Pulsed Power-Driven High-Power Microwave Sources

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Invited Paper

The advent of pulsed power technology in the 1960s has enabled the development of very high peak power sources of electromagnetic radiation in the microwave and millimeter wave bands of the electromagnetic spectrum. Such sources have applications in plasma physics, particle acceleration techniques, fusion energy research, high-power radars, and communications, to name just a few. This article describes recent ongoing activity in this field in both Russia and the United States. The overview of research in Russia focuses on high-power microwave (HPM) sources that are powered using SINUS accelerators, which were developed at the Institute of High Current Electronics. The overview of research in the United States focuses more broadly on recent accomplishments of a multidisciplinary university research initiative on HPM sources, which also involved close interactions with Department of Defense laboratories and industry. HPM sources described in this article have generated peak powers exceeding several gigawatts in pulse durations typically on the order of 100 ns in frequencies ranging from about 1 GHz to many tens of gigahertz.

Keywords*—*High-power microwave (HPM), intense electron beams, pulsed power.

I. INTRODUCTION

Research on the interaction of charged particle beams with electromagnetic fields is of considerable interest for various problems of plasma physics and chemistry, astrophysics, particle acceleration techniques, fusion energy research, high-power radar, and communications, as well as for defense applications. One of the directions of this research is the study of stimulated electromagnetic emission from electron beams and the development of powerful radiation sources over a wide range of wavelengths (frequencies) and pulsewidths. High-current electron beam accelerators having pulsed powers up to 10^{13} W present unique opportunities for these applications.

The first attempts to use high-current electron accelerators for the production of intense microwave radiation were made in the late 1960s, following the emergence of modern pulsed power. However, the first major result was obtained in 1973 in a joint experiment between the Institute of Applied Physics, Nizhny Novgorod, Russia, and the Institute of General Physics, USSR Academy of Sciences, Moscow [1]. In this collaboration, microwave pulses with $\sim 4 \times 10^8$ W peak power and $\sim$3-cm wavelength were generated. Comparable results were obtained subsequently at Cornell University, Ithaca, NY [2].

The maximum power of high-power microwave (HPM) pulses produced to date using pulsed power-driven intense electron beams in the centimeter and decimeter bands is 10^8–10^{10} W. Various mechanisms of HPM generation have been demonstrated: Cherenkov, transient, and various Bremsstrahlung radiation interactions. The most well known are the following HPM sources: the relativistic backward-wave oscillator (BWO), or carcinotron [1]–[4]; the multiwave Cherenkov generator (MWCG) [5], the relativistic klystron oscillator (RKO) and amplifier (RKA) [6]–[8]; the Reltron [9]; the plasma Cherenkov generator [10]; the Plasma-Assisted Slow-Wave Oscillator (PASOTRON) [11]; the relativistic magnetron [12]; a generator based on a magnetically insulated line [Magnetically Insulated Line Oscillator (MILO)] [13]; and generators based on an oscillating virtual cathode (vircators) [14]–[16].

An important problem for relativistic sources of HPMs, which increasingly use, as a rule, oversized (overmoded) electrodynamic systems, is to provide spatially coherent radiation. Many special methods of mode selection were developed [17] that facilitate the generation of gigawatt-level output power from relativistic oscillators and amplifiers. To name just a few: the cyclotron-resonance method [18] demonstrated in

Manuscript received February 9, 2004; revised March 8, 2004.
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Digital Object Identifier 10.1109/JPROC.2004.829020

a BWO using a weak guide magnetic field; application of sections with different symmetries demonstrated in cascade oscillators with premodulation of an electron beam and resonant traveling-wave tube (TWT) [19], in a BWO with a selective mode converter instead of a cutoff neck [20], and also in a gigawatt amplifier [21]; and the promising method of multichannel feedback [22], which could be demonstrated in oscillators such as a resonant TWT.

Mechanisms of stimulated electromagnetic emission by intense electron beams and many experiments in HPM production using generators and amplifiers are reviewed in the book series *Relativistic High-Frequency Electronics* published by the Institute of Applied Physics, Russian Academy of Sciences, collecting material from a regular Russian workshop of the same name [23], as well as in books and review articles [12], [14], [24], [25] published in the United States. A premier forum for archiving the latest advances in this field is the biennial Special Issue of the IEEE TRANSACTIONS ON PLASMA SCIENCE dedicated to HPM generation, with the next Special Issue appearing in June 2004.

This article presents a glimpse of recent ongoing activity in this field in both Russia and the United States. In Russia, we focus on the activities at the Institute of High Current Electronics, Siberian Branch of the Russian Academy of Sciences, which specializes in the use of SINUS pulsed power accelerators for HPM production, among other applications. For research activities in the United States, we focus on the HPM source research that was supported by, or affiliated with, a five-year DoD/AFOSR Multidisciplinary University Research Initiative in the second half of the 1990s, and their subsequent follow-up efforts. The interested reader can consult the references, particularly [12], [14], [24], and [25], for information that is of a more tutorial nature.

II. HPM SOURCES DRIVEN BY SINUS ACCELERATORS

A. *High-Current Nanosecond Electron Accelerators for HPM Production*

For investigations in the field of HPM production, a series of repetitive pulsed electron accelerators called SINUS were developed at the Institute of High Current Electronics, Siberian Division, of the Russian Academy of Sciences. The design of the accelerators includes a Tesla transformer as a charging device, a long oil-insulated coaxial line playing the role of a pulse-forming line (PFL) as capacitive energy store switched using a two- or three-electrode gas gap high-voltage switch, and a long nonuniform transmission line to match to a magnetically insulated coaxial vacuum diode with a cold explosive-emission cathode.

On the basis of years of research and development, a series of high-current, repetitively pulsed accelerators has been developed, having electron energy ranging from 0.2–2.0 MeV, a beam current of 0.2–20 kA, a pulsewidth of 4–130 ns, pulse-repetition rates up to 1000 pulses per second (pps), and average power up to 200 kW. These accelerators are compact and reliable. Further increase in the pulse-repetition rate and high-voltage pulse reproducibility can probably be achieved by using semiconductor switch-based modulators [26].

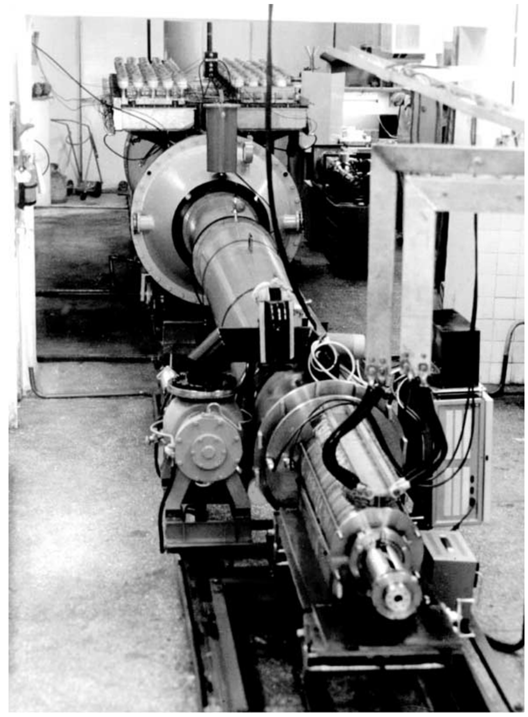

Fig. 1. The SINUS-7 electron beam accelerator.

