2002 Fusion Summer Study

Executive Summary

31 July 2002

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The 2002 Fusion Summer Study was conducted from July 8-19, 2002, in Snowmass, CO, and carried out a critical assessment of major next-steps in the fusion energy sciences program in both Magnetic Fusion Energy (MFE) and Inertial Fusion Energy (IFE). The conclusions of this study were based on analysis led by over 60 conveners working with hundreds of members of the fusion energy sciences community extending over 8 months. This effort culminated in two weeks of intense discussion by over 250 US and 30 foreign fusion physicists and engineers present at the 2002 Fusion Summer Study. The objectives of the Fusion Summer Study were three-fold:

- Review the scientific issues in burning plasmas, address the relation of burning plasma in tokamaks to innovative MFE confinement concepts, and address the relation of ignition in IFE to integrated research facilities.
- Provide a forum for critical discussion and review of proposed MFE burning plasma experiments (IGNITOR, FIRE, and ITER) and assess the scientific and technological research opportunities and prospective benefits of these approaches to the study of burning plasmas.
- Provide a forum for the IFE community to present plans for prospective integrated research facilities, assess the present status of the technical base for each, and establish a timetable and technical progress necessary to proceed for each.

In the MFE program, the world is now at a major decision point: to go forward with exploration of a burning plasma, opening up the possibility of discoveries in a plasma dominated by self-heating from fusion reactions and filling this crucial and now missing element in the MFE program.

In the IFE program, the decision to construct a burning plasma experiment has already been made. The National Nuclear Security Administration is currently building the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory. The NIF, and other facilities worldwide are expected to provide the needed data on inertial fusion burning plasmas. The IFE questions examined at the Fusion Summer Study revolve about the pace of development of the additional sciences and technologies needed for power production.

Magnetic Fusion Energy

Fusion energy shows great promise to contribute to securing the energy future of humanity. The science that underlies this quest is at the frontier of the physics of complex systems and provides the basis for understanding the behavior of high temperature plasmas. Grounded in recent excellent progress in the study of magnetically confined plasmas, the world is now at a major decision point: to go forward with exploration of a burning plasma, opening up the possibility of discoveries in a plasma dominated by self-heating from fusion reactions.

This exciting next step to explore burning plasmas is an essential element in the Fusion Energy Science Program whose mission is to “Advance plasma science, fusion science and fusion technology—the knowledge base needed for an economically and environmentally attractive fusion energy source.” The study of burning plasmas will be carried out as part of a program that includes advancing fundamental understanding of the underlying physics and technology, theory and computational simulation, and optimization of magnetic confinement configurations.

The participants of the 2002 Fusion Summer Study developed major conclusions regarding the opportunities for exploration and discovery in the field of magnetically confined burning plasmas. Below are summarized the principal conclusions:

> **1. The study of burning plasmas, in which self-heating from fusion reactions dominates plasma behavior, is at the frontier of magnetic fusion energy science. The next major step in magnetic fusion research should be a burning plasma program, which is essential to the science focus and energy goal of fusion research.**

Study of burning plasmas is a crucial and missing element in the fusion energy sciences program. It will make a large step forward in demonstrating magnetic fusion as a source of practical fusion energy for several applications, *e.g.*, electric power generation and hydrogen production.

The tokamak is now at the stage of scientific maturity that we are ready to undertake the essential step of burning plasma research. Present experimental facilities cannot achieve the conditions necessary for a burning plasma. A new experimental facility is required to address the important scientific issues in the burning plasma regime. The conditions needed to study the key physics phenomena expected in the burning plasma state have been identified.

Burning plasmas afford unique opportunities to explore, for the first time in the laboratory, high-temperature-plasma behavior in the regime of strong self-heating. Production of a strongly self-heated fusion plasma will allow the discovery and study of a number of new phenomena. These include the effects of energetic, fusion-produced alpha particles on plasma stability and turbulence; the strong, nonlinear coupling that will occur between fusion alpha particles, the pressure driven current, turbulent transport, MHD stability, and boundary-plasma behavior. Specific issues of stability, control, and propagation of the fusion burn and fusion ignition transient phenomena would be addressed.

Recent physics advances in tokamak research, aimed at steady-state and high performance, demonstrate the potential to significantly increase the economic attractiveness of the tokamak. Therefore, Advanced Tokamak (AT) research capability is highly desirable in any burning plasma experiment option.

Physics and technology learned in a tokamak-based burning plasma would be transferable to other configurations. Scientific flexibility, excellent diagnostics, and close coupling to theory and simulation are critical features of a program in burning plasmas. Such a program would contribute significantly to the physics basis for fusion energy systems based on the tokamak- and other toroidal configurations. The experience gained in burning plasma diagnostics, essential to obtaining data to advance fusion plasma science, will be highly applicable to burning plasmas in other magnetic configurations.

