Final Report on the Department of Energy Grant

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"Investigation of the Spherical Stellarator Concept"

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SUMMARY

This document is a final report on the U.S. Department of Energy grant entitled "Investigation of the Spherical Stellarator Concept" which supported theoretical and numerical investigation of a novel fusion concept, the ultra-low-aspect-ratio stellarator system called Spherical Stellarator (SS). This research was supported by DOE grants dated from January 15th,1997 to November 14th, 1999. However, the funds allocated were enough only to carry out this research up to February 1999, when the PI's final report (somewhat similar to the present one) was submitted to a DOE manager Michael Crisp.

The planned work was successfully completed, and numerous articles [1-28] have been published in the refereed journals and conference proceedings. The approach of compact stellarators became the leading fusion concept of a stellarator type in the U.S.A. Two main U.S. programs on compact stellarators, the NCSX program at PPPL and QOS program at ORNL have been started, which include also some other institutions, such as Columbia University, University of Texas, Auburn University, etc.

At the same time, among all the emerged U.S. compact stellarator research, the SS concept proposed by the PI has a unique position: a much lower aspect ratio and thus a very large plasma volume at a given major radius. Making a parallel with tokamaks, an SS is equivalent to a Spherical Tokamak (ST) approach, a leading concept in current fusion research.

The innovative SS concept includes very low aspect ratio (down to $A \sim 1$) configurations with stellarator features and with positive and significant plasma current (preferentially, via the bootstrap effect, at high β). The aspect ratio for a SS is significantly lower than that for any stellarator ever built. The beneficial use of the positive and significant bootstrap current in a stellarator is also a novel approach, not discussed before the SS concept has appeared. Various SS configurations have been analyzed by the PI during his research conducted at the Engineering Physics Department of the University of Wisconsin-Madison.

There are many explicit or potential advantages of the SS concept, which are discussed briefly in this proposal. One of them is the high efficiency of the coil system in producing strong magnetic fields within the plasma at moderate currents in the coils. For the same magnetic field in the plasma, the total current in the coils is reduced approximately in

inverse proportion to A, and in comparison with traditional stellarators, the best of them being W7-X, this gain can be a factor of ten. Because of the compactness of a SS device, there is also a significant decrease in the amount of material required for construction. Together with the simplicity of the coil system (which is also one of the goals of the SS approach), the cost of the SS device can be much lower than that of a traditional stellarator. The goals of the SS approach, however, are much more ambitious. The main ones are the following: steady-state operating device, very low aspect ratio, relatively strong and positive bootstrap current, large volume of closed flux surfaces, low level of magnetic islands, high β limits for MHD equilibrium and stability, improved particle and energy confinement, simple coil system, simple and convenient divertor, and enough space (when scaled to fusion reactor parameters) for a tritium-breading blanket and shield to protect the coils from intense fluxes of energetic particles, heat, and neutrons.

Because of the large volume of flux surfaces and low A in a SS, the ratio of the plasma volume to the plasma surface area is increased (approximately in inverse proportion to A) which is an important parameter for a fusion reactor (fusion energy is produced within the plasma volume while all particle and energy losses occur through the plasma surface). The terms we are using, strong and positive bootstrap current, mean that the bootstrap current is flowing in the direction to increase the vacuum rotational transform and its contribution to the rotational transform is significant. This feature of the bootstrap current is very important and corresponds to improved high β MHD characteristics and improved particle transport in the SS. For small-scale SS devices which cannot rely on significant bootstrap current, an ohmic or auxiliary driven current can be used in the corresponding experiments. Definition of the SS concept does not include specifications for the particular optimization procedure leading to improved particle transport, enhanced high β limits, or other advanced characteristics, because different optimization procedures are possible and different configurations can be found within the same SS concept.

It is relevant to mention here about a related novel concept, also invented by the PI, namely the stellarator-spheromak (SSP) [5]. Our 3D MHD calculations have demonstrated that the SSP-type configurations are feasible. Similar to a spheromak, the SSP does not have any material structure linking the torus, and thus has additional advantages for a fusion reactor in comparison with more traditional approaches.

