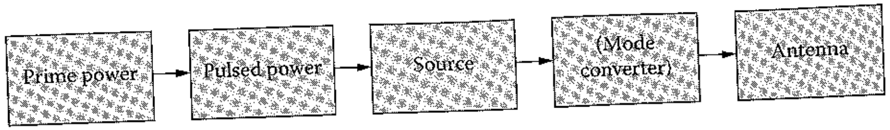


FIGURE 2.1
Components of an HPM system.

For example, *power conditioning*, which indeed is required for burst-mode operation, is missing.

The need for adopting a *system approach* stems from the nature of the process of designing and building a *complex* system that must meet the *requirements* posed by a user's application within a set of sometimes competing *constraints*. In addressing complexity, while striving to meet requirements within a set of constraints, one must learn to step back and view the system from end to end, considering the effect that each subsystem has on the other subsystems, both upstream and downstream in the sense of the power flow depicted in Figure 2.1. Before we characterize our systems approach, let us consider these three motivating elements: complexity, requirements, and constraints. The logical line of development is to follow a systems approach consisting of the steps below:

- Determine the goals in terms of a clearly stated application, typically performance (as distinct from cost and schedule).
- Define the objective criteria against which you will measure the achievement of your goals.
- Analyze various candidate systems.
- Select a system configuration and the subsystem configurations and component choices that realize that system.
- Construct the subsystems and integrate into the final system.

Unfortunately, these logical steps can rarely be performed in this order because, in practice, the system designer performs some or all of these functions simultaneously throughout the process. The reason for this is rather circular: problems cannot be adequately formulated until they are well understood, but they cannot be well understood until approximately solved. Thus, the two processes of *understanding the problem* and *devising solutions* are intertwined. Design of a system is extremely iterative. We can therefore see that *systems thinking involves considerable art as well as science; it makes heavy use of intuition based on experience.*

To get an idea of the complicated nature of system design, consider a case in which the application provides a rather straightforward set of overall requirements that specify the following: (1) the peak energy per pulse to be delivered to a target at a given range, (2) the pulse repetition rate within a burst of pulses, (3) the length of the burst of pulses, (4) the burst repetition rate, (5) the system volume, (6) the system mass, and (7) the maximum angular slew rate for redirecting the beam. To design a system to meet those seven requirements, we have a great deal of freedom.

Return to the system block diagram of Figure 2.1, which has subsystems for prime power, pulsed power, a microwave source, mode converter, and antenna. We have multiple candidate technologies for each of those six block elements, and the realization of some of those choices may involve making component choices within the subsystem and individual part choices within the components as well. We will return to this hierarchy of system–subsystem–component–part later in the chapter. Each block element accepts certain input parameters from the subsystem upstream of it in the energy flow depiction of the figure, and provides certain output parameters to the subsystem downstream. For example, a microwave source accepts electrical input characterized by the voltage, current, pulse length, and repetition rate from the pulsed power, and it provides microwave output in the form of a certain power, pulse length, and repetition rate. It also provides additional parameters — mass and volume contributions, platform-relevant parameters such as form factor and center of mass, and operational restrictions such as operating temperature, humidity, and vibration level — that in sum characterize the system as a whole. Individual components and parts have their own input and output parameters, and they provide their individual contributions to system mass, volume, and linear dimensions. Further, there are constraints on voltage, current, frequency, and efficiency. Some of those constraints come from individual parts of each component, e.g., you cannot buy an off-the-shelf gas thyratron switch for your pulsed power subsystem that handles over 40 kV.

Viewing the whole system branching tree structure, under each subsystem there is a set of component choices and under each component its individual parts, some of which have subbranches for different part choices, all contributing input and output and system parameters to the design calculations. This compounded complexity is called *combinatoric explosion*. The optimization process is made even more difficult by two factors. First, the system designer will not be an expert in the design of every possible system element and component, so that, in effect, he runs the risk of ignoring certain design options out of ignorance. Therefore, there is a design team. Second, not every component exists as a well-characterized off-the-shelf product. Some have to be designed as custom items to the specifications set by the overall system designer. Thus, it is difficult to characterize in advance, because one is not entirely certain what items are going to be available.

Considering the daunting complexity, one comes to see the value of the systems approach to design, which we will describe in this chapter. It is easier to begin by scoping the system with reduced scaling models, so that before going to the trouble of getting components designed, you can make choices about whether they are even in the ballpark. From an initial systems analysis you can do a better job of setting requirements.

Systems design involves optimization of the overall system, as distinct from piecemeal suboptimization of the elements of the system. *Suboptimiza-*

tion is the common failure mode in systems, and it is a problem that occurs with high frequency. Common ways to suboptimize are:

- *Win the battle/lose the war*: You optimize a subsystem to the detriment of overall system performance.
- *Hammer looking for a nail*: Your solution was decided in advance, so that all solutions employ your chosen subsystem or component.
- *A little knowledge is a dangerous thing*: Operating with limited knowledge, you miss or mischaracterize a better solution.

