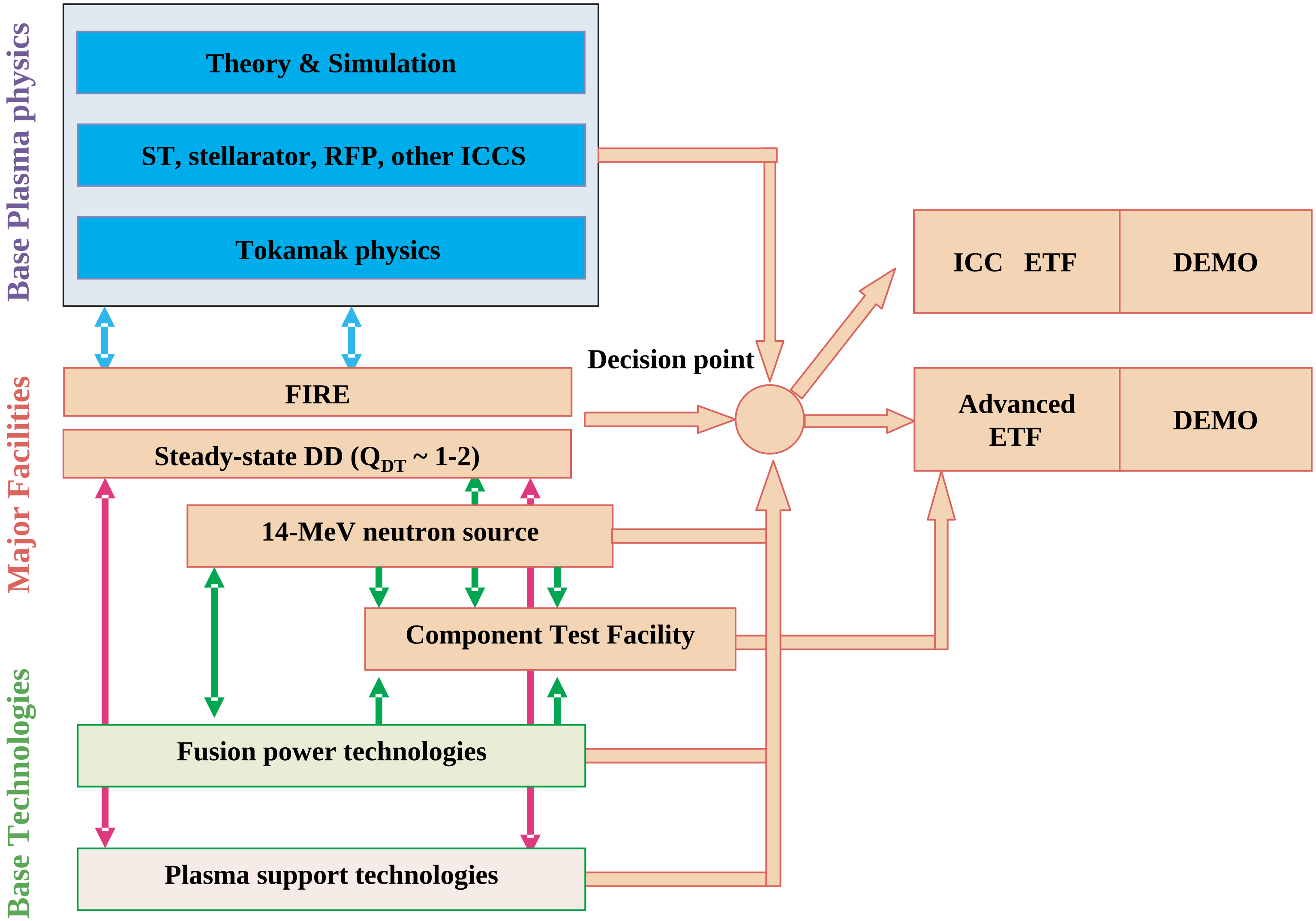


EU Variation on Early Integration Replaces CTF with 8 yrs Blanket Development on DEMO Phase I

