Magnetization loop modelling for a superconductor/ferromagnetic composite

F. Gömöry, M. Solovyov, J. Šouc

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Magnetization loop modelling for a superconductor/ferromagnetic composite *of a magnetic cloak (composite = 1SC/1FM)*

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Outline

1) Introduction

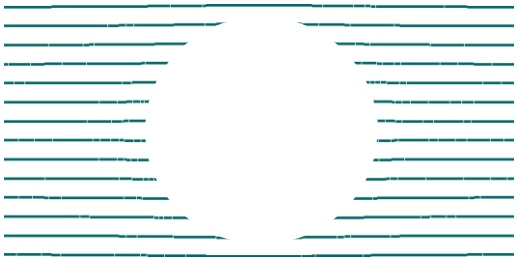
2) Numerical model

3) Experimental verification

4) Conclusions

Introduction

magnetic invisibility cloak: our ultimate goal

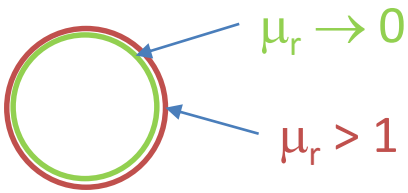


no distortion of the applied field
outside the shielded space

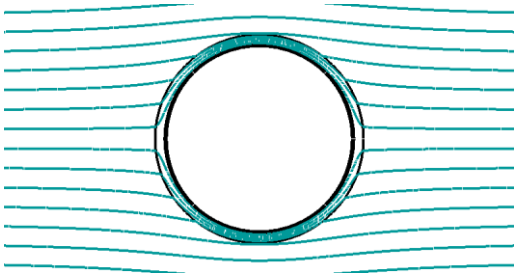
Introduction

magnetic cloak: more than a simple shield

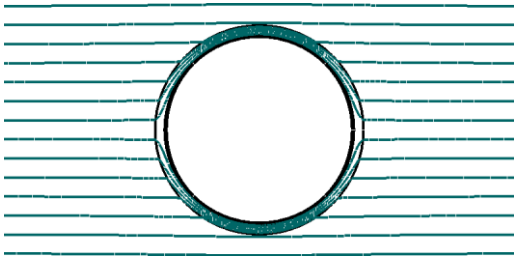
combination of diamagnetic and ferromagnetic material



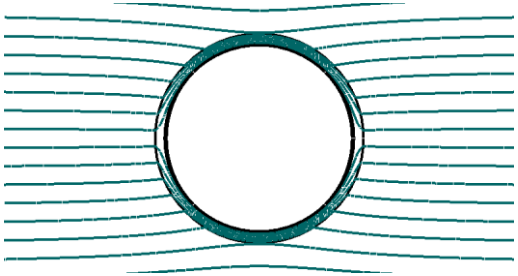
$\mu_r = 7$



$\mu_r = 10$



$\mu_r = 15$



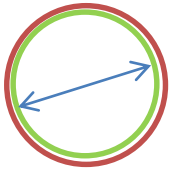
no distortion of the applied field outside the cloak

$$\mu_r = \frac{R_{Fo}^2 + R_{Fi}^2}{R_{Fo}^2 - R_{Fi}^2}$$

C. Navau, D.-X. Chen, A. Sanchez, N. Del-Valle, Appl. Phys. Lett. 94, 242501 (2009)

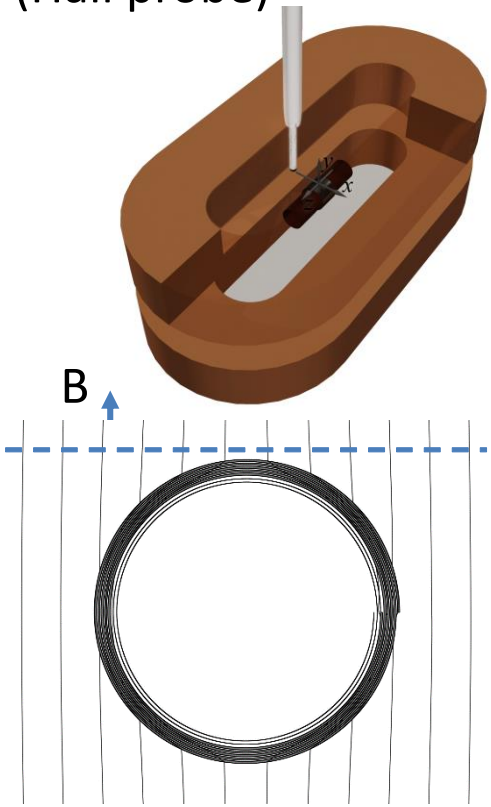
DC Cloak (#1)

SC tape (Superpower 12 mm wide, 2 turns)
Fe9Ni18Cr sheet (0.1 mm thick, 5 turns)

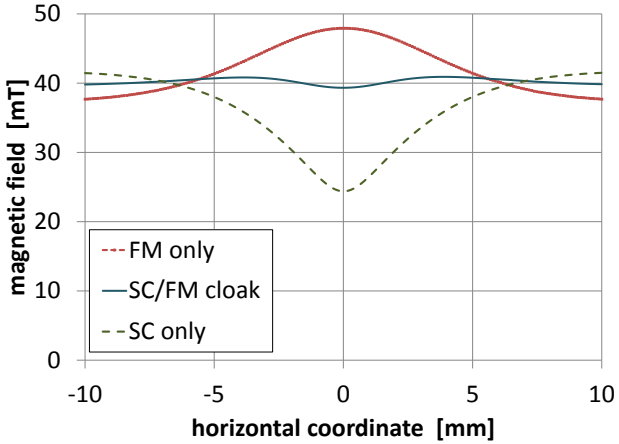


12.5 mm

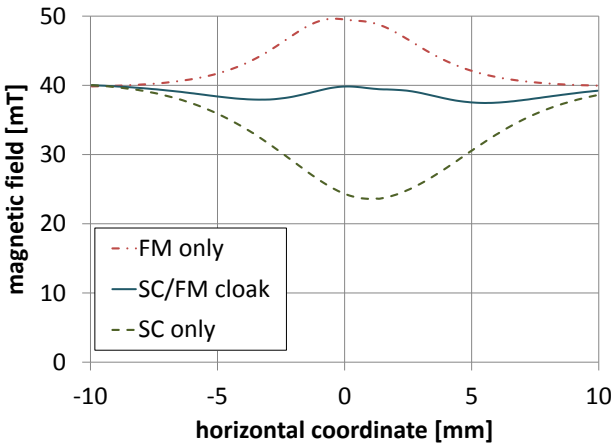
mapping of magnetic field
(Hall probe)



calculation



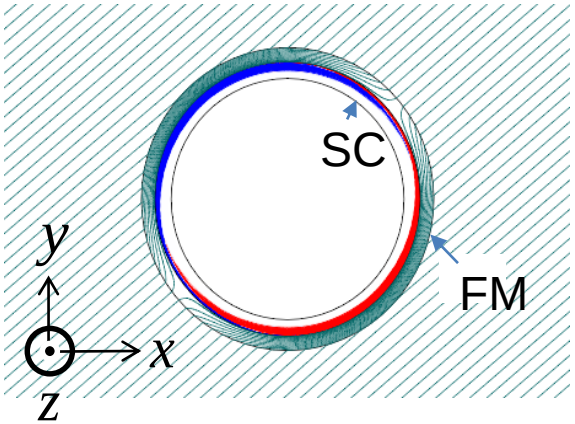
experiment



cloaking properties confirmed

F Gömöry, M. Solovyov, J. Šouc, C. Navau, J. Camps, A. Sanchez:
Science 335 (2012) 1466-1468

