PLASMA TECHNOLOGY CRITICAL ISSUES AND OPPORTUNITIES*

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ABSTRACT

Key elements of the U. S. Virtual Laboratory for Technology (VLT) plasma technology portfolio and the advances from the state-of-the-art which would contribute significantly to the world-wide fusion program's objective of developing a practical and attractive fusion product are discussed.

KEYWORDS:

Plasma technologies, magnet technology, plasma facing components, tritium processing, safety, plasma heating and current drive, plasma fueling, remote handling.

INTRODUCTION

The dramatic progress in fusion science seen in the last few decades has been possible, in part, due to equally dramatic progress in plasma technologies. The development of high-power auxiliary heating systems at levels above 30 MW for heating plasmas to fusion-relevant temperatures is an obvious example. Improved plasma performance and the achievement of advanced confinement modes have been facilitated by the application of plasma technologies on numerous confinement facilities. Examples include (1) wall-conditioning techniques, improved plasma-facing

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components (PFCs) and better understanding of plasma materials interactions which enabled low-Z operation and the H-mode; (2) the achievement of record Lawson parameters through pellet fueling on Alcator-C and the Tokamak Fusion Test Reactor (TFTR); and, (3) magnetohydrodynamic (MHD) mode stabilization, core plasma turbulence suppression and the establishment of internal transport barriers [such as the pellet enhanced phase (PEP) and shear optimized modes] through manipulation of various plasma profiles (fueling, heating and current density profiles). In addition, several operations related technologies and recent technological advances have enabled existing devices and next-step options to reach their ultimate performance objectives or full design potential. These include (1) tritium-handling systems which enabled TFTR to achieve record level energy producing plasmas; (2) high-performance superconducting materials and magnets, advanced plasma-facing materials, components and heat extraction techniques; (3) remote handling and maintenance technologies; and (4) understanding the behavior of plasma-facing materials and tritium and activation product mobilization during accident conditions and development of mitigation strategies which have yielded increased confidence that next-step options, such as the International Thermonuclear Experimental Reactor (ITER), will meet their performance objectives and operate in a safe and environmentally acceptable fashion. Continued exploitation of existing and planned experiments will depend on further advances in certain technologies, particularly those related to manipulation and control of the plasma, extension to longer pulses, and operation in a radiation environment. Within the context of the fusion program's goals to develop a low-cost, next-step device and the knowledge base for a more attractive fusion power source, the likely reduction in the size and complexity envisioned to accomplish these objectives coupled with the requirement of long-pulse advanced physics operation will require renewed commitments from the technologists to handle higher heat loads for energy extraction, produce lower cost superconducting magnet designs, develop safe and efficient tritium processing systems, and develop more efficient and flexible heating, current drive, and fueling systems and associated techniques to mitigate against major disruptions.

MAGNET TECHNOLOGY

Superconducting magnet systems represent a major cost component for long-pulse or burning-plasma next-step options based on the magnetic fusion energy (MFE) approach. Dramatic progress has been made recently in development of large-scale DC and pulsed Nb_3Sn magnets for ITER. Further reductions in cost for low-temperature superconducting (LTS) magnets could be realized by development of: (1) higher performance (higher current density and increased quench protection capability) superconductor strand; (2) higher strength structural materials; and (3) higher radiation resistant magnet insulators (which presently limit the life cycle of magnet systems). Equally dramatic progress has been made with the development of high-temperature superconductors (HTS) for applications to power transformers (1-MVA prototype unit size) and power transmission cables (1500 A) for industrial use. While the cost of the present generation (BSCCO) of HTS material is prohibitive compared to NbTi, the second generation of wire currently under development (YBCO) offers potential for higher field operation at significantly higher operating temperatures (tens of Kelvin). Quadrupole focusing magnets for heavy ion beam fusion are also a major contributor to the cost of the heavy ion driver. The development of large, warm bore quadrupole arrays has been identified as a key element in developing an affordable next-step Heavy Ion Fusion (HIF) system.

PLASMA FACING COMPONENTS AND PLASMA MATERIALS INTERACTIONS

The successful development of high-performance (high heat flux, low erosion) PFCs and the understanding of plasma materials interactions is central to the development of fusion energy. Significant progress has been made recently in the understanding of net divertor erosion, mixed materials and codeposited carbon-tritium films, the development of innovative wall conditioning techniques, and water cooled PFCs (Be/Cu and W/Cu) with steady-state heat removal rates at the 20-MW/m^2 level. A free surface liquid divertor project has recently been initiated to investigate the potential of active heat removal without concern for PFC lifetime limits. Critical issues that need to be addressed in this are the development of even higher surface heat flux PFCs (50-MW/m^2 goal) that do not require periodic maintenance to renew the plasma-facing material (i.e., liquid surfaces or He cooled nonsputtering refractories).

