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## Low frequency excess noise source investigation of off-diagonal GMI- based magnetometers

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# Outlines

1. Useful recalls about GMI effect and GMI-based magnetometer

2. Low frequency excess noise

2.1 Magnetization fluctuations in classical GMI

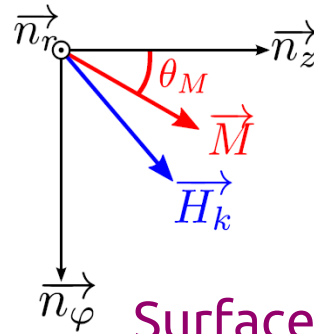
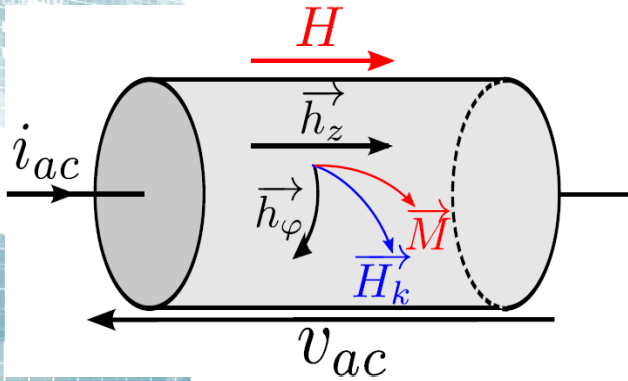
2.2 Extension to the off-diagonal configuration

3. Results

3.1 Simulation results

3.2 Discussion

# 1.1 GMI effect



$$Z = \frac{V_{ac}}{I_{ac}} \rightarrow V_{ac} = e_z l$$

$$I_{ac} = 2\pi a h_\varphi$$

Surface impedance tensor

$$\begin{pmatrix} e_\varphi \\ e_z \end{pmatrix} = [\zeta_s] \begin{pmatrix} h_\varphi \\ h_z \end{pmatrix} = \begin{bmatrix} \zeta_{\varphi z} & \zeta_{\varphi\varphi} \\ \zeta_{zz} & \zeta_{z\varphi} \end{bmatrix} \begin{pmatrix} h_\varphi \\ h_z \end{pmatrix}$$

Simultaneous solving of *Maxwell's* and *Landau-Lifshitz* equations :

1. Static equilibrium :  $\theta_M = (\vec{n}_z, \vec{M}_s)$  ( $H_z, H_k, H_\varphi$ )

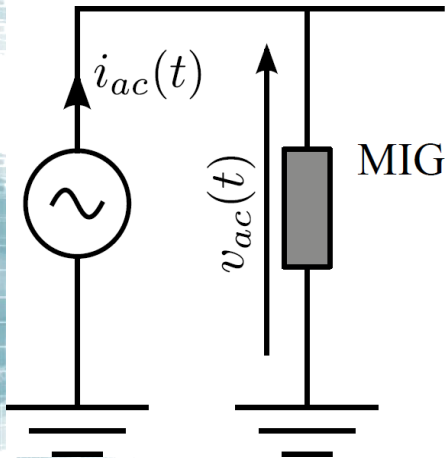
2. Solving of the linearized equations :

$$\rightarrow Z_M = k_M \rho \frac{J_0(k_M a)}{J_1(k_M a)} \text{ and } Z_N = k_N \rho \frac{J_0(k_N a)}{J_1(k_N a)}$$

$$\text{with } \begin{cases} k_M = k_N \sqrt{\frac{\mu_M}{\mu_0}} \\ k_N = \frac{1-j}{\delta_N} \\ \delta_N = \sqrt{\frac{2\rho}{\omega_p \mu_0}} \end{cases}$$

$$\begin{cases} \zeta_{zz} = Z_M \cos^2 \theta_M + Z_N \sin^2 \theta_M \\ \zeta_{\varphi\varphi} = -Z_M \sin^2 \theta_M - Z_N \cos^2 \theta_M \\ \zeta_{z\varphi} = -\zeta_{\varphi z} = (Z_M - Z_N) \sin \theta_M \cos \theta_M \end{cases}$$

