Roadmapping an MFE Strategy

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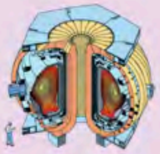
US MFE PROGRAM CAN MOVE TO A FUSION ENERGY DEVELOPMENT PROJECT

- The U.S. MFE program can break out into a directed energy development program whenever desired
  - An accelerated roadmap can make ITER the "penultimate" step to fusion energy

- Requires two major changes to the MFE enterprise
  - An accelerated fusion nuclear science and engineering program
  - Management of fusion energy development as a directed project rather than open-ended science research program

ACCELERATE MFE VIA FUSION NUCLEAR S&T PROGRAM IN ITER TIMEFRAME



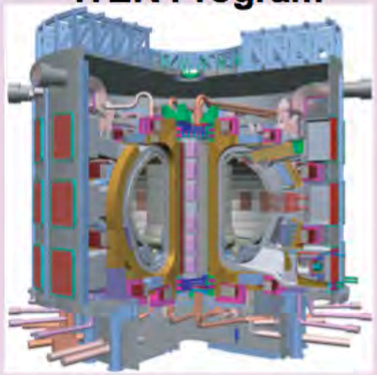
DIII-D

NSTX

Alcator Cmod

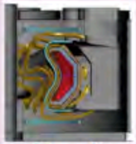
Plasma Confinement Sciences

ITER Program



Major Domestic Facilities

FNF



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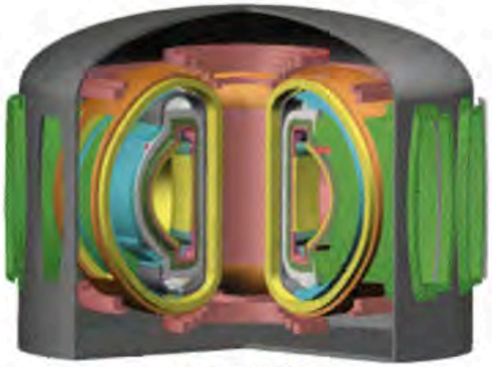
Fusion Nuclear Sciences And Technology

Plasma Confinement Sciences



“DEMO”

Present → ITER timeframe 2020 - 2035 → Construct Decision 2025-2030

THE ISSUES THAT NEED ADDRESSING FOR FUSION ENERGY HAVE BEEN REPEATEDLY IDENTIFIED

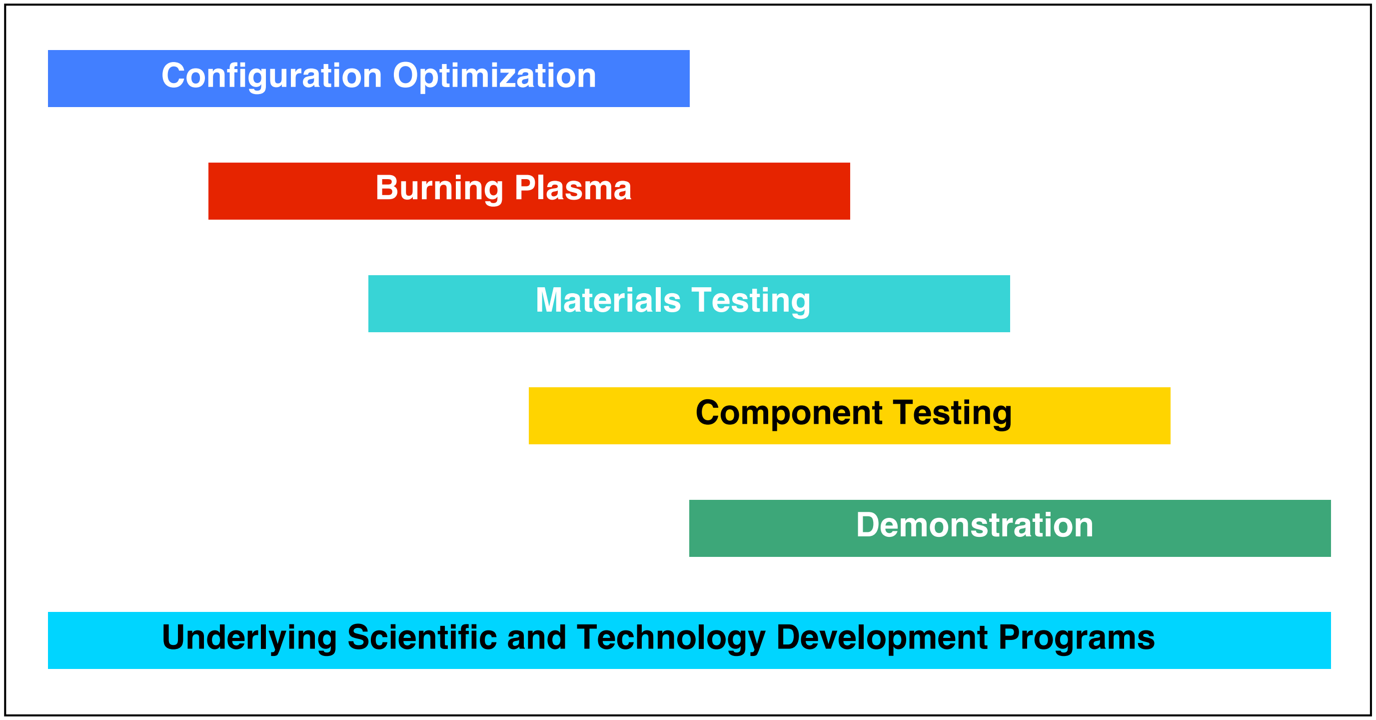
- ITER as one major element: the science of a high gain (Q~10) burning plasma
  - Reactor-scale plasma science: confinement; stability
  - Reactor-relevant technologies: SC magnets; Heating and Diagnostics; initial TBM tests, some PWI, etc.

