6th International Workshop on Numerical Modelling of HTS

Optimization methodology of race-track HTS magnets for transportations

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3. École Centrale de Lyon, France

Contents

1. Self introduction

Education

- **Southwest Jiaotong University, Chengdu, China 2018-now**
  Electrical Engineering, School of Electrical Engineering;
  Degree: PhD student
- **Southwest Jiaotong University, Chengdu, China 2015-2018**
  Electrical Engineering, School of Electrical Engineering;
  Degree: Master
- **China Three Gorges University, Yichang, China 2011-2015**
  Electrical Engineering, School of Electrical Engineering;
  Degree: Bachelor

Participation in projects

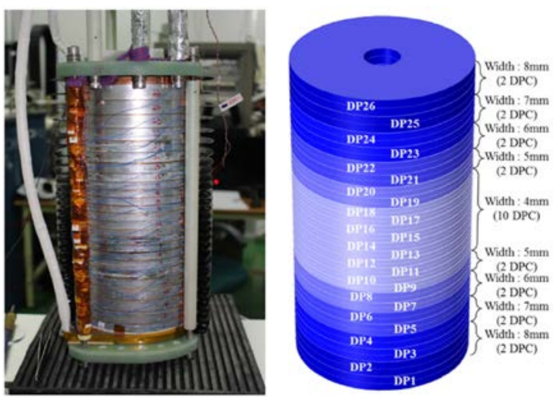
- Study on the vibration properties of superconducting bulk suspension based on three-dimension multiphysics field coupling model, China.
- Key technique research on the persistent-mode high-temperature superconducting magnets towards the application on the rail transit system, China.

Contents

2. Research background

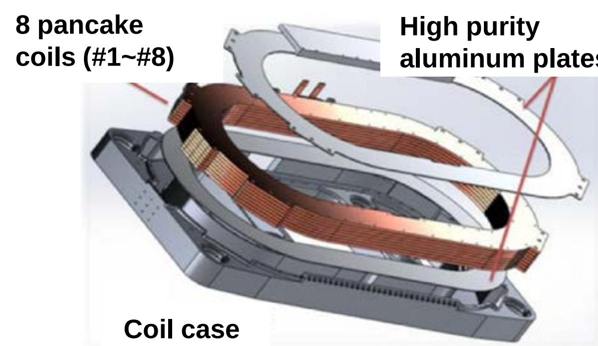
HTS Magnets

- Strong magnetic field and good mechanical properties
- Self-protecting characteristic of no-insulation HTS Magnet
- Decreasing the weight and volume of HTS motor
- Cost reduction and improved reliability of HTS Maglev



All-HTS magnets

HTS linear motor



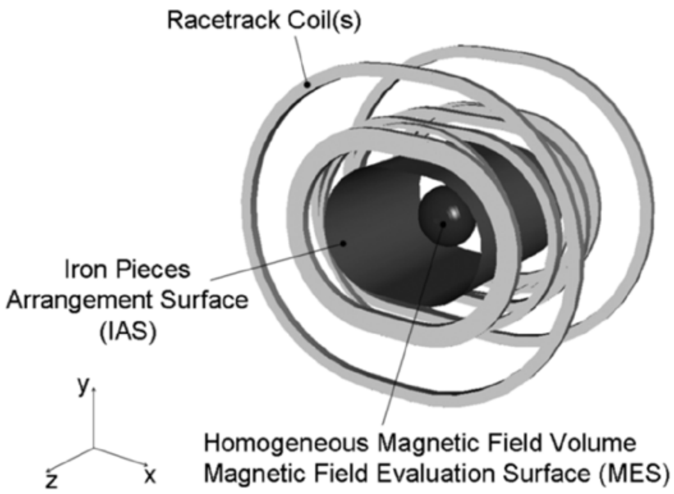
HTS magnet for Maglev

2. Research background

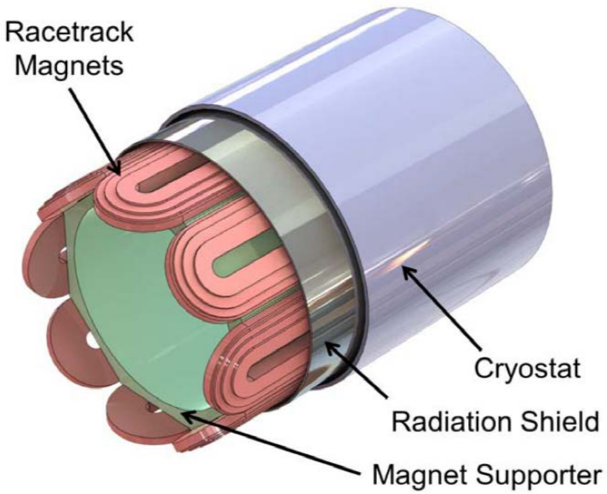
HTS Magnets

The design optimization of HTS magnets is essential:

- Expensive superconducting materials
- Susceptible to the operational environment



