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Advances in High-Temperature Superconducting Pinning Maglev for High-Speed/Ultra-High-Speed Rail Transport

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Abstract

This paper presents the advancements in high-temperature superconducting (HTS) pinning maglev technology, focusing on its application in high-speed and ultra-high-speed rail systems. Our research at Southwest Jiaotong University investigated the feasibility of HTS pinning maglev systems, highlighting their levitation load capacity, high-speed dynamic levitation force, and performance under various conditions, including low vacuum environments. We have developed and tested several experimental platforms, including a 400 km/h evacuated tube HTS pinning maglev high-speed test platform and a 700 km/h high-speed maglev simulation test platform. These setups have validated the stability and efficiency of HTS pinning maglev technology, demonstrating its potential for practical high-speed applications. To further explore this technology's capabilities, a multistate coupled rail transit dynamic model test platform for speeds up to 1500 km/h is nearing completion and will soon begin testing. Alongside the high-speed experiments, we have also completed the design of a high-speed engineering prototype. Despite its numerous advantages, HTS pinning maglev technology faces several challenges, which are also discussed. This paper aims to provide a comprehensive overview of the current state of HTS pinning maglev research, offering valuable insights for the future development and application of HTS pinning maglev systems in high-speed transportation.

Keywords: HTS pinning maglev, high-speed maglev, ultra-high-speed transport, ETT transport, dynamic test platform, engineering design

1 Introduction

Rail transportation has significantly shaped human society over centuries, with its continuous evolution closely mirroring our technological advancements. From the steam-powered locomotives of the early 19th century to today's high-speed trains, rail transport has consistently broken new ground in efficiency and connectivity, profoundly influencing economic and social landscapes by bridging vast geographical and cultural distances. Introducing magnetic levitation (Maglev) technology[1] marks a revolutionary leap in rail transport. By eliminating the friction between the train and the track, Maglev enables vehicles to achieve speeds previously thought unattainable. This innovation is a testament to how expanding technological capabilities foster advancements that minimize travel time and enhance global connectivity. Looking to the future, the integration of Maglev with evacuated tube technologies (ETT)[2] represents the next frontier, elevating rail speeds to levels comparable or even superior to those of air travel. Such developments could see trains traveling in low-pressure environments, drastically reducing air resistance and enabling unprecedented velocity. As rail transport has evolved over time, its speeds have progressively increased. Figure 1[3] illustrates the trend of rail transport operating speeds over time.

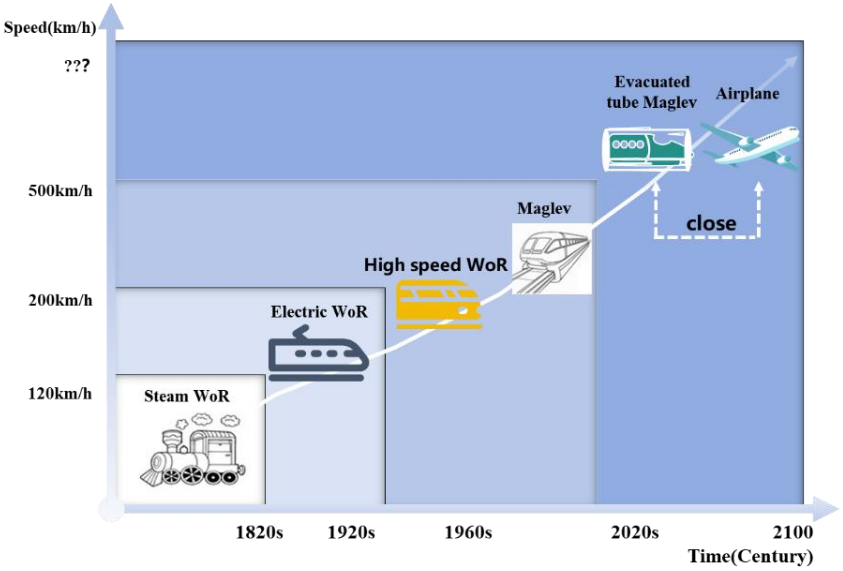


Figure 1. Evolution of rail transport speeds from the 19th to the 21st century[3]

The First Industrial Revolution, marked by the use of steam engines in the early 19th century, saw the introduction of rail transport systems with remarkable carrying capacities and speeds of approximately 80 km/h, which significantly boosted societal development. The Second Industrial Revolution occurred in the early 20th century, driven by the applications of electricity, chemicals, and petroleum. During this period, rail transport speeds approached 200 km/h. With continuous technological innovations and the onset of the Third Industrial Revolution, the speeds of wheel-on-rail high-speed trains exceeded 300 km/h. The introduction of electronic, information, and communication technologies brought enhanced convenience and comfort to rail transport systems. Meanwhile, Maglev transport systems achieved speeds exceeding 400 km/h. The new industrial era, characterized by digital networks, advanced information/communication technologies, artificial intelligence, new materials, and renewable energy usage, is now emerging. This new era is set to further advance rail transport development, inevitably leading to even higher operational speeds. The combination of Maglev technology with ETT holds the promise of achieving ultra-high-speed ground travel, with rail transport speeds approaching or even surpassing those of commercial airplanes. This progression encapsulates the profound relationship between technological advancements and transportation speeds, illustrating the ongoing quest for faster and more efficient transportation solutions.

