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A multifunctional highway system incorporating superconductor levitated vehicles and liquefied hydrogen

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ABSTRACT

Magnetic levitation for the transport of people and goods using bulk superconductors and electrical power transmission using superconductors have both been demonstrated, but neither has been developed for daily use due to technological deficiencies and high costs. We envision combining the transport of people and goods and energy transmission and storage in a single system. Such a system, built on existing highway infrastructure, incorporates a superconductor guideway, allowing for simultaneous levitation of vehicles with magnetized undercarriages for rapid transport without schedule limitations and lossless transmission and storage of electricity. Incorporating liquefied hydrogen additionally allows for simultaneous cooling of the superconductor guideway and sustainable energy transport and storage. Here, we report the successful demonstration of the primary technical prerequisite, levitating a magnet above a superconductor guideway.

INTRODUCTION

A magnetic levitating (maglev) train can employ a bulk superconductor stably levitated above a permanent magnet guideway and propelled using a linear motor due to the flux-pinning phenomenon of type-II superconductivity, as has been successfully demonstrated for transportation of people and goods.[1–4] However, we have not yet seen long-distance superconducting maglev trains since they would need many high-cost[5] permanent magnets to serve only two functions: high-speed mass transit and freight transport. Meanwhile, using superconducting cables to transmit and store electrical power without loss over long distances,[6] a significant advantage over current transmission cables that lose some power due to resistance, has also been demonstrated. Long-distance applications of superconducting power transmission cables, such as a recently announced 12-km system in Munich,[7] remain few mainly due to the technological deficiencies and high cost of the cables, which also serve only two functions, transmitting and storing electrical power. Finally, hydrogen (H_2) is a promising energy source to replace fossil fuels, and liquefied H_2 (LH_2) pipelines would be the best choice for transport and storage since hydrogen is the lightest element and the high pressure required to transport gaseous H_2 would pose a significant challenge. However, a system of LH_2 pipelines would need extremely reliable, high-cost thermal insulation to maintain the LH_2 at 20 K, below its condensation temperature, and it would not be economically feasible to build such an expensive system to serve only the two functions of LH_2 transport and storage.

To overcome the unrealistically high cost of any system that serves only limited functions, we envision a "super" system that combines multiple functions: lossless electrical power transmission and storage; transport and storage of LH_2 and liquefied nitrogen (LN_2); and high-speed levitated transport of people and goods over long distances. In this super system, vehicles with permanent magnets (or electromagnets) will be levitated above a superconductor guideway ("SClev") that is also transmitting and storing electrical power. The LH_2 transported and stored in the system is ideal for cooling the superconducting cables.[8] We envision that relatively low-cost LN_2 and a vacuum layer will be used to thermally insulate the LH_2. With such a super system, continental passenger air travel and airborne freight transport may become obsolete when appropriately adapted personal vehicles, buses, and trucks can operate at 500–800 km h^{-1}, or even at 1000 km h^{-1} when the system is further built inside a partially evacuated tube. No land acquisition may be needed to construct the super system since it can be built on existing highway infrastructure to provide easy access to vehicles adapted for use on both standard and super system roads, as shown in Fig. 1. In contrast to current long-distance, high-speed mass transit, and freight transport systems, the super system provides substantial flexibility since the individuals are not dependent on train schedules and goods do not have to be loaded or unloaded at specific points. Transport vehicles adapted to use the SClev will need a dual power system, including an internal combustion engine or electricity- or fuel-cell-powered motor for local operation not on the SClev, as well as a linear motor for operation on the SClev system. All vehicles, including commercial trucks, autonomous vehicles, personal vehicles, etc., will be designed to travel on the super system regardless of the vehicle's length, weight, and speed. Alternatively, the super system can also be built with the levitated magnetic platforms on which all vehicles can drive on and off so that they do not need any special magnetic features built in. The cost of each of the super system's many functions is only a fraction of the total, and costs to maintain and operate its levitated components are minimal due to lack of friction, making the system economically feasible overall. On the other hand, in contrast to the flux-pinning levitation of a bulk superconductor above a permanent magnet that has been well demonstrated in previously reported superconducting maglev systems, SClev transport in the super system relies on levitating permanent magnets (electromagnets) above a superconductor guideway since the latter is also transmitting and storing electrical power, and this has not yet been demonstrated. Such a super system will drastically reduce the carbon emission due to much less energy consumed for operation of the system and significant elimination of the intracontinental airplanes. Here, we address whether this configuration is adequate for SClev transport by successfully building and demonstrating a desktop superconducting guideway that is comprised of bulk yttrium barium copper oxide (YBCO) superconductors and that allows a permanent magnet to levitate and move. We use LN_2 as the coolant for experimental ease and to model the LH_2 that will be used in future studies and the actual super system, while evaluating handling and cost factors. When LH_2 is used, the levitating force of the YBCO guideway will be significantly larger. Additionally, the choice of superconductors for the super system will not be limited to YBCO, which is now commercially available in bulk and superconducting tape forms; other superconducting compounds, such as those in the bismuth (BSCCO) and mercury (HBCCO) families, will be highly promising candidates when their mass production is realized. Unconventional superconducting materials, like magnesium diboride (MgB_2), etc. may also be considered in the future. We discuss the critical links between the functionality of flux-pinning levitation, cryogenic cooling, and magnetization to design, manufacture, and test the concept of the super system for lossless electrical power transmission and storage, LH_2/LN_2 transport and storage, and high-speed SClev transport of people and goods over long distances.

