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Highlights in Early Stellarator Research at Princeton

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Abstract

This paper presents an overview of the work on Stellarators in Princeton during the first fifteen years. Particular emphasis is given to the pioneering contributions of the late Lyman Spitzer, Jr. The concepts discussed will include equilibrium, stability, ohmic and radiofrequency plasma heating, plasma purity, and the problems associated with creating a full-scale fusion power plant. Brief descriptions are given of the early Princeton Stellarators: Model A, Model B, Model B-2, Model B-3, Models B-64 and B-65, and Model C, and also of the postulated fusion power plant, Model D.

Keywords:

Spitzer, Kruskal, stellarator, rotational transform, Bohm diffusion, ohmic heating, magnetic pumping, ion cyclotron resonance heating (ICRH), magnetic island, tokamak

On March 31 of this year, at the age of 82, Lyman Spitzer, Jr., a true pioneer in the fields of astrophysics and plasma physics, died. I wish to dedicate this presentation to his memory.

Forty-six years ago, in early 1951, Spitzer, then chair of the Department of Astronomy at Princeton University, together with Princeton physicist John Wheeler, had been thinking about the physics of thermonoclear processes. In March 24 1951, President Juan Peron announced that an Austrian physicist, Ronald Richter, then working in Argentina, had made dramatic progress in laboratory experiments directed toward "the controlled liberation of atomic energy" at "enormously high temperatures of millions of degrees" without using uranium fuel. Richter's work turned out to be of no value, but these reports were an important stimulus for work in this area. Spitzer, then leaving for a ski trip to Aspen, Colorado, thought about how magnetic fields might be used to contain a thermonuclear plasma at densities appropriate to power production. Pursuing these questions on his return to Princeton, he arrived at the concept of a Figure-8 stellarator[1].

On May 11, 1951, the concept of the Figure-8 stellarator was brought to the headquarters of the U.S. Atomic Energy Commission in Washington where it received a favorable reception. Spitzer chose the name "Project Matterhorn" for the project which was to be sited in the Princeton area, on the newly acquired Forrestal tract, and funding began on July 1 of that year [2].

Spitzer's earliest stellarator papers comprise a truly impressive scientific achievement and I should like to spend some time telling what he wrote. The presentations are simple and direct. Deceptively so. Spitzer was always able to strip away the irrelevancies and move quickly to the essential elements of the problem at hand, and it is only on the second or third re-reading that one starts to appreciate their extraordinary depth. Equally remarkable in these first papers are the many instances where Spitzer anticipated problems and solutions that would be fully recognized only many years later.

PM-S-1: A Proposed Stellarator

The first paper is PM-S-1, "A Proposed Stellarator", dated July 23, 1951. In one and a half pages of

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this 13-page paper, Spitzer calculates the power generated in a 50 cm radius straight cylindrical D-T plasma at 10^8°C (37,000 watts per cm), compares it to bremsstrahlung loss (510 watts per cm) and finds the net synchrotron losses to be negligible. And in half a sentence, "this ... neglects the additional energy which might be obtained from the liberated neutrons in subsequent reactions outside the Stellarator", Spitzer touches on the possibility of power amplification by a blanket of fissile material.

At β=0.5, a magnetic field of 20,000 gauss is sufficient to contain this plasma. Spitzer estimates the power loss by (classical) radial diffusion, based on a random-walk model with ion-ion collisions, at 530 watts per cm, but also observes "from preliminary calculations it would appear that the outward drift results entirely from electron-positive ion encounters, is the same for both electron and positive ions, and is less by an order of magnitude than the value found from the interactions between positive ions considered above."

The steady-state reactor would be refueled by jets of deuterium and tritium which could aid in stabilizing the plasma by reducing unwanted space-charge-generated electric fields.

Spitzer points out that a steady-state plasma in contact with the cylinder walls would exhibit constant pressure at all radii, much reducing the size of the high-temperature reacting region. To reduce the wall interaction, and also to provide a means to vent the burnt nuclei, he invents the geometry that is now called a toroidal divertor. The sketch of the divertor in this paper is, in fact, very much like its realization, many years later, on the B-64 stellarator and then on the Model C stellarator. Neutral atoms are pumped out; the backflow of ions is reduced by their diamagnetic repulsion from the strong B field they would encounter on reentry.

