BOOK REVIEWS

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The JET Project and the Prospects for Controlled Nuclear Fusion

(Proceedings of a Royal Society Discussion Meeting)

Editors	R. S. Pease, R. J. Bickerton, and B. E. Keen
Publisher	Royal Society, London (1987)
Pages	211
Price	$42.00
Reviewer	Donald J. Grove

As stated in the preface, "This Royal Society Discussion Meeting was held to give the wider scientific community a timely account of the main features of the [JET] apparatus, [and] of how the physics is turning out, both in JET and in its U.S. counterpart, TFTR. The role of the project in the EURATOM fusion programme and the relation of the results to those needed in the ultimate reactor is described."

The successful development of fusion reactors would make available a safe, economical, and environmentally attractive energy source based on essentially unlimited fuel supply. This tantalizing prospect has led the major industrialized nations to pursue vigorously programs directed toward harnessing the energy released by fusion reactions. This book, containing the 15 papers presented at the Royal Society Meeting, should considerably expand the scientific community's knowledge of an important part of the worldwide effort to develop controlled fusion. Throughout, the papers emphasize essential features of the physics, engineering, and overall goals in a simplified, often elegant fashion. The pros and cons, the basic experimental results, and the defects in the present understanding are all there, with key references that lead in turn to detailed publications.

An introductory paper by R. S. Pease gives a concise description of thermonuclear reactions, plasma characteristics, tokamak confinement, and auxiliary heating. Following this are papers by the Joint European Torus (JET) staff members, Rebut and Lallia, Huguet, Stott, Gibson, Engelhardt, Duesing et al., Jacquenot et al., Düchs, and Bickerton et al. These papers describe the evolution, status, and prospects for JET: the design, manufacture, and assembly; the plasma measurements and diagnostics; ohmic heating and auxiliary radio-frequency (rf) and neutral-beam heating; wall effects and impurities; computational modeling; and, finally, a comparison of experimental results with theory.

The Tokamak Fusion Test Reactor (TFTR) results are described by Hawryluk et al., while papers by Kadomtsev, Troyon, and Palumbo provide complementary information on plasma magnetic insulation, magnetohydrodynamic (MHD) stability theory, and Euratom/worldwide cooperative efforts, respectively.

This collection of papers gives an excellent, integrated picture as of March 1985, and it should encourage the reader to inquire as to the *present* status (February 1988). In doing so, this reviewer was pleased to note that while Rebut and Lallia for JET and Hawryluk et al. for TFTR quoted in their papers approximately the same value for the product of the central density, central ion temperature, and global energy confinement time $[n(0)\tau_E T_i(0)]$, namely, 5 to $6 \times 10^{19}\ \mathrm{m}^{-3} \cdot \mathrm{s} \cdot \mathrm{keV}$, the present best value for these machines is in the 2.5 to 2.7×10^{20} range, a factor of ~4 to 5 improvement in a rather short time.

The Rebut and Lallia paper compares the operational parameters with the design objectives, noting generally that JET has achieved the intended levels of toroidal field, plasma current, etc. This discussion is followed by figures showing the latest results for the time evolution of the electron and ion temperatures, plasma current, energy content, etc., along with the global energy confinement time. The paper concludes with a discussion of an operating schedule to mid-1991, leading to an 18-month period of experiments using tritium.

The paper by Huguet describes the design, manufacturing, and assembly of the machine. Essentially, the paper states completely and concisely the engineering features, usually without discussion of the design logic—for which one must have recourse to the key references.

The paper on plasma measurements by Stott is nicely organized, with *complete* detail in tabular form and an expanded discussion on a few selected topics. The three-dimensional drawings, showing the machine in phantom with the diagnostics emphasized, should be extraordinarily helpful for expert and novice alike.

Gibson, in his paper on ohmic heating (OH) experiments in JET, gives an extensive discussion of the correspondence of the experimental results with various scaling laws, with special attention to the global energy confinement time (τ_E). Here, he expresses τ_E as the product of factors in n, B_T, q, R, a/r, A, and b/a, each raised to a power determined by a regression fit to the data. He gives the 95% confidence limits for the various indexes and the multiplying factor, but notes that such fits need to be treated with caution since clear evidence exists of saturation with density. Gibson also comments on results with auxiliary heating and remarks that, in this case, it is preferable to use a version of the possible scaling laws showing that the decrease of τ_E with P_{aux} flattens out at high power.

Looking to the future, Gibson states that radiation from impurities will not be a problem, but dilution of the hydrogen isotope content needs further consideration. He concludes by noting that "near ignition on JET requires $n_0 T_0 \tau_E = 3.7 \times 10^{21}$ m^{-3} sec keV; $\tau_E \approx 1.7$ sec; $\beta_t \approx 5\%$; $P \approx 25$ MW, whereas significant alpha heating would already be possible with $n_0 T_0 \tau_E = 7 \times 10^{20}$ m^{-3} sec keV; $\tau_E \approx 0.75$ sec; $\beta_t \approx 2.5\%$; $P \approx 48$ MW."