To avoid suboptimization, the system designer has to think one level up and one level down from his particular viewpoint at any step in the process. This is because the drivers he receives from above, at the system application level, and those he receives from below, from the component technologies, are never sufficiently well defined to make choices easy. Nevertheless, designing a system requires keeping both sets of requirements and constraints in mind simultaneously while integrating the full system.

2.2 Looking at Systems

The hope of the system designer is that the problem can be subdivided in such a way that the parts can be handled somewhat separately. Of course, a system can be described in many ways. For example, one can look at a system in terms of the phases of its chronological development and operation, a long timescale. Or one can look at only the short timescale of operation, the time sequence of system functioning, focusing on time evolution of quantities. Here we choose to describe systems in terms of the subsystems.

The nomenclature we will use is shown in Figure 2.2. The entire *system* is made up of *subsystems*, by which we mean the technological subassemblies that make it up. A common set of subsystems are prime power, pulsed power, etc., as in Figure 2.1. Each subsystem is composed of *components*. For example, a microwave source can have a slow wave structure and may require a magnet. In turn, components are made up of individual *parts*; a Marx generator's parts would be capacitors, inductors, and resistors. In an antenna, the components are a pedestal, a dish, and a feed horn.

Existing system design methods and expert systems use this system–subsystem–component–part breakdown point of view. An excellent example of this is HEIMDALL, the expert system for HPM weapons,[1] which does system concepts, meaning that it includes the subsystems but not all the ancillary equipment, such as vacuum pumps. In Figure 2.1 energy flows from prime power to higher-voltage, shorter-pulse-length pulsed power, then to the HPM source. Here the energy is converted into microwaves, is extracted in

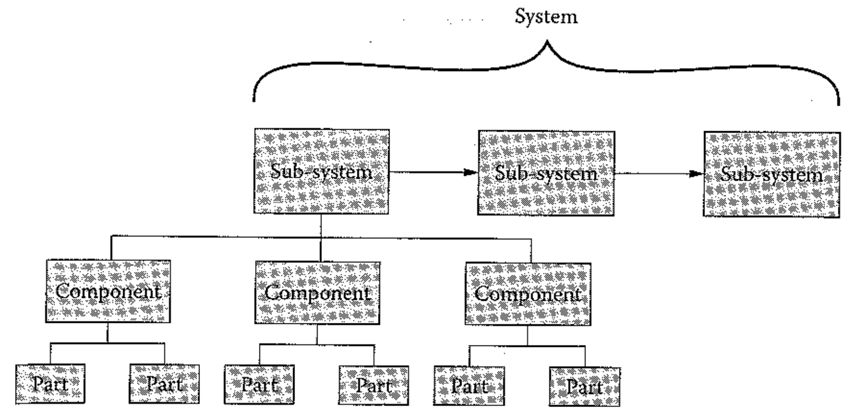


FIGURE 2.2
Nomenclature: Systems are made up of subsystems (pulsed power, etc.) that have components (Marx generator, etc.) composed of parts (capacitors, etc.).

a waveguide mode, which may be converted to another mode, and then radiates from an antenna. This diagram applies exactly to systems for power beaming and HPM weapons (see Chapter 3). In particle accelerators, the energy would not radiate, instead going directly to an accelerating cavity.

2.3 Linking Components into a System

Conceptually, think of systems as collections of subsystems in the way that, although an atom has a complicated internal structure, for the study of chemistry one needs to know only an atom's valence. The building blocks of a system, the subsystems, can be described as shown in Figure 2.3. Input parameters combine with features of the subsystem to produce the output parameters, which in turn become input parameters for the next subsystem. The output parameters flow to the next subsystem, providing it essential input information. System features such as the total weight, total size, and total electrical energy consumed can be calculated by summing those quantities for each subsystem.

Each subsystem in Figure 2.1 has many parameters. They vary from simple physical parameters such as sizes and weights, to electrical parameters such as current, voltage, and impedance, to microwave parameters such as frequency, bandwidth, and waveguide mode. To assemble components into a system, some choice of sets of parameters must be made. In this chapter, we describe a particular *linking parameter set* of input and output parameters and how to use them in designing conceptual systems.

Choosing to take some parameters as independent variables to describe components means that other parameters are then dependent, being derived

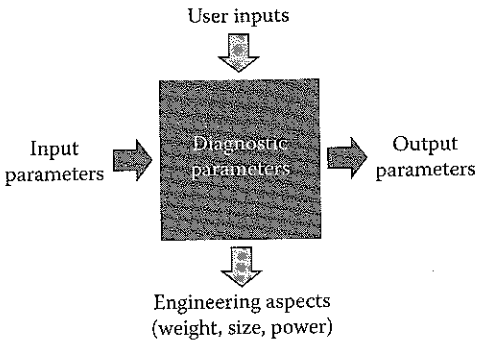


FIGURE 2.3
Interface parameters knit the components together. For examples of linking parameters, see Figure 2.4.

from independent parameters. (Choice of independent variables may not be the same for all systems; selecting which is part of the system art.) In order to capture a description of the components in terms of major parameters, the particular linking parameter set for each component class, such as pulsed power components, has its own particular characteristics. We show a well-tested set in Figure 2.4. These are one useful way to consistently connect component classes to operate with other component classes. This is the energy flow direction. However, for system design efforts, there is no *intrinsic* direction of flow for the exchange of information or parameters between subsystems.

