U.S. Fusion Road Map Study

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Magnetic Fusion Program Leaders Road Map Study Group

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http://fire.pppl.gov

Magnetic Fusion Program Leaders (MFPL) Road Map Study

Goal: Develop and assess three aggressive technically feasible paths for the US Fusion Program motivate a commitment to DEMO on the timescale of ITER Q ≈ 10 experiments (nominally 2028) with DEMO by mid-century.

1) ITER directly to a Tokamak DEMO (possibly staged)

2) ITER plus Fusion Nuclear Science Facility leading to a Tokamak DEMO

3) ITER plus additional facilities leading to a QS - Stellarator DEMO

Each of these paths will include major aspects of a broad supporting research program.

Working Group Members:
Meade (Chair), Garofalo, Hill, Kessel, Lipschultz/Whyte, Morley, Navratil, Neilson, Rasmussen, Zinkle

We have made one pass through the Road Map, this work is in Progress.

Status reports given at: APS/DPP-2013, FPA-2013, 2nd IAEA DEMO Workshop, MIT-2014, Fusion Energy System Study - 2014, Columbia Univ - 2014

General Considerations

- Road Map driven by Goal and Associated Missions
  - Goal is a Fusion Power Plant (FPP)
  - Use recent ARIES Study to define general characteristics of DEMO/FPP
  - Mission structure is similar to EU Fusion Road Map and 2007 FESAC Report

- Strive for quantitative milestones and metrics as mileage markers
  - Quantitative dimensional and dimensionless Figures of Merit (FESAC 2007).
  - Technical Readiness Levels
    - EU Road Map used TRLs for materials and technology
    - NAS IFE Assessment 2013 used TRLs in IFE Road Map (p.162)

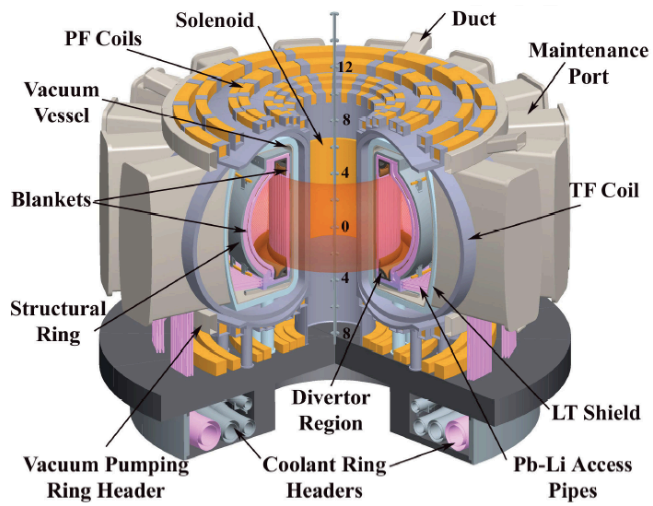
- Setup logic Framework for Mission milestones and Decision points

- Identify facilities needed to achieve mission milestones

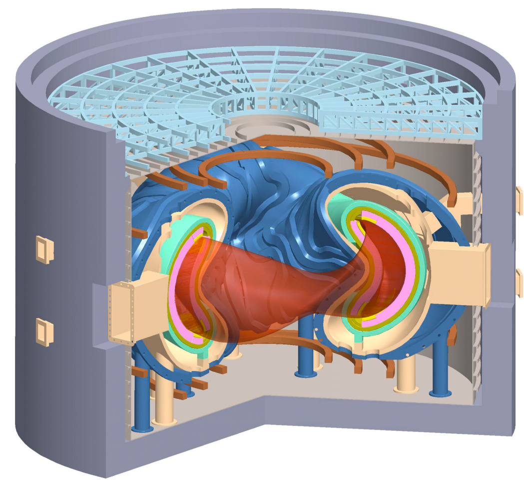
- Detailed cost estimates are beyond scope our exercise, however must
  - <u>identify compelling near term deliverables to bootstrap funding of later steps</u>

ARIES Studies Identified General Characteristics of Magnetic Fusion Power Plants

Advanced Tokamak



Compact Stellarator



	ARIES-ACT1	ARIES-ACT2	ARIES-CS
R(m)	6.25	9.75	7.75
B(T) / $B_{max\text{-}coil}$ (T)	6.0/10.6	8.75/14.4	5.7/15.1
β_N / β_{tot} (%)	5.6/6.5	2.6/1.7	-/6.4
P_{Fusion} (MW)	1813	2637	2440
f_{bs} (%)	91	77	~25
$\langle\Gamma_n\rangle$ MWm^{-2}	2.5	1.5	2.6

All steady-state at 1,000 MW_E

ARIES Reference

Major Mission Elements on the Path to an MFE Power Plant

Mission 1. Create Fusion Power Source

Mission 2. Tame the Plasma Wall Interface

Mission 3. Harness the Power of Fusion

Mission 4. Develop Materials for Fusion Energy

Mission 5. Establish the Economic Attractiveness, and Environmental Benefits of Fusion Energy

- Restatement of Greenwald Panel and ReNeW themes
- Each Mission has ~ five sub-missions

TRLs Express Increasing Levels of Integration and Relevance to Final Goal and can Identify R&D Gaps.

TRL	Generic Description *(defense acquisitions definitions)*
1	Basic principles observed and formulated.
2	Technology concepts and/or applications formulated.
3	Analytical and experimental demonstration of critical function and/or proof of concept.
4	Component and/or bench-scale validation in a laboratory environment.
5	Component and/or breadboard validation in a relevant environment.
6	System/subsystem model or prototype demonstration in relevant environment.
7	System prototype demonstration in an operational environment.
8	Actual system completed and qualified through test and demonstration.
9	Actual system proven through successful mission operations.

