Title
Survey of pulse shortening in high-power microwave sources

Journal
IEEE Transactions on Plasma Science, 25(2)

ISSN
0093-3813

Authors
Benford, J
Benford, G

Publication Date
1997-04-01

DOI
10.1109/27.602505

Survey of Pulse Shortening in High-Power Microwave Sources

James Benford, *Fellow, IEEE*, and Gregory Benford

(*Invited Survey Paper*)

***Abstract*—Observations show that the ubiquitous pulse shortening in high-power microwave (HPM) devices arises from the formation of plasma, electron streaming, high-E-field breakdown, and beam disruption. We review recent experiments in terms of these causes. Linear beam devices exhibit all of these mechanisms; in particular, beam disruption by $E \times B$ drifts in the strong microwave fields and diffusion in turbulent electric fields appear common. In relativistic magnetrons, the dominant effect is resonance destruction by cathode plasma motion, possibly from water contamination of the surface. Wall plasma effects shorten pulses in most sources. We call for the introduction of improved surface conditioning, cathodes which do not produce plasmas, and increased effort on the measurements of the high-field and plasma properties of HPM sources. Because of the broad nature of the phenomena in pulse shortening, we appeal for increased participation of the plasma, intense particle beam, and traditional microwave tube communities in pulse-shortening research.**

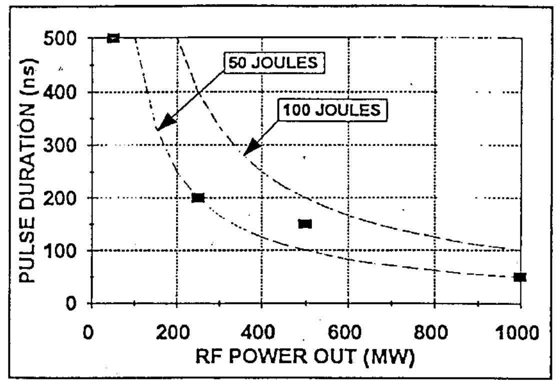

Fig. 1. Pulse shortening in the MILO. Constant energy observations are common to most HPM sources. (Courtesy of Forrest J. Agee.)

I. Introduction

HIGHER power in microwave devices reduces pulse duration, limiting present-day sources to radiated energies of a few hundred joules. For example, Fig. 1 shows roughly constant pulse energy in the magnetically insulated line oscillator (MILO) at Phillips Laboratory. Pulse shortening is the most important problem in the high-power microwave (HPM) field. Is this limitation fundamental, or can we avoid it entirely? The phenomena appear at microwave field levels of roughly 100 kV/cm. Pulse shortening is usually described as “gap closure” and “RF breakdown,” but these mechanisms do not describe the breadth of phenomena observed. (“RF” is a misnomer, for the frequencies are not radio, but microwave; “high-E field” captures the physics better.) There are several kinds of layered effects, but they first must be understood separately.

We have inherited from the microwave tube community a *plasmaless* view of sources as consisting only of electron beams, conducting structures, bunching, and radiation. Yet, pulse shortening is largely due to plasma effects. The high-energy densities of these beams produce plasma anywhere the beams terminate. Many other causes, such as X rays, allow plasma generation throughout the device. Therefore, we need to rethink how HPM sources really work, taking into account the plasma in them.

Manuscript received September 6, 1996; revised January 8, 1997.
J. Benford is with Microwave Sciences, Lafayette, CA 94549 USA (e-mail: jbenford@earthlink.net).
G. Benford is with the Department of Physics and Astronomy, University of California at Irvine, Irvine CA 92717 USA.
Publisher Item Identifier S 0093-3813(97)03786-7.

In this survey, we focus primarily on these plasma effects in HPM devices. We will show that there are several categories of mechanisms, but one way of looking at them is a general division between beam disruption and wall effects.

II. Categories of Mechanisms

Failure to properly implement the experimental design, of course, can be a cause of pulse shortening, for example, misalignment or failure to drive the source with a flat voltage pulse at the right impedance. Recent work on the MILO has increased the pulse length substantially, from 70 to 140 ns, by eliminating electron beam emission at the start of the slow-wave structure (SWS) [1]. Similarly, the Super Reltron pulse has been extended by using better materials, fabrication techniques, and conditioning [2].

We group the physical causes by which pulse shortening occurs into four basic types: plasma generation, electron streaming, high-electric-field breakdown, and beam disruption.

Plasma Generation

Anywhere plasma appears, shorting of the pulsed power or the microwave field can result. Examples are the following.