Several types of Maglev technologies exist, each with its unique working principles and application areas. Our team focuses on developing high-temperature superconducting(HTS) pinning maglev to create high-speed maglev transportation systems and further integrating these systems with ETT to develop ultra-high-speed maglev transportation systems. The principle of HTS pinning maglev involves the use of HTS bulks that, when cooled to their superconducting state, exhibit a "pinning effect" that locks magnetic flux lines in place, thereby achieving stable levitation. Specifically, when an HTS bulk is cooled in a magnetic field to its superconducting state, quantum magnetic flux quantums are trapped by defects or potential wells within the superconductor, creating the pinning effect. This effect generates both repulsive and attractive forces, enabling stable, contactless levitation. This levitation method requires no active control, features a simple structure, cost-effectiveness, and stability, making it highly applicable in maglev transportation systems.

In 1997, China and Germany developed an HTS pinning maglev model vehicle[4]. Led by Wang Jiasu at Southwest Jiaotong University, China developed the first manned test vehicle, "Century" in 2000[5]. Following this, several countries began their own research. Germany created the SupraTrans in Dresden[6], Italy built the UAQ4 in L'Aquila[7], Brazil developed the Maglev-Cobra in Rio de Janeiro[8], Japan worked on the AIST in Tokyo[9], and Russia also contributed with their own maglev vehicle[10]. Our team at Southwest Jiaotong University has also constructed an HTS pinning maglev ring test line[11] and continuously refined its structural design, transitioning it from a laboratory model to an engineering prototype. By 2021, we established a high-speed HTS pinning maglev prototype vehicle and test line. To further explore the integration of this technology with ETT, our team has devised a strategic approach for advancing high-speed maglev technology through a three-phase plan: starting with low-speed (50 km/h)[12], which has been completed; progressing to high-speed (400+ km/h)[13], currently undergoing testing; and ultimately reaching ultra-high-speed (1500 km/h), nearing completion.

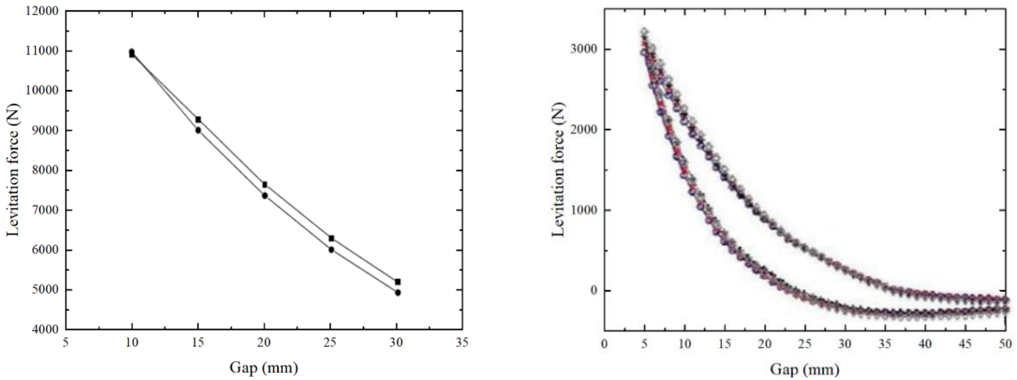
Although HTS pinning maglev technology offers many advantages, significant challenges remain before it can be widely applied in engineering. Key issues require further research, and high-speed simulation devices are necessary to validate the technology. This article presents the current state of HTS pinning maglev technology, discusses the remaining challenges, and explores potential solutions, providing insights into the future development and application of HTS pinning maglev system.

2 Feasibility Study of HTS Pinning Maglev in High-Speed and Ultra-High-Speed with ETT

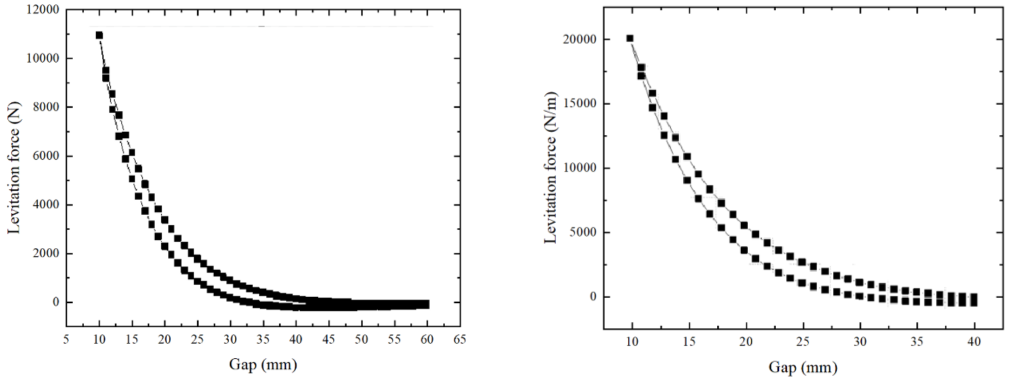
This section explores the feasibility of implementing HTS pinning maglev technology for high-speed and ultra-high-speed applications within ETT systems.

