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SUPERFLUIDITY

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Communication présentée à : CERN-DESY School on Superconductivity in Particle Accelerators

Hambourg (DE)
30 May - 3 Jun 1988

Note SBT/LCT/88-10

Présenté à CERN-DESY School on Superconductivity in Particle Accelerators
30 Mai - 3 Juin 1988 à Hambourg (RFA)

SUPERFLUIDITY

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ABSTRACT

The paper reviews the understanding of superfluid helium with regard to its use as coolant for superconducting devices. The topics to be addressed include heat transfer properties of the stagnant fluid, cooling by forced flow superfluid helium, design principles for superfluid helium cryogenic systems and, finally, an illustration of these principles by a few practical examples.

1. INTRODUCTION

This lecture is in no way intended as a comprehensive review of the physics of superfluidity. That subject would be quite beyond the scope of a course on superconductivity in particle accelerators. The authors have attempted to meet the needs of the audience by adopting an engineering approach to what may be called the use of superfluidity for superconductivity.

Today, the usual operating temperature for superconducting devices such as magnets or cavities is 4.2 K, the boiling point of liquid helium under atmospheric pressure. The reasons are that the relevant properties at that temperature of the most common technological superconductors - niobium titanium and niobium tin for magnets, pure lead or niobium for cavities - are suitable for a large variety of applications. In addition, implementation of heat sinks at 4.2 K is a relatively simple matter nowadays.

At the same time, it has long been known that the performance of superconductors may be enhanced by lowering the operating temperature. This is understood in terms of varying "critical" properties. The boiling point of a helium bath may be made to fall to lower values by progressively reducing the pressure in the vapour phase. The phase diagram of helium, presented in Fig. 1, clearly shows the behaviour of the boiling curve.

When liquid helium is cooled below a temperature of 2.17 K, the so-called lambda point, it undergoes a kind of quantum energy condensation not unlike the transition to the superconducting state. This condensed state is known as superfluid helium or helium II; it is characterized by a very low viscosity, a high specific heat, and a high thermal conductivity. Using superfluid helium as a coolant for superconducting devices, instead of just subcooled helium above 2.17 K, appears promising from a double point of view. The advantage would not only be an improvement in properties of the material but also a gain in thermal stability during operation of the considered device.

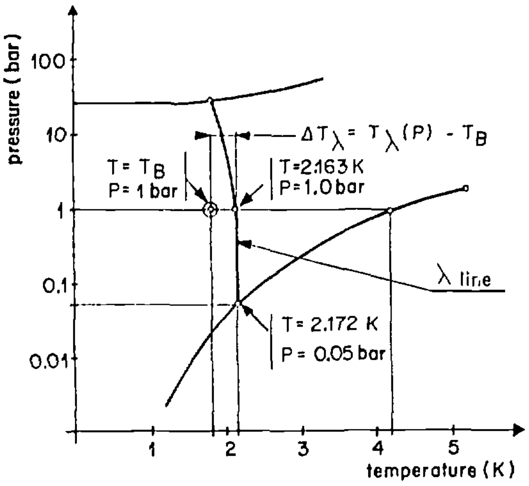

Figure 1: Phase diagram of helium

To illustrate the first point, the superconducting properties of niobium titanium and niobium tin at both 4.2 K and a typical helium II temperature (1.8 K) are presented in Fig. 2 /1,2/. Critical current density is plotted as a function of magnetic field in a range of particular interest for current accelerator projects. (It may be worthwhile recalling that superconductivity prevails so long as operating conditions remain below the critical characteristics). The values for niobium titanium appear to be shifted by 3 T towards higher fields when the temperature changes from 4.2 K to 1.8 K, while the effect is less substantial for niobium tin.