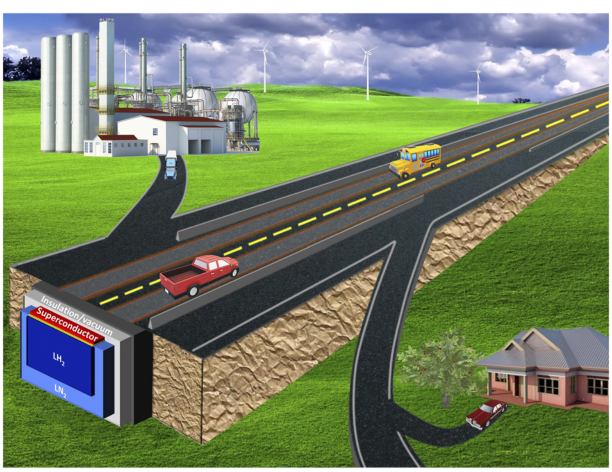

FIG. 1. Schematic illustration of the super system for energy transport and storage and SClev transport of people and goods. Superconductors are incorporated into existing highway infrastructure to levitate vehicles with magnetized undercarriages entering from or exiting to residential, business, industrial, and recreational areas while also transmitting and storing electrical power. LH_2 and LN_2 transported and stored in the system cool the superconducting cables, and the LN_2 and vacuum layers thermally insulate the LH_2.

RESULTS AND DISCUSSION

We built a superconducting guideway to demonstrate the levitation of a magnetic vehicle, a technical prerequisite for our proposed super system. Figure 2(a) shows a photograph of the major components of the experiment: (1) the superconducting guideway (SCG), (2) the permanent magnet magnetizer (PMM, about 3 kg), and (3) the levitating and moving magnetic vehicle.

Superconducting guideway

Figure 2(b) shows a computer-aided design (CAD) model of the SCG, which contains a linear array of nine YBCO bars. Each YBCO bar is one-half of a standard three-seed YBCO bulk sample[9,10] and measures 82 × 16 × 12 mm^3. Before being mounted into the SCG, a typical YBCO bar was characterized via Hall mapping following field cooling (FC) magnetization with an applied field of B_A = 1.4 T at 77 K, and the results are shown in Fig. S1. To cool the YBCO array to below its T_c and maintain this temperature, the array is thermally attached to a rectangular aluminum tube that can store up to 250 ml LN_2. To prevent warming to above its T_c, the YBCO array is wrapped with multi-layered insulation and, along with the LN_2 tube, is housed in a vacuum casing that consists of an outer rectangular aluminum tube that is 800 mm long with equal side widths of 60 mm.

After evacuation to below 5 × 10^{-5} mbar, the SCG was cooled with LN_2 via periodic pouring into its LN_2-filling tubes [denoted as 1 in Fig. 2(b)]. It took 20 min and 1.5 l of LN_2 to reach thermal equilibrium at 77 K. Without LN_2 refilling, the moderate thermal loss of 2.5 W allows this temperature to be maintained for 3–4 h. Levitation of the PMM and the magnetic vehicle above the cooled SCG is shown in Figs. 2(c) and 2(d), respectively (details provided below in the "Levitation demonstration" section).

