Comments on the Status of and Future Possibilities for the U. S. Magnetic Confinement Fusion Research Program

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Note: The following comments represent my personal opinions, and should not be construed as representing the opinion of any organization, governmental or non-governmental.

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Introduction: The Present Magnetic Fusion Confinement Research Situation

Having spent most of my career (since 1952) working on the problem of the magnetic confinement of fusion plasmas I continue to be intensely interested in its status and prospects, both with respect to the U. S. program and programs overseas. My comments will have to do both with some of my serious concerns with respect to the situation today, but they also will describe what I believe is an unique opportunity for the U. S. magnetic confinement program at this time.

First, I would like to express, in as nearly as possible an unbiased factual summary, my opinion of the present status of that research, worldwide. Clearly, as has been true now for more than three decades, it is dominated by research on the tokamak approach. That particular approach has now been studied for nearly fifty years and that fact allows one to draw some well-supported conclusions, as follows:

1) The fact that the cross-field diffusion constants in the best tokamak confinement studies are four to five orders larger than the “classical” diffusion constant derived by Spitzer[1] means that in order to produce substantial net fusion power the tokamak must be very large (e.g. ITER).

2) The tokamak, along with other toroidal confinement systems, such as the stellarator, have in common several plasma physics-based features that help to explain this large discrepancy in cross-field transport relative to the “classical” one.

3) These features include the following items:

   a) The drift surfaces of these toroidal systems are “open” in that there exist direct paths for the loss of particles across the magnetic field.

b) To achieve a state of equilibrium there must be current flow along the field lines. In the tokamak these currents are dominant; in the stellarator they may be lower in magnitude.

c) A direct result of the use of toroidal confining fields is that the plasma losses, being necessarily only across the field, must involve one or more transition areas where the plasma interacts with a wall that is closely located to the body of the plasma. This area may also be a turbulent one. These circumstances lead in turn to the problem of high wall heat fluxes, a problem that represent a major concern.

A corollary to the above-listed items is that without exception the confined plasma in these devices exhibits fluctuations with amplitudes that are large compared to those thermal fluctuations normally to be expected to exist in a quiescent plasma.

My conclusion from the above listing is the following: The tokamak and the stellarator, and variations on these, have confinement properties that are, and will continue to be, far from the ideal situation described by the Spitzer diffusion rate. This therefore leaves unanswered the question of how to substantially reduce the size, complexity, and plasma heat disposition problems faced by toroidal-field-based plasma confinement systems. These problems are, in my opinion, such as to cast doubt on the long-term engineering and economical practicality of the tokamak and its relatives.

Finally, I will not discuss the programmatic and budgetary difficulties that have delayed the progress of ITER. These have been discussed in detail elsewhere{2}. In this document my main intent is to bring attention to a present opportunity for the U.S. magnetic fusion program. If pursued, I believe the shift in approach involved could, on a substantially shorter time-scale and at a lower cost than ITER/DEMO, lead to fusion power systems that are simpler and substantially more engineering-friendly than either the tokamak or the stellarator. It could also return the U.S. to a lead role in the fusion quest, with future economic gains that that role would promote.

Optimizing Magnetic Plasma Confinement: Trail Markers from the Past

The sixty-plus years that magnetic confinement research has been pursued nationally and internationally provides us with many valuable theoretical and experimental "trail markers" concerning magnetic confinement. Some of these trail markers concern magnetic field configurations that have been shown to approach the ideal Spitzer cross-field diffusion constant. These configurations are the ones that I believe should now be actively pursued as an alternative to the tokamak/stellarator in order to shorten the development timescale, reduce the cost, and increase the probability of success of the magnetic fusion confinement effort.