Gap Closure: Both cathode and anode plasmas can move axially and radially, resulting in a diode impedance change, which then reduces beam/wave coupling in the SWS.

Electron Beam Expansion: Electron beams generated from plasma-based sources can expand dramatically in radius because the collisional plasma from which they are extracted

0093–3813/97$10.00 © 1997 IEEE

can diffuse across transverse magnetic fields, again affecting the beam/wave coupling processes.

Beam Interception: Expanding beams intercept surfaces, for example, on the cathode side of the diaphragm surface or on the SWS. This generates moving plasma that disrupts the coupling between the beam and electromagnetic modes.

Electron Beam Collection: When the electron beam dumps onto a clean collector surface at front surface doses exceeding ~100 J/g, plasma is generated, and may stream back along magnetic field lines into the microwave generation region.

Electron Streaming

Beam electrons emitted from the cathode plasma can move upstream, away from the accelerating gap, and cause deterioration of the diode impedance characteristics. Secondary electrons from the collector may overcome the beams' potential barrier and stream into the SWS.

High-Electric-Field Breakdown

High microwave electric fields within cavity structures can produce surface breakdown which disrupts the generation of microwaves. This is highly sensitive to surface treatment in cavity structures, vacuum conditions, and any plastic components (or other hydrocarbon sources) in vacuum systems. Breakdown may occur on the output window due to surface flashover phenomena. Closely related is *Multipactoring*; microwave fields resonantly accelerate particles (field-emitted and photo-emitted electrons, ionized residual gas molecules, plasma, etc.) toward surfaces, which deteriorate under the bombardment.

Beam Disruption

Instabilities: Since beam expansion can destroy the geometry needed for emission, resonant scattering of beam electrons may be critical. This occurs most easily when the beam itself produces waves in the background plasma which are very nearly resonant with the beam velocity, i.e., those which correspond to space-charge oscillations on the beam. Instabilities previously dismissed for short-pulse experiments can develop in long pulses and decrease beam/electromagnetic structure coupling. Computer simulations have assumed azimuthal symmetry and ideal vacuum conditions. Complications of three dimensions and plasma may allow instabilities to develop over ~100 ns. The most probable interruption instability is magnetic filamentation, but it requires some background plasma for instability.

Beam Drift and Diffusion: It is clear experimentally that high microwave fields can cause transverse-beam $E \times B$ drift, beam diffusion across field lines, and eventual beam breakup. This could also arise simply by perturbing the beam electron orbits so much that they oscillate, reverse, etc., as when instability saturation occurs because of these motions, simultaneously destroying resonances with the SWS. Excited electric modes can cause cross-field diffusion. In the diode, electromagnetic fields evanescent upstream from the cutoff neck may nevertheless interact with the electron beam and beam-generated plasma in that region, causing transverse diffusion.

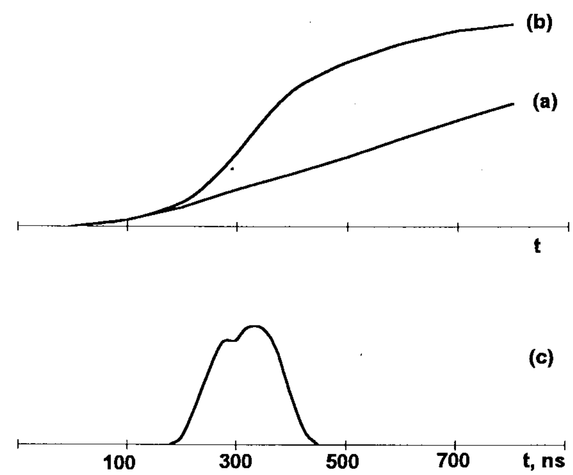

Fig. 2. Microwave discharge in the BWO. Microwave termination coincides with appearance of luminous plasma in the slow wave structure: (a) microwave generator off, (b) microwave generator on, (c) microwave pulse. From [3].

III. Linear Beam Devices

The most extensive series of experiments on the cause of pulse shortening in linear beam devices has been done by the group at the General Physics Institute (GPI), Russian Academy of Sciences, Moscow. In an extensive series of experiments, they have shown in detail that pulse shortening accompanies the sudden appearance of undesirable plasmas [3]. They use an electron beam produced in a magnetically insulated diode emerging through a graphite anode diaphragm and propagating through a slow-wave structure, ending in a horn with a vacuum dielectric window.