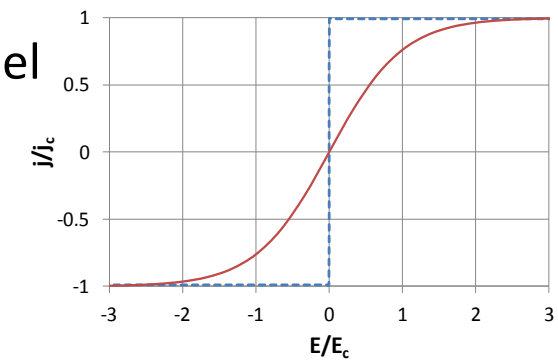
Finite element calculations in 2D



superconductor: $J(\boldsymbol{A}, \nabla\varphi)$ formulation

"smoothed" critical state model

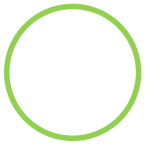
$$J = J_c \tanh(E/E_c)$$



$$E_z = -\frac{\partial A_z}{\partial t} - \nabla\varphi$$

zero net transport current achieved through electrostatic charges:

single element (tube)



$$\nabla\varphi = 0$$

in the neutral zone $E_z = 0$ $\quad \dfrac{\partial A_{z0}}{\partial t} = -\nabla\varphi$

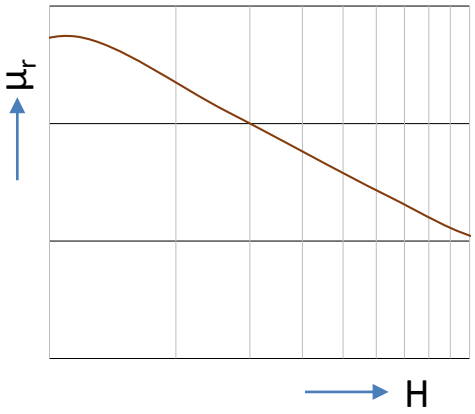
parallel elements (tapes)

$$\nabla\varphi = \nabla\varphi_i$$

$$J(x,y)\big|_i = J_c \tanh\left(-\frac{1}{E_c}\frac{\partial\left[A(x,y) - A_{0,i}\right]}{\partial t}\right)$$

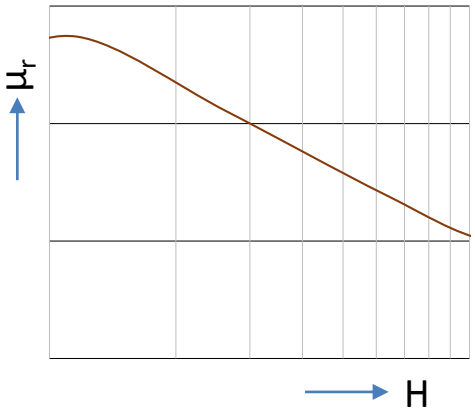
Finite element calculations in 2D

ferromagnetic material: magnetic permeability

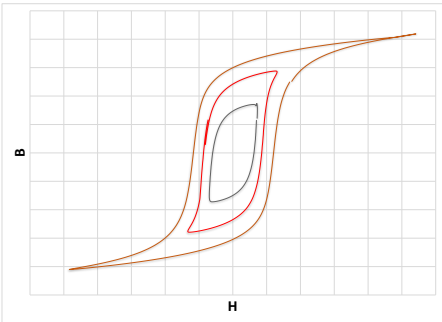


Finite element calculations in 2D

ferromagnetic material: magnetic permeability

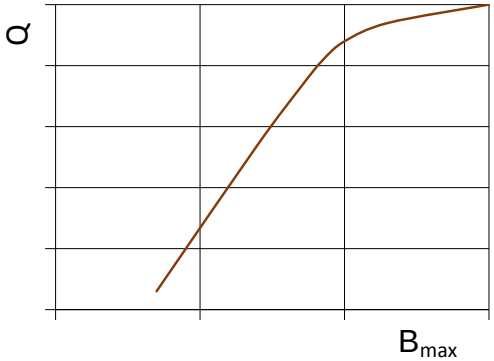


AC regime: AC loss because of magnetic hysteresis



FM loss (per unit length)

$$Q_{FM} = \int_{FM} Q(B_{\max}(x,y))\mathrm{d}x\mathrm{d}y$$



D N Nguyen, S P Ashworth, J O Willis, F Sirois, F Grilli, Supercond Sci Technol 23 (2010) 025001

F Gömöry, M Vojenčiak, E Pardo, M Solovyov, J Šouc, Supercond Sci Technol 23 (2010) 034012.

FM loss is added to the SC loss to obtain the total loss

Cloaking of AC fields

new phenomenon: irreversibility of *m(B)*

→ dependence on history

→ phase shift of induced magnetic field

→ AC loss

$M = m/V_{cloak}$

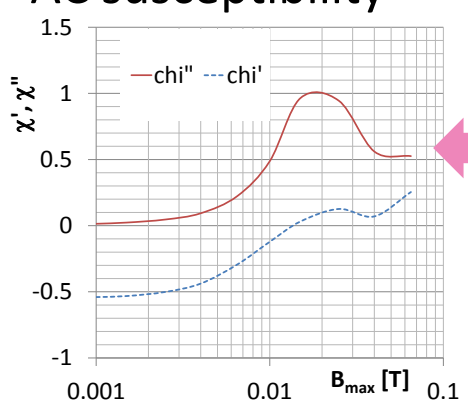
$(\chi = \mu_0 M/B)$

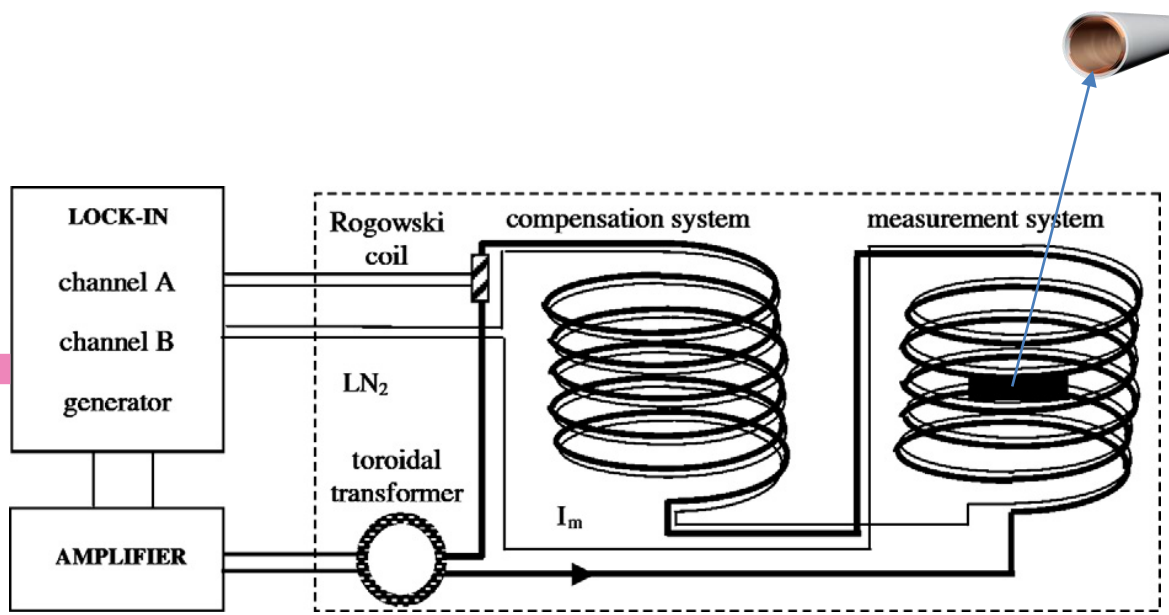
$\chi' = \mu_0 m'/(V_{cloak}\, B_{max})$

