Thesis subject

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Subject's title: **Highly magnetized plasmas through classical Molecular Dynamics**

The modeling of radiative properties of plasmas is a constantly evolving field of research. The presence of strong magnetic fields, in astrophysical plasmas (Sun, white dwarfs) and in laboratory plasmas, brings new challenges to this topic. Strong magnetic fields are generated in magnetic confinement fusion experiments (MCF) or Z-pinch machines. In the context of inertial confinement fusion (ICF), plasma magnetization is a promising way to achieve ignition. Different experimental schemes are developed in the ICF community such as the MagLIF method (magnetized liner inertial fusion), which consists in generating strong magnetic fields by preheating the plasma created in the Z-pinch. In imploding magnetized targets, intense laser beams are used to irradiate a target subjected to a static magnetic field of around one hundred teslas. The target's implosion also compresses the magnetic field (which then amounts to several kilo-teslas) at the tracer. The analysis of the X-rays produced in these experiments makes it possible to characterize the plasma, [Santos2018]. These developments require the development of kinetic, hydrodynamic, atomic physics and line-shape models coupled to radiation transport modeling for the synthesis of spectra in high energy density (HED) plasmas.

In this context, we are developing models and numerical simulations dedicated to the study of the radiative properties of such extreme plasmas. We are partner in a French and International consortium for the development of novel experimental and simulation platforms for studying fundamental properties and transport mechanisms of magnetized high energy-density (HED) plasmas. This research involves multiple collaborations with experimental and theoretical teams specialized in plasma spectroscopy, atomic physics and radiation transport.

The presence of strong B-fields may have different effects on the plasma radiative properties and sustains the interest for atomic physics developments in such extreme conditions: (i) Due to the atomic magnetic moment, the external B-fields interact with plasma emitters, resulting in a splitting of atomic energy levels and thus, in a splitting and polarization of the spectral lines (Zeeman effect). (ii) Due to the bending of the charged particles into helical paths around the B-lines of force, introducing resonance at the cyclotron frequency, it affects the plasma structure and dynamic statistical properties, such as the high- and low-frequency micro-field distribution functions or the dielectric properties.

In dense plasmas, the Stark effect, produced by the interaction of the electric dipole of the emitter with electronic and ionic electric micro-fields, created locally by the plasma charges, may govern the line shape. It is a computationally challenging contribution to the line broadening because the stochastic electric perturbation needs to be modelled over different time-scales, depending on the emitters' response to the electronic and ionic perturbations. In the presence of B-fields, the calculations of the combined Stark and Zeeman effects reaches a higher step of complexity. Different line shape models have been developed or extended to magnetized plasmas. Most of them are based on simplifying assumptions depending on the relative importance of the Stark and Zeeman effects. As for example, our Stark-Zeeman Stark-Zeeman line shape code, PPPB [Ferri2011], is based on the APEX electric micro-field model [Iglesias2000] and on a semi-classical impact collisional electron operator including strong collisions and interference terms, [Sobelman1972, Griem1979]. None of these models account for the anisotropy effects and the helical trajectories caused by the B-fields, that could be important to consider.

We aim to extend the BinGo code, [Talin 2003], a classical Molecular Dynamics technique (MD) developed and maintain in our group, to highly magnetized plasmas in order to study the effect of a static B-field on their structure and dynamic statistical properties.

Classical MD provides trajectories in the phase space of interacting particles, allowing one to follow the evolution of particles positions and velocities necessary to evaluate the static or dynamic statistical plasma properties. This technique is well appropriate to provide time-dependent micro-field histories at emitters that can be used for plasma spectroscopy purposes. They can be used directly in a step-by-step integration of the Schrödinger equation, providing benchmark spectral line shapes. Their statistical analysis can also provide benchmark field distribution functions to be used for the development of micro-field models required in line shape codes. Thus, the introduction of B-field effects in MD will permit to investigate the anisotropy and screening effects on the micro-fields properties in order to improve the corresponding models in line shape codes.

Moreover, having access to the trajectories, the free electron dynamic structure factors (DSF) can be evaluated through the MD, [Calisti2014]. DSF are the basic input for the Thomson scattering cross-section calculations able to reveal density fluctuations on the wavelength scale of the scattered photons. Thomson scattering spectra were recently calculated for magnetized dense plasmas, predicting many peak features linked to the sound speed and the B-field [Bott2019]. Experimentally, such kind of spectra were measured in the visible range in the 1970's [Evans1970], showing evidence of ion features modulation at the electron gyrofrequency. Linking the calculations to the spectrally-resolved X-ray Thomson scattering measurements could be a possible way of extracting the plasma-embedded B-fields.

The first part of the PhD work will be devoted to the implementation of static magnetic field into our classical molecular dynamics simulation. The numerical development will be then applied to the study of the influence of bending trajectories on the plasmas structure and dynamic statistical properties. For simplicity sake, the investigation of the influence of bending trajectories on the statistical properties (dynamic structure factors, transport coefficients, etc.) will first be performed on a One Component Plasma (Yukawa model). This technique will then be applied to the simulation of an ionic impurity in electron magnetized plasma in order to investigate electrons non-linear dynamics around the impurity, screening effects, electronic micro-field distribution. In a third step, the B-field influence on the particle coupling effects will be assessed by the BinGo-TCP code [Calisti2011] (models a neutral two-component plasma of interacting ions and electrons via a regularized potential at short distance that avoids Coulomb collapse and accounts for some quantum effects). All these developments and results will be compared to theoretical developments and experimental observations if exist.

For a successful implementation of this theoretical and numerical project, we are looking forward a phD student interested in plasma physics, atomic physics and plasma spectroscopy. Programming skills relevant for numerical calculations (in Fortran, C, or C++) are more than welcomed.

Bibliography:

[Bott2019] *Thomson scattering cross section in a magnetized* high-density plasma, Phys. Rev. E 99, 063204 (2019).

[Calisti2014] *Warm dense matter through classical molecular dynamics*, High Energy Density Phys. 13, 1 (2014).

[Evans1970] *Measurement of magnetic field in a laboratory plasma by Thomson scattering of laser light*, Phys. Rev. Lett. 25, 1605 (1970).

[Ferri:2011] *The Frequency Fluctuation Model applied to Stark-Zeeman spectral line shapes in plasmas*, Phys. Rev. E 84, 026407 (2011).

[Griem1979] *Stark-profile calculations for Lyman-series lines of one-electron ions in dense plasmas*, Phys. Rev. A 19, 2421 (1979).

[Santos2018] *Laser-driven strong magnetostatic fields with applications to charged beam transport and magnetized high energy-density physics*, Phys. Plasmas **25**, 056705 (2018).

[Iglesias2000] *Fast electric microfield distribution calculations in extreme matter conditions*, J. Quant. Spect. Radiat. Transfer 65, 303 (2000).

[Sobelman1972] *Excitation of Atoms and Broadening of Spectral Lines*. Springer-Verlag, Berlin, 1980, V.I. 1972.

[Talin2003] *Molecular dynamics simulation for modelling plasma spectroscopy*, J. Phys. A Math. Gen. 36, 6049 (2003).