Generation and manipulation of a strong magnetic fields in cluster gas irradiated by intense circularly polarized laser pulses

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Intense magnetic-field amplitude up to (sub)kilo-tesla has been developed in conventional devices, as superconductive magnets [1]. Higher magnetic fields were achieved in Z-pinch experiments [2] and destructive devices [3]. Recently, owing to the development of high-power lasers, new Z-pinching methods have been investigated in nanowire array targets, which could provide even higher magnetic field amplitudes with micrometer scale lengths [4]. Big azimuthal magnetic fields are relatively easy to produce by intense laser pulses on a flat target surface [5]. Axial magnetic fields are commonly produced by circularly polarized laser pulses via the effect of inverse Faraday rotation [6]. Special laser pulses with screw-shaped intensity distribution have been proposed for the generation of sub-MT axial magnetic field in [7]. On the macroscopic level, in a submillimeter spatial domain nanosecond-long pulses with kJ energy have been applied to generate kT magnetic field with a capacitor-coil configuration [8]. In the previous publications [9-11] we proposed the new method of generating large amplitude magnetic-dipole moment based on the electron inertia in cluster rare-gas targets irradiated by circularly polarized ultrashort pulses. It is stable and stays almost constant on the timescale of modern short laser pulses. In contrast with the uniform density underdense plasma in our method, the magnetic dipoles are well localized at the positions of the overdense droplets and their number is equal to the number of droplets inside the laser focal volume. The most unique feature of this nanoscale magnet is the toroidal current surrounding the droplet.

For stable and efficient generating of large amplitude magnetic field in clusterized gas the required laser intensity slightly above the relativistic threshold and the pulse duration not longer than few laser periods is sufficient [9]. The magnetic field amplitude depends on the laser intensity and it is proportional to the pulse duration: $\frac{H_{\max}(\tau_L)}{E_L} = \frac{e\eta E_L \tau_L}{4 m_e \omega \gamma_L p} = \eta \frac{a}{\sqrt{1+a^2}} \frac{c\tau_L}{4p}$

The magnetic field decreases slowly after the interaction and the decay rate is proportional to the laser electric field and inversely proportional to the cluster mass. The lifetime $\tau_{cl} \approx p/c\sqrt{Zm_e(\sqrt{1+a^2}-1)/Am_p}$ of magnetic field is defined by the expansion velocity of the droplet and it can be on the order of picoseconds if heavy droplets are considered, i.e. if the clusterized gas consists of high-Z material, or relatively low intensity laser pulses are used.

At a sufficient n_{cl} - concentration of clusters $\langle H \rangle \approx H_{\max}\left(\frac{p}{n_{cl}^{-1/3}}\right)^3 = H_{\max} n_{cl} p^3$, $n_{cl} p^3 < 1$, after the end of the laser pulse, the magnetic moments of the dipoles undergo vibrations and the magnetic field oscillates with $\Omega \approx eH_{\max} p^3 n_{cl} / 4\gamma m_e c$, $\frac{\Omega}{\omega} \approx \frac{\eta a^2 c\tau_L}{16p(1+a^2)}(p^3 n_{cl})$, which is accompanied by the appearance of a secondary terahertz radiation. Magnetic dipoles behavior is similar to the processes in the magnonics. The period of the dipole turn is $\Delta t \approx \Omega^{-1}$, thus the condition of the rotation of dipoles during cluster lifetime is $\Omega\tau_{cl} > 1$. Let us introduce the unit vector $\vec{n}_i(t)$ in the direction of the magnetic moment of the i -cluster. The magnetic field of the cluster system $\vec{H}(\vec{r}_{ik})$ outside the cluster ion core is the sum of the fields of the separated dipoles, thus the equation of motion of the separated dipole "*i*" is:

$$\frac{d\vec{n}_i(t)}{dt} = \frac{eH_{\max}p^3}{4\gamma m_e c}\sum_{\substack{k=1\\k\neq i}}^{N_{cl}}\left(-\frac{\vec{n}_i \times \vec{n}_k}{R_{ik}^{\,3}} + \frac{3\vec{n}_i \times \vec{e}_{ik}(\vec{n}_k\vec{e}_{ik})}{R_{ik}^{\,3}}\right) - \frac{\vec{n}_i(0)\tau_{cl}}{(t+\tau_{cl})^2} \qquad (1)$$

$$\vec{e}_{ki} = \vec{R}_{ki}/R_{ki}$$

The last term added to the right side describes relaxation of the cluster's magnetic momentum due to cluster expansion. To produce magnonic oscillations (waves) for clusters in laser focal volume, the following additional three conditions have to be fulfilled:

$R_{i,i+1} > 2p$ (the electron clouds do not touch); $\tau_L < p/c\sqrt{Zm_e(\sqrt{1+a^2}-1)/Am_p}$ (negligible expansion);

$a < a_{tr} = 2Ze^2 n_i R\lambda / 3m_e c^2$ (no Coulomb explosion).