> **2. The three experiments proposed to achieve burning plasma operation range from compact, high field, copper magnet devices to a reactor-scale superconducting-magnet device. These approaches address a spectrum of both physics and fusion technology, and vary widely in overall mission, schedule and cost.**

The following mission statements were provided by the proposing teams:

IGNITOR is a facility whose mission is to achieve fusion ignition conditions in deuterium-tritium plasmas for a duration that exceeds the intrinsic plasma physics time scales. It utilizes high-field copper magnets to achieve a self-heated plasma for pulse lengths comparable to the current redistribution time. IGNITOR will study the physics of the ignition process and alpha particle confinement as well as the heating and control of a plasma subject to thermonuclear instability.

FIRE is a facility whose mission is to attain, explore, understand and optimize magnetically confined fusion-dominated plasmas. FIRE would study burning plasma physics in conventional regimes with Q of about 10 and high-beta advanced tokamak regimes with Q of about 5 under quasi-stationary conditions. FIRE employs a plasma configuration with strong plasma shaping, double-null poloidal divertors, reactor level plasma exhaust power densities and pulsed cryogenically cooled copper coils as a reduced cost approach to achieve this mission.

The overall objective of ITER is to demonstrate the scientific and technological feasibility of fusion energy. ITER would accomplish this objective by demonstrating controlled ignition and extended burn of deuterium-tritium plasmas, with steady-state as an ultimate goal, by demonstrating technologies essential to a reactor in an integrated system, and by performing integrated testing of the high heat flux and nuclear components required to utilize fusion energy for practical purposes.

Construction schedules were reported as 5 years for IGNITOR, 6 years for FIRE, and 9 years for ITER. FIRE is not at the same level of readiness as ITER and IGNITOR and will require some additional time to be ready for construction. ITER must complete international negotiations and agreement before construction can commence.

Cost information was obtained from the ITER and FIRE teams and was assessed within the limited resources available for the Snowmass work. All costs were converted to 2002-US dollars. ITER assumes an international cost-sharing approach while FIRE costs are estimated as a US project.

- The purpose of the ITER cost information is to provide accurate estimates of the relative "value" of all the tasks necessary for construction to facilitate international negotiations on task sharing. The cost information is based on a large engineering effort (about 1000 PPY) and a large R&D effort (about $900M) with prototypes of all key components. Also, the ITER cost information (about 85 procurement packages) is based on input from the industries in all the parties. The estimate of the ITER total "value", when converted to 2002 US dollars, is about $5 billion. The actual cost estimate is to be developed by each party using its own procedures, including the use of contingency. Thus, the ITER cost information does not included explicit contingency.

  The US will need to carefully estimate the cost of any potential contributions to ITER. These estimates should include adequate contingency and any additional required R&D to mitigate against potential cost increases.

- The estimate for FIRE is about $1.2 B including about a 25% contingency. It is based on an advanced pre-conceptual design using in-house and some vendor estimates. However, substantial further engineering is needed as well as some supporting R&D.
- As an Italian project, IGNITOR has been designed in detail with supporting R&D. It has a detailed cost estimate that is confidential for business purposes and was not made available to the assessment team.

3. IGNITOR, FIRE, and ITER would enable studies of the physics of burning plasma, advance fusion technology, and contribute to the development of fusion energy. The contributions of the three approaches would differ considerably.

- **IGNITOR offers an opportunity for the early study of burning plasmas aiming at ignition for about one current redistribution period.**
- **FIRE offers an opportunity for the study of burning plasma physics in conventional and advanced tokamak configurations under quasi-stationary conditions (several current redistribution time periods) and would contribute to plasma technology.**
- **ITER offers an opportunity for the study of burning plasma physics in conventional and advanced tokamak configurations for long durations (many current redistribution time periods) with steady state as the ultimate goal, and would contribute to the development and integration of plasma and fusion technology.**

The three candidate burning plasma devices would contribute a number of key benefits, i.e., capabilities for studies of the physics and technology of burning plasmas (under the assumption that each facility will achieve its proposed performance).

Common benefits from all three candidate burning plasma devices include the following:

PHYSICS

1. Strongly-coupled physics issues of equilibrium, stability, transport, wave-particle interactions, fast ion physics, and boundary physics in the regime of dominant self-heating.

TECHNOLOGY

2. Plasma support technologies (heating, fuel delivery, exhaust, plasma-facing components, and magnets) will benefit most because parameters and plasma conditions will be close to those required for power production.
3. Nuclear technologies (remote handling, vacuum vessel, blankets, safety and materials) will advance as a result of the experience of operating in a nuclear environment. The level of benefit will depend on tritium inventory, pulse length, duty factor, and lifetime fluence.

