Magnetic Fusion Concept Working Group
Fusion Summer Study

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Summary

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INTRODUCTION

The Magnetic Fusion Concept Working Group (MFCWG) reviewed the challenges and opportunities in magnetic fusion energy for the next decade. The schedule and structure of the MFCWG is illustrated in Fig. 1. Following the plenary session on Monday, the MFCWG met each morning for four hours. We began the first three mornings with everyone in joint session for approximately two hours. In these joint sessions, we had invited speakers give a presentation on a specific magnetic configuration. The speaker was instructed to discuss the status, identify issues for each of the subgroups, and provide background for the discussions to follow in the breakout groups. On Thursday, we met in joint session with the emerging concept group, since both the EC and MFCWG had a responsibility to discuss three magnetic configurations; the reverse field pinch (RFP), the spheromak, and the field reversed configuration (FRC). Following the joint sessions, we then separated into the breakout groups for further discussion. Each breakout group was to focus on the configuration introduced in joint session earlier in the morning, as appropriate. On Tuesday, July 20, we met in joint session for approximately one hour primarily to discuss how we might reach closure on unresolved issues. Then we met in breakout the rest of Tuesday morning and all of Wednesday morning. Two sessions were held that are not shown in Fig. 1. On Wednesday evening, July 21, the MFCWG met for two hours to review issues to be included in the summary presentation. On Thursday evening, July 22, the MFCWG met for two hours to discuss the issue of readiness for the tokamak to proceed to a high gain burning plasma experiment.

We organized the breakout discussion groups along scientific issues common to the confinement concepts in order to enhance discussion across magnetic configurations and develop better understanding of the opportunities to address the critical issues. The six breakout sessions are transport in magnetic confinement concepts, magnetohydrodynamics (MHD) stability in magnetic confinement concepts, plasma boundary and particle control, achieving stead-state operation in magnetic fusion energy (MFE) devices, burning plasmas in magnetic confinement concepts, and MFE concept integration and performance measures.

MAGNETIC CONFINEMENT PORTFOLIO

The present approach to research in magnetic fusion energy is to address critical scientific issues through experiments using a portfolio of magnetic concepts. The different toroidal magnetic configurations can be classified by the degree to which the magnetic field is externally imposed. At one extreme lie externally controlled configurations

