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Peltier Current Leads with conical configuration

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ABSTRACT

Current leads in cryogenic systems are a major heat source which eventually affects the entire system. It has been shown in recent years that Peltier elements are useful in reducing incoming heat into the cold system. In this article we present a new tapered cone-like configuration of the Peltier Current Leads which increases the power saving. This configuration is compared to the standard cylindrical configuration utilizing advanced ANSYS simulations. The simulations show an additional power saving of 4% when using the tapered lead configuration.

1. Introduction

As advanced cryogenic systems for superconducting magnet applications become more and more popular and accessible, the need for optimizing such systems is evident. One of the key parameters, which should be taken into account during the optimization process, is the geometry of the current leads running into the system, transporting and generating heat [1,2].

When applying an input current I from the external ambient temperature (typically about 300 K) into a cold magnet system (about 4.2 K), the current leads conduct heat from the outside and generate heat due to Joule heating. It is relatively easy to deal with this heat flow below ~77 K, using HTS made current leads. These offer zero electrical resistance and low thermal conductivity, reducing significantly the heat flow. Thus, the main problem is in the intermediate temperature range, between 300 K and 77 K, where use of a normal conducting metal is required [3].

The methodology for handling the heat leakage problem caused by the current leads was first developed in 1959 by McFee [4] and reproduced later on by others [1,5]. According to McFee, for a conventional current lead made of a cylindrical conducting metal with a constant cross-section A and length l, minimum heat leakage may be achieved by optimizing the quantity I/A. This optimization also relies on the type of the conductor, and because of its electrical and thermal conductivity, copper is usually selected.

Recently, an advanced approach, lead by Yamaguchi [6–8], showed that the use of thermoelectric elements (TE), also known as Peltier elements, reduces the heat leakage from the current leads, yielding 20–30% in power saving [7]. In this paper we show a further advance in this field by using a tapered conical-shaped current lead with Peltier elements, increasing the power saving by additional 4%.

2. Peltier Current Leads – conventional configuration

A typical Peltier Current Leads configuration is shown in Fig. 1. It is composed of a TE and a metal (usually copper) leading the current to stage 1 (77 K) and an HTS wire leading the current to its final stage (usually 4 K). The one-dimensional formulation relating the heat flow Q to the current I running in the Peltier Current Leads is presented by [9]:

$$Q = -kA\frac{dT}{dx} \pm \alpha IT \quad (1)$$

$$I = -\frac{A}{\rho}\left(\frac{dV}{dx} \pm \alpha\frac{dT}{dx}\right) \quad (2)$$

where α, ρ and k are the Seebeck coefficient, electrical resistivity and thermal conductivity of the lead material, respectively. A denotes the cross-sectional area and V denotes the electrical potential. The sign in front of α is (+) for p-type TE and (−) for an n-type TE.

Our analysis below is based on the TE properties measured by Hasegawa [7] on Bismuth–Telluride (Bi_2Te_3). The Seebeck coefficient, α, increases linearly from a value of 154 μV/K at 200 K to 185 μV/K at 300 K, while the electrical resistivity, ρ, increases from a value of 5.5 μΩ m to a value of 9 μΩ m. The thermal conductivity,

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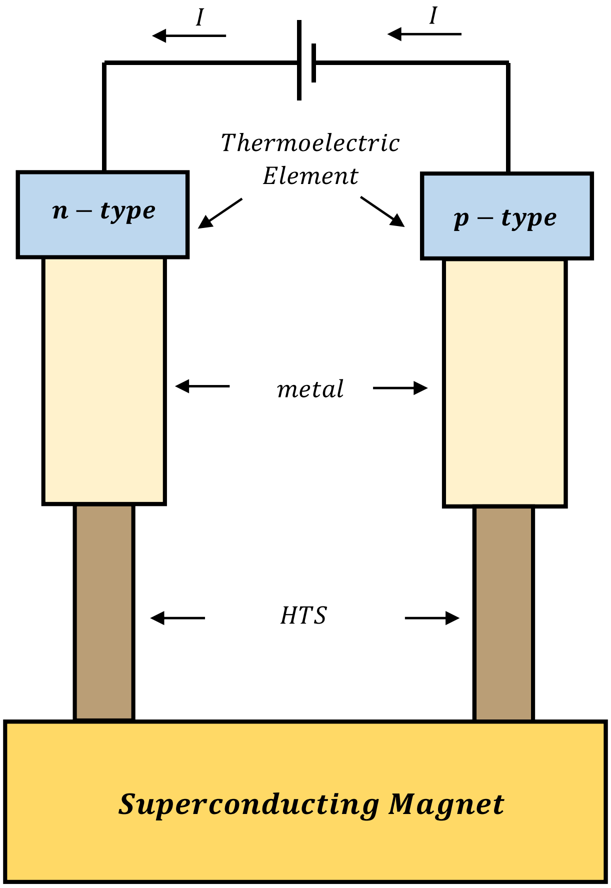


