Application of Superconductivity in Thermonuclear Fusion Research

Anwendung von Supraleitung in thermonuklearer Fusionsforschung

A.P. Martinelli

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ABSTRACT

Recent technological developments of high field superconducting materials and cryogenic, adiabatic, and dynamic stabilization methods are briefly examined.

The high current densities attainable in superconducting magnets, the design and operation reliability, and the economy in comparison with traditional magnets make superconducting magnets attractive for plasma physics experiments. Furthermore, the absence of ohmic resistance in superconductors makes experimental configurations feasible that could not be built otherwise. Two experiments are described, the WENDELSTEIN 6 quadrupole and the WENDELSTEIN 7 stellarator which are being constructed and planned respectively at Garching.

The geometric dimensions and the high magnetic field values required for possible future thermonuclear reactors can only be achieved by using superconducting magnets. Since they represent the major expenditure for a reactor, the total cost will depend on the production and economic use of high and very high field materials.

CONTENTS

APPLICATION OF SUPERCONDUCTIVITY IN THERMONUCLEAR FUSION RESEARCH [+]

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INTRODUCTION

This paper describes the application of superconductivity to controlled fusion research at Max-Planck-Institute of Plasma Physics in Garching, i.e. mainly in the quadrupole (Wendelstein 6) and stellarator (Wendelstein 7) experiments, which are respectively under construction and at the advanced planning stage.

First, however, it is convenient to examine the recent technological progress in the field of superconducting materials and then to examine briefly the most important plasma experiments in Western Europe and in the United States which use superconducting magnets.

The paper finishes by outlining the part that will be played by superconducting magnets in possible future thermonuclear reactors.

RECENT DEVELOPMENTS OF HIGH FIELD SUPERCONDUCTORS

The properties of a superconducting material are described by the three parameters, critical magnetic field H_c, critical current density J_c, and critical temperature T_c. These parameters define a surface in a three-dimensional representation H, J, T which divides the space H, J, T into a region where the material is superconducting and another where the material is normal.

Critical Temperature T_c

A high T_c value is desirable both because the efficiency of refrigerators (ideally the efficiency of the Carnot cycle) rapidly decreases as the temperature necessary to keep the material superconducting drops, and because a material having a higher T_c is less sensitive to thermal disturbances, the other parameters such as operating temperature, critical current, stabilization etc. being the same. This material will undergo normal transition less easily than a material having a lower T_c since $I_c(T)$ decreases about linearly with increasing T.

The ternary compound $Nb_3(Al_{0,8}Ge_{0.2})$ is the material having the highest critical temperature of $T_c = 20.7^{\circ}K$. The compound Nb_3Sn has $T_c = 18^{\circ}K$, and the alloy Nb-Ti has $T_c = 10\ ^{\circ}K$. A T_c of about 25°K is considered to be the upper limit for materials such as those mentioned above, in which the superconducting state is induced by phonons. Other mechanisms susceptible of generating superconductivity at higher temperatures have been suggested (e.g. organic superconductors), but materials for technological applications do not appear probable in the near future.

Critical Magnetic Field

Recent measurements show that the compound $Nb(Al_{0,8}Ge_{0.2})$ has a critical field $H_c = 410$ kOe, $Nb_3Al^{(1)}$ has $H_c = 295$ kOe, and $V_3Ga^{(2)}$ has $H_c = 220$ kOe.

Although the first two materials are not commercially available, the recent development of high field materials is promising for the future realization of magnets capable of producing fields higher than those obtained up to now by using Nb_3Sn ($H_c = 210$ kOe).

The third material, V_3Ga ($T_c = 14.5^{\circ}K$), which recently appeared on the market at a price competitive with that of Nb_3Sn would afford, according to recent measurements$^{(2)}$, a considerable advantage over Nb_3Sn in the construction of magnets generating fields greater than 120 kOe. This can be seen by considering the product $J_c \cdot B_c = F_V$. It has the dimensions of a force per unit volume and corresponds physically to the strength of the pinning forces in the superconductor volume. The product F_v has a maximum at about 175 kOe

(0.8 H_c) for V_3Ga (F_{vmax} = 1 to 2 x 10^3 kg/cm^3), while for Nb_3Sn it has about the same maximum value F_{vmax} at 120 kOe and then drops rapidly. Therefore, for fields higher than 120 kOe a magnet using Nb_3Sn requires a greater volume of superconducting material than an equivalent magnet made of V_3Ga, so that using V_3Ga is more economical than Nb_3Sn, assuming the same specific cost for both materials.

Critical Current Density J_c and Stabilization

The high values of the critical current density J_c ($> 10^3$ A/mm^2) that have been reached in short samples of high field superconductors since their discovery are considerably reduced (degradation) once the superconductor is wound in a coil.

In order to limit the degradation of the superconductor, this is stabilized by, for instance, adding a material of low electrical and thermal resistivity, e.g. copper. Although the cross section of the composite, copper plus superconductor, is larger than that of the superconductor alone, the current density obtained in the composite is higher than that reached in the degraded superconductor. Therefore the current density value is a function of the type and extent of stabilization to which the superconductor is subjected.

Cryogenic Stabilization. In the case of "cryogenic" stabilization a material of high electrical and thermal conductivity is in close contact with the superconductor so as to take over part or all of the current which the superconductor, partially or totally turned normal owing to a thermal or magnetic instability, cannot momentarily transport. Let us suppose that the current momentarily flowing in the stabilizing material of resistivity ρ has a density J such that the heat $q = \rho J^2$ (watt/cm^3) is generated. Let us suppose further that the total heat $Q = qV$ generated in the volume V of the stabilizing material is smaller than the maximum power which can be transferred in the "nucleate boiling" regime from the surface of the composite to the surrounding liquid helium. The composite can then revert to thermal equilibrium and the current will again flow in the superconductor. The composite is thus "stable". The critical value of the power transferred from the surface unity of the composite to the liquid helium in the nucleate boiling regime is approximately $q_c = 0.5$ watt/cm^2, beyond which the heat transfer process switches from nucleate boiling to "film boiling". Correspondingly the temperature differences ΔT between composite surface S and liquid helium passes from a few tenths of degree in the nucleate boiling regime to a few degrees in the film boiling regime (3).