（1） Levitation Load Capacity and High-Speed Dynamic Levitation Force

Achieving sufficient levitation force is crucial for this system. Increasing the interface area of the permanent magnetic guideway (PMG) and the cross-sectional area of the superconducting bulks can enhance levitation force. However, optimizing the PMG structure can significantly improve levitation efficiency. Figure 2 shows the levitation capabilities of different maglev test vehicles. We have achieved a levitation force density of 2 t/m in the high speed engineering prototype.



(a) “Century” in China[5] (b) “Maglev-Cobra” in Brazil[6]



(c) “Super-Maglev” in China[11] (d) Engineering prototype in China

Figure 2. Levitation capabilities of different vehicles

Verifying high-speed adaptability and dynamic levitation force is crucial for HTS pinning maglev systems, especially for rail transportation. The HTS pinning maglev bearing has achieved a maximum experimental rotation speed of 520,000 rpm[14], corresponding to a linear speed of approximately 900 km/h, demonstrating the potential for high-speed applications. We also conducted some operational tests and simulations. Figure 3(a) shows the levitation force during linear high-speed travel tests, while Figure 3(b) presents the multi-field coupled model simulation results. Simulation validations indicate that the levitation force remains stable even at speeds up to 1,018 km/h, confirming the feasibility and potential of HTS technology for high-speed and ultra-high-speed maglev systems.

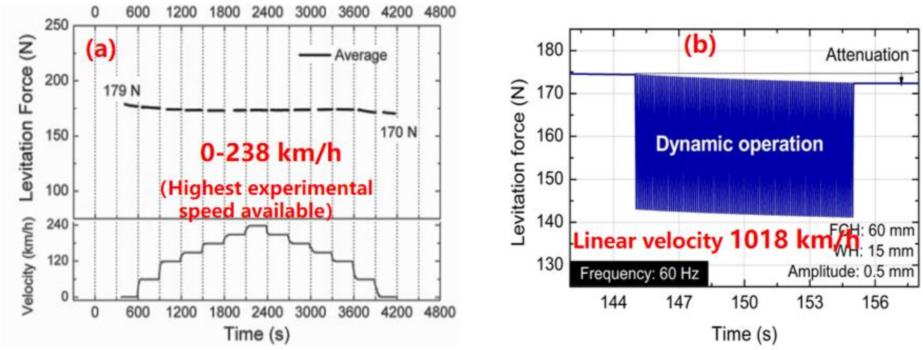


Figure 3. Dynamic levitation force: (a) experimental test and (b) multi-field coupled simulation.

（2） Thermal Effects Inside Superconducting Bulks and Magnetic Resistance

Theoretically, spliced PMGs can result in magnetic field inhomogeneity. When operating in an inhomogeneous external magnetic field, the system will experience periodic changes or vibrations that cause magnetic flux lines to penetrate and exit the superconductors, leading to hysteresis losses and heat generation. In the direction of travel, this could result in magnetic resistance. To investigate this issue, we conducted experiments using the SCML-03 test platform[15], as shown in Figure 4(a). The results are shown in Figure 4(b). At a speed of 136 km/h, magnetic resistance was minimal, and no measurable temperature rise was observed during the experiments. Figure 4(c) further illustrates that, in multi-field coupling simulations, the temperature increase in the HTS bulk material was very small (less than 0.1 K).

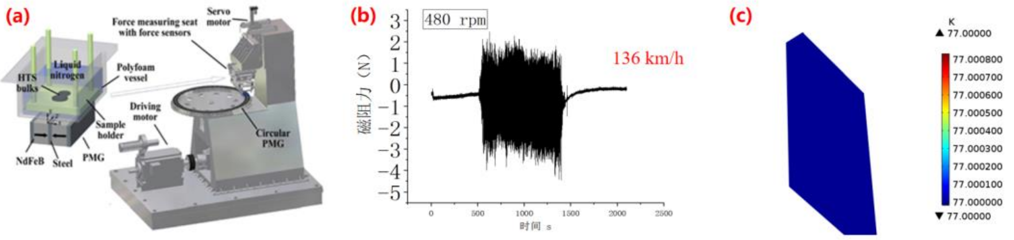


Figure 4: Verification of magnetic resistance and thermal stability: (a) experimental setup SCML-03, (b) magnetic resistance at 136 km/h and (c) thermal field in multi-field coupling simulation.