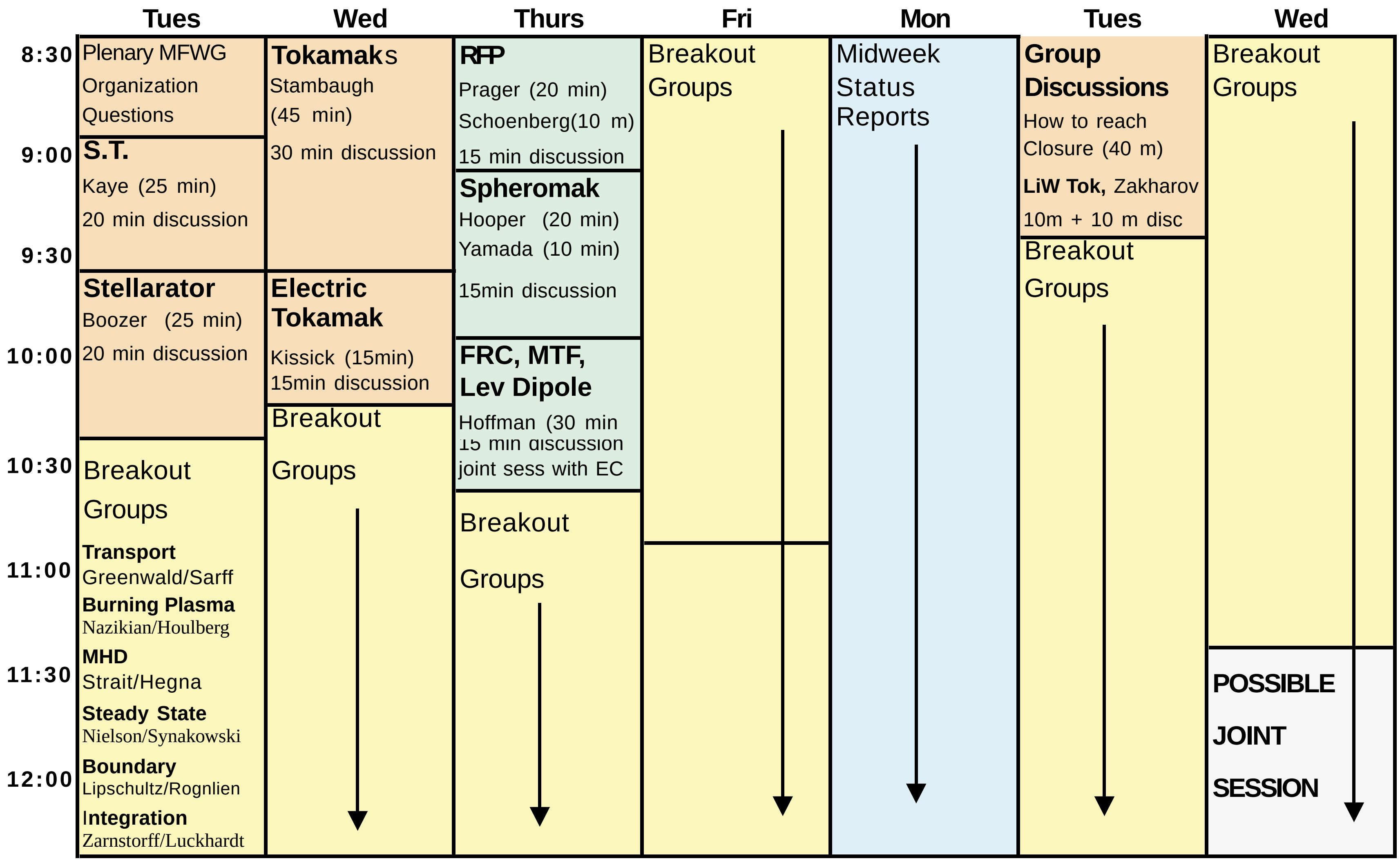

Fig. 1. Schedule for Magnetic Fusion Working Group

with the confining magnetic field supplied almost entirely from external coils. At the other extreme lie the self-organized concepts where the confining field self-generated largely by the plasma. For the configurations discussed by the MFCWG, the externally controlled configurations have larger toroidal magnetic fields and a relatively larger safety factor q, typically q > ~1 everywhere in the plasma. Self-organized concepts have lower toroidal magnetic fields, and relatively lower safety factors, q < 1 everywhere in the plasma. The specific magnetic configurations considered, from self organized to externally controlled, are the FRC, which has zero toroidal magnetic field and is self-organized; the Spheromak; the RFP; the Spherical Torus (ST); Tokamaks, including the Advanced Tokamak (AT); and the Stellerator, with a strong toroidal magnetic field, and in many cases the confining field generated entirely with coils outside the plasma. These configurations, considered by the working group, all have nested closed flux surfaces. There is a strong degree of complementarity and commonalty in the scientific issues addressed by the concepts. The study and evaluation of one magnetic configuration enhances our ability to understand and develop other configurations, and many scientific issues are best addressed by approaching the issue with more than one magnetic configuration.

A SCIENTIFIC MFE RESEARCH PROGRAM

An approach to a scientific research program, which utilizes the complimentary of the different magnetic configurations, is illustrated in Fig. 2. First, fundamental plasma science and technology provides the basis for fusion energy science, and all the magnetic configurations can contribute to developing the scientific building blocks for fusion energy; the configurations specifically listed as well as others. Second, it is important to recognize that all the magnetic configurations have a common set of issues that must be addressed at a reasonably basic level, before progressing very far along the fusion energy development path. These basic issues, common to all magnetic fusion energy configurations are: MHD; energy, particle, and momentum transport; particle and wave interactions; and plasma boundary physics. The box for particle-wave interactions is shown with a dotted boundary in Fig. 2. Figure 2 was also used to indicate our organizational structure at the Snowmass meeting, and during the meeting the wave-particle physics was subsumed under the steady-state issues. The importance of this basic physics element is widely recognized and so is included here.

The view of the fusion research program illustrated in Fig. 2 recognizes the importance of developing fundamental understanding of the physics principles in each of the scientific disciplines. This view also highlights the importance of a strong coupling between experiments and theory, including realistic code development and computer modeling. Shown explicitly in the figure is the importance of advances in technology, providing improvements in basic machine design and plasma control tools necessary for the innovative and precise experiments required.

When sufficient progress has been made in each of the four science areas, these elements can be combined to move to higher levels of integration. At this next level, there are two extremely important issues. The steady-state issues deals with bringing together the science elements, MHD, transport, wave-particle, and boundary, to develop the scientific basis for fusion energy systems with high, average power. In most magnetic configurations, high average power implies steady-state operation, but there are magnetic fusion energy systems proposed that are pulsed. Another major issue for magnetic fusion energy is demonstration of high gain in a burning plasma. A burning plasma has sufficiently high energy gain that the self-heating by fusion products significantly exceeds the auxiliary heating in the plasma core. The burning plasma physics must properly integrate the four science elements to obtain high performance. Finally our goal is to develop a fusion energy production system, which must integrate all the elements into economically and environmentally attractive fusion power production. In Fig. 2, progressing from the science elements to steady state and burning plasma requires an increase in the level of integration; and a further level of integration is required to progress to the integrated fusion energy system. Part of the charter of the integration breakout group was to determine the metrics and the extent of integration needed for each magnetic configuration to move the next level of development.