Fig. 1. Schmatic diagram of a superconducting magnet system with standard Peltier Current Leads.

k, of the TE does not vary significantly down 200 K; its value was set to 1.7 W/m K, independent of temperature. The temperature-dependent thermal and electrical conductivity of the copper lead section are taken from Refs. [10,11]. The Seebeck coefficient for copper is taken as zero.

3. Peltier Current Leads – new tapered configuration

The new configuration, which we propose here, deals with the current leads connecting between room temperature (300 K) and stage 1 (77 K). It differs from the standard cylindrical PCLs by varying the cross-section near the high-temperature edge of the current lead, as illustrated in Fig. 2. As can be seen in Fig. 2, the new configuration is composed of a metal electrode near room temperature, a conical-shaped TE, a tapered conical-shaped metal and cylindrical metal. The simulations described here show a non-monotonic temperature profile along the conical configuration, with a maximum temperature above room temperature somewhere in the middle of the cone-lead.

The working principle of the new conical configuration is thus as follows. The TE is functioning now not only as a heat pump, but also as an hot spot, ensuring partial heat flow backward to room temperature. The conical shape takes advantage of the cross-section dependence of the heat flow Q (Eq. (1)); heat flows backward towards the hot end (300 K) because of the relative smaller thermal resistance in the relatively large cross section.

We note that a similar effect should work for a cone-shaped copper without using the TE. The simulations, however, show that the effect in such case is much smaller and the power saving due to the metallic cone is negligible.

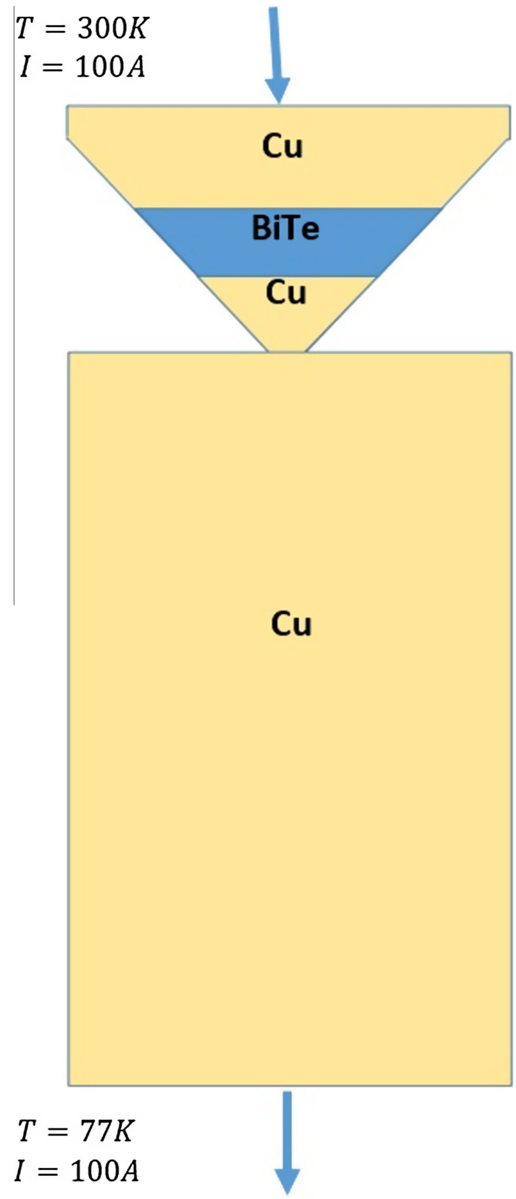
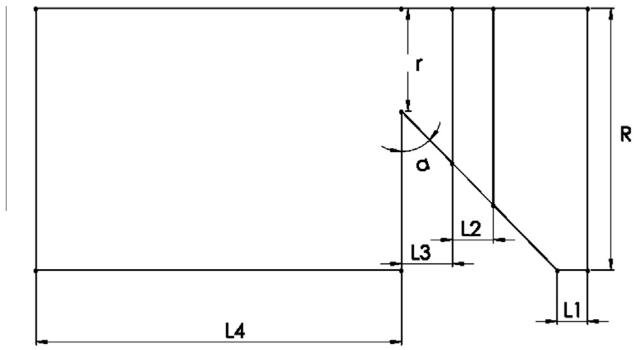


