Realization of Fusion Energy: An alternative fusion roadmap

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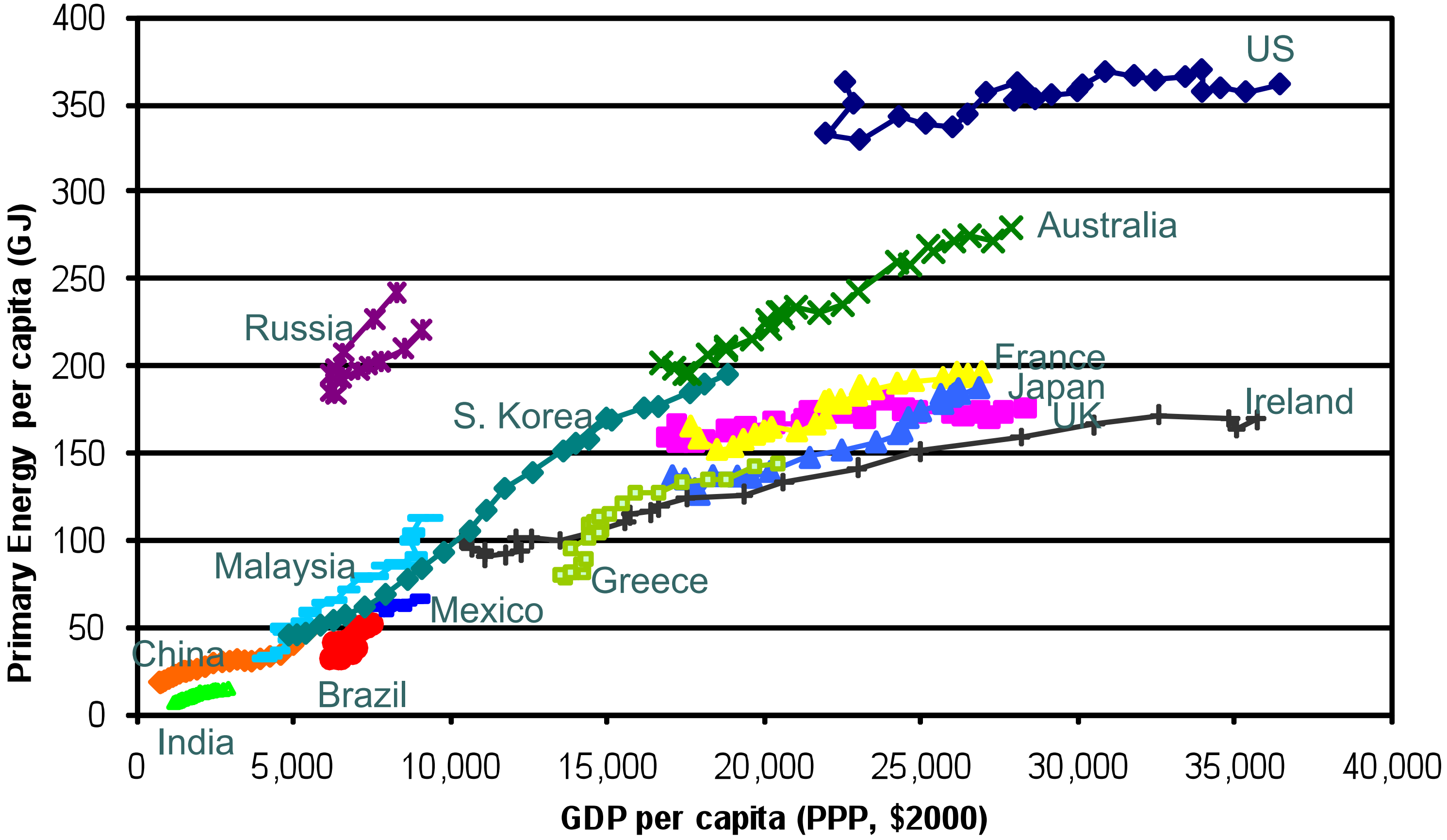
Is there a case for a “unified” international road-map for fusion?

<u>Rationale for fusion development</u> varies substantially around the world.