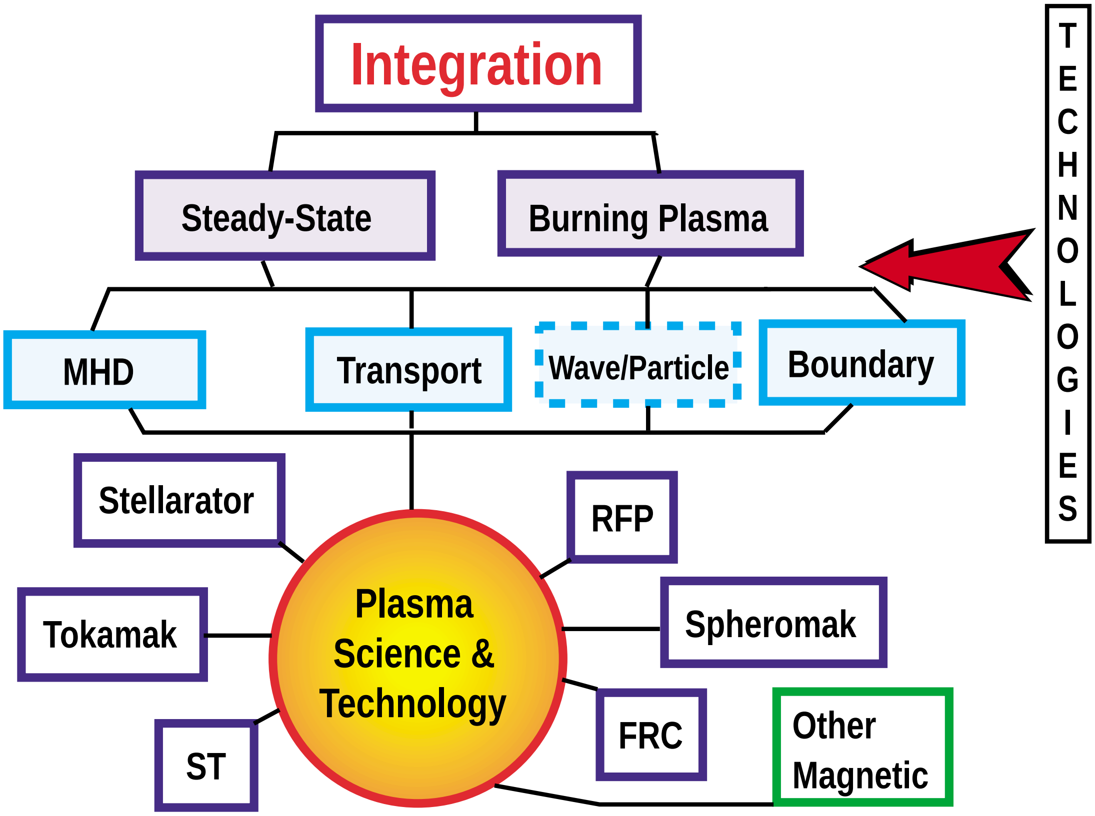

Fig. 2. Elements for a scientific roadmap for MFE.

LEVELS OF DEVELOPMENT

Within the MFE program, each of the magnetic configurations can be classified according to the level of development and scientific understanding. The development path of any magnetic configuration in the portfolio can be mapped through a series of distinct stages; Concept Exploration (CE), Proof-of-Principle (PoP), Performance Extension (PE), Fusion Energy Development (FED), and fusion power demonstration (DEMO). At the concept exploration level, a promising new idea is typically first tested in a low-cost exploratory experiment designed to validate the most basic aspects of the concept. The proof-of-principle stage of development includes more complete experimental tests of a range of key scientific and technical principles. At the performance extension stage, the extension of the concept toward fusion parameters is verified, typically requiring integration of all the basic physics elements. The fusion energy development stage produces fusion relevant plasmas and begins to integrate a fusion plasma core with the technologies for fusion power plants. These levels of development have been adopted by the community and are defined by in the report on alternative concepts of the SciCom Review Panel of the Fusion Energy Advisory Committee, July 1996.

GOALS

At the fusion summer study, the Magnetic Fusion Concept Working Group identified three major goals for magnetic fusion energy research. The first goal is to determine the optimum magnetic configuration(s) for attractive fusion energy production. This goal would be pursued by using the spectrum of magnetic configurations ranging from externally controlled to self-organized; to understand the scientific foundations of MFE (equilibrium and stability, transport, wave-particle, boundary, and plasma control); and to integrate these elements to optimize a steady-state, high-performance magnetic fusion plasma. Our second goal is to be prepared to move forward with the next stage of development for MFE. Opportunities for the next stage of development include pursuing burning plasma physics in proposed experiments like JET–Upgrade, FIRE, and Ignitor; pursuing steady-state plasma development in devices such as KSTAR, now being constructed in Korea; and participating in an integrated test of sustained burning plasmas in ITER-RC, if Europe or Japan decide to construct. Our third goal is to provide a fertile environment for new ideas and innovation in MFE by actively pursuing new confinement configurations and improvements and hybrids of existing configurations, and by fostering cross-fertilization of ideas and research across configurations.

OVERARCHING THEMES

In the Magnetic Fusion Concept Working Group discussion and discussions in breakout groups, two over-arching themes emerged. These themes were clearly evident across the magnetic configurations, and across all the scientific disciplines. The first of the major themes is the development of physics understanding and predictive capability to develop the scientific basis for fusion energy. Such an effort allows (and fosters) commonalty of physics amongst the configurations and across different levels of development. It allows and fosters the transferability of physics learned from one magnetic configuration to another. This effort would assist the rapid development of concepts, perhaps allowing skipping a stage of development in one configuration if a strong scientific base, with adequate predictive capability, were obtained in another configuration. A strong scientific base provides the opportunity to reduce the cost of fusion energy development by allowing a more optimal design of experiments and new facilities, and thus allowing more rapid development.

