Micromagnetic modelling and simulation of inertial magnetization dynamics in ferromagnets

M. d'Aquino[1*]

[1]University of Naples Federico II, Department of Electrical Engineering and ICT, 80125, Naples (Italy)
*mdaquino@unina.it

The study of ultra-fast magnetization processes is of utmost importance for the development of future generations of nanomagnetic and spintronic devices[1]. In the last decades, after the pioneering experiment[2] revealing subpicosecond spin dynamics, the investigation of ultra-fast magnetization processes has increasingly stimulated the production of considerable research. The advent of intense high-frequency magnetic field sources has recently allowed for the direct experimental detection of terahertz spin nutation in ferromagnets[3] confirming the presence of inertial effects in magnetization dynamics theoretically predicted several years ago[4].
From the theoretical point of view, inertial magnetization dynamics can be modelled by augmenting the classical Landau-Lifshitz-Gilbert (LLG) precessional dynamics with a torque term taking into account angular momentum relaxation[3,4] proportional to the second time-derivative of magnetization. When extended to spatially-inhomogenous ferromagnets, such a torque transforms the classical LLG equation into a wave-like equation, termed inertial LLG (iLLG), which gives rise to dynamical phenomena significantly deviating from those described by classical precessional LLG dynamics, such as propagation of inertial spin waves oscillating at terahertz frequency in nano- and micro-scale samples.

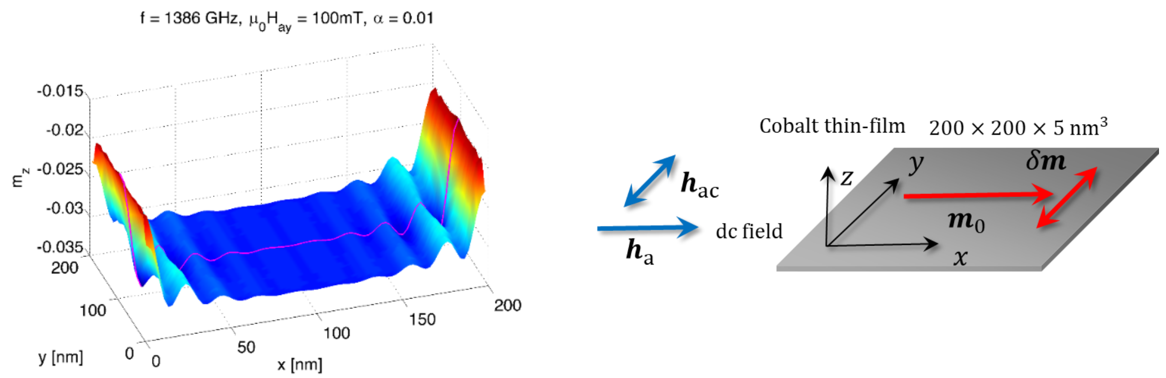

Figure 1. Snapshot of steady-state out-of-plane ac magnetization response (normalized by saturation magnetization) at driving frequency f = 1386 GHz for a Cobalt square nanodot. The color code represents the value of out-of-plane magnetization at each spatial location, ranging from minimum (blue) to maximum (red).

In this presentation, the general qualitative properties of the iLLG dynamics are derived and discussed evidencing the profound differences from the classical LLG despite including remarkably similar conservation properties[5]. These properties are also exploited to design time-integration schemes for the iLLG dynamics that allow to realize accurate and efficient inertial micromagnetic simulations.
By combining analytical theory and full micromagnetic simulations of iLLG dynamics, we analyze the possibility to excite ultra-short inertial spin waves (see Fig. 1) that propagate in confined ferromagnetic nanodots[6] driven by the action of terahertz fields with amplitude similar to those achievable with state-of-the art terahertz experimental setups.

References

[1] B. Dieny et al., *Nature Electronics*, **2020**, *3*, 446.
[2] E. Beaurepaire et al., *Physical Review Letters*, **1996**, *76*, 4250.
[3] K. Neeraj et al., *Nature Physics*, **2021**, *17*, 245.
[4] M.-C. Ciornei et al., *Physical Review B*, **2011**, *83*, 020410.
[5] M. d'Aquino et al., *J. Comput. Phys.*, **2024**, *504*, 112874.
[6] M. d'Aquino et al., *Physical Review B*, **2023**, *107 (14)*, 144412.