$$G = 5.18\left(\frac{D}{\lambda}\right)^2 = 5.18\left(\frac{Df}{c}\right)^2 \quad (2.5)$$

For our X-band frequency, we choose f = 10 GHz, so that $\lambda = 3$ cm. Now, if we choose a gain of 45 dB, so that $G = 3.2 \times 10^4$, we can use Equation 2.5 to find the antenna diameter: D = 2.4 m.

We can now compute several other output parameters of the system. The output beam width of the microwave beam (or the width of the central antenna lobe) from a parabolic dish antenna (see Chapter 5) is the following:

$$\theta(radians) = 2.44\left(\frac{\lambda}{D}\right) = 2.44\left(\frac{c}{Df}\right) \quad (2.6)$$

For our X-band frequency and computed diameter D, $\theta = 30$ mrad. The *effective radiated power* (ERP), the product of the radiated power and the gain, is

$$ERP = GP_{RAD} \quad (2.7)$$

which, in the case at hand, has the value ERP = 16 TW for a radiated power of P_{RAD} = 500 MW. Finally, the peak angular radiation intensity, measured in watts/steradian, is given by

$$J\left(\frac{W}{steradian}\right) = \frac{ERP}{4\pi} \quad (2.8)$$

To move farther upstream to the BWO, we need only two other parameters: the power conversion efficiency of the antenna, η_A, and the efficiency of the mode converter that converts the TM_{01} output of the BWO to a TE_{11} mode required by the antenna, η_M. For our system, we choose $\eta_A = 0.85$ and $\eta_M = 0.95$. Note once again that we do not need to know the details of the coupling to the antenna or the mode conversion process. We simply use values that are consistent with past practice.

2.5.4 Backward Wave Oscillator

For the power level and repetition rate, the best choice for X-band is the BWO. At lower frequencies, magnetrons and klystrons become competitive. BWOs have reached powers of 5 GW, so 0.5 GW is well within their capability. Working backward from the 500-MW output radiated from the antenna, given the antenna and mode converter efficiencies of $\eta_A = 0.85$ and $\eta_M = 0.95$, we infer an output from the BWO of

$$P_{BWO} = \frac{P_{RAD}}{\eta_A \eta_M} = \frac{500\,MW}{(0.85)(0.95)} = 620\text{ MW} \quad (2.9)$$

in a pulse of length τ_{RF}.

Next, to determine the electrical input requirement for the BWO, we must take account of both the instantaneous power efficiency for converting electron beam energy to microwave power and the differences in pulse length between the microwave output and the electron beam input. In our earlier treatment of BWO efficiency in Equation 2.2, we combined both effects. To compute the electrical input requirement for the BWO, we make the following assumptions:

- To take account of the longer pulse length of the SuperSystem relative to the NAGIRA system, we assume a constant difference between the electron beam and output microwave pulse lengths, rather than a constant proportionality. Thus, we retain the 5-nsec difference for NAGIRA to arrive at an electron beam pulse width for the SuperSystem of $\tau_{BEAM} = \tau_{RF} + 5$ nsec. This 5 nsec is the time required for the electron beam current to rise to the level required to sustain oscillation in the BWO and for those oscillations to build up to their full amplitude.
- Factoring out pulse-length effects, we assume that the power efficiency for generating microwaves, the relationship between the electron beam power and the microwave output power of the BWO, is the same for the SuperSystem as it was for NAGIRA. In NAGIRA, a 3-GW electron beam produced a 500-MW BWO output, so that the power efficiency $\eta = 0.17$. Therefore, to produce a 620-MW BWO output, an electron beam power of P_{BEAM} = 3720 MW is required.
- We assume that the SuperSystem BWO will have the same 150-ohm impedance, Z_{BWO}, as the BWO in the IHCE system, as this is typical of BWOs (see Figure 5.2). Thus, with V_0 the anode–cathode voltage in the diode,

$$P_{BEAM} = V_0 I_b = \frac{V_0^2}{Z_{BWO}} = 3720\text{ MW} \quad (2.10a)$$

so

$$V_0 = \left(P_{BEAM} Z_{BWO}\right)^{1/2} = 747\text{ kV} \quad (2.10b)$$

$$I_b = \frac{V_0}{Z_{BWO}} = 4.98 \text{ kA} \tag{2.11}$$

As indicated in the system-level diagram of Figure 2.17, the BWO will require a magnet. In the NAGIRA system, the magnet is superconducting, as is typical of fielded systems (such as ORION; see Chapters 5 and 7). This magnet adds mass to the system, and it requires its own small power supply and cooling system. Field systems use superconducting magnets because, while they need cryogenics for cooling, their ancillary power supply and vacuum equipment are far smaller and lighter than the power supply of normal magnets and they are lighter than permanent magnets.

2.5.5 Pulsed Power Subsystem

The internal structure of the SINUS generator consists of three components, as indicated in Figure 2.14. From the end closest to the prime power, these are the low-voltage capacitive energy store, the integrated Tesla transformer/pulse-forming line (PFL), and the tapered output transmission line. A layout of a SINUS machine is shown in Figure 2.18. The low-voltage capacitive store charges up at the output voltage of the power conditioning end of the prime power subsystem. The Tesla transformer is integrated with a cylindrical PFL. A single-turn primary is wound around the inner wall of the outer conductor, while the secondary crosses the gap between the coaxial conductors in the PFL, so that its high-voltage end contacts the center conductor, driving it to a large negative voltage. The Tesla transformer steps up the voltage from the capacitive store to the required output voltage, and the PFL shapes the output pulse and defines the duration of the voltage pulse at the output.

Unfortunately, for reasons related to the volume efficiency of storing electrical energy, the output impedance of the oil-insulated PFL itself, Z_{PFL}, tends

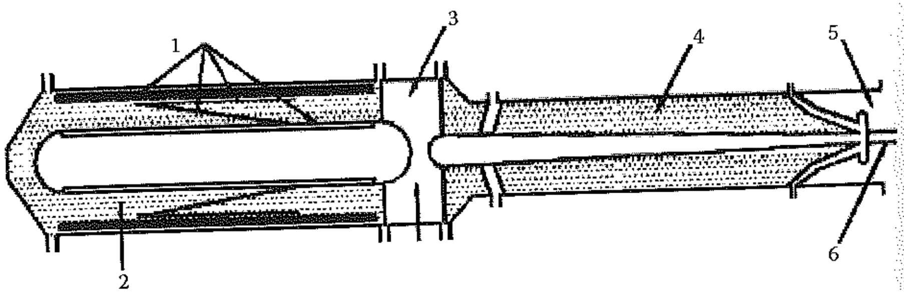

FIGURE 2.18
Physical configuration of SINUS pulsed power devices: 1, pulsed transformer; 2, coaxial oil-insulated PFL; 3, gas spark gap; 4, output tapered transmission line; 5, vacuum region; 6, cathode for beam generation, driving BWO. (From Rostov, V.V. With permission.)

to lie between 20 and 50 Ω (Section 5.2). The role of the tapered transmission line is to transform between the output impedance of the PFL and the impedance of the BWO, $Z_{BWO} = 150\ \Omega$. The length of the tapered transmission line is directly proportional to the length of the electron beam pulse, τ_{BEAM}:

$$L_{TL} = \frac{3}{2} c' \tau_{BEAM} \tag{2.12a}$$

Because we expect that the transmission line will be filled with insulating oil, the speed of light in the line is reduced to $c' = 2 \times 10^8$ m/sec, so that in units appropriate to the problem,

$$L_{TL}(m) = 0.3\tau_{BEAM}(nsec) \tag{2.12b}$$

Presuming that we wish to align the transmission line with the Tesla transformer/PFL, as was the case for NAGIRA in Figure 2.16, this length must be added to that of the PFL when one is determining the overall length of the platform that would carry this system. The length of the Tesla transformer/PFL, which will also be filled with insulating oil, is approximately the length of the PFL itself, which for a pulse length of τ_{BEAM} is given by

$$L_{PFL} \approx \frac{1}{2} c' \tau_{BEAM} \tag{2.13a}$$

or

$$L_{PFL}(m) \approx 0.1\tau_{BEAM}(nsec) \tag{2.13b}$$

Adding Equations 2.12b and 2.13b, we get

$$L_{TL}(m) + L_{PFL}(m) = 0.4\tau_{BEAM}(nsec) \tag{2.14}$$

From this relation, we can see that for a 10-nsec pulse, the length is about 4 m, while for a 20-nsec pulse, the length doubles to about 8 m. Because 8 m may be too long for some containers, we must consider the options with and without the transmission line, evaluating the trade-off between the added length of the tapered transmission line and the inefficiency that results if it is not used.