Roadmap to Fusion Power



FESAC/Snowmass Report: FIRE-Based Development Path

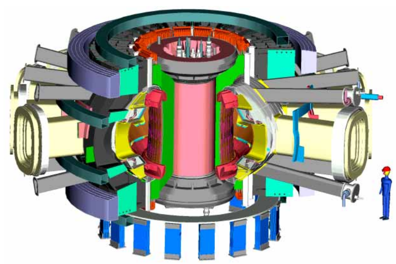


Does FIRE establish scientific feasibility of fusion energy?

- YES! With the information from the other elements of the strategy.
- The FIRE burning plasma duration covers many energy & alpha slowing down times and up to 5 current relaxation times.
- The parallel steady-state DD facilities [K-STAR, JT-60SC, …] provide steady-state data on heat & particle removal.

U. S. Dual Path Strategy for Magnetic Fusion

Primary Burning Plasma Experiments (same scale)



FIRE (1,400 tonnes)

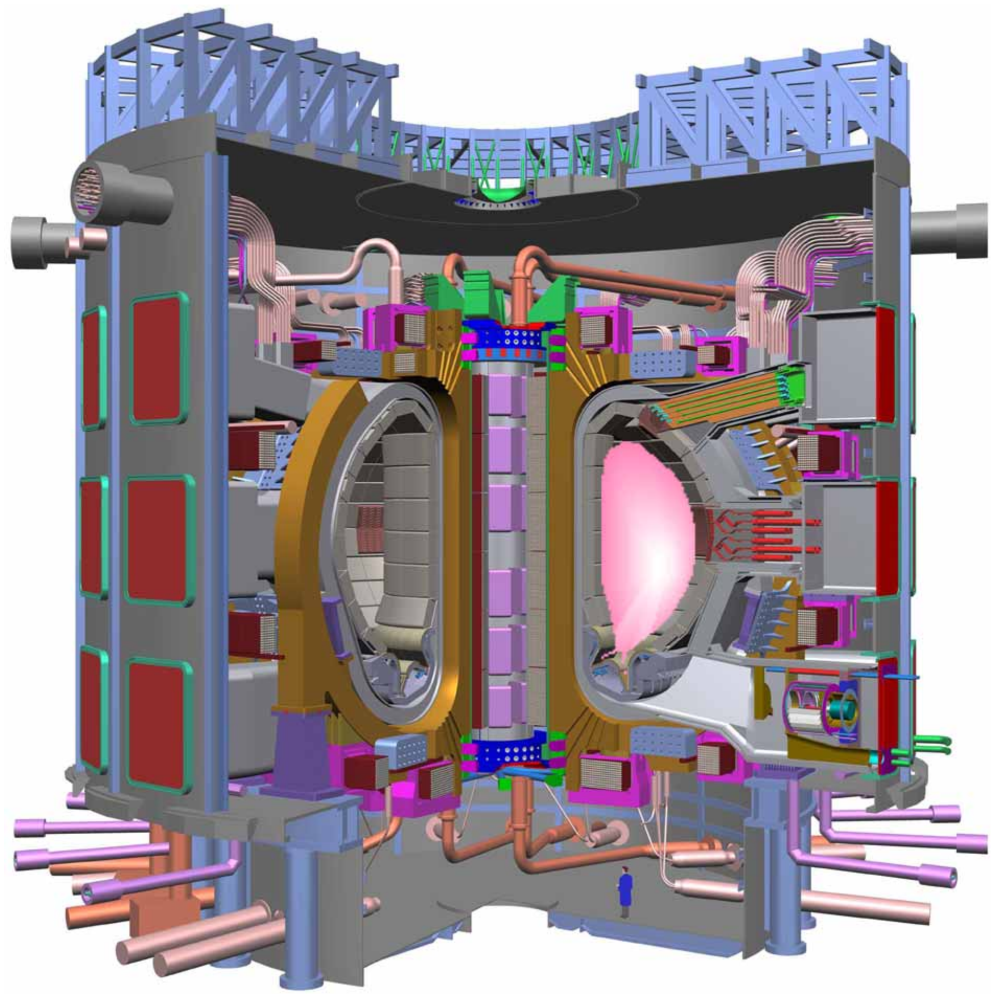
Conventional Operation

Q ~ 10 @ 86% J(r) equilibration
(FIRE and ITER)

