Superconducting Magnetic Bearings

L. Quéval

GeePs, CentraleSupélec, University of Paris-Saclay, France

EASISchool2

CEA Paris-Saclay

Overview

I. A (short) introduction to superconductivity

What is a superconductor ?

Type II

Type I

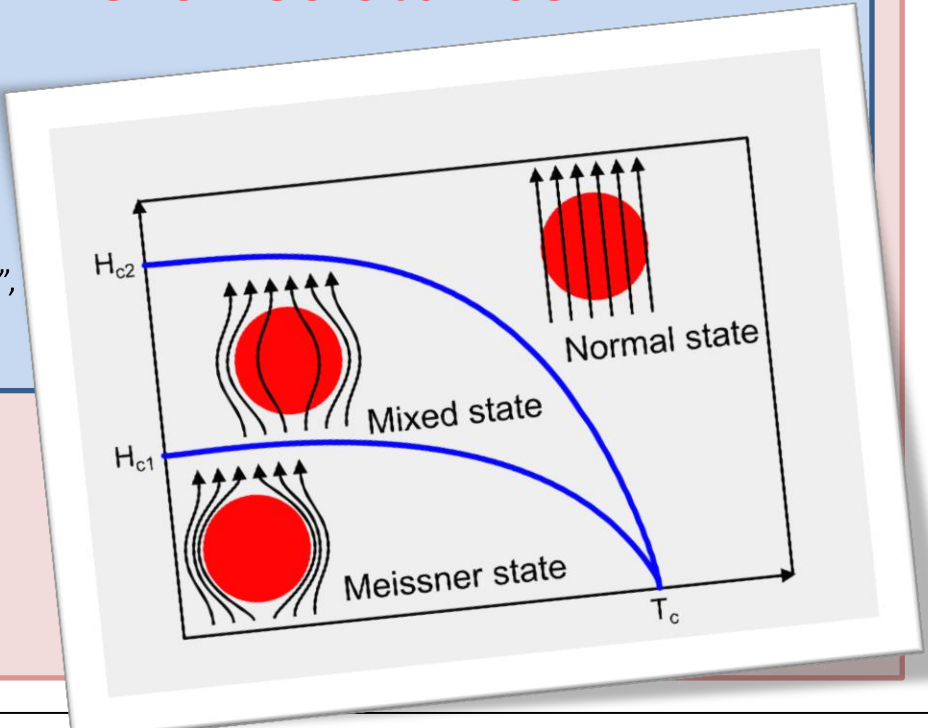
- Perfect conductivity = Zero resistance

Video 1 from “BBC Story of Electricity - Superconductivity”, (47s – 1m40s), © BBC.

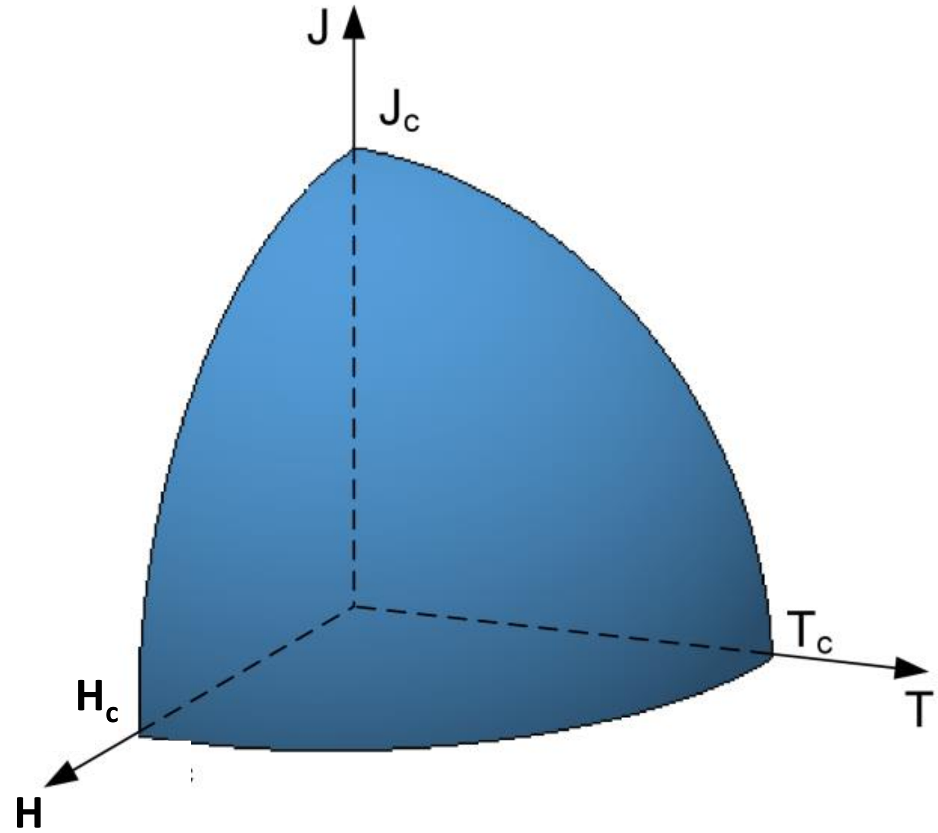
- Meissner effect

Video 2 from “How superconducting magnetic levitation works ?”, (1m25s – 3m25s), © I.G. Chen.

- Flux trapping effect



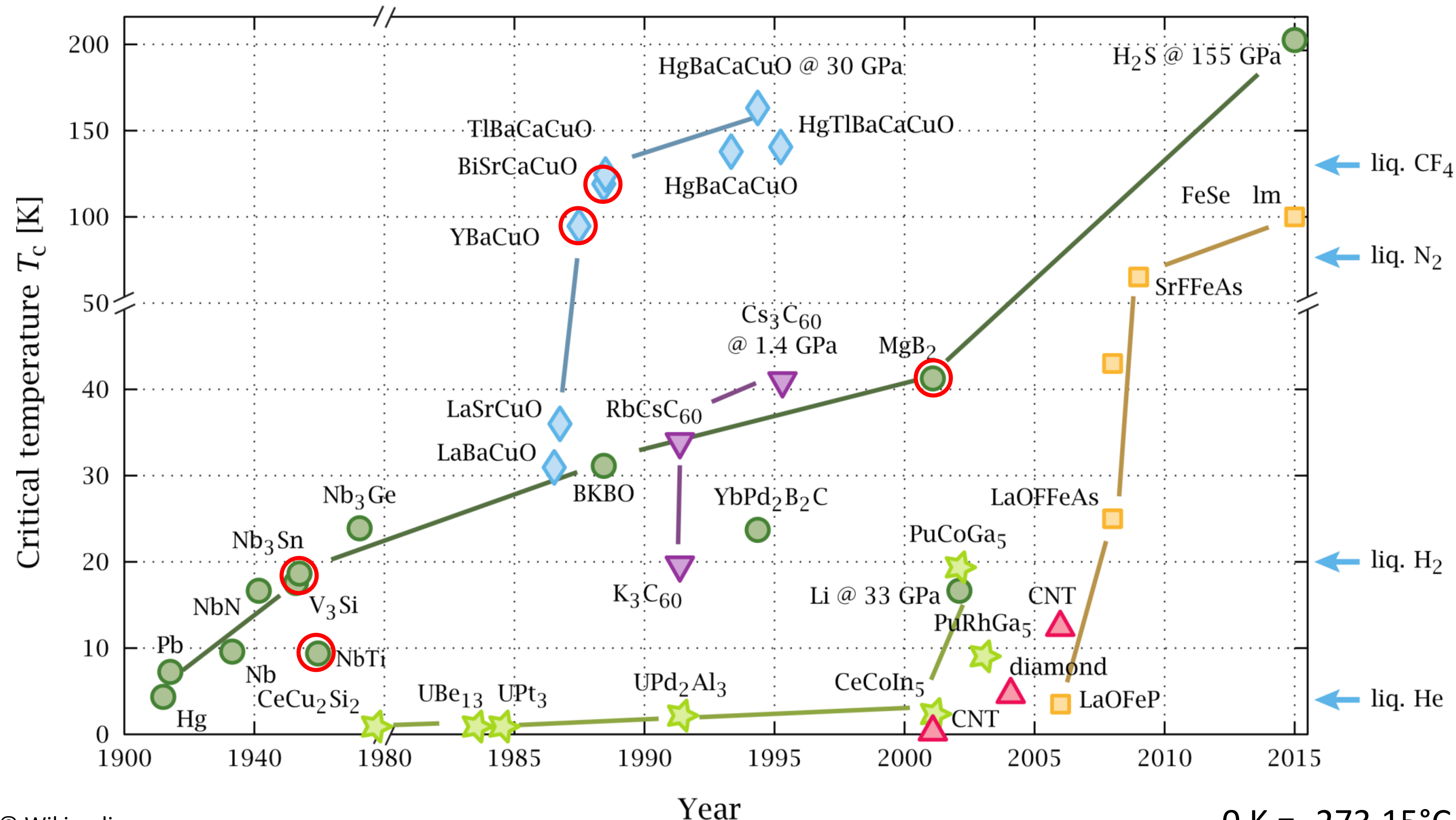
What is a superconductor ?



[1] B.B. Jensen, A.B. Abrahamsen, M.P. Sørensen, J.B. Hansen, “A course on applied superconductivity shared by four departments ,” US-China Education Review A, vol. 3, no. 3, 141-152, 2013.

GeePS
Group of electrical engineering - Paris

Superconductors development history



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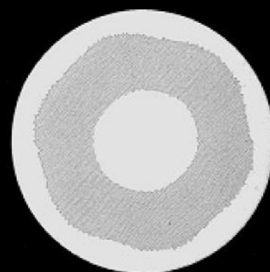
0 K = -273.15°C

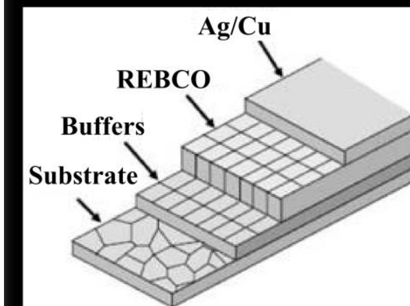
Conductors

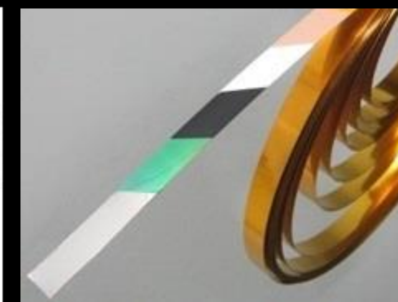
Metallic
NbTi (Nb_3Sn etc.)

