CHAPTER 1
Introduction

1.1 Brief description of spheromaks

Plasmas are gases composed of free electrons and ions. Typically, the electron and ion charge densities are nearly the same so that the plasma is an approximately neutral electrically conducting gas which is subject to electrical and magnetic forces in addition to the usual hydrodynamic forces. The process by which an ordinary gas is transformed into plasma is called ionization. For most plasmas, ionization take place when free electrons strike neutral atoms with sufficient force to eject bound electrons, thereby creating more free electrons and ions. In order for this process to occur, there must be some free electrons with kinetic energy exceeding the binding energy of the most weakly bound outer electron in a neutral atom. This means that plasmas typically have an electron temperature of at least a few electron volts (1 eV=11,604 K). Plasmas occur naturally in space environments (e.g., the solar corona, Earth's magnetosphere, the aurora) but must be created in the laboratory using artificial means.

If one wishes to trap a laboratory plasma, then some kind of confinement scheme is required, because otherwise the plasma will quickly convect to the surrounding walls and recombine. Substantial effort has been directed during the past half century towards developing devices which use magnetic fields to confine plasmas. These magnetic confinement schemes can be understood at many levels of sophistication, but ultimately are based on the magnetic force $\mathbf{F} = q\mathrm{v} \times \mathbf{B}$ acting on individual charged particles.

Spheromaks are a toroidal confinement configuration where the magnetic field is produced almost entirely by currents flowing in the plasma. The spheromak configuration is defined as an axisymmetric magnetohydrodynamic equilibrium with (i) a simply connected bounding surface, (ii) both toroidal and poloidal magnetic fields, and (iii) at least some closed poloidal flux surfaces. What distinguishes spheromaks from other toroidal configurations is that the toroidal magnetic field in spheromaks vanishes at the bounding surface (i.e., at the wall). Therefore no external coils link the spheromak and so the spheromak manages to have an internal toroidal field while still being simply connected. In contrast, tokamaks, reversed field pinches (RFP's), and stellarators all have finite toroidal magnetic field at the wall; this corresponds to having external coils linking the plasma. Field reversed configurations (FRC's) have zero toroidal magnetic field everywhere and so, like spheromaks, do not have coils linking the plasma. Thus, spheromaks manage to have a toroidal field without having toroidal field coils; FRC's do not have toroidal field coils but also do not have a toroidal field.

Figure 1.1 compares spheromak topology to the other toroidal confinement methods and Table 1.1 lists the similarities and differences. The device complexity increases going down the table; this is also obvious from Fig. 1.1. All devices except the stellarator use a toroidal current to produce the poloidal field required for confinement; the poloidal field in the stellarator is created by external helical coils so that current-free operation is obtained at the expense of loss of axisymmetry. The FRC is the simplest device but, having no toroidal field, is MHD-unstable and also has a field null on the magnetic axis.

device	**Axi-symmetric**	**Poloidal field B_{pol}**	**Toroidal field B_ϕ**	**B_ϕ at wall**	**Chamber topology**
FRC	yes	yes	no	no	spheroidal
spheromak	yes	yes	yes	no	spheroidal
RFP	yes	yes	yes	yes	toroidal
tokamak	yes	yes	yes	yes	toroidal
stellarator	no	yes	yes	yes	toroidal

Table 1.1 Comparison of topologies of various toroidal confinement devices

According to the magnetohydrodynamic (MHD) point of view, plasma is modeled as an electrically conducting fluid and confinement involves balancing the outward force of hydrodynamic pressure against the inward force due to interaction between magnetic fields and electric currents in the plasma. This balancing is most effective when the magnetic field lines in the plasma form nested surfaces called flux surfaces. The existence of flux surfaces means that any field line traces out a surface in three dimensional space and does not fill up a volume.

A point of view complementary to MHD and also more physically correct is provided by Hamiltonian-Lagrangian theory which shows that if there is symmetry about an axis, then confinement results from the conservation of canonical angular momentum for each particle. In this case, particle trajectories are restricted to surfaces on which the canonical angular momentum is a constant and confinement is akin to a spinning top standing upright because of conservation of angular momentum. Both the microscopic Hamiltonian-Lagrangian point of view and the macroscopic magnetohydrodynamic point of view arrive at the same conclusion because as particle mass goes to zero, invariance of canonical angular momentum becomes equivalent to the existence of flux surfaces. Thus, symmetry is important for confinement whether one uses the MHD point of view or the single particle point of view.