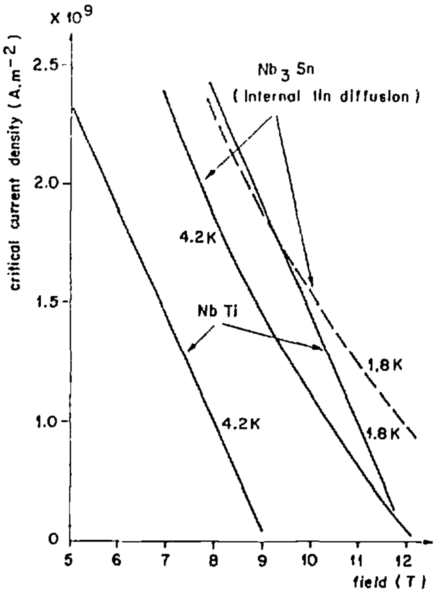

Figure 2: Critical current density of industrial scale NbTi and Nb_3Sn wires

It is the authors' understanding that the microwave surface resistance of superconducting cavities made from niobium also drop by a factor of significant size (between 2 and 10) upon cooling from 4.2 K to helium II temperatures.

The great sensitivity to temperature of superconducting properties makes thermal stability an extremely important condition for safe operation of devices built from these materials. Superfluid helium, when used as coolant, can act as a very efficient thermal stabilizer because of its excellent heat removal capability. The following section will explain this point in more detail.

1. PRACTICAL HEAT TRANSFER IN SUPERFLUID HELIUM

There are two distinct aspects of superfluid heat transfer : heat transport between the solid surface and the liquid (or vice versa) and heat transport through the bulk liquid. The first process is governed by a kind of solid-liquid interface conductance. It is known as Kapitza boundary conductance and depends somewhat on the material of the solid, its chemical and physical surface condition etc. Examples of practical data for copper are shown in Fig. 3 /3,4/.

For comparison the characteristics of heat transfer to normal liquid helium boiling at 4.2 K are also presented. One may identify the nucleate boiling region where the slope of the curve is roughly the same as that of superfluid helium and the film boiling region where heat transfer is rather poor.

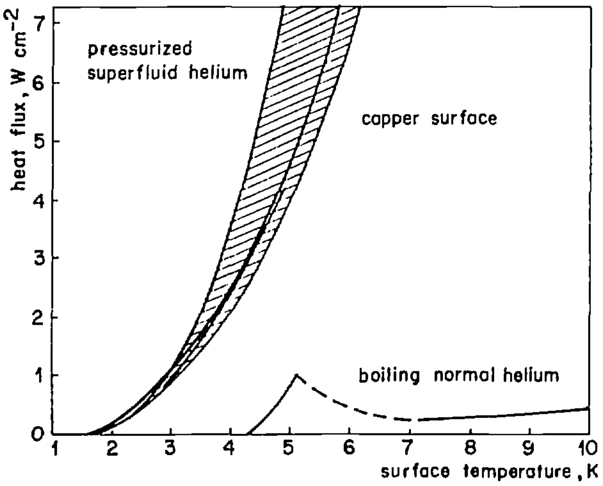

Figure 3: Heat transfer from a copper surface to liquid helium I and II

All heat transfer characteristics refer to flat heated surfaces which are immersed in a large bath of liquid helium. The peak nucleate boiling flux for normal helium is about 1 W/cm^2 in that condition. By contrast the Kapitza conductance regime in superfluid helium appears to extend beyond 5 W/cm^2. The reason for that discrepancy lies in the fundamental difference between the two heat transport mechanisms involved.

In normal boiling helium, heat transport takes place by natural convection which is strongly enhanced by the motion of vapour bubbles near the heated surface. In superfluid helium, there is no natural convection nor any nucleate boiling. Instead, heat is transported by a strange kind of conduction mechanism.

This mechanism has received a quite satisfactory description within the framework of the two-fluid theory of superfluid helium. Roughly speaking, it may be said that this theory views the bulk liquid as a homogeneous mixture of two interpenetrating fluids, one normal and the other superfluid. Heat conduction is then envisaged as a counterflow process in which the energy is carried to the cold source by the normal component while the superfluid component (which is a zero entropy state) returns in the opposite direction. At the hot surface superfluid atoms receive energy which pushes them into the normal state.