Normally TRLs are applied to technology projects, here we are attempting to apply the concept to R&D activities – NAS IFE Report 2013 page 162, Table 4.3

Add CE, POP, POPerf, BP, DEMO

ITER + FNSF => Advanced Tokamak Demo Pathway

Mission 1: Create Fusion Power Source

Technical Readiness Level	1	2	3	4	5	6	7	8	9
Attain Burning Plasma Performance				Now	ITER		DEMO		Power Plant
Ba5/4, $n\tau_E T_i$, Q_{DT}									
Control High Performance Burning Plasma			Now	Support Fac.	ITER		DEMO		Power Plant
β_N, nT, disruptivity, $\tau_{controlled}$, $P_{\alpha\text{-loss}}/P_{heat}$					FNSF				
Sustain Magnetic Configuration	AT			Now	Support Facilities (JT-60SA/		ITER	DEMO	Power Plant
f_{CD}, P_{CD}/P_{heat}, … $\tau_{sustained}/\tau_{CR}$, etc	ST		Now	Support Facilities		◆	FNSF ◆		
					Choose AT or ST for FNSF		OK for Steady State?		
Sustain Fusion Fuel Mix and Stable Burn				Now		ITER		DEMO	Power Plant
$n_D(0)n_T(0)/n_e(0)^2$, Pop.Con stable, τ long						FNSF			
Attain High Performance Burning Plasma			Now	Support Fac.	ITER				
Compatible with Plasma Exhaust					Support Fac.	FNSF		DEMO	Power Plant
T_{ped}, n_{ped}, fuel dilution, $P_{core\text{-}rad}$									

Major Issues

- Can AT be sustained in DEMO relevant mode with low disruptivity?
- Does QSS confinement extend to BP regime?
- Can high performance be sustained in either with DEMO relevant PFCs?
- Can fuel mix be sustained in either?

More Work Needed here

- Compare with EU, NAS IFE Rpt, FESAC Materials Rpt
- Describe reqmts for each TRL with issues, milestones

Support Facilities

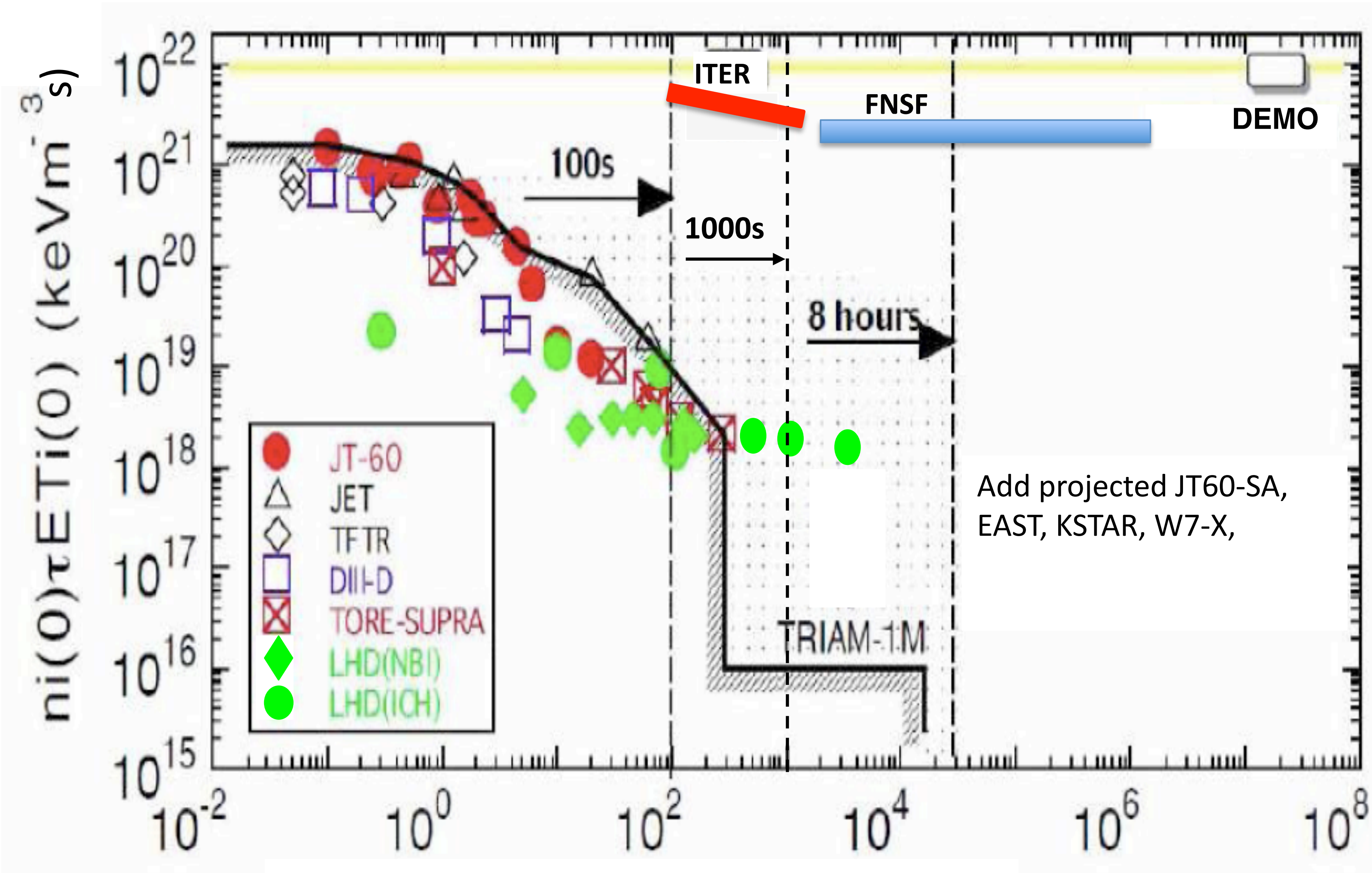
- Existing DD tokamaks (domestic and foreign)-ITPA List
- Upgrades to existing facilities
- New Facilities

Milestones can be Defined to Clarify TRLs

Key: Now = Now; * = Support Facilities

- ***Attain high burning plasma performance***
  - Now TRL 4: Q~1 achieved in DT experiments in TFTR/JET & extended with DT in JET 2017 with a Be wall
- ***Control high performance burning plasma***:
  - Now TRL 3: Q~1 DT experiments in TFTR/JET see self-heating
  - * TRL 4: DIII-D ECH dominated ITER baseline experiments
    JET DT experiments on TAE transport in Q~1 DT plasmas with Be walls
- ***Sustain fusion fuel mix and stable burn***:
  - TRL 5: NBI Tritium fueling in TFTR/JET & cryo pellet injection technology
- ***Sustain magnetic configuration-AT Configuration***:
  - Now TRL 4: Bootstrap current widely observed; non-inductive sustained plasmas observed on JT-60U & DIII-D using NBI-CD/LHCD/ECCD
  - * TRL 5-6: DIII-D/K-STAR/JT-60SA observation of ≥80% bootstrap sustained plasma
    EAST/K-STAR/WEST observation of RF & bootstrap sustained SS plasma
- ***Sustain magnetic configuration-ST Configuration***:
  - Now TRL 3: Bootstrap current observed in NSTX; CHI demonstrated non-inductive current drive
  - * TRL 4: NSTX-U demonstrate non-inductive start-up and sustainment extrapolable to FNSF-AT
- ***Attain high burning plasma performance compatible with plasma exhaust***:
  - Now TRL 3: JET/DIII-D/ASDEX-U demonstration of detached divertor operation
  - * TRL 4: JET/DIII-D/K-STAR demonstration of detached divertor in SS AT ITER like plasma
  - • TRL 4: NSTX-U demonstration of advanced divertor operation in FNSF-ST like plasma
  - * TRL 5: Test stand validation of long lifetime divertor PMI material

