Microwave Generation from Filamentation and Vortex Formation within Magnetically Confined Electron Beams

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The generation of microwaves from interacting vortices formed in thin magnetized electron beams is investigated experimentally and with three-dimensional electromagnetic particle simulations. Fine-detail photographs of relativistic and nonrelativistic beams show that vortex formation transcends 12 orders of magnitude in beam current. The simulations show a burst of microwave radiation from a rapid magnetic line connection and breaking between vortices when the vortex structure is well defined.

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One of the outstanding problems in the propagation f electron beams along an axial magnetic field is the reakup of the beam into discrete vortexlike current undles when a threshold determined by either the eam current or distance of propagation is surassed.[1-6] The phenomena observed closely resembles at associated with the Kelvin-Helmholz fluid dynamal shear instability, in which vortices develop roughout a fluid when a critical velocity in the flow exceeded, with a large increase in the resistance to ow.[7]

While structural changes in the azimuthal direction e observed in solid, annular, or sheet beams, it is ith thin electron beams that the vortexing pheomenon is most pronounced. Since thin annular eams are easily produced and are capable of conductg currents exceeding those given by the characteris Alfvén value,[8] they have found wide application in ossed-field microwave generators[9] as well as in deces employing intense annular relativistic electron eams (reb's) such as free-electron lasers,[10] highower backward-wave oscillators,[11] multigapped aclerators,[12] and reb fusion drivers.[13]

In contrast to most applications, where beam lamentation and vortices are viewed as disruptive and abilized by means of conducting walls placed close to e beam, we investigate the unstabilized beam as a urce of microwaves in terawatt pulsed-power generars. The geometry treated is reminiscent of the relavistic magnetron.[14] However, the magnetron is unitable in multimegavolt pulsed-power generators beuse of cavity gap closure due to wall-emitted plasma on after the voltage pulse is delivered to the vacuum ode. Additionally, the method described does not ffer a disruption of source power due to a breakwn in magnetic insulation about a cylindrical thode, as in the case of vaned and smooth-bore magetrons. In this Letter we report the generation of miowaves from a freely propagating (along a magnetic eld) beam in the absence of conducting walls and vity vanes. The strength and duration of the microwave radiation is found to be determined by the lifetime of well-developed beam-vortex interactions. Thus, knowledge of the vortex particle dynamics and the concomitant field lines is essential to understanding the radiation observed. Detailed space-time resolution of vortex spiraling in both nonrelativistic (glass wall container) electron beams and relativistic (wall/beam radii ≈ 17) electron beams are reported.

Historically, vortex structure and vortex interactions in charged particle beams have been known since the turn of the century when Birkeland first photographed the passage of particle beams through low vacuum in his terrella cathode experiments.[15] Webster,[1] Cutler,[2] and Kyhl and Webster[3] were able to investigate thin beam vortices in fine detail by photographing low-current beams impinging on phosphor-coated anodes [Fig. 1(a)].

A linear theory by Pierce[16] based on the diocotron effect caused by the transverse shearing induced in nonneutral beams interacting with their guide magnetic fields followed these experiments. As discussed in Refs. 2 and 3, this same mechanism had been earlier suggested earlier by Alfvén in an entirely different context in connection with auroral curtains.[17] Azimuthal structure in high-current reb's have since been reported but fine-detail vortex investigation was not possible.[4-6]

The dioctron (or slipping stream) instability for beams in cylindrical geometries, with and without the presence of stabilizing walls, has been investigated in some detail.[18,19] The extension of these results into nonlinear regimes was carried out by Levy and Hockney,[20] who with 1000 electron rods of infinite axial extent, were able to obtain qualitatively correct results in diocotron-induced vortex formation in thin sheet beams. Recent investigations by Kapetanakos *et al.*[4] and Mostrom and Jones[21,22] have extended these analyses to include reb's.

