General Scaling of Pulse Shortening in Explosive-Emission-Driven Microwave Sources

David Price and James N. Benford, *Fellow, IEEE*

***Abstract*— Microwave generation in devices that depend on synchronization between an electron beam and a resonant cavity or slow wave structure can be disrupted by changes in either. Explosive-emission-driven microwave sources use plasma as the electron source in the diode. This plasma is conductive enough to act as the boundary for both the applied diode voltage and the microwave electric field. The motion of this plasma can effectively change the dimensions of either the electron beam diode or the cavity and will thereby cause resonance destruction. This shortens the microwave pulse length τ_μ. A general model of the process predicts that, for a Child–Langmuir diode, microwave power will fall as $P \propto \tau_\mu^{-5/3}$ and that pulse energy will fall as $E \propto \tau_\mu^{-2/3}$. Therefore, energy efficiency declines as the pulse length is extended. We compare with data from magnetrons, MILO's and BWO's, and find that over some regions of operation the pulse length and energy from these explosive-emission-driven microwave sources agree with the plasma motion model scaling. At these applied drive voltages and output powers the microwave pulse length can be increased by finding cathode materials that generate slower plasmas.**

***Index Terms*— Child–Langmuir, diode plasma motion, high power microwave, pulse shortening.**

I. Introduction

ONE principal cause of microwave pulse shortening at high power is the presence of plasmas in the diode or interaction regions [1]. Diode plasma is the root cause of many shortening mechanisms, such as electron beam expansion, detuning of the resonances upon which the source operation depends, gap closure in diodes and beam interception along its path. Other related mechanisms are high microwave field breakdown, multipactor, and beam-plasma instability. Here we address only pulse shortening caused by plasma expansion in the accelerating gap. It is widely observed that microwave power falls as pulse duration increases, and it falls at a rate such that energy in the pulse falls as well.

We advance a general proposition that all explosive emission devices will be driven out of resonance (detuned) by plasma motion which produces either a sufficiently large change in the dimensions of the diode or a change in the dimensions of the slow wave structure or microwave cavity. Using simple models of cathode plasma motion and plasma speed dependence on diode current, we derive a scaling relation between microwave power and microwave pulse length. Both the scalings predicted here and those observed in experiments run counter to attempts to produce high energy microwave pulses by lengthening the pulse: higher energy will be obtained in shorter pulses, not longer pulses. Gains can be made by making the plasma heavier, thereby slowing down the perturbing plasma effects.

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D. Price is with Maxwell Physics International, San Leandro, CA 94577 USA (e-mail: hdprice@san.prmx.com).

J. N. Benford is with Microwave Sciences, Lafayette, CA 94549 USA.

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II. General Scaling

The simplest expression for output power, P, from any microwave source is

$$P = \eta V I = \eta V j A \tag{1}$$

with

V, I	diode voltage and current;
j	cathode current density;
A	cathode surface area;
η	electronic conversion efficiency at resonance.

We assume that the emission characteristics are represented by a general scaling similar to the Child–Langmuir relationship

$$j \propto \frac{V^n}{d^\ell} \tag{2}$$

with d the AK gap spacing and n and ℓ diode physics dependent exponents. For Child–Langmuir scaling, appropriate for parallel-field linear beam sources, $n = 1.5, \ell = 2$. For parapotential diodes, such as for most vircators and magnetically insulated line oscillators (MILO's), $n \sim 1, \ell = 1$. (Here we have approximated the voltage dependence of parapotential flow as linear, a good fit for the domain of high power microwave (HPM) experiments, where the diode voltage is typically between 300 kV and 1 MeV.) Corrections to (2) for relativistic effects and cylindrical geometry are not significant [2]–[4].

Next we make the key assumption that the microwave pulse length τ_μ, is limited by plasma expansion across the accelerating gap. In Fig. 1 this gap is in the radial direction in the magnetron and MILO, but it can be both radial and axial in the linear beam sources. In fact the radial gap in linear beam geometry is usually smaller than the axial gap, so it is crucial to the pulse shortening phenomenon. When the plasma expands across some fraction of the gap, resonance is destroyed and microwaves cease. Therefore, the microwave pulse length scales like the cathode plasma transit time across the gap

