Evidence for a Magnetic Seebeck Effect

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SWISS CONTRIBUTION

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Outline

1. **Theory :** Irreversible thermodynamics of a continuous medium with magnetisation
2. **Experiment :** YIG slab excited at 4 GHz

Irreversible thermodynamics of electron continua

Linear relation : (Eur. Phys. J. B 86, 318 (2013))

- $\mathbf{j}_e = \mathsf{L}_{es} \cdot (-\boldsymbol{\nabla}\, T) + \mathsf{L}_{ee} \cdot (-\boldsymbol{\nabla}\, \mu - \, e\, \boldsymbol{\nabla}\, V + \mathbf{m}\, \boldsymbol{\nabla}\, \mathbf{B})$

Material : YIG (insulator)

- $\mathbf{j}_e = \mathbf{0}$ (no electronic transport)
- $\boldsymbol{\nabla}\, V = \mathbf{0}$ (no charge accumulation)
- $\boldsymbol{\nabla}\, \mu = \mathbf{0}$ (uniform spatial distribution)

Stationary state :

- $\mathbf{M}\, \boldsymbol{\nabla}\, \mathbf{B} = \lambda\, n\, k_B\, \boldsymbol{\nabla}\, T$ *where* $\mathbf{M} = n\, \mathbf{m}$ *and* $\lambda > 0$

Bulk identity :

- $\mathbf{M}\,\nabla\,\mathbf{B} = \mathbf{j_M} \times \mathbf{B}$ where $\mathbf{j_M} = \nabla \times \mathbf{M}$

Magnetic Seebeck effect

- $\mathbf{B} = \varepsilon_{\mathbf{M}} \times \nabla\, T$ where $\varepsilon_{\mathbf{M}} = -\,\lambda\, n\, k_B\, (\nabla \times \mathbf{M})^{-1}$

Linear response (to RF excitation field)

Linearisation :

- $\mathbf{B}_{\text{ext}} = \mathbf{B}_0 + \mathbf{b}$
- $\mathbf{M} = \mathbf{M}_S + \mathbf{m}$ where $\mathbf{m} \ll \mathbf{M}_S$

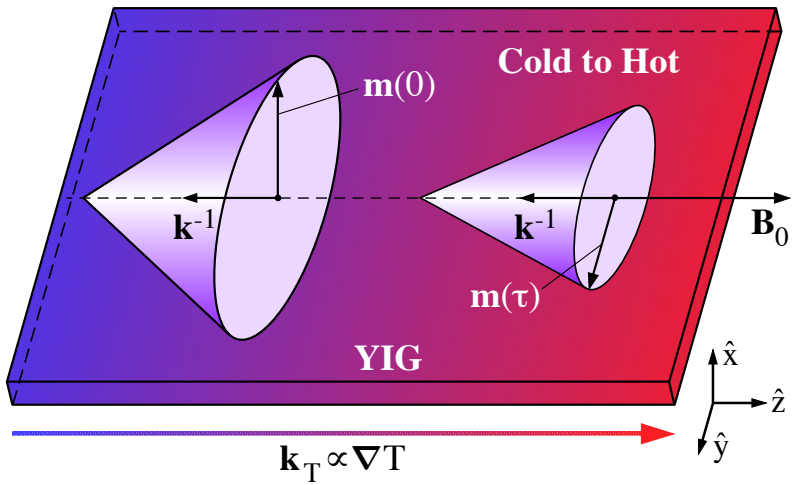
Eigenmodes :

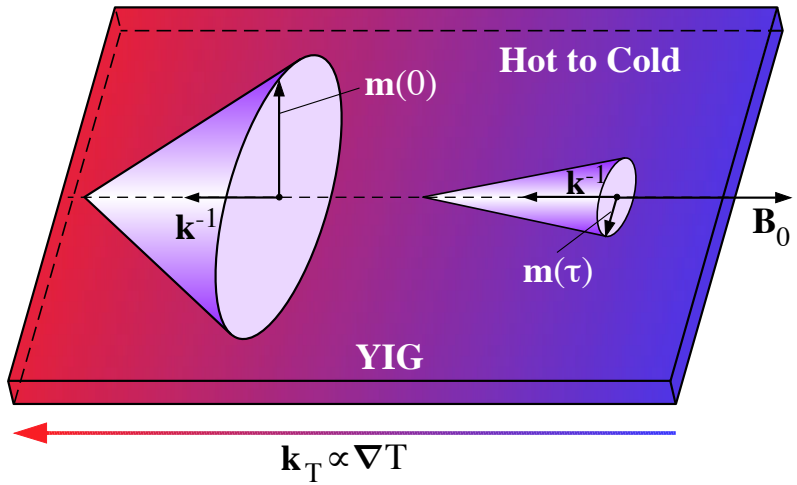
- $\mathbf{m}_{\mathbf{k}x,y} = \chi_{\mathbf{k}x,y}\, \mathbf{b}_{\mathbf{k}}$
- $$\chi_{\mathbf{k}x,y} = -\frac{1}{\Omega - \sqrt{\Omega_0\,(\Omega_0+1)} + i\, r_{x,y}\left(\alpha\,\Omega + \mathbf{k}_T \cdot \mathbf{k}^{-1}\right)}$$