To treat the power flow, in Figure 2.11 we rename the voltage source and its output impedance V_{PFL} and Z_{PFL}. The beam voltage across Z_{BWO} and beam power through Z_{BWO} are

$$V_0 = V_{PFL}\left(\frac{Z_{BWO}}{Z_{PFL}+Z_{BWO}}\right) \tag{2.15}$$

$$P_{BEAM} = \frac{V_0^2}{Z_{BWO}} = V_{PFL}^2 \frac{Z_{BWO}}{\left(Z_{PFL}+Z_{BWO}\right)^2} \tag{2.16}$$

The maximum value of P_{BEAM} for a given PFL output impedance is given by Equation 2.16 when $Z_{BWO} = Z_{PFL}$:

$$P_{BEAM,\max} = \frac{V_{PFL}^2}{4Z_{PFL}} \tag{2.17}$$

We define the pulsed-power efficiency to be the fraction of the maximum available pulsed-power output that goes into the beam:

$$P_{BEAM} = \eta_{PP} P_{BEAM,\max} \tag{2.18}$$

If a tapered transmission line is used, Z_{BWO} will appear to the PFL to be approximately equal to Z_{PFL}, no matter what its actual value, because the line is an impedance transformer. The line is not perfectly efficient, and our rule of thumb is that with tapering

$$\eta_{PP} = \eta_{TL} = 0.85 \tag{2.19}$$

If the tapering is not used, perhaps because it is too long for a given platform, we combine Equations 2.16, 2.17, and 2.18 to get

$$\eta_{PP} = \frac{P_{BEAM}}{P_{BEAM,\max}} = \frac{4Z_{BWO}Z_{PFL}}{\left(Z_{PFL}+Z_{BWO}\right)^2} \tag{2.20}$$

The decision to use the tapered line or not will depend on overall system length. Two cases will arise; we will:

- Use the tapered line if it doesn't make the system too long for the platform. It will have optimum impedance from the standpoint of minimizing the volume in which its energy is stored, so that Z_{PFL} = 20 Ω and η_{PP} = 0.85.
- Not use it if it makes the system too long. The impedance will be higher, Z_{PFL} = 50 Ω; from Equation 2.21b, η_{PP} = 0.75 for BWO impedance Z_{BWO} = 150 Ω.

The SINUS is a well-engineered pulsed power system, so about 90% of the energy stored in the PFL is available to deliver power to the beam, the remainder being lost to rise and fall times and other intrinsic losses. When the tapered line is used, Z_{BWO} appears to have the value Z_{PFL}, no matter what its actual value. With and without the tapered line, P_{PFL}, the power flowing out of the voltage source V_{PFL} into the series impedances Z_{PFL} and Z_{BWO}, is given by the two expressions (with V_0 = 747 kV, Z_{PFL} = 20 or 50 Ω, depending on whether the tapered line is used, and Z_{BWO} = 150 Ω):

With the tapered line (Z_{PFL} = 20 Ω)

$$P_{PFL} = \frac{V_{PFL}^2}{2Z_{PFL}} = 2\frac{P_{BEAM}}{\eta_{PP}} = 8.75 \text{ GW} \tag{2.21}$$

Without the tapered line (Z_{PFL} = 50 Ω)

$$P_{PFL} = \frac{V_{PFL}^2}{Z_{PFL}+Z_{BWO}} = \frac{V_0^2}{Z_{BWO}}\left(\frac{Z_{PFL}+Z_{BWO}}{Z_{BWO}}\right) = 4.96 \text{ GW} \tag{2.22}$$

In either case, assuming a 5-nsec rise time for the microwaves, $\tau_{BEAM} = \tau_{RF} +$ 5 ns, the energy stored in the PFL must be

With the tapered line (Z_{PFL} = 20 Ω)

$$E_{PFL}(J) = \frac{P_{PFL}\tau_{BEAM}}{0.90} = 9.72\tau_{RF}(ns) + 48.6 \tag{2.23a}$$

Without the tapered line (Z_{PFL} = 50 Ω)

$$E_{PFL}(J) = \frac{P_{PFL}\tau_{BEAM}}{0.90} = 4.69\tau_{RF}(ns) + 23.4 \tag{2.23b}$$

To find the values of V_{PFL} are

With the tapered line (Z_{PFL} = 20 Ω)

$$V_{PFL} = 2\left(\frac{P_{BEAM}Z_{PFL}}{\eta_{PP}}\right)^{1/2} = 592 \text{ kV} \tag{2.24a}$$

Without the tapered line (Z_{PFL} = 50 Ω)

$$V_{PFL} = V_0\left(\frac{Z_{PFL}+Z_{BWO}}{Z_{BWO}}\right) = 966 \text{ kV} \tag{2.24b}$$

The energy in the fast energy store, E_{FAST}, is transferred to the PFL with 90% energy efficiency:

With the tapered line (Z_{PFL} = 20 Ω)

$$E_{FAST}(J) = \frac{E_{PFL}(J)}{0.90} = 10.8\tau_{RF}(ns) + 54.0 \tag{2.25a}$$

Input power required to recharge the capacitive energy store between shots is approximately given by

With the tapered line (Z_{PFL} = 20 Ω)

$$P_{FAST} \approx E_{FAST}PRR = PRR\left[10.8\tau_{RF}(ns) + 54.0\right] \tag{2.25b}$$

A comparison of the parameters required for SuperSystem with the ranges for the SINUS series is given in Table 2.2. One can see that the required input power to charge the capacitive energy store of the SINUS generator is about 53% above the level seen in previous versions of this device.

Moving upstream, we come to the burst-mode prime power options of Figure 2.7. Starting with the converters at the right of the figure, we note that AC/DC converters (transformer-rectifiers) and DC/DC converters (essentially switching power supplies) have typical power transfer efficiencies of 0.88. Therefore, the input power into the controllers is

$$P_C = \frac{P_{FAST}}{\eta_C} = \frac{P_{FAST}}{0.88} \tag{2.26}$$

Note that this is the power that must be transferred through either the AC/DC or DC/DC converters, depending on the option chosen, to recharge the capacitive store for each shot. The energy per shot that must be transferred into the controller is

$$E_C = \frac{P_C}{PRR} \tag{2.27}$$

At this point, we make the decision that the output voltage for the controllers, V_C, is the default input voltage to the SINUS generator: 300 V.