$$\tau_p \propto \frac{d}{v_p} \propto d\sqrt{\frac{m_p}{T_p}}. \tag{3}$$

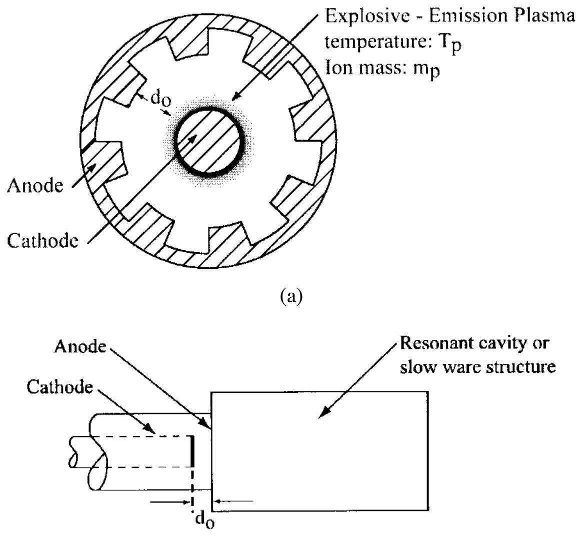

Fig. 1. The model proposed is applicable to both (a) cross-field microwave devices such as the magnetron and MILO, as well as (b) linear beam sources such as the virtual cathode and the backward wave oscillator.

T_p is the temperature of the cathode plasma and m_p is the mass of the (hottest and lightest) ion species which governs the location of the conducting surface.

Finally, following Mesyats and Proskurovsky [5], we assume that the cathode plasma temperature is derived from the joule heating due to the diode current:

$$T_p = \int_0^t \rho j^2(t')\,dt' \propto \rho j^2 \tag{4}$$

with ρ the cathode plasma resistivity. Equation (4) should be considered more a construct than a detailed theoretical model of the cathode plasma. Here we simply imagine that a number of different dissipative mechanisms (plasma expansion, radiation, electron thermal conduction) balance the joule heat flux input and rapidly establish an equilibrium temperature at a given current density level.

Combining (1) and (2) and using (4)

$$P \propto \eta j^{\frac{n+1}{n}} \propto T^{n+1/2n} \propto \frac{m_p^{n+1/2n}}{\tau^{n+1/n}}. \tag{5}$$

Using (3), the pulse-shortening relation becomes

$$\tau_\mu \propto \frac{\sqrt{m_p}}{P^{n/n+1}}. \tag{6}$$

This our basic result, which will be discussed for specific sources below.

There are two consequences of this model. The first is that the fundamental pulse length dependence on the square root of the plasma ion mass from (3) persists in the combined scaling in (6). Pulse lengths can be extended at a given power by increasing the plasma ion mass number. The second consequence is that the scaling of the pulse length with the microwave power will be

$$P \propto \tau^{-(n+1/n)}. \tag{7}$$

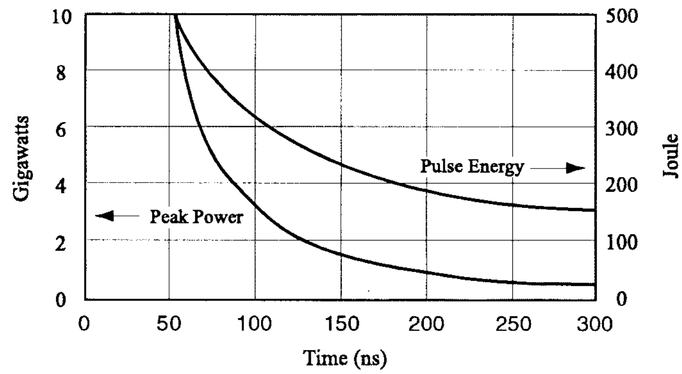

Fig. 2. Scaling of peak microwave power and pulse energy with microwave pulse length for $n = 1.5$ (Child–Langmuir). The decline in peak power with increasing pulse length is so severe that the pulse energy (the product of power and pulse length) also declines. (For parapotential diode scaling, which occurs in some types of vircators and MILO's, $n \sim 1, \ell = 1$, so $P \propto \tau^{-2}, E \propto \tau^{-1}$. Therefore, pulse energy declines with increasing pulse length in this instance as well.)

