MFE Concept Integration and Performance Measures
Magnetic Fusion Concept Working Group

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INTRODUCTION

This subgroup of the Magnetic Fusion Concepts Working Group discussed the plans for developing the major magnetic confinement concepts: standard pulsed tokamak, advanced tokamak, spherical torus, compact stellarator, reversed-field pinch, and spheromak The goal was to identify, for each concept, what understanding and capability must be developed to establish its basis for a useful magnetic fusion energy system.

The group initially discussed the concept development process, metrics for development, and the FESAC classification of development levels. This was followed by a discussion of international collaboration opportunities and strategies. Of particular interest was a presentation (by N. Sauthoff) on the National Academy method of (quantifiably) classifying the strengths of a US program by measuring it against the international program.

This was followed by separate consideration of each confinement concept. For each, advocates were asked to present and lead discussions answering the following questions:

1) *For each MFE concept, what are the highest priority new developments required to demonstrate its viability for a practical energy producing system? What facilities and programs are needed to address these? Are there opportunities to minimize costs compatible with a realistic development program?*

2) *What are the perceived strengths and weaknesses of each concept? What opportunities are offered by each concept to reduce fusion development costs and achieve attractive economic and environmental features?*

3) *For each MFE concept, what issues must be resolved in order to motivate and justify advancing to its next stage of development and performance? What are the ideas, plans, and prospects for their resolution, including the entire world program? What metrics should be used to measure progress and readiness to advance?*

4) *What significant roles should the US program seek as part of the international fusion program, and in collaborating with the major international MFE research facilities?*

The answers were summarized during the meeting and discussed further, until there was general agreement by all participants (across the concepts). These summaries formed the basis for the sections which follow, presenting the opportunities, required developments, and metrics for the development of each of the concepts.

Only the tokamak sections are included in this file, if you want other Concepts see the Snowmass Proceedings on the FIRE web site.

I. Pulsed Conventional Tokamak Integration and Performance Measures

1. Benefits

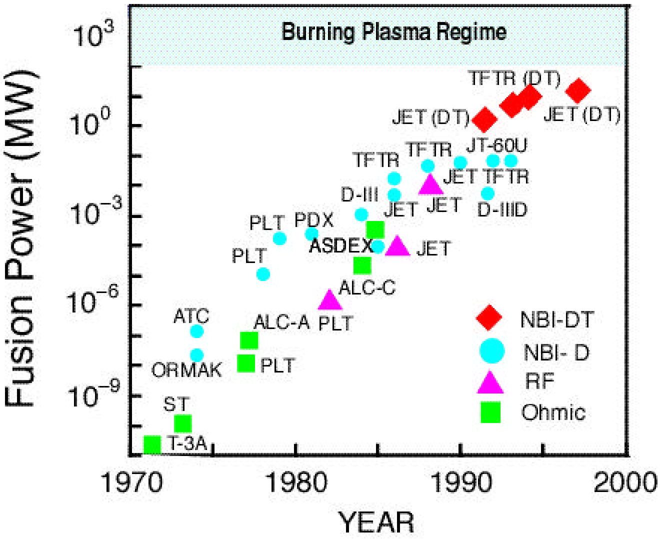

Fig. 1. Tokamaks have made excellent progress in fusion power.

The pulsed conventional tokamak combines magnetic coils and plasma current to magnetically confine a stable toroidal plasma. The plasma current is generated by an electrical transformer so its magnetic field is inherently a pulse of finite duration. Worldwide pulsed tokamak research has demonstrated that fusion energy is feasible, producing up to 16 MW of fusion power (Fig. 1) and 21 MJ of fusion energy in single pulses with a worldwide database nearest to the goal of fusion energy with alpha particle confinement. Able to reliably and controllably produce high temperature plasmas and equipped with extensive diagnostics to benchmark theory and simulation, the pulsed tokamak is an excellent research vehicle for advancing fusion energy science and supporting the development of related magnetic concepts. The pulsed tokamak is technically ready for a high gain burning plasma experiment and enjoys international support for proceeding to this integrated next step to explore the new scientific frontier of burning plasma physics and to develop plasma technologies for power generation.

