Thomson Backscattering from a Relativistic Electron Beam as a Diagnostic for Parallel Velocity Spread

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Thomson backscattering of CO_2-laser radiation is used to determine the parallel momentum spread of a 1-kA/cm^2, 700-kV magnetized electron beam, emitted from a cold cathode in an apertured diode. The beam is found to be suitable for Raman free-electron-laser applications: a normalized momentum spread of $(0.6 \pm 0.14)\%$ was obtained for the inhomogeneous broadening; it is also found that the use of an undulator will cause an increase of the broadening.

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In order to obtain high gain and efficiency for a free-electron laser (FEL) operating in the Raman regime, $\omega_p L/\gamma c \gg 1$, an intense relativistic electron beam must be cold, that is the parallel component of normalized momentum spread should satisfy $(\delta\gamma/\gamma)_{\parallel} < (l_0/2\gamma)(\omega_p/2c)$, where $\omega_p = (4\pi n e^2/\gamma m)^{1/2}$, $\gamma = (1 - v^2/c^2)^{-1/2}$, n is the electron density, and l_0, L are the undulator period and length. In the regime of long wavelength and comparatively low γ, inhomogeneous broadening caused by electron beam emittance, space charge, and gradients in the undulator field must be held to $(\delta\gamma/\gamma)_{\parallel} \approx (1-2)\%$ in order that FEL gain remain high.[1] However, available electron-beam data relevant to this question rely principally on interactive diagnostics. What is needed is a noninteractive diagnostic which is sensitive to the spread of electron velocities parallel to the axis of the beam. In this Letter, we describe a Thomson-backscattering diagnostic which is capable of resolving momentum spread $<1\%$ in dense relativistic electron streams. We review the theory, describe the apparatus, and quote data for the first experiment of this nature.[2] Backscattering of photons from a very energetic (10 GV) electron beam has been reported several years ago.[3]

In the laboratory frame, a thermal spread of electron parallel velocities $\delta v_{\parallel}/c$ is related to the spread of electron momentum or energy by $(\delta v_{\parallel}/c) = \gamma^{-2}(\delta\gamma/\gamma)_{\parallel}$; it is also related to the broadened spectrum of scattered light:

$$\delta\lambda/\lambda \approx 2(\delta\gamma/\gamma)_{\parallel} \approx 2(1 - 1/\gamma)(\delta W/W)_{\parallel}, \tag{1}$$

where $W = (\gamma - 1)mc^2$. The ratio of the frequency of scattered light (ω_s) to frequency of light incident upon the electron stream (ω_i) is

$$\omega_s/\omega_i \approx \frac{1 + v/c}{1 - (v/c)\cos\theta} \approx \frac{4\gamma_{\parallel}^2}{(1 + \gamma^2\theta^2)}, \tag{2}$$

where $\gamma_{\parallel} = (1 - v_{\parallel}^2/c^2)^{-1/2}$ and θ is the angle between the electron velocity and the scattered wave vector (in the backscattered direction, where the scattered photons travel parallel to the electrons and the incident photons antiparallel, $\theta \approx 0$). Scattering into finite solid angle, $d\Omega$, will cause another spread of frequencies, $\delta\omega_s/\omega_s = \gamma^2 d\Omega/\pi$; to make this type of spectral broadening negligible (say $\lesssim 0.1\%$), we shall take $d\Omega \lesssim 10^{-3}$ which is roughly $f/30$ optics. If $W = 670$ kV, from Eq. (2) one finds $\omega_s/\omega_i = 19.2$: transversely-excited-atmospheric (TEA) CO_2-laser radiation at 9.6 μm would be shifted to a scattered wavelength $\lambda_s = 0.5$ μm.

