Design Optimization of 2G High-Tc Superconducting Magnet for High-Speed Transportation

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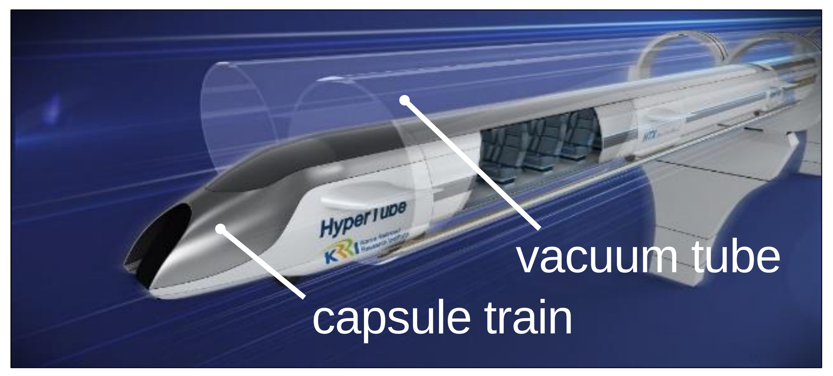
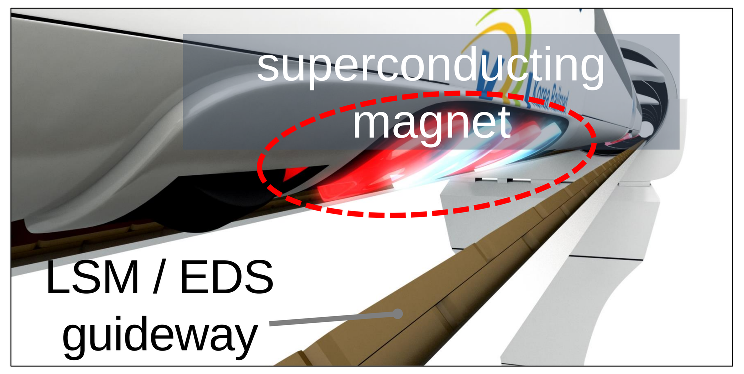
Abstract

◆ Motivated by growing interests on Hyperloop system, we have researched on a new mode of transportation that runs inside vacuum tube above 1,000km/h. 2G high temperature superconducting (HTS) magnet with detachable cryocooler system has been developed to efficiently thrust and levitate the capsule train as well as reduces its weight. To compensate performance loss caused by increased operating temperature, HTS coil shape of the on-board superconducting magnet is topologically optimized in the view of the cost and performance respectively. With a number of linear constraints converted from nonlinear superconductivity conditions, many linear topology optimization problems are solved, and then most preferred design is determined by considering its shape, cost, and performance

Concept of High-Speed Transportation Hyper Tube eXpress (HTX)

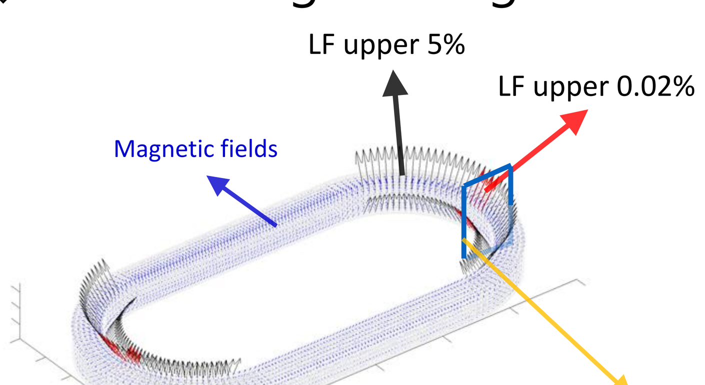




◆ Main Characteristics of HTX

- **Vacuum (0.001 atm) tube** infrastructure to minimizing air resistance
- **Electrodynamic** large air gap (100 mm) **levitation** using on-board **superconducting electromagnets with detachable crycoolers**
- **Superconducting linear synchronous motor** for subsonic (over 1000 km/h) propulsion
- Streamline shaped aircraft material capsule with **subsonic driving stabilization** device