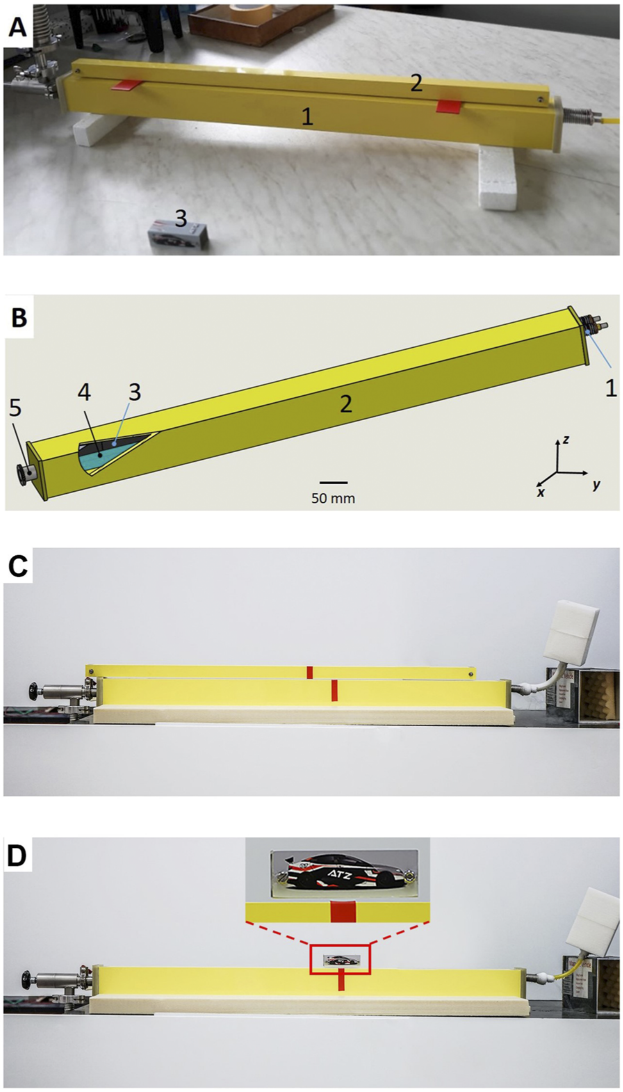

FIG. 2. Demonstration of levitation of a magnetic vehicle above a superconducting guideway. (a) Major components of the levitation experiment: (1) superconducting guideway (SCG); (2) permanent magnet magnetizer (PMM); and (3) levitating vehicle. The red components are spacers used in the field cooling magnetization of the SCG. (b) CAD model of the superconducting guideway: (1) LN_2-filling tubes; (2) outer vacuum casing; (3) YBCO bars; (4) inner LN_2 tube; and (5) vacuum valve. Levitation of (c) the PMM (about 3 kg) and (d) the magnet vehicle above the SCG. The inset to (d) shows the gap of about 3 mm. Multimedia views: (c) https://doi.org/10.1063/5.0139834.1; (d) https://doi.org/10.1063/5.0139834.2

Permanent magnet magnetizer and vehicle

The permanent magnet magnetizer (PMM), denoted as 2 in Fig. 2(a), is 780 mm long and consists of a series of double repulsive arrays of NdFeB (N45) blocks separated by an iron plate collector and housed in a rectangular aluminum tube with a wall thickness of 1.5 mm. Each NdFeB block measures $20 \times 20 \times 10$ mm^3, whereas the iron plate collector has a width of 2 mm and serves to turn, amplify, and homogenize the magnetic flux density, as schematically illustrated in Fig. 3(a).

The PMM surface was characterized via Hall mapping. Figure 3(b) shows its magnetic flux density $B_z(x)$ at z = 1.5 mm, where z denotes the distance between the upper surface of the NdFeB magnet and the Hall probe. The measured $B_z(x)$ exhibits a homogeneous triangular profile with a peak (^PB_z) of about 648 mT. $^PB_z(y)$ was also measured along the PMM at different z distances, as depicted in Fig. 3(c). The mean value of $^PB_z(y)$ at each measured z distance was then calculated and the results are shown in Fig. 3(d). The obtained $^PB_z(y)$ data show that the PMM has a nearly constant magnetic flux density with a minor $^PB_z(y)$ deviation of less than 3%, thereby suggesting that it will be effective in magnetizing the SCG.