Mission 1: Create Fusion Power Source Gap



Fusion Plasma Sustainment Time (sec)

FESAC IC Version,
Modification of Kikuchi figure

ITER + FNSF => Advanced Tokamak Demo Pathway

Mission 2: Tame the Plasma Wall Interface

Technical Readiness Level	1	2	3	4	5	6	7	8	9
Remove Plasma Exhaust Heat and			Now	Support Fac.	ITER				
particles on Divertor and First Wall						FNSF		DEMO	Power Plant
P_{div}/A_{div} < 10 MWm^{-2}, pulse length, T_{PFC}									
Mitigate Transient Heat Loads (Elms/Disruptions)			Now	Support Fac.	ITER				
(integrated with plasma control issue)					♦	FNSF		DEMO	Power Plant
MJm^{-2}, freq, freqxMJm^{-2}						Disruption contolled			
Reduce Material Migration (erosion), dust		Now	Support Fac.	ITER					
mm per $FPYm^{-2}$, lifetime(FPY)					FNSF		DEMO		Power Plant
Control Plasma Contamination (He ash, impurities)			Now	ITER					
Z_{eff}, $P_{rad\text{-}core}$, $P_{rad\text{-}edge}$					FNSF		DEMO		Power Plant
Minimize Tritium Retention			Now	ITER		higher?			
$T_{inventory}$(kG-T), Material, dpa, T_{PFC}					FNSF		DEMO		Power Plant
Develop Neutron Resistant PFC/FW mat'l		Now		ITER					
dpa, FPY			Support Facilities		FNSF		DEMO		Power Plant

Major Issues

- System analysis to establish plausibility of concept
- choice of material for FNSF- when?, How?, R&D needed
- Test improved divertor configuration - where, when
- Identify critical PMI integration issues and focus facilities
- Integrated test of PFC concept/material/tokamak-plasma
- Required pulse length, H/D/T, n-fluence,

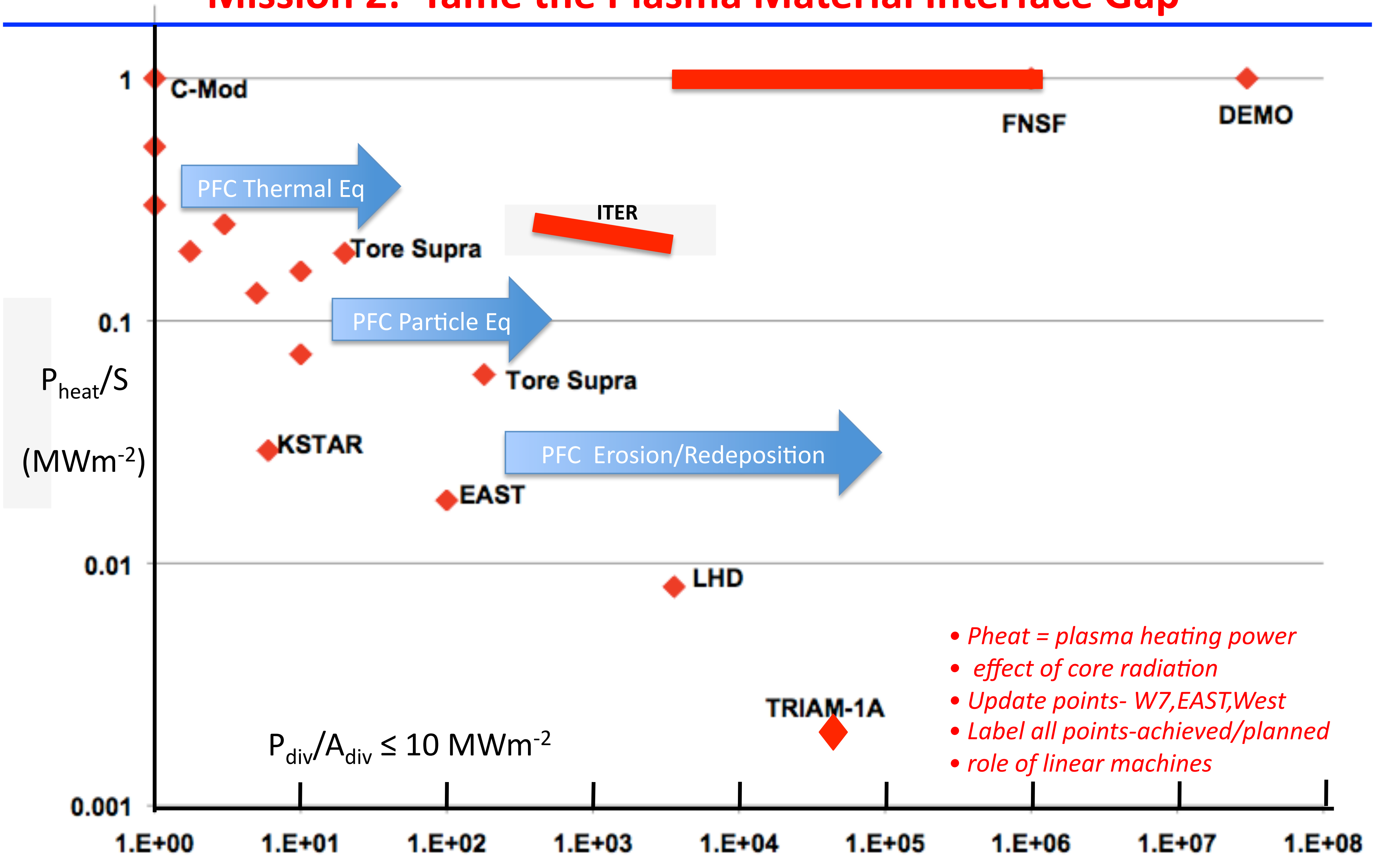
Similar to FESAC Materials and Technogy Rpt TRL Chart
Table 3.2.3 and 3.2.4

Compare with EU assessment esp. DTT Road Map Annex 2, p.19

Support Facilities

- single effect - high power steady-state linear
- toroidal - dedicate/upgrade existing facilities (JET-ILW, AUG, WEST, W7-X, MAST, EAST, KSTAR, JT-60SA, LHD, C-Mod, DIII-D,NSTX-U), or new specialized facility

Mission 2: Tame the Plasma Material Interface Gap



Modification of FESAC-IC fig.