From the above, one can construct the following interval of the possible pulse duration:

$$\frac{0.5}{\eta}\sqrt{\frac{Z}{A}}\sqrt{a} < \frac{c\tau_L}{\lambda} < \frac{170R_0}{\lambda\sqrt{a}}\sqrt{\frac{A}{Z}}$$

One can draw the area $(c\tau_L/\lambda, a)$, where the effect of dipole rotation is realized:

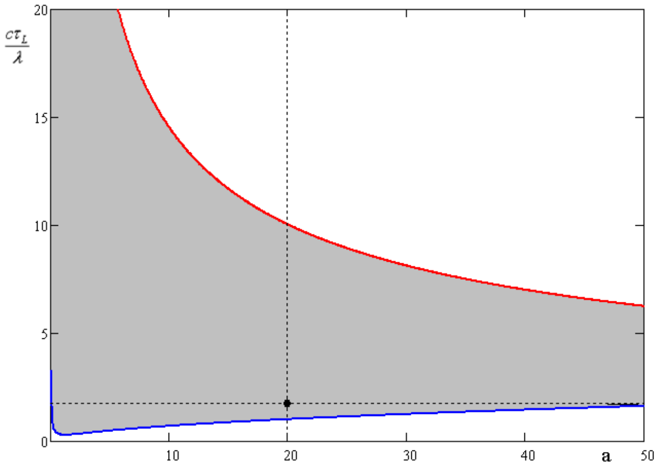
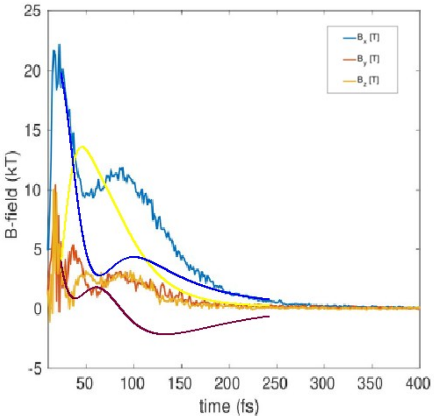
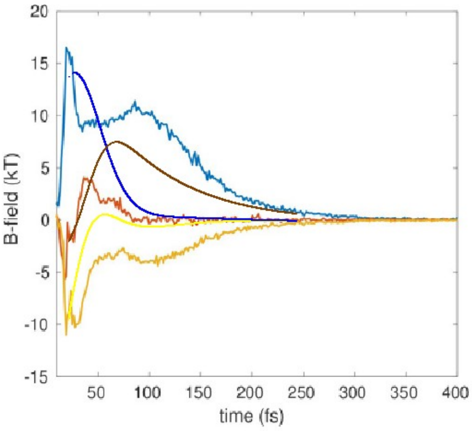


Fig.1 The range (grey area) of laser parameters where magnonic oscillations of cluster plasma can be realized. Here Z=30, A=196, η=0.2, R_0=100 nm, λ=1000 nm, p=4R_0. The distance between the nearest clusters is R_{12}=2p=800 nm. The black dot shows the laser pulse of 6 fs and 5.6x10^{20} W/cm^2, used in our PIC simulations.

To confirm the effect of magnetic dipole rotation, we simulated Au^{+30} clusters of 100 nm radius at a higher laser intensity of 5.6x10^{20} W/cm^2 and 6 fs pulse duration and a super-Gaussian shape. The simulation box was: 3x3x3 μm^3. The cluster locations in the box are the following: R_1 = (510, -490, 0), R_2 = (1490, 490, 0), R_3 = (1000, 0, 400), R_4 = (1000, 0, -400) nm. The results of the simulations and the analytical model (1) show that the evolution of the magnetic field components is not only relaxation, but clear oscillations of the Y and Z components (even during one period) prove magnetic interaction of the clusters.





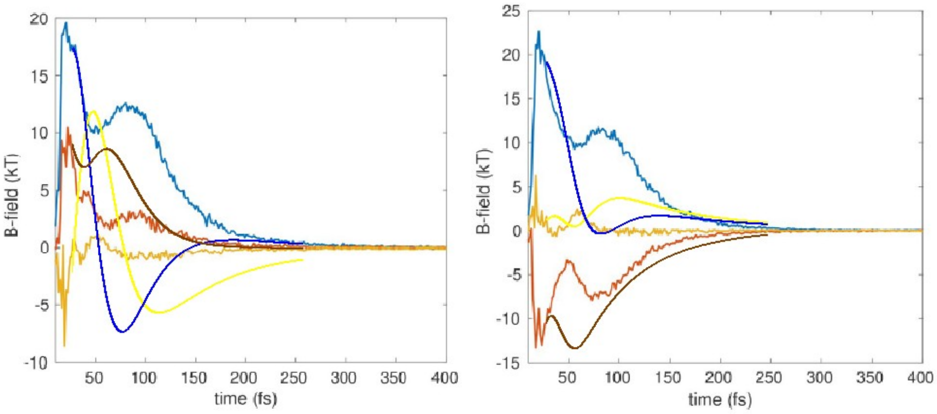


Fig.2 The time dependence of the magnetic field components for Au^{+30} 4-x clusters irradiated by a laser pulse of I_L = 5.6 × 10^{20} W/cm^2 intensity and 6 fs duration, obtained by PIC simulations (modulated lines) and analytically (smooth lines of the same colors).

Conclusion

The generation, interaction and dissipation of the giant magnetic moments of clusters in laser-plasma interaction was demonstrated in the focal volume of circularly polarized relativistic intense laser pulses, interacting with the clusters of radii from tens up to hundreds of nanometers. It is shown that at a laser intensity of 10$^{18-20}$ W/cm^2, one can get a magnetic field of up to 0.5 MT at lifetime hundreds of femtoseconds in the focal volume of the laser pulse. At cluster density above 10^{11} cm^{-3} the THz oscillations of magnetic moments of clusters (magnons) can be generated. The magnonic waves appear at specific laser intensity and pulse duration, because the duration should be high enough to convert the absorbed impulse momentum into cluster electron one, but on the other side, duration must not exceed cluster plasma lifetime. This time is determined by cluster expansion, thus the conditions for the experimental realization is relatively large diameter heavy clusters.

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