Framework for a Road Map to Magnetic Fusion Energy

Status Report

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for MFPL Working Group

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Why Work on a Fusion Roadmap Now?

- To demonstrate that there are realistic technical paths to a Magnetic Fusion DEMO
  - essential to convince others that fusion is worth supporting even if the funding is not yet available to follow an aggressive path

- To update previous studies, and develop some initial views on the relative attributes of various paths.

- This exercise is not to down select !!

- In difficult of times, it is even more important to have a plan to make progress
  - Be ready when external conditions change – R. Conn, Snowmass 1999
  - That was the case in the mid 1970s, and the US MFE was able to exploit the change.

Magnetic Fusion Program Leaders (MFPL) Initiative

Magnetic Fusion Program Leaders: S.Prager, PPPL; T. Taylor, GA; N. Sauthoff, USIPO; M.Porkolab, MIT; P. Ferguson, ORNL; R. Fonck, U.Wisc; D. Brennan, UFA.

Goal: Develop and assess three aggressive technically feasible, but constrained, paths for the US Fusion Program to support or motivate a commitment to DEMO on the timescale of ITER $Q \approx 10$ experiments (nominally 2028).

Task: Building on previous Fusion Community workshops and studies, assess the technical readiness and risks associated with proceeding aggressively along three potential paths:

1) ITER plus Fusion Nuclear Science Facility leading to a Tokamak DEMO
2) ITER directly to a Tokamak DEMO (possibly staged)
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.

Process:

1. A core group (10) has been formed
2. Solicit review from a large (30) group of technical experts and external advisors
3. Aiming for interim report to Magnetic Fusion Program Leaders by Spring 2014