$\chi'' = \mu_0 m''/(V_{cloak}\, B_{max})$

$$\frac{Q}{V_{cloak}} = \pi\chi''\frac{B_{max}^2}{\mu_0}$$

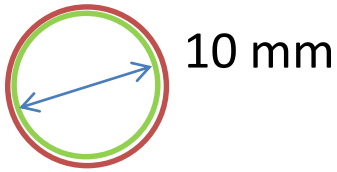
AC susceptibility



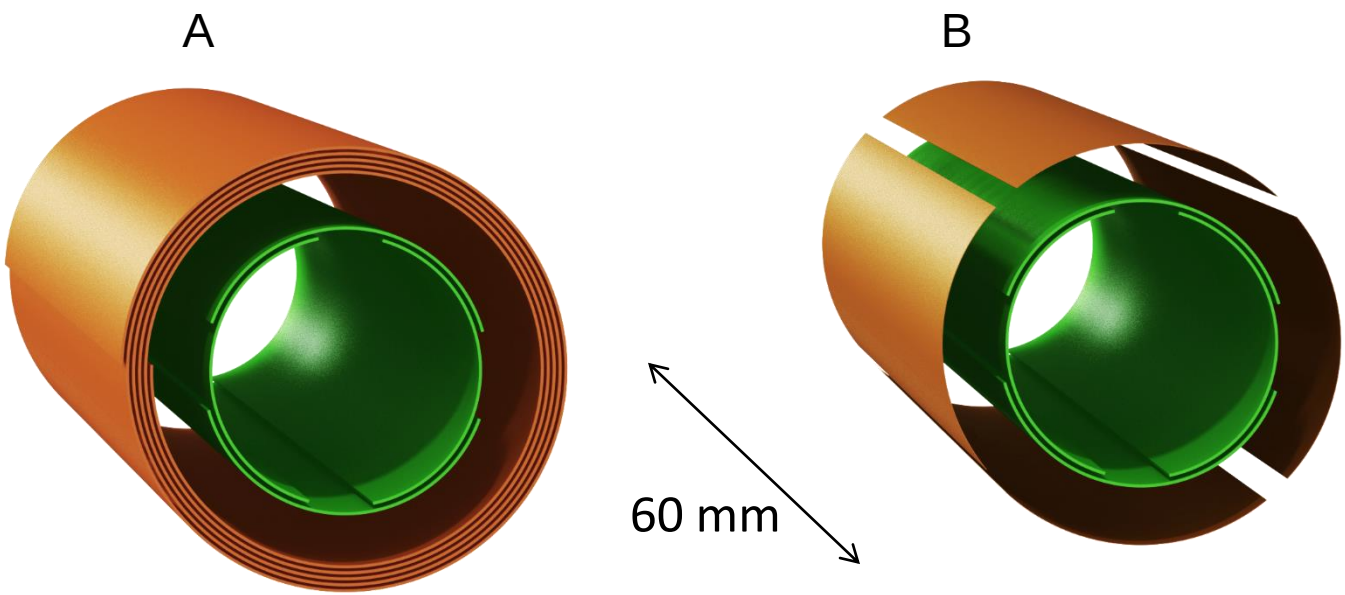


Cloaking of AC fields

SC tape (Superpower 12 mm wide, 4 strips)

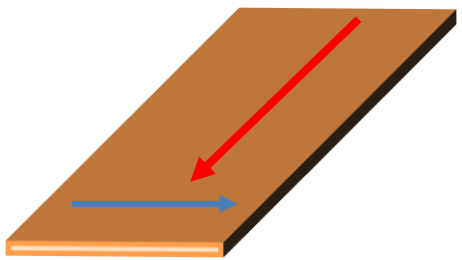


Cloak A: Fe9Ni18Cr sheet (0.1 mm thick, 5 layers)
Cloak B: Fe-Si-B-Cu-Nb metallic glass (0.025 mm thick, 4 strips)

