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SPHERICAL FUSION PLASMA CONFINEMENT FIELD OF SURMAC TYPE

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The concept of a Surmac confinement field that can be completely closed is presented. The internal conductor is magnetically suspended inside large corrugations of a superconducting spherical shell structure that carries the return current. Presently available superconductor technology using superfluid helium cooling allows fields above 1.5T throughout the wall region. Such a Surmac has potential for the study of advanced fuel cycles.

A. INTRODUCTION

Magnetic confinement fields that have most of their field energy concentrated near the surface of the plasma and leave the interior, i.e. the major part of the volume of the plasma, in a very low field are known under the name of SURMAC. The chief advantage compared to conventional toroidal confinement fields such as tokamaks is a vastly reduced total field energy and correspondingly reduced structure to cope with the magnetic forces.

The 'picket fence' was an early suggestion of a Surmac confinement field.[1] It consists of a row of equally spaced straight parallel current carriers with neighboring currents in opposite directions. The field produced provides absolute MHD stability because it increases everywhere away from the plasma. This advantage is offset by the field openings through the line cusps between each pair of conductors. The suggestion of a 'caulked picket fence' in a device called 'Helixion'[2] aimed at overcoming the disadvantage of the open line cusps by pairwise reconnecting neighboring cusps with each other. In the connecting region the field drops off toward the outside of the plasma resulting in the loss of absolute MHD stability. Another disadvantage is that the inner conductors are totally surrounded by plasma which creates problems for current and cooling connections. The stability was investigated in multipole experiments[3] Superconductivity allows the persistence and magnetic levitation of the inner current carriers, avoiding current leads and force supports. Dipole experiments with single levitated rings, 'levitrons', were built and investigated.[4] It was found that a true minimum B field is not necessary for MHD stability, an average minimum B condition is sufficient. In continuation of the multipole experiments several Surmac geometries have been suggested and tested, notably at UCLA.[5] They may prove to be the best tools to study advanced fuel cycles.

The topic of the present paper is an advanced Surmac field that is spherical and can be completely closed. A discussion of technical problems indicates that today's superconducting magnet technology opens the possibility of a practical realization of such a field concept.

B. A SPHERICAL SURMAC FIELD.

Important conditions for a plasma confinement field are that the field lines do not penetrate an outside boundary, and that the magnetic field is nowhere zero at the boundary. A coaxial cable, closed a both ends (Fig.1a), with persistent current flow satisfies these conditions. The toroidal field as used in a tokamak is, of course, the standard closed confinement field geometry. The closed coaxial cable is topologically homeomorphic with a torus. By elongating the torus in the axial direction the central torus hole becomes a tube; if the tube then shrinks to a solid wire the coaxial geometry is produced.

The coaxial cable can be deformed - always assuming that it is out of rubber as is usual in topological arguments - first into a balloon with a straight wire through its axis (Fig.1b). In the next step the central wire is spiralled so it is located everywhere equidistant from the outer surface and with a (different) equal distance between turns (Fig.1c). In the final step the outer surface is necked in between the turns of the inner spiral so as to form a roughly 2/3 closed shell with circular cross section around the spiral wire (Fig.1d). If the outer surface remains superconducting throughout the deformation process the currents will assume a distribution which insures that the field nowhere penetrates the surface. Furthermore, as there are no singularities in the deformation, the field is nowhere zero. The described transformation shows that the resulting field is topologically homeomorph with a simple toroidal field; it is completely closed.*

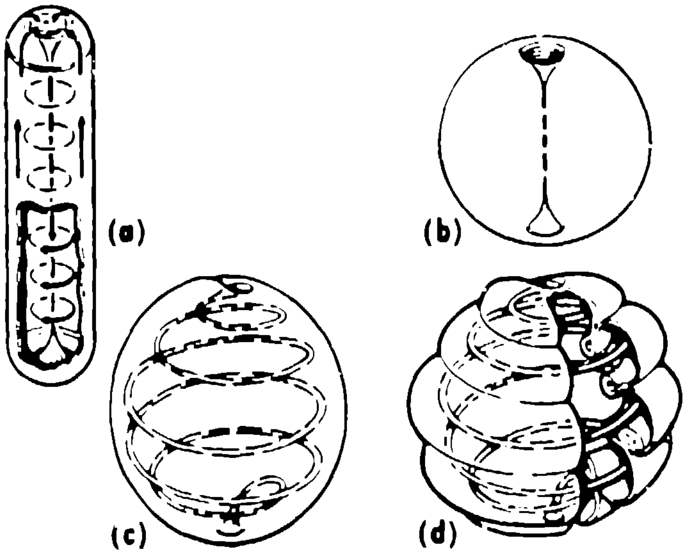

Fig. 1 Deformation of Cylinder with Co-Axial Conductor.