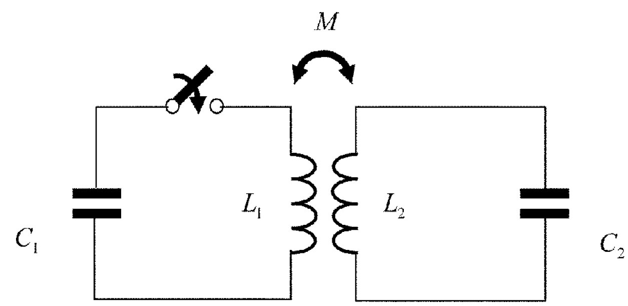

Fig. 2. Electrical circuit of the Tesla transformer.

Fig. 1 shows one of the most powerful high-current electron accelerators, SINUS-7, using transformer charging of a coaxial PFL. Its maximum electron energy is 2 MeV, the beam current is 20 kA, and the pulsewidth is 50 ns.

1) Tesla Transformer: The Tesla transformer, a system of two inductively coupled circuits (Fig. 2) with equal resonant frequencies $(1/\sqrt{L_1C_1} = 1/\sqrt{L_2C_2})$ operating in the free oscillation mode transforms a constant or quasi-constant low voltage into a high-voltage pulse. The maximum efficiency of energy conversion in a Tesla transformer can only be achieved for certain values of the coupling coefficient $k = M/\sqrt{L_1L_2}$. The optimum k is defined by the relationship

$$k = k_{\text{opt}} = \frac{2N}{N^2+1} \tag{1}$$

where N is an odd integer; in particular, for $N = 1,\ 3,$ and 5, we have $k_{\text{opt}} = 1,\ 0.6,$ and 0.385, respectively. The quantity $(N-1)/2$ determines the number of changes in the polarity of the charge voltage during the charging time of the energy store. For $1-k \ll 1$, charging may occur without a change in the charging voltage polarity.

In order to increase the electrical strength of the PFL and provide the possibility of using a thyristor switch in the primary circuit of the Tesla transformer, its coupling coefficient is taken close to unity in the SINUS accelerators. To increase the coupling coefficient, an open ferromagnetic core built in the PFL is used. In this case, the value of the coupling coefficient is independent of the properties of the core material and is completely determined by the geometrical parameters of the PFL. In particular, when the length of a coaxial PFL is much greater than its radius

$$k^2 \approx 1 - \frac{4}{3}F(\beta)\left(\frac{r_2}{L_{\mathrm{PFL}}}\right)^2 \tag{2}$$

where L_{PFL} is the length of the PFL; $F(\beta) = a((\beta-1)(3\beta+1)/\beta^2)\ln\beta$, $\beta = r_2/r_1$, r_2 and r_1 are the radii of its outer and inner conductor, respectively; and a is a factor depending on the geometry of the Tesla transformer secondary winding. For actual accelerators, the coupling coefficient is typically 0.85–0.95. This allows charging of the PFL during the first half-period of the charging voltage with rather high energy efficiency. The operating voltage of the primary capacitive energy store does not exceed 1 kV.

2) PFL: The choice of electrical and geometrical parameters of the PFLs in the SINUS accelerators is made accounting for the amount of stored energy, energy losses during the charging of the line, as well as specific conditions of electron beam formation and transportation. For the most applications of repetitively pulsed high-current accelerators, the impedance of the vacuum diode R_d is the load of the PFL during its discharging and may be considered as a specified parameter. The impedance value depends on specific conditions of the accelerator operation.

The maximum value of potential at the cathode of the vacuum diode φ_c may be achieved with R_d being varied over a wide range if there is a mismatch between the PFL and the vacuum diode. This results in a decrease in the efficiency of the conversion of energy stored in the line into the energy of the electron beam, resulting in the appearance of a series of reflected pulses. One of the possible solutions to this problem is to use matching devices. In this case, for a specified value of the outer dimension of the PFL and the electrical strength of its insulation, we have $\varphi_c = \varphi_c^{\max}$ for

$$\ln\beta \approx \frac{1}{2}\frac{1}{1-\beta\frac{\left(\frac{d\eta}{d\beta}\right)}{2\eta}} \tag{3}$$

where $\eta(\rho_{\mathrm{PFL}}/R_d)$ is the efficiency of energy transfer from the PFL into the load and ρ_{PFL} is the wave impedance of the line. For $\beta\eta'/\eta \ll 1$ we have $\beta_{\mathrm{opt}} \approx \sqrt{e}$, which corresponds to a wave impedance of 20 Ω for a coaxial line with oil insulation, where $\eta' = d\eta/d\beta$.

Increasing the pulsewidth of the accelerator requires using longer PFLs. In the case of relatively high resistance loads, the problem may be addressed, alternatively, by utilizing spiral PFLs. This allows an increase in the generator impedance and pulsewidth, keeping the same stored energy, with no substantial increase in the generator size [27].

3) High-Voltage Switches: For production of high-power nanosecond pulses with voltages $> 10^5$V, various types of

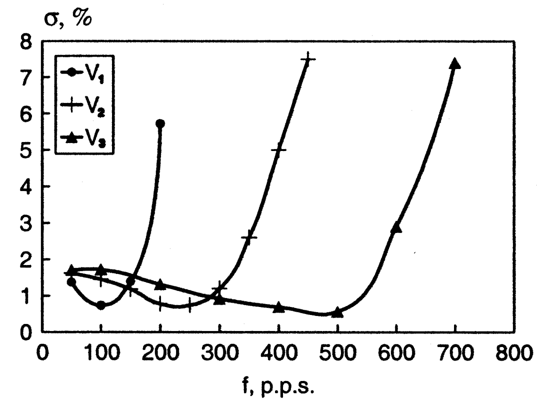

Fig. 3. Voltage instability as a function of pulse-repetition rate for different gas circulation speeds ($V_1 < V_2 < V_3$).

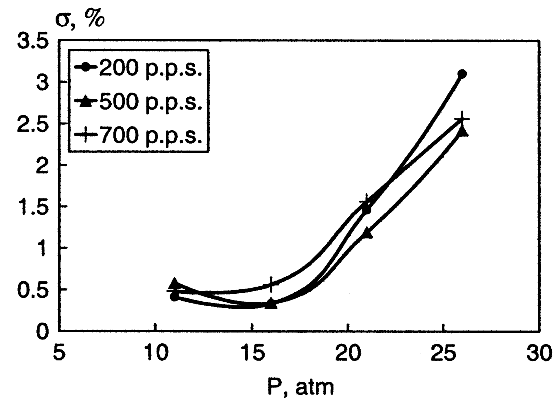

Fig. 4. Voltage instability as a function of gas pressure for different pulse-repetition rates and optimum gas flow speed.

spark gap switches, such as liquid, solid-state, and gas gap ones can be used. Gas gaps are preferable at high pulse-repetition rates when the recovery time must be short. In gas switches, it is possible to quickly sweep away the discharge by-products from the gap.