Therefore, if the current density J is such that $Q > Q_c = qS$, the superconductor will turn completely normal and will revert to superconductivity only after the current has been noticeably reduced or reduced to zero. In this case the composite is "unstable".

A high current density of the composite is generally required, and for reasons of economy the current density in the superconductor should be close to the critical value. On the other hand, the copper-to-superconductor ratio of the composite as well as the composite cooling environment determine the stability behavior as described above.

Bearing the above conditions in mind, one can consider a cryogenically stabilized copper-superconductor composite as being in a state of stability, limited stability, or instability, if the total current density is approximately $J < 80$ A/mm^2, $J = 100 - 200$ A/mm^2, and $J > 300$ A/mm^2 respectively (4).

<u>Adiabatic Stabilization.</u> Under any operating conditions, apart from when the superconducting material carries its maximum current, the current distribution in the superconductor consists of a transport current and a local current ("magnetization" or "shielding" current). The latter can decay in a short time (a few tens of /usec) owing to a thermal or magnetic disturbance, and the associated energy is liberated thermally (flux jumps). The related temperature rise of the superconductor can ultimately lead to a quench.

Theoretical and experimental work shows that such shielding currents can be substantially reduced or eliminated by decreasing the diameter of the individual superconducting strands embedded in the matrix (copper or cupro-nickel) to a value of about 20 /u or smaller and by transposing them (5). The filamentary structure thus obtained is said to be adiabatically, intrinsically or enthalpically stable. This stabilization method probably represents the most significant contribution to superconducting technology in the last two or three years.

By this technique the copper constituting the matrix of the filamentary composite can be reduced, thereby achieving copper-to-superconductor ratios of 1 to 1 and total current densities in excess of 300 A/mm^2. Furthermore, no special cooling arrangements such as liquid helium cooling channels are needed for the magnets, thus allowing more compact mechanical design and higher overall current densities. The coils can be potted with epoxy and give the same performance when operated in liquid or gaseous helium, since they are adiabatically stable and not directly affected by the cooling environment.

Dynamic Stabilization. A third stabilization method is referred to as dynamic stabilization, which allows for the fact that the thermal diffusivity of the superconducting material ($D_{th} = K/c$, where K is the thermal conductivity, and c the specific heat) is much smaller (factor 10^3 for Nb-Ti) than that of copper, and that the thermal diffusivity is much smaller than the magnetic diffusivity $D_{mag.} = \rho 10^9/4\pi$ (the opposite is true of copper). Consequently, the heat generated in the superconductor during penetration of the magnetic field following a sudden variation of the field itself (flux jump) does not get removed at the same rate at which it is produced, and therefore causes dangerous temperature rises.(4)

This method consists in embedding the superconductor in a metal matrix (e.g. copper), the purpose here being to transfer rapidly the generated heat from the superconductor to the helium bath and to shield, at least partially, the superconductor from variable magnetic fields, either externally superposed on the winding or internally caused by flux jumps taking place in the superconductor located in the more or less immediate neighbourhood, i.e. in the same layer or in contiguous layers.

This method also covers the known technique of interleaving thin copper sheets between two or more contiguous layers of a winding. The sheets are thermally and electrically insulated from the layers and are intended both to shield the superconducting layer from the variable magnetic fields and directly transfer the heat, generated by these fields, to the helium bath, with which the sheets are in good contact.

Actually, there is a certain overlapping of the three stabilization methods, which are described above as separate, and in practice one of them will be predominant.

APPLICATION TO PLASMA PHYSICS

Owing to the interaction of electrically charged particles with a magnetic field, the latter is ideal for confining a plasma, which is composed of charged particles (ions and electrons) in which a gas at a high or very high temperature ($> 10^4$ °K) is dissociated. In fact, if the magnetic field is sufficiently high, the trajectory of each particle takes the form of a spiral with the axis parallel to the magnetic field, which therefore acts as a non-material container and, given the high temperature of the plasma, is incombustible.

Magnetic Configurations

If the confining magnetic field is so constituted that none of its field lines leaves the confinement volume of the plasma, the particle and energy losses of the plasma can only take place in a direction perpendicular to the magnetic field and are limited. These conditions are met in "closed" magnetic configurations, e.g. in toroidal machines such as the "Stellarator" and "Tokamak".

In "open" configurations, on the contrary, serious plasma losses occur at the two ends, where the field lines leave the plasma confinement volume. One attempts to reduce these losses by considerably increasing the magnetic field value at the ends to produce "magnetic mirrors" so as to reflect the plasma.

The experimental results achieved in open configurations (mirror machines, theta pinches) have been better, as far as the temperature and density of the plasma are concerned, than in closed configurations, where, on the other hand, better results have been obtained for the confinement time.

One tends to believe now that a possible future thermonuclear reactor will preferably have a closed geometry, especially owing to the absence of the end losses present in open configurations. It should be noted, however, that the open-ended or closed configurations built up to now or still in the construction or design stage are only intended for studying the properties of the plasma, viz. temperature, density, stability and confinement etc., and do not even represent miniature prototypes of thermonuclear reactors.

