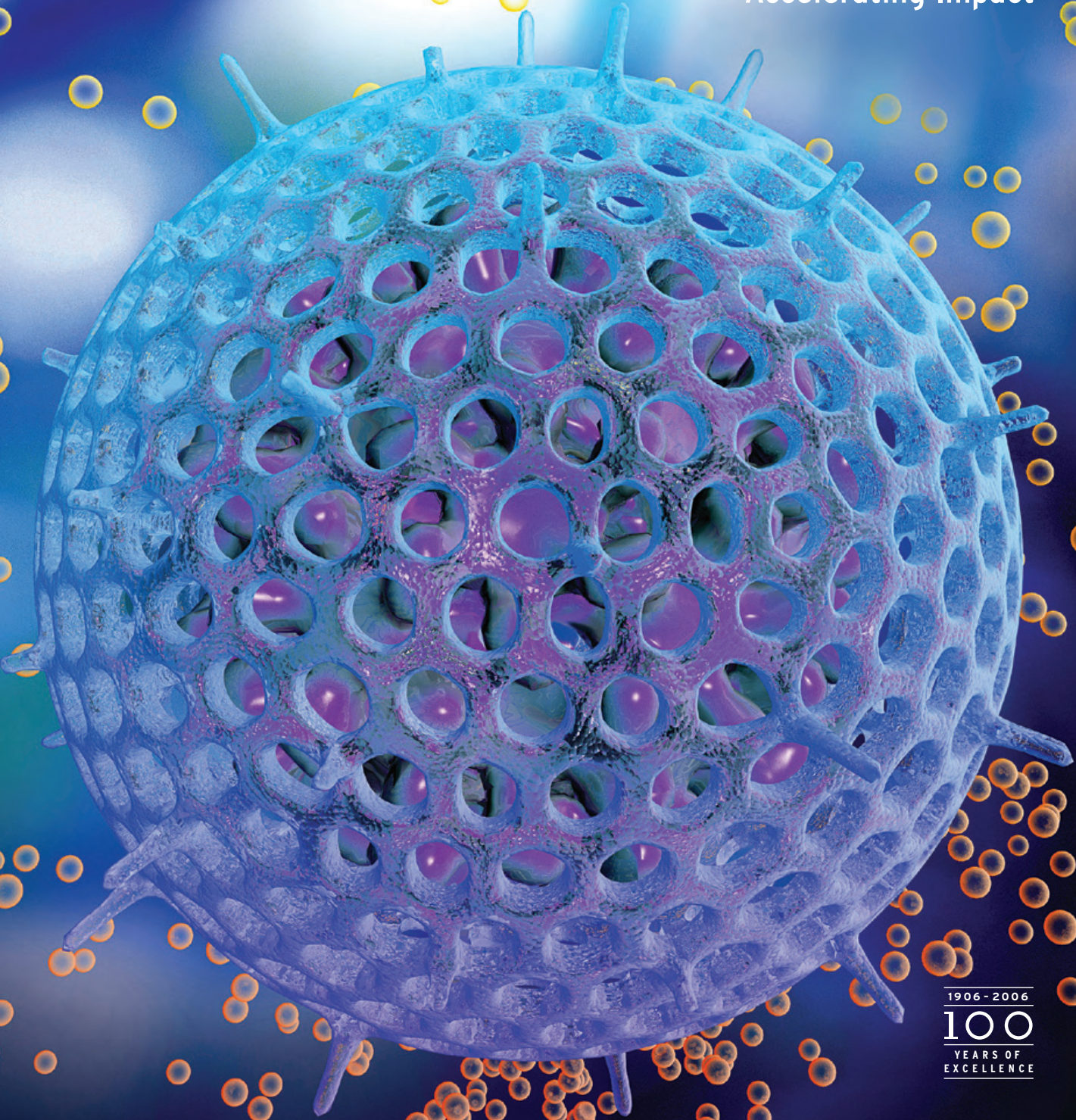


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## Maestro of Microwaves

For two decades, **Edl Schamiloglu** has conducted high power research on high power microwave sources.

IN THE late 1880s, Heinrich Hertz used Leyden jars, two iron point sparks, and zinc gutter sheets as antennas to broadcast and detect microwaves. He was the first person to experimentally verify Maxwell's equations and support his contention that visible light was but a small portion of the electromagnetic spectrum.