Seeking to close the magnetic geometry, Spitzer recognizes that a toroidal stellarator would lead to rapid loss of particles by curvature drifts and by $\boldsymbol{E}\times\boldsymbol{B}$ loss resulting from the charge separation. His well-known solution to this problem is the Figure-8 stellarator in which the effects of particle drifts in one U-bend are cancelled by the drifts in the second U-bend.

PM-S-2: A Survey of Possible Oscillations in the Stellarator

Dated just 8 days after PM-S-1, this paper stands out as unbelievably far-sighted. With a fusion plasma just barely emerging from the concept stage, with experimental apparatus not even on the drawing board, this paper begins the examination of what – 46 years later – is still the dominant problem. The abstract begins, "Low-frequency ion oscillations in a normal plasma are known to produce much more rapid diffusion across a magnetic field than would be expected from collisions in a quiescent medium." The paper cites Bohm diffusion, derives the dispersion relation for ion sound waves (to which Bohm attributed the diffusion observed in plasma arc experiments).

A few more sentences from this report deserve verbatim quotation. "Little is known about the instability of plasma oscillations in otherwise quiescent plasma. Bohm has stated that whenever there exist density gradients or electrical fields across a magnetic field, instability is necessarily present." And then, "In a system with so many particles and with so few collisions as a Stellarator plasma, almost any type of behavior would not be too surprising."

A discussion of possible sources of plasma instability then leads to this interesting suggestion: "It is evident that much further work is needed on plasma oscillations to yield conclusive results. In particular, experiments should be carried out with plasmas where the ionization is maintained by the photoelectric effect, or by some other process that does not, in itself, produce instabilities." Years later, Spitzer's suggestion was beautifully realized in an entire class of experiments based on the ionization of cesium atoms by contact ionization with a hot tungsten surface.

PM-S-4: Magnetic Fields and Particle Orbits in a High-Density Stellarator

Dated January 28, 1952, a little more than six months after PM-S-1, this paper discusses rotational transform theory, introduces the concept of "magnetic surfaces", treats the stellarator equilibrium plasma with fluid theory, and finds a ß limit for the plasma.

In more detail, Equation (1) in this paper is the fluid equation for an equilibrium steady-state plasma and includes the quadratic velocity hydrodynamic term, the divergence of the plasma stress tensor, the free-space-charge electrostatic force term, and the magnetic force term. Although Spitzer quickly drops all but isotropic pressure and magnetic force effects, the equation is noteworthy for its accuracy and completeness.

In the following section, Spitzer proves that an equilibrium is not possible with closed $\boldsymbol{B}$ lines in toroidal geometry. Then, discussing what Spitzer terms a "Type C system", he observes, "If, for example, external coils are used to produce H_θ around a toroidal tube, and a current is also induced along the lines of force,

the secondary field will cause the lines of force to spiral around the tube axis." And two sentences later, "In addition, a large induced current is open to the two practical objections that it cannot be sustained in a steady equilibrium and that the rapid generation of such a current is likely to lead to plasma oscillations." In this one paragraph, the tokamak is independently invented and discarded.

At this time, Spitzer had just one scientist working with him – a very young Martin D. Kruskal. Kruskal's security clearance was still in process, so he was not told of the application of the mathematical problem Spitzer gave him. The results of Kruskal's efforts appear in his paper, PM-S-5, "Some Properties of Rotational Transforms", which carries the same date as PM-S-4. In the latter paper, Spitzer summarizes Kruskal's findings concerning transforms that are primarily rotational.

"a) One fixed point must be present, which transforms into itself; this point may be identified with the point O referred to above.

"b) If Q is the number of transforms required for approximately one complete rotation about the plane, the path traced out by the successive transforms of a single initial point will be a closed curve in the T plane, to arbitrarily high powers of 1/Q."