$$\Omega = \frac{\omega}{\gamma\,\mu_0\,M_S}, \qquad \Omega_0 = \frac{\gamma\,B_0}{\gamma\,\mu_0\,M_S}, \qquad \mathbf{k}_T = \frac{\lambda\,n\,k_B}{\mu_0\,M_S^2}\,\boldsymbol{\nabla}\,T$$

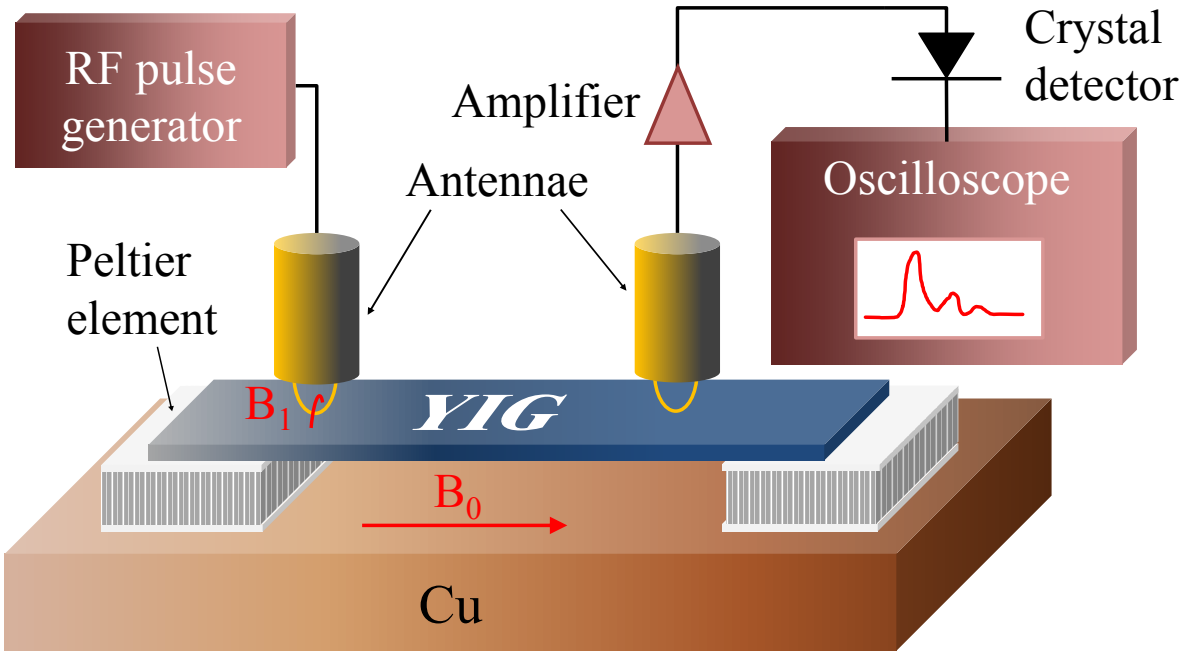
Magnetisation waves propagation (YIG) :

- Magnetostatic backward volume modes
- **Cold to Hot** : negative thermal damping ($\mathbf{k}_T \cdot \mathbf{k}^{-1} < 0$)
- **Hot to Cold** : positive thermal damping ($\mathbf{k}_T \cdot \mathbf{k}^{-1} > 0$)