ITER + FNSF => Advanced Tokamak Demo Pathway

Mission 3: Harnessing the Power of Fusion

Reference: FESAC Materials and Technology Report, p 88-90, Feb, 2012, Zinkle et al

Technical Readiness Level	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Demonstate Fusion Power Conversion			now	BT3F			FNSF	DEMO	Power Plant
			Benchtop /Lab			ITER-TBM			
Produce Required Tritium		now	Benchtop /Lab			ITER-TBM		DEMO	Power Plant
				BTEF			FNSF		
Establish MTBF/MTTR of Blanket/FW Systems		now	Benchtop /Lab		ITER-TBM			DEMO	Power Plant
				BT3F / BTEF			FNSF		
					RHDF				
Tritium Fueling and Exhaust Processing				now	ITER, Other Tokamaks			DEMO	DEMO
				Benchtop/Lat	FCDF			FNSF	

Major Issues

- PbLi MHD Flow Control, Pressure Drop, Transport Phenomena
- PbLi Chemistry Control/Processing
- Helium-cooled FW and Structure Thermomechanics
- Fabrication and Reliability of Complex Structures Under Combined loads
- Component synergistic failure modes, rates and effects
- Mechanisms for n decrease in MTTR
- Plasma Exhaust Processing Time and Availability
- Simulating Fusion Environment in Non-Fusion Test Facilities

Support Facilities

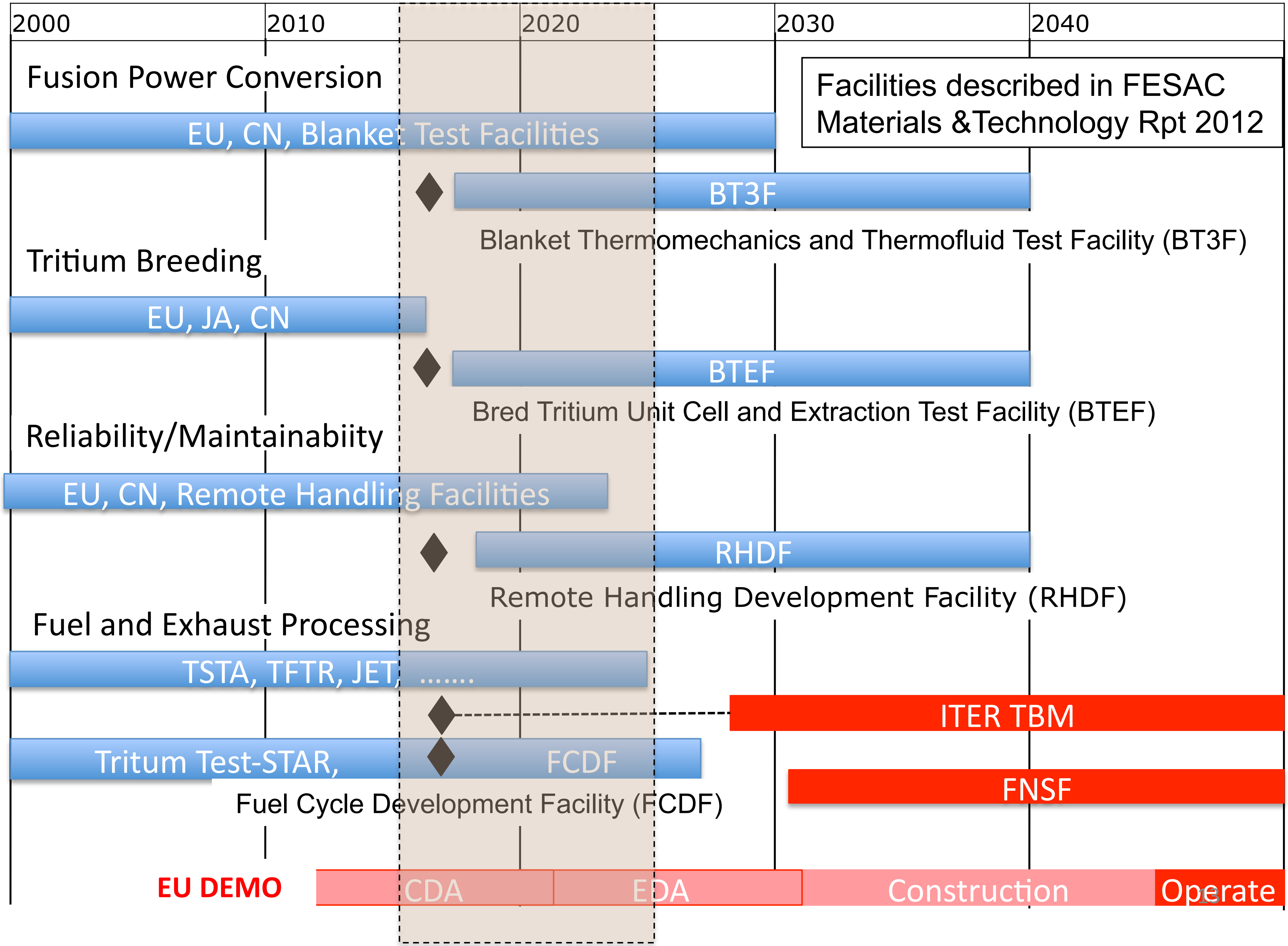
- Blanket Thermomechanics and Thermofluid Test Facility (BT3F)
- Bred Tritium Unit Cell and Extraction Test Facility (BTEF)
- Fuel Cycle Development Facility (FCDF)
- Remote Handling Development Facility (RHDF)
- ITER Test Blanket Module Experiments (ITER-TBM)

Summary of 1st IAEA DEMO Workshop Priority Activities

1) thermofluid-MHD behaviour of complex geometry, multi-channel blanket designs;
2) impact of neutron irradiation on properties and performance;
3) high duty-cycle plasma exhaust processing; and
4) remote handling and maintenance of blanket/FW components.

Facilities to address these issues are required for TBM, FNFs, and DEMO.