Key benefits from IGNITOR are the following:

PHYSICS

1. Capability to address the science of self-heated plasmas in a reactor-relevant regime of small ρ^* (many Larmor orbits) for globally MHD-stable plasmas at low β_N (normalized plasma pressure).
2. Capability to study sawtooth stability at low beta with isotropic alpha particles and self-consistent pressure profile determined by dominant alpha heating.

TECHNOLOGY

3. Development of high-field copper magnets with advanced structural features, including bucking and wedging and magnetic press.
4. Development of high-frequency RF antennas for wave heating in a burning plasma environment.

Key benefits from FIRE are the following:

PHYSICS

1. Capability to address the science of self-heated plasmas in reactor-relevant regimes of small ρ^* (many Larmor orbits) and high β_N (normalized plasma pressure) with a large fraction of non-inductive current sustained for up to a few current relaxation times.
2. Exploration of high self-driven current regimes with strong shaping and active MHD stability control.
3. Study of removal of helium ash and impurities with exhaust pumping.

TECHNOLOGY

4. Development of electrical insulation for high-field pulsed copper magnets in a high neutron fluence environment.
5. Development of high heat flux plasma-facing components with steady-state heat removal capability (tungsten/beryllium).

Key benefits from ITER are the following:

PHYSICS

1. Capability to address the science of self-heated plasmas in reactor-relevant regimes of small ρ^* (many Larmor orbits) and high β_N (plasma pressure), and with the capability of full non-inductive current drive sustained in near steady state conditions.
2. Exploration of high self-driven current regimes with a flexible array of heating, current drive, and rotational drive systems.
3. Exploration of alpha particle-driven instabilities in a reactor-relevant range of temperatures.
4. Investigation of temperature control and removal of helium ash and impurities with strong exhaust pumping.

TECHNOLOGY

5. Integration of steady-state reactor-relevant fusion technology: large-scale high-field superconducting magnets; long-pulse high-heat-load plasma-facing components; control systems; heating systems.
6. Testing of blanket modules for breeding tritium.

4. There are no outstanding engineering-feasibility issues to prevent the successful design and fabrication of any of the three options. However, the three approaches are at different levels of design and R&D.

There is confidence that ITER and FIRE will achieve burning plasma performance in H–mode based on an extensive experimental database. IGNITOR would achieve similar performance if it either obtains H–mode confinement or an enhancement over the standard tokamak L–mode. However, the likelihood of achieving these enhancements remains an unresolved issue between the assessors and the IGNITOR team.

The three options are at very different stages of engineering development.

- ITER and IGNITOR have well-developed engineering designs.
- ITER has been supported by a comprehensive R&D program. Also, ITER has demonstrated full-scale prototypes for essentially all major components of the fusion core and their maintenance.
- FIRE is at the advanced pre-conceptual design level. It has benefited from previous R&D for CIT/BPX/IGNITOR and, most recently, from ITER R&D.
- IGNITOR has carried out R&D and built full-size prototypes for essentially all major components.

Projections for the three options are based on present understanding of tokamak physics.

- Based on 0D and 1.5D modeling, all three devices have baseline scenarios which appear capable of reaching $Q = 5 – 15$ with the advocates' assumptions. ITER and FIRE scenarios are based on standard ELMing H–mode and are reasonable extrapolations from the existing database.
- IGNITOR's baseline scenarios, based on cold edged L–mode, depend on a combination of enhanced energy confinement and/or density -peaking. An unresolved issue arose as to whether an adequate database exists (proposers) or does not exist (assessors) for assessing confinement projections in the proposed IGNITOR operational modes: L–mode limiter or H–mode with x-point(s) near the wall. Further research and demonstration discharges are recommended.
- More accurate prediction of fusion performance of the three devices is not currently possible due to known uncertainties in the transport models. An ongoing effort within the base fusion science program is underway to improve the projections through increased understanding of transport.
- Each device presents a reasonable set of advanced scenarios based on present understanding. ITER and FIRE have moderate- and strong-shaping respectively and the control tool set needed to address the issues of high beta and steady-state related to Advanced Tokamak regimes. FIRE has the capability to sustain these regimes for one to three current redistribution times, while ITER has the capability to sustain these regimes for up to 3000 s allowing near steady-state operation. IGNITOR presents credible advanced performance scenarios using current ramps and intense heating to produce internal transport barriers on a transient basis.

