Fusion Energy Sciences

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Science Area Summary

The long–term goal of magnetic fusion research is to develop a reliable energy system that is environmentally and economically sustainable. To achieve this goal, it has been necessary to develop the science of plasma physics, a field with close links to fluid mechanics, electromagnetism, and nonequilibrium statistical mechanics. Nuclear fusion, the power source of the stars, has been the subject of international research since its worldwide declassification in the late 1950s [1]. As a result of the highly collaborative nature of Fusion Energy Sciences (FES) research combined with a few experimental facilities and a computationally intensive theoretical program, the community is facing new and unique challenges.

FES research is a worldwide effort conducted at some 90 sites in the United States, 60 in Europe, 40 in Japan, and several each in South America, China, and Australia. Fusion experiments have a dual role: providing data for the advancement of plasma science and increasing plasma parameters (densities, temperatures, etc.) toward the levels that would be needed in a power production reactor. In the United States, experimental magnetic fusion research is centered at three large facilities (Alcator C–Mod, DIII–D, NSTX [2,3,4]) with a present day replacement value of over $1B; clearly too expensive to duplicate. As these experiments have increased in size and complexity, there has been concurrent growth in the number and importance of collaborations between large groups at the experimental sites and smaller groups located at universities, industry sites, and national laboratories.

Teaming with the experimental community is a theoretical and simulation community whose efforts range from the applied analysis of experimental data to more fundamental theory like the creation of realistic non–linear 3D plasma models. The development of a science-based predictive capability for fusion-relevant plasmas is a challenge central to fusion energy science, in which numerical modeling has played a vital role for more than four decades. A combination of the wide range in temporal and spatial scales, the extreme anisotropy, the importance of geometric detail, and the causality requirement make it impossible to parallelize computation over time. Modeling of this problem is one of the most challenging tasks in computational physics. Computation and simulation are critical to progress in the field both to enable scientific understanding, and to design and interpret new experimental devices containing burning, reactor grade plasmas.

Recognizing the important role computer science plays in the success of fusion energy research, the SciDAC initiative [5] funded high–end computational fusion projects and a collaboratory project [7]. These projects are creating new simulation capabilities, creating and deploying a fusion computational and data Grid, new and innovative collaborative visualization capabilities, and impressive capabilities for remote control room participants.

Challenges, Priorities and Requirements

Magnetic fusion experiments operate in a pulsed mode, producing plasmas up to 10 seconds duration every 10 to 20 minutes, with 25 to 35 pulses per day. For each plasma pulse, up to 10,000 separate measurements versus time are acquired, representing about a gigabyte of data. Throughout the experimental session, hardware and software plasma control adjustments are discussed by the experimental team and made as required to optimize the use of the available experimental time. The experimental team is typically 20 to 40 people, with many participating from remote locations. Decisions regarding changes to the next plasma pulse are informed by data analysis conducted during the roughly 15 minute between pulse intervals. Unlike large experimental collaborations in other fields, such as high-energy or nuclear physics which operate essentially in a "batch" mode, fusion experiments put a premium on near real-time interactions with data and among members of the team. This mode of operation requires rapid data analysis that can be assimilated and debated in near real time by a geographically dispersed research team.

Experimental fusion energy research will be greatly enhanced by facilitating more, and more complex, between pulse data analysis combined with the ability to effectively utilize the increased information flow. A more informed decision on the next plasma pulse can lead to higher quality science and therefore accelerated progress. The cyclical nature of experimental fusion research has been termed the collaborative control room. To be fully functional, the collaborative control room requires (1) secured computational services that can be scheduled as required, (2) the ability to rapidly compare experimental data with simulation results, (3) a means to easily share individual results with the group by moving application windows to a shared display, and (4) the ability for remote scientists to be fully engaged in experimental operations through shared audio, video, and applications. The National Fusion Collaboratory Project has created prototypes of different pieces of the collaborative control room that are being tested and used in present day FES research. This work has demonstrated the value of implementing such a capability.

As specified in the USDOE Facilities for the Future Report [38], the highest priority for the Office of Science is the International Thermonuclear Experimental Reactor (ITER), an international collaboration to build the first fusion science experiment capable of producing a self-sustaining fusion reaction. This $5B device, which will be built outside the United States, is expected to be operational by the middle of the next decade and would produce fusion power at the level of an industrial power plant. The importance and cost of this device requires that it operate at the highest possible level of scientific productivity. In this sense, it is useful to think of ITER as the largest and most expensive scientific instrument ever built for fusion research.

The ITER device will be a unique collaboration for the fusion program, involving very large numbers of scientists from many different countries. It is reasonable to assume that not all members of the experimental team will be on-site for all experiments. In fact, it is probably desirable and practical to carry out a significant amount of the scientific work remotely. Effective international collaboration on this scale is a technically demanding problem since it requires the presentation of a working environment to off-site personnel for experimental operations that is every bit as productive and engaging as when they are physically in the control room. Thus, a fully functional and implemented collaborative control room is required for the success of the ITER project and to maximize the value of ITER to the U.S. program. The technologies needed for ITER will push the frontiers of data acquisition, data management, visualization, and remote participation and will be significant to a broad range of other scientific research disciplines.

The second highest priority in the USDOE Facilities for the Future Report is Ultra Scale Scientific Computing Capability. This capability is expected to increase the computing capability available to fusion energy, by a factor of 100. The proposed Fusion Simulation Program (FSP) has the goal in the next decade of reliably predicting the behavior of plasma discharges in a toroidal magnetic fusion device on all relevant time and space scales; a fully integrated simulation. The long-term goal is in essence the capability to carry out "virtual experiments" of a burning magnetically confined plasma through faithful representation of the salient physics process of the plasma. One key to the success of the FSP will be effective collaboration between fusion scientists and computer scientists, between fusion simulation scientists specializing in different plasma regimes, and between fusion simulation and experimental scientists. Thus the collaborative technology that is critical for the success of the experimental science program is equally critical to the success of the simulation science program.

A Vision for the Future of Fusion Energy Sciences

With the successful creation and deployment of collaboration technology, the future working environment for fusion scientists in the United States will be substantially enhanced. The first plasma for ITER is scheduled around 2015. One can imagine a U.S. based scientist remotely participating in real-time in experimental operations. Audio and video from the control room is seamlessly available to the scientist's desktop where it is easy to follow the 30 minute plasma cycle. Data from ITER is available locally and remotely concurrently. The scientist can analyze in detail the most recent ITER discharge and participate in the planning for the next plasma pulse through communication her findings back into the control room. This communication takes the form of audio, video, and a shared visualization so that her findings can be debated and discussed amongst the experimental team members including those physically located in the control room. During times of non-operation, this remote scientist can actively participate in detailed working meetings that include interactive data analysis sessions and also give and attend technical seminars.

To help achieve the 10-year goal of an integrated simulation, a scientist working on the FSP will need an enhanced working environment like that of their experimental colleagues. Detailed remotely held working meetings including shared code debugging and shared visualization for discussion of results should become routine. In addition, a closer collaboration between the experimental and simulation scientists will be developed. For experimental science including ITER, simulations can be used to predict experiments through close collaboration between experimental and theoretical scientists.

Creating an enhanced collaborative environment for fusion research within the next decade is critical to the success of the U.S. fusion program. With ITER's construction outside of the United States, effective remote participation is the only way that the U.S. program will remain vital and keep pace with that of Europe, Japan, China, South Korea, and Russia. By leading the way in collaborative technology in the next decade, the U.S. can work to assure substantial and beneficial involvement in fusion's next generation experimental program.

References

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