Blanket Facilities to Reduce Gaps for all Pathways



ITER + FNSF => Advanced Tokamak Demo Pathway

Mission 4: Materials for Fusion Power

Technical Readiness Level	1	2	3	4	5	6	7	8	9
Conquer Neutron Degradation									
Science Based Design Criteria Them/Mech		Now	Non-Nucl Test Stand Integ		FusNeutS	FNSF			
				ITER TBM			DEMO		Power Plant
Explore Fabrication/Joining Trade offs		Now	Non-Nuc Test	FusNeutS	NNTS Integ	FNSF		DEMO	Power Plant
			Ion/Fiss neut		ITER TBM				
Resolve Compatibility and Corrosion Issues		Now		Non-Nuc TS	NNTS Integ	FNSF		DEMO	Power Plant
Radiation Effects in Fusion Environment		Now	Ion/Fiss neut	FusNeutS					
Mat'l Qualification in Fusion Environment		Now	Ion/Fiss neut	FusNeutS		FNSF			
Structural Stability				ITER TBM			DEMO		Power Plant
Mat'l Qualification in Fusion Environment		Now	Ion/Fiss neut	FusNeutS		FNSF			
Mechanical Integrity							DEMO		Power Plant
Fusion Environment Effects on Tritium	Now	NNTS	Ion/Fiss neut		ITER TBM	FNSF			
Retention and Permeation					FusNeutS		DEMO		Power Plant

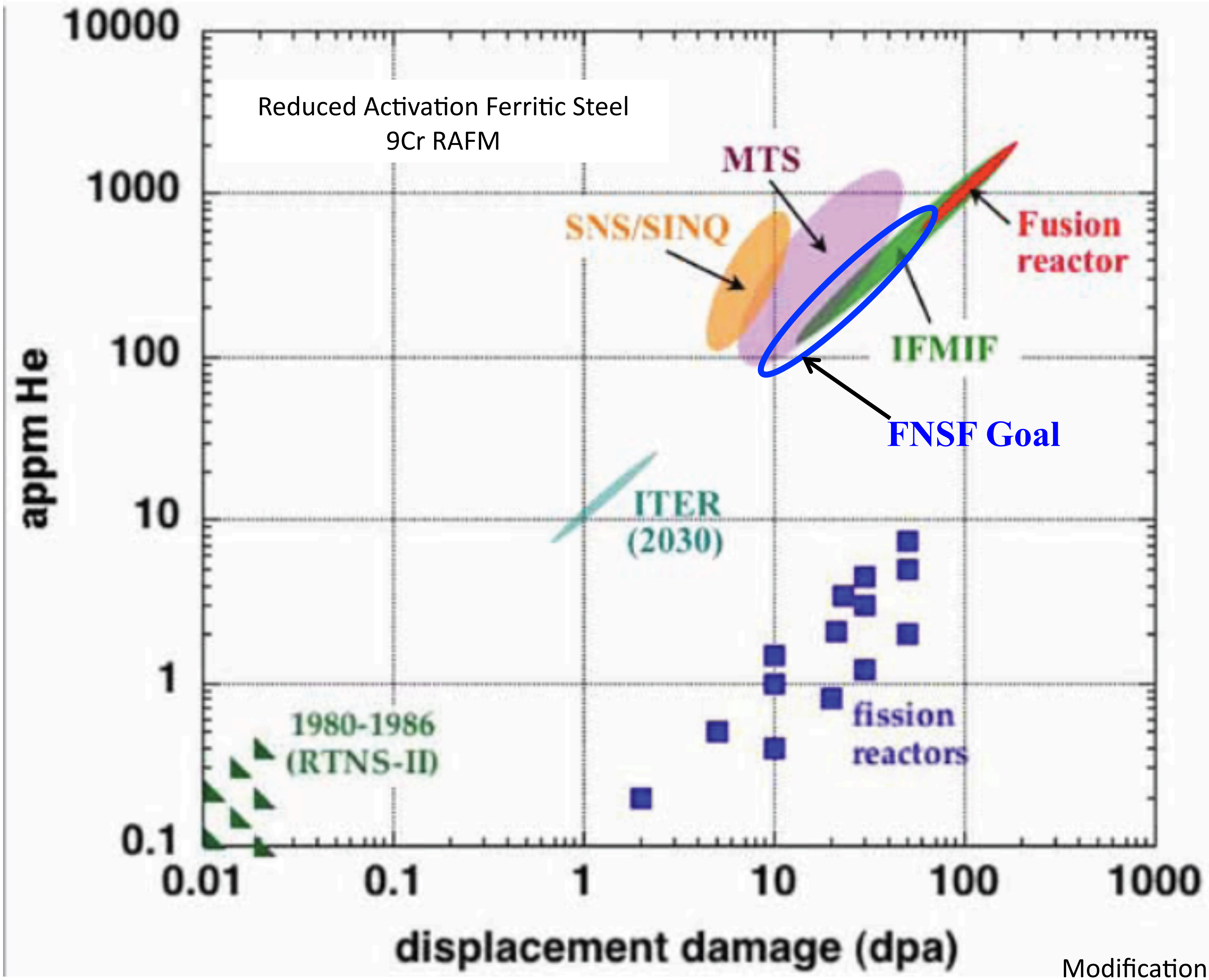
Based on Table 3.3.1 in FESAC Report: Opportunities for Fusion Materials Science Technology Research Now and in the ITER ERA, DOE/SC-0149

Major Issues:

Support Facilities:

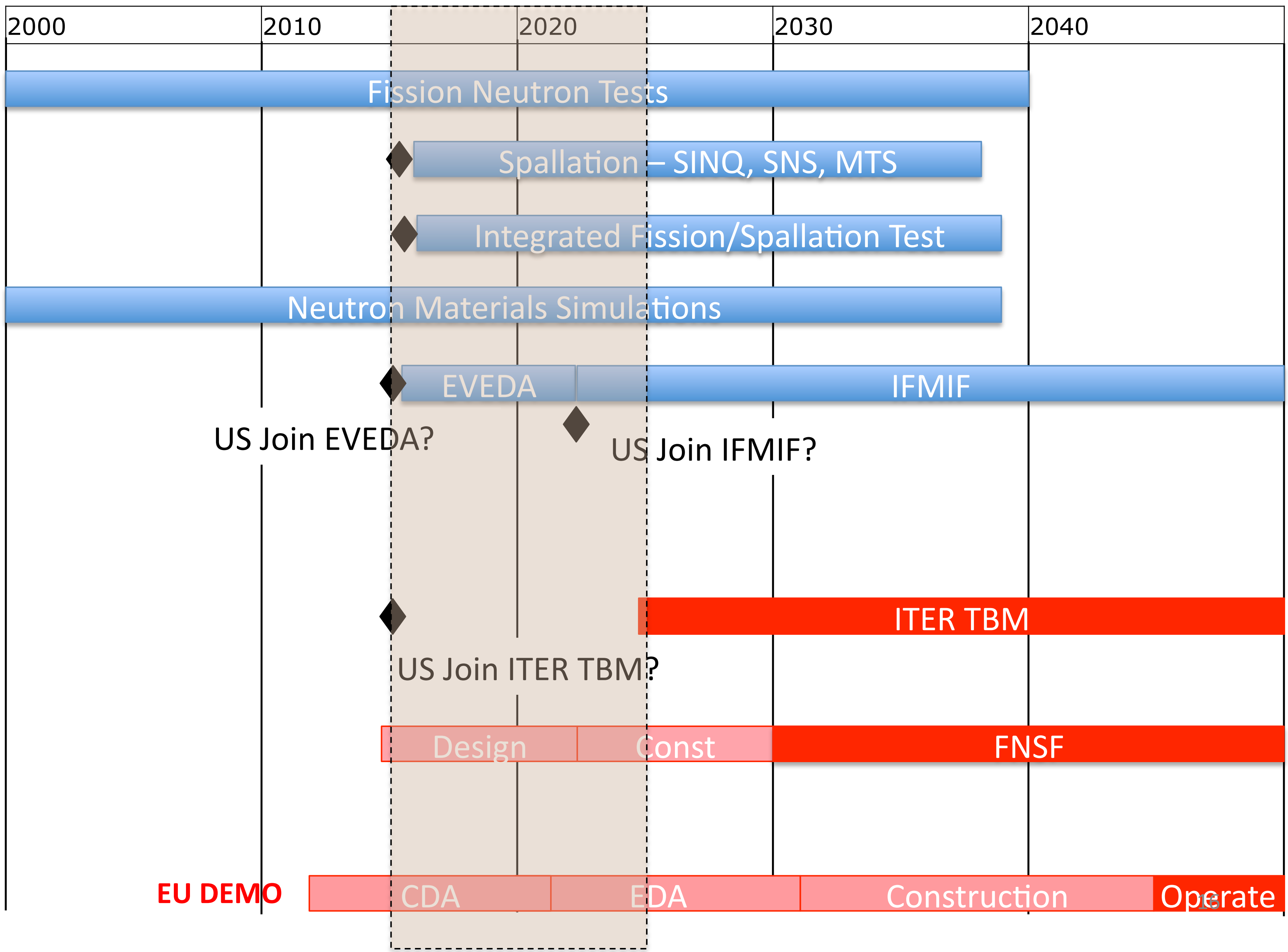
- Non-nuclear Test Stands
- Non-nuclear Test Stands Partially Integrated
- Ion Beams and Fission Reactors
- Fusion Relevant Intense Neutron Source

Mission 4: Create Materials for Fusion Power Gap



Modification of Zinkle fig.

Materials Facilities to Reduce Gaps for all Pathways



ITER + FNSF => Advanced Tokamak Demo Pathway

Mission 5: Establish the Economic Attractiveness and Environmental Benefits of Fusion Energy

Technical Readiness Level	1	2	3	4	5	6	7	8	9
Establish Competitive Cost of Electricity		Now							
Reduce Plant Capital Cost	Now	(eg- reduce complexity, establish fusion relevant regulations, ….)							
Increase Operating Availability									
Demonstrate Safety and Environmental				Now - TFTR/JET	ITER		DEMO		Power Plant
Benefits (separate Safety and Environmental?)				Support Pgm	FNSF				
Establish Safety Regulations for Fusion		Now	ITER						
Facilitate and Exploit Innovation in		Now							
Physics, Technology and Manufacturing	(eg- higher B,more efficient current drive, reduce complexity, cheaper manufacturing, ….)								

Major Issues:

Total cost of fusion must be competitive

Fusion program must remain vigilant to ensure that the safety and environmental advantages of fusion energy are realized.

Support Facilities:

Other Important Activities that need to be considered

Mission 6: Establish Enabling Plasma Technology for Fusion Power Plant

Should we have a full mission on this?? it tends to get lost

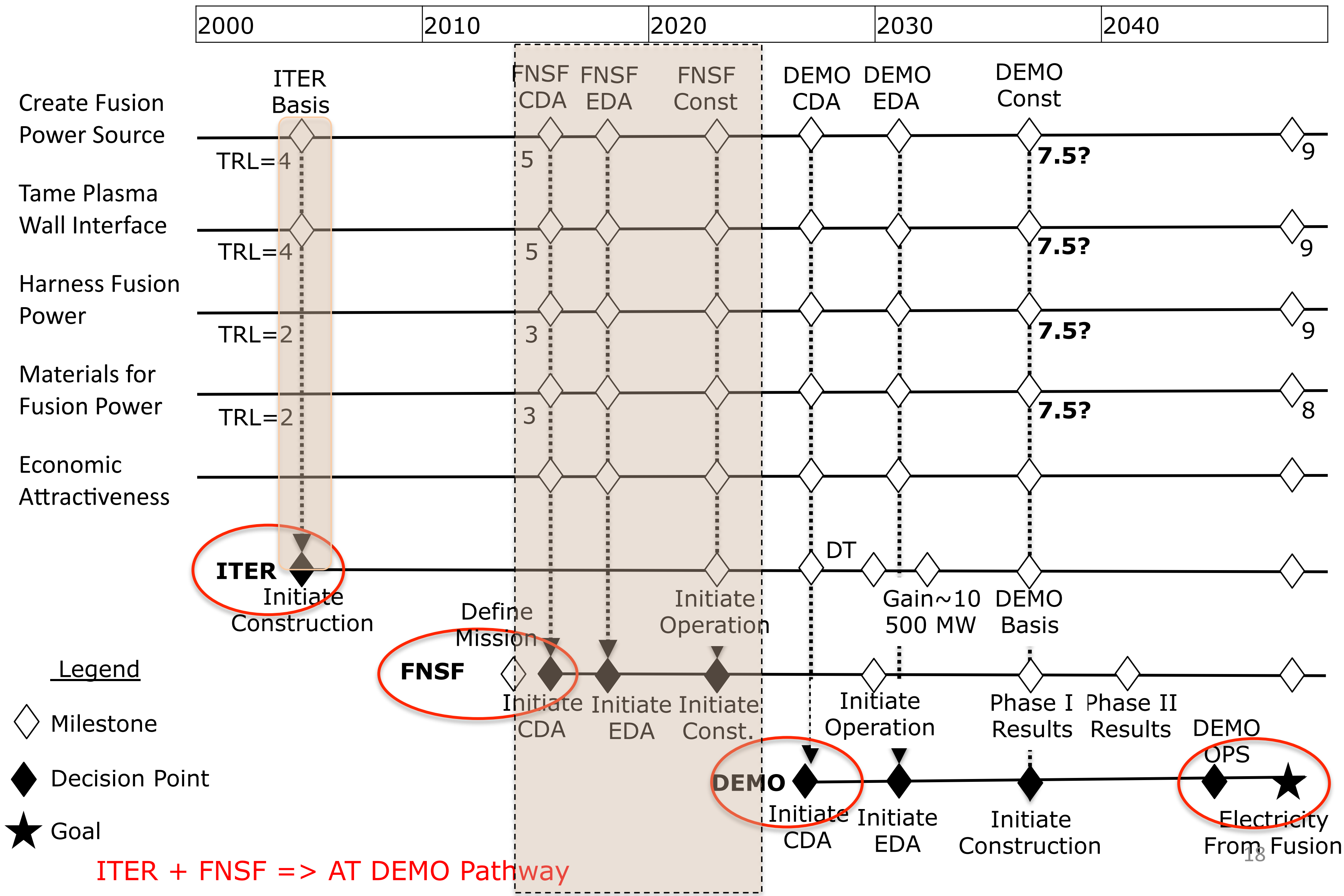
Enabling Plasma Technologies
- Plasma Actuators
- Development of Low Cost High Field Magnets
- ie a section on R&D to support Missions above

