# RATIONAL DESIGN OF HIGH-CURRENT CABLE-IN-CONDUIT SUPERCONDUCTORS*

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## ABSTRACT

Cable-in-conduit superconductors are composed of a cable of many fine composite strands encased in a strong, protective jacket, with helium coolant filling the interstices of the cable. Because of the high degree of subdivision of the composite and its consequent large cooled surface, such conductors are capable of stable operation at quite high current densities.

The designer of such conductors is frequently given the field at the conductor and the overall current density and asked to specify the remaining variables of the conductor (e.g., the strand diameter, the hydraulic path length, the void fraction of the cable, and the Cu/SC ratio). This paper outlines a rational procedure for determining the most problematic variables, the two composition variables that determine the proportions of copper, superconductor, and helium in the cable space. All other variables of the conductor are assumed known.

Two thermodynamic states of the helium coolant, supercritical He-I and 1-atm He-II (superfluid helium), are considered. For these states of helium, hydrodynamic phenomena exist that add to the stability of the superconductor. The allowed compositions with helium in the supercritical state are limited by three constraints: (1) that the stability margin be single valued, (2) that the quench pressure not exceed some preset value, and (3) that there be sufficient superconductor to carry the transport current. These three constraints define an allowed region of the composition plane (variables: fraction of strands in the cable space and the fraction of copper in the strands). With the helium in the superfluid state, the stability margin is single valued, but a constraint on composition involving stability arises from the Kapitza interfacial resistance. Thus, in this case, too, there are three constraints. For each state of helium, a computer program plots the allowed region of the composition plane and draws contours of the stability margin and the pressure. A composition of the desired conductor can then be chosen rationally.

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Two examples, an 8-T fusion magnet and a 15-T detector magnet, are given and are discussed in detail.

## INTRODUCTION

Cable-in-conduit superconductors are composed of a cable of many fine composite strands encased in a strong, protective jacket; the interstices of the cable are filled with helium. Because of the high degree of subdivision of the composite and its consequent large cooled surface, such conductors are capable of stable operation at quite high current densities.

The designer of such conductors is frequently given the field at the conductor and the overall current density and asked to specify the remaining variables of the conductor (e.g., the wire diameter, the hydraulic path length, the void fraction of the cable, and the Cu/SC ratio). Of the variables, the most problematic are the two composition variables that determine the proportions of copper, superconductor, and helium in the cable space. In this paper, all the variables of the conductor are assumed known except the two composition variables, and a rational procedure is outlined for their determination.

Two thermodynamic states of the helium coolant are considered in this paper: supercritical He-I and 1-atm He-II (superfluid helium). For both of these states of helium, hydrodynamic phenomena exist that contribute to the high stability of the superconductor. When the helium is in the supercritical state, it undergoes strong heating-induced flow transients during recovery that augment heat transfer from metal to helium and greatly improve stability. When the helium is in the superfluid state, the high heat transfer caused by Gorter-Mellink counterflow leads to very high stability.

A quantitative measure of the stability of a cable-in-conduit conductor is the so-called stability margin, i.e., the largest, sudden, uniform energy deposition in the strands still allowing recovery of the superconducting state. When the helium is in the supercritical state, the stability margin is sometimes multivalued. That is, as the energy deposition is progressively increased in a series of experiments, the conductor sometimes exhibits the double sequence of responses recover, quench, recover, quench rather than the single sequence recover, quench. Which response occurs depends strongly on the current density. A semiempirical correlation exists to calculate the limiting current density that avoids multiple stability and its attendant reduction in stability margin.

Another limitation on the conductor design is that the maximum quench pressure following the worst case of the sudden normalization of an entire hydraulic path should not exceed some preset limit. A formula exists for the computation of this quench pressure. A third, obvious limitation is that there should be enough superconductor to carry the entire operating current.

These three limitations define an allowed region of the composition plane (variables: fraction of strands in the cable space and the fraction of copper in the strands). A computer program plots this region and draws contours in it of the stability margin and the maximum quench pressure. The program also identifies the points of maximum stability and minimum quench pressure. With this plot before him, the designer is able to choose rationally the composition of the desired conductor.

When the helium is in the superfluid state, the stability margin is single valued. A theory exists for the computation of the stability margin; this theory indicates that there is a constraint on stability arising from the Kapitza interfacial resistance that limits the possible conductor compositions. Thus in this case, too, there are three constraints. A computer program again plots the allowed region of the composition plane and plots contours of stability margin and pressure.

Two examples are given of conductor design carried out with the procedure outlined above. One is a 4.0-K NbTi conductor destined for use in a fusion magnet at a maximum field of 8 T. The second is a 1.8-K $Nb_3Sn$ conductor intended for use in a detector magnet at 15 T.

## PHENOMENOLOGY OF CABLE-IN-CONDUIT SUPERCONDUCTORS

As mentioned earlier, a cable-in-conduit conductor is one in which the superconductor is contained in a braided cable that is enclosed in a protective jacket. Helium, usually supercritical but also possibly superfluid, fills the interstices of the cable. The strands composing the cable are made of a matrix material (usually copper but sometimes aluminum) in which are embedded many fine filaments of pure superconductor. Such cabled conductors contrast sharply in form with pool-cooled conductors in which the matrix and superconducting filaments form a solid bar that is immersed in a pool of boiling helium.

The most important property of superconductors is their ability to recover the superconducting state after a sudden heat input. Such inputs typically arise from conductor motion caused by the Lorentz force, but other causes are possible (e.g., plasma disruptions in tokamaks). If the heat input is large enough, it may cause the superconductor to become resistive. Then, because the conductor is carrying current, it produces more heat. If it is well-enough cooled by the helium, it may recover the superconducting state. If not, the supply of current to the conductor must be interrupted, or the conductor may be destroyed. When the conductor fails to cool down and recover the superconducting state, it is said to "quench." The recovery of pool-cooled conductors can be guaranteed by supplying enough copper (often 10 to 20 times the amount of superconductor). Such conductors are called "cryostable." Because of the large amount of copper they contain, their average current density is low. For example, the pool-cooled conductors of the International Energy Agency's Large Coil Task had current densities over the winding pack of about 2.6 kA/cm$^2$ [1].