A second way of forming the shape in Fig.1d allows a better feeling for the resulting fields and current flow. Assume a fairly long coaxial cable, closed and with current flowing as in Fig.1a. Wind it around a sphere, with all the turns touching, starting with a spiral at one pole, and ending at the other pole. In the next step slit the outer coax shell along the line where it touches the sphere, bend the slit edges out until they touch (overlap) the bent edges of the neighboring turn. The current density in the outer coax shell was originally nearly uniform; after connection of the bent edges with their neighbors the current distribution will have to change if flux is not allowed to penetrate the walls, with a higher current density in the parts closer to the center of the sphere and lower in the outer parts. The resulting field will have two regions: one with field lines closing around the internal conductor and the other with field lines closing along the corrugated outer shell of the sphere. The separatrix has lobes that reach to the center of the sphere. The field falls off rapidly away from the wall region towards the center of the sphere and is quite negligible throughout most of the inner volume. The location of the separatrix in the polar regions is less

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* A rather similar argument was first given by Skornyakov[6] and formed the basis for the Tornado device[7] which, however, has a spherical separatrix and is not completely closed.

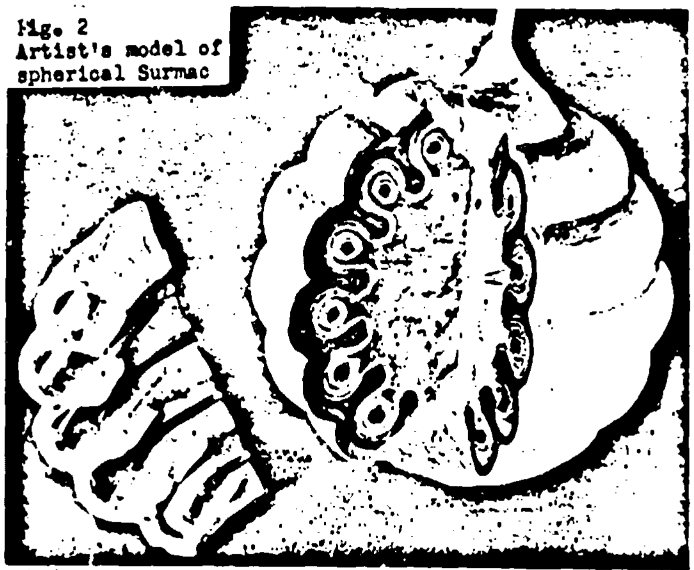

Fig. 2
Artist's model of spherical Surmac

obvious; there must be a large rotational transform and many field lines from the outer region continue by spiralling round the internal conductor. Fig.2 is an illustration of a 3-dimensional model. A model for a closed polar region is in Fig.3a. There is no difficulty in opening the magnetic field at the poles into a coaxial cable as in Fig.3b.

a) closed b) open

Fig.3 Model of polar region

Both inner and outer conducting structures are to be superconducting. An important feature of the described field geometry is the magnetic suspension for the internal conductor. The suspension has stiffness in radial and latidudinal direction. A further advantage is the access to the inner conductor at the polar regions. There is no need for plasma penetrating supports or current leads.

C. PLASMAPHYSICAL CONSIDERATIONS.

Stability. Outside the separatrix the field lines are alternately convex and concave towards the plasma. Concave regions have the radius of curvature outside the plasma and indicate increasing field away from the plasma; they are favorable for MHD stability. Convex regions have the radius of curvature inside the plasma, indicate decreasing field and are bad for stability. The regions outside the internal conductors that form the bridge between the two cusps either side of the internal conductor have bad curvature. Average minimum B condition for stability requires that along a field line $\int R^{-1}B^{-2}dl > 0$. The radius of curvature R is counted negative for the convex regions. The equal sign gives the critical field line Ψ_0 outside of which the plasma is no longer contained. If a field line has concave sections at a constant radius over an angle θ_1 at a field B_1, alternating with convex sections at another constant radius over an angle θ_2 at a field B_2, the stability condition[8] becomes $B_1^2/\theta_1 < B_2^2/\theta_2$.