To calculate the differential scattering cross section we use standard formulas from quantum electrodynamics in the limit $\hbar\omega/mc^2 \ll 1$, setting $\theta \approx 0$. The photon differential cross section, $(d\sigma/d\Omega)_p$, is given by

$$(d\sigma/d\Omega)_p \approx \left(\frac{1 + v/c}{1 - v/c}\right) r_0^2 \approx 4\gamma^2 r_0^2, \tag{3}$$

where $r_0 = e^2/mc^2$. Since the experiment uses a photomultiplier (PMT) detector, the number of scattered photons (N_s) can be written in terms of the number of incident photons (N_i) as

$$N_s/N_i \approx 2(4\gamma^2) r_0^2 (nl) d\Omega, \tag{4}$$

where the factor of 2, actually $(1 + v/c)$, is the photon flux compression factor appropriate to backscattering geometry, and l is the length of the electron beam illuminated. Taking $nl = 3\times10^{12}$ cm^{-2} yields $N_s/N_i = 3.5\times10^{-14}$. The energy-differential cross section can be obtained by multiplying Eq. (4) by the frequency upshift factor, from Eq. (2). This result can be obtained from classical theory, taking care to apply the retarded-time factor correctly. (Unfortunately, an erroneous "finite-volume" effect[4] has been propagated in the literature, and has only recently been laid to rest by Kukushkin[5]; the actual finite-volume effect is very difficult to observe.)

The spectrum of scattered radiation can be calculated once the electron velocity distribution is assumed. A suitable *Ansatz* is a narrow Gaussian in the beam frame (characterized by temperature T_0), in which case[6]

$$(d^2\sigma/d\omega\, d\Omega)_W \propto \exp(-mc^2/T_0), \quad T_0 \ll mc^2, \qquad (5)$$

where the Doppler half-width of the line in the laboratory frame is $2[2T_0 \ln 2/mc^2]^{1/2}$. (The formulas of Ref. 6 contain a few minor errors having to do with the normalization of the electron distribution.)

Turning now to experimental matters, we use a TEA laser oscillator and a Lumonics 922s amplifier to provide about 20 MW in a sequence of mode-locked narrow spikes, spaced over a 100-ns interval. The oscillator is tuned to one line by a diffraction grating. The mode-locked spikes make a convenient signature for identifying the scattered signal. The radiation is directed through a NaCl window into the drift tube of the accelerator via a long-focal-length optical system, oriented $\approx 1°$ off axis so that the incident light misses the cathode, and hits a beam dump (Fig. 1). The scattered beam line is also tilted 1° off axis to reduce visible-light pickup from the diode and the TEA beam dump. The scattered light is apertured, and passed through a window in a shielded room and into a copper box, which is enclosed in a wall of lead 5 cm thick and in which is located an RCA C31000A PMT. At this point the optical radiation is filtered with a set of $\frac{1}{2}$-μm interference filters having variable width. Background light must be kept below the saturation level of the PMT; the stray-light level, which increases throughout the accelerator pulse, is discriminated against by a high-pass filter (50 MHz) in the output circuit.

A Physics International pulse-line accelerator applies a square pulse ≈ 700 kV to a cold, graphite-tipped cathode immersed in a uniform magnetic field, $B_0 = 9.5$ kG. The pulse is very flat (within 2%) and lasts about 150 nsec (see Fig. 2). Electrons are field emitted across a 2-cm gap into a graphite anode; a small fraction of the total current passes through an axially-centered hole (5 mm diam) and propagates down a 2-cm-diam drift tube as a cylindrical beam (this arrangement is similar to one used in the recent high-power Raman FEL experiment at U. S. Naval Research Laboratories[7]). Optical alignment with a movable jig and mirror in the electron beam line is relatively easy. The upstream pressure in the drift tube is in the range 10^{-4} to 10^{-5} Torr; the electron beam is then at least 95% nonneutral.