- U.S. community studies have many times identified the additional elements needed to move to fusion energy, recently
  - 2003: FESAC Plan for Fusion Energy Development
  - 2007-2009: FESAC Priorities, Gaps & Opportunities + ReNew
  - 2010: Fusion Nuclear Science Program (FNSP) White Paper
  - 2010: Pilot Plant concept development

- Similar efforts, and results, pursued by international partners

THE SEQUENCE OF A FUSION ENERGY PROGRAM IS WELL-KNOWN

- Acceleration of generic steps involves parallelization and increased risk management



Configuration Optimization

Burning Plasma

Materials Testing

Component Testing

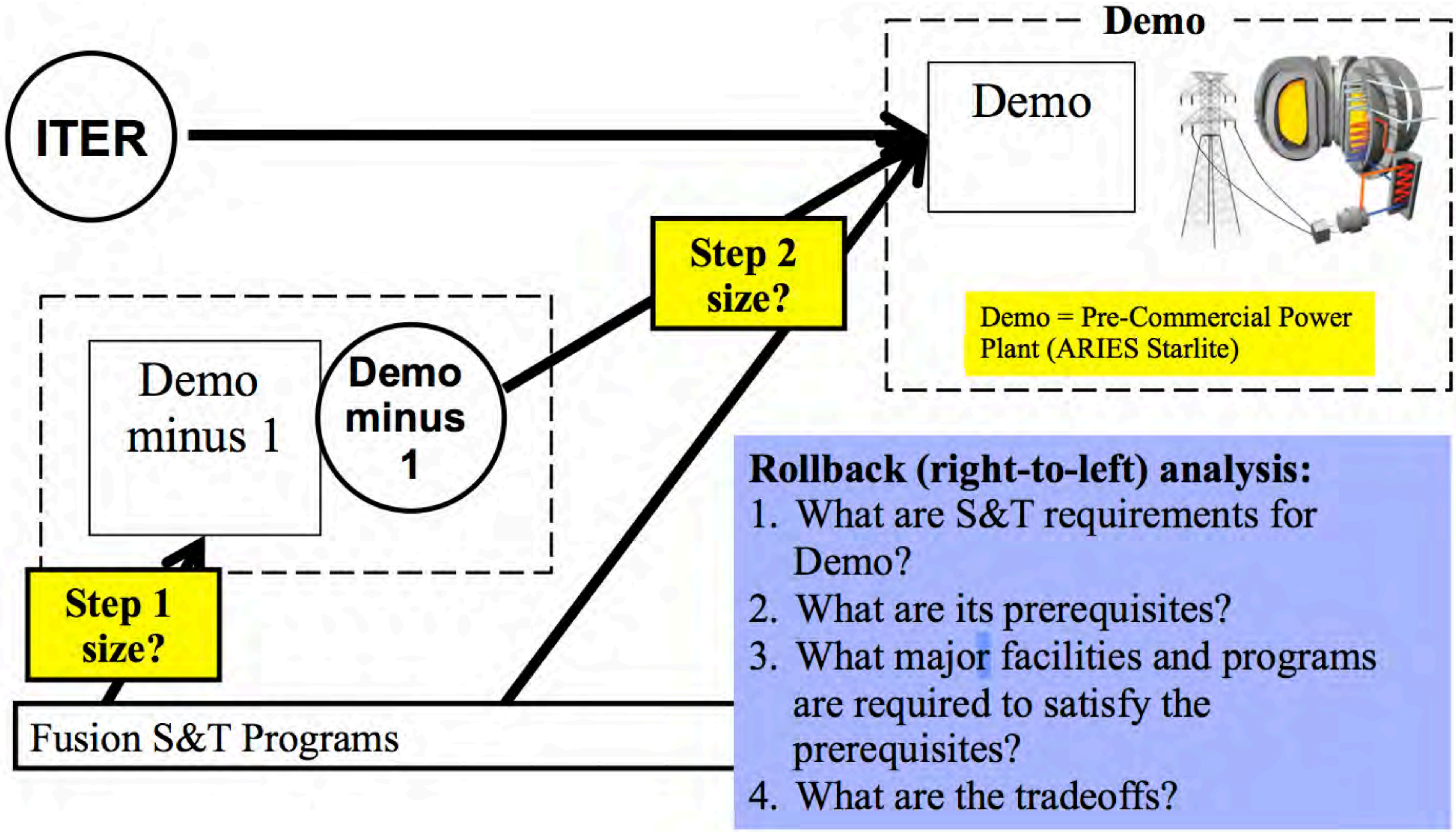
Demonstration

Underlying Scientific and Technology Development Programs

Figure XS3. Overlapping scientific and technological challenges define the sequence of major facilities needed in the fusion development path. Programs in theory and simulation, basic plasma science, concept exploration and proof of principle experimentation, materials development and plasma, fusion chamber and power technologies form the foundation for research on the major facilities.

(from FESAC "Plan for Development of Fusion Energy" DOE/SC-0074; 2003)

Rollback Logic and Risk Assessment to Identify Critical Paths & Issues



ITER

Demo

Demo

Demo = Pre-Commercial Power Plant (ARIES Starlite)

Step 2 size?

Demo minus 1

Demo minus 1

Step 1 size?