TRITIUM PROCESSING AND SAFETY

The safe handling of tritium fuel and tritiated exhaust streams, the minimization of tritium holdup and inventory in in-vessel components, and the understanding (and mitigation) of tritium and activation product mobilization and release are critical to the goal of demonstrating fusion power with attractive safety and environmental characteristics. Significant progress has been made in the development of cryogenic distillation systems for isotope separation and the demonstration of a novel fuel cleanup system (Palladium Membrane Reactor) that efficiently processes tritiated water and has the potential to eliminate tritiated water altogether in fuel processing systems. From data generated on the mechanisms for mobilization and migration of radiologically hazardous materials and the development of state-of-the-art safety analysis tools, ITER was designed with the confidence that public evacuation would not be required under worst case accident scenarios. Critical/development issues in this area which could have a positive influence on fusion power are: (1) the minimization or elimination of waste streams (such as tritiated water from fuel cleanup systems) and demonstration of the feasibility of recycle and reuse of fusion materials; (2) minimization (and removal and processing) of tritium in first-wall materials and codeposited layers and understanding the interaction between energy sources and the mobilization of tritium and other radiological hazards; and, (3) safety R&D and development of techniques for removal of tritium from advanced coolants (i.e., liquid walls) now being considered for future MFE and IFE reactor-class devices.

PLASMA HEATING AND CURRENT DRIVE

Heating and current drive technologies are essential for heating plasma to fusion-relevant betas and temperatures and manipulating plasma properties to access advanced operating scenarios (reversed shear, MHD stabilization). Significant progress has been made in (1) developing and deploying high-power gyrotrons in the ~1-MW level at 110 GHz and the development of 170-GHz prototype units for electron cyclotron heating /current drive (ECH/ECCD) and (2) fast-wave (FW) antenna arrays in the >1-MW unit size for Ion Cyclotron Heating (ICH) and current drive (via direct electron heating). With the present program emphasis on increasing plasma performance and reducing next-step option costs, the emphasis of the development of these and other heating and current drive technologies will concentrate on (1) improving power density (higher voltage limits for ICRF launchers, higher gyrotron unit power (2 to 3 MW); (2) increasing efficiency (gyrotrons featuring multistage depressed collectors and ICRF tuning and matching systems that are tolerant to rapid load changes and arcs); (3) steady-state gyrotrons and actively cooled ICRF launchers for long-pulse/burning-plasma, next-step options; and, (4) flexibility (real time phase control for FW systems and tuneable frequency gyrotrons) to provide efficient heating and current drive over wide ranges of density and magnetic field.

FUELING

Fueling is another technology that is essential for the achieving fusion-relevant plasma parameters and manipulating plasma parameters to achieve improved performance (peaking of the density profile for higher reactivity and enhanced confinement via turbulence suppression). Recent success include sustained operation above the density limit on DIII-D, high-field side launch with improved density profile peaking, internal transport barrier generation, the development of steady-state pellet injectors operating in the 1.5-km/s speed range, and the demonstration of core fueling in proof-of-principal experiments using accelerated compact toroids (CTs). Pellet fueling technology has also been used recently to ameliorate the effects of major disruptions in tokamaks by delivering massive amounts of low- and high-Z material that rapidly quench the current in vertically unstable plasmas. A critical issue for fueling in next-step device plasma regimes is the degree to which profile peaking is needed (for higher density operation and improved reactivity and confinement) and the technological requirements to meet that need (pellet speed, CT density and the physics of CT deposition). For IFE, critical fueling issues include the mass production of targets with a cost objective of $0.25 each and delivery of the target assemblies at 5- to 10-Hz to the target chamber while maintaining the stability of the DT cryo layer and a precision that meets the allowable spatial tolerance of steerable drivers.

REMOTE HANDLING

In eventual MFE and IFE fusion reactors, all in-vessel maintenance will need to be performed remotely because of activation of materials in the intense radiation environment. Recent successes include limited remote-handling operations performed on Joint European Torus, the development of precision in vessel metrology systems, and demonstration of ITER blanket and divertor remote-handling concepts. Significant additional development will be required to reduce costs, improve reliability and human interfaces, develop dexterous servo manipulation of heavy payloads, and techniques for remote welding and refurbishment of in-vessel components.

The cost-effective approach to meeting the development challenges facing each of these technologies includes a combination of: (1) utilization of the many dedicated test facilities in the United States to perform advanced R&D; (2) applications of prototypes on existing domestic plasma experimental facilities and emerging alternate concepts to meet their ultimate performance potential while advancing the technological state of the art; and, (3) enhanced international collaboration and deployment of technologies on foreign experimental facilities as a way to pursue development issues associated with long-pulse operation, high-power density, and energy-producing plasmas while leveraging the international program's large investment in new and planned proof-of-performance facilities.