Although this "internal convection" is a remarkedly efficient method of transporting heat it is far from what could be called thermal superconductivity. In other words, a small but finite temperature gradient is needed to drive the heat current.

The situation of one-dimensional heat flow in tubes or channels is well understood. The relevant variable for heat transport is the heat current density q which is defined as the heat flow rate per unit cross-sectional area of the channel. At very small values of q, this quantity appears to be proportional to the temperature gradient in formal analogy with classical conduction of heat in solids. The only, but substantial, difference lies in the value of apparent thermal conductivity: at 2 K, helium II in a capillary of 1 mm diameter would have a thermal conductivity which is about 10^6 times larger than that of a copper wire of the same diameter!

At higher heat current densities (above typically a few tenths of W/cm^2), q is found to vary approximately as the cube root of the temperature gradient. This regime, known as the Gorter-Mellink regime, is effective in most technical applications of superfluid helium. It is still extremely powerful when compared to classical conduction.

$$q = (f(T)dT/dx)^{1/m} \qquad (1)$$

The conductivity function f(T) is temperature dependent: it starts from zero at 0 K, passes through a fairly broad maximum near 1.9 K and drops to zero again at the lambda temperature. There is some disagreement over the value of m for which values between 3.0 and 3.5 have been published in the literature /5,6,7,8/. Results are not too divergent as long as consistent combinations of m and f(T) are being used. In their own studies the present authors have found m=3.4 (or 1/m=0.294). Some numerical values of the conductivity function in that case are $f(1.8, 1.9, 2.0\ K) = 4.8, 6.5, 4.7 \times 10^{14}\ m/K(W/m^2)^{3.4}$.

To understand the intrinsic limits set to "internal convection" a look at the phase diagram of helium will be helpful (Fig. 1). Consider a heat source immersed in a bath of boiling superfluid helium. The state of the liquid in the immediate vicinity of the source may be represented by a point situated near the liquid/vapour phase boundary and slightly shifted in pressure towards the inside of the superfluid phase region. The small hydrostatic pressure head caused by immersion at a certain depth determines the exact value of the shift. At zero heat flow, temperature is equal to the bath temperature. As the source starts to release heat a temperature gradient builds up and the point in the phase diagram moves to the right along a horizontal (isobaric) straight line. The end point of that temperature trace may, at most, lie on the phase boundary if film boiling is to be avoided. This defines the largest possible temperature rise in the bulk liquid and hence the largest possible heat current.

The density of the liquid and slope of the vapour pressure curve are such that an immersion depth of, say, 10 cm would lead to a maximum allowed temperature rise of little more than 0.02 K at 1.8 K. Not surprisingly, therefore, it has been found that in saturated helium II the heat transfer switches to film boiling at heat flux values not much higher than those of normally boiling helium. In addition, local film boiling involves a high risk for superconducting magnets when occurring under reduced pressure since it is likely to cause a rapid rise of pressure which would trigger a fatal thermal runaway of the whole system.

Boiling in superfluid helium may be suppressed by increasing the pressure over the liquid beyond 0.05 bar (lambda point pressure) and cooling by means of a separate heat exchanger. Technical details concerning pressurized superfluid helium cryostats will be given later. For the moment it will be assumed that the bath is kept at atmospheric pressure and at a temperature near 1.8 K. The lambda transition at 1 bar occurs at 2.16 K. This is now the upper end point for the temperature rise within the liquid. It allows higher heat flux values which, in addition, are practically independent of immersion depth. The heat transfer characteristics of superfluid helium shown in Fig. 3 were obtained in that condition.