（3） Partial Decay of Levitation Force During Prolonged Operation

Verifying the effect of speed (vibration frequency) on levitation performance is essential to ensure the reliability of HTS pinning maglev systems at various speeds. Assuming the length of each PMG segment is 8 meters, the vehicle will experience a disturbance each time it passes over a segment. Figure 5 shows the levitation force over time at different speeds: 432 km/h (15 Hz), 633 km/h (22 Hz), and 720 km/h (25 Hz). The results indicate that increased speed does not lead to a significant decay in levitation force, demonstrating the system's suitability for high-speed applications. Further experiments and simulations confirm that the levitation force remains stable after prolonged operation. The ring test line[11] was used to evaluate this stability. The average levitation height over time, both with and without pre-load, showed that after 7 hours of operation, only decreased by 1.5%, indicating long-term stability [16].

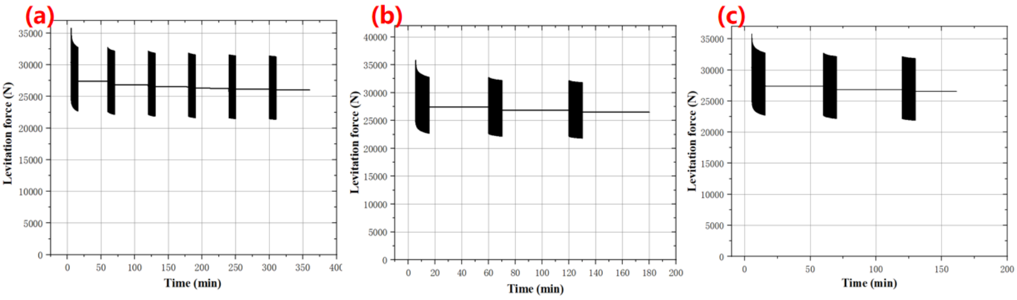
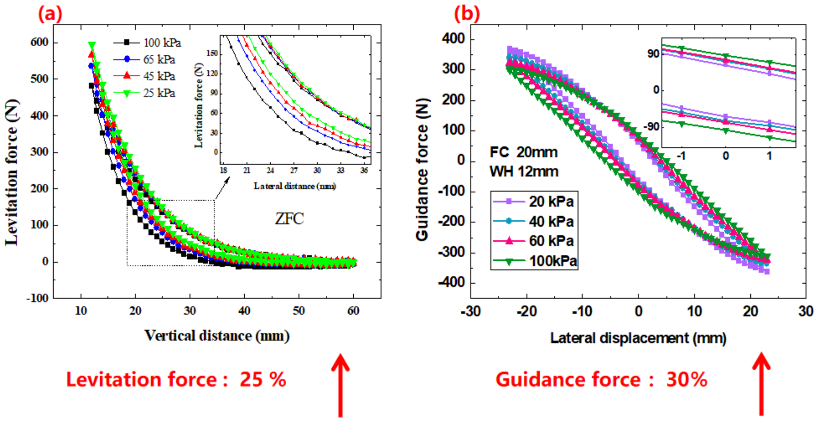


Figure 5. Verification of the effect of speed (frequency) on levitation performance: (a) 432 km/h (15Hz), (b) 633 km/h (22Hz) and (c) 720 km/h (25Hz).

(4) Performance of Levitation and Guidance Forces Under Low Vacuum

To combine the HTS pinning maglev system with the ETT system, verifying its levitation and guidance forces under low vacuum conditions is necessary. Figure 6 shows that under low vacuum conditions, the levitation force increased by 25%, and the guidance force enhanced by 30% compared to standard atmospheric conditions. Additionally, levitation relaxation decreased, ensuring robust levitation performance. These findings confirm that integrating the vacuum tube with HTS pinning maglev systems can significantly enhance overall performance[17].



Levitation force : 25 % ↑

Guidance force : 30% ↑

Figure 6. Verification of low-pressure adaptation: (a) levitation force and (b) guidance force.

（5） Vacuum Extraction Efficiency

The efficiency of vacuum extraction is critical for HTS pinning maglev-ETT systems, especially for long-distance and ultra-high-speed applications within evacuated tubes. Figure 7[12] illustrates the setup with a series of water ring pumps and roots pumps controlled by a computer system, efficiently managing the vacuum extraction process. Vacuum extraction technology is mature and reliable, using two water ring vacuum pumps to evacuate a 140 m³ tube to 0.1 atm in 15 minutes. This process ensures an optimal operational environment for HTS pinning maglev systems, minimizing air resistance and maximizing levitation and guidance forces. The vacuum extraction setup illustrated in Figure 7 demonstrates that not only is the principle of operating a maglev train in a vacuum tube feasible, but the technical feasibility is also robust. By maintaining a low-pressure environment, air resistance is significantly reduced, which enhances the levitation and stability of the maglev system.