The initial attempts to increase the pulse-repetition rate of high-current electron accelerators failed. The main reason was the high-jitter operation of the high-voltage gas switches that were used. While in single-pulse mode, the instability of the switched current is typically a few percent of the total current; at $f_r > 10$ pps, it becomes greater than 10%–20%. Investigations have shown [3] that in the repetitive pulse regime, a gas (N_2) region with reduced electrical strength appears in the interelectrode gap of the switch whose position (with respect to the electrodes) varies due to the convective motion of the gas. This causes considerable destabilization of the gas switch operation at pulse-repetition rates higher than 10 pps. To eliminate this effect, forced renewal of gas between electrodes is used in the SINUS accelerators. The gas flow velocity is such that during the interpulse period, the main part of gas in the interelectrode gap is displaced by a distance of the order of the electrode radius where the properties of this gas no longer affect the switch operation. Experiments [3] have shown that the optimum gas flow velocity is $V_{\mathrm{opt}} \approx Rf_r$ where R is the electrode radius. For this case, the relative standard deviation of the switch current pulse amplitude from its average value is of the order of 10^{-2} (Figs. 3 and 4) [28].

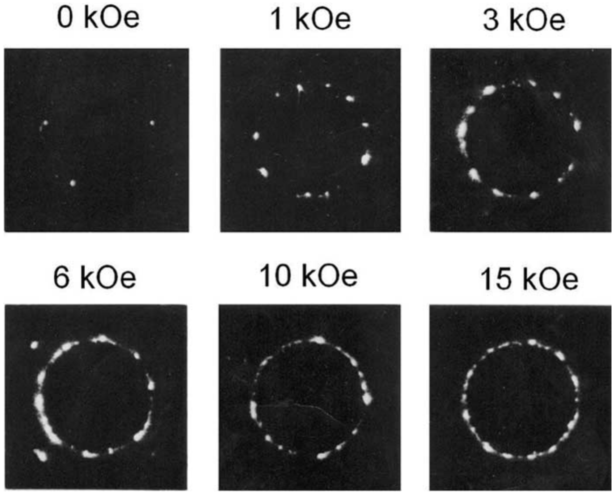

Fig. 5. Photographs of the cathode emitting surface for different values of magnetic field strength.

4) Vacuum Diode: The type of vacuum diode used in an accelerator, its impedance, geometrical dimensions, electrode configuration, and other characteristics depend on the specific applications of the accelerator. For example, high-current electron accelerators used to produce HPM with Cherenkov sources generally use magnetically insulated coaxial diodes.

One of the specific features of high-current electron accelerators is the use of cold explosive-emission cathodes [29]. Unlike conventional cathodes, the emission area of a cold cathode is formed under the action of the electric field applied to accelerate the charged particles. The emission area of a cold cathode consists of numerous plasma "blobs" at the cathode surface, appearing under the action of electric field over a finite time [29]. The conditions for plasma generation at the cathode surface may vary as a result of a variation in the cathode microstructure or modification of the surface by ion bombardment, temperature effects, and the like. This generally shortens the lifetime of a cathode. The lifetime is also affected by various external factors such as electric field strength in the vacuum diode, the presence of an external magnetic field and its magnitude, vacuum conditions in the diode, the cathode material, etc.

The formation of emission area in a coaxial vacuum diode is affected considerably by the magnitude of the external magnetic field that is applied. Fig. 5 presents six photographs of an emitting cathode immersed in magnetic fields of different strengths. The discrete character of the emission area seems to be caused by the so-called screening effect [29]. The delay time for the appearance of plasma flares at the cathode is strongly dependent on the electric field strength. The electron space charge reduces the electric field near the leading emission centers, thereby screening the emitting region and impeding the birth of new plasma blobs. The geometrical dimensions of the screened area determine the scale of nonuniformity for the electron beam L. Direct measurements show $L \approx r_H$, where r_H is the Larmor radius of electrons near the cathode surface.

Fig. 6. Metal-dielectric cathode.

A coaxial vacuum diode operating in single-pulse mode may use cathodes made of various materials, such as copper and steel, among others. Under these conditions, individual properties of the cathode material do not manifest themselves. The key role in initiation of the explosive emission is played by natural contamination of the cathode surface: dielectric inclusions and adsorbed gas. At a high pulse-repetition rate and after 10^3–10^4 pulses and more, cleaning of the cathode surface occurs. For most materials, this causes worse emission properties: increased time for the first emission centers to occur and a decrease in their number [29]. For high pulse-repetition rates, the best results were obtained with graphite cathodes [14]. For electron energy of ~ 500 keV, beam current of ~ 5 kA, cathode current density of 10 kA/cm^2, and pulse duration of ~ 20 ns, the lifetime of graphite cathodes exceeds 10^8 pulses. Limitation of the cathode lifetime is due to material erosion ($\sim 1.7 \times 10^{-4}$ g/Coulomb for graphite [29]).

In planar vacuum diodes, the current density is much lower than in coaxial diodes and typically is between 1 and 100 A/cm^2. Therefore, the cathodes in such diodes should operate at lower electric fields. Experiments show that the emission area of cathodes having a simple geometry and made of pure materials is highly nonuniform and the lifetime of such cathodes is no greater than 10^4 pulses [30]. Using local irregularities on the cathode surface to enhance the electric field increases the cathode lifetime somewhat. A lifetime of more than 10^8 pulses was achieved using a metal-dielectric cathode (Fig. 6).

B. Relativistic BWO

Cherenkov devices are preferred for repetitively pulsed sources in the centimeter band and for a considerable part of the millimeter band. Among these devices, one should mention the relativistic BWO, which adapts well to variations in electron beam parameters. The BWO was naturally the first HPM device implemented both in single-pulse and in repetitively pulsed regimes (at 50 pps) [3]. The maximum HPM power obtained with a single-mode relativistic BWO in the X band was 3 GW with ~ 100 J energy in a single pulse [31]. The resonant relativistic BWO was proposed to operate in the S band [32]. The radiated microwave power was 5 GW and the energy was 100 J in a single pulse. Both experiments were performed using the SINUS-7 accelerator.

There is a complex magnetic field dependence of microwave power inherent in relativistic Cherenkov devices [3], [33]. For certain values of the applied magnetic field, there is no microwave generation because of cyclotron absorption of the backward electromagnetic wave [33]. This effect causes perturbation of the starting conditions both in generators with a fixed longitudinal field structure [34] and in a BWO [35]. For a BWO operating in the TM_{01} mode at $\lambda \approx 3.2$ cm, the cyclotron resonance is at $B \approx 0.8$ T for 300-keV electron energy and $B \approx 1.3$ T for 500-keV electron energy. The cyclotron absorption width is relatively broad ($\Delta B/B \approx 1$), which is inherent to high-current microwave devices because the parameter of force bunching, which is responsible for the cyclotron interaction, is proportional to $J_b^{1/2}$, whereas the parameter of inertial bunching, which is responsible for the Cherenkov interaction, is proportional to $J_b^{1/3}$ for beam current density J_b. The maximum microwave efficiencies are achieved under experimental conditions where the magnetic field is 1.5–2 times the resonant value. For lower values of the applied magnetic field (compared to the cyclotron resonance), lower microwave powers are obtained. One of the causes for this phenomenon is the growth of transverse electron velocities in the beam at lower magnetic fields and increased spread in longitudinal velocities. This is why superconducting magnets were usually used in continuously repetitive microwave sources [4]. Over the last few years, burst mode repetitive regime operation has been achieved where strong magnetic fields (~ 3 T) were obtained using a "warm" solenoid for a limited period (~ 1 s) [36].

Another direction of research was to increase the microwave efficiency in low magnetic fields (for the case producible by permanent magnets) by modifying a BWO to achieve a spatially nonuniform slow-wave structure (SWS) [37].