Cooling methods frequently employ narrow channels, as in the case of most magnet windings. The consequence is a reduction of the peak heat flux when compared with the open bath. The result for steady state heat transport in channels may be obtained by integrating the Gorter-Mellink relation (Eq.(1)) over the available temperature margin. If superfluid helium at atmospheric pressure is used the limiting heat current density q_l can be written

$$q_l L^{1/m} = \left(\int_{T_0}^{2.168} f(T)\,dT \right)^{1/m} \qquad (2)$$

where L is the channel length and T_0 the cold end temperature. As a numerical example, the results of Ref. /8/ give for a cold end temperature of 1.8 K /9/

$$q_l L^{0.294} = 1.45\times10^{4}\ \mathrm{m^{0.294} W/m^2} \qquad T_0 = 1.8\ \mathrm{K} \qquad (2a)$$

One of the practical consequences of Eqs. (2), (2a) is the possibility of transporting heat in superfluid helium over fairly long distances: doubling the channel length would divide the available peak flux by a factor of only $2^{0.294} = 1.231$

As a matter of fact superconducting magnet windings are very often subject to transient heat loads. The causes may be mechanical disturbances which have their origin in the large forces exerted on the windings by the magnetic field or disturbances which come about as the result of external actions (particle beams, electromagnetic transients etc.). The characteristic times involved may be quite short, generally in the range 10^{-4} - 10^{-1} s. Energies may, of course, also vary over a wide range. The order of magnitude of mechanical disturbances is thought to be 10^4 J/m^3.

Two properties of the conductor and its environment determine the rise in temperature induced by a transient heat load: the specific heat and the thermal conductivity. Both should be large to keep the rise in temperature low. The specific heat of solids at liquid helium temperatures is very small (for copper : 2×10^3 J/m^{3}K at 1.8 K and 8×10^3 J/m^{3}K at 4.2 K). Even if the thermal conductivity is large, as for pure metals (copper, aluminium), their effective thermal capacity is in many cases much too small to accomodate transient heat loads safely. The liquid helium which is present in the windings of the magnet may then play a decisive role.

The specific heat per unit volume of normal boiling helium and superfluid helium is about 100 times larger than that of solids. Both fluids respond to heat pulses of the kind which is considered here with a diffusive propagation of heat. The efficiencies of the two processes are very different however. Normal helium has a rather poor thermal conductivity (10^4 times less than copper, of the same order of magnitude as Kapton or Araldite) and heat can diffuse only a short distance (about 10 µm for pulses of 10^{-3} s duration) before onset of film boiling. By contrast, the large apparent thermal conductivity of helium II (cf. Eq.(1)) allows the heat to diffuse a distance into the liquid which is generally in the mm range. If pressurized helium II is used heat transfer is limited by the helium II/helium I transition at the lambda temperature. The well known anomaly of the specific heat associated with this transition then increases the effective heat capacity of helium II even further.

Experimental results for channels filled with pressurized helium II are shown in Fig. 4 /3/. The amount of heat ΔE absorbed by the fluid when rectangular heat pulses are applied to one channel end is plotted as a function of the "normalized" peak heat current density $q_l L^{0.294}$. L is again the channel length. The energy scale is divided in units of the total helium II heat capacity $\Delta E_0 = H_\lambda L$ of the considered channel. H_λ is the integral of specific heat per unit volume from initial temperature to lambda temperature. The numerical value of $H_\lambda(1.8\ K)$ is 0.28 J/cm^3 = 280×10^4 J/m^3. The dimensionless energy variable thus gives the fraction of ΔE_0 that is available for heat transfer when a pulse of amplitude q_l is applied to a volume of unit cross-sectional area and of depth L filled with helium II. The upper branch in the diagram refers to channels with fixed cold end temperature, here 1.8 K, while the lower branch is associated with channels that have no thermal connection to a bath. All channels have uniform initial temperature of 1.8 K.