Electrons caused part of the pulse shortening. When a linear source geometry was used, so that the electron beam directly struck the collector, electrons scattered back from the collector, overcame the 100-kV beam potential, and traveled back along the axis outside the beam, hitting the slow-wave structure. Later, the arrival of collector plasma at about 10 cm/μs provoked a microwave breakdown and terminated the microwaves—see Fig. 2. To prevent this, the electron beam was diverted from the accelerator transversally and a magnetic trap was placed at the collector. The curvature drift in the trap prevented plasma and electrons from entering the SWS. This doubled the microwave pulse duration from 200 to 400 ns. In fact, anything that produces electrons in the slow-wave structure will terminate the microwaves because electrons moving in such a high-field region create a plasma, which is a load that absorbs microwave energy. Even very high RF fields themselves can initiate the discharge.

Plasma also contributed to pulse shortening. Cathode plasma expands both axially and radially. Axial motion can short the electron generator to the anode diaphragm if accompanied by radial motion. Transverse expansion of the cathode plasma at velocity about 0.1–0.5 cm/μs causes the electron beam to approach the slow wave structure. Microwave generation in the system cuts off when beam electrons strike the diaphragms.

Zhai *et al.* [4] reported emerging wall plasma in BWO's, measured by the appearance of spectral lines of H and C (the earliest, probably from the anode–cathode) and Cu (later, from the wall). They used optical pipes and lensing to detect optical emission from the wide and narrow portions of the BWO structure, in the eighth and ninth ripple. All neutral atom radiation appeared about 100 ns after microwave cessation, with copper from the wall 100 ns later. Emission came first from the narrow portion of the SWS. If copper plasma then moved along the magnetic field to the wide portion, the implied temperature was several kiloelectronvolts.

Later work on the same device yielded the first measurements of the microwave electric fields during the beam pulse in a plasma-filled BWO. They used forbidden Stark effect lines. Strengths as high as 34 kV/cm accompanied 75 MW extracted microwave power throughout the 60 ns power pulse, with lower frequency fields of 10 kV/cm persisting until beam shutoff, presumably from Gould–Trivelpiece modes.

Beam expansion can destroy the geometry needed for emission. One observed effect is that the high fields in the slow-wave structure cause motion of the electron beam across field lines. Fig. 3 shows the drift and diffusion of a beam transiting the GPI group BWO. Outward radial excursion increases in time for 500 ns, with beam bombardment of walls eventually ending the microwave pulse, coincident with observed X rays. Beam diffusion was also evident and of comparable magnitude, so the annular beam filled in somewhat. They show that when the SWS is hidden by inserting a metallic sleeve, cross-field drift is much smaller.

Garate and Zhai [5] observed no instability of an annular beam in a BWO, but saw both expansion and 2 mm spreading when microwave emission was enhanced by the production of helium plasma in the tube. Again, spreading was comparable to expansion so that the inner beam radius did not change, within the measured accuracy of 0.3 mm.

To analyze these effects, we assume that the electromagnetic wave in the radiating region is phase locked to the radiating electrons because such synchronization extracts energy efficiently. With wave phase constant with respect to the radiating bunched particles, the problem resembles particle drift in equivalent static fields. Diffusion will also occur in fields which affect electron dynamics randomly, producing radial motion both inward and outward for the (annular) beam. These effects have different signatures, so a beam both drifting and diffusing will show both broadening and outward motion.

Thus, the drift velocity is due to the radial drift outward in the strong-wave fields of the TM mode: $E_z \times B_\theta$. As they move along a slow-wave structure length L, drift can move beam electrons a distance

$$r = 0.33\ \mathrm{cm}\, \frac{(L/30\ \mathrm{cm})}{\left(\frac{v_b}{c}\right)\cos\psi} \left(\frac{c}{\lambda\nu}\right) \left[\frac{\left(E\Big/\frac{100\ \mathrm{kV}}{\mathrm{cm}}\right)}{(B/10\ \mathrm{kG})}\right]^2 \quad (1)$$

where $(c/\lambda\nu)$ is the ratio of light speed to the relevant wave phase velocity, ψ is the beam electron pitch angle, and v_b is the beam velocity. Equation (1) is consistent with measurements of beam growth of 0.2 cm by the GPI group. The limitations of (1) are clear: the average of $E \times B$ is used in the drift velocity calculation, and we do not know how this averages over the (probably substantially perturbed) electron orbits. Thus this is just a rough estimate using the full microwave electric and magnetic field values.