Design optimization for the racetrack HTS magnet construction

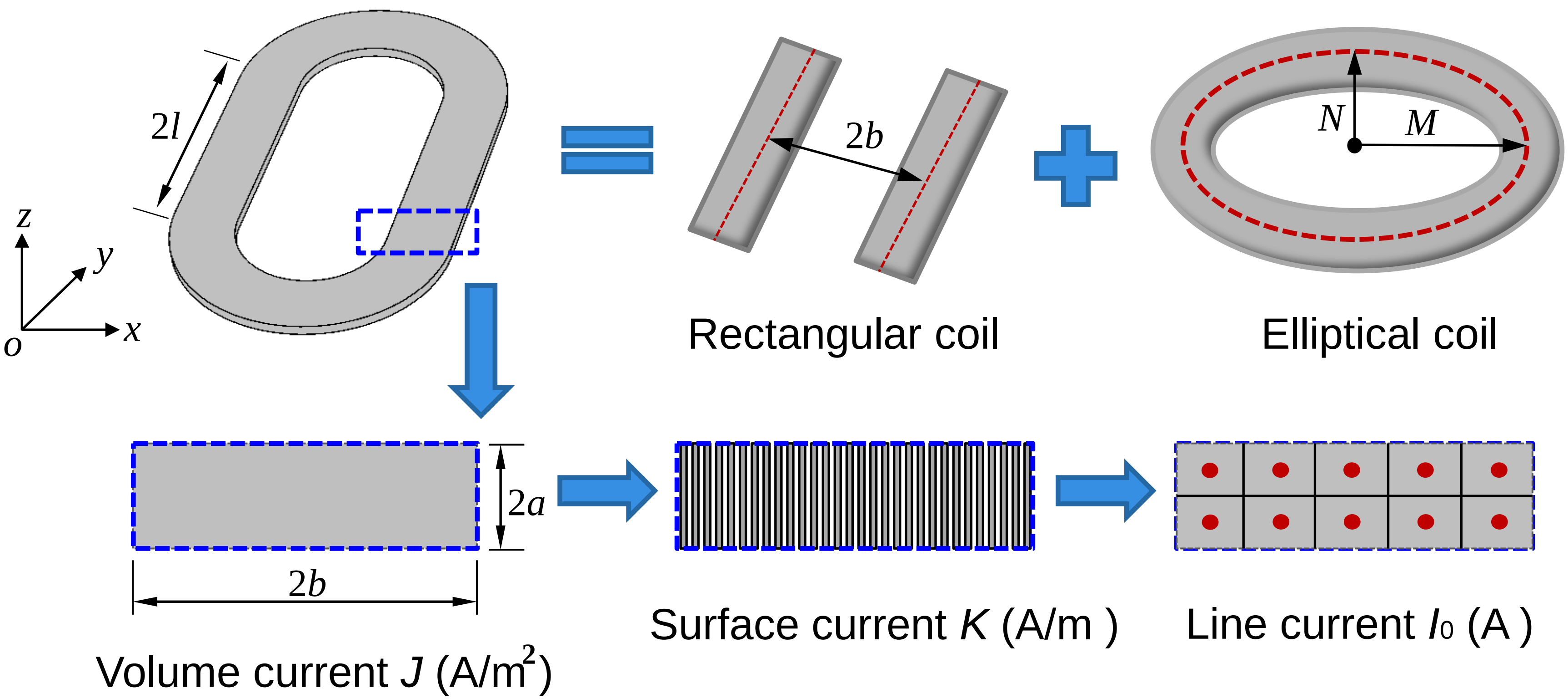


Design optimization for the HTS magnet of an HTS generator

Contents

Analytical model of magnetic field

The geometry of the race-track magnet is devided into two parts: **rectangular and elliptical coils,** and the magnet current were assumed as **volume, surface and line currents**.



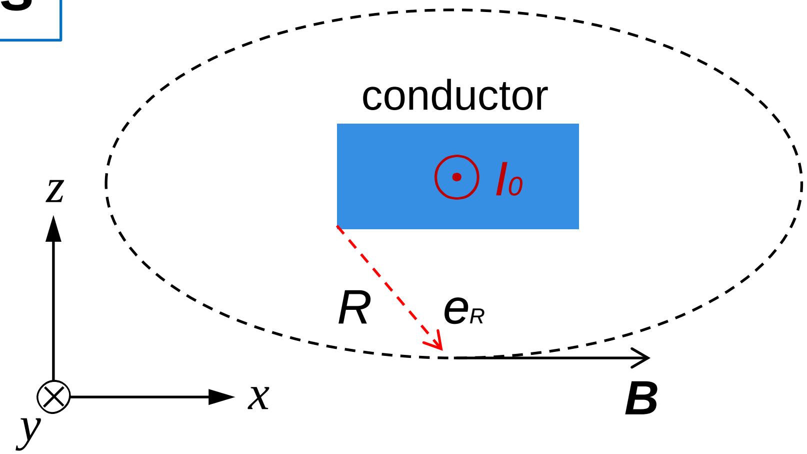
3. Optimization of race-track HTS magnet

Mathematical principles

➢ Line current

$$\mathbf{B}_L = \frac{\mu_0}{4\pi}\int_L \frac{\mathbf{I}dl \times \mathbf{e}_R}{R^2}$$

$$B_z = \frac{\mu_0 I_0}{4\pi}\int_0^{2\pi} \frac{R^2 - b(x-x_0)\cos(\theta) - a(y-y_0)\sin(\theta)}{r(x,y,z,\theta)^3} d\theta$$



Model of calculating magnetic field

➢ Surface current

$$\mathbf{B}_S = \frac{\mu_0}{4\pi}\iint_S \frac{\mathbf{K}dS \times \mathbf{e}_R}{R^2}$$

$$B_z = \frac{\mu_0 K}{4\pi}\int_{-\pi}^{\pi} \frac{(M^2\sin(\theta)y + N^2\cos(\theta)x - r(\theta)(M^2\sin(\theta)^2 + N^2\cos(\theta)^2)(z_0 - z)\sqrt{r(\theta)^2 + r'(\theta)^2}}{\sqrt{M^4\sin(\theta)^2 + N^4\cos(\theta)^2}(x^2 + y^2 + r(\theta)^2 - 2r(\theta)(x\cos(\theta) + y\sin(\theta)))R(\theta, z_0)} d\theta$$

