

RESEARCH AND PROSPECTS ON CONTROLLED THERMONUCLEAR FUSION IN THE U.S.A.

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The near-term objective of the U.S. Controlled Thermonuclear Research Program is to further develop understanding of the plasma state, especially in those magnetic confinement configurations and heating methods which may be suitable for development into fusion reactors. Experiments now in progress or being fabricated (see Table 1) are preparatory for moving ahead toward larger experiments capable of producing plasmas which meet the Lawson criterion, thus demonstrating fusion scientific feasibility. It is believed that, with favorable results from the existing or planned experiments and with increased level of effort, this may be possible within about ten years.

Three main lines of effort are being emphasized in magnetic confinement. These are magnetic mirror open systems, pulsed high-beta pinch systems, and near steady-state toroidal systems. In addition, a program of laser initiated fusion is being carried out, aimed at studying inertial confinement of highly compressed fusion pellets. Basic research in plasma phenomena and supporting theoretical studies, as well as plasma technology developments, are carried out. Over the past two years exploratory studies of reactor concepts and associated technological questions have been initiated, which now amount to about five percent of the program budget.

Magnetic Mirror Research. In the magnetic mirror open systems area, three major experiments are underway : 2X-11 and Baseball II at Lawrence Livermore Laboratory and IMP at Oak Ridge National Laboratory.

The research objective of the 2X-II is to continue correlations between theory and the observed loss processes of high temperature (~ 6 keV), high density ($\sim 10^{13}$ cm⁻³) plasma formed by adiabatic compression. Plans for FY 1973 include a study of the effects of adding neutral beam injection to the 2X-II plasma. The objective of the Baseball II is to achieve a high temperature plasma by neutral injection in which the ion distribution is randomized by collisions. Experimental studies are in progress. No major program modifications are anticipated in FY 1973. The objective of the IMP is to study the buildup of plasma by neutral injection combined with trapping on a "target" plasma formed by electron cyclotron resonance heating. Research to date has been concerned with studying the properties of the target plasma. Plans for the next year are to study the injection and trapping with ~ 100 ma neutral beams at 20 keV.

A theory which seems to account for the enhanced losses (a factor of 2 to 15) previously reported in the 2X-II magnetic mirror device has recently been advanced by Baldwin and Callen. The origin of the extra loss is an amplification by the Rosenbluth-Post convective loss-cone instability of individual particle

fluctuation level. The theory predicts that the enhancement of particle scattering is small for large n/B^2 so should not be of major consequence in a reactor regime.

High-Beta Research. The principal activity in this area involves the Scyllac Facility at the Los Alamos Scientific Laboratory. The research objective of Scyllac is to study the high-beta toroidal equilibrium in a high-beta stellarator-like configuration, and to test the idea of feedback stabilization. The plasma is produced and heated by implosion followed by magnetic compression. Experiments in a 5-meter toroidal sector and a 5-meter linear section with magnetic mirrors are under-way and should be completed in order to make begin conversion to a full torus in the first half of 1973.

The toroidal Z-pinch, also at Los Alamos, has achieved a reversed field equilibrium with $\beta_\theta = 0.4$, in which the temperature is inferred to be several kilovolts. At the Oak Ridge National Laboratory, a high-beta bumpy torus (EBT) is under construction and should be completed during 1973. The EBT will utilize a series of 24 connected magnetic mirrors with high-beta annular relativistic-electron plasmas sustained and heated by microwaves as in the ELMO device. It is expected that the high-beta relativistic electron plasma will stabilize the less energetic toroidally confined plasma.

Experiments on a sector comprising one-third of the 4.8 meter diameter Scyllac torus have been performed during the past year. The toroidal force and the outward plasma drift are compensated by a combination of $l = 1$ helical fields and $l = 0$ bumpy fields. Toroidal equilibrium has been observed followed by a sideward motion ($m = 1$) of the plasma column. This motion is nearly the same all along the torus, independent of the $l=0$ periodicity. Plasma containment times are as large as 11 microseconds, comparable to the times for plasma end loss. The sideward motions, which occur predominantly in the horizontal plane of the torus, suggest either an imbalance between the $l = 1, 0$ and toroidal forces at later times or a long wavelength $m = 1$ instability. Measurements of the applied magnetic fields show that the product of $l = 1$ and $l = 0$ fields for plasma equilibrium agrees with sharp-boundary MHD theory. A toroidal compression coil with $l = 1$ and $l = 0$ grooves is under fabrication. An $l = 0$ MHD feedback experiment to control the $m = 1$ sideward motion is underway on Scylla IV-3 and is planned for the Scyllac toroidal sector as well as on the complete Scyllac torus.