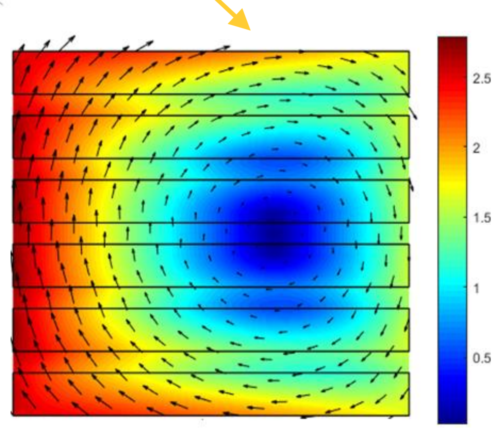
◆ 2G HTS Magnet Design



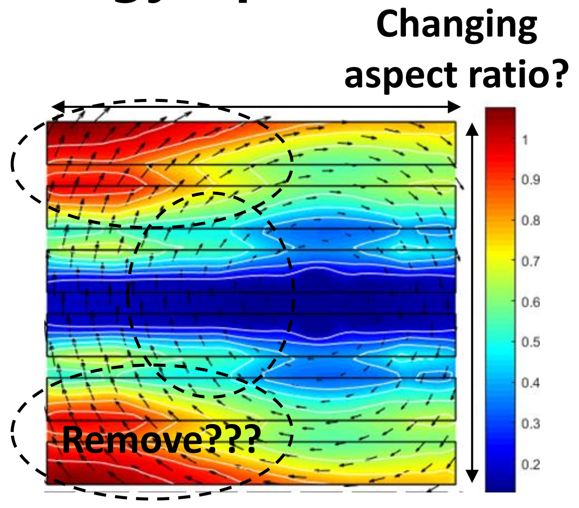
To improve performance/cost

- Change aspect ratio (radial / axial thickness)
- Modify coil shape and distribution

⇒ **topology optimization**



Magnetic field distribution



Load factor distribution

$$LF = I_c/I_{ci}\ ,\ I_c = \min(I_{ci})$$

Optimization Model

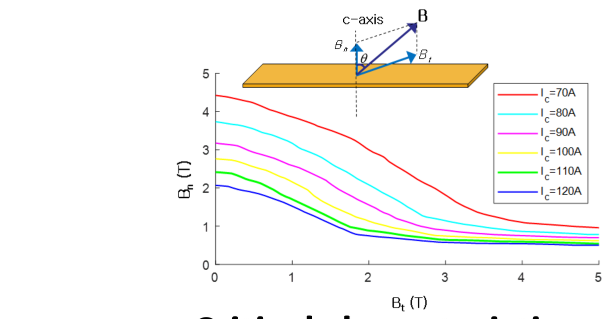
◆ Critical Characteristics of 2G HTS Wire

- Multi-layer REBCO-coated tape
- **Critical current depends on magnetic field magnitude and angle**
- Nonlinear superconductivity condition