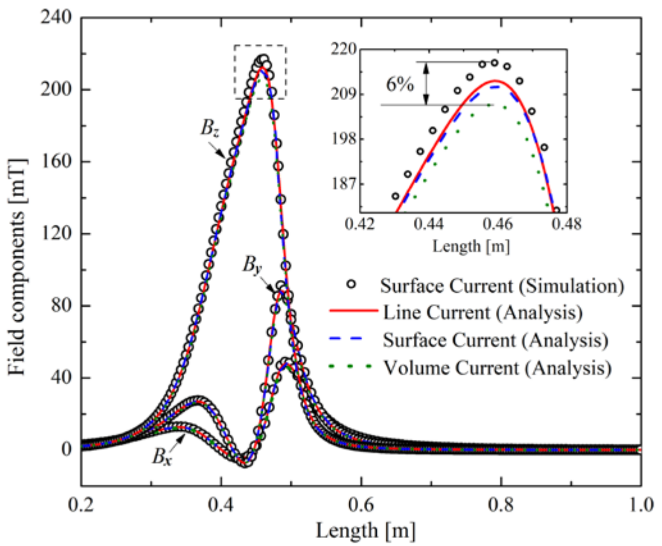
➢ Volume current [1]

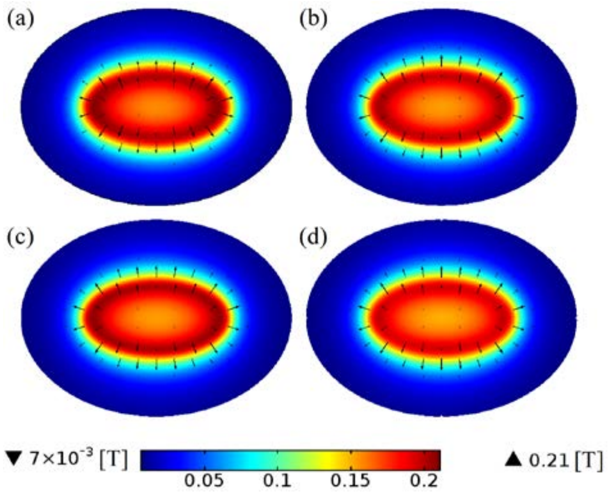
$$\mathbf{B}_V = \frac{\mu_0}{4\pi}\iiint_V \frac{\mathbf{J}dV \times \mathbf{e}_R}{R^2}$$

$$B_x = \frac{\mu_0 J}{4\pi}\int_{-\pi}^{\pi} \frac{N^2\cos(\theta)}{\sqrt{M^4\sin(\theta)^2 + N^4\cos(\theta)^2}}(R_u(\theta,a) - R_u(\theta,-a) - R_l(\theta,a) + R_l(\theta,-a) + U\ln\frac{r_u(\theta) - U + R_u(\theta,a)}{r_l(\theta) - U + R_l(\theta,a)} - U\ln\frac{r_u(\theta) - U + R_u(\theta,-a)}{r_l(\theta) - U + R_l(\theta,-a)})d\theta$$

[1] S. Crozier. A novel, open access, elliptical cross-section magnet for paediatric MRI. *Measurement Science and Technology*. 9 (1998) 113–119.

Magnetic field of the race-track magnet





Distribution of magnetic field generated by a race-track magnet, (a) Simulation, (b) Line current, (c) Surface current, (d) Volume current

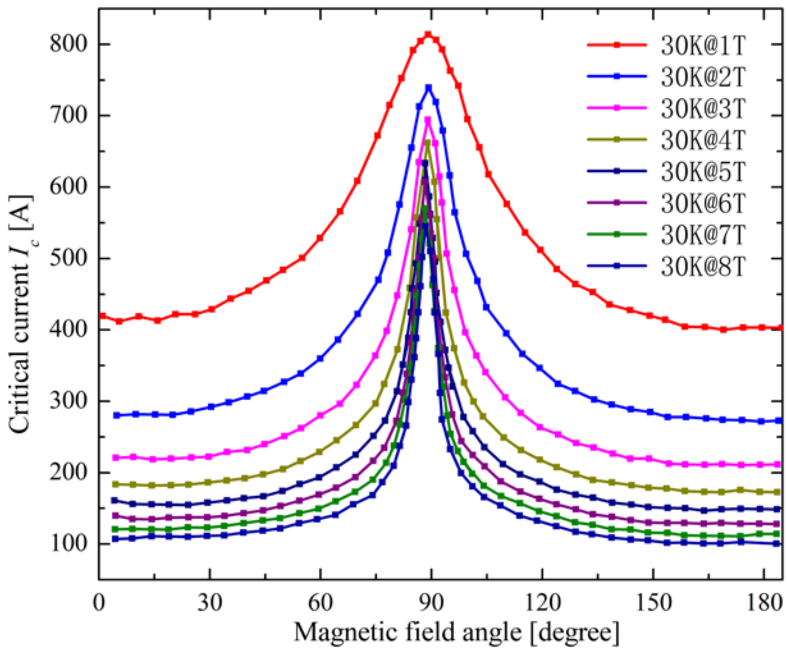
Calculated times t [s] (error)	Surface Current (Simulation)	Line Current (Analysis)	Surface Current (Analysis)	Volume Current (Analysis)
B_x	0	**2.8(-2.8%)**	8.8(2.1%)	25.5(-4.4%)
B_y	0	**2.9(-2.1%)**	8.5(2.0%)	25.5(-2.9%)
B_z	0	**3.7(-2.5%)**	13.3(-2.0%)	46.7(-5.9%)
B_m	0	**8.7(-3.1%)**	31(-1.5%)	97(-5.9%)

3. Optimization of race-track HTS magnet

Optimization of the race-track magnet

Target: Maximize the ratio of central magnetic field *B*$_{oz}$ to the needed tape length of the race-track HTS magnet.