Spitzer summarizes the implications of Kruskal's work:

"We may therefore conclude that each line of force, when followed many times around the Stellarator, generates a practically closed surface which we shall call a 'magnetic surface.' Evidently each magnetic surface is topologically equivalent to a torus. A degenerate case is provided by the line of force which passes through the fixed point, O; this line of force may be called the 'magnetic axis' of the tube."

The next section addresses the fluid equilibrium. A finite-pressure solution is sought by successive approximation, but the condition for a significantly large distortion of the magnetic surfaces by the secondary currents (now called Pfirsch-Schlüter currents) leads to a limitation of the plasma ß, namely, 5a/L, where a is the minor radius of the plasma and L is its length along ***B***. But Spitzer qualifies this result. "It is possible that by means of external currents a magnetic field could be produced which would diminish the distortion shown in Figure 1 and permit an equilibrium solution at higher ß. It is even conceivable that an equilibrium solution might exist with ß only slightly less than unity, but the nature of such a solution, if any, is obscure." Two years later, in planning the Model D Stellarator, Spitzer had already devised a solution to this problem.

PM-S-14: Problems of the Stellarator as a Useful Power Source

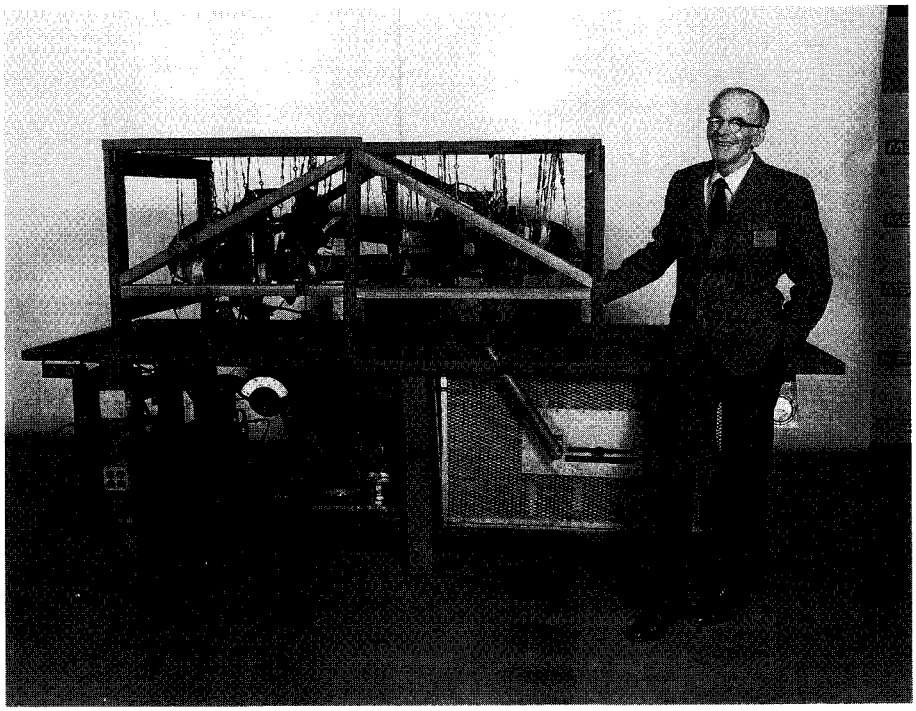
At a time when only the 1000-gauss 2.5 cm minor radius Model A Figure-8 Stellarator was operating, Spitzer assembled a team of engineers to examine the problems of a full-scale d-t fusion reactor. Their work assumed that the magnetic confinement and the supplementary heating of the plasma would be found to be adequate. The team that worked with Spitzer consisted of Lewi Tonks and Willem F. Westendorp, from the General Electric Corporation, and Donald J. Grove and Woodrow E. Johnson, from the Westinghouse Corporation. Their 281-page study, Reference [6], often referred to as the "Model D Report", is dated August 1, 1954.