An example of the backscattered signal is shown in Fig. 2. The lower portion of the figure shows the synchronism between the diode voltage pulse and the TEA-CO_2-laser spikes (detected by a photon drag device which monitors a portion of the beam). The timing is adjusted on the oscilloscope so that the laser beam intercepts the electrons at coincidence. The PMT signal is delayed an extra 35 ns by transit-time effects. A set of spikes, having the same spacing as the mode-locked spikes at 9.6 μm, is clearly evident on the $\frac{1}{2}$-μm channel. A change of the diode voltage by $\lesssim 2\%$ will cause the scattered spikes to disappear. Having calibrated the diode voltage as 700 kV, and expecting scattering for $\gamma = 2.3$ (670 kV), the difference of 30 kV is apparently due to the space-charge potential depression of the beam. From this follows the estimate of the beam electron density, 3×10^{11} cm^{-3}. Comparing the observed level of the signal with that pre-

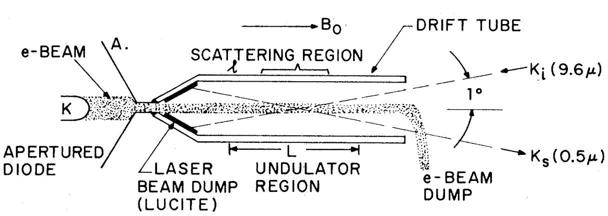

FIG. 1. Schematic of the apertured diode and beam line. Anode-cathode gap, cathode diameter, and drift tube i.d. are each 2 cm. Undulator length is 40 cm and period is 1.7 cm; the first and last three periods are tapered so that $B_\perp$ varies gradually.

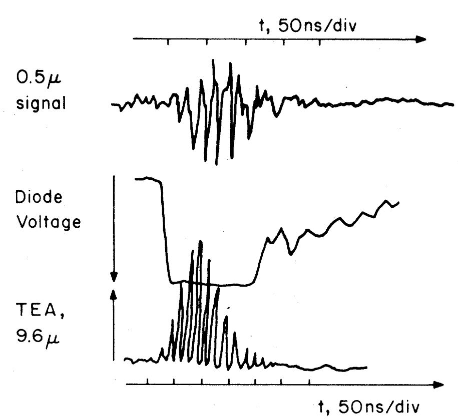

FIG. 2. (Bottom) Diode voltage (700 kV) and TEA laser signal and (top) scattered signal at $\frac{1}{2}$ μm.

dicted by Eq. (4) (including PMT gain and optical losses), we find that the scattered power is of the expected order.

The quantitative scattering data are shown in Fig. 3. The dashed line is the scattered spectrum signal which would be detected by use of a set of ideal Gaussian filters characterized by half-power width $\delta\lambda$, centered at 5000 Å, under the assumption that the electron velocity distribution is a narrow, Doppler-shifted Gaussian characterized by inhomogeneous width $(\delta\gamma/\gamma)_\parallel$. The data points, obtained by averaging many shots under nearly identical conditions of accelerator performance, were obtained with use of filters which did not have exactly Gaussian response functions. Each filter transmission characteristic was measured, and the data points were normalized so that each channel could be compared as a Gaussian filter. The best data fit, for zero undulator field $B_\perp$, gave $(\delta\gamma/\gamma)_\parallel = (0.6 \pm 0.14)\%$. We estimate the electron momentum spread caused by the beam space charge as $(\delta\gamma/\gamma)_{\parallel\,\mathrm{s.c.}} = \omega_p{}^2 r_b{}^2/4c^2 \approx 0.5\%$ (r_b is the beam radius).

Next, data were taken when the bifilar helical undulator was energized. The period of the undulator is 17 mm and $B_\perp =$ 225 or 375 G. Because of the proximity of magnetoresonance ($2\pi\gamma v_\parallel/l_0 = eB_0/mc$), the corresponding electron quiver velocity, given by

$$v_\perp/c \approx \left(\frac{eB_\perp l_0}{2\pi\gamma mc^2}\right)\left[\frac{eB_0 l_0}{2\pi\gamma mc^2} - 1\right]^{-1}, \qquad (6)$$

is $0.06c$ or $0.1c$. The enhancement factor in square brackets is ≈ 4. The radius of the electron spiral orbit due to the undulator is only $\approx 0.10 r_b$.