1) Burst Mode Regime of Generation: Producing magnetic fields of ~ 3 T in a volume of $\sim 10^3$ cm^3 by partially discharging a capacitor bank into a solenoid requires ~ 1 MJ of stored energy in order to keep the decrease in magnetic field amplitude during the pulse within 10%–15%. A capacitor bank made using molecular capacitors with high-energy storage density (~ 1.5 kJ/kg) has quite a reasonable size. This approach allowed producing several microwave sources with maximum output up to 700 MW in the X band. The pulsewidth was 15–30 ns and the pulse-repetition rate was up to 200 pps for magnetic field pulsewidths of 1–3 s (Fig. 7). The bursts typically repeated each 30–40 s, and the average power drain of the solenoid was in the range of several kilowatts.

Operation in the burst mode regime largely facilitates cooling of the solenoid and accelerator components and enables operation at 600–1000 pps. The maximum repetition rate in this case is limited by increase in the jitter of high-voltage gas gap switch operation.

2) Low Magnetic Field Regime: The quality of a high-current electron beam can be substantially improved by decreasing the electric field strength at the cathode edge (maintaining the magnetic field strength). One way

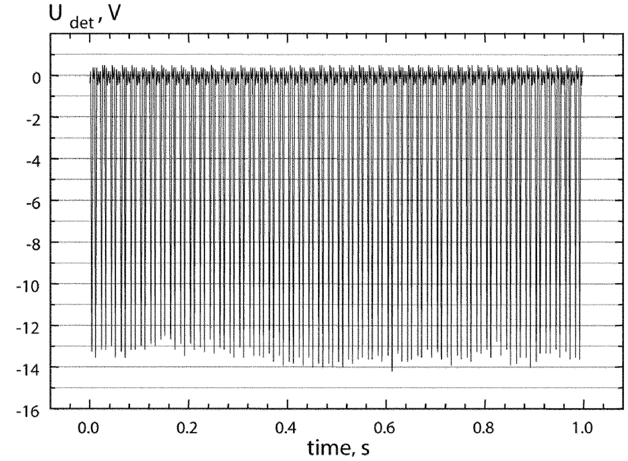

Fig. 7. A burst of 100 pulses from the microwave power detector.

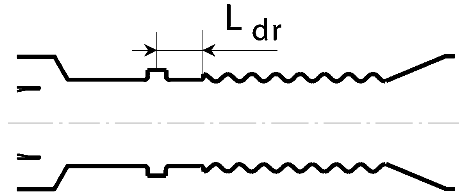

Fig. 8. Relativistic BWO with resonant reflector.

to accomplish this is to increase the cathode, anode, and SWS cross-sectional dimensions. It is remarkable that this simultaneously weakens the role of the transverse interaction in the BWO (narrowing of cyclotron resonance region), and allows operation in the lowest order of the operating wave (TM_{01}). However, in the conventional BWO configuration with the TM_{01} operating wave, the electron beam diameter is limited by the cutoff neck (which is ≈ 2 cm for $\lambda \approx 3$ cm). Another problem arising when switching to oversized SWSs is mode selection. A known way to solve this problem is the use of a higher operating mode where the cyclotron absorption can be eliminated for a certain beam radius [18], [38]. It is useful to have a beam radius close to the surface of the SWS in order to maximize the coupling between the beam and the electromagnetic field that can be achieved with proper choice of the operating wave. For all other waves, growth is suppressed in the zone of cyclotron absorption. This method of cyclotron selection of waves requires precise alignment of the electron beam [35]. The problem of reducing the guide magnetic field can be resolved (while maintaining operation in the TM_{01} mode) by using for radiation output a selective reflector, which simultaneously plays the role of a modulating section [37] (Fig. 8).

The amplitude of the RF field in the reflector area is due to the presence of a locked TM_{02} mode. The distance between the reflector and the SWS (L_{dr} in Fig. 8) determines the phase of RF current modulation relative to the microwave field of the synchronous harmonics. Theoretical and experimental studies of this configuration demonstrated the capability of efficiency improvement for low magnetic fields. Using a pulsed solenoid with magnetic field strength

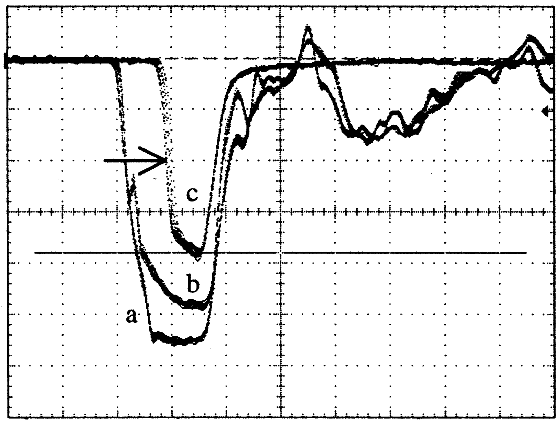

Fig. 9. A series of 15 consecutive pulses during burst mode operation of the HPM source at 150 Hz.

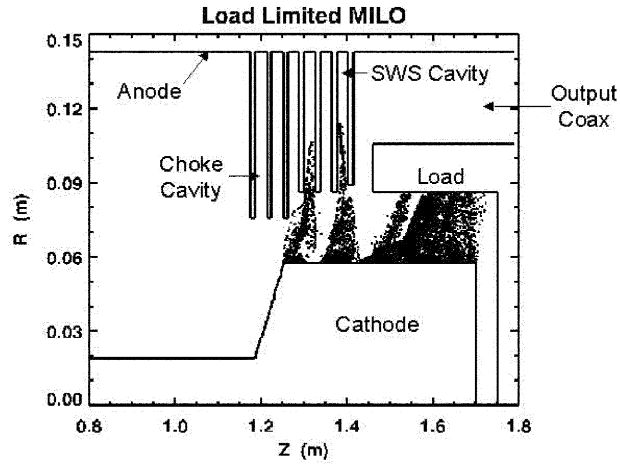

Fig. 10. Axial cross-section schematic of a MILO as depicted in an electron flow plot from a 2.5-D PIC simulation using the TWOQUICK code.

of $\sim$ 0.6 T and a 600-keV, 5.5-kA electron beam, microwave pulses with peak power of 0.8 GW at $\lambda \approx 3$ cm were produced. This result allowed implementation of a periodically pulsed regime of BWO operation with peak output up to 500 MW at 150 pps using a cooled dc solenoid with magnetic field of 0.6 T and power consumption of up to 20 kW. The electron energy in these experiments was up to 530 keV and the beam current was up to 5 kA.

Experiments demonstrated a long lifetime of this HPM source (about 10^8 pulses) [29]. The lifetime limitation may be caused by erosion of the cathode material. Fig. 9 shows typical waveforms of vacuum diode voltage (Fig. 9, curve a); electron beam current (Fig. 9, curve b); and microwave detector signal (Fig. 9, curve c).

III. HPM Source Research in the United States

We present an overview of HPM source research activities that were performed under the auspices of, or in collaboration with, a five-year DoD/AFOSR Multidisciplinary University Research Initiative (MURI) that began in fiscal year 1994 [24], and comment on those efforts that are receiving the greatest attention at the moment. In contrast with the material presented in Section II, the pulsed power accelerators used in the research summarized in this section were typically based on a Marx generator coupled to a PFL.[1] The HPM source research activities we present are organized in terms of specific classes of sources that were studied.