Note that there usually are several stages of electrical pulse compression, called *power conditioning*. It is less common to use an additional stage of compression of the microwave pulse itself. Although it is quite common to

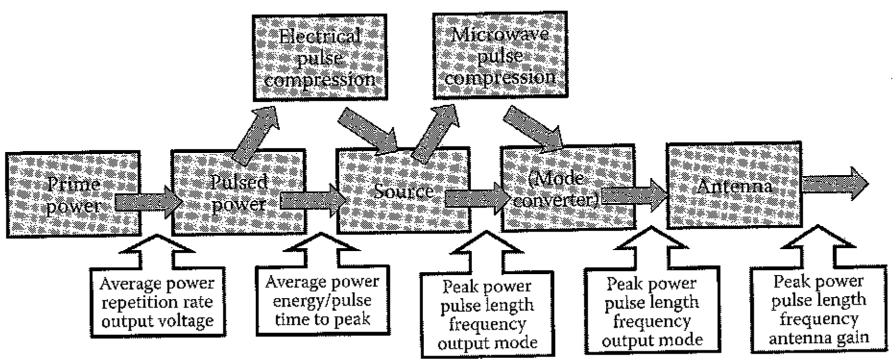


FIGURE 2.4
Energy flow between component classes in an HPM system. Quantities between component classes are those needed for linking them into a system. Optional branches are for an additional stage of electrical pulse compression (e.g., Marx to PFL) and pulse compression of microwaves after their generation.

see microwave pulse compression in conventional radar systems, it is less commonly used in the HPM world, although it was considered at the level of 100 MW for the Next Linear Collider (see Chapter 3 and Section 5.4). The advantage of microwave pulse compression allows use of lower-power, and therefore lower-voltage, pulsed power components.

Compatibility, i.e., which other technologies a subsystem can or cannot be mated to, is important to linking components together into a system. Beyond compatibility are *preferences*, the typical best design practice in linking subsystems. For example, each microwave source will produce radiation in a specific waveguide mode. That mode will influence the type of antenna with which a microwave source can operate. Whether available hardware can handle the mode via commercial availability or easy fabrication influences the design choice. Therefore, one must consider and specify which modes a source will produce and which modes an antenna can accept and radiate.

2.3.1 Prime Power

For linking prime power to pulsed power (Figure 2.5), the important parameters are the average power, the repetition rate — which together define the energy per pulse — and the output voltage. There are many technology choices for prime power. In Figure 2.6, we show a set of options that could be employed to provide continuous prime power output to a number of pulsed power options mentioned at the right of the figure, which would ultimately drive a microwave source. Our use of the term *continuous* is somewhat guarded, since the subsystem at the bottom of the figure, which involves an explosively driven magneto-cumulative generator, is purely a single-shot subsystem. For clarity, we emphasize that the diagram is not the connection diagram for a prime power subsystem, but rather a presentation of possible component choices within a prime power subsystem. A common choice for many systems is to use a generator powered by an internal combustion engine, such as the diesel alternator or the turbo alternator, but it is also possible to drive systems with batteries for long periods. In either case, the common feature of these subsystem options is that either an alternating current (AC) internal combustion generator or a direct current (DC) battery provides long-pulse or continuous power that is converted to a DC output that functions as input to the pulsed power.

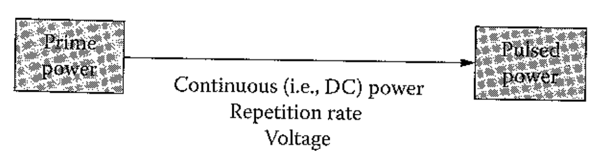


FIGURE 2.5
Linking parameters for connecting prime power to pulsed power.

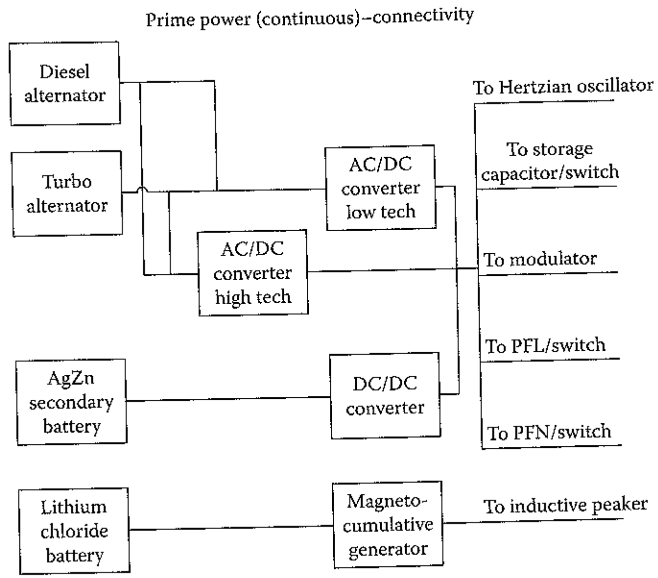


FIGURE 2.6
Possible prime power component connections for continuous power.

