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Collective Effect of Radiation Friction in Laser-Driven Hole Boring of Dense Plasma Targets

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We aim at numerically modelling classical and quantum dynamics of charged particles and electromagnetic fields under conditions realised in the interaction of superintense laser pulses with various types of massive targets. The focus of our research is put on an interaction regime where the particles' dynamics and their radiation emission exert a strong mutual influence on each other. This interaction regime is referred to in the modern research literature as the radiation-dominated regime and attracts a constantly growing interest in connection with the soon expected increase of the record intensities available in laser laboratories. Laser sources of the next generation including the Extreme Light Infrastructure (ELI) pillars in the Czech Republic, Hungary and Romania, the Apollon laser in France and several other facilities, providing laser powers up to 10 Petawatt are expected to raise the available intensity by two orders of magnitude putting first laboratory experiments in the radiation-dominated regime within reach.

1 Introduction

Advanced, predictive numerical simulations are an essential tool both to interpret current experiments and to give directions for the design and performance of facilities under development. In a strong connection with the proposal, design and interpretation of experiments, our project focuses on the newly emerged topic of laser-plasmas in the radiation-dominated regime (RDR). Here we refer to the RDR having in mind any interaction setup where radiation of quanta by elementary particles significantly affects their individual or/and collective dynamics. Apparently this distortion of particle's dynamics influences the process of radiation itself, making the whole problem self-consistent and, due to the extreme intensities of the applied laser fields, highly nonlinear and even nonperturbative. For many years, the theoretical studies of elementary particles and plasma strongly coupled to their radiation were separated from possible experimental verifications by a huge gap in laser intensity and therefore remained on the level of academic theory. Nowadays, with the new generation of laser sources expected to come into operation in the nearest years[1, 2] or in a foreseeable future[3] this research became of topical interest and already resulted in a number of new fundamental findings.

A high, especially in the last decade, interest in effects of *radiation friction* (RF), *i. e.* of the back-action on the electron of the electromagnetic field emitted by the electron itself, in the physics associated with ultra-intense laser pulses interacting with matter is justified, among others, by the fact that some qualitative effects owe their very existence to the radiation friction force. Such phenomena, if observed experimentally, can provide an unambiguous proof of the crucial role the radiation friction plays at high intensities of laser fields and high energies of plasma electrons. A specific realisation[4] of the inverse Faraday effect (IFE), *i. e.* the generation of magnetic fields due to absorption of angular momentum by the plasma, in the interaction of extremely strong, with intensity $10^{23} - 10^{24}$ W/cm^2, *circularly polarised* (CP) infrared laser pulse with *dense optically thick* plasma target, is such an effect. In this particular setup no other mechanism but radiation friction can provide the transfer of angular momentum from the laser field to plasma.[a] The results of three-dimensional particle-in-cell simulations (PIC) with the radiation reaction force included within the framework of classical physics, have demonstrated that the generated magnetic field could achieve the value of several Gigagauss at the laser field intensity around 10^{24} W/cm^2. This finding calls for two extensions. First, signatures of an IFE-generated magnetic field can be detected already at 10^{23} W/cm^2, *i. e.* at intensities expected at the laser facilities on the near future including ELI and Apollon.[1, 2] In this prospect our calculations[4] require further exploration, which will aim at identifying laser and plasma parameters optimal for an experimental search. Second, extending our results into the domain of even higher intensities[b] one needs to take into account effects of quantum electrodynamics on the plasma motion. We expect that our analytic and numerical investigations will allow answering the question on the existence of principal limitations to the value of the magnetic field generated in the interaction of superintense laser radiation with plasma.

The interaction of intense and super-intense coherent radiation with plasmas offers some of the most challenging problems for numerical physics. This is because the most important and interesting phenomena are multiscale and cannot be described hydrodynamically. The first feature imposes the use of very large numerical grids since the spatial size and/or evolution time of the system is much larger than the smallest spatial and temporal scales to be resolved. The second one implies that hydrodynamic description in real space must be abandoned and much more demanding kinetic equations in phase space have to be solved. This leads to an estimate that a "realistic" simulation would require a three-dimensional (3D) spatial grid with thousands of grid-points in each spatial direction, resulting in a total number of grid-points exceeding some tens of billions. In addition, while PIC method allows a great saving of memory in allocating the momentum space with respect to an Eulerian approach, thousands of particles per cell may be needed to properly resolve high energy tails in the distribution as well as sharp density gradients which always occur in intense laser-plasma interactions. Thus, the progress in this area is directly related to the possibility to access larger high performance computer resources.