Cable-in-conduit conductors contain less copper than cryostable pool-cooled conductors and accordingly operate at higher current densities than pool-cooled conductors. For example, the Westinghouse coil of the Large Coil Task, which was wound with a cable-in-conduit conductor, had a current density of 4.3 kA/cm$^2$ over the conductor area. The advantage of higher current density is offset by the disadvantage that cable-in-conduit conductors are not cryostable. The reason they are not is this: recovery from a sudden heat input takes only tens of milliseconds, whereas the helium often resides in the conductor for minutes. Therefore, the helium inventory available for promoting recovery is limited. A large-enough heat input can thus quench the conductor. In cryostable pool-cooled conductors, in contrast, the helium inventory available for recovery is effectively infinite because helium vaporized by contact with the conductor is immediately replaced by cold liquid helium from the pool. (However, if the winding pack is tight and the helium passages are small, vapor locking of these passages may occur, and the conductor may fail to recover.)

Small heat inputs do not quench cable-in-conduit conductors; large ones do. The largest, sudden, uniform heat input to the strands after which recovery of the superconducting state is still possible is called the "stability margin." As noted earlier, the stability margin is a quantitative measure of the stability of the superconductor. Cable-in-conduit conductors are usable in any application in which the stability margin is larger than any heat inputs to the conductor. The stability margin is limited by the enthalpy difference of the helium between ambient temperature and the current-sharing threshold temperature of the superconductor. (The current-sharing threshold temperature is the temperature at which the superconductor is no longer able to carry all the current and some current spills over into the matrix.) Not all of this enthalpy is available, because the Joule heat produced during recovery must be subtracted from it.

The stability margin of some cable-in-conduit conductors cooled with supercritical helium has been measured in experiments in which the conductor was exposed to a succession of heat inputs, each of which was larger than its predecessor. In experiments done at the Oak Ridge National Laboratory (ORNL) [2], we expected an eventual switch in the outcome of the experiments from recovery to quench. This was usually what happened, but in some experiments a double switch was observed; that is, the sequence of outcomes was recovery, quench, recovery, quench. In the data from ORNL shown in Fig. 1, for example, when the transport current is 380 A, heat inputs to the metal strands less than 50 mJ/cm$^3$ lead to recovery; inputs between 50 and 90 mJ/cm$^3$ lead to quenching; inputs between 90 and 300 mJ/cm$^3$ again lead to recovery; and inputs above 300 mJ/cm$^3$ again lead to quenching. The results of many experiments done at ORNL are summarized in the three-dimensional sketch in Fig. 2. Plotted on the vertical scale is the stability margin, and plotted on the horizontal scales are the current and the imposed helium flow velocity. (The imposed flow is created by the refrigerator or by pumps.) The surface that represents the stability margin is folded, and the fold is connected with the double switch in outcomes.

Inside the shaded region under the fold, the sequence of outcomes as the heat input is raised is recovery, quench, recovery, quench. Outside this region, the sequence is recovery, quench. This unusual situation is caused by the heating-induced flow transients that occur during recovery [2]. It turns out that, on the upper sheet of the folded surface, the stability margin is approximately equal to the available enthalpy of the helium, whereas, on the lower sheet, it is much smaller. Accordingly, it is worth while to design cable-in-conduit conductors to operate at currents less than the current at point B in Fig. 2. In this way, we can fully exploit the available enthalpy of the helium.

The current at point B, which is called the "limiting current," can be determined for any conductor from the results of the experiments already carried out and a scaling rule given in Ref. [3]. The validity of the scaling rule itself has been tested experimentally [4] and the rule corroborated.

The information summarized previously enables us to determine by calculation the stability margin of proposed cable-in-conduit conductors cooled by supercritical

