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The Performance Potential of Superconducting Linear and Planar Motors

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Abstract
Electromagnetic motors currently used in lithography systems are pushed to their limit and it is challenging to increase acceleration without introducing additional disturbances. Superconductors could provide an improvement in magnetic flux density and/or current density compared to the permanent magnets and copper coils currently used. The improvement potential of three superconducting (SC) alternatives is analysed in this paper. The achievable magnetic flux density with SC electromagnets and SC bulk magnets is derived and the (alternating) current density in a SC coil is presented as a function of cooling power. All three are analysed for a range of cryogenic temperatures. An increase in magnetic flux density of a factor of three is computed at a temperature of 30 K and the same increase in current density is found at 50 K with equal cooling power compared to copper coils. As a result, superconductivity is expected to provide a significant improvement with respect to magnetic flux density and/or current density in a motor application.

Keywords: linear motors, planar motors, superconductivity, magnetic flux density, current density, AC losses

1. Introduction
The throughput of lithography systems is partly determined by the acceleration of motion stages which are currently pushed to their limit. An example motion stage is the planar motor shown in Figure 1. High temperature superconductors (HTS) provide an alternative to neodymium-iron-boron (NdFeB) magnets and copper coils currently used. HTS materials are available in tapes with a thickness of 0.1 mm and a width of 4 mm – 12 mm and in mono-crystalline pieces (referred to as HTS bulks) up to 65 mm in diameter and 30 mm in height. Large scale prototypes of rotating motors and generators using HTS have been realized [1] and show a clear improvement in efficiency and volume with respect to conventional motors. Linear motors based on HTS have been realised as well [2]. However, the improvement potential as function of temperature for different SC alternatives is not clear for linear and planar motors.

![Figure 1. Electromagnetic planar motor configuration.](image)

Firstly, the properties of superconductors are introduced. Next, the achievable magnetic flux density above an HTS tape-wound electromagnet and above an HTS bulk magnet is determined and compared to the field currently achieved with NdFeB magnets. Furthermore, the achievable current density in a SC tape-wound racetrack coil is determined and compared to the current density achieved in copper coils.

2. Analysis of magnetic flux density and current density
Superconductors can carry a high but limited current. This limit is called the critical current and depends on the temperature and the magnetic flux density. At higher currents, the resistivity of the superconductor increases dramatically. Figure 2 shows the critical current of a 4 mm wide HTS tape as a function of magnetic flux density for different temperatures [3].

![Figure 2. Critical current for a 4 mm wide tape](image)

2.1. HTS tape-wound electromagnet
HTS tapes can be wound into coils with an axial length (referred to as the height) equal to the tape width. A stack of multiple coils connected in series forms an electromagnet. The inner and outer diameter are chosen at 15 mm and 55 mm respectively and three different heights are investigated, viz. 12 mm, 24 mm and 36 mm.

The magnetic flux density throughout the electromagnet is computed using a 2D finite element model. Based on Figure 2, the critical current density of the electromagnet is computed. This current density is used to compute the magnetic flux density 10 mm above the electromagnet using the Biot-Savart law. Where it is assumed that a magnetic gap of 10 mm is achieved in the electromagnetic motor with an efficient and thin insulation.

This results in the magnetic flux density shown in Figure 3 (squares). An increase in peak magnetic flux density of a factor of 3.4 is computed for an electromagnet with a height of 24 mm at a temperature of 30 K compared to 0.7 T achieved with NdFeB magnets (dashed line). A factor of 5.5 is seen at a temperature of 4.2 K for the same electromagnet.
2.2. HTS bulk magnet

As an alternative, an HTS bulk can be magnetised reaching a trapped magnetic field up to $17.6 \text{T}$ [4]. Trapped field data reported in literature [4-8] is shown in Figure 4 for HTS bulks with a variation in dimensions and magnetisation methods. The highest fields achieved with field cooling magnetisation (FCM) and with pulsed field magnetisation (PFM) are presented in [4] and [5], respectively.

Figure 4. Trapped field values from literature [3-7].

It is not straightforward to predict the achievable trapped field in an HTS bulk. Therefore, an equivalent current density is computed for the bulks described in literature using a relation based on the trapped flux density measurement standard IEC 61788-9 [7]. The current density is used to compute the magnetic flux density, shown in Figure 3 (crosses), $10 \text{ mm}$ above an HTS bulk with a diameter of $55 \text{ mm}$ and a height of $24 \text{ mm}$. Only the bulks magnetised with the PFM method are analysed because the FCM method is impractical for a motor application.

An increase in magnetic flux density of a factor of 4.4 is computed for the HTS bulk at a temperature of $40 \text{ K}$ compared to the value achieved with NdFeB magnets. It is assumed that the equivalent current density based on literature can be achieved in the bulk described above. Larger HTS bulks have been magnetised [9] but only with lower current densities.

2.3. HTS racetrack coil

In linear and planar electromagnetic motors, racetrack shaped coils carrying alternating currents (AC) are used. An SC racetrack coil with a length of $300 \text{ mm}$, width of $60 \text{ mm}$ and height of $12 \text{ mm}$ is analysed to compare with currently used copper coils. In contrast to direct currents (DC), transient currents in SC coils result in heat generation usually referred to as AC losses. These AC losses are calculated with a 2D transient finite element model [10] based on the critical current (Figure 2) and the normalized transient current shown Figure 5. The transient current represents the phase current in a linear or planar motor application and is defined by the motion profile.

Figure 5. Normalized current waveform for the AC loss computation.

The generated heat at cryogenic temperature needs to be removed by a cooling device. The necessary cooling power at room temperature is computed assuming a coefficient of performance (COP) of 5% of the Carnot limit [11]. Figure 6 shows the relation between cooling power (at room temperature) and current density in the SC racetrack coil for four different operating temperatures. Furthermore, the power dissipation in a copper racetrack coil of the same dimensions is shown. Currently, a root mean square (rms) current density of $35 \text{ A/mm}^2$ is achieved in copper coils resulting in a dissipation of $2.8 \text{ kW}$. The current density achieved in an HTS racetrack coil is a factor of 2.9 higher at the same cooling power. However, heat leaks into the cryogenic system are not taken into account. On the other hand, a COP of 5% of the Carnot limit is conservative, especially for operating temperatures of $20 \text{ K}$ or higher.

Figure 6. Cooling power needed for a copper and an HTS racetrack coil.

3. Conclusion and discussion

High temperature superconductors (HTS) are analysed as an alternative material for use in linear and planar electromagnetic motors. An increase in magnetic flux density of a factor of 3.4 is computed when NdFeB magnets are replaced with HTS tape-wound electromagnets with a diameter of $55 \text{ mm}$ and a height of $24 \text{ mm}$ at a temperature of $30 \text{ K}$. An increase of a factor of 4.4 is seen for an HTS bulk magnet with the same dimensions at a temperature of $40 \text{ K}$. Furthermore, an increase of a factor of 2.9 in current density is computed for replacing the copper racetrack coils with superconducting (SC) tape-wound coils at a temperature of $50 \text{ K}$.

Only the electrical elements of a SC electromagnetic motor have been analysed and compared. This analysis showed that the improvement potential of a SC electromagnetic motor is significant. However, an elaborate mechanical design and analysis of AC losses is needed for all three cases to predict the heat leak of the cryostat and the achievable temperature.

References