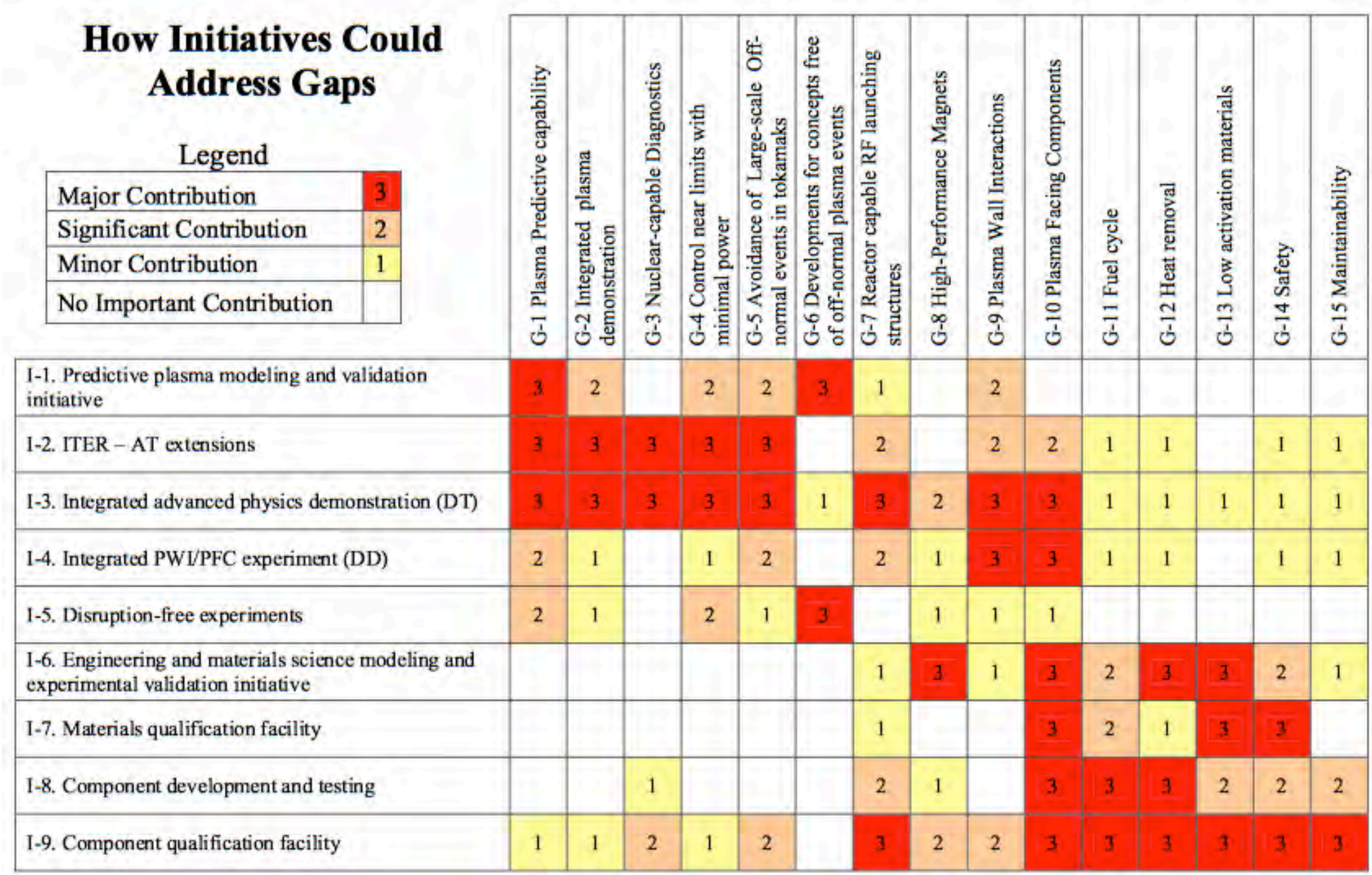
Fusion S&T Programs

Rollback (right-to-left) analysis:

1. What are S&T requirements for Demo?
2. What are its prerequisites?
3. What major facilities and programs are required to satisfy the prerequisites?
4. What are the tradeoffs?

(courtesy G. H. Neilson)

The FESAC 2007 Study Identified Gaps and Potential Means of Filling Them



How Initiatives Could Address Gaps

Legend

Major Contribution	3
Significant Contribution	2
Minor Contribution	1
No Important Contribution	

	G-1 Plasma Predictive capability	G-2 Integrated plasma demonstration	G-3 Nuclear-capable Diagnostics	G-4 Control near limits with minimal power	G-5 Avoidance of Large-scale Off-normal events in tokamaks	G-6 Developments for concepts free of off-normal plasma events	G-7 Reactor capable RF launching structures	G-8 High-Performance Magnets	G-9 Plasma Wall Interactions	G-10 Plasma Facing Components	G-11 Fuel cycle	G-12 Heat removal	G-13 Low activation materials	G-14 Safety	G-15 Maintainability
I-1. Predictive plasma modeling and validation initiative	3	2		2	2	3	1		2						
I-2. ITER – AT extensions	3	3	3	3	3		2		2	2	1	1		1	1
I-3. Integrated advanced physics demonstration (DT)	3	3	3	3	3	1	3	2	3	3	1	1	1	1	1
I-4. Integrated PWI/PFC experiment (DD)	2	1		1	2		2	1	3	3	1	1		1	1
I-5. Disruption-free experiments	2	1		2	1	3		1	1	1					
I-6. Engineering and materials science modeling and experimental validation initiative							1	3	1	3	2	3	3	2	1
I-7. Materials qualification facility							1			3	2	1	3	3	
I-8. Component development and testing			1				2	1		3	3	3	2	2	2
I-9. Component qualification facility	1	1	2	1	2		3	2	2	3	3	3	3	3	3

(from FESAC "Priorities, Gaps, and Opportunities…" 2007)

FUSION NUCLEAR SCIENCE AND TECHNOLOGY: USING AND DEALING WITH FUSION REACTIONS

- Producing significant fusion power in true steady state
- Breeding the T fuel
- Producing high-grade process heat from fusion
- Making chambers and blankets that survive high plasma and neutron fluences
- Measuring plasma properties in a high neutron environment
- Demonstrating advanced plasma performance at DEMO-scale
- Making electricity from the process heat