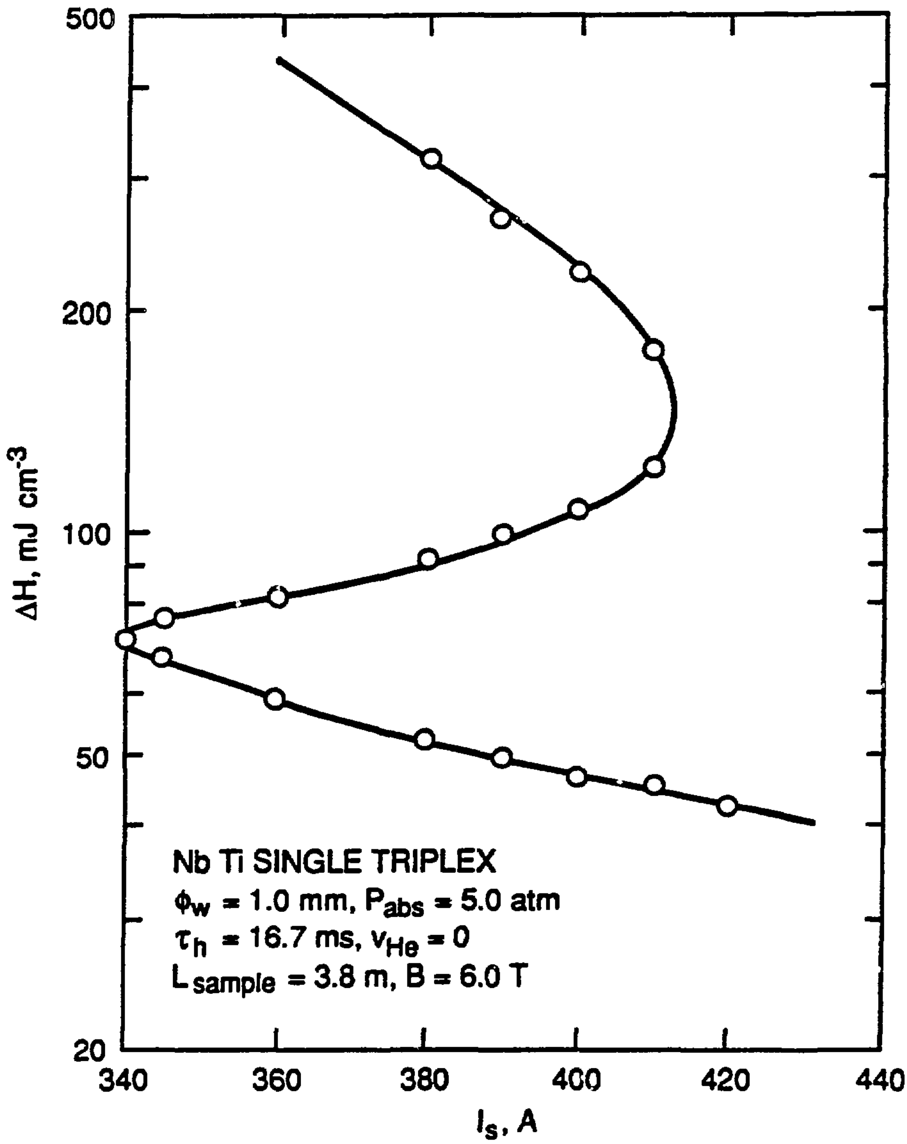


Fig. 1. Experimental data from the Oak Ridge National Laboratory [2] showing the double sequence of outcomes recovery, quench, recovery, quench.

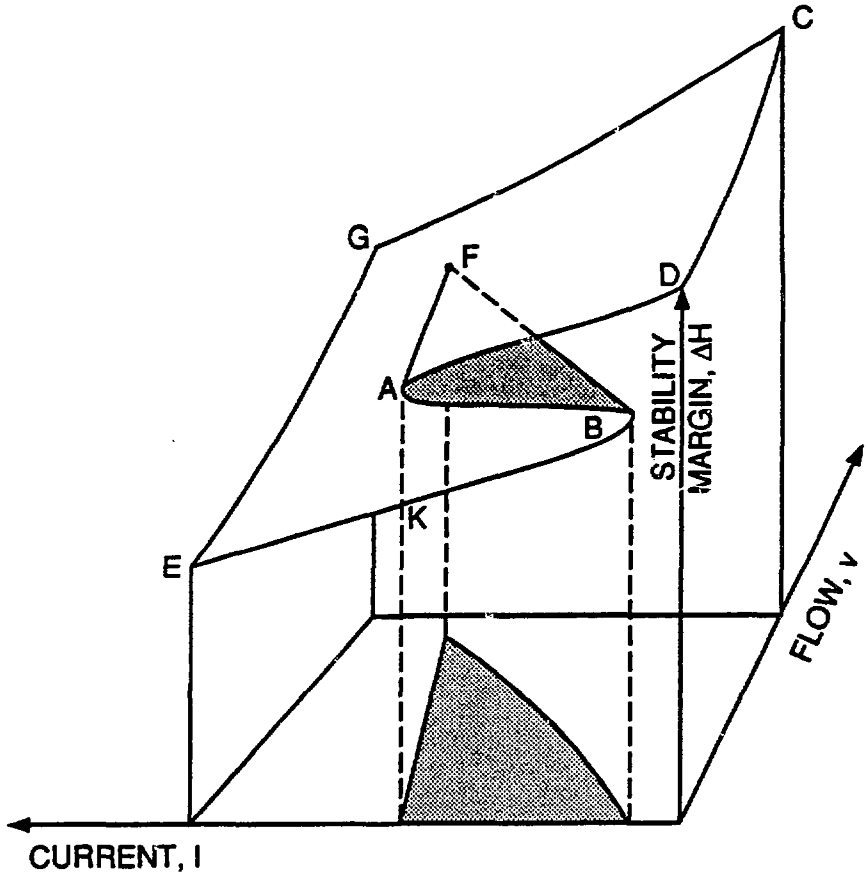


Fig. 2. A three-dimensional sketch summarizing the results of many experiments done at the Oak Ridge National Laboratory. The fold in the surface is connected with the double sequence of outcomes recovery, quench, recovery, quench.

helium and to design conductors that are not likely to quench. But, if they should quench, we must be sure that they will not suffer damage. When cable-in-conduit conductors quench, they may be exposed to a high internal pressure, which they must be designed to withstand. In the worst case of an entire hydraulic path going normal all at once, the maximum quench pressure can be calculated by using a simple formula given in Ref. [5]. This formula has been tested for quench pressures between 4 and 200 atm [5, 6] and found to be accurate.

The stability margin of cable-in-conduit superconductors cooled with superfluid He-II is defined slightly differently from that for superconductors cooled with supercritical helium. It is defined as the largest, sudden, uniform energy deposition in the strands still allowing recovery of the superconducting state without the helium temperature being raised above the He-II–He-I transition temperature. The restriction on the temperature of the helium is necessary to allow computation of the stability margin [7, 8]. Conductors cooled with He-II may actually be stable against larger perturbations.

When defined in this way, the stability margin is single valued; thus, the limitation of the allowed area in the composition plane having to do with the limiting current no longer applies. However, a new limitation, having to do with the Kapitza interfacial resistance, takes its place. If the normal-state Joule heat flux from the conductor to the helium is large enough, the temperature difference across the phase boundary induced by the Kapitza resistance will be large enough to keep the metal temperature above the current-sharing threshold. Recovery is then impossible. So again there are three limitations that define an allowed region of the composition plane that can be plotted together with contours of the stability margin.