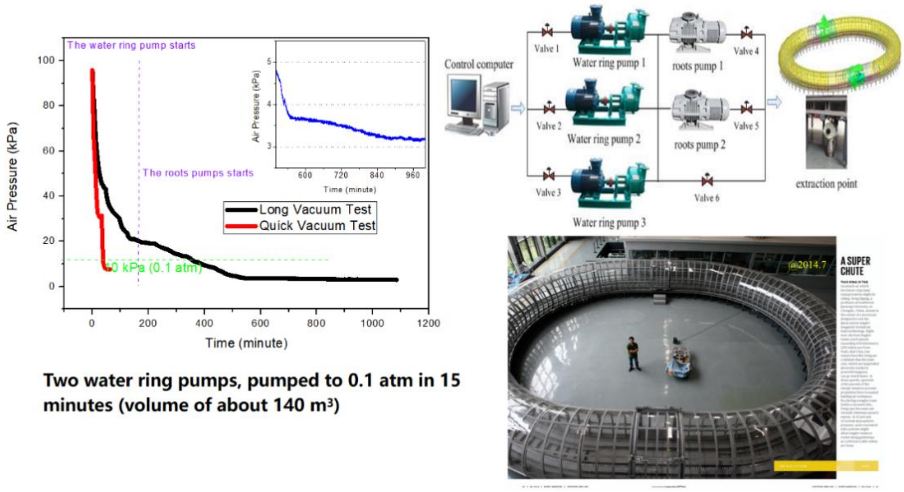


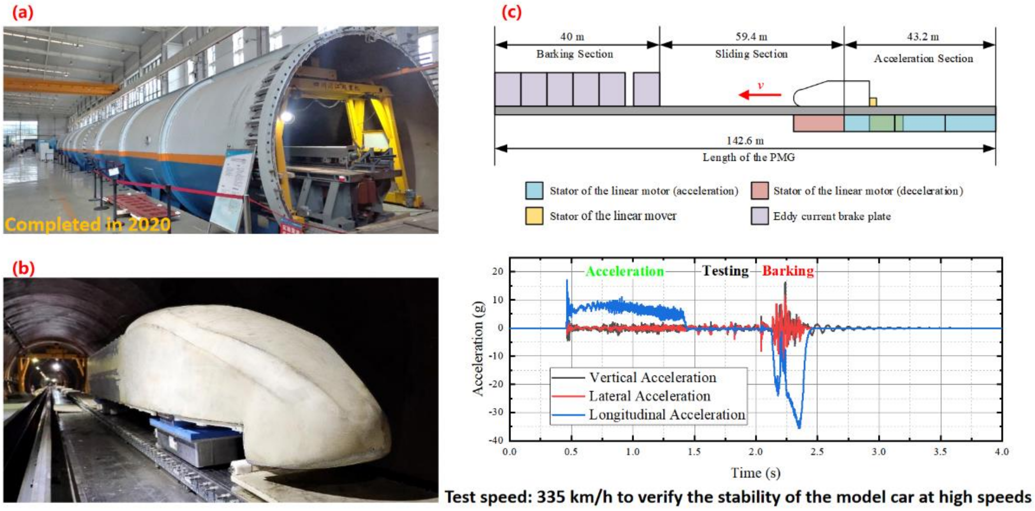
Figure 7. Efficiency and setup of pipe evacuation for ETT-HTS pinning maglev systems[12]

3 Experimental Setup for High-Speed/Ultra-High-Speed Maglev

High-speed testing complements simulation and theoretical research, providing practical validation and deeper insights. This section introduces the key equipment developed by our team for high-speed and ultra-high-speed maglev studies.

（1） 400 km/h High-Speed Running Test Platform for HTS Pinning Maglev[13]

Due to the challenges posed by centrifugal forces in the previously constructed circular test line, which made high-speed tests difficult, we established a 400 km/h ETT-HTS pinning maglev high-speed test platform in 2020, as shown in Fig 8. This platform is built at a 1:10 scale with a tube diameter of 4.2 meters. It can achieve speeds up to 430 km/h and operate at pressures as low as 0.05 atm, with a rated levitation load of 200 kg. The platform comprises various sections for acceleration (43.2 meters), sliding (59.4 meters), and braking (40 meters), allowing comprehensive testing of the maglev vehicle's stability at high speeds. Tests have validated the vehicle's stability at speeds up to 335 km/h.



Test speed: 335 km/h to verify the stability of the model car at high speeds

Figure 8 High-speed test platform: (a) The completed test platform, (b) The model vehicle within the vacuum tube and (c) The schematic of the test sections[13].