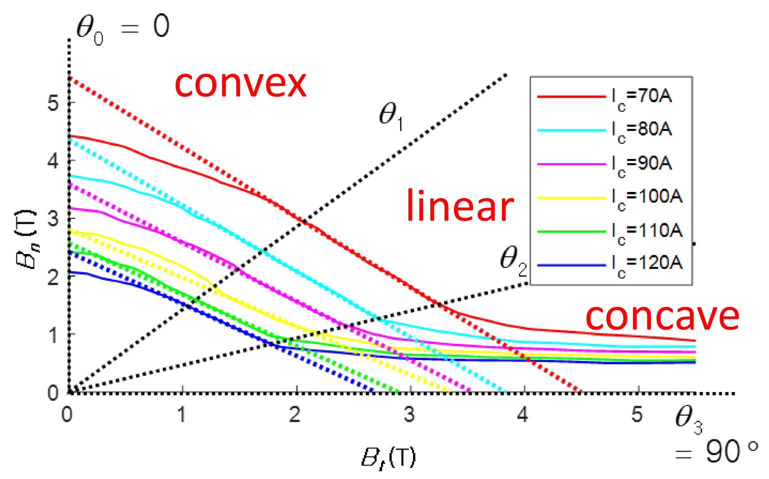
$$B_n(I_c) \leq f\,(B_t(I_c))$$

→ linearizing for $\theta_1 \leq \theta \leq \theta_2$

$$B_n \leq a(I_c) + b(I_c)B_t$$

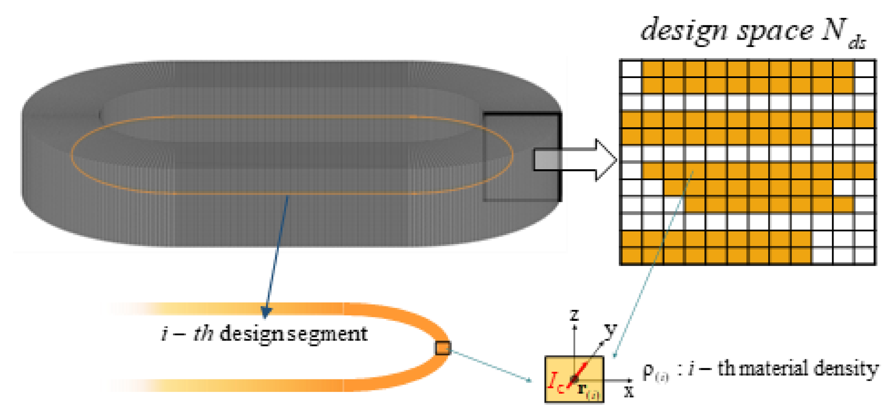


Critical characteristics



Linearization of superconductivity condition

◆ Linear Topology Optimization



Objective function:

$$\max_{\rho} \sum_p w_p^T B_p \text{ subjected to } 0 \leq \rho_{(i)} \leq 1$$

Superconductivity constraint:

$$-\frac{b(I_c)}{a(I_c)}B_{t(i)} + \frac{1}{a(I_c)}B_{n(i)} \leq 1$$

Wire volume (or length) constraint:

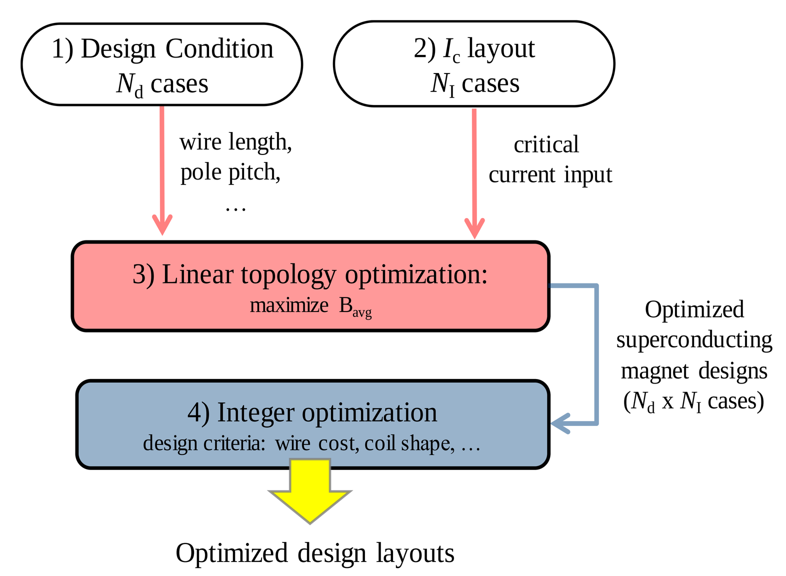
$$V_r = V/V_{ds} \quad where\ V_{ds} = \sum_{i=1}^{N_{ds}} V_{(i)}$$

Magnetic field relation:

$$\boldsymbol{B}(\boldsymbol{r}) = \sum_{i=1}^{N_{ds}} \rho_{(i)} I_c A_w^{-1} \bar{\boldsymbol{B}}_{(i)}(\boldsymbol{r})$$