While there is little doubt that a future thermonuclear reactor will utilize superconducting magnets owing to both the large dimensions and high field required, several experiments using superconducting magnets have recently been built or are being planned. The main reasons for this are as follows:

a) The magnetic fields necessary for the experiments have increased both in volume and in magnitude. They can now be more economically and conveniently realized with superconductors than with traditional techniques. Furthermore, many experiments require the use of stationary instead of pulsed magnetic fields.

b) High current densities are possible particularly if intrinsically stable superconductors are used. The resulting reductions in volume of the magnets allow better access for plasma production and diagnostics. A current density J = 100 - 200 A/mm^2 is generally required, which would correspond to a region of limited stability in the case of cryogenic stabilization.

c) Reliability of superconducting magnets, recently shown by the satisfactory operation of a number of large magnets, e.g. the magnet for the bubble chamber at the Argonne National Laboratory, which is 4.80 m in diameter and produces 18 kOe at the center.(6)

Table I, compiled by Hancox (7), gives an up-to-date picture of the plasma experiments either in operation or under construction in the United States and Western Europe which make use of superconducting magnets and shows that most plasma laboratories are engaged on at least one important project applying superconductivity.

The Application of Superconducting Magnets at Garching

The work on superconductivity at Garching was initially restricted to the construction of a few small

Table I
Plasma physics experiments using superconducting coils

Laboratory	Type	Dimensions (cm)	Field or Current	Material
	Open Configurations			
Oak Ridge N.L. (USA)	I.M.P. Mirror and Quadrupole	35 dia 70 long	20 kG central 75 kG peak	Nb-Ti + Nb$_3$Sn
N.A.S.A. Lewis (USA)	Mirror	51 dia	75 kG central	Nb-Ti + Nb$_3$Sn
L.R.L. Livermore (USA)	Baseball II	120 dia	20 kG central 75 kG peak	Nb-Ti
	Closed Configurations			
Princeton P.P.L. (USA)	Spherator	90 ring dia	130 kA	Nb$_3$Sn
Princeton P.P.L. (USA)	F.M.1 Multipole a) 1 ring	150 ring dia	375 kA	Nb$_3$Sn
	b) 2 rings	100 " " 200 " "	460 kA 325 kA	
L.R.L. Livermore (USA)	Levitron	80 ring dia	500 kA	Nb$_3$Sn + Nb-Ti
Culham (England)	Levitron	60 ring dia	500 kA	Nb-Ti
Garching (West Germany)	Wendelstein 6 Multipole	60 ring dia 120 " "	400 kA 190 kA	Nb$_3$Sn
Garching (West Germany)	Wendelstein 7 Stellarator	400 maj. dia 40 min. dia	40 kG mean 65 kG peak	Nb-Ti

magnets for laboratory use and to the evaluation of new commercial materials.

Module system of 100 kOe. A system of superconducting magnets with much larger dimensions was built during 1967 - 1968 for the purpose both of obtaining a field of 100 kOe in a 5 cm bore for material testing and of developing superconducting magnets with the dimensions required for a number of plasma experiments (8). Particular attention was paid to developing standard types of coils for assembly into different configurations (e.g. mirror configurations, cusp fields, etc.), as already done with copper coils.

Thus, three different coils of the modular type have been designed and built. These have inner diameters of 350, 170, and 50 mm and are referred to in Fig. 1 as SSp 350, SSp 170, and SSp 50. Fig.1 shows an assembly of 12 coils (four of each type concentrically mounted). This system produced a maximum field of 105 kOe.

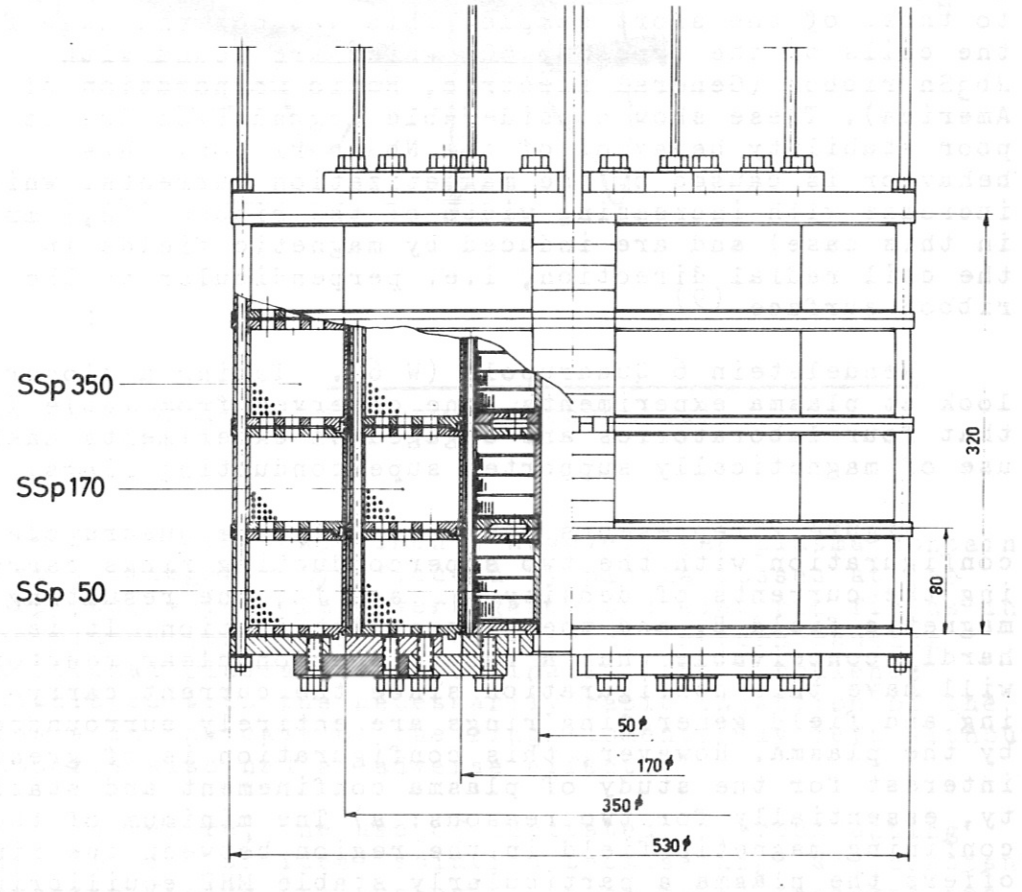

Fig.1. Assembly of twelve superconducting coils SSp 350, SSp 170, and SSp 50 (four of each) forming a 100 kOe magnet system.