The vehicle, denoted as 3 in Fig. 2(a), has the same magnetic structure as the PMM, but is only 70 mm long.

SCG magnetization and field distribution measurements

To activate the SCG, field cooling (FC) magnetization is applied as follows: using spacers as shown in Fig. 2(a), the PMM is placed 3–6 mm above the SCG, which is subsequently cooled down to 77 K. When thermal equilibrium is achieved in the SCG, a trapped magnetic flux density B_T (hereafter B_T indicates the $|B_z|$ component of vector **B**) is retained throughout the entire YBCO array after removal of the PMM due to the trapped flux and resultant induced superconducting current. Figure 4(a) shows that, after FC at 3 mm, B_T exhibits a triangular profile along the x-axis and reaches maximum at $^PB_T(x)$ = 86 mT. The slight $B_T(x)$ asymmetry observed is related to the steeper trapped field gradient in the vicinity of the seed surface cut. $B_T(y)$ was measured after FC at 3 and 6 mm and the results are displayed in Fig. 4(b), which shows a series of maxima and minima. It is also evident that the B_T value decreases with increasing FC distance, with a corresponding decrease in the $B_T(y)$ variation between maxima and minima. This observation is consistent with that of Deng *et al.*,[11] who found that FC distance can play a functional role in changing the shape and magnitude of the B_T distribution in trapped field applications. They also pointed out that a multi-seed YBCO bulk sample exhibits superior levitation performance compared to a corresponding array of single-grain YBCO bulk samples due to the additionally induced supercurrent in intergrain coupling.

To study the field distribution in more detail, we repeated the 77 K FC magnetization at 3 mm and Fig. 4(c) shows $B_T(y)$ for 150 mm $\le y \le$ 550 mm at 2 mm intervals. This $B_T(y)$ behavior mimics the macro-scale structure of at least three YBCO bars within the measurement range. For instance, the three maxima in the 150 mm $\le y \le$ 240 mm range [B_T(mT), y(mm)] = [(111, 178); (115, 204); (116, 232)], shown in magnified detail in Fig. 4(d), are consistent with the actual seed locations of a YBCO bar, as shown schematically in the inset to Fig. 4(d). The first and fourth minima [(86, 160) and (90, 240), respectively] delineate one three-seed YBCO bar in the array, whereas the second and third minima [(91, 186) and (96, 212), respectively] correspond to the locations of its grain boundaries, which are 26 mm apart.[8] These maxima and minima can be easily eliminated by using two or more layers of YBCO bars with each layer shifted a certain distance so that the maxima and minima are overlapped to homogenize the flux density.

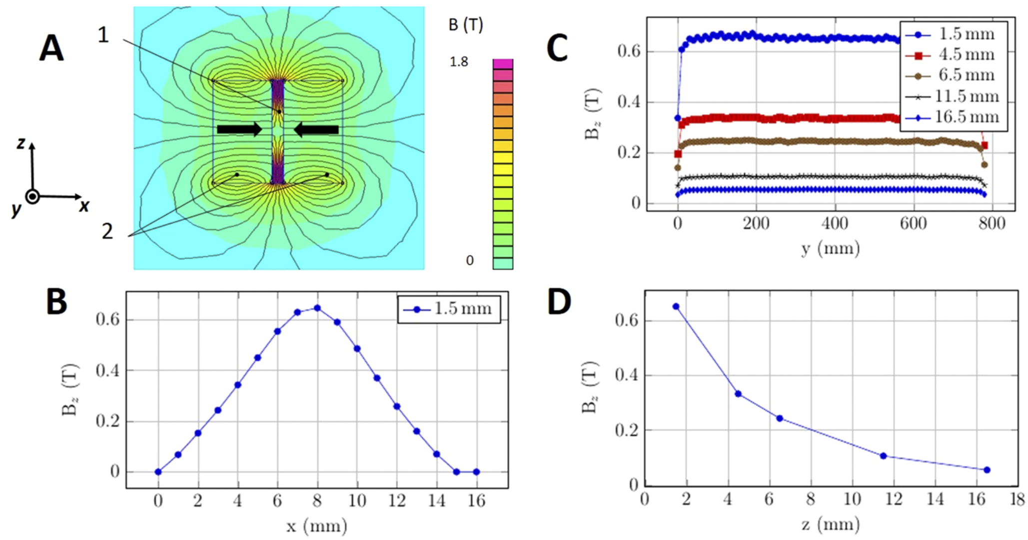

FIG. 3. Permanent magnet magnetizer and its magnetic flux density distribution. (a) Schematic magnetic configuration of the permanent magnet magnetizer (PMM) consisting of (1) an iron plate and (2) NdFeB magnets. (b) Magnetic flux density distribution $B_z(x)$ measured at distance z = 1.5 mm. (c) $^pB_z(y)$ measured along the PMM at different distances. (d) Mean values of $^pB_z(z)$.