A number of issues have been identified and are documented in the body of the report. For example, on ITER and FIRE, the predicted ELM-power loads are at the upper boundary of acceptable energy deposition; ELM-control and amelioration is needed. On FIRE, control of the neoclassical tearing mode by lower hybrid current drive is not sufficiently validated.

Also, FIRE has a concern about radiation damage of magnet insulators. On ITER, tritium retention is a concern with carbon-based divertor materials. These issues are the subjects of continuing R&D.

5. The development path to realize fusion power as a practical energy source includes four major scientific elements:

- **Fundamental understanding of the underlying science and technology, and optimization of magnetic configurations**
- **Plasma physics research in a burning plasma experiment**
- **High performance, steady-state operation**
- **Development of low-activation materials and fusion technologies**

A diversified and integrated portfolio consisting of advanced tokamak, ICCs, and theory/simulation is needed to achieve the necessary predictive capability. A burning plasma experiment should be flexible and well-diagnosed in order to provide fundamental understanding.

Fusion power technologies are a pace-setting element of fusion development. Development of fusion power technologies requires:

- A strong base program including testing of components in a non-nuclear environment as well as fission reactors.
- A materials program including an intense neutron source to develop and qualify low-activation materials.
- A Component Test Facility for integration and test of power technologies in fusion environment.

An international tokamak research program centered around ITER and including these national performance-extension devices has the highest chance of success in exploring burning plasma physics in steady-state. ITER will provide valuable data on integration of power-plant relevant plasma support technologies. Assuming successful outcome (demonstration of high-performance AT burning plasma), an ITER-based development path would lead to the shortest development time to a demonstration power plant.

A FIRE-based development plan reduces initial facility investment costs and allows optimization of experiments for separable missions. It is a lower risk option as it requires “smaller” extrapolation in physics and technology basis. Assuming asuccessful outcome, a FIRE-based development path provides further optimization before integration steps, allowing a more advanced and/or less costly integration step to follow.

IGNITOR allows early demonstration of an important fusion milestone, burning plasmas with a low initial facility investment cost. Because of its short pulse length, IGNITOR cannot thoroughly investigate burn control and/or advanced tokamak modes. IGNITOR could be an element of a portfolio of experiments supporting ITER-based or FIRE-based development scenarios.

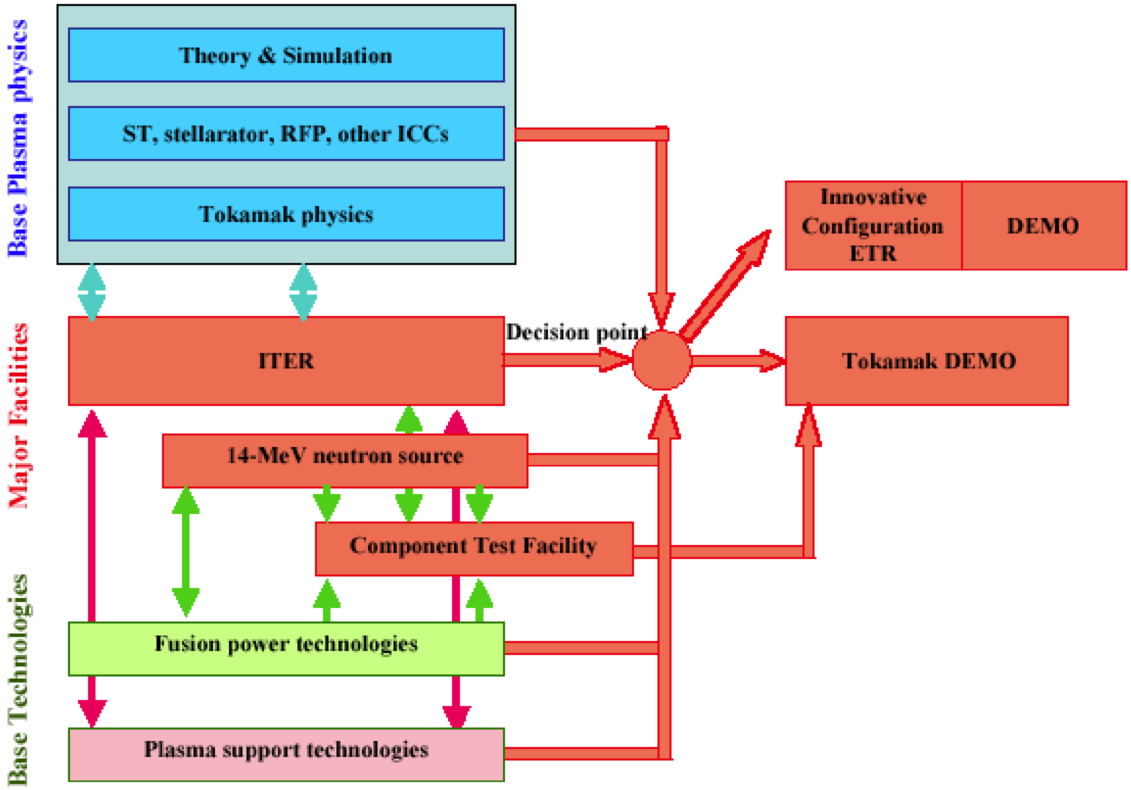

Fig 1. Schematic of development path based on ITER-class burning plasma experiment.