In the steady state, the divergence of the electric field $r^{-1}d(rE_r)/dr = -e(n_e - n_i)/\epsilon_0$ gives rise to a shear in the drift velocity. This shear (precisely, the z

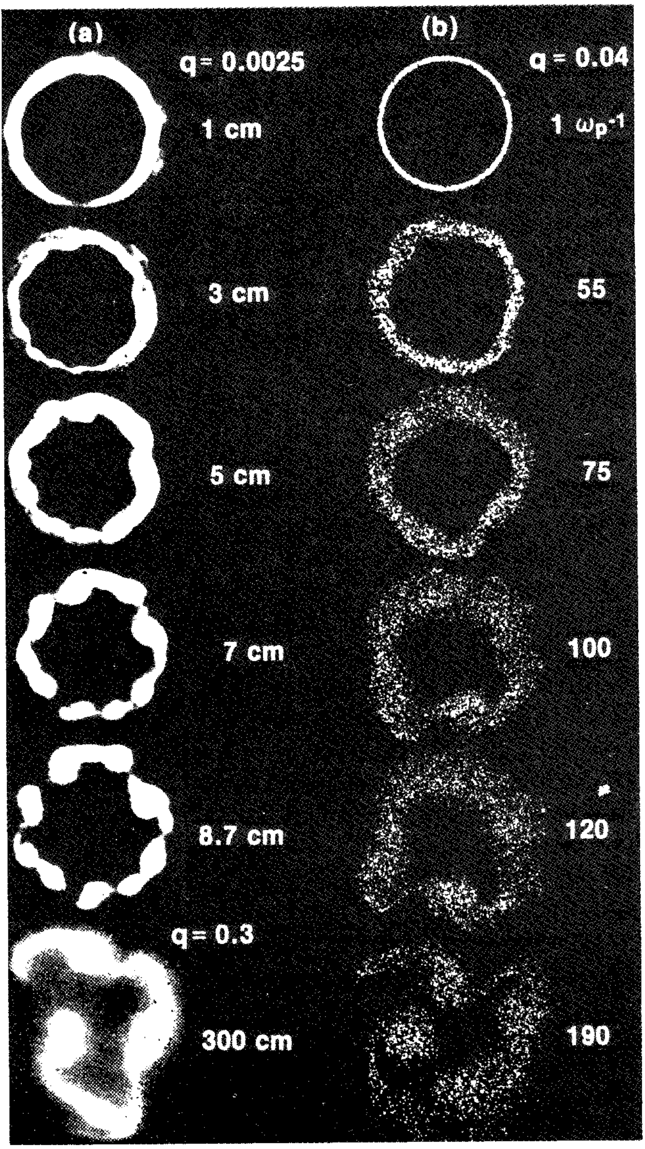

FIG. 1. Cross-sectional views of a 3.8×10^{7}-cm^{-3} beam. (a) Fluorescent-screen photographs. The patterns shown correspond to those measured at different distances for a 60-μA beam and nearly match data taken at 8.7 cm for $I=7$, 23, 42, 52, and 62 μA (Ref. 3) and 2.1 mA (Ref. 2). (b) Simulation frames. 1% of the electrons are plotted. The vorticity is clockwise for the outwardly directed B_z.

component of the vorticity) is given by

$$\omega_s=(\nabla\times v)_z=r^{-1}\partial(rE_r/B_z)\partial r$$
$$=e(n_e-n_i)/\epsilon_0B_z=q\omega_{ce}(1-f_e),$$

where $q=\omega_{pe}^2/\omega_{ce}^2$ is the cross-field electron beam parameter,[19] $\omega_{pe}^2=n_ee^2/m_e\gamma\epsilon_0$, $\omega_{ce}=eB/m_e\gamma$, $\gamma=(1-\beta^2)^{-1/2}$, and $\beta=v_z/c$ for a beam of axial velocity v_z. The factor $f_e=n_i/n_e$ represents the degree of charge neutralization. For strong-magnetic-field "low-density" beams ($q<0.1$) of thickness Δr, the instability occurs at long wavelengths $\lambda\approx(\pi/0.4)\Delta r$,[19] or at wavelengths about 8 times the beam thickness.[1] The e-folding length for instability buildup is[3, 16]

$$L=\lambda CB_zV/I, \qquad (1)$$

where C is the beam circumference, B_z is the magnetic field, V is the voltage, and I is the beam current, in mks units.