Fig. 2. Schematic sketch of the new conical Peltier Current Lead.

It is important to mention that the effect depends strongly on the shape of the cone and its position. Our simulations show that in order to achieve maximum heat flow backwards, towards the hot end, the cross section gradient has to be maximized, which means that the angle between the cone and the cylinder has to be as small as possible. The simulations also show that it is important to have the cone-shaped section as close as possible to the hot end, ensuring that the TE element operates at a mode of maximum temperature difference [12].

4. Simulations

In order to demonstrate the advantages and working principle of the new tapered conical-configuration we used advanced multi-physics simulations by ANSYS. We compared the heat flow into Stage 1 in three different configurations: Conventional Current Lead (CCL), standard Peltier Current Leads (standard PCL) and conical PCL. The setup we used includes two end-points with different



R	r	L_1	L_2	L_3	L_4	α
1.9 mm	0.55 mm	0.05 mm	0.1 mm	0.025 mm	255 mm	5^0

Fig. 3. Axisymmetric sketch of the conical PCL with a table specifying its dimensions used for the ANSYS simulations.

temperatures: *A* “cold-end” at 77 K and a “hot-end” at 300 K. *A* current, $I = 100$ A, flows between the two end-points.

In order to obtain conclusive results an optimization of *l* and *A* was made to all three configurations under the temperature and current conditions mentioned above, making sure that we achieve minimum heat flow in each one of them. The CCL was made of a cylindrical copper with a 7 mm^2 cross-section and 268 mm length. The PCL was made of a 320 μm long cylindrical TE and 210 mm long cylindrical copper both with a 8 mm^2 cross-section. A schematic description of the conical PCL dimensions can be found in Fig. 3. Because the conical PCL consists of more parameters (than CCL and standard PCL), and because it is a much more complex problem (2D as oppose to 1D), its optimization was achieved numerically with ANSYS simulations by differing all the parameters that define it as described in Fig. 3.

Because of the small element sizes, two major precautions are being taken for the accuracy and reliability of the simulations. The first is using a high-resolution mesh including 30 nm mesh elements at problematic places such as sharp corners and edges. The second is reducing the sharp edges by making them round as much as possible. By this we avoid convergence points which may cause unreliable results.

5. Simulations results

5.1. Demonstrating the working principle of the conical PCL

In Fig. 4 the temperature along the cone in the conical PCL (first 200 μm) is shown. In the figure, $x = 0$ is the contact point to the external world, i.e. $T = 300$ K. The temperature initially rises slightly to 300.24 K (seen in the figure insert), but then the Peltier effect becomes effective and the temperature drops to 201.47 K at the end of the cone.

The fact that *T* exceeds 300 K means that heat flows from the “new hot-maximum point” (300.24 K) to both ends: the hot-end (300 K) and the cold-end (77 K). Due to the varying cross-section in the conical-TE, the amount of heat flowing towards the hot-end is larger than that flowing towards the cold-end. This is demonstrated in Fig. 5 which shows a screenshot from the heat flow simulation showing the direction of the heat flow in the middle of the TE-cone. The size of the arrows indicates the size of the heat flow. Heat flow preference towards the hot-end is apparent. This occurs because of the conical shape of the TE and this is the reason for the additional power saving in the conical PCL as we show in the next section.