Roadmap Building Blocks Come in Two Types

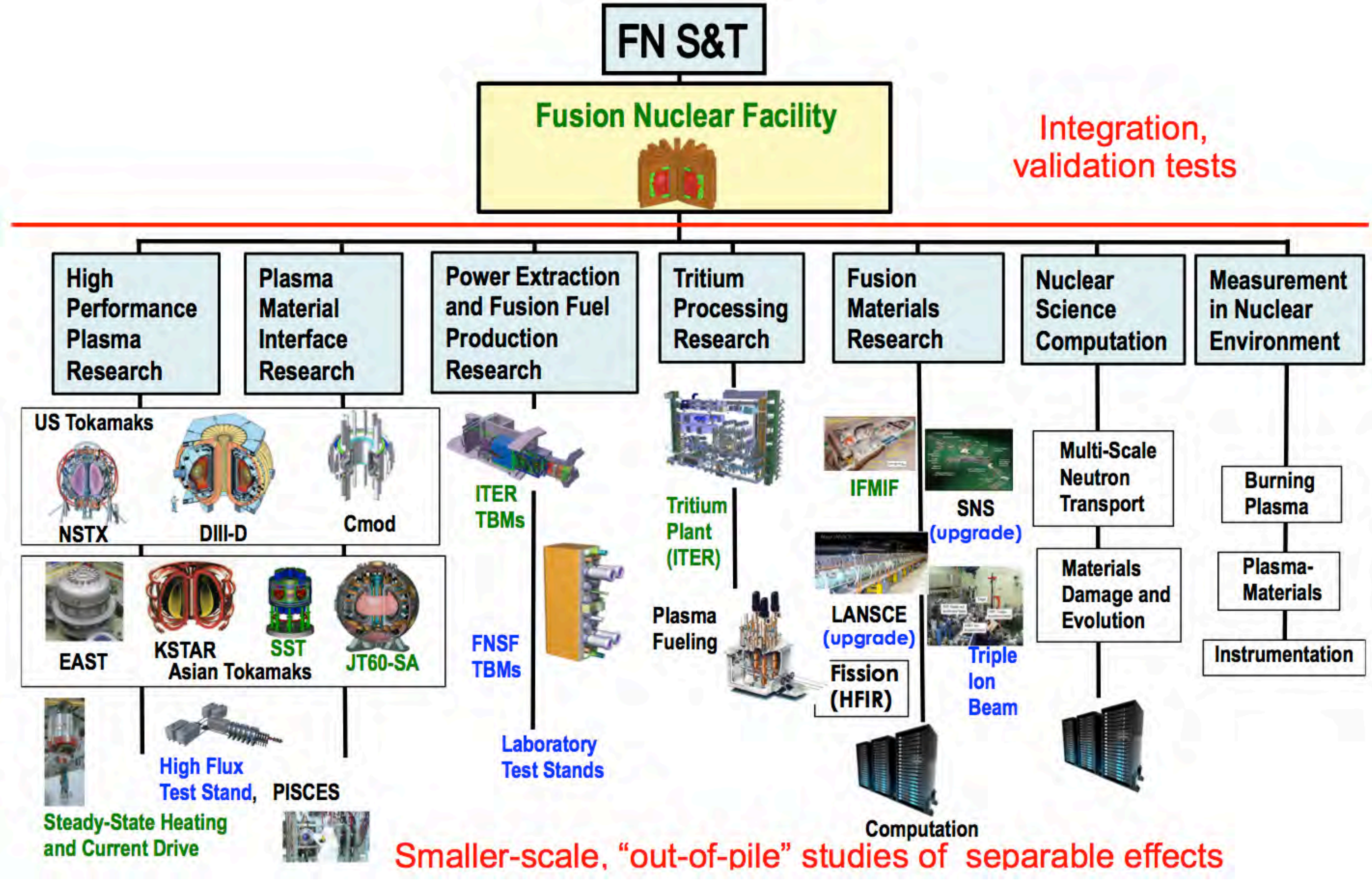
Major Integration Facilities

- Nuclear (e.g., ITER, Demo, Fusion Nuclear Facility)
- Best for integrated testing, validation, and demonstration.

Supporting Research and Development Activities

- Develop physics scenarios and engineering & technology elements individually or in subsets.
- Less integrated, more modular, more flexible.
- Range of sizes from small to > $1B.
- Best for developing and down-selecting options for integration facilities.

Tools for the Necessary Fusion Nuclear Science & Technology Program



FN S&T

Fusion Nuclear Facility

Integration, validation tests

High Performance Plasma Research
- US Tokamaks: NSTX, DIII-D, Cmod
- Asian Tokamaks: EAST, KSTAR, SST, JT60-SA
- Steady-State Heating and Current Drive
- High Flux Test Stand, PISCES

Plasma Material Interface Research

Power Extraction and Fusion Fuel Production Research
- ITER TBMs
- FNSF TBMs
- Laboratory Test Stands

Tritium Processing Research
- Tritium Plant (ITER)
- Plasma Fueling

Fusion Materials Research
- IFMIF
- SNS (upgrade)
- LANSCE (upgrade)
- Fission (HFIR)
- Triple Ion Beam
- Computation

Nuclear Science Computation
- Multi-Scale Neutron Transport
- Materials Damage and Evolution

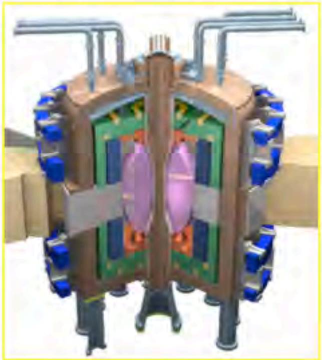
Measurement in Nuclear Environment
- Burning Plasma
- Plasma-Materials
- Instrumentation

Smaller-scale, “out-of-pile” studies of separable effects

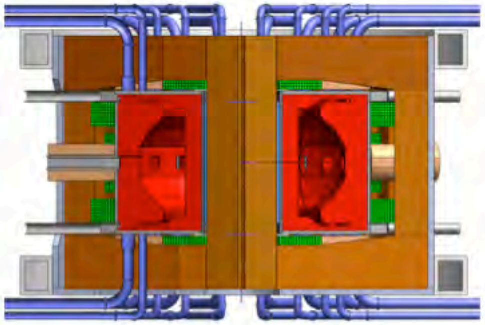
OPTONS FOR THE FUSION NUCLEAR FACILITY

- *Program Mission:*
  Fill the gaps in ITER and existing fusion programs to support a FOAK DEMO construction

FNF-ST

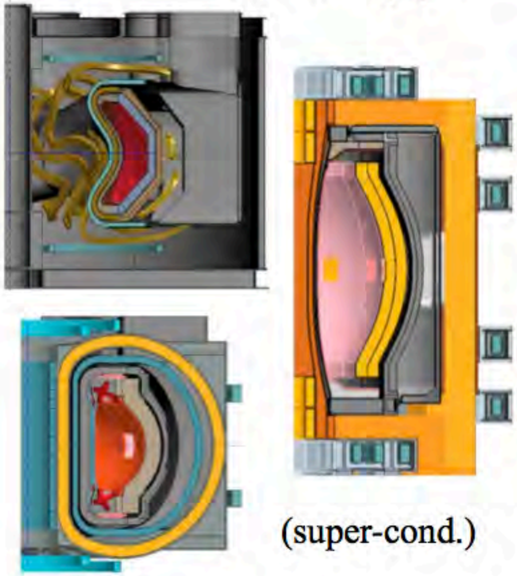


FNF-AT



(copper)

FNF-Pilot Plant(s)



(super-cond.)