When absolute values of the amount of absorbed heat are considered and compared with the order of magnitude of mechanical disturbances, as quoted above (10^4 J/m^3), it clearly appears that a void fraction of only a few percent in a magnet winding filled with helium II is likely to improve the stability a great deal. It should not be forgotten however that the solid is thermally coupled to helium II by the Kapitza boundary conductance in any case. Large heat current densities may thus raise the conductor temperature considerably without exceeding the limits of the heat absorbing capability of the adjacent helium II reservoir.

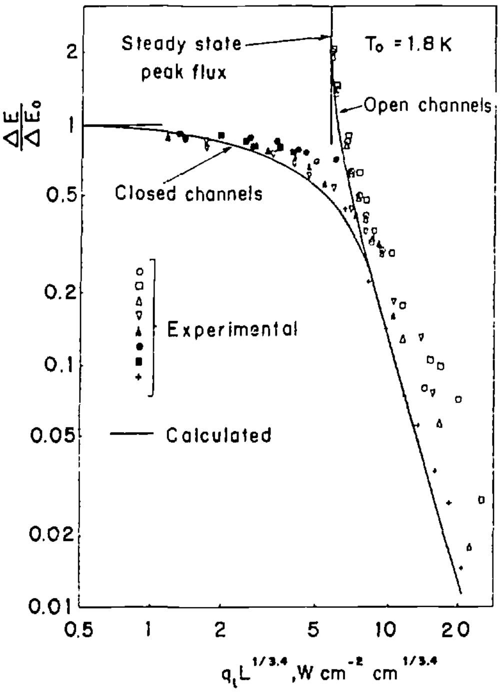

Figure 4: Limiting heat current density for step function heat pulses

3. COOLING BY FORCED FLOW OF SUPERFLUID HELIUM

It has been noted above that the cube root dependence of heat current density on temperature gradient in the Gorter-Mellink regime favours heat transport over long distances. There may be technical applications however, where heat transport by the internal convection mode in stagnant superfluid helium is not large enough. In such cases as very long (>80 m) strings of accelerator dipoles or very big fusion magnets cooling by forced convection of superfluid helium might be a solution.

The problem of flowing superfluid helium has received increasing attention in recent years. Heat transfer by combined internal and forced convection has been studied by several authors /10,11,12/. Two points of general technical interest have been established:

i) as expected from classical thermodynamics the contribution of flow to heat transport can be described by the term $v\rho c_p\Delta T$, where v is the flow velocity, ρ the fluid density, c_p the fluid specific heat and ΔT the local temperature rise in helium II. To avoid transition to film boiling or to helium I the same rule as for stagnant superfluid applies:

the maximum allowed temperature rise is determined by the isobaric temperature span between initial state and superfluid phase boundary (Fig. 1).

ii) for all practical conditions of forced convection flow dynamics of superfluid helium reduces to ordinary fluid dynamics. Pressure drops can be reasonably well predicted by means of classical correlations when the macroscopic flow velocity and the viscosity of the "normal" fluid component are used in calculating the Reynolds number /13/. The anomalous "zero viscosity" flow observed with small velocities (<0.1 m/s) in narrow capillaries (<10^{-5} m) is unfortunately of no direct use for forced convection.

From the last point, and from the fact that helium II has a very small (and negative) expansion coefficient, it follows that a negative Joule-Thomson effect is observed in flow tubes, i.e. fluid temperature rises as pressure falls. The fluid behaves as if an extraneous heat source of size $v\Delta P$ existed in the flow tube, where v is again the flow velocity and ΔP the local pressure drop. This effect is clearly detrimental to the heat removal capability of the forced convection cooling mode. In practice an optimal flow velocity must be sought as the result of a compromise between the requirements of high heat absorption and low pressure drop. Values in the range of 0.5 metres per second up to a few metres per second have been considered by current design studies.

4. SOME REMARKS ABOUT HELIUM II CRYOGENIC SYSTEMS

The classical method of producing superfluid helium consists of reducing the pressure over the liquid to values below the lambda point pressure of 0.05 bar. The superfluid is then in thermodynamic equilibrium with the saturated vapour. Superfluid cryostats of this kind suffer from severe practical limitations which concern their operation and the cost of the associated system of refrigeration.