MAIN RESULTS FROM SS RESEARCH

The relevant research performed under this DOE grant was concentrated on a few issues of importance for the SS concept: (a) search for principally different types of SS configurations, (b) optimization of SS configurations by varying the parameters of the coil systems, (c) finite β and finite plasma current (including bootstrap current) equilibria in the SS, and (d) Monte Carlo particle transport simulations for the SS. Progress in these areas is summarized briefly in this section.

1. BRIEF DESCRIPTION OF A SPHERICAL STELLARATOR.

Spherical Stellarator (SS) is an ultralow plasma aspect ratio, A, (typically, $A \leq 3.5$) configuration with stellarator features having a more spherical-shaped plasma than that in traditional stellarators and with a relatively modest central opening through which segments of the coil system extend. The coil system normally include the toroidal field (TF) coils which are generally twisted and, in some cases, can be locally combined in a single or a few windings, such as a helical center post. The configuration normally includes also poloidal field rings. An important element of the SS concept (and unique, relative to other stellarators) is the strong and positive plasma current (which is preferentially due to the bootstrap effect at high β). The SS configurations feature closed vacuum flux surfaces with large enclosed volume and a helical magnetic axis, appreciable rotational transform, absence of large magnetic islands disturbing particle transport, and a simple divertor configuration. The positive bootstrap current improves properties of the magnetic field of these configurations and leads to accessing high beta equilibria with good particle transport characteristics. Advantages for a fusion reactor include also steady-state operation with attractive characteristics, modular, compact, simple and inexpensive design, good access to the plasma, and enough space between the TF coil segments (including inboard segments) and the plasma surface to put the blanket and protect the coils from the intense fluxes of particles, heat, and neutrons.

It is commonly believed (see [29-32], for example) that the plasma current produces negative effects for stellarators, so the ohmic plasma current or the bootstrap current, even when small, have to be avoided. This is a general philosophy supported by many stellarator researchers, including the W7-X group. In contrast, for the SS configurations, we have found very positive effects of the plasma current, both inductively driven ohmic current and bootstrap current. The plasma current brings the following main advantages to the SS: it (a) increases the total rotational transform, (b) raises the β limits for plasma equilibrium and stability, (c) improves plasma position control via the vertical magnetic field, (d) gives wide flexibility of operational regimes, from a currentless SS to those similar to a ST with strong current, (e) gives an additional knob in controlling the plasma shape and the bootstrap current.

2. DIFFERENT TYPES OF SPHERICAL STELLARATOR CONFIGURATIONS.

The major effort during the past few years of PI's research has been directed to searching and exploring the different possibilities and different coil systems capable of producing the SS configurations. Four principally different and simple SS coil systems have been identified and analyzed: the SS with a straight center post [1-4, 6, 13-16, 20], the SS with planar (although not necessarily circular) coils [6, 8, 13, 16], the SS with outboard stellarator windings (OSW) [7, 17-20], and the SS with a helical center post [9-12, 21-27]. All SS configurations share a number of common features such as large enclosed volume of vacuum flux surfaces, strong magnetic well (important for plasma stability) existing in a vacuum or appearing already at relatively low plasma pressure or low plasma current, tokamak-like behavior of the average vacuum rotational transform (however, some cases with the hollow current profile, such as those with the bootstrap current, show opposite trend), absence of notable islands, relatively strong bootstrap current flowing in the direction such that the total rotational transform increases, and a number of others. Some other features, however, are substantially different, and represent the specific characteristics of a particular SS configuration. Below we describe briefly the main different types of the SS considered by the PI in the past. More details can be found in the corresponding publications.

2a. SS configurations with a straight center post [1-4, 6, 13-16, 20].

The originally proposed SS configuration [1] was the one with a center post. This kind of configurations can be obtained by moving the inboard parts of all TF coils closer to each other and combining them in a single straight center post (similar to that in a ST). The difference from an ST, however, is in the inclination of the outboard parts of all TF coils in accordance with some winding law (part of helical winding). These configurations feature large volume of closed flux surfaces and very low aspect ratios A. The main results have been published for A ~ 1.45 to A ~ 1.9, although cases with A as low as 1.2 have been considered. The unique feature of these SS configurations is the toroidal symmetry of inboard parts of flux surfaces. Adding the plasma current makes these configurations efficient for transition between the stellarator and tokamak regimes. Increasing the vertical magnetic field moves the plasma closer to the center post and regimes similar to that in an ST can be obtained. On the other hand, without such additional vertical field, clear stellarator regimes with strongly 3D-shaped toroidally asymmetrical flux surfaces can be obtained. Strong and positive bootstrap current appears in these configurations at high β.