[a] A number of different laser-plasma setups provide conditions necessary for the generation of superstrong quasistatic magnetic fields via the excitation of high electron currents. Recently reported records of the experimentally achieved magnetic field strengths approach the value of 1 Gigagauss, while the theory suggests several schemes for generating of even higher fields.

[b] This work currently remains in the realm of theoretical speculations, which could also become of practical interest with the next generation of laser sources[3] coming into play.

2 Description of Methods and Algorithms

All simulations presented in this paper were performed with the JURECA Supercomputer at the John von Neumann Institute for Computing (NIC) using the 3D electromagnetic PIC code UMKA,[5] developed for studying laser-plasma interactions in the strong-field regime. Generally speaking, a PIC code implements a particle-grid numerical method, where a collisionless plasma is sampled by a large number of computational particles and electromagnetic fields are discretised on a grid. The computational particles move across the grid cells and are accelerated by the electromagnetic fields defined at the grid points, which are computed by reconstructing the source current density from the particle positions and velocities. UMKA employs state-of-art, widely used numerical algorithms such as an Yee Cartesian lattice for electromagnetic fields, the Boris pusher to integrate the Lorentz force and the current reconstruction scheme[6] to satisfy the continuity equation. UMKA results have been benchmarked with other codes, compared with both analytical modelling and experimental results and reported in several publications.

At optical laser intensities exceeding $I \sim 10^{23}$ W/cm^2 the plasma electrons become ultrarelativistic within a fraction of the laser wave period. They experience a very strong acceleration and therefore emit relatively large amounts of electromagnetic radiation, causing radiation friction effects, which arise from the back-action on the accelerated electron of the electromagnetic field generated by the electron itself,[7] more and more important as the laser intensity increases. First PIC simulation that included RF[8] in the frame of the Lorentz–Abraham–Dirac (LAD) equation with the RF force that is exact for a point particle,[9] showed that RF effects become important at intensities exceeding 5×10^{22} W/cm^2, and are thus expected to play a crucial role in experiments. It is therefore important to incorporate RF in PIC simulations of laser-plasma by an appropriate modelling, keeping the essential RF effects into account while retaining at the same time the capability to perform large-scale simulations. In order to take RF effects self-consistently into account one should solve the LAD equation. This equation, however, suffers from inconsistencies such as the existence of the so-called "runaway" solutions in which the electron momentum grows exponentially in the absence of external fields. In the realm of classical electrodynamics, *i. e.* neglecting quantum effects, the LAD equation

$$mc\frac{du^\mu}{d\tau} = eF^{\mu\nu}u_\nu - e\tau_0\left(\frac{d^2u^\mu}{d\tau^2} + u^\mu u^\nu \frac{d^2u_\nu}{d\tau^2}\right),\ \tau_0 = 2e^2/(3mc^3) \tag{1}$$

can be consistently approximated by the Landau–Lifshitz (LL) equation

$$mc\frac{du^\mu}{d\tau} = eF^{\mu\nu}u_\nu + e\tau_0\left[u_\nu u^\alpha \partial_\alpha F^{\mu\nu} + \frac{e}{mc}F^{\mu\nu}F_{\nu\alpha}u^\alpha + \frac{e}{mc}\left(F^{\nu\beta}u_\beta F_{\nu\alpha}u^\alpha\right)u^\mu\right]$$

which is obtained by inserting the unperturbed Lorentz acceleration in Eq. 1.[10] This automatically removes the third order derivative of the position and thus runaway solutions, and brings us back to a more conventional phase space description. In 3D notation the above equation reads

$$\frac{d\mathbf{p}}{dt} = e\left(\mathbf{E} + \frac{\mathbf{v}}{c}\times\mathbf{B}\right) + e\tau_0\gamma\left[\left(\frac{\partial}{\partial t} + \mathbf{v}\cdot\nabla\right)\mathbf{E} + \frac{\mathbf{v}}{c}\times\left(\frac{\partial}{\partial t} + \mathbf{v}\cdot\nabla\right)\mathbf{B}\right]$$
$$+\tau_0\frac{e^2}{mc}\left\{\left[\left(\mathbf{E} + \frac{\mathbf{v}}{c}\times\mathbf{B}\right)\times\mathbf{B} + \left(\frac{\mathbf{v}}{c}\cdot\mathbf{E}\right)\mathbf{E}\right] - \gamma^2\left[\left(\mathbf{E} + \frac{\mathbf{v}}{c}\times\mathbf{B}\right)^2 - \left(\frac{\mathbf{v}}{c}\cdot\mathbf{E}\right)^2\right]\frac{\mathbf{v}}{c}\right\}$$