2. Required Developments for Fusion Energy

While being relatively close to fusion energy conditions a number of developments are required for fusion energy. Improvements in the avoidance and mitigation of disruptions at high beta and normalized beta must be developed to increase the reliability of operation and to reduce erosion of plasma facing components. Physics understanding of plasma energy transport, stability, and alpha physics must be developed at sufficient gyroscale with dominant alpha heating. Reliable methods must be demonstrated for handling intense exhaust heat and particle loads with sufficient impurity control. Common to all fusion concepts, engineering materials, breeding blankets, and methods for reliable maintainability must be developed.

3. Other Issues and Concept Weaknesses

The size and cost of the pulsed conventional tokamak power plant leads to a costly development path. Its pulsed nature generates cyclic heat and stress loads and the need for energy storage. Common with the advanced tokamak it must be designed to survive disruption loads and for complex maintenance of superconducting toroidal magnet system and vacuum vessel.

4. Opportunities to Reduce Development Costs

Earlier investments in international tokamak facilities now enables research to be carried out at the performance extension level with only modest upgrades. These facilities (see Table I) are seeking ways to reduce development costs. At the level of fusion energy development (FED) an international consortium is willing to share costs to produce generic science and technology. At an intermediate level a smaller copper burning plasma experiment with lesser technical objectives could be built to decrease the near-term cost and risk, but would delay the eventually needed FED step.

Table I
Characteristics of Operating World Tokamaks

	Plasma Current (MA)	Magnetic Field B(T)	Major Radius R (m)	Comment
Performance Extension Tokamaks				
JET	6.0	4.0	3.0	E.U.
JT–60U	3.0	4.4	3.3	Japan
DIII–D	3.0	2.1	1.7	U.S.
Alcator C–Mod	2.0	9.0	0.65	U.S.
Tore Supra	1.7	4.0	2.3	France (superconducting)
ASDEX Upgrade	1.6	3.1	1.7	Germany
Proof-of-Principle Tokamaks				
FT–U	1.6	8.0	0.93	Italy
TCV	1.2	1.4	0.88	Switzerland
TEXTOR	1.0	3.0	1.75	Germany
JFT–2M	0.5	2.2	1.3	Japan
T–10	0.4	3.0	1.5	Russia
Compass-D	0.4	2.1	0.55	England
Triam-1M	0.15	8.0	0.84	Japan (superconducting)
Concept Exploration Tokamaks (partial list)				
JFT–2M	0.5	2.2	1.3	Japan
ET	0.3	0.25	5.0	U.S./UCLA
Truman-3M	0.18	1.2	0.5	Russia
HBT–EP	0.025	0.35	0.95	U.S./Columbia U.
Steady State Tokamaks (under construction)				
KSTAR	2.0	3.5	1.8	Korea (2004)
HT–7U	1.0	3.5	1.7	China (2004)
SST–1	0.22	3.0	1.1	India (2002)

5. Conventional Tokamak Metrics to Advance to the Next Stage (Fusion Energy Development)

The existing international tokamak physics database and completed technology and development establishes that the pulsed tokamak is technically ready to proceed to a high gain burning plasma experiment at the level of fusion energy development (FED). Deuterium-tritium experiments have already achieved a gain of fusion output power to input power of 0.6. A next stage would require the fusion gain to exceed 5 in order for the alpha particle heating to exceed the auxiliary heating power. Physics and technology options have enabled several next-step burning plasma experiment designs with differing technical objectives (e.g., BPX, ITER, RC–ITER, Ignitor, FIRE, …). Performance metrics to advance to the next step include:

- Adequate MHD stability at $\beta A > 6\%$ ($2.5 < A = R/a < 6$) with scaling of sufficient normalized beta $\beta_N = \beta\ (aB/I) > 2$ and adequate disruption mitigation.
- Adequate energy confinement with a quality factor $H_{89} = \tau_E/\tau_{89} > 1.8$ in regimes of reactor relevance ($T_e = T_i$, $\tau_{He}/\tau_E < 10$, scaling to low ρ_*, at sufficient density $n/n_{GW} \sim 0.7$). Energy confinement projections are shown in Fig. 2.

- Demonstration power handling with $P/R > 15$ MW/m with adequate core impurity control of $Z_{\text{eff}} < 1.5$.

A summary of further performance metrics are given in Table II and Fig. 3.