1962

Oxide
YBCO

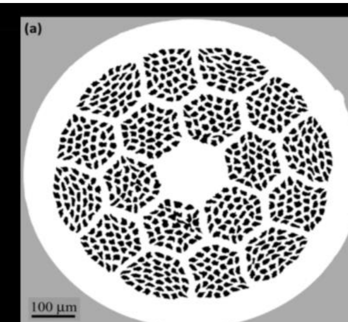




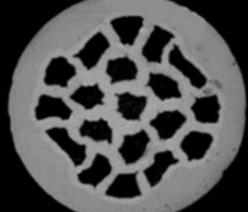
1986
1987
1988

Discovery of high temperature superconductors (HTS)

Oxide
Bi2223
Bi2212

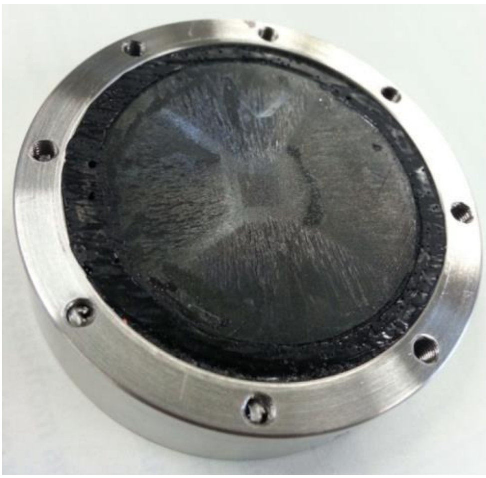


Metallic
MgB_2 / Fe based

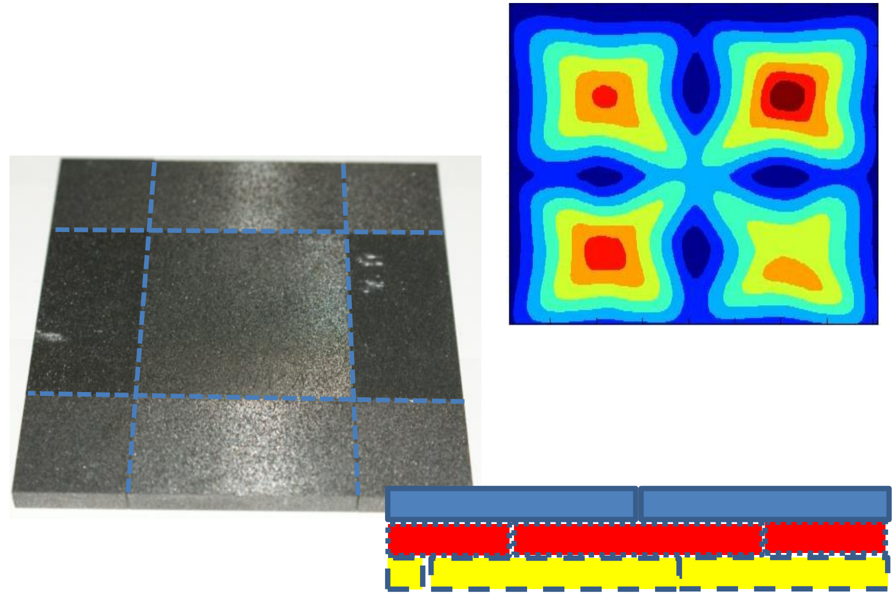



2001

Bulks



GdBCO bulk [2]
D = 41 mm

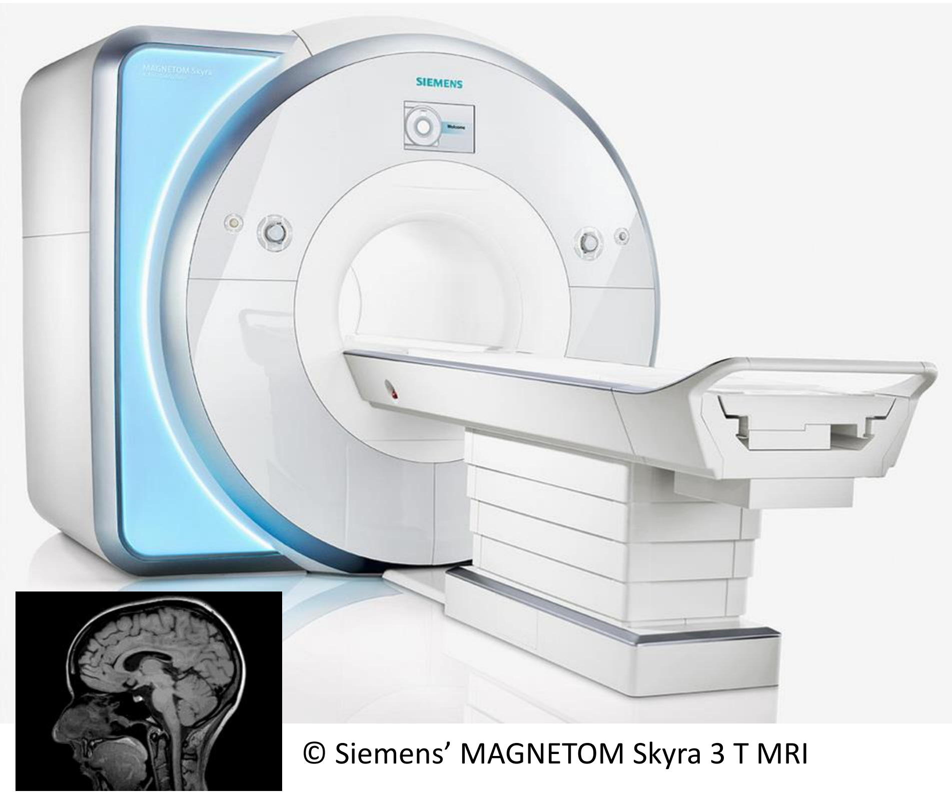


YBCO bulk [1]
40 x 40 x 15 mm

Bi-2223 [3]
D = 59 mm, L = 100 mm

[1] Y. Terao, M. Sekino, H. Ohsaki, H. Teshima, M. Morita, “Magnetic shielding characteristics of multiple bulk superconductors for higher field applications,” *IEEE Transaction on Applied Superconductivity*, vol. 21, no. 3, pp. 1584-1587, 2011.
[2] M.D. Ainslie, H. Fujishiro, T. Ujiie, J. Zou, A.R. Dennis, Y.-H. Shi, D.A. Cardwell, “Modelling and comparison of trapped fields in (RE)BCO bulk superconductors for activation using pulsed field magnetization,” *Superconductor Science and Technology*, vol. 27, id. 065008, 2014.
[3] “Bi-2223 tubes for current limiters,” [Online]. Available: www.can-superconductors.com/current-limiters.html

Some applications today



© Siemens' MAGNETOM Skyra 3 T MRI

LHC, ATLAS Experiment © 2014 CERN

And tomorrow ?

Energy	Defense	Transport	Industry	Medicine	Science
• **AC cable** • **DC cable** • **FCL** • Generator - Wind - Hydro • Transformer • Storage - SMES - Flywheel (bearing)	• Naval propulsion • Degaussing cable • Directed energy weapons	• Maglev • Naval propulsion • Aircraft propulsion	• **Induction heater** • Motor • Generator • Bearing • Magnetic separation	• **MRI (HTS)** • NMR	• **Magnet (HTS)** • Space exploration • SQUIDS • Electronics

Short-term 1-5 ans
Mid-term 5-10 ans
Long-term 10-20 ans

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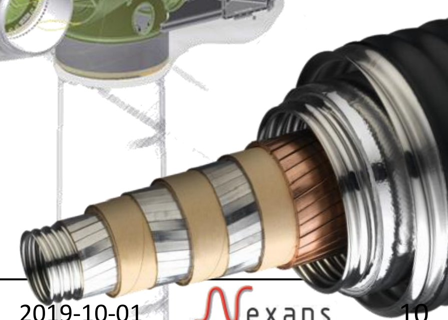


Nexans

II. Superconducting maglev vehicles

Maglev Technologies

EML Transrapid

EDL JR-Maglev

SML Maglev-Cobra

EML = Electromagnetic levitation

EDL = Electrodynamic levitation

SML = Superconducting magnetic levitation

How SML works ?

Type II

Type I

- Perfect conductivity = Zero resistance

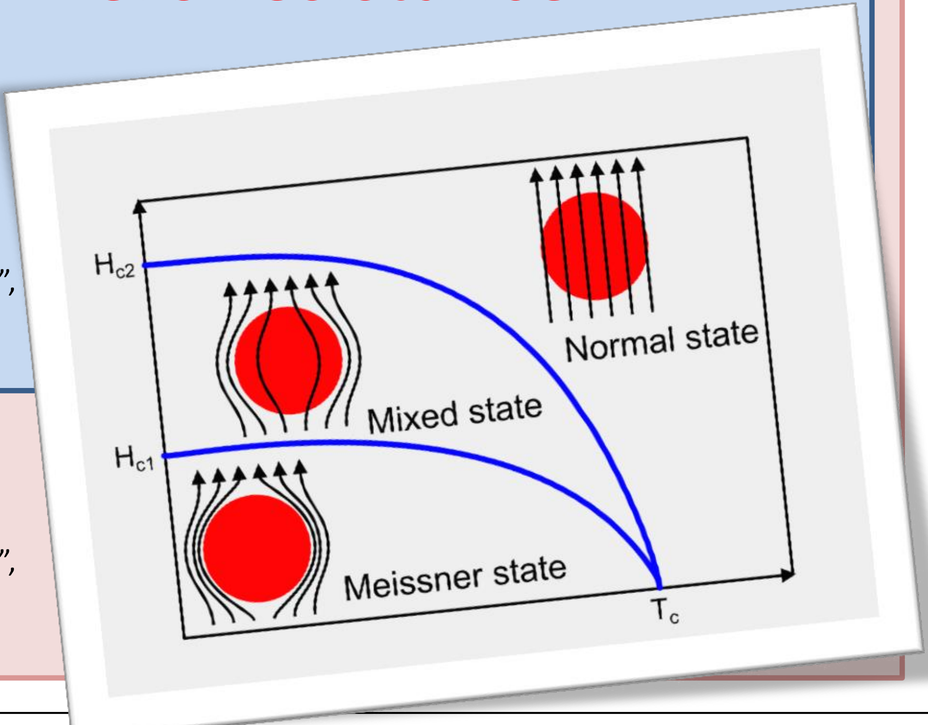
Video 1 from “BBC Story of Electricity - Superconductivity”, (47s – 1m40s), © BBC.

- Meissner effect

Video 2 from “How superconducting magnetic levitation works ?”, (1m25s – 3m25s), © I.G. Chen.

- **Flux trapping effect**

Video 3 from “How superconducting magnetic levitation works ?”, (3m20s – 4m55s), © I.G. Chen.