The composite used for the coils SSp 350 and SSp 170 (Supercon, Atomics International) is a cable made of strands of NbTi and copper twisted together and impregnated with indium. This method of manufacturing superconducting composites became obsolete soon after and was replaced by the manufacturing process used now. This consists in embedding the NbTi in the copper ingot already at the beginning of the mechanical manufacturing process and then in swaging the ingot down to the final composite diameter. Excellent contact of a metallurgical type is thereby assured between copper and Nb-Ti.

The field strength and critical current density (100 - 200 A/mm^2) reached by these coils are very close to those of the short sample. This was not the case for the coils of the type SSp 50, which are wound with Nb_3Sn ribbon (General Electric, Radio Corporation of America). These show considerable degradation due to the poor stability behavior of the Nb_3Sn ribbon. This behavior is caused by the magnetization currents, which increase with increasing width of the ribbon (12,7 mm in this case) and are induced by magnetic fields in the coil radial direction, i.e. perpendicular to the ribbon surface (9).

Wendelstein 6 Quadrupole (W 6). Taking a closer look at plasma experiments, one observes from Table I that four laboratories are engaged on experiments making use of magnetically supported superconducting rings.

Figure 2 represents schematically the quadrupole configuration with the two superconducting rings carrying the currents of density J_1 and J_2, the resulting magnetic field B, and the plasma distribution. It is hardly conceivable that a future thermonuclear reactor will have this configuration since the current carrying and field generating rings are entirely surrounded by the plasma. However, this configuration is of great interest for the study of plasma confinement and stability, essentially for two reasons: a) The minimum of the confining magnetic field in the region between the rings offers the plasma a particularly stable MHD equilibrium condition; b) The uncomplicated geometry of the configuration allows relatively simple theoretical treatment of the experimental results (10).

In previous similar experiments a current pulse was sent through the rings to produce the magnetic field. The rings were sustained either by thin supports or even left momentarily without supports for the short

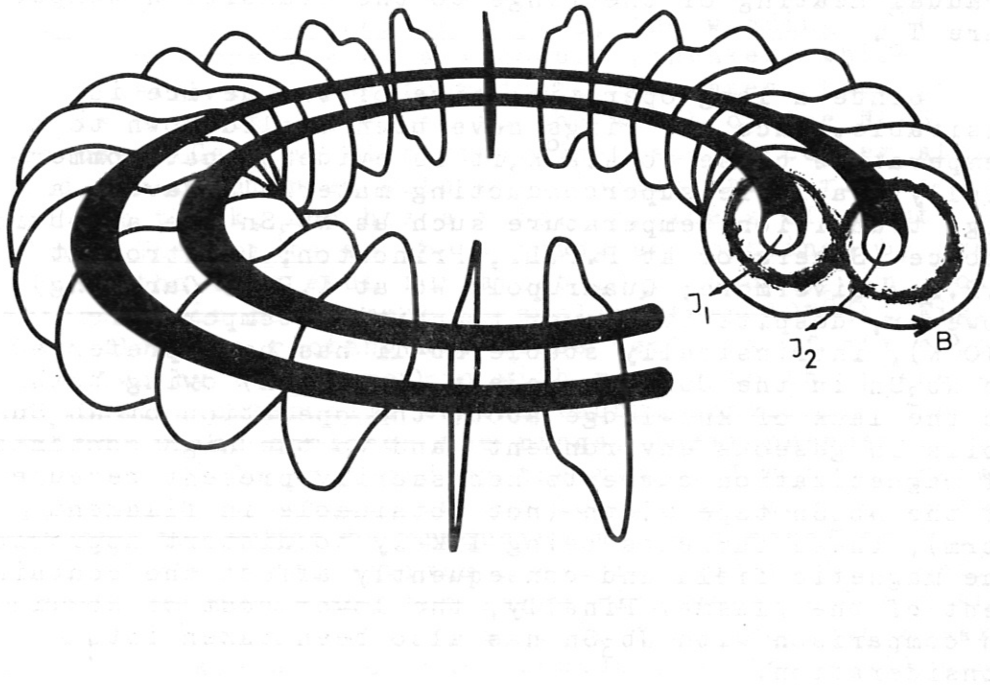

Fig.2. Toroidal quadrupole (schematic).

duration of the experiment. However, the plasma containment was negatively affected by plasma losses at the supports, which, moreover, generated electric fields in the plasma (these electrical fields in turn causing additional plasma losses). Finally, the turbulence associated with the necessarily rapid injection of the plasma in the case of the rings momentarily left without supports also had an adverse effect.

Therefore, the use of levitated superconducting rings offers an ideal solution because high and constant magnetic fields are achieved, no material supports are required, and the experiment can last minutes or hours. In this specific case the application of superconductivity allows a configuration which could not be constructed otherwise. A cost comparison between the use of superconducting or non-superconducting technique is therefore neither here nor there.

Through the magnetic supports the rings have no mechanical or electrical contact with the environment, and the thermal connection with it is limited to radiation. The radiation losses are responsible for the gradual heating of the rings to the transition temperature T_c.