Compared to Hertz's experimental setup, today's microwave sources are considerably more sophisticated, powerful, and ubiquitous. They cook dinners, carry cell phone signals, and accelerate particles to tremendous speeds in colliders, giving us unique glimpses into the subatomic world. Since the invention of radar during World War II, they have also played a decisive role in military ventures. Today, high power microwaves (HPM) can disrupt enemy electronics and disperse unruly crowds.

Instrumental to many of the advances in the understanding of HPM sources is UNM's Edl Schamiloglu, Professor in the Department of Electrical and Computer Engineering. Schamiloglu's insights into how the kinetic energy of a beam of electrons is transferred to the electromagnetic (EM) energy of microwaves are paving the way for devices operating with higher efficiency, greater power, longer lifetime, and more compact size. (Figure 1 shows the power and frequencies of typical HPM applications.) Some of Schamiloglu's specific contributions include the first tunable Backward Wave Oscillator, insight into "pulse shortening" phenomena that limit all HPM devices, a novel magnetron design, and improved computer simulations.

"Edl Schamiloglu is one of the world leaders in the field of HPM generation and

applications, says Ronald M. Gilgenbach, Professor of Nuclear Engineering and Radiological Sciences at the University of Michigan. "He is considered the top HPM researcher of his mid-career generation." Gilgenbach adds that Schamiloglu is the coauthor and editor of two of the most important books on HPM: the textbook *High-Power Microwaves* and *High Power Microwave Sources and Technologies*, a state-of-the-art compilation for the five-year Multidisciplinary University Research Initiative.

An IEEE Fellow and Senior Editor of *IEEE Transactions on Plasma Science*, as well as Associate Editor of the *Journal of Electromagnetic Waves and Applications*, Schamiloglu is also the Director of the Institute for Infrastructure Surety, which he co-founded in 2004 to study ways of

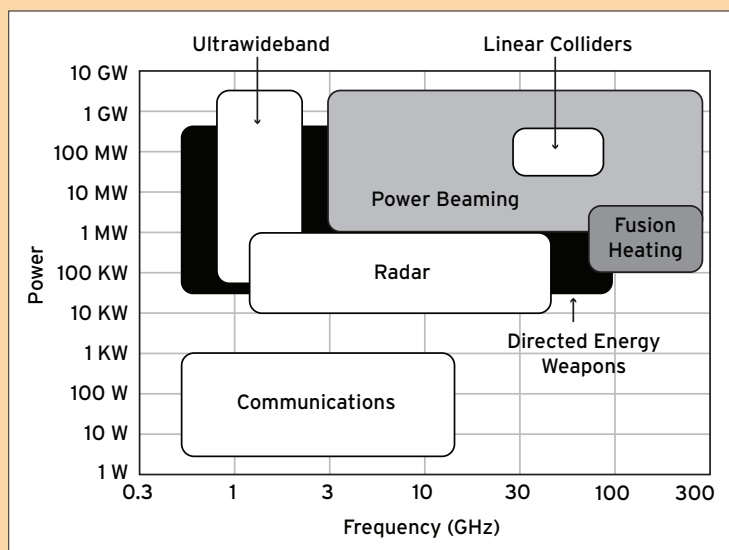


Figure 1. Range of applications for high power microwave sources.

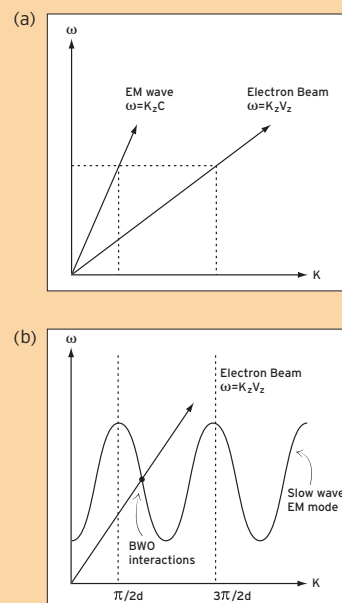


Figure 2. Dispersion diagrams. In (a) the dispersion line for the electromagnetic wave (EM) does not intersect that of the electron beam so no energy is exchanged between them. Adding a corrugated structure (with a period of length  $d$ ) into the tube undulates the EM dispersion curve and slows down its phase velocity so that it does cross the beam line (b). The EM phase velocity is negative at the intersection point, meaning that the wave travels against the beam. Hence the name backward wave oscillator (BWO).