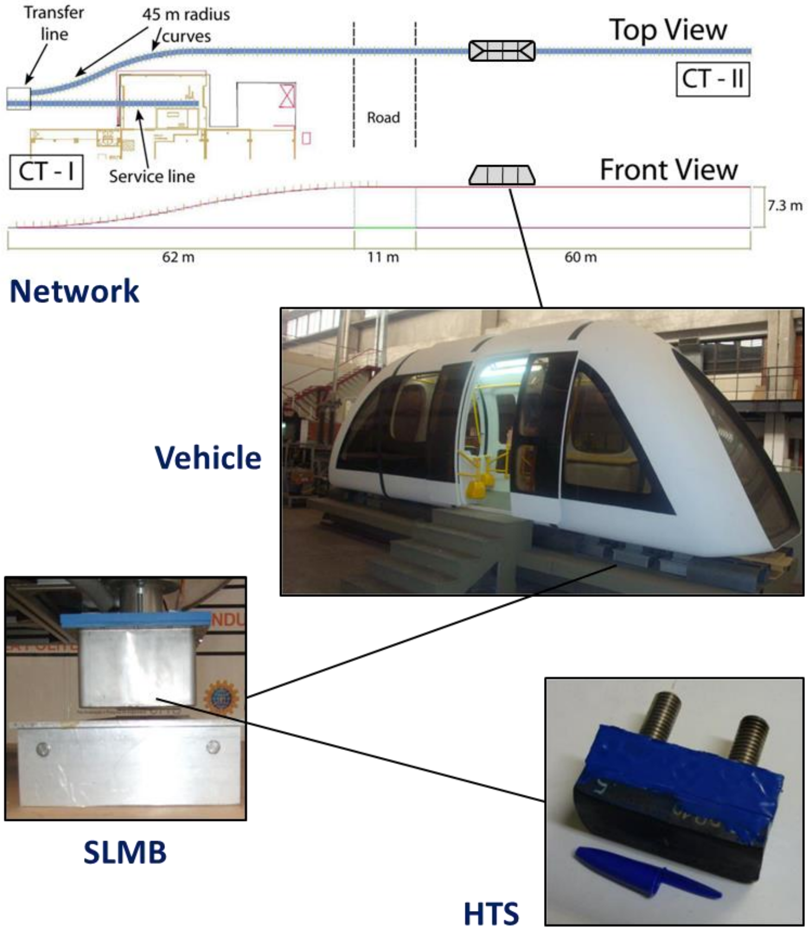
SML vehicules

(a) “Century”, Southwest Jiaotong Univ., China, 2014.

(b) “SupraTransII”, IFW Dresden, Germany.

(c) “Maglev Cobra”, Federal Univ. Rio de Janeiro, Brazil, 2015.

MagLev Cobra overview



© Functional prototype line [1], Network [2], Vehicle [3], SLMB [2], HTS [3].

[1] R.M. Stephan *et al.*, "Superconducting light rail vehicle: a transportation solution for highly populated cities," IEEE Vehicular Technology Mag., vol.7, no.4, pp.122-127, 2012. [2] G.G. Sotelo *et al.*, "Experiments in a real scale maglev vehicle prototype," Journal of Physics: Conf. Series, vol. 234, no. 3, pp. 032054, 2010. [3] A.E.L. Luizar, "Operação sincronizada dos motores lineares de tração para um veículo de levitação magnética," M.S. thesis, COPPE, UFRJ, Rio de Janeiro, 2010.

MagLev Cobra superconducting maglev bearing

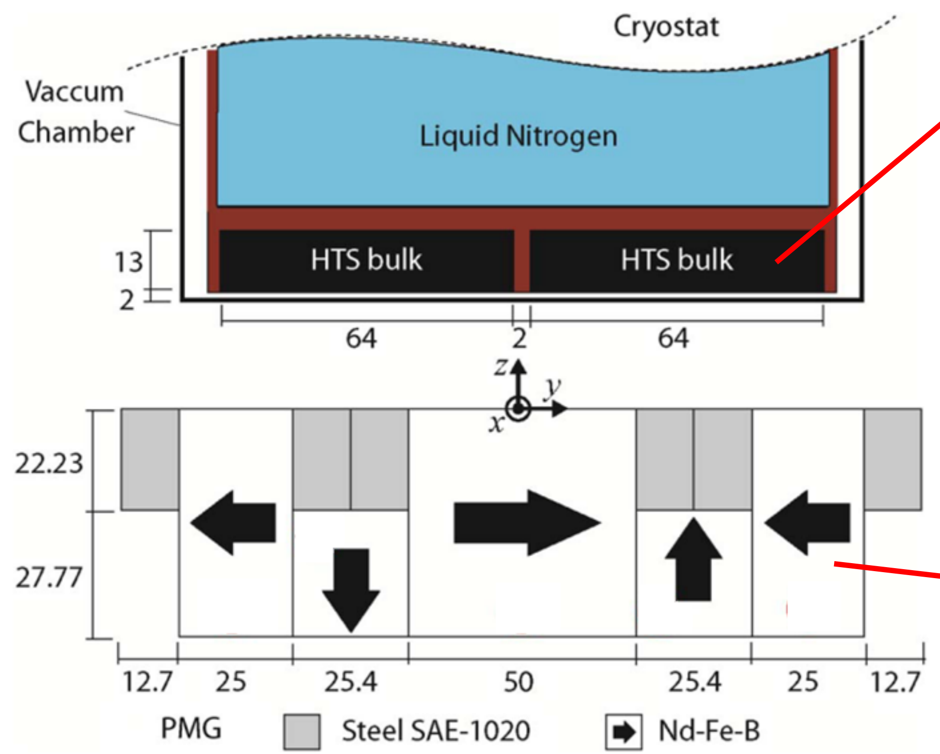
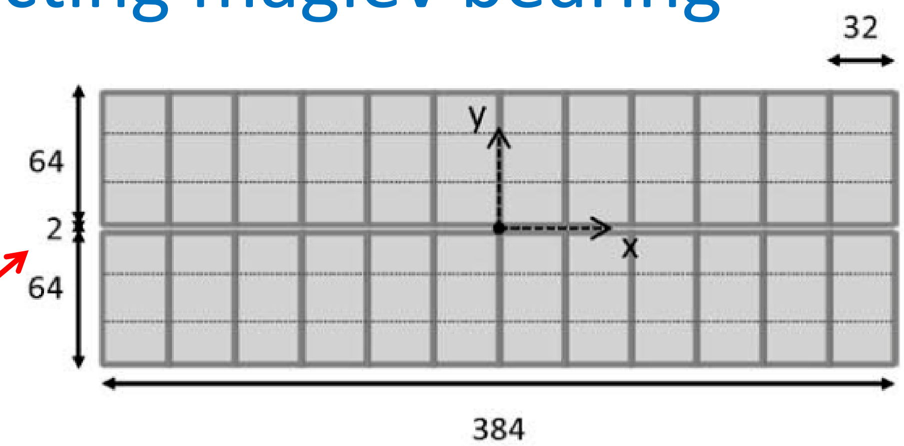


Fig. 2. Permanent magnet guideway and cut view of the cryostat (dimensions in mm). The numbers on the magnets are used to identify them. (from [1])



- 3 seeded YBCO bulks from ATZ

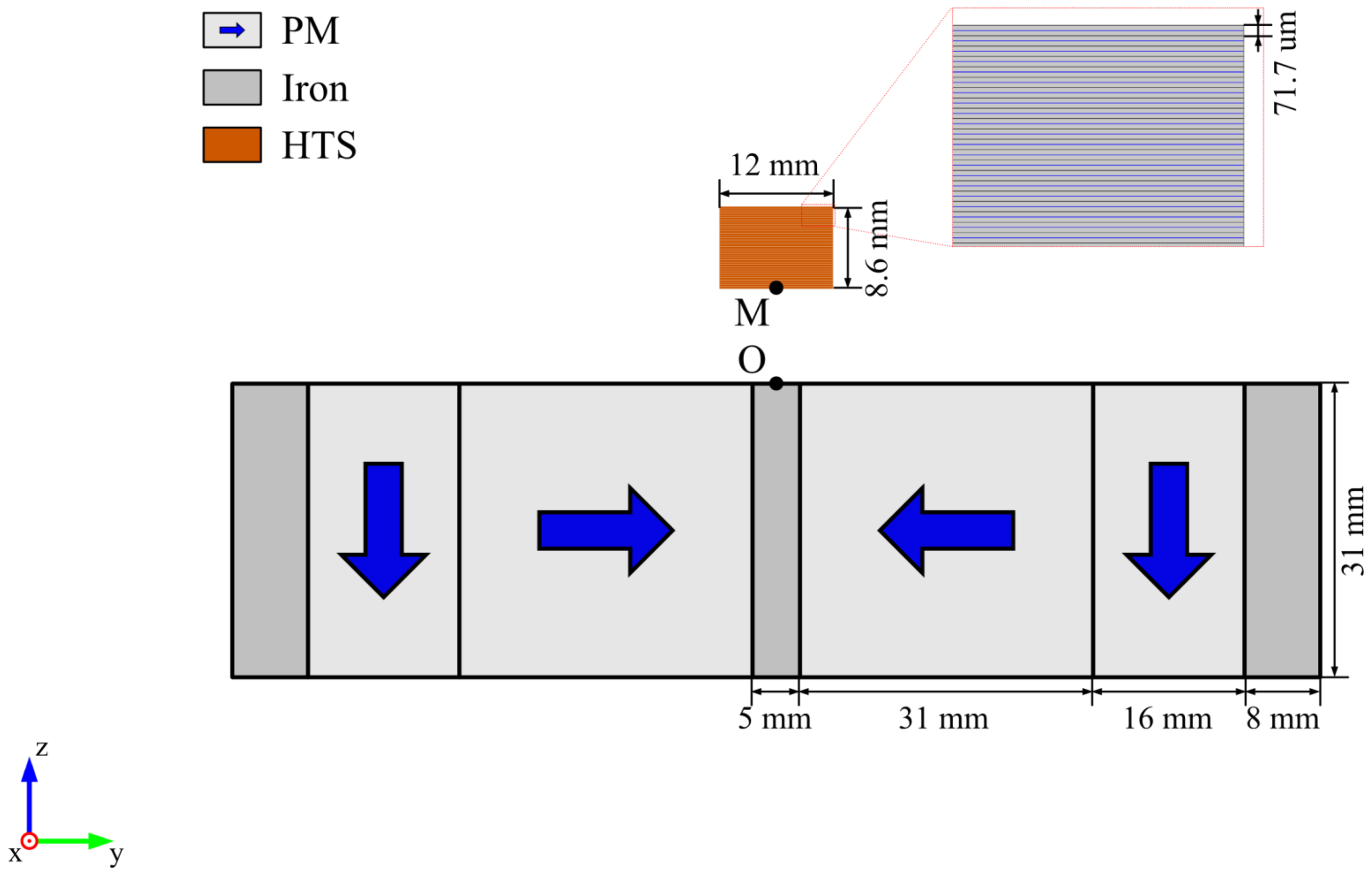
- Nd-Fe-B 35M (Br=1.198 T)
- Steel SAE-1020

[1] G.G. Sotelo *et al.*, “Tests with one module of the brazilian Maglev-Cobra vehicle,” *IEEE Trans. on Applied Superconductivity*, vol. 23, no. 3, 2013. [2] W.T.B. de Sousa *et al.*, "Projeto MagLev Cobra - Levita¸c˜ao Supercondutora para Transporte Urbano," Revista Brasileira de Ensino de F´ısica, vol.38, no.4, 2016.