The low pressure required in the cryostat vessel gives rise to a number of annoying problems. They include risks of air leakage into the system, "one-shot" operation when working with an external storage dewar, and low breakdown voltage in the vapour phase. The latter property has been found to vary linearly with the vapour density /14/, in accordance with Paschen's law.

For continuous operation a special refrigeration system must be added to the cryostat which, by comparison with normal helium refrigeration, will cause a significant rise in running cost and in capital cost: specific power consumption (defined as power consumption per unit cooling power) is roughly doubled at 1.8 K and the greatly increased volume of boil-off gas must be handled by big pumps and additional large heat exchangers.

From a technical and economical point of view it is often much more appropriate to proceed in a different way by using superfluid helium under atmospheric pressure and by providing a normal helium heat sink at 4.2 K for collection of the various heats leak into the cryostat /15/.

Figure 5 sketches the arrangement schematically. For the sake of clarity it may be described as being composed of three distinct sections:

Section 1 is a bath of normal helium boiling under atmospheric pressure. It acts as a heat sink for the principal heat leak associated with the mechanical support structure, thermal radiation, current leads and so on. It also serves as a buffer tank when the system is replenished with liquid helium.

Section 2 is the helium II bath. It houses all objects to be kept at helium II temperatures. It is completely filled with superfluid helium under atmospheric pressure and is characterized by its extremely homogeneous temperature. An external refrigeration source removes the heat dissipated at this stage.

Section 3 is the connecting channel between the upper and lower bath. It is used to fill and empty the helium II bath and provides passage for electrical connections, etc. An appropriate design has to take into account the various functions of this section. It should constitute a minimal heat leak between the two helium baths and, as well, have the capability of opening rapidly in order to avoid a hazardous pressure rise in case of accidental heat release to the helium II bath (e.g. quench of superconducting magnet, failure in the vacuum system, etc.).

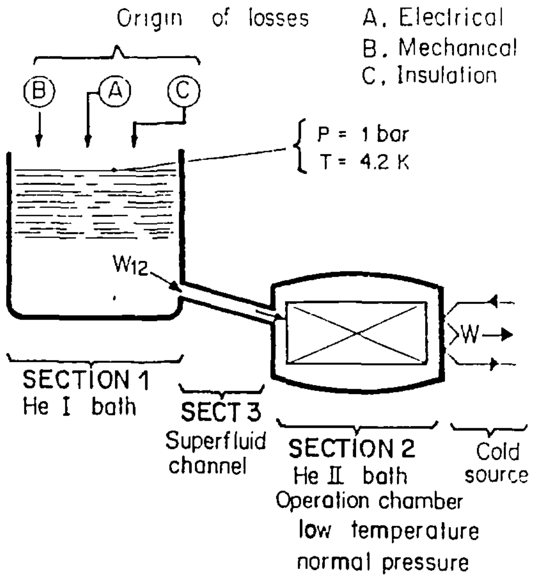

Figure 5: Pressurized superfluid helium cryogenic system

The connecting channel in conjunction with the helium II bath acts as a heat sink for the helium I bath, where a permanent downward flow of heat establishes. Since downward heat transport through a normal liquid can only take place by conduction and thermal conductivity of helium I is very low, a steep vertical temperature gradient builds up just below the boiling surface. Within a fairly short distance – typically a few centimetres – temperature falls from

4.2 K to 2.16 K, the temperature of the lambda line at 1 bar. Isothermal helium II at 2.16 K fills the rest of the bath from below the thermally stratified layer of normal helium down to the bottom.

The refrigeration load at helium II temperature level results from losses generated by the objects placed in the helium II bath and from heat leaks. Generally, the only noticeable heat leak comes from superfluid helium heat transport in the connecting channel. It is determined by the difference in temperature between 2.16 K and the working temperature of the helium II bath and, of course, by the geometry of the channel. All contributing heat sources above 4.2 K are connected to the heat sink formed by the surface of the boiling helium I bath.