Since a long operating time of the device is desirable, once the rings have been cooled down to a temperature close to 4.2°K, it is evident that commercially available superconducting materials having a high transition temperature such as Nb_3Sn are an obvious choice (Spherator at P.P.L., Princeton; Levitron at L.R.L., Livermore; Quadrupole W6 at I.P.P. Garching). However, despite its lower transition temperature (10°K), intrinsically stable Nb-Ti has been preferred to Nb_3Sn in the Culham project (Levitron) owing both to the lack of knowledge about the operation of Nb_3Sn coils in gaseous environment and to the high contents of magnetization currents necessarily present because of the Nb_3Sn tape width (not obtainable in filament form), these currents being likely to distort appreciably the magnetic field and consequently affect the containment of the plasma. Finally, the lower cost of Nb-Ti in comparison with Nb_3Sn has also been taken into consideration.

The utilization of liquid helium for the cooling and operation of the rings implies the use of cryostats around the rings and therefore a larger total volume of the rings and of the whole experiment (e.g. Spherator at Princeton). This is one of the main reasons why helium gas has been preferred at Livermore and Garching.

At Garching a series of tests have been carried out just to establish the behavior of Nb_3Sn in a gas environment. These consisted of measurements of the characteristics $(H, J, T)_c$ of short samples to establish particularly the maximum temperature the superconducting rings can reach before reverting to normality when they carry the nominal current $I_n = 100$ A; magnetization measurements at different temperatures, particularly to see at what temperature the rings can be most conveniently energized to reduce the diamagnetic currents, both to increase the magnetic stability of the superconducting windings and to reduce the field distortion; measurements on small superconducting coils carrying the same current and in the same field as the W6 rings, the temperature of which is varied to obtain an indication of the stability of the rings when their temperature increases (11).

Figure 3 shows schematically a design cross section of the quadrupole W6(12). The two rings have a diameter of 60 and 120 cm, and are wound with 4,000 and 1,900 turns respectively. For both rings the nominal current is $I_n = 100$ A. As seen in Fig. 3, the winding of the small ring consists of six double pancakes, while that of the large ring has four double pancakes. Each pancake is 5 mm thick, equal to the width of the Nb$_3$Sn tape used (General Electric). The tape is copper stabilized, is reinforced with a stainless steel ribbon 0.025 mm thick, and has a total thickness of about 0.2 mm. The joints in the winding are obtained by overlapping the tape ends for about 10 cm and by tin soldering. Their resistance is smaller than $10^{-8}\,\Omega$. Fig. 3 shows also the rectangular cross sections of six copper coils two by two symmetric with regard to the plane AA, and located externally to the vacuum container (see Fig. 4c) which encloses the rings. Their purpose is to shape the field produced by the rings. The two remaining copper coils indicated in the lower part in Fig. 3 support the two rings by producing a field equal to 0.1 to 0.2 % of the total maximum field reached in the configuration. The small and the large ring weigh 200 and 400 kg respectively, and the magnetic field reaches a maximum of 30 kOe at the inner boundary of the small ring.

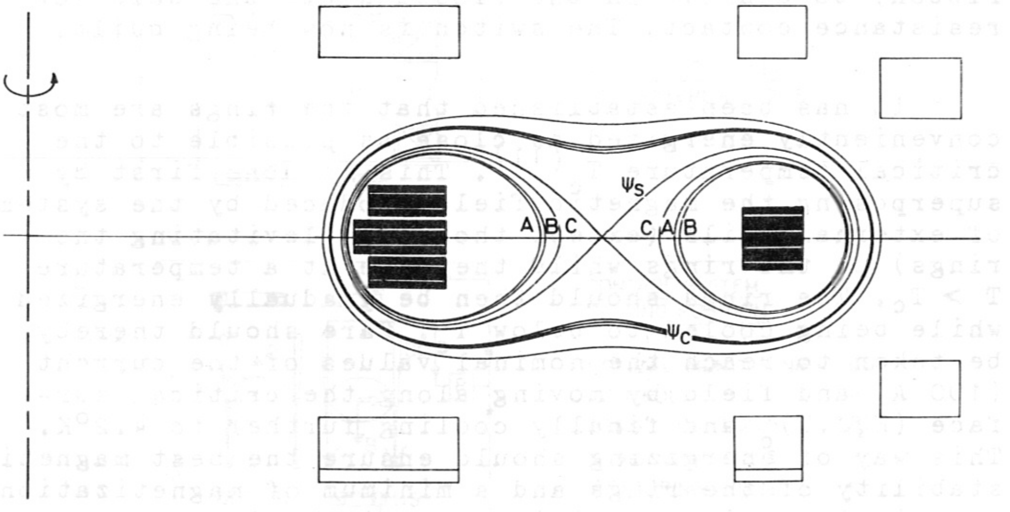

Fig. 3 Wendelstein 6 quadrupole (design scheme).

The singular field line named Ψ_s in Fig.3 is called the separatrix and has approximately an 8 shape in a quadrupole (13). This line divides the magnetic configuration into two regions, the field lines in the one closing around one ring, and in the other around both rings. At the crossing of the separatrix the magnetic field B goes to zero; the configuration is of the type "zero-minimum B". Inside the lines Ψ_c the plasma is stable (MHD stability). The three curves A, B, C, correspond two by two to three possible configurations of the plasma confinement. The innermost curves delineate the material sheaths of the rings. These sheaths are vacuum tight and contain the windings constituting the superconducting rings, the relevant mechanical structure, and the other devices described in Fig. 4a.

Figure 4 shows schematically some technical, particularly cryogenic, details of W6(14). In Fig. 4a the inductance L indicates the superconducting winding; the switch S closes after the generator G has energized both windings; finally, the electrical connections between generator and superconducting rings are withdrawn. In this fashion a practically permanent current flows in the rings; in the relevant time constant $\tau = L/R$, R is given practically by the resistance of the switch in the closed state (about $10^{-7}\ \Omega$). The switch is an electro-mechanical one, has an infinite resistance in the open state, and makes use of superconductors (Nb_3Sn ribbon) to achieve in the closed state the said low resistance contact. The switch is now being built.