Engelhardt's paper on impurities begins by noting that the physical processes are *very* complex, and that "a reliable prediction for fusion-reactor conditions is practically impossible." The paper, like most of the papers in this collection, contains detailed statements of the current status as a point of departure for the future, including some very well-presented data on the spectra and global Z_{eff}, before and after carbonization of the walls. He concludes as follows: "According to what is known so far, JET should not fail to reach its goal because of impurity problems."

The papers by Jacquenot et al. and by Duesing et al. continue in detail the discussion of auxiliary heating and the attending degradation of confinement introduced by Gibson. An interesting comment on rf heating is the concept of "high grade power," defined as that power deposited in the 25% of the plasma volume around the magnetic axis (or loosely, the "center of the plasma"). For JET, 25 MW of ion cyclotron radio-frequency power at the generator output is expected to produce 16 MW of high grade power.

An important feature of plasma heated with rf is the production of "giant sawteeth," a term aptly describing the observed oscillation in the central electron temperatures that have periods of ~0.1 s and amplitudes of nearly 2 keV. These dominate the energy transport from the center region. As in the case with neutral-beam injection, the global energy confinement time degrades with increasing power but levels off at values about one-third the OH value. Thus, while the temperature increases substantially, a factor of 4 increase of input power raises the stored energy only a factor of 2.5. In both JET and TFTR, discharges that use the inner wall as a limiting surface have lower impurity levels that are virtually independent of existing maximum power levels.

Hawryluk et al. describe the experimental results from TFTR. A brief description of machine status, together with a discussion of the operating range, is followed by summaries of ohmic and neutral-beam heated discharges. As in JET, the data show a strong tendency for these plasmas to maintain the shape of the temperature profile, even with broadly distributed, or even hollow, energy deposition profiles.

An especially interesting discussion follows on what is called the energetic-ion mode, obtained by operating at densities of order 1×10^{19} m^{-3} and high beam powers. As noted by Duesing et al. in the JET paper, with intense auxiliary heating, the plasma energy content is typically independent of the density, resulting in high-ion temperatures. In TFTR, these low-density, high-power experiments using three beamlines injecting tangentially (and in the same direction around the torus) have resulted in negative surface voltages that could not be accounted for even after taking into account the plasma rotation. Later work on TFTR (Ref. 1) suggests strongly that several hundred kiloamperes of plasma current is being driven by the so-called "bootstrap effect" predicted nearly 20 yr ago by Galeev,[2] and also by Bickerton et al.[3]

A paper by Düchs on quantitative modeling of JET plasmas by computational methods and one by Troyon on theoretical studies of MHD stability give simplified, but well-organized, descriptions of the status in these areas. Düchs carefully notes that the path goes from complete descriptions, which unfortunately are totally intractable even with the fastest computers, to highly simplified codes that have practical usefulness. He draws attention to the omission of rotation effects, three-dimensional equilibria, including magnetic islands, etc. The Troyon paper gives a concise introduction leading from low-β tokamak plasmas to limiting cases that would restrict the maximum β to values too small for a reactor, assuming circular plasma cross section. He notes, of course, that elongated (noncircular) plasmas offer a possible escape route.

The introduction of the paper by Bickerton et al. on the comparison between experimental and theory is worth repeating here in its entirety.

> Comparison between theory and experiment in the field of tokamak physics is a very complex topic. At present, theory is unable to predict the observed performances of tokamak systems in basic respects. An observed example is the lack of understanding of the thermal insulation of the plasma and the resulting energy confinement. There is a vigorous and sophisticated theory of the performance expected from tokamaks in the absence of plasma instabilities. We outline this theory and calculate its implications for a particular set of JET parameters. These results are in strong disagreement with those found experimentally. We then discuss briefly the types of plasma instabilities to be expected and their possible influence on other performance of the device. Finally, we discuss the consequences of one particular simplifying assumption; namely, that the current profile is controlled by instabilities and limited to functional forms depending only on global discharge characteristics, such as the ratio of the magnetic field due to the plasma current to the externally applied toroidal magnetic field.

Proceeding this way, the authors show how one can obtain a reasonable fit to the thermal transport on the basis of an assumed profile together with the external energy sources. A corollary of the profile consistency approach is that the temperature at the boundary is the only thing that matters. Correspondingly, they note that the global energy confinement time will degrade if the thermal flux in the scrape-off region depends more steeply than linearly with the boundary temperature.