6. International Roles to Advance Goals

The U.S. has ceased focusing on conventional tokamak research in favor of advanced tokamak research and no longer has its large TFTR tokamak facility. The U.S. should therefore vigorously collaborate with the large tokamak facilities in Europe and Japan. U.S. experiments pioneered advanced tokamak physics and should aim to sustain an innovative lead by upgrading two national facilities (Alcator C–Mod and DIII–D) for steady-state advanced-tokamak research with current profile control systems. The U.S. has established and should maintain leadership in theory, simulation, diagnostics, and plasma control.

The U.S. should encourage the international parties to construct the redesigned Reduced-Cost International Thermonuclear Experimental Reactor (RC-ITER), maintain a watching brief, and if the parties choose to construct, the U.S. should seek to participate. At the same time, the U.S. should identify contingency smaller next-step burning plasma experiment options, as illustrated in Fig. 4.

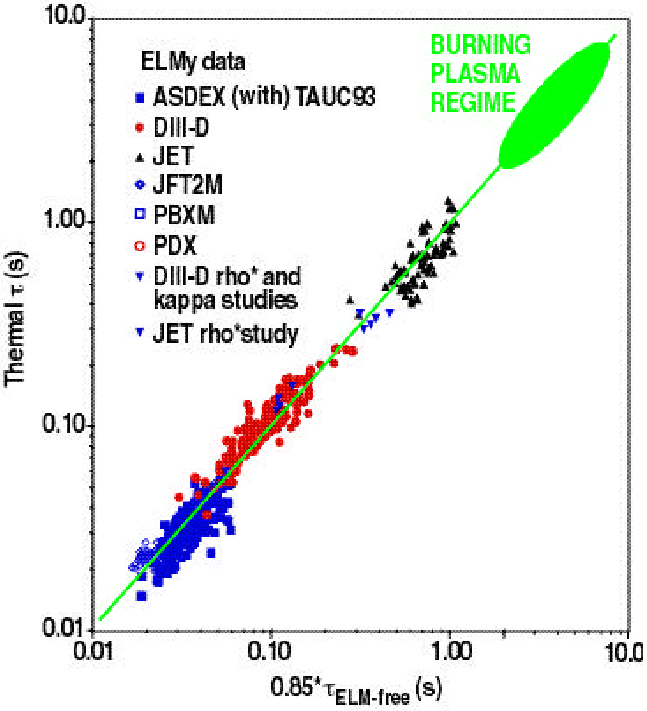

Fig. 2. Tokamak energy confinement studies provide the basis for design of a burning plasma experiment.

Table II
Pulsed Conventional Tokamak Performance Metrics

Attribute	Conventional Tokamak (ITER-EDA)	Best Achieved Values (not simultaneously)	DIII–D Shot 96686	TFTR D–T Shot 80539	JET Shot 47413
MHD Stability					
Plasma pressure relative to magnetic field pressure: $\beta = 2\,\mu_o\,\langle p\rangle/B^2$ (%)	3	12 (DIII-D)	4.8	1	
Normalized plasma stability factor: $\beta_N = B/(I/aB)$ (% m-T/MA)	2.3	5 (DIII–D)	3.8	1.8	1.95
Energy Confinement					
Confinement improvement relative to 1989 standard: $H_{89} = \tau_E/\tau_{89L}$	1.8	3.5 (AUG, DIII–D, TFTR)	3.2	2.1	2.3

Heat and Particle Exhaust					
Divertor upstream normalized heat flux q (MW/m^2)	1.0	0.5 (C–Mod)	0.1	–	
Helium ash removal: τ_{He}/τ_E	10	10 (DIII–D, JT–60U, TFTR)			
Integrated Performance					
Fusion power (MW)	1500	16 (JET)	–	10.7	10
P_{fusion}/Pa_{ux}	Ignition (>10)	0.6 (JET)	–	0.27	0.4
Ion/electron temperature: $T_{i/}T_e$ (keV)	30/35	40/15 (TFTR/JET)	10/6	36/13	35/10
Density: n_e (10^{20} m^{-3})	1.0	10 (C–Mod)	0.6	1.0	0.4
Triple product: $n\tau T$ (10^{20} m^{-3} s keV)	10	8 (JET, JT–60U, TFTR)	1	4	7

