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Stabilité des supraconducteurs

Stability of superconductors

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Stabilité des supraconducteurs en hélium I et hélium II

Stability of superconductors in helium I and helium II

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SUMMARY OF THE WORKSHOP ON THE STABILITY OF SUPERCONDUCTORS

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1. GENERAL REMARKS

The question of margins and limits of stability of the superconductor accompanied magnet designers from the beginning of their development work, less than 20 years ago. While in the early days the simple cryogenic stability criteria guided the principal way "to live" with disturbances, the multifilament conductors indicated a way to reduce or avoid an origin for disturbances, namely flux jumps. As M. Wilson pointed out in his overview of the last workshop at LASL, these two approaches remained more or less independent for several years, in spite of improvements in understanding and theories. Many magnets,built successfully by "advanced" designers, worked with margins much better than predicted by classical stability approaches, while some others built rather "safely", failed for unexpected reasons.

Just in time before the first workshop on stability of superconductors, held at Los Alamos in 1977, intensified effort on stability investigations could be observed world wide, triggered partially by the introduction of He II-cooling aiming at improved magnet performance and partially by the start of big superconducting magnet projects for thermonuclear fusion research. This effort has been continued intensively, so that at the present workshop, 4 years later, a great spectrum on results in fundamental areas such as heat transfer properties as well as in applied areas such as stability investigations on magnets,demonstrate the progress.

It was the general impression of the workshop participants, that the understanding of stability in superconductors has been improved greatly within the last years. It is the subject of this paper to summarize the progress for the different areas by statements agreed upon by the workshop participants in the final round table session.

The question of an optimal cooling mode dominated many discussions. Classical He I-pool boiling has good references due to the large number of magnets built in this fashion. Less magnets have been built so far with forced flow supercritical He, but also very successfully. Finally, He II-cooling turned out to be a new approach with interesting features too.Not surprisingly, the discussions showed advantages and disadvantages for all three cooling modes, leaving the designer to decide on the best compromise based on his boundary conditions for the specific project.

2. HEAT TRANSFER AND THERMAL PROPERTIES

The steady state heat transfer is well established for all cooling modes, thereby absolute values can be optimized. Special characteristics are:

- The heat transfer is independent of the channel direction for He II and for supercritical He I-forced flow, but dependent on channel direction for He I-pool boiling.

- The He II-heat transfer values are very high if the channel geometry is chosen properly, the forced flow He I values can be adjusted by the mass flow rate (Reynoldsnumber), the He I-pool boiling values mainly by surface treatment only.

- Cooling channel length limitations exist basically in all cooling modes.

- He I-two phase, forced-flow cooling has not been investigated as well as the other cooling modes. Its application is perhaps limited due to the tendency for thermal instabilities (oscillations).

The occurance of an enhanced time dependent "transient heat transfer" have been investigated essentialy during the past few years. It is of great importance for conductor stability against pulse disturbances. This kind of heat transfer is now

- established experimentally and understood theoretically in He I-pool boiling,

- potentially high in He II, due to the very high thermal conductivity of the superfluid phase, but limited by the Kapitza resistance.

- not well investigated yet in supercritical Helium.

The decision on the cooling mode cannot be made without consideration of the cryogenic engineering implications. This area has not been discussed within the workshop, but it must not be neglected in the design decision.

While the whole area of heat transfer and thermal properties is generally in good shape now, there remain several tasks which require additional work in the next future:

- The investiation of transient heat transfer and recovery in forced flow supercritical He.

- The study of two phase forced flow of He I in comparison to the other cooling (heat transfer, thermal properties, flow instabilities).

- The completion of heat transfer properties of He II, especially in complicated channel geometries. Emphasis should be put on reproducable values, e.g. for the Kapitza resistance of "technical surfaces", specific cases of transient behaviour, and on triple phase transition. Also the question of forced flow heat transfer properties in He II has not been investigated yet (turbulence factor).

- In all cases where similar investigations are carried out in different laboratories, comparable experiments are desirable to interpret scatter of data.

3. STABILITY STUDIES

This area concerns stability theories and stability experiments on superconductors.

The theories for conductor stability have been improved further and justified by experiments since the last workshop in 1977:

In pool boiling He I and in He II (including pressurized condition)

- the theories give good agreement with experimental results, taking into account transient heat transfer and recovery,
- so called "critical" lengths for spacers could be identified, and
- computer codes for quench propagation analysis are available, which are obviously also very important for magnet safety analysis;

For forced flow of He I:

- "cable in conduit"-conductors are also treated in detail now, with good theoretical interpretation of experimental results, fitting well in the general theories, when the occurance of a so called "transient flow" is taken into account;
- theory predicts that medium size normal conducting zones might be more dangerous than large or small zones, because they can remain quasistable;
- no transient heat transfer and recovery behaviour could be included in the theories yet, due to the lack of data;

Material input parameters are not completely sufficient.

