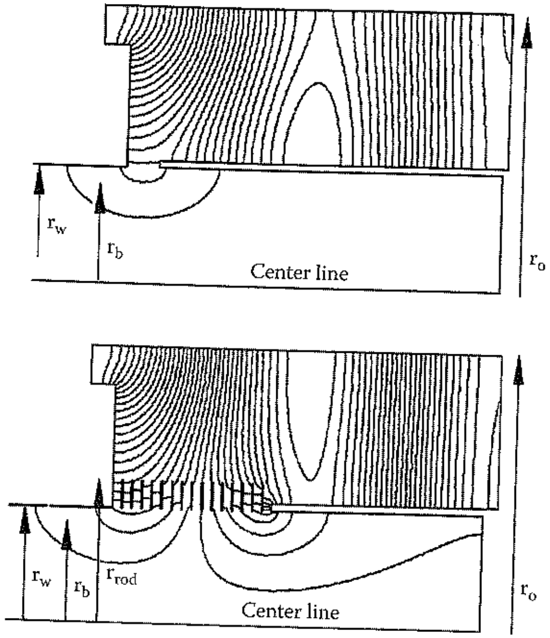

FIGURE 9.27
Electric field line calculations with SUPERFISH for narrow (upper) and wide (lower) gaps. (From Friedman, M. et al., *Phys. Rev. Lett.*, 74, 322, 1995. With permission.)

energy efficiency at 0.3 T; at 0.8 T, the output pulse length was considerably shorter, resulting in a lower energy efficiency. The reason was that at the lower magnetic field, electrons slowed by giving energy up to the microwaves were lost to the washers, while at the stronger magnetic field, those electrons remained in the gap, continuing to absorb microwave energy.

9.4.4 Reltrons

Reltrons are a compact source offering high efficiencies of 30 to 40% and a wide range of operating frequencies, from UHF (700 MHz) to X-band (12 GHz). This broad range was achieved in a system using several interchangeable modulating cavities and output sections at the fundamental frequency and multiples of two and three times the fundamental frequency.[54] An L-band reltron is shown in Figure 9.28. In L-band experiments, a 250-kV, 1.35-kA electron beam was bunched and then postaccelerated an additional 850 kV to produce a 600-MW microwave output at 1 GHz. The efficiency of converting electron beam power to microwave power output was about 40%. Pulse energy in the microwaves was about 200 J. Data from a long-pulse experiment in the L-band with output power of 100 MW over a pulse length of about 1 μsec are shown in Figure 9.29 (see Problem 26). Note that the microwave power begins about 200 nsec after the electron beam is injected. This time delay is the filling time of the modulation cavity, $\tau_f = Q/\omega$.

TABLE 9.7
Comparison of Wide- and Narrow-Gap RKAs

	Wide Gaps	Narrow Gaps
Beam current (kA)	16	16
Diode voltage (kV)	500	500
Beam mean radius (cm)	6.3	6.3
Drift tube radius (cm)	6.7	6.7
Washer inner radius (cm)	6.7	—
Washer outer radius (cm)	9.2	—
Washer thickness (cm)	0.075	—
Number of washers	23	—
First Cavity		
Gap width (cm)	10	~2
Q	~200	1000
RF current (kA)	4	5
Bandwidth	±5 MHz reduces RF current by 20%	<1 MHz reduces RF by 50%
Second Cavity		
Gap width (cm)	10	~2
Q	~450	1000
RF current (kA)	>40	14
Bandwidth	~3 MHz	—

Source: From Friedman, M. et al., Intense electron beam modulation by inductively loaded wide gaps for relativistic klystron amplifiers, *Phys. Rev. Lett.*, 74, 322, 1995.