The stability of cable-in-conduit superconductors cooled by superfluid helium does not depend on heating-induced flow. In fact, the coefficient of thermal expansion of superfluid helium is much smaller than that of normal helium [9]; thus, there may be very little induced flow in the superfluid. Moreover, there is good evidence that the heat transfer coefficient to superfluid helium is independent of the cross-flow velocity [10]. Instead, stability in He-II depends on heat transfer by the highly efficient Gorter-Mellink counterflow. Therefore, tight confinement of the helium bathing the strands is not necessary as it is for supercritical helium, where it promotes axial heating-induced flow over the strands. For example, when He-II is the coolant, the jacket of the conductor might be perforated and allowed to communicate with an outside space, thereby providing pressure relief during a quench. Thus, quench pressure is not a critical limitation for cable-in-conduit superconductors cooled with superfluid He-II. The cable-in-conduit superconductor is still advantageous because of the fine subdivision of the strands which provides a large cooled surface. The jacket, whether closed, perforated, or open (as in a U-shaped channel), provides mechanical protection for the strands. Furthermore, it serves as co-wound structure that prevents the buildup of the Lorentz force on the cable.

## EXAMPLE 1: AN 8-T NbTi/Cu CONDUCTOR FOR A FUSION MAGNET

The design goal in the first example is to achieve a current density over the cable space of 20 $kA/cm^2$ at 4.0 K and 8 T in a NbTi/Cu cable-in-conduit conductor. The critical current density in pure NbTi at 4.0 K and 8 T was taken to be 1340 $A/mm^2$, following the data reported by Larbalestier et al. [11]. According to these authors, this current density was typical of the best available industrial material at the time (1986) they wrote their article. The residual resistivity ratio of the copper was taken to be 100, and the strand diameter was taken to be 0.7 mm, which is the strand diameter of the Westinghouse coil of the Large Coil Task. The ambient pressure of the helium was taken to be 5 atm. The length of a hydraulic path was taken to be 20 m. The quench pressure was limited to no more than 500 atm.

Figure 3 shows the allowed area of the composition plane under the constraints. Three sets of contours cross this area, one set for the stability margin, one set for the quench pressure, and one set for the ratio of transport to critical current. The largest stability margin attainable is 123 $mJ/cm^3$; the smallest quench pressure attainable is 258 atm. Note that these extremes refer to different conductors.

We deem a stability margin of 123 $mJ/cm^3$ to be adequate mainly on the experimental evidence of Lue and Miller [12], who operated an experimental NbTi cable-in-conduit coil at 7.7 T and 4.2 K and at 8.1 T and 3.9 K. The measured stability margin of the conductor was less than 50 $mJ/cm^3$, and the magnet never quenched spontaneously. The Lue-Miller 36-strand cable was a rather loose one (void fraction of 43%) and thus presumably had a greater potential for strand motion than the tighter cables shown in Fig. 3 (void fractions of 10–20%). It would therefore appear that a stability margin around 100 $mJ/cm^3$ should be sufficient to ensure stable operation.

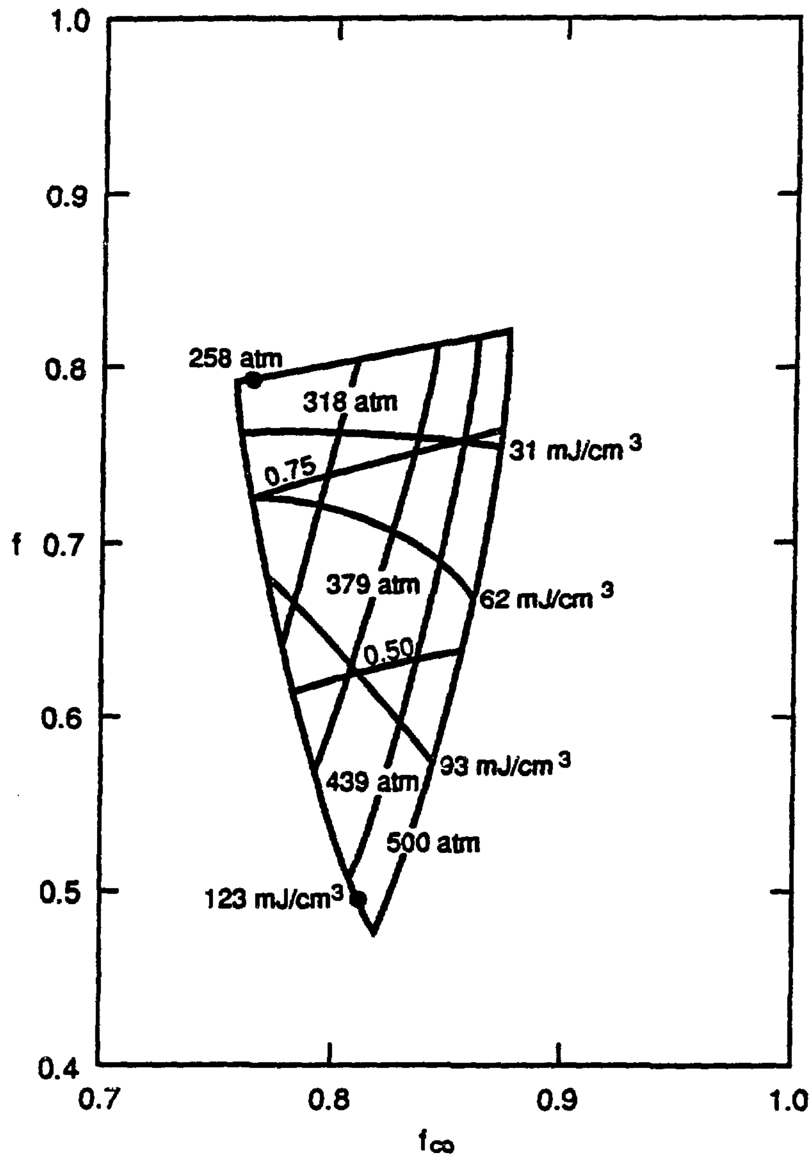


Fig. 3. The allowed area of the composition plane for the NbTi/Cu cable-in-conduit conductor (20 kA/cm² at 4.0 K and 8 T).

The quench pressures in the allowed area are rather high. For example, the conductor with 20% voids and a Cu/SC ratio of 1.8, for which the stability margin is about 95 $mJ/cm^3$, has a maximum quench pressure of roughly 350 atm. This figure corresponds to a 20-m hydraulic path length, which is rather small for a fusion magnet and means added complexity in the plumbing. So it appears that, for the rather high current density we have chosen to aim at, the limiting factor is quench pressure, not stability.

