Ultrafast spin dynamics in ferromagnetic films

Vlasovia 2016

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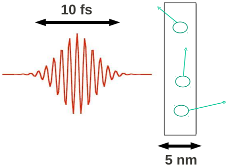
Outlines

Introduction: Motivations

- Theoretical aspect :
  - Ultrafast ($\sim 100\ fs = 10^{-13}\ s$) magnetization dynamics at the nanometric scale
  - Spin and relativistic effects (Zeeman + Spin-orbit coupling)
  - Non linear effects
  - Mean field model



- Experimental aspect :
  - Ultrafast demagnetization in ferromagnetic films induced by a femtosecond laser pulse : (E. Beaurepaire et al. Phys. Rev. Lett. 76, 4250 1996)

Introduction: Description of the system

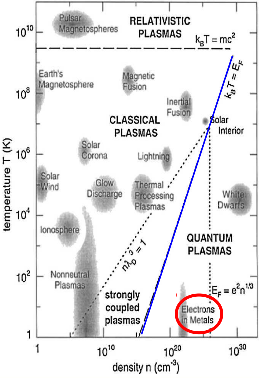
Thin ferromagnetic films of Nickel : L = $5 - 20$ nm (1D problem)

Two types of charges: electrons & ions :

	Electrons	Ions
Charge	-e	+2e
Density (10^{29}m^{-3})	1.8	0.9
Temperature (K)	300	300
mass (a.u)	1	$1.1 * 10^5$
$\omega_p^{-1}(fs)$	0.25	330
Magnetic moment (μ_b)	0.066	0.54

Ultrafast dynamics ($\sim$ 100fs) $\rightarrow$ Ions fixed $(1fs = 10^{-15}s)$

Electrons $\leftrightarrow$ Quantum plasmas



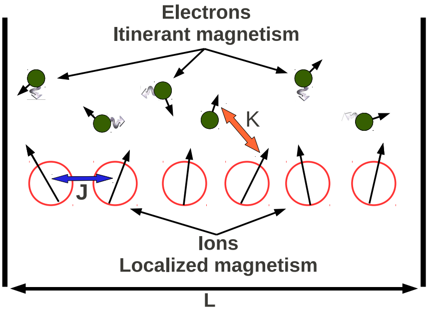
Shukla and Eliasson, Rev. Mod. Phys., 2011

Introduction: Description of the system

Interactions:

- Coulomb
- Magnetic exchange ions-ions (J)
- Magnetic exchange ions-electrons (K)

Effective magnetic field (100 - 1000 Tesla)



Introduction: Wigner and Vlasov equations

Phase-space quantum mechanics (Equivalent to Schrödinger)

Wigner without spins:

$$\frac{\partial f}{\partial t} + v\frac{\partial f}{\partial x} = \frac{ime}{2\pi\hbar^2}\int ds\, dv' e^{-im\left(v'-v\right)s/\hbar}\left[V_H\left(x+\frac{s}{2},t\right) - V_H\left(x-\frac{s}{2},t\right)\right] f\left(x,v',t\right)$$

$$\nabla^2 V_H = \frac{e}{\epsilon_0}\left(\int f\left(x,v,t\right) dv - n_i\right)$$

Semi-classical limit $\left(\frac{\hbar}{m\langle v\rangle_e} << L\right) \rightarrow$ Vlasov equation :

$$\frac{\partial f}{\partial t} + v\,\partial_x f + \frac{e}{m}\partial_x V_H \cdot \partial_v f = 0$$

Wigner function with spin

Generalisation of the Wigner function :

$$f(\boldsymbol{r}, \boldsymbol{v}, t) \rightarrow \mathcal{F}(\boldsymbol{r}, \boldsymbol{v}, t) \qquad \mathcal{F} = \begin{pmatrix} f^{\uparrow\uparrow} & f^{\uparrow\downarrow} \\ f^{\downarrow\uparrow} & f^{\downarrow\downarrow} \end{pmatrix}$$

Projection onto the Pauli matices:

$$\mathcal{F} = \frac{1}{2}\sigma_0 f_0 + \frac{1}{\hbar}\boldsymbol{f} \cdot \boldsymbol{\sigma}$$

with

$$f_0 = \mathrm{tr}\left\{\mathcal{F}\right\} = f^{\uparrow\uparrow} + f^{\downarrow\downarrow} \qquad \boldsymbol{f} = \frac{\hbar}{2}\mathrm{tr}\left(\mathcal{F}\boldsymbol{\sigma}\right)$$