A. Advances in Gigawatt-Class Sources

The gigawatt-class sources described in this section are being researched at the Air Force Research Laboratory (AFRL), Kirtland Air Force Base, NM, as well as being developed by industry in the United States and the United Kingdom. Although the universities themselves do not perform experimental research on these sources in-house, many of the investigators have supported the activities at AFRL in gigawatt-class sources. The sources that have been receiving the greatest attention at AFRL include the MILO, the RKO/RKA, and most recently the relativistic magnetron. A variant of the RKA, the triaxial RKA, is being researched at the Mission Research Corporation, Newington, VA. The tapered MILO is being studied at AEA Technology, Harwell, U.K. (although this will not be discussed further here). The relativistic magnetron was developed at Maxwell Physics International, San Leandro, CA, and is being actively investigated at AFRL and the University of Michigan, Ann Arbor, and the Reltron tubes are developed at Titan/PSD, San Leandro, CA. (See [24, Ch. 3] for more detailed information and references on these sources.)

One important lesson that was learned from research early on in the work at AFRL is that proper tube design, construction, and matching to the pulsed power driver is critical for HPM sources driven by space-charge-dominated electron beams. In addition, tailoring the pulsed power waveform leads to further improvement. An example of proper tube design and construction can be found in the MILO [39]. The MILO is a cross-field source that is closely related to the more familiar magnetron. Referring to Fig. 10, electrons that are emitted from the cathode electrode have a self-magnetic field that inhibits electron flow from reaching the anode prior to onset of oscillation. Strong oscillation occurs when the average electron flow velocity is synchronous with the phase velocity of the π-mode in the SWS. Earlier versions of this source suffered from pulse shortening due to the interception of energetic electrons by the cavity vanes. Through particle-in-cell (PIC) simulation, researchers were able to tailor the electron emission to avoid this interception of the vanes and as a result microwaves were generated for the duration of the pulsed power waveform. The RKO [40] vacuum diode was redesigned to operate at a constant impedance for a constant voltage load. This is an example of how device performance can be improved through tailoring of the waveform.

The triaxial klystron amplifier was designed to overcome some of the shortcomings of the RKA [41] (such as beam interception leading to the formation of background plasma). The triaxial geometry consists of an annular electron beam

[1]One exception is that a portion of the research performed at the University of New Mexico (UNM), Albuquerque, utilized a SINUS-6 pulsed power accelerator that was developed by the Institute of High Current Electronics and delivered to UNM in 1992 as part of an ongoing collaboration.

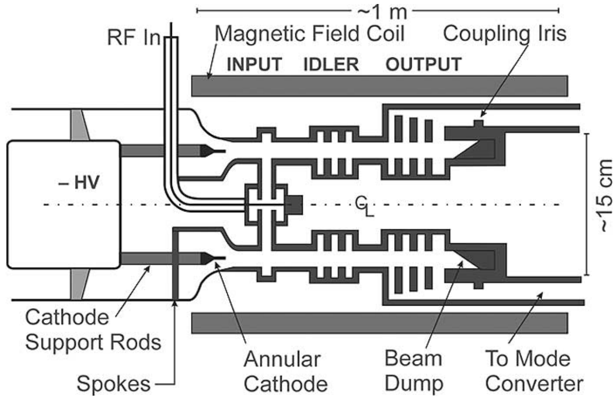

Fig. 11. Triaxial klystron amplifier.

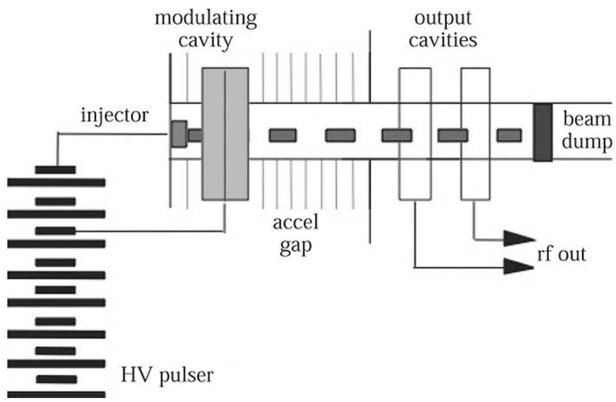

Fig. 12. Schematic diagram of the Reltron source.

propagating between two coaxial conductors, as indicated in Fig. 11. Because of the return current and image charges on the inner conductor, this geometry significantly reduces the beam's potential energy. In effect, the triaxial configuration offers the same advantages of sheet beam and multiple beam klystrons. Ongoing work on the RKA and the triaxial variant is devoted to demonstrating the ability to operate gigawatt HPM sources for microsecond pulse durations.

The Reltron [9] family of commercial tubes is available through Titan/Pulse Sciences Division. In addition to its high efficiency and large stable tuning range, the Reltron tube has several other unique features.

1) The bunching distance is short, resulting in a compact tube.
2) The high peak power tubes require no external magnets and the high average power tubes require only small permanent magnets.
3) The straightforward output coupling delivers power directly through the fundamental mode in standard rectangular waveguide.
4) The excellent beam modulation permits significant power extraction at multiples of the beam modulation frequency, although at reduced efficiency.

Fig. 12 presents a schematic drawing of the Reltron. The L-band Reltron tubes generate 400–500 MW (rms) when operated with an injector voltage of 200 kV and a postacceleration gap voltage of 800 kV. The impedance is about 700 Ω and the efficiency $> 40\%$. With flattop pulse durations of a

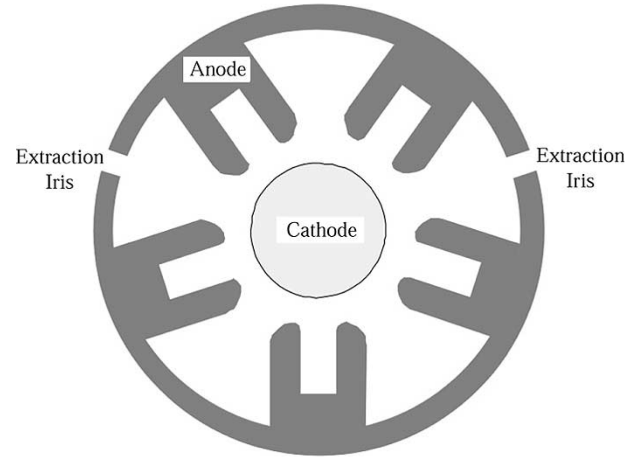

Fig. 13. Radial cross-section view of a traditional relativistic magnetron.

few hundred nanoseconds, the L-band tubes deliver hundreds of joules of energy per pulse.

Titan/Pulse Sciences Division (formerly Maxwell Physics International) has developed and brought to market a family of tunable relativistic magnetrons [42]. They have achieved an increase of greater than a factor of two in the tuning bandwidth and two orders of magnitude in peak power compared with conventional magnetrons (see Fig. 13 for a schematic of a magnetron). Their basic configuration is a ten-resonator rising sun design with alternating vane and rectangular cavities. To obtain optimal operation, the magnetic field is adjust simultaneously with the tuning, maintaining the product of frequency and magnetic field constant. This technique yields about 35% tunability. Fig. 14 presents a photograph of the ORION HPM Test Facility, manufactured by Titan/Pulse Sciences Division and based on a series of pulsed power-driven relativistic magnetrons.

Improved understanding of the scaling laws for relativistic magnetrons and techniques to extend the pulse duration are issues that are topics that continue being investigated.