Road Map Study Group

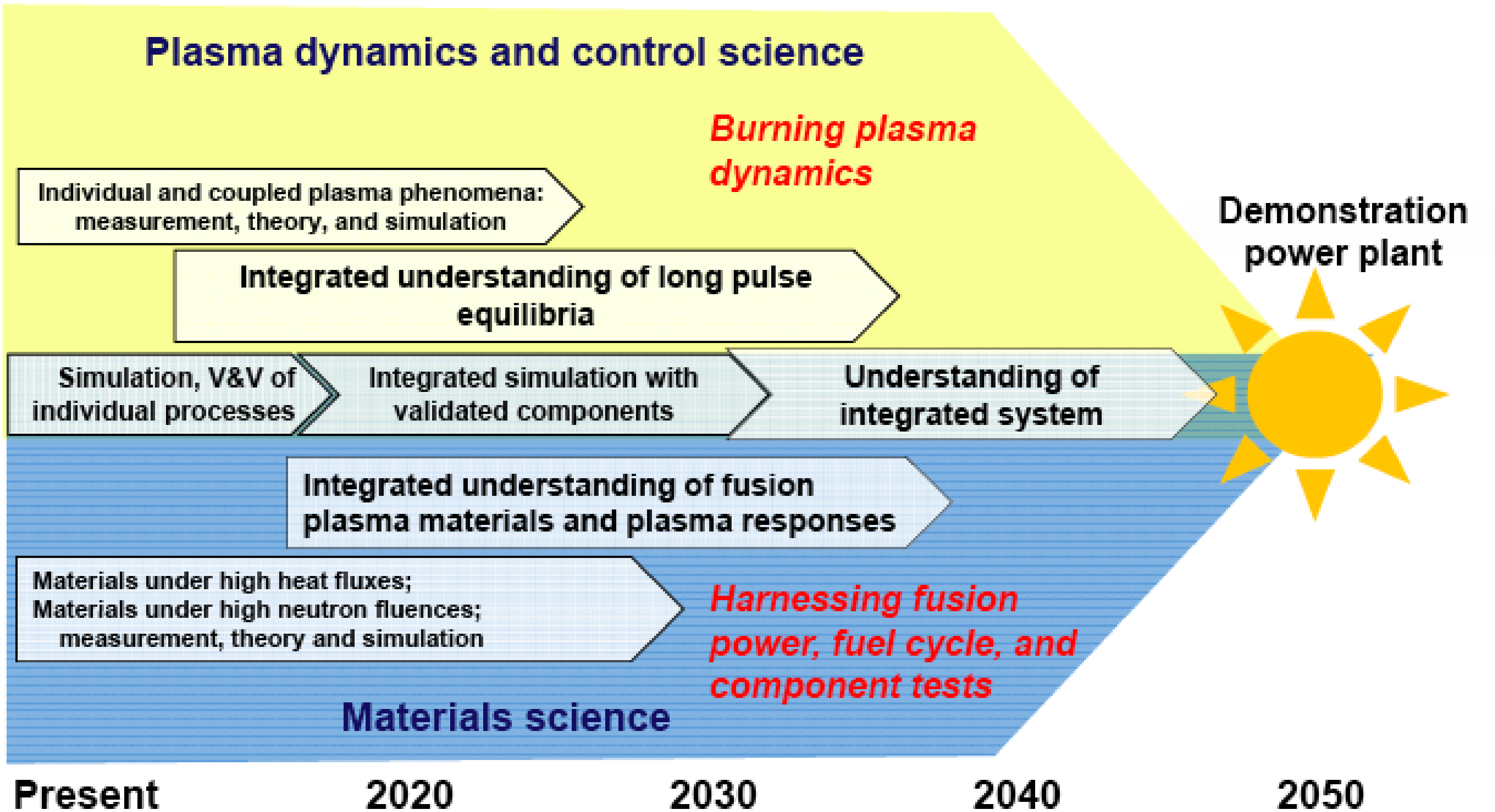
Members

Dale Meade	Chair
Steve Zinkle	Materials
Chuck Kessel	Power Plant Studies, FNSPA
Andrea Garofalo	Toroidal Physics
Neil Morley	Blanket Technology
Jerry Navratil	University Experimental Perspective
Hutch Neilson	3-D Toroidal, Road Map Studies
Dave Hill	Toroidal Alternates
Dave Rasmussen	Enabling Technology, ITER
Bruce Lipschultz/Dennis Whyte	Plasma Wall Interactions
	Reactor Innovations

Background

FESAC 35 Yr RJG	(2003)	FESAC Opportunity MG	(2007)
ReNeW Study	(2009)	FNSP Assessment CK	(2011)
FESAC Materials SZ	(2012)	FESAC Int Collab DM	(2012)
FESAC Priorities RR	(2013)	FESAC Facilities JS	(2013)
EU Road Map/Annex	(2013)	China CFETR Plan	(2013)

What I have argued for in the Administration regarding fusion per se: two major thrusts need to be pursued to demonstrate practical fusion power on a relevant time scale



Path to fusion demonstration: scientific thrusts a la ReNeW

Ed Synakowski, UFA talk, APS-DPP 2012

All Road Map exercises start with where you are today, and where do you want to be at the end

Today – the scientific basis for MFE is very strong but incomplete

- Detailed understanding and predictive capability for plasma equilibrium, MHD stability, energetic particles, etc. Improving understanding of plasma material interactions,…….

- Fusion energy production demonstrated 7.5-22 MJ/pulse, >1.5 GJ fusion energy total, alpha heating and alpha dynamics confirmed , fusion gain Q ~ 1