III. Measurement of the performances of a (stack-type) superconducting magnetic bearing

Geometry

Stack of 120 tapes
(SuperPower SCS12050-AP)



Practical realization of the stack

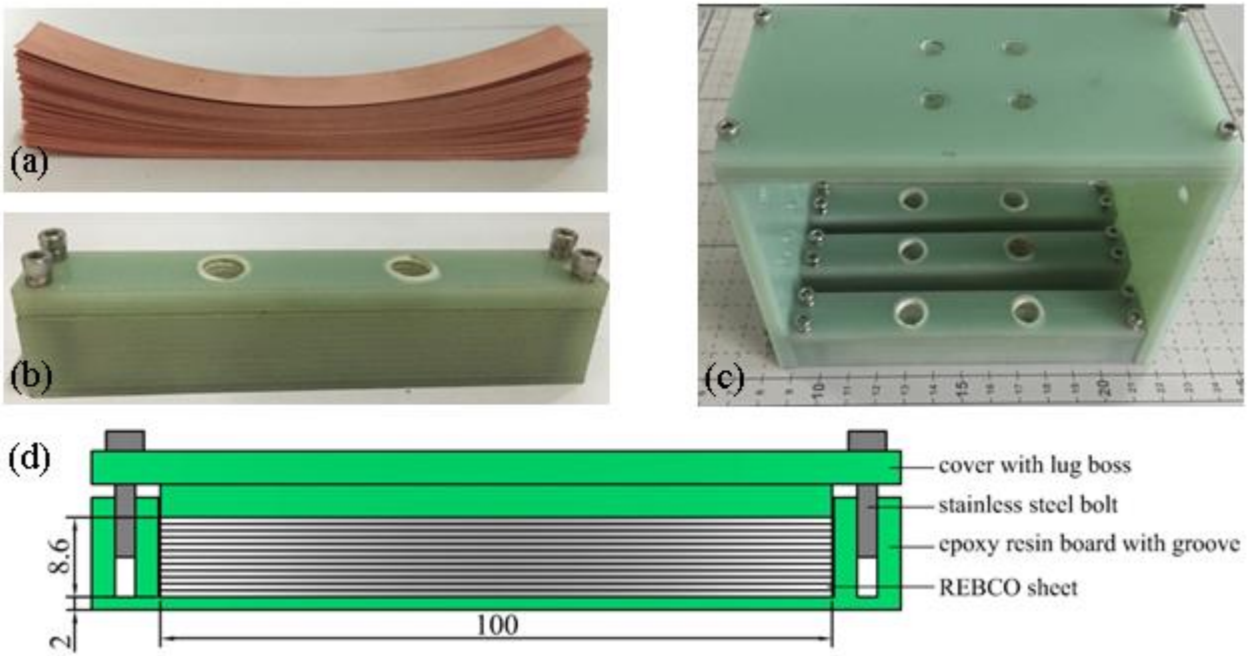
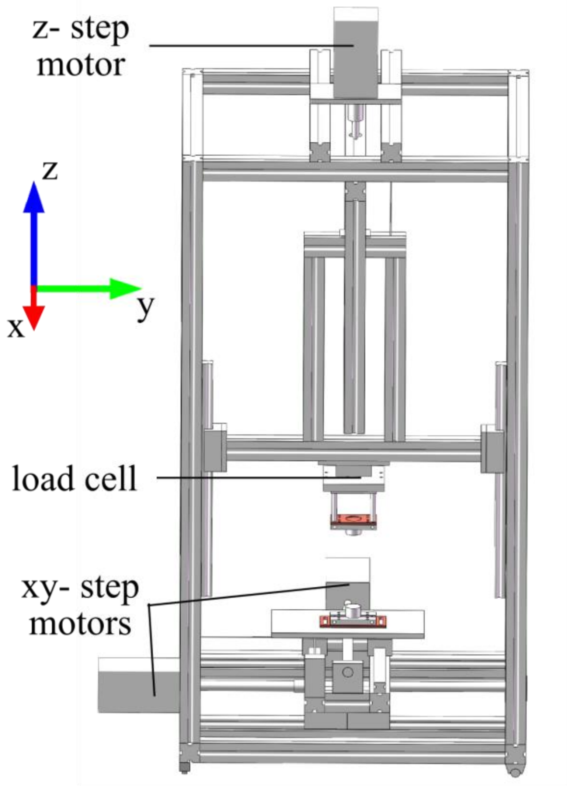
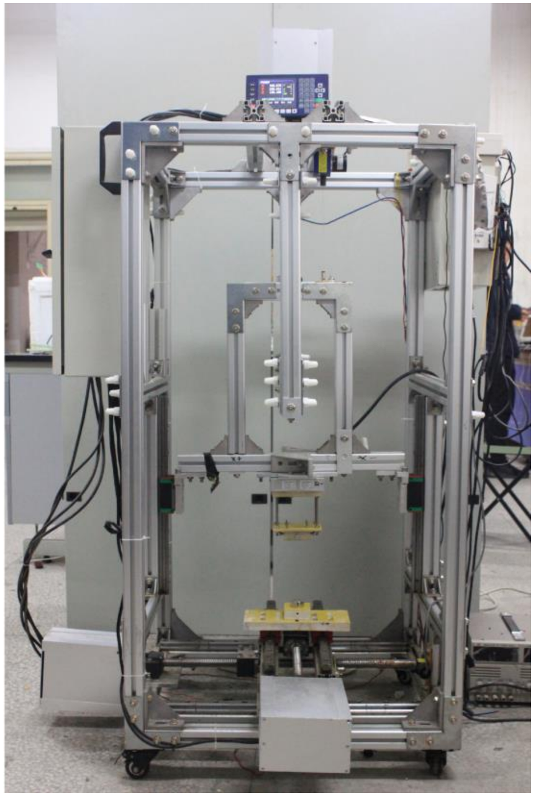


Figure - (a) stack of 120 REBCO tapes, (b) container,
(c) module made of 3 stacks, (d) dimensions.

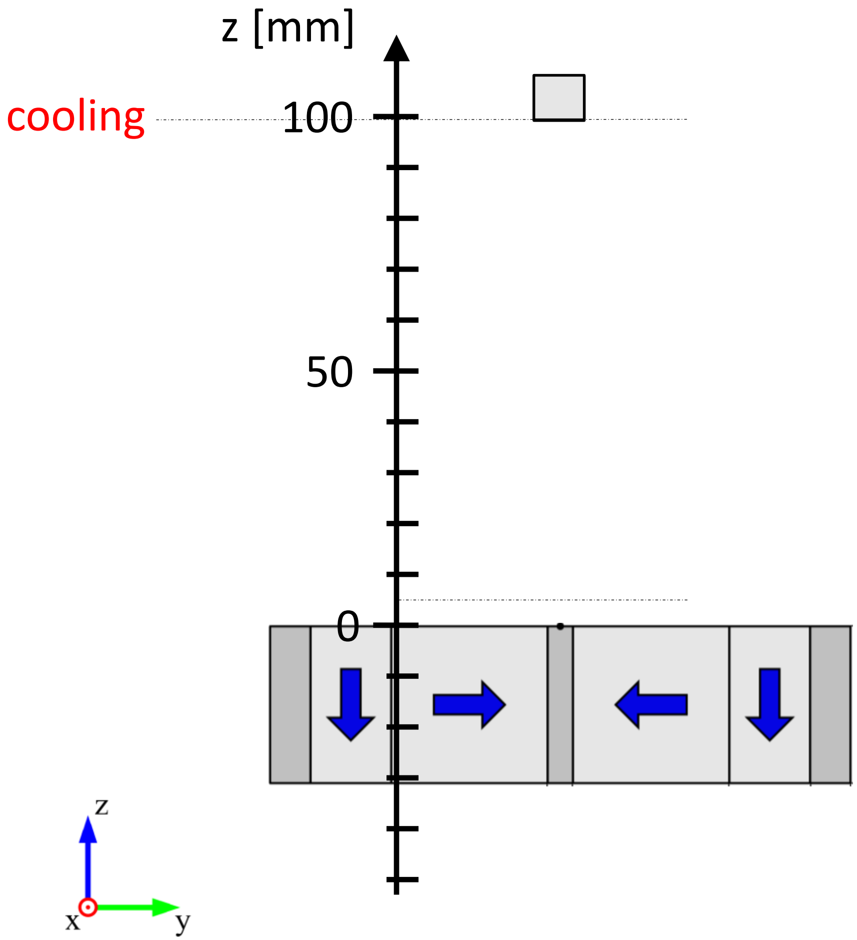
[Liu2017] K. Liu, W. Yang, G.T. Ma, L. Quéval, T. Gong, C. Ye, X. Li, Z. Luo, "Experiment and simulation of superconducting magnetic levitation with REBCO coated conductor stacks," *Superconductor Science and Technology*, vol. 31, no. 1, pp. 015013, Dec. 2017.