World needs a lot of energy!



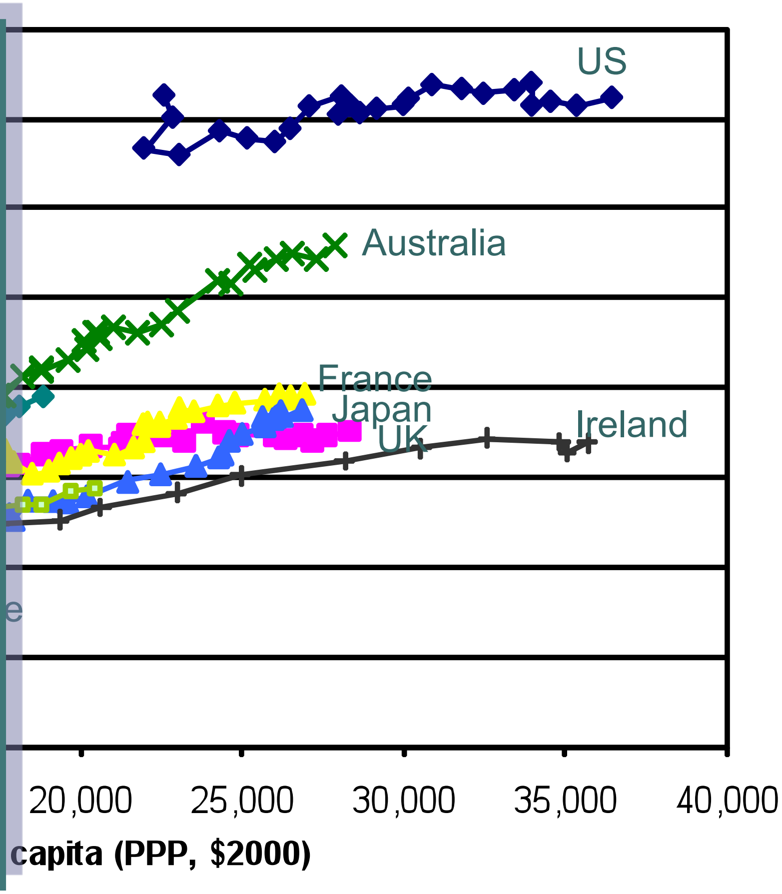
- With industrialization of emerging nations, energy use is expected to grow ~ 4 fold in this century (average 1.6% annual growth rate)

* Data from IEA 2006 annual energy outlook

However, energy needs are different in different parts of the world:

US, EU, Japan:

- Electricity supply needs are mainly for the replacement of existing power plants.
- Government regulations have been driving the choice of energy supply.
- Different level of access to indigence fossil fuels for electricity production.
- Different socio-political atmospheres.



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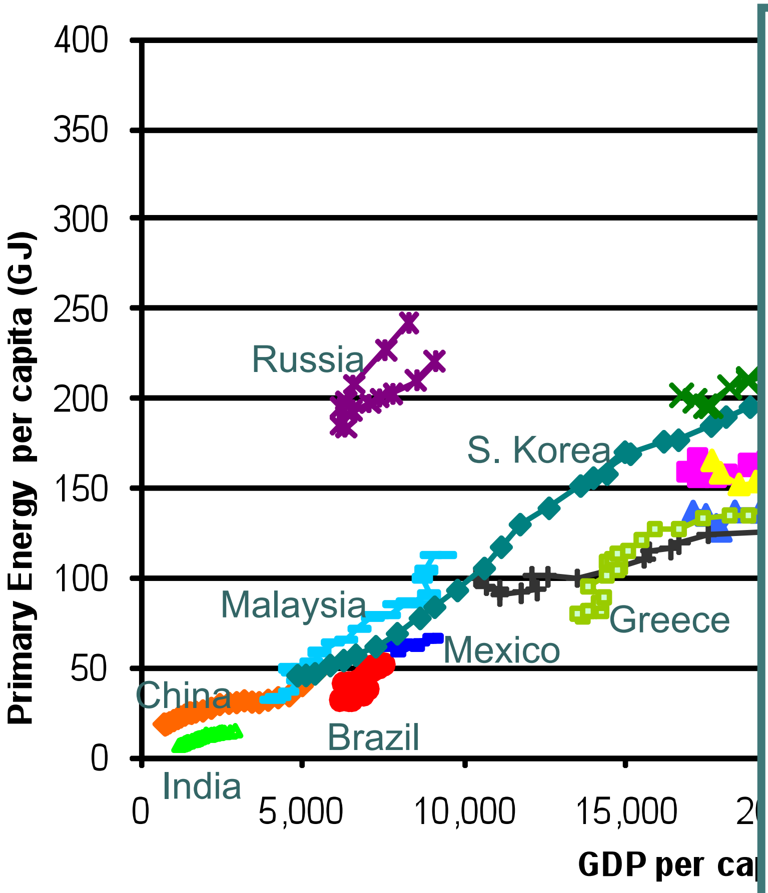