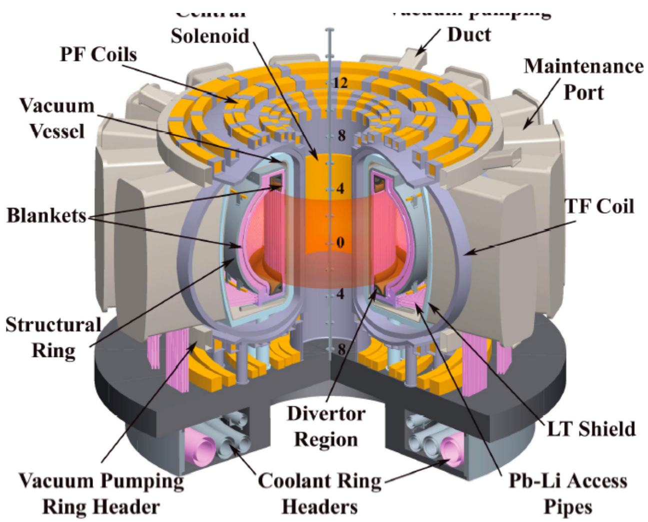
- MFE has initiated, and is solving the challenges of building world's 1st reactor-scale fusion facility that will establish burning plasma physics, and demonstrate fusion gain Q ≈ 10, 500 MW, 200 GJ/pulse and fusion technologies.

- Ongoing research program is addressing technical issues to ensure ITER's success

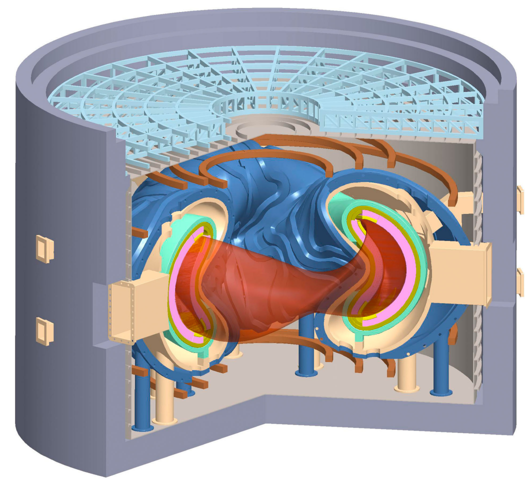