For firing a system in a burst mode so that the energy store is exhausted over the course of firing a burst of pulses, then replenished between bursts, other alternatives exist, as shown in Figure 2.7. Note that each option within this set of subsystem options has four components: an internal combustion prime mover producing an AC output; an interface component followed by an energy store and electrical source that, depending on the option, operates at either AC or DC; and a converter, the output of which provides a series of switched DC pulses to the pulsed power.

To better understand the operation, consider the timing diagram of Figure 2.8. The upper plot shows the power pulses delivered by the burst-mode prime power store to the input of a pulsed power system, with power pulses of duration τ_B separated by an interburst period of length τ_{IB}. Below, we see the timing for the individual pulses of duration τ_P delivered by the pulsed power during the period τ_B. The prime mover component delivers power continuously to the energy store and electrical source, which stores it over the interburst period and then delivers it at a higher power over the course of a burst. The pulsed power in turn stores the power during the burst and delivers it at much higher power during each pulse. For example, it is possible to store the energy in a flywheel or pulsed alternator and then convert it to AC or DC.

Thus, the key difference between the continuous and burst-mode systems is the added energy storage in the latter. Average power is much higher in continuous mode, so thermal management becomes a larger issue. In the burst mode, the system has four operational states: firing, charging, charged and waiting, or off.

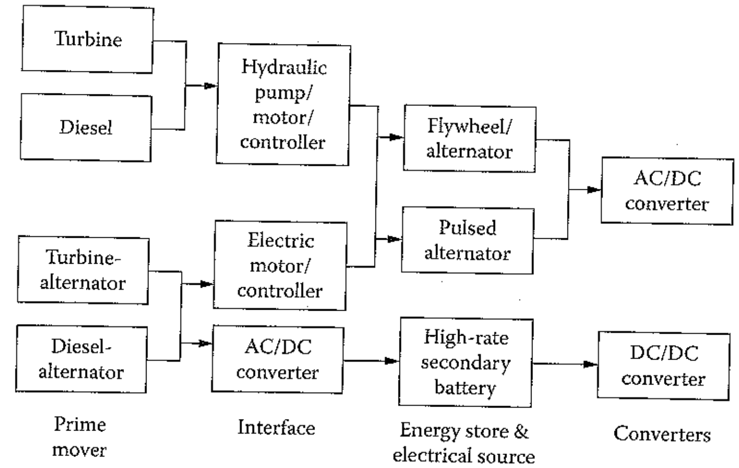


FIGURE 2.7
Possible prime power component connections for burst-mode power. High-tech converters use modern solid-state and digital technologies, and low-tech converters use older transformer/rectifier technologies.

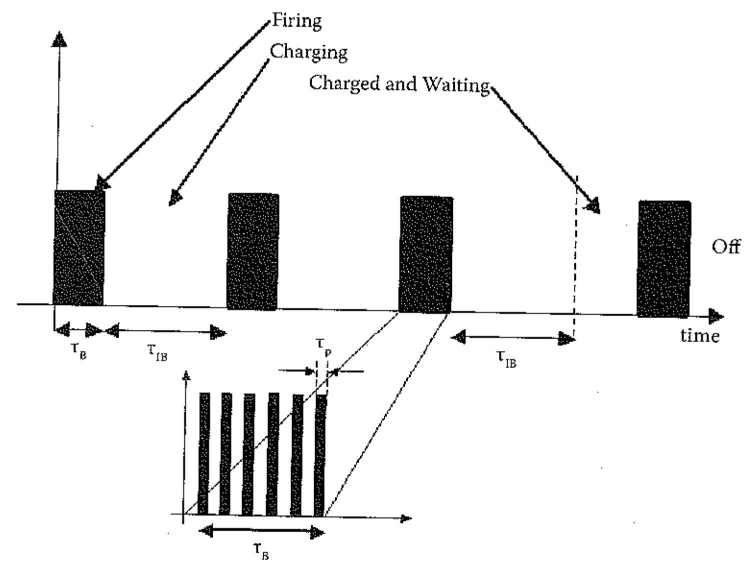


FIGURE 2.8
The four states of burst-mode operation.

The repetition rate for peak power selects the switching technologies available to the system. For example, pulsed power repetition rates above 150 Hz suggest a preference for spark gap, magnetic, or solid-state switches. For airborne systems with stringent requirements to limit size and weight, the prime power is a major driver because it is heavy, or the system must tap the platform power system, usually coming from the engine. Ground-based systems can use more conventional prime power, such as internal combustion engines. The designer of airbourne systems tries to avoid adding another internal combustion engine, so will prefer tapping the system power.