Therefore, microwave pulse energy E, the product of power and pulse length, will scale as

$$E \propto \tau^{-(1/n)}. \tag{8}$$

In this model, the energy in a pulse does not rise linearly with the pulse duration. For example, with Child–Langmuir scaling, $P \propto \tau^{-5/3}$, and $E \propto \tau^{-2/3}$. This scaling is shown in Fig. 2. To double the pulse duration requires power be reduced by a factor of 0.32, and as a result energy efficiency decreases by a factor of 0.64. Clearly, if more energy per pulse is the goal, it doesn't pay to extend the pulse duration. Contrary to expectation, energy scaling with pulse duration is not favorable; pulse shortening due to plasma in the diode drives seekers of higher energy efficiencies to shorter pulses.

III. Relativistic Magnetrons

The initial motivation behind this study was the realization that magnetron experiments conducted over the past two decades at a number of different laboratories, over a frequency range from L- to X-band fit the scaling derived above. Fig. 3 incorporates data [6] taken by eight other groups of magnetron workers besides ourselves. There is a $P \propto f^{-2}$ scaling, which fits expectations [7]. There is also a clear $P \propto \tau^{-5/3}$ dependence out to 500 ns. Therefore, the scaling of (6) and (7) is verified experimentally for $n = 3/2$, which implies Child–Langmuir scaling.

We now look more closely at magnetron data from the recently developed tunable relativistic magnetrons [8]–[10]. To begin, we must learn why Child–Langmuir scaling should apply to a cut-off device, the magnetron. So, we examine the magnetron as a diode.

Treado has shown that magnetron microwave power scales with a power of the voltage [11]

$$P \propto V^m. \tag{9}$$

For a specific magnetron we expect m to depend on geometry. If we ignore any dependence of efficiency on voltage and

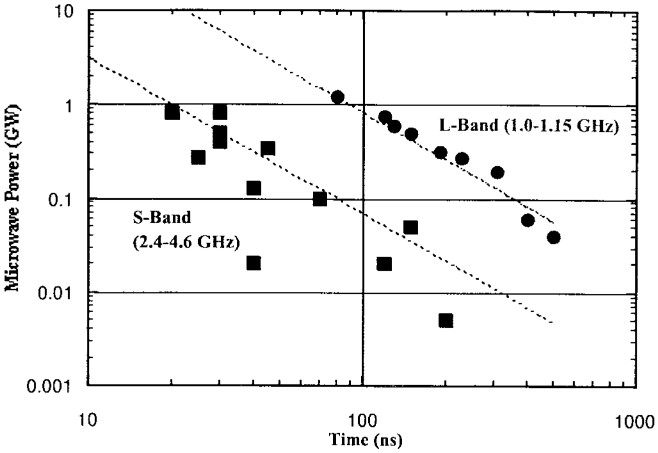

Fig. 3. Both S-Band and L-Band magnetron data from a number of different laboratories (MPI, MIT, NCSU, SRINP, NRL, Stanford Univ., Rafael, Varian and T-CSF) exhibit a power versus pulse length scaling consistent with the model (the curves are fits to $P \propto \tau^{-5/3}$) based on cathode plasma motion proposed herein.

combine (1) and (9)

$$I \propto \frac{V^{m-1}}{\eta}. \qquad (10)$$

So, in our model, $m = n+1$. To test this model against a single magnetron, Fig. 4(b) shows the power scaling of the ORION L-band magnetron at a frequency of 1.3 GHz. The points are for the highest output power at a given voltage, obtained by scanning the magnetic field. The best fit is $m = 2.52 \pm 0.32$, or $n = 1.52 \pm 0.32$, (the appended error represents one standard deviation, σ). This implies that in (2)

$$I \propto V^{1.5} \qquad (11)$$

which is Child–Langmuir scaling. This in turn implies that the relativistic magnetron operates as a space-charge limited flow device, in distinct contrast to the conventional magnetron.

The magnetron power versus pulse length data fits well with the model. For example, Fig. 4(b) also shows power scaling with pulse duration for the L-band magnetron. The best fit is for

$$P \propto \tau^{-1.59} \qquad (12)$$

which implies [see (7)] that $n = 1.69$. This roughly agrees with the value $n = 1.52$ that is derived from the power versus voltage scaling. For a larger data set we analyzed several operating points in all four of the ORION magnetrons (Table I), which span frequencies from 1.07–3.23 GHz, voltage ranges 220–500 kV, powers from 130 MW to 1.34 GW and pulse lengths from 17–85 ns. The average value for n from the six power scalings with voltage is 1.60 ± 0.43. This implies the pulse length exponent should be −1.63 ± 0.21. The independently-measured average exponent for the pulse lengths is −1.68 ± 0.23. Therefore, we conclude that the model of pulse shortening proposed here agrees remarkably with this experimental data.

