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High stiffness fixation and thermal insulation in a superconducting planar motor

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Abstract

A superconducting planar motor is being investigated to provide higher acceleration potential compared to existing planar motors. Currently used permanent magnets are replaced by superconducting electromagnets, at a temperature below 20 K, providing a higher magnetic field density. Fixation of superconductors is a challenge due to the requirements on stiffness and thermal conductivity, which are conflicting in existing fixation designs. In contrast, an electromagnetic position actuator in closed loop control provides stiffness without a path for thermal conduction. The radiative heat flow through such an actuator is analyzed. Furthermore, a thin thermal insulation is required to achieve a high magnetic field density at the location of the warm motor coils. Two insulation concepts are analyzed and compared based on the remaining heat flow. First order heat transfer equations are solved and the results show the potential of the solutions proposed. Further work entails detailed design and experimental verification.

Cryogenic support, high stiffness, low heat load, thin thermal insulation, vacuum insulation

1. Introduction

A superconducting planar motor is investigated to provide higher accelerations for lithography stages. Superconducting electromagnets provide a significant improvement in magnetic field density compared to rare-earth magnets currently used [1]. A schematic representation of a superconducting planar motor is shown in Figure 1. Horizontal and vertical forces are exerted on the moving copper coils providing the possibility of magnetic levitation and in-plane positioning. According to Newton's third law, the same forces are exerted on the superconducting coils, which require a stiff mechanical fixation to allow for high bandwidth control. However, the temperature of these coils is below 20 K, which requires an efficient thermal insulation. The conflicting requirements of high stiffness and low thermal conductivity are discussed below and a solution is presented. Furthermore, the thin layer in between the copper coils and superconducting coils is loaded by a pressure difference, therefore, requiring a supporting structure such that an insulating vacuum is maintained. Three promising conceptual designs (one support design and two insulation designs) are presented and analyzed based on their thermal performance.

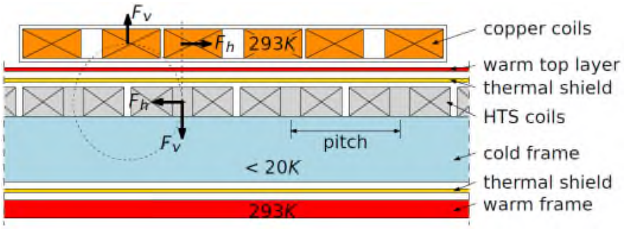

Figure 1. Planar motor with DC superconducting and AC copper coils

2. High stiffness support with minimal thermal leak

Existing mechanical supports impose a significant heat load on a cryogenic system. These are typically made out of glass fiber reinforced plastic for its high ratio of Young's modulus to thermal conductivity [2]. Here, the heat flow through the support is proportional to the stiffness required, as given by Equations (1) and (2), where c represents the stiffness, E the Young's modulus, A the cross-sectional area and l the length of the support strut. Furthermore, Q represents the heat flow, λ the thermal conductivity and T the temperature. Minimizing the heat flow without loss of stiffness would be favourable for the dynamically loaded support.

$$c = \frac{EA}{l} \tag{1}$$

$$Q = \frac{A}{l}\int \lambda dT \tag{2}$$

2.1. Support solution

An electromagnetic actuator with position feedback control is proposed to support the cold frame without contact. Figure 2 shows a reluctance actuator in closed loop control. The stator is connected to the warm frame while supporting the mover, which is connected to the cold frame. The gap is measured and subtracted from a reference value g_0 providing an error e which is translated to a force setpoint F by the controller C. The electrical controller C_e translates the force into a voltage setpoint for the amplifier, which provides current in the coil.

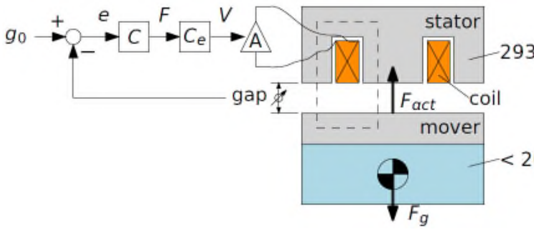

Figure 2. Electromagnetic cryostat support with position control

In the proposed solution, conductive heat transfer via structural components is eliminated while a tunable electro-magnetic stiffness is provided with the possibility for additional damping. The remaining heat leak is defined by radiative heat transfer, which scales with the actuator surface area. Equation (3) describes the actuator force based on the total surface area A_t of the teeth assuming no saturation. Here, B represents the magnetic field density in the gap and μ_0 the vacuum permeability.

$$F_{act} = \frac{A_t B^2}{2\mu_0} \tag{3}$$

Radiative heat transfer in the actuator gap, from the stator at 293 K to the mover at 20 K, is in the order of 0.2 W for an actuator supporting 100 kg, assuming B equals 0.5 T and an emissivity of 0.1 for both surfaces. Actuation through a shield is feasible [3] and reduces the heat load at 20 K significantly. An actively cooled shield at 80 K in between results in heat transfer in the order of 0.2 W to 80 K and 1.2 mW to 20 K. Further research into the electric heating of the mover is to be conducted. Use of thin laminations and low hysteresis ferromagnetic materials is foreseen.