# 1.2 Application to the magnetometry

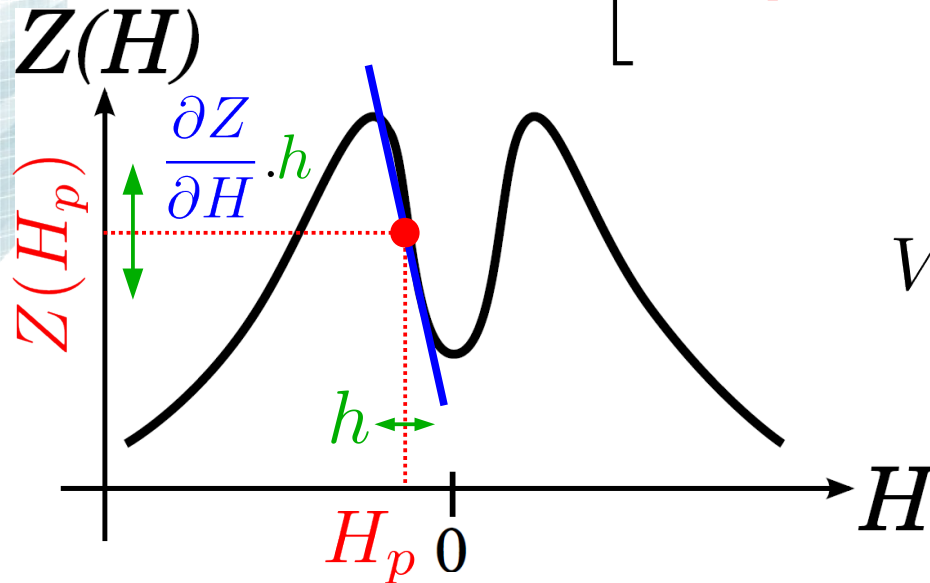


$$i_{ac}(t) = I_{ac} \sin(\omega_p t)$$

$$v_{ac}(H) = Z(H) I_{ac} \sin(\omega_p t)$$

$$Z(H) = Z(H_p) + \left. \frac{\partial Z(H)}{\partial H} \right|_{H=H_p} \cdot h$$

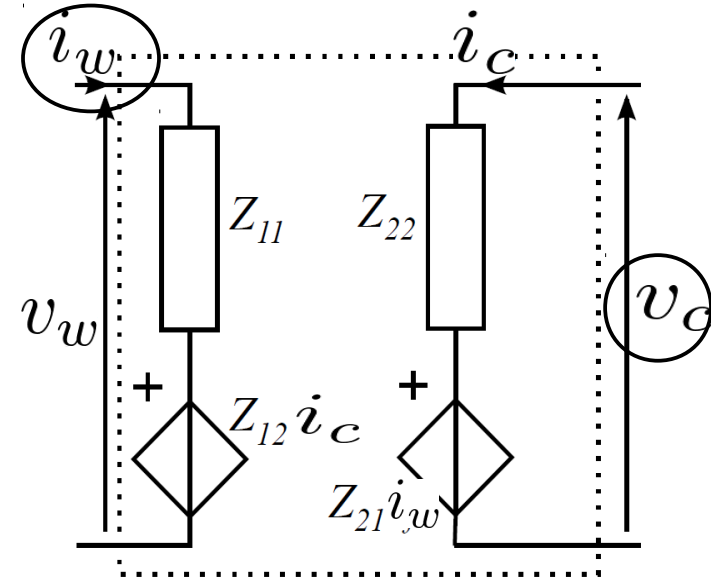
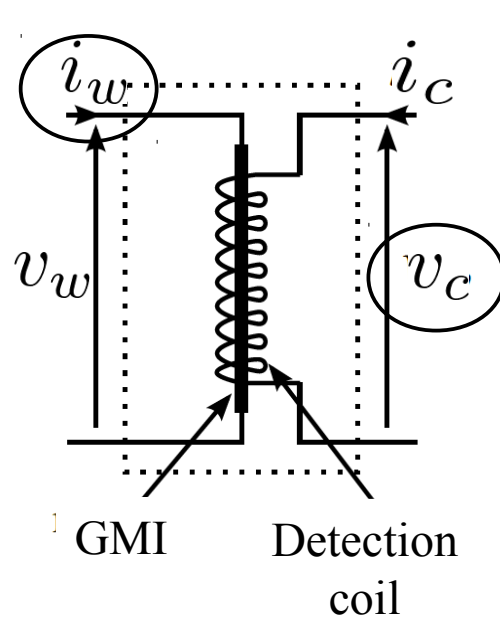
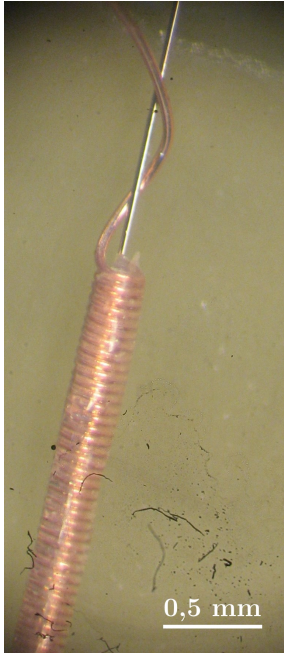
$$v_{ac}(t) = \left[ Z(H_p) + \left. \frac{\partial Z(H)}{\partial H} \right|_{H=H_p} \cdot h \right] I_{ac} \sin(\omega_p t)$$