Physical observable : $i, \alpha = \{x, y, z\}$

$$n(\boldsymbol{r}, t) = \int f_0(\boldsymbol{r}, \boldsymbol{v}, t) d\boldsymbol{v} \qquad m_i(\boldsymbol{r}, t) = \int f_i(\boldsymbol{r}, \boldsymbol{v}, t) d\boldsymbol{v}$$

$$J_i(\boldsymbol{r}, t) = \int v_i \; f_0(\boldsymbol{r}, \boldsymbol{v}, t) d\boldsymbol{v} \qquad J^s_{i\alpha}(\boldsymbol{r}, t) = \int v_i \; f_\alpha(\boldsymbol{r}, \boldsymbol{v}, t) d\boldsymbol{v}$$

Vlasov with spin

Zeeman + Spin-orbit hamiltonian :

$$\mathcal{H} = \left[\frac{(P+e\boldsymbol{A})^2}{2m} + V(\boldsymbol{r},t)\right]\sigma_0 + \mu_B \boldsymbol{\sigma}\cdot\boldsymbol{B}(\boldsymbol{r},t) + \frac{\mu_B}{8mc^2}\boldsymbol{\sigma}\cdot\left[\boldsymbol{E}\times(\boldsymbol{p}+e\boldsymbol{A}) - (\boldsymbol{p}+e\boldsymbol{A})\times\boldsymbol{E}\right]$$

Wigner + semi-classical limit $\qquad i = \{x,y,z\}$

$$\frac{\partial f_0}{\partial t} + \boldsymbol{v}\cdot\nabla f_0 - \frac{e}{m}(\boldsymbol{E}+\boldsymbol{v}\times\boldsymbol{B})\cdot\nabla_{\boldsymbol{v}} f_0 + \frac{\mu_B}{2mc^2}(\boldsymbol{E}\times\nabla)_i f_i - \frac{\mu_B}{m}\nabla\left[B_i - \left(\frac{\boldsymbol{v}\times\boldsymbol{E}}{2c^2}\right)_i\right]\cdot\nabla_{\boldsymbol{v}} f_i - \frac{\mu_B e}{2m^2c^2}\left[\boldsymbol{E}\times(\boldsymbol{B}\times\nabla_{\boldsymbol{v}})\right]_i f_i = 0$$

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Maxwell equations

Maxwell equations with spin corrections

$$\nabla \cdot \boldsymbol{E} = \frac{\rho}{\epsilon_0} - \frac{\nabla \cdot \boldsymbol{P}}{\epsilon_0}$$

$$\nabla \cdot \boldsymbol{B} = 0$$

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$$

$$\nabla \times \boldsymbol{B} = \mu_0 \boldsymbol{j} + \mu_0 \epsilon_0 \frac{\partial \boldsymbol{E}}{\partial t} + \mu_0 \frac{\partial \boldsymbol{P}}{\partial t} + \mu_0 \nabla \times \boldsymbol{M}$$

Source terms depend on the spin (Semi-relativistic expansion)

$$\rho = -e \int f_0 d\boldsymbol{v}, \qquad \boldsymbol{j} = -e \left[\int \boldsymbol{v} f_0 d\boldsymbol{v} + \frac{\boldsymbol{E} \times \boldsymbol{M}}{2mc^2} \right]$$

$$\boldsymbol{M} = -\mu_B \int \boldsymbol{f} d\boldsymbol{v}, \qquad \boldsymbol{P} = -\frac{\mu_B}{2c^2} \int \boldsymbol{v} \times \boldsymbol{f} d\boldsymbol{v}$$

A Dixit, Y. Hinschberger, J. Zamanian, G. Manfredi, et P.-A Hervieux, Phys. Rev. A 88, 032117 (2013).