As long as a classical description is adequate, RF effects are relevant and quantum effects are subdominant, one can safely use the RF force given in textbooks[10]

$$\mathbf{F}_{\rm RF} \simeq -\frac{2}{3} r_c^2 \left[\gamma^2 \left(\mathbf{F}_{\rm L}^2 - \left(\frac{\mathbf{v}}{c} \cdot \mathbf{E} \right)^2 \right) \frac{\mathbf{v}}{c} - \mathbf{F}_{\rm L} \times \mathbf{B} - (\frac{\mathbf{v}}{c} \cdot \mathbf{E})\mathbf{E} \right] \quad (2)$$

Here, $r_c \equiv e^2/mc^2 \simeq 2.8 \times 10^{-9}\,\mu$m is the classical electron radius, $\mathbf{F}_{\rm L} = \mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B}$, and we dropped the small terms containing the temporal derivatives of the fields.

To account self-consistently for the effect of radiation emission on the *electron dynamics* we implemented in UMKA the radiation reaction via the LL approach, using a numerical scheme,[11] based on the assumption that the acceleration of particles is dominated by the Lorentz force, with the RF force giving a smaller, albeit non-negligible contribution.[c] The numerical implementation[11] allows the addition of RF effects to any PIC code based on the standard Boris pusher algorithm for the acceleration of the particles at a small computational cost. We emphasise that the inclusion of the radiation loss as a dissipative process via the RF force requires the following assumptions: (i) the dominant frequencies in the escaping radiation are much higher than the highest frequency that can be resolved on the numerical grid, (ii) the radiation at such frequencies is incoherent, (iii) the plasma is transparent to such frequencies.

In the UMKA code, parallelisation is implemented by a decomposition in the (y, z)-discretised coordinates, perpendicular to the x-propagation of the laser pulse. This choice provides an initially balanced partition of the particles for problems where the particle density is initially uniform in the (y, z)-plane. A dynamical load-balancing keeps the data partition balanced as particles move across different domains.

3 Simulations

Based on the equations of macroscopic electrodynamics and conservation laws, a description of IFE in the field of an intense laser pulse[4] predicts the maximal amplitude of the quasistatic longitudinal magnetic field excited on the axis of a laser beam to be linear with respect to the laser magnetic field amplitude $B_{\rm L}$ and to the fraction of the laser energy η associated with the irreversible transfer of angular momentum from the laser field to the plasma

$$B_{xm} = C\eta a_0 B_0 \equiv C\eta B_{\rm L} \quad (3)$$

Here, $a_0 = eE_{\rm L}/m_e c\omega \equiv E_{\rm L}/B_0$, $B_0 = m_e c\omega/e$ are the dimensionless laser field amplitude and the characteristic magnetic field, respectively, $E_{\mathbf{L}} = B_{\rm L}$ and ω is the laser field frequency. For a laser pulse with $\lambda = 2\pi c/\omega = 0.8\,\mu$m wavelength $B_0 = 1.34 \times 10^8$ G. A dimensionless coefficient C is determined by the shape of the laser pulse envelope and has typical values $C \simeq 0.1 - 0.2$. The structure of Eq. 3 is consistent with the general theory of IFE.[12] The coefficient η reads

$$\eta = \frac{\omega L_{\rm abs}}{U_{\rm L}} \quad (4)$$

[c] For a benchmark with other approaches see M. Vranic, J. L. Martins, R. A. Fonseca, L. O. Silva, *Classical Radiation Reaction in Particle-In-Cell Simulations*, Computer Physics Communications **204**, 141-151, 2016.