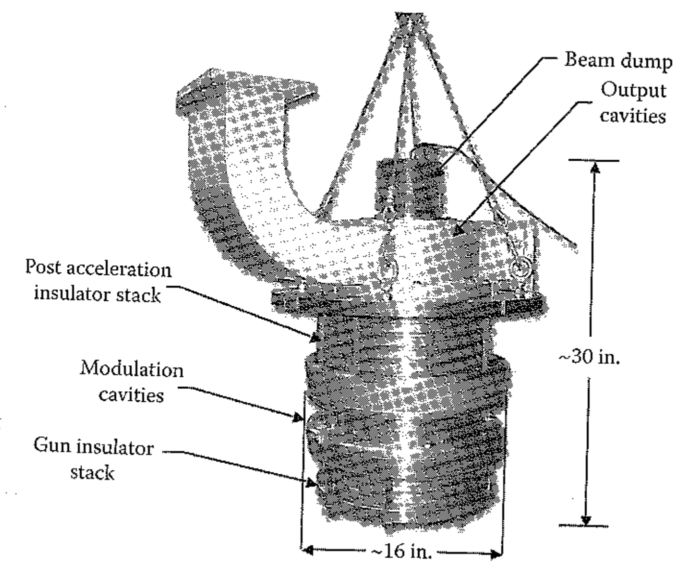

FIGURE 9.28
An L-band reltron. (Photograph provided by L3 Communications Pulse Sciences.)

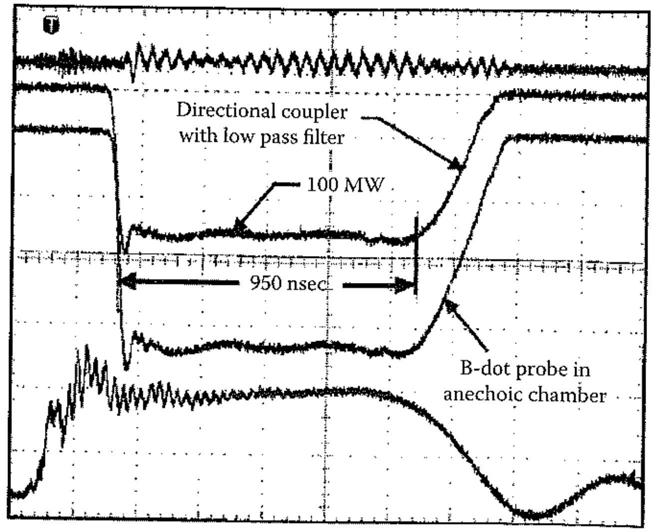

FIGURE 9.29
Long-pulse performance by an L-band reltron. (Courtesy of L3 Communications Pulse Sciences.) From the top down, the traces are for the local oscillator signal, the microwave power, the microwave signal in the far field, and the driving voltage. The horizontal sweep is 200 nsec/division.

In S-band operation, at 3 GHz, a 200-kV, 1-kA beam postaccelerated to 750 kV produced 350 MW of output power in 40-J pulses. Additional experiments demonstrated mechanical tunability of the output frequency by deforming the bunching cavity, giving a tunable range of ±13% and third-harmonic operation by using the 1-GHz bunching cavity with the 3-GHz output cavity. Based on these results, the performance chart shown in Figure 9.30 gives a rough idea of reltron scaling.[55] There, curves of constant output power and efficiency are plotted against the injector and postacceleration voltages. Reltrons continue to develop as a commercial product and are widely used in HPM effects testing facilities.

9.5 Research and Development Issues

In this section we focus on the areas of research and development that have been aimed at revolutionary, as opposed to evolutionary, changes in both the high- and low-impedance klystrons. In the former realm, researchers have proposed multibeam klystrons, in which a number of beams, each of which individually is generated at high impedance, are exposed collectively to the fields from the same cavities. In the latter realm of low-impedance klystrons, the focus has been on a larger-diameter, higher-current triaxial configuration.