The basic field configuration that I am referring to is a linear, cylindrical, axisymmetric magnetic field such as was investigated early on in the U. S. Magnetic Mirror fusion program[3]. First, for this configuration early theoretical analysis, by Teller and Northrop[4], showed that the drift surfaces of this field configuration are "closed," i.e. plasma ions and electrons in moving back and forth on the field lines of such configurations remain on closed cylindrical drift surfaces. A later corollary to this theory is that all plasma equilibria in such configurations have net zero parallel currents.

There were, early on, experimental confirmations of the Teller-Northrop theory. Perhaps the most dramatic example was given by the so-called "Argus" experiment proposed by Christofilos and carried out in the Pacific Ocean. In that experiment a rocket-launched atomic explosive was detonated in the stratosphere, creating a cloud of energetic electrons that were trapped in the axi-symmetric magnetic-mirror field represented by the earth's magnetic field. A decade later these electrons could still be detected – after of order 10^9 reflections by the mirrors created by the North and South magnetic poles!

A second example of the power of the Teller-Northrop theory came early on in the "Table Top" magnetic compression mirror experiment at the Lawrence Livermore National Laboratory[5]. In this experiment a dense ($\sim 10^{20}/m^3$) hot (~20 keV) electron mirror confined plasma column about 20 cm. long and about 2.0 cm. in diameter was created by the magnetic compression of plasma injected from a plasma gun. The experiment was carried out at about the same time that Lyman Spitzer's stellarator at Princeton was exhibiting cross-field diffusion at a rate equal to the turbulence-dominated "Bohm" diffusion constant. In Table Top the plasma column was not only observed to be stable against MHD activity, but its cross-field diffusion rate was almost immeasurably small, being at least 5 orders of magnitude less than those being observed on the Princeton stellarator. Though at the time we did not understand why the Table Top plasma did not exhibit the theoretically predicted MHD cross-field drift predicted by Teller[6] and by Rosenbluth and Longmire[7], we now believe it can probably be explained by theory proposed by Ryutov[8] and confirmed in the Gas Dynamic Trap experiment[9] at Novosibirsk, Russia. In this Russian mirror-based experiment plasmas with beta values in excess of 40 percent have been stably contained without any evidence of MHD-induced cross-field drifts. It has been shown that in GDT these drifts can be stabilized by the effluent plasma as it traverses the expanding field outside the mirrors. The proof of the power of this means of stabilization has been to be able to turn off the stabilization by terminating the plasma just outside the mirror. Also shown in these Russian experiments was the important fact that, consistent with theory[10], when the expansion ratio exceeds the square root of the ion-to-electron mass the end-loss heat transport is limited to approximately the amount carried by the escaping ions, a far smaller rate than the rate that would be calculated from electron thermal conduction.

With respect to experiments that exhibit cross-field transport close to the “classical” Spitzer value, the GDT results appear to approach this value within experimental error. Looking farther back in history, the long linear theta pinch experiment at Culham Laboratory in the U.K. also showed close-to-classical cross-field rates as did other axisymmetric theta pinch experiments.

While it has been shown that near-classical cross-field transport can be achieved in axisymmetric mirror confinement systems, there still remains the question of reducing the collision-induced end losses[11] in such systems in order to increase the fusion “Q” value. The answer to this question lies in the invention of the tandem mirror by Fowler and Logan[12] at Livermore and by Dimov[13] at Novosibirsk. After its proposal several tandem-mirror experiments were built worldwide and the validity of the tandem mirror end-loss plugging concept was proved, with end-loss confinement times scaling up with plugging potential in agreement with theory by Pastukov[14] and by Cohen et. al.[15] For further details on these matters a review of the status of mirror research as of October 1987 can be found in a review article in Nuclear Fusion[16].

While early simple mirror experiments were sometimes dominated by losses from “loss cone” instabilities, the nature of these instabilities and means to stabilize them were predicted by theory[16,17] and confirmed experimentally. Furthermore the invention of the tandem mirror with its confinement of the central plasma by ambipolar potentials eliminated virtually all of these “microinstabilities” in the central plasma, and scaling and velocity-space distribution control has been shown theoretically and experimentally to be able to eliminate them in the tandem-mirror plugging cells.