Method: Monte Carlo Optimization Algorithm of MATLAB program



Critical current $I_c(B,\theta)$ of HTS tape

Objective Function:

$$\max : \frac{B_{oz}}{L},\ B_{oz} \approx 2\,[\mathrm{T}]$$

$$L = 4nl + n(2\pi(N + \frac{b}{n} - b) + 4(M - N)) + 2\pi b(n-1)))$$

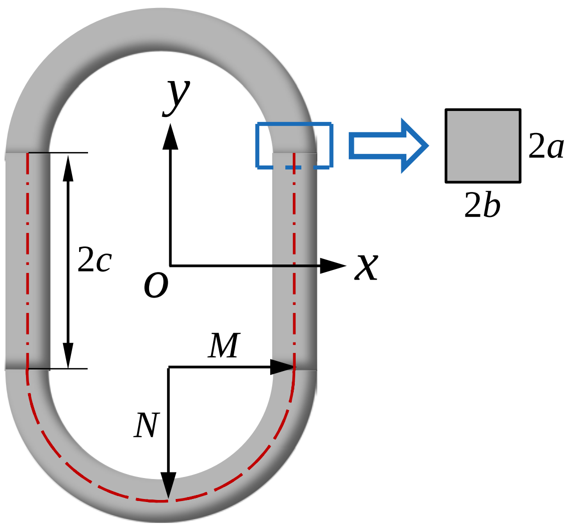
Constraint Conditions:

$$N - b > 20,\ M - b > 50$$

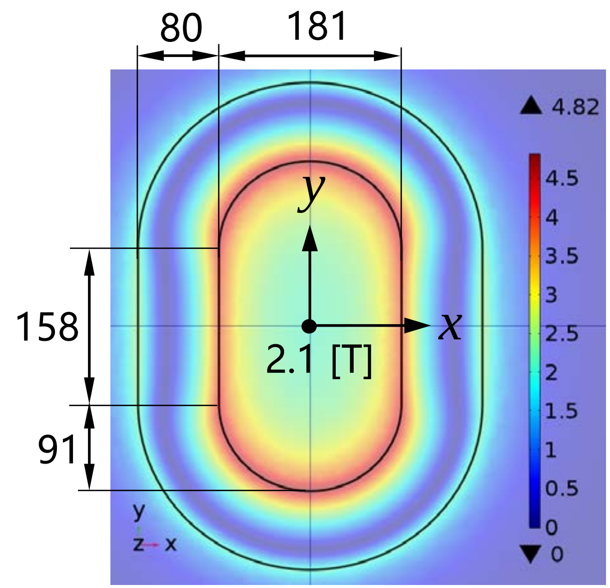
$$\frac{(N-b)^2}{M-b} > 50,\ I_0 - I_c(B,\theta) < 0$$

3. Optimization of race-track HTS magnet

Optimization results



Planform of race-track magnet



Magnetic flux density

Optimization parameters	a [mm]	c [mm]	M [mm]	N [mm]	I0 [A/mm]	n (turns)
Upper limit	6	37.5	100	0.1M	10	250
Down limit	25	150	131	M	100	405
Optimization results	20	79	131	131	34	401

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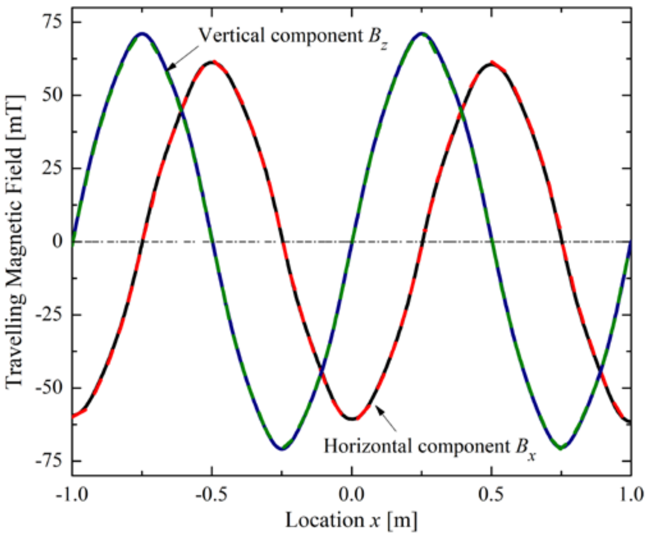
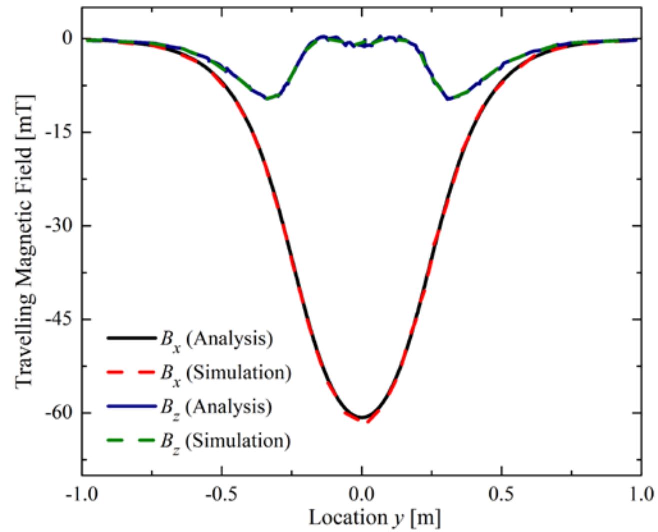
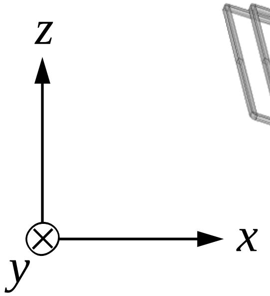
3.1 Optimization of air-core linear motor

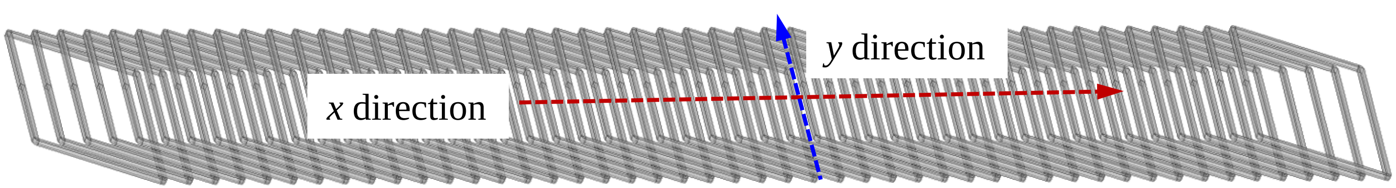
Magnetic field of air-core stator





The travelling magnetic field generated by a flat air-core stator, including the horizontal component B_x and vertical component B_z





The geometric structure of a flat air-core stator windings

3.1 Optimization of air-core linear motor

Optimization of the air-core stator

Target: maximize the ratio of thrust to length of the stator windings.