- What additional issues need to be resolved for fusion power? - look back from the Fusion Demo.

ARIES Studies Identified General Characteristics of Magnetic Fusion Demonstration 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

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

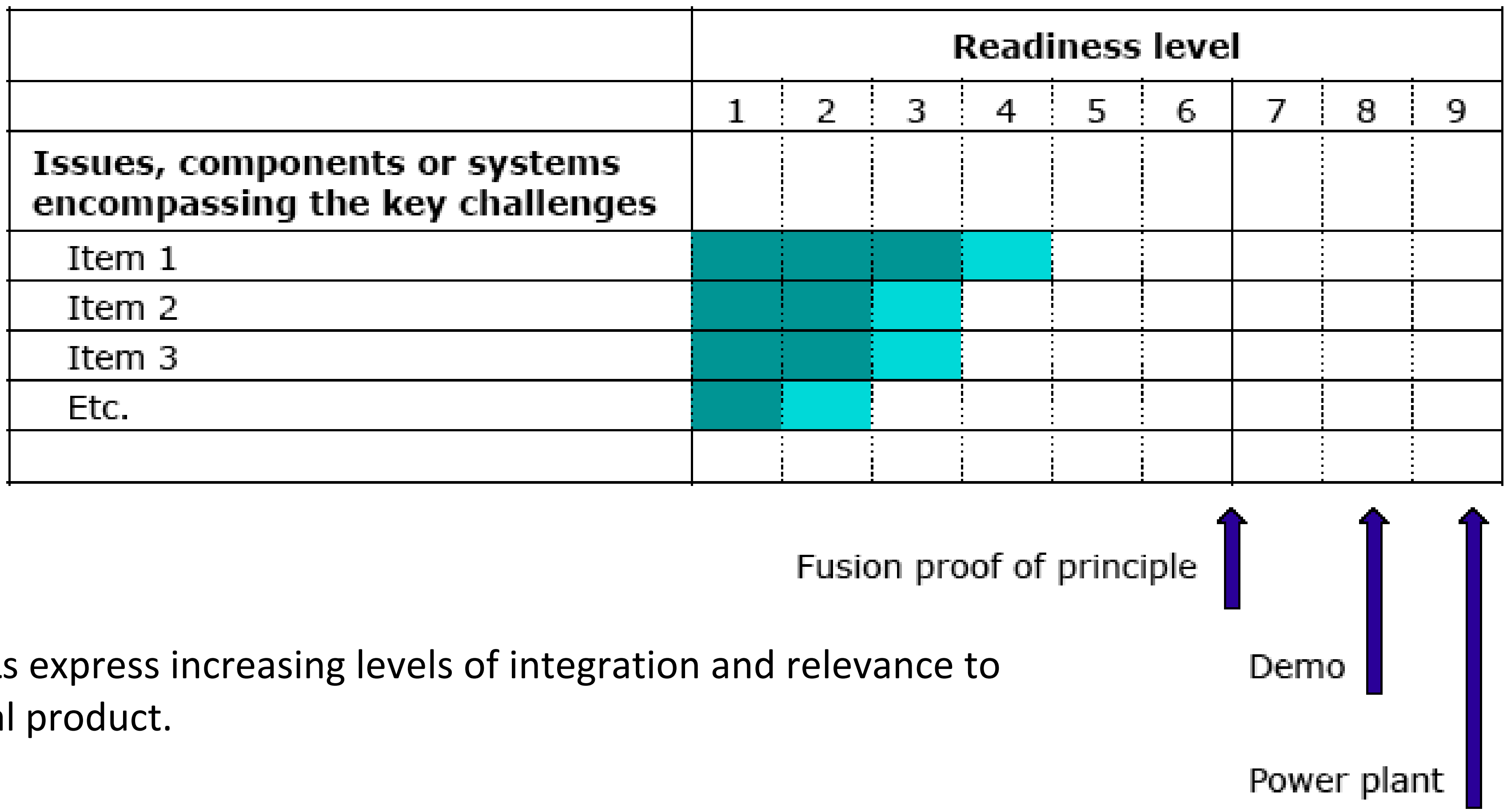
Mission 4. Develop Materials for Fusion Energy

