High-intensity synchrotron radiation from compact magnetic-plasma structures

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An electron beam propagating in a plasma magnetic mode emits synchrotron radiation.

As technological devices become more compact, their ability to generate small-scale electric and magnetic structures becomes increasingly important. In most cases, reducing the size of these structures runs into stringent technical limits, especially in terms of the field amplitudes and the shortest length scales attainable. Plasma is an attractive medium in this context because of its ability to sustain strong fields on small spatial scales. Successful examples include high-gradient electrostatic structures—generated by the propagation of an intense laser pulse in a plasma—that are used to accelerate particles to high energies in compact systems.1 Excitation of analogous periodic-magnetostatic structures to drive a plasma magnetic mode (PMM) by colliding a light pulse with a relativistic ionization front had been predicted theoretically,2,3 but a method to detect and characterize PMMs was designed only recently.4

Propagation of a relativistic electron beam through the PMM can provide ultrashort-wavelength synchrotron radiation,5 in a similar fashion to beam propagation in the undulator structure of a free-electron laser.6 In addition, narrow spectra and, consequently, high-intensity radiation can be generated, since the larger the number of oscillation periods in the structure, the narrower the spectrum of the resulting emission. Development of a compact radiation source would offer a powerful tool to study the dynamics of materials on the timescale of atomic motions7 and for biomolecular imaging.8 We show that controlled excitation of the magnetic structure is possible with existing state-of-the-art laser technology, thus enabling its exploration, in particular, for the generation of high-intensity synchrotron radiation.

Figure 1. Schematic setup used to generate synchrotron radiation through the propagation of an electron beam in the plasma-magnetic-mode (PMM) structure.

Current high-power laser sources can generate sharp relativistic ionization fronts using tunneling ionization of a background gas. When a secondary counter-propagating light wave impinges on the ionization front, the electrons originating at the point of ionization (with zero mean velocity) experience the electromagnetic field of the incident wave, gaining transverse momentum according to the phase of the counter-propagating wave. As the ionization front propagates, these electrons are left behind, drifting transversely, and creating a modulated current pattern. The latter gives rise to a transverse magnetostatic field that is modulated at twice the radiation frequency, with a wavelength and spatial extent approximately half those of the wavelength and pulse length of the incident wave. For ionization

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Figure 2. Snapshot of the PMM (red and dark blue) induced by the collision of a CO$_2$ laser pulse (yellow and light green) with a relativistic ionization front in a computer simulation. A 100MeV electron beam (dark green) trails the ionization driver pulse. The pulse propagates in the positive-x direction, whereas the CO$_2$ laser propagates in the negative-x direction. The ionization front is located at $x \sim 100\mu m$.

 fronts that are opaque to the counter-propagating wave, almost all wave energy is absorbed by the PMM, leading to magnetic-field amplitudes as high as 100T. If an electron beam trails the ionization front, it will experience the Lorentz force associated with the magnetostatic structure and the electrons in the beam will wiggle transversely—and thus radiate (see Figure 1). IR laser sources can be used as secondary pulse generators, inducing magnetic structures with wavelengths in the micrometer and submicron range.

To confirm PMM excitation with existing laser sources and to generate synchrotron radiation from the propagation of a relativistic electron beam in the PMM, we performed a series of simulations with the electromagnetic, fully relativistic, and massively parallel 3D particle-in-cell computational code OSIRIS.$^9$ The ionization front was generated self-consistently by tunnel ionization, using the propagation of a short ($\sim 20-50$fs), intense ($\sim 10^{15}$W/cm$^2$) laser pulse (wavelength $\sim 0.8\mu m$) through a hydrogen-gas jet (neutral density $\sim 10^{19}-5 \times 10^{20}$cm$^{-3}$). A secondary, less intense ($\sim 10^{13}$W/cm$^2$) CO$_2$ laser pulse (wavelength $\sim 10.6\mu m$) was launched in counter-propagation with respect to the ionization front. The ensuing collision with the ionization front excited the PMM. An electron beam ($\sim 5-100$MeV) trails the ionization front and propagates through the generated magnetostatic structure.

Typical results are shown in Figures 2 and 3. Behind the ionization front, a modulated magnetic field is induced (with approximately half the wavelength of the secondary pulse), while no transmission of the incident pulse in the ionization-front region is observed, thus confirming the conversion of the secondary-laser energy into the PMM (see Figure 2). The electron beam traverses the magnetic structure without perturbing it. The evolution of the spectrum emitted due to the wiggling motion of the beam electrons in the magnetostatic structure illustrates the generation of high-energy photons in a narrow spectrum (see Figure 3).

In summary, we have shown the feasibility of producing ultracompact high-amplitude magnetostatic structures in plasmas by exciting the PMM, a plasma mode of relativistic ionization fronts. We also managed to generate high-intensity, ultrashort-wavelength radiation from the propagation of an electron beam in this structure. Further work will concentrate on both a more in-depth analysis of the features of the radiation spectrum and exploration of the PMM for other applications.

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