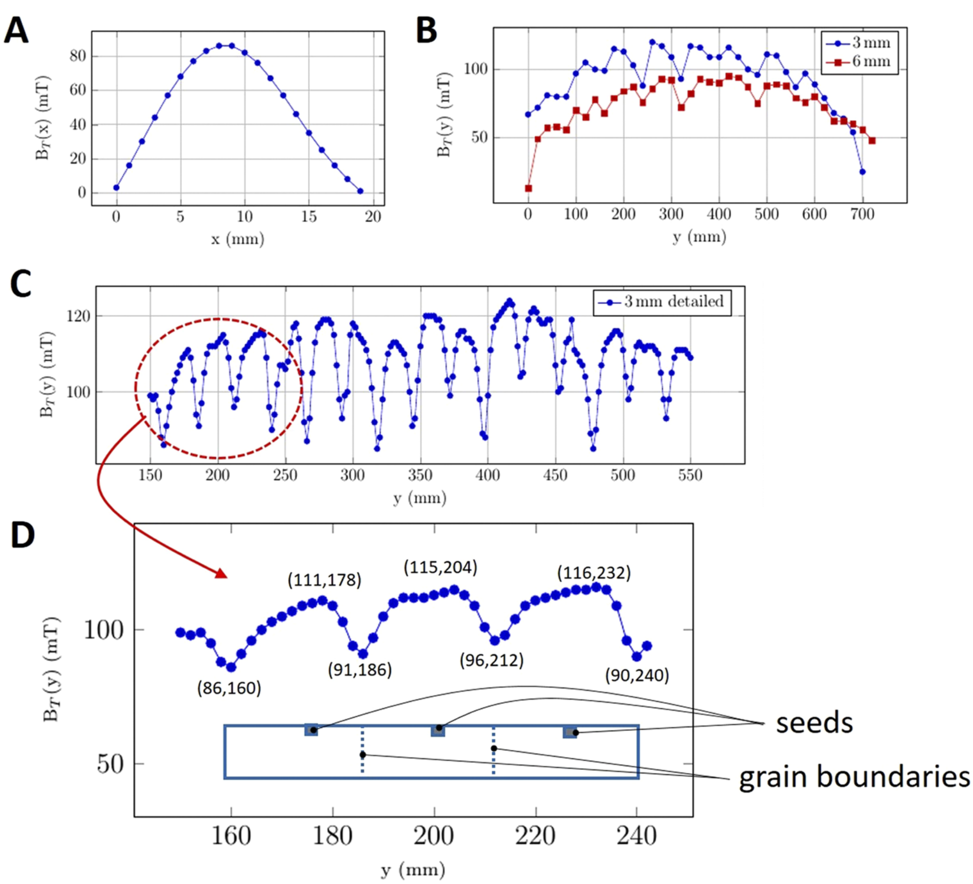

FIG. 4. Trapped magnetic field of the superconducting guideway after field cooling. Trapped magnetic flux density (a) along the x axis after FC at 3 mm and (b) along the y axis after FC at 3 and 6 mm. (c) Detailed $B_T(y)$ measurements along the superconducting guideway surface after FC at 3 mm. (d) Magnified view of detailed $B_T(y)$ measurements after FC at 3 mm for 150 mm $\leq$ y $\leq$ 240 mm. Inset: schematic illustration of a three-seed YBCO bar.

Levitation demonstration

Following the FC magnetization procedure, the red spacers [Fig. 2(a)] were removed from between the PMM and the SCG, and the PMM, weighing about 3 kg, clearly levitated above the SCG, as shown in Fig. 2(c), and moved freely in both directions along the guideway, as shown in Fig. 2(c) (Multimedia view). We then gently removed the PMM from its location above the SCG in the longitudinal direction and placed the permanent magnetic vehicle above the SCG, where it is levitated, as shown in Fig. 2(d), and moved in both directions along the guideway, as shown in Fig. 2(c) (Multimedia view). We noticed that the vehicle does not move as freely as the PMM due to its small mass and the inhomogeneity of the trapped flux in the SCG.