FNF Objectives:
- 2-6 MW/m^2 neutron fluxes for long times
- Test/validate materials
  (low activation, high strength,
  high temperature, radiation resistant)
- Tritium breeding; self-sufficiency
- Produce high-grade process heat

Add:
- Enable DEMO-class high-performance plasma research

Add:
- Generate net electricity
- Reactor maintenance schemes

FNF choices lie on continuum between present program and DEMO

Present

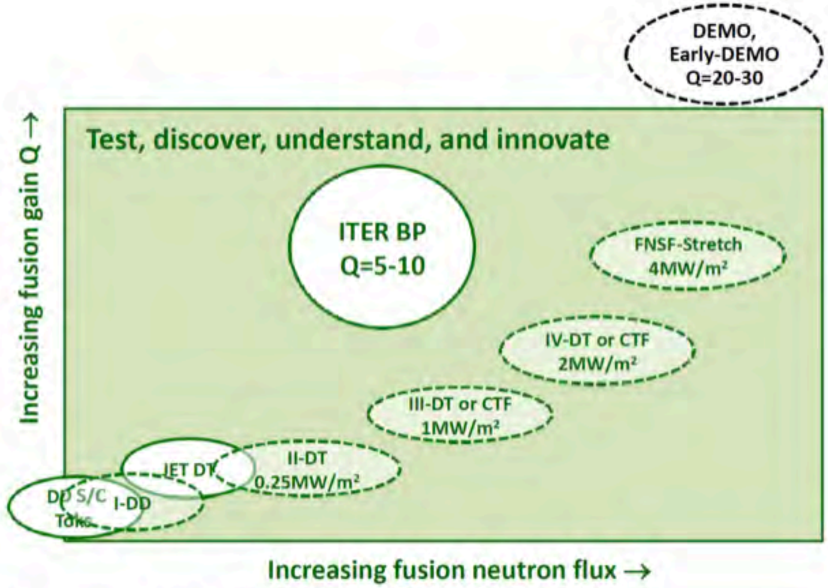
DEMO step (2) size

FNF step (1) size

DEMO

RJF EPRI 2011

ANY INTERMEDIATE FUSION NUCLEAR FACILITY WILL EVOVLE IN STAGES; E.G., FNF-ST

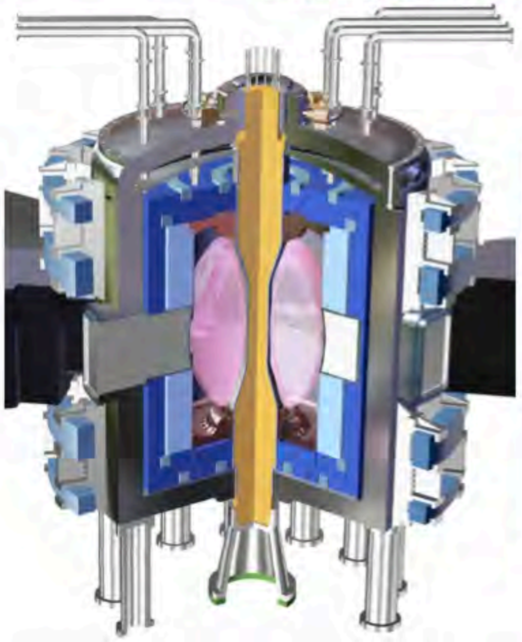


I-DD: 1xJET, verify plasma operation, PMI/PFC, neutronics, shielding, safety, RH system

II-DT: 1xJET, verify FNS research capability: PMI/PFC, tritium cycle, power extraction