Advanced Operation

Q ~ 5, f_{bs} ~ 80%, β_N ~ 4 @ 98% equil.
(FIRE)

Q ~ 5, f_{bs} ~ 50%, β_N ~ 3 @ 99.9% equil.
(ITER)



ITER (19,000 tonnes)

FIRE Aims to Test Advanced Physics for ARIES-RS

	ITER-FEAT	FIRE	ARIES-RS
κ_x plasma elongation	1.85	2.0	2.0
δ_x plasma triangularity	0.49	0.7	0.7
Divertor Configuration	SN	DN	DN
β_N, normalized beta, AT	~3	~4	4.8
Bootstrap fraction, AT	50	80	88
P_{loss}/R_x	20	20	100
Target material	C(W?)	W	W
R (m)	6.2	2.14	5.5
Plasma Volume, m^2	840	27	350
B (T)	5.3	10	8
Fusion Core Mass, tonne	19,000	1,400	13,000
P_{fusion}(MW)	400	150	2170
P_{fusion}/Vol (MW/m^3)	0.5	5.6	6.2
$Q = P_{fus}/P_{ext}$ Conventional	10	10	n.a.
$Q = P_{fus}/P_{ext}$ Advanced Tok	5	5	27
Burn Time			
seconds	400 - 3,000	20 - 40	months
Current Profile Equilb,%	86 – 99.99	86 - 98	100

ITER & FIRE are both ‘Phase Changes’ - Neither is ‘Incremental’