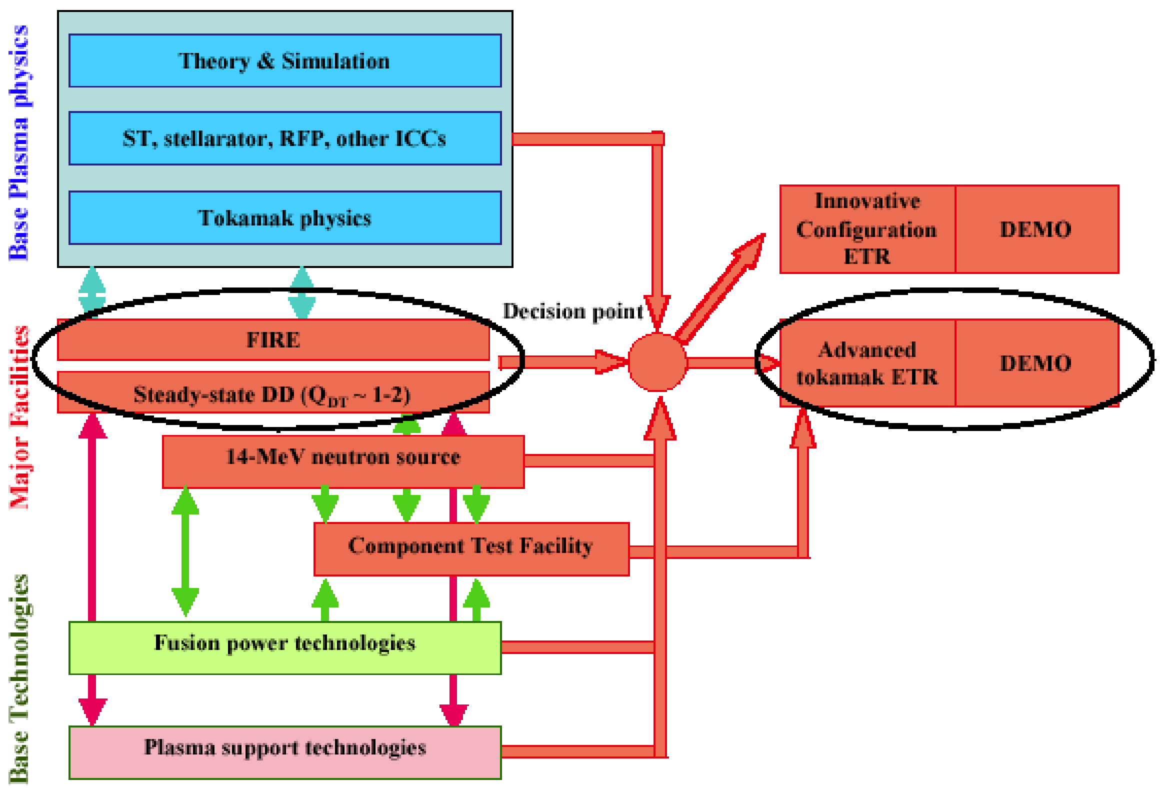

Fig. 2. Schematic of development path based on FIRE-class burning plasma experiment.

6. A strong base science and technology program is needed to advance essential fusion science and technology and to participate effectively in, and to benefit from, the burning plasma effort. In particular, the development path for innovative confinement configurations would benefit from research on a tokamak-based burning plasma experiment.

It has been a much-affirmed premise of the current fusion energy program that a strong base program forms a foundation for the field. The base program develops a broad array of underlying fusion physics and technology, and provides the knowledge base to optimize the magnetic configuration for plasma confinement. The science associated with burning plasma science requires a major step beyond the base program. The science associated with a significant variety of other critical, fundamental issues constitutes the base program.

The base program is also essential to the successful and full exploitation of a burning plasma effort. U.S. participation in a burning plasma experiment clearly requires a cadre of fusion physicists and engineers. In addition tokamak experiments are needed to contribute to the database that helps guide and influence a burning plasma experiment. For the U.S. to benefit fully from a burning plasma experiment requires not only experimentalists and engineers, but also theorists and computational scientists who can interpret the results, and generalize them for application to future tokamak experiments and non-tokamak configurations.