TABLE 2.2

Comparison of the SuperSystem Parameters to Those of the SINUS Series of Pulsed Power Machines

Parameter	SuperSystem Value	SINUS Range
Average input power, P_{FAST}	40.5–76.5 kW	0.1–50 kW
Output voltage, Φ_{BEAM}	747 kV	100–2000 kV
Output pulse width, τ_{BEAM}	15–25 nsec	3–50 nsec
Output impedance, Z_{BWO}	150 Ω	20–150 Ω
Pulse repetition rate, PRR	500 Hz	10–1000 Hz

TABLE 2.3

Eight Parameters Describing the Burst Mode of Operation

Mission Parameters		Burst Store Parameters	
PRR	Pulse repetition rate	E_S	Energy stored in the energy store and electrical source component to deliver one microwave pulse
N_S	Number of shots in a burst	E_B	Energy stored in the energy store and electrical source component to deliver one burst
τ_B	Time duration of one burst	P_{AVE}	Average output power delivered by the energy store and electrical source component during a burst
τ_{IB}	Interburst (recharge) interval	P_{RC}	Average power delivered into the energy store and electrical source component during the interburst recharge time

As we move upstream into the prime power system options captured in Figure 2.7, we note that burst-mode prime power options are defined by eight parameters, four *mission parameters* and four *burst store parameters*, which are shown in Table 2.3; we rename some of the parameters here for convenience in making them consistent with our SuperSystem model. Of the four mission parameters shown in the table, we are familiar with three already; the fourth, the number of shots in a burst, N_S, is given by

$$N_S = PRR \times \tau_B \tag{2.28}$$

Given the range of possible user choices for τ_B, N_S can range from 500 to 2500 shots per burst. The burst store parameters relate to stored energies and power flows within the prime power. The energy per shot, E_S, is defined as the amount of energy that must be stored in the energy store and electrical source component to ultimately deliver one 500-MW radiated microwave pulse with a pulse length of τ_{RF} at an efficiency η_{ESES}. Thus,

$$E_S = \frac{E_C}{\eta_{ESES}} \tag{2.29}$$

TABLE 2.4

Power Transfer Efficiencies of the Different Energy Store and Electrical Source Options of Figure 2.7

Energy Store and Electrical Source Option	h_{ESES}
Flywheel/alternator	0.96
Pulsed alternator	0.96
High-rate secondary battery	0.50

The efficiency η_{ESES} varies as shown in Table 2.4 for the three energy store and electrical source options of Figure 2.7. The energy per burst, E_B, is the amount of energy extracted from the energy store and electrical source component at an efficiency η_{ESES} in the course of a full burst:

$$E_B = N_S E_S \tag{2.30}$$

The average power, P_{AVE}, is defined as the average power flow *into* the converter component from the energy store and electrical source component over the course of a burst; in fact,

$$P_{AVE} = P_C = \eta_{ESES} E_S PRR = \eta_{ESES} \frac{E_B}{\tau_B} \tag{2.31}$$

The last step in this equation involved the use of Equations 2.23 and 2.25. Now, the average recharging power, P_{RC}, is the power that flows into the energy store and electrical source component to recharge it during the inter-burst recharging period. Thus,

$$P_{RC} = \frac{E_B}{\tau_{IB}} = \left(\frac{\tau_B}{\tau_{IB}}\right)\frac{P_{AVE}}{\eta_{ESES}} \tag{2.32}$$

The power from the prime mover components required to supply this power must pass through the interface components. From the literature, the efficiency with which this power passes through, η_I, varies with each interface component option, as shown in Table 2.5. Thus,

$$P_{PM} = \frac{P_{RC}}{\eta_I} \tag{2.33}$$

Estimation of the volumes and weights of the subsystems and the total SuperSystem can then proceed. Figure 2.19 shows a concept of the subsystem

TABLE 2.5

Efficiencies for the Different Interface Options of Figure 2.7

Interface Option	Efficiency, η_I
Hydraulic pump motor controller	0.80
Electric motor controller	1.00
AC/DC converter	0.88

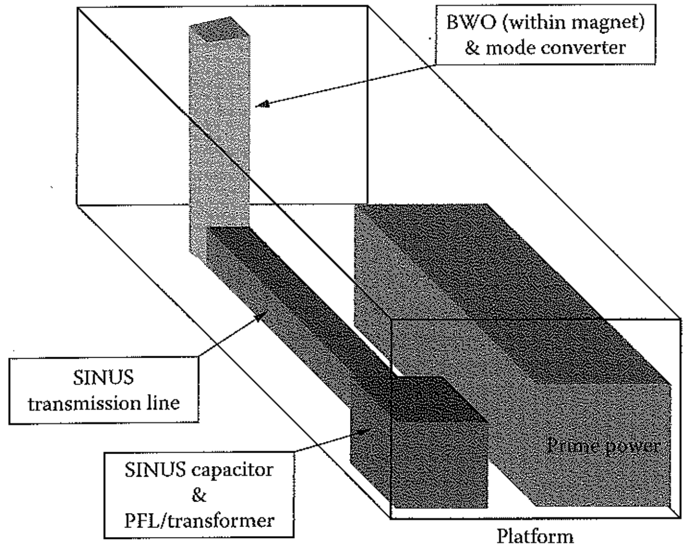

FIGURE 2.19
Internal configuration of the SuperSystem.

layout based on the layout of NAGIRA (Figure 2.16). For a higher power system, see Problem 2.2.

2.6 Conclusion

As an art, not a science, only experience with choices and detailed analysis can make systems design and the underlying issues clear. It is a school of hard knocks, as optimistic initial assumptions are frequently followed by detailed considerations that reduce performance. Nevertheless, it is the only way to move forward to allow the building of advanced HPM systems that the applications described in the next chapter need.

Problems

1. For SuperSystem, at a range of 10 km what is the power density and energy density for a single pulse?
2. Design a more advanced SuperSystem with increased peak power, longer pulse duration, but lower repetition rate and microwave frequency: 5 vs. 0.5 GW, 100 vs. 20 nsec, 100 vs. 500 Hz, 3 vs. 10 GHz. Keep the burst time and interburst time fixed at 1 and 10 sec. Keep the antenna gain fixed at 40 dB, to keep the diameter reasonable.

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3

High Power Microwave Applications

3.1 Introduction

There is a strong, symbiotic relationship between a developing technology and its applications. New technologies, or dramatic increases in the performance of an existing technology, can generate applications previously either unrealizable or impractical. Conversely, the demands posed by an existing application can spur the development of a new technological capability. Examples of both types can be found in the evolution of high power microwaves (HPM). The high power and energy output made possible by HPM research have created a technology-driven interest in HPM directed energy weapons. On the other hand, the requirements for electron cyclotron resonance heating of fusion plasmas have resulted in an application-driven program to develop high-frequency, high-average-power microwave sources. In this chapter, we will address the present state of such applications.

Compared to the first edition 15 years ago, some applications have grown, some have declined, and some are no more (for example, laser pumping using microwaves has disappeared). The most successful is HPM directed energy weapons, now at the point of deployment. Funding over the past few decades has been highest for defense-oriented work. Power beaming research is vibrant, as is microwave-driven plasma heating. Plasma heating is perhaps the longest studied application. High power radar is currently inactive, except for short-pulse mesoband ultrawideband. Following the rejection of high power klystrons for the International Linear Collider, particle acceleration has receded toward the distant horizon and laser pumping using microwaves has disappeared.

3.2 High Power Microwave Weapons

A time in the near future ...

We came in low toward the target. It was a black night and for now there was no sign that they had detected us as we came in from the sea. There were four other pilots making the same attack plan against nearby nodes at the same time. One of them would get painted for sure, and then the whole air defense system would light up and they'd start finding us. Best to get on with it.

We had a couple of these new model HPM systems hanging off hard points under the wing, and we were going to try using them tonight. We'd tried the first model last year and it didn't work out. Too much trouble to use out here in real life.

So I activated the HPM icon on the HUD* display and looked over the settings menu. Last time it'd been as long as my arm. This time they had a new interface and claimed it was "smart." We'd see. It sure was simpler.

Last time we'd had to set everything on it. First, we'd use the emissions detection gear to tell which systems they were using. These days everything is for sale, so it could be Russian, French, even ours.

So we had to figure out from its comparison library what we had looking at us. Plus what they were using for comm. Then we'd send that to the HPM system. Then we'd have to tell it what frequencies it should produce, how fast to shoot, all sorts of stuff. Stuff we didn't have time for.

The slow part was us, mere slo-mo humans.

Now it was different. I just picked the target set. The HPM's new operating mode identified what emissions to listen for. Then it looked up electronic vulnerability tables based on real field tests, tests to burnout, of assets captured in some Third World scrap or just bought on the international arms market. Then it set its own parameters: repetition frequency, burst length, and things I hadn't a clue about, like polarization.