China, India, Russia, (S. Korea), ….

- <u>Large supplies of Electricity</u> is needed to maintain economic growth.
- Governments actively following policies to expand energy supply.
- Different level of access to indigence fossil fuels for electricity production
- Different socio-political atmospheres.

While current rationale for R&D differs, the ultimate goal would be the same.

- Fusion R&D expenditures are justified to government agencies who have different priorities and, therefore, respond to different “Roadmaps.”
  - Different R&D plans for the next decade.
- However, large-scale (multi-billion $) fusion facilities beyond ITER and NIF can only be justified in the context of their contribution to energy supply. We will have
  - Different Customers (e.g., Power Producers)
  - Different criteria for success (e.g., Commercial viability)
  - Timing (e.g., Is there a market need?)
    - **Fusion is NOT the only game in town!**

- Fusion roadmaps should include <u>all R&D needed to achieve commercial fusion power</u>

All fusion roadmaps focus on large machine.

Is this the cheapest/fastest approach?

Fusion Energy Development Focuses on Facilities Rather than the Needed Science

- Current fusion development plans relies on large scale, expensive facilities:*
  - Long lead times, $$$
  - Expensive operation time
  - Limited number of concepts that can be tested
  - Integrated tests either succeed or fail (difficult to ascertain why they failed or succeed), this is an expensive and time-consuming approach to optimize concepts.

* Observations by ARIES Industrial Advisory Committee, 2007.

What should a fusion roadmap

- Current fusion roadmaps which focus on "Demo" have a high probability of leading to lengthier and costlier programs (for commercial fusion).
  - Mission will be redefined to fit the "promised" time frame.
  - Cost, available data base, etc. will lead to further mission contraction, expanding the R&D needed after the next step and may also to un-necessary R&D.

- Recall ITER history (proposed in mid-80s, many revision of its mission, considerable expenditure, …).

Currently envisioned development paths rely on large facilities

Reference “Fast Track” Scenario

10 years	+ 10 years	+ 10 years	≈ 30-35 years
build ITER	*exploit ITER*	*build*	
+ IFMIF	*+ IFMIF*	*DEMO*	
		(Technology Validation)	

ITER construction delay, First DT plasma 2029?
IFMIF?

TBM Experimental Program is not defined!
+10-20 years
~ 2029-2040

1) Large & expensive facility, Funding, EDA, construction ~ 20 years.
2) Requires > 10 years of operation
~ 2060-2070

2070:
Decision to field 1st commercial plant barring NO SETBACK

Bottle neck: Sequential Approach relying on expensive machines! Huge risk in each step!

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This is in contrast with the normal development path of any product in which the status of R&D necessitates a facility for experimentation.

Developing Fusion Power Technologies (FNS)…

Developing commercial fusion energy requires changes in our folklore:

- Fusion power technologies (fusion nuclear sciences) are in their early stages of development. We are NOT ready!
- Development of fusion nuclear sciences requires a large amount of resources.
  - We readily talk about multi-billion-$ plasma-based facilities but frown at $1B price tag of IFMIF.
- The perception that the only way to develop fusion nuclear sciences is to have 14-MeV neutrons is not correct (cook and look approach is very expensive and time-consuming)
  - A large potion of R&D can and should be performed in simulated environments (non-nuclear and/or fission test).
  - Fusion nuclear testing is needed only to validate the predicted performance plus all synergetic effects that were not foreseen.
  - 14-MeV neutron sources are NOT equal.