◆ Layout Optimization

: most preferred design considering additional criteria (wire cost or coil shape)

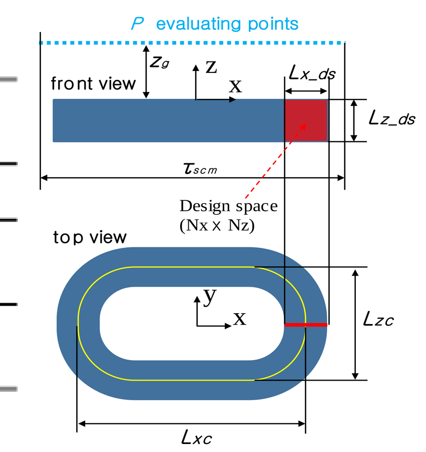


Optimization Example

◆ Design Specification

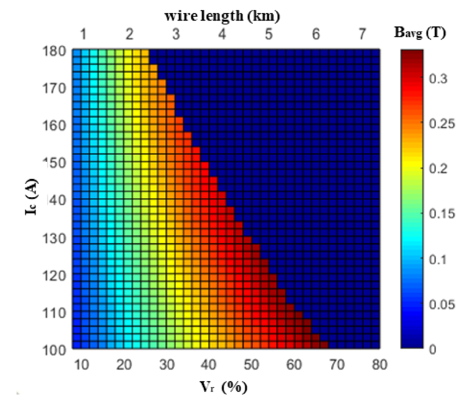
- HTS wire (SuNAM, SAN04200) width 4mm length 3 km

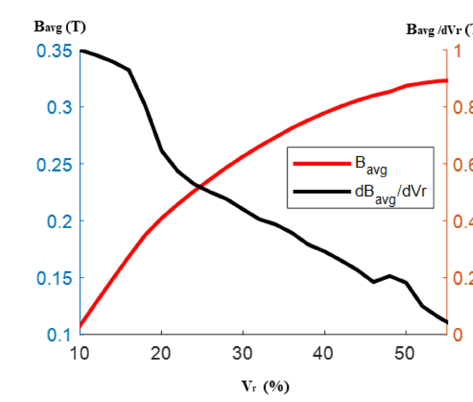
SCM shape (racetrack)	Lxc, Lzc	600 mm, 300 mm
	τ_{SCM}	810 mm
	coil gap	2 mm
Design space	L_{x_ds}, L_{z_ds}	100 mm, 60 mm
	N_x, N_z	50, 30
Optimization parameters	z_g	150 mm
	P	361
	w_p	1/P
HTS wire	T_c	40 K
	wire width	4 mm
	wire length	3 km/pole