In this way, the increase in cost of refrigeration due to cooling at superfluid helium temperatures may be kept to reasonable limits. In most cases, the refrigeration power to be provided at that temperature level will only amount to 10 to 20% of the total refrigeration power.

5. PRACTICAL ASPECTS OF SUPERFLUID HELIUM REFRIGERATION

Finally the principal features of some existing projects will be briefly outlined. Three examples have been chosen which illustrate the technology of pressurized superfluid helium on three different scales.

The first to be presented is a test facility for superconducting magnet development /16/. Figure 6 presents a schematic drawing. Only the helium vessel is shown. It is designed as a simple "tub" with a horizontal separating plate in the lower part which divides the liquid helium space in two: a helium II bath at the bottom and a helium I bath just above. The plate is made of glass-fibre epoxy composite and has a demountable central part which allows easy access to the test object in the helium II chamber. A built-in refrigeration unit produces saturated superfluid helium by means of a simple Joule-Thomson expansion stage and feeds it to a liquid/liquid heat exchanger immersed in the pressurized helium II. Normal liquid helium may be supplied by transfer from an external storage dewar.

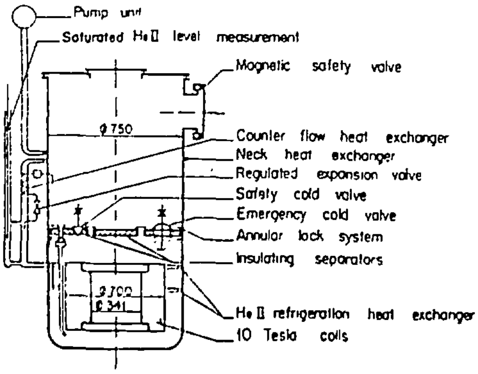

Figure 6: A laboratory cryostat for pressurized superfluid helium

The second example, larger in size, is the Grenoble Hybrid Magnet /17/. Overall dimensions are about 4 m in height and 1.5 m in diameter. Figure 7 shows an artist's impression. A big superconducting magnet is placed in a complicated re-entrant type cryostat. A high performance water-cooled magnet fits in the warm bore. The total field of the assembly attains 30 T in a useful bore of diameter 50 mm. The superconducting NbTi magnet produces 11 T and is run at 1.8 K. It is immersed in a bath of 500 l of pressurized superfluid helium. A 4.2 K/1.8 K refrigeration unit (Joule-Thomson loop) is placed in a kind of 'chimney' attached to the top of the magnet casing. A second 'chimney', also filled with normal boiling helium, provides a passage for the current leads (860 A). Two thermal shields at 4.2 K and 80 K surround the magnet casing to keep the heat leak into the system as low as possible. A transfer line for normal liquid helium connects the cryostat to a small liquefier (capacity about 10 l/h). A break-down of running cost for refrigeration gives 55 kW for the 4.2 K level and 11 kW for the 1.8 K level.