Flux surfaces are formed from the magnetic field produced by the combined effect of internal plasma currents and external coil currents. The various schemes for producing flux surfaces can be categorized according to the extent to which the flux surfaces are

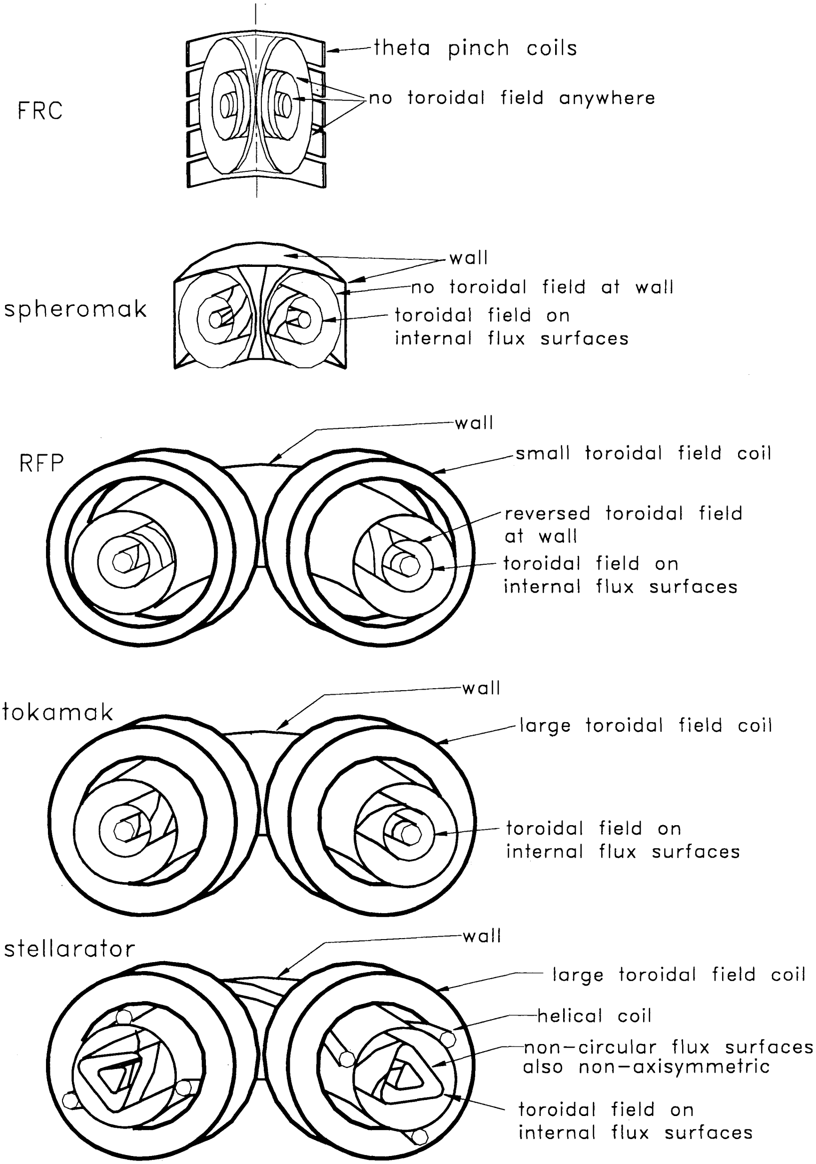


Fig.1.1 Comparison between various toroidal confinement devices. FRC's and spheromaks have simply connected vacuum chambers, others have doubly connected vacuum chambers.

prescribed by plasma or external currents. Flux surfaces in stellarators are produced entirely by currents in external coils which link the toroidal plasma: these precision-engineered helical coils create accurate flux surfaces minimally affected by the plasma because the plasma is nearly current-free. Flux surfaces in tokamaks are prescribed by the dominantly toroidal internal current profile; the reason the plasma current is dominantly toroidal is because large external coils linking the plasma produce a strong toroidal magnetic field which provides stabilization against kinks. Flux surfaces in RFP's result from the interaction between the small toroidal field produced by coils linking the plasma and poloidal flux directly injected by induction. The coil-produced toroidal field can be considered as a seed field which is considerably modified by plasma instabilities.

Spheromaks are closely related to RFP's but have no coils linking the plasma so that flux surfaces are entirely the consequence of instabilities. Since the spheromak configuration results from spontaneous instabilities, spheromaks have the notable advantage of not having to be as precisely engineered as tokamaks, stellarators, or RFP's. The tendency to form spontaneously also suggests that spheromak-like configurations should occur in nature, and indeed, certain space and solar plasmas are closely related to spheromaks.

The question often arises whether a spheromak is a device or a plasma configuration. This question is reasonable, because the nomenclature 'tokamak' refers to the device, not the plasma, and yet one often hears spheromaks referred to as the plasma configuration. The reason for this semantic ambiguity is that there is no unique way for making spheromak configurations because spheromak plasmas form spontaneously given the appropriate initial conditions. What is important is the plasma configuration and not the device.

A traditional way for dealing with a complicated three dimensional problem is to reduce the problem to a simplified one- or two-dimensional version which contains the essential phenomenology but because of the reduced dimensionality is much more amenable to analysis. This traditional method cannot be applied to spheromaks, because spheromaks are intrinsically three dimensional and, in particular, involve helical geometry.