They discovered that the BWO's finite length makes the reflected wave and its harmonics more important to BWO operation than anyone had previously realized.

Exploiting the periodic effects afforded by the spacers, the group also constructed the first BWO that can be tuned over a bandwidth of 500 MHz (centered around 9.5 GHz) without sacrificing power. The BWO is now one of only a few pulsed, tunable HPM sources.

Schamiloglu teamed up with Professor of Electrical and Computer Engineering Chaouki Abdallah and M.S. student Vatche Soualian to go one step further. They computerized an iterative learning feedback system that regulates the output frequency and peak power by moving the SWS and controlling the beam current between pulses. This was the first practical demonstration of what is known as a "smart tube" in the gigawatt range, a device capable of automatically learning and adjusting its output to achieve power and/or frequency specified by the user.

The first application of the smart tube was to explore photonic crystals. Schamiloglu's group demonstrated for the first time that the bandgap of a photonic crystal could be

exploited as a HPM filter, beam shaper, and quasi-optical reflector. The researchers also used the smart tube to study the dispersion diagram of a photonic crystal (a 1-D, 2-D, or 3-D spatially periodic structure). Previously, textbooks had declared that a curiosity in the dispersion curve predicting group velocities faster than the speed of light were experimentally meaningless because the attenuation of the wave propagating through the crystal would prevent observation. But the group demonstrated otherwise and produced the first direct observation of superluminal group velocities. The BWO's ability to produce high-power, short pulses at convenient frequencies is what made the experiment possible.

### Pulse Shortening

Schamiloglu's group has also addressed the pulse shortening problem. In the early 1990s as the race to develop HPM sources with ever higher peak powers and longer pulses progressed, it became apparent that all devices were limited by a phenomenon called pulse shortening. Peak power can be increased, but at some point the pulse will be cut off even though energy is still being fed to the system. A maximum pulse energy of about 1 kilojoule seems to be the limit of delivered energy. Pulse shortening changed the focus of research towards testing the idea that unwanted surface plasmas were somehow affecting the HPM source operation.

Looking for these plasmas with real time, in situ measurements in these inaccessible devices and their hostile environments is a challenge. But Schamiloglu's post-doc, Frank Hegeler, (now at the Naval Research Laboratory) succeeded in setting up a laser interferometer to conduct the first measurements of plasma electron density inside an HPM BWO. The researchers discovered two episodes of plasma production. The first, they believe, is due to the electron beam scraping the cutoff neck wall, and they have in fact reduced this initial phase by replacing the neck with a non-intercepting Bragg reflector. The second is caused by intense electric fields breaking down the SWS walls. Particle-in-cell computer simulations show that the resultant plasma ions effectively shut down the growth of oscillations, terminating the pulse.

### A New Idea for the Magnetron

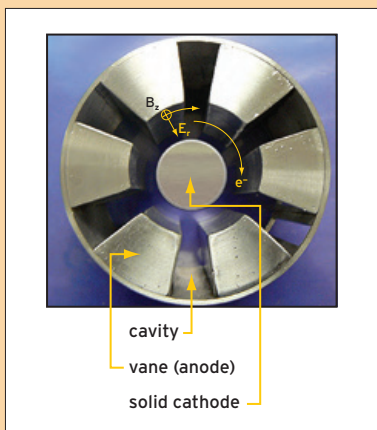
Schamiloglu's contributions are not limited to the BWO. He and Research Professor Mikhail Fuks have also improved the operating features of the magnetron. In a sense, a magnetron is a BWO bent into a closed ring, with the periodic SWS turning into the anode resonance cavities whose sizes and shapes determine the microwave frequency (see Figure 5). In a magnetron, however, a voltage between the electron-emitting cathode and the outer anode propel electrons out radially. Moreover, a magnetic field applied axially (into the page in Figure 5) deflects the electrons in the  $E \times B$  (circular) direction around the cathode.

Invented by the late George Bekefi at the Massachusetts Institute of Technology in 1976, the relativistic A6 magnetron is a high-voltage, high current, pulsed power version of the conventional device, which maxed out at about 10 MW of power. The relativistic magnetron is one of the most compact, powerful, robust, and mechanically tunable HPM sources, able to produce frequencies from about 1-10 GHz with single-shot powers up to 4 GW.

