Lorentz Force Velocimetry using a bulk HTS magnet system

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Abstract
Design of the Lorentz Force Flow-meter (LFF-meter) for weakly-conducting and slow-flowing fluids, e.g., glass melts, place stringent requirements on the magnetic field generation and force measurements. In the scope of the Research Training Group “Lorentz Force Velocimetry (LVF) and Lorentz Force Eddy Current Testing”, a LFF-meter considers: first - a magnetic field source, where NdFeB permanents magnet system is replaced with a bulk high-temperature superconductors (HTS), which promise higher flux densities (> 1 T) and thus higher output force resolution; second – a high-precision force measurements, where electromagnetic force compensation weighing balance (EMFC) setup is replaced with torsion balance based system (TFMS) , which claims an increase of the force resolution up to 1 nN. Furthermore, in order to raise the issue of the limiting total mass (which is always an issue for high-precision force measurements), the bulk HTS and TFMS are merged within the cryostat. This work discusses LVF experiments, calculations and numerical simulations, where a magnetic field is generated by the bulk HTS.

Key words: lorentz force velocimetry, bulk high-temperature superconductors, flow rate measurement, glass melts, trapped field magnets.

Introduction
The velocity or mass flux measurement in flowing substances is of great importance in industry with the regard of its ability to provide an efficient and, therefore, economic production process control. Apart, there is a growing need for non-invasive measurements, especially, in a view of a hygienic requirements in pharmacy and food; either the necessity to sustain a severe condition of opaque, hot or aggressive surroundings in a number of practical application, such as: i) liquid metals for high-quality aluminum, cooper and steel production [1]; ii) glass melts for the manufacture of high-quality glass products; iii) salt melts for solar power or storage systems [2].

The LVF have been studied extensively in the pursuit of absolutely contact-less flow measurements for electrically conducting substances [1,3–6]. It has been shown that LVF works well in liquid metals due to a high electrical conductance (σ ~ 10^6 S m^-1) [1]. However, for a weakly conducting and slow flowing substances LVF works only under the laboratory condition in narrow measurement range. The experimental investigation of LVF for salted water (as a model fluid) of varying electrical conductivity and flow velocity was reported in several past works [5,6]. This was realized by employing a high-precision force measurement system, i.e. electromagnetic force compensated weighing cell (Sartorius Lab Instruments), in a combination with an optimized Halbach array of permanent magnets (PMs) [7] of 1 kg. However, in the case of aggressive fluids (i.e. glass melts) the realization of close magnetic interaction with the fluid is not possible due to the large isolation walls and harsh environment.

A vital technical challenge of LVF for a weakly conducting and slow flowing substances remain in magnetic field generation and adaptation of corresponding magnet system. The conventional NdFeB permanent magnets have been considered the most practical strategy to generate a maximum possible Lorentz force with a load restriction needed to ensure force high-precision measurements [6]. However, the surface magnetic flux density of the strongest available NdFeB PMs is limited to about 0.5 T. The bulk HTSs have the ability to act as quasi-permanent trapped field magnets. Effective flux pinning permits high current densities which in turn can generate large persistent magnetic fields. The largest achieved trapped field to date is 17.6 T in silver-alloying Gd-Ba-Cu-O samples bulk using field-cooled magnetization (FC) [8], and over 5 T using compact and fast pulsed field magnetization [9]. Nonetheless, for any practical application the use of the bulk HTS magnets requires cooling and magnetization. If the bulk HTS is to be incorporated into the LFF-meter, its integration with the force measurement system is an issue to be resolved.

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Experimental
The LFV measurements were conducted using a “dry calibration” set-up [10], developed at the Department of Engineering, Technische Universität Ilmenau, but upgraded with the bulk HTSs. The idea of the “dry calibration” implies the replacement of a fluid flow with the controlled motion of a metal rod of a fixed geometry. Two types of metal rods were used: copper with an electrical conductivity of $\sigma_{\text{Cu}} = 59 \, \text{MS m}^{-1}$ and aluminum alloy (AlMgSi) with $\sigma_{\text{Al}} = 20 \, \text{MS m}^{-1}$.