（2） 700 km/h High-Speed Maglev Simulation Test Platform[18]

To achieve higher test speeds in a compact space, we have constructed a 700 km/h high-speed maglev simulation test platform, as shown in Figure 9[18]. This platform is designed to study the dynamic behavior of various maglev models, including HTS pinning and electrodynamic suspension, under ultra-high-speed conditions. The platform features a versatile circular track system that supports extended testing durations, low energy consumption, and data collection and analysis. The track has a diameter of 2,140 mm, and the system can achieve a maximum rotational speed of 700 km/h. Currently, this equipment is being used for experiments, and detailed experimental data will be reported in forthcoming articles. This setup allows for comprehensive evaluation of different maglev technologies, ensuring their suitability for high-speed applications.

Figure 9. 700 km/h high-speed maglev simulation test platform [18]

（3） 1500 km/h Multisate Coupled Rail Transit Dynamic Model Test Platform

As previously mentioned, combining HTS pinning maglev technology with ETT aims to achieve speeds comparable to commercial airplanes. To this end, an extended vacuum tube maglev test line has been constructed. As shown in Figure 10, the multistate coupled rail transit dynamic model test platform is designed to explore maglev transportation dynamics under various conditions. Key specifications include a 3-meter diameter tube, 1620 meters in length, a maximum speed of 1500 km/h, and a minimum pressure of 0.005 atm. This platform facilitates research on maglev dynamics, multi-field coupling effects, nearing completion, it will soon begin testing. Addressing fundamental scientific issues, the platform integrates advanced systems for testing, communication, environmental control, propulsion, levitation, and vacuum maintenance. Selected as a pilot project for China's transportation infrastructure initiative, it is crucial for advancing maglev technology and developing practical solutions for future ultra-high-speed transportation systems.

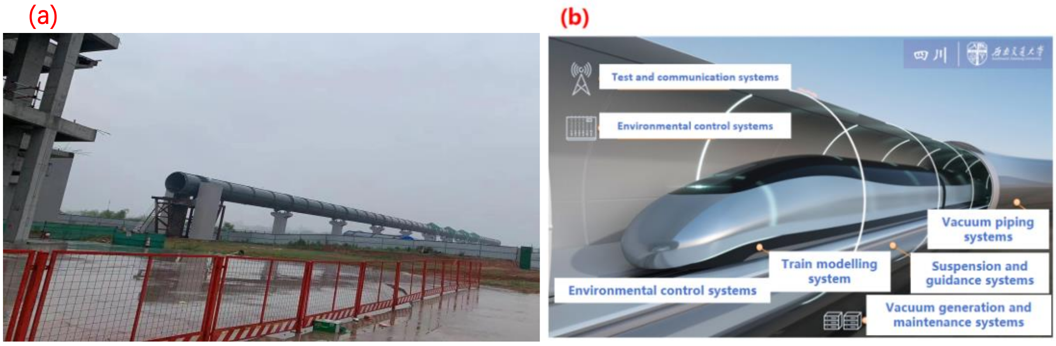


Figure 10. 1500 km/h multisate coupled rail transit dynamic model test platform: (a) construction site and (b) system architecture

4 Engineering Design and Prototype Development of High-Speed HTS Pinning Maglev

After completing the research and validation of high-speed maglev technology, our ultimate goal is to apply it to passenger rail transportation. To achieve this, we have designed a comprehensive engineering plan aimed at achieving speeds of up to 620 km/h. This section briefly introduces the suspension frame, bridge structures, and engineering prototype.

（1） Design of the levitation frame and linear motor

The design of the suspension frame is crucial for the HTS pinning maglev train system. Inspired by the bogie structure of wheel-on-rail high-speed trains, as shown in Figure 11(b), we designed the suspension frame structure depicted in Figure 11(a). The suspension frame includes a permanent magnet linear motor for propulsion, HTS levitator with bulks inside for stable levitation, and a combination of Z-shaped and horizontal pull rods for traction of the carriage. Additional components such as limitguided sliding shoes, a braking system, air spring suspension, and horizontal and vertical dampers ensure precise guidance, safety, and enhanced ride comfort.

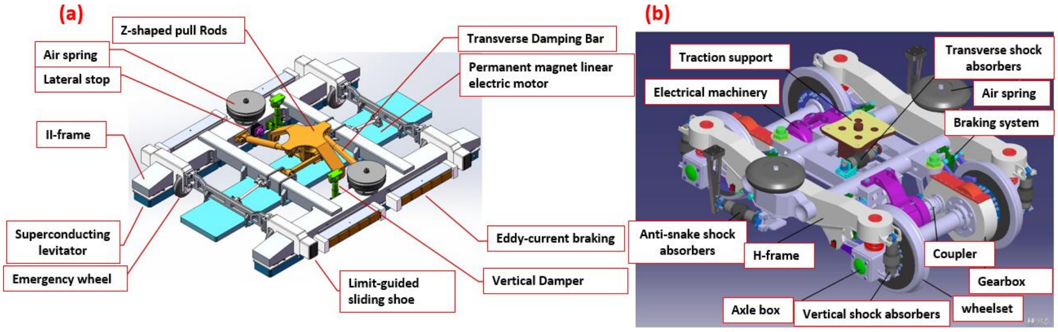
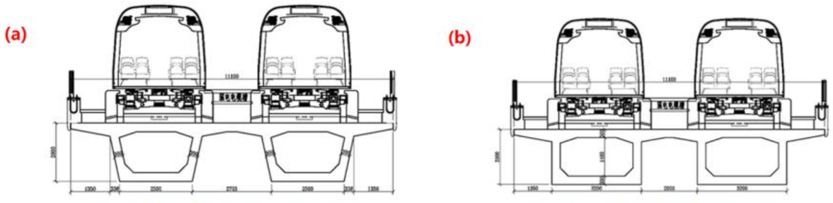