It has been established that the rings are most conveniently energized as close as possible to the critical temperature T_c (11). This is done first by superposing the magnetic field produced by the system of external coils (except those for levitating the rings) on the rings while they are at a temperature $T > T_c$. The rings should then be gradually energized while being cooled to below T_c. Care should thereby be taken to reach the nominal values of the current (100 A) and field by moving along the critical surface $(H,J.T)_c$ and finally cooling further to 4.2°K. This way of energizing should ensure the best magnetic stability of the rings and a minimum of magnetization in the windings, i.e. a minimum of field distortion.

To increase the useful experimental time, it is planned to increase the thermal capacity of the rings by incorporating a metal of high enthalpy (K in

Fig. 4a). For this purpose mercury is slightly more advantageous than lead, but the latter is preferable since it is not so toxic as mercury.

The rings are cooled by means of three vertically retractable supports (SR in Fig. 4b) spaced at 120° intervals on a circumference of diameter equal to the average diameter of the two rings. The supports have the double purpose of mechanically supporting the rings when they are not in operation and contact cooling them

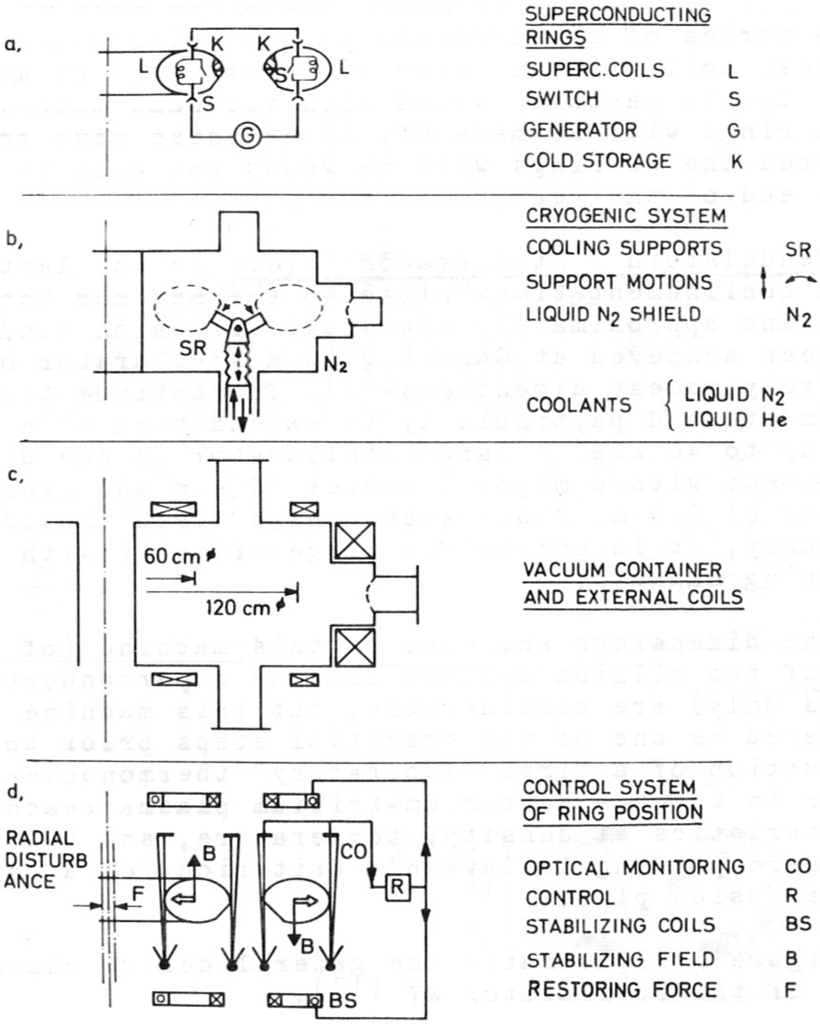

Fig.4. Wendelstein 6 quadrupole (technology).

from 300°K to about 4.5°K by using first liquid nitrogen and then liquid helium. The top part of the supports can rotate a few degrees, as indicated in Fig. 4b, so that they can readily be detached from the two rings once the latter have been cooled.

The shield N_2 in Fig. 4b is kept at liquid nitrogen temperature and has the purpose of slowing down the gradual heating of the rings due to radiation.

Figure 4d schematically illustrates a control system for the ring position, which uses photocells as sensors.

A series of measurements is now being concluded on a test coil with an inner diameter of 22 cm and made of two double pancakes wound with the same material as the W6 rings will be made of. After these have been completed the W6 rings will be wound and will be tested by the end of the year.

Wendelstein 7 Stellarator (W7). In the last years plasma confinement times close to the maximum theoretical values and approximately classical diffusion conditions have been achieved at Garching in a stellarator of relatively modest dimensions(15). To continue these experiments and particularly to extend them to a magnetic field up to 40 kOe, a large stellarator is now under development with a major diameter of 4 m and minor diameter of 0.4 m. Since such a high field should be stationary, it is convenient to generate it with superconducting magnets.

The dimensions and cost of this machine (of the order of two million dollars for the superconducting magnets only) are considerable, but this machine can be considered as one of the essential steps prior to construction of a first "laboratory" thermonuclear reactor in which a deuterium-tritium plasma reaches the characteristics of density, temperature, and confinement time corresponding to Lawson's criterion for a thermonuclear fusion plasma(16).

Figure 5 illustrates the general design characteristics of the stellarator W7 (17).

Forty superconducting magnets are arranged along the torus 4 m in diameter and produce the toroidal field of 40 kOe in a useful circle 0.4 m in diameter. The minimum number of magnets is primarily imposed by the maximum field ripple which can be tolerated for the experiment. Each magnet is provided with its own cryostat. This solution has been preferred since it allows easier assembly and disassembly, access to the plasma, possibility of modification of the magnet system compared with the case where all the magnets had a common cryostat. Furthermore, it allows a final adjustment of the magnet system which is most important owing to the severe mechanical tollerances imposed by the magnetic configuration of the stellarator.