My navigator said the GPS had us 10 miles out from the target area, so I took her down to 100 yards and we began the approach. Then they found us.

First the RWR† sound started up and our ECM‡ cut in, singing and flashing direction lights. A fiery stream of antiaircraft shells snaked toward us, looking like red bubbles in black champagne. We evaded. The ground lit up like a Christmas tree. Then they launched a surface-to-air *missile* somewhere and I got a big red "missile" on the HUD. The new HPM system had a self-protect mode, so I clicked that icon and it started an omni broadcast around us. And I jammed the stick hard over right, jinking to evade. But I needn't have bothered. The HPM caused the brains of the thing to lose interest in us and it slammed into the sand below. But the shells still streamed through the night; we had to get on with it.

The HPM weapon was mounted as an expendable, so we just had to get it close enough to launch it. So I set up to release it, first presetting the "release" icon. By then the bird had listened to the electronic traffic around us and knew what to go after. I squeezed off the release. The HPM bird fell from the rack. We felt an upward jolt as the plane lightened. The "release complete" indicator on the display flashed and then began reading the telemetry from the launched bird. I jinked hard left and glanced outside. I could just barely see its low-observable engine plume as it snaked to the right after its first target. Before long I heard in my earphones its electronic chatter as it fired a burst of pulses into the first concentration it found. It would adaptively adjust all those parameters until it reached a set the tables said would put each target in the node out of action. Then it moved on. It would go ahead, burning out their electronic eyes and ears, clearing a path through the primary nodes of their defense, bringing their system down. Then the fighter-bombers could get through to the big targets.

As we set off on a course to drop the next smart bird, I remembered the first time we used HPM. We had to set up a slew of parameters for the specific target and then fire some test shots to make sure we were getting the right power and such. Now we just let her go and she tuned her parameters as she went. The guys who make these things have finally got the true meaning of "fire and forget" and "man out of loop." We don't have time to fiddle with their gadget when there's live fire around us!

Science fiction? A realistic projection? This section introduces you to the main proposed application for high power microwaves: electromagnetic nonlethal weapons.

Weapons that direct energy instead of matter on targets have undergone extensive research in the last two decades. They have two potential advantages over existing weapon systems. First, they use a power supply rather than a magazine of explosive munitions; this "deep magazine" is unlikely to be expended in battle. Second, they attack at the speed of light, 160,000 times faster than a bullet, thus making avoidance of the incoming bolt impossible and negating the advantage of increasingly swift tactical missiles.

Directed energy weapons (DEWs) generally fall into three categories: lasers, microwave or radio frequency (RF) energy weapons, and charged particle beam weapons. HPM has an advantage over the other DEWs in that microwaves do not face a serious propagation issue. Particle beams and lasers have difficulties in propagating through the atmosphere, and electron beams cannot propagate in space. Moreover, both are pinpoint weapons with small spot sizes requiring precise pointing to hit the target. Antenna directed microwaves, on the other hand, spread through diffraction and have spot sizes large enough to accommodate some lack of precision in pointing and

* HUD: Heads-up display.
† RWR: Radar warning receiver.
‡ ECM: Electronic countermeasure.

tracking. Lasers and particle beams are also much less electrically efficient, more complex, and therefore more costly.

3.2.1 General Aspects of High Power Microwave Weapons

One of two outcomes is expected of a DEW attack: soft kill, in which mission-critical components are disabled while the target body remains largely undamaged, and hard kill, with large-scale physical destruction of a target. The military prefers a hard-kill capability, "smoking rubble," or at least an assurance that an adversary cannot circumvent the weapon effect; however, most DEW scenarios for HPM are soft-kill missions. This is similar to radar jamming and electronic warfare, which can be predicted with confidence, but not directly verified.

The concept of using powerful microwave pulses as a weapon dates at least as far back as British radar studies during World War II. The idea has had several reincarnations, including early ideas of thermal and structural damage, which require enormous powers. Now both antielectronics and nonlethal antipersonnel HPM weapons are deployed.

In the 1980s the prospect became more credible because of two converging technology developments: (1) the development of sources capable of producing peak powers in excess of a gigawatt and (2) the increasing miniaturization of, and dependence on, electronic components in military and consumer electronics. The small scale of today's electronic components makes them vulnerable to small amounts of microwave energy — thus the emergence of the "chip gun" and "E-bomb" concepts, a transmitter designed to upset or burn out integrated circuits in the electronic brains of modern systems.[4] The continuous trend toward miniaturization and lower operating voltages has made HPM weapons more attractive. Vulnerability has increased because the recent use of unhardened commercial equipment at lower cost has meant replacement of metal packaging by plastic and composite materials.

Some virtues of electronic attacks with HPM are:

- Electronic attacks produce little or no collateral damage, nonlethal to humans.
- Most defense systems are not hardened, so to counter, an entire system must be hardened. An HPM weapon made effective against a deployed system requires modification of a large inventory in order for confidence to be restored.
- Entry can be by front door or back door.
- Area attacks, with many targets, are possible.
- Little sensitivity to atmospheric conditions such as fog and rain.
- Few legal barriers to their development or use.
- Cost little relative to conventional munitions per target.
- Repair requires high level of expertise, so probably cannot be done at the site.
- Can provide additional rungs on an escalation ladder, expanding the range of options available to decision makers.

A limitation of electromagnetic weapons is the difficulty of kill assessment. Absence of emissions does not necessarily mean that an attack has been successful. Targets successfully attacked may appear to still operate. Radiating targets such as radars or communications equipment may continue to radiate after an HPM attack, even if their receivers and data processing have been damaged or destroyed. A deceptive response for a system coming under attack is to shut down.

In descending order of required power density on target, the hierarchy of HPM directed energy effects is the following:

1. *Burnout*: Physical damage to electronic systems.
2. *Upset*: Temporary disruption of memory or logics in electronic systems.
3. *Jamming*: Blinding of microwave or RF receivers or radar.
4. *Deception*: Spoofing of the system into mission failure.

This last category is akin to *electronic warfare* (EW) at higher power levels, and therefore at much greater effective ranges. The third level in the above list is an overpowering of enemy systems in the same manner as contemporary battlefield jamming systems, but HPM-based super-jammers would be capable of totally dominating the battlefield, allowing no chance for "burn-through" of their jamming signal. Between high power jammers and burnout devices lies a middle ground where electronics can be upset, e.g., lose information in digital systems so that a missile may become disoriented (break lock) or tactical communications confused. As the hierarchy above is ascended, the associated missions become increasingly generic; i.e., broader classes of targets can be attacked at the higher power levels, while electronic warfare techniques are very target specific.