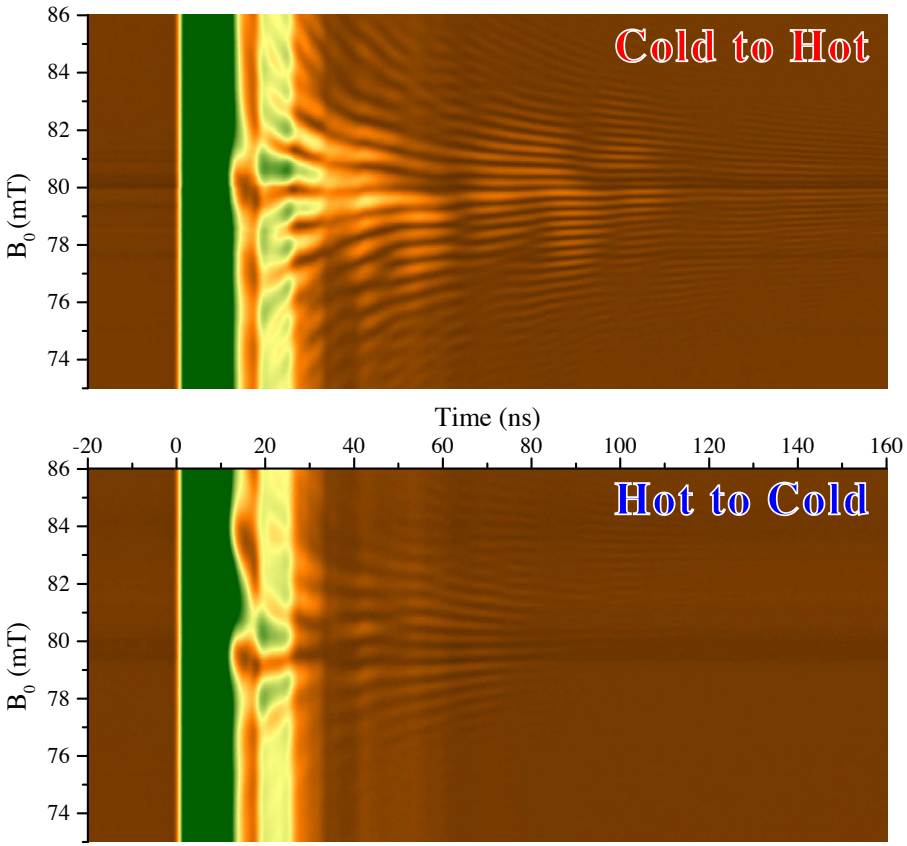


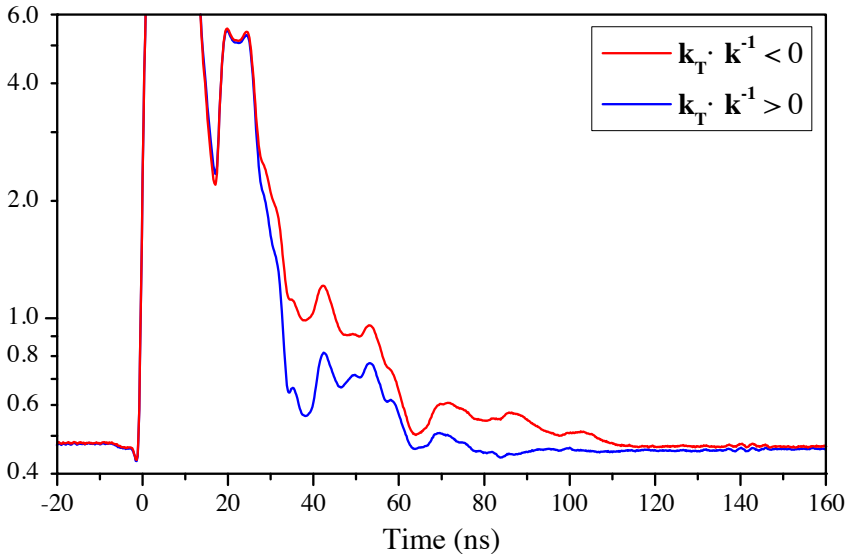
Transmission measurement of magnetisation waves

