MEETING REPORT

SUMMARY OF MEETING ON CONTROLLED THERMONUCLEAR FUSION, PISA, ITALY, NOVEMBER 9–10, 1992

This meeting was planned to provide both scientists and government officials in Italy an opportunity to develop planning for fusion research. Approximately 70 Italian fusion scientists attended the meeting, along with several dozen representatives from fusion laboratories throughout the world. The meeting was organized by Emilio Picasso and Edoardo Vesentini at the Scuola Normale Superiore (SCN) and the Istituto Nazionale di Fisica Nucleare (INFN).

The first $1\frac{1}{2}$ days of the meeting had individual presentations from scientists throughout the world, who addressed background problems related to the current status of energy sources and future projections (including fusion's possible role). The status of and directions taken in research and development (R&D) of both magnetic and inertial confinement (ICF) fusion were discussed, along with directions in international programs and Italy's potential role in this overall strategy. Ample time for discussion was allowed after each presentation, and the meeting closed with an intense round table discussion with panelists from key government support organizations in Italy.

In his opening address, Emilio Picasso (SCN) cited the development of new energy sources as one of the key challenges facing humanity. He commented that accelerator physics has enjoyed success through a diversified program that includes a wide variety of accelerators and facilities, along with extensive collaboration among government laboratories, universities, and industry. He proposed that this provides a good model for future fusion research.

Sergio Garribba (International Energy Agency) reviewed the current energy situation and the world outlook through 2005. Among various trends, he stressed the importance of the increasing energy demand and usage by non-Organization for Economic Cooperation and Development nations (developing countries), combined with the drastic changes in Russia, as key factors affecting future energy planning. He noted that the fastest growing energy supply sector during this period is natural gas, which is no longer the "sad sister of oil." He noted that fission power plants currently produce $\sim$17% of the world's electrical power, but he warned that nonproliferation concerns may block a "second wave" of nuclear power plant development. Thus, with the developing gap between energy demand and supply, he projected that fusion could play a vital role, provided that its development is carried out so that the public is fully informed at all steps. In this way, the technology could be accepted without encountering the serious delays encountered in fission power due to the public's distrust of its developers. He also stressed the importance of international collaboration in fusion development in order to share limited resources and to promote technical breakthroughs. Such collaboration also has the advantage of ultimately providing wider market support.

Arthur Kerman [Massachusetts Institute of Technology (MIT)] discussed the influence of scientific research on energy development. He chose as a model the current program for development of a national ignition facility for ICF research at Lawrence Livermore National Laboratory. This project would upgrade the existing NOVA laser to a 1- to 2-MJ system delivering 400 to 800 TW of power at 0.35 μm. The target chamber would be designed to handle large yields, up to 45 MJ. A key characteristic of this program, which Kerman stressed, is the dedication to studies of fundamental physics as the way to ultimately develop an attractive ICF power plant. In that respect, he outlined issues under study for both Hohlraum target physics and hydrodynamic "equivalent physics," including experimental results in both areas obtained from the existing NOVA facility. One difficulty with this approach that remains is the classification of aspects of the indirect-drive-type targets. However, recently, there has been growing hope that the U.S. Department of Energy, under Admiral Watkins' direction, would declassify much of this program. That would then open the way to international collaboration, which is currently blocked by these difficulties.

