Topical Area: **MFE** Title: **Burning Plasma Experimental Options**

• **Description** The options for a Next Step Burning Plasma Experiment are defined by the overall strategic pathways available for the development of MFE as shown in Fig 1. The One Step to DEMO Pathway would combine the Proof of Performance experiment with the demonstration of the scientific and technological feasibility of MFE. This pathway is dominated by a single large facility, such as ITER, with multiple missions of developing and integrating burning plasma physics, long pulse physics and technology, and fusion technologies. The Enhanced Concept Innovation Pathway would delay burning plasma experiments to emphasize experimentation on several magnetic configurations at small scale before deciding on which configurations warranted testing using burning plasmas. There have been over 20 facilities around the world evaluating stellarators, spherical tori, reversed field pinches, spheromaks, multipoles, etc. at the concept exploration and Proof of Principle level for the past two decades. None of these configurations could be ready for a burning plasma test at $Q \geq 10$ in less than a decade. The Modular Pathway employs multiple facilities each focused on resolving a key MFE issue at conditions approaching those expected in a MFE system. The Modular Pathway significantly reduces the technical risk relative to both the One Step to DEMO and the Enhanced Concept Innovation Pathway, and represents the most direct pathway to develop MFE by addressing the key technical issue (High Q burning plasmas) in the near term with modest near term costs. The Modular Pathway is the natural way to develop long range high technology and would mirror the Modular Pathway being proposed for IFE.

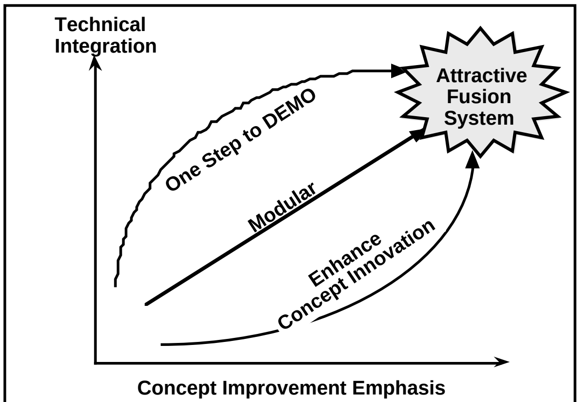

Fig. 1. Pathways for the Development of Magnetic Fusion

• **Status** The burning plasma issues to be resolved for MFE are described in the section on MFE Burning Plasma Science. The status of the leading magnetic configurations to address MFE burning plasma issues is given in terms of the extrapolation required from parameters achieved in laboratory experiments to those required in that concept's reactor assessment by the ARIES studies (Table I).

Table I. Extrapolation Required	Tokamak	Stellarator	Spherical Torus	ARIES
$n\tau_E T_i$	10	1,000	100,000	1
plasma pressure	3	100	>100	1
neutron wall load MWm^{-2}	50	>1,000	>1,000	1
duty cycle	50	>1,000	>10,000	1

Only the tokamak is sufficiently advanced to permit the design, construction and initiation of a next step burning plasma experiment within the next decade that could address the burning plasma physics issues of MFE. The crucial issues of understanding the science of plasma transport, MHD stability in advanced configurations where the profiles are defined by alpha heating can be studied thoroughly in the tokamak configuration and this knowledge can be used to understand and predict burning plasma physics phenomena in other magnetic configurations. Presently, the MFE program does not have a Proof of Performance experiment which would allow the simulation and study of deuterium/hydrogen plasmas with physics similar to that of a strongly burning plasma. A Next Step MFE experiment capable of achieving $Q \geq 10$ in D-T plasmas would serve both as Proof of Performance and as a facility to explore, understand and optimize burning plasmas for MFE in parallel with the NIF/LMJ experiments for IFE.

• **R&D Goals and Challenges** Previous design studies of Next Step burning plasma experiments (TFCX, CIT, BPX and the ITER EDA) have all produced technically credible designs but have not garnered the required scientific and financial support to proceed with construction. The challenge is to develop a design proposal with a more focused mission that will address the critical burning plasma issues within a constrained budget profile.