Despite the promising results from the several tandem-mirror experiments built in the U.S. Russia, and Japan the world-wide programmatic shift to the support of the tokamak has meant that there is now only one major tandem-mirror, Gamma 10 at Tsukuba in Japan, in operation. Furthermore, as a means to suppress MHD-induced cross-field drifts the Japanese tandem mirror system employs non-axisymmetric fields in its plugging cells, carrying with them the issue of enhanced radial losses associated with such fields. Budgetary constraints have prevented the Gamma 10 group from replacing their non-axisymmetric end cells with axisymmetric ones, so as to achieve closed drift surfaces.

The Axisymmetric Tandem Mirror Concept: Plasma Physics Considerations

Perhaps in part stimulated by the remarkable results of the GDT experiment, and in part stimulated by a desire to find a better, faster to achieve, approach to fusion power than the ITER/DEMO scenario, there has been a resurgence of interest in axisymmetric mirror-based confinement geometries, both in the U. S. and abroad. Specifically, axisymmetric tandem mirror ATM} systems have been analyzed, with promising results. These studies have addressed the common previous objections to such systems, such as the problem of stabilizing MHD-induced cross-field drifts, the presumed problem of excessive heat loss out the ends, coupled with too low an electron temperature to permit high reaction “Q” values, and the problem of suppressing microinstabilities. It has been shown in published studies that existing experimental results (e.g from GDT or Gamma 10), give favorable answers to virtually all of these questions. For the few issues not yet thoroughly studied experimentally, theory has provided practical means to avoid them.

As an example of one of these issues, namely stabilizing the classical Rosenbluth/Longmire transverse MHD modes, it has long been known from theory, and confirmed experimentally, that finite-orbit effects can stabilize all but the lowest mode (an m =1 sideways drift of the plasma column). As to that drift mode, the GDT experiment and other experiments e.g. the Wisconsin Phaedrus tandem mirror experiment, are examples from a myriad ways to stabilize this mode. As an example, Table I, taken from a recent paper on the ATM[18], lists many of these techniques.

Table I: MHD Stabilization Methods of Axisymmetric Mirrors

Expansion plasma pressure: Plasma end loss provides plasma pressure in good curvature region near mirror throats and beyond.[19]

Cusp anchor: Good curvature in end cusps stabilizes central plasma.[20]

Divertor anchor: Good curvature of axisymmetric divertor stabilizes central plasma.[21]

Vortex stabilization: Sheared azimuthal plasma flow short-circuits electric fields of MHD modes.[22]

Nonparaxial mirror: Sharp magnetic curvature provides stability.[10]

Line tying: Currents to end walls short out electric fields of MHD modes.[23]

Wall stabilization: Similar to tokamak wall stabilization with feedback to control slow growing modes.[24]

Ponderomotive: Radio-frequency power produces ponderomotive stabilizing force.[25,26,27]

Pulsed ECH: ECH pulses at rate exceeding MHD growth rate provides dynamic stabilization.[28]

Plasma rotation: Rapid plasma rotation provides centrifugal force that provides stability.[29]

Kinetic stabilization: Injected ions in exhaust region of device provide plasma pressure where magnetic curvature is favorable to provide stability.[30]

End-wall funnel: Electron compressibility forces plasma to remain centered.[31]

An important experimentally observed consequence of suppressing the m = 1 drift, as exemplified by the results from the GDT experiment and other earlier experiments, is that the radial transport can approach the classical Spitzer value, some 4 to 5 orders of magnitude below those typical of the tokamak. A second important consequence is that these MHD-stable plasmas can have very high beta values, e.g. 60 percent in recent GDT experiments. Since fusion plasma power rates vary as beta squared, this fact has major favorable economic consequences for the ATM when compared with the much lower limiting beta values encountered in the tokamak.