$$(B = \mu_0 H)$$

$$V_s = G I_{ac} \left. \frac{\partial Z(B)}{\partial B} \right|_{B=B_p} \cdot b$$

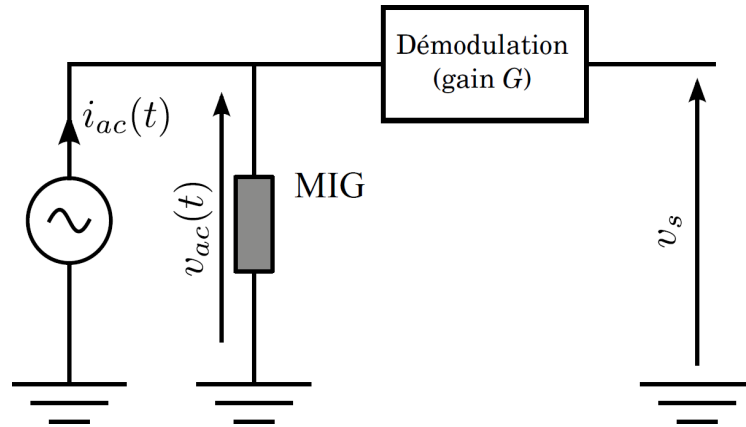
# 1.3 Two-port Network configuration



$$\begin{pmatrix} v_w \\ v_c \end{pmatrix} = \begin{pmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{pmatrix} \begin{pmatrix} i_w \\ i_c \end{pmatrix}$$

# 1.2 Application to the magnetometry

## Noise performance



$$S_v = I_{ac} S_\Omega \quad [\text{V/T}]$$

$$V_s = G I_{ac} \left. \frac{\partial Z(B)}{\partial B} \right|_{B=B_p} \cdot (b + b_{br}(t)) + e_{total}(t)$$