The magnetron data gives $n = 1.6$, essentially Child–Langmuir scaling, indicating the cross-field flow is limited only by space-charge. This may be due the flow

TABLE I
SUMMARY OF MEASURED SCALING EXPONENTS

Magnetron	Frequency (GHz)	Slope P vs. V (n+1)	Slope P versus τ −(n+1)/n
L-band (770)	1.07–1.09	2.73 ± 0.52	−1.59 ± 0.19
L-band (770)	1.30–1.33	2.52 ± 0.32	−1.51 ± 0.30
L-band (510)	1.69–1.72	2.60 ± 0.50	−1.76 ± 0.09
LS-band (510	1.86–1.89	2.46 ± 0.35	− 1.76 ± 0.14
S-band (340)	2.29–2.36	2.74 ± 0.41	−1.79 ± 0.45
S-band (340)	3.10–3.23	2.54 ± 0.50	—————

interacting only weakly with the microwave fields and agrees with the observation that experimental values of microwave production efficiency are typically half that of theory and $\ll 1$ in all cases. The microwaves are just sufficient to allow flow across the gap but not strong enough to determine the flow. The inhibition of flow is caused, as in typical intense diodes, by space-charge.

IV. MILOS

The magnetically-insulated line oscillator (MILO) is a crossed-field device like the magnetron, but with the insulating field provided by the source current itself. Plasma is created by the cathode and by electrons impinging on the slow wave structure. Plasma in either region can, if the density is sufficient, cause geometry changes as the pulse proceeds. The sensitivity to geometry is greatest in the slow wave structure, where microwave fields are high.

There is evidence of mode shifts that are accompanied by power changes in the MILO because different modes have different electronic efficiencies [13]. We have taken a sample of high power MILO data, courtesy Mike Haworth, and analyzed it as shown in Fig. 5. The diode voltage exponent is $m = 2.66 \pm 0.13$, implying $n = 1.66 \pm 0.13$. Again we see Child–Langmuir behavior. From (7), for this n, the pulse length exponent should be -1.60 ± 0.05. The fit from the pulse length data gives an exponent of -1.24 ± 0.18. Therefore, the data agrees with the model within 2σ. The increased scatter in the MILO data may indicate that several different pulse shortening mechanisms are competing. Alternately, choosing only the maximum power at each pulse length produces an observed scaling much closer to the expectation $P \propto \tau^{-1.6}$.

V. BACKWARD WAVE OSCILLATORS

The backward wave oscillator (BWO) consists of a foilless diode that injects a thin annular beam into a slow wave structure (SWS). The beam couples to the microwave fields in the SWS most efficiently if it skims the wall closely. Cathode plasma expands axially (along magnetic field lines) at fairly high speed and radially (across field lines) at lower speed. Closure of the accelerating gap due to the axial plasma motion would occur on a timescale far too long to account for the observed pulse shortening. However, the radial plasma motion can expand the beam's annular width, changing the BWO coupling efficiency and therefore changing the microwave power.

Even though the BWO is very different from the cross-field devices, both geometrically and with regard coupling physics, the BWO may fit the relations of the general model that we