Method: The Coordinate Search Optimization Algorithm of MATLAB program which seeks the minimum of a scalar function

Objective Function:

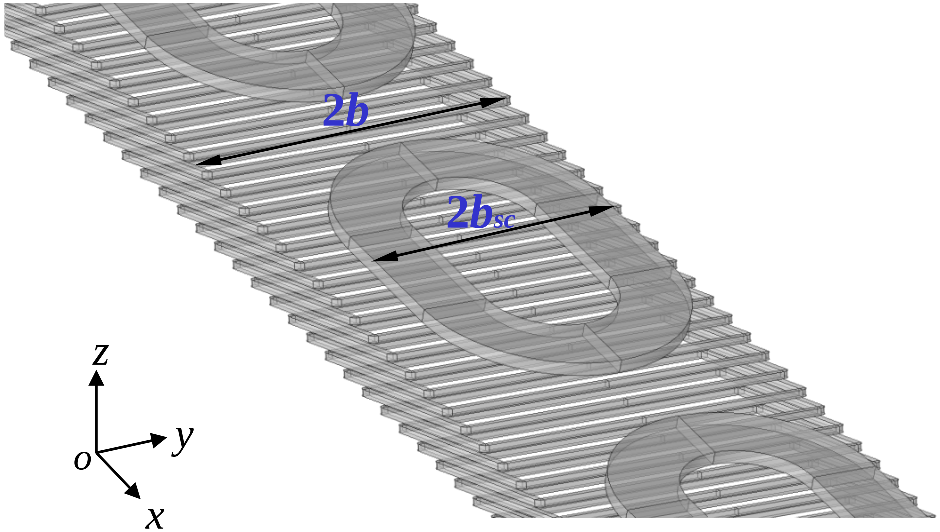
$$\max : \frac{F_x}{L_{cu}},$$

$$L_{cu} = 2N\sqrt{\left(\frac{5\tau}{6}\right)^2 + (v_c + v_g)^2} + 4b$$

Optimization Parameter:

The width of air-core stator: 2*b*,

with constraint: $0.1b_{sc} < b < 2b_{sc}$



Geometric structure of air-core linear motor

Optimization of the air-core stator

Objective Function:

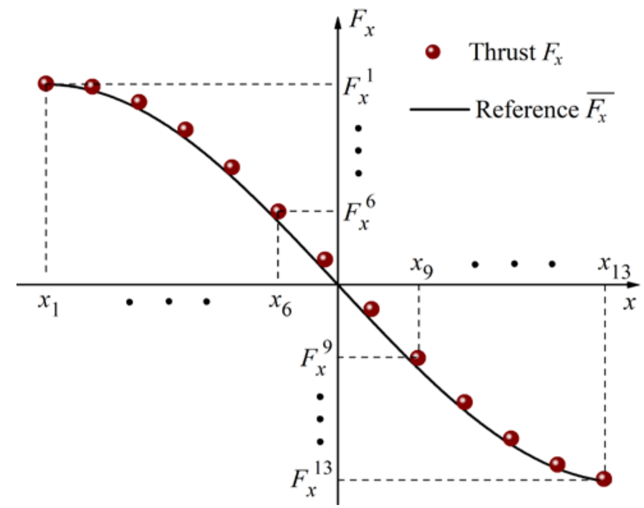
$$\min : \sum_{i=1}^{n} \left| F_x^{\,i} - \overline{F_x^{\,i}} \right|,$$

$$\overline{F_x^{\,i}} = -\frac{F_x^{\,1} + F_x^{\,n}}{2} \sin\left(\frac{\pi}{\tau} x\right)$$

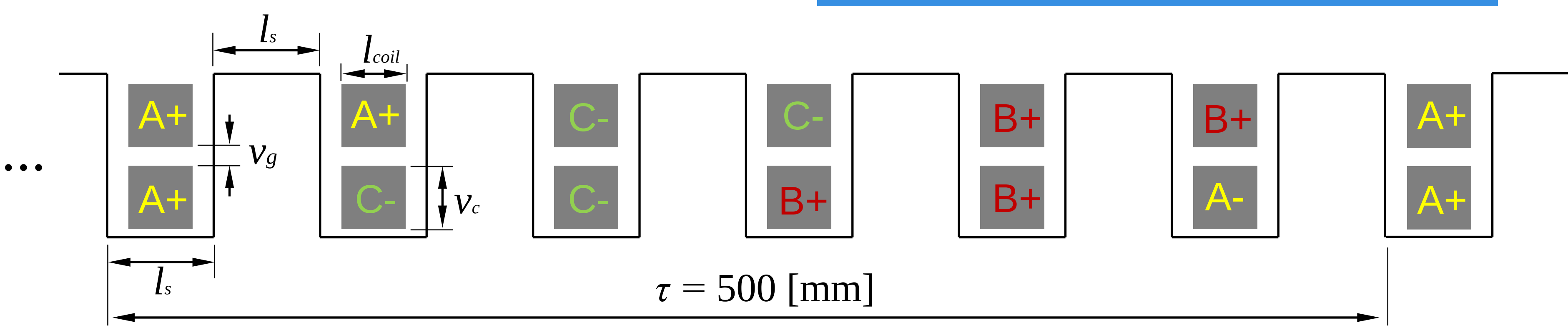
Optimization Parameter:

The vertical gap of windings: v_g,

with constraint: $v_c < v_g < \tau$



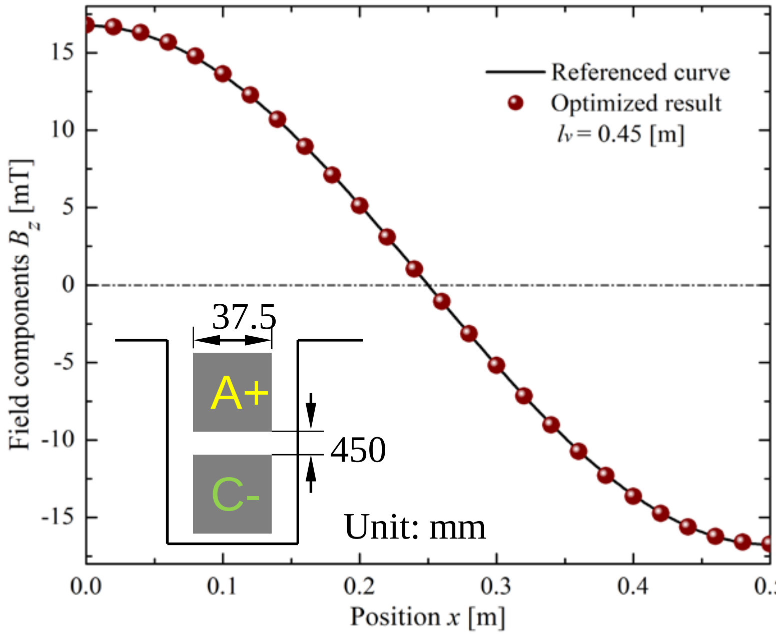
The thrust F_x of air-core linear motor



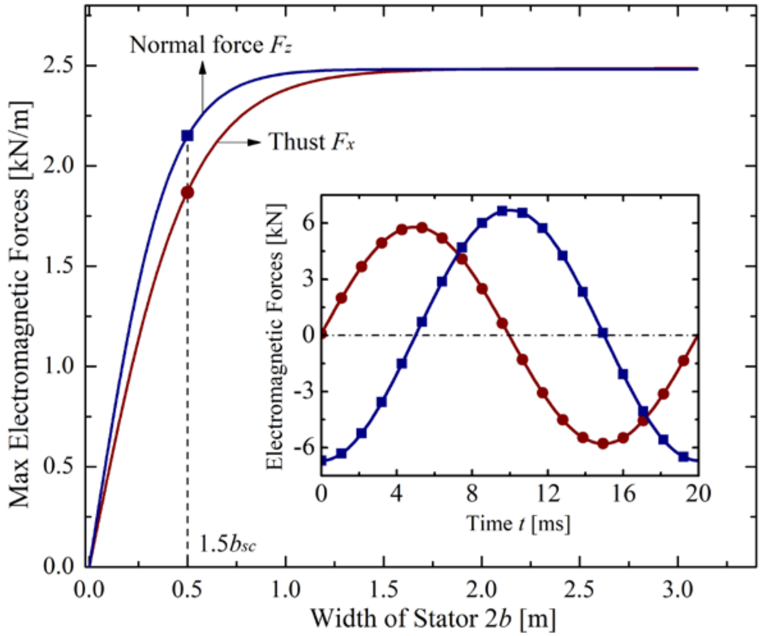
The geometric structure of air-core stator with double-layer copper windings

3.1 Optimization of air-core linear motor

Optimization results



The thrust curve using optimized parameter



Magnetic forces versus width of stator

The thrust harmonic is the smallest when the vertical gap v_g reaches 450 mm.

To decrease the volume of stator, the width of stator was set as $2b = 3b_{sc}$.

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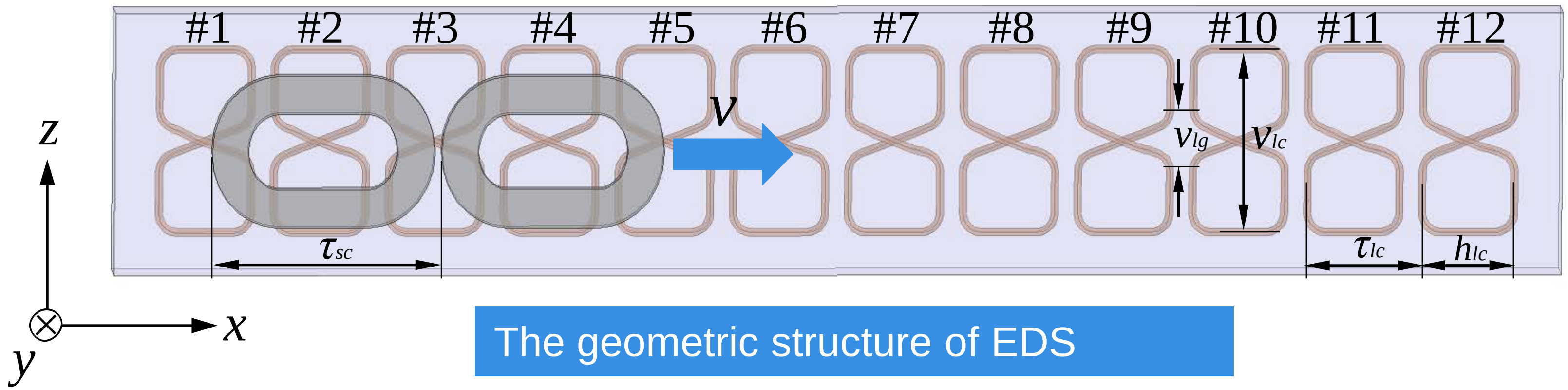
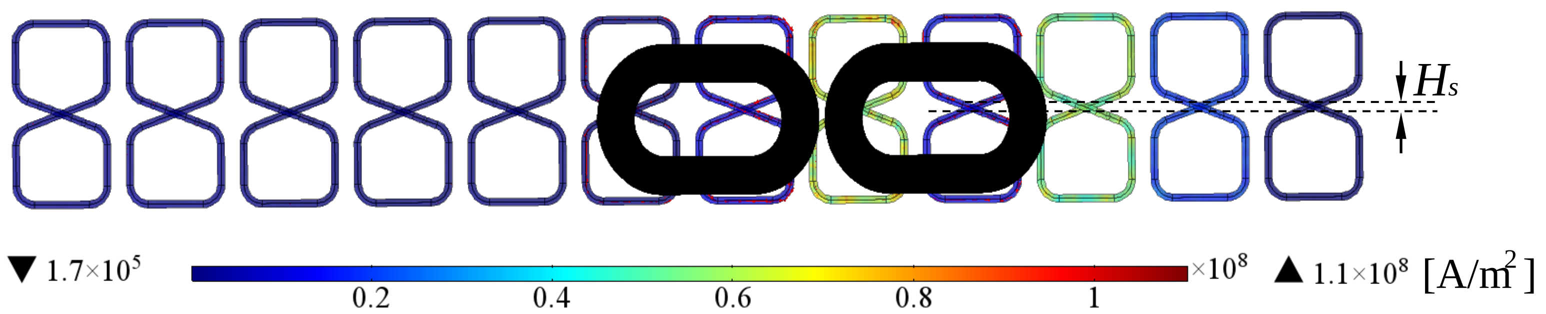
3.2 Calculation of EDS system