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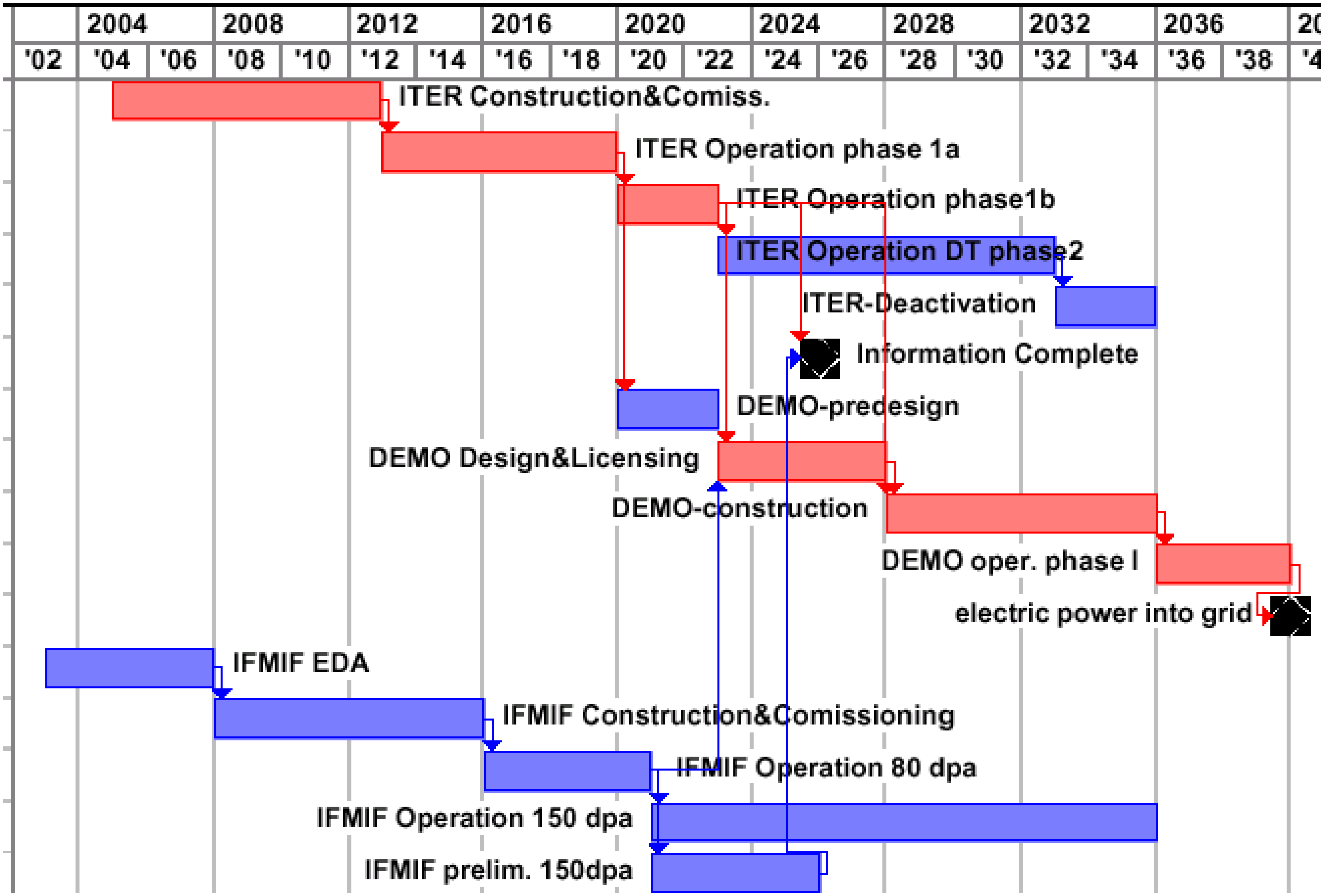
"If ITER & FIRE are so similar, why are the EU and JA so…?"

- There has always been a difference between US and EU/JA visions of an acceptable fusion power plant:
  - ✓ State owned utilities with high energy tax structure in EU/JA make multi-GW plants with relatively higher costs acceptable: simple ITER extrapolation.
  - ✓ Private utilities and independent power producers in US are looking for small unit size (< 1 GW) and competitive power costs in low energy tax environment of the US: requires significant innovation beyond ITER physics basis.
- The US has always placed a high emphasis on concept innovation to lead to **attractive** fusion energy sources.
- Deferred Integration path uses concept innovation more effectively, hence is better accepted in the US.
- US prefers shorter time scale steps-greater flexibility.

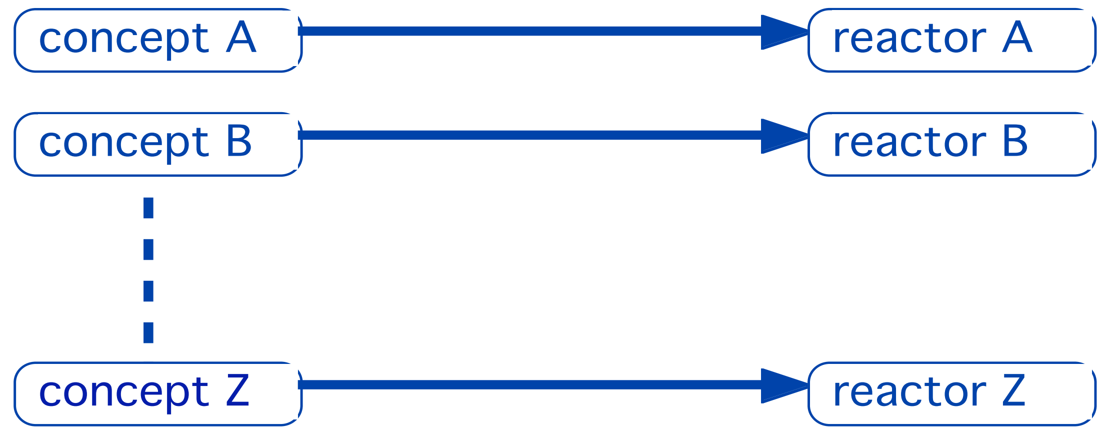
EU Variation on Early Integration Replaces CTF with 8 yrs Blanket Development on DEMO Phase I