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

Technical Readiness Levels

Readiness levels can identify R&D gaps between the present status and any level of achievement



TRLs express increasing levels of integration and relevance to final product.

ITER + FNSF => Advanced Tokamak Demo Pathway

Mission 1 Create Fusion Power Source

	Concept Development			Proof of Principle			Proof of Performance		
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 Pgm	ITER		DEMO		Power Plant
β_N, nT, disruptivity, $\tau_{controlled}$, $P_{\alpha\text{-loss}}/P_{heat}$					FNSF				
Sustain Magnetic Configuration	AT			Now	Support Pgm	ITER		DEMO	Power Plant
f_{CD}, P_{CD}/P_{heat}, ... $\tau_{sustained}/\tau_{CR}$, etc	ST		Now	Support Program		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 Pgm	ITER				
Compatible with Plasma Exhaust					Support Pgm	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

- Need to review
- Compare with EU
- NAS IFE
- DOE TRL Guidelines
- Describe reqmts for each TRL with issues, milestones

Support Facilities

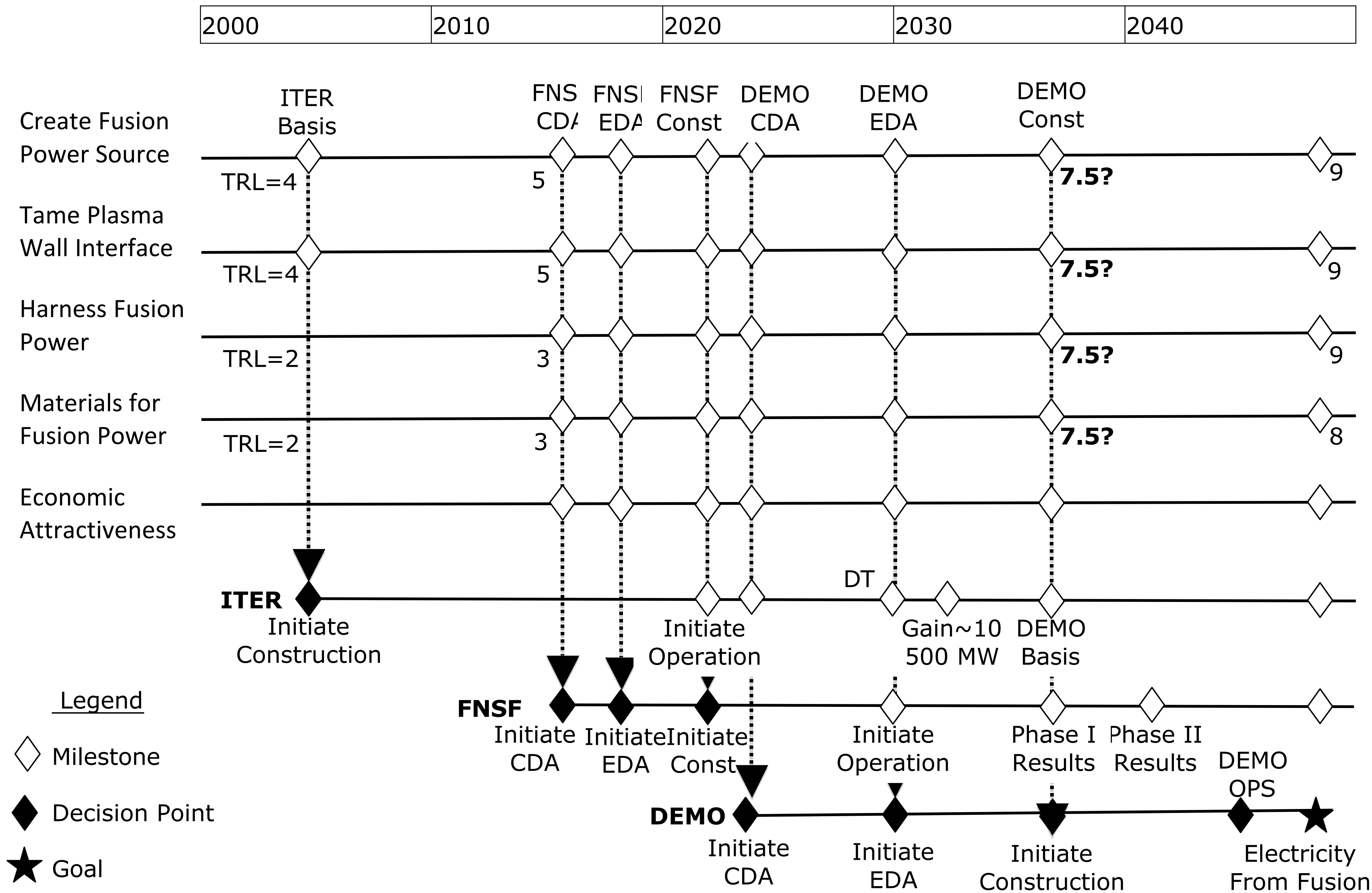
Existing DD tokamaks (domestic and foreign)
Upgrades to existing facilities
New Facilities

Note- this is linked to an active Excel spreadsheet
Double click to open spreadsheet