Simulation of EDS train



The geometric structure of EDS



The distribution of current density inside the eight-figure

Table: Geometric parameters of EDS system

τ_{sc} [m]	τ_{lc} [m]	v_{lc} [m]	h_{lc} [m]	v_{lg} [m]	L_{sc} [H]	L_{lc} [mH]	R_{lc} [Ω]	H_s [mm]
0.5	0.25	0.38	0.166	0.129	0.515	32.384	5.7684	20

3.2 Calculation of EDS system

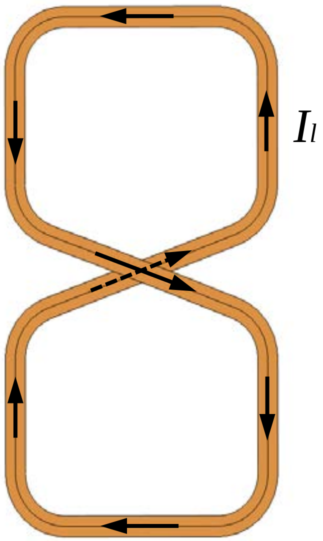
Dynamic circuit of EDS train

Calculation of induced current in levitation coils: RL circuit

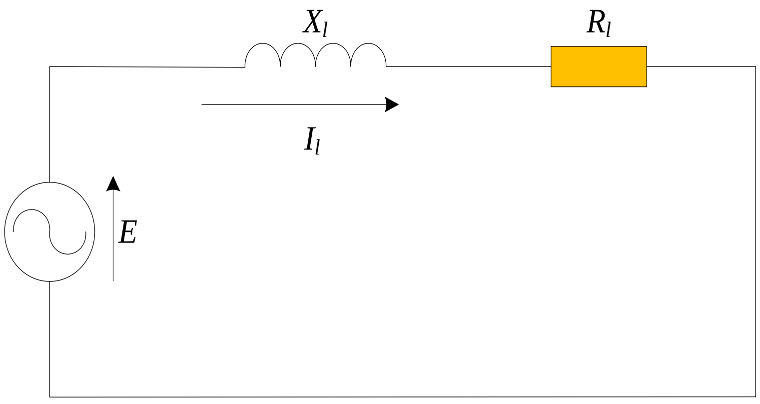
$$E = I_0 \frac{\partial M}{\partial t} \qquad E = L\frac{dI_l}{dt} + R_l I_l$$

Calculation of electromagnetic forces: Virtual displacement method

$$F_x = I_0 I_l \frac{\partial M}{\partial x} \qquad F_z = I_0 I_l \frac{\partial M}{\partial z} \qquad F_y = I_0 I_l \frac{\partial M}{\partial y}$$



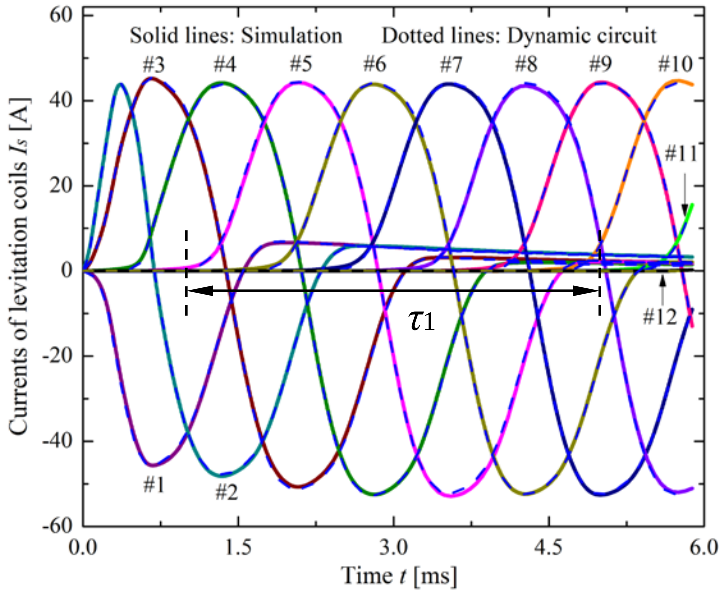
The direction of current in levitation coil