Fig. 1 shows a photograph of the experimental set-up used to test LFV using a bulk HTSs. The installation consists of five main components: HTS magnet system (1), force sensor (2), solid conductor (3), linear vertical drive (4) and aluminum rack (5). The experimental procedure is fully automated: an IBA-Automation environment controls the linear drive and is used for data acquisition. The linear drive executes a repetitive motion of the metal rod with a constant velocity, that ranges from 50 to 81 mm/s. The force measurements is realized by using a commercial load cell (Model PW6D, Hottinger Baldwin Messtechnik GmbH) in a combination with a data analog measuring amplifier (SOEMER Messtechnik GmbH). The force is measured in terms of a voltage. In order to calibrate the output voltage signal from the measuring amplifier directly into a force, the masses of 5, 10, 20 and 100 g (KERN & SOHN GmbH) were used.

![Fig. 1: Photograph of the realized LFV experimental setup, which consists of five main components: (1) HTS magnet system, (2) force sensor, (3) metal rod, (4) linear drive and (5) aluminum rack.](image1)

The bulk HTS magnet system consists of two Y-Ba-Cu-O samples in the form of a cylindrical disc with a diameter of 46 mm and a thickness of 16 mm, provided by Adelwitz Technologiezentrum GmbH. The Y-Ba-Cu-O bulks were encapsulated in an aluminum holder, arranged opposite each other with a distance of 64 mm between and wrapped with styrofoam. Such arrangement enables to locate the bulk HTS magnets on either side of the metal rod. After field cooling (FC) magnetization with an applied field of 1.5 T at 77 K (using liquid nitrogen), the bulk HTS magnet system provides a quasi-permanent magnetic field enabling Lorentz force measurements to be carried out with a constant velocity of the metal rod. A maximum field of about 1 T at the bulk surfaces was recorded for each bulk HTS, respectively, as indicated in Fig. 2.

![Fig. 2: The peak trapped magnetic flux density $B_T(y)$ for each bulk HTS as a function of distance (along the y-axis) with a maximum field of 1.08 T (left) and 0.8 T (right) at the bulk surfaces. The shaded rectangles indicate the measurement system: HTS bulks (left and right) and metal rod (center).](image2)

Numerical Model
The numerical model is implemented as a fully 3D model using COMSOL’s AC/DC module, where the bulk HTS pair is assumed to be fully magnetized with an appropriate constant $J_c$ flowing through the cross-section of each bulk to reproduce measured trapped field profiles [11, 12]. A velocity (Lorentz term, where $\mathbf{J} = \sigma(\mathbf{E} + \mathbf{v} \times \mathbf{B})$) is then prescribed for a copper rod moving between the bulk pair, reflecting the experimental setup and conditions, which then allows the Lorentz force to be calculated.
Results
The results of the measurements are plotted in Fig. 3, showing the Lorentz force linearly depends on the velocity and the electrical conductivity of the moving metal rods, which is consistent with the fundamental theory of the LFV [3, 4]. The mean velocities of the copper rod were $u = [54; 64; 76; 81]$ mm/s. For the aluminium rod, $F_L$ - measurements with only two velocities of $u = [70; 81]$ mm/s were possible, due to its lower conductivity and limitations related to the resolution of the present LFV measurement system. Nevertheless, $F_L$ values obtained with same-sized copper and aluminium rods for one prescribed velocity, e.g. $u = 81$ mm/s, scales as $\sigma_{Cu}/\sigma_{Al}$.

Besides, the obtained experimental data were used to verify a numerical model developed in COMSOL Multiphysics to predict and optimize LFV performance through numerical simulation. Fig. 4 shows the sensitivity diagram of the actual LFF-meter. It is immediately clear that the use of the bulk HTS with higher trapped fields of 3 T and 5 T enhances the resultant sensitivity approaching the values lower than $10^{-6}$ Nm/s. This provides evidence that the bulk HTSs are feasible and enable a further extension of the LFV application with small ($\sigma u$), thereby covering the number of industrial weakly-conducting and slow-flowing fluids, e.g. glass, molten salts melts and/ or acid. It should be noted that the $F_L$ values are valid only for our particular design of the proof-of-principle LFV setup (see Figure 1b) and may vary for each individual system differently.