Technical Readiness Levels provides a basis for assessing the development strategy

Increased integration

Increased Fidelity of environment

Level	Generic Description
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.

Basic & Applied Science Phase

Demo Phase

- Developed by NASA and are adopted by US DOD and DOE.
- TRLs are very helpful in defining R&D steps and facilities.

TRLs provide a frame-work for cheaper/faster R&D

- Each concept (e.g., fusion power technology component) has its own feasibility/performance issue as well as material requirement. As such, fusion power technology research (fusion nuclear sciences) cannot be performed in abstract.
- However, there is a large "infant mortality" associated with concepts in low maturity.

- TRL methodology provides a framework for R&D:
  - Ensures an integrated research programs for each concept so that all issues are addressed and all "gaps are filled."
  - Idenitfy decision points in narrowing down the options for each concept to make progress.

Application to power plant systems highlights early stage of fusion technology development

Example application of TRLs to power plant systems

	TRL								
	1	2	3	4	5	6	7	8	9
Power management									
Plasma power distribution	■	■	■	▨					
Heat and particle flux handling	■	■	▨						
High temperature and power conversion	■	■	▨						
Power core fabrication	■	■	▨						
Power core lifetime	■	■	▨						
Safety and environment									
Tritium control and confinement	■	■	■	▨					
Activation product control	■	■	■	■					
Radioactive waste management	■	■	▨						
Reliable/stable plant operations									
Plasma control	■	■	■	■					
Plant integrated control	■	■	▨						
Fuel cycle control	■	■	▨						
Maintenance	■								

■	**Completed**
▨	**In Progress**

For Details See ARIES Web site: http://aries.ucsd.edu (TRL Report)

Example: TRLs for Plasma Facing Components

	Issue-Specific Description	Facilities
1	System studies to define tradeoffs and requirements on heat flux level, particle flux level, effects on PFC's (temperature, mass transfer).	Design studies, basic research
2	PFC concepts including armor and cooling configuration explored. Critical paramete	Code development, applied research
3	Data from coupon-scale heat and particle flux experiments; modeling of governing heat and mass transfer processes as demonstration of function of PFC concept.	Small-scale facilities: *e.g.,* e-beam and plasma simulators
4	Bench-scale validation of PFC concept through submodule testing in lab environment simulating heat fluxes or particle fluxes at prototypical levels over long times.	Larger-scale facilities for submodule testing, High-temperature + all expected range of conditions
5	Integrated module testing of the PFC concept in an environment simulating the integration of heat fluxes and particle fluxes at prototypical levels over long times.	Integrated large facility: Prototypical plasma particle flux+heat flux (*e.g.* an upgraded DIII-D/JET?)
6	Integrated testing of the PFC concept subsystem in an environment simulatin levels ov	Integrated large facility: Prototypical plasma
7	Prototypic PFC system demonstration in a fusion machine.	Fusion machine ITER (w/ prototypic divertor), CTF
8	Actual PFC system demonstration qualification in a fusion machine over long operating times.	CTF
9	Actual PFC system operation to end-of-life in fusion reactor with prototypical conditions and all interfacing subsystems.	DEMO

Power-plant relevant high-temperature gas-cooled PFC

Low-temperature water-cooled PFC

Application to power plant systems highlights early stage of fusion technology development