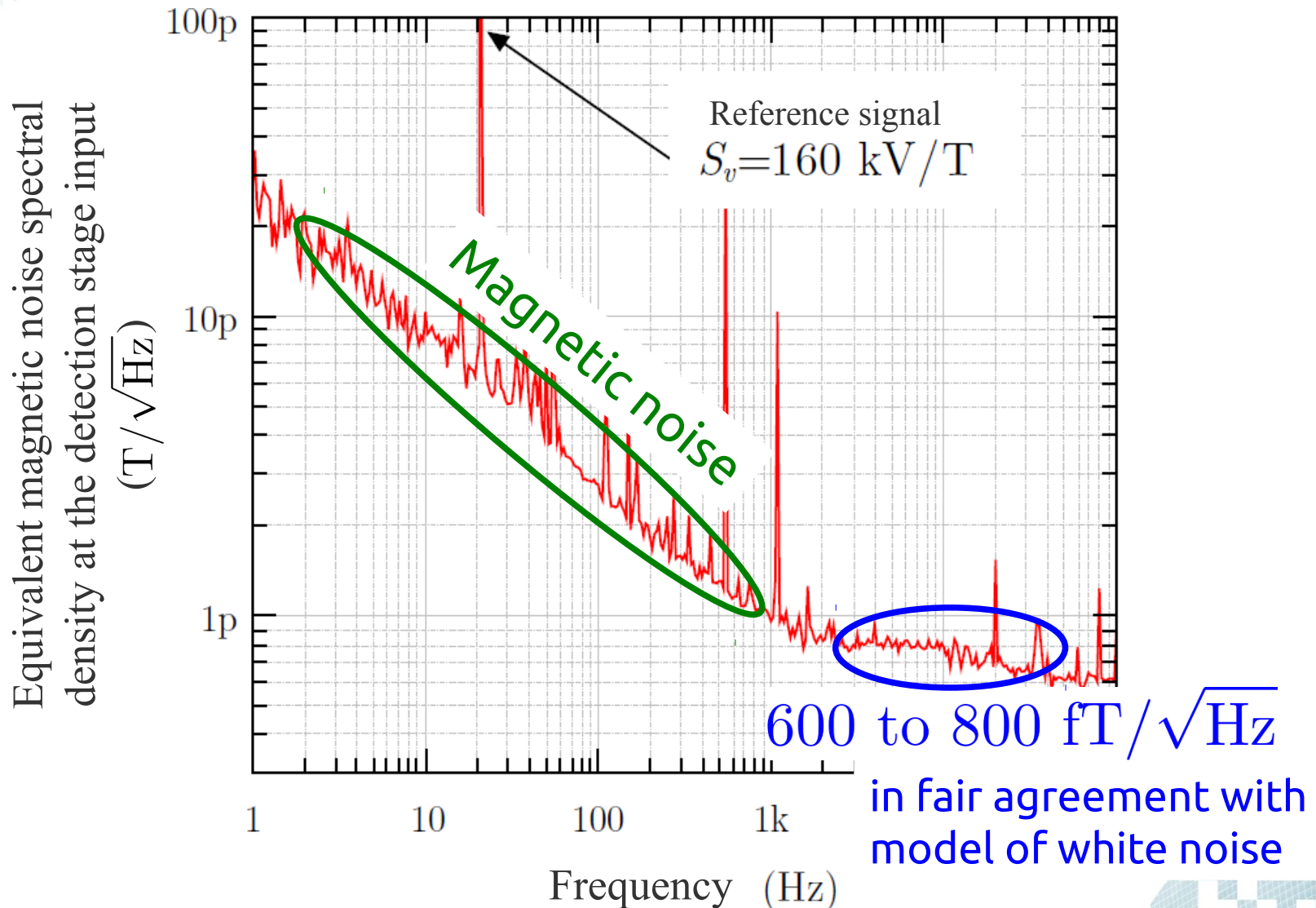
$$b_n = \sqrt{\frac{e_{n_{total}}^2}{S_v^2} + b_{n_{br}}^2}$$

10 to 100 fT/ $\sqrt{\text{Hz}}$   
in white noise region

L. Melo, et al., *Formalism to optimize magnetic noise in giant magnetoimpedance-based devices*, IEEE Transactions on Magnetics, vol. 43, no. 6, p. 29922994, 2007.

L. Melo, et al., *Optimization of the magnetic noise and sensitivity of giant magnetoimpedance sensors*, Journal of Applied Physics, vol. 103, no. 3, p. 033903033903, 2008.

# 4 Previous results ( EMSA 2012 – MO30 [1] )



[1] B. Dufay, et al., *Development of a high sensitivity GMI magnetometer: comparison with a commercial flux-gate*, IEEE Transactions on Magnetics, vol. 49, no. 1, pp. 85-88, 2013.

