Undulator radiation of relativistic electrons in a polydomain ferromagnetic

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The radiation emitted by a relativistic electron moving in a ferromagnet perpendicular to the magnetization axis is studied. Some possibilities for controlling the radiation frequency are examined. Under certain conditions this radiation has both a higher power and a higher photon energy than the radiation of a channeled particle.

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Undulator radiation has attracted interest primarily because of the possible use of this mechanism to produce radiation over a broad wavelength range, particularly at short wavelengths. The radiation frequency in an undulator is determined by the length of the periodicity element of the undulator. A spatially periodic magnetostatic field is produced by a macroscopic system of magnets, whose period λ_0 cannot be made sufficiently small (ordinarily, $\lambda_0 \sim 1$–10 cm).

In this letter we suggest passing an electron beam through a ferromagnet in a polydomain state in order to make use of the periodic magnetic field of the domain structure to produce undulator radiation. This approach has the advantage that the periodicity element of the undulator is the period of the domain structure, which is quite small (see Ref. 1, for example) and can be varied over a broad range from ~ 100 to ~ 1 μm. In thin single-crystal Ni-Fe films, for example, this period is[2] $\lambda_0 \sim 2$ μm. Obviously, such small values of λ_0 are completely unattainable in "ordinary" undulators.

A particle moving in a spatially periodic magnetic field of amplitude $\mathbf{B}_0$ at a velocity $v_z = \beta c$ (the z axis is along the direction of the periodicity) oscillates at a frequency $\Omega_0 = 2\pi v_z / \lambda_0$ and radiates at the Doppler-shifted frequencies

$$\omega = \frac{\Omega_0}{1 - \beta \cos\theta}, \tag{1}$$

where θ is the angle between the radiation propagation direction and the velocity of the particle. In the ultrarelativistic case, $\gamma = (a - \beta^2)^{-1/2} \gg 1$, and for forward emission we would have $\omega \approx 2\gamma^2 \Omega_0$. It has been established[3] that the frequency conversion in an undulator is more efficient than in a channeling situation, where the maximum radiation frequency is $\omega_m \approx 2\gamma^{3/2} \Omega_c$, where Ω_k is the electron oscillation frequency in the channel. With $\lambda_0 \sim 2$ μm, $\Omega_k \sim 10^{16}$ s^{-1} (Ref. 3), and an electron energy ~ 50 MeV, the radiation frequency in a ferromagnetic undulator is comparable to the maximum radiation frequency in the channeling situation, while for electrons with ~ 10 GeV the radiation frequency in a ferromagnetic undulator is ~ 15 times that in channeling; the radiation wavelength is $\lambda \sim 2.5 \times 10^{-5}$ Å.

In channeling, the emission spectrum[3] stretches from zero up to ω_m, while in a ferrogmagnetic undulator the emission is more nearly monochromatic: In a fixed direction θ, the emission frequency band is $\Delta\omega \sim \omega / M$, where M is the number of domains traversed by the relativistic electron in the crystal. Furthermore, a ferromagnetic undulator is not afflicted by a particular characteristic of channeling which tends to suppress the radiation[4]: Only a fraction R/a of the electrons in the case of planar channeling, or a fraction $(R/a)^2$ in the case of axial channeling, participate in the radiation, where R is the channel width and a is the distance between the crystal planes or axes (typically, $R/a \sim 0.1$–0.03).

The ferromagnetic undulator presents a unique possibility for controlling the radiation frequency, by modifying the properties of the original domain structure. The imposition of an external magnetic field, for example, will change both the geometry of the structure (the width of the domains directed along the field will increase in comparison with the width of oppositely directed domains) and the period of the structure. This period can also be adjusted by changing the thickness of the ferromagnetic sample. Furthermore, the frequency of the radiaion emitted by an electron in a ferromagnetic undulator can be altered by changing the angle at which the electron beam is incident with respect to the magnetization axis.

Turning to the intensity of the radiation, we note that the following expression can be derived for the differential intensity with respect to the frequency and the solid angle for a structure with a Bloch wall:

$$\frac{dI_0}{d\omega\, d\theta} = \frac{e^2\beta}{\pi^2 c\lambda_0 M}\left| \sum_{k=-\infty}^{\infty} \frac{\sin \dfrac{\pi M[\omega(1-n_z\beta)-k\Omega_0]}{\Omega_0}}{\omega(1-n_z\beta)-\Omega_0} \right.$$

$$\left. \times \frac{1+\cos(k\tau\Omega_0)}{\pi k} \frac{[(\mathbf{n}-\beta\mathbf{k})n_x - \mathbf{i}(1+n_z\beta)]\,\omega_c\beta}{(1-n_z\beta)^2} \right|^2 . \tag{2}$$

Here τ is the time required for an electron to traverse the domain wall, $\mathbf{n} = (n_x, n_y, n_z)$ is a unit vector along the emission direction, $\omega_c = eB_0/mc$ is the cyclotron frequency of an electron (the relativistic scaling factor is ignored), and $\mathbf{i}$ and $\mathbf{k}$ are unit vectors along x and y, respectively. Accordingly, in this situation, as in an undulator with a more smoothly oscillating field,[5] the frequency spectrum observed at the angle θ is

$$\omega_k = \frac{k\Omega_0}{1-\beta\cos\theta} \tag{3}$$

with progressively smaller harmonic amplitudes. The domain walls simply introduce a factor $(1/2)[1+\cos(k\Omega_0\tau)]$, which differs only slightly from unity (for $\tau \ll 2\pi/\Omega_0$) at the low-order harmonics.

Comparing the total intensity of the radiation in the frequency band of the undulator in the case of a channeled electron, I_k, with that in the case of an electron in an undulator, I_0, we find

$$\frac{I_0}{I_c} \sim \frac{M}{3}\left(\frac{\omega_c}{\Omega_0}\right)^2 \frac{c^2}{R^2\Omega_c^2} . \tag{4}$$

Here we have used an expression for $dI_c/d\omega$ from Ref. 3.

With $B_0 \sim (6\text{–}8)\times 10^3$ G (Mn-Bi, Ni-Fe), $\Omega_c \sim 10^{16}\ \text{s}^{-1}$, $\lambda_0 \sim 1\ \mu\text{m}$, and $M \sim 100$ we find $(I_0/I_c) \sim 0.4\text{–}.7$. With $\lambda_0 \sim 10\ \mu\text{m}$ and $M \sim 10$ we find $(I_0/I_c) \sim 4\text{–}7$. We might note that in (4) and in these estimates the quantity I_c is the intensity emitted by an electron which has already entered the channel; for an electron beam in the case of planar channeling there is an additional attenuation factor $(R/a)^{-1}$, as mentioned earlier.

The "channeling emission" is, of course, accompanied by "undulator emission" only if the electron is moving in a channel, i.e., only if the angle (φ) made by the electron velocity with the crystal plane as the electron enters the crystal satisfies $\varphi < \varphi_{cr}$.

In summary, the mechanism[1)] proposed here for arranging radiation by an electron, while an "in-crystal" mechanism, as channeling is, has several advantages over channeling: High radiation frequencies and intensities can be achieved, the radiation spectrum can be very narrow, the events are insensitive to the angle at which the particles enter the crystal with respect to symmetry planes (or axes), and the frequency can be tuned.

[1)]The radiation emitted by an electron moving above a domain structure was discussed in Ref. 6.

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