Conclusions and Outlook
Current work demonstrates the applicability of the bulk HTS in Lorentz Force Velocimetry. The bulk HTS offers higher magnetic field than previously used the NdFeB permanent magnets with the similar mass, despite it does require appropriate cooling and magnetization. Obtained experimental and numerical simulation results agree well exhibiting the linear relationship between the Lorentz force and product of the electrical conductivity and velocity, in accordance with a fundamental theory of the LFV [3, 4]. Hence, these results serve as a starting point for the future development of a new LFV prototype with improved performance.

Still, for practical application of the bulk HTS in LFV further aspects has to be resolved:
- The bulk HTS magnets require a robust and long-term operation at temperature T > 77 K. This implies that an encapsulation of bulk HTS in a vacuum cryostat is needed to increase the functional and long-term operation. Also, it allows a suitable adaptation of the cooling source (with liquid cryogen or cryogen-free technology).
- Upgrade of the force measurements from electromagnetic force compensation weighing balance setup to torsion balance based system. This promise to achieve the force resolution up to 1 nN
- In order to raise the issue of the limiting total mass of TFMS, the bulk HTS must be merged with the TFMS and be encapsulated in the integrated cryostat, where both systems are cooled together. This idea was patented by the authors [13] and the relevant portable LFV prototype is currently under construction.
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References

1. Kolesnikov, Y., Karcher, C., Thess: A.: Lorentz force flowmeter for aluminum – laboratory experiments and plant tests. Met. Trans. B., Vol. 42B, pp. 441–450, 2011.
2. Herrmann, U.; Kelly, B.; Price, H. Two-tank molten salt storage for parabolic trough solar power plants. Energy 2004, 29, 883 – 893.
3. Thess A., et al.: Lorentz Force Velocimetry. Physical Review Letters, Vol. 96, No. 4, pp. 164501, 2006.
4. Thess A., et al.: Theory of the Lorentz Force flow meter. New J. Phys, Vol. 9, pp. 299, 2007.
5. Halbedel, B.; Resagk, C.; Wegfrass, A.; Diethold, C.; Werner, M.; Hilbrunner, F.; Thess, A. A Novel Contactless Flow Rate Measurement Device for Weakly Conducting Fluids Based on Lorentz Force Velocimetry. Flow, Turbulence and Combustion 2013, 92, 361–369.
6. Vasilyan, S.; Ebert, R.; Weidner, M.; Rivero, M.; Halbedel, B.; Resagk, C.; Fröhlich, T. Towards metering tap water by Lorentz force velocimetry. Measurement Science and Technology 2015, 26, 115302.
7. Werner, M.; Halbedel, B. Optimization of NdFeB Magnet Arrays for Improvement of Lorentz Force Velocimetry. IEEE Transactions on Magnetics 2012, 48, 2925–2928.
8. J H Durrell, A R Dennis, J Jaroszynski, M D Ainslie, K G B Palmer, Y-H Shi, A M Campbell, J Hull, M Strasik, E E Hellstrom, and D A Cardwell. A trapped _eld of 17.6 t in melt-processed, bulk gd-ba-cu-o reinforced with shrink_-t steel. Superconductor Science and Technology, 27(8):082001, 2014.
9. H Fujishiro, T Tateiwa, A Fujiwara, T Oka, and H Hayashi. Higher trapped field over 5t on HTSC bulk by modified pulse field magnetizing. Physica C: Superconductivity and its Applications 2006, 445-448:334, 338.
10. V Minchenya, C Karcher, Y Kolesnikov, and A Thess. Calibration of the Lorentz force flowmeter. Flow Measurement and Instrumentation, 223(3):242 247, 2011.
11. Vakaliuk O , Ainslie M D and Halbedel, Lorentz Force Velocimetry using a bulk HTS magnet system: proof-of-concept, Supercond. Sci. Technol. accepted, 2018.
12. Ainslie M D and Fujishiro H Modelling of bulk superconductor magnetization, Supercond. Sci. Technol. 28 053002, 2015.
13. B Halbedel, O Vakaliuk, T Fröhlich, N Yan. Vorrichtung zur Ermittlung von Parametern einer elektrisch leitfähigen Substanz und dazugehöriges Verfahren, DE 10 2017 005 210.7, submitted: 30.05.2017.