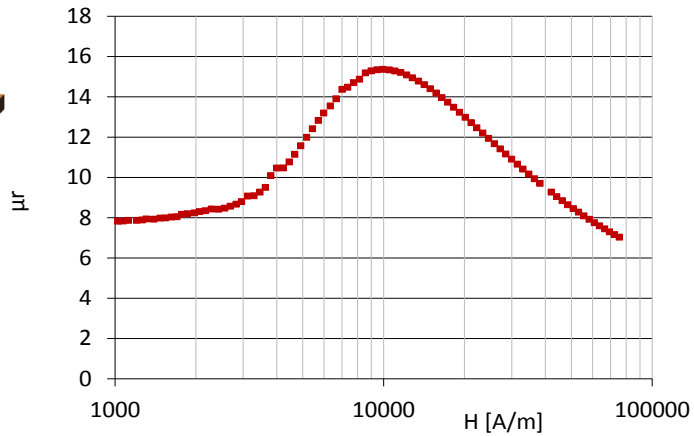


Properties of FM materials

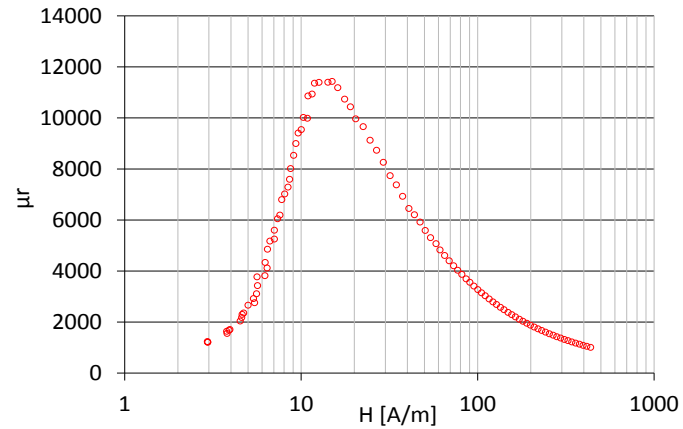
Fe9Ni18Cr sheet



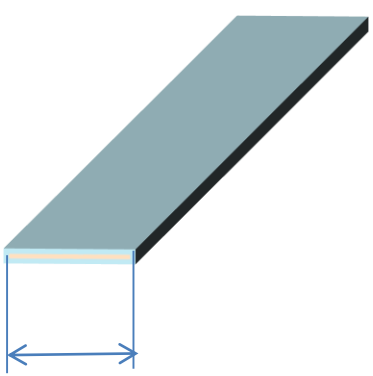
Fe-18%Cr-9%Ni sheet



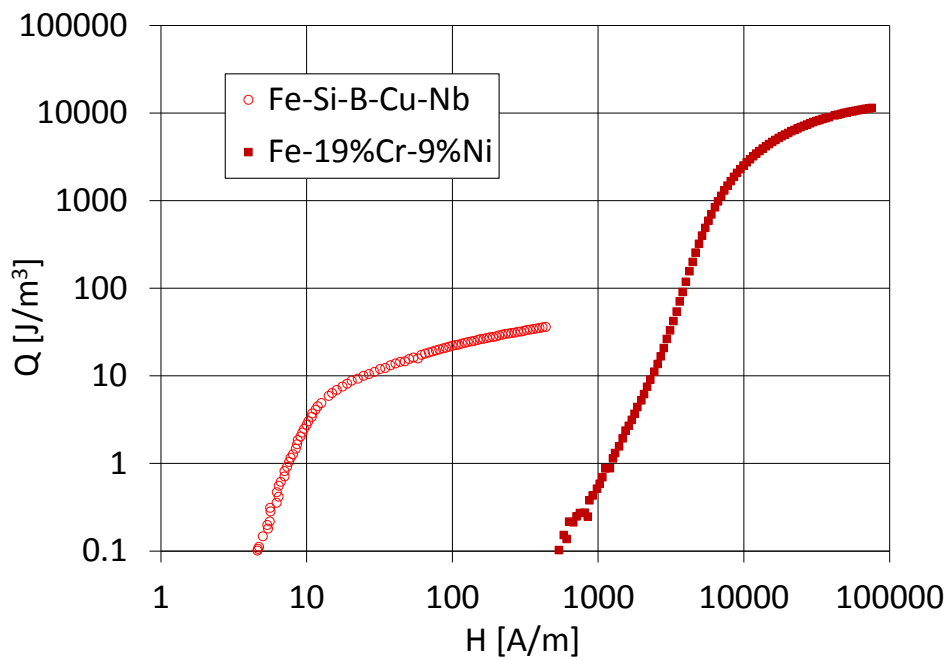
Fe-Si-B-Cu-Nb ribbon



Fe-Si-B-Cu-Nb ribbon



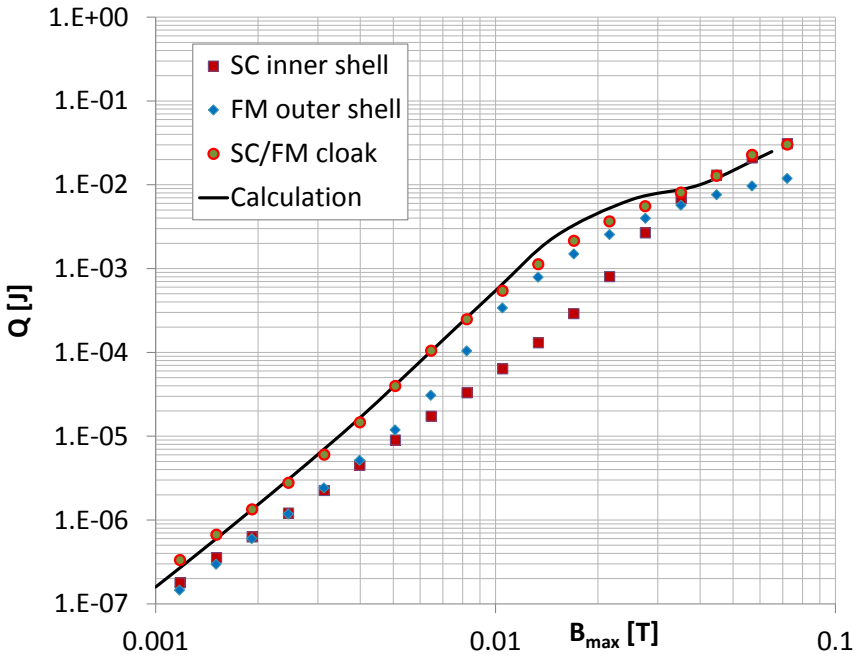
10 mm



P. Duhaj, P. Švec, D. Janickovic, I.Matko, M. Hlasnik, Mat. Sci. Eng. B14, 357 (1992).

Cloak A in AC field

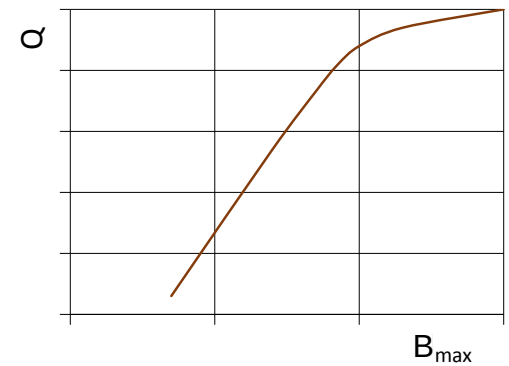
f = 36 Hz

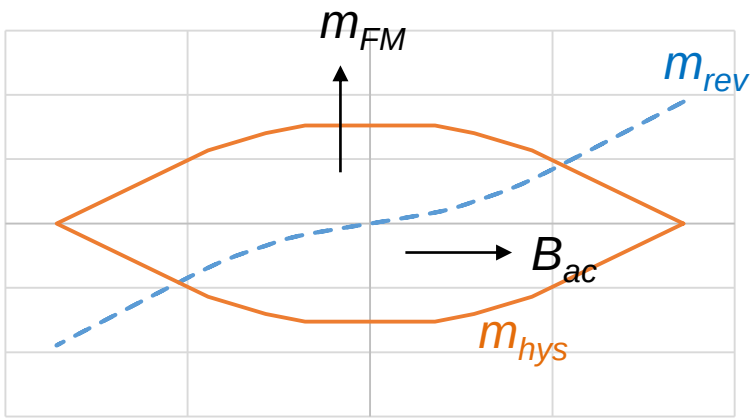


Estimation of FM hysteresis loop

basic idea: Rayleigh's approach $Q \propto B_{\max}^3$

S Chikazumi and C D Graham, "Physics of Ferromagnetism", Oxford: Oxford University Press (1997)





magnetic moment (per unit length) of FM:

$$m_{FM} = m_{rev} + m_{hys}$$

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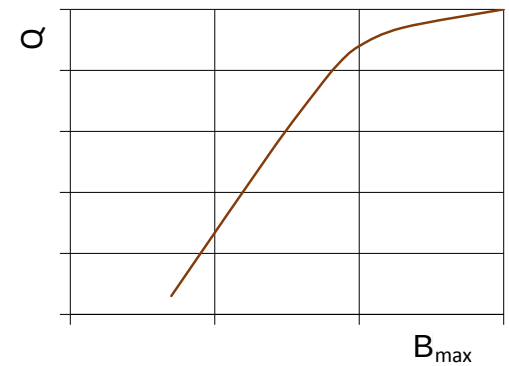

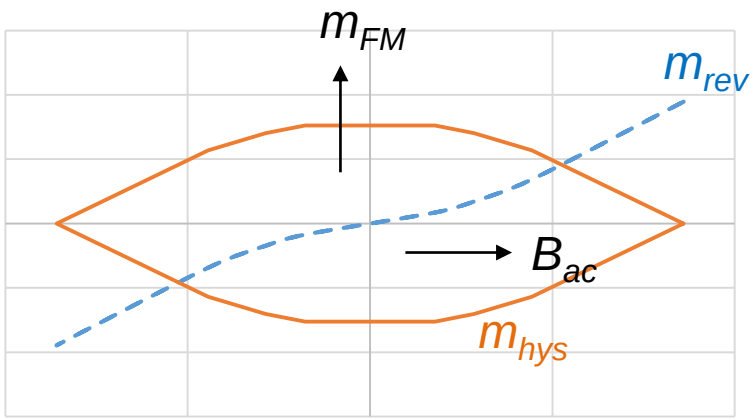

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$$m_{FM} = m_{rev} + m_{hys}$$

$$m_{hys} = \pm\gamma(B_{ac}^2 - B_{\max}^2)$$

$$Q_{FM} = \oint m_{FM}\,\mathrm{d}B_{\mathrm{ac}} = 2\int_{-B_{\max}}^{B_{\max}} \gamma\left(B_{ac}^2 - B_{\max}^2\right)\mathrm{d}B_{\mathrm{ac}} = \frac{8}{3}\gamma\, B_{\max}^3$$

$$\gamma = Q_{FM}\,\frac{3}{8}\,\frac{1}{B_{\max}^3}$$

J Souc, M Solovyov, F Gömöry, J Prat-Camps, C Navau, A Sanchez New J. Phys. 15 053019 (2013).