The development of innovative confinement configurations would benefit from a burning plasma experiment based on the tokamak configuration. Research in innovative configurations is essential for the broad development of fusion science and for the evolution of an optimal approach to fusion energy. The results from a tokamak burning plasma experiment will be sufficiently generic to accelerate the development of other toroidal fusion configurations. The tokamak shares many physics features with the spectrum of toroidal configurations, including nonaxisymmetric tori (the stellarator family), axisymmetric tori with safety factor $q > 1$ (including advanced tokamaks and spherical tokamaks), and axisymmetric tori with $q < 1$ (including the reversed field pinch, spheromak, and field reversed configurations). The behavior of alpha particles in these configurations is expected to have features in common, so that tokamak results can influence research in other configurations.

There are many geometric differences between a tokamak and these neighboring configurations; however, if the results from a tokamak burning plasma experiment are understood at the level of fundamental physics, then these results can be transferred through theory and computation. This transferability is expected to apply to the classical confinement of alpha particles, alpha-generated instabilities, the effect of alpha particles on existing instabilities, the effect of turbulence and MHD instabilities on alpha confinement, and aspects of burn control. Clearly, the transferability is largest for configurations that are geometrically closest to the tokamak. However, nearly all physics results obtained in the tokamak configuration have had influence on the large family of toroidal configurations, and it seems clear that this influence will extend to results from tokamak burning plasma experiments.

The technological information learned from a tokamak burning plasma experiment will strongly apply to other configurations. Areas of technology transfer include superconducting magnets, plasma facing components, fueling, heating sources, blankets and remote handling.

Inertial Fusion Energy

In 1990 the Fusion Policy Advisory Committee recommended that magnetic fusion energy and inertial fusion energy be developed in parallel. This policy was reaffirmed by the Fusion Energy Sciences Advisory Committee in 1999 and The Secretary of Energy Advisory Board in 2000.

As noted earlier, the programmatic issues facing inertial and magnetic fusion are quite different. The burning plasma experiments for inertial fusion, namely the National Ignition Facility (NIF) in the United States and the LMJ in France, are already under construction. Currently plasma ignition on NIF is expected around FY2010, depending on future funding decisions about the pace of funding for diagnostics and cryogenic capabilities. Existing facilities in the United States (e.g., Omega, Z, and Nike) and other facilities worldwide are providing information leading to burning plasma experiments at the NIF and at the LMJ. The domestic facilities have been built, or are being built, under the auspices of the National Nuclear Security Administration (NNSA), primarily for defense purposes.

Although the NIF will provide the needed data on burning IFE plasmas, it does not have the capability to operate at high repetition rates or to manage the fusion power that high repetition rates produce. Moreover the NIF has neither the efficiency nor the durability needed for commercial power production. Substantial scientific and technical issues must be studied and resolved in parallel to enable high repetition rates, good efficiency, and adequate lifetime. The modularity of IFE drivers and the separability of power plant components make it possible to study these issues and issues associated with supporting subsystems in scaled facilities. The IFE community refers to these facilities as “integrated research facilities” or IREs. They are the next major steps in inertial fusion. They are expected to be substantially less expensive than either the magnetic burning plasma experiment or the NIF. While the NIF can demonstrate the creation of fusion energy in single shots, the IREs will provide the foundation of science and technology needed for the subsequent demonstration of net fusion power, and the delivery of net fusion electricity to the grid.

OVERVIEW OF IFE

An IFE power plant will produce energy by focusing intense beams of light or charged particles, or concentrating intense x rays, onto a small target containing fusion fuel. The fuel will ignite with a burst of fusion reactions releasing much more energy than was invested to cause ignition. The fusion heart of the power plant will have several important systems:

- The fusion targets containing the fuel.
- A factory designed to fabricate millions of targets per year.
- A chamber approximately 6 meters or more in diameter to capture the energy produced by the fusion pulses.
- An injection system to inject or place the targets into the chamber.
- A driver to produce the energy needed for ignition.
- A focusing or concentration system to deliver the driver energy to the target.

There are several types of drivers and focusing systems, many different types of targets, and several types of chambers. To some extent these systems or components are independent so there are many possible combinations. This independence allows modular, cost-effective research on key issues with synergy among the integrated concepts.

