ated international interest in the technology. While earlier experiments have demonstrated very high power levels over a broad range of frequencies, users and the research community have fixed on a few systems with very versatile features and relatively compact dimensions.

In our first edition we made seven predictions about HPM's future directions. By our accounting, two of those seven predictions have borne out. Revisiting them tells us something about the changes that have occurred in the last decade and perhaps will occur in the next decades.

We learn more from failed predictions than from successful ones. First, the wrong predictions: We predicted that the peak power would exceed 100 GW, because 10 GW had been achieved by the RKA and MWCG. But this was not to be. The most important change that has occurred in the last decade is that *the power derby is over.* Peak power itself is not the driving factor in HPM, although it is always important. In the 1990s it became clear that peak power is limited by plasma formation and breakdown inside the sources. Substantial efforts have occurred in the last decade to attack the pulse-shortening problem, and they have been somewhat successful.

Pulse energy is more important for some applications, and at the highest powers energy is limited by pulse shortening. We predicted that most sources would achieve a microsecond pulse — some sources 10 μsec — and that sources not capable of microsecond operation would not be further developed. In retrospect, this did not happen because we did not understand that pulse shortening is such a serious limitation. The reality today is that sources are limited to the range of 100 J to 1 kJ at most, meaning 1 GW for a microsecond or 10 GW for 100 nsec. The limits are set by a plasma production in the sources and by breakdowns at high internal electric field. These limitations are discussed in Chapters 3, 7, and 8.

We predicted 100-kW average powers would be common, approaching 1 MW, because ~10 kW had been achieved in the early 1990s and higher repetition rates had been demonstrated for a few sources. But it did not happen because neither higher repetition rates nor higher peak powers were pursued. At present there appear to be no applications that require repetition rates above about 100 Hz.

In the 1990s phase locking of both amplifiers and oscillators had been demonstrated at high power (2 GW) operation in a module of seven sources, together with good phase stability and phase control (1 to 10°). We predicted phase locking would be extended to gangs of 100 sources, by which we meant that modules of about 10 sources would be built and that a group of ~10 such modules could reach ~100 GW. These would couple to antenna arrays to produce extremely high radiated powers with very narrow beams. This did not occur because no application required it. Technology exists but the need does not.

Now for a minor success. A decade ago most sources had power efficiencies of 10 to 20% with energy efficiencies less than 10% due to pulse shortening. We predicted the sources would develop to 50% energy efficiency. That has occurred, but only for continuous gyrotrons, not for pulsed sources.

The problem is that although theoretical efficiencies are high, in practice few devices have been truly optimized. Efficiency is low because it is hard to maintain resonance throughout the electrical pulse; so efficiency is low at the beginning and trailing ends of the pulse.

Another prediction we can be proud of is the merging of HPM and conventional microwave technologies and their research communities. They both follow the demands of applications. This has driven them to work together, as can be seen from two volumes uniting the two communities, sponsored by the U.S. Department of Defense.[3,4] We predict that this community will in the future produce better sources and HPM full-scale systems.

We anticipate that the two fields of HPM and conventional microwave devices, which have constituted different communities, technologies, and traditions, will converge further in the future. HPM can benefit from many aspects of conventional technology. Perhaps the most important of these is clean environments, most especially improved surface and vacuum techniques. Another area of importance is the control of breakdown.

The techniques of production technology, in which quality control is preeminent in building reliable and maintainable devices for a long lifetime, will be transferred from the conventional tube houses into the HPM community. This may lead to performance improvements in commercial HPM sources, usually for HPM testing facilities, in the next decade. Most types (magnetrons, vircators, BWOs, klystrons, reltrons, and gyrotrons) are available commercially, and we expect that many other source types with improved parameters will become available as applications take on more reality and the market for these sources grows. There is a substantial international market in HPM equipment, with Russia and the U.S. as the major suppliers. For example, Russia's military export company is offering buyers the opportunity to participate in the co-development of an HPM weapon, RANETS-E, that would operate in the X-band at 1-GW peak power, 5-nsec pulse duration, and 100-Hz repetition frequency (see Chapter 3). For a future extrapolation, see SuperSystem, Section 2.5.

HPM systems will follow the demands of the applications. We expect that flatness of the driving voltage pulse will become very important in the future because it is necessary for some applications, such as linear colliders, and it improves the overall energy efficiency of the device. Some devices will need broad bandwidth, especially if HPM is coupled with electronic warfare. Fundamental properties of sources, such as phase stability, will have to be improved if electronic warfare systems are to be improved by using high power sources. The use of modulations on the microwave power envelope will necessitate the development of amplifiers rather than oscillators. All applications will require reliability, a virtue little developed in HPM to date. For military applications, compact, low-mass, and transportable systems will be essential for deployments other than a fixed site. Mass and volume are driven by either system elements ancillary to the source — such as magnets, beam collection, and cooling in high average power applications — or prime and pulsed power on one end or antennas for high power radiation into air on the other.

Ultimately, the ability of HPM to achieve maturity will depend upon its ability to serve applications with a true market. These markets are only beginning to emerge and could include many defense applications, particle acceleration, industrial processes, or power beaming.

Following the extraordinary technical successes achieved by HPM in the last 30 years, HPM is finding applications driven by real needs. We remain confident that the international effort to expand the HPM technology and its emerging applications will help this new domain of electromagnetics continue to flourish in the years ahead.

Further Reading

HPM is a broad enough field that finding the appropriate references is not simple. There are several books in English[2–6] and an excellent review article by Gold.[7] The basic book on conventional tubes is by Gilmour.[8] The best reference in the technical journals is *IEEE Transactions on Plasma Science*, especially the special biannual issues dealing with HPM sources, and there are special issues on pulsed power as well. Otherwise, papers on HPM appear primarily in the *Journal of Applied Physics*, *Physics of Fluids B*, *Physical Review A*, and the *International Journal of Electronics*. The proceedings of the International Conferences on High Power Particle Beams, known popularly as, for example, BEAMS '06, contain state-of-the-art reports on HPM sources driven by pulsed power electron beam generators. UWB work is chronicled in IEEE special issues and in *Ultra-Wideband, Short-Pulse Electromagnetics*, a continuing series from Kluwer Academic/Plenum Publishers.

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2

Designing High Power Microwave Systems

2.1 The Systems Approach to High Power Microwaves

One of our primary goals in writing this book is to develop in the reader a systems perspective toward high power microwaves (HPM). This chapter describes that perspective and its application to the design and construction of HPM systems. To illustrate some of the points in this chapter, we draw upon our experience in assembling systems for various applications.

Our operational definition is that a system is an *orderly working totality*. More concretely, an HPM system can be represented by the simple block diagram shown in Figure 2.1. From left to right, we have:

1. A prime power subsystem that generates relatively low power electrical input in a long-pulse or continuous mode
2. A pulsed power subsystem that takes the low power/long-pulse electrical power, stores it, and then switches it out in high power electrical pulses of much shorter duration
3. A microwave source in which the short-duration, high power electrical pulses are transformed into electromagnetic waves
4. Perhaps a mode converter to tailor the spatial distribution of electromagnetic energy to optimize transmission and coupling to an antenna
5. An antenna, which directs the microwave electromagnetic output, essentially compressing that output spatially into a tighter, higher-intensity beam

As presented, the arrows in the figure depict the flow of power and energy within the system, from the prime power generator on the input end to the radiation of microwaves from the antenna on the output end. In assembling such a system, *the selection of individual components is subordinate to the overall goal of optimizing the system as a whole for a chosen purpose*. Note that this is the outline of a system; later diagrams will show much greater complexity.