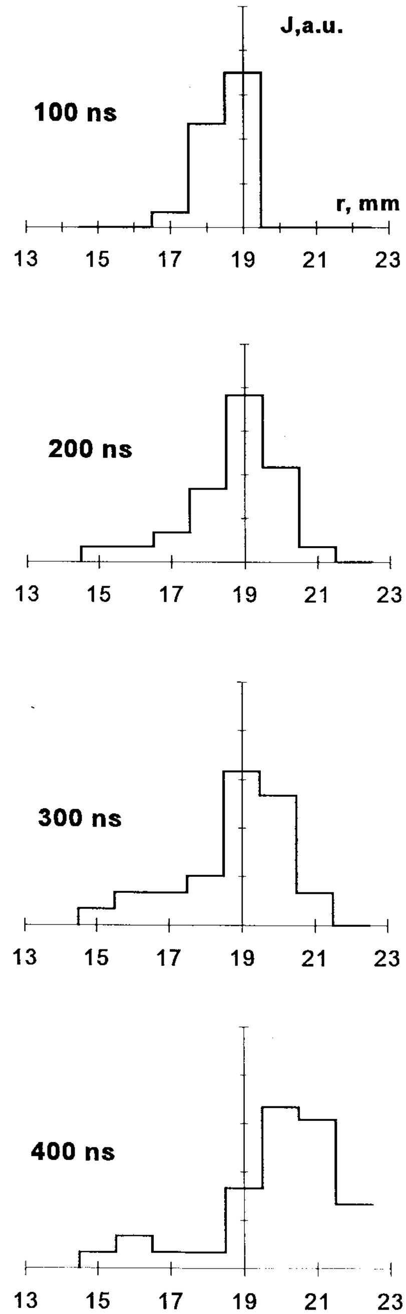

Fig. 3. Beam radial expansion and diffusion caused by high microwave fields in a BWO. Radial profile of the beam current density; cathode edge is at 19 mm. From [3].

But it does imply a constant energy scaling, in general agreement with experiments: the drift velocity is proportional to $E_z \times B_\theta$, which is proportional to microwave power P_μ. If t is the time to cross a radial or other characteristic distance D for geometry disruption, i.e., $t = (D/v_d)$, then $P_\mu t$ is constant. Therefore, microwave energy is fixed for a given device. Since source geometry is usually determined by requirements ultimately due to resonance conditions, energy is fixed for each class of source. Thus, drift due to the microwave power leads to microwave destruction, and high-power microwaves are essentially self-limited in energy.

Beam diffusion in turbulent fields should yield spreading both inward and outward. Strong turbulence theory suggests that beam–plasma instabilities growing at a fraction of the plasma frequency begin at wavelengths resonant with the beam, $\lambda \sim (v_b/\omega_p)$. At a critical strength level, wave energy begins to move to shorter wavelengths, building compact "cavitons" of high E-field. Eventually, this wave energy dissipates as heat through Landau damping, but the strongest effect on beam electrons occurs when strong turbulence is at a scale of 10–100 Debye lengths (λ_D).

Recent theory [6] predicts that beam cross-field diffusion depends only as a square root upon three related factors: d, the average correlation length, i.e., the distance over which beam electrons are acted on coherently by the resonant fields; f, the volume packing fraction of turbulence; and the system length L (usually the SWS length)

$$\Delta x = a\left[\frac{E}{10\ \mathrm{kV/cm}}\right]\left[\frac{B}{10\ \mathrm{kG}}\right]^{-1} \cdot [(d/\mathrm{cm})(L/10\ \mathrm{cm})f]^{0.5}\ \tan\ \psi. \quad (2)$$

We collapse unknown complexity of relativistic particle motion in the highly nonlinear dynamics of strong fields into the packing fraction f, a term from atomic physics, which is the percentage of the plasma volume containing high electric field strengths. The packing fraction of strong scattering fields was found by Levron *et al.* [7] to be ~0.1. It is difficult to determine d, but the 0.2 cm spreading seen by Garate and Zhai implies that if $\psi \sim 1$, the factor Lf is ~0.4 cm. This is comparable with other significant lengths, the beam electron gyroradius, and the typical scale of strong Langmuir turbulence, $\sim 100\lambda_D$. Coherence might appear on such scales, but the details are not known.

From (2), even 10-kV/cm electric fields may cause high beam spreading if $d \sim \mathrm{mm}$. Such significant expansions suggest that beam scattering alone may be the observed cause of microwave cutoff. If so, only increasing B or lowering d through more precise geometry seem to be practical cures, and may be harmful to other properties such as stability or can be expensive.

Bugaev *et al.* [8] reported beam breakup into filaments in multiwave Cerenkov generators. As the beam exits the 0.5–1 m SWS, it filaments in azimuth and spreads in radius by ~1 cm. The beam strikes and damages the SWS.