In a beautifully elegant but short paper, Kadomtsev discusses plasma magnetic insulation. He begins with a dimensional analysis and proceeds to sawtooth oscillations, profile consistency, profile relaxation, and a short discussion on energy confinement. Two main conclusions are as follows: "The heat transfer is controlled by weak stochastization of the magnetic field. At low density, this results in the T11 scaling law and the neo-Alcator one. In this case, the local diffusion and electron heat conduction coefficient have quite a definite sense. In another limiting case, when β reaches its critical value β_c with respect to the ballooning modes, the plasma pressure profile is fixed, and further increase in the power deposition does not result in a rise in its energy." Between these two limits, Kadomtsev makes the point that the density can be extended while maintaining the ohmic scaling law for confinement if the power deposition for the auxiliary heating only slightly perturbs the relaxed state profiles; sooner or later, however, the transition to degraded confinement must take place.

The book concludes with a discussion of reactor requirements by Toschi et al. and a paper by Palumbo on the nature and prospects of the Euratom fusion program. The discussion by Toschi et al., on the progression from JET to the Next European Torus (NET) to DEMO to a prototype commercial-sized reactor, addresses the extrapolations needed for each step. The nominal considerations of power density, confinement, particle and power load at the divertor, burn length, etc., have a universal character. Although here they are discussed in the direct context of NET, they apply as well to today's progression from TFTR/JET through the Compact Ignition Tokamak to the International Thermonuclear Engineering Reactor, and beyond. The authors believe that "among the physics issues the plasma power density (which is directly related to operating limits on beta, plasma density and plasma current), the power and particle loads on the walls of the device as well as the plasma exhaust requirements, and the prospects for steady-state operation, are of primary importance. Technologically the most severe requirements are in operational reliability, lifetime of plasma-facing components and remote-handling."

In the concluding paper by Palumbo, the reader can find a short discussion of the need for fusion reactors. It is interesting to read the European point of view on this topic, typified by the remark that the cost of all fusion programs in Europe for the entire year 1984 was only a little more than the cost of oil imports for 1 day. Palumbo reiterates the theme expressed in the preceding paper by Toschi et al. of the necessity for parallel development of technology in the areas of superconducting magnets, blanket and first-wall engineering, tritium technology, etc.

Perhaps as much as anyone in the world today, Palumbo can speak for the virtues (and difficulties) of international collaboration. Palumbo's comment regarding the Reagan-Gorbachev initiative toward wider international cooperation bears repeating.

> Of course, the engagement of the world fusion community will be a prerequisite, but it is also evident that a lot of political, managerial and administrative problems have to be solved. For this, good will and the commitment of the political authorities is necessary. However, we should avoid thinking that the solution of our problems can be in the hands of ambassadors and foreign ministers. The main problems remain with the physicists and engineers.

This reviewer thinks that is just the right note for the last chapter of this book.

Don J. Grove's first work in basic research was on ionization by electron impact, mass spectroscopy, and ultra-high vacuum (UHV) research. In 1954, Grove came on loan to the Princeton Plasma Physics Laboratory (PPPL) from Westinghouse Electric Corporation. Working with Lyman Spitzer, he was one of four scientist-engineers who made the first evaluation of controlled thermonuclear processes for power production and was a major contributor to the conceptual design reports on the C-Stellarator. He also planned, constructed, and put into operation at PPPL the first UHV laboratory for large systems. From 1960 to 1970, he was the physicist-in-charge of C-Stellarator operations. He managed the entire facility and generated more than 50 papers on plasma physics and controlled thermonuclear research. From 1970–1972, he managed a crash conversion of the C-Stellarator to the ST Tokamak and managed the operations for the project. More recently, Grove was project manager for the Princeton Large Torus, responsible for its design, fabrication, installation, and physics operations. He joined the TFTR project in May 1976 as deputy project manager and became manager in November 1982 after retiring from Westinghouse and joining Princeton University as a principal research physicist. In October 1986, he became deputy director for technical operations at the PPPL, stepping down from this position in January 1988 to work on special assignments involving the University, the U.S. Department of Energy, and local community officials.

Grove received his PhD in physics from Carnegie Mellon University in 1953.

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Superconducting Magnets

Author	Martin N. Wilson
Publisher	Oxford University Press, New York, New York (1983)
Pages	335
Price	$45.00 hardback, $23.95 paperback
Reviewers	Roger Boom and Y. M. Eyssa

Superconducting Magnets by Martin N. Wilson was published in 1983 and only recently has become generally available in the United States, either in hard cover or paperback. It is an outstanding text and reference treatise for engineers and is recommended to all *Fusion Technology* readers.

Superconductive magnet systems consist of turns of conductors wound or mounted to produce specific magnetic fields and field gradients. The engineering challenge is to provide adequate structure and cooling to maintain superconductivity during operation. A basic problem is heat deposition, for example, from ac or dc currents, ac fields, or mechanical friction. Good designs eliminate or accommodate all expected thermal disturbances so that superconductivity either is maintained or is recovered without difficulty. This technology