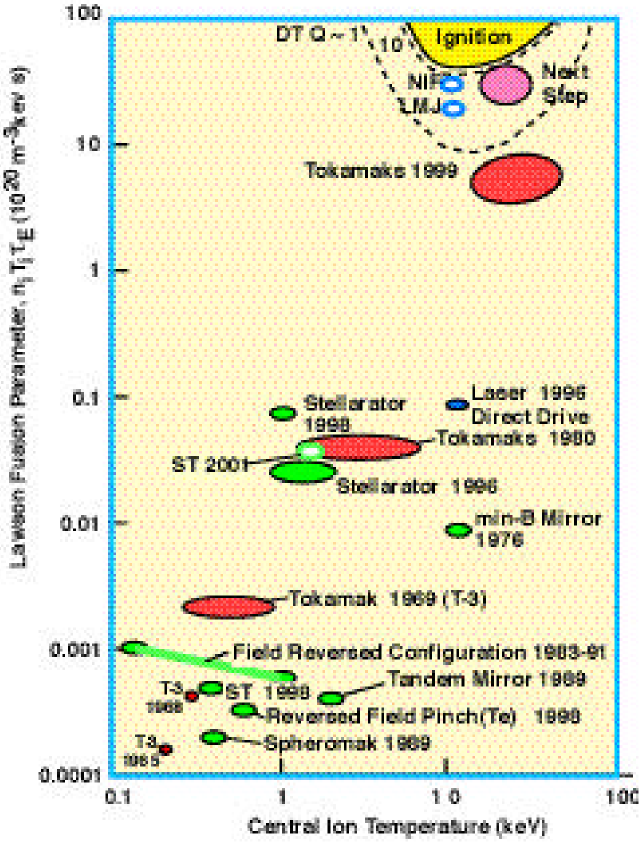

Fig. 3. The conventional tokamak is technically ready for a next-step high-gain burning plasma experiment.

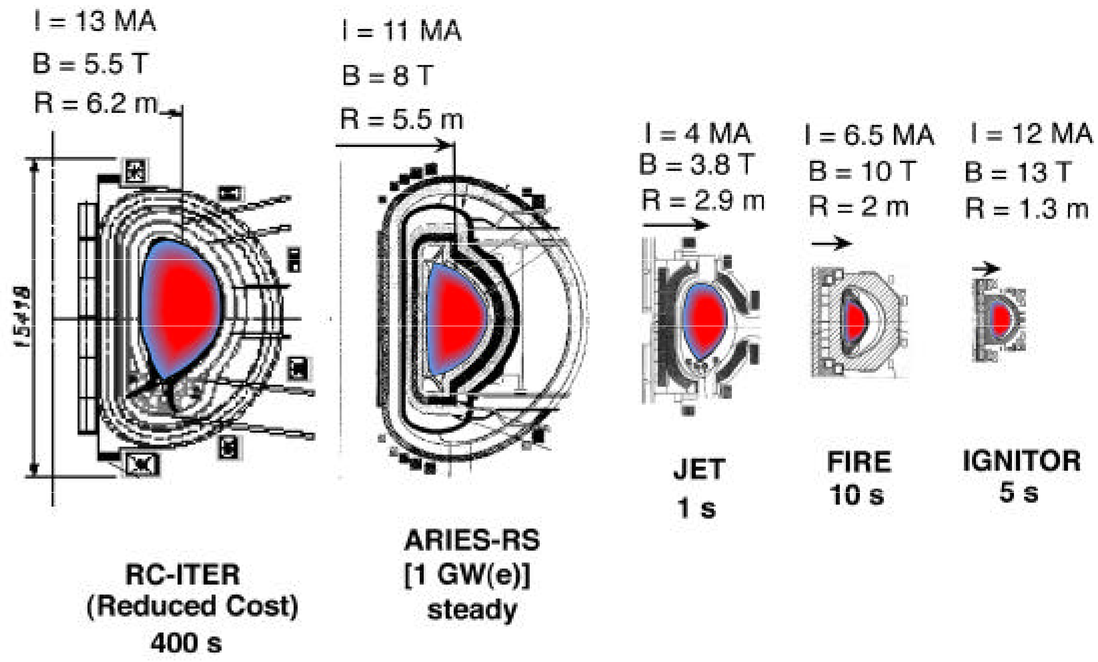

Fig. 4. Potential next-step tokamak burning plasma experiments relative to ARIES-RS power plant.