We performed several magnetizations at FC distances in the 1–10 mm range. We noticed that at distances of 3–4 mm, the vehicle stably levitates and can move along the guideway after being gently pushed [see Fig. 2(c) (Multimedia view)]. At greater distances, however, the levitation becomes unstable, especially in the lateral direction, due to the simple arrangement of the magnets inside the vehicle and the narrowness of the SCG. In the actual super system application, the components will need to be engineered to avoid such instability. We also saw that the vehicle's movement along the SCG is negatively affected by the inhomogeneous $B_T(y)$ resulting from the grain boundaries in the YBCO bars and the joint gaps between them. This effect could be eliminated by using multilayered superconducting tapes with ultra-fine grains, which are discussed below.

To improve the longitudinal $B_T(y)$ homogeneity, superconducting joints could be applied to eliminate the critical current or magnetic flux loss resulting from the joint gap.[12,13] Various reliable joining techniques for YBCO bulk and films, including effective welding agents, have been successfully demonstrated.[14–16] A YBCO–Ag composite and single-crystal YBCO serving as welding agents were found to maintain superconducting performance comparable to that prior to applying the joints. Additionally, high-temperature superconducting (HTS) tapes could be used in place of, or combination with, the YBCO bulk array. The record trapped field of a small (~30 mm) stack of tapes[17,18] using FC magnetization is comparable to that of a bulk HTS double stack.[19–21] For example, Sass *et al.*[22] built a stacked block using 500 tape layers and compared its levitation force with that of a three-seed bulk sample. They found that although both superconductors have comparable dimensions and the same magnetization condition, the levitation force of the tapes was only 44% of that achieved by the bulk sample. Thus, the use of stacked tapes must be carefully designed in terms of the levitation performance required over long distances for our proposed super system combining energy transport and storage with SClev transport of people and goods, as well as the system's material and operational costs. Considering that the actual super system will incorporate thousands of kilometers of superconducting guideway, superconducting joining techniques play a critical role in producing the long lengths of superconducting bulk and tape needed. A good superconducting joint allows for negligible contact resistance and the absence of critical current loss. REBCO (RE = rare earth) coated conductors over 1000 m in length have been commercially developed, while REBCO ceramic layers ~5 μm thick and with the critical current of 1300–1500 A/cm have been achieved.[23] Therefore, the superconducting tape would be a feasible solution for producing long, continuous guideways for SClev. If high-quality, uniform superconducting tapes with adequate levitation force were incorporated into the system at 20 K, vehicles would be able to move considerably more freely for much longer distances, reducing operation costs dramatically and offering a significant advantage over the current high-speed trains that require frequent and expensive maintenance, impose schedule limitations on passengers, etc.[24]

SUPPLEMENTARY MATERIAL

See the supplementary material for trapped magnetic flux density distribution in a YBCO bar after FC.

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AUTHOR DECLARATIONS

Conflict of Interest

A patent entitled "SClev Vehicle System for Transporting Energy, People, and Goods" was filed with the U.S. Patent and Trademark Office by the University of Houston.

Author Contributions

O.V. and S.S. contributed equally to this work.

O. Vakaliuk: Conceptualization (equal); Data curation (equal); Investigation (equal); Supervision (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Shaowei Song**: Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Validation (equal); Writing – original draft (equal); Writing – review & editing (equal). **U. Floegel-Delor**: Data curation (equal); Investigation (equal); Methodology (equal); Validation (equal); Writing – original draft (equal); Writing – review & editing (equal). **F. Werfel**: Data curation (equal); Investigation (equal); Validation (equal); Writing – original draft (equal); Writing – review & editing (equal). **Kornelius Nielsch**: Data curation (equal); Funding acquisition (equal); Writing – original draft (equal); Writing – review & editing (equal). **Zhifeng Ren**: Conceptualization (equal); Data curation (equal); Funding acquisition (equal); Investigation (equal); Methodology (equal); Supervision (equal); Validation (equal); Writing – original draft (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available within the article and its supplementary material.

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[24] Just after finishing all the experiments and the first draft of the manuscript, we learned of a patent issued to KIT that has some components of our super system, but not nearly as many, https://www.kit-technology.de/en/technology-offers/details/686; accessed 18 August 2022.