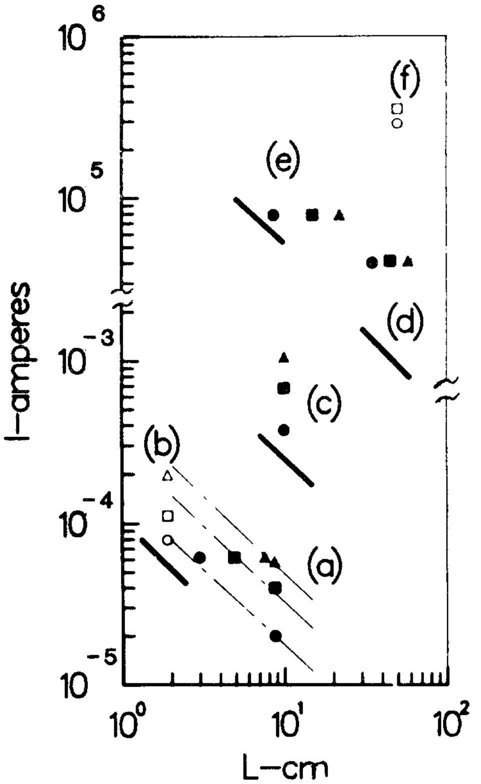

FIG. 2. Beam current vs distance for instability onset (circles), simple vortex patterns (squares), and vortex interactions (triangles). Experiment (solid symbols), simulation (open symbols), and Eq. (1) (dark lines). (a) $q=2.5\times10^{-3}$, 80 V, $l=10$, Fig. 1(a). (b) $q=0.04$, 50 V, $l=4$, $n_i=0$, Fig. 1(b). (c) $q=7.3\times10^{-3}$, 80 V, $l=10$, $p=10^{-5}$ T, Ref. 3. (d) $q=0.39$, 400 kV, $l=4$, $p=0.2$ T, Ref. 4. (e) $q=0.59$, 1.9 MV, $l=10$, $p=0.3$ T, Fig. 4. (f) $q=0.11$, 10 MV, $l=16$, $n_i=n_e$.

The advent of three-dimensional, electromagnetic, relativistic particle codes has allowed, for the first time, the simulation of *propagating* annular electron beams with and without the presence of ions in which considerable departures from azimuthal symmetry, necessary to study nonlinear vortex interactions, are resolvable. The code SPLASH is used and 250 000 particles are employed.[23] The parameter space under investigation includes q's of 1 to 0.001, time step $\omega DT=0.25$, thermal velocities $v_{\text{th}}\ll v_z$, and accelerating potentials spanning the range of 10 V to 10 MV

Figure 1(b) illustrates the time evolution of an annular beam scaled to the parameters of Fig. 1(a).

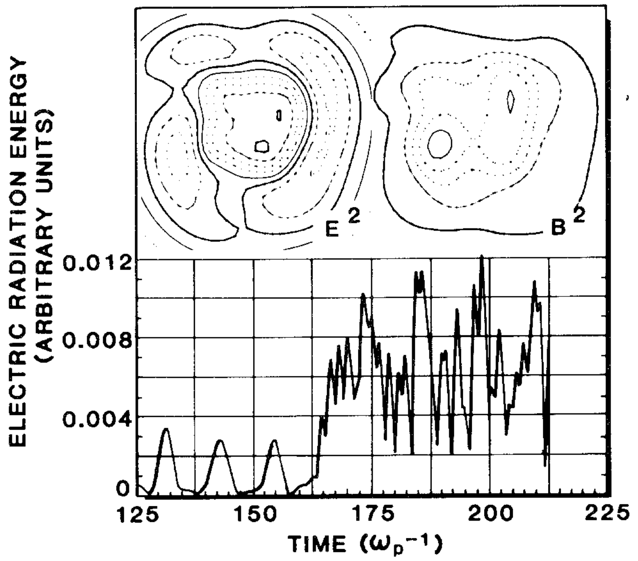

FIG. 3. Transverse electric field radiation energy vs time in ω_p^{-1}. Inset: Contours of E^2 and B^2 at $175\omega_p^{-1}$.

However, a lower value of magnetic field strength, $q = 0.04$, was used in order to reduce the simulation time to instability. As shown in Fig. 1(b), the onset of instability occurs when $\Delta r \approx 10\lambda_D$ (after expansion from an initial $2.5\lambda_D$ thickness) for a beam of circumference $314\lambda_D$ (λ_D is the electron Debye length). Thus, the number of vortices expected is $l \approx C/\lambda \approx 4$, as found in the simulation.