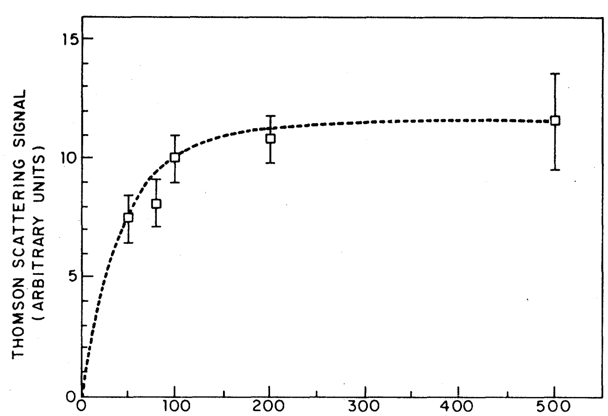

FIG. 3. Fit of Thomson-scattering data with a calculated curve corresponding to scattering from a electron momentum spread $(\delta\gamma/\gamma)_\parallel = 0.6\%$ at $\gamma = 2.3$ into filters characterized by a Gaussian transmission response.

The data show that the total inhomogeneous broadening increases to 0.8% ($B_\perp = 225$ G) and 1.1% ($B_\perp = 375$ G), ±0.1%. The additional broadening expected from the undulator is due to the parallel velocity shear which arises from the radial gradient in quiver velocity, and is an important factor in this experiment since $2\pi r_b/l_0 \approx 1$. The anticipated undulator contribution to the momentum spread is $(\delta\gamma/\gamma)_{\parallel\,\mathrm{und}} \approx (\gamma v_\perp/c)^2 \delta B_\perp/B_\perp$, where $\delta B_\perp/B_\perp$ represents the systematic variation in undulator field amplitude across r_b of $\approx 20\%$. Therefore we expect the undulator to contribute an additional 0.3% or 1.0% momentum spread, respectively, for $B_\perp = 225$ G and $B_\perp = 375$ G. Combining the predicted space charge and undulator broadenings will give the experimental value that we report (within error limits) provided that these two sources of inhomogeneous broadening are added as the root-mean-square sum.

Thomson backscattering from an intense relativistic electron beam has certain advantages compared with the plasma case. One factor is the enhancement of the differential scattering cross section by $4\gamma^2$. Another is that, for comparable laser power, photons are more plentiful in the infrared source by another factor of $4\gamma^2$. There is no ion bremsstrahlung light, but diode light, x-ray background, and the large f-number requirement contribute to experimental difficulties.

Finally, our measurement of a beam energy spread <1% is consistent with the claim of Jackson *et al.* to have achieved low-energy spread in their Raman FEL experiment.[7] Accordingly, one can contemplate practical, efficient Raman FEL systems in the submillimeter spectral region.

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[1]L. F. Ibanez and S. Johnston, IEEE J. Quantum. Electron. 19, 339 (1983).

[2]S. C. Chen, T. C. Marshall, and S. P. Schlesinger, in Proceedings of the LASERS 1982 Conference (to be published), and in Proceedings of the 1983 Free Electron Laser Workshop (unpublished), and Bull. Am. Phys. Soc. 28, 1062 (1983); see also H. Davis and

O. Willi, Bull. Am. Phys. Soc. 28, 1040 (1983).
[3]C. K. Sinclair *et al.*, IEEE Trans. Nucl. Sci. 116, 1065 (1969).
[4]See R. E. Pechacek and A. W. Trivelpiece, Phys. Fluids 10, 1688 (1967); G. Ward and R. E. Pechacek, Phys. Fluids 15, 2202 (1972); J. Sheffield, Plasma Phys. 14, 783 (1972); J. H. Williamson and M. E. Clark, J. Plasma Phys. 6, 211 (1971).
[5]A. B. Kukushkin, Fiz. Plazmy 7, 110 (1981) [Sov. J. Plasma Phys. 7, 63 (1981)].
[6]V. A. Zhuravlev and G. D. Petrov, Fiz. Plazmy 5, 7 (1979) [Sov. J. Plasma Phys. 5, 3 (1979)].
[7]R. H. Jackson *et al.*, IEEE J. Quantum. Electron. 19, 346 (1983).