Estimation of FM hysteresis loop

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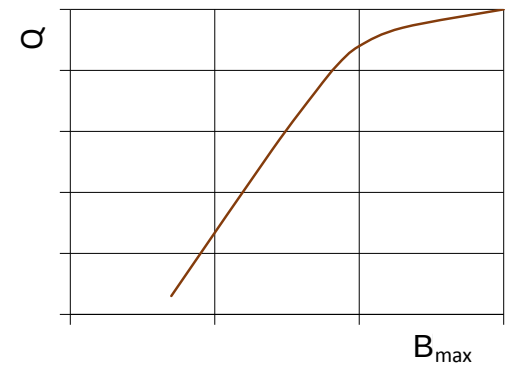

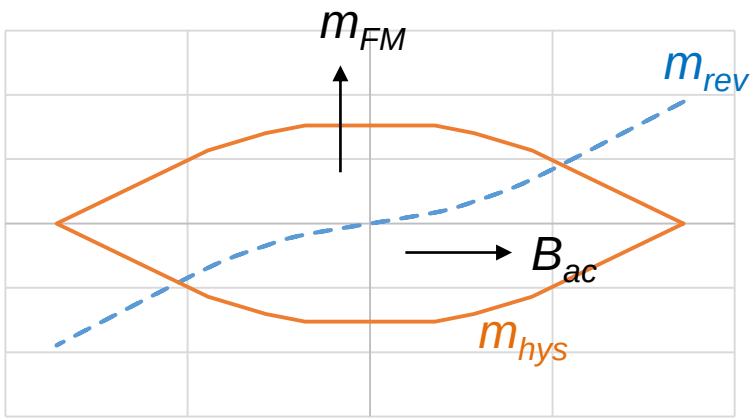

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$$\gamma = Q_{FM}\,\frac{3}{8}\,\frac{1}{B_{\max}^3}$$

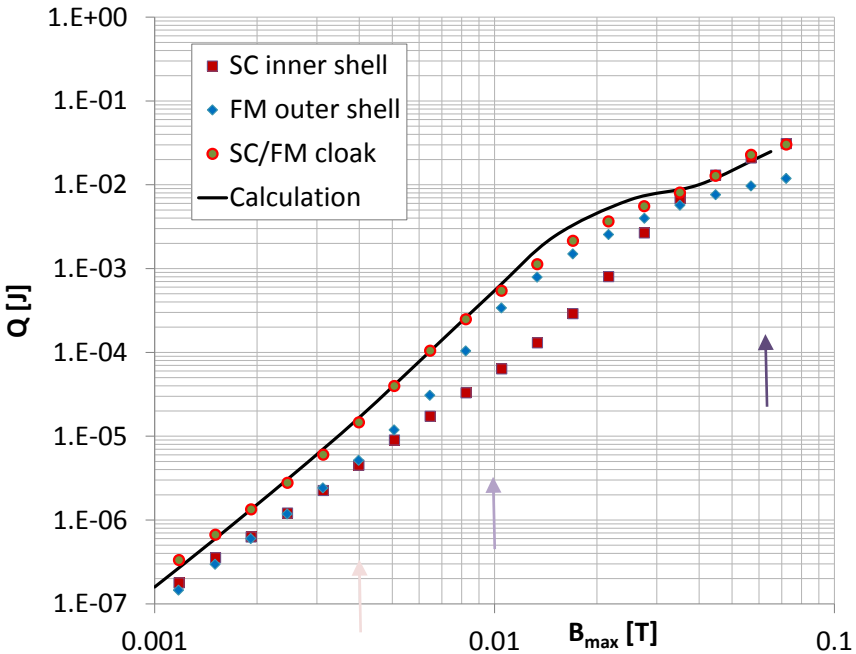
$$m_{hys,\downarrow} = Q_{FM}\,\frac{3}{8}\,\frac{(B_{\max}^2 - B_{ac}^2)}{B_{\max}^3}$$

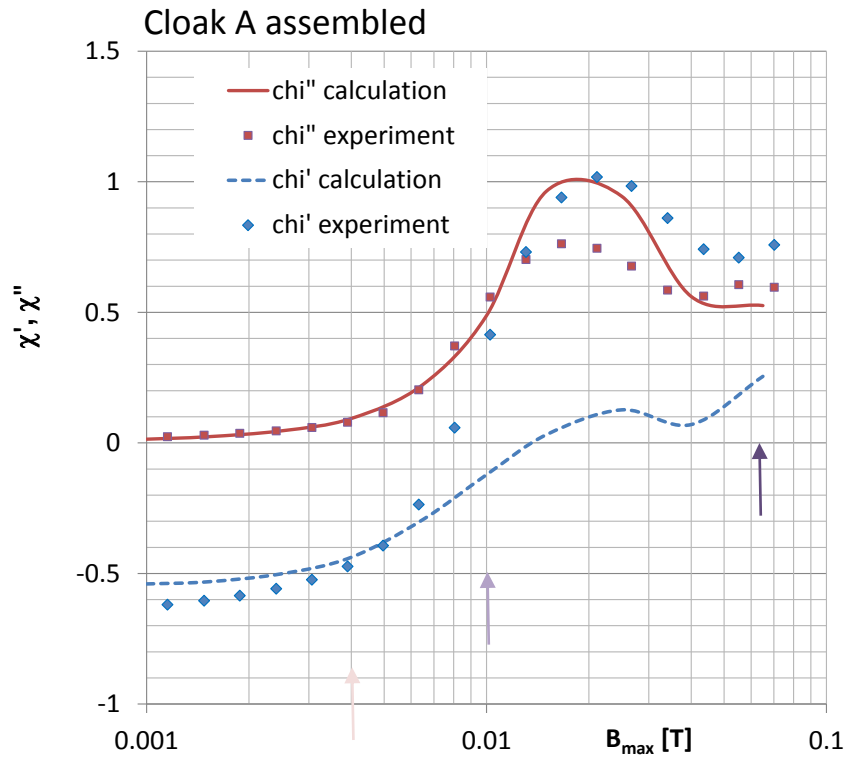
$$m_{hys,\uparrow} = Q_{FM}\,\frac{3}{8}\,\frac{(B_{ac}^2 - B_{\max}^2)}{B_{\max}^3}$$

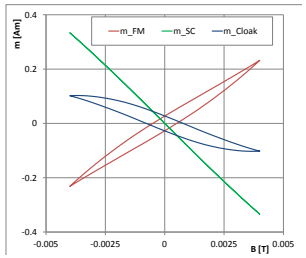
J Souc, M Solovyov, F Gömöry, J Prat-Camps, C Navau, A Sanchez New J. Phys. 15 053019 (2013).