Figure 2 plots the current required to initiate the instability, the formation of simple vortex patterns, and the onset of vortex interactions as a function of the beam length L for a number of experimental and simulation cases. Also plotted is the linear-theory prediction for instability onset [Eq. (1)] in the absence of stabilizing walls, whose 2 to 3 times underestimation is known.[3] In all cases the evolution of the beam is the same: Charge ripples appear on the beam that cause the beam to fold into vortices along its circumference.

Microwaves from the following radiation mechanism are observed in the simulations. The initially concentric ring contours of the electrostatic field $E_r(r)$ and the induced magnetic field $B_\theta(r)$ form cross-sectional "islands" as the nonlinear state evolves. The helical electron flow in a vortex can be generalized into axial and azimuthal current components, thereby producing both long-range attractive ($F \approx -r^{-1}$) and short-range repulsive ($F \approx +r^{-3}$) magnetic forces between neighboring vortices[24] in addition to the electrostatic line-charge repulsive force [$F \approx +n_e e(1-f_e)/r$]. This effect causes the most neighborly filaments to spiral together in coalescence (when $f_e \approx 1$) and also produce microwaves from the rapid changes in the magnetic field during this process (Fig. 3, inset). The rotating vortex electrons produce a dipolelike radiation pattern polarized transversely to the axial flow.

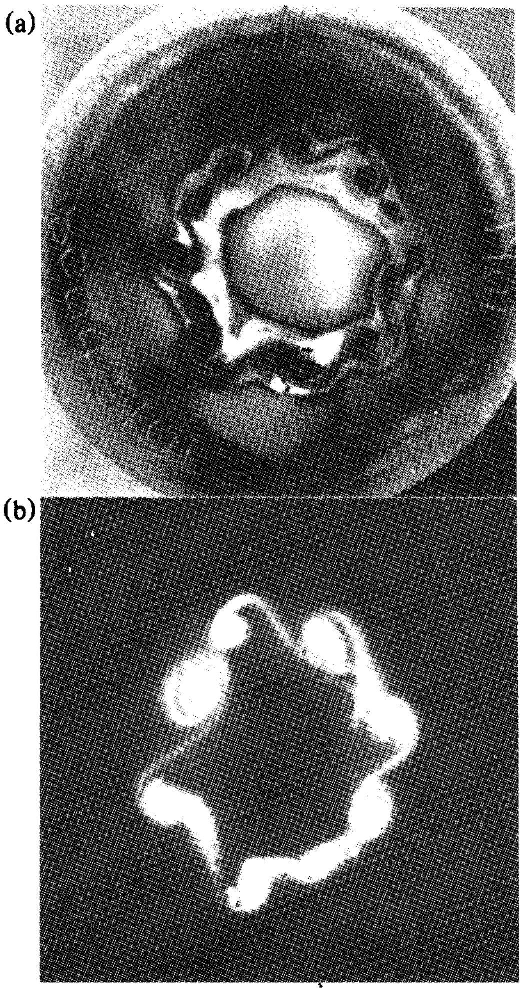

FIG. 4. (a) Vortices of 90-kA beam etched onto carbon witness plate. Data courtesy of H. Davis (unpublished). (b) Vortices of 58-μA beam photographed on a fluorescent screen. Data courtesy of H. F. Webster (unpublished).

The reb experiments were performed with the Los Alamos Physics Division pulsed-power facility. Operation is with beam energies of 1.9 MeV, diode currents up to 90 kA, and pulse durations of 60 ns. The initial beam is an annulus of 1.8 cm diameter and thickness of about 300 μm, and flows along a 20–90-kG guide field. The reb patterns are etched onto carbon witness plates. As illustrated in Fig. 4, the development of well-defined vortices is found to take place over some 12 orders of magnitude in beam current.

The radiated frequency is significantly higher than the beam rotation frequency

$$\omega_{\mathrm{rot}} = q\omega_p(1-f_e-\beta^2)(1-r_{id}^2/r^2) \approx \omega_p/13$$

within the beam where r_{id} is the inside beam radius. For a 90-kA beam, the simulations yield a fundamental microwave signal at 12.8 GHz, in agreement with K-band far-field microwave measurements.

In summary, fine-detail measurements of vortices in thin, annular, magnetized electron beams establish that the phenomenon encompasses at least 12 orders of magnitude in beam current. Microwaves from magnetic line connection in vortex interactions are observed in a configuration that is closely related to the smooth-bore magnetron. The duration and strength of the microwave signal is found to depend on ω_p/ω_c and the background pressure of the ambient medium.

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