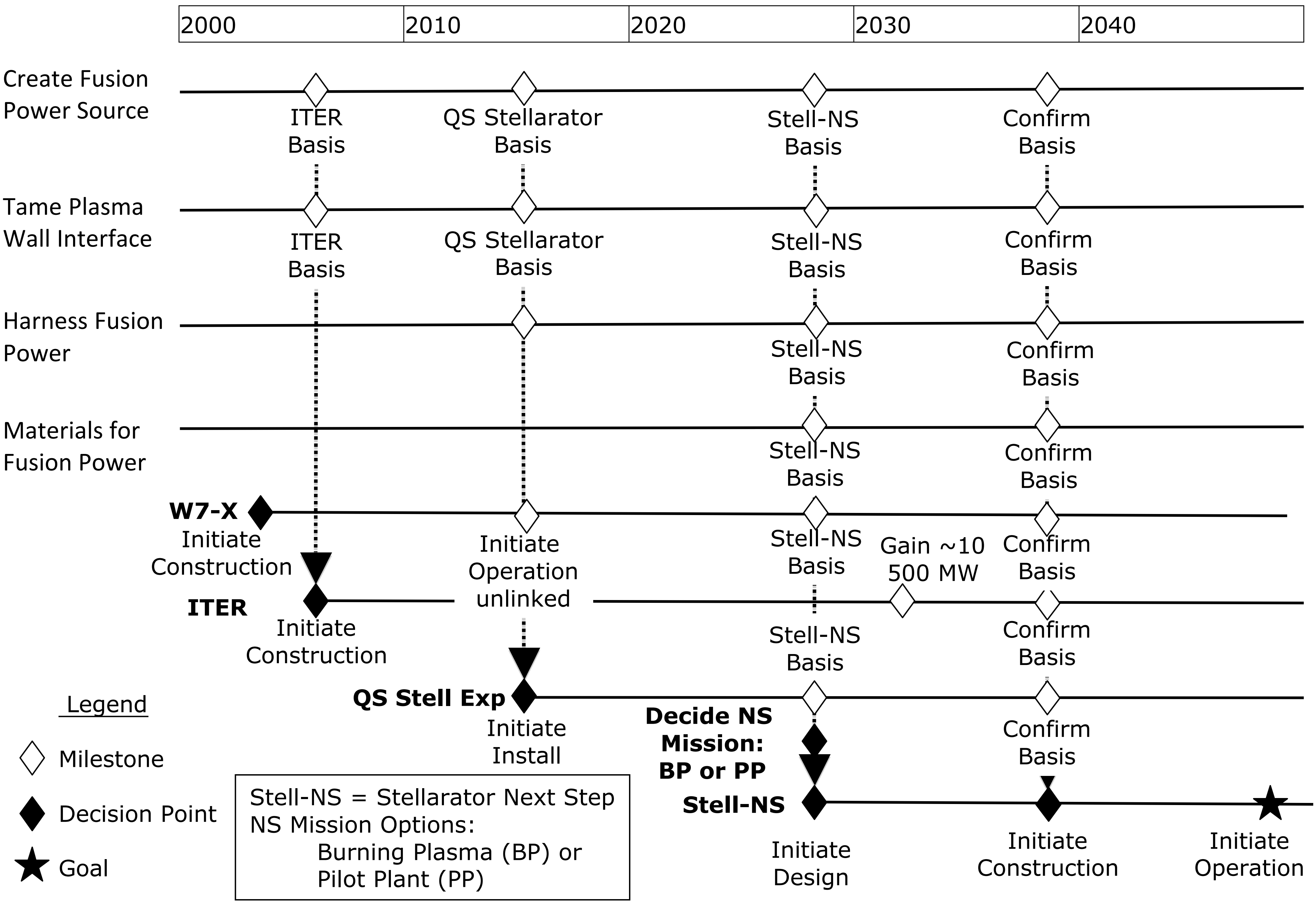
Mission 1: Create Fusion Power Source (AT DEMO Pathway)

- ***Attain high burning plasma performance***
  - Now TRL 4: Q~1 achieved in DT experiments in TFTR/JET & extended with DT in JET 2015 with a Be wall
- ***Control high performance burning***:
  - 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: 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
  - NSTX 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
  - NSTX 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