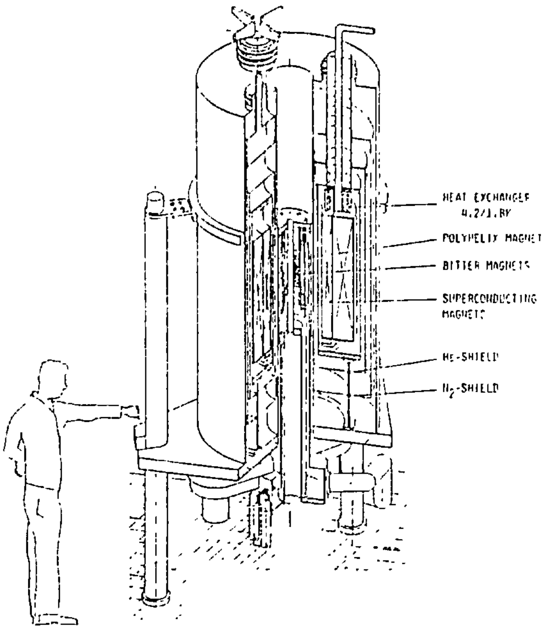

Figure 7: The Grenoble hybrid magnet

The last example in the list is the superconducting magnet tokamak Tore Supra located at Cadarache in southern France /18/. To-date it is the world's largest installation using pressurized superfluid helium. Very briefly, it may be said that a tokamak is a device for research on controlled thermonuclear fusion. It possesses two magnetic systems: toroidal coils which produce a steady field in azimuthal direction and poloidal coils which superimpose a time-varying vertical field. In Tore Supra the toroidal magnet is made up of 18 superconducting coils. The field strength is 4.5 T at the centre and attains a peak value of 9 T in the coil winding. Figure 8 shows a schematic section of one coil with the associated cooling circuit. Note the scale, given by some dimensions. The NbTi windings (total weight 50 t) are cooled by pressurized superfluid helium. The heat leak into them is roughly 16 to

17 W per coil. Refrigeration units are placed outside the iron yoke. They are connected to the magnets by means of 7 to 10 m long 'heat pipes'. Heat transport in these pipes solely relies on conduction in stagnant superfluid helium. The temperature difference between the warm and the cold end is typically 0.05 K. The total inventory of pressurized superfluid helium is 3000 l.

The construction of Tore Supra was completed during the winter of 1987/88 and operation of the machine started the following spring.

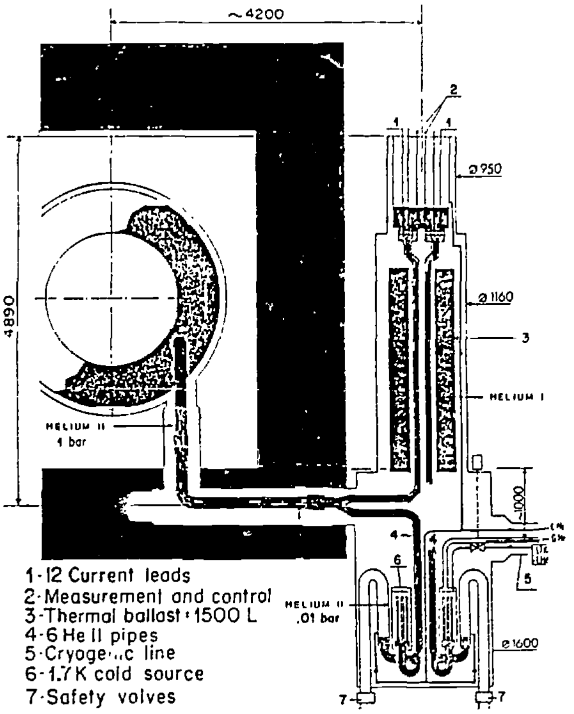

Figure 8: Cross-section of the toroidal coil system of Tore Supra

6. CONCLUSION

The use of superfluid helium as coolant can improve not only the superconducting properties of the current conductor materials but also the stability of devices built from these. All relevant aspects of heat transfer in this somewhat particular fluid are well understood at present and a broad data base is available for design work.

A particular attention should be paid to the design of superfluid helium cryogenic sytems. To keep investment and running cost within tolerable limits it is always preferrable to use an ultimate heat sink at 4.2 K for all heat leaks into the system which can be collected at that temperature level. Moreover, it is often appropriate to use pressurized superfluid helium as the working liquid.

A number of superfluid helium systems with cooling capacities ranging from a few watts to 300 watts have been built and operated successfully. A system of very large size (ring structure of 27 km circumference) and cooling capacity (12 kW at 1.8 K) is presently being studied for the CERN Large Hadron Collider and has appeared to be feasible from the technical point of view.

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