2.3.2 Pulsed Power

Pulsed power is used in most applications, with the major exceptions being continuous power beaming and plasma heating. The existing types of pulsed power (see Chapter 5) are modulators, Marx generators, pulse-forming lines (PFLs), pulse-forming networks (PFNs), and inductive energy storage in combination with opening switches. With the input voltage, average power, and repetition rate taken from prime power, the output of pulsed power components can be characterized by three classes of possible downstream elements: (1) another pulsed power component for further pulse compression, (2) directly to a microwave source, or (3) an impedance and voltage transformer. In the last case, the pulsed power component may produce the correct pulse length, but not the voltage or impedance, in which event one could use a pulse transformer, voltage adder (linear induction accelerator [LIA]; see Chapter 5), or a tapered transmission line, which is another kind of impedance transformer.

The most typical case is connecting a series of pulsed power components. A component, such as a Marx generator, provides the input to a further stage of electrical pulse compression, such as a PFL. The other, less typical, case is that the output of the first pulsed power component is connected to a microwave source, such as a Marx directly driving an antenna. For both cases, the output qualities that must be specified are output voltage, impedance (therefore current, the ratio of voltage to impedance), and pulse length (Figure 2.9). It is also important to specify rise and fall times because of resonance conditions that must be met for the source to generate microwaves. Electrical energy sent into the source before and after the resonance is met is useless, and unused electrical energy passed through the source must eventually be handled by the cooling system. A complex issue at the pulsed

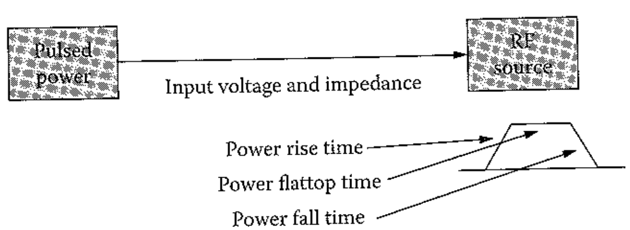


FIGURE 2.9
Linking parameters for connecting pulsed power to microwave source.

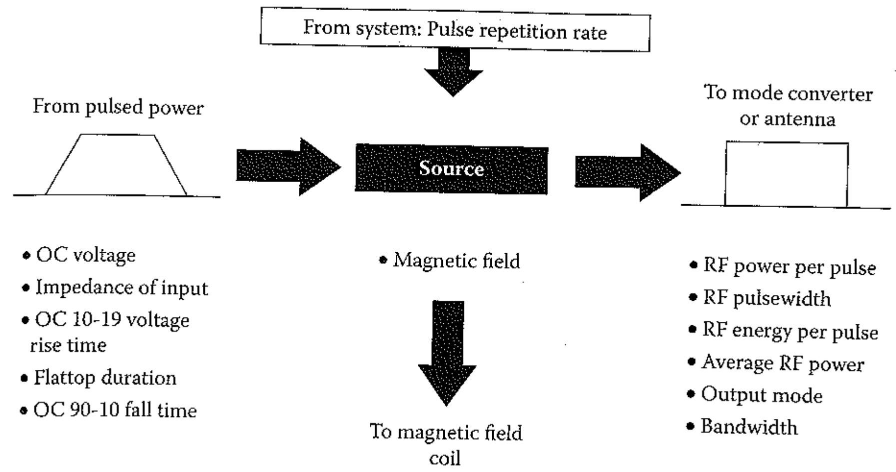


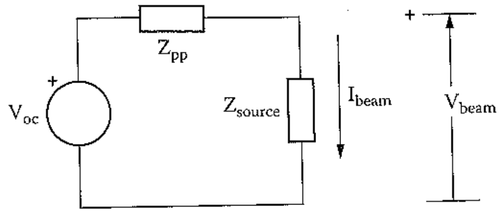
FIGURE 2.10
Linking parameters for connecting pulsed power to microwave source and on to the antenna. The source will have ancillary equipment: vacuum pumps, cooling. A master oscillator will be required for amplifiers. OC = open circuit.

power–microwave source interface comes from the dynamic impedance of the microwave source, making impedance matching a serious design issue. Source impedance almost always varies in time and is voltage dependent as well (see Sections 4.6 and 5.3).

2.3.3 Microwave Sources

Microwave sources are usually the most complex element of the system, as Figure 2.10 shows. Simply put, for purposes of connecting to downstream elements (most typically a direct connection to the antenna), the essential features of the source can be taken as the peak microwave power, frequency, pulse length, and output waveguide mode. The bandwidth can also influence the choice of downstream components. Sources also have substantial supporting equipment: a vacuum pump, a magnet in many cases, a cooling system (as do other subsystems), and a collector or "dump" to capture the beam. There may be a master oscillator if the source is an amplifier. Its power, frequency, pulse duration, and pulse width describe this oscillator. The magnetic field will be specified by the physics of the source. There may also be a need for an x-ray shield to protect personnel.