III-DT: 2xJET, full FNS research, basis for CTF

IV-DT: 3xJET, “stretch” FNS & CTF research

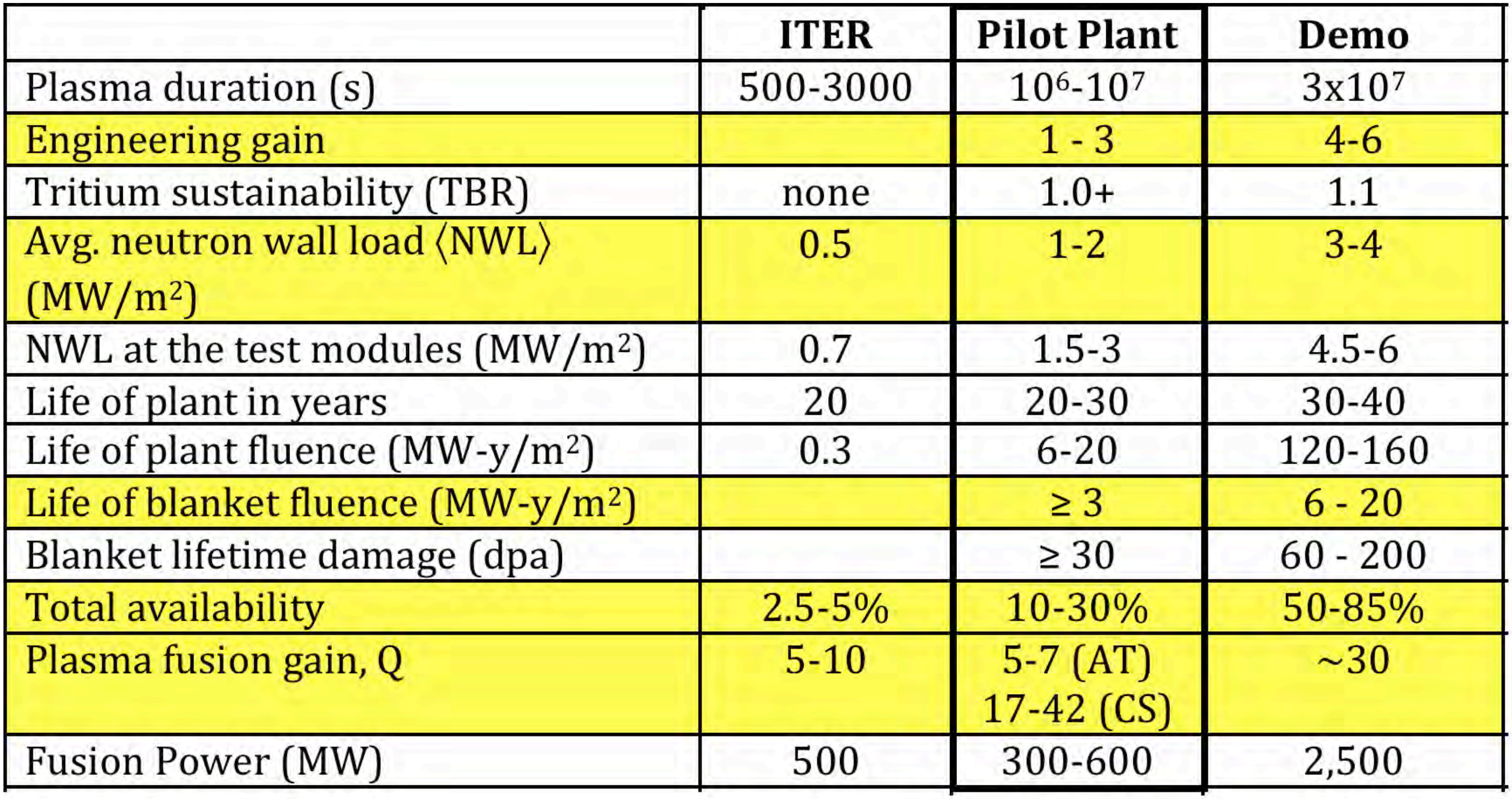


- $R_0 = 1.3\text{m}, A = 1.7$
- $H_H \leq 1.25$, $\beta/\beta_N \leq 0.75$
- $q_{cyl} \geq 4$
- $J_{TF\text{-}avg} \leq 4\text{kA/cm}^2$
- Mid-plane test area $\geq 10\text{m}^2$
- Outboard T breeder $\sim 50\text{m}^2$

Stage-Fuel	I-DD	II-DT	III-DT	IV-DT
Current, I_p (MA)	4.2	4.2	6.7	8.4
Plasma pressure (MPa)	0.16	0.16	0.43	0.70
W_L (MW/m²)	0.005	0.25	1.0	2.0
Fusion gain Q	0.01	0.86	1.7	2.5
Fusion power (MW)	0.2	19	76	152
Tritium burn rate (g/yr)	0	≤105	≤420	≤840
Field, B_T (T)	2.7	2.7	2.9	3.6
Safety factor, q_{cyl}	6.0	6.0	4.1	4.1
Toroidal beta, β_T (%)	4.4	4.4	10.1	10.8
Normal beta, β_N	2.1	2.1	3.3	3.5
Avg density, n_e ($10^{20}/m^3$)	0.54	0.54	1.1	1.5
Avg ion T_i (keV)	7.7	7.6	10.2	11.8
Avg electron T_e (keV)	4.2	4.3	5.7	7.2
BS current fraction	0.45	0.47	0.50	0.53
NBI H&CD power (MW)	26	22	44	61
NBI energy to core (kV)	120	120	235	330

(courtesy M. Peng)

Pilot Plant is Within a Factor ~2 of Demo in Key Metrics to Minimize Risks in Last Step

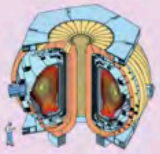


	ITER	Pilot Plant	Demo
Plasma duration (s)	500-3000	10^6-10^7	$3\mathrm{x}10^7$
Engineering gain		1 - 3	4-6
Tritium sustainability (TBR)	none	1.0+	1.1
Avg. neutron wall load ⟨NWL⟩ (MW/m^2)	0.5	1-2	3-4
NWL at the test modules (MW/m^2)	0.7	1.5-3	4.5-6
Life of plant in years	20	20-30	30-40
Life of plant fluence (MW-y/m^2)	0.3	6-20	120-160
Life of blanket fluence (MW-y/m^2)		≥ 3	6 - 20
Blanket lifetime damage (dpa)		≥ 30	60 - 200
Total availability	2.5-5%	10-30%	50-85%
Plasma fusion gain, Q	5-10	5-7 (AT) 17-42 (CS)	~30
Fusion Power (MW)	500	300-600	2,500

- Largest remaining gap is fusion gain Q (factor ~6), unless Pilot Plant is a stellarator.

(courtesy G. H. Neilson)

ACCELERATE MFE VIA FUSION NUCLEAR S&T PROGRAM IN ITER TIMEFRAME



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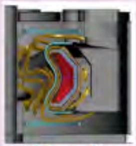