Plasma and Machine Diagnostics
- Plasma Control
- Development of Diagnostics Compatible Fusion Environment

Mission 7: Strengthening the Infrastructure supporting Fusion Research

- Educational
- Industrial

Mission /TRL Milestones can be used to Inform Decisions



FNSF(AT) Mission for ITER + FNSF => AT DEMO Pathway

Create Fusion Power Source

- Attain required AT BP Parameters (H_{98}>1.1; β_N>2.8; 100% NI) for Steady-state
- Demonstrate AT BP plasma control and elimination of plasma transients
- Demonstrate fusion power stability and control of fusion power output
- Verify and Validate BP scenario Simulations for DEMO– what does this mean?

Tame Plasma Wall Interface

- Demonstrate Div Power Handling at DEMO Power Densities in Steady state
- Test Candidate Divertor Materials – Power & Particle, reactor relevant
- Verify and Validate for DEMO

Harness Fusion Power

- Demonstrate a closed fusion fuel cycle with TBR ~ 1 that projects to TBR>1 in DEMO
- Validate Candidate Fusion Blanket concept in a fusion environment (Γ_n>1 $MW_n m^{-2}$)
- Extract high grade heat and produce some electricity for extended period of time
- Thermal mechanical tests of blanket modules in fusion enviroment, reliability data

Materials for Fusion Power

- Demonstrate components for ~ 20 - 30 dpa, He ~100-300 ppm
- Initial data of neutron effects on welds, etc (Engineering Feasibility-Finesse Stage II)
- Initial data component lifetime, reliablity and replacement time

ITER + FNSF => AT DEMO Pathway

(Milestones to Initiate Construction of AT FNSF)

Create Fusion Power Source

- attain required AT Parameters (H_{98}>1.1; β_N>2.8; 100% NI) for 4 τ_{cr}
- demonstrate plasma control (≤ 1 unmitigated disruption per year)
- V&V AT Plasma Simulations for FNSF operating scenario,

Tame Plasma Wall Interface

- Demonstrate Exhaust Power Handling: P/S =1-2 MWm^{-2} with P_{div}/A_{div}<10 MWm^{-2}, 1 week
- Qualify Candidate Divertor Materials – Temp, $T_{retention}$, erosion life, neutron effects
- V&V PMI Simulations for FNSF exhaust power handling integrated with core plasma

Harness Fusion Power

- Leading Candidate blanket concept identified and R&D taken to TRL~5
- Qualify Tritium Handling Plan
- Qualify Remote Maintenance Scheme

Materials for Fusion Power

- Identify blanket structural material and qualify up to 25 dpa
- Demonstrate viable materials and technology for continuous tritium extraction from fusion blankets
-

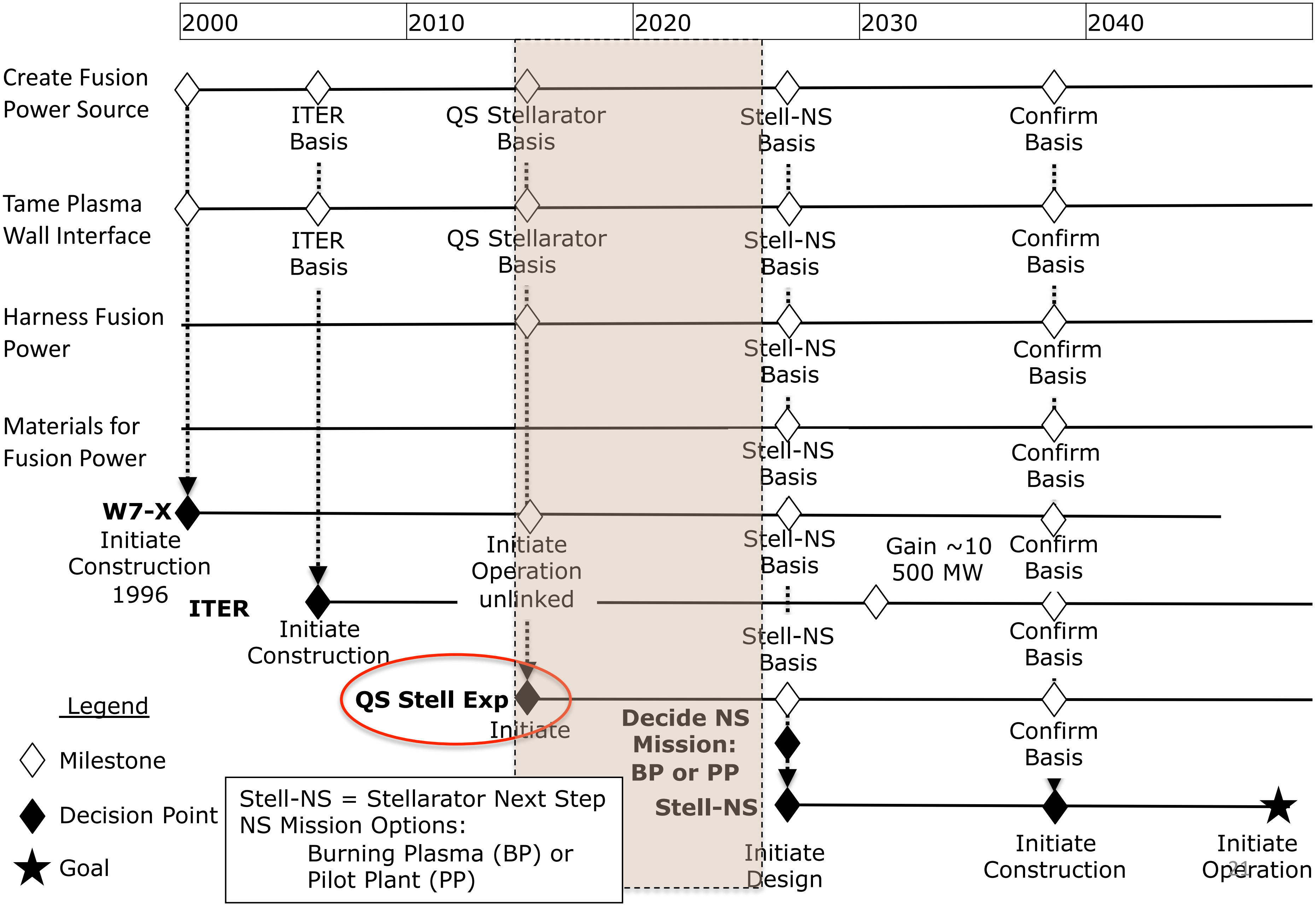
Establish Economic Attractiveness and Enironmental Benefits of fusion