Perhaps the most important interface in an HPM system is between the pulsed power and microwave source. Electrically, it can be characterized as shown in Figure 2.11, where the pulsed power is represented by an equivalent circuit with a specified open-circuit voltage, V_{OC} (voltage produced in an open circuit by the pulsed power), and a pulsed power output impedance, Z_{PP}, while the microwave source is characterized by its impedance, Z_{SOURCE}.



$$I_{beam} = \frac{V_{oc}}{Z_{pp} + Z_{diode}}$$

$$V_{beam} = I_{beam} Z_{diode} = V_{oc}\left(\frac{Z_{diode}}{Z_{pp} + Z_{diode}}\right)$$

FIGURE 2.11
Circuit for the vital pulsed power–microwave source interface. The combination of impedances determines electrical input to source.

The importance of this interface comes from the need for the impedances of the pulsed power and the microwave source to be well matched, or serious energy and power efficiency losses will occur (see Section 5.2). This in turn affects the size, mass, and cost of the system. Impedance matching is made complex by the fact that typically the source impedance varies with time. It usually falls from an initial value because of gap closure in the beam-generating diode. For a Child–Langmuir and foil-less diodes (see Section 4.6.1), which many sources have, the impedance varies with the anode–cathode gap d, but weakly with voltage. For Child–Langmuir diodes,

$$Z_{source} \sim \frac{d^2}{V^{1/2}} \tag{2.1}$$

so plasma generated at the cathode or anode and moving to close the gap can change impedance steadily. Therefore, the time when peak microwave power should occur (when the microwave resonance is reached) is the best time for impedance match to occur.

2.3.4 Mode Converter and Antenna

The output parameters of the source determine the connection to the antenna (Figure 2.12). The most crucial factor is a waveguide mode, which must be made compatible with the desired antenna. The characteristics of the output of the antenna are the power, frequency, and antenna gain or angular beam width. They determine the output beam propagation characteristics (Figure 2.13). Antennas are discussed in Section 5.5.

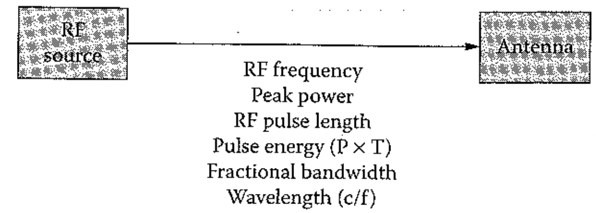


FIGURE 2.12
Linking parameters for connecting microwave source to the antenna.

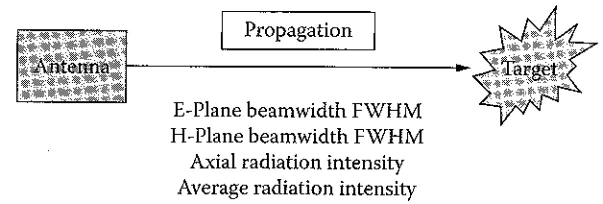


FIGURE 2.13
The antenna output parameters determine propagation of the microwave beam.

2.4 Systems Issues

It is frequently thought that the factor that drives selection of components for sources is efficient transfer of energy from electricity to microwaves. While this is a factor, it is actually a stalking horse for the truly important factors. Various applications have different driving factors. In Chapter 1 we described the early years of HPM, when peak power was the driving factor. But more recently, the compatibility of sources with the other elements in the system has become more important. There are also other factors, such as reliability, complexity, maintainability, and mobility. It has been said that we are now in a new era of "-ilities."

For military applications, which typically require a mobile system, the driving parameters for the system are usually the volume and on-board average power requirement of the system. Weight is less important, which may seem counterintuitive. For example, airborne usually means lightweight. An HPM weapon will usually be fitted onto an existing platform in the space previously reserved for another weapon. Such weapons are usually denser than HPM devices. For example, if an HPM system, with some vacuum volume, substitutes for an explosive warhead with high density, the weight actually drops. So, often the real constraint is volume.

Power-beaming applications are usually limited by the available antenna apertures at either the transmitting antenna or the receiving rectenna. For particle accelerators, on the other hand, one major driving factor is the cost of the source when manufactured in quantity. This is true because of very stringent performance requirements on lifetime, average power, and energy per pulse. Another is reliability, which stems from the complexity of the system: when there are so many microwave sources, frequent breakdowns would be intolerable. This requirement argues in favor of more conservative technology choices.

The key distinguishing electrical parameters of the system components are the voltage and current and their ratio, *impedance*. Impedance is a quite general quantity, as it also relates to appropriate components of E and B through the component geometry and to particle drifts in the source, which are proportional to local electric and magnetic fields, E/B. Impedance also relates to antennas through the complex impedance, including both the real part, resistance, and the imaginary part, reactance.[2] Antenna design frequently consists of reducing the reactive component, making impedance matching simpler. The voltage–impedance parameter space into which HPM source technologies fall is shown in Figure 5.2. With voltages of <100 kV and impedances of >1 kΩ, conventional microwave applications (radar, electronic countermeasures, communications) lie at the low power end (power = V^2/Z). Most, but not all, present-day HPM devices cluster at 10 to 100 Ω. Voltages generally span the range of 0.1 to 1 MV, but some sources have been operated up to several megavolts.

