If electrical equipment, such as a superconducting magnet drawing currents of more than 100 A, is run at liquid He temperature, the heat input from the current leads to the equipment begins to form an appreciable part of the total heat input into the cryostat and has to be taken into account if a design with a minimal total refrigeration cost is aimed at.

Decisions have to be made on the following points:
1) material of current lead;
2) length/cross-section ratio;
3) counter current cooling by an appropriate flow of cold He gas;
4) safety against burn-out in case of accidental overload or lack of cooling.

The ideal material should combine high electrical and low thermal conductivity, which in reality does not exist (Widemann-Franz law). The problem has been discussed by Locke\(^1\). He shows that very high purity copper gives highest efficiency. But then the tendency to thermal runaway is particularly pronounced since resistivity increases strongly with temperature. A less pure copper cures this weakness with little loss in efficiency. For the BEBC current leads, therefore, ETP copper with \(\rho_0 = 2 \times 10^{-8} \text{ }\Omega\cdot\text{cm}\) has been chosen.

Points 2 and 3 have been discussed up to now in assuming that all the gas evaporated by heat flow \(Q_c\) from the cold end of the lead is used for counter current cooling. This is a good assumption if dewar cooling is used and all the gas is anyway recovered at room temperature. But in installations which like BEBC are refrigerator-cooled, the reliquefaction of warm gas is about five times more expensive than that of cold gas.

So if only a mass flow corresponding to a part \(Q_m\) of \(Q_c\) is used for cooling, the total cost of lead cooling will be proportional to

\[
Q_t = 5 Q_m + (Q_c - Q_m) = Q_c + 4 Q_m .
\]  
(1)
or, introducing the mass flow \( \dot{m} \) corresponding to \( Q_m \) (1 W evaporates 0.05 g/sec),

\[
Q_t \ [W] = Q_c \ [W] + 80 \ [W \sec/g] \times \dot{m} \ [g/sec].
\]  
(1a)

BEBC current leads are designed to minimize \( Q_t \). Some essential design features are shown in Fig. 1.

In a full copper cylinder, slotted disks are machined leaving at the centre the desired cross-section \( A_c \) for conduction of the current. Then the cooling gas channel is closed by shrinking on a stainless-steel cylinder. This construction assures high mechanical stability, excellent heat transfer, and a good thermal inertia from the considerable copper mass in the disks.

Included in Fig. 1 is information on heat transfer factor \( H \) and pressure drop. The measured temperature and flow dependence of \( H \) is in agreement with a non-dimensional relationship for turbulent flow.

Evaluation was done in a purely numerical form but including full detail of data on geometry, heat transfer and material properties of this special design.

The computer program starts for a given cross-section \( A_c \), current \( I \), and cooling flow \( \dot{m} \), with an arbitrary value of heat flow \( Q_c \) from the cold end.

The differential equation of the temperature distribution \( T(x) \) along the lead can now be integrated step-wise from the cold end with \( x = 0 \) towards the warm end with \( x = L \). The temperature \( T(L) \) found is compared with \( T_0 = 300 \) K. If \( T(L) \) is different from \( T_0, Q_c \) is varied systematically until the distribution with \( T(L) = 300 \) K is found.

Results are summarized in Fig. 2 with parameters normalized to a current of 1 A. \( Q_t \) is plotted against flow rate \( \dot{m} \) for different length/cross-section ratios. Minimum cooling flow rate is marked by a black dot. For smaller flow rates, thermal runaway occurs. In addition, the straight line which characterizes a flow rate equivalent to that produced by \( Q_c \) is drawn in. \[
\text{[Then } Q_m = Q_c, \text{ and consequently with Eq. (1): } Q_t = 5 Q_m \text{ or } Q_t = 100 \dot{m}.]\]

Obviously now the minimum minimorum of \( Q_t \) is obtained for \( (L/L)/A_c = 26 \times 10^6 \) A/cm at a mass-flow \( \dot{m} \) as produced by \( Q_c \). But further on one sees that this working point is at the limit of thermal stability and therefore not acceptable if safety against burn-out of the lead is essential.

The BEBC current leads therefore have a bigger cross-section, \( (L/L)/A_c = 15 \times 10^6 \) A/cm. This reduces efficiency compared to the optimum optimorum by 16% but gives a good safety margin between nominal cooling flow rate and the minimal one necessary to prevent thermal runaway:

- nominal rate at 6000 A: 0.32 g/sec
- minimal rate at 6000 A: 0.24 g/sec

\[\dot{m} = 0.05 \text{ g/sec for } 1 \text{ W evaporates.}\]