◆ Optimization Example 1

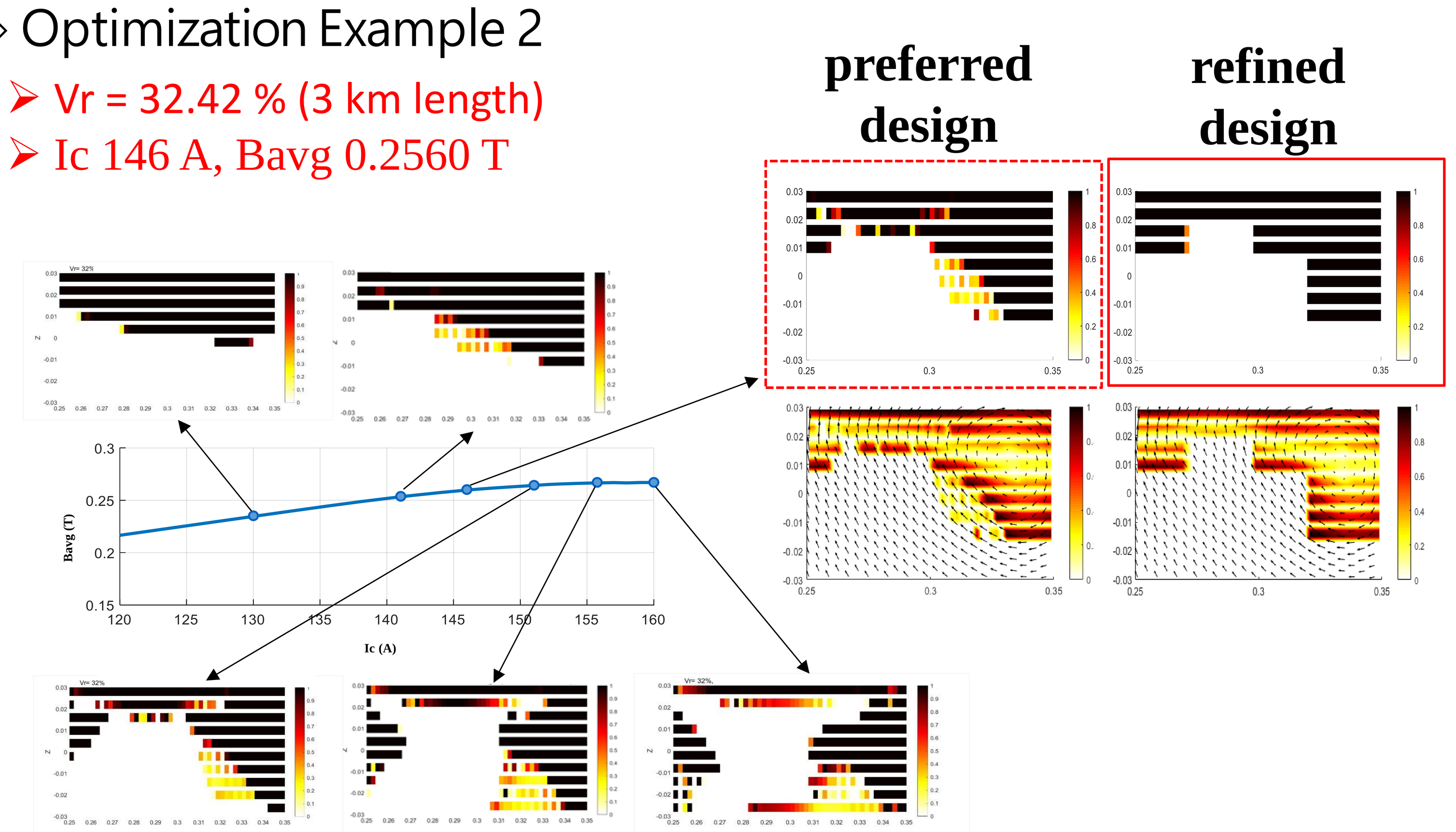
- 10 % ≤ V_r ≤ 80 %
- 100 A ≤ I_c ≤ 180 A
- Vr (or wire length) ↑
  → Bavg ↑
  → Bavg/dVr ↓