II. Steady-State Advanced Tokamak Integration and Performance Measures

1. Benefits

The steady-state advanced tokamak has the potential for continuous operation with low recirculating power and thereby avoids cyclic heat and stress loads associated with the pulsed conventional tokamak. Low recirculating power is achieved by utilizing inherent pressure gradient driven bootstrap currents that are maximized by operation at high plasma pressure relative to the poloidal magnetic field pressure (ie high beta-poloidal). In addition, operating at high beta ($\beta = 4\, \mu_o\, nT/B^2$) increases the fusion power since $P_{fusion} \propto \beta^2\, B^4 \times$ volume. Reactor studies indicate that the steady-state advanced tokamak leads to attractive reactor prospects with lower size, cost of electricity, and capital cost than a pulsed conventional tokamak (see Fig. 1).

The steady-state tokamak builds on the mature pulsed tokamak and emerging advanced tokamak database at the performance extension level. Examples of advanced tokamak research in high beta plasma stability and in internal transport barrier formation are illustrated in Figs. 2 and 3. Advanced tokamak research facilities with existing extensive diagnostics provide new benchmarks to challenge theory and simulation to advance generic fusion energy science as well as developing plasma technologies for power generation.

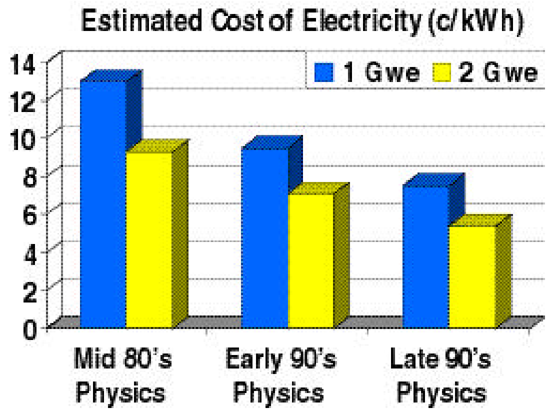

Fig. 1. Steady-state advanced tokamak power plant system studies indicate competitive costs of electricity are attained with advanced physics and technology development.

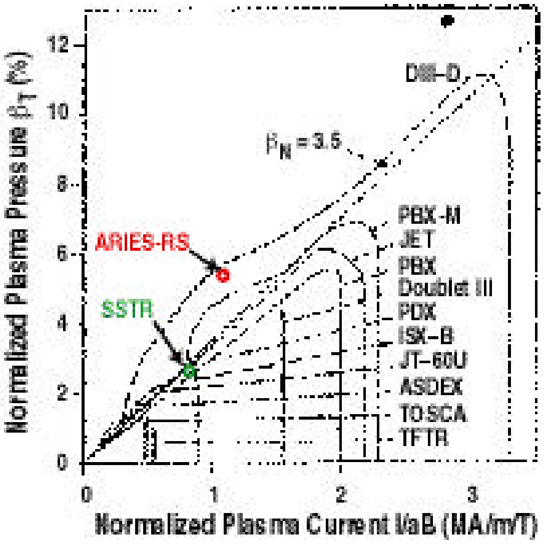

Fig. 2. Accurate guidance on operational boundaries is provided by ideal MHD theory and experiment. Plasma shaping enables increasing I/aB and the b-limit by increasing elongation, triangular shape, and inverse aspect ratio. High values of $b_N = B_T/(I/aB)$, achieved through profile effects and wall stabilization, increase the bootstrap current fraction.

2. Required Developments for Fusion Energy

A number of developments are required to establish an advanced tokamak database that is comprehensive enough to warrant extrapolation. Foremost is achieving simultaneous sustained high plasma beta, good confinement, and high well-aligned bootstrap current fraction. Since advanced tokamak plasmas are somewhat self-organized and operate near stability boundaries, effective disruption avoidance and mitigation are critical. Sustaining such optimized performance will require efficient current drive and effective profile control. An example of the projected stable operating space is shown in Fig. 4. Common to the pulsed tokamak development, a physics understanding of energy transport, plasma stability, and alpha physics must be developed at sufficient gyroscale with dominant alpha heating. The more compact higher performance advanced tokamak will require reliable methods for handling intense exhaust heat and particle loads with adequate impurity control.