A variation of the ordinary cable-in-conduit conductor that may allow reduction of the quench pressure is shown in Fig. 4*b*. The inner conduit is perforated and allows the cable space to communicate with the four open helium spaces in the corners. These open spaces are intended to relieve the quench pressure. They have the disadvantage that they and the inner conduit take up space that in the conductor of Fig. 4*a* is devoted to carrying current. If the conductors of Figs. 4*a* and 4*b* are to carry the same total current, the current density over the cable space in the conductor of Fig. 4*b* must be higher than that of the conductor of Fig. 4*a*.

To quantify these considerations, I took the physical dimensions of the plain cable-in-conduit conductor of Fig. 4*a* to be those of the Westinghouse conductor (i.e., 20.8- by 20.8-mm exterior dimensions with a jacket thickness of 1.75 mm). The thickness of the inner jacket I took to be 0.5 mm and assumed it to have a circular shape just tangent to the interior of the square jacket. To help reduce the Joule heat production, I assumed the inner jacket to be made of the same copper as used in the strands (RRR = 100). In order to carry the same current as the conductor of Fig. 4*a*, the current density over the cable space in the conductor of Fig. 4*b* must be 28.7 $kA/cm^2$.

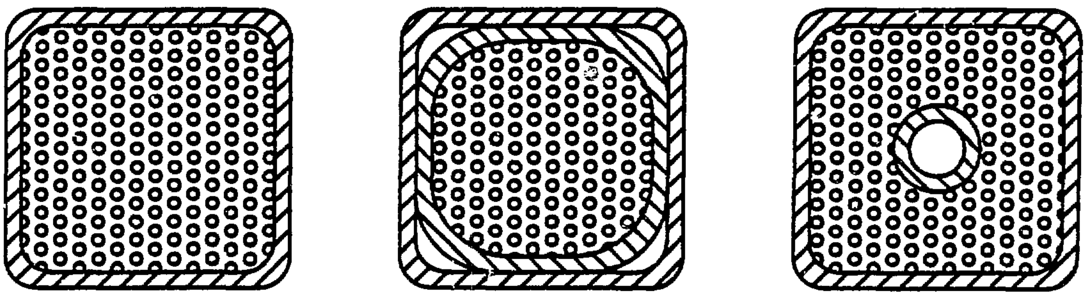


Fig. 4. A sketch of a plain cable-in-conduit conductor and two variations that may allow reduction of the quench pressure.

The plain cable-in-conduit conductor of Fig. 4*a* has a length-to-diameter (L/D) ratio of about $5 \times 10^4$ (the hydraulic diameter is roughly 0.2 mm for 20% voids, and the half-length of a flow path is 10 m). For such a large L/D ratio, the inertial terms in the momentum equation can be neglected; the pressure gradient is expended in overcoming wall friction, not in accelerating the fluid. This simplification, as explained in Ref. [5], leads to a simple formula for the maximum quench pressure that has been used to calculate the quench pressure for the conductor of Fig. 4*a*. The experiments that corroborated this formula were carried out with L/D ratios of $1.23 \times 10^5$ and $6.16 \times 10^4$ [5].

The hydraulic diameter of the corner spaces in the conductor of Fig. 4*b* is 2.08 mm, so the L/D ratio is now only 4810. Is this too small to allow the use of the frictional theory previously described? The condition for the validity of the frictional theory is that $fL/D \gg 1$, where $f$ is the Fanning friction factor of the flow path. For typical Reynolds numbers ranging from $10^5$ to $10^6$, the smooth-tube friction factor ranges from 2.5 to $4.0 \times 10^{-3}$; thus, L/D should exceed the 250 to 400 range in order for the frictional theory to be valid. Hence, even for the conductor of Fig.4*b*, we use the frictional theory to calculate the quench pressure.

Figure 5 shows the allowed area of the composition plane together with the contours of stability margin, quench pressure, and fraction of critical current. The cables are even tighter than before, having void fractions of 15% or less. The stability-optimized conductor has a stability margin of 56.6 mJ/cm$^3$ and a maximum quench pressure of 144 atm. So we appear to have achieved an appreciable reduction in quench pressure at the expense of some reduction in stability.

An even more convenient disposition of the open helium space is shown in Fig. 4*c*. When the diameter of the perforated inner copper tube is reduced, the volume it occupies can be made smaller. Therefore, the current density in the cable space need not be as high as that for the conductor of Fig. 4*b*. For example, if the thickness of the copper tube is kept at 0.5 mm but its outer diameter is reduced to 7 mm, the current density in the cable space must be 22.5 kA/cm$^2$ to match the current in the conductor of Fig. 4*a*. The L/D ratio is 1667, which is probably enough to continue using the limiting frictional theory to compute the quench pressure. Figure 6 shows the allowed area of the composition plane together with the contours of stability margin, quench pressure, and fraction of critical current. The void fraction is 20% or less; the stability-optimized conductor has a stability margin of 97.2 mJ/cm$^3$ and a quench pressure of 109 atm. So with this arrangement we have increased the stability margin and reduced the quench pressure modestly.