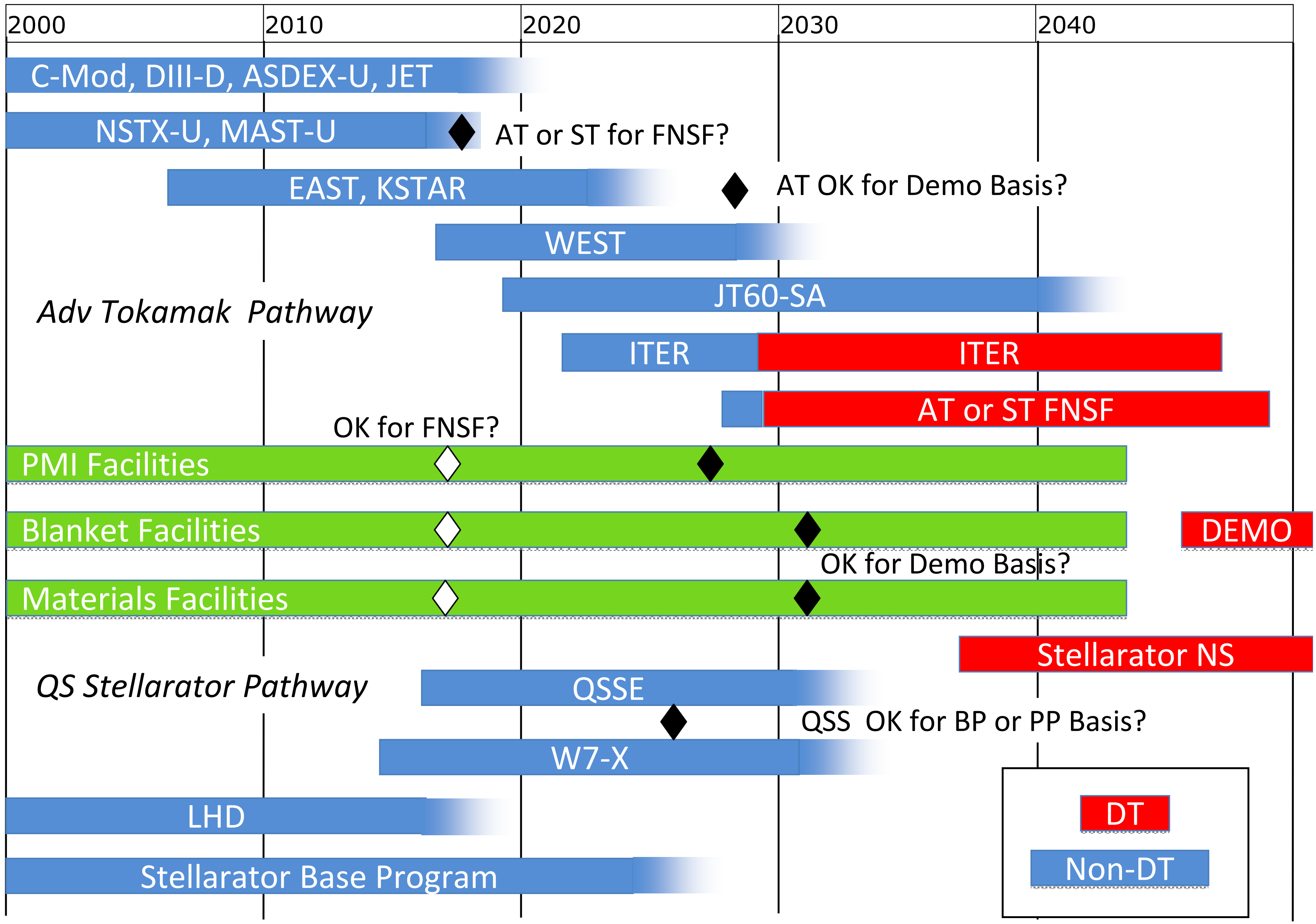
ITER + FNSF => AT DEMO Pathway (Logic)



ITER + QS-Stell Program => Stellarator DEMO Pathway (Logic)



Facilities for US Magnetic Fusion Program Road Map



Next Steps for Road Map Activity

- Complete draft framework for each path forward:
  - Review critical issues
    - TRL assessments
    - Milestones
    - Decision points
  - Review aggressiveness of the schedule (More or less)
  - Compare relative technical gaps and risks
  - Resource needs (more than hardware)

- Seek input and review by technical experts and the fusion community

- Continue working with international groups that are developing Road Maps for their National Programs (e.g., 2nd IAEA DEMO Programme Workshop, Dec 16-20, 2013)

Comments – to the working group or me dmeade@pppl.gov

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