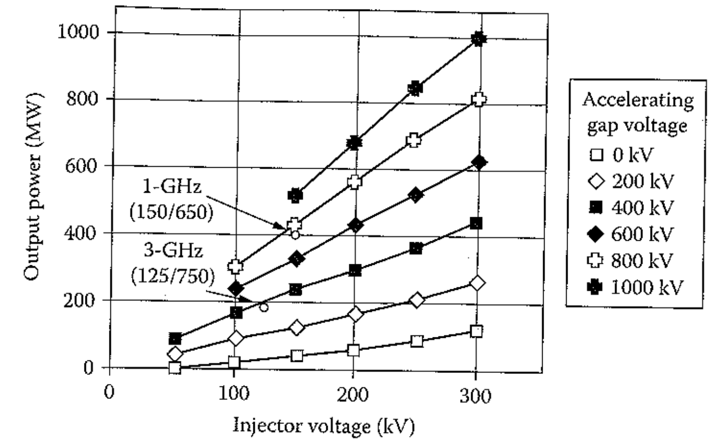

FIGURE 9.30
Reltron output power from calculations and data for different values of injector voltage. (From Miller, R.B. et al., *IEEE Trans. Plasma Sci.*, 20, 332, 1992. With permission.)

9.5.1 High Power Multibeam and Sheet-Beam Klystrons

SLAC researchers have considered, but not yet built, two design alternatives derived from SLAC klystron technology: the gigawatt multibeam klystron (GMBK),[56] aimed at truly high power operation, and the sheet-beam klystron (SBK),[57] conceived as a lower-cost alternative to more traditional pencil-beam klystrons. In the case of the former, multibeam klystrons have been around for some time, and a number of companies sell commercial versions that operate at the multimegawatt level, offering advantages in low-voltage, high-efficiency, wide-bandwidth performance. Figure 9.31 gives a sense of the size of a proposed gigawatt-level GMBK. Ten independent beams are to be launched from thermionic cathodes (necessitating a vacuum of ~10^{-8} torr)

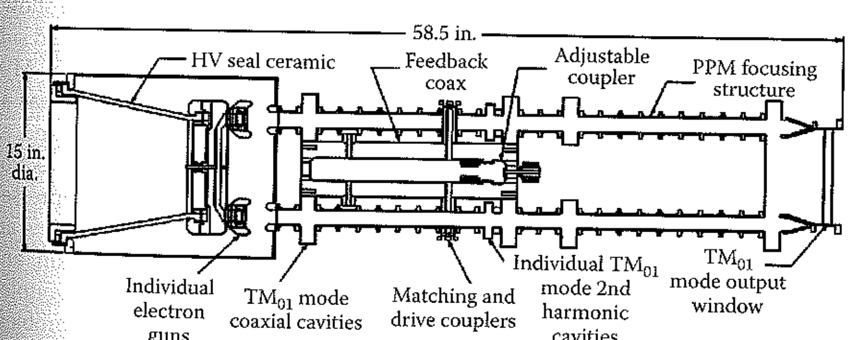

FIGURE 9.31
Proposed design for the gigawatt multibeam klystron (GMBK). (Courtesy of George Caryotakis, SLAC.)

at current densities of about 40 A/cm², which is within the state of the art, with a microperveance of 1.4 (which is comparable to the microperveance of the SLAC tubes shown in Table 9.3). The design voltage is 600 kV, and the total current is 6.7 kA, with a projected pulse length of 1 μsec and repetition rate of 10 Hz. The beams pass through four common stagger-tuned cavities, as well as an individual second-harmonic cavity for each beam to enhance bunching. Internal feedback and a gain of 30 dB would allow the tube to oscillate at a frequency of 1.5 GHz without a separate driving source. PPM focusing is used for each beam line separately. With a design output power of 2 GW, the efficiency is to be 50%; fields of 200 kV/cm in the output cavity are comparable to those in previous SLAC klystrons. Although the project was terminated before the tube was constructed, it was to have a length of about 1.5 m and a mass of about 82 kg, both parameters stated without including the power supply and auxiliary equipment such as cathode heaters and vacuum pumps.

