Status of Thermonuclear Research

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The question if and how reactions between light nuclei can be used for the production of energy on an economical scale has been under active investigation since the early fifties. When results of the work that had up till then been kept under cover of secrecy were made public at the 1958 Geneva Conference, it became apparent that among the major problems to cope with would be various kinds of instabilities of magnetically confined high-temperature plasmas. When matter in this state is insulated from a relatively cool vacuum-containing wall by means of a magnetic field, deviations from thermodynamic equilibrium such as gradients in pressure, density, temperature, and magnetic field strength, as well as departures from the Maxwellian velocity distribution for ions or electrons represent sources of free energy that can in principle be converted into energy of growing electromagnetic, acoustic, electrostatic, or magneto-hydrodynamic waves. During the sixties, a suspicion grew that it would forever be impossible to contain a plasma in a magnetic field for times predicted by classical binary-collision diffusion theory, and that confinement would always be destroyed, if not by large-scale plasma motion due to magneto-hydrodynamic instability, then by enhanced diffusion caused by the fluctuation electric fields associated with waves in the plasma. A semi-empirical anomalous-diffusion law proposed by Bohm and implying that voltage fluctuations in the plasma grow to a saturation level corresponding to the electron temperature through the relation $eV \approx kT_e$ seemed to be supported by many experiments.

The 1968 IAEA Conference in Novosibirsk marked the turning point, after which an increasing variety of containment devices displayed confinement times in excess of Bohm's formula by factors of ten and even hundred. Since then, confidence has grown that by enlarging the scale of the apparatus, one may get closer to the thermonuclear regime; larger devices have been put into operation and encouraging results have kept flowing in. Crucial experiments, aiming at heating a deuterium-tritium mixture to ignition and confining it long enough to burn a significant fraction, are now being planned, and one is looking at their outcome with considerable optimism. Scientific feasibility demonstrations are confidently predicted for the early eighties.

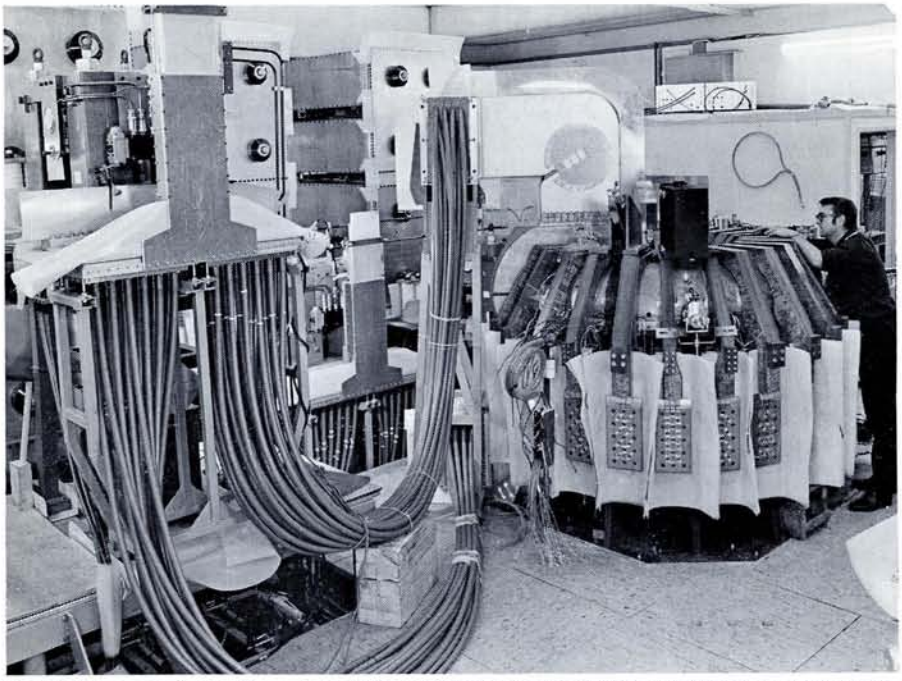
Among the most successful confinement schemes is the Tokamak, originally developed in the Kurchatov Institute in Moscow by a team led by the late L.A. Artsimovich, and now studied in research centres all over the world. It is a ringshaped plasma container, surrounded by coils that produce a toroidal magnetic field and encircling the central core of a transformer by which a toroidal current can be induced in the plasma. The poloidal magnetic field associated with this current, together with the toroidal field of the external coils, adds up to a helical field confining the plasma, balancing its pressure and insulating it from the metallic container. Magneto-hydrodynamic stability analysis performed by Kruskal and Shafranov has shown that the toroidal plasma current must be restricted to a value proportional to the strength of the toroidal field, to the minor radius of the tube and to the ratio of the minor to the major tube radius. As it turns out that both the attainable temperature and the containment parameter $n\tau$ (density times containment time) depend on field strength and geometry in approximately the same manner as does the limiting toroidal current, the latter is often taken to be a figure of merit for a Tokamak machine. In present experiments the toroidal current can be brought up to some 300 kA, if one takes into account that a safety factor of 2 to 3 with respect to the Kruskal-Shafranov limit has to be maintained. Experiments under construction in the USSR and the USA will operate around 1.5 MA. In the associated laboratories in the European Economic Community a design is being worked out for a 3 MA experiment named JET for Joint European Tokamak, to be in operation before the end of the decade. A thermonuclear reactor would, according to the scaling laws now thought to be valid, operate at 10-15 MA.