where $L_{\rm abs}$ is the angular momentum absorbed by the plasma and $U_{\rm L} = \mathcal{A}\lambda^3 a_0^2 B_0^2$ is the energy stored in the laser pulse. The dimensionless coefficient $\mathcal{A}$ is determined by the pulse duration, time envelope and focusing. Eqs. 3-4 are insensitive to a particular physical mechanism of the angular momentum transfer. In particular, Eq. 3 applies independently of the impact of quantum effects on the plasma dynamics. In the high-field regime, radiation of plasma electrons is the only mechanism for energy absorption, thus $\omega L_{\rm abs} = U_{\rm rad}$ where $U_{\rm rad}$ is the radiation energy emitted by the electrons, and Eq. 4 reads

$$\eta \equiv \eta_{\rm rad} = \frac{U_{\rm rad}}{U_{\rm L}} \equiv \frac{\int d^3r \int dt P_{\rm rad}(\mathbf{r},t) n_e(\mathbf{r},t)}{U_{\rm L}} \leq 1 \tag{5}$$

Here, $P_{\rm rad}$ is the emission power for a single electron moving under the action of the local electromagnetic field with a time- and space-dependent envelope and n_e is the electron concentration. The *conversion efficiency* η is the key value for the determination of the magnetic field amplitude.

Below we present and discuss typical results from 3D PIC simulations of the interaction of an intense, tightly focused CP laser pulse with an optically opaque plasma target of thickness $D > 10\lambda$, where $\lambda = 0.8\,\mu$m corresponding to a Ti:Sapphire laser. The initial plasma density is $n_0 = 90 n_c = 1.55 \times 10^{23}\,\mathrm{cm}^{-3}$. The charge-to-mass ratio for ions is taken Z/A = 1/2. The supergaussian laser pulse is introduced via the time-dependent boundary condition at the plasma surface as

$$\vec{a}(r, x=0, t) = a_0 \left(\vec{e}_y \cos\omega t + \vec{e}_z \sin\omega t\right) \exp\left(-(r/r_0)^4 - (ct/r_L)^4\right) \tag{6}$$

with $r = \sqrt{y^2+z^2}$, $r_0 = 3.8\lambda, r_L = 3.0\lambda$ and duration (FWHM of the intensity profile) 14.6 fs. In our PIC calculations we varied the laser amplitude in the interval $a_0 = 300 - 750$, which corresponds to the peak intensities $(3.8 - 23.7) \times 10^{23}$ W/cm^2 and the total pulse energy at $1.08 \div 6.71$ kJ. The numerical box had a $[30 \times 25 \times 25]\lambda^3$ size, with 40 grid cells per λ in each direction and 125 particles per cell for each species. The simulations were performed on $5000 \div 10\,000$ cores of the JURECA Cluster Module.

Radiation Friction Losses in Laser-Driven "Hole Boring" of Dense Plasma Targets

In the considered laser-plasma interaction scenario the ponderomotive force of the laser field pushes and piles up electrons in the skin layer creating a static field that acts on the ions, so that effectively the radiation pressure is exerted on the whole plasma target. In a thick target, ions are thus accelerated at the front surface, causing steepening of the density profile and "hole boring" through the plasma, Fig. 1.

Analysis of the 3D distribution functions of the radiation power density $\mathcal{P}(x, r, v_x)$, calculated as $\mathcal{P} = n_e \mathbf{v} \cdot \mathbf{F}_{\rm RF}$, and of the electron and ion density $n_{e,i}(x, r, v_x)$ extracted from the simulation shows that most of the emitted radiation comes from electrons having velocities $v_x > 0$, and located close to the receding front of the ion density. This is illustrated for $a_0 = 500$ in Fig. 2 where space-time plots in the (x, t) plane are shown for the radiation power and the particle densities along the $x-$axis and at $r = 1\lambda$ distance from the axis. The density fronts move in the forward direction with average velocity $0.41c$ (see also Fig. 1), in fair agreement with the value of the hole boring velocity[13] $v_{\rm HB} = 0.47c$. Small oscillations in the front position are visible in correspondence with the generation of plasma bunches in the forward direction. The power density plot shows that most of