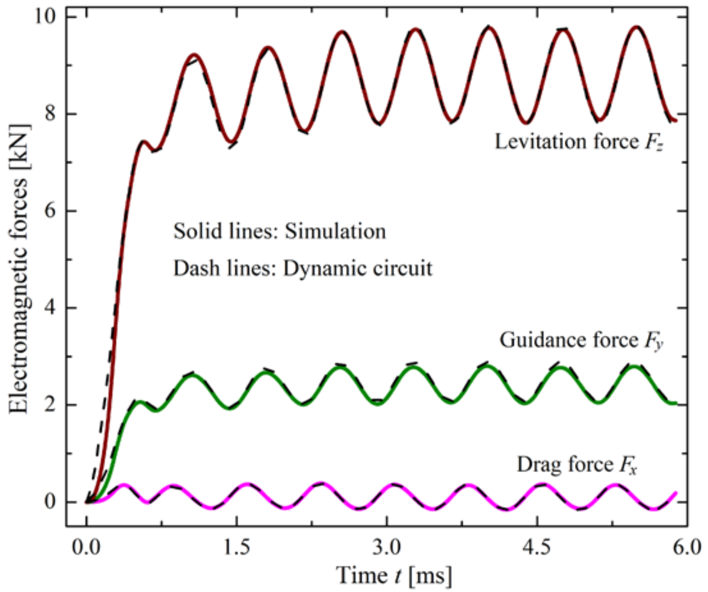
The equivalent dynamic circuit

3.2 Calculation of EDS system

Obtained results



The induce current in levitation coils



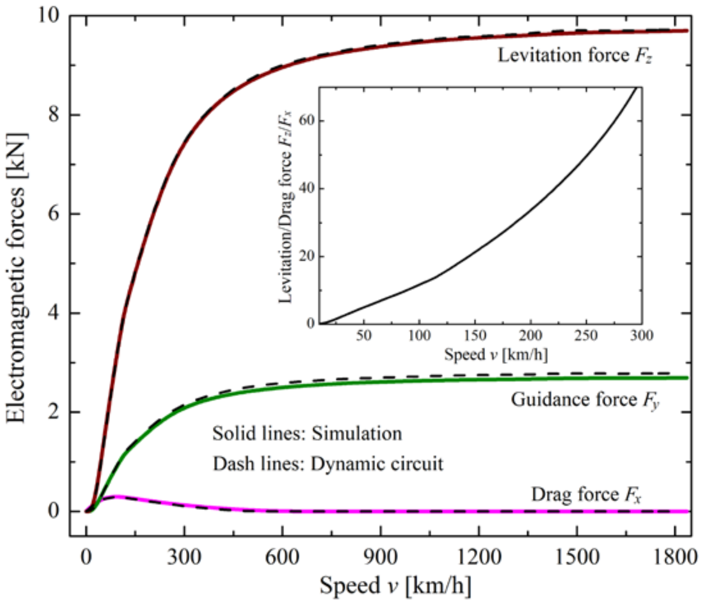
The instantaneous electromagnetic forces

This induced currents generated only while the superconducting magnets and levitation coils are face to face.

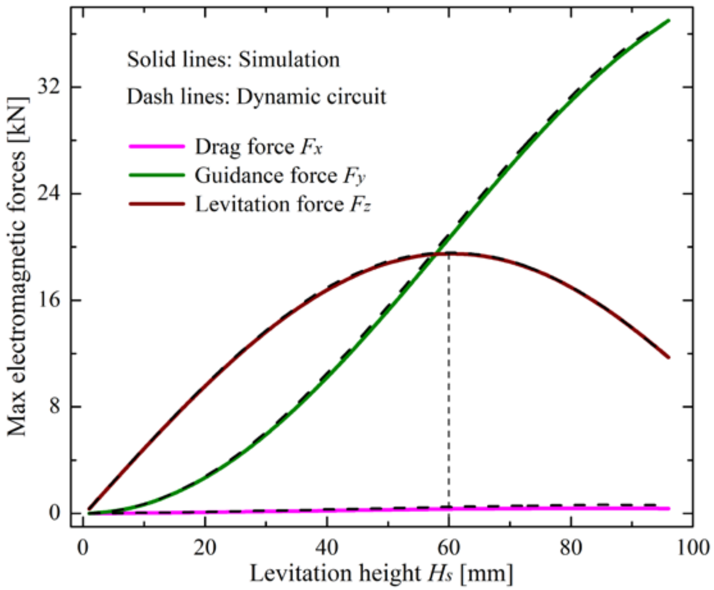
The levitation force and guidance force hold same phase, while the drag force has a 90-degree lag than the others.

3.2 Calculation of EDS system

Obtained results



Maximum electromagnetic forces versus v



Maximum electromagnetic forces versus H_s

When the speed reaches 600 km/h, the maximum drag force is close to zero.

When the levitation height reaches 60 mm, the levitation force begins to decrease.

Contents

4. Conclusions

1. Based on the Biot-Savart law, the magnetic field of the race-track magnet was calculated when considering the magnet current as volume current, surface current and line current. **It was found that the line current model for the race-track shape coils has faster computation speed and high calculation accuracy;**

2. **The geometric parameters of the race-track HTS magnet were optimized** using Monte Carlo Optimization Algorithm of MATLAB program and **the geometric parameters of air-core stator were also optimized** using the Coordinate Search Optimization Algorithm of MATLAB program;

3. **The electromagnetic properties of an electrodynamic suspension system were calculated by simulation model and dynamic circuit model,** the electromagnetic forces and induced currents are in good agreement between the two models.

Acknowledgments

Main collaborators:

Zhengwei Zhao （Doctor）

Wenjiao Yang （Doctor）

Manuel Perez （Master）

Yao Cai （Master）

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Thank you！

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