The Pursuit of Fusion Energy:
Where are we, and where should we be going?

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Plasma Physics Colloquium
Applied Physics and Applied Mathematics Department
Columbia University
April 11, 2014

http://fire.pppl.gov

Today’s Talk (Discussion)

- The need for an abundant non-CO2 emitting energy source is generally accepted. However, there is debate about whether there is a near term urgency and the best way to produce abundant non-CO2 emitting energy.

- Fusion would be an ideal long term energy source, but…….

  - it is a very difficult scientific and technical challenge

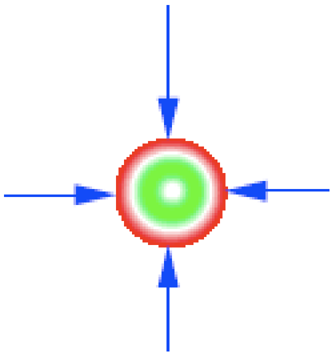
- Where are we today in the pursuit of fusion energy?

Fusion Fire Powers the Sun

“We need to see if we can make fusion work.”

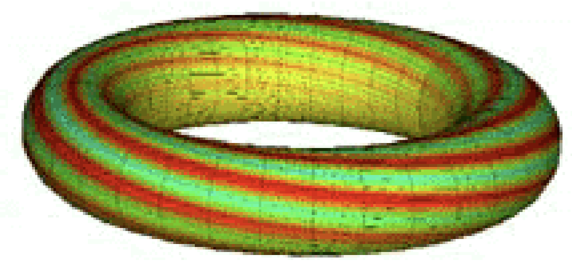
John Holdren, @MIT, April, 2009

There are Three Main Fusion Concepts



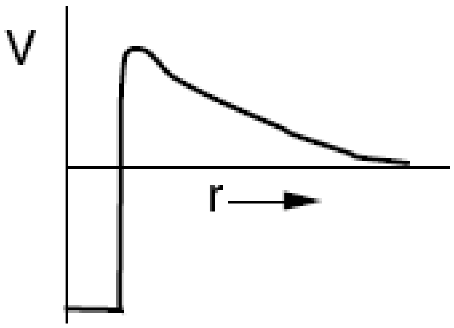
Spherical Inertial

- gravitational
- transient compression
  - drive (laser-D/I, beam)
  - radial profile
  - time profile
- electrostatic



Toroidal Magnetic

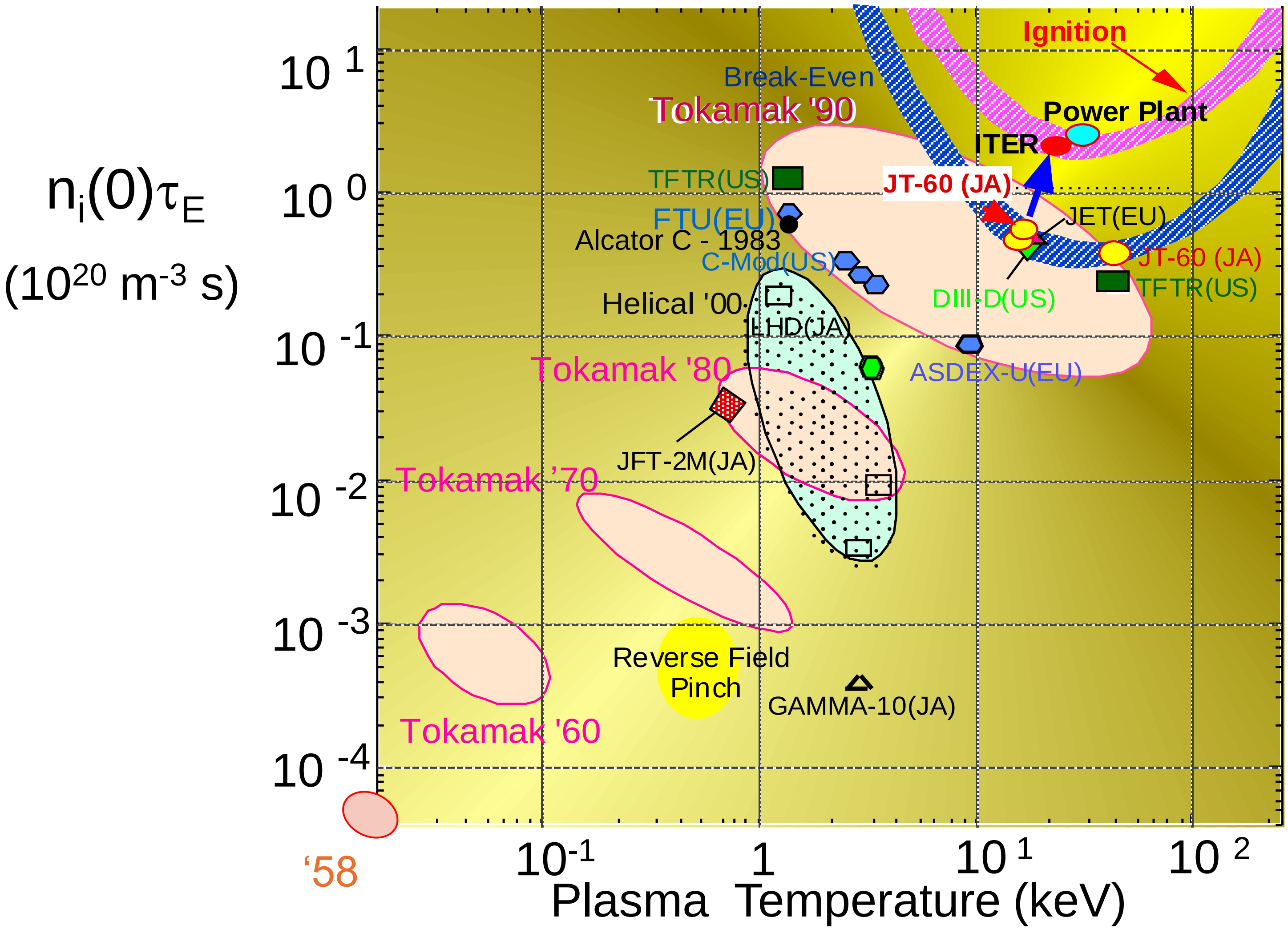
- surface of helical B lines
  - twist of helix
  - twist profile
  - plasma profile
  - toroidal symmetry



Reactivity Enhancement

- muon catalysis
- polarized nuclei
- others?

Fusion Temperatures Attained in the Laboratory, Fusion Confinement One Step Away



$n_i(0)\tau_E T_i$ increased by ~10^7 since 1958

JAEA

Significant Fusion Power (>10MW) Produced 1990s

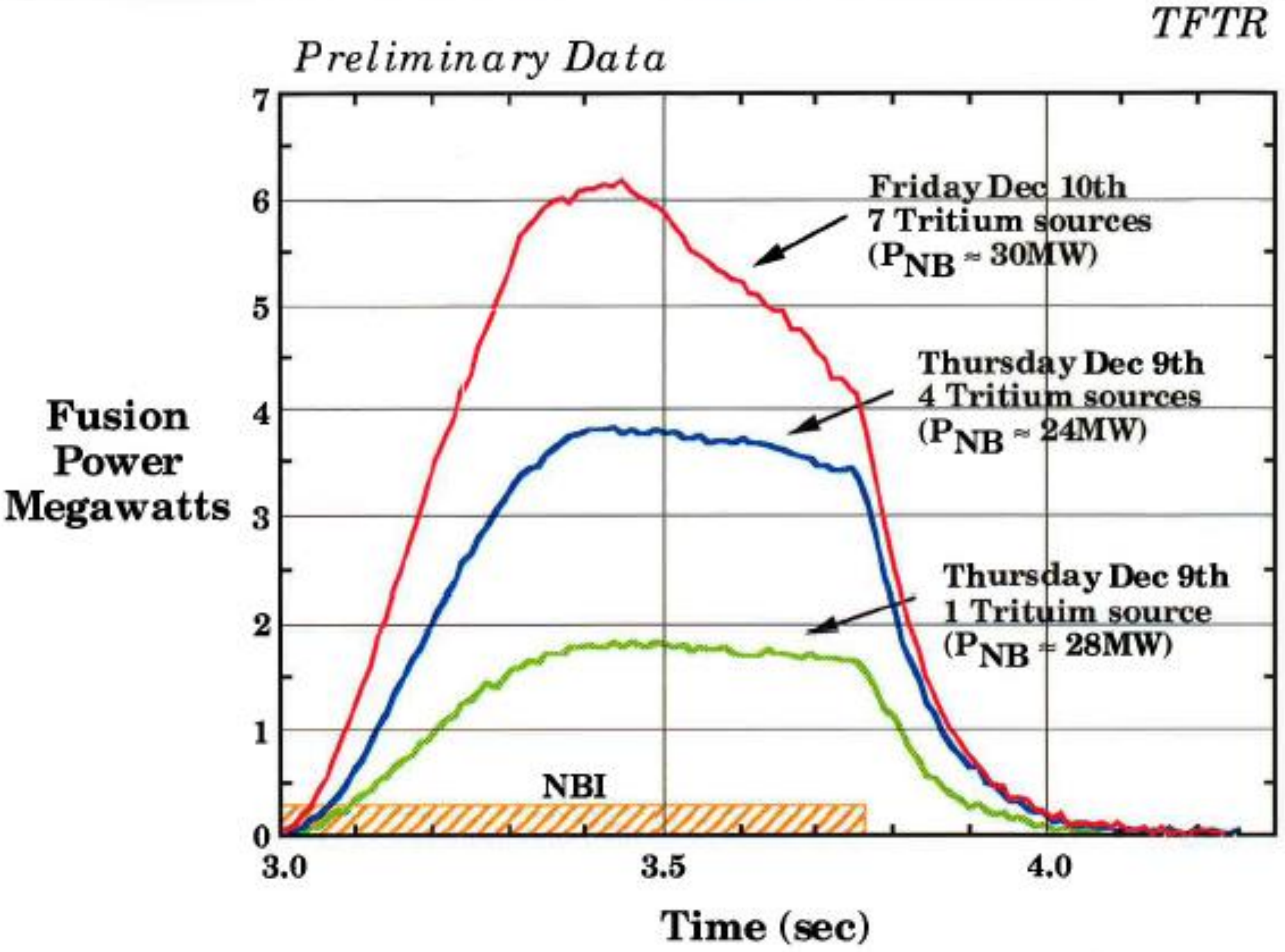
- 1991 JET 90/10-DT, 2 MJ/pulse, Q ~ 0.15, 2 pulses

- 1993-97 TFTR 50/50-DT, 7.5MJ/pulse, 11 MW, Q ~ 0.3, 1000 D-T pulses,
  - Alpha heating observed, Alpha driven TAEs - alpha diagnostics
  - ICRF heating scenarios
  - 1 MCi of T throughput, tritium retention
  - 3 years of operation with DT, and then decommissioned.

- Advanced Tokamak Mode Employed for High Performance
  - Improved ion confinement TFTR, DIII-D, $Q_{DTequiv}$ ~ 0.3 in DIII-D 1995
  - $n\tau_E T$ record => $Q_{DTequiv}$ in JT-60U DD using AT mode 1996
  - Bootstrap and current drive extended

- 1997 JET 50/50-DT 22MJ/pulse, 16 MW, Q ~ 0.65, ~100 D-T pulses
  - Alpha heating extended, ICRF DT Scenarios extended,
  - DT pulse length extended
  - Near ITER scale D-T processing plant
  - Remote handling