The filamentation instability is an obvious candidate to explain these observations. Yet, without plasma present, beams cannot filament. If plasma invades the resonant region or is already there (as in the plasma BWO), return currents induced in the plasma repulse the beam currents. Splitting into magnetic filaments is well known in intense beam propagation [9]. The effect grows at a substantial fraction of the beam plasma frequency, as quickly as any electrostatic instability, and can disrupt the microwave source geometry. Filamentation can be suppressed by high beam electron transverse angles. A critical current neutralization fraction $f_M = (I_r/I_b)$ determines whether or not this instability occurs; the threshold is defined by

$$\left(\frac{\omega_p}{\omega_c}\ \frac{v_b}{c}\right)^2 > \frac{1}{2f_M - 1} \quad (3)$$

with ω_c the electron cyclotron frequency and ω_p the ambient plasma frequency.

Diagnostics of return currents are difficult, so it will prove hard to estimate whether or not filamentation should occur. Generally, the earlier the plasma appears, the more likely that rising beam current will induce return currents in the plasma exceeding the critical f_M needed for filamenting to begin.

IV. Relativistic Magnetrons

Pulse shortening afflicts all high-power cross-field devices. Explosive emission generates a cool, collisional plasma near the cathode surface. Optical measurements have observed plasmas from both anode and cathode [10]. Correlation of the plasma motion with the microwave pulse shortening is difficult because the dense plasma radiating in the optical is not necessarily the plasma that determines the microwave emission boundary condition.

Recent experiments at Physics International (PI) show that the time variation of the microwave frequency is the signature of the mechanism that shortens the microwave pulse. The mechanism appears to be the motion of the cathode plasma. A sequence of modes are excited sequentially until either: 1) the resonance is destroyed: the phase velocity distribution associated with the newly excited magnetron mode changes so that it comes to have no overlap with the circulating electron azimuthal velocity distribution, ending the pulse or 2) the frequency of the next newly excited mode is below the cutoff of the magnetron output circuit, so microwaves are generated, but cannot be extracted.

With constant applied dc voltage and magnetic field, the effect of plasma expansion across the anode–cathode gap at velocity v_p is to shift ω, the electron bunch angular frequency [11]

$$\frac{1}{\omega}\ \frac{d\omega}{dt} = \frac{2v_p}{(r_a - r_c)}. \quad (4)$$

For two magnetrons at PI, both operating near 1.2 GHz over 100 ns, this effect should shift the resonant layer frequency upward by ~100 MHz. The PI group [11] observed upward shifts of ~50 MHz, consistent with this model with $v_p \sim 2$ cm/μs. Many researchers have observed $1 < v_p < 3$ cm/μs, which can be consistent with the cool $(T_i \sim 1$–10 eV) plasma we expect only if the plasma ion mass is low. This implies that the main plasma constituent is hydrogen. The source of the hydrogen plasma is either water vapor condensed on interior surfaces, hydrocarbons from O rings, or hydrogen from the lattice of the metal walls.

In the PI magnetrons, the slow-wave frequency shift due to the expanding plasma is of opposite sign to that of the electron bunch angular frequency shift. Instead of being steady, the Bunemann–Hartree resonances are time varying as described above. The higher the magnetic field, the longer the time required for the resonance to "rotate past" the operating point. To confirm this model, Price and co-workers fixed the driver voltage at 250 kV and parametrically mapped the magnetic field, and found the π-mode microwave power maximum at 1.58 kG. As the field increased above this value, the output power *should* decrease as the operating point passes to the high-field side of the Bunemann–Hartree resonance, where oscillations will not grow, but it does not. Instead, the microwaves continue to occur, but their onset time was continuously delayed as the applied magnetic field strength was increased above 1.58 kG. Clearly, the resonance condition changes with time. The data are consistent with a cathode plasma motion model with $v_p \sim 1$ cm/μs.

If residual surface water vapor is the culprit, the above plasma-driven effects can be reduced by ridding the system, especially the cathode, of water. Elevating the cathode temperature drives away water molecules and prevents their subsequent reabsorption. This should increase the effective plasma ion mass by a factor of about 10, in turn reducing the plasma expansion rate and increasing the microwave pulse length by at least 3.

V. Plasma Mechanisms in Wall Emission

The theme of this paper is that, if plasma other than the electron beam permeates the interaction volume, disruption of the microwave pulse seems likely. The most elementary version of such mechanisms is plasma emission from the walls, driven by bombarding electrons and microwave fields.