The second of the major themes is the development and employment of plasma control tools. These plasma control tools are needed to carry out innovative experiments to develop the scientific understanding and they are required for optimizing the performance of the plasmas. Adequate plasma control tools will need innovative technological and scientific solutions, and a true partnership between technology and physics is needed to develop them.

A number of program elements are required for an MFE program with a focus on the development of physics understanding and predictive capability. Innovative and comprehensive diagnostic measurements are essential to be able to compare experimental results with theories and models. Operational time on our experimental facilities is needed for detailed scientific investigations as well as a very strong coupling between theory, modeling and experimental results. More complete plasma physics and detailed geometric effects must be include into the modeling codes, using advanced computational tools, and taking advantage of new computer hardware capabilities. Plasma control tools needed to modify and control the plasma for detailed physics investigations must be developed and deployed. Finally, the fusion program must emphasize a strong focus on the science.

MHD STABILITY IN MAGNETIC CONFINEMENT CONCEPTS

MHD stability at high beta, $\beta = \langle p \rangle / B^2$, is crucial for a compact, cost-effective magnetic fusion reactor. Fusion power density varies roughly as β^2 at constant magnetic field. In many cases MHD stability represents the primary limitation on beta and thus on fusion power density. MHD stability is also closely tied to issues of creation and sustainment of certain magnetic configurations, energy confinement, and steady-state operation. A possible consequence of violating stability boundaries is a plasma disruption with associated thermal and electromechanical loads to the first wall.

Critical issues include understanding and extending the stability limits through the use of a variety of plasma configurations, and developing active means for reliable operation near those limits. Accurate predictive capabilities are needed, which will require the addition of new physics to existing MHD models. Although a wide range of magnetic configurations exists, the underlying MHD physics is common to all and understanding of MHD stability gained in one configuration can benefit others.

There are number of MHD instabilities that limit plasma performance. Ideal MHD instabilities, kink and ballooning modes, driven by plasma current and pressure gradients, are well understood. Although the limits defined by ideal MHD are well understood, many opportunities remain to optimize performance through plasma shape modification and internal profile modification. Resistive wall modes (RWM) develop in plasmas that require the presence of a perfectly conducting wall for stability. RWM stability is a key issue for many magnetic configurations. Resistive tearing instabilities are an issue for all magnetic configurations, since the onset can occur at beta values well below the ideal limit. The stability of neoclassical tearing modes (NTM) is a key issue for magnetic configurations with a strong bootstrap current. The RWM, resistive tearing modes, and NTM are less well understood than the ideal modes and remain active area of rapidly advancing research.

There are four main opportunities to improve the stability limits. First the stability limit can be improved by configurational innovation. Two-dimensional and 3-D discharge shaping can improve the stability limits: Two-dimensional shaping effects will be evaluated in C–Mod, DIII–D, NSTX, MAST, and others; and 3-D shaping effects will be evaluated in HSX and the proposed NCSX. Low aspect ratio and profile modification at low aspect ratio also can improve stability, including stabilization of NTMs by the “Glasser” effect: these effects will be evaluated on MAST, NSTX, and Pegasus. Negative magnetic shear is predicted to be stabilizing to NTMs, and this prediction can be tested on LHD, NCSX, and tokamaks with reverse shear.

A second opportunity to improve the stability limit is the avoidance of the instability by controlling the internal structure of the plasma profiles. The stability limit can be increased by optimizing the current density and the pressure profiles, either open loop, or by active feedback control. Work to optimize the profiles has begun on many tokamaks (ASDEX–U, C–Mod, DIII–D, JET, JT–60U) and on the reverse field pinch, MST. Strong rotation can stabilize the RWM, rotational shear is predicted to stabilize resistive modes. Rotational stabilization can be tested on devices with high natural rotation (ST, Speromak, FRC), and in the electric tokamak with high driven rotation.

Active feedback stabilization of MHD modes is a third opportunity to improve plasma stability. NTMs can be stabilized with localized rf current drive. Experiments exploring this stabilization have begun on ASDEX–U and COMPASS–D and are planned for DIII–D. Feedback stabilization of the RWM by external coils is planned for DIII–D and HBT-EP.

Finally, in case MHD instabilities are not avoided and a disruption ensues, techniques to mitigate the disruption effects are needed. Exploration of operating at the neutral point is planned for JT–60U, and there are opportunities to evaluate solid or gas injection on C–Mod, JT–60U, ASDEX–U, and DIII–D.

Ideal and resistive MHD has had much quantitative success, but standard ideal MHD and resistive MHD is not sufficient to describe some magnetic configurations and the observed phenomena. New physical effects and details need to be better understood and implemented in existing codes or new codes. Among these are large plasma flow and flow shear, neoclassical effects, two fluid physics, finite Larmor radius effects, kinetic effects, and 3-D magnetic field structure. There is a need to support both analytical theory and large-scale code development, and a strong coupling of theory, numerics, and experiment.