The implication is that efficient transfer of electrical energy to microwave sources that span a broad range of impedances will require pulsed power technologies that similarly span a substantial impedance range. When adjoining circuit elements do not have the same impedance, voltage, current, and energy transferred to the downstream element can be very different (Figure 5.3). Efficient energy transfer suffers if impedance mismatch exists, especially if the downstream component is of lower impedance than the circuit driving it. Nevertheless, there are exceptions: mismatching upward to higher-load impedance is sometimes used as an inefficient means of increasing load voltage.

As an example of the effect of system considerations, consider the case of the use of flux compression generators (FCGs, see Section 5.2.2), also known as explosive generators and magneto-cumulative generators (MCGs), to drive single-shot HPM weapons. These devices have been extensively developed in Russia and the U.S. and are now being widely studied. FCGs operate at time-varying impedances well below 1 Ω, producing very high currents at low voltages. As a consequence, workers use transformers, in part to get better rise times for inductive loads. Because of the very high currents, the preferred pulsed power system for such devices is inductive energy storage with an opening switch (see Section 5.2). The impedance transformation required to couple FCGs to ~100-Ω sources would be very inefficient. In the 1990s the search for high power, low-impedance microwave sources to better match FCGs led to interest in the Magnetically Insulated Line Oscillator (MILO) (Chapter 8), which has an impedance of ~10 Ω. But the MILO is not tunable, is heavy, and requires a more complex antenna to radiate in a useful pattern. Consequently, the Russians chose to use both a vircator (Chapter 10), which, although higher in impedance, is lower than other Russian sources, and the backward wave oscillator (BWO) (Chapter 8). The vircator's other advantages are its small size and simple, inexpensive construction. Its very low efficiency is made up for by the very high energies available from FCGs and low mass due to the very high energy density of high explosives as a source of energy. This shows why system considerations will determine what components are actually used rather than single parameter choices, such as impedance or efficiency.

2.5 Scoping an Advanced System

As we have said, designing a system is at least as much art as it is science, and creating a design concept is a highly iterative process. To show the thought processes, here we construct and work through a specific example at the state of the art in HPM systems. Our example system does not actually exist, but, as we shall see, it is similar to those either built or proposed by others. We will call it the SuperSystem, which we specify by the top-level system requirements shown in Table 2.1 (see Problem 1). All of those requirements govern the output of the system. There are no explicit constraints on size or mass; however, we assume the system will be ground mobile, so that the choice of a platform would ultimately limit the size and mass of the system.

Operating in the burst mode is essential if the SuperSystem is to have a transportable size and weight. Figure 2.14 shows a time plot with the four states for a system firing four bursts. Within each burst of duration τ_B, during which the system is in the firing state, individual shots of pulse length τ_{RF} are radiated from the antenna at a pulse repetition rate PRR of 500 Hz. Between bursts, during which the system is in the charging state, an interburst charging period of duration τ_{IB} is required to recharge the system for the next burst. If the period between bursts exceeds τ_{IB}, as it does between the third and fourth bursts in Figure 2.14, the system goes into the charged-

TABLE 2.1

Specifications for an Advanced HPM System Called SuperSystem

Parameter	Value	Comment
Radiated power	500 MW	ORION system level
Pulse length	10–20 nsec	Means smaller pulsed energy store
Pulse repetition rate	500 Hz	Has been done for BWOs and relativistic magnetrons
Frequency	X-band	Much BWO experience here
Antenna gain	45–50 dB	Sufficient for long range
Burst duration	1 sec	Consistent with defense missions
Interburst period	10 sec	Consistent with defense missions

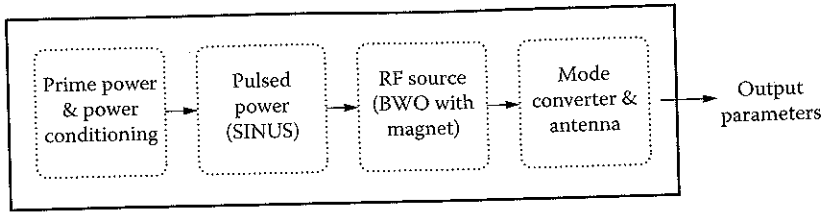


FIGURE 2.14
Internal structure of the SINUS pulsed power generator.

and-waiting state. When no more bursts are fired, the system is off. For this example, we choose to make the two timescales, τ_B and τ_{IB}, 1 and 10 sec, respectively. These timescales are consistent with those for defense missions. We will describe burst-mode operation and the effect of the parameter choices on system performance in detail below. First, we discuss technology choices.