These effects do not necessarily suffice to explain microwave shutoff, although they may set the time scale. Electric fields near the walls can extract plasma, deforming cavity geometry and lowering efficiency. Secondary plasma itself adds an absorbing load which can subtract a fraction of the available microwave energy. There are reviews of these effects by Mesyats [12] and Butler [13]. We summarize the principal points.

A typical cathode plasma of density 10^{15} cm^{-3} and a few electronvolts of temperature can propagate 1 cm across the ambient magnetic field in 1 μs. This scale agrees with several measurements in the Soviet literature by Bugaev *et al.* [14], Alexandrov *et al.* [15], and Voronkov *et al.* [16] which Bugaev *et al.* [17] explained by several connected mechanisms, principally layer formation and centrifugal instability in the radial electric field. Such motion would close the diode or greatly change the microwave-generating geometry, expanding the beam at about 1 cm/μs; 1 μs for beam deformation probably defines the upper limit on microwave pulse duration set by current geometries.

Plainly, emission worsens in cavities with poor vacuum conditions, plastics, and dirty surfaces. For walls not specially prepared, vacuum discharge can begin at field values as low as 100 kV/cm. Microscopic bumps and spires on the metal surfaces can enhance electric fields by factors of 100 or even 1000. Contaminants such as oil or absorbed gases also can lower the effective work function of a metal. The field emission current J obeys the Fowler–Nordheim relation for a metal with work function $W, J = BE^2 e^{D/E}$ with the coefficients $B \alpha W^{-1}$ and $D \alpha W^{3/2}$. This strong dependence on W causes rapid changes in J as well as in response to the current itself. Typical behavior is short, explosive bursts of secondary electrons.

Once plasma emission begins, it can be amplified quickly by multipactoring. Secondaries can migrate away from the wall if the phase of the local electric field drives them outward. On the opposite phase, secondary electrons return to the wall, causing further impact ionization. Short-trajectory electrons can leave the metal, turn around, and return during the same phase. This drives an avalanche process obeying

$$N(t) = N' \frac{Act}{L}. \tag{5}$$

Here, the secondary electron emission amplification factor A has a typical range of 1.05–1.3 [12]. The number of impinging secondaries is N', and the length L is a typical distance over which secondaries return.

The upper limit of L is set by the wavelength of the fields λ, although shorter lengths are more effective. Taking $L = \lambda$, a typical time to multiply the initial secondary flux N' (typically a few per centimeter squared) by 11 orders of magnitude is about 5 ns. This is for amplification factor $A = 1.2$, a value close to that of clean surfaces used in present devices. Thus, within a few tens of nanoseconds, a substantial secondary electron cloud can appear throughout the corrugated structure. HPM devices are especially susceptible to secondaries produced by X rays; production of X rays scales as $\sim V^{2.5}$.

Other types of wall plasmas can arise from secondary-induced arcs, breakdown of dielectric films, and gas desorbtion. In <100 ns, the wall as a whole does not heat significantly, but spot eruption from secondaries bombarding with 10 kV energy can be very efficient. Still more effective are beam electrons at 700 kV, which may arrive after disruption by instabilities or scattering. At <100 kV, a single electron can still release up to ten molecules.

Above this energy, apparently the liberation scales with the net charge delivered, i.e., the current deflected from the beam. A typical gas velocity is to $V^* \sim 0.02$–0.07 cm/μs. Typical area densities of desorbed gas in even fairly clean surfaces are $N_a \sim 10^{15}$/cm^2. Then, within the time t of a microwave pulse ($t \sim 50$ ns), the gas density available for ionization by secondary electrons moving in intense electric fields is $\sim N_a/V * t \sim 10^{18} - 10^{19}$ cm^{-3}. This is a typical density expected from beam ionization of a gas at a thousand torr or more, and plainly can affect geometry and microwave absorption greatly.

Dielectric liners can allow ions to accumulate near bumps, providing sites for later microexplosions, with fast secondary emission. Ion accretion on films can reduce the minimum field needed for field emission to field values 0.1 MV/cm, which is readily available in powerful devices. Similarly, breakdown can occur preferentially at output windows in classic surface flashover effects.