Roadmap to Fusion Power

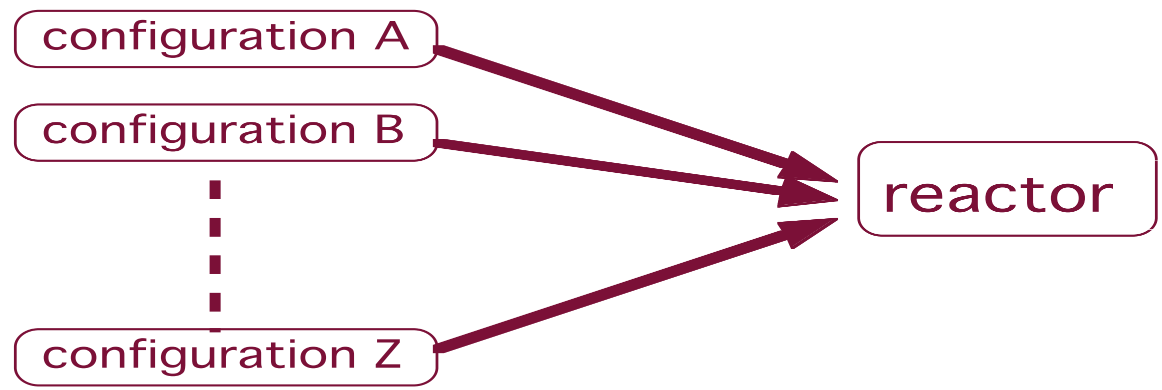


Two Paradigms for Concept Development

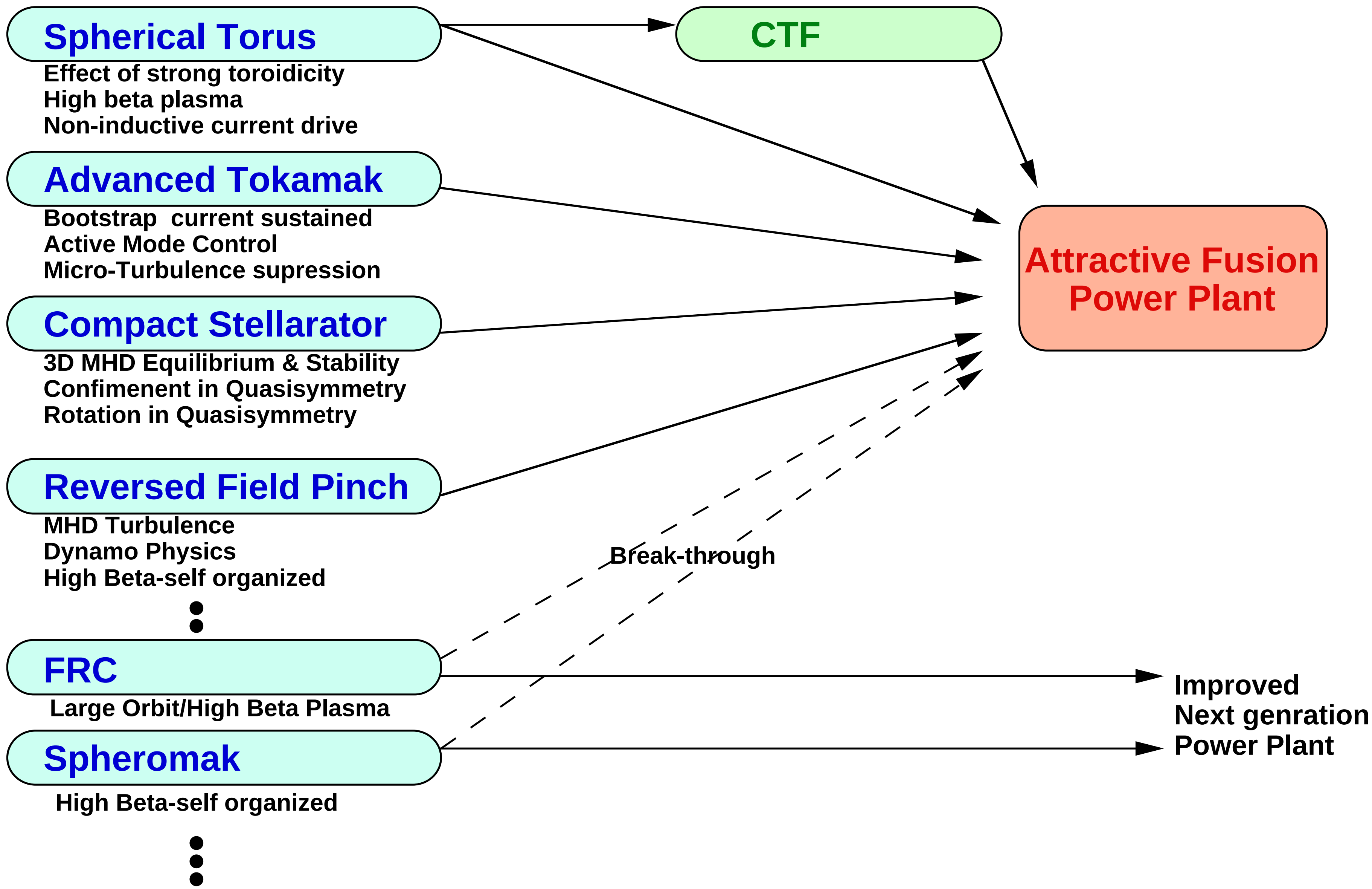
Each concept as a fusion reactor



each configuration building fusion science



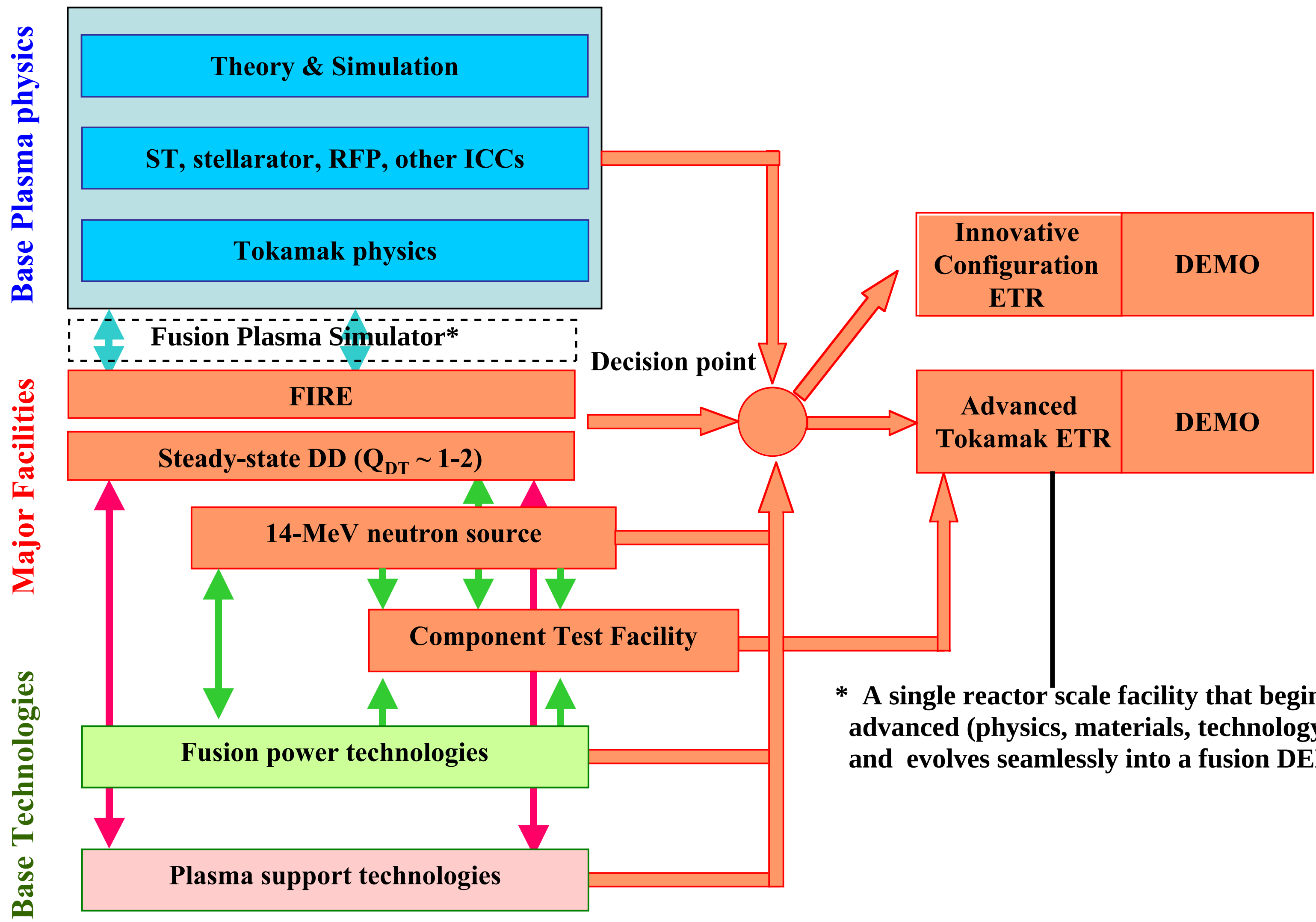
Attractive Fusion Power Requires Spectrum of Configurations to Drive the Intellectual Breadth Necessary for Success



Deferred Integration [Modular Strategy] is Advantageous Technically and Financially

- Deferred Integration (pursuing FIRE for BP physics) is more appropriate for present pace of toroidal plasma development - target date 2020-2025 integration step:
  - Progress in toroidal physics from PoP & PE devices [NSTX, NSST, NCSX, MST+, K-STAR, JT-60SC, LHD, W7-X…] can all be used for design of optimal BP+Technology integrated test facility: ETF