A key question for all stability discussions is the uncertainty about the absolute values of possible disturbances. The use of stability investigations as a design tool is only of limited significance as long as the internal disturbance spectrum of a designed magnet is unknown. So far only trends, like an increase of the capability for disturbances with magnet size, perhaps also with the maximum field can be stated. Future work should possibly be concentrated more strongly on this subject, but the right kind of experiments cannot be defined easily. It was a clear understanding that the knowledge of detailed stress distributions and of microscopic energy releasing effects is stringent. Other areas of desired further advancements in stability theories concern the inclusion of a limited amount of helium and its thermal effects and the probability for replenishment of He within the recovery time.

The presentation on quench propagation analysis initiated some emphasis on the necessity for a trade off between stability and protection constraints:

- Especially the stabilizer cross section needs to be chosen such that it meets also a "hot spot temperature"-criteria for safety discharge.
- The occurance of "stable" normal conducting zones must be avoided.

4. STABILITY OF ACTUAL MAGNETS

Well performing magnets are not very often tested in such a manner as to find out their stability limits, especially when the magnets are very big. Thus, their stable behaviour can usually only be used as a qualitative reference for a successful design. More thorough investigations are performed, when magnets show degrated performance, but it is difficult to find a common basis, to compare different magnets. It was therefore suggested to look at the ratios of $I_{design}/I_{quench}/I_c$ in different magnets, as indicators for the probability of a quench.

In order to compare performance data of magnets it was proposed to introduce the following ratios in the list of specific design data for a magnet:

- A "current design factor" CD as the ratio of design current (rated current) I_{design} to the critical current I_c at the design field and the design cooling temperature (in a forced flow cooled system the temperature in the cooling channel point of B_{max})

$$CD \equiv \left. \frac{I_{design}}{I_c} \right|_{\substack{B = B_{design} \\ T = T_{design}}}$$

- A "current safety function" CS (Q) as the ratio of the design current I_{design} (at rated field and rated cooling condition) to the quench current $I_{quench}(Q)$ for a given disturbance energy Q.

$$CS(Q) \equiv \left. \frac{I_{design}}{I_{quench(Q)}} \right|_{B = B_{design}}$$

$I_{quench}(Q)$ can be derived from stability calculations or sample experiments, in principle. Thereby Q must be defined (instantaneous point disturbance, extended disturbance). Obviously standard tests might be desirable, but difficult to define.

All experts around the world are encouraged to use these factors to facilitate later communications about magnet stability. It was also a common opinion of the workshop participants that for later large scale engineering applications of superconducting magnets, e.g. in fusion reactors, standard tests with $I_{test} > I_{design}$ might be requested, e.g. by regulatory commissions, similar to present high voltage tests in electrical engineering, requiring a further factor such as I_{design}/I_{test}, which can become of importance.

In reviewing the success of magnets built so far it can be stated, that based on the potential of the different stabilization modes, a variety on design options exist, but no single optimal solution meeting the design constraints in all applications, e.g. concerning the cooling mode:

- Classical 4 K-pool boiling is best proven for large magnets, in part also classical 4 K forced flow. For well designed windings, the stability in He I is already sufficient, and it can be enhanced further (e.g. by Al-stabilizers);

- Other options (He II-cooling, cable in conduit cooling with small flow) are well prepared by basic experiments now and demonstration projects are in progress.

The different cooling modes require different conductor types for optimal stability, but it must be emphasized that the development of new conductors is always time consuming and costly, thus present magnet systems (built or under construction) should be evaluated carefully to most effectively guide further development effort with limited funds.

5. CONCLUSIONS

Superconducting magnet technology is a young branch of engineering. It is therefore not surprising, that the discussions about magnet performance problems and stability will not be finished with this workshop. However, a lot of progress has been reached so far. The present status can be summarized as following:

The understanding of stability was significantly improved since the 1977 workshop on this subject, in particular

- improved theories are available now,
- much more experimental data are collected, which verify the theories,
- new options on cooling modes, as pressurized He II, are investigated and ready for application.

The stability margin is only one of several factors dominating the magnet design, thus no unique design solution optimal for all applications can exist. For nearly all cooling and stability options, magnets are built or under construction. Thus careful evaluation of their data can guide future designs. For classification of a magnet, the introduction of a "current safety function" $CS(Q) \equiv I_{design}/I_{quench}(Q)$ and a "current design factor" $CD \equiv I_{design}/I_c$ is proposed.

Unsolved fundamental questions still remain, e.g. several specific topics concerning heat transfer or details on stability limits, but first of all, the quantification of the internal disturbance energy spectrum. As long as this question is not solved, advanced stability considerations as a design tool remain unfortunately of limited significance only.