Another approach to further development of relativistic magnetrons [43] is the use of axial extraction [44], as demonstrated in the device shown in Fig. 15. This type of relativistic magnetron may lead to higher efficiency operation, including significant decrease of power consumption in creating the magnetic field and more compactness and agility in the output mode, since a mode converter can be naturally integrated within the transition region leading to the antenna.

B. Cherenkov Sources

The activities in Cherenkov source research have taken place primarily at Cornell University (TWT amplifiers); the University of Maryland, College Park (BWOs, both vacuum overmoded and plasma-filled, single-mode configuration); and UNM (BWOs). Cherenkov sources have been investigated using pulsed power-driven relativistic electron beam sources for over 30 years. Recent advances in TWTs and BWOs have occurred because of careful studies using computational tools in conjunction with experimentation. Single-stage and two-stage TWT research at Cornell

Fig. 14. HPM test facility ORION (manufactured by Titan/Pulse Sciences Division), which is based on a series of relativistic magnetrons.

Fig. 15. Relativistic magnetron with diffraction output, an alternative approach to RF extraction.

University has been supported through both macroparticle analyses and electromagnetic PIC simulations. In recent work at Cornell [45], several configurations of a two-stage amplifier were investigated. The first stage of the amplifier was designed to have a phase velocity approximately equal to the speed of light at the center of the amplifier passband. A short, four-cell transition section then leads to a seven-cell output section where the cold wave phase velocity is about 0.78 c. It was shown experimentally that in the case of a field-immersed cathode, up to 60 MW microwave power could be obtained at 9 GHz for about 80 ns before the pulse was terminated due to pulse shortening. At 150-MW power level, the pulse duration was 10 ns. The output signal varied linearly with the input signal for power levels up to about 60 MW. The 3-dB bandwidth of the amplifier was greater than 500 MHz. Fig. 16 presents a typical output microwave

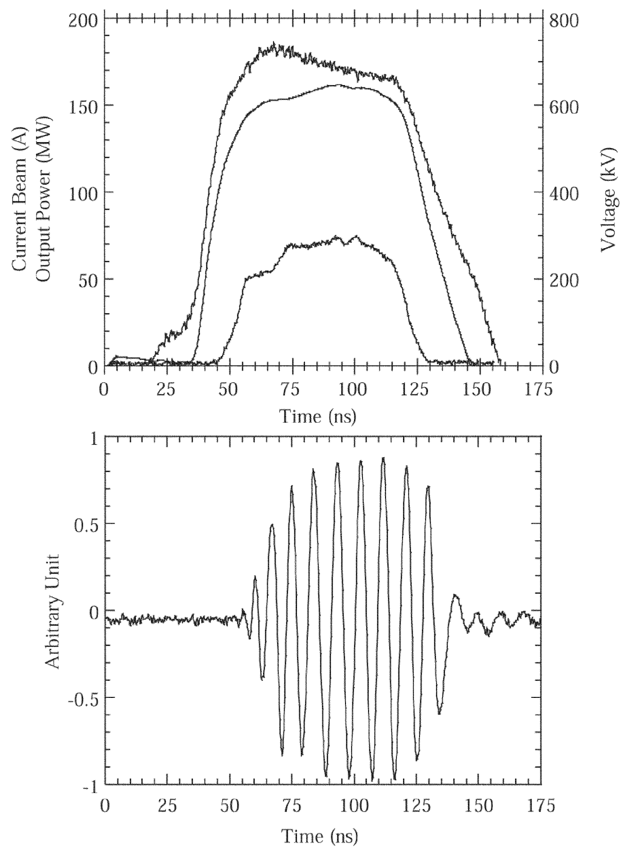

Fig. 16. Top: Typical beam voltage (730 kV) (upper trace), current (160 A) (middle trace), and RF power envelope (77 MW) (lower trace) shown on the same time scale. Bottom: Downshifted signal from a double balanced mixer.

pulse as a function of time superimposed on the same figure as the beam current and voltage traces.

Advances in the understanding of intense beam-driven BWOs were partly a result of the MAGY code developed at

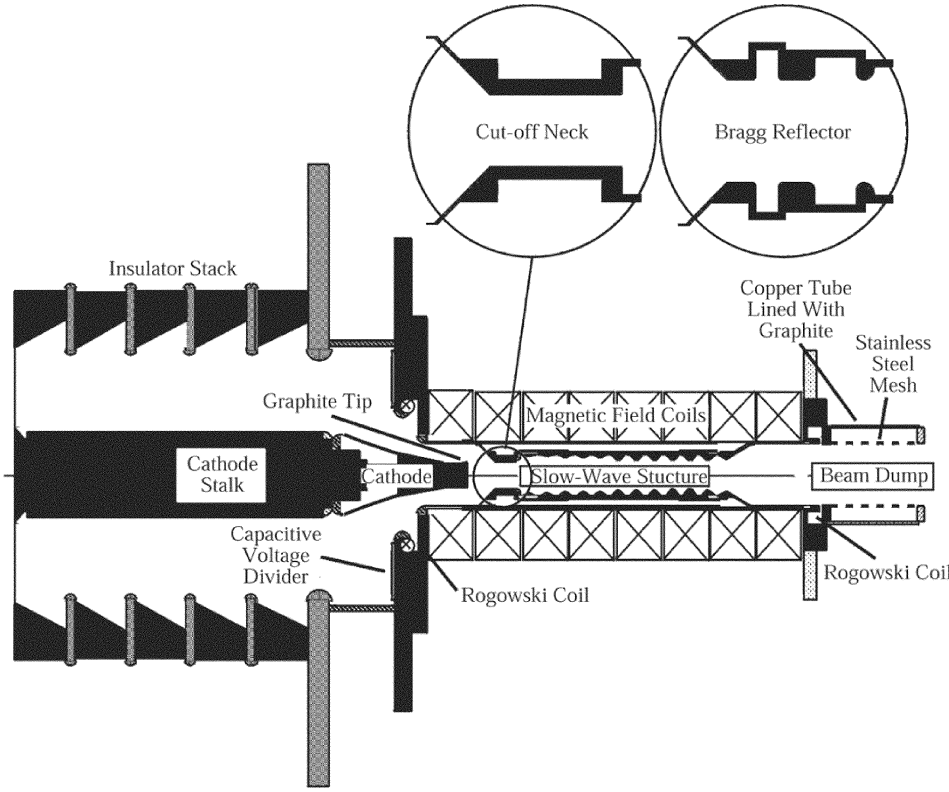

Fig. 17. Cross-sectional diagram of UNM's long-pulse BWO with cutoff neck or Bragg reflector at upstream end.

the University of Maryland [46]. Researchers at Maryland used MAGY to analyze the field's rippled-wall SWSs. Combined with careful experimental characterization of the quality factors (Qs) of the SWSs, the MAGY simulations showed that careful design of the transition from the SWS to the radiating antenna can signicantly reduce the Qs of all modes except for the modes close to the ends of the passband. Such a reduction can lead to a substantial increase in the starting and optimal currents of the BWO, allowing for higher efficiency and higher power operation.

As an example of experimental research on BWOs, investigators at UNM studied the importance of end reflections on short-pulse BWO operation [47], and demonstrated BWO operation in the "cross-excitation regime" during long-pulse operation [48]. The latter research was performed using the setup described in Fig. 17. For these experiments, very shallow SWSs were used in order to set the beam-to-start current ratio slightly greater than unity. In this regime, the start current and gain of one mode is modified by the presence of another saturated mode, enabling the second mode to compete with the first, as is evident from the data in Fig. 18. Although this mode of operation is usually avoided, it might be exploited in some applications where the generation of two distinct frequencies during a single HPM pulse would be of interest.