Experiments have also been performed on the Scyllac 5-meter linear theta-pinch with and without strong magnetic mirrors. Operation without mirror fields produced a 2-3 keV plasma column which lasted about 15 microseconds. The plasma showed considerable "wobble". When mirror field with a mirror ratio of 2-3 are applied at the same time as the main field, the plasma column shows evidence of an $m = 1$ instability.

Consideration of a pulsed high-beta fusion reactor based on the theta-pinch configuration indicate that it may be desirable to employ wall stabilization of the plasma column with a smaller degree of magnetic compression, preceded by a separate implosion heating phase.

Low-Beta Toroidal Research. This area, which encompasses tokamaks and internal current devices, receives the greatest emphasis in the U.S. program. The internal current devices are employed, generally, for supporting studies in toroidal confinement physics, whereas the tokamak devices are seen as leading to reactors. The Princeton ST has been the principal operating tokamak during the past year, with the ORMAK, Doublet, and ATC just beginning to yield results. A new large tokamak (plasma minor diameter 90 centimeters or 3 times that of the ST) the PLT, is under fabrication and is expected to be completed in 1975.

Studies of plasma transport rates in the D.C. octupole at Gulf General Atomic, in which a toroidal field has been added, have shown the transition from classical to neoclassical diffusion as the mean free path increases so as to become comparable with the machine size. Diffusion rates have been found to agree with theoretical predictions over a wide range of density and temperature. In the short mean free path regime, the experimental results agree with the Pfirsch-Schluter theory and in long mean free path regime with the Galeev-Sagdeev theory. In both regimes, the diffusion rates were found to vary inversely as the square of the magnetic field.

Particle containment times in excess of 1 second have been observed in the Princeton FM-1, which is a single levitated superconducting ring device with a magnetic configuration similar to that of the Spherator. For temperatures less than 1 to 2 electron volts and for densities from $2.5 \times 10^{10} \text{ cm}^{-3}$ to $2 \times 10^{11} \text{ cm}^{-3}$ the confinement time has been found to increase with temperature T^m with $m \sim 3/4$) and decrease with increasing density. The classical confinement time is exceeded by about a factor of 5. At higher temperature where the plasma is sustained by continuous application of as much as several hundred watts of non-resonant microwave Power the confinement time appears to be independent of density and to decrease with temperature. The confinement time is about $300 \tau_{\text{Bohm}}$ and the cause of the latter behavior, though possibly connected with the method of plasma production or magnetic field asymmetries, is not known.

The past year has been a productive period for the ST tokamak at Princeton. As reported earlier, electron and ion temperatures of 2000 eV and 600 eV, respectively, have been obtained-Efforts are now concentrated on trying to obtain a detailed understanding of the tokamak discharge which, not unexpectedly, is turning out to be rather complicated. The density range for "good" operation is somewhat limited. As density is reduced, a runaway distribution of energetic electrons is achieved and when the density is increased, disruptive instabilities are encountered. The density of neutral particles, including impurity atoms, seems to play a major role in the particle and energy balance.

Nevertheless, some very important trends have emerged. When impurities are taken into account, the Spitzer formula seems to account for the observed resistivity. Plasma energy content increases as the square of the plasma current (a e-, 5) Particle and energy confinement time are approximately equal and increase with temperature and magnetic field in accord with the pseudo-classical theory (not Bohm). Measurements of radial profiles are still not sufficiently detailed so as to permit a determination of local values of the transport coefficients and hence to compare with theory. The recently developed thallium ion beam probe has already given space and time resolved density and potential measurements and should soon be able to give the plasma current distribution. Meanwhile from Thompson scattering measurements of electron temperature profiles, the expected skin effect has been inferred, at early time in the discharge. However the skin disappears more rapidly than expected.

The Ormak, Doublet II, and Adiabatic Toroidal Compressor (ATC) were brought into operation and only after extensive discharge cleaning could significant electron temperatures be reached. While definitive results are yet to be obtained, early results from each of these devices are encouraging. The Ormak, which as a plasma minor radius of 23 cm has operated stably for 100 msec at a plasma current of 140 kiloamperes. The Doublet II, a non-circular cross-section tokamak, or plasma current multipole has operated at 500 kiloampere plasma current. Possibly the most important feature of the initial operation of ATC is that stable operation at about 50 kiloampere plasma current is obtained at $q = 3$ with the equilibrium field being supplied by the vertical (shaping) field with no copper shell. Furthermore the plasma column can be positioned in major radius by varying the vertical field strength. The plasma remains stable upon compression and the plasma current and temperature rise as expected.