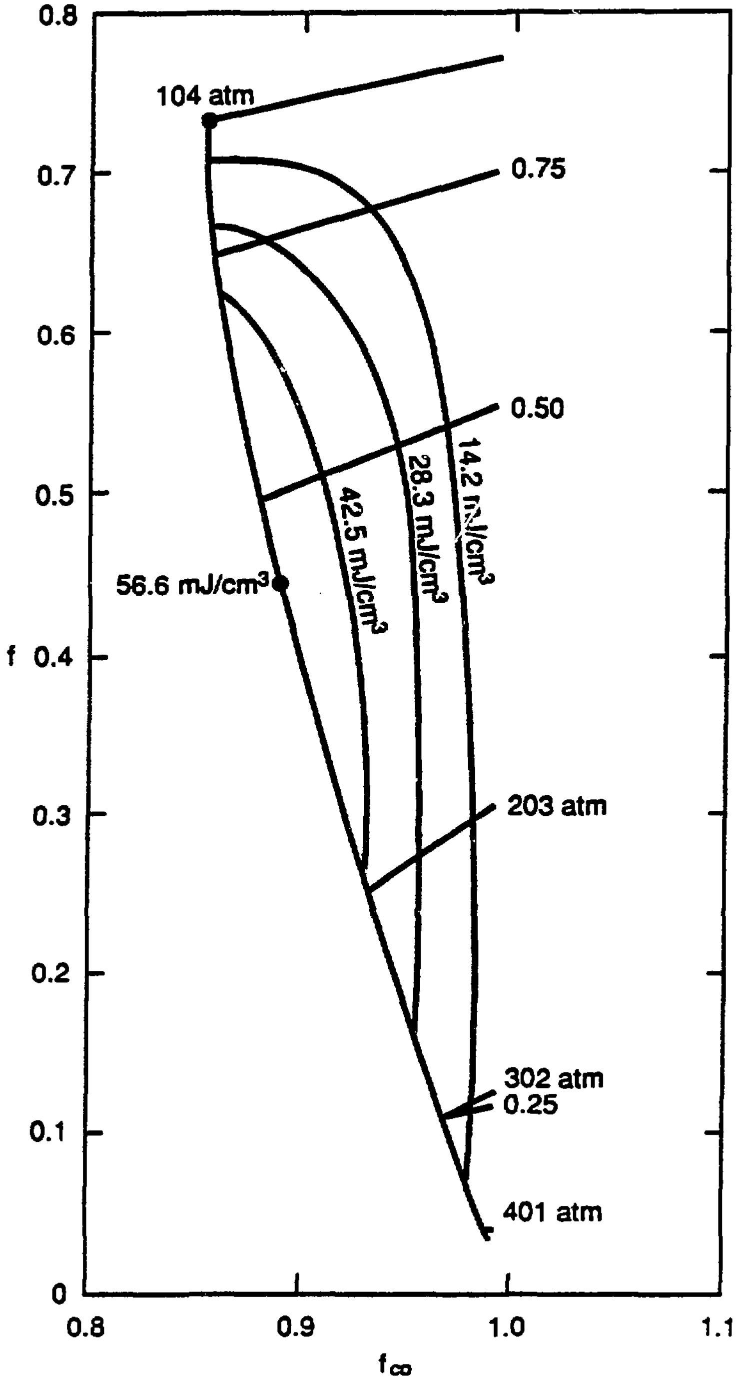


Fig. 5. The allowed area of the composition plane for the cable in a double conduit (Fig. 4b).

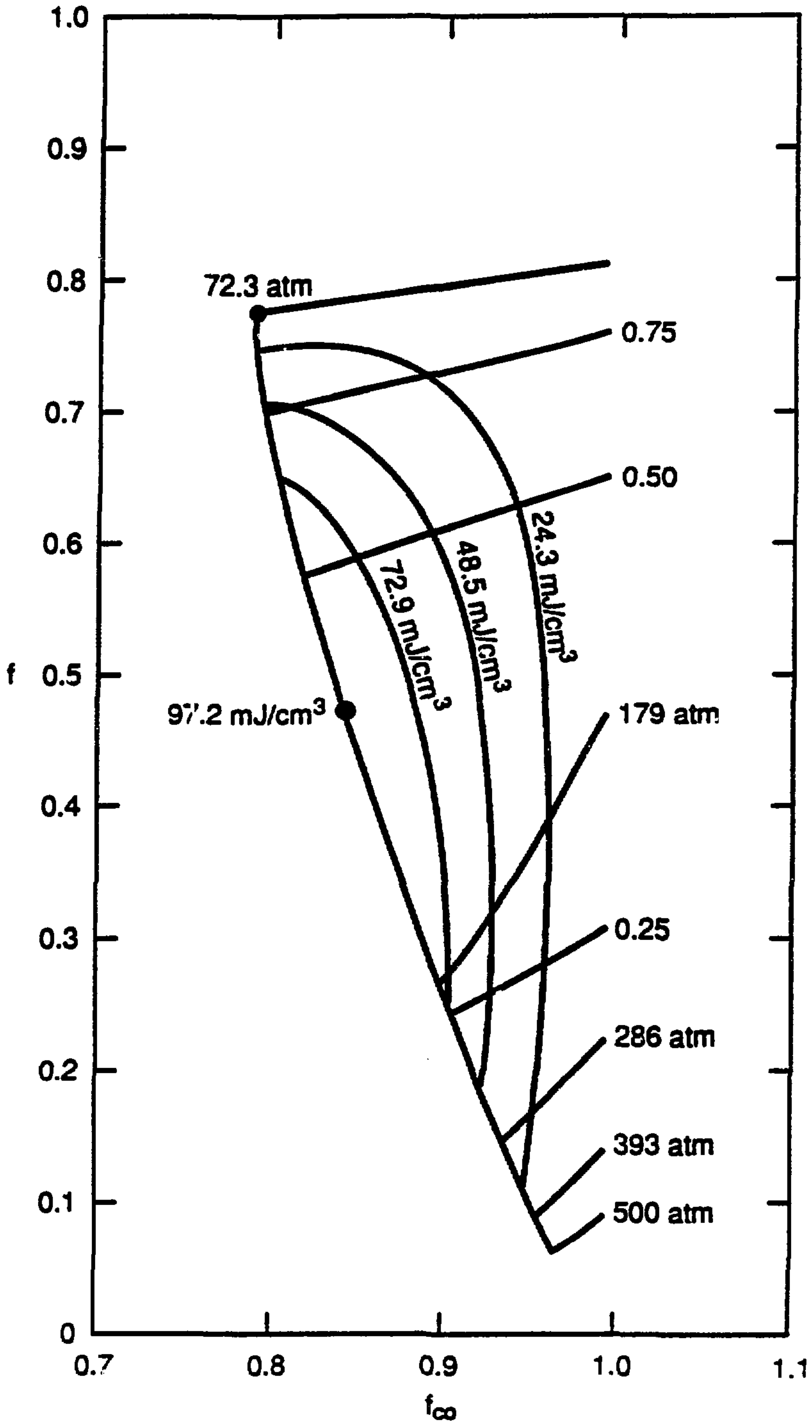


Fig. 6. The allowed area of the composition plane for the tube-in-cable configuration (Fig. 4c).