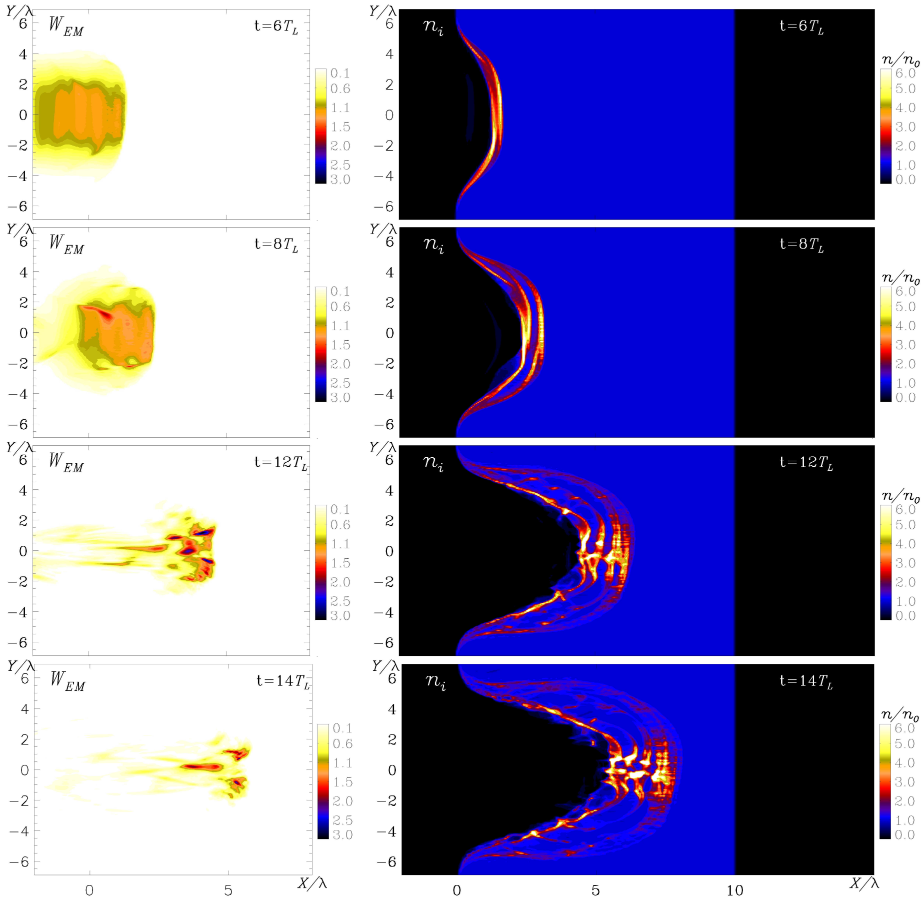

Figure 1. (left) Distribution of the ion density and (right) electromagnetic energy density $W_{\rm EM}/a_0^2$ at $t = 6, 8, 12, 14 \cdot (2\pi/\omega)$. The plasma target of an initial density $n_0 = 1.55 \times 10^{23}\,\mathrm{cm}^{-3}$ is irradiated by a short, tightly focused laser pulse with $a_0 = 600$. See text for further details.

the emission originates close to the hole boring front. Emission due to returning electrons with velocity $v \simeq -c$ is visible after $t = 11 \cdot 2\pi/\omega$, but its contribution to the total emitted power is small, presumably because of the low density in the returning jets, as seen in Fig. 2 of the $n_e(x,t)$ plot. This is also confirmed by the time-velocity plot of the radiation power density $\mathcal{P}(v_x, t)$, shown in Fig. 3.

Quantum Effects on Radiation Friction Driven Magnetic Field Generation

Overall, the results of our simulations demonstrated a good qualitative agreement to the predictions of the theoretical model,[14] which provides an accurate estimate of the radiation friction losses η for CP fields under the assumption that the classical RF regime is retained. In particular, the model[14] reproduces results of 3D PIC simulations with a 20 % accuracy and shows that longitudinal acceleration of the plasma and attenuation of the laser field on