TRANSPORT IN MAGNETIC CONFINEMENT CONCEPTS

Sufficiently low transport is required in magnetic fusion devices in order to achieve high gain at reasonable magnetic fields and moderate sized devices. A key challenge (and opportunity) for magnetic fusion energy is to develop a reliable and accurate means of predicting transport and confinement in future devices, and to develop control schemes to improve the confinement. There emerge a strong consensus in support of a research program to understand and control transport.

There is a clear need to develop a science based predictive capability for transport. Our challenging, but realistic, goal is a comprehensive predictive transport models, based on physically reasonable assumptions and well tested against experiments. This predictive capability must include particle and impurity transport, electron thermal transport, as well as ion transport, neoclassical transport, and discharge dynamics. Developing the predictive capability is essential to improve the confidence in design. Uncertainty and costs for the “next stage” of development will be reduced for all configurations, and the ability to transfer physics experience between magnetic configurations will be greatly enhanced. As result of improvements in predictive capability, we can expect more rapid innovation of new or improved concepts. We view understanding and controlling turbulent transport as a physics “grand challenge.”

Developing a physics based predictive capability will demand improved cooperation and comparison of experiment, theory, and computation. Key additional physics will need to be added in the turbulence simulations; electromagnetics, electron and impurity dynamics, general geometry, flows, and coupling of the edge plasma and the core. Extended diagnostic coverage of turbulence in the core and edge is needed. Key quantities (density, potential, temperature, magnetic field) of the turbulence need to be measured over a wide range of spatial scales, and new measurement and analysis techniques need to be developed. Additional resources are needed to meet the challenge developing as physics based predictive capability including: experimental runtime, turbulent and transport studies in new facilities, and new generation computing capabilities.

Control of transport in magnetic fusion devices is needed to improve performance, to control pressure and current profiles consistent with MHD stability, to optimize bootstrap current for steady-state operation, and for the formation and dynamic control of bifurcations and transport barriers. Opportunities exist to deploy and test new transport control tools. Especially important for transport control is plasma flow control, especially using rf sources. Localized current drive, particle fueling and pumping, induced rotation, and power deposition all have potential for use as transport control tools. Profile diagnostics, which measure the key control parameter, are required for transport control. Successful transport control should lead to a demonstration of high beta, high confinement, steady-state plasma operation.

PLASMA BOUNDARY AND PARTICLE CONTROL

The progress of boundary control in MFE devices is very good. The tokamak has been the primary vehicle for this work, consistent with most of the MFE effort on this concept. We have a reasonable scientific basis for a conventional long-pulse tokamak divertor solution at high density (collisional edge, detached). Such low T_e recombining divertor plasmas lead to low heat and particle fluxes at the first-wall, as well as adequate ash control, compatible with ELMing H–mode confinement. We have concerns about simultaneously handling disruptions/ELMs and tritium inventory, which shorten divertor lifetime. The challenge is to find self-consistent boundary solutions for other magnetic configurations.

We identified four boundary control issues or challenges for the next 5–10 years, common across configurations. The first issue is to extend boundary control techniques to lower-collisionality plasmas and other magnetic geometries. Opportunities in this area include: the development of the poloidal divertor at low density consistent with current drive requirements (AT, ST, Spheromak), the development of boundary solutions for non-axisymmetric magnetic geometries (Stellarator, RFP toroidal divertor), exploring radiative mantle boundary solutions, and including kinetic effects and particle drifts in the modeling and boundary solutions (ST and LDX).

A second challenge is the development of the control of impurity sources and transport to maximize boundary radiation and core cleanliness. There are opportunities to develop boundary flow techniques, induced scrape off layer flow (tokamaks and ST). Better impurity source and transport in the boundary are needed. There are opportunities to explore the use of biasing, helicity injection, and rf launchers in impurity assessment and control (tokamaks, ST, Spheromak).

The development of reactor relevant materials, with low tritium retention and low nuclear damage, compatible with clean core plasmas is a third challenge. There are opportunities to evaluate several candidate materials: low Z such as Be (JET) and high Z such as molybdenum (Mo) (C–Mod). Liquid surfaces are also an opportunity (lithium (Li) divertor planned for CDX–U). Mitigating the effects of disruptions on the first wall, with pellets or strong He puffs, is also needed.

A fourth challenge for the boundary area is the development of physics understanding of the coupling between the edge and the core plasma. There are opportunities for diagnosis and modeling of perpendicular transport in the presence of open field lines, particularly J, n_o, and flow in edge (RFP, tokamaks, Stellarator, ST). Deep core fueling, wall conditioning, and the effect of materials on the core are particularly important in emerging concepts and steady-state devices. Understanding and control of heat and particle flux during transients, for example ELMs, is needed in all devices.