Spheromaks result from plasma self-organization and represent a minimum energy state towards which the plasma evolves. The study of spheromaks is relevant to a wide range of topics including thermonuclear fusion, solar physics, magnetospheric physics, astrophysics, magnetic reconnection, topology, self-organization, inaccessible states, magnetic turbulence, Ohm's law, magnetohydrodynamics, vacuum techniques, pulse power engineering, and various diagnostics.

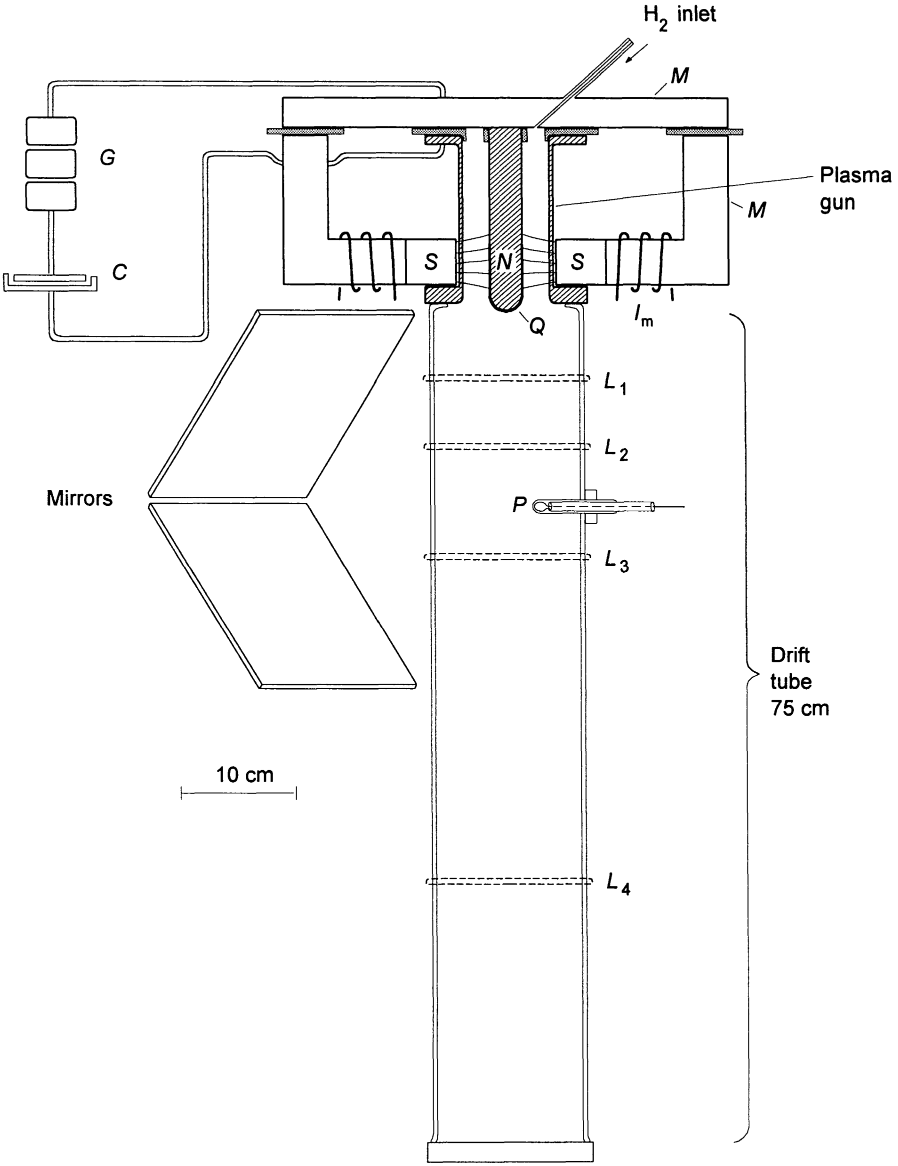


Fig. 1.2 Experimental setup of Alfvén, Lindberg, and Mitlid [8] (reconstructed drawing kindly provided by L. Lindberg).

1.2 History and time-line

The history of spheromaks can be loosely divided into several eras:

1. During 1950-70 isolated individuals and small groups developed important underlying concepts. The development was discontinuous in both space and time so that there was no coordinated effort. The ideas developed were very much out of the mainstream of plasma physics and many of these ideas were forgotten only to be rediscovered one or two decades later.
2. During the mid 1970's the relevant concepts were espoused in a more practical form and the mainstream plasma community developed an interest. The term "spheromak" was coined and several groups started working on developing the spheromak concept as a fusion confinement device.
3. During the 1980's there was a considerable development with much interaction between research groups. For fiscal reasons unrelated to physics, budgetary support of spheromak research (and other fusion research) was severely cut in the late 1980's.
4. During the early 1990's attention turned towards finding applications other than fusion confinement. In particular, the spheromak concept was used to investigate the physics of magnetic reconnection, a fundamental issue in plasma physics. By the late 1990's the spheromak attracted renewed interest as a fusion confinement device when it was realized that confinement in the earlier experiments might have been much better than originally believed.