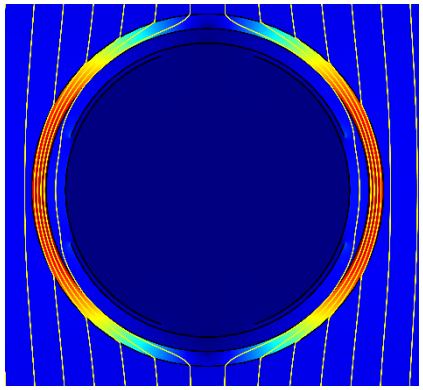
Cloak A in AC field

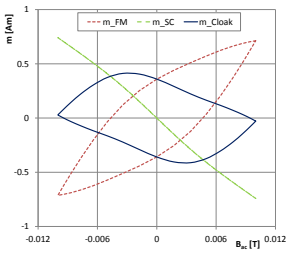
f = 36 Hz

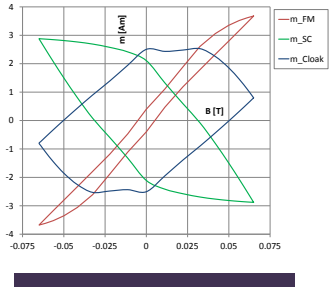






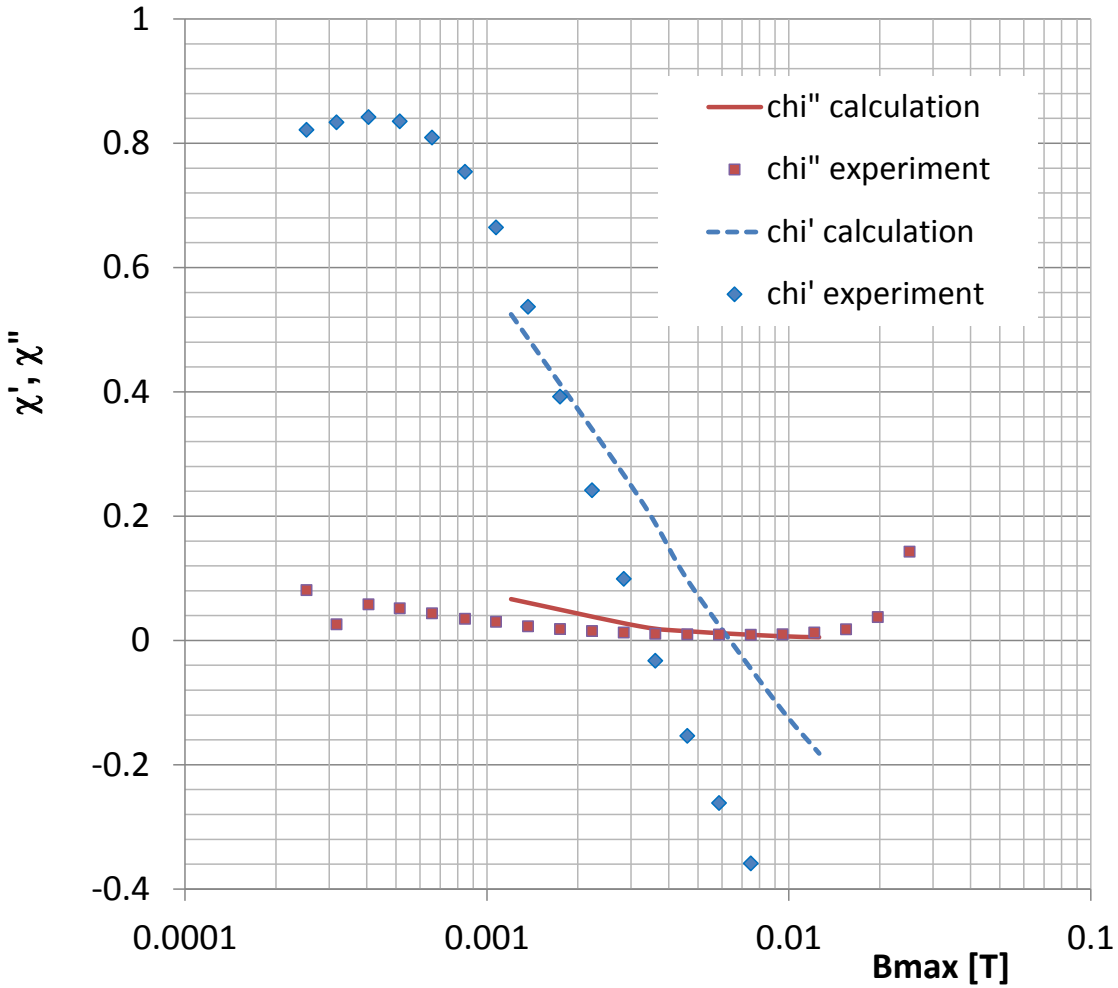




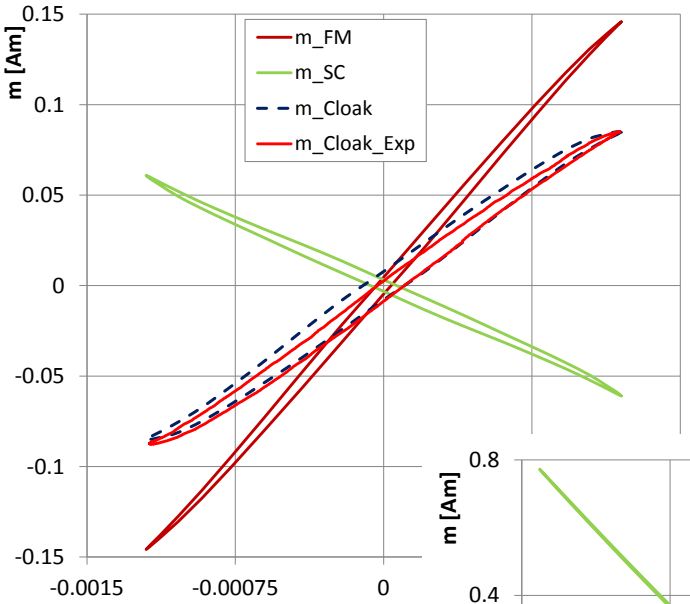


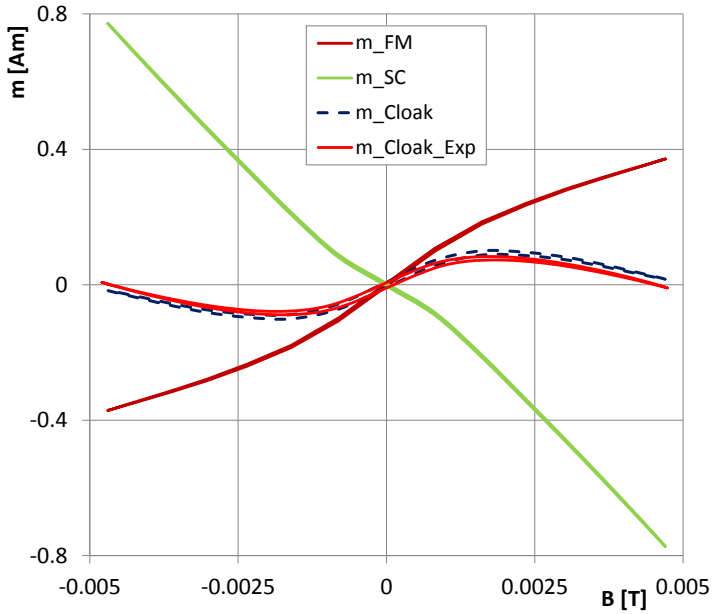
FM hysteresis dominates

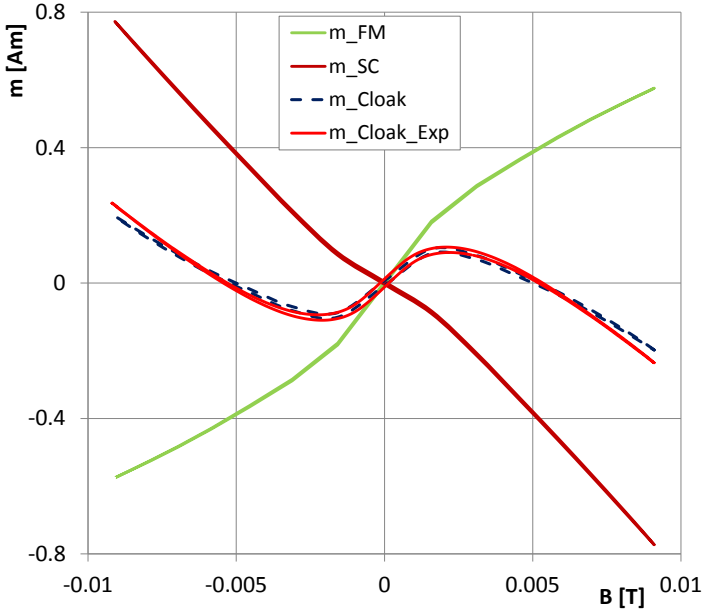
Cloak B in AC fields



Cloak B in AC fields

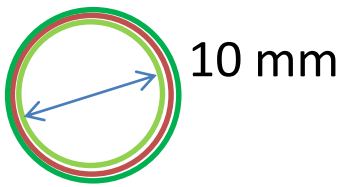