Minimal self consistent model

1d-1v distribution function $(x, v_x) \rightarrow$ (no spin-orbite)

$$\frac{\partial f_0}{\partial t} + v\ \partial_x f_0 + \frac{e}{m}\left(\partial_x \phi\right)\left(\partial_v f_0\right) - \frac{\mu_b}{m}\partial_x\left(B_i - \frac{K n_i S_0}{2\mu_b} S_i\right)\partial_v f_i = 0$$

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$$- \frac{K N_0 S_0}{\hbar}\left\{\boldsymbol{f} \times \boldsymbol{S}\right\}_i - \frac{2\mu_B}{\hbar}\left\{\boldsymbol{B} \times \boldsymbol{f}\right\}_i = 0$$

$+$ Electrostatic limit of Maxwell equations : $\quad i = \{x, y, z\}$

$$\frac{\partial^2 \phi}{\partial x^2} = \frac{e}{\epsilon_0}\left(n(x) - n_{ions}\right) \quad \frac{\partial B_i}{\partial x} = -\mu_B \mu_0 \frac{\partial}{\partial x} m_i(x) \quad n = \int f_0 dv \quad m_i = \int f_i dv$$

Landau Lifchitz Gilbert (LLG) equation for the magnetic moment of ions :

$$\frac{\partial \boldsymbol{S}(x)}{\partial t} = \frac{a^2 J S_0}{\hbar}\left[\boldsymbol{S}(x) \times \frac{\partial^2}{\partial x^2}\boldsymbol{S}(x)\right] + \frac{K}{2\hbar}\left[\boldsymbol{S} \times \int \boldsymbol{f}\, d\boldsymbol{v}\right] - \gamma \boldsymbol{S} \times \boldsymbol{B}_{ext}$$

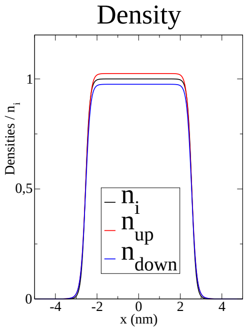
Ground state : Thin film of Nickel

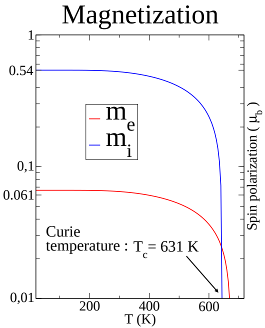
Collinear magnetism + Pauli exclusion principle :

$f_0^{ground} = \mathcal{F_D}^+ + \mathcal{F_D}^-, \; f_z^{ground} = \mathcal{F_D}^+ - \mathcal{F_D}^-$

$$\mathcal{F_D}^{\pm} = \frac{2\pi k_b T}{m}\left(\frac{m}{2\pi\hbar}\right) \ln\left[1 + \exp\left(-\frac{1}{k_b T}\left(\frac{m}{2}v^2 - e\phi \pm \mu_B B_z - \mu(T)\right)\right)\right]$$

Ions : $\langle \boldsymbol{S} \rangle = S\mathcal{B}_S\left(\beta S h_{eff}\right), \quad h_{eff} = \frac{K}{2} m_e(\boldsymbol{r}) + JN_v\langle \boldsymbol{S} \rangle + g\mu_B \boldsymbol{H}$





Linear regime : Film of Nickel ($\sim$ 5nm)

Laser Excitation : $E(t) = E_0 \sin(\omega t)\, e^{-[(t-t_0)/\Delta t]^2}$ $E_0 \sim 10^8 V/m$

Two modes : Plasmon $\omega_p = \sqrt{e^2 n/m\epsilon_0}$ & Ballistic $\omega_b = (2L/v_F)^{-1}$

Observable : $\mathrm{D}_{electric} = \int x\ f_0 dxdv$; $\mathrm{D}_{magnetic} = \int x\ f_z dxdv$

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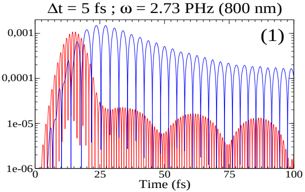