Initial D-T Results From TFTR



1st DT Experiments with 50/50 DT fuel, Dec 9-10, 1993

L. Johnson
J. Strachan

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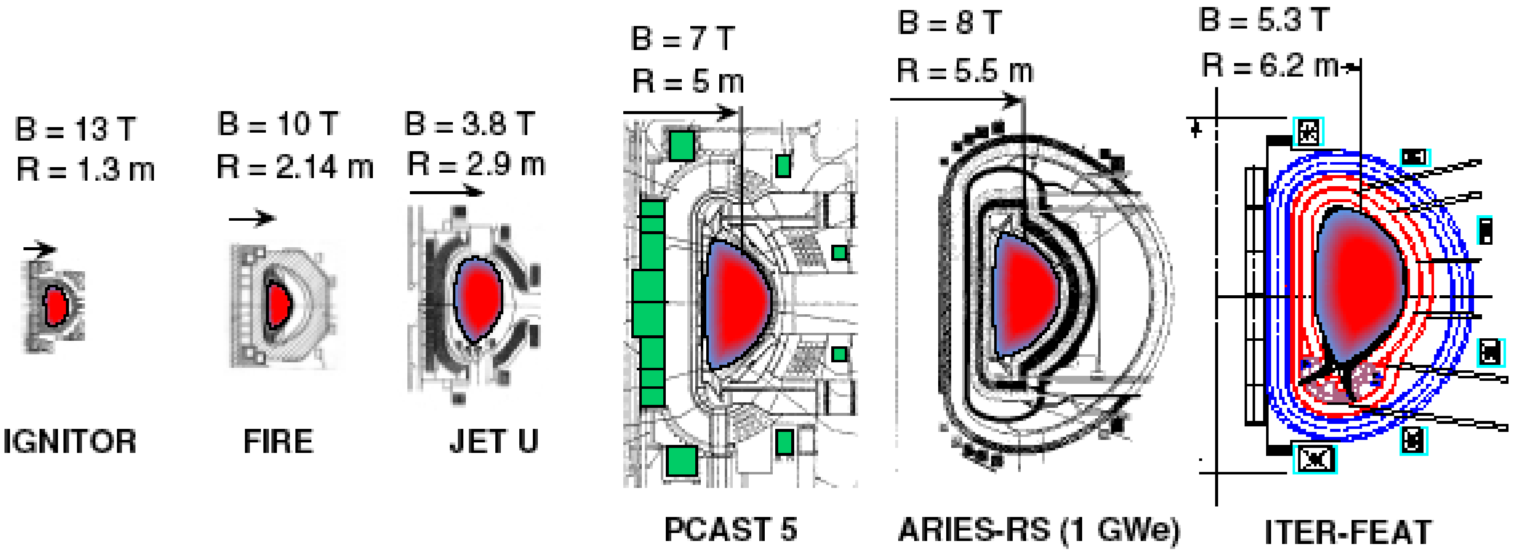
From 1996 to 2004 the US Considered the NEXT Step in MFE

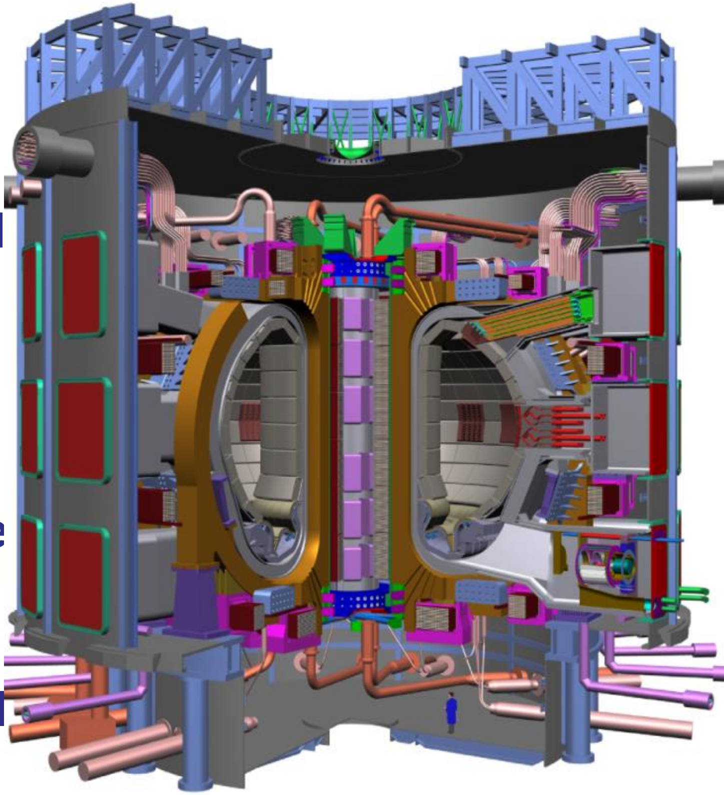


Cost Drivers	IGNITOR	FIRE	JET U	PCAST	ARIES-RS	ITER-FEAT
Plasma Volume (m^3)	11	27	108	390	350	828
Plasma Surface (m^2)	36	60	160	420	420	610
Plasma Current (MA)	12	7.7	6	15	11.3	15
Magnet Energy (GJ)	1.3	5	1.6	40	85	41
Fusion Power (MW)	100	150	30	400	2170	400
Burn Duration (s), inductive	~1	20	10	120	steady	400
τ Burn Flat-top/ τ CR		~2	0.6	1	steady	2
Cost Estimate ($B-2000$) -proposers		1.2	~0.6	7.1	11.2*	5.0
Fusion Core Mass (kilo tonnes)		1.4		10	13	19

* first , $5.6 B for 10th of a kind

AR RS/ITERs/PCAST/FIRE/IGN

ITER was proposed in 2000 by EU, JA and RF to Demonstrate the Scientific and Technological Feasibility of Fusion Power



- **ITER is a large step. The core tokamak is the physical size of a fusion power plant.**
- **For the first time the fusion fuel will be dominantl heated by the fusion reactions.**
  - Today: *10 MW(th) for ~1 second with gain ~1*
  - ITER: 5*00 MW(th) for >300 seconds, gain >10*
- **Many of the technologies used in ITER will be the same as those required in a power plant.**
- **Further science and technology development will be needed to bridge the gap to a fusion DEMO.**

On January 30, 2003 President Bush announced that the US would join the negotiations on the construction and operation of ITER. The US cost was expected to be roughly 10% of the total estimated cost of $5B.

In November 2006 the World Decided to Build ITER

- ITER is now under construction by a seven party (EU, JA, RF, KO, IN, CN and US) international organization. However , as predicted by several wise people - there are issues associated with management structure, etc……….

- This has caused schedule delays and cost increases. Now 1st Plasma ~ 2023, 1st DT plasma >2030, US cost ~$4B

- I personally have confidence that the management problems of ITER can be solved, and that ITER could achieve its technical mission.

- When ITER produces 500MW for 300s at a gain of 10 – there will be a sea-change in how people view fusion energy.

- We (you) must anticipate that sea change, what needs to be done in addition to ITER to realize the promise of Fusion Energy?

Today’s Talk (Discussion)

- The need for an abundant non-CO2 emitting energy source is generally accepted. However, there is debate about whether there is a near term urgency and the best way to produce abundant non-CO2 emitting energy.

- Fusion would be an ideal long term energy source, but…….

  - it is a very difficult scientific and technical challenge

- Where are we today in the pursuit of fusion energy?

- What are the steps that still need to be taken on the road to fusion energy?

- A technical road map with hazards identified, options available and mileage markers is one the first steps in developing a strategic plan for fusion energy.

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. Unfortunately, the US DOE has been resisting the development of a Strategic Plan for fusion energy by the fusion community.

- The European Union has developed a Road Map for Fusion Energy, it has been accepted by the European Commission and was used to justify budget increases for the next EU framework plan – Horizon 2020.

Magnetic Fusion Program Leaders (MFPL) Initiative

U. S. 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

An Advanced Tokamak Path to Fusion Energy

Fusion is Plausible

Fusion is Feasible

Fusion is Practical, Attractive

Fusion is Economical

Fusion Facilities of the World

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)

General Considerations

- Road Map driven by Goal and Associated Missions (Goal is a Fusion Power Plant)

- Strive for quantitative milestones and metrics as mileage markers
  - Technical Readiness Levels
  - Quantitative dimensional and dimensionless Figures of Merit

- Setup logic Framework for Mission milestones and Decision points

- Identify facilities needed to achieve mission milestones

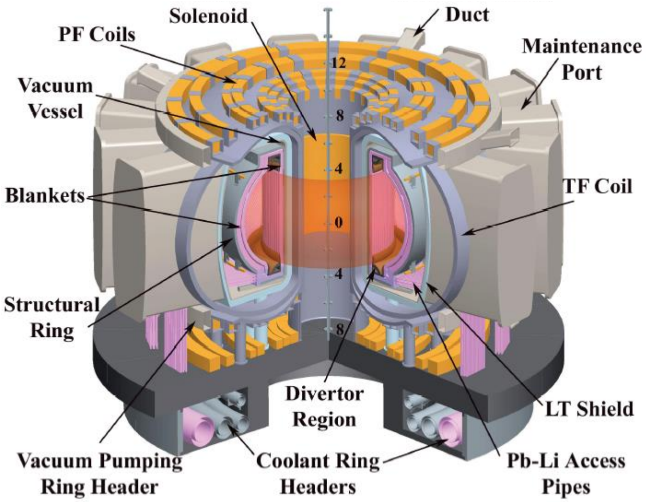
- Must have parallel (overlapping) steps (as in the 1970s) for a reasonable schedule

- Detailed cost estimates are beyond scope our exercise, however
  - Consider ball park cost when choosing steps, avoid Mountain of Death
  - Our charge assumes funding capability to move forward as in 1970s
  - look for near term deliverables to bootstrap funding of later steps

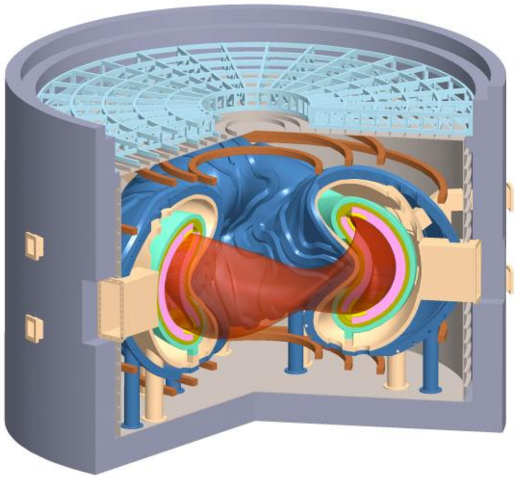
- Gap/Risk Assessment
  - Gap assessment is straight forward, but quantitative risk assessment is difficult.

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) / $B_{\text{max-coil}}$ (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

