Plasma physics and controlled nuclear fusion

by M. Leiser*

The recent progress in controlled thermonuclear fusion research has been rapid and significant on a world-wide basis, and the prospect of further development of fusion as a source of energy is now considered excellent. Because fusion is one of the few viable energy alternatives for the future, it is of global importance to demonstrate the technical feasibility of fusion power as soon as possible.

The estimated amount spent world-wide on fusion research is US $2.5 thousand million annually, yet a fusion reactor producing commercially usable power will not be built before the second decade of the next century. The achievement of such a power plant has been described as one of the most challenging scientific endeavours ever undertaken. Every industrialized country conducts research in fusion, roughly proportional to its industrial capacity and, in addition, an increasing number of developing countries are initiating their own fusion programmes.

One result of all this activity is the large number of meetings held every year throughout the world devoted to various aspects of fusion research. The largest of these meetings are the biennial IAEA conferences; the ninth conference of this series took place in September 1982** (For a report on the eighth conference, held in Brussels in 1980, see *IAEA Bulletin* Vol.22, No.5/6, pp.131–2.) Since a large number of experts representing every major laboratory attended the 1982 conference, participants were also able to hold several informal meetings on various topics in addition to attending organized sessions.

On the afternoon prior to the opening of the conference, a special session on the International Tokamak Reactor (Intor) workshop was held. The Intor project is a collaborative effort between the European Communities, Japan, the USA, and the USSR, as described in "Bringing together fusion research" in *IAEA Bulletin Supplement 1982.* Its purpose is to design the next large experiment beyond those currently under construction. Included in the Intor presentation were some of the main issues of that project, i.e. physics, impurity control, mechanical configuration, magnetics and tritium considerations.

One of the important aspects of the Intor presentations was that they delineated critical areas of the Intor concept: areas where sufficient information is presently lacking on which to fix the final design of several Intor components. Progress of the Intor project was well received by the conference participants and a number of constructive comments were expressed.

The results presented at the conference indicated that significant progress has been made both in understanding of plasma behaviour and in the enhancement of plasma confinement parameters. Confidence that the next generation of large tokamak machines – TFTR (USA), JET (EEC), JT-60 (Japan) and T-15 (USSR) – will succeed in demonstrating the scientific feasibility of fusion has correspondingly increased.

The technical sessions showed that the collective efforts of the major fusion countries are expanding. New and important results were reported at the conference in plasma theory research and in achievement of higher plasma parameters. On the Doublet III tokamak (a joint Japanese – US experiment), a record value of $\beta = 4.7\%$ (β = ratio of plasma pressure to the pressure of the toroidal magnetic field) was achieved using neutral-injection heating of 3.5 MW power. This result confirms theoretical predictions that the critical value of β for elongated plasmas is higher than for circular plasmas. Since the β value needed for a fusion reactor is about 5%, this result confirms that the basic assumptions made in the Intor design are realistic. More of the major machines are successfully operating with a low safety factor of q = 2; on PDX (USA) and Doublet III the q-value for elongated plasmas were 1.6 and 1.4 respectively. Encouraging results were reported from Alcator (USA) using radio frequency (RF) current drive. On this machine RF current drive was demonstrated at a density level of $(4–6)\cdot 10^{13}$ cm^{-3}, which is an order of magnitude higher than results reported at the latest meeting on this subject in March 1982. This means that non-inductive current drive in toroidal devices is effective not only initially when the density is low, but also during the stage of current maintenance. Efficiency of the RF current drive has been considerably improved (from 0.8 to 1.2) but is still not great enough for a steady-state reactor (for which the value should be ~8). Considerable increase in RF power level in the ion cyclotron resonance heating

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** The Ninth International Conference on Plasma Physics and Controlled Fusion Research, held in Baltimore, Maryland, USA, from 1 to 8 September 1982. The conference was organized by the IAEA in conjunction with the US Department of Energy and the Princeton Plasma Physics Laboratory. It was attended by 588 scientists and some 250 non-registered observers from 32 countries and five international organizations.

(ICRH) experiments on PLT (USA) permitted an increase in the ion temperature of $T_i = 2$ keV, as compared to the $T_i = 0.4$ keV reported at the eighth IAEA conference in Brussels. This conference showed that a large effort in research on tokamaks is devoted to RF plasma heating and current drive because successful demonstration of both techniques will simplify future fusion reactor design requirements. Modifications made to the ZT-40 (USA) reversed field machine substantially improved plasma parameters. Replacement of the alumina liner with an Inconel bellows-type liner and use of the external poloidal field primary windings allowed the electron temperature to reach $T_e = 300$ eV and reduce the pinch resistance by a factor of ~30. The current sustainment time has also been increased by an order of magnitude and reached 22 msec. The general tendency in all reversed field pinch (RFP) experiments showed that the main plasma parameters of density and temperature improve with rising plasma current.

The present status of theoretical studies has reached the level where theory is able to explain many of the experimentally observed phenomena. Theoretical papers presented at the conference were closely coupled with experiments. Linear instabilities of the toroidal plasmas continue to be the subject of interest for theoretical activity. Ideal and non-ideal instabilities were considered in many presentations. There is a discrepancy between a low β-value of 3% predicted by theory and of 4.7% demonstrated on Doublet III. There were a number of new ideas discussed at the conference. One of them shows that nuclei polarization can lead to the enhancement of the D-T reaction rate by the factor of 1.5. It is however not clear which approach is simpler: polarizing of nuclei or the improvement of plasma confinement parameters. One problem in the field of plasma theory requiring attention in the near future is that of anomalous electron thermal conductivity in toroidal plasmas. Here, as elsewhere, a successful theory must not only be able to explain experimental results but should also be able to predict them. In general, in spite of the uncertainties in our understanding of plasma confinement, prospects for an eventual successful reactor are encouraging.

In the field of inertial confinement fusion (ICF) research during the last two years, effort was expanded in ablative compression experiments. Enough experimental information has been accumulated to be able to discuss the scaling laws in the ablation process. It seems that use of the shorter wave-length lasers will solve the problem of the target preheat. As a result of extensive programmes in the ICF field, it is expected that during 1983 to 1986 experiments will be performed to demonstrate the scientific feasibility of the concept, i.e. $Q = 1$ (where Q is the ratio of fusion power released to the input driver power). Issues such as hydrodynamic efficiency, the preheat problem, higher compression and symmetry of the pellet irradiation must be resolved in the near future in order to demonstrate the potential of the ICF approach.

Reactor design issues were extensively summarized at the special session on Intor; only papers with new and different ideas were given at the conference. It now is possible to assert that a reasonably well-defined family of tokamak reactor concepts has been developed and could be taken to construction. Other concepts which offer higher β-values have been pushed towards conceptual reactor designs, and in several ways show improvement over the tokamak reference family.