The Model D Stellarator, recognized in the report as an optimistic and highly tentative design, would have a minor radius for the Figure-8 vacuum chamber of 67 cm, and a total length along the magnetic axis of 165 meters. The vacuum chamber is enveloped by a 60 cm thick lithium blanket. A toroidal divertor is located in each U-bend, and a novel system of alternate high-field positive curvature and low-field negative curvature sections in the U-bends (called "scallops") raises the equilibrium ß to 0.75 in the straight sections and positive curvature sections, and 0.24 in the negative curvature sections. (An impressive improvement – the 5a/L limit cited above would limit the equilibrium ß to about 2%.) Auxiliary heating to raise the plasma to ignition temperature would be supplied by a 10-meter long transit-time magnetic pumping section energized at 5200 Hertz with a source power of 1.5×10^9 watts. The toroidal-field magnet coils are liquid-cooled copper and weigh 20,000 tons. Maximum magnetic fields on the magnetic axis of 50,000, 75,000 and 100,000 are considered, and the net electric power output in these three cases would be 0.6, 4.5 and 17×10^9 watts respectively. The overall power-plant efficiency, exclusive of magnet power, is 35%.

Some other issues explored in detail in PM-S-14 include equilibrium plasma profiles, mechanical stresses, heat generation and dissipation, refueling, neutron moderation, tritium inventory, and lithium-blanket design.

Model A Stellarator

Spitzer invited Prof. James A. Van Allen, University of Iowa, to come to Princeton in 1953–54 to initiate an experimental program. It was Van Allen's idea



Lyman Spitzer, Jr., standing next to the Model A Stellarator. This photograph was taken just before the experimental device was sent to the Smithsonian Museum, in Washington, D.C.

to start with a table-top facility that could demonstrate some of the Stellarator concepts. The vacuum chamber of the Model A Stellarator was made from sections of 5 cm diameter Pyrex glass tube comprising a figure-8 shape about 350 cm in length. Magnet coils to produce a 1000-gauss steady-state field were wound directly onto the Pyrex tubing and were energized by a dc motor-generator set. Model A came into operation early in 1953. The plasma was produced with a radio-frequency electric field linked inductively to the stellarator loop. Some years ago, the Model A Stellarator was taken out of storage and given to the Smithsonian Museum in Washington, D.C.[2].

Model B Stellarator

The Model B Stellarator appeared in several successive embodiments, with construction for the first version beginning in 1953. The vacuum tubes were 5 cm in diameter and about 450 cm in length. The pulsed magnetic field was to reach 50,000 gauss but the magnet coils on the first two versions were inadequately braced to maintain a good magnetic aperture. However, the observation, on occasion, of several-hundred-kilovolt X-rays did give evidence of excellent single-particle confinement. Following instructive failures, the third version, B-1", featured suitably rigid coil supports and a bakeable stainless-steel gold-ring-seal ultra-high vacuum system. B-1" operated until 1959 and yielded plasma temperatures up to 100 eV, albeit with a relatively short confinement time.

Model B-2 Stellarator

This variation on the basic figure-8 design continued to use a 5 cm diameter vacuum tube, but the overall length was about 6 meters and included a 50 cm magnetic pumping section with an expanded diameter of 15 cm. The L/C ringing circuit modulated the magnetic field in this section with an oscillation frequency of 240 kHz and was able to reach a peak value of 2300 gauss. With a bakeable vacuum system installed by 1957, helium ion temperatures of 45 eV were reached, but conventional magnetic pumping only increased this value by 15%. However, a new operation regime appeared when the modulation was increased above 70%, leading to very strong loading of the rf coil and electron temperatures in the pumping section estimated to be as high as 1000 eV[2].

Model B-3 Stellarator

The last of the figure-8 machines, with a 5 cm

diameter vacuum tube and a 468 cm overall length, this machine began operation in 1958 and was the workhorse for an extensive series of confinement studies of ohmically heated plasmas. The vacuum system was bakeable and incorporated a baked palladium leak system to purify the working hydrogen gas. The magnetic field was operated up to 40,000 gauss. B-3's magnetic geometry included helical windings for magnetohydrodynamic stabilization, but experiments failed to reveal any increase in plasma confinement with the helical coils. The anomalously rapid plasma loss — a phenomenon then termed "pump-out" — proceeded, under a wide range of conditions, at about three times the Bohm rate, and plasma confinement in B-3 never exceeded a few tens of microseconds[2].