Figure 11. Comparison of the support structures: (a) suspension frame of HTS pinning maglev and (b) bogie for high-speed trains.

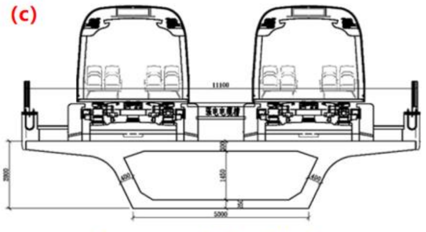
(2) Elevated Bridge Structure

To achieve higher control over track smoothness, HTS pinning high-speed maglev systems are suggested to be constructed on elevated bridges, providing the stability and durability typical of high-speed rail structures. Based on the technical specifications of the maglev system, design options include straight web box girders (Figure 12a), inclined web box girders (Figure 12b), and integrated box girders (Figure 12c). These girders are prefabricated and assembled on-site to ensure efficient construction. Considering economic benefits, visual appeal, and superior mechanical performance, integrated box girders are recommended as the primary choice. The other two structures can be used in complex mountainous areas, allowing for single-line bridge construction. Each box girder type has been analyzed for its vibration mode, static load deflection, deflection ratio, and beam end rotation angle.



Straight Web Box Girders

Incined Web Box Girders



Integrated Box Girders

Figure 12. Structural designs for elevated bridges in high-speed HTS pinning maglev systems: (a) straight web box girders, (b) inclined web box girders and (c) integrated box girders.

（3） Electromagnetic Radiation Issues

Passengers are particularly concerned about whether this transportation system, which relies on electromagnetic forces for levitation, guidance, and propulsion, poses any radiation risks to the human body. Therefore, we conducted detailed simulations to address these concerns. Figure 13 shows the magnetic field values at different positions within the vehicle. The electromagnetic radiation levels are well below the GB8702 standard limits. Similar results were observed in the electromagnetic simulations near the station, with levels significantly lower than the limits. The highest observed magnetic flux densities were substantially below the regulatory thresholds, confirming that the system design effectively minimizes electromagnetic radiation exposure, ensuring the safety of passengers and personnel.

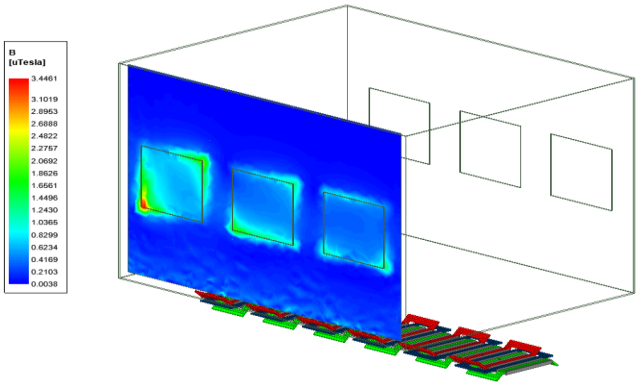


Figure 13. Magnetic flux density at various positions of the maglev vehicle.

（4） High-speed HTS pinning maglev Engineering Prototype and Test line

Based on the engineering design, we constructed a high-speed HTS pinning maglev engineering prototype vehicle and test line, as shown in Figure 14. This system integrates various engineering disciplines, covering levitation, propulsion, and control aspects, forming a comprehensive maglev system. The prototype vehicle features a levitation height of 10-20 mm with a levitation ratio of 1:20. In the direction of travel, it experiences minimal resistance, almost negligible. The magnetic track generates a static magnetic field with no electromagnetic radiation, making it safe and efficient. The vehicle has been lightweight for cost considerations, and the superconducting levitators are not fully laid above the track as initially designed.

The test line has a track gauge of 2 meters a maximum load of 15 tons, allowing for comprehensive testing of the vehicle's performance. The system has a synchronous linear motor, ground positioning systems, and U-shaped track plates. It also includes mechanical brake pads and a safety support wheel track. This project demonstrates the potential of HTS pinning maglev systems in revolutionary high-speed transportation, combining advanced engineering with innovative design.