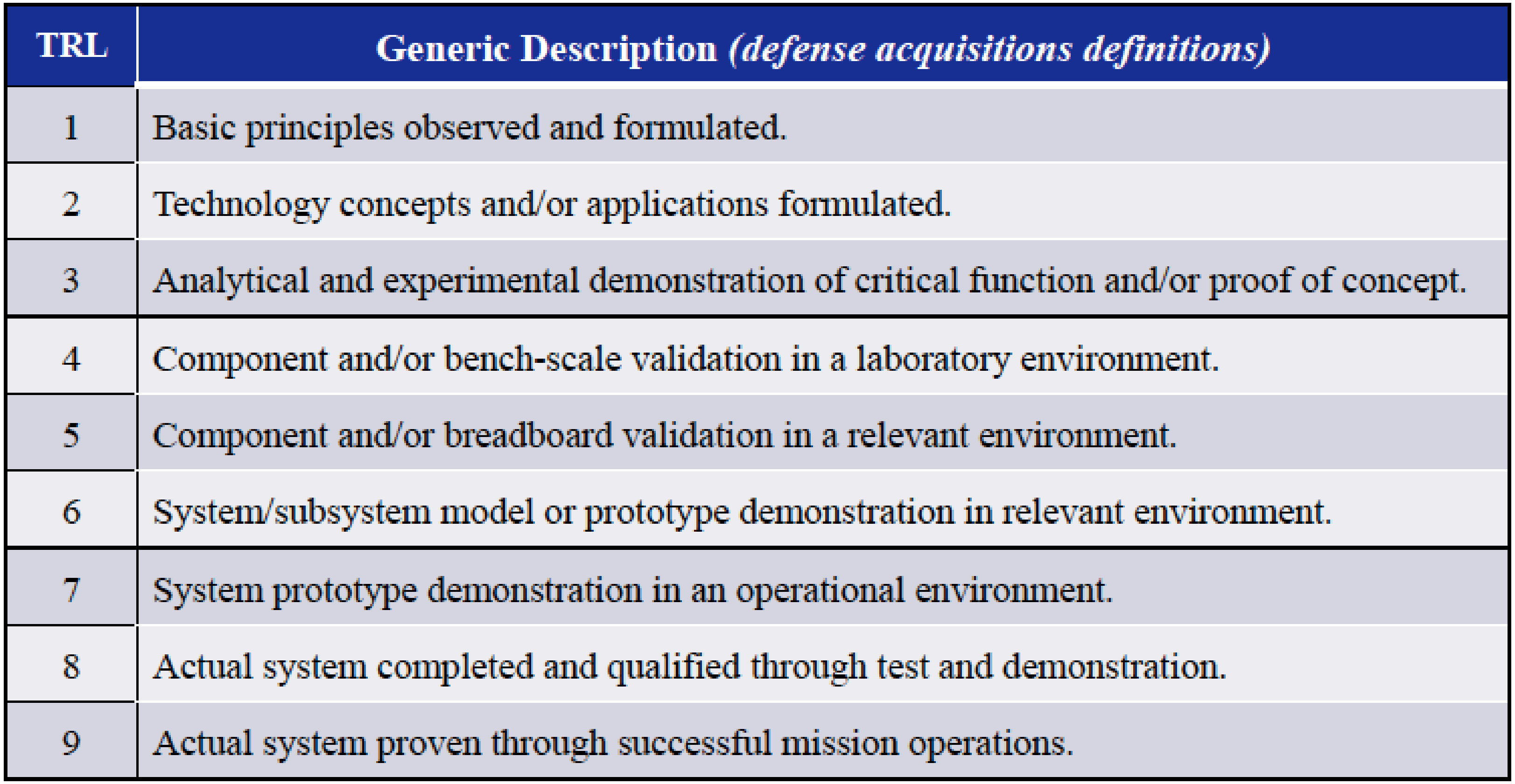
Mission 3. Harness the Power of Fusion

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

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

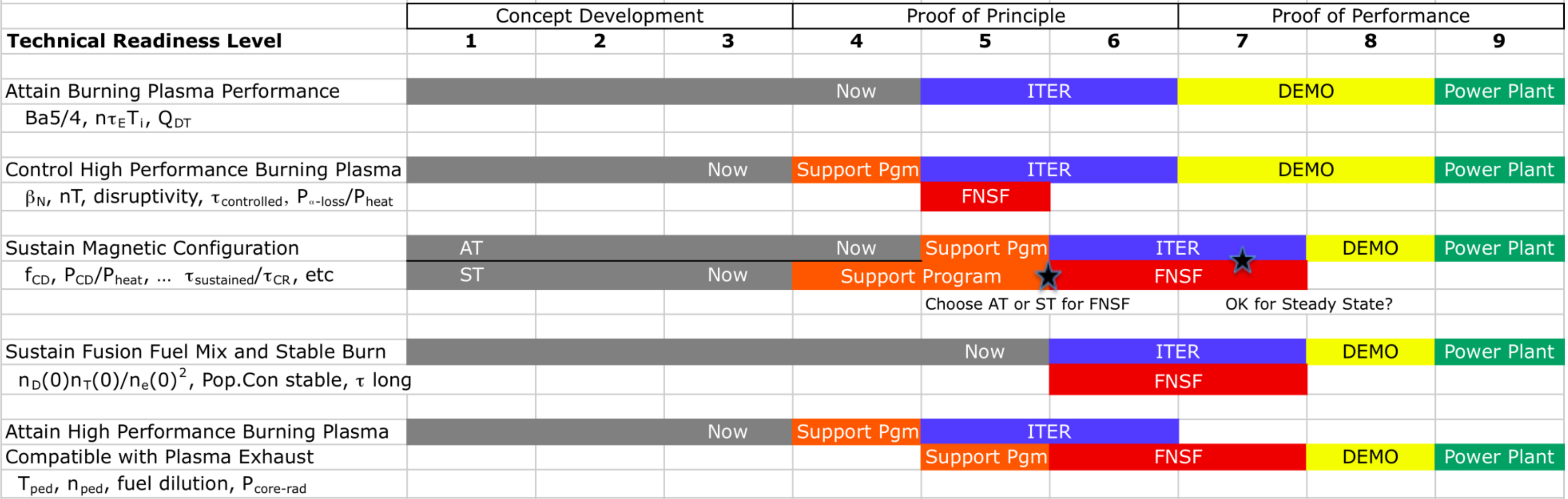


TRL	Generic Description *(defense acquisitions definitions)*
1	Basic principles observed and formulated.
2	Technology concepts and/or applications formulated.
3	Analytical and experimental demonstration of critical function and/or proof of concept.
4	Component and/or bench-scale validation in a laboratory 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.

These terms must be defined for each technology application

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

- Show JT60-SA, etc explicitly
- 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

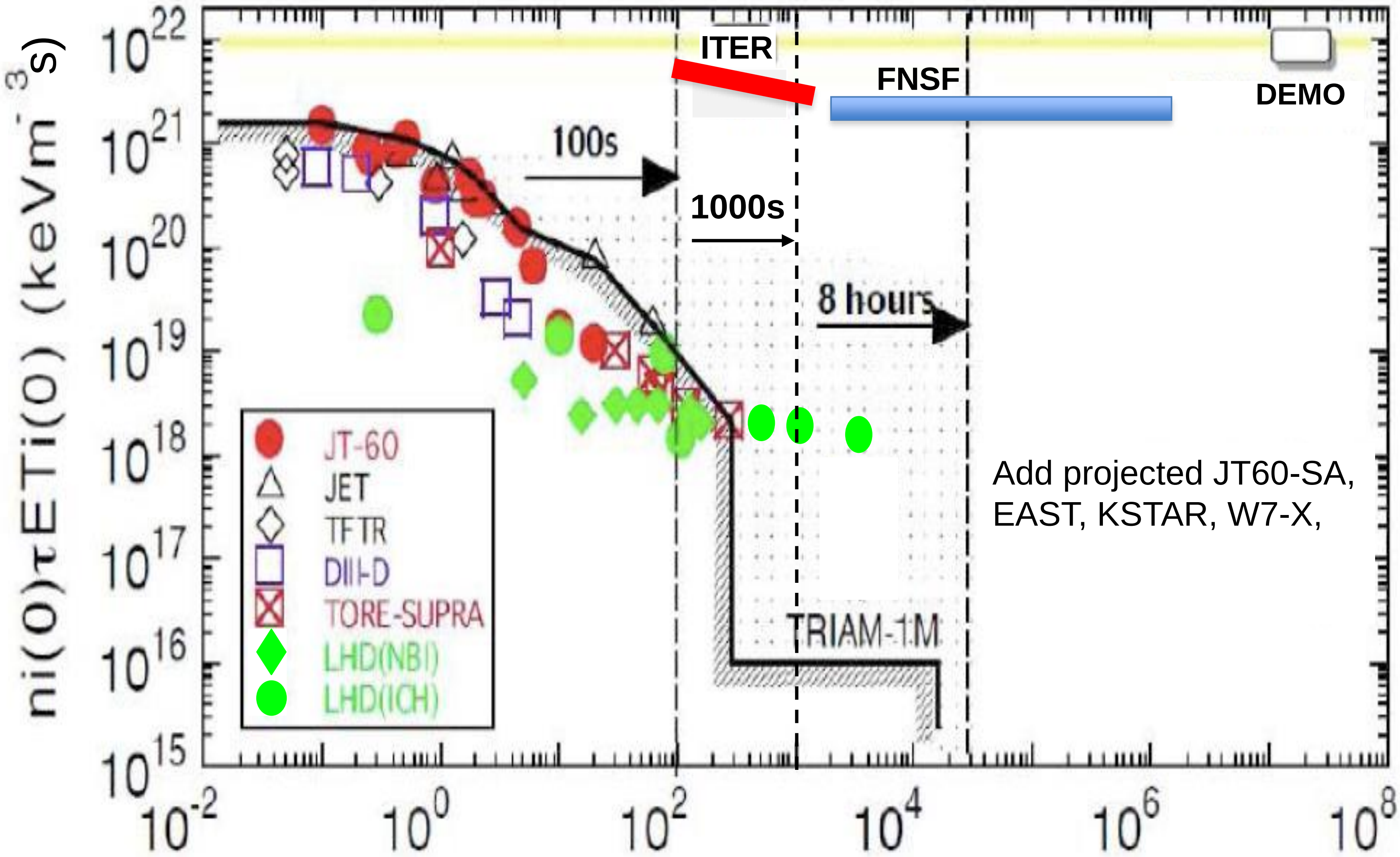
Note- this is linked to an active Excel spreadsheet

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

Mission 1: Create Fusion Power Source



Add projected JT60-SA, EAST, KSTAR, W7-X,

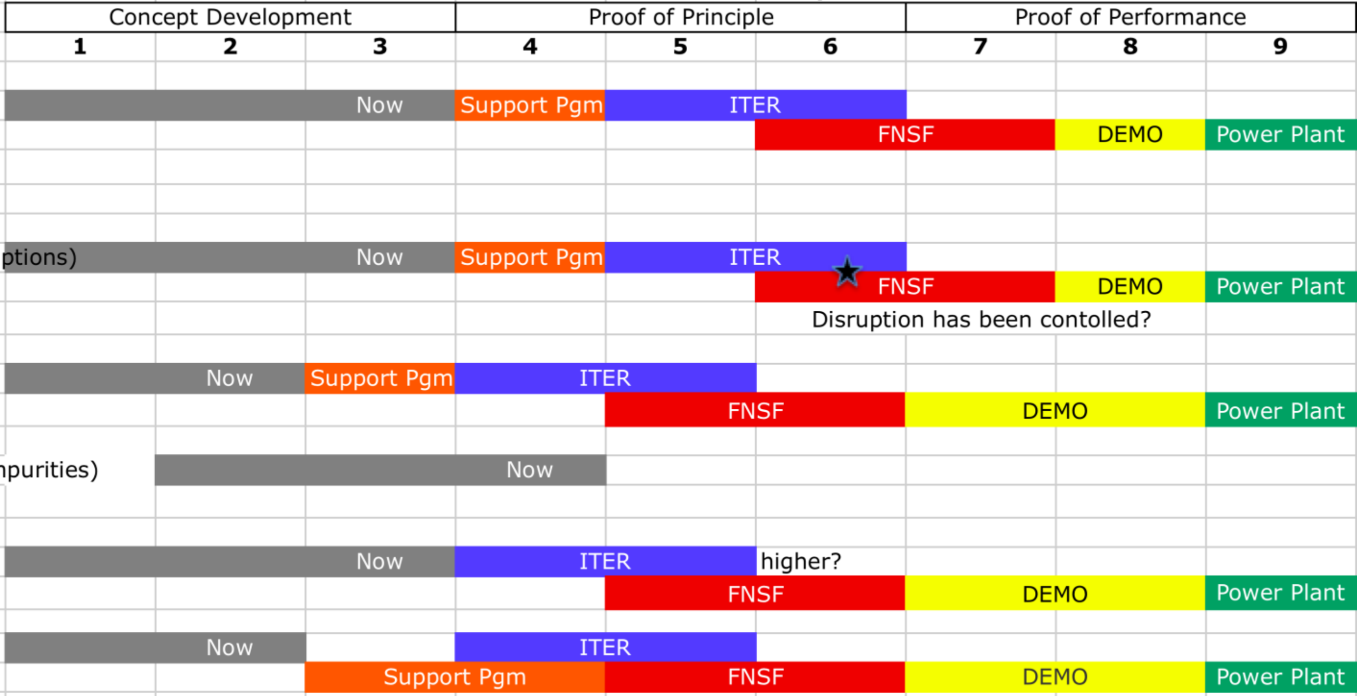
Fusion Plasma Sustainment Time (sec)

FESAC IC Version,
Modification of Kikuchi figure

ITER + FNSF => Advanced Tokamak Demo Pathway

Mission 2: Tame the Plasma Wall Interface

Compare with FESAC Zinkle Pane PMI TRL Chart



	Concept Development			Proof of Principle			Proof of Performance		
Technical Readiness Level	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Remove Plasma Exhaust Heat and			Now	Support Pgm	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 Pgm	ITER				
(integrated with plasma control issue)						★ FNSF		DEMO	Power Plant
MJm^{-2}, freq, freqxMJm^{-2}						Disruption has been contolled?			
Reduce Material Migration (erosion), dust		Now	Support Pgm	ITER					
mm per FPYm^{-2}, lifetime(FPY)					FNSF		DEMO		Power Plant
Control Plasma Contamination (He ash, impurities)				Now					
Z_{eff}, $P_{rad-core}$, $P_{rad-edge}$									
Reduce Tritium Retention			Now	ITER		higher?			
$T_{inventory}$(kG-T),					FNSF		DEMO		Power Plant
Develop Neutron Resistant PFC/FW mat'l		Now		ITER					
dpa, FPY			Support Pgm		FNSF		DEMO		Power Plant