The distinctions between HPM directed energy and electronic warfare can be viewed in terms of the trade between the sophistication and power level of an attack, as shown in Figure 3.1. Historically, the line between electronic warfare and HPM directed energy weapons has been fairly sharply drawn, at least in the West. On the one hand, electronic warfare uses sophisticated techniques at orders of magnitude lower power (~1 kW) to deny an opponent effective use of communications and weapon systems, while protecting one's own use of the electromagnetic spectrum. Electronic warfare has emerged as a vital element of military strategy and an effective way of neutralizing enemy forces and enhancing the power of friendly forces. It has also become extremely expensive in its increasing sophistication because of the diversity of threats and a continuing race between the techniques of generating *elec-*

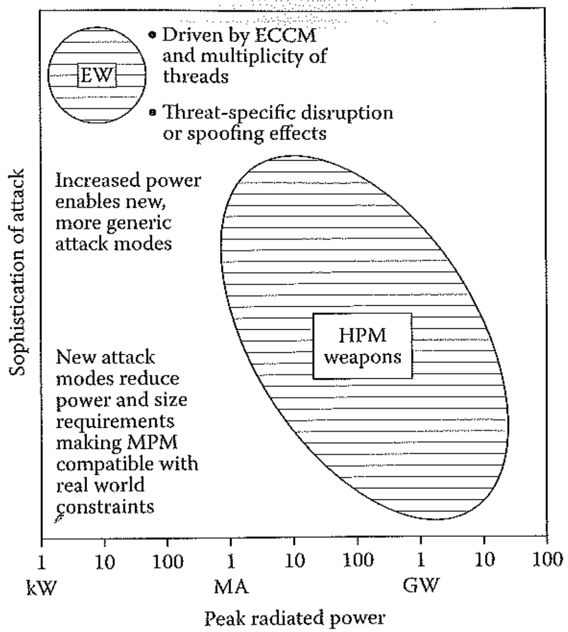

FIGURE 3.1
Domains and trends of HPM and electronic warfare.

tronic countermeasures (ECMs) and countering such interference with *electronic counter-countermeasures* (ECCMs). On the other hand, HPM DEWs, in their earliest embodiment, were seen as a means of attacking a multitude of targets, using simple pulses from a generic weapon at >1 GW to provide higher cost effectiveness than EW. Then efforts turned to developing intermediate alternatives, combining features of HPM and EW, known as *smart microwaves*, or medium power microwaves (MPM).[1] The emphasis is on employing more sophisticated waveforms at a power reduced relative to HPM. Whereas some applications of HPM have envisaged burnout of the target in a single pulse, smart microwave attacks would use repetitive pulsing or amplitude and frequency modulation and other forms of pulse shaping to lower the damage level of electronics.

Two types of attack modes against electronics have been proposed: point weapons and area weapons. In one, an HPM weapon fires intense pulses to disable a specific target at substantial range. A high power density is produced on that target by the weapon and upset or burnout is obtained. In the modern armory there are substantial numbers of target radars, semiactive homing missiles, and communications and control systems that could be vulnerable to such attacks. For example, several modern aircraft are marginally unstable and require sophisticated control electronics to fly. Burning out the chips of such an aircraft flight computer could destroy the aircraft itself. Civil aircraft use electronic systems for critical safety functions such as flight control, engine control, and cockpit display. Such systems may be susceptible to interference or damage from terrorists.

In the second class of HPM attack, large areas are swept with a radiating pulse in hopes of disabling a significant number of targets. For an area weapon to be effective, either the amount of radiated energy must be large or the threshold vulnerability level of the target must be very low. For example, the fluence to cause bit errors in unshielded computers is roughly 10^{-7} J/cm^2, so that an area weapon would be disruptive to many consumer electronic items. It is debatable that this is an effective military attack, but it could have substantial economic consequences. One method of delivering high fluences to large areas is the microwave bomb proposed in the 1980s for the Strategic Defense Initiative, in which a microwave pulse radiated in space from a nuclear explosion would damage electronic equipment over a large area.[2] Another example of an area weapon would be an RF system on a dedicated airframe, flying at low altitude and sweeping battlefield areas. Such an attack might blank out battle management systems and disable tactical communications.

The requirements of the services will differ substantially depending upon their mission and the platforms available. Since shipboard systems are larger, the Navy might be the first to use HPM because it would be less stringently limited by the size and weight of HPM systems. The threat to navies is clear: the sinking of the *Sheffield* and the near sinking of the *Stark* show that modern ships are particularly vulnerable to low-flying, sea-skimming cruise missiles. (Air defense destroyer HMS *Sheffield* burned to the waterline after being hit by a single Aerospatiale AM39 Exocet ASCM.) Such missiles have become cheaper, smarter, and longer in range, and are now being deployed in the Third World. Defense against a saturation attack by such missiles is disadvantageous since the fleet can carry only a limited number of missiles for defense.

Ground-based point attack HPM weapons would probably be mounted on large tracked vehicles with high gain antennas on a mast to provide targeting, such as the Ranets-E system shown in Figure 3.2. The size and weight requirements would be more restrictive than for the fleet, and the antenna sizes would be large to produce high directivity to avoid fratricide.

The air forces have a more difficult problem. Airborne systems need to be much smaller and operate at lower power levels because of limited on-board power. Airborne missions place severe requirements on antennas to be steerable (mechanically or by phase) and small but still avoid air breakdown around them. Aircraft reach their volume limitation long before their weight limitation, so long dimensions and size are the true issue. An example of this is the case of the forthcoming U.S. system UCAV. The HPM possibilities have been explored by L3 Communications, as shown in Figure 3.3 and Figure 3.4 below.[3]

Compactness is in fact a general problem of military applications of HPM. The size and weight limitations of military platforms require squeezing as much power into a specific volume as possible, and HPM systems to date

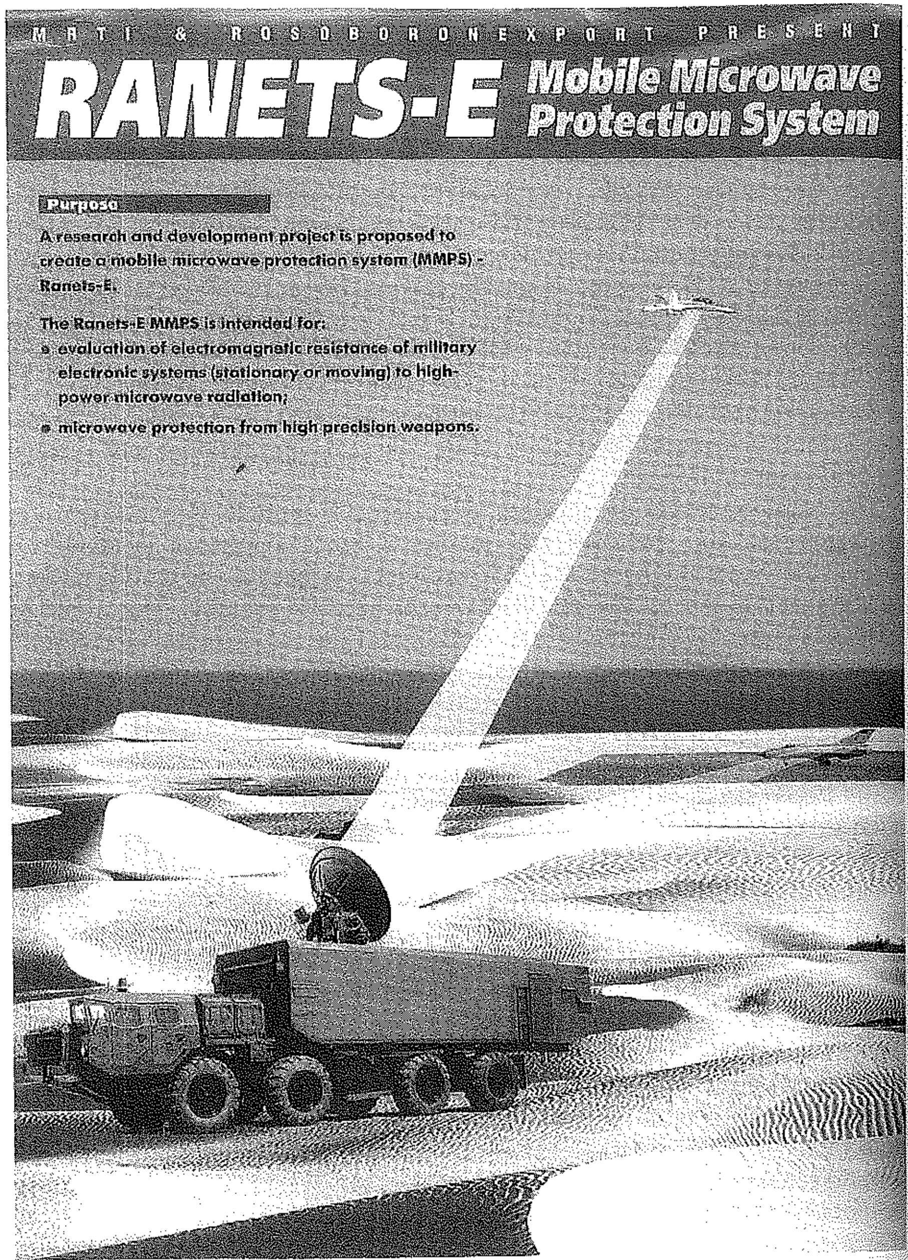

FIGURE 3.2
Brochure for an air defense HPM weapon. Russian firm offers to co-develop a system with goals of 0.5 GW, 10 to 20 nsec, 500 Hz in X-band, with 45- to 50-dB gain antenna.

