A Path to Practical Fusion Power

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Main Message:

1. The success of ITER is essential for the future of Magnetic Fusion Energy; the continued support of the US tokamak program is vital to achieving that success.

2. The present path toward a tokamak DEMO has a high degree of risk because:

i) The physics for robust steady-state operation of tokamaks is unproven, and

ii) the requisite nuclear-qualified materials do not exist and are not being developed

3. Over the remaining part of this decade the MFE program should, in addition to supporting ITER, plan for a major stellarator facility and expand the Fusion Nuclear Science (FNS) program.

The Success of ITER is Essential for the Future of MFE

Demonstrating a burning plasma, elucidating the underlying physics, and demonstrating key elements of fusion-specific technologies, are steps which will go a long way toward building confidence that fusion can play a role in the future of the world's energy supply.

ITER is and must continue to be the single highest priority element in the US program!

The US Tokamak Program Continues to Remain Vital to ITER's Success

Examples:

Reduction of transient and steady state heat loads to acceptable levels:

- **Development of regimes free from Edge Localized Modes, e.g., Use of Resonant Magnetic Perturbations, I-Modes**
- **Development of impurity seeded scenarios– type and quantity**
- **Characterization of edge plasma, divertor heat footprint**

Development of steady-state regimes

Reduction of plasma-wall interactions from in-vessel heating and current drive antennas

The US Tokamak Program is Needed to Ensure Return on the ITER Investment

The US tokamak program is training the generation of US plasma scientists and engineers needed to operate and exploit ITER.

Both the relevance of the contributions and the quality of the training would be diminished by basing the US tokamak program on overseas devices.

Continued support of the US tokamak effort is essential to capitalize on the investment that the US is making in ITER, and to ensure its success.

However, ITER's Success While Necessary is Not Sufficient for Realizing Magnetic Fusion Energy

Successfully completing ITER construction and achieving its main objectives will not be sufficient to establish a tokamak-based path toward practical fusion energy because:

- **Steady-state tokamak operation may turn out to be impractical, while pulsed tokamaks such as ITER have issues of thermal fatigue and energy storage**
- **Structural materials qualified for ≥ 75 dpa, a threshold below which fusion may not make economic sense, still need to be developed.**

It's Time for the US to Participate in the World Wide Effort to Develop Stellarators

Stellarators have natural advantages over tokamaks, namely a resilient steady-state, no central transformer, and no (or modest) need for current drive

Stellarator reactor designs have been criticized in the past because of large major radius. However:

> **low power density (large size) may be an advantage – higher availability can offset increased capital cost;**
>
> **Pulsed tokamak reactor designs, which reduce need for current drive, are moving toward larger size, R ~ 10 m or more.**

The opportunity may exist to collaborate with an ITER partner (e.g., China) on a large scale stellarator late in this decade. The time for planning is now!

Conceptual Stellarator Reactor Designs Are Being Developed in Germany

W7-X and Helias Reactor Parameters

	W7-X	HSR5/22	HSR4/18
Periods/Coils per period	5/10	5/10	4/10
Major radius, R_0 (m)	5.5	22	18
Plasma radius, a (m)	0.51	1.8	2.1
Plasma volume, V (m^3)	28	1407	1567
Average coil radius, a_c (m)	1.25	5.0	5.5
First wall surface area (m^2)	180	3200	2700
Average magnetic field, B_0 (T)	2.5	5.0	5.0
Stored magnetic energy (GJ)	0.4	100	98
Edge rotational transform	5/5	5/5	4/4

Average wall loading < 1 MW/m^2

C. D. Beidler Roadmapping Workshop

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Materials Science & Technology Irradiation Effects Data Base Maturity

Note: He levels are for RAF/M steels, lower and higher values for other materials

Data Base Need	~ITER 10 dpa/100 appm He						~FNSF 50 dpa/500 appm He						~DEMO 150 dpa/1500 appm He					
	RAF/M	NFA	V	W	SiC	Adv Mat	RAF/M	NFA	V	W	SiC	Adv Mat	RAF/M	NFA	V	W	SiC	Adv Mat
Radiation Effects																		
Hardening & Embrittlement	Green	Yellow	Yellow	Red	Yellow	Red	Yellow	Red	Yellow	Red	Yellow	Red	Red	Red	Red	Red	Red	Red
Phase Instabilities	Green	Red	Yellow	Red	Yellow	Red	Yellow	Red	Red	Red	Yellow	Red	Red	Red	Red	Red	Red	Red
Irradiation Creep	Green	Yellow	Yellow	Red	Yellow	Red	Yellow	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
Volumetric Swelling	Green	Red	Yellow	Red	Yellow	Red	Yellow	Red	Yellow	Red	Yellow	Red	Yellow	Red	Red	Red	Red	Red
High T Helium Effects	Green	Red	Red	Red	Red	Red	Yellow	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red

Green = Adequate Knowledge Base Exists
Yellow = Partial Knowledge Base Exists
Red = Knowledge Base Does Not Exist of Completely Inadequate

Rick Kurtz and Don Rej, Roadmapping Workshop

Even if all the Plasma Physics Issues Were Solved, We Couldn't Build a DEMO Today (1)

At present, the leading candidate for a fusion structural material is Eurofer, a ferritic martensitic steel. It is "qualified" to perhaps 10 dpa, or 1 year @ 1 MY/m^2

Dpa's can be produced in fission reactors, but without the concomitant helium. A 14 MeV neutron source is needed to determine synergistic effects.

Existing US facilities may be sufficient for materials testing (TBD); if not, US should seek a role in construction and operation of IFMIF, the International Fusion Materials Irradiation Facility being designed through an EU-Japan collaboration.

Even if all the Plasma Physics Issues Were Solved, We Couldn't Build a DEMO Today (2)

Tritium breeding is an essential technology for a fusion reactor. ITER offers the only near-term possibility to test tritium breeding in a realistic (although imperfect) environment. The US should participate *as an equal* among the ITER partners in the ITER Test Blanket Module (TBM) program.

Longer term, component testing and qualification will need nearly steady-state fluxes in the range of several MW/m^2 and fluences of 5-10 MW a/m^2.

Tokamaks (small to medium aspect ratio) are well suited for this purpose. Plans for an Fusion Nuclear Science Facility should be developed for possible construction during ITER operation.

A Path to MFE Should Support ITER but Must Address Steady-State and Materials Issues

My vision for the future of the US program is therefore one that:

1. Exploits existing machines (hand-in-hand with theory and simulation) to ensure that ITER will achieve its objectives and maximize the US taxpayer's return on the ITER investment;

2. Initiates a US stellarator program aimed at identifying and constructing an optimized stellarator – perhaps JET class -- using "ITER rolloff" resources later in this decade and building on results from LHD, W7-X and HSX.

3. Initiates a fusion materials program and participates in IFMIF and the TBM program in ITER

A Path that Addresses Steady-state and Materials Issues