Finally, the magnet with its own cryostat constitutes a module which can be variously combined with other units to form different magnetic configurations according

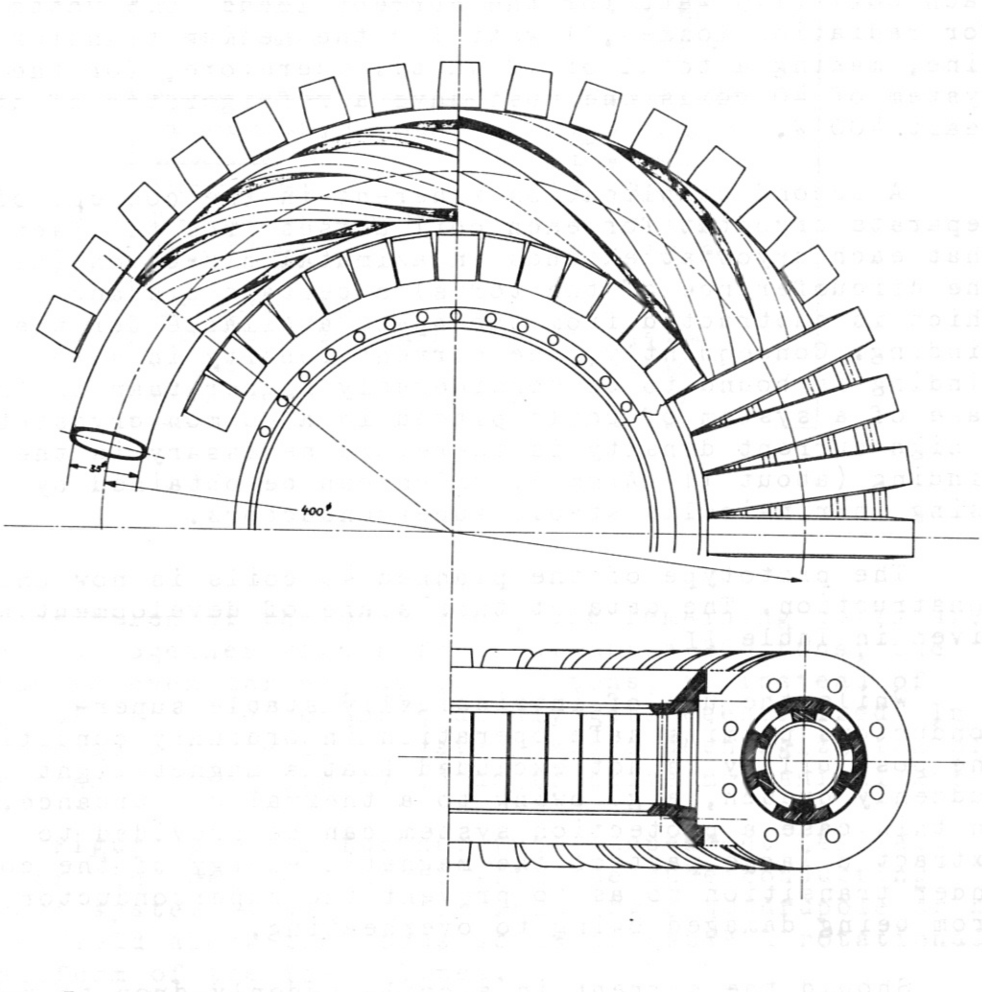

Fig. 5. Wendelstein 7 stellarator (general view).

to the concept already mentioned in relation to the system shown in Fig. 1.

Besides the advantages mentioned, this solution of having a cryostat for each magnet entails considerable complications. In fact, the magnetic forces to which each of the 40 magnets is subjected from the others have to be transferred from the superconducting winding at helium temperature, through the cryostat, to room temperature, before they are transferred to the mechanical supporting structure. For this purpose it is intended to use supports of glass fiber reinforced epoxy which offer a maximum value of the ratio σ/k between compression resistance and coefficient of thermal conductivity (18). However, even under optimum conditions these supports cause a heat flux of about 7 watt, which represents approximately 70 % of the total heat flux in each coil (1.5 watt for the current leads, 0.5 watts for radiation losses, 1 watt for the helium transfer line, making a total of 10 watt). Therefore, for the system of 40 coils one must have a refrigerator of at least 400 W.

A second complication inherent in the concept of a separate cryostat for each coil arises from the fact that each cryostat extends in azimutal direction (along the circumference of the torus) a certain distance which is subtracted from the space available for the winding. Consequently, the current density in such a winding is bound to be considerably higher than in the case of a system of coils placed in a common cryostat. A high current density is therefore necessary in the winding (about 111 A/mm^2), which can be obtained by using intrinsically stable superconductors.

The prototype of the planned 40 coils is now under construction. The data at this stage of development are given in Table II.

While the use of intrinsically stable superconductors permits safe operation in ordinary conditions, the possibility is not excluded that a magnet might suddenly quench, e.g. owing to a thermal disturbance. In this case a protection system can be provided to extract a large part of the magnetic energy of the coil under transition so as to prevent the superconductor from being damaged owing to overheating.

Should the current in a coil suddenly drop to zero because of the destruction of part of the winding or

Table II
Data of prototype coil for the stellarator W 7

Conductor: intrinsically stable, rectangular cross section, 3.35 x 1.42 mm, 580 Nb-Ti filaments 50 µ in diameter in copper matrix, copper/superconductor ratio 3.1/1.