C. Gyrotron Oscillators and Amplifiers

Gyrotrons are one of the most promising devices for producing both high average power, and high peak power at millimeter wavelengths (30–300 GHz). The highest average power gyrotrons have been developed for plasma heating in controlled fusion experiments. This high power capability is basically attributable to two factors.

1) Gyrotrons employing magnetron injection guns use very large hollow electron beams whose average radius is large compared with the Larmor radius and the operating wavelength. This large average radius allows a reduction in space charge effects at a given current. Each electron in the beam takes a helical path with a Larmor radius much less than the beam radius. The large beam consisting of many beamlets with individual guiding centers offers advantages similar to those in a multiple-beam klystron.
2) Gyrotrons have successfully operated in very high-order transverse modes of their interaction cavities. This is made possible because their mode stability is enhanced by matching the operating frequency in the desired mode to an intrinsic resonant frequency of the electrons (i.e., the electron cyclotron frequency or its higher harmonics).

The focus of the MURI-related research on gyrotrons is on compact high-frequency devices that operate at harmonics of the cyclotron frequency (since the gyrotron magnetic field requirement is inversely proportional to the harmonic number). In the absence of superconducting magnetics, gyrodevices can operate at the second harmonic in the Ka band (around 35 GHz), whereas operation at the fourth and higher harmonics are of interest in the W band (around 95 GHz). The MURI research on gyrodevices was led by the University of Maryland and the University of California,

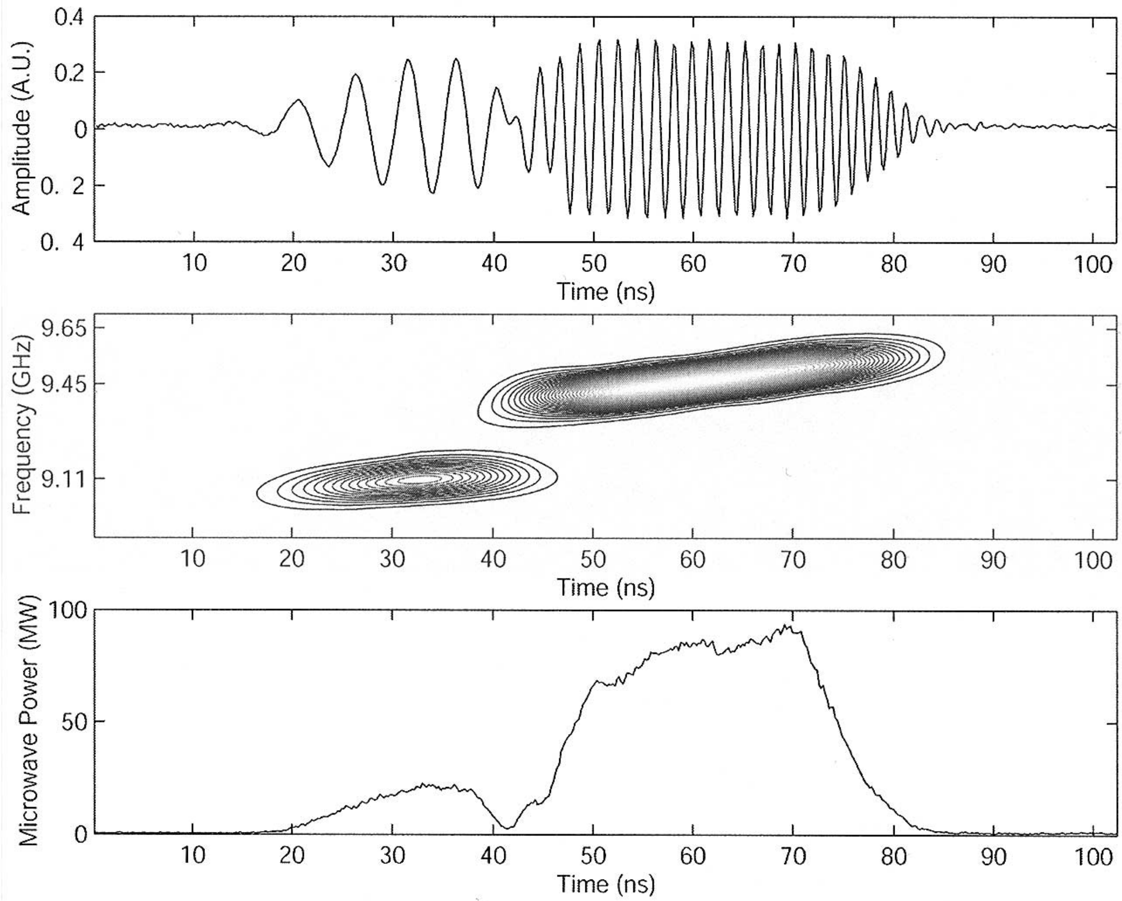

Fig. 18. Evidence of the cross-excitation instability in the UNM long-pulse BWO. Top: heterodyned signal corresponding to radiated output frequency. Middle: time-frequency plot of heterodyned signal, demonstrating shift in axial mode, and bottom: radiated power.

Davis (UC Davis). Collaborators include the University of Michigan on intense beam gyrotrons, and industrial collaborators include CPI, Palo Alto, CA, and GYCOM, Nizhny Novgorod, Russia.

The key achievements from the gyrodevices that are being researched include the development of gyromonotrons (operating at power levels approaching 1 MW with several-second pulse lengths), gyroklystron amplifiers (100-MW output power using 1–μs duration, 500-kV pulses), and intense beam gyrotrons with hundreds of megawatts of output power in tens of nanoseconds pulses. Novel devices being studied include the PHIGTRON at Maryland, which in its highest power variant outputs 720 kW in Ka band in the TE_{03} mode with 34% efficiency and 33–dB gain; gyrotwystrons, gyro-traveling-wave amplifiers, and multistage traveling-wave amplifiers at UC Davis. These configurations are summarized in Fig. 19.

Three important challenges for gyrodevices that have been identified include: 1) the need to operate gyroamplifiers in high order transverse modes in order to increase average power capability; 2) the need to increase bandwidth, gain, and efficiency in gyroamplifiers; and 3) the need to have efficient operation at high cyclotron harmonics for both gyrooscillators and gyroamplifiers in order to reduce magnetic field requirements.

A comprehensive review of gyrotrons can be found in a recent review paper [49].

D. Plasma-Filled Devices

Experimental work in plasma-filled devices has taken place at the University of Maryland, UNM, and Hughes Research Laboratory. Researchers at Maryland have achieved an impressive 300% tunability (8–24 GHz) in a plasma-filled BWO using a window-mounted pulsed plasma fill source and coaxial extraction [50]. Researchers at UNM developed a novel cathode-mounted plasma prefill source in a BWO that was used to achieve a modest 30% efficiency enhancement over the vacuum case [51]. Researchers at Hughes have, over the past decade and a half, developed the PASOTRON source that utilized electron beam propagation in the ion focused regime to couple energy with slow waves in a BWO-like structure, as indicated in Fig. 20. Recent PASOTRON research that is ongoing at Maryland has been focusing on experimental and theoretical studies to better understand the operation of the device. By taking advantage of the two-dimensional motion of electrons in the PASOTRON, a 50% conversion efficiency of beam-to-microwave energy was demonstrated experimentally in a 1-MW-class device operation at a beam voltage of 40 kV. Theoretical studies suggest that an efficiency of 60%–70% is possible [52].