ACHIEVING STEADY STATE OPERATION IN MFE DEVICES

For electric-power generating stations based on MFE, it would be highly desirable to have a fusion core device that could operate continuously. Although desirable for most MFE concepts, it is important to note that steady state is not a requirement, and there are some power plant concepts developed based on pulsed operation. The physics goal for steady-state MFE is to understand the physics of a continuously sustainable high-performance fusion plasma. Steady-state operation requires the integration of basic science elements; stability, transport, wave-particle, and boundary. Developing a steady-state MFE system involves closely coupled issues of physics and technology, and a close partnership with technology is needed for success.

There are two key issues limiting the progress toward steady state MFE operation. These are power and particle handling, compatible with a high performance plasma configuration, and plasma control to achieve and sustain a high performance plasma configuration. These are serious issues, which do not have easy solutions. A range of complementary approaches, pursued in parallel and making use of a portfolio of magnetic configurations, are needed to provide a high probability of successful resolution. Plasma control issues are addressed in what follows and the power and particle handling issues are addressed in the Plasma Boundary and Particle Control section.

We have identified five key plasma control opportunities for achieving steady-state plasmas. The first opportunity is current profile control to prevent evolution to unstable configurations. There is a near-term opportunity, in a complementary pair of programs using U.S. tokamaks, to resolve the issue of maintaining a stable advanced-tokamak plasma configuration by current profile control. Electron cyclotron current drive will be tested in combination with neutral beam-driven and bootstrap currents on DIII–D over the next three years. The planned complementary program will test lower hybrid current drive in combination with ion cyclotron heating and bootstrap currents on Alcator C–Mod from 2002 through 2008. In the longer term, the NSTX (from 2001) will extend advanced-tokamak current profile techniques to the spherical torus concept and the new Korean KSTAR superconducting tokamak (from 2004) will extend the pulse length of advanced-tokamak discharges to 20–300 s.

The use of helical fields and 3-D shaping for disruption suppression is a second plasma control opportunity. The stellarator proof-of-principle program proposed by U.S. stellarator researchers will, in the next decade, test the use of externally-generated helical fields to avoid disruptions in high-beta plasma configurations with tokamak-like aspect ratios. Complementary design approaches have been developed and it is planned to test both. The quasi-axisymmetric (QA) approach, which has bootstrap current levels and physics properties similar to the advanced tokamak, will be tested in the NCSX proof-of-principle experiment. The quasi-omnigenous (QO) approach, which minimizes the bootstrap current and is similar to optimized stellarators, will be tested in the QOS concept-exploration-level experiment.

A third plasma control opportunity is the use of active MHD mode control for steady-state, high-beta scenarios. A complementary set of programs planned for the next five years provides a good opportunity to test the elements of a strategy for controlling dangerous MHD instabilities using the tokamak, spherical torus, and reversed-field pinch. Feedback control of the neoclassical tearing mode with electron cyclotron waves, and of the resistive wall mode with coils will be investigated in the DIII–D tokamak over the next three years. The NSTX spherical torus will operate for its first 2–3 years without its active control of the passive plate structure to provide a baseline for assessing the performance gains once the conducting wall is installed thereafter. The physics understanding will be relevant to tokamaks as well as the ST. The RFP proof-of-principle program includes an opportunity for a concept-exploration-level study of kink mode stabilization with a resistive shell.

Innovative current drive for startup and sustainment is an important plasma control opportunity. Several innovative approaches to magnetic configuration startup and sustainment will be studied in the next five years. In the NSTX spherical torus, coaxial helicity injection (CHI), high-harmonic fast waves, neutral beams, and bootstrap current are available. Experiments to determine the best startup and sustainment scenarios using these elements have high priority. The new SSPX spheromak will add to the understanding of CHI and the associated edge physics and transport implications. Oscillating-field current drive will receive its most significant test to date in experiments on the MST reversed-field pinch device. In addition there is a need and an opportunity now for theoretical research to strengthen the physics foundations for this approach. Finally rotating magnetic field sustainment (the Rotomak concept) will be undergoing an important test in the University of Washington field-reversed configuration facility.

The fifth and final plasma control opportunity identified is local turbulence and transport suppression for pressure and bootstrap profile control. We highlight this as an area in need of attention, where the currently planned research is inadequate in comparison with its importance. Local transport control is the only possibility for controlling pressure and bootstrap current profiles in self-sustained magnetic plasma configurations. There has been substantial progress in understanding how to improve confinement by forming transport barriers using transient methods, but sustainable techniques are needed. Flow-shear control by radiofrequency waves is the most likely tool, and experiments with mode-converted ion Bernstein waves (IBW) are being carried out on Alcator C–Mod. However, direct-launch IBW also needs an in-depth investigation, and more new ideas are needed. Scientific and technological innovations in this area should be encouraged and initiatives to test promising ideas should be undertaken.