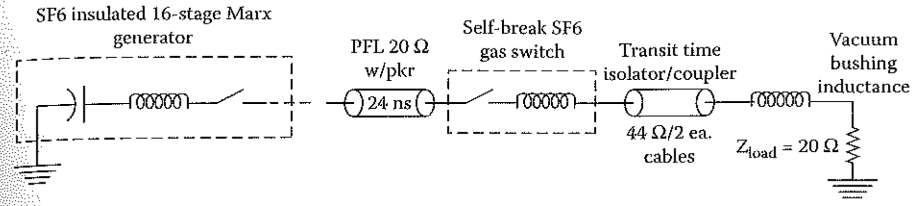

FIGURE 3.3
Circuit diagram of pulse power driving a magnetron. The layout is shown in Figure 3.4. (Reprinted from Price, D. et al., Compact pulsed power for directed energy weapons, *J. Directed Energy*, 1, 56, 59, 2003. By permission of DEPS.)

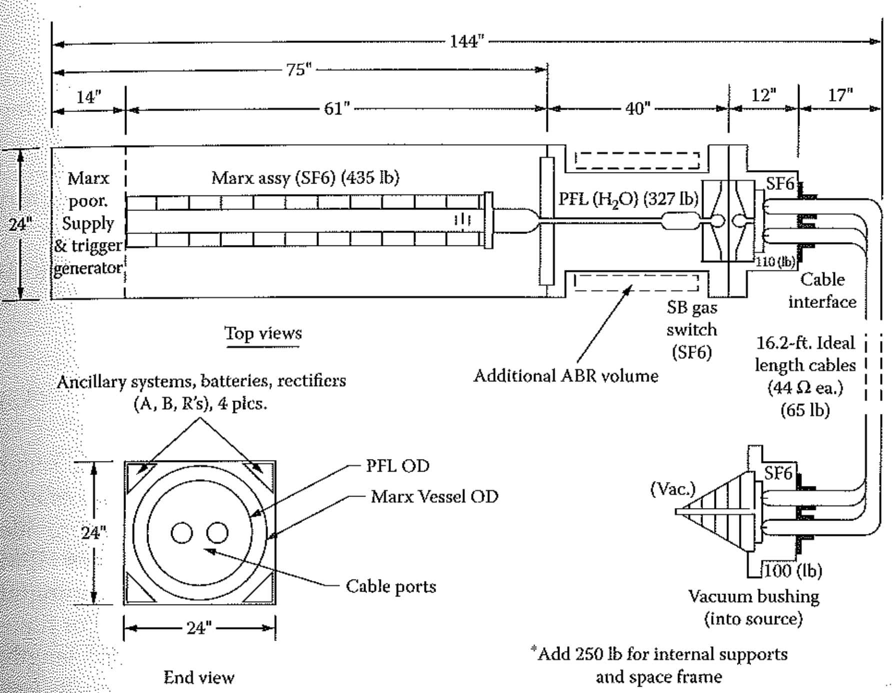

FIGURE 3.4
Top and end view of a compact pulse power system concept for mounting into the two pods of UCAV. Pulsed power (see Figure 3.3) fits into one pod and connects through cables to the second pod's vacuum bushing. Magnetron source is not shown. (Reprinted from Price, D. et al., Compact pulsed power for directed energy weapons, *J. Directed Energy*, 1, 56, 59, 2003. By permission of DEPS.)

have not been designed with this as a criterion, their purpose being HPM effects testing. In recent years, great strides have been made in compactness of capacitive energy stores, so that now the bulk of an HPM system is likely to be in other elements, such as insulating dielectrics and magnetic field coils. The specific microwave source used also has a big impact on size and weight. For example, free-electron lasers requiring a magnetic wiggler are frequently longer and heavier than other sources. The vircator and MILO (see Section 7.7), in contrast, require no magnetic field and are therefore quite simple and compact. Here efficiency comes into play. Low-efficiency sources, such as the vircator, require a large energy store to produce a given microwave power output, hence the emphasis in HPM circles on efficiency.

The relevant parameter is the *energy efficiency* of conversion from electricity to microwaves averaged over the entire electrical pulse. This is not the *power efficiency*, which can be high at some part of a pulse but low elsewhere. The difference is due to *pulse shortening*.[4] Let ε_p be the power efficiency, the ratio of instantaneous microwave power P_μ to beam power P_b, and ε_E be the energy efficiency, the ratio of microwave energy in the pulse E_μ to the pulsed electrical energy that drives the beam, E_b. For simplicity, assume powers are constant in time. Then, with t_μ the pulse duration of microwaves and t_b the pulse duration of the beam, the relations are

$$E_\mu = P_\mu t_\mu \tag{3.1}$$

$$E_b = P_b t_b \tag{3.2}$$

Therefore,

$$\varepsilon_E/\varepsilon_p = t_\mu/t_b \tag{3.3}$$

The pulse-shortening ratio t_μ/t_b is the ratio of the energy efficiency to the power efficiency. Present values are $\varepsilon_p \sim 0.2$ to 0.4, but pulse shortening makes $\varepsilon_E <$ 0.1. The HPM system designer is concerned with the *energy* he must provide from prime power and store in pulsed power because energy drives HPM system volume and mass. Therefore, for designers, ε_E is more meaningful than ε_p. The distinction between them is the pulse-shortening ratio. For time-varying P_b and P_μ, one integrates over the power over the pulse length; details of P_μ, which tends to vary rapidly, can strongly influence results (see Problem 1).

Since most microwave devices operate with a resonance condition, which depends on current and voltage, and both typically vary during the pulse, a good deal of the electrical pulse may not be useful in producing microwaves. The solution is to satisfy the resonance condition (usually a stringent requirement on voltage constancy) during virtually the entire pulse, requiring sophisticated circuitry, which increases the cost if it can be done at all. Pulsed power technology that is particularly appropriate for compact HPM is the *linear induction accelerator*, also called a *voltage adder* (see Chapter 5), but its cost and weight are high.

A further practical limitation on military HPM is the constraint of on-board power. For example, if an airborne HPM device generates 1 GW for a microsecond, thus producing 1 kJ/shot, repetitive operation at 10 Hz will require an average power of 10 kW. Such powers are available on military aircraft, but this power is usually already allocated. Making room for an HPM weapon will require additional power or eliminating some other military system on board. Therefore HPM must show its utility to justify its power consumption. In this example, a higher repetition rate, for example, a kilohertz, would be beyond the available power on an airframe. Power constraints are not as demanding on ground vehicles or on Navy vessels.

There are tactical issues associated with HPM DEWs. The disadvantages inherent in an antenna directed weapon are sidelobes and strong local fields (see Chapter 5). These produce potential problems for friendly forces, which, in the HPM community, are termed *fratricide* and *suicide*. Fratricide is unintended damage to nearby electronics or personnel due to sidelobe emission. In the "fog of war" the potential for damage to friendly forces near at hand could be a serious limitation. Since the modern battlefield is so dependent upon electronics, damage or interference with electronic systems such as the extensive electromagnetic environment of fleet defense may prevent HPM from being deployed. The problem may be mitigated somewhat by sidelobe suppression (see Chapter 5). One solution is to operate HPM only in an area empty of friendly systems, such as behind enemy lines. The second problem, suicide, is unintended damage to the subsystems of the HPM platform itself due to its own emitted pulse. This problem may be soluble by shielding or shutting down subsystems while the HPM is operating.