The GMBK is one direction of possible development for conventional (SLAC) klystron development aimed at genuine HPM performance. The sheet-beam klystron is another suggested direction for development aimed at producing a simpler, lower-cost alternative to SLAC klystrons operating around 100 MW. The sheet-beam klystron employs a planar, strip-like electron beam, much wider in one cross-sectional dimension than the other. Although first proposed in the Soviet Union in the late 1930s, and despite the advantages its large lateral dimensions offer in terms of reduced cathode current density and lower power density in the cavities, sheet-beam klystron operation is complicated by the need for large drift tubes and overmoded cavities and by the attendant questions about beam transport. Further, the design of a sheet-beam electron gun promises to be a demanding engineering challenge, and to date, none have been built for this application. Nevertheless, the cost-driven requirement of the Next Linear Collider for a 150-MW peak, 50-kW average, 11.4-GHz klystron was regarded as potentially too demanding for a pencil-beam klystron with a 1-cm bore in the drift tube, which led to the recommendation for the double sheet-beam klystron shown in Figure 9.32.[57] This device features two sheet-beam klystrons operated side by side, each generating 75 MW of X-band radiation for a total of 150 MW, assuming roughly 50% power efficiency. Each klystron in this pair has an input cavity followed by two gain cavities, a penultimate cavity, and an output cavity. In this design concept, the beams from 450-kV, 320-A electron guns with a cathode current density of 5 A/cm² are magnetically compressed to a current density of 50 A/cm². The beam cross-sectional dimensions are 0.8×8 cm², and the drift tube has a height of 1.2 cm. The input, gain, and penultimate cavities are so-called triplets, consisting of three closely coupled cavities, as one can see in Figure 9.32, a cavity design that solved the problem of inadequate cavity coupling for a singlet cavity. The output cavity, on the other hand, has five of these cavities, and output from each beam and output cavity is coupled out through its own window. Calculations indicate a cavity isolation of 50 dB over 5 cm, and MAGIC simulations point to a 68-dB overall

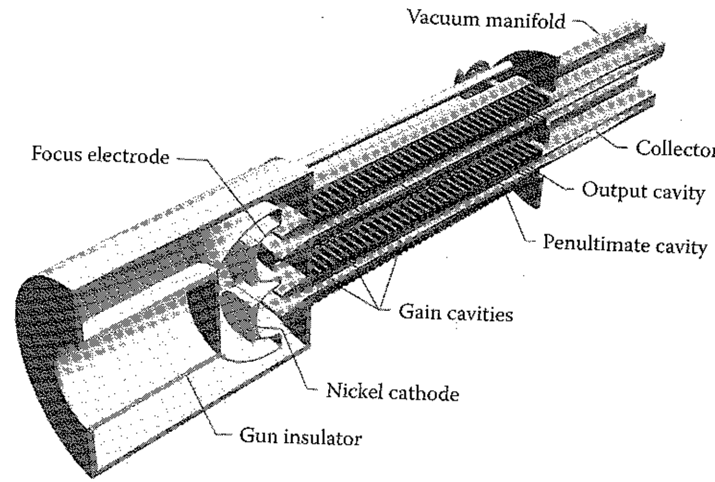

FIGURE 9.32
Cutaway schematic drawing of the double sheet-beam klystron. (Courtesy of George Caryotakis, SLAC.)

tube gain. Although the gun design issues were not yet fully addressed, the suggested performance, the greater simplicity of the device relative to a multibeam klystron, and the technical risk associated with a pencil-beam, 150-MW klystron argued in favor of building a SBK or double SBK for further experimental investigation.

9.5.2 Low-Impedance Annular-Beam Klystrons

Following the first two phases of development for low-impedance, annular-beam klystrons, the NRL group proposed a major design modification, the triaxial klystron with an annular electron beam propagating through a drift space bounded by both inner and outer cylindrical walls (see Problem 24).[47] The schematic layout of an experimental version is shown in Figure 9.33.[58] This configuration has two major advantages over the coaxial version. First, provided the transverse electromagnetic modes are suppressed — and they did not pose a problem in the experiments — this geometry can support large-radius electron beams as long as the distance between the inner and outer conductors is limited to about half of the vacuum wavelength of the microwaves produced. Second, the space-charge-limiting current for this geometry is, in principle, about twice that of the coaxial geometry, which we can see from the expression for the space-charge-limiting current for a thin annular beam, which is of the general form

$$I_{SCL} = I_s \left(\gamma_0^{2/3} - 1\right)^{3/2} \tag{9.35}$$