5.2. Comparison results

The simulation results of the heat flow and temperature gradient of the conical PCL, standard PCL and CCL are shown in Figs. 6 and 7. These results show that the heat leak of the conical PCL was smaller than that of the standard PCL and CCL. Fig. 6 describes the heat flow along the current leads in the three configurations. The minimum heat flow in the conical PCL, from room temperature to 77 K, is 2.92 W (which yields a normalized cryogenic heat load of 0.0292 W/A). By comparison, the optimized standard PCL and CCL had a normalized heat load of 0.0303 W/A and 0.0422 W/A, respectively. When using the conical PCL configuration, the cryogenic heat load is decreased by ~31% from the CCL and ~4% from the PCL.

Fig. 7 describes the temperature profile in the various leads. The figure shows clearly the large temperature drop in the conical PCL and standard PCL due to the Peltier effect. Apparently, the initial temperature drop is larger for the conical PCL bringing it to ~201 K as compared to ~220 K for the standard PCL. The results

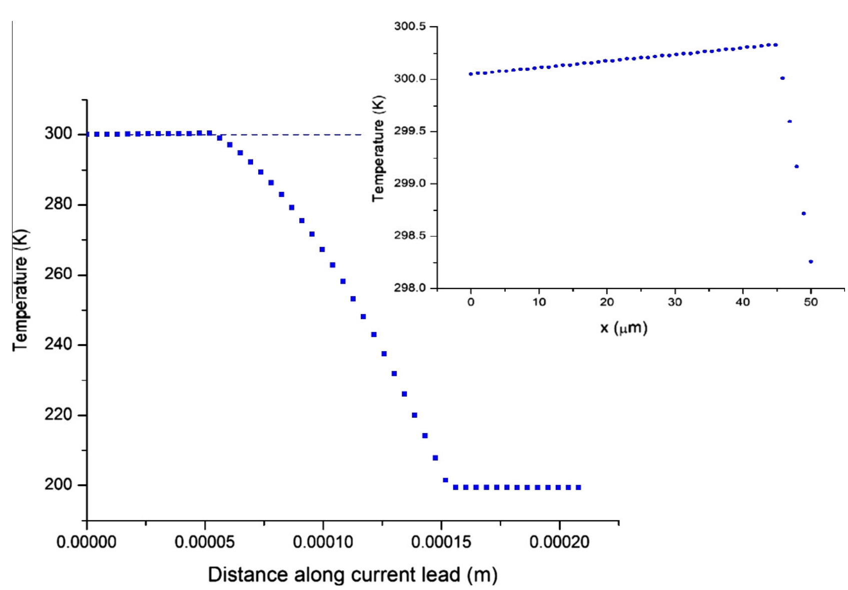


Fig. 4. Temperature profile along the cone in the conical PCL. Inset: Zooming on the area close to the external world, showing an initial increase of temperature.

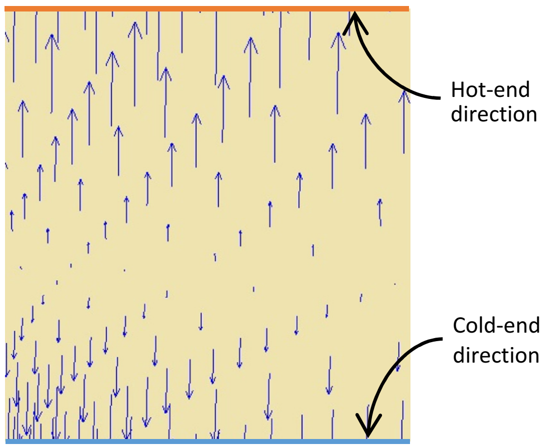


Fig. 5. Zoom-in screenshot from the heat flow simulation showing the direction of the heat flow in the middle of the TE-cone. The size of the arrows indicates the size of the heat flow.