Because they are high power radiators, HPM weapons will have their greatest potential vulnerability to antiradiation missiles (ARMs), which home in on microwave signals. ARMs are the natural enemies of HPM; therefore, HPM systems must be able to attack ARMs if they are to survive. Potential attack mechanisms include interference with the guidance system circuits, to make them break lock, or predetonation of the warhead.

3.2.2 E-Bombs

The use of HPM warheads on precision munitions is an attractive coupling of electronic attacks with precision guided munitions (PGM): accurate missiles, glidebombs, and unmanned aerial vehicles (UAVs). Carlo Kopp, who coined the term *E-bomb* in 1995, when the U.S. Air Force originally published his work, envisioned combining a smart bomb with a HPM warhead.[5]

The massed application of such electromagnetic weapons in the opening phase of an electronic battle can quickly command the electromagnetic spectrum. This would mean a major shift from physically lethal to electronically lethal attacks. Potential platforms for such weapons are the USAF-deployed

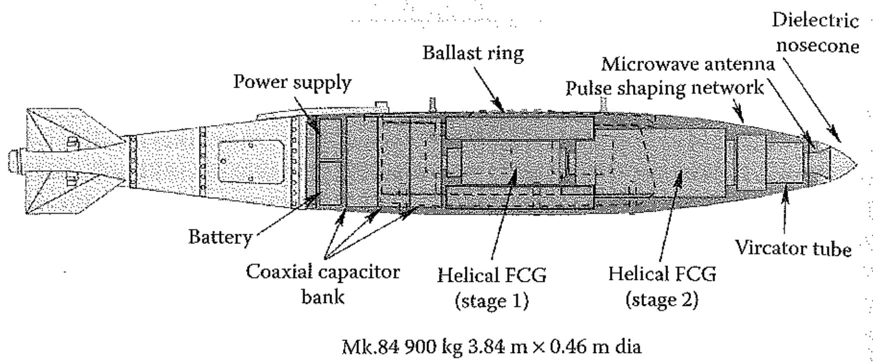

FIGURE 3.5
E-bomb concept, with two-stage flux compressor driving a vircator, fits into envelope of Mark 84 bomb. (Reprinted by permission of Dr. Carlo Kopp.)

global positioning system (GPS) aided munition on the B-2 bomber and the GPS/inertially guided GBU-29/30 JDAM (Joint Direct Attack Munition) and the AGM-154 JSOW (Joint Stand Off Weapon) glidebomb. Other countries are also developing this technology. The attractiveness of glidebombs delivering HPM warheads is that the weapon can be released from outside the effective radius of target air defenses, minimizing the risk to the launch aircraft, which can stay clear of the bomb's electromagnetic (EM) effects. In principle, all aircraft that can deliver a standard guided munition become potential delivery vehicles for an E-bomb. But, E-bombs must fit onto existing weapon platforms. Failure to do so, by requiring a dedicated new platform such as a specialized UAV, would make E-bombs unattractive due to cost and logistics. Fitting onto existing platforms can be difficult, as Figure 3.4 shows. This is a conceptual design, by L-3 Communications, of an HPM system fitted to the UCAV unmanned aerial vehicle. The UAV has two payload pods, so the challenge is to divide the system onto two portions, yet have efficient operation. The prime and pulsed power are in the first pod, with cables connecting to the other pod containing the vacuum interface, followed by the relativistic magnetron source and antenna, which are not shown. The circuit, in Figure 3.4, is Marx/pulse-forming line (PFL)/magnetron. Another approach by Kopp is use of a single-shot vircator driven by a flux compressor,[5] as shown in Figure 3.5 (see Chapter 5). Kopp also originated the idea of using circular antenna polarization to improve HPM power coupling into targets.

3.2.3 First-Generation High Power Microwave Weapons

HPM DEWs are not a panacea, a silver bullet, and must be used in missions where it is uniquely qualified. Below are several applications that are actually being developed.

3.2.3.1 *Active Denial*

Beamed microwave energy can inflict intense pain without actually injuring the people against whom it is directed.[6] This *pain gun* concept uses a continuous-wave beam at a frequency near 94 GHz. The radiation passes almost unattenuated through the atmosphere to be absorbed in the outer layer of a target individual's skin. The energy is deposited near the nerve endings, where water in the skin absorbs the radiation, creating a sensation like that of touching a flame. This less than lethal weapon, as it has been classified by the U.S. Pentagon, can be used to disperse an angry mob — which may offer cover for a more dangerous terrorist — or prevent unauthorized individuals from entering a prohibited area.

An Active Denial System (ADS) has been developed by Air Force researchers and built by Raytheon. It fires a 95-GHz continuous microwave beam produced by a gyrotron (see Chapter 10). The ADS weapon's beam causes pain within 2 to 3 sec, which becomes intolerable after less than 5 sec. People's involuntary reflex responses force them to move out of the beam before their skin can be burned. It exploits a natural defense mechanism that helps to protect the human body from damage. The heat-induced pain is not accompanied by actual burning, because of the shallow penetration of the beam, about 0.4 mm, and the low levels of energy used. Tests show that the effect ends the moment a person is out of the beam, and no lasting damage is done as long as the person exits the beam within a certain, rather long, duration. The transmitter needs only to be on for a few seconds to cause the sensation. The range of the beam is >750 m, farther than small arms fire, so an attacker could be repelled before he could pull a trigger (see Problem 2).

The system is compact enough to be fielded (Figure 3.6) and is dominated by the hardware for generating the high average power. Since gyrotrons are at best 50% efficient in conversion of electricity into microwaves, a 100-kW beam requires at least 200 kW of electron beam energy; inefficiencies in the power converter from the alternating current prime power generator to the direct current electron beam accelerator increase the prime power requirement to a somewhat greater number. Because the operating range would need to be much larger, making ADS airborne would require serious mass reductions; kW/kg would have to drop to make the higher-power system manageable in size and mass.

The antenna is the innovative Flat Parabolic Surface (FLAPS), which seems to be a contradiction, but it is in fact possible to design a geometrically flat surface to behave electromagnetically as though it were a parabolic reflector.[7] A FLAPS can directly replace a parabolic dish. It has advantages such as being easy to store and offering less wind resistance. The FLAPS consists of an array of dipole scatterers. The dipole scatterer unit consists of dipoles positioned approximately 1/8 wavelength above a ground plane. In Figure 3.7, a crossed shorted dipole configuration is shown; each dipole controls its corresponding polarization. Incident RF energy causes a stand-

FIGURE 3.6
Active Denial System, a nonlethal microwave weapon.

ing wave to be set up between the dipole and the ground plane. The dipole reactance is a function of its length and thickness. The combination of standing wave and dipole reactance causes the incident RF to be reradiated with a phase shift, which can be controlled by a variation of the dipole's length, thickness, its distance from the ground plane, the dielectric constant of the intervening layer, and the angle of the incident RF energy and adjacent dipoles. Typically, the dipole lengths vary to achieve a full 360° range of phase shifts.