Carlo Rubbia (CERN) presented an important perspective on ICF development. He described how interest in using a heavy-ion-beam (HIB) accelerator as the driver for ICF power plants has gradually increased in recent years because this approach offers a higher driver efficiency than any other. While he views the HIB approach to be technically feasible and well advanced, prior reactor studies have indicated that a very large power plant results. In contrast, Rubbia stressed that what we need is an energy source that is relatively simple and small. Consequently, he said that he had directed an accelerator group at CERN to undertake studies for a much simpler, smaller accelerator than had been previously considered. This new accelerator approach could lead to facilities or target experiments with radius scale lengths of ~100 to 150 m and a cost, according to Rubbia, of a few hundred million dollars. He stated that more details on this approach would be presented at the upcoming American Physical Society Plasma Physics Division meeting in Seattle, Washington. Rubbia continued to stress that several advantages of ICF include the ability to hold T_e/T_i low and to keep the targets optically thick in order to reduce bremsstrahlung. Thus, he held out strong hope for learning how to burn p-^{11}B targets and cited that as the true goal for the second-generation ICF plants. He again stressed the importance of the expected declassification in ICF, in order to gain a broader university involvement and expanded international collaboration. Next, Rubbia described current design concepts for indirect-drive Hohlraum targets for HIB using a pedestal/filament concept for X-ray production. Problems with this approach include nonuniformities caused by the pedestal and the need for a diffuser to "close" the beam entrance hole. He cited several options under study to overcome these difficulties. The use of a specific angle for the incoming beams would eliminate the fundamental mode, while higher frequency modes would rapidly be attenuated. Another interesting concept that he described was the possibility of using a "direct" Hohlraum target for HIB fusion work. The outer shell would be heated with a broad ion beam to maintain relative uniformity. The heat wave created would propagate to the inner surface generation X rays to drive the subsequent implosion.

Edoardo Vesentini (SCN) discussed in some detail various pieces of Italian legislation as part of the fusion program. He noted that the government has provided a multiple-level approach, with support for dedicated laboratories, individual university projects, and industry fusion R&D. While this legislation has been reasonably successful, he stated that much remains to be done. Of course, in view of the current worldwide economic depression, increased support for large scientific projects is very difficult to generate.

George Miley (University of Illinois) gave a talk on "The Role of Controlled Thermonuclear Fusion as a Source of Energy." He described the great transition in energy sources that humanity faces. In a brief period of time, humanity is consuming all of the fossil fuels and must move on to new energy sources. If this transition is not made smoothly, humanity may face severe difficulties: at best, a lower standard of living; at worst, war and chaos. The components that seem logical in the longer term are a mixture of nuclear energy and solar energy. Certainly, fusion represents the most important source of nuclear energy because of its limitless fuel supply. Hence, its development holds the key to humanity's success in getting through this "great transition." Miley also commented on the current approaches and strategies for fusion development. He discussed the two main approaches to development that could be selected: the achievement of a "parameter-driven" program rather than a development program based on reactor merit. With the demise of many alternate confinement concepts throughout the world due to funding problems, the current approach is almost entirely devoted to parameter achievement. This leaves open the question of whether the worldwide program can meet the test of economic competitiveness, flexibility, and desired levels of environmental attractiveness. Appraisal optimism is a danger that must be avoided, as has been shown in previous large projects. In view of these concerns, Miley proposed that an international collaboration on the development of alternate concepts be undertaken that would be on the same scale as and would be modeled after the International Thermonuclear Experimental Reactor (ITER) project development process. This issue was referred to the panel for discussion.

Francesco Pegoraro (University of Turin) presented a comprehensive review of "Physics Problems in Controlled Thermonuclear Fusion." He pointed out that fusion-grade plasmas open up a whole new field of physics involving "intermediate-energy" systems. Such systems are dominated by collective effects that cannot be described by simple binary interactions. This phenomenon has been widely recognized, especially in terms of understanding the energy confinement in particle transport and tokamak reactors. Pegoraro commented on the connection to solar physics pulsars and Wakefield accelerators. He summarized the phenomenon in terms of the mathematics of dynamic systems, which encompasses the popular field of chaotic behavior. He then discussed various issues related to the ignition of a fusion plasma. Among these topics are the need to thoroughly understand the current scaling laws, particularly the behavior with power injection and the applicability of the $p^{-1/2}$ power law relative to alpha-particle heating. For ignition studies, he favored exploiting high fields and high densities. He described high density as playing two important roles: reducing instabilities and providing an important reduction in impurity concentration. He stressed the importance of keeping open the possibility of going to D-^{3}He fusion, because of its favorable environmental characteristics.