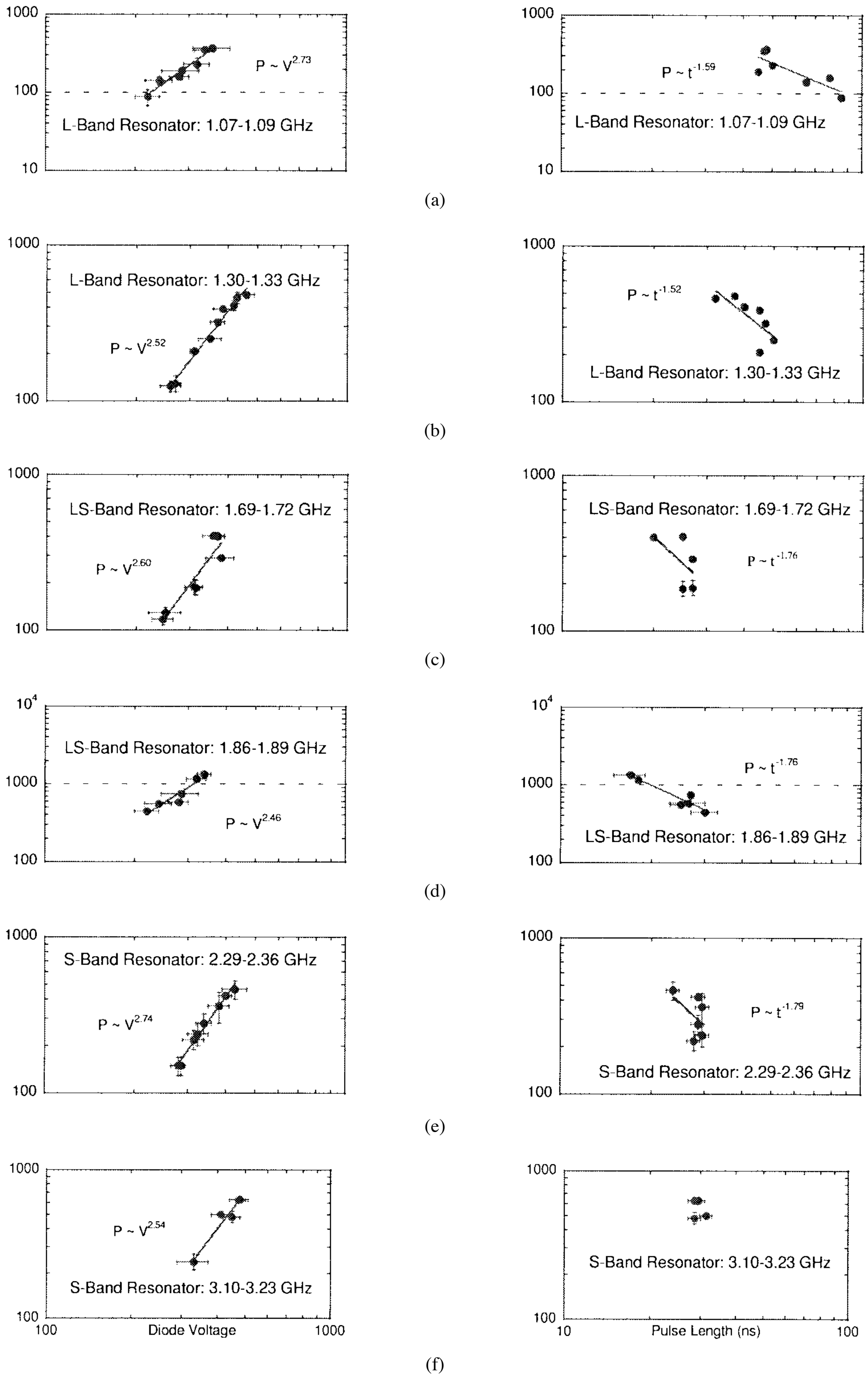

Fig. 4. Microwave power (MW) versus diode voltage (kV), and microwave power versus microwave pulse length (ns) scalings for a suite of four tunable relativistic magnetrons. Power law fits to the data are summarized in Table I.

propose. As voltage and current are raised to produce higher power, the higher currents in the diode cause faster radial plasma expansion and shorter pulses. Equations (1)–(3) should still apply, with the gap in (3) the BWO diode's radial gap. The foilless diode operates with a Child–Langmuir characteristic, so the model predicts $P \propto \tau^{-5/3}, E \propto \tau^{-2/3}$.

Fig. 6 shows data from a 3 GW BWO at the Institute for High Current Electronics at Tomsk [14]. For the lower powers, up to about 2 GW, the scaling is: $P \propto \tau^{-1.63}$, corresponding to $n = 1.59$, which fits the Child–Langmuir expectation ($n = 1.5$) well. Above 2 GW, the scaling is: $P \propto \tau^{-0.50}$. Clearly, another mechanism (with a different