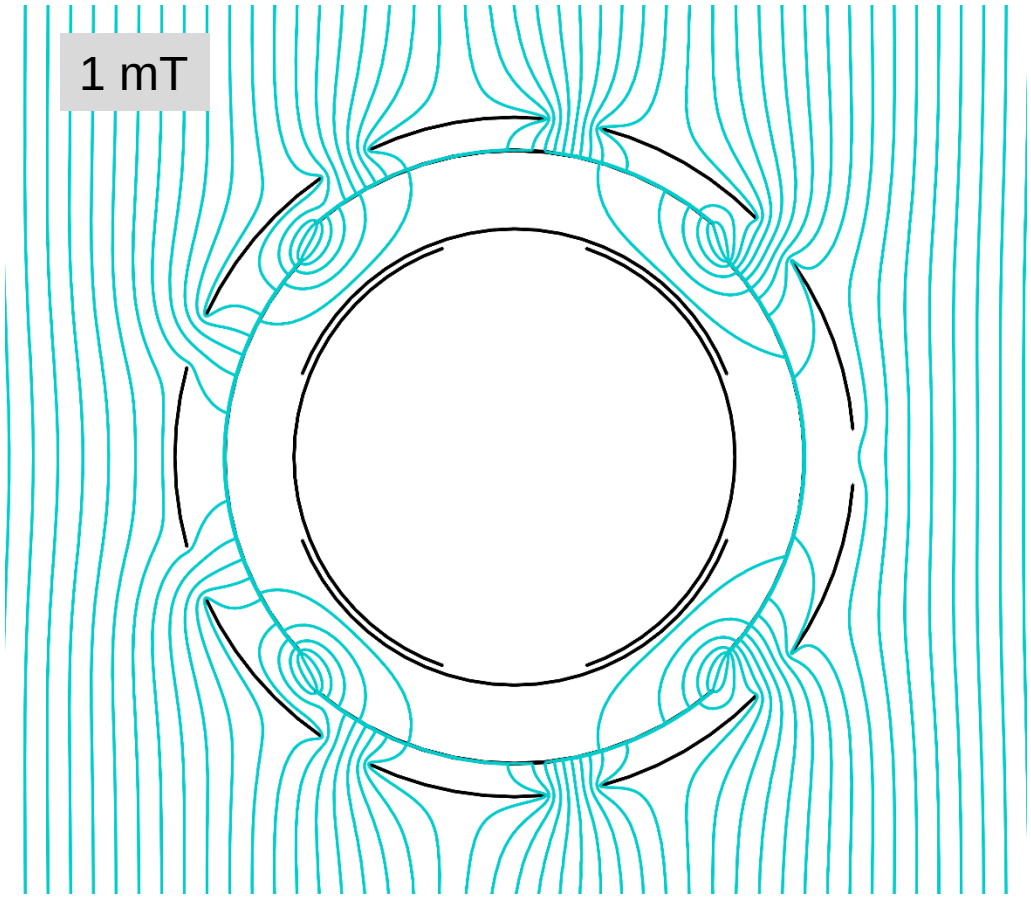




Cloak C = Cloak B + additional SC layer

SC tape (Superpower 12 mm wide, 4 strips)
Fe-Si-B-Cu-Nb ribbon (0.025 mm thick, 4 strips)
SC tape (Superpower 4 mm wide, 9 strips)





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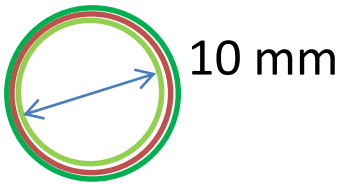
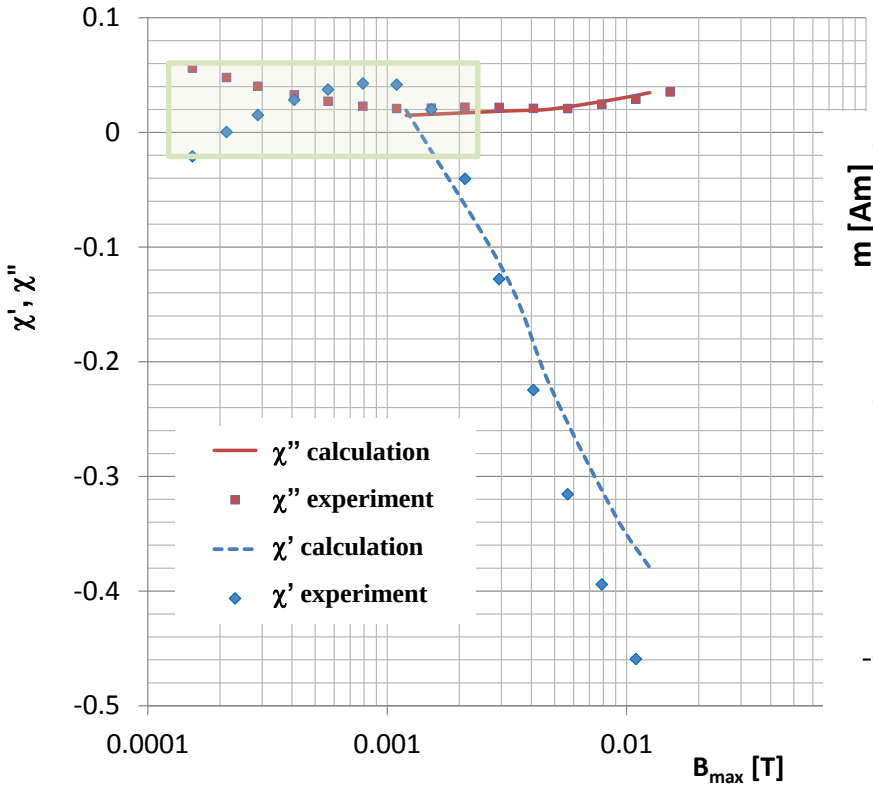
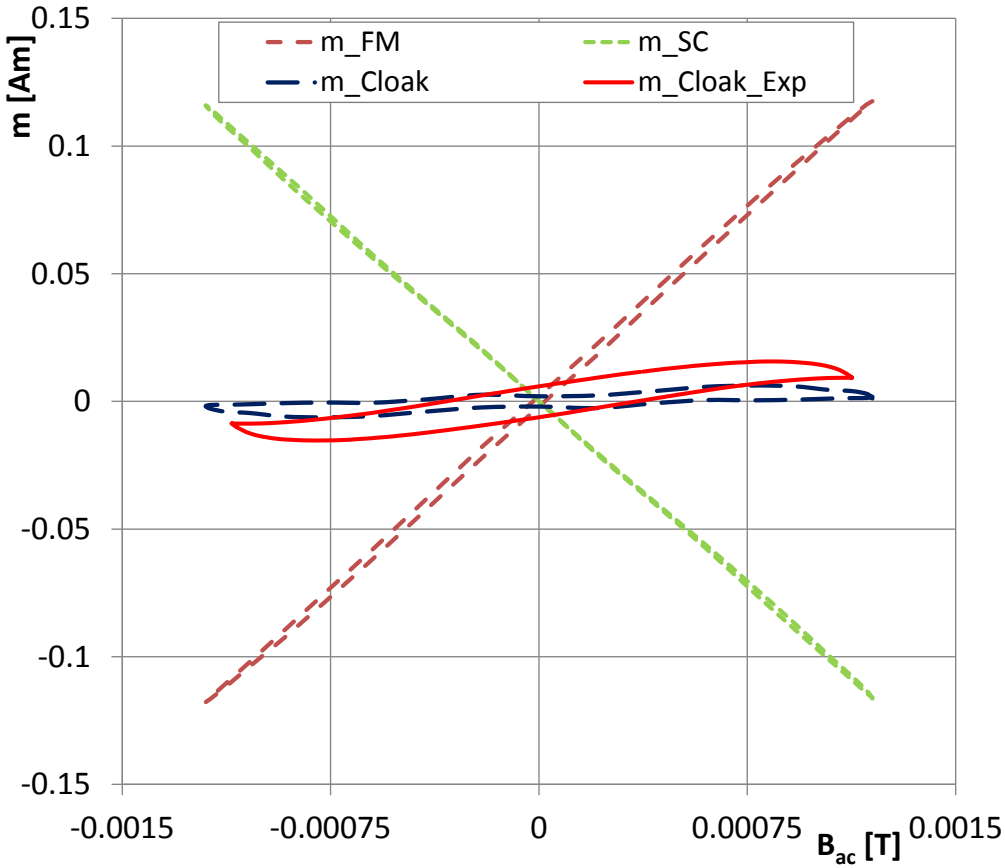