According to Lue et al. [13], the current density over the entire winding pack could be 35–65% of that over the cable space, the precise value depending on the size and shape of the cable-in-conduit conductor and the amount of external insulation wrapped around it. On the basis of this estimate, a target value of 10 $kA/cm^2$ over the entire winding pack seems a reasonable target for an 8-T, 4.0-K NbTi cable-in-conduit conductor. I wish to emphasize again at this point that such a conductor should operate stably in spite of its high current density.

## EXAMPLE 2: A 15-T $Nb_3Sn$/Cu CONDUCTOR FOR A HIGH-FIELD DIPOLE MAGNET

The design goal in the second example is to achieve as large a current density as possible over the cable space consistent with a stability margin of 100 mJ/cm$^3$ at 1.8 K and 15 T in a $Nb_3Sn$ cable-in-conduit conductor. The critical current density in pure $Nb_3Sn$ at 1.8 K and 15 T was taken to be 3700 A/mm$^2$, following the data reported by Foner et al. [14] for (Nb–4 at. % Ta)$_3$Sn. The residual resistivity ratio of the copper was again taken to be 100, and the strand diameter was again taken to be 0.7 mm. The ambient pressure of the helium, which is now in the superfluid state, was taken to be 1 atm.

As mentioned earlier, the stability of a cabled superconductor cooled with superfluid helium depends, not on heating-induced flow of the helium over its surface, but on heat transfer by the highly efficient Gorter-Mellink counterflow. Thus, tight confinement of the helium is not necessary. If we start by assuming the conduit to be perforated and to communicate hydraulically with a large plenum allowing pressure relief, we can ignore the constraint of quench pressure. Figure 7 shows the allowed area of the composition plane along with contours of stability margin and fraction of critical current for a current density over the cable space of 45 kA/cm$^2$. The stability-optimized conductor has a stability margin of 98.6 mJ/cm$^3$. On the basis of this estimate, target values of 15–30 kA/cm$^2$ over the entire winding pack seem a reasonable target for a 15-T, 1.8-K $Nb_3Sn$ cabled conductor. Again I emphasize that such a conductor should operate stably in spite of its high current density.

If the conductors surveyed in Fig. 7 were confined in an impervious conduit with a hydraulic path length of 20 m, the quench pressure they would suffer in the event of the simultaneous quench of a whole hydraulic path would be in excess of 800 atm. (This number may not be very accurate owing to the extension of the theory of Ref. [5] outside the range for which it has been checked experimentally, but there is no question that the quench pressure would be very high.) Therefore, for a plain cable-in-conduit conductor, a current density over the cable space of 45 kA/cm$^2$ is too large. However, if we reduce the current density over the cable space to 20 kA/cm$^2$, we see (from Fig. 8) that conductors with acceptable quench pressures exist. The allowed region of the composition plane is rather large, but only the lenticular region above and to the left of the 275-mJ/cm$^3$ contour is really interesting. This is the region of conductors with quench pressures around 200 atm and stability margins around 300 mJ/cm$^3$. These conductors have Cu/SC ratios in

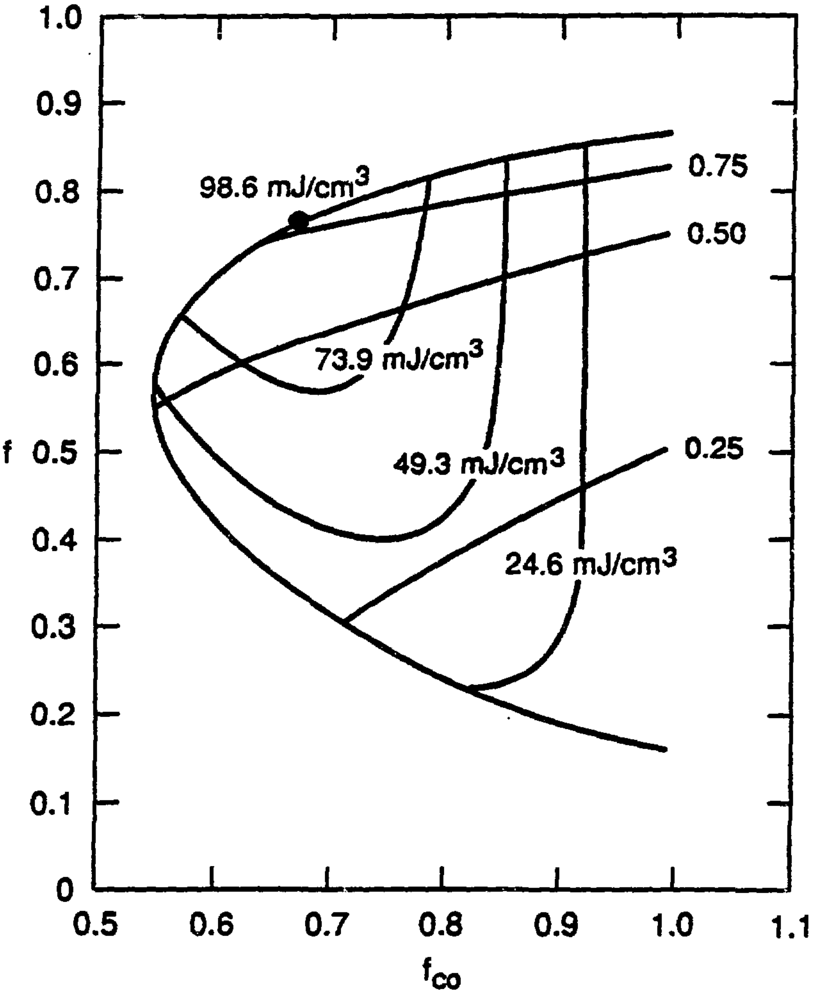


Fig. 7. The allowed area of the composition plane for the (Nb–4 at. % Ta)$_3$Sn/Cu cable-in-conduit conductor (45 kA/cm$^2$ at 1.8 K and 15 T).