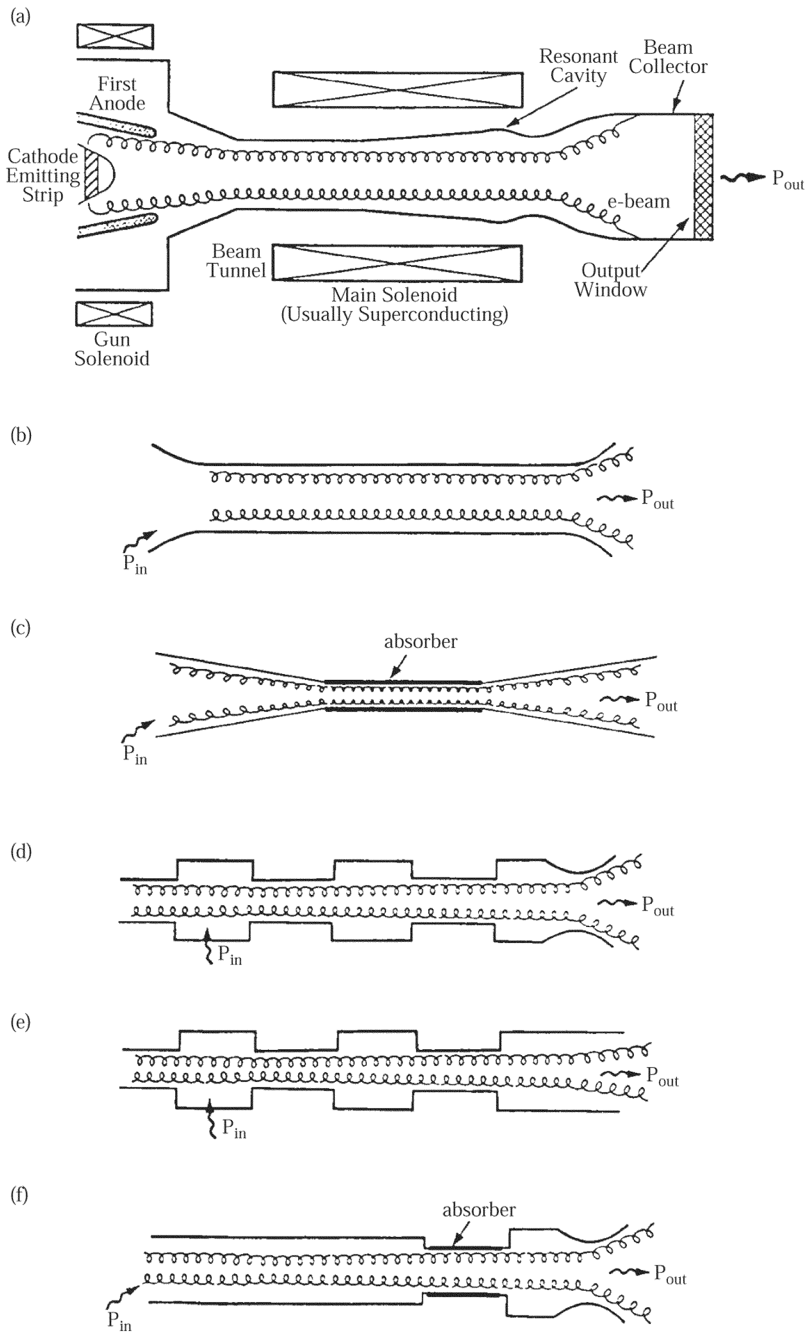

Fig. 19. Gyrotron oscillator and amplifier circuits. (a) Gyromonotron oscillator. (b) Gyro–TWT amplifier. (c) Two-stage tapered gyro–TWT amplifier. (d) Gyroklystron amplifier. (e) Gyrotwystron amplifier. (f) Inverted gyrotwystron amplifier (PHIGTRON). The electron gun, solenoids, beam collector, and output window have been omitted in (b)-(f) for clarity.

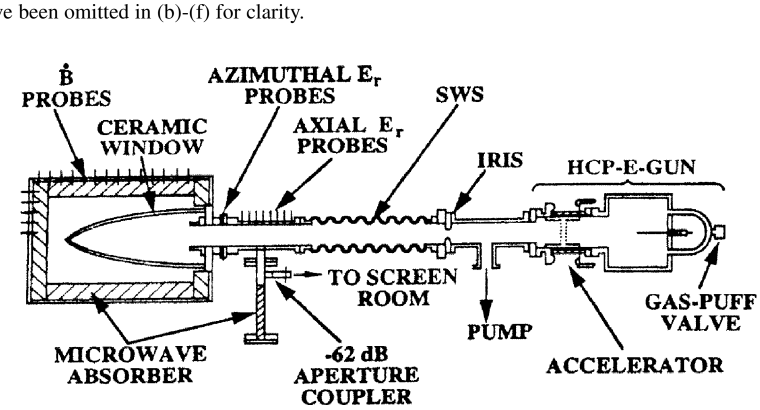

Fig. 20. PASOTRON device.

IV. Conclusion and Future Directions

Research into pulsed power-driven sources of HPM is an applications-driven area. The demand for ever-increasing levels of both peak and average powers, across a continuum of frequencies from 1 GHz to 1 THz, ensures that significant efforts in this area will continue. Although this article focused attention on the ongoing activities of one institute in Russia and a consortium of U.S. universities (and their affiliated laboratories in government and industry), significant activities are taking place internationally in over a dozen countries, and the interested reader can find detailed information in [53].

Acknowledgment

The authors would like to thank their colleagues at the University of New Mexico, Albuquerque—faculty, staff, and students—that participated in the research programs described in this paper, and in particular, the various university principal investigators: V. Granatstein (University of Maryland, College Park), J. Nation (Cornell University, Ithaca, NY), K. Kristiansnen (Texas Tech University, Lubbock), R. Gilgenbach (University of Michigan, Ann Arbor), N. Luhmann (University of California, Davis), N. Birdsall (University of California, Berkeley), G. Caryotakis (Stanford Linear Accelerator Center, Stanford, CA), and T. Lin (University of California, Los Angeles). They also express their thanks to the industrial collaborators: H. Jory (CPI, Palo Alto, CA), C. Armstrong (L-3 Communications, San Carlos, CA), and J. Benford (Microwave Sciences, Inc., Lafayette, CA).

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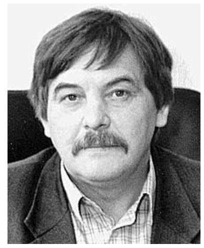

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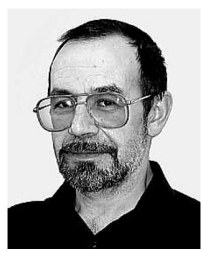

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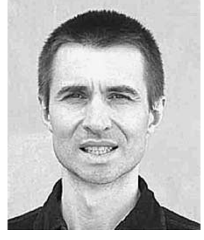

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Dr. Barker is a member of the American Physical Society. He was elected Fellow of the Air Force Research Laboratory in 1998. He has served in various capacities on the organizing committees of numerous international conferences, including cochairing the IEEE Joint Pulsed Power Plasma Science (PPPS) Conference in 2001.