Major Issues

choice of material for FNSF- when?, How?, R&D needed

Test improved divertor configuration - where, when

Integrated test of PFC concept/material/tokamak-plasma

Required pulse length, H/D/T, n-fluence,

Compare with EU assessment esp DTT

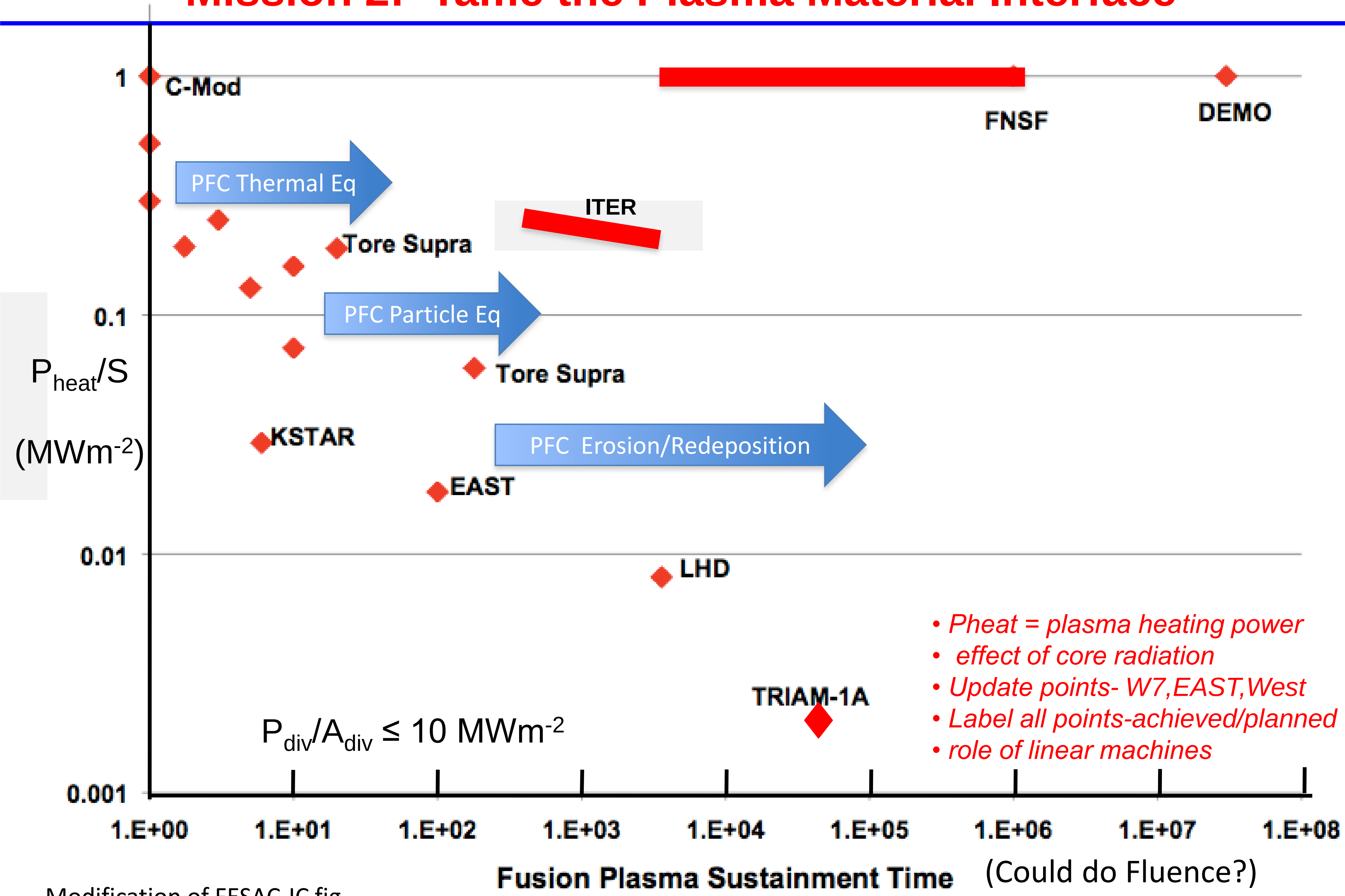
Support Facilities

single effect - high power steady-state linear

toroidal - dedicate existing facilities, upgrade existing or new specialized facility

Need to identify critical PMI facilities

Mission 2: Tame the Plasma Material Interface



$P_{div}/A_{div} \leq 10\ MWm^{-2}$

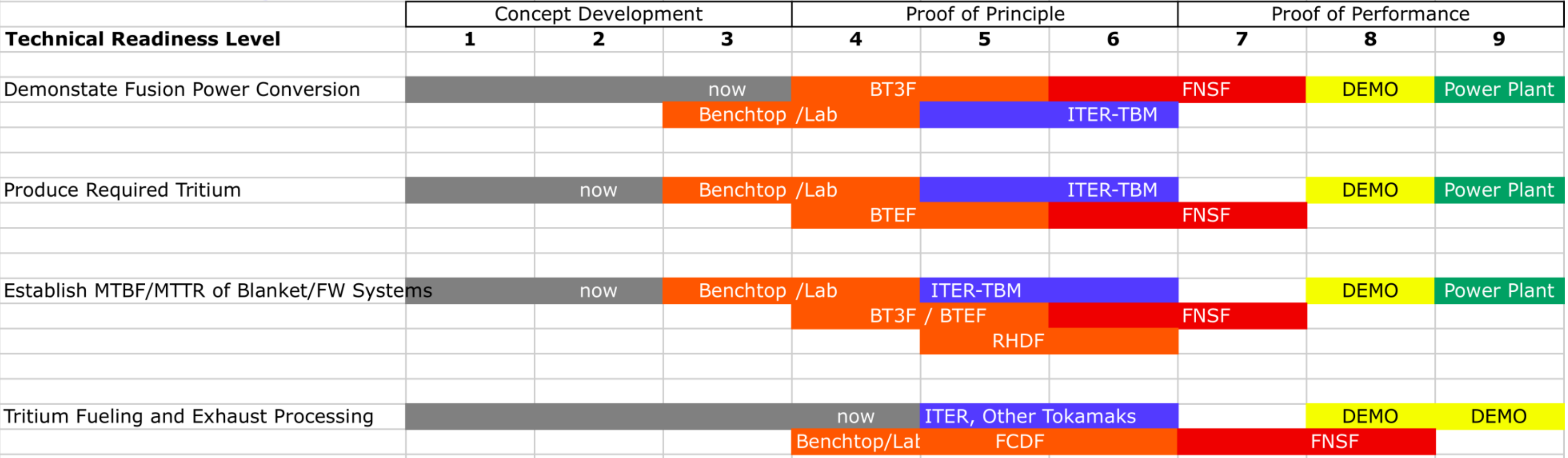
- *Pheat = plasma heating power*
- *effect of core radiation*
- *Update points- W7,EAST,West*
- *Label all points-achieved/planned*
- *role of linear machines*

(Could do Fluence?)

Modification of FESAC-IC fig.

ITER + FNSF => Advanced Tokamak Demo Pathway

Mission 3: Harnessing the Power of Fusion



	Concept Development			Proof of Principle			Proof of Performance		
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

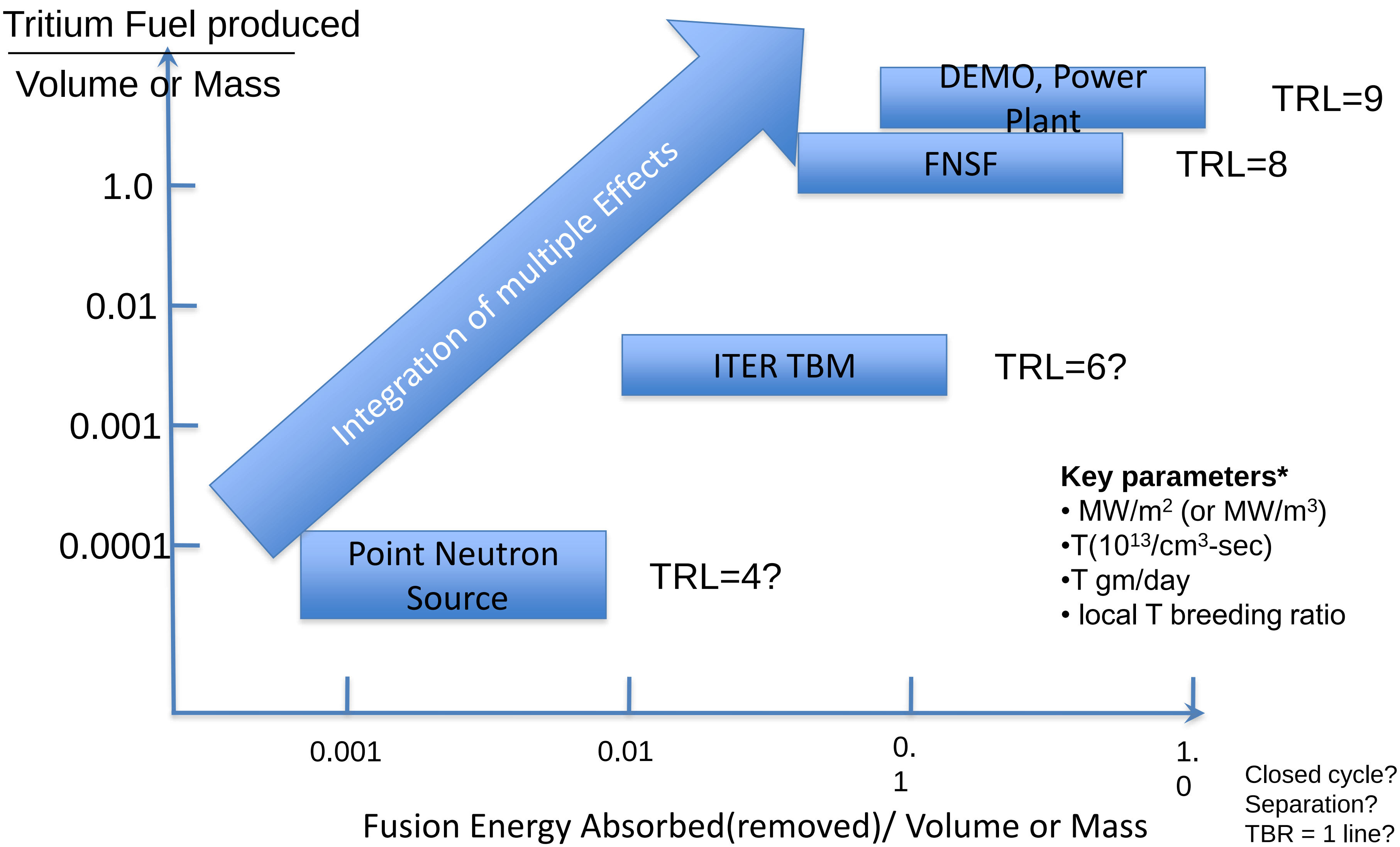
Support Facilities

- 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 (FHDF)
- ITER Test Blanket Module Experiments (ITER-TBM)

Summary of 1st IAEA DEMO Workshop
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.

Mission 3: Harness the Power of Fusion

DRAFT



Tritium Fuel produced / Volume or Mass

1.0

0.01

0.001

0.0001

Integration of multiple Effects

DEMO, Power Plant

TRL=9

FNSF

TRL=8

ITER TBM

TRL=6?

Point Neutron Source

TRL=4?

0.001

0.01

0.1

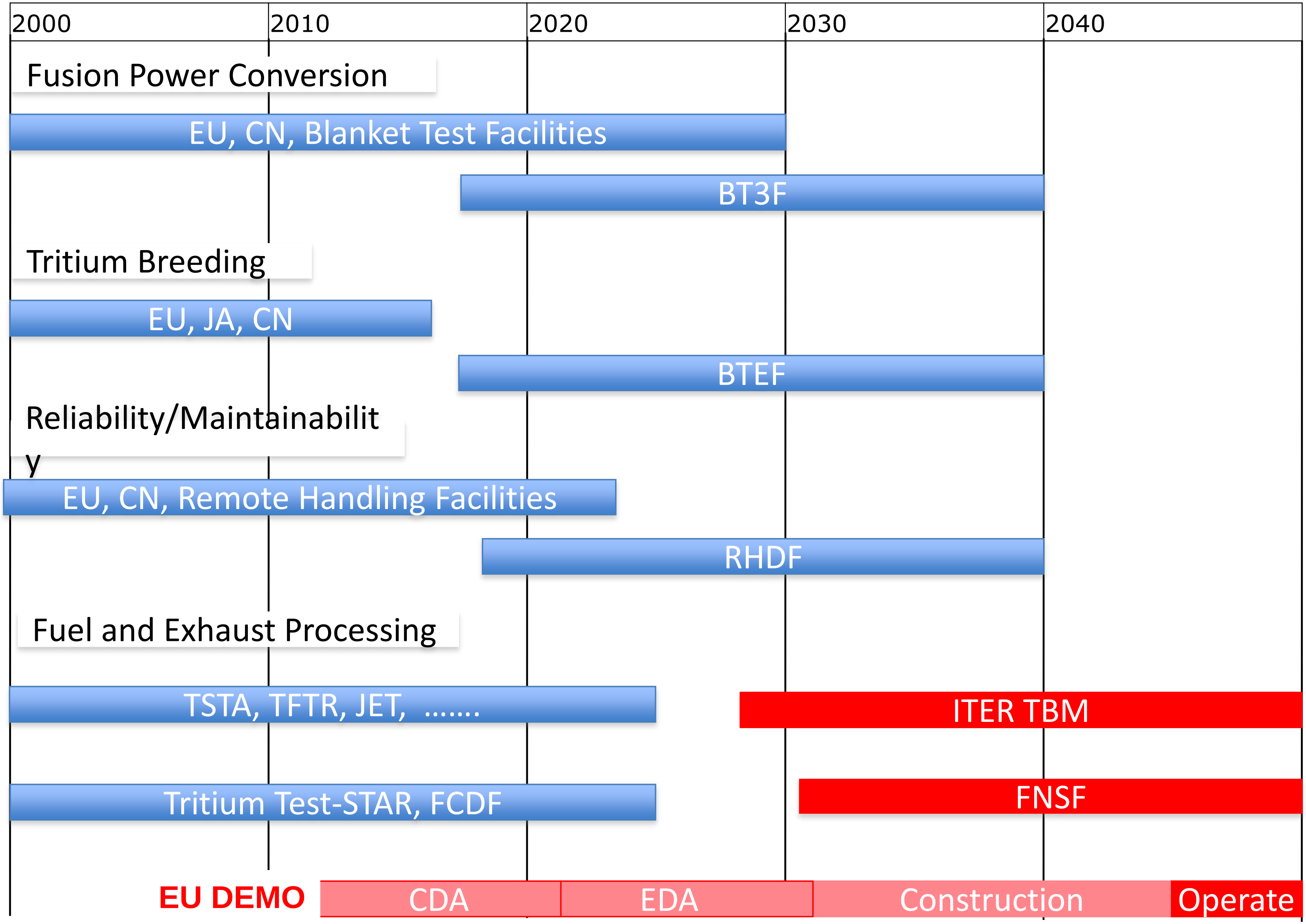
1.0

Fusion Energy Absorbed(removed)/ Volume or Mass

Key parameters*
- MW/m^2 (or MW/m^3)
- T(10^{13}/cm^3-sec)
- T gm/day
- local T breeding ratio