HEAT TRANSFER AND THERMAL PROPERTIES

A RESUME OF THE WORKSHOP SESSION ON HEAT TRANSFER

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The sessions on heat transfer which took up the first day were very lively and instructive and covered a broad range. The day started with a review by Schmidt on He I pool boiling. After giving a clear outline of the principal features of the steady state heat transfer he described the transient temperature variation of a heated surface from the moment the heat is switched on. Experiments using fast thermometers show that the gas film that forms at the surface for large enough heat currents does not appear for about 1 ms which, he explained, is consistent with heat transfer by diffusion. In time t, the heat diffuses a length proportional to $t^{1/2}$ so that to evaporate the liquid in this length it is necessary that the heat transferred $Qt > Ct^{1/2}$ where C is proportional to the latent heat. There is then a minimum time $t_m = (C/Q)^2$ which must be exceeded before a film can form and for He I, $t_m \sim 1$ ms in agreement with experiment. For a time $t < t_m$, Schmidt noted that the temperature rise $\Delta T \propto Q$ (apart from an unexplained and apparently steep rise in ΔT at very small Q) with a slope consistent with Kapitza resistance values obtained below T_λ and appropriately reduced for these higher temperatures. He concluded his review by discussing how the surface temperature recovers when the heat current is switched off and the improvements obtained with coated surfaces and he emphasised the need for further work in this area.

The following paper by Komarek, who had generously stepped in at only three days notice, described the heat transfer in a hollow conductor for supercritical helium with forced flow. He made interesting comparisons with He I pool boiling and natural convection in helium under high g conditions produced by rotation. He then discussed in some detail how the characteristics depended on the flow velocity and also described the pressure build up with heat transfer and related these to thermodynamic arguments. The pressure increase is mainly responsible for the fall in the mass flow rate as the heat current in increased. He also discussed the effect of encouraging turbulence by changing the nature of the surfaces of the channels. Komarek concluded that we now had a rather clear picture of the heat transfer characteristics for steady state behaviour. However the position was much less satisfactory for transient effects and more work was needed here. The published paper also includes a description the EURATOM/LCT coil.

The morning session ended with a paper by Brechna who discussed how the heat generated as well as the efficiency of its transfer were affected by the thermodynamic and mechanical properties of the solids used. He briefly reviewed the ways in which heat was generated and he noted for example that plastic sheets placed between different components could significantly affect the way in which they moved relative to each other and so the energy generated by slip. He emphasised the number of variables, temperature, magnetic field etc which affected the thermodynamic behaviour and made a plea both for more data and for more systematic collection and storage.

The afternoon session was concerned with He II. Vinen gave a clear review of the properties of superfluid helium and discussed the additional thermal resistance caused by the resistance to the normal fluid motion, which carries the heat, associated with superfluid turbulence. This was originally described by the Gorter-Mellink law $\nabla T \propto Q^3$ which predicts that the maximum heat flux that a channel containing He II can sustain before the hot end reaches T_{sat} (or T_λ for pressurised helium) is $Q_m \propto L^{-1/3}$ but Vinen pointed out that experimentally there are significant departures from this law. He also discussed the nature of the equation describing the propagation of temperature excursions. At low frequencies the damping term due to superfluid turbulence dominates and the propagation is diffusive (δT decays with distance). However at high frequencies the second sound term dominates and the excursion propagates with only weak decay. (The frequency dividing these ranges depends on the heat current). Finally he discussed briefly the mechanism of Kapitza conductance and noted that although the detailed explanation of why this is so much better than acoustic theory is still not known, it is becoming clearer that this is associated with surface defects.

The following talk given by Seyfert showed how these properties affected the practical aspects of heat transfer. He first compared Kapitza conductance values for the sort of surfaces encountered in practice and noted that at high heat currents

($T_S^n >> T_L^n$) the usual expression $Q \propto (T_S^n - T_L^n)$ could be replaced by a single term which for copper was typically $Q = 0.049\ T_S^{2.8}\ W/cm^2$. He then described measurements in pressurized helium (1 bar) of heat transfer along tubes varying in length, ℓ, by more than two orders of magnitude. These were better fitted by the relation $Q \propto \ell^{-1/3.4}$ than the Gorter-Mellink law ($\ell^{-1/3}$). Seyfert also described experiments carried out with his colleagues in which heat pulses were applied to the end of tubes which were either closed or open to a helium bath. For a particular pulse length Δt they measured the maximum power Q and so energy $E = Q\Delta t$ that could be applied before burnout occured. As expected E is greatest when spread over a long time and its dependence on Δt (or $Q\ell^{1/3.4}$) is rather well described by the diffusion regime discussed in Vinen's talk. He also described experiments in which a pulse large enough to produce burnout was superimposed onto a steady heat current. Of particular interest was the information obtained on the largest energy pulse that the channel could accept if the system was going to recover.