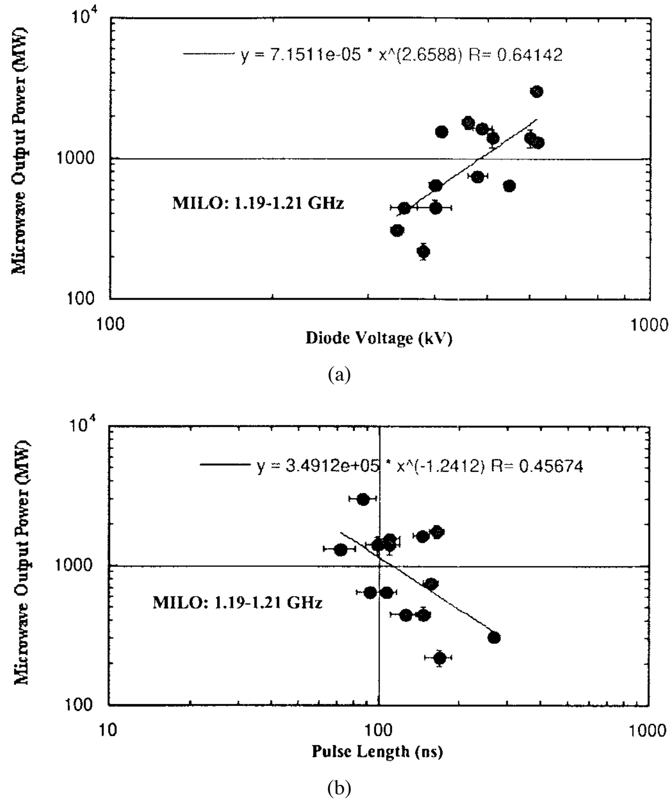

Fig. 5. (a) Microwave power versus diode voltage and (b) microwave power versus microwave pulse length scalings for an L-Band magnetically-insulated line oscillator.

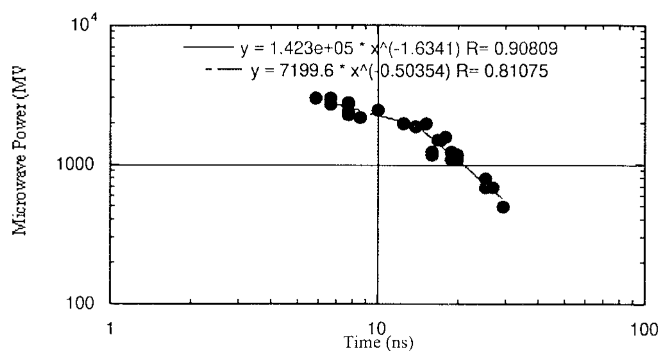

Fig. 6. Microwave power versus microwave pulse length scaling for an X-Band backward wave oscillator.

characteristic scaling) operates at higher powers and depresses the power relative to the plasma motion model prediction. RF breakdown *is* the likely culprit. The exponent in this measured BWO power versus pulse length scaling, −0.50, is close to the range −1/2—−1/3 that is normally [15], [16] observed when RF breakdown at the output gap limits the microwave pulse of high power klystrons. The data in Fig. 6 suggest that the power saturates in the experiment of Gunin *et al.* above 2 GW when RF breakdown takes over.

Gunin *et al.* assume that the pulse shortening mechanism in their experiment is microwave induced explosive emission in the SWS. At 3 GW, the very high microwave fields in the SWS (∼1500 kV/cm) make the mechanism plausible. The scaling for this mechanism, from Mesyats and Proskurovsky [17], is $P \propto \tau^{-2/3}$. The data in Fig. 6 do not fit such a scaling. More observations on BWO's will be required to sort out the precise mechanism that causes the pulse shortening at lower powers. Currently, some manifestation of RF breakdown appears to limit the BWO pulse length at its highest achievable output power levels.

VI. Reltrons

The reltron, a klystron variant, is not as vulnerable as the BWO to the radially expanding plasma mechanism that we are modeling. In the reltron the beam is launched far from the wall of the modulating cavity because it couples to a cavity mode which peaks on axis. Therefore, radial plasma motion will take much longer to affect microwave operation. Changes due to axial motion in the diode will be small because the gap is large (the reltron operates at low current density, ∼10 A/cm^2). Therefore, we expect the above model to not apply.

This agrees with observations by Miller [18]; no dependence of power on pulse duration. (But, plasma generally being a problem in HPM devices, there is a second effect produced by plasma motion seen during the conditioning procedure. Plasma from the grids of the modulating cavity change its length and therefore its Q. This causes an upward frequency chirp which if not treated would eventually carry the bunched beam frequency outside the passband of the extraction circuit.)

VII. Vircators

The basic virtual cathode oscillator or vircator, has the disadvantage that the region downstream from the diode is highly overmoded, i.e., it can support many modes and the mode density is high. As the diode gap closes due to cathode and anode plasma expansion, the decreasing impedance allows the current to increase, in turn increasing the electron beam plasma frequency, ω_p. The virtual cathode oscillations vary with this time-changing frequency and couple to different modes (closely located or overlapping in frequency) as the pulse proceeds. The resulting chirping waveform has been observed and documented by many experimenters.