These eras will now be discussed in more detail.

1.2.1 Pre-1970: Antecedents of the spheromak

In essence spheromaks depend on topological features of the hydromagnetic $\mathbf{J} \times \mathbf{B}$ force. Alfvén[1] in 1943 was the first to investigate how this force acts on an electrically conducting fluid and proposed the waves that bear his name. In 1950 Lundquist [2] examined equilibria involving the $\mathbf{J} \times \mathbf{B}$ force and showed that for plasmas with hydrodynamic pressure small compared to magnetic energy density, the equilibrium would consist of a balance between opposing magnetic forces. Mathematically this corresponds to $\mathbf{J} \times \mathbf{B} \approx 0$ which implies

$$\nabla \times \mathbf{B} = \lambda \mathbf{B} \tag{1.1}$$

where λ is effectively an eigenvalue. Lundquist showed this balancing of magnetic forces provides the very simple equilibrium

$$\mathbf{B} = \bar{B}J_1(\lambda r)\hat{\theta} + \bar{B}J_0(\lambda r)\hat{z} \tag{1.2}$$

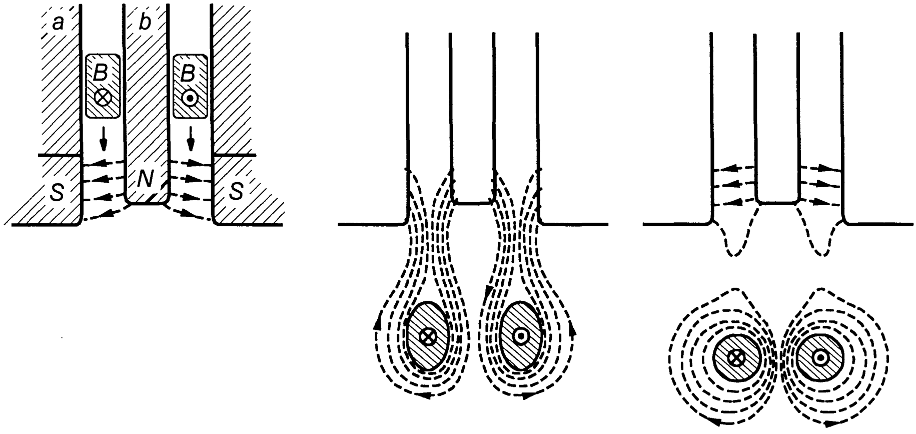
where J_0 and J_1 are Bessel functions and $\bar{B}$ is a constant. This is called the Lundquist solution or the Bessel function model (BFM) and prescribes a helical magnetic field.

In the early 1950's researchers in the USA, the UK, the USSR, and several other countries started to work on the problem of controlled thermonuclear fusion. This required confinement of high temperature plasmas and considerable resources were devoted towards developing magnetic configurations exploiting the $\mathbf{J} \times \mathbf{B}$ force so as to provide confinement. Both Alfvén and Lundquist were thinking in terms of space plasmas (e.g., the magnetosphere, the solar corona, and astrophysical plasmas) while the fusion researchers were preoccupied with designing and constructing laboratory plasmas. Thus began a parallelism between space and laboratory MHD research which has continued and which has lead to many useful interchanges of ideas.

In 1957 Furth, Levine, and Waniek[3] considered the physical limits on coils producing large transient magnetic fields and showed that the ultimate limitation was coil rupture due to large magnetic forces. They proposed winding a coil in such a way that the $\mathbf{J} \times \mathbf{B}$ force would vanish within the coil and derived the required magnetic field profile to produce this force-free situation. This profile is precisely the same as the magnetic field profile of a spheromak confined by a cylindrical flux conserver.

In 1958 Woltjer[4, 5] considered the various constraints acting on a magnetohydrodynamic system, noted these constraints could be expressed in terms of integrals, and showed these constraints could be used to determine minimum energy states for a plasma. One constraint is the conservation of the magnetic helicity, a measure of the linkage of magnetic flux tubes with each other. Woltjer showed that, for a given magnetic helicity, the lowest energy state satisfied $\mathbf{J} = \lambda\mathbf{B}$ with λ spatially uniform. Chandrasekhar and Kendall [6] discussed this equation in cylindrical geometry and derived solutions now called Chandrasekhar - Kendall functions; these are generalizations of the Bessel function solution given by Lundquist. Chandrasekhar[7] also examined solutions in spherical geometry.