BURNING PLASMAS IN MAGNETIC CONFINEMENT CONCEPTS

A burning plasma has sufficiently high energy gain that the self heating by fusion products significantly exceeds the auxiliary heating in the plasma core, and the physics effects associated with self-heating and finite alpha particle population can be effectively evaluated. A near-term burning plasma experiment will have to deal with a plasma that has achieved the thermal confinement properties that will allow the power produced by confined charged fusion products to approach the power removed by intrinsic plasma losses. The energy in the confined charged fusion products will then be transferred via collisional processes to the background plasma to help maintain the plasma fuel at the temperatures needed to sustain the fusion reaction, a process which can be called self-heating. If the self-heating power matches or exceeds the rate energy is lost from the plasma, the fusion system has achieved ignition where in principle it is not necessary to supply additional external power to sustain the plasma. If the self-heating power is somewhat less than the power loss, burning plasma conditions can be sustained by supplying additional external power.

Given the uncertainties involved in whether any existing concept can eventually provide an economic source of power, the question arose as to how a burning plasma experiment based on the inductively driven tokamak concept could be justified at this time. The predominant agreement in the magnetic fusion concepts group was that a burning plasma experiment, based on a conventional tokamak operating regime, needs to be planned in order to: (a) demonstrate the feasibility of a controlled plasma burn; (b) resolve transport, stability and other plasma science issues at large dimensionless scale (a/ρ_i) in a burning plasma regime; (c) develop methods of burn, profile and instability control relevant to high Q regimes which are also likely to be applicable to other MFE concepts; (d) access advanced modes of tokamak operation for concept improvement under burning plasma conditions.

Presently, there are three proposals in development to demonstrate burning plasma operation. These are: RC/ITER, an international tokamak design with a divertor that employs improved understanding of tokamak operation to reduce the cost and objectives of the original ITER proposal; IGNITOR which exploits the benefits that can be achieved with high magnetic field, high density and compactness, supported primarily by Italy; the FIRE proposal, a compact high field divertor design with strong shaping capability, being studied in the United States.

The Magnetic Fusion Concept Working Group adopted the following resolutions, developed largely by the Burning Plasma Subgroup.

1. On the question of justification for a burning plasma experiment, we agreed to the following.
    a. "The excitement of a magnetically-confined burning plasma experiment stems from the prospect of investigating and integrating frontier physics in the areas of energetic particles, transport, stability, and plasma control, in a relevant

fusion energy regime. This is fundamental to the development of fusion energy."

b. "Scientific understanding from a burning plasma experiment will benefit related confinement concepts, and technologies developed for and tested in such a facility will benefit nearly all approaches to magnetic fusion energy."

2. On the question of what constitutes frontier physics in a burning plasma experiment, the group agreed to the following.
   a. Frontier Physics To Investigate And Integrate In A Self-Heated Plasma
      - Energetic Particles
        – Collective alpha-driven instabilities and associated alpha transport.
      - Transport
        – Transport physics at dimensionless parameters relevant to a reactor regime (L/ρ_i scaling of microturbulence, effects on transport barriers).
      - Stability
        – Non-ideal MHD effects at high L/ρ_i, resistive tearing modes, resistive wall modes, particle kinetic effects…
      - Plasma Control
        – Wide range of time-scales: feedback control, burn dynamics, current profile evolution
      - Boundary Physics
        – Power and particle handling, coupling to core.

      (*L/ρ_i is the system size divided by the Larmor radius.)

3. On the issue of scientific transferability, we adopted the following.
   a. Scientific Transferability: A well-diagnosed, flexible burning plasma experiment will address a broad range of scientific issues and enable development and validation of theoretical understanding applicable in varying degrees to other magnetic concepts.
      - Energetic particle density gradient driven instabilities
      - Transport and burn control techniques
      - Boundary Physics, power and particle handling issues

4. On the opportunities which the U.S. should pursue, we adopted the following resolution:
   a. Burning Plasma Opportunities
      - The tokamak is technically ready for a high gain burning plasma experiment
      - The U.S. has exciting opportunities to explore BP physics by:
        – Pursuing burning plasma physics through collaboration on potential international facilities (JET–Upgrade, IGNITOR, ITER-RC),
        – Seeking a partnership position if the ITER construction proceeds,
        – Continued design/studies of moderate cost burning plasma experiments (e.g., FIRE) capable of exploring advanced regimes,
        – Exploiting the capability of existing and upgraded tokamaks to explore and develop advanced operating regimes suitable for burning plasma experiments.

There was some reservation by a small minority on the issue of the technical readiness of the tokamak to proceed to a high gain burning plasma experiment. A special session to discuss the issue was held Thursday evening, July 22. A number of participants indicated their reservations based on significant uncertainties remaining in confinement projections from present day tokamaks to some designs for the next step, and based on concerns of tritium retention in the first wall. Overall, the group, by a large margin (~5:1) agreed that the standard tokamak was technically ready to proceed to a high gain burning plasma experiment.

MFE CONCEPT INTEGRATION AND PERFORMANCE MEASURES

In all the breakout groups, there was a clear intent to focus on issues that spanned across the portfolio of magnetic configurations. However, to realize fusion power, all of the scientific elements must be integrated in the magnetic configuration under question. In this section, we attempt to address the key potential benefits of a particular magnetic configuration and the key remaining issues to resolve to advance the configuration to the next stage of development.