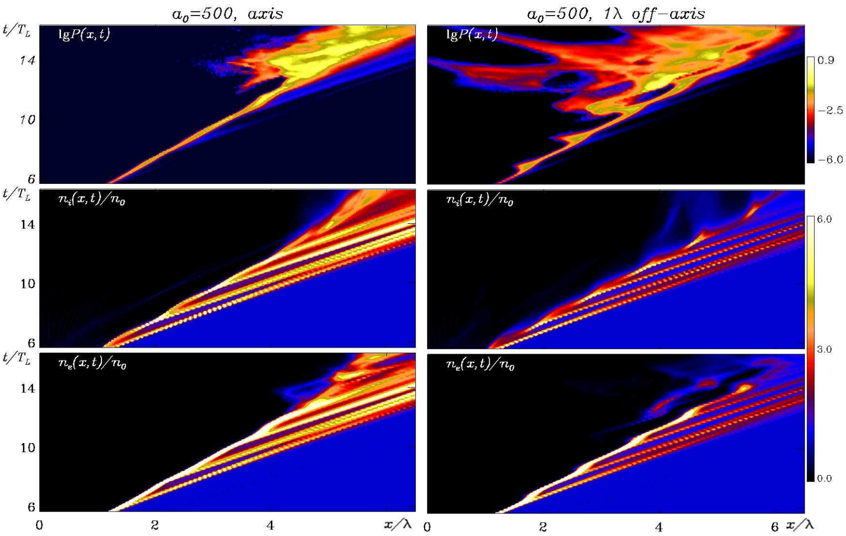

Figure 2. Space-time plots of the radiation power density $\mathcal{P}(x,t)$ (top, logarithmic scale, arbitrary units), ion density $n_i(x,t)$ (middle) and electron density $n_e(x,t)$ (bottom) all evaluated along the $x-$axis (left) and at $r = 1\lambda$ distance from the $x-$axis (right). The plasma target is irradiated by a short, tightly focused laser pulse with $a_0 = 500$.

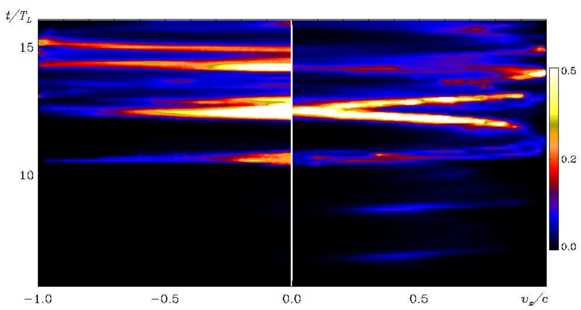

Figure 3. The distribution of the radiation power density $\mathcal{P}(v_x,t)$ (linear scale, arbitrary units) evaluated at $r = 1\lambda$ distance from the $x-$axis. Note, that the values of $\mathcal{P}$ for $v_x < 0$ are magnified by 20.

a small evanescence length inside the plasma, together with effects of time-space averaging, lead to a considerable suppression in the conversion efficiency so that, ultimately, it appears on the level of $\eta \approx 0.2$ for $a_0 = 600$, leading to the upper limit of the magnetic field $B_{\rm xm} \approx 3.2 \times 10^9$ G at the laser intensity 7.5×10^{23} W/cm^2. However, both the above presented simulations and the theoretical approach[14] completely discard the effect of quantum recoil on the spectrum of emitted radiation. On the one hand the parameter $\chi = \dfrac{e\hbar}{m^3c^4}\sqrt{(-(F_{\mu\nu}p^\nu)^2} = \dfrac{E'_{\rm L}}{E_{\rm cr}}$ which determines the significance of quantum effects and equals the ratio of the external (laser) electric field in the electron rest frame $E'_{\rm L}$ to the critical field of quantum electrodynamics, $E_{\rm cr} = m^3c^3/e\hbar$, remains smaller than unity up to intensities $\sim 10^{25}$ W/cm^2, making a classical description of dynamics and radiation of electrons applicable at least on the qualitative level. On the other hand the spectrum of emitted photons appears considerably modified by quantum effects already[15, 16] for $\chi \approx 0.1$. For the considered parameters this is achieved already at $a_0 \simeq 200$ and therefore for $I \simeq 1.9 \times 10^{23}$ W/cm^2, so that quantum corrections to the power of radiation may become numerically important. We therefore account for the suppression of the radiation power due to the off-set in the emission spectrum by introducing the quantum factor $g(\chi)$.[d] To that end we have further modified our code by introducing the factor χ in the expression for the radiation friction force $\tilde{\mathbf{F}}_{\rm RF} = g(\chi)\mathbf{F}_{\rm RF}$. The quantum parameter χ is calculated at each time step by taking the values of electric and magnetic fields at the position of each electron.

The distribution of the electron concentration, of the g-factor and of the radiation power extracted from the simulations are shown in Fig. 4 (a-c) and the comparison of the space distribution of the generated axial component of the magnetic field for the simulations with $g = 1$ and $g(\chi) \neq 1$ is presented in Fig. 4 (c, d). The value of the magnetic field for $g = g(\chi)$ is approximately two times smaller than for $g = 1$. This is in agreement with the corresponding decrease of the value of the radiation friction losses. Notwithstanding, the qualitative behaviour of both values hardly changes, and the scaling laws[14] found within the fully classical model remain valid in the semiclassical domain. The space-time structure of the magnetic field appears considerably modified by the quantum effect. This implies that the axial magnetic field remains of the same order of magnitude but is quite sensitive to the quantum modification of the radiation friction force.