There are currently three main kinds of drivers: heavy ion accelerators, lasers, and z pinches driven by pulsed power. The drivers are expected to be the single most expensive part of the power plant. There are substantial research programs in heavy ion accelerators and in krypton fluoride lasers (KrF) and diode pumped solid-state lasers (DPSSLs). The heavy ion fusion program is currently funded through the Office of Fusion Energy Sciences (OFES) and the laser programs are funded through NNSA. There is a smaller, concept exploration program in z pinches that builds on an expanding z-pinch program supported by the NNSA for defense purposes. There are also important IFE programs in target physics, target fabrication (including mass production techniques), target injection, chambers, and focusing systems. These programs are funded through both OFES and NNSA. Despite different funding sources, all the various inertial fusion research programs are very well coordinated

As noted above, there are many types of targets. In all IFE targets the fusion fuel is compressed before it is ignited. There are two broad methods of compression and two methods of ignition. The fuel is compressed either through an implosion driven directly by the driver beams (direct drive) or by converting the driver energy to x rays that then drive the implosion (indirect drive). The two classes of ignition are hot-spot ignition and fast ignition.

Chambers also fall into a number of general types. The types currently receiving the most attention are dry-wall chambers, wetted-wall chambers, and chambers in which the wall is protected by thick liquid layers. Often the dry wall chambers contain some gas to protect the wall from x-rays, charged particles, and target debris. The wetted walls use thin liquid layers on the wall or sprays of fluid in the chamber to do the same. Thick liquid layers are used to protect the wall from neutrons as well as from x-rays, charged particles, and target debris.

Although there are many possible combinations of drivers, targets, and chambers, resources do not allow the exploration of all combinations. Each integrated approach puts most of its effort into the combination that currently appears to be most compatible. The various combinations of drivers, targets, and chambers must work together and not all combinations are equally compatible or self-consistent. Currently the laser programs emphasize directly driven targets and dry wall chambers. The heavy ion and z pinch programs emphasize indirectly driven targets and thick liquid wall protection.

IFE PLANS

Several years ago the IFE community developed a program plan or roadmap (Fig. 3) leading to the integrated research experiments and ultimately to a demonstration power plant.

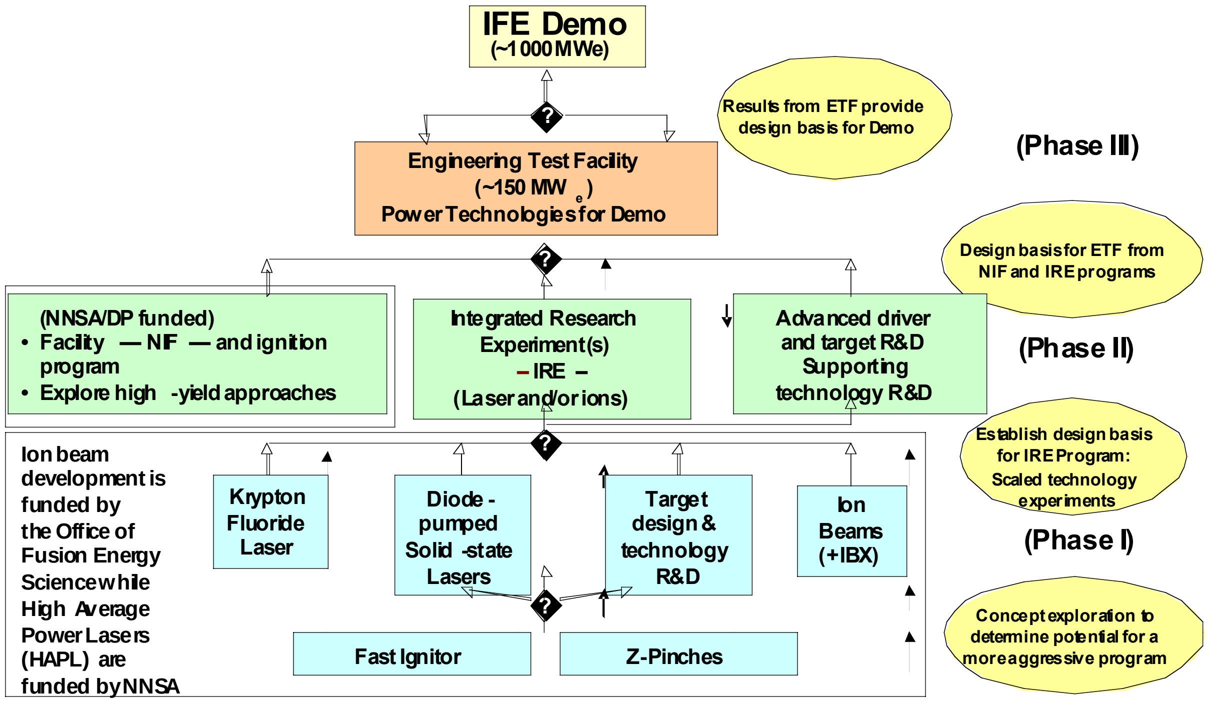

Fig. 3. The Inertial Fusion Energy Roadmap

This plan has three phases preceding a demonstration power plant. The first phase contains research elements at the levels referred to as concept exploration and proof of principle. The IFE community has developed specific milestones that must be met at each level before a concept is ready to advance to the next step.