Model B-64 Stellarator

Designed and operated, starting in 1955, by the author and his colleague Richard Palladino, the B-64 stellarator was of modular construction. The vacuum chamber was made of straight sections and 90° sections of 10 cm diameter stainless-steel tubing. The magnet coils were wound directly onto the outside of the steel tubing and held in place by epoxy-fiberglass insulation. The machine typically operated at pulsed magnetic field strengths up to 18 kilogauss. The "square" corners gave this stellarator its name — like the figure-8 geometry, B-64 was assembled to also obtain a rotational transform in the vacuum magnetic field. Eight squared equals sixty-four. Hence B-64.

A divertor was first tried out on the B-64 machine, with dramatic success. Ion temperatures rose by a factor of 5, to 50 eV, and electron temperatures to 80 eV.

For a series of experiments in 1956, the B-64 segments were assembled in race-track geometry, that is, in such a manner that the magnetic axis formed a simple planar loop, and the rotational transform of the vacuum magnetic field was zero. Operated with strong ohmic heating, the B-640 "stellarator" (as this geometry was named) was, in fact, America's first tokamak. Again benefitting from the divertor, ion temperatures above 100 eV were reported[2].

Model B-65 Stellarator

Also built and operated by Stix and Palladino, B-65 was in racetrack geometry but incorporated Spitzer's discovery that helical windings could provide both a rotational transform for the vacuum magnetic field and magnetic shear for improved magnetohydrodynamic stability. In B-65, $l=3$ windings underlay the toroidal field coils in each of the two modular U-bends. Single-particle confinement in the modified racetrack vacuum field was evidenced by the observation of runaway x-rays at a time when the ohmic current had decayed to zero. More important, B-65, equipped with the B-64 divertor, was the test-bed for the original high-power ion cyclotron heating experiments. Again, ion temperatures above 100 eV were reported, and neutrons from experiments of ICRH in deuterium were reported in Geneva in 1958 on the occasion of the first IAEA Conference[7].

Model C Stellarator

Planning for the Model C Stellarator actually began in 1954, and machine operation started in 1961 and continued until the facility was converted, in 1969, to tokamak geometry. The machine was in the form of a racetrack 1,200 cm in length with 5—7.5 cm minor radius for the plasma. The toroidal magnetic field was typically operated at 35,000 gauss. One of the two straight legs of the racetrack contained a divertor, the other one a section to supply 4 megawatts of 25 MHz ion cyclotron resonance heating (ICRH). $l=2$ and $l=3$ helical windings installed on the U-bends provided a rotational transform up to about 180°.

A principal finding over a broad range of experiments on Model C was confinement consistent with Bohm scaling, that is, a confinement time inversely proportional to the electron temperature and linearly proportional to the magnetic field strength. Much more promising were the results achieved with ICRH with which, in 1965, local ion temperatures (mirror-confined) up to 9 keV were measured in a deuterium minority heating experiment, while in 1969 a global average plasma ion temperature of 400 eV was reported. Modest radiofrequency current drive was also observed [8,9].

In the late stages of Model C operation, it was suspected that the deficient plasma confinement might be due to magnetic islands. However, careful measurements with a phase-stabilized multi-pass electron beam found significant island formation only when the magnetic surfaces were intentionally distorted by applying a strong vertical magnetic field. Islands occurring under normal vertical field settings could not account for the anomalous plasma losses in Model C[9].

Fusion physics has made enormous advances in the three decades that have followed the Model C work. Physicists and engineers who are expert in this field and who have contributed to the impressive growth of knowledge now number in the thousands. Their accomplishments, in theoretical understanding, in experimen-

tal realization and in computational simulation are a source of pride for the entire scientific world. For the purpose of this presentation, this increased comprehension provides a platform from which we can look back with renewed appreciation for the vision and foresight in the work of Lyman Spitzer, Jr., and his group.

Acknowledgments

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