3.2.3.2 *Neutralizing Improvised Explosive Devices*

In the War on Terror, a new equalizer has appeared, the improvised explosive device (IED). Made from plastic or other explosive and triggered frequently by cell phone, pager, or other radio command, IEDs are cobbled together from whatever the people that plant them can find, so there is no magic bullet that will universally apply to the IED threat. One hope is that a pulse of electromagnetic energy can fry the circuits, and there are several methods that might apply, from jamming the cell phone to setting off the fuse remotely. The NIRF system (neutralizing IEDs with RF) pro-

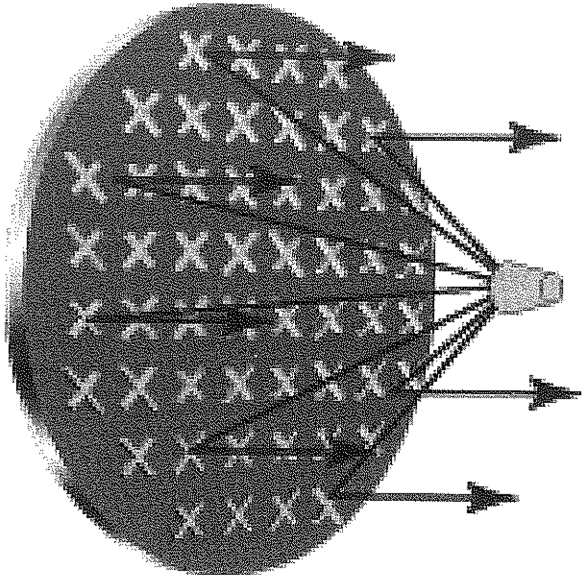

FIGURE 3.7
FLAPS planer antenna with crossed dipoles. Although flat, it converts a quasi-spherical wave from the feed into a focused beam, much as a parabolic dish would. (Reprinted by permission of Malibu Research, Camarillo, CA.)

duces high power, in the microwave range, at very short range to attack an IED's electronics.

3.2.3.3 *Jamming or Predetonating Proximity-Fused Munitions*

Proximity fuses in artillery or mortar shells use a radar signal to determine their range to a target so that the shell can be detonated at a preselected distance to the target, without actually having to hit it. A countermeasure is to silence the rounds by jamming or predetonation. The U.S. military uses *Warlock Green* and *Warlock Red* for this task, which are descended from an earlier antiartillery predetonation weapon system called the *Shortstop Electronic Protection System* (SEPS). It was introduced as a proximity fuse countermeasure for prematurely detonating incoming artillery and mortar rounds by receiving the fuse signal, modifying it, and sending a reply that makes the fuse think it is close to the ground. These weapons, already in the U.S. inventory, essentially instruct the target shell to detonate. Packaged in a suitcase-sized case and fitted with a small multidirectional antenna (in a way strikingly similar to that of the ultrawideband [UWB] short-range weapon DS100 described in Chapter 6), the Shortstop system can be activated and operational within seconds. Shortstop's passive electronics and operational features make it resistant to detection by enemy signal intelligence sensors. Shortstop weighs about 10 kg; versions designed as backpacks and vehicle-mounted units are on the near horizon.

3.2.3.4 *Vigilant Eagle*

Another credible mission moving toward deployment is Vigilant Eagle, a ground-based high-average-power microwave system providing protection of aircraft from shoulder-launched surface-to-air missiles (SAMs). The system is a network of sensors and weapons installed around an airport instead of on individual planes.[8] That is advantageous because planes are most vulnerable to such missiles at takeoff and landing because of the short range of the missiles. The system's estimated cost is much less than a system mounted directly on many potential target aircraft.

Vigilant Eagle has three interconnected subsystems: a distributed missile warning system (MWS), a command and control computer, and the high power amplifier-transmitter (HAT), which is a billboard-sized electronically steered array of highly efficient antennas linked to thousands of solid-state modular microwave amplifiers driving an array antenna. The MWS is a prepositioned grid of passive infrared sensors, mounted on towers or buildings much like cell phone towers (Figure 3.8). Missile detection by at least two sensors gives its position and launch point. The sensors track a heat-seeking SAM and trigger firing of HAT. The control system sends pointing commands to the HAT and can notify security forces to engage the terrorists who fired the missile. The HAT radiates a tailored electromagnetic waveform to confuse the targeting of the missile and can damage the targeting electronics, so that the missile loses track of the aircraft and deflects away from it. The beam is about 1° wide, with spot size much larger than the missile, so it has easier pointing requirements than a laser weapon would. EM fields are within safety standards for human exposure limits (Chapter 5) (see Problem 3).

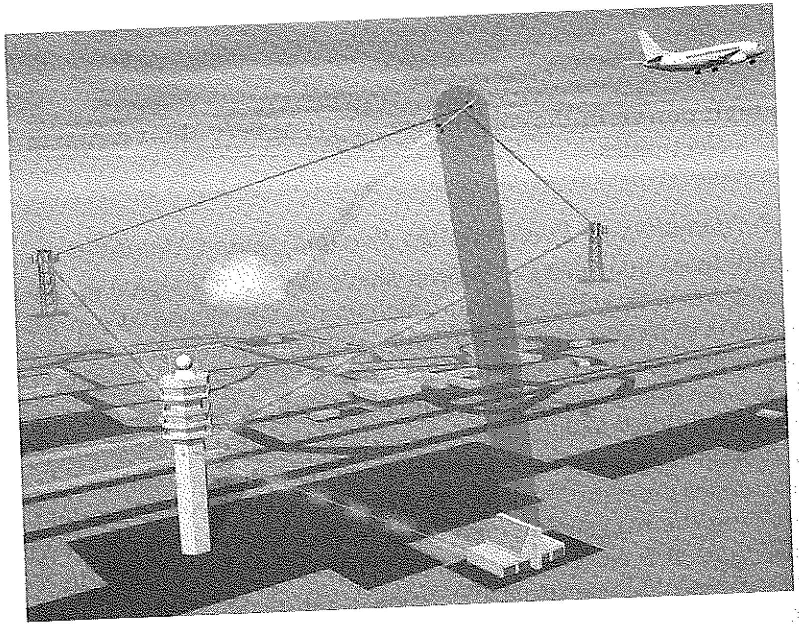

FIGURE 3.8
Vigilant Eagle (VE), a ground-based high-average-power microwave system protecting aircraft from shoulder-launched surface-to-air missiles. Missile detection by at least two sensors from a grid of passive infrared sensors on towers gives position and launch point. VE radiates a tailored electromagnetic waveform to confuse missile targeting. (Reprinted by permission of Raytheon Company, Tucson, AZ.)

3.2.4 Missions

The host of DEW missions proposed for HPM cover a broad parameter space. They vary from short-range missions, such as fighter self-defense against SAMs, to longer-range missions, such as the defense of fleets against missiles and the direct attack of ground systems from the air. The longest-range missions are antisatellite (ASAT; a constellation of satellites with HPM weapons with the capability of disrupting, disabling, or destroying wide varieties of electronics) and its inverse, the attack of ground systems from orbit. Most ASAT devices have been kinetic energy (KE) warheads, meaning that they collide with or explode near satellites. However, KE weapons would add to the growing problem of debris in orbit, so they are unlikely to be deployed by the U.S.[9] HPM, however, is an electronic kill and has no such deployment drawback.

In order to assess the practicality of such missions, engagement analysis must be performed, a process aided by the nomograph in Figure 3.9. This analysis assumes a parabolic antenna with 100% efficiency; a typical practical value is 50 to 80%. The radiated power is twice that calculated from the product of power density and spot sizes because about half the beam falls outside the diffraction spot. There will be propagation loss at the higher frequencies and longer ranges (see Chapter 5). One starts by choosing any one of the variables and then drawing a rectangle by choosing the remaining variables, determining the final variable.

For example, in Figure 3.9, choosing 10-GHz operating frequency and a 10-m antenna diameter gives a beam width of 3.7 mrad. Following a horizontal line and choosing a target range of 10 km gives a spot 37 m wide. Following a vertical line and choosing to irradiate the spot at 100 W/cm^2, the power density chosen by Velikhov,[10] gives a radiated power of 15.6 GW. A horizontal line leads to a point beyond the state of the art for single-pulse HPM sources. (The shaded area in Figure 3.9 is based on Figure 1.3.) A source requirement within the existing art could be obtained, for example, by choosing a larger antenna or shorter range.

The nomograph could be used to argue in either of two ways: (1) Assuming a required power density to produce the desired effect on a target, one can deduce that the effective radiated power (ERP) has to exceed a critical value. This places the burden of HPM weaponry on the technologist to find a source that is powerful and yet compact enough to fit onto the proposed platform.