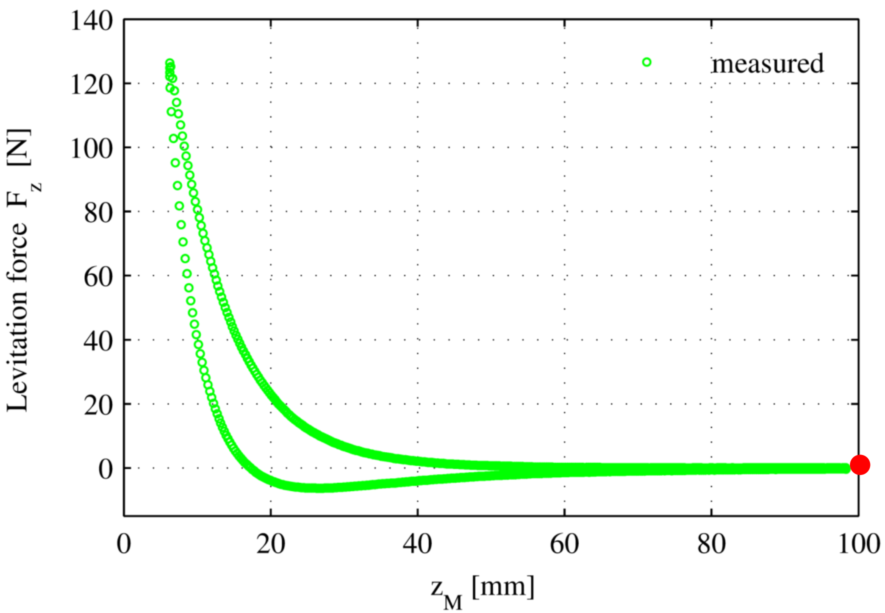
Testbench



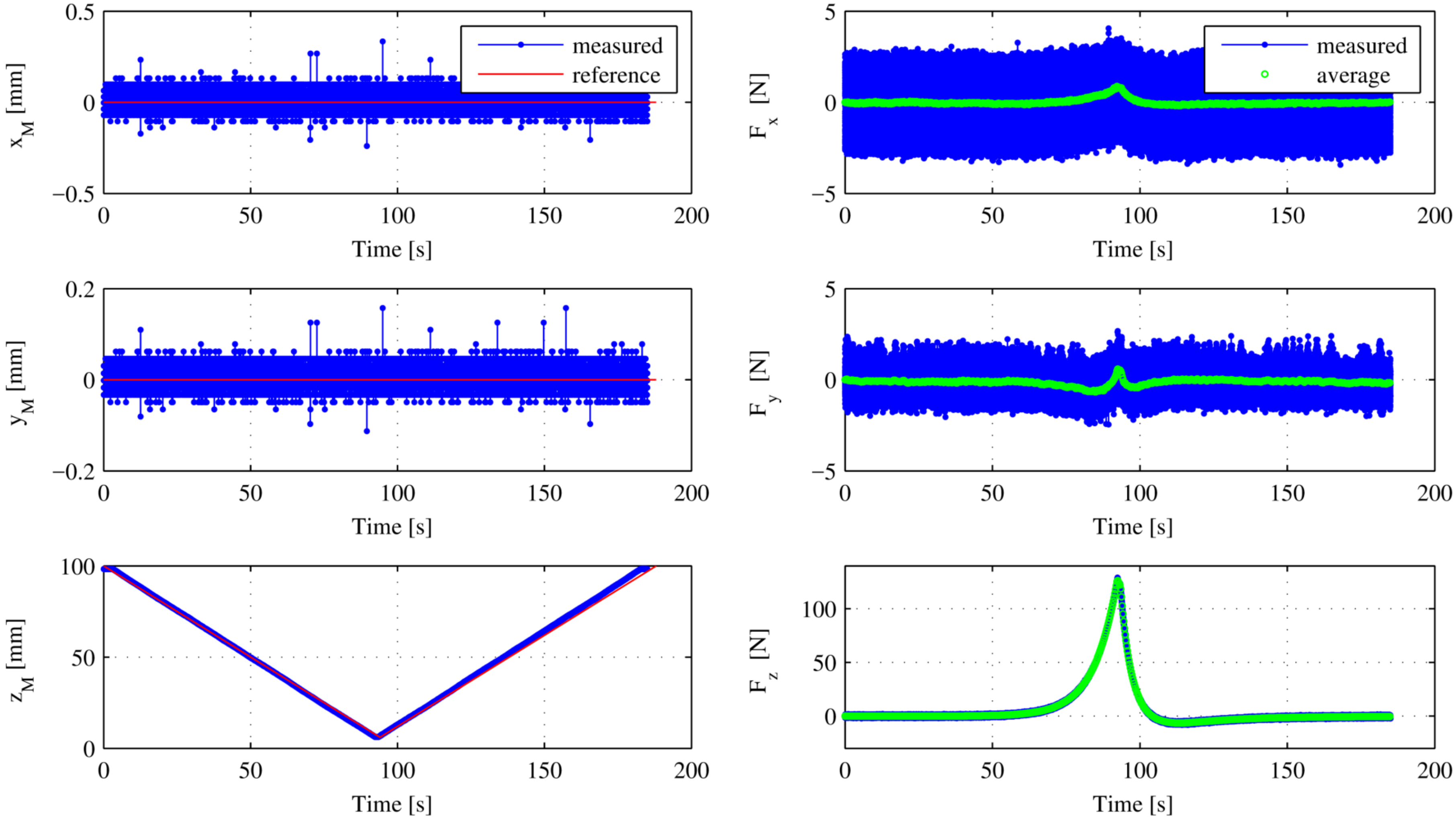


Measurement protocol

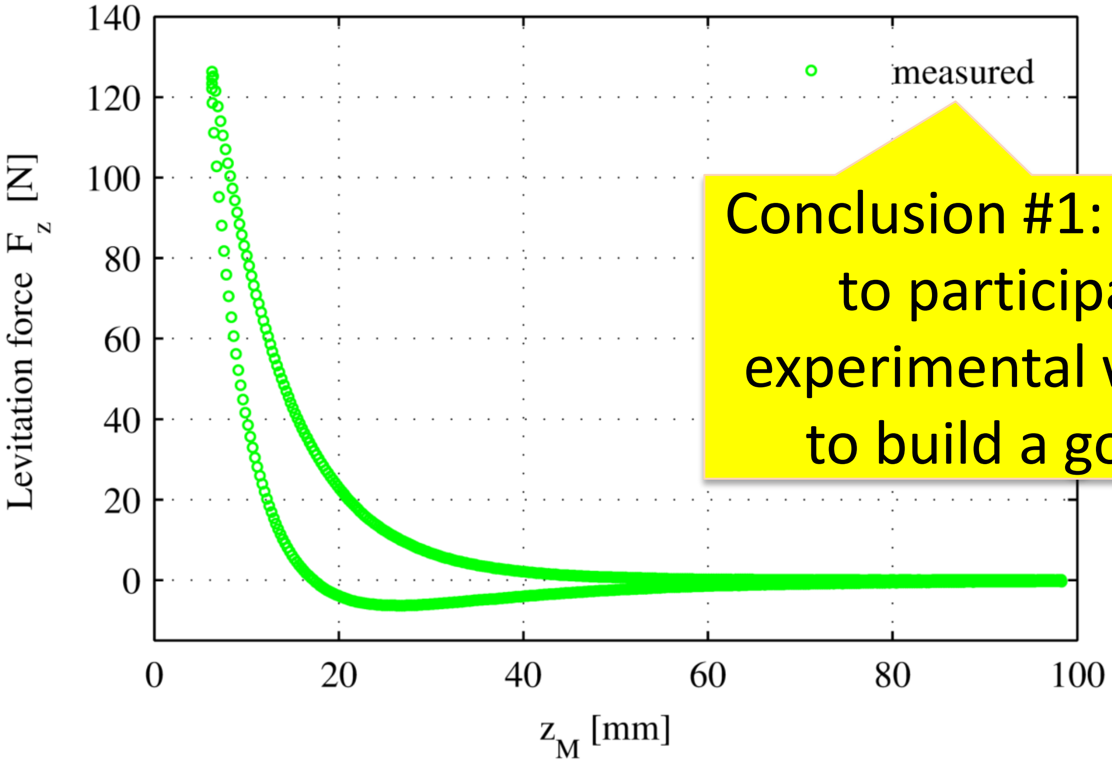




What I really measure...



After some post-processing …



Conclusion #1: It's important to participate to the experimental work in order to build a good model.

IV. Modeling of a (stack-type) superconducting magnetic bearing

Conclusion #2: SMB modeling is an old problem.

SMB Finite Element Models

		2-D	2-D AXI	3-D
A-V	Homemade	Hofman2001 Dias2009 Ma2013	**Sugiura1991** Takeda1994 Chun2001 Ruiz-Alonso2004 Wang2006 Sotelo2009	Ueda2006
	Software	-	Li2008	Hauser1997
T-Ω	Homemade	Zhang2008	Zheng2007 Gou2007	**Uesaka1993** Tsuchimoto1994 Tsuda1998 Ma2010 Pratap2015
	Software	-	-	-
E	Homemade	-	-	-
	Software	-	-	-
H	Homemade	Lu2015	-	Lu2008 Yu2015
	Software	Sass2015 Quéval2016	Patel2015 Quéval2018	Patel2015 Quéval2016

[Queval2018] L. Quéval, K. Liu, W. Yang, V.M.R. Zermeño, G.T. Ma, "Superconducting magnetic bearings simulation using an H-formulation finite element model," *Superconductor Science and Technology*, vol. 31, no. 8, pp. 084001, March 2018.

Motivation to develop (again) SMB models

Need for flexible, fast, trustworthy models to predict and optimize the performances of SMB for various applications, including maglev vehicles, magnetic launchers, flywheel energy storage systems, motor bearings and cosmic microwave background polarimeters.

Modeling of a HTS domain

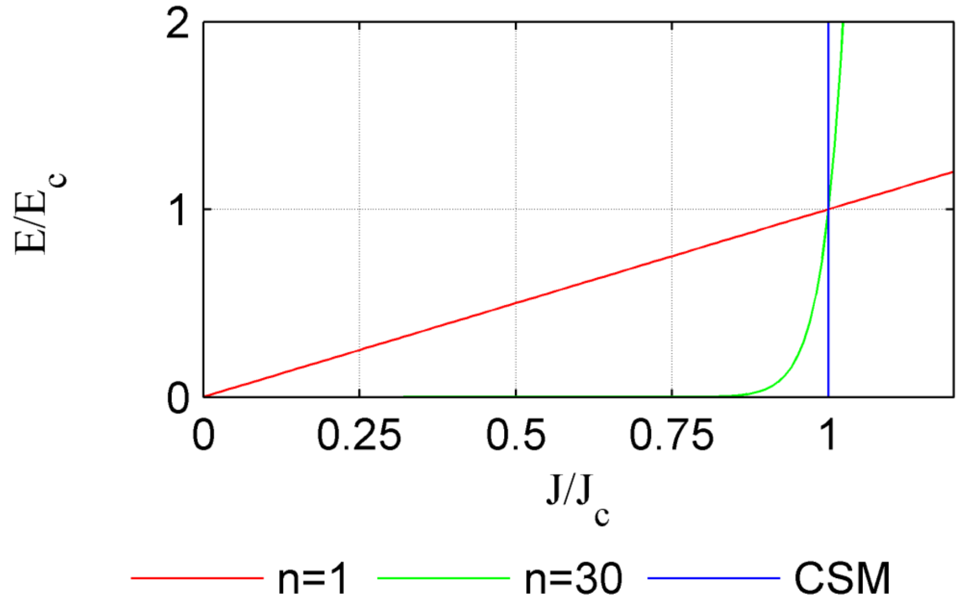
Finite element method

H-Formulation: $$\nabla \times (\rho \nabla \times \mathbf{H}) + \mu \frac{\partial \mathbf{H}}{\partial t} = 0$$

$$\rho_{sc} = \frac{E_c}{J_c} \left(\frac{|\mathbf{J}|}{J_c} \right)^{n-1}$$

$$J_c = J_c(\theta, |\mathbf{B}|)$$

$$n = n(\theta, |\mathbf{B}|)$$



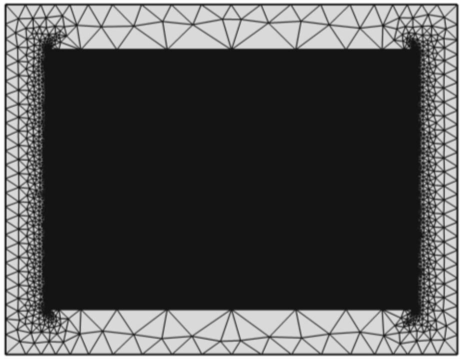
Modeling of a stack of HTS tapes

- Option 1 : Mapped mesh

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 21, NO. 3, JUNE 2011 3273

Towards Faster FEM Simulation of Thin Film Superconductors: A Multiscale Approach

V. M. Rodriguez-Zermeno, N. Mijatovic, *Student Member, IEEE*, C. Træholt, T. Zirngibl, E. Seiler, A. B. Abrahamsen, N. F. Pedersen, and M. P. Sørensen

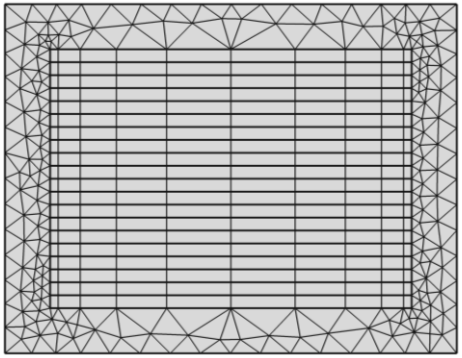


- Option 2 : Anisotropic homogenized bulk

IOP Publishing Superconductor Science and Technology
Supercond. Sci. Technol. **29** (2016) 024007 (10pp) doi:10.1088/0953-2048/29/2/024007

Numerical models for ac loss calculation in large-scale applications of HTS coated conductors

Loïc Quéval[1,3], Víctor M R Zermeño[2] and Francesco Grilli[2]



Simulation of a superconducting magnetic bearing

Conclusion #3: Divide, simulate and conquer.