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# 2.1 Magnetization fluctuations

- [Z] strongly depends upon the magnetization direction  
 → Any fluctuations of  $\theta_M$  will induce an impedance variation.

$$z_{n_{ij}}^2 = \left( \frac{\partial Z_{ij}}{\partial \theta_M} \right)^2 S_{\theta_M}$$

In classical GMI ( $Z_{11}$ ):

L.G.C. Melo, et al., *Optimization of the magnetic noise and sensitivity of GMI sensors*, Journal of Applied Physics, vol. 103, no. 3, p. 033903, 2008.

$$\frac{\partial Z_{11}}{\partial \theta_M} = \frac{l}{2\pi a} Z_N \left\{ -\frac{\xi}{2M_s} \sqrt{\mu_t^3} \left[ \frac{3H_k}{2} \sin(2\theta_k - 2\theta_M) - H_{int} \cot \theta_M \right] \cos^2 \theta_M - \xi (\mu_t - 1) \sin(2\theta_M) \right\}. \quad [\text{Ohm/rad}]$$

$$S_{\theta_M} = \frac{4k_B T}{2\pi f V \mu_0 M_s^2} \chi'' \quad [\text{rad}^2/\text{Hz}]$$

C. Dolabdjian, et al., *Is low frequency Excess noise of GMI induced by magnetization fluctuations*, Key Engineering Materials, vol. 605, pp. 437-440, 2014.

- which will induce output voltage noise

$$V_s(B) = \frac{I_{ac}}{2} \left[ Z_{ij0} + \left. \frac{\partial Z_{ij}(B)}{\partial B} \right|_{B=B_0} \cdot (b(t) + b_{br}(t)) + z_n(t) \right] + e_n(t)$$

## 2.2 Extension to off-diagonal configuration

$$z_{n_{ij}}^2 = \left( \frac{\partial Z_{ij}}{\partial \theta_M} \right)^2 S_{\theta_M}$$

Does not depend upon the configuration  $ij$

1. To be numerically evaluated by differentiation from the two-port network model for the all 4 configuration cases.

→ Computation results fit with the analytical expression obtained for the  $Z_{II}$  case.

→ If the impedance fluctuation is expressed as an equivalent magnetic noise:

*noise level does not depend upon the configuration  $ij$  anymore !!*

## 2.2 Extension to off-diagonal configuration

$$z_{n_{ij}}^2 = \left( \frac{\partial Z_{ij}}{\partial \theta_M} \right)^2 S_{\theta_M}$$

Does not depend upon the configuration  $ij$

2. Express the impedance fluctuations as an equivalent magnetic noise [T/ $\sqrt{\text{Hz}}$ ]:

$$b_{n_{LF}} = z_{n_{ij}} \left( \frac{\partial Z_{ij}}{\partial B} \right)^{-1}$$

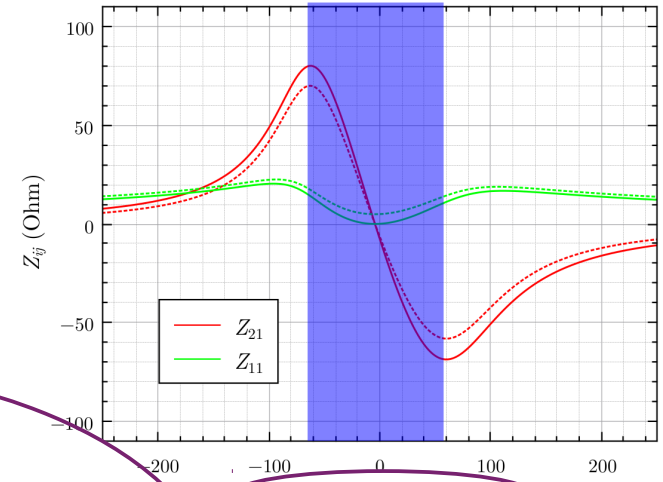
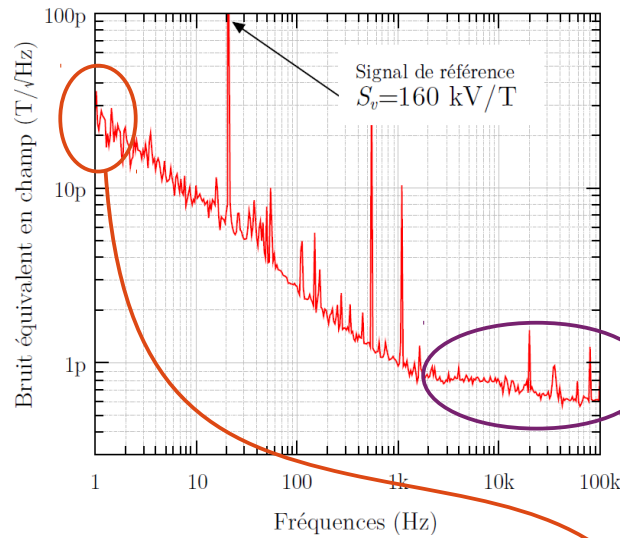
→ Analytical expression which:

- Does not depend upon the configuration  $ij$  anymore.
- Only relies upon the static magnetization direction.
- Depicts an  $1/f$  behavior

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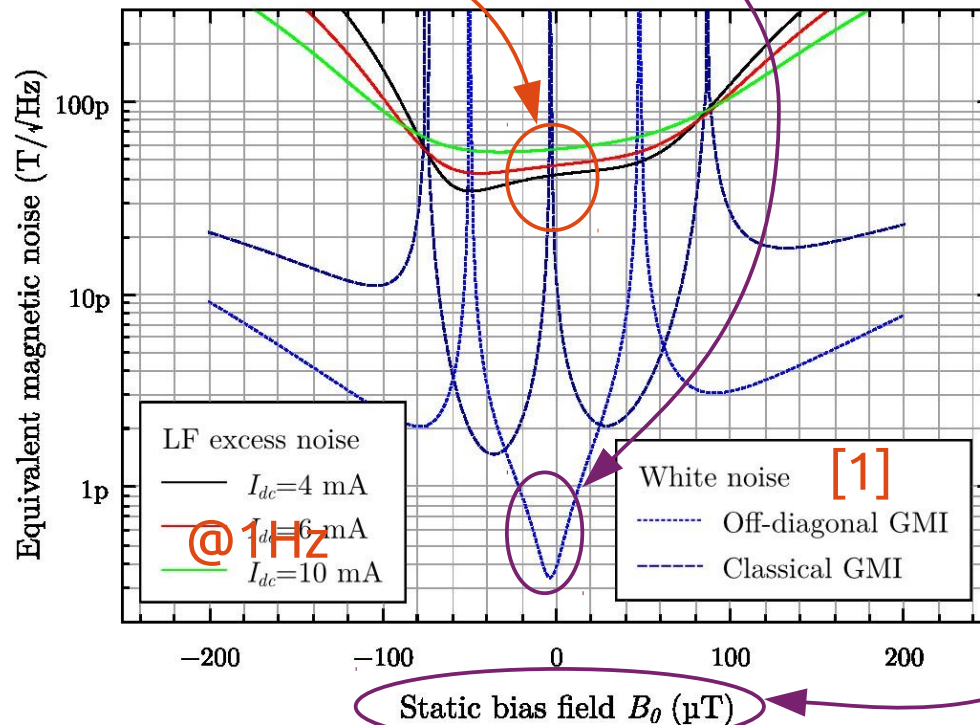
# 3.1 Results



$\chi''$  linked with hysteresis area of magnetization loop.

→ Worst case :  $\chi'' \approx \frac{M_s}{H_k}$

Low frequency excess noise level is the same in all  $ij$  configurations  
 → may appears only in cases for which the electronic white noise is low enough.



[1] B. Dufay, et al., Characterization of an optimized off-diagonal GMI-based magnetometer, IEEE Sensors Journal, vol. 13, no. 1, pp. 379-388, 2013.

## 3.2 Discussion

Worst case:  $\chi'' \approx \frac{M_s}{H_k} \approx 10^4$

→ Linked to losses in the magnetic material which may depends upon :

- Excitation current frequency
- Excitation current amplitude
- DC bias current value

Coherent with some other experimental results (M. Butta *et al.*).

→ Modelization of  $\chi''$  is under investigation.

Based on modelization of non-linear GMI effect (D. Seddaoui *et al.*).