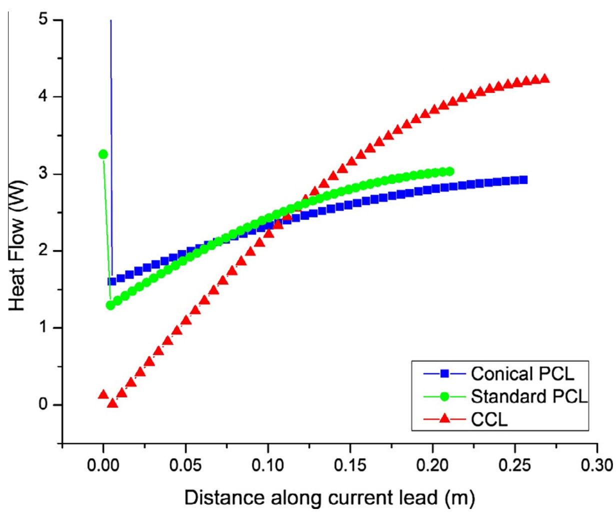


Fig. 6. Heat flow profile comparison for optimized conical PCL, standard PCL and CCL.

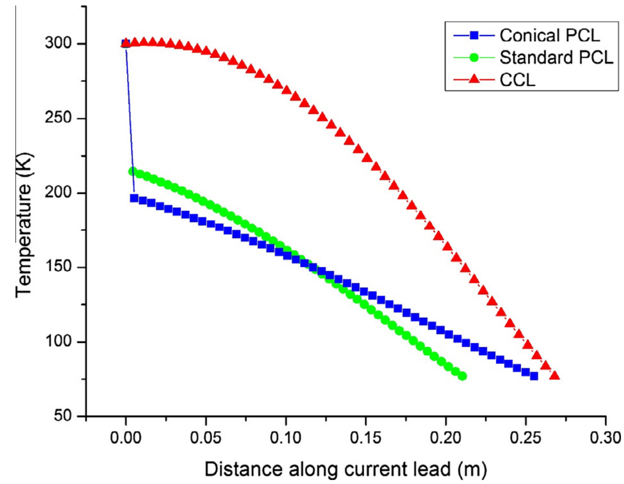


Fig. 7. Temperature profile comparison for optimized CPCL, PCL and CCL.

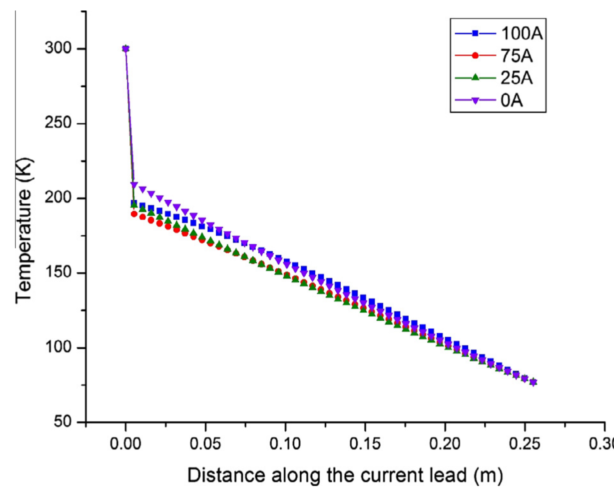


Fig. 8. Temperature along the CPCL, for currents between 0 and 100 A.

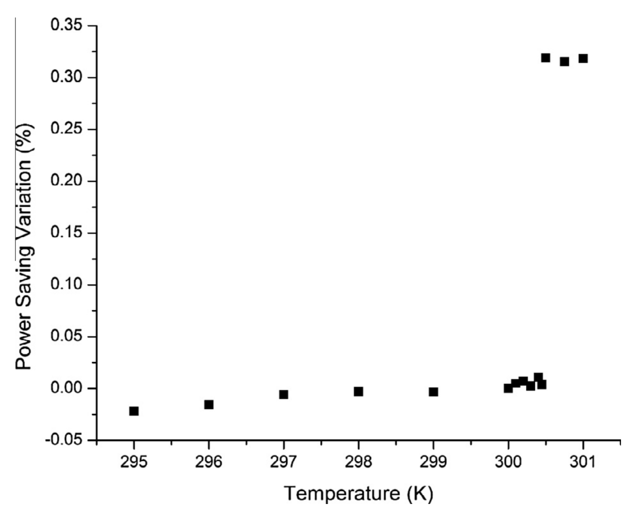


Fig. 9. Changes in power saving changes resulted in by changes in the temperature at the boundary of the hot-end.

obtained for the CCL and standard PCL match those obtained by others [13,14].