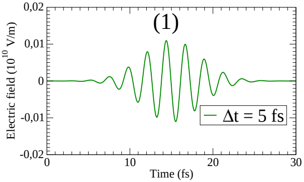

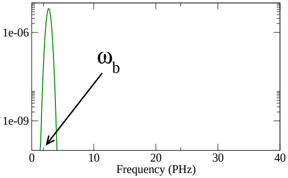

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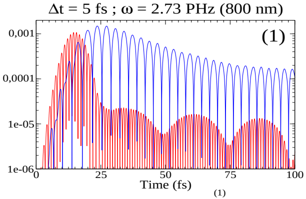
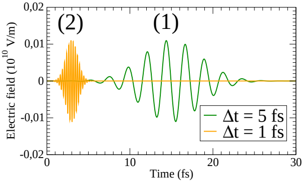
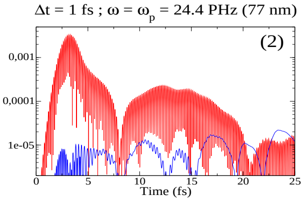
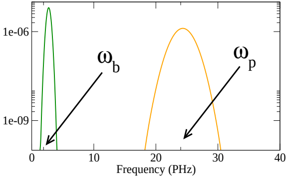
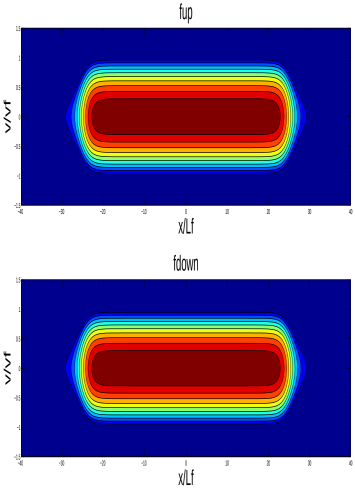


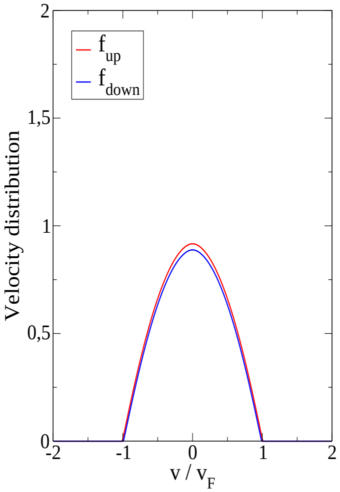






Initial distribution function : Water bag model





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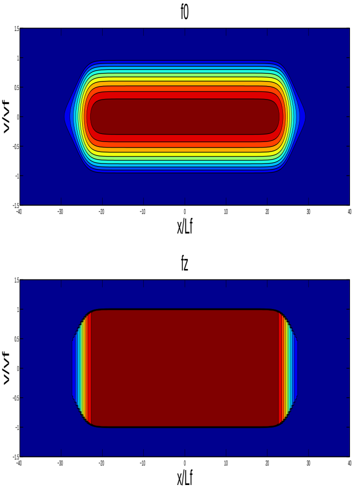
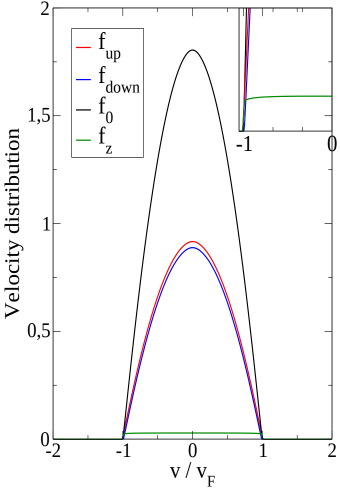




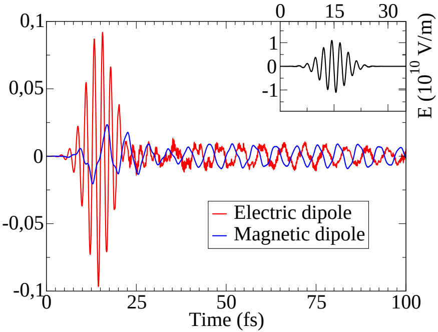
Non linear regime

$$E(t) = E_0 \sin(\omega t) \exp\left(-[(t-t_0)/\Delta t]^2\right)$$

$E_0 \sim 1.1\ 10^{10}\, V/m$; $\Delta_t = 5\text{fs}$; $\omega = 2.73$ PHz (800 nm)

Plasmon mode $\rightarrow$ Non linear effects

The magnetic dipole remains



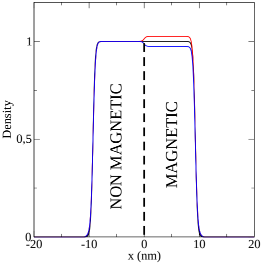
Conclusions and future investigations

Conclusions :

- We built a self consistant model to study ultrafast magnetization dynamics in thin ferromagnetic films
- We show the existence of an oscillating magnetic dipole at ultra high frequency (PHz) NEW

Futur investigations:

- Non collinear dynamics
- Non magnetic/magnetic bilayers
- Extension to 4D (Spin orbite)



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