These and other results have encouraged the design of a new larger tokamak, the Princeton Large Torus. The PLT is the largest device consistent with the existing generator capacity and will have $8 = 49$ kGauss, $I = 1.6$ megaampere, major and minor vacuum vessel radius of 130 cm and 50 cm respectively. Since no copper shell will be provided in PLT initially, the ATC results are especially significant. While there are potential problem areas, such as a pronounced skin effect preventing the establishment of a proper current profile, it is necessary to confront the important questions such as the radial transport and scaling of confinement times in larger tokamaks. Construction of PLT has begun and it is estimated to require 3 1/2 years to complete at a cost of 13 million of dollars. Since Ohmic heating of tokamaks cannot be relied on to reach ignition temperatures, provision is made in PLT for later addition of one or more possibly supplementary heating methods: neutral beam injection, ion cyclotron resonance, lower hybrid resonance. Heating experiments on existing devices (e.g. neutral beam injection on Ormak) are expected to determine which of the supplementary methods are employed on PLT.

Laser Initiated Thermonuclear Fusion. Interest in this approach has increased significantly. Until recently, most discussions centered on the use of laser energy to simply heat a liquid target of fusion fuel to ignition temperature. Simple arguments suggest that the laser energy required for a scientific breakeven experiment (thermonuclear energy = laser light) might be a few megajoules, but the laser energy required for a reactor with net energy gain would be impractically high.

During the past year, the notion that the laser could be used to drive a spherical implosion, thus reaching possibly 10^4 times liquid density and reducing the laser energy requirement by many orders of magnitude, was revealed. In essence, a series of spherically converging shock waves are driven by ablation of material from outer layer of the pellet. The pressure thus generated exceeds the light pressure by the order of c/v_s . The pulse shape of the incident laser must be chosen so as to produce a series of weak shocks of successively increasing pressure which converge simultaneously at the origin.

By ablating about 3/4 of the mass, computer calculations by the Livermore group show that compressions of 10^4 times liquid density can be achieved with some 5-10% of the laser energy having been delivered to the remaining mass. According to these calculations it may be possible to reach the condition: (thermonuclear energy = laser light energy) with less than 1 kilojoule and an overall net energy gain (assuming laser efficiency of 10% and thermal conversion efficiency of 40%) with between 0.1 and 1.0 megajoule. No experiments have yet been performed to demonstrate that such large compressions can be achieved and a large part of the U.S. effort is going into development of energetic short pulse lasers, of the Neodymium-glass and CO₂ types. By 1973 AEC Laboratories project 1000 joule outputs, which should provide a means for performing critical physics experiments to determine whether the physics of laser fusion is favorable.

Fusion Reactor Studies. While Lawson criterion plasmas may not be reached for another decade, there is sufficient optimism that these plasma conditions can be reached by one or more of the approaches now being pursued to begin examining more seriously the technological questions of fusion reactors. Furthermore early research on these questions could materially shorten the time to the ultimate application of fusion reactors. Also because of the increased public interest in the United States in all methods of energy generation, there greater demand for assessments of potential environmental and economic impact of new methods. Such assessments for fusion, will be, by necessity, incomplete. Fusion reactor studies in the U.S. are largely exploratory and designed to identify as clearly as possible the nature of the technological problems, their severity and potential solutions. Presently about 2 million of dollars annually or 5% of the budget for fusion research, is spent on approximately 25 individual studies of varying size. These studies capitalize in existing expertise in AEC laboratories and include -calculations of neutron economy in blankets, cost estimates

for large superconducting magnets, methods of recovery and processing of tritium, thermal and electrical stress of materials, magnetic energy storage systems, radiation effects in fusion reactor materials, fuel injection, and general design, system, economic and environmental studies. It is generally felt that these studies should not only be increased but that serious efforts be started over the next decade to solve the technical problems which are so identified, so as to lead into a fusion reactor development program in the 1980's.

Table I

MAJOR U.S. CTR DEVICES

MAGNETIC MIRRORS

IMP	ORNL	Neutral injection
Baseball II	LLL	Neutral injection
2X-II	LLL	Magnetic compression

HIGH BETA

Scyllac - Linear	LASL	θ -pinch with mirrors
Scyllac - Sector	LASL	θ -pinch toroidal sector
ZT-1	LASL	Toroidal Z-Pinch
EBT	ORNL	Bumpy Torus

TOKAMAKS

ST	PPPL	Small bore
ORMAK	ORNL	Intermediate bore
PLT	PPPL	Large bore
Doublet	GGA	Noncircular cross-section
ATC	PPPL	Magnetic compression
Alcator	MIT	High field
TT	Texas	Turbulent heating

INTERNAL CURRENT DEVICES

FM-1	PPPL	Superconducting ring
Superconducting Levitron	LLL	Superconducting ring
D.C. Octupole	GGA	Supported rings
octupole	Wisconsin	Levitated rings
Astron	LLL	Relativistic beam