During the period 1959-1964 Alfvén, Lindberg, and Mitlid[8] and Lindberg and Jacobsen[9, 10] built and operated a device which produced rings of magnetized plasma. Figure 1.2 shows the setup of this experiment while Fig.1.3 shows the sequence of operation. While these experiments pre-date the modern spheromak concept, they can be considered as the first spheromak-related experiments because the essential features of modern coaxial spheromak guns were observed and identified. The original purpose [8] of these experiments was to determine whether RFP properties depended explicitly on how the configuration was formed; this issue was addressed by forming an RFP-like plasma using a coaxial magnetized plasma gun instead of the conventional method, transformer induction. During the course of the experiments several interesting and unexpected features were noted and these were investigated in some detail[9, 10]. Features relevant to spheromaks included: magnetic reconnection resulting in a detached plasma ring breaking off from the electrodes, conversion of toroidal flux into poloidal flux by helical instabilities, formation of closed poloidal flux surfaces, and amplification of the poloidal flux[11]. It is amazing that after these experiments were completed, the coaxial magnetized plasma gun concept lay dormant for nearly two decades.



(a) (b) (c)

Fig. 1.3 Sequence of operation as described by Alfvén, Lindberg, and Mitlid[8]: A poloidal field is established going between the N and S poles shown in (a). An accelerated plasma ring is initially captured by this poloidal field and distends it as shown in (b). Finally, as shown in (c) the poloidal field breaks and reconnects around the ring (reconstructed drawing kindly provided by L. Lindberg).

The 1950's and 1960's were a time of great diversity in fusion magnetic confinement concepts: stellarators were being developed in the USA, tokamaks in the USSR, and mirror machines in both the USA and USSR. In the UK development efforts focussed on the toroidal Z-pinch, now known as the RFP. The RFP looks similar to a tokamak, but differs in having a much weaker toroidal field and a much larger toroidal current. ZETA, a large RFP operated at Culham in the 1950's and 1960's displayed a mysterious behavior: after an initial period of violent instability, the plasma would settle into a quiescent state. If the ratio of toroidal current to toroidal field in this state exceeded a threshold, the toroidal field had a spontaneously reversed polarity near the surface[12], hence the name Reversed Field Pinch (RFP). The ZETA program was discontinued in 1968 and from 1969 onward attention in fusion research shifted to tokamaks (and to a lesser extent, magnetic mirrors).

In the 1960's Bostick and Wells[13] investigated the conical θ-pinch and found that this developed a spontaneous toroidal field; this unexpected effect was attributed to Hall terms. Wells[14] interpreted the dynamical evolution of the conical θ-pinch in terms of Woltjer's helicity-constrained energy minimization and proposed that these plasmas would develop a $\mathbf{J} = \lambda\mathbf{B}$ equilibrium. Wells and colleagues built a series of small conical θ-pinches first at the Princeton Plasma Physics Lab and later at the University of Florida. These devices involved extremely rapid dynamics which were difficult to follow with the diagnostics available at the time. However, it is interesting that magnetic probe measurements on one of these devices demonstrated[15] the toroidal magnetic field profile which is the hallmark of spheromaks, i.e., the toroidal field was zero on axis, rose to a maximum at some interior point, and then went to zero at the wall; Fig. 1.4 shows the data from Wells' measurement. In 1972 Nolting, Jindra, and Wells[16] discussed the magnetic field profile for force-free spherical MHD configurations produced by a conical theta pinch and presented measurements consistent with the theoretical profiles. Research activity on conical θ-pinches ceased in the 1970's except for one device [17] at the University of Washington.

1.2.2 Advances in theory: Taylor relaxation and development of the theoretical model for the spheromak

In 1974, long after ZETA had been shut down, Taylor[18] proposed an explanation for ZETA's mysterious tendency to develop reversed toroidal magnetic fields at the plasma edge. Taylor proposed that magnetic turbulence does not change the global helicity content of plasma but does dissipate magnetic energy. The turbulence would cause changes in magnetic topology such that every time a microscopic flux linkage was broken, another would be created; thus, global helicity, the measure of flux linkages, would be conserved. This point of view recast Woltjer's abstract variational principle into a practical prescription for how a real plasma would behave — a turbulent plasma would spontaneously relax (or self-organize) to a simple, well-defined state now called the Taylor state. The relaxation process would conserve helicity but dissipate energy until reaching a lowest energy state. The relaxed state (Taylor state) satisfies Eq.(1.1) and, for a large aspect ratio RFP, the solutions of this equation are just Lundquist's Bessel function equilibrium. The field reversal was simply a consequence of the $J_0(\lambda r)$ Bessel function passing through zero when λr became larger than the first root of J_0.

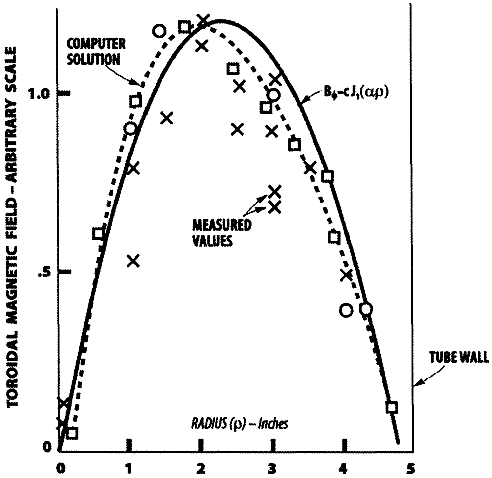


Fig. 1.4 Wells' [15] 1964 conical theta pinch measurement showing that the toroidal field vanishes at both the geometric axis ($r = 0$) and the wall ($r = 5$ inches).