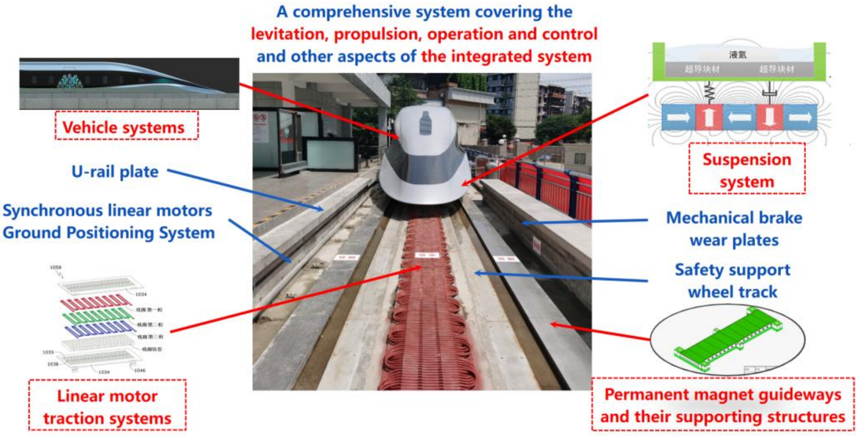


Figure 14. Comprehensive overview of the high-speed HTS pinning maglev engineering prototype vehicle and test line.

5 Major Challenges

Developing high-speed HTS pinning maglev and ETT systems involves addressing several key challenges. These include the use of permanent magnets, managing heat accumulation in evacuated tubes, ensuring precise control and response times of high-speed motors, and maintaining air-tight seals in expanding pipes.

（1） Sustainable Solutions for the Use of Permanent Magnets

A challenge in high-speed HTS pinning maglev systems is the cost of permanent magnets. However, these magnets are recyclable and retained in track infrastructure. We're negotiating with manufacturers for a rental scheme to lower costs. Additionally, alternative designs and ferromagnetic materials optimize magnetic field distribution, reducing reliance on permanent magnets. These innovations ensure the effective management of permanent magnets in maglev systems, providing a sustainable and economically viable solution for high-speed transportation.

（2） Heat Accumulation and Dissipation in Evacuated Tubes

Heat accumulation and dissipation within evacuated tubes pose another critical challenge for HTS pinning maglev systems. In a high-speed vacuum environment, managing the heat generated by the superconducting materials and the propulsion system is crucial to maintaining operational efficiency and safety. Effective thermal management strategies, such as advanced cooling systems and heat dissipation materials, are essential to prevent overheating. Ensuring the superconducting materials remain at required temperatures is vital for sustaining their longevity.

（3） Control Precision and Response Time of High-Speed Motors

The control precision and response time of high-speed motors are paramount in ensuring the stability and safety of HTS pinning maglev trains. Advanced control systems, incorporating real-time monitoring and feedback mechanisms, are necessary to achieve the required precision. These systems must be capable of handling the dynamic conditions of high-speed travel, providing smooth acceleration and deceleration, and maintaining the desired trajectory with minimal deviations.

（4） Pipe Expansion and Air-Tight Dynamic Seals

Maintaining air-tight conditions in evacuated tubes while allowing for pipe expansion due to temperature variations is a complex engineering challenge. The dynamic seals used in constructing these tubes must be capable of accommodating expansion and contraction without compromising the vacuum integrity. Innovative seal designs and materials that can withstand the physical stresses and maintain a tight seal are critical. Ensuring these seals function effectively over long periods and under varying conditions is essential for the reliability and efficiency of the maglev system.

6 Conclusion

The advancements in HTS pinning maglev technology has demonstrated the feasibility of HTS pinning maglev systems, emphasizing their potential applications in modern transportation. Key findings include the verification of levitation capacity and dynamic levitation force, demonstrating that HTS pinning maglev systems can achieve stable levitation and efficient operation even at high speeds. The heat generated within superconducting bulks remains minimal, ensuring operational safety and performance. Additionally, our investigations into the effects of prolonged operation and low vacuum environments indicate that HTS pinning maglev systems can maintain their levitation force and guidance capabilities. The construction of an ultra-high-speed multisate coupled rail transit dynamic model test platform marks a significant milestone, with speeds up to 1500 km/h. This state-of-the-art facility will provide valuable insights and pave the way for future advancements in maglev technology. Despite the numerous advantages, HTS pinning maglev technology faces challenges such as the use of permanent magnets, heat management in evacuated tubes, precision control of high-speed motors, and maintaining airtight seals in expanding pipes. Addressing these challenges is crucial for the widespread adoption and practical application of HTS pinning maglev systems.

In conclusion, our research underscores the potential of HTS pinning maglev technology to revolutionize high-speed transportation. Through continued innovation and overcoming existing challenges, HTS pinning maglev technology is poised to become a viable and efficient option for next-generation transportation.

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