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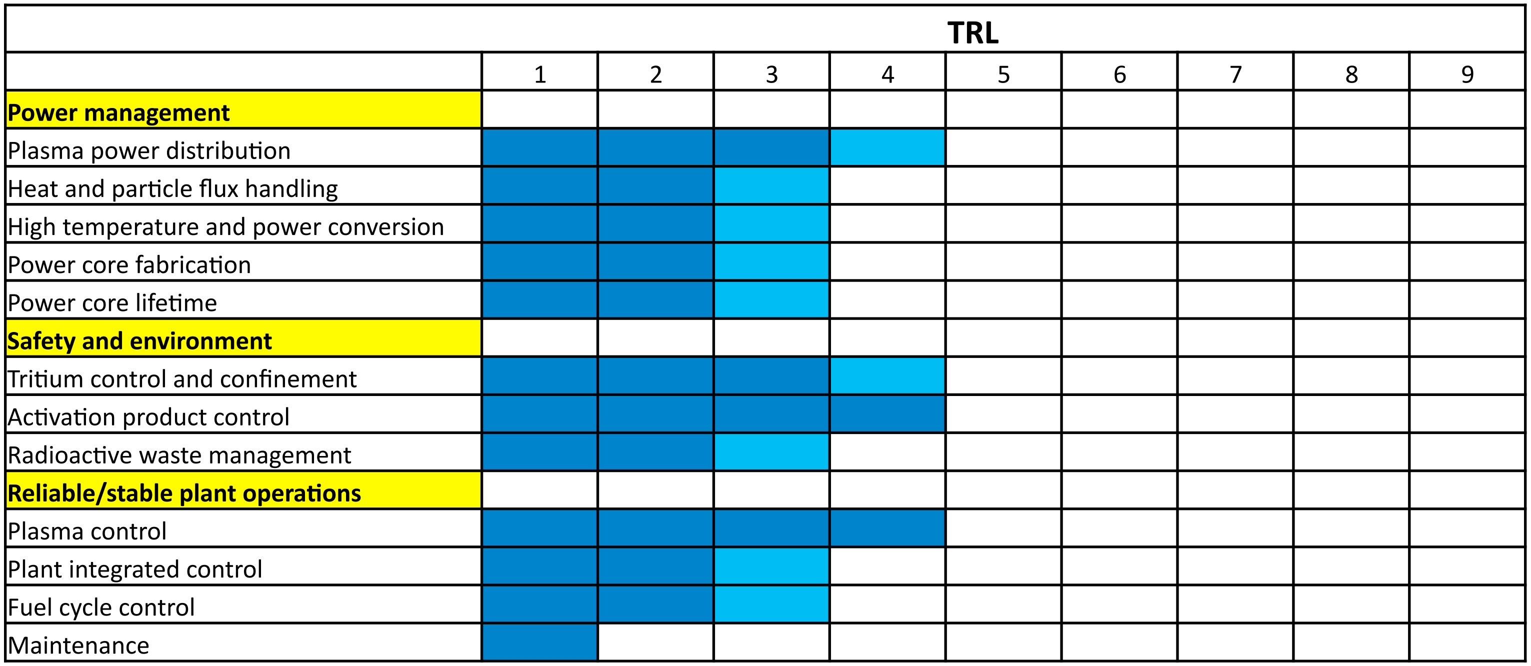