This is not to say there is no room for improvement. Relativistic magnetrons suffer from pulse shortening like all other devices. While conventional magnetrons operate at efficiencies up to 90 percent, the efficiency of their relativistic cousins has yet to match half that value.

Fuks and Schamiloglu came up with a novel approach that takes on both these problems. In place of the large solid cathode, they proposed a transparent cathode consisting of a series of axial, emitter strips or rods spread out evenly around the original cathode outer boundary, as shown in Figure 6. Its name is due to the fact that the cathode emitters are transparent to the azimuthal wave electric field inside the magnetron. This is the first novel design approach to increasing magnetron power and efficiency proposed in many years.

In traditional magnetrons, Maxwell's equations require that the wave electric field tangential to the conducting cathode surface go to zero. Fuk's and Schamiloglu's idea instead makes the field go to zero at the *axis*, allowing it to penetrate the emitters (Figure 6c) and immediately act on the electrons as they emerge from their surface.



**Figure 5.** Cross-sectional view of a magnetron. Electrons emitted from the cathode travel toward the more positively charged anode, but because of the magnetic field (applied into the page), they move in the  $E \times B$  direction, spiraling around the cathode. At steady state, the electrons radiate at the magnetron frequency, which is determined by the size and shape of the resonance cavities.

to improve the fidelity of computations by spending a year meticulously tracking down the source of a discrepancy between experimental observations and simulations.

Today there is so much faith in these simulations that the Air Force Research Laboratory, as an example of one of many HPM research centers, will not begin to build an HPM source until scientists are entirely happy with the predicted device characteristics, a turn of events which, of course, saves time and money.

Sometimes the computer simulations come up with behavior that is not expected. Conventional wisdom holds that electron spokes form in magnetrons because of a periodic physical structure like the anode vanes or due to an additional magnetic field ripple. George Bekefi introduced the latter when in 1982 he proposed the relativistic smooth bore magnetron or free electron laser, a cylindrical cathode surrounded by a featureless cylindrical anode. In addition to the crossed E and B fields, Bekefi sandwiched the two electrodes between an annular magnetic wiggler or a series of magnets with north and south poles alternating around the ring. It had been assumed that this wiggler is needed to get the electrons to bunch and form spokes, but in simulations Fuks and

Schamiloglu have discovered this isn't necessary. Given a smooth bore magnetron of a set circumference, they can form electron spoke patterns with different symmetries, depending on the value of the applied magnetic field. The researchers call this structure the "simplest crossed field ubitron" (ubitron was the ersatz name first given to the original free electron laser).

So 120 years after Hertz, there are still EM mysteries to be solved. Even the conventional magnetron is not fully understood; it's assumed, for example, that oscillations grow from noise, but how this process works has yet to be fleshed out — lots of interesting questions to be passed along to the next generation. Here, Schamiloglu has contributed as well, serving the community by chairing many committees and conference sessions and reviewing manuscripts and proposals for numerous journals. In June 2007, for instance, he organized and chaired the joint IEEE International Conference on Pulsed Power and Plasma Science. He has graduated 18 Ph.D. and M.S. students, most of whom work in national, DoD, and commercial labs.

His two-decade focus has also been a boon to UNM. "The vast majority of EE departments have shortsightedly limited their

coursework strictly to solid state, low power electronics," says Robert J. Barker, Program Manager at the Air Force Office of Scientific Research. "It's noteworthy that thanks to Edl, UNM has one of the very few EE curricula in the U.S. in which students can learn to master high power electronics." ■

### Further Reading

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#### Rapid Start of Oscillations in a Magnetron with a "Transparent" Cathode

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(Received 1 March 2005; published 10 November 2005)

We report on the improvement of conditions for the rapid start of oscillations in magnetrons by increasing the amplitude of the operating wave that is responsible for the capture of electrons into spokes. This amplitude increase is achieved by using a hollow cathode with longitudinal strips removed, thereby making the cathode transparent to the wave electric field with azimuthal polarization. In addition, an optimal choice of the number and position of cathode strips provide favorable prebunching of the electron flow over the cathode for fast excitation of the operating mode. Particle-in-cell simulations of the A6 magnetron demonstrate these advantages of this novel cathode.

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