2b. SS configurations with planar coils [6, 8, 13, 16].

Another simple type of SS configurations can be obtained with planar coils. Generally, such configurations feature somewhat higher aspect ratio than those with the center post. Still, plasmas with aspect ratios of $A \sim 2$-3 can be produced. Simplicity means not only that the corresponding device will be inexpensive for construction (which is very important by itself), but also that the coil system manufacturing and spatial assembly can be done much more precisely than for a typical stellarator. Hence, the magnetic field disturbances, causing appearance of magnetic islands and poor plasma confinement, might be much lower. One of the distinctive characteristics of many SS configurations with planar coils is the natural (i.e. without using any special coils) toroidally symmetric divertor region. Very interesting SS configurations with bean-shaped plasmas or plasmas accommodating the central transformer have been obtained with non-circular, although planar, TF coils. Similar to other SS-type configurations, the SS with planar coils considered feature positive bootstrap current beneficial for reaching higher β and improved particle confinement.

2c. SS configurations with outboard stellarator windings [7, 17-20].

Outboard stellarator windings (OSW) are unique in the sense that they do not encircle the plasma in the poloidal direction and are located only on the outboard side of the device. This feature makes it easy to integrate OSWs with the standard ST coil system. Another advantage is that OSWs, as additional coils, can be turned on or off at any time thus making the device to operate as a pure ST or adding the stellarator features when necessary. Among the main potential advantages of using OSWs in a ST are the possibility of non-inductive plasma start-up or improved inductive operation caused by the existence of closed vacuum flux surfaces and an external rotational transform. Two types of OSWs have been studied--a classical-stellarator type and a torsatron type--and both were shown to be effective.

2d. SS configurations with helical center posts [9-12, 21-27].

Helical Post Stellarators (HPS) can be produced by replacing the straight center post of a ST with a helical center post that can be a single helix or may consist of a few helices. The HPS configurations belong to a new sub-class of the SS which we call the Extreme-Low-Aspect-Ratio Stellarators (ELARS) because they feature the plasma aspect ratios as low as $A \sim 1$. The main advantages of the HPS discovered so far include extremely high-β MHD equilibria ($\beta_0 = 86\%$, $\beta = 20\%$) accessible with bootstrap current alone (no externally driven current), significant rotational transform, large plasma volume, improved particle transport characteristics caused by the absence of magnetic field ripple on the outboard of the torus, and a natural divertor protecting the center post from the fluxes of heat and particles.

3. STELLARATOR-SPHEROMAK [5, 17, 19-21]

Our investigation of the SS devices has brought us to a limit when the SS actually transforms to a novel type of a device - the stellarator-spheromak (SSP). Our 3D MHD calculations have demonstrated that the SSP-type configurations are feasible. The SSP concept is of interest as it allows exploration of wide variety of novel physical phenomena and may also hold promise as a new and relatively inexpensive approach to controlled fusion. Similar to a spheromak, the SSP does not have any material structure linking the torus, and thus has large potential advantages for a fusion reactor in comparison with more traditional approaches. The advantages will be realized, however, only if the SSP will be able to overcome the severe problems of traditional spheromaks, such as difficulty of plasma generation and sustainment, difficulty to avoid the tilt/shift instability, and difficulty of obtaining steady-state operation. Initial analysis indicates that the stellarator features of an SSP are important factors in overcoming all these difficulties.

4. OPTIMIZATION OF SS CONFIGURATIONS.

Due to their 3D nature, stellarator configurations are more complicated than many other fusion systems that possess toroidal symmetry, such as tokamaks, spheromaks, FRCs, RFPs, etc. Stellarators, thus, have more parameters which can be adjusted to optimize a configuration. Past experience with stellarators shows that optimization might take many years of group research efforts (as was the case with the W7-X stellarator, which is presently under construction in Germany). Our past two years of research were devoted to the searching and partial optimization of different SS configurations, briefly mentioned above, and to the demonstration of their attractiveness for controlled fusion. However, further optimization is necessary, especially regarding the improved particle transport and enhanced high-β characteristics. As discussed above, a notable progress has been achieved during the past years on the novel concept of a Spherical Stellarator, and four principally different types of SS configurations have been discovered, analyzed, and partially optimized. We are confident that further search and optimization will discover and demonstrate significant improvements and further advantages of various SS configurations for the fusion program.