The ZETA observations were in good agreement with the Bessel function model, and this agreement persisted for other RFP's. The Taylor relaxation model explained the dominant features of RFP equilibrium and received much attention.

Rosenbluth and Bussac[19] extended Taylor's approach to spherical geometry and discussed minimum energy states having zero toroidal field on the bounding surface. This means that there is no externally driven current on the device axis and so there are no external toroidal field coils. The remarkable consequence of this freedom from external coils is that the magnetohydrodynamic equilibrium becomes simply connected. Thus the plasma container has the topology of a sphere in contrast to tokamaks, stellarators and RFP's all of which are doubly connected and require containers with the more complicated topology of a toroid (doughnut). Figure 1.5 shows the distinction between simply connected and doubly connected topologies.

The mathematical form of Rosenbluth and Bussac's spherical solutions was the same as what Chandrasekhar[7] had studied many years earlier. Rosenbluth and Bussac called this simply-connected, spherical, force-free equilibrium a "spheromak". Thus, a spheromak is a configuration with the topology of a sphere and with a magnetic field satisfying Eq.(1.1). Because of its minimalist design the spheromak immediately attracted widespread attention. The features of simply connected geometry, no external coils linking the plasma, and no toroidal magnetic field at the wall offered the possibility of a fusion confinement device much smaller and less costly than the more familiar doubly-connected devices. The interest in the spheromak was so great in the late 1970's that several different groups decided to attempt making spheromaks using a variety of methods.

1.2.3 The 1980.'s: The spheromak investigated as a fusion confinement scheme

It was not clear at the time which, if any, of the proposed methods for spheromak formation would work. This is because the spheromak was essentially a detached magnetic bubble and there seemed a possibility that the spheromak equilibrium might be mathematically self-consistent, but physically inaccessible. A rough analogy to this quandary would be demonstrating the concept of a soap bubble without knowing any technique for actually making bubbles.

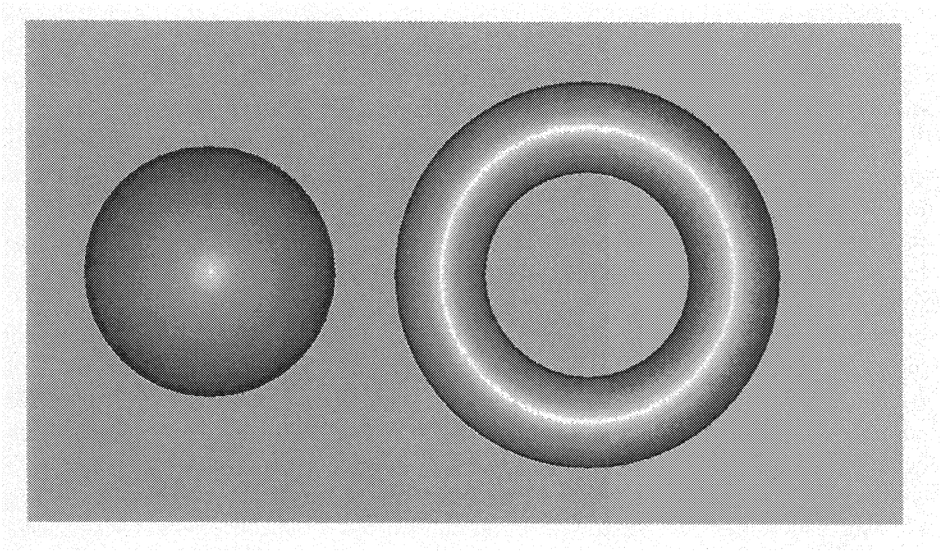


Fig.1.5 Left: Simply connected topology (spheroid); right: doubly connected topology (toroid).

The first spheromak experiments were at Nihon University [20], the PS-1 $Z - \theta$ experiment[21] at the University of Maryland, the Beta II experiment[22, 23] at Livermore, the CTX experiment[24] at Los Alamos, the proto-S1 experiment [25] at Princeton, and an experiment at Osaka University[26]. Even though these experiments used three different methods for making spheromaks ($z - \theta$ pinch, coaxial magnetized plasma guns, inductive source), they all succeeded in producing spheromak configurations. This broad success was remarkable and showed that detached spheromaks would form spontaneously given the right initial conditions. The demonstration that there is no unique way to make a spheromak showed convincingly that the spheromak is a lowest energy state towards which a magnetohydrodynamic system naturally evolves. The status of these early spheromak experiments was reviewed in 1983 by Furth[27].