Divide

Guideway

- Permanent magnet
- Exact geometry
- Iron B-H curve

SC bulk

- 3D
- Movement
- Number of elements

Conquer !

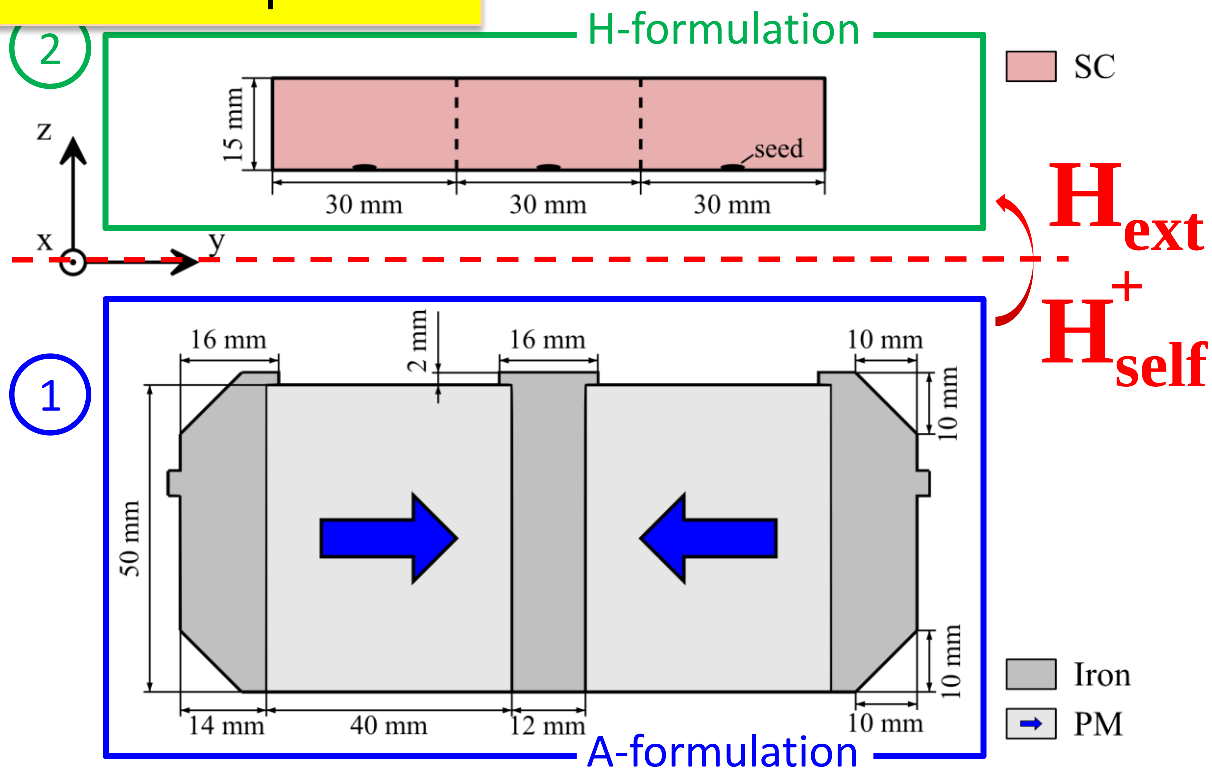
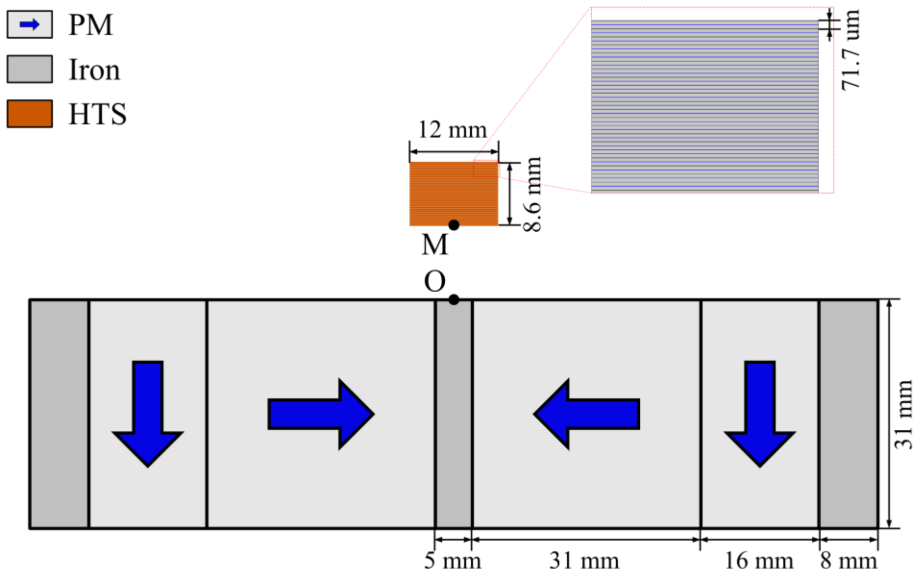


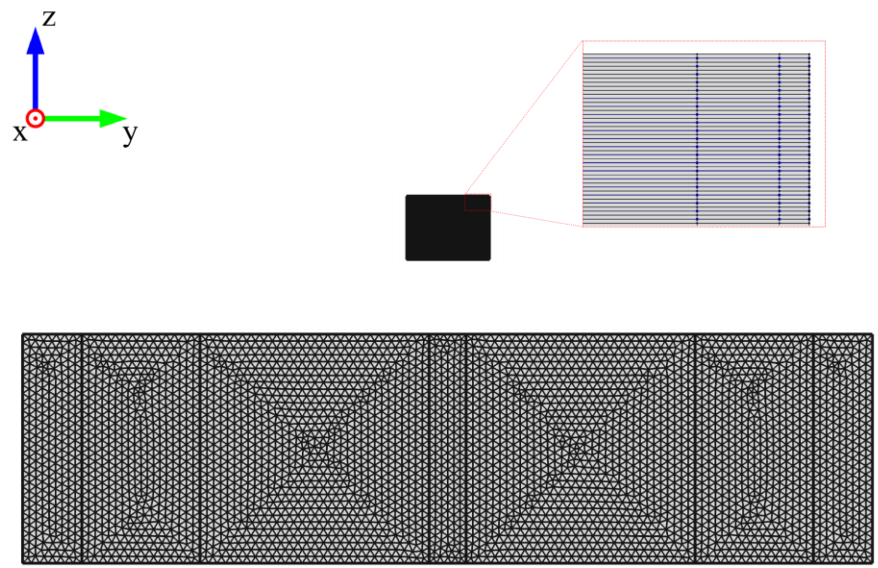
Fig.1 – Superconducting magnetic bearing of the SupraTrans vehicle

V. Simulation of a superconducting magnetic bearing

Geometry



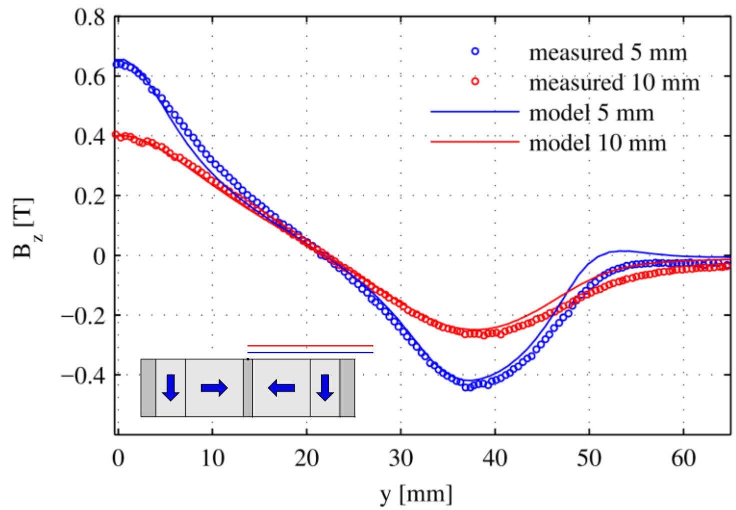
Mesh



Calibration

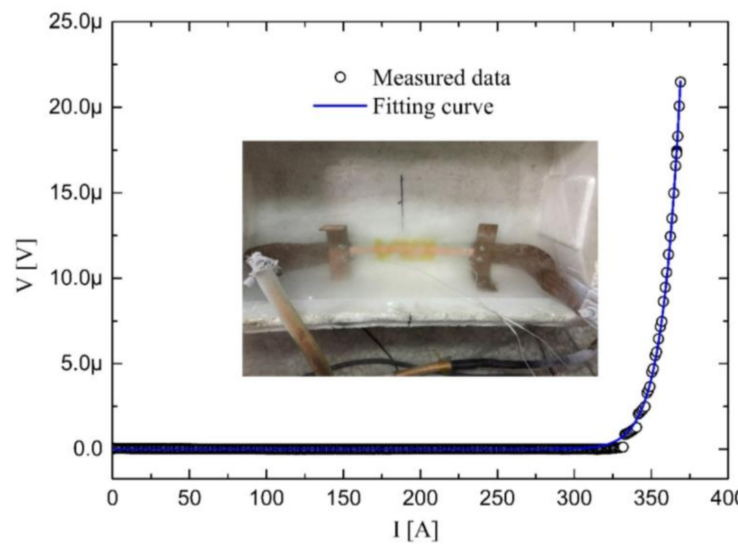
For the PM assembly model, we need:

- iron B-H curve ➡ datasheet
- remanent flux density *Br* of the PM
  ➡ fit to Bz measured above the PM