Phase I, the current phase of the plan, consists of the research preceding the integrated research experiments. In this phase there are research programs in target physics, target fabrication and injection, fusion chambers, and driver physics and technology. The target physics program includes research on the so-called fast ignition approach; an approach that may lead to higher target energy gains at reduced driver energy. In Phase I, two laser driver facilities, Electra and Mercury are under construction and are making excellent progress. Electra is a krypton fluoride (KrF) laser and Mercury is a diode pumped solid-state laser. The needed Phase I facility for heavy ion fusion, the Integrated Beam Experiment (IBX), has not yet been approved. Another driver option, the z-pinch approach, is currently being studied but does not yet have official Department of Energy funding.

In Phase II, those drivers that meet their milestones advance, using the IREs, to the point that the driver information, together with the NIF and advanced research in chambers and target technologies provide the information to determine if IFE is ready to proceed to an Engineering Test Facility (ETF). The ETF will provide a test bed for demonstration of all IFE plant systems at reduced scale, including tritium breeding and recovery and power conversion, as well as accelerated materials and component reliability testing. Information from scaled testing of all IFE plant subsystems will be used in decision making to determine if a full-scale IFE demonstration power plant (Demo) should be built. If the decision is positive, the ETF will also provide the information that is necessary to design and build all plant systems in the Demo.

Assessment of the plans and status at this workshop led to three important conclusions:

- **The various driver programs (lasers, heavy ion accelerators, and Z-pinches) are advancing at different rates because of funding differences and their relative maturity. The most advanced programs are unlikely to be in position to propose an integrated research experiment for several years.**

- **The inertial fusion community (both proponents and critics of the individual approaches) believes that the Phase I research plans are sound and that they address the correct technical issues.**

- **Phase I funding rates are the programmatic issue. Resolution of this issue will require coordination of the inertial and magnetic programs.**

Regarding the second conclusion, it is important to note that there is less agreement about Phase II and some of the quantitative aspects of the milestones needed to advance to Phase II. The various disagreements must be resolved by additional workshops and peer review.

Regarding the third conclusion, there are several important points: The laser approaches have been funded, as a Congressional initiative through NNSA, at approximately the rate recommended by the Fusion Energy Sciences Advisory Committee in 1999. Nevertheless, there is an important issue: The budgets submitted by NNSA do not contain funding for these important laser activities so future funding is uncertain. The heavy ion fusion approach, funded through the Office of Fusion Energy Sciences, has been funded at a little over half the rate recommended by the Fusion Energy Sciences Committee; and, as noted above, the IBX has not yet been approved. The z-pinch approach has not been officially funded and the target physics program (including fast ignition research) is inadequately funded.

PROGRESS AND ISSUES

Despite the significant near-term issues relating to funding, there has been important progress since the last Snowmass Summer Study. We conclude with a summary of this progress and a summary of some of the important remaining issues:

- **Laser systems have made impressive progress in efficiency, pulse rate, and lifetime. Efficiency and lifetime remain important issues for KrF lasers. Cost of major components and beam quality are important issues for solid state lasers.**

- **The heavy ion fusion program has made excellent progress in basic beam science. Several new science experiments have recently begun operations. Fielding integrated experiments (for example the IBX) at moderate beam energy and current and focusing intense beams in the chamber environment remain the important technical issues.**

- **There has been impressive progress in z-pinch targets and good progress in conceptual power plant designs. Producing economical recyclable transmission lines at low cost remains the most important issue.**

- **Recent calculations indicate that fluid instabilities in the targets may be controlled by appropriate choice of pulse shape. Both directly driven and indirectly driven targets appear to be feasible.**

- **Chamber technology and target fabrication and injection are being placed on a sound scientific basis. For example, experiments on dry-wall damage limits are underway. Scaled hydraulics experiments have identified nozzle designs that can create all liquid jet configurations required for thick liquid chambers, and a target injection experiment is under construction. For heavy-ion fusion there is now a chamber design where the final focus magnets and chamber structures have predicted lifetimes exceeding 30 years.**

- **There is broad international interest in fast ignition. If fast ignition is successful, it will produce higher energy gains than conventional targets. So far the target experiments have been encouraging, particularly the recent Japanese results. Fast ignition power production is at a rudimentary level for all drivers. An integrated research plan is required.**