The 1980's were a golden age for spheromak research; machines were built and upgraded, diagnostics were improved, and the Taylor relaxation concept was generalized. The advent of multi-channel transient digitizers (devices which collect temporal sequences of data in digital form and store this data in easily accessed computer memory) made it possible to measure internal magnetic fields with high spatial and temporal resolution and so verify the details of the relaxed state model. These transient digitizers gave the researchers of the 1980's a tremendous advantage compared to previous researchers who had to interpret oscilloscope photos manually so that measurements with combined space and time resolution were impractical.

The gross MHD stability of spheromaks was also investigated and, in particular, the tilt instability was identified experimentally and simulated numerically[28].

Despite these improvements in understanding spheromak formation, equilibrium, and gross MHD stability, little was known regarding the intrinsic confinement properties of spheromaks because the intrinsic confinement was typically masked by spurious loss mechanisms, especially atomic line radiation. The observed confinement properties of spheromaks were certainly not competitive with tokamaks and, in particular, it was not possible to obtain electron temperatures higher than about 100 eV in spheromaks for most of the 1980's. However, by the end of the 1980's achieved confinement improved significantly (electron temperatures as high as 400 eV were obtained at Los Alamos). Unfortunately, and despite these promising results, all major US spheromak confinement experiments were shut down by the early 1990's because of budget cutbacks in US fusion research. Smaller spheromak programs begun in Japan in the 1980's continued and some smaller experiments also continued in the USA. In the late 1980's a coaxial spheromak gun, SPHEX[29], was constructed at the University of Manchester in England and used for studying fundamental spheromak physics. There was also dialogue with the space physics community, and in particular, Heyvaerts and Priest [30] in 1984 applied the Taylor relaxation hypothesis to model the topology of solar coronal structures.

1.2.4 The 1990's: Search for other applications and renaissance in confinement efforts

Faced with the prospect that spheromaks might not be developed as fusion confinement devices, by the late 1980's and early 1990's spheromak researchers in the USA looked for other possible applications. Hammer, Hartman et al.[31] showed that spheromaks could be translated in space and accelerated to extremely high velocity using a coaxial rail gun and proposed several interesting applications for an accelerated spheromak. Perkins et al.[32] and Parks[33] examined how accelerated spheromaks could be used to refuel tokamaks; this was investigated experimentally by the Caltech group [34] and by Raman et al.[35] at INRS in Canada. Degnan, Peterkin et al. [36, 37] at Kirtland Airforce Base investigated the possibility of using accelerated spheromaks as a high power x-ray source (x-rays would be produced when a rapidly moving spheromak collided with a target); they also considered using the moving spheromak as the armature in a plasma opening switch[38].

Jensen and Chu[39] proposed that spheromak-like plasma guns could transfer magnetic helicity to a tokamak and act as an effective current drive. This was demonstrated in 1990 on a small scale by Brown and Bellan[40] at Caltech and in 1994 served as the basis of Jarboe and Nelson's Helicity Injection Tokamak[41, 42] at the University of Washington. Raman et al.[35] demonstrated non-disruptive refueling of the medium size Tokamak de Varennes. The SPHEX group[43, 44] continued to investigate many important aspects of spheromak physics, especially dynamo action. Spheromak research from 1979-1993 was summarized in a 1994 review article by Jarboe[45].

In the late 1990's spheromak concepts were applied towards the study of fundamental plasma physics, especially the problem of magnetic reconnection. Yamada et al.[46] and Ono et al.[47] at the University of Tokyo investigated the three dimensional magnetic reconnection associated with colliding, merging spheromaks. At Princeton, Yamada, Ji, et al.[48] built MRX, a spheromak-based device specifically designed to provide a well-defined reproducible magnetic reconnection layer. Geddes, Kornack and Brown[49] used an interacting double spheromak experiment at Swarthmore College to investigate magnetic reconnection.

Also during the 1990's interest increased among space and solar physicists in the spheromak-related concepts of magnetic helicity and relaxation. In particular, Rust and Kumar[50, 51] applied these concepts to solar prominences and modeled the dynamical evolution of these structures in terms of Taylor's relaxed states. Bellan and Hansen[52] exploited spheromak techniques in a laboratory experiment which simulated solar prominences.

In the mid 1990's Fowler et al.[53] and Mayo[54] re-evaluated the confinement performance of the Los Alamos CTX spheromak (which had ceased operating several years earlier) and postulated that core confinement was substantially better than previously believed. By the late 1990's, with energy prices low, the strategy of the US fusion program shifted towards developing speculative non-tokamak concepts which might ultimately prove more attractive than tokamaks. In 1998 construction began on a new spheromak at Livermore. This device, the Sustained Spheromak Physics Experiment (SSPX) is designed[55] to take into account the revised analysis of the 1980's experiments. Arguments in favor of the spheromak as a fusion reactor were summarized in Ref. [56].

Selected spheromak-related papers are listed in Tables 1.2-1.4; the time-line provided by these tables gives a sense of the pace and direction of spheromak development.