  - BP Step (FIRE) is only a 20 year device, not 40 year as for ITER: more appropriate level of 'opportunity cost'.
- Follows paradigm used successfully by IFE Program: make progress in minimum sized parallel steps; only integrate when needed to take the next step. Premature integration drives up cost, slows schedule, & interferes with innovation.

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

Deferred Integration [Modular Strategy] is Advantageous Technically and Financially

- Deferred Integration approach makes full use of the CTF facility, and can incorporate developed tritium and heat removal blanket technology into a staged ETF-DEMO facility.
  - o ITER technology mission drive up size and cost for relatively small gain: IFMIF and CTF provide all nuclear & material info; W7-X, LHD, K-STAR, JT-60SC will provide basis for superconducting magnet design in ETF-DEMO facility.
- Integration Step is closer to the Commercial Plant Stage: optimal configuration for 1st generation fusion power plant emerges naturally from ETF-DEMO.

Deferred Integration [Modular Strategy] is Advantageous Technically and Financially

- Total Cost and Cash Flow are significantly reduced over next 15 to 20 years for BP element making it easier to support rapid and timely development of the essential other elements: Concept Innovation, CTF, and IFMIF.
- Deferred integration path is technically more robust against failure of AT to establish a BP compatible steady-state configuration: ICC advances will naturally be folded into choice of optimal configuration ETF-DEMO facility.
- Deferred Integration path is an opportunity for US to resume leadership of world fusion program and help to reconfigure it along an effective path, if ITER fails to proceed.