Closed cycle?
Separation?
TBR = 1 line?
Net Elect line?
TSTA, T facilities

Blanket Facilities for all Pathways



ITER + FNSF => Advanced Tokamak Demo Pathway

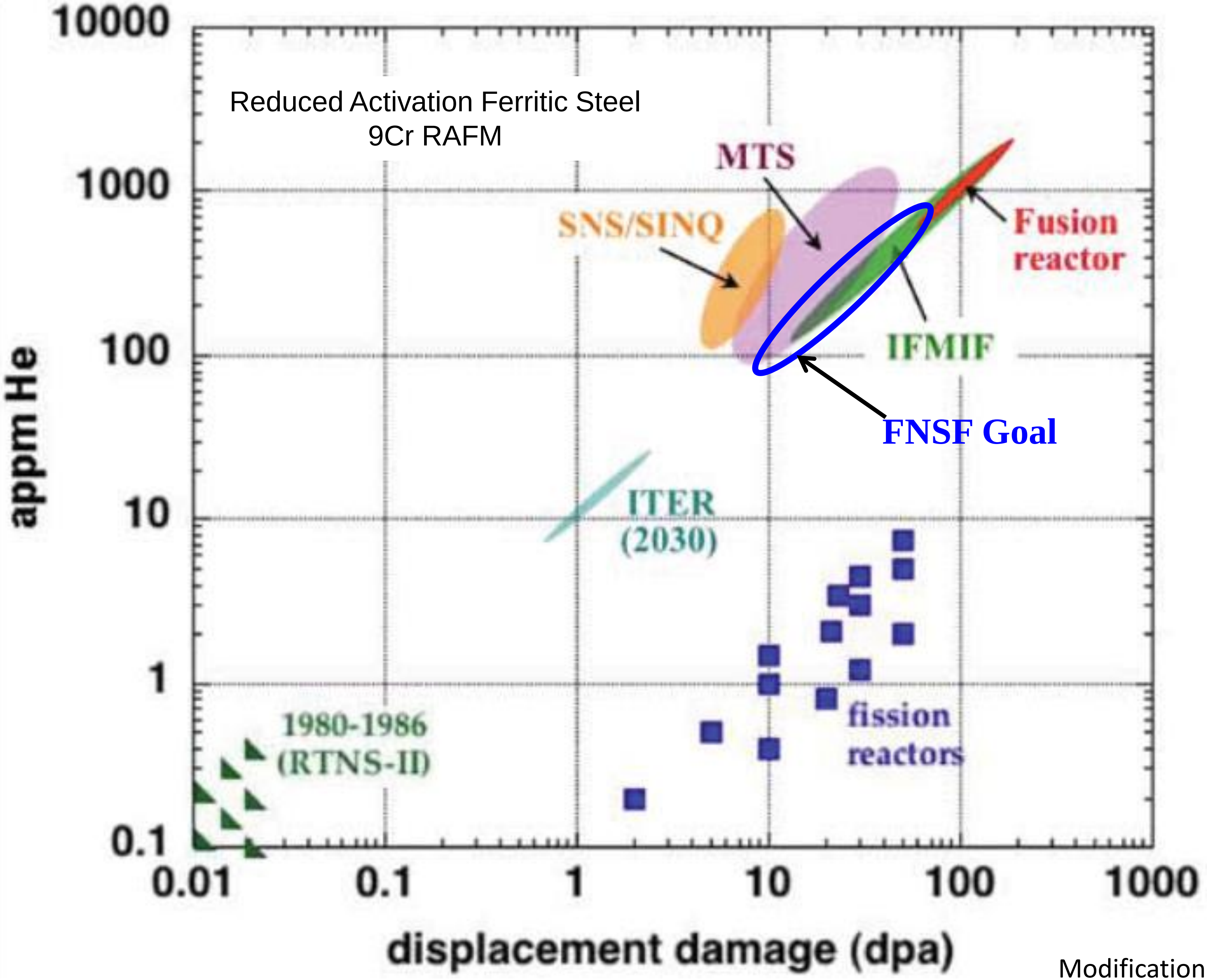
Mission 4: Materials for Fusion Power

	Concept Development			Proof of Principle			Proof of Performance		
Technical Readiness Level	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Conquer Neutron Degradation	Zinkle Table from May 16 Call - this is now a separate Mission.								
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

Major Issues:

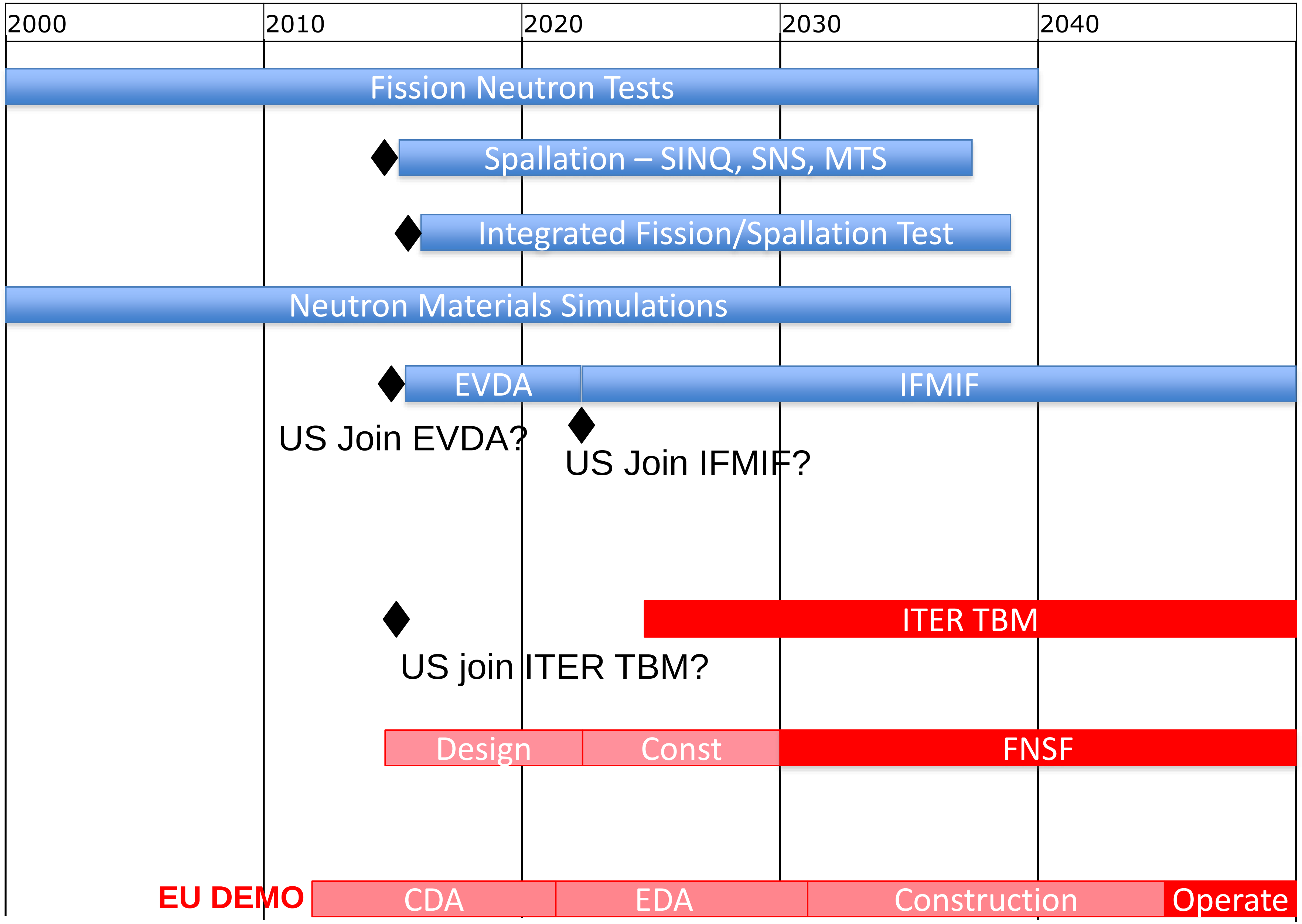
Support Facilities:

Mission 4: Create Materials for Fusion Power



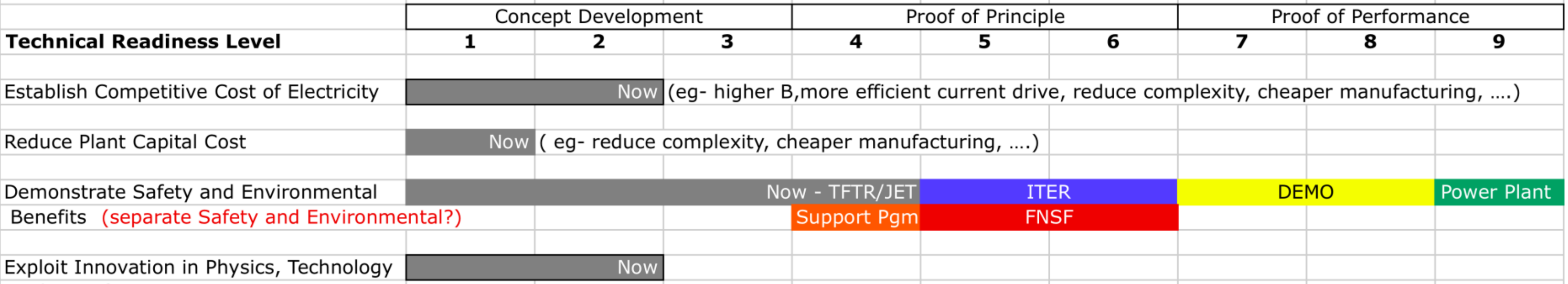
Modification of Zinkle fig.

Materials Facilities for all Pathways



ITER + FNSF => Advanced Tokamak Demo Pathway

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



	Concept Development			Proof of Principle			Proof of Performance		
Technical Readiness Level	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Establish Competitive Cost of Electricity	▨	Now	(eg- higher B,more efficient current drive, reduce complexity, cheaper manufacturing, ….)						
Reduce Plant Capital Cost	Now	(eg- reduce complexity, cheaper manufacturing, ….)							
Demonstrate Safety and Environmental	▨	▨	▨	Now - TFTR/JET	ITER	ITER	DEMO	DEMO	Power Plant
Benefits (separate Safety and Environmental?)				Support Pgm	FNSF	FNSF			
Exploit Innovation in Physics, Technology and Manufacturing	▨	Now							

Major Issues:

Total cost of fusion must be competitive

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

Support Facilities:

Other Important Activities that need to be mentioned somewhere

Supporting Resource 1: Establish Enabling Plasma Technology for Fusion P

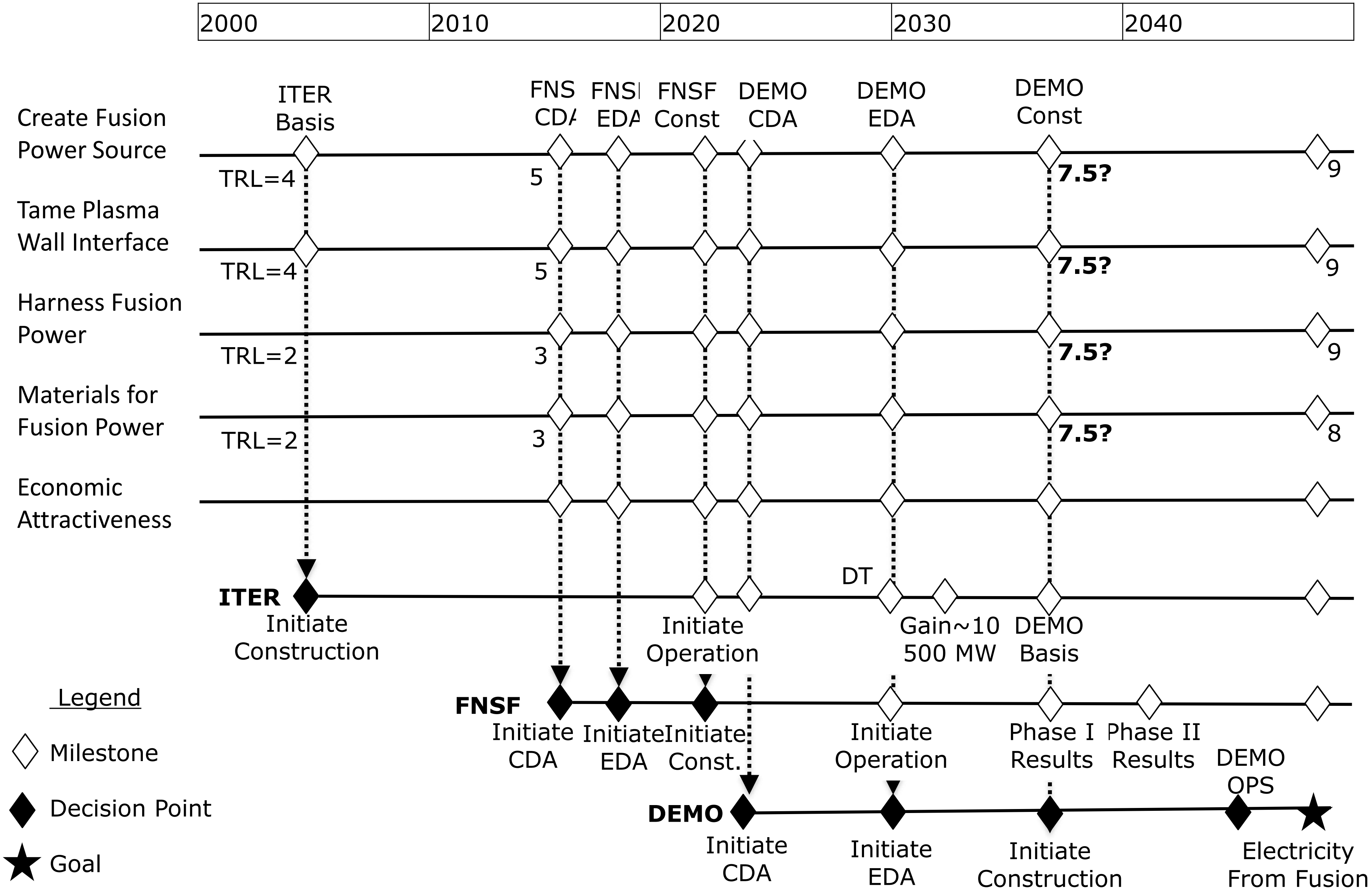
Should we have a full mission on this?? it tends to get lost

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

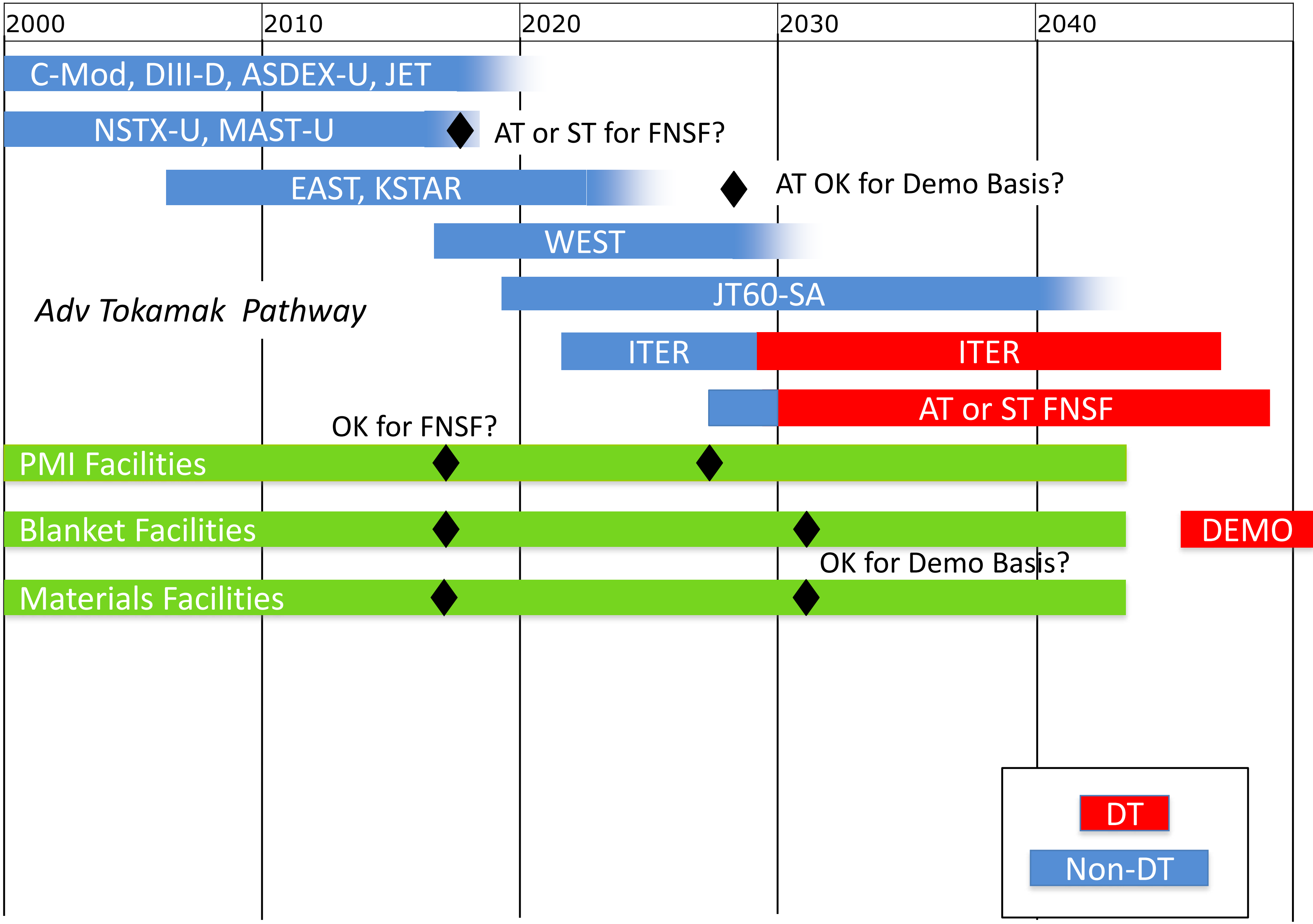
Plasma and Machine Diagnostics
- Plasma Control
- Development of Diagnostics Compatible Fusion Environment

Supporting Resource 2: Strengthening the Educational Infrastructure supporting Fusion Research

ITER + FNSF => AT DEMO Pathway (Logic)

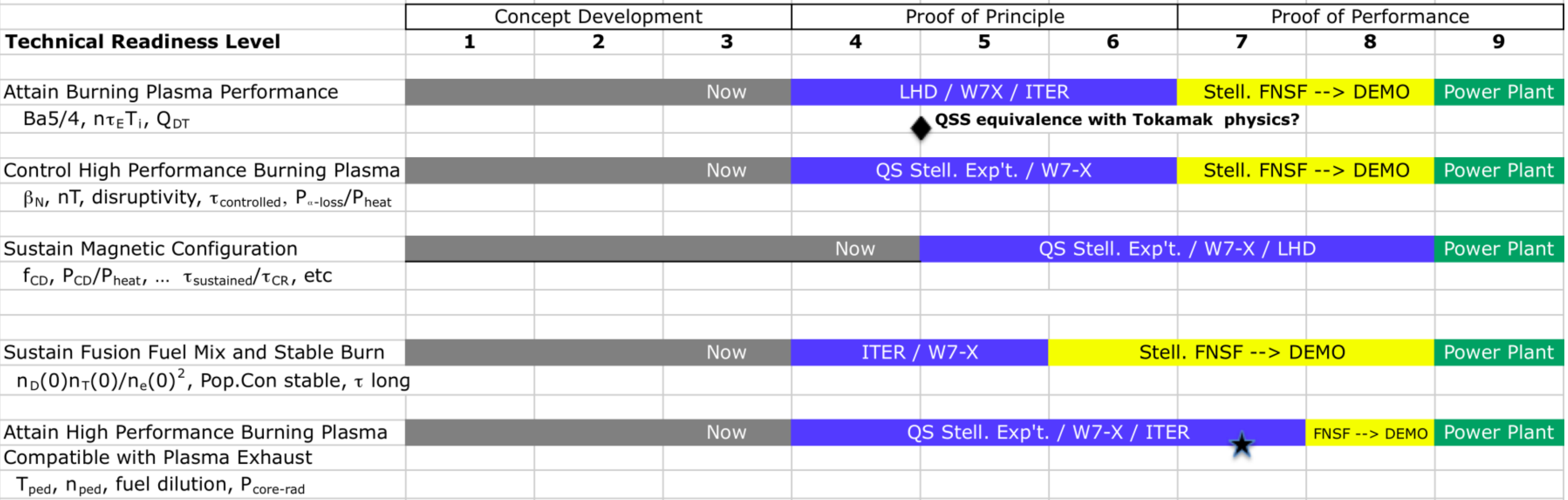


Facilities for US Magnetic Fusion Program Road Map



ITER + Stell Program => Stellarator 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	LHD / W7X / ITER			Stell. FNSF --> DEMO		Power Plant
Ba5/4, $n\tau_E T_i$, Q_{DT}					◆ QSS equivalence with Tokamak physics?				
Control High Performance Burning Plasma			Now	QS Stell. Exp't. / W7-X			Stell. FNSF --> DEMO		Power Plant
β_N, nT, disruptivity, $\tau_{controlled}$, $P_{\alpha\text{-loss}}/P_{heat}$									
Sustain Magnetic Configuration				Now	QS Stell. Exp't. / W7-X / LHD				Power Plant
f_{CD}, P_{CD}/P_{heat}, … $\tau_{sustained}/\tau_{CR}$, etc									
Sustain Fusion Fuel Mix and Stable Burn			Now	ITER / W7-X		Stell. FNSF --> DEMO			Power Plant
$n_D(0)n_T(0)/n_e(0)^2$, Pop.Con stable, τ long									
Attain High Performance Burning Plasma Compatible with Plasma Exhaust			Now	QS Stell. Exp't. / W7-X / ITER			★	FNSF --> DEMO	Power Plant
T_{ped}, n_{ped}, fuel dilution, $P_{core\text{-}rad}$									

Major Issues

Can QS stellarator take credit for ITER burning plasma results?

Does confinement extend to BP regime?

Can high performance be sustained in either with DEMO relevant PFCs?

Can fuel mix be sustained in either?

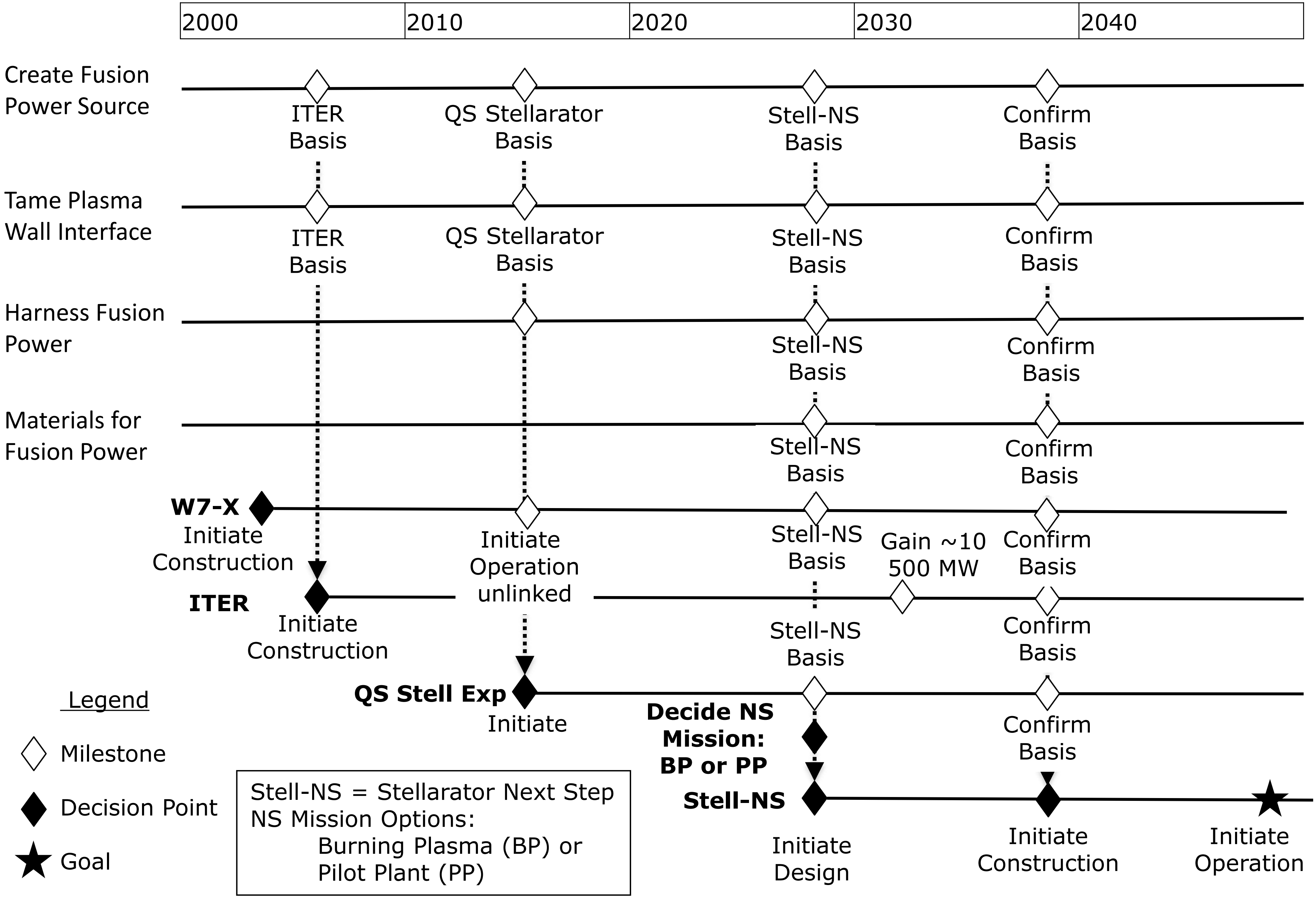
Comments

Stell. FNSF is most likely a pilot plant. Definition of DEMO needs to be clarified.