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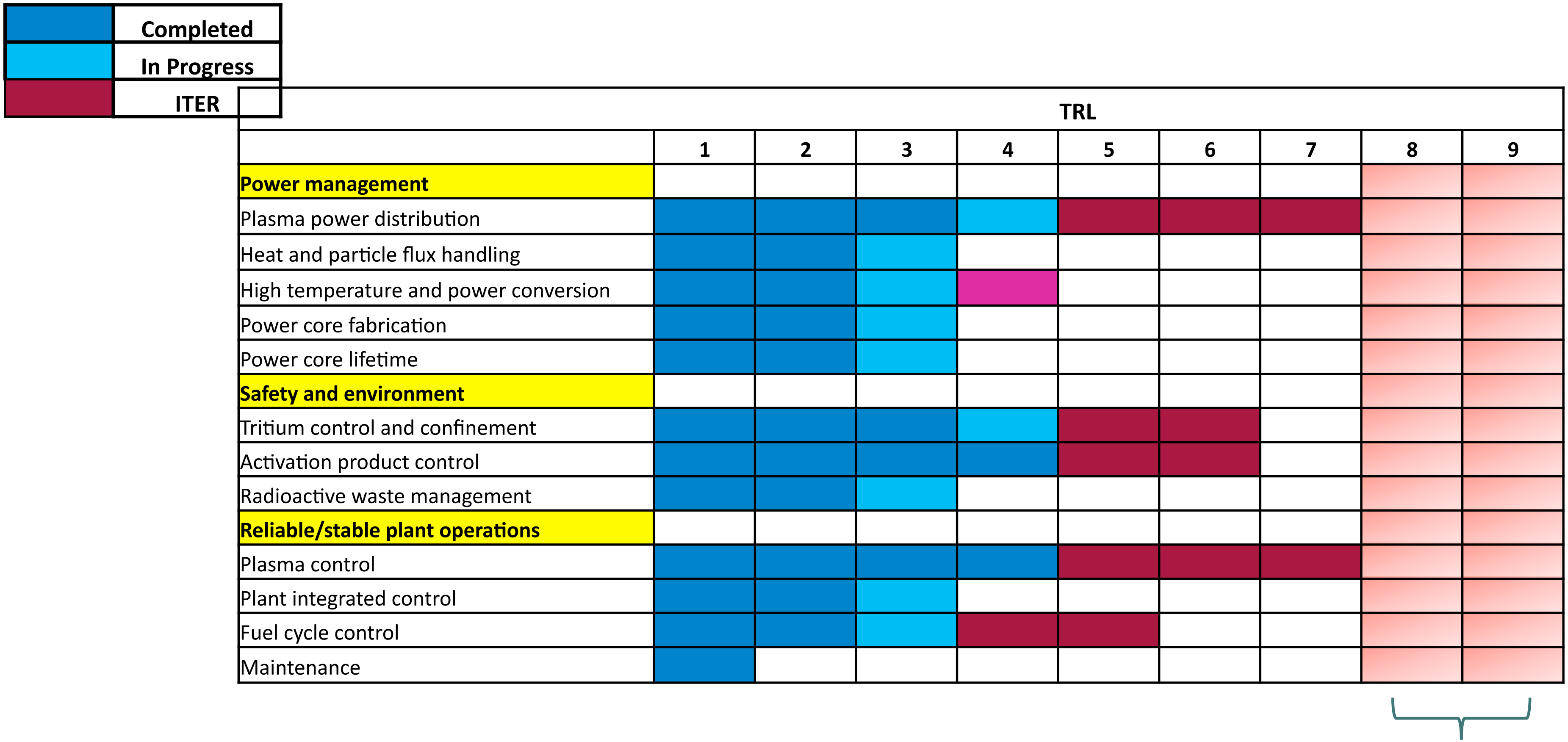
ITER will provide substantial progress in some areas (plasma, safety)



🟦	**Completed**
▨	**In Progress**
🟥	**ITER**

	TRL								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Power management									
Plasma power distribution	🟦	🟦	🟦	▨	🟥	🟥	🟥		
Heat and particle flux handling	🟦	🟦	▨						
High temperature and power conversion	🟦	🟦	▨	🟪					
Power core fabrication	🟦	🟦	▨						
Power core lifetime	🟦	🟦	▨						
Safety and environment									
Tritium control and confinement	🟦	🟦	🟦	▨	🟥	🟥			
Activation product control	🟦	🟦	🟦	🟦	🟥	🟥			
Radioactive waste management	🟦	🟦	▨						
Reliable/stable plant operations									
Plasma control	🟦	🟦	🟦	🟦	🟥	🟥	🟥		
Plant integrated control	🟦	🟦	▨						
Fuel cycle control	🟦	🟦	▨	🟥	🟥				
Maintenance	🟦								

Absence of power-plant relevant technologies and limited capabilities severely limits ITER’s contributions in many areas.

TRLs provide a frame-work for cheaper/faster R&D

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- However, there is a large “infant mortality” associated with concepts in low maturity.

- TRL methodology provides a framework for R&D:
  - Ensures an integrated research programs for each concept so that all issues are addressed and all “gaps are filled” before moving to the next level.
  - Identifies decision points in narrowing down the options for each concept to make progress.
  - Minimizes the risk/cost/and length of each following step.