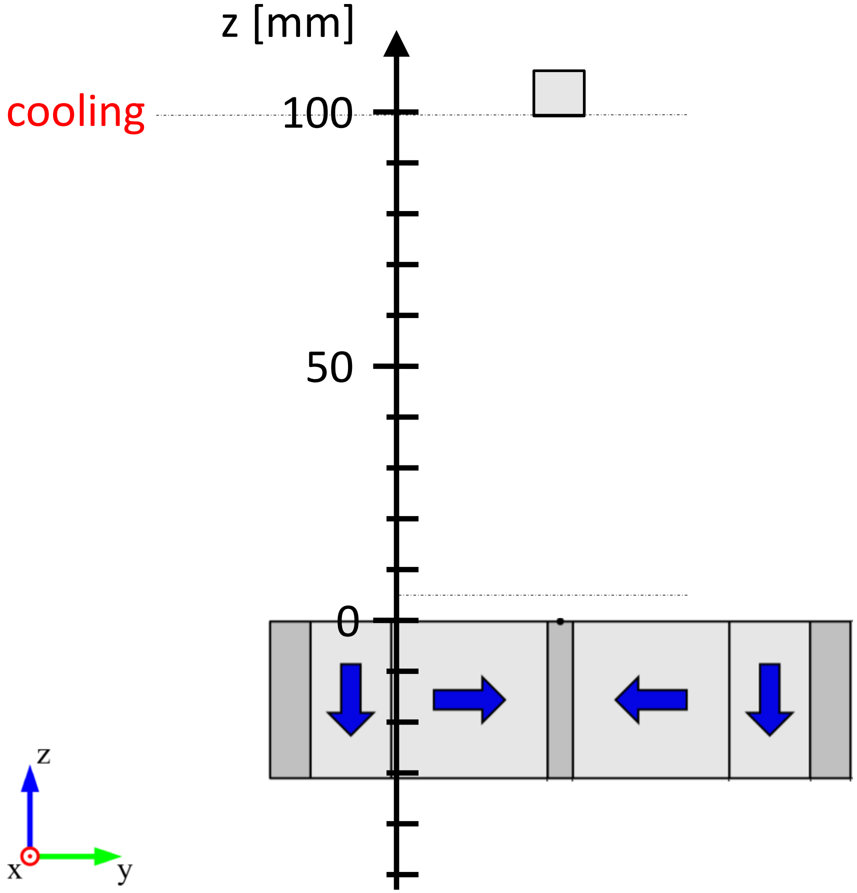
For the HTS assembly model, we need :

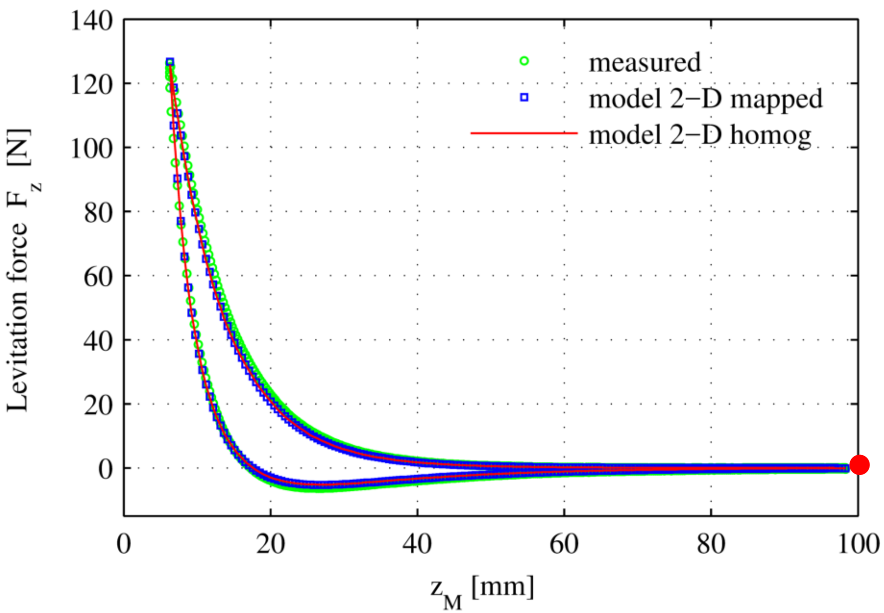
- J_{c0}, n ➡ fit to measured VI curve of SC tape
- B_0, k and α ➡ fit to the measured ZFC100 levitation force



Simulation results

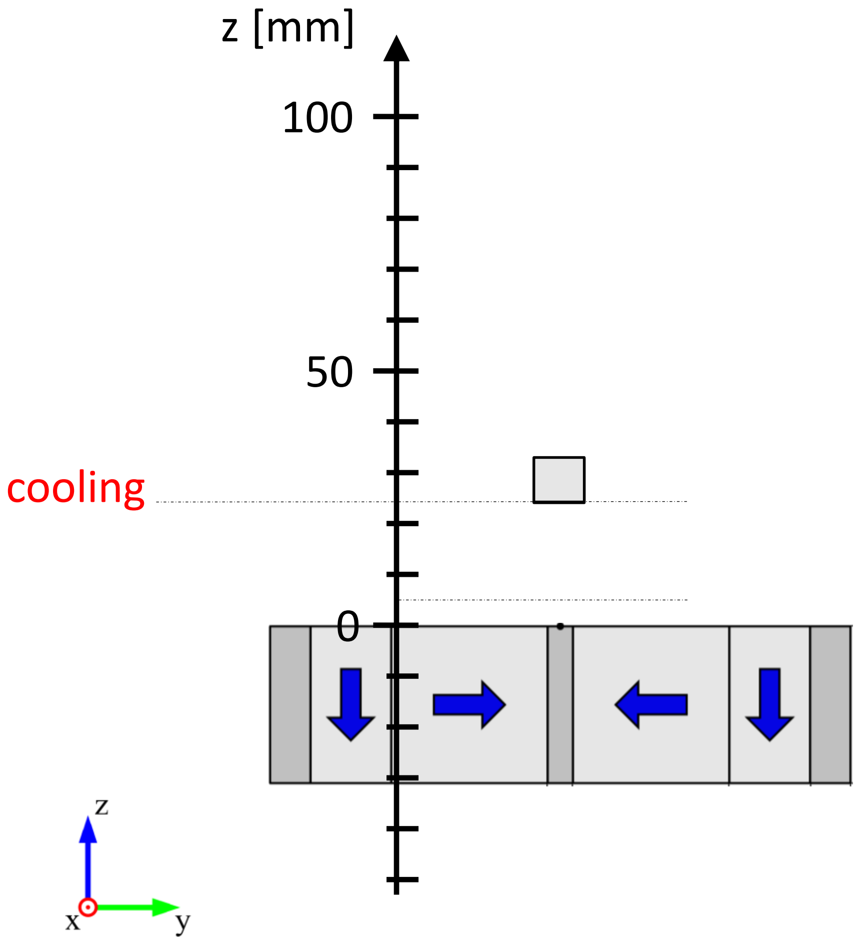
Zero field cooling case

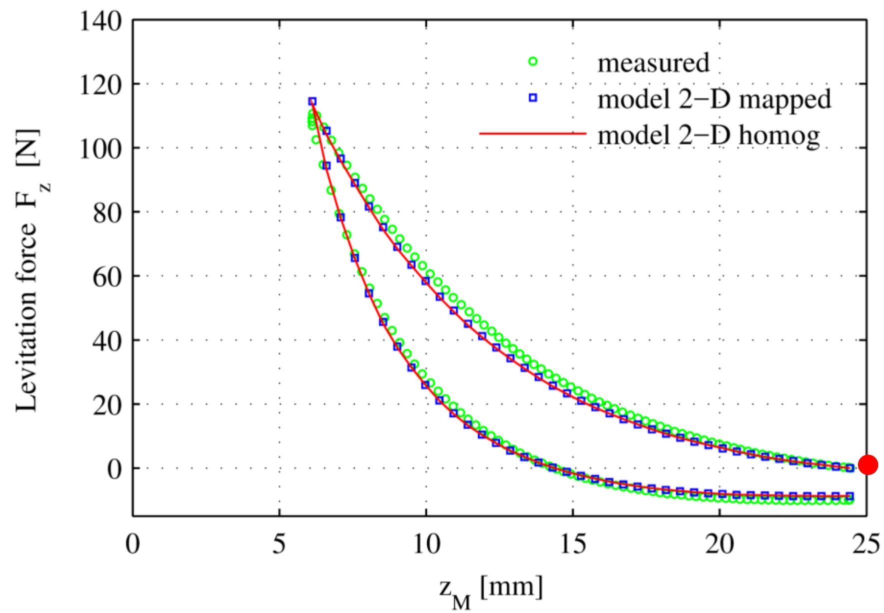




[Liu2017] K. Liu, W. Yang, G.T. Ma, L. Quéval, T. Gong, C. Ye, X. Li, Z. Luo, "Experiment and simulation of superconducting magnetic levitation with REBCO coated conductor stacks," *Superconductor Science and Technology*, vol. 31, no. 1, pp. 015013, Dec. 2017.
[Queval2018] L. Quéval, K. Liu, W. Yang, V.M.R. Zermeño, G.T. Ma, "Superconducting magnetic bearings simulation using an H-formulation finite element model," *Superconductor Science and Technology*, vol. 31, no. 8, pp. 084001, March 2018.