The average minimum B stability criterion demands that the total volume of a flux tube, if displaced farther out, becomes smaller. In effect it works because, on its motion along the field lines, plasma does not stay long enough in the bad regions for an instability to develop. This puts a limit on the actual length L of a section of bad curvature with radius R, and this length depends on plasma pressure and temperature. A theoretical estimate of the limit gives a critical plasma pressure as

$$\beta_{crit} = R\,L^{-2}(\Delta n/n)^{-1}$$

where $\Delta n/n$ is the density gradient. While the avg. min. B criterion has ample confirmation in multipole experiments, the pressure criterion, giving the onset of ballooning modes, is experimentally not yet well investigated.[9]

One of the advantages of Surmacs is the low cyclotron radiation because the bulk of the plasma is in a low field. This is most attractive for the containment of high temperature plasmas for advanced fuel cycles. Therefore one may want to find ways of enhancing β_{crit}. It could be that putting a pattern of concave dents into the outside wall (which is now smooth at an approx. radius r_0, s. Fig.4) or corrugating it might reduce L; also, twisting the internal conductor thus providing shear into the bridge field might increase β_{crit}.

Many other plasmaphysical considerations in Surmacs are not much different from other plasma machines. Injection can be by plasma gun, pellets or neutral beams and heating by laser or RF methods.

D. TECHNICAL CONSIDERATIONS

A practical realization of a Surmac will be limited by today's technical capabilities. A short discussion of the fields and currents in relation to the size, the suspension forces and the cooling capacity at cryotemperatures and higher temperatures is given.

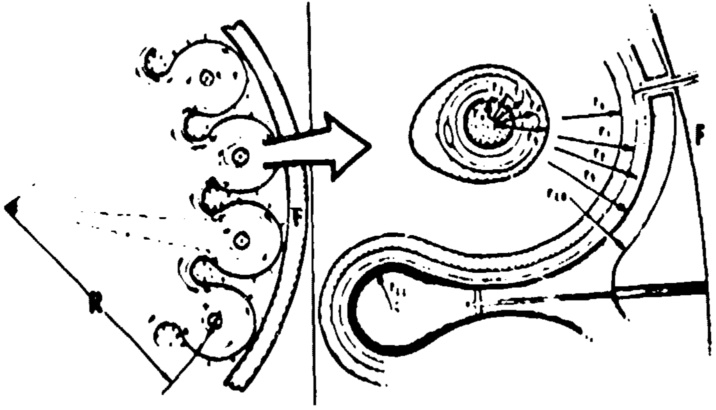

Fig. Cross Section and Detail of Wall Structure.

Fig.4 is a schematic cross section of the wall. It indicates the structure of the internal conductor, with a superconducting winding of cross sectional radius r_1, in a cryostat with a cold wall at radius r_2, a heat shield of radius r_3 at 70 - 90 K with one or more cooling tubes of flattened cross section, and superinsulation between r_2 and r_4. The cryostat is surrounded by a space for coolant at room temperature or higher, and a first wall at r_5. The outside is clad with a suitable first wall material. The outer shell has the reverse arrangement, starting with a first wall at r_6, a coolant space between r_6 and r_7, cryostat wall with heat shield and superinsulation between r_7 and the superconducting wall at r_9, and a liquid helium space to r_{10}. In the concave region of the shell the superconducting wall has a radius of r_{11} and is thickened to indicate a winding capable of carrying a return current of about 1/3 of the total current in the internal conductor winding. The other 2/3 of the return currents flow in the convex part (r_9). Outside the outer shell is a structure F to contain the considerable magnetic forces. Since these forces originate in the superconducting windings at 4 K or lower, it will be prudent to keep the main force structure also at cryogenic temperatures; structural materials are stronger at low temperatures and a large heat leak can be avoided. The supports for the warm parts of the shell can be made, as indicated, through small ports in the superconducting wall and the cold structure to a warm structure farther outside.