Avoiding field emission from walls and cavities is difficult. Surface features (cracks, micropoints, etc.) and dielectrics (dust, thin films, oxides) can be reduced by the use of correct materials, high-temperature bakeout, and by prolonged electric field conditioning at high vacuum. Long experience by the microwave tube industry has shown the effectiveness of these techniques [18], [2]. Some examples are the following. 1) The work of Loew and Wang [19] shows that careful measures produce devices which display field enhancements from wall effects of order 40–50, i.e., effective fields well above a megavolt per centimeter. So if the effective limits of roughly 100-kV/cm fields in present-day HPM devices can be overcome, the next barrier is at fields greater than a megavolt per centimeter, a level not required by present-day applications. 2) The University of New Mexico group is studying the effect of surface coatings on pulse length in a BWO [20]. For identical beam parameters and slow-wave structure geometry, uncoated slow-wave structures yielded radiated power pulse lengths on the order of 100 ns, TiO_2-coated structures gave 150 ns, and Cr-coated structures gave pulses approaching 200 ns. Firing 10–100 pulses was required to achieve the improvement.

A cautionary note: applying fully the techniques of sealed tubes would have implications. It will stress microwave windows in both breakdown strength and bandwidth. Capital investment for furnaces and other equipment will be substantial. Operating expenses will increase if extensive conditioning is required. Flexibility may be reduced. For example, effects tests are now conducted by changing source parameters frequently; this will be difficult with sealed tubes.

VI. Conclusions

One must always keep in mind that proper construction and alignment of the source, producing an optimized device, are essential to long pulses.

Once the source is optimized, the bulk of the observations shows that most pulse shortening is due to mechanisms dependent on plasma formation. The GPI group showed pulse extension by controlling the electron flow to reduce plasma formation and backward injection of beam and secondary electrons. In virtually all contemporary HPM sources, wall cleanliness is not sufficient to prevent plasma formation from surface layers of water. Improved surface conditioning is essential to pulse lengthening; we have much to learn from the microwave tube industry. The cathode plasma formed in the explosive emission process leads to pulse shortening, so we must investigate lower velocity cathodes as well as nonplasma beam production, such as field emission arrays and ferroelectric cathodes.

Unintended electron flows, especially from the collector, must be eliminated. This generally means larger apparatus. Higher power broad-band windows are needed.

There is clear evidence in linear beam devices for beam cross-field diffusion enhanced by high microwave fields. The interaction of microwaves with the electron beam deteriorates beam quality so that it becomes unable to produce microwaves and moves radially to intercept the slow-wave structure. It sometimes causes severe breakup of the beam. Means of reducing these microturbulent effects must be found, preferably by avoiding instability onset altogether.

A simple way to reduce wall electric fields in linear beam devices lies in expanding the corrugated structure radius, thus reducing the field needed to radiate a given power. This can complicate single-mode generation, but may be justified by higher efficiency and longer pulses. More promising is multimode operation, but at a single frequency, accomplished by careful design. But the Russian work [8] shows pulse lengths still less than 100 ns, and beam disruption seems to be the cause.

Perhaps the most basic issue in any specific device lies in deciding whether or not, in a specific device, beam disruption or wall effects are dominant in pulse shortening. Only then will design tradeoffs become clearer.

We know little of the plasmas inside HPM devices. The HPM community must better measure the high E-field and plasma properties of HPM sources to better understand pulse shortening. More detailed diagnostics are needed, particularly of microwave field distributions *in situ*, plasma distribution, and velocity distribution of both electrons and ions. Nonintrusive methods have been developed for plasma physics, and should be applied to HPM.

Clearly, an understanding of the complexities of HPM sources, which contain unintended but sometimes unavoidable plasmas, will require talents from the communities of intense particle beams, conventional "tube" microwaves, and plasma physics. These groups appeared at different times in recent decades, and so speak in different jargons. We need the skills of all of these communities if we are to understand and solve the pulse-shortening problem, the most formidable obstacle to progress in high-power microwaves.

References

[1] K. Hendricks *et al.*, "Recent results on pulse sortening of GW class HPM sources," *APS Plasma Phys. Meet.*, Denver, CO, 1996.

[2] R. B. Miller, "Pulse-shortening in high-peak-power Reltron tubes," *Proc. SPIE 2843*, in press.

[3] O. T. Loza, P. S. Strelkov, and S. N. Voronkov, "Plasma in a high-power relativistic generator retarding structure," *Plasma Phys. Rep.*, vol. 20, p. 418, 1994. See also same authors, vol. 20, pp. 686–688 and vol. 19, pp. 309–311, 1993.

[4] X. Zhai, E. Garate, R. Prohaska, A. Fisher, and G. Benford, "Electric field measurement in a plasma-filled X-band BWO," *Phys. Lett. A*, vol. 186, p. 330, 1994.

[5] E. Garate and X. Zhai, private communication, 1996.