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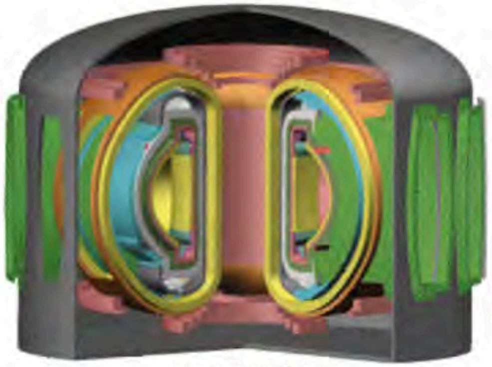
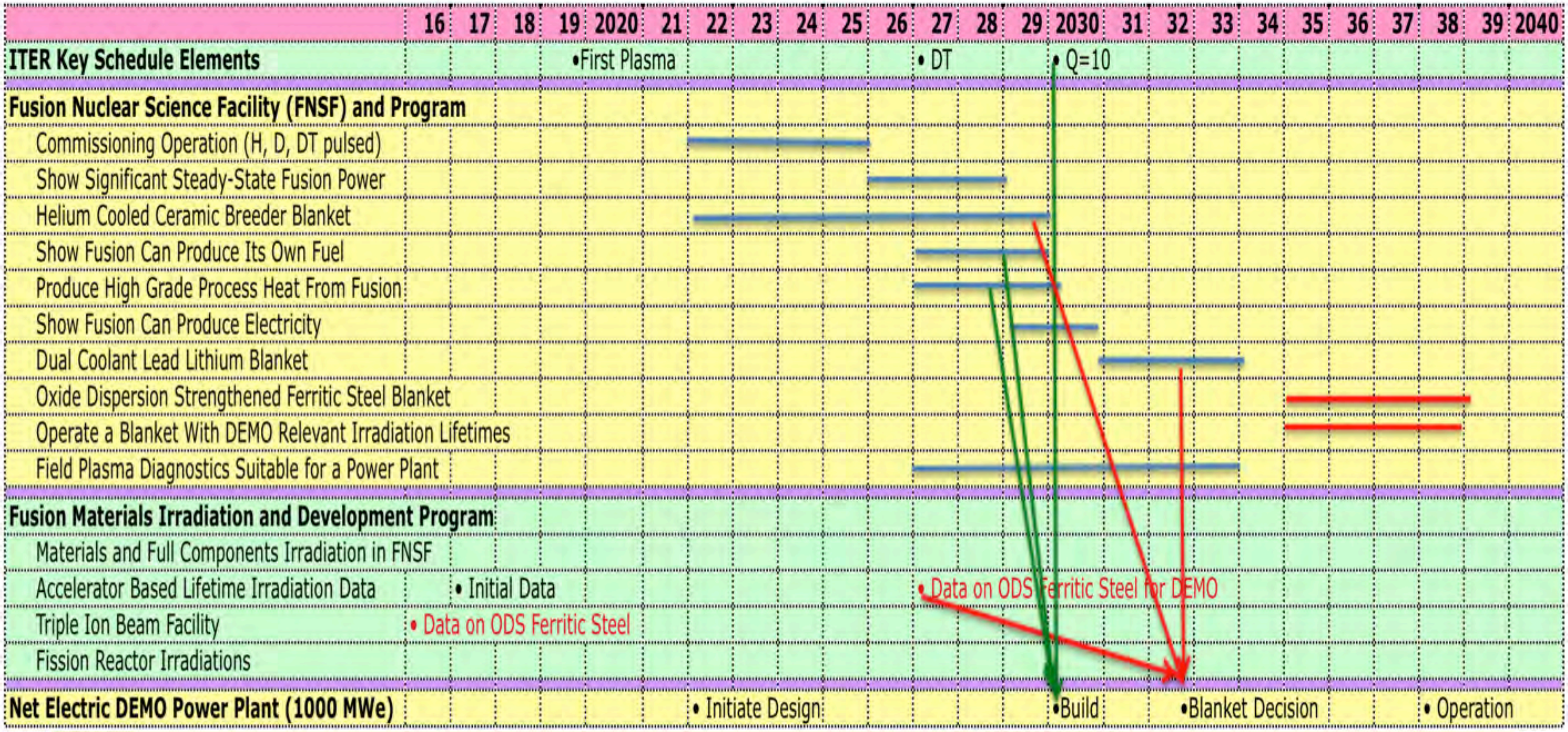


“DEMO”