5.3. Partial current operation

Next we address the question of the performance of an optimized CPCL when operated at currents other than the designed value. Fig. 8 shows the temperature profiles for current leads carrying currents smaller than the 100 A current, for which the leads optimization has been performed (temperatures at both ends of the lead are fixed at 300 K at the hot-end and 77 K at the cold-end). The conical-TE provides cooling for current less than 100 A. Above that, it results in heating.

5.4. Stability

Due to the precise numbers of the dimensions projected from the optimization of the conical PCL simulations, a question of stability arises when it comes to realization. This question arises mostly because of the difficulty to determine the 300 K temperature at the hot side of the current lead. In order to resolve this issue, we have made simulations showing the power saving variation versus the temperature at the hot end of both standard PCL and conical PCL, as can be seen in Fig. 9. The simulations show very little variation in power saving and a decrease of only $\sim 10^{-2}\%$ under 300 K.

6. Conclusions

By utilizing multi-physics simulations we have demonstrated that an addition of a tapered conical section to Peltier Current Leads (conical PCL) may increase power saving in comparison to the ‘standard’ PCL. The conical cross-section induces a bi-directional heat flow and a larger temperature drop at the TE.

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References

[1] Herrmann PF, Current leads. In: Seeber B, editor. Handbook of applied superconductivity, Philadelphia, PA, USA; 1998. p. 801–43.
[2] Yamaguchi S, Emoto M, Yamamoto N, Sun J, Watanabe H, Hamabe M, et al. Refrigeration process to realize a multistage and gas-cooled current lead. Appl Supercond 2013;23(3).
[3] Bromberg L, Michael P, Minervini J. Current lead optimization for cryogenic operation at intermediate temperatures. Cambridge (USA): MIT Plasma Science & Fusion Center; 2009.
[4] McFee R. Optimum input leads for cryogenic apparatus. Rev Sci Instrum 1959;30(2).
[5] Buyanov Y. Current leads for use in cryogenic devices. Principle of design and formulae for design calculations. Cryogenics 1985;25.
[6] Yamaguchi S, Takita K, Motojima O. A proposal for a Peltier current lead. In: Proceedings of the 16th international cryogenic engineering conference; 1996. p. 1159–62.
[7] Hasegawa Y, Sato K, Okumura H, Nakamura K, Yamaguchi S, Miyake K. Reduction of heat leak in cryogenic system using Peltier current leads. Cryogenics 2002;42:495–500.
[8] Yamaguchi S, Yamaguchi T, Nakamura K, Hasegawa Y, Okumura H, Sato K. Peltier current lead experiment and their applications for superconducting magnets. Rev Sci Instrum 2004;75(1):207–12.
[9] Jeong ES. Optimization of conduction-cooled Peltier current leads. Cryogenics 2005;45:516–22.
[10] Matula RA. Electrical resistivity of copper, gold, palladium and silver. J Phys Chem Ref Data 1979;8(4):1147–298.
[11] Powell RW, Ho CY, Liley PE. Thermal conductivity of selected materials. West Lafayette (Indiana): Thermophysical Properties Research Center; 1966.
[12] Xuan X, Ng K, Yap C, Chua H. Optimization and thermodynamic understanding of conduction-cooled Peltier current leads. Cryogenics 2002;42:141–5.
[13] Yamaguchi T, Mizutani S, Moriguchi M, Okumura H, Nakamura K, Yamaguchi S. Experimental and numerical characteristics of Peltier current lead for direct current mode. Trans Appl Supercond 2004;14(2).
[14] Michael PC, Galea CA, Bromberg aL. Cryogenic current lead optimization using Peltier elements and configurable cooling. Trans Appl Supercond 2015;25(3).