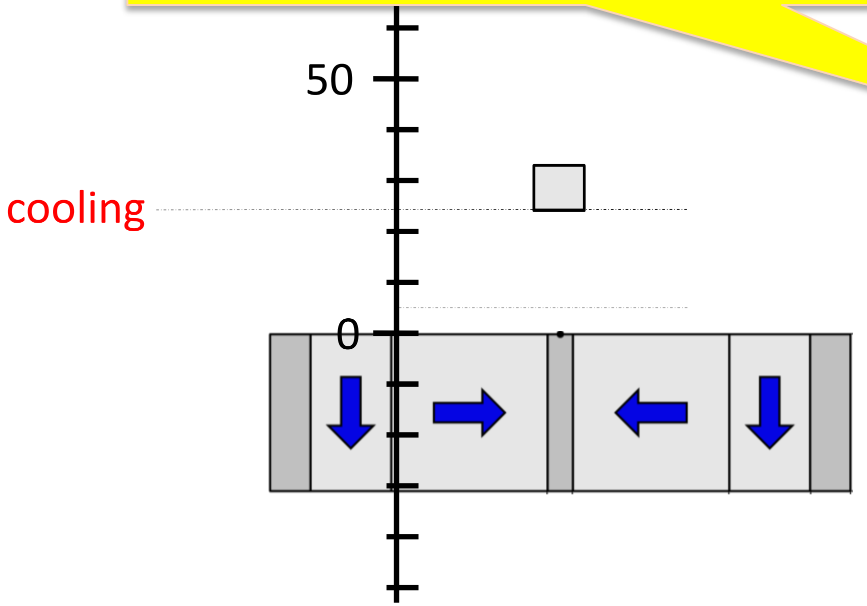
Validation – FC25 sequence

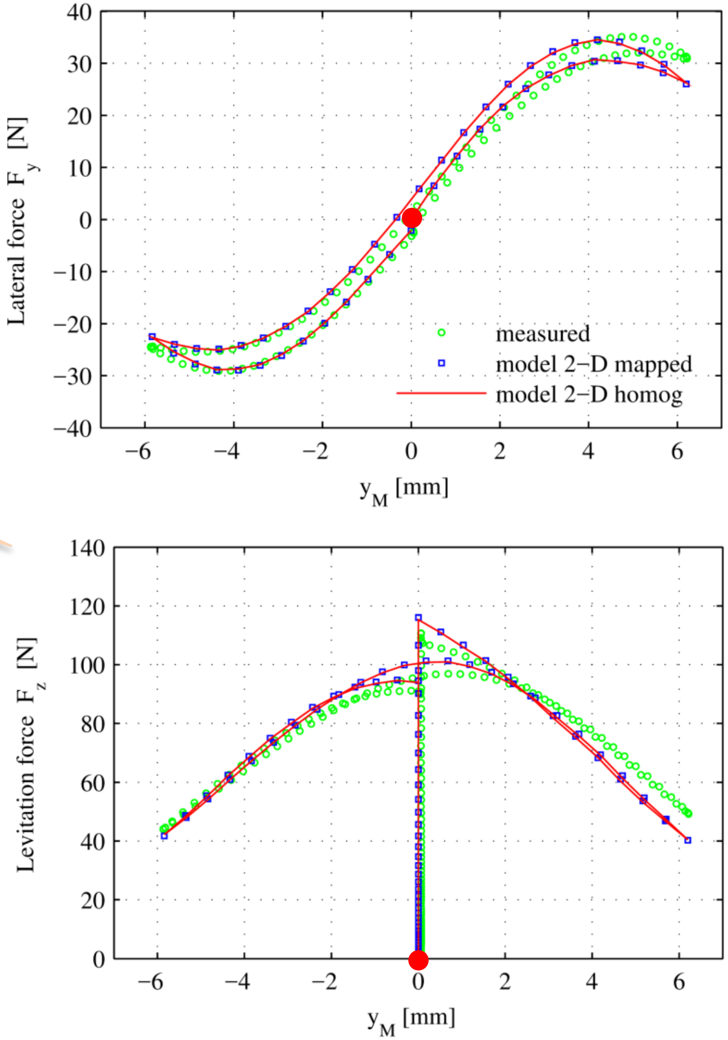




Validation – FC25_LD results

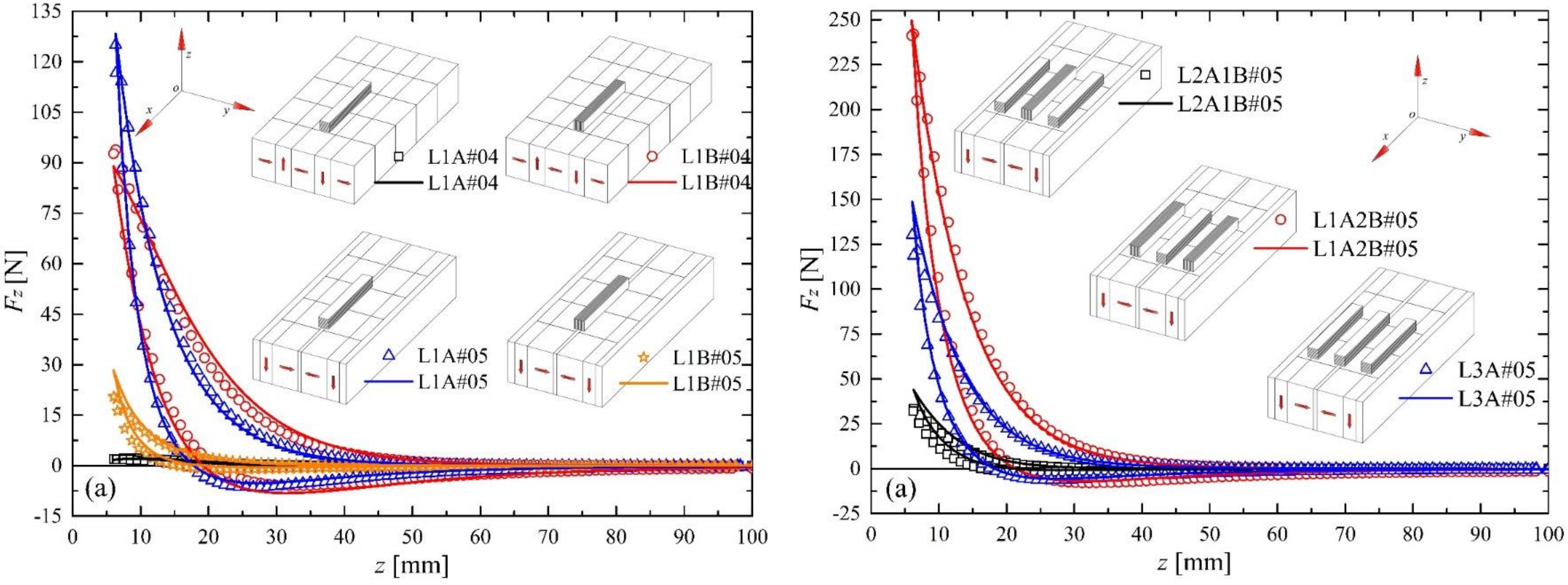
Conclusion #5: mapped mesh vs. anisotropic homogenized bulk: 0-1





More about stack-type SMB

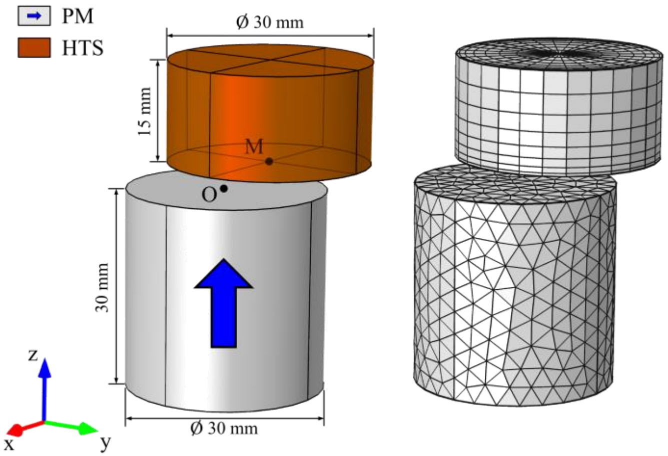
- 1 stack of 120 tapes
- 3 stacks of 120 tapes
- Systematic validation (homogenized model)

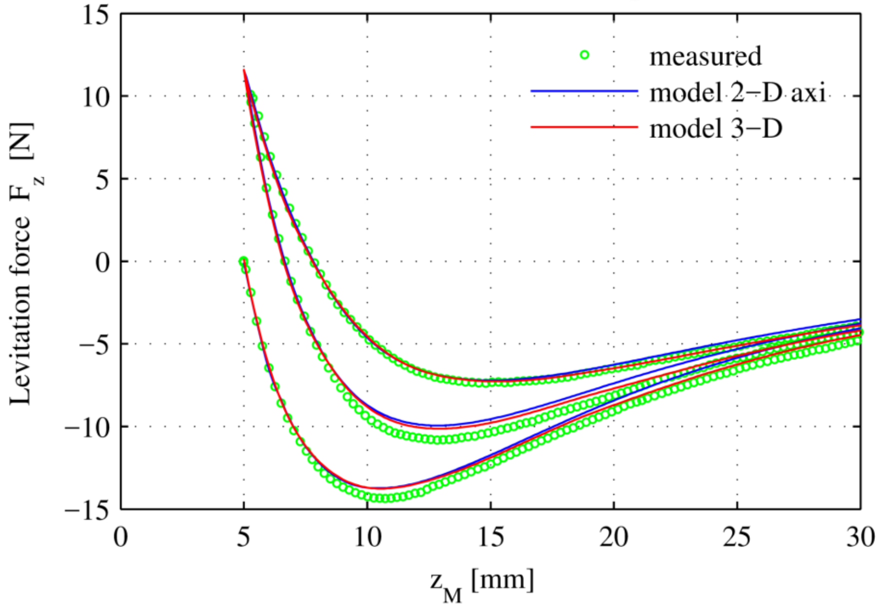


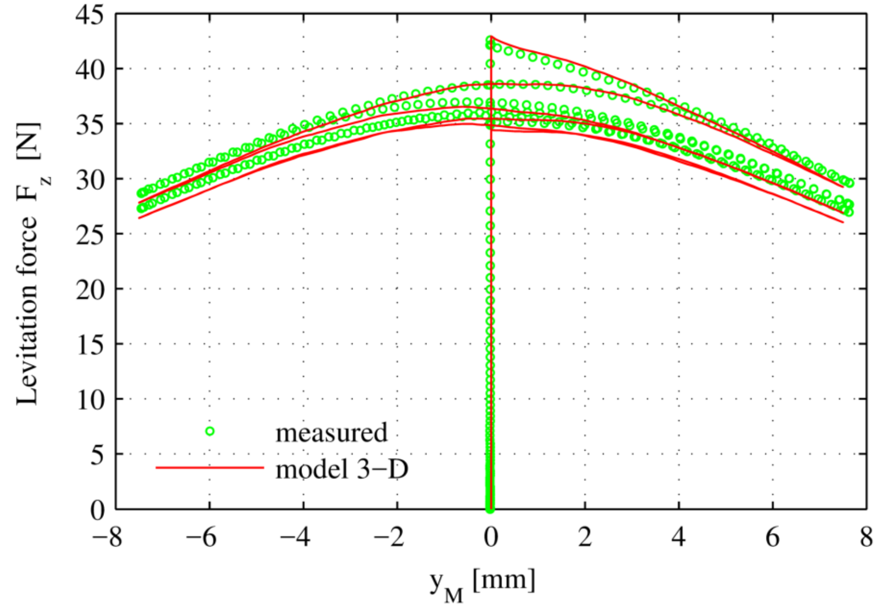
[Liu2017] K. Liu, W. Yang, G.T. Ma, L. Quéval, T. Gong, C. Ye, X. Li, Z. Luo, "Experiment and simulation of superconducting magnetic levitation with REBCO coated conductor stacks," *Superconductor Science and Technology*, vol. 31, no. 1, pp. 015013, Dec. 2017.

What about bulk-type SMB ?

Conclusion #6: 2-D, 2-D axi and 3-D SMB models are now ready for realistic applications.







[Queval2018] L. Quéval, K. Liu, W. Yang, V.M.R. Zermeño, G.T. Ma, "Superconducting magnetic bearings simulation using an H-formulation finite element model," *Superconductor Science and Technology*, vol. 31, no. 8, pp. 084001, March 2018.

VI. Conclusions

Conclusions

- It's important to participate to the experimental work in order to build a good model (experimental error).
- SMB modeling is an old problem (Sugiura1991).
- Divide, simulate and conquer !
- Careful with the calibration (BH curve + 6 parameters).
- mapped mesh vs. anisotropic homogenized bulk: 0-1.
- 2-D, 2-D axi and 3-D SMB models are now ready for realistic applications.

References

[1] L. Quéval, K. Liu, W. Yang, V.M.R. Zermeño, G.T. Ma, “Superconducting magnetic bearings simulation using an H-formulation finite element model,” *Superconductor Science and Technology*, vol. 31, no. 08, pp. 084001, March 2018.

[2] K. Liu, W. Yang, G.T. Ma, L. Quéval, T. Gong, C. Ye, X. Li, Z. Luo, “Experiment and simulation of superconducting magnetic levitation with REBCO coated conductor stacks,” *Superconductor Science and Technology*, vol. 31, no. 1, pp. 015013, Dec. 2017.

[3] L. Quéval, G.G. Sotelo, Y. Kharmiz, D.H.N. Dias, F. Sass, V.M.R. Zermeño, R. Gottkehaskamp, "Optimization of the superconducting linear magnetic bearing of a maglev vehicle," *IEEE Transactions on Applied Superconductivity*, vol. 26, no. 3, pp. 3601905, Apr. 2016.

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