The cavity vircator [19], [20] restricts the oscillation to a single mode and produces higher efficiency and a narrower bandwidth (Fig. 7). The commercial version is a right circular cylinder, tunable at one end [21]. The resonance is produced by tuning a cavity TM_{01p} mode ($p = 1, 2$, or 3) such that the virtual cathode frequency, $f_{vc} = \omega_p/2\pi$, and the resonant cavity mode frequency, f_{rc}, are equal.

This effect of plasma changing the beam-cavity resonance condition is akin to the magnetron pulse shortening mechanism. The vircator diode operates in the parapotential mode, so $n = 1, \ell = 1$. Therefore, the above model predicts that $P \propto V^2$ and $P \propto \tau^{-2}$. There are also vircators with strong magnetic guide fields, which operate as a Child–Langmuir diode, and so should scale the same as the magnetron. We know of no data to compare to either of these predictions.

Using the basic assumptions of our model we can derive an expression for an upper bound on the cavity vircator output pulse duration τ_μ. Microwave oscillations persist until the chirping virtual cathode frequency moves through the cavity

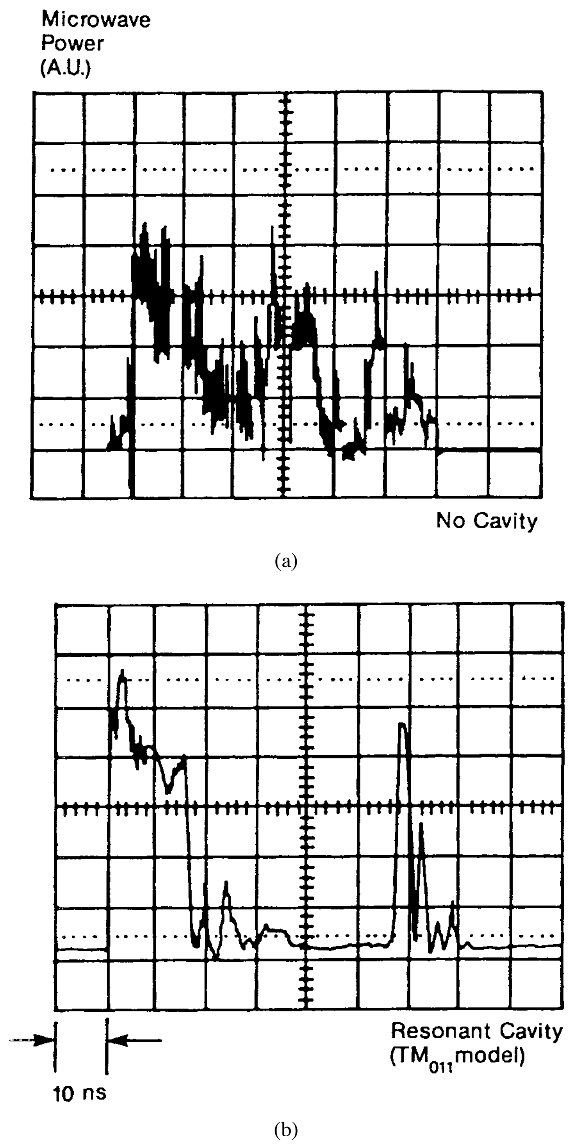

Fig. 7. Data (from [19]) showing the (a) overmoded and (b) resonant cavity vircator output pulses. The cavity vircator microwave pulse width decreases (relative to the free-running, overmoded configuration) as the virtual cathode frequency chirps to a region of frequency space that the cavity boundary conditions cannot support.

mode bandwidth $\Delta f_{vc} = f_{rc}/Q$ (where Q is the cavity mode's loaded quality factor):

$$\tau_\mu = \Delta f_{vc}/(df_{vc}/dt). \tag{13}$$

An expression by Woo for the vircator frequency, using parapotential flow in the diode, compares well with observation [22]

$$f_{vc}(\text{GHz}) = \frac{4.77}{d(\text{cm})} \ln\left(\gamma + (\gamma^2 - 1)^{1/2}\right). \tag{14}$$

Using (14) along with the usual linear model for the effects of plasma closure at speed v_p on the original gap d_o:

$$d(t) = d_o - v_p t \tag{15}$$

the pulse length can be simply expressed

$$\tau_\mu = 4.77 \ln\left(\gamma + (\gamma^2 - 1)^{1/2}\right)/Q v_p f_{vc}. \tag{16}$$

Since the gap is collapsing, we have the inequality

$$\tau_\mu \leq \frac{d_0}{Q v_p}. \tag{17}$$

This relation assumes implicitly that the external Q is low so that cavity fill and ring-down times are short compared to the microwave pulse length. For experimentally-measured values of Q (20–100), v_p (1–3 cm/μs) and f_{vc}, the predicted values of μ (10–300 ns) are in agreement with the observed values (20–500 ns) [18], [19].