- Preliminary Safety Analysis approved
- Environmental Impact Statement approved

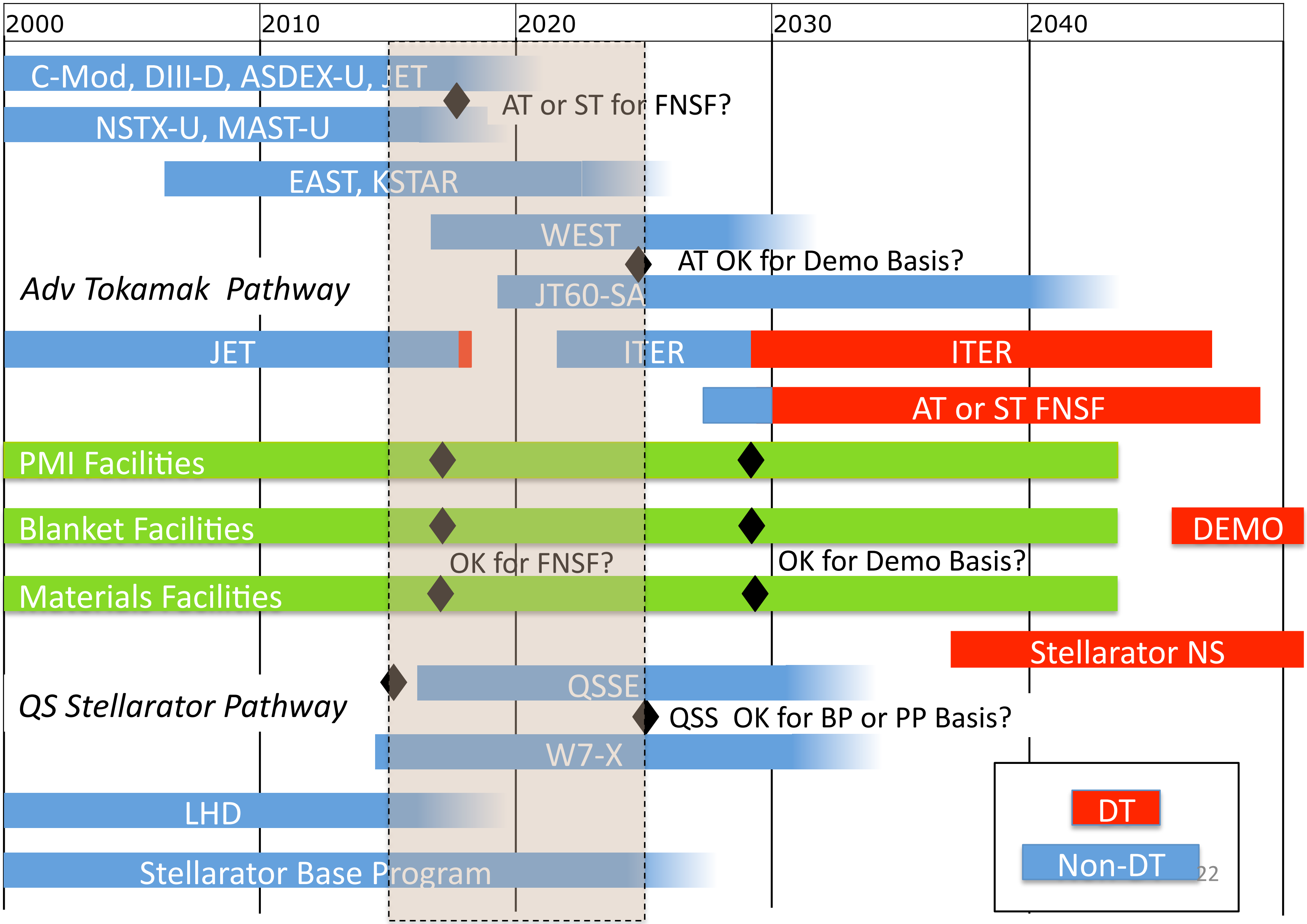
Need similar for ST FNSF

Is Pilot Plant FNSF a DEMO?

Milestones and Major Decisions in the QS-Stell Pathway



Major Decisions for US Magnetic Fusion Program Road Map



Concluding Remarks

- A 10 Year Strategic Plan should not be a simple roll forward, but must be based on, and driven by, a longer term vision i.e. a Road Map.

- The 10 Year Strategic Plan for fusion must identify several compelling deliverables that when accomplished will serve to increase support for fusion in the US. This will also help serve to focus the activities, and create a sense of urgency in the community.

- The Framework for a Fusion Road Map can help in identifying and assessing the critical issues, milestones and decision points. Congress/Adminstration need to be able to track progress through milestones and decision points.

- If one of the goals of the 10 Year Strategic Plan is for the U. S. to be among the world leaders in fusion – this will require a significant increase in funding, to levels comparable to EU funding ($1.34B in 2014).