Present → ITER timeframe 2020 - 2035 → Construct Decision 2025-2030

An Example Fast Track to Get to a Net Electric DEMO via Fusion Nuclear Facility

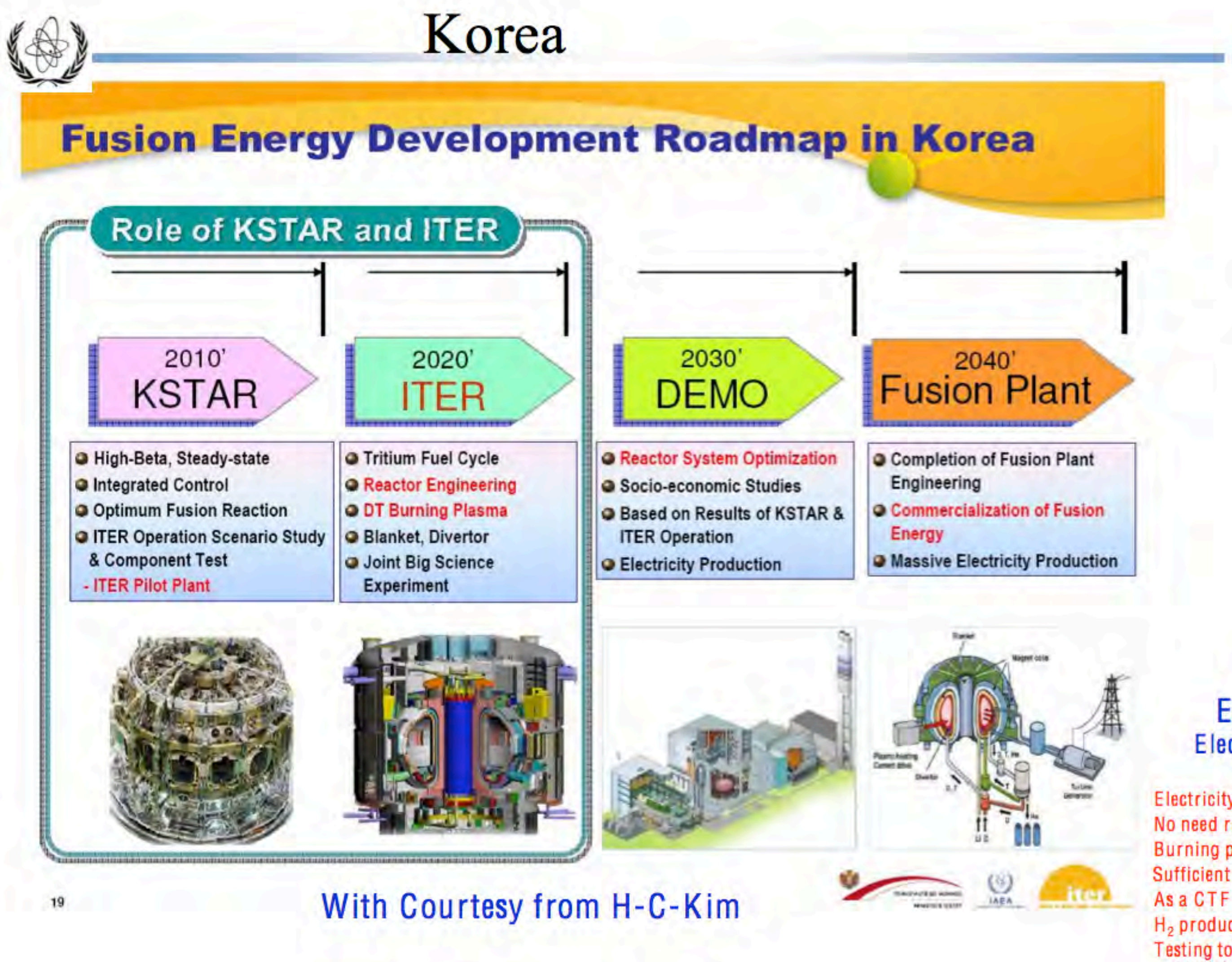


	16	17	18	19	2020	21	22	23	24	25	26	27	28	29	2030	31	32	33	34	35	36	37	38	39	2040
ITER Key Schedule Elements				•First Plasma								• DT			• Q=10										
Fusion Nuclear Science Facility (FNSF) and Program																									
Commissioning Operation (H, D, DT pulsed)							▬	▬	▬	▬															
Show Significant Steady-State Fusion Power											▬	▬	▬												
Helium Cooled Ceramic Breeder Blanket							▬	▬	▬	▬	▬	▬	▬	▬											
Show Fusion Can Produce Its Own Fuel												▬	▬	▬											
Produce High Grade Process Heat From Fusion												▬	▬	▬											
Show Fusion Can Produce Electricity														▬	▬										
Dual Coolant Lead Lithium Blanket																▬	▬	▬							
Oxide Dispersion Strengthened Ferritic Steel Blanket																				▬	▬	▬	▬		
Operate a Blanket With DEMO Relevant Irradiation Lifetimes																				▬	▬	▬	▬		
Field Plasma Diagnostics Suitable for a Power Plant												▬	▬	▬	▬	▬	▬	▬							
Fusion Materials Irradiation and Development Program																									
Materials and Full Components Irradiation in FNSF																									
Accelerator Based Lifetime Irradiation Data		• Initial Data										• Data on ODS Ferritic Steel for DEMO													
Triple Ion Beam Facility	• Data on ODS Ferritic Steel																								
Fission Reactor Irradiations																									
Net Electric DEMO Power Plant (1000 MWe)							• Initiate Design								•Build		•Blanket Decision						• Operation		

DEMO design initiated by first plasma in ITER. DEMO construction triggered by Q=10 in ITER, first phase accomplishments in FNF, and materials data on ODS Ferritic Steel. FNF enables choice between two most promising blanket types for DEMO.

(R. Stambaugh, FPA 2010 Annual Meeting)

EAST ASIAN PARTNERS ALSO CONSIDERING FAST TRACKS TO DEMO



Korea

Fusion Energy Development Roadmap in Korea

Role of KSTAR and ITER

2010' KSTAR	2020' ITER	2030' DEMO	2040' Fusion Plant
High-Beta, Steady-state Integrated Control Optimum Fusion Reaction ITER Operation Scenario Study & Component Test - ITER Pilot Plant	Tritium Fuel Cycle Reactor Engineering DT Burning Plasma Blanket, Divertor Joint Big Science Experiment	Reactor System Optimization Socio-economic Studies Based on Results of KSTAR & ITER Operation Electricity Production	Completion of Fusion Plant Engineering Commercialization of Fusion Energy Massive Electricity Production

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With Courtesy from H-C-Kim

EU-JA "Fast-Track" on same time-scale

- Expedite further via eDEMO

China

EDEMO /Pilot plant (20 years)

Electricity generation with reduced mission

Electricity generation
No need real steady state
Burning plasma control
Sufficient T Breeding
As a CTF
H_2 production
Testing tokamak system availability (reliability, buildability, operability and maintainability)
P_{fusion}~200MW, t = a few hours to weeks

Based on existing technologies:
Option 1: Pure Fusion
 A FDF-class with SC coils
 A ST-type compact device
Option 2: Fusion –Fission hybrid
 Fusion: Q=1-3, Pth=50-100MW
 Fission: M= 20-30, Pt = 0.3-1.5GW
Or:
ITER-type machine with different blanket: Pt =5GW, Pe=1.5GW

(from J. Li, " The Future of Fusion" SOFE 2011)

Need to Projectize Fusion Energy Development

- Accelerated program will require analysis and capacity to decide on acceptable risk for each program element
  - An open-ended science research program will not take such decisions

- Run as directed project to move to DEMO
  - Existing fusion science program remains as performing support research

- Use modern project management for energy development
  - Risk management and mitigation, not risk avoidance
  - Expeditious directed decisions and risk assessment
    - Cost
    - Scope
    - Schedule
  - Likely needed for final selection of specific path(s) to follow

A SIMPLE ROADMAP RESOLVES REMAINING ISSUES FOR A DECISION FOR DEMO

- Development path goes through ITER and a Fusion Nuclear Facility
  - Includes underlying fusion nuclear S&T support activities
  - Underlying fusion nuclear S&Tprogram is needed now

- Roadmap and Prioritization Studies Underway
  - Evaluate risks/costs/readiness/schedule to facilitate prioritization
  - Complement world program and opportunities
  - Target down-select to specific FNF concept in 1-2 years

- The interests of the customer will determine the pace and prioritization of fusion energy choices
  - Especially true for near-term accelerated energy program, and for large next (FNF) steps
  - Need for magnetic fusion energy project