Finally, another important distinction between axisymmetric "open-ended" confinement systems and toroidal systems is that after expansion the end-escaping plasma can terminate on insulated ring-shaped conductors the electrodes of which can be maintained at graded potentials so as to control the radial electric field in the confined plasma in such a way as to further suppress residual instabilities. This technique has been employed in several mirror experiments, including Gamma 10, where it resulted in the elimination of residual radial transport effects.

The Axisymmetric Tandem Mirror Concept: Reactor Engineering Issues

Perhaps one way to characterize the fusion-favorable plasma physics characteristics of the ATM is that it could be described as the result of "discerning what the plasma wants to do, rather than trying to tell it what to do." In the same spirit the ATM can be scrutinized to determine its favorable characteristics in terms of the engineering and economic aspects of fusion power systems based on that concept. There are several such aspects that can already be discerned. Among them are the following:

(1) The diameter of the confined plasma column can be made to be substantially smaller than the inner diameter of the plasma vacuum chamber. As a consequence the wall heat load caused by plasma contact with the chamber wall can be reduced to near-zero, as can the existence of instabilities that originate in the transition region of toroidal systems. Since the plasma loss in the ATM is essentially only out the ends, the area of the end region where the plasma terminates on a physical surface can be as large as desired.

2) The configuration of the “expander” region outside the outer mirror of the ATM is such that it can be fitted with direct conversion electrodes, concepts for which were studied early on in the LLNL mirror program, where plasma kinetic energy to electrical energy conversion efficiencies in excess of 86 percent were measured.[32]

3) The size of a net-power producing ATM is predicted to be far smaller than that of a comparable tokamak, owing the high beta values and lowered radial diffusion rates of the ATM and the linear and modular nature of its geometry.

These, and other engineering-related features of the ATM are such as to indicate that the development time for ITER and DEMO ATM counterparts could be both more rapid and less expensive to carry out than to construct those systems. This possibility is the basis for my claim that the U.S. has an almost unique opportunity to take the lead role in the development of the first practical fusion power system, the first to show that fusion will indeed be the energy source of the future.

The Axisymmetric Tandem Mirror Concept: A Programmatic Opportunity for the United States Magnetic Confinement Fusion Research Program.

One of the signs of a resurgence of interest among U.S. fusion researchers has been the formation of the “Mirror Forum” group by Dmitri Ryutov at the Lawrence Livermore National Laboratory. This group, the members of which come from many U. S. Labs and universities, “meets” through periodic conference calls during which members present, via the Internet, their ATM-related research activities and/or their proposed papers on that subject at upcoming meetings. As a member of this group I see in its existence the seeds of a major opportunity for the U. S. magnetic confinement fusion effort.

The opportunity: Building on the GDT and Gamma 10 experimental results, the U.S, should begin a theoretical/experimental program the goal of which is to achieve fusion ignition and significant fusion power release from an ATM en route to a practical fusion power system.

As shown by the GDT, unlike ITER and its large predecessors, significant demonstration of the plasma-physics viability of an ATM can be achieved in University-sized experiments, and proof of plasma ignition should be obtainable in an experiment about the size of the Livermore TMX or the Tsukuba Gamma 10 experiment. TMX was built within 18 months, start to finish, and it should be possible to build the ATM ITER-equivalent experiment in a far shorter time than it will take to build ITER. The neutral beam and other technologies needed in the ATM have already been developed for the tokamak program.

Another motivation for undertaking an ATM-based program, as several ATM-related papers have emphasized, is its application as a source of 14 MeV neutrons in materials testing[33,34].

Finally, consider the spectrum of world-wide energy-related issues and problems, e.g. depletion of petroleum resources and the political instabilities that this causes, global warming from CO2 and its negative impacts, to mention a few. In view of these growing worrisome problems fusion power needs to become viewed in the public eye as something real and obtainable rather than being only a distant dream. I believe the ATM offers that possibility, and I believe the U.S. can be the place where that technology is developed and proved out.

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