very good performance at $B_{max} < 1$ mT

Conclusions

Numerical modeling for magnetic properties of SC/FM composites in 2D provides reasonable predictions

Adding the approximation of FM hysteresis to the calculated loops allows to understand better the magnetic behavior

Design of cloaks reducing the AC magnetic signal 20x is possible

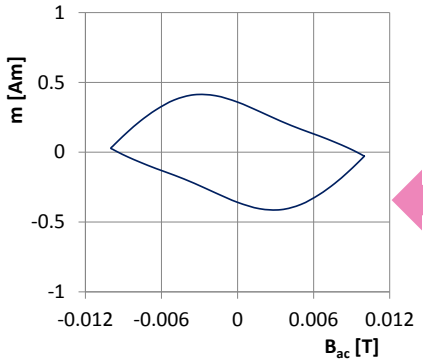
AC field cloaking

Experimental apparatus

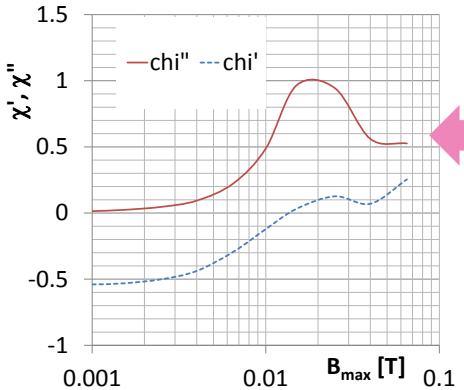
$B_{ac} = B_{max} \cos(\omega t)$

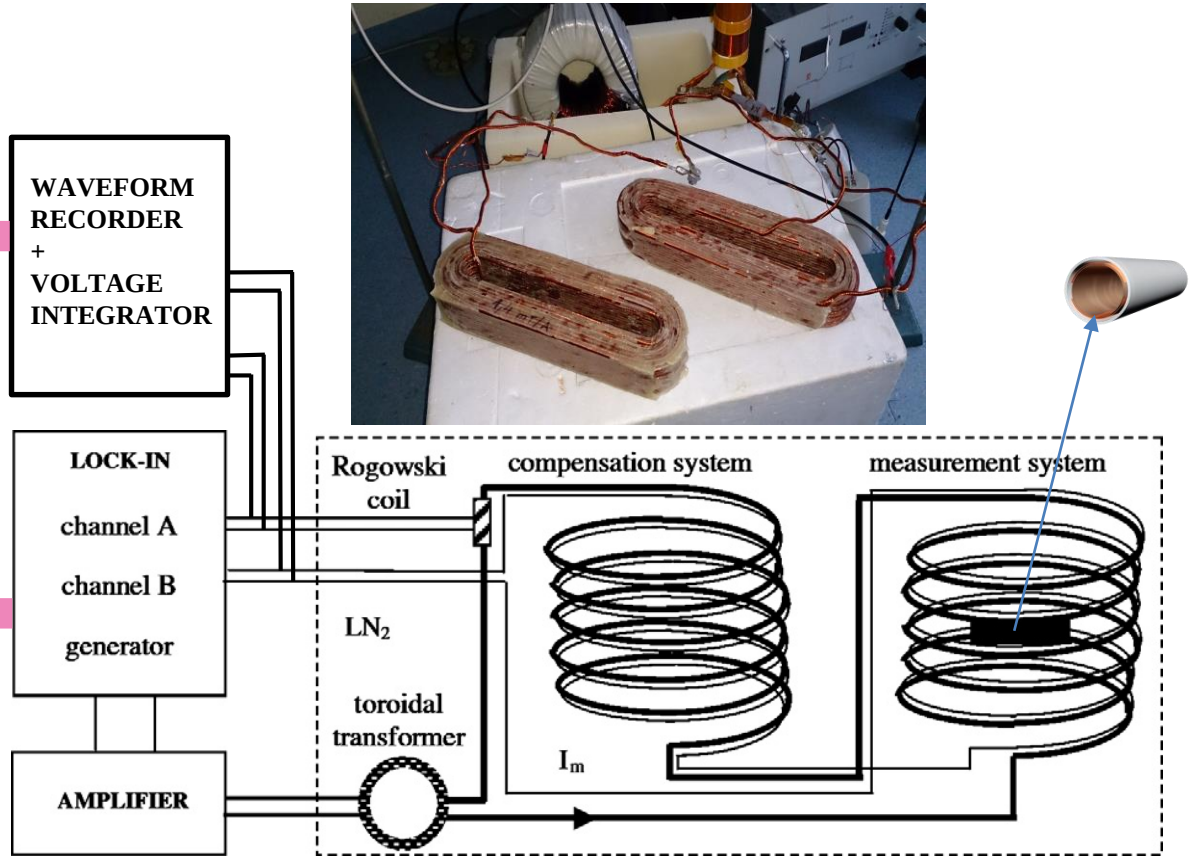
$\omega = 2\pi f,\ f \in (36 \div 288\ \text{Hz})$

magnetic hysteresis loop



AC susceptibility





Properties of FM material(s)

~ 1 meter of tape wound
in toroidal sample