• **Related R&D Activities** The base theory, modeling and confinement program will interact closely with the burning plasma experiment. Enabling technology development in plasma heating, current drive and fueling (pellet injection) will be needed for the burning plasma experiment. Fusion technology development especially tritium handling, remote handling will be integrated with the experiment.
IFE burning plasma experiments on NIF/LMJ will be complementary to the MFE burning plasma experiment(s).

• **Recent Successes** Recent experiments on medium and large size tokamaks have clarified key issues (confinement, MHD limits, bootstrap current, plasma exhaust and D-T operation) that are needed to design a burning plasma experiment. The ITER EDA study has produced a well documented physics basis for analyzing burning plasma performance. Several representative options for a next step burning plasma experiment in MFE have been identified during the Next Step Options Study that followed the Madison Forum with parameters in the ranges illustrated in Table II.

Table II	R(m)	B(T)	Coils	Ip(MA)	Gain	Pfusion (MW)	Exhaust	Burn time(s)	Cost($M)
IGNITOR	1.32	13	30°K Cu	12	>10	~200	limiter	5	<500
FIRE	~2.0	~10	70°K BeCu	<7	~10	~200	DND	≥10	<1,000
ITER- RC	6.2	5.5	NbSn S/C	13	10	~500	S-DND	≥400	<6,000

ITER-RC is very similar to the ITER EDA with the same overall program objective, to establish the scientific and technological feasibility of magnetic fusion, but with slightly reduced size and performance in order to reduce the construction cost by 50%. ITER-RC would have superconducting coils capable of allowing up to steady-state under driven plasma conditions. IGNITOR is a very compact high field moderately shaped tokamak with cryogenically cooled copper coils. The plasma is heated to high Q by ohmic and ICRF, and the plasma power and particles are exhausted using the first wall as a limiter. The Fusion Ignition Research Experiment (FIRE) is based on previous U. S. compact copper-conductor burning plasma experiment designs (CIT, BPX, BPX-AT), but responds to recent tokamak physics developments. FIRE is a compact high field tokamak similar to IGNITOR but with higher triangularity and a double null closed divertor configuration.

• **Budget -** The construction budgets for the representative Next Step Options are estimate in Table II. IGNITOR is viewed as an Italian Project with potential EC support. ITER-RC is viewed as a Japanese, European and Russian Project with potential U. S. support. FIRE is viewed as a U. S. Project with potential international support.

Anticipated Contributions Relative to Metrics

Table III. Extrapolation Required	IGNITOR	FIRE	ITER-RC	ARIES
$n\tau_E T_i$	~1	~1.5	<1.5	1
plasma pressure	~0.6	~0.8	2	1
neutron wall load MWm^{-2}	~1	~1	8	1
duty cycle	>1,000	>1,000	~10	1

In the Modular Pathway the duty cycle metric will be addressed in a separate steady-state advanced toroidal facility.

• **Near Term ≤ 5 years**
Comprehensive technical assessment of all approaches to fusion and identification of key metrics. (1999)
Performance optimization and cost reduction design activities with supporting physics and technology R&D.
Proposal ready for technical review and decision by end of 2000 in concert with international decision on ITER.

• **Mid Term ~ 20 years** Initiate construction of Next Step burning plasma experiment by 2002 with first operation by 2009 with high Q D-T plasmas by 2012 (if Compact High Field) or first plasma by 2012 and high Q D-T by 2016 (if ITER-RC). Major programmatic decision in 2015 to 2020 time frame on the selection of potential concept(s) for further development as an Advanced Integrated Experimental Reactor or for burning plasma tests of additional concepts.

• **Long Term > 20 years** If successful the key burning plasma issues would be addressed and resolved by 2020.

Proponents and Critics Claims The tokamak is favored by vast majority of the world MFE program for a next step burning plasma experiment, the issue is whether the tokamak will lead directly to an economical reactor. The JA, EC and RF fusion programs favor the One Step to DEMO strategy and it has been central to their official program plans. A majority of the US fusion community (e.g., the Madison Forum) favor the Modular Pathway which was the MFE pathway prior to the ITER initiative and is similar to the IFE pathway. The Enhanced Concept Innovation pathway would delay initiation of a burning plasma experiment to develop the optimum magnetic configuration at small size and cost prior to large scale testing. This approach will extend the time scale and possibly cost if difficulties arise at the Proof of Performance and Burning Plasma phase with dominant alpha heating.