[6] G. Benford, to be published, *Phys Lett. A*, 1997.

[7] D. Levron, G. Benford, A. Baranga, and J. Means, "Diagnosing super-strong turbulence by forbidden line measurements," *Phys. Fluids*, vol. 31, p. 3026, 1988.

[8] S.P. Bugaev *et al.*, "Relativistic multiwave Cerenkov generators," *IEEE Trans. Plasma Sci.*, vol. 18, pp. 525–536, 1990.

[9] R. Miller, *An Introduction to the Physics of Intense Charged Particle Beams.* New York: Plenum, 1982, pp. 177–180.

[10] J. Benford and J. Swegle, *High Power Microwaves*. Boston, MA: Artech House, 1992, p. 162.

[11] D. Price, "Pulse shortening in tunable relativistic magnetrons," PI HPM Research Note no. 49, 1996.

[12] G. A. Mesyats, "The problem of pulse shorting in relativistic microwave generators," in *High Power Microwave Generation and Applications*, P. Caldirola, E. Sindoni, and C. Wharton, Eds. Bologna, Italy: SIF, 1992, p. 345.

[13] J. M. Butler, Ph.D. dissertation, p. 61, Cornell Univ., Ithaca, NY, 1991, p. 61.

[14] S. P. Bugaev *et al.*, "Movement of emission boundary of cathode plasma across uniform magnetic field in diodes with explosive emission," *Reports USSR Academy of Sci.*, vol. 46, pp. 78–83, 1982.
[15] A. F. Alexandrov, "Broadening of a relativistic electron beam in Cerenkov-radiation source," *Sov. Tech. Phys. Lett*, vol. 14, pp. 3499–350, 1988.
[16] S. N. Voronkov *et al.*, "Effect of the cathode plasma on the operation of a relativistic carcinatron with microsecond pulselength," *Plasma Phys. Rep.*, vol. 19, pp. 309–311, 1993
[17] S. P. Bugaev *et al.*, "Method for the propagation of the cathode plasma across the magnetic field in foilless diodes," *Sov. J. Plasma Phys.*, vol. 7, pp. 286–292, 1981.
[18] G. Caryotakis, "High power microwave tubes: In the laboratory and on-line," *IEEE Trans. Plasma Sci.*, vol. 22, pp. 683–691, 1994.
[19] G. A. Loew and J. W. Wang, "Progress report on high gradient RF studies in copper accelerator structures," *Proc 14th Int. Symp. on Discharge and Electrical Insulation in Vacuum*, 1990; also SLAC-PUB-5320, 1990.
[20] C. Grabowski and J. Gahl and E. Schamiloglu, and C. B. Fleddermann, "Pulse shortening in high power backward wave oscillators," *Proc. SPIE Intense Microwaves IV*, vol. 2843, pp. 251–259, 1996.

James Benford (SM'91–F'97) received the B.S. degree in physics from the University of Oklahoma, Norman, in 1963, and the M.S. and Ph.D. degrees in physics from the University of California at San Diego in 1964 and 1969, respectively.

In 1969, he worked at Physics International Company, founding the High Power Microwave Division. In 1996, he founded Microwave Sciences, Inc. His principal interests are HPM systems, from conceptual designs to hardware, HPM effects testing, and power beaming and advanced applications. His past experience includes work on electromagnetic launchers, pulsed power design, system studies, and the use of electron beams for many applications. He has authored over 96 papers related to his research on microwave sources and pulsed power applications.

Gregory Benford received the B.S. degree from the University of Oklahoma, Norman, and the Ph.D. degree from the University of California, San Diego, in 1967.

He spent the next four years at Lawrence Radiation Laboratory, CA, as both a Postdoctoral Fellow and a Research Physicist. Currently, he is a Professor of Physics at the University of California, Irvine, where he has been since 1971. He conducts research in plasma turbulence theory and experiment, and in astrophysics.

Dr. Benford is a Woodrow Wilson Fellow and a Visiting Fellow at Cambridge University, and has served as an advisor to the Department of Energy, NASA, and the White House Council on Space Policy. In 1995, he received the Lord Prize for contributions to science and the public comprehension of it. In 1989, he was host and scriptwriter for the television series, "A Galactic Odyssey," which described modern physics and astronomy from the perspective of the evolution of the galaxy. The eight-part series was produced for an international audience by Japan National Broadcasting. He is also the author of over a dozen novels. A two-time winner of the Nebula Award, he has also won the John W. Campbell Award, the Australian Ditmar Award, and the United Nations Medal in Literature.