As in the magnetron case, microwave pulse lengths can be extended if successful measures are taken to slow the plasma expansion speeds. Pelletier [23] achieved microsecond vircator operation by constructing a 550–750 MHz vircator. The large AK gaps (7–10 cm) and velvet cathodes running at low voltage (<340 kV) and low current density ($\sim$10 A/cm^2) resulted in slow closure speeds ($v_p < 1.6$ cm/μs). In experiments with about 10 times higher current densities, good vacuum has been shown to be essential for long pulse operation. Poulsen [24] achieved three-fold improvements in pulse length by prepulsing the anode and pumping the desorbed hydrogen gas and water vapor with liquid nitrogen-cooled surfaces.

VIII. Conclusions

The agreement between this analytical model and the measurements on a large variety of magnetrons and a single BWO experiment supports the hypothesis that cathode plasma motion is a culprit causing pulse shortening observed in many types of high power microwave sources. Above 2 GW, the BWO scaling changes and perhaps is due to RF breakdown. The MILO does not fit the model as well. We predict scaling for both versions of the vircator (with either the parapotential diode or the Child–Langmuir diode [zero and large magnetic guide field]). The model should not apply to the reltron and no such scaling is seen.

An implication of the model (6) is that the mass of the material causing diode gap closure is a key determinant of pulse duration. Three clear ways to extend the microwave pulse duration are: 1) to reduce the plasma temperature by decreasing the current density, 2) to eliminate the plasma, or 3) to increase the plasma ion mass. The first tack leads to either large devices with large cathodes at moderate impedances or higher impedance designs that require high voltage (>1 MV) in order to obtain high power. The second tack requires the development of high current density cathodes that do not rely on explosive emission. As for the third tack, most HPM source experiments have not had wall cleanliness sufficient to prevent the plasma formed by explosive emission from being determined by contaminants. The usual surface layer of water and hydrocarbons is quickly disassociated into hydrogen and other light elements. The lightest, fastest atoms determine the plasma speed. Therefore, improved surface conditioning is essential to lengthening pulses. From Equation (6), using heavier cathode materials will increase pulse energy. Some success with this approach has been reported with carbon fiber doped with Cesium Iodide [25], [26].

The model of pulse shortening scaling proposed here agrees remarkably well with a variety of HPM devices. We urge other workers to compare their data with this model and to produce models of the other pulse shortening mechanisms.

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David Price received the B.S. degree in mathematics from the University of California, Davis, in 1974 and the M.S. and Ph.D. degrees in nuclear engineering from University of California, Berkeley, in 1979 and 1982, respectively.

After working in the controlled thermonuclear fusion community at UC Berkeley, LLNL, and GA Technologies, he joined the HPM-directed energy group at Physics International, San Leandro, CA, in 1985. His recent work has focused on the development of high peak and high average power microwave sources, including vircators, relativistic and conventional magnetrons, and low perveance klystron amplifiers. He is currently the Maxwell HPM Division Manager.

James N. Benford (SM'91–F'96) received the B.S. degree from the University of Oklahoma, Norman, in 1963, and the M.S. and Ph.D. degrees from the University of California, San Diego, in 1965 and 1969, respectively.

He founded Microwave Sciences, Inc., Lafayette, CA, in 1996. He also founded the High Power Microwave Division at Physics International Company, San Leandro, CA. His principal interests are HPM sources from conceptual designs to hardware, HPM power beaming and advanced applications. In the 1980's, he co-authored *High Power Microwaves*, the basic text in the field, and has authored 101 papers on pulsed power, microwave sources and applications. He's been active in teaching HPM in the United States and abroad.

Dr. Benford was he was elected a Fellow of the IEEE in 1996. The citation reads "For development of high power microwave sources and for transferring this technology into custom products."