5. MAIN ADVANTAGES OF A SPHERICAL STELLARATOR

Our past research indicate a few advantages of the SS approach for controlled fusion. Some of these advantages are clear already, while others can be currently considered only promising indications within our limited analysis and requiring further investigation. This section briefly summarizes the main advantages of the SS concept which we see at the present time. It is anticipated that the research on the proposal will lead to finding better SS configurations with improved characteristics and additional advantages.

- increased ratio of enclosed plasma volume (where the fusion reaction might occur) to the plasma surface (where the losses of energy and particles occur)
- extreme compactness for a stellarator device: plasma aspect ratio $A \leq 3.5$ for a SS and $A \leq 1.5$ for a ELARS
- extremely high β MHD equilibria ($\beta_0 \sim 90\%$, $\beta \sim 20$-30%) have been found, approaching those of a ST
- improved confinement characteristics; in case of HPS configurations, they are accessible because of absence of the magnetic field ripple on the outboard of the

torus; no evidence of poor confinement 1/v regime; particle transport is close to that in an equivalent ST

- relatively strong bootstrap current flowing in such a direction that it increases the vacuum rotational transform; this current is enough to access the advanced characteristics
- the coil system is simple and inexpensive for construction
- simple divertor configuration (toroidally symmetric, in many cases)
- high efficiency of the coil system in producing confining magnetic fields: strong magnetic field in the plasma region can be produced by a moderate currents in the coils
- strong magnetic well is found in vacuum configurations or at moderate plasma current or finite-β (important for stability)
- wide flexibility of SS configurations; possibility of approaching specific symmetry or advanced optimizations such, for example, as QAS, QOS, or S-optimization
- flexibility of rotational transform profile which can be radially decreasing (tokamak-type, found normally in vacuum cases) or radially increasing (stellarator-type, found in a few cases with the strong bootstrap current)
- no noticeable magnetic islands (at least for vacuum cases); this important feature should be checked and optimized for high-β regimes.

The SSP configurations have additional advantages related to the lack of material structures such as conducting walls or magnet coils linking the torus. The topology is effectively toroidal for thermal particles and it is spherical for neutrons and energetic particles.

6. CONCLUSIONS.

Work on DOE grant "Investigation of the Spherical Stellarator Concept" has been successfully completed. The PI would advise to continue DOE support for this research, so the studies could go from the initial exploratory stage to the concept improvement and optimization stage. Among all the emerged U.S. compact stellarator projects, the SS has a unique position: a much lower aspect ratio and thus a very large plasma volume at a given major radius. Making a parallel with tokamaks, an SS is equivalent to a Spherical Tokamak (ST) approach, a leading concept in current magnetic fusion research.

REFERENCES

[1] P. E. Moroz, "Spherical stellarator configuration", Phys. Rev. Lett. **77**, 651 (1996).

[2] P. E. Moroz, "Spherical stellarator with plasma current", Phys. Plasmas **3**, 3055 (1996).

[3] P. E. Moroz, D. B. Batchelor, B. A. Carreras, S. P. Hirshman, V. E. Lynch, D. A. Spong, J. S. Tolliver, A. Ware, J. Whitson, "Ultra low aspect ratio stellarator or hybrid configurations", Fusion Technology **30**, 1347 (1996).

[4] P. E. Moroz, "Spherical Stellarator concept", Stellarator News **48**, 2 (1996).

[5] P. E. Moroz, "Stellarator-Spheromak", Phys. Lett. **A** **236**, 79 (1997).

[6] P. E. Moroz, "Spherical Stellarator or Hybrid Configurations", Plasma Physics Reports **23**, 502 (1997).

[7] P. E. Moroz, "Spherical tokamaks with outboard stellarator windings", Nuclear Fusion **37**, 1045 (1997).

[8] P. E. Moroz, "Low aspect ratio stellarators with planar coils", Plasma Phys. Contr. Fusion **39**, 1841 (1997).

[9] P. E. Moroz, "Compact Stellarator Configurations with Helical Post", Stellarator News **54**, 6 (1997).