3. Thin thermal insulation

An efficient superconducting motor requires a thin thermal insulation between the copper coils and the superconducting coils (Figure 1) due to the decay of magnetic field density with distance. A total magnetic gap of 10 mm is acceptable, however, a smaller gap allows for a much higher field density (inversely proportional to gap cubed). Packaging of the copper coils requires a thickness in the order of 4 mm leaving 6 mm for thermal insulation of the superconducting coils.

Commonly used insulation materials are based on foams for which the gas inside the foam defines the thermal conductivity. Polyurethane foam (filled with low conductivity gas) has a thermal conductivity in the order of 10 mW/mK [4]. Using (2), this results in a heat flow of 710 W/m^2 to 80 K and 200 W/m^2 to 20 K. These heat flows are very large for cryogenic systems due to the limited cooling efficiency (in the order of 0.3 % at 20 K). Using up to four commercially available cryocoolers allows for a maximum of 6 W of heat that can be removed at 4 K.

3.1. Vacuum insulation using struts

Insulation based on vacuum is commonly used in systems with large temperature differences. Radiative heat transfer is independent of distance between the radiating bodies, which results in thin insulation layers. Equation (4) describes the radiative heat flow as function of the surface area A, T_1 and T_2 the surface temperatures and ε the combination of surface emissivities, which depends on geometry and view factor [5].

$$Q_{rad} = \sigma A \varepsilon (T_1^4 - T_2^4) \quad (4)$$

Figure 3 shows a conceptual scheme of an evacuated insulation based on struts supporting the thin top plate at room temperature with respect to the room temperature frame. The heat flow is indepent of the thickness (t), which is defined by the thickness and deflection of the top plate. Using 280 struts per square meter, the radiative heat flow from 293 K to 80 K equals 40 W/m^2 and from 80 K to 20 K equals 0.39 W/m^2, which is considered an acceptably low number.

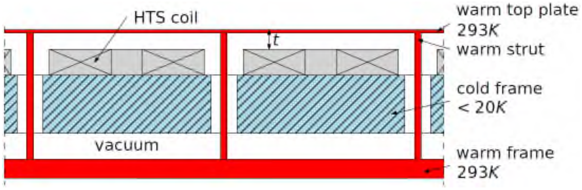

Figure 3. Vacuum insulation using struts

Figure 3 does not show an actively cooled shield at 80 K. However, the same principles can be applied for the shield with vertical tubes in between the strut and cold frame shown above. A cryostat support, as described in Section 2.1, is used to define the position of the cold frame with respect to the warm frame.

3.2. Vacuum insulation using spheres

Instead of supporting the top plate using struts at room temperature, a thermally high resistance interface can be used that supports the top plate relative to the cold frame. Zirconium oxide ceramic spheres (common in ball bearings) can widthstand a high load while the thermal conductivity is low. The small Hertzian contact area and low thermal contact conductance [6, 7] allow for suitable thermal insulation. Spheres with a diameter of 4 mm arranged in a rectangular array with a pitch of 20 mm can support the vacuum pressure.

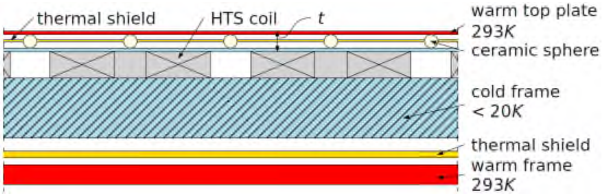

Figure 4. Vacuum insulation using ceramic spheres

The heat flow is defined by the contact conductance, the conductivity of the sphere and the radiative heat. The contact conductance can range multiple orders of magnitude and is influenced by many factors such as contact pressure and surface roughness [8]. Here, the contact conductance is estimated at 10^3 W/m^{2}K. Equation (5) gives the thermal resistance of a sphere with two contacts. The thermal resistance is in the order of 5 × 10^4 K/W based on a thermal conductivity of 2.2 W/mK.

$$R_{sphere} = 2R_{contact} + R_{conduction} \quad (5)$$

Correspondingly, the heat flow through a half sphere from 293 K to 80 K equals 22 W/m^2 and from 80 K to 20 K equals 6.1 W/m^2, which indicates a potential solution. However, the radiative heat should be taken into account, which results in the values given in Table 1. Furthermore, the contact resistance requires verification through experiments.

Table 1: Summary of expected heat loads

Heat loads	**80K**	**20K**
Supports (6x)	1.3 W	7.3 mW
Foam insulation	710 W/m^2	200 W/m^2
Strut insulation	40 W/m^2	0.39 W/m^2
Sphere insulation	44 W/m^2	6.3 W/m^2

4. Conclusion

Two significant aspects of the design of a superconducting planar motor are discussed. Firstly, a support solution is presented that provides stiffness without thermal conductance which reduces heat flow compared to existing solutions. This is a significant improvement and a key enabler for applications requiring high stiffness such as planar motors. Secondly, a thin insulation is required in the magnetic gap of the motor. Simply using an insulating foam is not feasible due to the high heat flow to low temperature. Two vacuum insulation concepts are presented and analyzed. First computations show that both insulation concepts achieve a heat flow in the order of a few watts at 20 K, which makes them promising for the application discussed here. Further steps would include detailed design and experimental validation of the solutions presented.

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