Ernesto Mazzucato (Princeton University) presented an overview of "Plasma Confinement in Tokamaks." As background, he emphasized the need for terminating our dependence on fossil fuel for power and stressed the importance of fusion as a benign substitute, so the sooner it is achieved, the better. He stated that impressive progress has been made in developing scaling laws for confinement physics in tokamaks, but he questioned the empirical nature of much of this work. In particular, Mazzucato noted the lack of full understanding of turbulent effects and observed that the key question in scaling laws is whether or not the characteristic length to be employed involves the ion gyroradius or the density scale length. If, as it currently appears, the density scale length is the relevant parameter, then, he stressed, the best direction for success is to use high-field devices. Mazzucato directly addressed the question of whether we really want a deuterium-tritium (D-T) tokamak or whether we should attempt to bypass this goal in order to go to deuterium or D-^{3}He cycles? He cited as the key issues the problem of wall damage due to the high neutron flux in a D-T tokamak and the relatively large tritium inventory in such a device. He challenged the fusion community to recognize the great concern that society has about environmental issues and urged us not to repeat the mistakes made by our predecessors in the fission industry. In his view, then, ITER should be redefined or redirected in order to address the issue of finding a way to burn D-^{3}He.

Jean Jacquinot [Joint European Torus (JET) Joint Undertaking] presented a comprehensive discussion of "Results from the JET Tokamak—Future Plans in Support of the Fusion Programme." Jacquinot stressed that JET provides scientists with an opportunity to carry out comprehensive physics experiments in a device that truly approaches thermonuclear conditions. He noted that based on extensive and detailed experimental work on JET, two alternative lines of research for the generation regime devices such as ITER have emerged. The first approach would employ semicontinuous (long-pulse) operation (including a 5-min shutdown recharge between pulses). A device of this type would employ a 7.7-m major radius, a 0.8-m minor radius, and a 25-MA current with a 6-T field. The other approach would use a continuously operating machine. It would rely strongly on bootstrap current and profile control and would probably evolve into a 15-MA machine. In either case, Jacquinot stressed the role that important new physics from JET played in these concepts. Other notable experimental results included studies of stochastic losses of energetic alpha particles as a function of field ripple and the results from the famous tritium burn experiment. In that connection, he stressed that important conclusions included the successful handling of the tritium (95% tritium recovered) and the various diagnostic measurements for energetic particle orbits, etc., that confirmed a reasonably good understanding of the physics of this operation. Future plans after the installation of a pump convertor are to move to D-T burn experiments. JET currently has a license to handle 90 g of tritium. The wisdom of the sunset clause, which will force shutdown after those runs, can be questioned since many experiments can still be envisioned. This is especially bad because of the time gap between the shutdown of JET (and the Tokamak Fusion Test Reactor) and the startup of ITER.

Bruno Coppi (MIT) presented an important overview of the proposed Ignitor device. As background, he reviewed key requirements for ignition, including the need for the alpha-particle slowing-down time to be short compared with energy confinement time. Based on these various objective ignition criteria, he finds that as proposed earlier, the best approach for ignition studies is to use magnetic field and high density. This approach follows many of the motivating factors behind the design of the highly successful Alcator experiment, where the unique density-squared dependence of the confinement parameter was first observed. Coppi stressed that the Ignitor device has always been designed to ignite ohmically in order to provide adequate safety margin. He noted that now the ITER project has recognized the virtue of this approach. Thus, the revised ITER design (ITER-R) follows this same strategy. Of course, ITER has a lower field and density, so the dimensions of the device are much larger. Coppi went on to compare the Ignitor and ITER from a detailed parametric point of view. In addition to some concern about impurity penetration (reduced by the high density of Ignitor), he indicated that ITER's stability with poloidal beta <0.25 remains to be demonstrated. Coppi also emphasized that the Ignitor approach provides a way to scale up to operation with D-^{3}He without drastic changes. He showed photographs of various components (e.g., coils) for Ignitor that have already been manufactured by various industrial concerns in Italy. He noted that the device needs to be located where adequate electrical power is available. A suitable location, from this point of view, is a site near Torino, Italy. Coppi concluded with a discussion of various physics topics related to future devices. He stressed that ash buildup may be a crucial issue, and he discussed the possibility of using fishbone resonance coupling to expel lower energy alpha particles to avoid "ash poisoning."