[10] P. E. Moroz, "Helical Post Stellarator", accepted for publication in Plasma Phys. Contr. Fusion (1998).

[11] P. E. Moroz, "Novel Stellarator Configuration with Double-Helix Center Post", accepted for publication in Nuclear Fusion (1998).

[12] P. E. Moroz, "Extremely Low Aspect Ratio Stellarators", accepted for publication in Physics Letters A (1998).

[13] P. E. Moroz, "Non-standard stellarator configurations", Sherwood International Fusion Theory Conf., Philadelphia, PA, 3C26 (March, 1996).

[14] P. E. Moroz, "Spherical stellarator approach", 23rd IEEE Conf. on Plasma Science, Boston, MA, p. 190, (1996).

[15] P. E. Moroz, D. B. Batchelor, B. A. Carreras, S. P. Hirshman, V. E. Lynch, D. A. Spong, A. Ware, J. Witson, "Physical Characteristics of a Spherical Stellarator or Hybrid", Bull. Amer. Phys. Soc. **41**, 1567 (1996).

[16] P. E. Moroz, "Innovative confinement concepts with stellarator features", Innovative Confinement Concepts Workshop, March 3 - 6, Marina del Ray, CA (1997).

[17] P. E. Moroz, "From Spherical Stellarator to Stellarator-Spheromak", Innovative Confinement Concepts Workshop, March 3 - 6, Marina del Ray, CA (1997).

[18] P. E. Moroz, "Outboard windings for noninductive start-up and compact torus plasma formation in NSTX", NSTX Research Forum, PPPL, Princeton, February 5-7, 1997.
[19] P. E. Moroz, "On the way to Stellarator-Spheromak", Sherwood International Fusion Theory Conference, Madison WI, April 28-30, Paper 3C31 (1997).
[20] P. E. Moroz, "Spherical Stellarators and Stellarator-Hybrids", Bull. Amer. Phys. Soc. **42**, 2070 (1997).
[21] P. E. Moroz, "Two Novel Compact Toroidal Concepts with Stellarator Features", IAEA Tech. Comm. Meeting on Innovative Approaches in Fusion Energy, Pleasanton, CA (Oct. 20-23, 1997).
[22] P. E. Moroz, "Extreme Low Aspect Ratio Stellarators", Bull. Amer. Phys. Soc. **42**, 1914 (1997).
[23] P. E. Moroz, "Properties of Helical Post Stellarators", US/Japan/IEA Workshop on Stellarator Concept Improvement, January 27-29, 1998, PPPL, Princeton, N.J.
[24] P. E. Moroz, "Extreme Limit of the Spherical Stellarator Approach", Sherwood Int. Fusion Theory Conf., Atlanta (23-25 March, 1998).
[26] P. E. Moroz, "Helical Post Stellarators with Plasma Aspect Ratio A = 1", Innovative Confinement Concepts Workshop, PPPL, April 6-9, 1998.
[27] P. E. Moroz, "Spherical Tokamak with Helical Center Post", Japan-U.S. Workshop on Spherical Tokamaks, University of Wisconsin, Madison, March 9-11 (1998).
[28] P. E. Moroz, S. P. Hirshman, D. A. Spong, D. B. Batchelor, "Analysis of self-consistent MHD equilibria with bootstrap current for SMARTH", Innovative Confinement Concepts Workshop, PPPL, April 6-9, 1998.
[29] C. Beidler, G. Grieger, F. Herrnegger, E. Harmeyer, J. Kisslinger, W. Lotz, H. Maassberg, P. Merkel, J. Nuhrenberg. F. Rau, J. Sapper, F. Sardei, R. Scardovelli, A. Schluter, H. Wobig, "Physics and Engineering Design for W7-X", Fusion Tech. **17**, 148 (1990).
[30] G. Grieger, W. Lotz, P. Merkel, J. Nuhrenberg, J. Sapper, E. Strumberger, H. Wobig et al., Phys. Fluids **B4**, 2081 (1992).
[31] P. R. Garabedian and H. J. Gardner, "Reduction of bootstrap current in the modular helias-like heliac stellarator", Phys. Plasmas **2**, 2020 (1995).
[32] H. Wobig, Plasma Phys. Contr. Fusion **35**, 903 (1993).