The operating parameters of the SuperSystem are all compatible with a number of known systems that are based on the SINUS series of pulsed power generators originally developed at the Institute of High-Current Electronics (IHCE) in Tomsk, Russia. Examples of different versions of SINUS pulsed power generators are listed in Table 8.3, which shows a range of voltages, currents, pulse lengths, and repetition rates. The same basic technology is involved in the construction of each of these, as shown in Figure 2.14: capacitive input energy storage, an integrated pulse-forming line and resonant Tesla transformer, a high-repetition-rate gas switch, and a voltage- and current-transforming transmission to match the radio frequency (RF) source electrical requirements. We therefore assume that the SuperSystem utilizes SINUS technology, based particularly on the distinctive pulse length and repetition rate.

2.5.1 NAGIRA: Prototype for the SuperSystem

To model the SuperSystem, first consider a SINUS-based system produced by IHCE: the NAGIRA[3] high power microwave radar (acronym for Nano-second Gigawatt Radar). It was delivered to the U.K. Ministry of Defense and the British company GEC-Marconi in 1995 and is now in the U.S. The radar system is housed in two containers, the transmitter cabin and the operations container. The transmitter cabin is shown in Figure 2.15, a photograph taken from the rear of the transporting trailer. The SINUS accelerator in the NAGIRA system produces an electron beam of 600 kV and 5 kA in a 10-nsec pulse with a 150-Hz repetition rate. This 3-GW electron beam is injected into a backward wave oscillator (BWO) to generate an RF output in the X-band with a power of nominally 500 MW, implying a *power efficiency* in the BWO of about 17%. The TM_{01} output mode of the BWO passes through a TM_{01}-to-TE_{11} mode converter, after which a quasi-optical coupler passes the output to a 1.2-m-diameter parabolic dish. The superconducting magnet for the BWO produces a 3-T magnetic field.

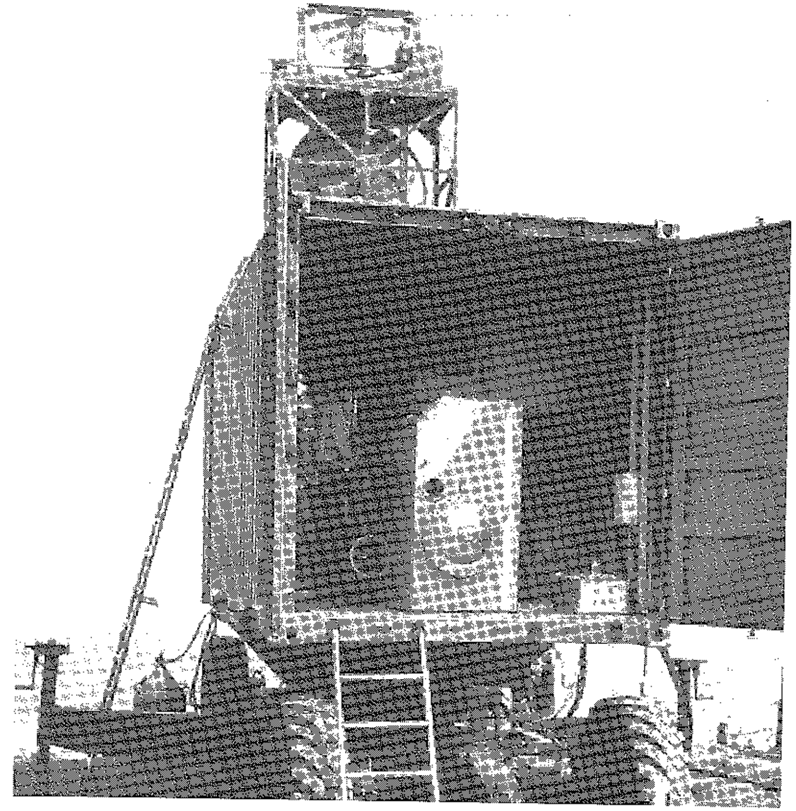


FIGURE 2.15
Transmitter cabin for the NAGIRA system. Most prominently, note the back end of the SINUS pulsed power generator. The motor generator supplying prime power is seen to the lower right. The lower dish on the roof is the transmitting antenna, while the upper dish is the receiving antenna.

The radiated output is about 400 MW in a 5-nsec pulse. Since the power from the BWO is 500 MW and the mode converter is said to have an efficiency of $\eta_M = 95\%$, we infer that coupling to the antenna has an efficiency of about $\eta_A = 85\%$. The electrical power into the BWO is, as stated previously, 3 GW in a 10-nsec electron beam, so we define an *energy efficiency* for the BWO of

$$\eta_{BWO} = \left(\frac{\tau_{RF}}{\tau_{BEAM}}\right)\left(\frac{P_{RF}}{V_0 I_b}\right) = \left(\frac{5}{10}\right)\left(\frac{500}{3000}\right) = 0.083 \tag{2.2}$$

where τ_{RF} is the length of the microwave pulse, τ_{BEAM} is the length of the beam pulse, P_{RF} is the microwave output of the BWO (500 MW vs. the 400 MW radiated from the antenna), and V_0 and I_b are the beam voltage and current. To trace back and determine the prime power requirement, we also need the electrical efficiency of the SINUS pulsed power machine, η_S, and the efficiency of the power conditioning system, η_{PC}, which we take to be a transformer-