The work described by Frederking was also concerned with transient effects. The heated solid was in a chamber connected by a channel to a pressurized helium bath and its temperature was recorded as a function of the time following the switching on of a heat current. Two steps in temperature were observed as expected. The first at t_L is associated with the formation of a macroscopically thick He I film and the second with a gas film. For $t < t_L$, the temperature rise is associated with heat transport down the channel when t_L is long and with localized Gorter-Mellink turbulences near the solid when t_L is short. The latter data provide a further test of the application of the Gorter-Mellink law to transient behaviour. The order of magnitude agreement is reasonable although significant departures were again seen.

Van der Sluijs' paper was concerned with Kapitza conductance and in particular the anomalous behaviour that has been reported in the relationship between Q and ΔT. The expected behaviour if, say $Q \propto |(T_L + \Delta T)^4 - T_L^4|$ is that $Q/\Delta T$ should remain constant to say 3% if $\Delta T/T_L < 2\%$ ($Q/\Delta T = 1 + 3\Delta T/2T_L$). However it has been found that it departs from the limiting value ($\Delta T \rightarrow 0$) at smaller values of $\Delta T/T_L$ and in the opposite direction to that expected. This has been attributed to variations in Kapitza conductance across the surface. If these are large enough, the local heat flux can be much larger than its average value so that superfluid turbulence can occur locally at quite low average values of heat flux producing an effective increase in the measured Kaptiza resistance. Van der Sluijs concluded his talk by describing a recent experiment in which surfaces were heated locally using a laser. This produced very localised film boiling, that is the formation of a small gas bubble which could be moved about the surface by moving the laser beam. The bubble was observed using a second laser and van der Sluijs suggested this technique might be used to see if film boiling recurred at hot spots on surfaces just before the main film formed.

Van Sciver described the variety of heat transfer characteristics that can occur if the tube geometry is varied. Much higher heat currents could be obtained before burnout if the channel was divided by filling it with a large number of fine tubes. He commented also on the enhanced heat transfer seen in saturated He II experiments when the heater area is larger than the channel cross-section. He also described experiments carried out when the liquid is made to flow past the heater (forced flow). The heat transfer is again enhanced. Finally Van Sciver discussed the suggestion that additional heat transfer might occur in pressurized He II if bubbles of He I and vapour formed. This multiphase mixture could then have a gravitationally induced forced convention much the same as occurs in saturated He II.

The paper given by François described the behaviour of saturated He II in geometries where the heat current was greatest at points away from the heater. In these situations the helium first crosses the liquid-gas phase boundary away from the heater. The liquid becomes superheated and then returns to the saturated state by releasing a cloud of bubbles. The cloud is accompanied by a temperature pulse and these events occur with regular periodicity. The authors have investigated how the period depends on the degree of superheating and also the effect the boiling has on the overall heat flow. It would be of interest to see if related effects could occur in pressurized helium; although the work of Van Sciver suggests that any increase in heat transfer may be small, the negative slope of the λ-line indicates that the pressure gradient would now need to be opposite to the temperature gradient and more extreme geometry might be needed.

These sessions on heat transfer demonstrated that considerable progress has been made in our knowledge and understanding of heat transfer characteristics in the last few years. It also became clear that there was still work to be done. Schmidt and Komarek stressed the need for further studies of transient behaviour in He I (transient recovery) and supercritical helium under forced flow and still more needs to be done in He II where our knowledge of even steady state characteristics reamins somewhat incomplete. Because of the variation in the Gorter-Mellink parameter with both geomety and heat flux, it would at present be difficult to make accurate calculations of steady state heat flow in complicated channel geometries so that experimental work is needed here. Another problem, which may take some time to solve, is the variation of Kapitza resistance among surfaces prepared in apparently identical conditions. There is also more to be investigated in the transient regime. The work described in the sessions is consistent with turbulence achieving its equilibrium value instantaneously. This is clearly impossible and we need to measure how fast it takes under the variety of conditions occuring in practical situations. It would also be useful to know how fast the He I film and the gas film take to form; that is the time between the start of formation and its completion. It is clear too that we must continue thinking about non-equilibrium situations, instabilities etc such as the possibility of a gas bubble or a He I "bubble" forming and causing a temporary block to the normally efficient heat transfer. This could presumably cause problems if it coincided with a large heat pulse and suggests the need for further studies on the formation and lifetime of these bubbles. Finally we should perhaps anticipate the possibility of operating magnets in the presence of ionizing radiation and investigate the effect of the He ions formed on the heat transfer. The ions will collect preferentially along vortices and might modify their interaction.