Winding: 12 double pancakes

Nominal current	I_n = 700 A
Number of turns	N = 1,430
Total ampere turns	NI = 10^6 A
Inner diameter of coil	D_i = 950 mm
Outer diameter of coil	D_o = 1,130 mm
Current density in conductor	J = 147 A/mm^2
Current density in winding	J_w = 111 A/mm^2
Inductance	L = 2.9 H
Energy stored	E = 1.4 MJ
Maximum field at winding	H_w = 45 kOe
Central field	H_o = 12.2 kOe
<u>System of 40 coils</u>	
Maximum field at winding	H_w = 65 kOe
Central field	H_o = 40 kOe
Energy stored	E_t = 57 MJ

interruption of the conductor, the remaining coils are pressed together with a force of about 200 tons; the force is even larger, up to 600 tons, if instead of one coil a whole sector suddenly gets deenergized. In this case a protection system causes deenergization of the other magnets to avoid destructive mechanical stress.

Figure 5 shows further two independent helical copper windings concentric with the superconducting magnet system. They are for inducing a quadrupole or hexapole field along the torus so as to cause a rotational transform of the field lines.

It is necessary for the experiment that the constant magnetic fields, approximately 5 kOe in amplitude, which are produced by the helical windings, reach the maximum in a rise time of a few msec after being switched on. During the rise time the variable fields permeate the superconducting windings, which can revert to normality, both owing to the direct effect of the increased field and to the heating caused in the composite copper-superconductor by eddy currents and hysteresis losses induced by the field variation. Calculations and experimental work show that in the specific W7 configuration the helical field rise time in the superconducting windings should be slowed down (e.g. by means of copper shields) to at least 0.2 sec.

This problem, i.e. the superposition of a variable magnetic field on a stationary field produced by superconducting magnets, is inherent in several plasma configurations and has already been treated in configurations where the variable magnetic field is pulsed, has rise times much shorter (5-10 µsec) than those considered for the W7, and returns to zero in an equally short time after reaching the maximum value (19, 20, 21).

Apart from this problem, which has required and still requires particular theoretical and experimental investigation, the project W7 does not deviate from the relatively conventional superconductivity application. For this reason, and because of its dimensions and time schedule, the W7 development has been contracted to an industrial firm (Siemens Central Laboratories, Erlangen) which has enough trained personnel to meet tight schedules and years of experience in the field which can be further consolidated in a technology of interest to national industry. Close collaboration is still maintained of course with Garching.

On the other hand, the project W6, which has limited dimensions and requires the investigation of singular problems, is well sited at Garching.

APPLICATION OF SUPERCONDUCTING MAGNETS TO THERMONUCLEAR REACTORS. INFLUENCE OF MAGNET COST ON TOTAL PLANT COST

Some design studies of thermonuclear reactors operating with constant magnetic fields have been made (22). Since the magnetic fields involved are very high (100 kOe and more), conventional magnets are unsuitable owing to the enormous power losses, which can be avoided by using superconducting magnets (23).

By analogy with the total current density attained in large magnets such as those for bubble chambers of diameter 4 m and more, the total current density required for magnets of the dimensions necessary for thermonuclear reactors will probably not be larger than 25 A/mm^2. This is due to the stabilizing copper, to the necessary protection system, and, most of all, to the mechanical supporting structure in the magnet. In fact, the yield strength the superconducting composite is subject to in the winding is expressed by

$$\sigma_t = r \; J(r) \; H(r).$$

Therefore, assuming the product $J(r) \; H(r)$ to be constant, the volume of steel or similar material which reinforces the superconducting composite and which has the purpose of balancing σ_t must increase with increasing r.

In the case of magnets for thermonuclear reactors superconducting materials must have high H_c and relatively low J_c, the opposite being the case for magnets for plasma experiments. In this connection the importance of the compounds Nb_3Sn, V_3Ga, etc. and future materials having a still higher H_c is evident. The latter can be used more economically than V_3Ga and Nb_3Sn. It would also be desirable that such very high field materials be available in non-brittle form.

The superconducting materials in a thermonuclear reactor are subject to neutron irradiation. The relevant damage caused in superconductors have been the object of study for some time; however, the results have not yet shown a general connection between the metallurgy of the material and the damages derived due to neutron irradiation. Progress in this direction is desirable.

Of fundamental importance is also the influence of the magnet cost on the total cost of a reactor. A number of studies have been made which show the capability of a thermonuclear reactor of toroidal form to produce electricity economically (7). Preliminary studies made at Culham on a 750 Mw reactor with mirror magnetic configuration show the competitivity of such a reactor in comparison with traditional systems, and that the superconducting magnet represents the major cost. Similar results are obtained in the study of a 2.500 MW toroidal reactor.(7)

As already observed, the cost of a superconducting magnet increases noticeably with increasing maximum field required owing to the considerable increase of the superconducting material volume which has to be used when the material has a maximum critical field close to the magnet maximum field. It is therefore evident that the cost of a reactor is governed, besides by the cost of the superconducting material, by the availability of superconductors having a critical field considerably higher than the maximum field required for the magnet in order to guarantee economical application.

CONCLUSIONS

The developments during the last years of high field superconducting materials and particularly adiabatic stabilization permit the construction of very reliable high field magnets.

Superconducting magnets are an extremely important tool for constructing plasma experiments and are a marked improvement on the traditional magnet for economy, smaller volume, and possibility of higher fields. This will become increasingly true since these experiments tend to have still larger dimensions and higher fields. The planning of the magnetic system for the stellarator W7 at Garching is a conspicuous example of this application.

The application of superconductivity offers moreover the possibility of constructing experiments not possible by traditional means, an example being the quadrupole W6 under construction at Garching.

The application of superconducting magnets is a key element in a possible future thermonuclear reactor. Since the magnet cost considerably affects the total cost of the plant, a reduction of the superconducting material cost is desirable, together with the development of very high field materials which would allow their economical use in producing the high fields required for thermonuclear reactors.

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