We should focus on developing a technical roadmap

A detailed technical Road Map based on TRL methodology

- Includes what needs to be done (both critical and “non-critical”)
- Highlights the order they need to be done
- Includes clear mile-stones or check points showing progress
- Provides the justification for and the mission of needed facilities
- A times-less exercise that needs updating

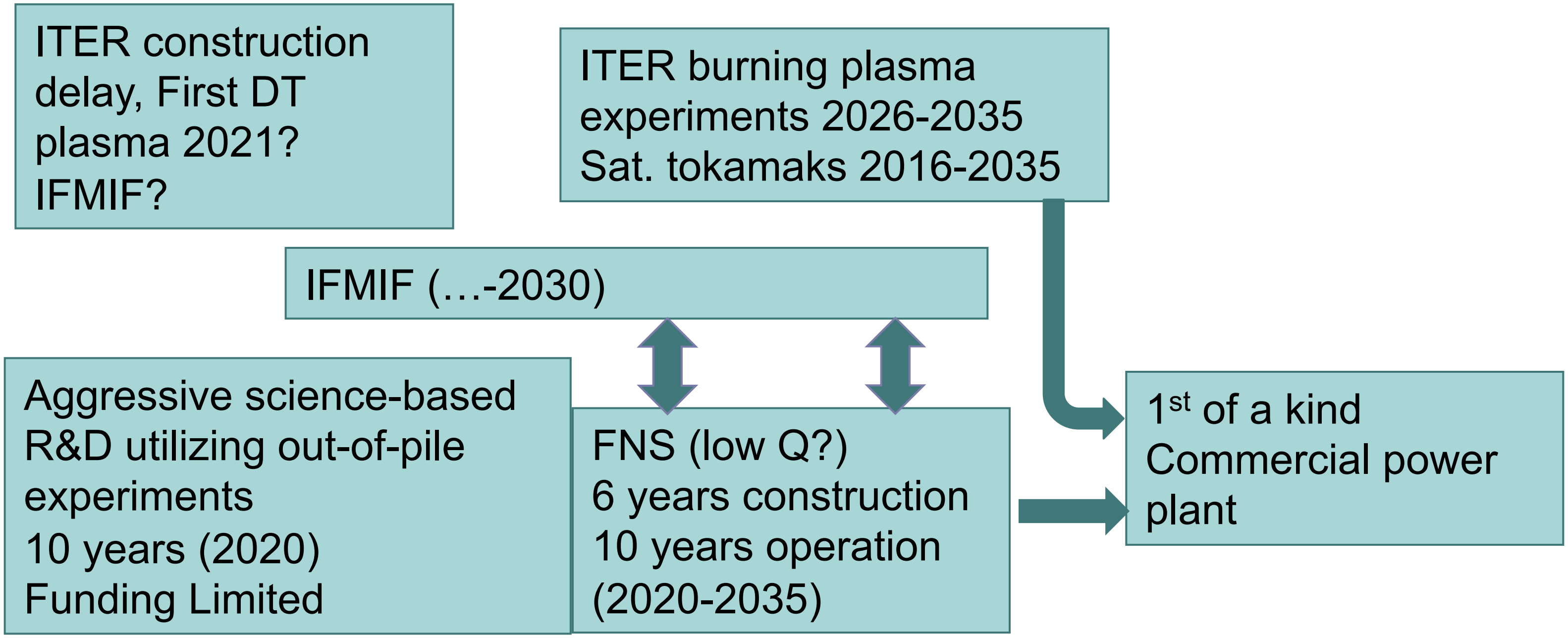
Such a Technical Roadmap provides the technical basis to develop policies and program portfolio.

- Allows flexibility in implementation scenarios (aggressive or slow)
- Allows multi-year program planning
- Provides a firm basis on cost/benefit analysis
- Provides a mechanism for “coordination” internationally and with plasma physics research.

Framework for technical roadmap

- Phase 1: Achieve TRL level 4 for all components ("Component and/or bench-scale validation in a laboratory environment)
  - Examples: demonstration of thermo-mechanical response of a blanket and divertor unit-cell, tritium extraction system in lab scale, fundamental material property demonstration and optimization.
- Phase 2: Achieve TRL level 6 for all component ("System/ subsystem model or prototype demonstration in relevant environment.)
  - Examples: demonstration of an integrated full scale blanket/divertor module/sectors in non-nuclear (simulated environment). Demonstration of blanket/divertor unit-cell in fission environment.
- Phase 3: Achieve TRL level 7-8 for all components ("System prototype demonstration in an operational environment")
  - Example: Validation in a fusion nuclear facility. Resolution of synergetic effects.