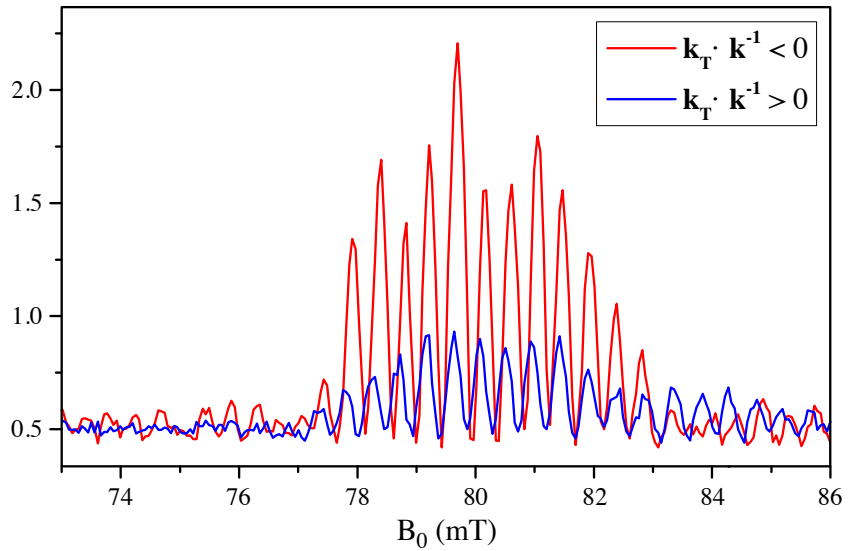


- Excitation frequency : 4 GHz
- Distance between antennae : 8 mm
- Thickness : 25 μm
- Temperature gradient : 20 K/cm

Magnetic Seebeck Effect (YIG slab at 4 GHz)

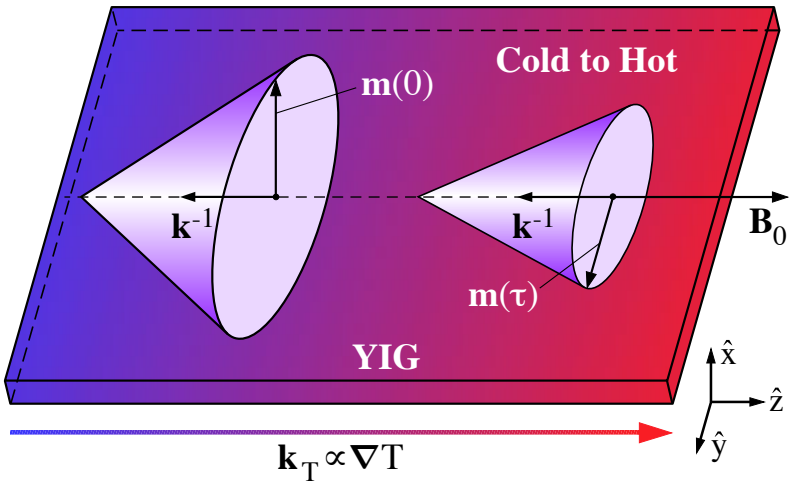


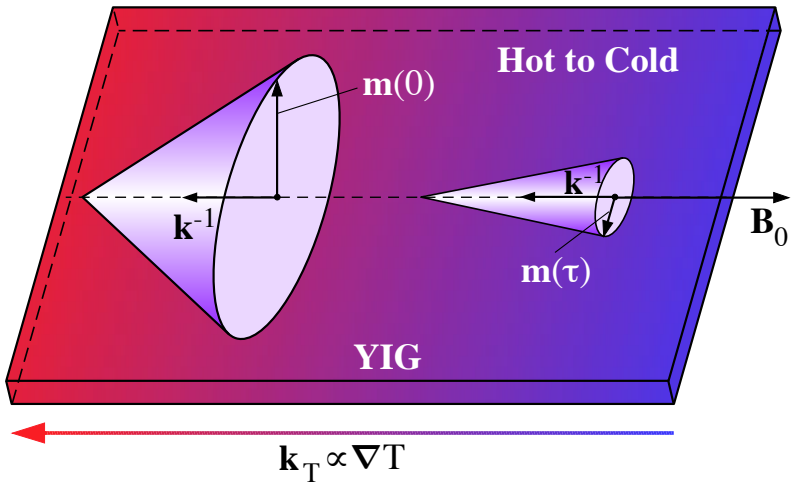




Evidence for a Magnetic Seebeck Effect

- Propagation of magnetisation waves from cold to hot
  $\Rightarrow$ **less attenuation**
- Propagation of magnetisation waves from hot to cold
  $\Rightarrow$ **more attenuation**
- Effect on propagation of magnetisation waves $\propto \mathbf{k}^{-1}$





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