Common to all fusion concepts, engineering materials, breeding blankets, and methods for reliable maintainability must be developed.

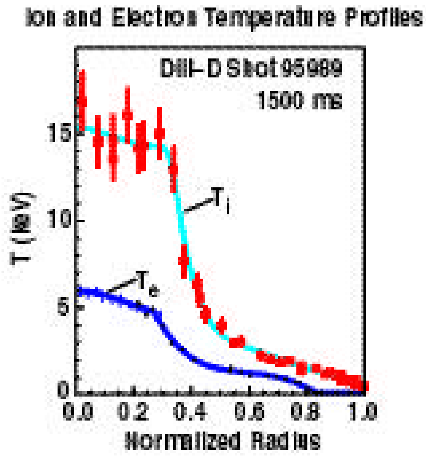

Fig. 3. Localized internal transport barriers improve core confinement. when turbulence is reduced or eliminated by combinations of sheared ExB flow and negative magnetic shear. Control of the steep pressure gradients which can precipate MHD instabilities is a key ongoing research challenge.

3. Other Issues and Concept Weaknesses

Optimization of advanced tokamak performance will require the utilization of current and transport profile control as well as more complex feedback control of MHD modes and equilibrium. Common with the pulsed conventional tokamak it must be designed to survive disruption loads and for complex maintenance of the vacuum vessel and the superconducting toroidal magnet system..

4. Opportunities to Reduce Development Costs

Developing advanced tokamak physics will reduce the cost of subsequent development steps as well as the eventual cost of electricity (Fig. 1). Past investments in existing international tokamak facilities is now enabling advanced tokamak research to be carried out at the performance extension level with modest upgrades for plasma control (e.g., ASDEX–U, Alcator C–Mod, DIII–D, JET, JT–60U). At the level of fusion energy development (FED) an international consortium is willing to share costs to produce generic science and technology (RC-ITER) with some AT capability. At an intermediate level, smaller copper burning plasma experiments (Ignitor, FIRE) with much lower technical objectives (to study transient AT burning plasma physics, but not steady-state physics) could be built to decrease the near-term cost and risk, but would delay the eventually needed FED step. These burning plasma experiments depend on conventional tokamak physics for their baseline design but have varying degrees of capability to develop advanced tokamak physics.

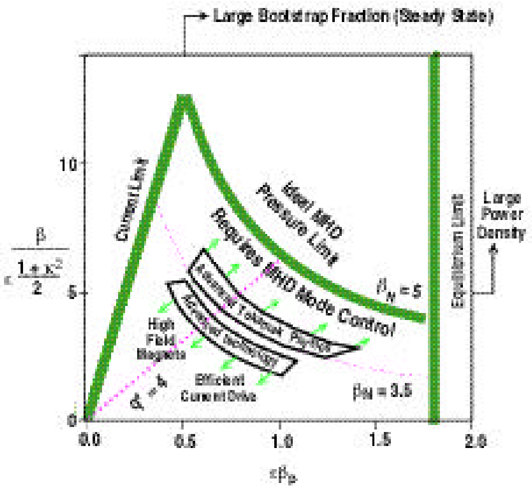

Fig. 4. A compact steady-state advanced tokamak requires operation at high b_N*. High power density requires high toroidal beta,* b_T*. Steady-state requires high* I_{bs}/I_p *which requires high poloical beta,* b_p*, high* b_T *and high* b_p *require high normalized beta since* b_N*.* $b_T b_p$ µ *(1+*k^2*/2) and* b_N ” b_T*/(I/aB).*

5. Metrics to Advance to the Next Stage (Fusion Energy Development)

The existing international tokamak physics database and completed technology development establishes that the tokamak is technically ready to proceed to a high gain burning plasma experiment at the level of fusion energy development (FED). . Non-stationary advanced tokamak deuterium discharges in JT-60 have achieved a DT equivalent gain of fusion output power to input power of 1.25. The next stage requires the actual fusion gain to exceed 5 in order for the alpha particle heating power to exceed the auxiliary heating power, and for the sustainable time to exceed all relevant time-scales. Performance metrics which would enable a next-step design based on advanced tokamak physics would include:

- Adequate MHD stability at $\beta A > 9\%$ ($2.5 < A = R/a < 6$) with scaling of sufficient normalized beta $\beta_N = \beta\ (aB/I) > 3$ and adequate scalable disruption mitigation.
- Adequate energy confinement with a quality factor $H_{89} = \tau_E/\tau_{89} > 2.2$ in regimes of reactor relevance ($T_e \quad T_i$, $\tau_{He}/\tau_E < 10$, scaling to low ρ_*, at sufficient density $n/n_{GW} \sim 0.7$.
- Efficient net current drive and profile control: with aligned bootstrap current fraction $f_{BS} > 60\%$ and current drive efficiency $\gamma_B = n_e R I_p / P_{CD}$ projecting to $0.3 \infty 10^{20}$ MA/MW•m^2.
- Demonstration power handling with $P/R > 15$ MW/m with adequate core impurity control of $Z_{eff} < 1.5$.

A summary of these steady-state advanced tokamak performance metrics are given in Table I and examples of recent progress are shown in Fig. 5.

Table I
Steady-State Advanced Tokamak Performance Metrics

Attribute	Steady-State Tokamak Reactor (SSTR) Japan	Advanced Tokamak Reactor (ARIES-RS) US	Best Achieved Values (not simultaneously)	DIII–D #96686	JET AT #47413	Metric for AT Next-Step
MHD Stability						
Plasma pressure relative to magnetic field pressure: $\beta = 2 \mu_o$ •p®/B^2 (%)	2.5	5	12 (DIII–D)	4.8	1.5	3
Normalized plasma stability factor: β_N = B/(I/aB) (% m-T/MA)	3.2	4.8	5 (DIII–D)	3.8	1.95	3
Energy Confinement						
Confinement improvement relative to 1989 standard: $H_{89} = \tau_E/\tau_{89L}$	1.8	2.4	3.5 (AUG, DIII–D, TFTR)	3.2	2.3	2.2
AT parameter: $\beta_N H_{89}$	5.8	11.5	17 (DIII–D)	12	4.5	6.6
Current Drive						
Plasma duration (s)	Steady-state	Steady state	2 h (TRIAM)	1	2	Steady
Percent bootstrap current (%)	75	89	80 (JT–60U, TFTR)	50		60
Current drive efficiency: $n_{CD}/R/P_{CD}$ (10^{20} A/W·m^2)	–	2	0.4 (JT–60U)	–		
Heat and Particle Exhaust						
Divertor upstream normalized heat flux q (MW/m^2)	2	2	0.5 (C–Mod)	0.1		2
Helium ash removal: τ_{He}/τ_E	10	10	10 (DIII–D, JT–60U, TFTR)			10
Integrated Performance						
Fusion power (MW)	3000	1800	16 (JET)	–	10	200
P_{fusion}/Pa_{ux}	50	29	0.6 (JET)	–	0.4	5
Ion/electron temperature: $T_{i/}T_e$ (keV)	17/17	21/22	40/15 (TFTR/JET)	10/6	35/12	
Density: n_e (10^{20} m^{-3})	1.4	2.5	10 (C–Mod)	0.6	0.4	
Triple product: $n\tau T$ (10^{21} m^{-3} s keV)	3.3	5.0	5.0 (JET, JT–60U, TFTR)	0.1	0.7	