A faster fusion development program requires decoupling of fusion technology development from ITER



ITER construction delay, First DT plasma 2021?
IFMIF?

ITER burning plasma experiments 2026-2035
Sat. tokamaks 2016-2035

IFMIF (…-2030)

Aggressive science-based R&D utilizing out-of-pile experiments
10 years (2020)
Funding Limited

FNS (low Q?)
6 years construction
10 years operation
(2020-2035)

1st of a kind Commercial power plant

2035:
Decision to field 1st commercial plant

Key is aggressive science-based engineering up-front

In summary: Why? How (not to)?

- World needs a lot of new supply of energy.
  - Fusion is NOT the only game in town.
  - But, it can fit all criteria for energy growth if we solve the fusion engineering grand challenge!

- All published Fusion Development Paths are based on large and expensive facilities. This cook and look approach is doomed to failure:
  - Requires expensive nuclear facilities with long lead times.
  - Leads to large Risks between steps.
  - Needs extensive run-time in each step.
  - No attention to science & technology requirements before fielding a step.

In summary: How?, When?

- We need to develop a fusion energy technical roadmap ("Fusion Nuclear Sciences" road-map).
  - Large-scale facility should be only validation facilities.
  - Required science and engineering basis for any large facility should be clearly defined and included in such a Road-map.
  - We need to start implementing such a road-map to show that we are serious (only the "pace" is set by funding).
  - We need to start work-force development.

- Increased funding and emphasis for fusion have always been driven by external factors.
  - We need to be prepared to take advantage of these opportunities.
  - It is possible to field fusion power plant before 2050, but we lay the ground work now!

Thank you!

Evolution of ARIES Tokamak Designs

	1st Stability, Nb_3Sn Tech.	**High-Field Option**	**Reverse Shear Option**	
	ARIES-I’	**ARIES-I**	**ARIES-RS**	**ARIES-AT**
Major radius (m)	8.0	6.75	5.5	5.2
β (β_N)	2% (2.9)	2% (3.0)	5% (4.8)	9.2% (5.4)
Peak field (T)	16	19	16	11.5
Avg. Wall Load (MW/m^2)	1.5	2.5	4	3.3
Current-driver power (MW)	237	202	81	36
Recirculating Power Fraction	0.29	0.28	0.17	0.14
Thermal efficiency	0.46	0.49	0.46	0.59
Cost of Electricity (c/kWh)	10	8.2	7.5	5

COE insensitive of power density

COE insensitive of current drive

An Alternative Approach for building up the FNT research in US

- Address the man-power and limited single-effect data base immediately by starting a program to fund university-based research in FNT (RFP for 3-4 proposals totaling \$1M/y, build to \$3M/year in 3 years).
- Develop a detailed plan for FNT development with a focus on short term goals (5-7 years). Define experimental facilities with clear milestones, detailed research plan, diagnostics development, etc. This is an essential ingredient for selling the FNT research to the rest of fusion community.
- Start planning for user-facilities in national labs for proof-principle and multi-effect test in national labs (e.g., He loop, LiPb loop, heat sources, etc.) to be constructed in 3-4 years time.
- It would be “good” to have the option (in ~7 years) to participate in ITER TBM if the above program is put in place.

Utilize Modern Product Development

- Use modern approaches for to “product development” (e.g., science-based engineering development vs “cook and look”)
  - Extensive “out-of-pile” testing to understand fundamental processes
  - Extensive use of simulation techniques to explore many of synergetic effects and define new experiments.
  - Experiment planning such that it highlights multi-physics interaction (instead of traditional approach of testing integrated systems to failure repeatedly).
  - Aiming for validation in a fully integrated system
- Can we divide what needs to be done into separate “pieces”
  - R&D can be done in parallel (shorter development time)
  - Reduced requirements on the test stand (cheaper/faster!)
  - **Issues:** 1) Integration Risk, 2) Feasibility/cost?