Year (type)	*Description*
1950 (Theory)	Lundquist[2] proposes force-free equilibrium $\mathbf{J} \times \mathbf{B} = 0$
1954 (Theory)	Lüst and Schlüter[57] discuss force free magnetic fields
1957 (Theory)	Furth et al.[3] investigate force-free coils and derive magnetic equilibria analogous to spheromaks
1958 (Theory)	Woltjer[4] shows $\mathbf{J} = \lambda\mathbf{B}$ is a minimum energy state, introduces concept of conservation of magnetic helicity
1959 (Expt.)	Alfvén et al.[8] produce magnetized plasma rings with a coaxial plasma gun, observe reconnection and flux amplification
1964 (Expt.)	Wells[15] observes toroidal field going to zero at wall in conical θ pinch, proposes $\mathbf{J} \times \mathbf{B} = 0$ equilibrium
1974 (Theory)	Taylor[18] proposes that magnetic turbulence causes relaxation to $\mathbf{J} = \lambda\mathbf{B}$ equilibrium, shows this provides good model for RFP
1979 (Theory)	Rosenbluth and Bussac[19] describe the "spheromak", a simply-connected force-free equilibrium, consider tilt stability

Table 1.2 Selected spheromak-relevant publications from 1950-1979

Year (type)	*Description*
1980 (Expt.)	Nogi et al.[20] form $Z-\theta$ spheromak at Nihon University
1980 (Expt.)	Goldenbaum et al.[21] form $Z-\theta$ spheromak at U. Maryland, start of PS program
1980 (Expt.)	Jarboe et al.[24] form coaxial gun spheromak at Los Alamos, start of CTX program
1981(Expt.)	Yamada et al.[25] form flux-core spheromak at Princeton, start of S-1 program
1981(Expt.)	Turner et al.[22] describe Beta II coaxial gun experiment at Lawrence Livermore
1981(Expt.)	Watanabe et al.[26] form a detached spheromak in an experiment at Osaka University
1982 (Theory)	Katsurai and Yamada[58] discuss spheromak fusion reactor design
1983 (Expt.)	Katsurai et al.[59] initiate the TS series of spheromak experiments at Univ. of Tokyo
1983 (Theory)	Sato and Hayashi[28] create 3D numerical simulation of spheromak tilt instability
1983 (Expt.)	Jarboe et al.[60] demonstrate slow formation and sustainment of spheromak using coaxial gun
1984 (Theory)	Jensen and Chu[39] propose that helicity injection could be used for toroidal current drive in tokamaks
1985 (Expt.)	Hagenson and Krakowski[61] discuss spheromak fusion reactor design
1986 (Expt.)	Barnes et al.[62] at Los Alamos provide experimental verification of helicity conservation in the CTX spheromak
1987 (Expt.)	Honda et al.[63] at Osaka Univ. describe the CTCC-1 spheromak
1987 (Expt.)	Bruhns et al.[64] at Univ. of Heidelberg add vacuum toroidal field to a spheromak to make ultra low aspect ratio tokamak (ULART)
1988 (Expt.)	Hammer et al.[31] at LLNL demonstrate spheromak acceleration/compression on RACE
1988 (Expt.)	Wysocki et al.[65] find pressure-driven instability in CTX to be well above β limit predicted by MHD

Table 1.3 Selected spheromak-relevant publications from the 1980's

Year	*Description*
1990 (Expt.)	Wysocki et al.[66] demonstrate 0.18 ms energy confinement times in CTX
1990 (Expt.)	Jarboe et al.[67] report $T_e \sim 400$ eV in a spheromak with small flux conserver
1990 (Expt.)	Brown and Bellan[40] at Caltech demonstrate helicity injection current drive on the Encore tokamak
1990 (Expt.)	Yamada, Ono et al.[46] investigate magnetic reconnection of two colliding spheromaks
1990 (Expt.)	Wira and Pietrzyk[68] demonstrate spheromak formation by a conical θ pinch
1993 (Expt.)	al-Karkhy, Browning et al. [69] observed dynamo effect in SPHEX spheromak
1993 (Expt.)	Degnan et al.[36] describe the very large MARAUDER spheromak at Kirtland AFB
1994 (Theory)	Fowler et al.[53] proposed possibility of Ohmic ignition in a spheromak fusion reactor
1994 (Expt.)	Raman et al.[35] demonstrate central fueling in Tokamak de Varennes by spheromak injection
1994 (Expt.)	Nelson et al.[42] report formation and sustainment of Helicity Injection Tokamak at U. Wash.
1997 (Expt.)	Yamada et al.[48] use spheromak concepts to investigate magnetic reconnection on MRX at Princeton
1998 (Expt.)	Geddes, Kornack and Brown[49] investigate magnetic reconnection at Swarthmore
1998 (Expt.)	Hooper et al.[55] initiate new spheromak program at Lawrence Livermore National Lab

Table 1.4 Selected spheromak-relevant publications from the 1990's