The magnetic concept portfolio conveniently falls into two categories. One group has high magnetic toroidal field and q ~>1: conventional tokamak, advanced tokamak, electric tokamak, stellarator, compact stellarator, and spherical torus. The key challenge for this group of magnetic configurations is to optimize stable, steady state, high performance plasmas using 2-D and 3-D shaping, MHD stability control, and profile control. The other group has low magnetic field and q < 1: reversed field pinch, spheromak, field-reversed configuration. This group of magnetic configurations is highly self-organized. The key challenge for this group is to demonstrate adequate confinement for fusion energy and explore techniques to improve confinement and extend pulse duration.

The conventional pulsed tokamak is presently at the performance extension stage of development. Some of the prospective fusion energy benefits of this magnetic configuration are as follows. The pulsed tokamak provides a testbed for developing technology and generic fusion energy science. The tokamak has demonstrated stability and confinement. There is a mature experimental database and the performance of the tokamak is nearest the goal of fusion energy. The tokamak has several key issues to resolve. It must avoid and mitigate disruptions and ELMs at the operation values of beta to reduce thermal and electromechanical loads. The conventional pulsed tokamak projects to a large and costly reactor. The pulsed operation gives cyclic heat and stress loads, and may require energy storage. As discussed previously, the conventional pulsed tokamak is technically ready to proceed to a high gain burning plasma experiment.

The Advanced Tokamak is presently at the performance extension stage of development. The advanced tokamak achieves high performance confinement, high beta, and high bootstrap fraction by control of the internal profiles. Prospective fusion energy benefits of the advanced tokamak include: steady-state operation via high bootstrap fraction, high performance at lower plasma current, and the ability to build on an extensive tokamak database and understanding. Steady-state operation reduces the cyclic stress experienced in pulsed operation. The higher performance reduces capital costs and reduces disruption loads as a consequence of the lower plasma current. A number of issues remain to be resolved for the advanced tokamak. Profile control and active feedback stabilization need to be developed to sustain the high performance equilibrium and stabilize MHD modes. The advanced tokamak must avoid or mitigate disruptions and ELMs at high beta. There remains some uncertainty of the compatibility of the advanced tokamak with edge particle and power handling strategies.

The Spherical Torus is presently at the proof of principle stage of development. The ST has a number of prospective fusion energy benefits. The high beta, obtained at low aspect ration, and the reduced toroidal field, compared to a standard tokamak, can lead to reduced capital costs and simpler maintenance. The ST has the potential to operate steady state based on similar physics to the advanced tokamak. There is an intrinsic stabilization of microturbulence predicted for the ST. The ST can provide a near term volume neutron source even if performance projections fall short of what is required for fusion energy production. A number of issues need to be resolved for the ST to progress to the next stage of development. A noninductive current ramp-up and sustainment technique needs to be developed. The radiation effects and resistive losses of the center column remain an issue. There is a need to develop profile control and feedback stabilization to sustain equilibrium and stabilize wall modes. The divertor is predicted to have very high heat loads, and disruption avoidance and mitigation techniques need to be developed.

The compact stellarator is proposed for the proof of principle phase. There are other stellarators (internationally) already at the proof-of-principle stage of development. There are two key prospective fusion energy benefits of the compact stellarator. Three-dimensional magnetic field shaping is predicted to provide MHD stability and improved disruption stability with very low disruption loads. Reduced development costs are anticipated by combining stellarator and tokamak characteristics and advantages at an aspect ratio of 3–4. The key issues are several. High beta, low disruption loads and adequate confinement must be demonstrated experimentally: this is the main goal of the proposed experiment. A compatible particle and power handling scheme must be developed. Nonplanar, and more costly coils are required, and it must be determined if adequate coil plasma spacing is obtainable for reactors.

The reversed field pinch is presently proposed for proof of principle stage of development. The prospective fusion energy benefits are reduced capital cost due to low B coils, high engineering beta, and lack of need for high cost superconducting coils. A number of key issues are identified. The magnetic turbulence must be reduced to improve confinement. A method to efficiently sustain all the current must be developed. A stabilization technique for the kink/resistive wall mode needs to be developed, and reactor relevant power and particle handling issues need to be addressed.

The spheromak is presently at the concept exploration stage of development. The prospective fusion energy benefits are very simple geometry without a center post and possible sustainment by helicity injection. The simple geometry could lead to reduced development costs. The main issue is for the spheromak is to develop a current sustainment technique consistent with good confinement. Helicity injection may produce excessive magnetic turbulence and lead to large transport. The kink/resistive wall mode also needs to be addressed on the spheromak, and adequate power and particle handling and impurity control techniques need developing.

SUMMARY

In summary, magnetic fusion concepts provide a path to an optimized energy source. The portfolio of magnetic configurations provides an opportunity to pursue a broad range of important scientific issues for fusion energy. The development of physics understanding with predictive capability leads to rapid progress in the science base for fusion energy and rapid progress in the individual magnetic configurations. A burning plasma experiment offers the prospect of investigating and integrating frontier physics in the areas of energetic particles, transport, stability, and plasma control in a relevant fusion energy regime. Scientific understanding and innovation are key features of the magnetic fusion energy program. Together these are leading to attractive configurations for the production of fusion energy.