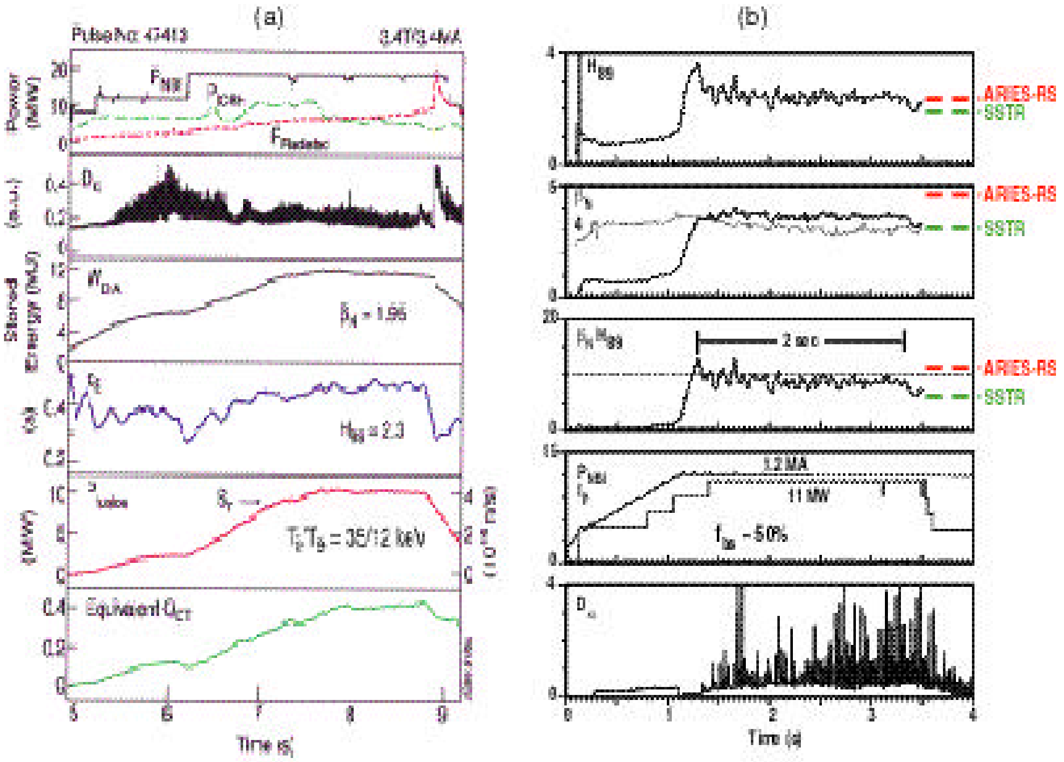

Fig. 5 Two examples of recent progress in advanced tokamak research extending the duration of high performance to 2 seconds..(a) Steady high performance advanced tokamak plasma in JET with high fusion yield, b$_{N,}$ *and confinement having an equivalent* Q_{DT} *= 0.4. (b) A steady advanced tokamak plasma in DIII–D with simultaneous high plasma beta and confinement and ~50% bootstrap current fraction.*

6. International Roles to Advance Goals

The US has ceased focusing on conventional tokamak research in favor of advanced tokamak research and no longer has the large tokamak facility TFTR. The U.S. should ocntinue to vigorously collaborate on advanced tokamak research with the large tokamak facilities in Europe and Japan and the other AT facilities (Table II). U.S. experiments have pioneered advanced tokamak physics and should aim to sustain this role in innovation by developing and demonstrating the required profile control systems. . The U.S. has established and should strive to maintain leadership in theory, simulation, diagnostics, and plasma control. The U.S. should collaborate on two future superconducting international steady-state tokamaks (KSTAR, HT-7U) which will be in full AT operation in ~2004.

The U.S. should encourage the international parties to construct the redesigned Reduced-Cost International Thermonuclear Experimental Reactor (RC-ITER) with advanced tokamak research capability, maintain a watching brief, and if the parties choose to construct, the U.S. should seek to participate. At the same time, the U.S. should work to identify contingency smaller next-step advanced tokamak burning plasma options.

Table II
World Advanced Tokamak Research Thrusts

Research Facility	**Unique Research Thrust**
Performance Extension Tokamaks	
JET (E.U.)	DT capability at large size, LHCD
JT–60U (Japan)	Steady state high performance physics at large size, ECH
DIII–D (GA)	High shape flexibility, high beta, CD divertor, ECH
Alcator C–Mod (MIT)	High field, high density divertor, LHCD
Tore Supra (France)	Long pulse superconducting, LHCD
ASDEX Upgrade (Germany)	AT physics, ECH
Proof-of-Principle Tokamaks	
FT–U (Italy)	High field, IBW
TCV (Switzerland)	High elongation
Concept Exploration Tokamaks	
ET (UCLA)	High beta via omgenity
HBT–EP (Columbia U.)	High beta via feedback