For the cooling of the internal winding, superfluid helium at atmospheric pressure and a temperature of 1.6 - 2 K is recommended. This cooling method is now used in a large tokamak, Tore Supra.[10] Experimental studies[11] indicate that the temperature difference between the λ-point (2.17K) and 1.6K can drive a heat flux of 0.5 W/cm² over a length of about 50m. Suppose the internal conductor is 75 m long (as in the 3m diam example below) and connected at both end to a 1.6K helium supply; further assume that the superinsulation (20 layers/cm) is 1 cm thick and has an average thermal conductivity between 100K and 2K of k = 0.3 μW/cmK. The heat leak from the heat shield to the helium space will be 100 mW/m, resulting in a flow of 3.8W out of each end of the 75m internal conductor. A cross section of 7 cm² will amply accommodate this flow and keep the middle (near the equator) of the conductor well below the λ-point. The coolant duct could be as indicated in Fig.4, or, better for the superconducting winding, in a central tube, or, still better, distributed through the winding; superfluid helium technology is quite new and experimentation is needed to confirm the best solution.

The superconducting winding can be NbTi. The fields at the surface r_1 are <5T and therefore not very high; an overall current density of at least 20 kA/cm² for the internal conductor winding should be possible. It could be that with Nb_3Sn and superfluid helium cooling the current density can be doubled. The conductor thickness will be chosen according to considerations of ease of winding, insulation, power supplies and making connections at both ends of the internal winding to the windings of the external shell.

The external superconducting wall has three functions: 1. carry the return current of the internal conductor; 2. carry correction currents to make the magnetic field parallel to the walls (insure closed confinement field); 3. carry the currents necessary for the magnetic suspension of the internal conductor. The return current is to be carried in discrete wires that connect individually to wires of the internal winding. The spacing of these wires will be the subject of careful calculation. Such calculation will also determine the exact shape of the shell for the condition that in equilibrium position the internal conductor is free of longitudinal compression that could cause buckling. The internal conductor will be somewhat inward of the center of curvature of the shell and the shell will be somewhat elliptical. The 2. and 3. function is handled by a superconducting screen outside the windings. The currents to be carried are relatively small and the location of the screen is in very small background fields; a motion of the internal conductor by 1 mm creates field increases of only about 100 gauss. It is therefore likely that the screen can be made out of Pb which has an H_c(2K) of 750 gauss. The screen could also be a mesh of fine superconducting wire.

Table I lists approximate sizes and other data on two examples: a smaller device for feasibility and experiments and a larger device of roughly reactor size. Accurate data and shapes of the outer shell, even for a two dimensional approximation, would need extensive calculations; the pole regions, needing a three dimensional treatment, are especially challenging.

TABLE I: Approx. data for two spherical Surmac devices

Nominal O.D. (m)	1	3
R (m)	0.4	1.35
r_9 (m)	0.1	0.15
Internal conductor:		
Number of spiral turns	6	13
Length (m)	11	75
Total current (MA turns)	0.5	1.0
r_2 (cm)	3.0	4.5
He coolant cross section (cm²)	2.0	12.5
r_4 (cm)	4.5	6.5
r_5 (cm)	5.0	8.0
Field in bridge region (T)	2.0 1.18	2.5 1.54
r_6 (cm)	8.5	13.0
r_7 (cm)	9.0	14.0
Magnetic pressure at r_{9_2} (MPa)	0.4	0.7
Spring constant (kN/m²)	80	90
Levitated mass (kg/m)	25	50

E. OUTLOOK AND CONCLUSIONS

The advantages of Surmacs, some general and some specific to the version proposed here, are:

- A closed, MHD-stable confinement field without loss cones.
- A large volume of plasma in a nearly field-free region. This reduces cyclotron radiation and favors the high-temperature plasmas needed for advanced fuel cycles including D - D, p - Li^6, p - B^{11}.
- The magnetic field energy, because it is contained in a surface layer, is small compared to conventional toroidal confinement systems for plasma volumes of similar size. The simplified force containing structure represents a great engineering advantage.
- The internal conductor is magnetically suspended and has access at the poles for current and coolant supply.
- Reactor potential: It would be premature to make promises at this stage, before a feasibility model has been built. Nevertheless, a reactor based on a spherical Surmac, but with open cusps, has been proposed.[12] The present geometry undoubtedly has advantages over an open system; a problem is the lack of space for a neutron absorbing blanket and the difficulty of removing large amounts of heat from the internal conductor. A justified hope is that a fusion reaction poor in energetic neutrons can be made to work with a Surmac confinement as described. The potential for a reactor using a direct conversion process cannot be ruled out.

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