Assumes Quasi-Symmetric (QS) Stellarator development path, and ITER BP physics results are transferable to QS stellarators.

See next slide for explanation

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



2000 | 2010 | 2020 | 2030 | 2040

Create Fusion Power Source: ITER Basis; QS Stellarator Basis; Stell-NS Basis; Confirm Basis

Tame Plasma Wall Interface: ITER Basis; QS Stellarator Basis; Stell-NS Basis; Confirm Basis

Harness Fusion Power: Stell-NS Basis; Confirm Basis

Materials for Fusion Power: Stell-NS Basis; Confirm Basis

W7-X Initiate Construction; Initiate Operation unlinked; Stell-NS Basis; Confirm Basis

ITER Initiate Construction; Gain ~10 500 MW; Stell-NS Basis; Confirm Basis

QS Stell Exp Initiate; Confirm Basis

Decide NS Mission: BP or PP

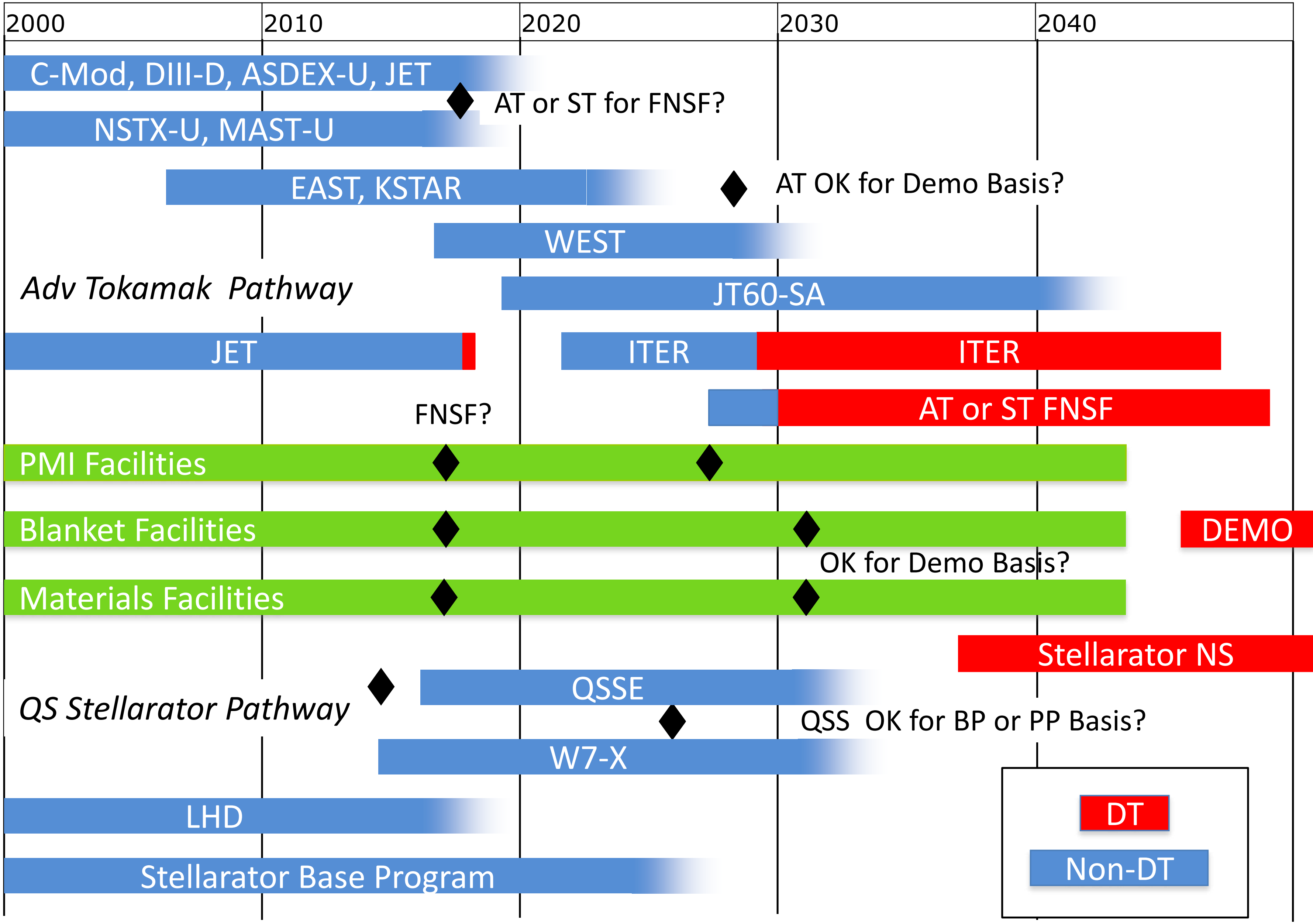
Stell-NS Initiate Design; Initiate Construction; Initiate Operation

Legend

- ◇ Milestone
- ◆ Decision Point
- ★ Goal

Stell-NS = Stellarator Next Step
NS Mission Options:
Burning Plasma (BP) or
Pilot Plant (PP)

Facilities for US Magnetic Fusion Program Road Map



Next Steps for MFE Road Map Activity

- Complete draft framework for each path forward:
  - Review critical issues
    - TRL assessments
    - Milestones-much more work needed, esp. for next 10 years
    - Decision points
    - Complete facility schedules, esp. PMI facilities
  - Define and review the range of possible missions for an FNSF (CTF =>Pilot)
  - 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

Concluding Remarks

- The technical basis for the US to move aggressively to a next major step in MFE is strong. A sufficient basis has been there for 20 years.

- The technical issues to be solved are well understood and a framework has been identified that could help develop a plan to achieve MFE.

- For the other fusion partners in ITER, an abundant energy source with benign environmental impact is a near term urgency, they (esp. the Chinese) are moving forward aggressively.

- The US is out of synch with the world magnetic fusion community, and is in danger of falling from among the leaders to a follower.

- The Lesson of March Madness

- *The Fusion Energy Sciences Advisory Committee has just been asked to prepare a report on priorities for fusion research activities for the next 10 years.*

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

What about Inertial Fusion Energy?

- The construction of the National Ignition Facility (NIF) was initiated in 1994 by the DOE National Nuclear Security Administration, with the goal of supporting stockpile stewardship. The primary NNSA project milestone for NIF is to achieve ignition defined as

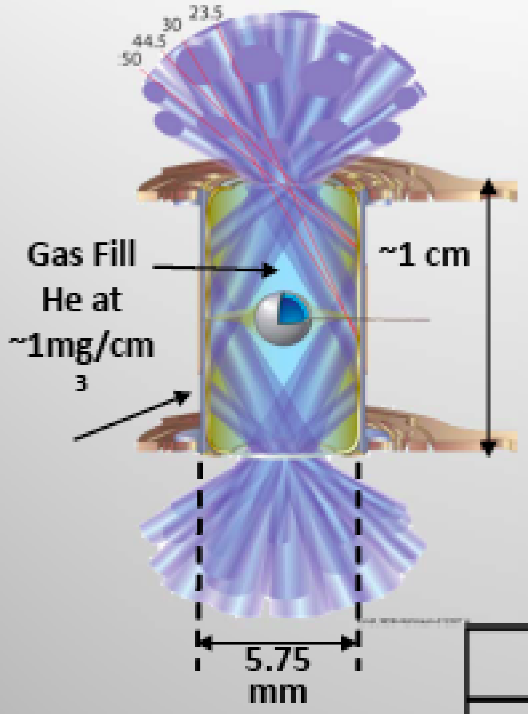
  Fusion Gain = Fusion Energy Produced/Laser Energy on Target = 1

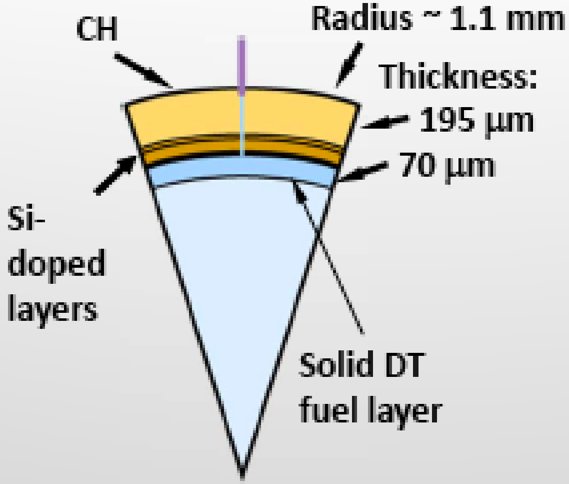
- The NIF was completed in May, 2009 at a cost of ~$4B, and began DT experiments in Sept 2010.

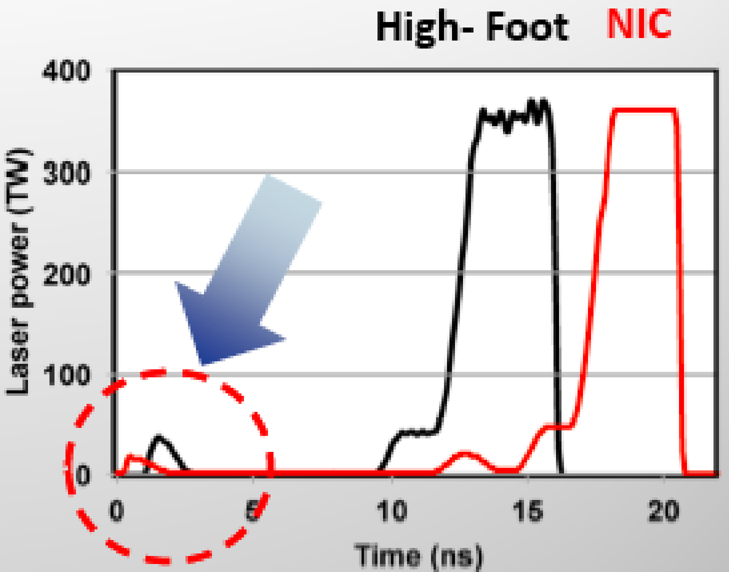
- The NIF laser has performed extremely well at high power (1.8 MJ) and an extensive set of diagnostics has been installed.

- The fusion energy produced has been increased steadily to ≈ 27 kJ, with a corresponding Fusion Gain ≈ 0.015.