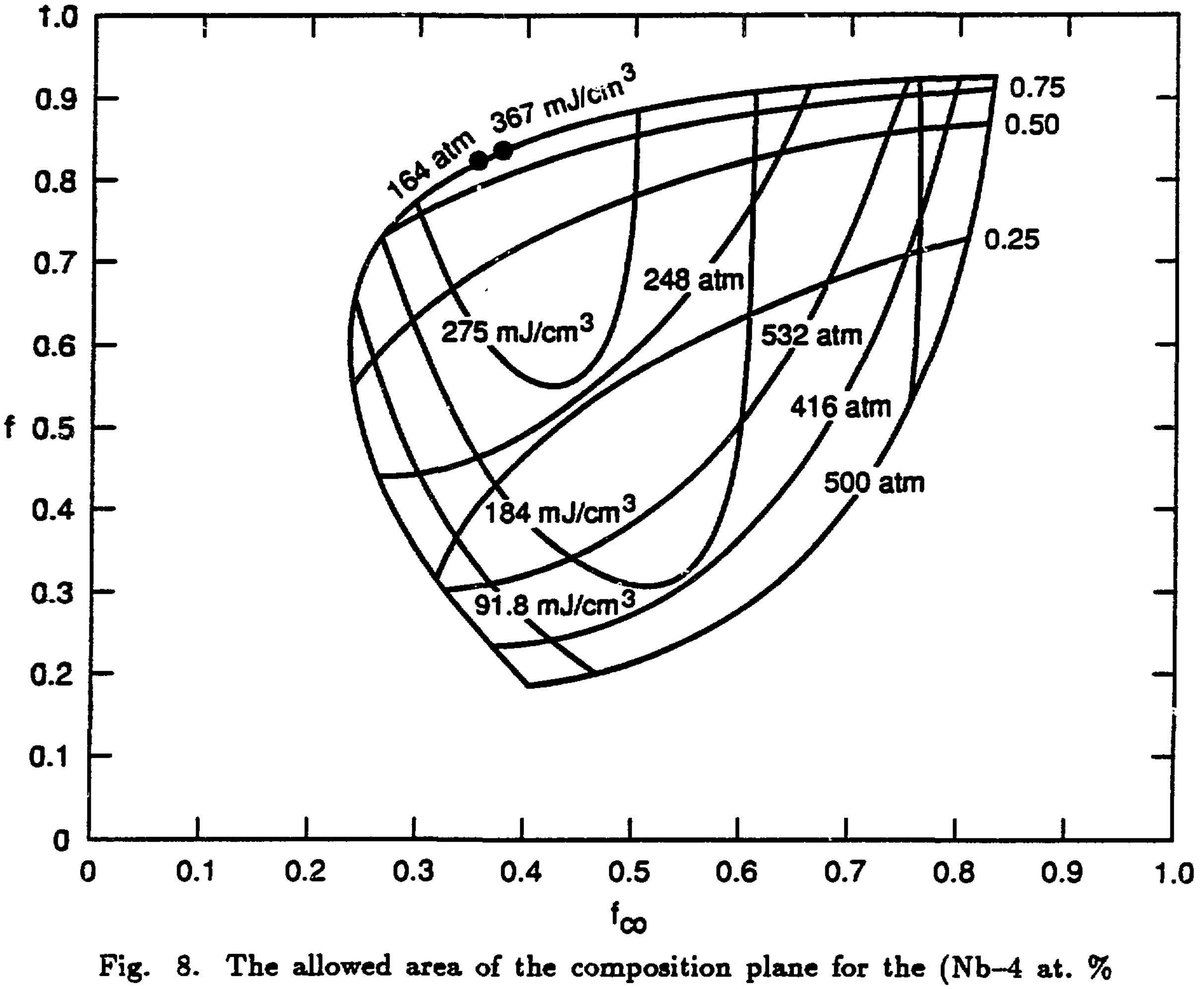


Fig. 8. The allowed area of the composition plane for the (Nb–4 at. % Ta)$_3$Sn/Cu cable-in-conduit conductor at a lower current density than that of Fig. 7 (20 kA/cm$^2$ at 1.8 K and 15 T).

the neighborhood of 3 and void fractions of roughly 60%. If such cables are believed to be too loose, moving to void fractions of 30% would increase the quench pressure to roughly 300 atm and reduce the stability margin to roughly 150 mJ/cm$^3$. Some improvement is doubtless possible by using the configurations of Figs. 4*b* and 4*c*, but the best solution to the quench pressure problem in the superfluid case is to abandon the idea of tight confinement of the helium. This will, however, vitiate the advantage cable-in-conduit conductors have of being completely surrounded by insulation and thus of being able to withstand a large voltage.

## CONCLUDING REMARKS

As we have seen, cable-in-conduit superconductors should be capable of stable operation at high current densities, which means smaller and therefore cheaper magnets. Furthermore, smaller magnets may mean smaller machines overall, so that the savings won by the high current density may be magnified beyond just the savings on the magnets themselves. The capability for withstanding high voltage (>10 kV) due to their unbroken exterior insulation is another advantage of these conductors. In addition, because the jacket acts as co-wound structure and because the conductors may be potted in epoxy, the winding pack can be quite rigid. Finally, the helium inventory is lower than that in pool-cooled magnets. Taken all together, these advantages make cable-in-conduit superconductors an attractive alternative for superconducting magnets. The preceding rational design procedure, which is the fruit of basic research carried out over the last decade, eliminates the guesswork from the design of these conductors.

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