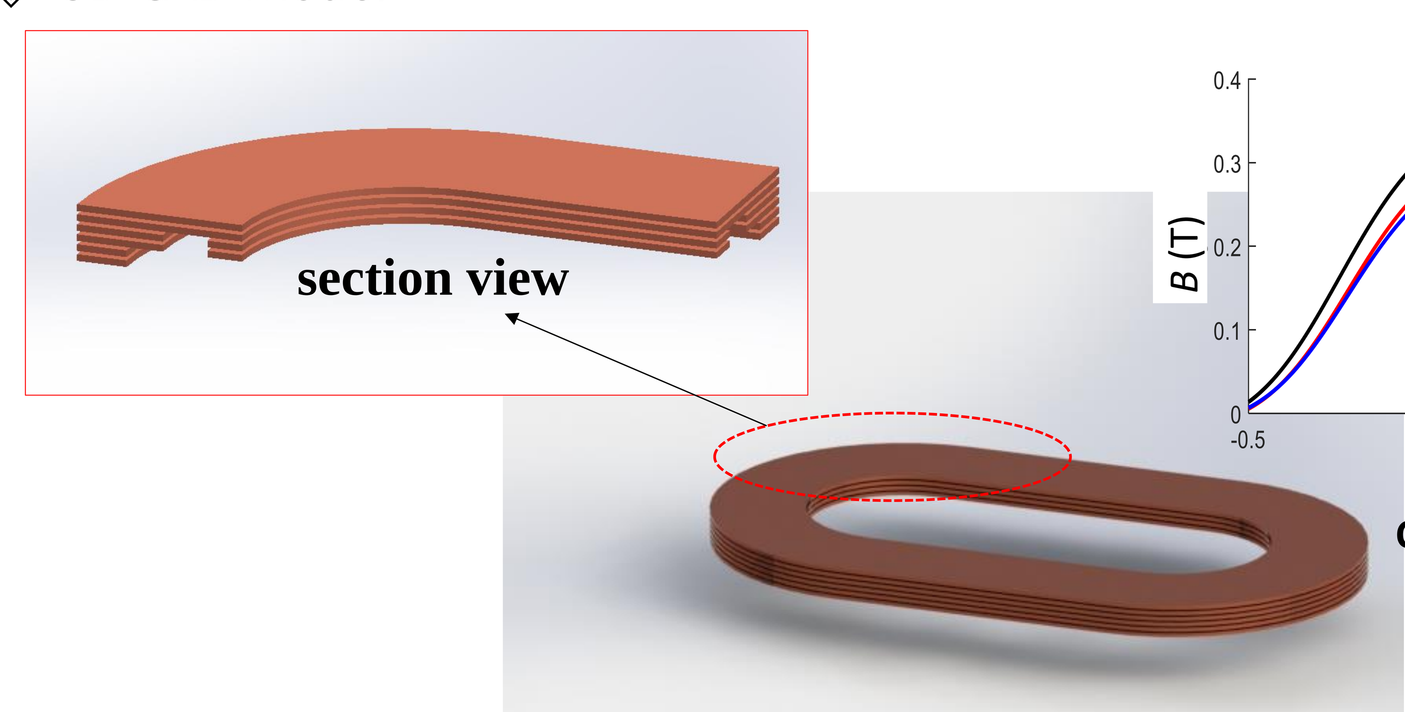
◆ Optimization Example 2

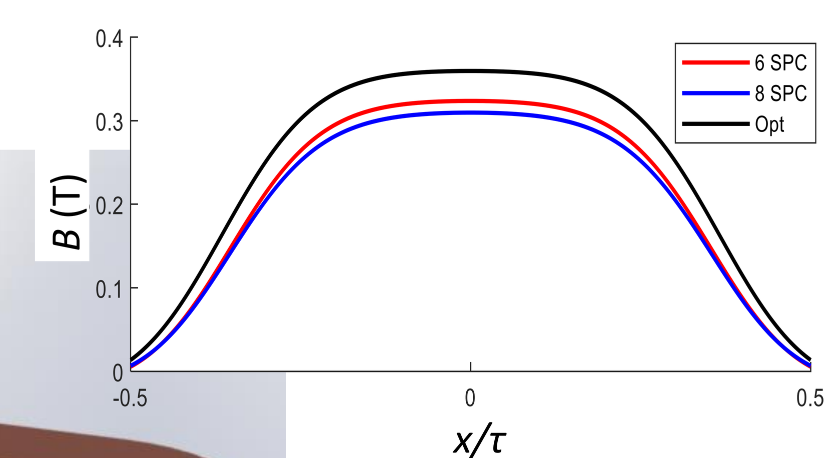
- Vr = 32.42 % (3 km length)
- Ic 146 A, Bavg 0.2560 T



Design Example and Conclusion

◆ 3D CAD Model





Comparison on air gap B

◆ Performance Improvement

	Bavg (T)	Ic (A)	MMF (kAt)
6 SPC	0.2165	122.5	238.2
8 SPC	0.2071	121.5	235.3
opt.design	0.2487	140.2	261.2

- Bavg 15~20% ↑
- Ic 14~15% ↑
- MMF 10~11% ↑
- Additional ways:
  Optimize design with other product, enlarge SCM size, or increase wire length