A new "High-foot" design uses same target but higher initial laser power to reduce growth of surface perturbations







	NIC Low-foot	High-foot
Adiabat	~1.5	Increased to: ~2.5
In-flight aspect ratio, (IFAR)	~30*	Reduced to: ~10*
Convergence	~45	Reduced to: ~30

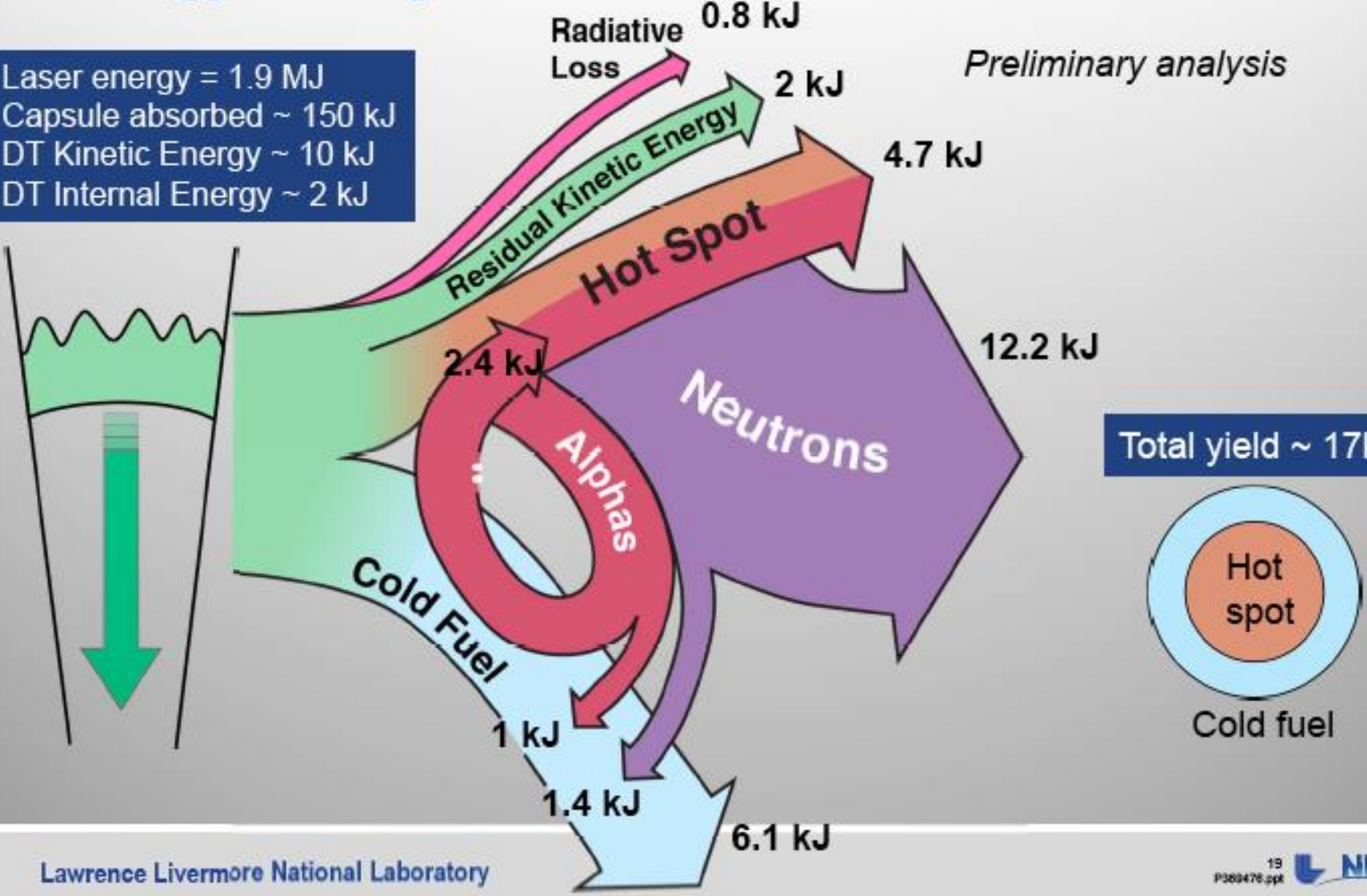
* Analysis ongoing

GOAL: Performance that is understood and well matched to calculations

Alpha energy contributed ~ 50% of the hot spot energy at stagnation for DT shot N131119

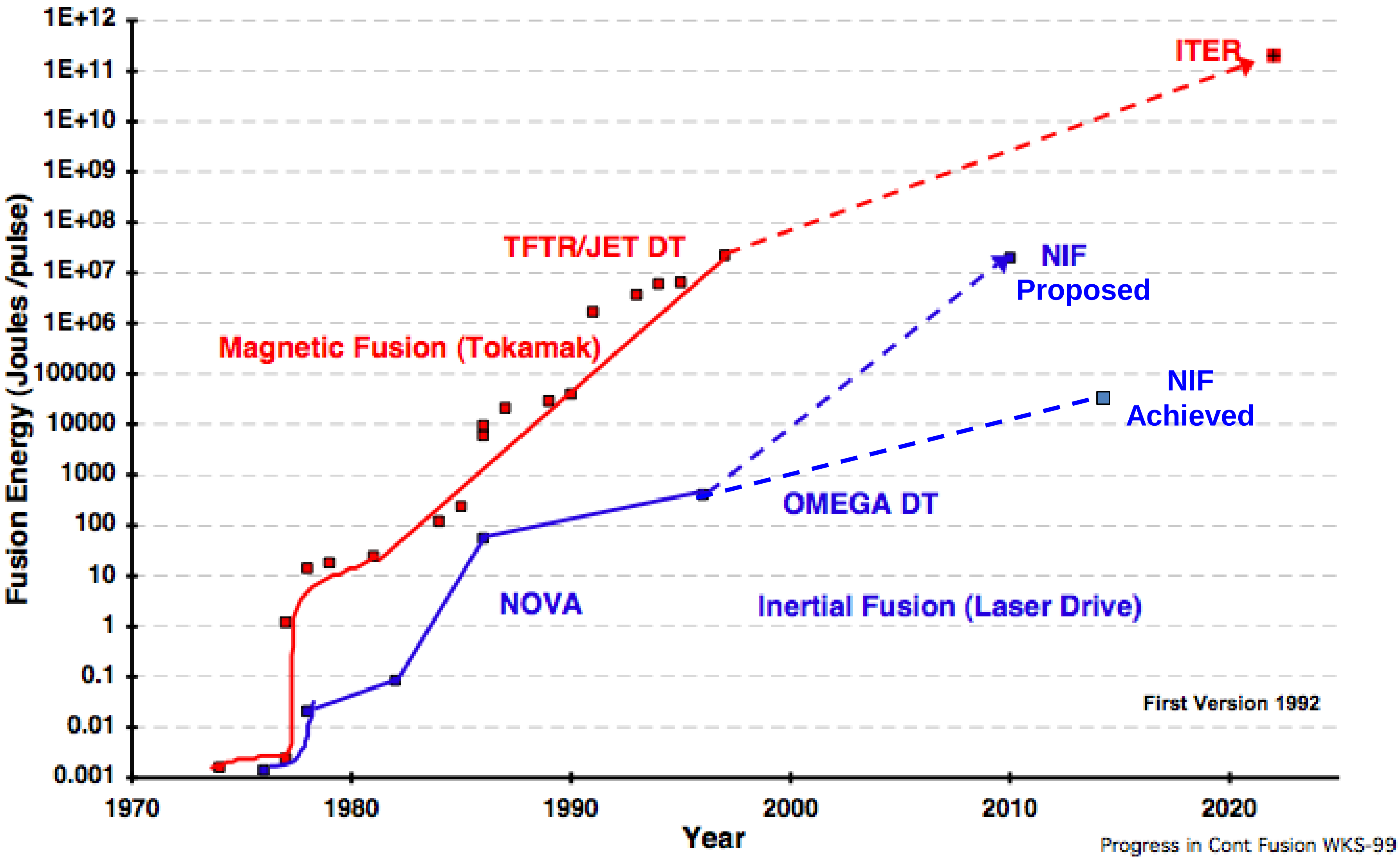
Laser energy = 1.9 MJ
Capsule absorbed ~ 150 kJ
DT Kinetic Energy ~ 10 kJ
DT Internal Energy ~ 2 kJ

Preliminary analysis



Total yield ~ 17kJ

Fusion Energy per Pulse is a Measure of Progress in Fusion Energy



Progress in Cont Fusion WKS-99

Fusion Plasma Performance Required for Fusion Power

The performance achieved on MFE and IFE fusion experiments using DT fuel is compared with the fusion performance required for a Fusion Power Plant.

	Const. Cost $B	Date of Fusion Result		Fusion Yield MJ	Fusion Gain Achieved	Fusion Gain Required for Power Plant		Fuel Gain Achieved	Fuel Gain Required for Power Plant	GAP in Fuel Gain to Power Plant
MFE										
TFTR	$0.5B[1]	1994		7.5	0.28	35		0.28	35	125
JET	$0.5B[1]	1997		22.2	0.65	35		0.65(~1)	35	54
IFE										
NIF	$4.5B[2]	2013		0.028	0.015	65		~2	8,125	4,075
MFE- Under construction				Goal	Goal					Goal
ITER	$20B[3]	2030		200,000	10	35				3.5

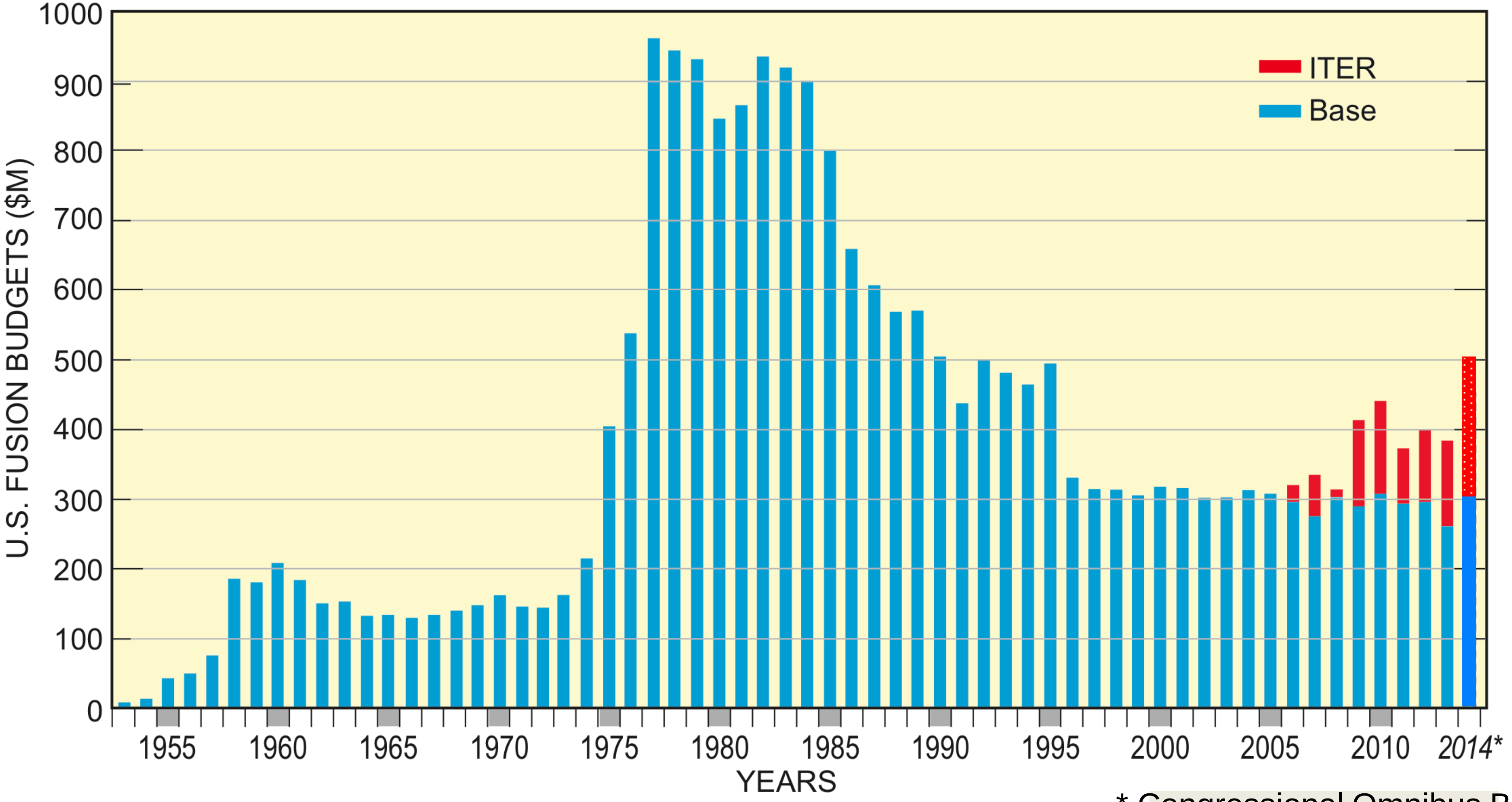
Fusion Yield = fusion energy produced during a single experimental pulse,
MJ is 1 million joules of energy or 1 million watts for 1 second.
Fusion Gain = fusion power produced/ power used to heat fuel (standard definition)
Fuel Gain = fusion power produced/ power absorbed by fuel (a new definition)
In definitions above power is used for magnetic fusion, and energy for inertial fusion

Notes:
1. TFTR and JET construction costs in 1980 dollars
2. NIF construction costs in 2004 dollars
3. ITER Construction Costs estimated by EU in 2013 dollars

May 26, 2014

U.S. Fusion Energy Sciences Funding

(2012 Dollars)



* Congressional Omnibus Bill