4 Conclusion

The collective laser-plasma dynamics can play a crucial role in determining the amount of radiation friction losses.[4, 14, 18] Our fully dimensional relativistic PIC simulations with the radiation reaction implemented via the LL force show that in the interaction of a CP pulse with a thick plasma slab of overcritical initial density the collective effects greatly reduce radiation losses with respect to electrons driven by the same laser pulse in vacuum. The important consequence of this result[14] is that the reliability of classical calculations can be shifted up to intensities $\sim 10^{24}$ W/cm^2. The simulation results show a good agreement of the calculated conversion efficiency of the laser energy into incoherent radiation with the predictions of analytic calculations, which account for the influence of radiation losses on the single electron trajectory, the global "hole boring" motion of the laser-plasma interaction region under the action of radiation pressure, and the inhomogeneity of the laser field in both longitudinal and transverse direction.

Radiation losses in the interaction of superintense CP laser pulses with high-density plasmas can lead to the generation of strong quasistatic magnetic fields via absorption of the photon angular momentum. Magnetic field strengths of several Gigagauss can be achieved at laser intensities 10^{24} W/cm^2 which proceed at the border between the classical and the quantum interaction regimes. Such huge magnetic fields, besides affecting the plasma dynamics, provide an unambiguous signature of RF effects and may be measured by polarimetry methods. We improve the classical modelling of the laser interaction with

[d]General formulas for the quantum factor $g(\chi)$ can be found in the literature.[15] For practical calculations we use a fit[17] $g(\chi) = (1 + 12\chi + 31\chi^2 + 3.7\chi^3)^{-4/9}$.

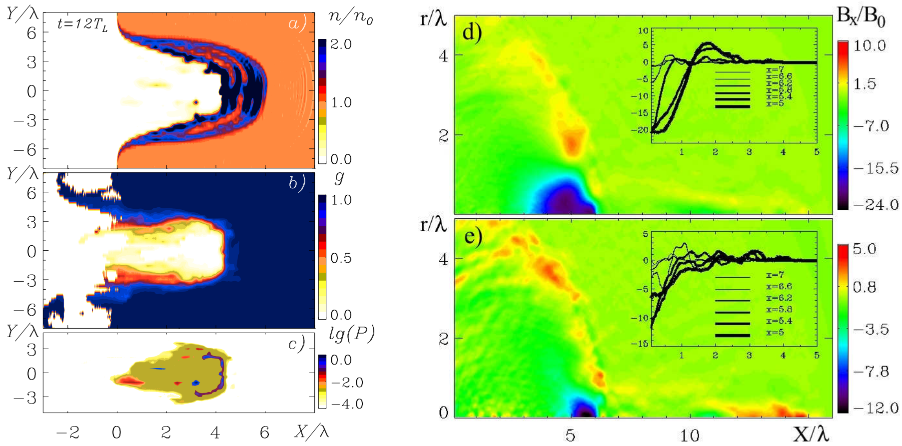

Figure 4. (left) Distributions of the electron concentration (a) of the g-factor (b) and of the radiation power (c) in (x, y) plane, extracted from the simulation for $a_0 = 500$ at $t = 10 \cdot (2\pi/\omega)$ when the total radiation power is close to its maximum. (right) The magnetic field component B_x along the laser pulse propagation direction for g=1 (c) and $g = g(\chi) \neq 1$ (d) for $a_0 = 400$ is recorded at $t = 26 \cdot (2\pi/\omega)$, *i. e.* after the laser pulse is already reflected from the plasma. The onsets in (c) and (d) show the distributions of the magnetic field along the radial direction for fixed values of x.

overcritical plasma in the "hole boring" regime by using a modified radiation friction force accounting for quantum recoil and spectral cut-off at high energies. The results of analytic calculations and full dimensional PIC simulations show that in foreseeable scenarios the quantum effects may lead to a 50 % decrease of the magnetic field amplitude, possibly making the effect a suitable diagnostics for benchmarking of the radiation friction theories.

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