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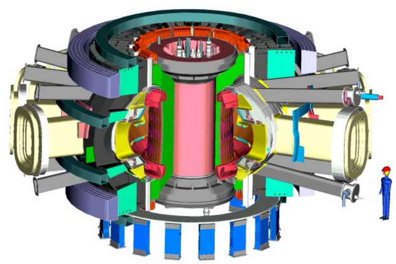

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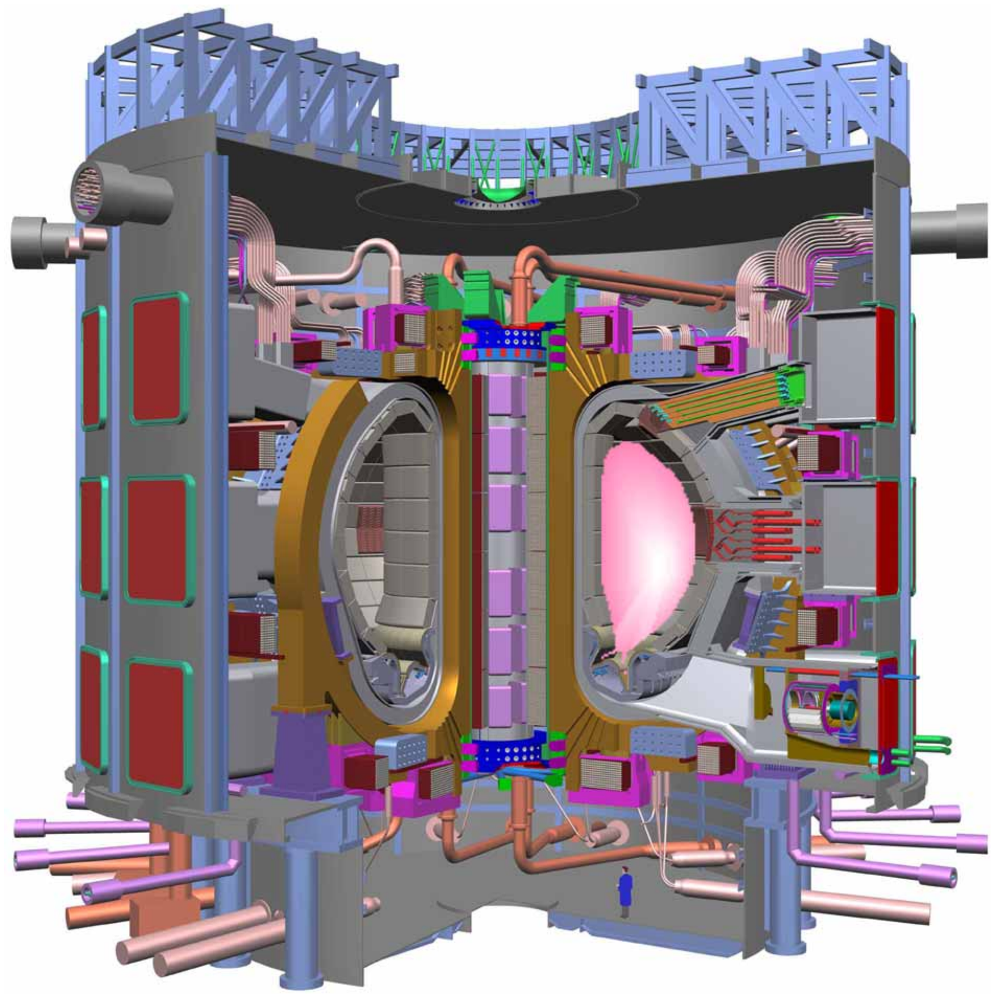

ITER (19,000 tonnes)

Both Early & Deferred Integration Are Viable Fusion Development Plans