Didier Gambier (ITER San Diego Co-Center) presented an in-depth presentation on "The Challenge of ITER." Gambier stated that the objective of ITER is to provide a core plasma equivalent to that required for a reactor, in order to demonstrate fusion as an energy source. It will also provide a test bed for various physics and engineering experiments; plus it will drive forward technology related to first-wall plasma exhaust and blankets. He stated that the current design phase could be viewed as successful if directions toward the development of a site evolve in a timely fashion, allowing a construction agreement to be signed within 6 years. Gambier stressed that the ITER organization expects the participating nations to maintain an internal fusion program that, when taken as a whole, is comparable to the ITER project in size. If carried out in this fashion, considerable flexibility should be maintained, so that the community can move ahead on an optimal path to commercial fusion. Gambier outlined the basis for many of the current design parameters for ITER, which largely come from experiments on JET and other major experimental devices. One topic he discussed was density limits that appear to be controlled by edge effects rather than by center plasma (i.e., possibly controlled by radiation effects in the edge plasma). The electron channel generally governs energy losses. Results showing the degradation of energy confinement were discussed. Several points that were stressed include the fact that while degradation occurs, there is still an increase with ohmic current. Also, the current physics understanding would be that the effect on confinement is independent of the particular type of heating source involved, other than in terms of how the heating might affect local gradients, etc. With the present reference design operating in the L-mode and with helium ash held to <20%, calculations show that adequate ignition margin is obtained. Alternating current (pulsed) operation is envisioned. Based on the JET results noted earlier, the downtime between pulses does not interrupt the reformation and control of the plasma. Toroidal field ripple effect on energy and alpha-particle confinement is under study. The current ITER concept with 30-MA current and 6-T field can be characterized as giving temperatures roughly three times the maximum achieved in existing experiments. The amount 50 MA of ion cyclotron resonance heating would be employed with the D-T fuel. With L-mode operation, helium ash would be appropriately maintained below 20%. Sawtoothing could be tolerated. Relatively high density flat profiles are anticipated. The divertor would be coupled to the plasma through a thick scrape-off layer. Then, energy could be transported at high density, and hot neutrals would be larger from perpendicular to the scrape-off layer. A fanlike construction would be used for the divertor plate structure. Startup and burn control would be by fuel injection controlled by a feedback system. Concepts for the first-wall blanket components were also presented. The design is intended to provide a simple structure that can still carry out the desired functions. The facing wall, of course, must meet a number of criteria ranging from low-Z and good resistance to 14-MeV neutron damage along with low activation and low retention of tritium. The simplest first wall and blanket might involve a multiphase coolant such as helium loaded with granules. Water would be excluded from the system in order to avoid potentially violent reactions with lithium. In conclusion, Gambier expressed confidence that the challenges provided by ITER could be met, based on the existing data base combined with an active R&D program during the current design phase.

The concluding round table was chaired by E. Picasso and included the following panelists: N. Cabibbo (INFN); G. Chiarotti (CNR); G. Rostagni (Euratom/ENEA); C. Boffa (ENEA); and R. Ricci (ENEA). Following statements by the panelists, a lively interaction with the audience ensued. The discussion was so wide ranging that it is not practical to cover it in detail in this limited space. Just a few points are noted. It was stressed that Italy has long played a leading role in the development of high-field fusion experiments. Consequently, the development of the Ignitor device appears to be a natural evolution. Several speakers stressed the need for a continuing basic R&D program with broad-based objectives. This program should rely on a close collaboration among industry, universities, and national laboratories. Relative to university involvement, the need to create a critical mass of people involved in fusion studies in university departments such as engineering, materials, etc., in addition to physics, was noted. The need for development of added university-level plasma physics courses was also generally agreed to be an important objective. Expansions of this type may be difficult at this time, however, because of the recent decline in the worldwide economy. Still, perhaps it is a good time to face such issues, since difficulties force realism and demand answers to hard questions.

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February 8, 1993