In several respects, the Stellarator — first proposed by L. Spitzer — is similar to a Tokamak, the main difference being that the poloidal field in the Stellarator is produced by helical windings outside the plasma rather than by an induced current. The ultimate advantages and disadvantages of this, when it comes to a fusion reactor, have not yet been fully evaluated, but Tokamaks are certainly simpler and cheaper devices and, therefore, promise more rapid progress towards attainment of thermonuclear plasma parameters.

Both Tokamak and Stellarator are generally thought of as systems in which the plasma is maintained for a period long compared to the burning time of the fuel, if not indefinitely. This poses the problem of continuous supply of fuel (a deuterium-tritium mixture) and removal of ashes (helium nuclei). This can be circumvented in pulsed confinement systems, if the pulse duration can be adjusted to the burning time. Plasmas with ample densities, with temperatures very close to those needed for ignition, but with confinement times severely restricted by end losses, have been produced in open-ended magnetic compression devices of the theta-pinch type. Unfortunately, a closed or toroidal version of these does not present itself without calling for a fundamental modification of the exceedingly simple and attractive theta-pinch concept: a cylindrical, more or less field-free plasma column compressed by an axial magnetic field produced by a single-turn coil. Several types of toroidal pinch devices are now under investigation; one may hope that by the end of the decade one of these can be selected for further development as a reactor, provided that conceptual design studies yield credible solutions to some problems associated with pulsing the magnetic fields.

Among magnetic confinement systems, mirror devices have been kept alive, not so much because they look very plausible as efficient economical power producers, but rather because they offer a promise of development towards relatively small, simple, and accessible materials testing reactors. The loss of energy carried by particles escaping along field lines through the mirrors presents a formidable barrier on the way towards economic power production.

In recent years, spectacular advances in the performance of lasers, as regards both pulse energy and duration, have focussed attention on the possibility of compressing and heating small spherical pellets of



Toroidal screw pinch experiment in the FOM Institute for Plasma Physics, Rijnhuizen, The Netherlands.

thermonuclear fuel to ignition. No magnetic confinement would be necessary if the fraction of the fuel burnt before the freely expanding target falls significantly in density, could be high enough. Comparing the reaction energy (17.6 MeV in a D-T reaction) with the energy required for igniting the fuel (a few tens of keV per ion pair), and taking conversion efficiencies into account, one can derive that at least several percent must burn up if a net energy production is required. Since the time for burning a given fraction is inversely proportional to the density, whereas after compression the expansion time at given temperature scales only inversely proportional to the radius, hence to the cubic root of the density, the advantage is proportional to the two-thirds root of the density-compression ratio. Pursuing this scaling argument, one can show that the volume of the pellet, and consequently the energy necessary for igniting it, is reduced hundredfold if the density is increased thousandfold. With that reduction one can start contemplating laser ignition, a scheme that would otherwise be hardly imaginable.

Compression should result from the recoil of material evaporating off the surface of the pellet.The compression, heating, and burning process has been studied extensively by numerical simulation, the results of which justify the expectation that with foreseeable laser performance ignition of small pellets can be achieved. It requires some imagination, however, to foresee the further developments in laser characteristics, notably in power, efficiency, and repetition frequency, that would be necessary for economic power generation. Nevertheless, the concept of compression by laser irradiation may lead to studies of matter in an unusual state and to powerful new sources of neutron and X-ray flashes coming available.

It is generally accepted that the first generations of fusion reactors will burn a mixture of deuterium and tritium. This has by far the highest reaction rate and the lowest burning temperature of all conceivable fuels. Whether, in the long run, other reactions may prove to be feasible is an open question. Since tritium can be bred in a D-T reactor by bombarding lithium with the neutrons coming from the reaction, the limiting natural resource is lithium. Fortunately, this is available in quantities equivalent to all fossil energy resources combined. Its distribution over the globe is highly uneven, but it would be a trivial expense to stockpile a twenty-years supply with each reactor installed.

Plasma Physics, along with high-energy nuclear physics, has come to maturity during recent times. It has already had some impact on other branches of physics, but, more strikingly, it has had a profound influence on astronomy. In approximately ten years, it should be able to tell to the world how to produce thermonuclear energy. If some remaining technological - and far from simple - problems can be solved in an economically acceptable way, one may hope that its impact on the world's energy supply could begin to be felt around the turn of the century.