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Abstract

Future linear colliders will require high peak power RF sources at high frequencies which are significantly beyond present source technology. Considerable progress has been made during the past several years in this direction. This paper summarizes the present state of high power RF source technology, and identifies the critical remaining technical issues.

INTRODUCTION

All new concepts for next generation linear colliders [1] require substantial advances in the area of the RF source technology. Whether the concept involves scaling accelerating structures to significantly higher frequencies (SLAC-NLCTA, CERN-CLIC, KEK-JLC, and INP-VLEPP concepts) or the use of higher peak powers at more conventional frequencies (DESY/Darmstadt DLC concept, KEK JLC concepts), the conventional klystron amplifier technology employed in the past (e.g. 65 MW at 2.856 GHz for SLC) is inadequate for future linear collider schemes based on room temperature structures. Collider concepts based on superconducting structures (such as the TESLA project [2]) will require long pulse (~ 2 ms) RF sources at lower frequencies and relatively lower peak powers. Because of the difference in RF requirements, RF systems for superconducting structures are not discussed in this review. For TeV collider concepts based on room temperature structures, large efforts have been expended over the past several years in pushing the RF source technologies to higher frequencies and higher powers.

Such a task is by no means an easy one. Technological as well as fundamental limitations conspire to restrict the operational capabilities of any given source. The choice of the optimal RF source technology is tied closely with the choice of accelerator frequency; the choice of accelerator frequency is in large part determined by the predicted availability of the RF source. Consequently, the choice of RF structure frequency is tightly coupled with the capability of RF source technologies. The objective of this review paper is to describe the present status of RF sources which are capable in principle of meeting the demands of

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next-generation collider designs. Future research directions for RF source technology and a more detailed discussion of the present limitations of alternate sources are reviewed in the RF working group summary for this workshop [3]. The advances in RF pulse compression technology and in high-power RF handling is described separately in these proceedings [4].

LINEAR COLLIDER RF REQUIREMENTS

One of the principle advantages in pushing RF collider designs to higher frequencies is the scaling of the RF stored energy required per unit accelerating gradient [5, 6]. By way of motivation for the following discussion of RF sources, it is instructive to review some basic scalings for collider design.

Wilson has determined useful scalings for the required RF power versus RF frequency and gradient [5, 7]. For typical disk-loaded traveling wave structures with an iris radius to wavelength ratio of $a/\lambda = 0.175$, the microwave power per unit length required to achieve a gradient E_a with RF power of frequency ν is given by

$$P\,[\mathrm{MW/m}] \approx 6.6 \times 10^{-2}\,\frac{E_a^2\,[\mathrm{MV/m}]}{\nu^{1/2}\,[\mathrm{GHz}]}. \tag{1}$$

Structure fill time decreases with increasing frequency according to

$$t_f\,[\mathrm{ns}] \approx \frac{3.8 \times 10^3}{\nu^{3/2}\,[\mathrm{GHz}]}, \tag{2}$$

and the required microwave pulse energy per unit length u for a prototypical structure then scales as

$$u\,[\mathrm{J/m}] \equiv P\,t_f \approx 0.25\,\frac{E_a^2\,[\mathrm{MV/m}]}{\nu^2\,[\mathrm{GHz}]}. \tag{3}$$

As is apparent from these scalings, collider design at a given gradient requires considerably less RF average power at higher frequencies.

For a given amount of RF energy per pulse, many RF sources operate more efficiently with longer pulses and lower currents. Consequently, this effort includes the development of efficient high-gain RF pulse compression schemes. The total RF system efficiency, η_T, depends on the efficiency of three main subsystems: the modulator efficiency, η_M, the RF source intrinsic efficiency, η_{RF}, and the efficiency of the RF pulse compression system, η_{PC}, if such a system is required. The overall efficiency is then $\eta_T = \eta_M\,\eta_{RF}\,\eta_{PC}$. Modulator advances are very briefly summarized here, and the efficiency scaling of RF pulse compression technologies is discussed in a separate paper in these proceedings [4].

HIGH-VOLTAGE MODULATORS

Although perhaps the least glamorous of the three technologies required for the overall RF system, the modulator technology is no less an important part. The present high-voltage line-type modulators required for virtually all sources presently operate at 75-80% efficiency for pulse widths of 1 μs or longer. Improvements to this efficiency, primarily by shortening the rise and fall times of the modulator high-voltage waveforms, are under investigation.

The present SLAC baseline design for the next generation of linear collider calls for klystron operation at 600 kV. Development of modulators capable of operation at this voltage at high efficiency is proceeding at SLAC and elsewhere [8, 9]. Low average power modulators at comparable voltages have been in use for some time (e.g. the MIT 700 kV modulator [10]), but the development of efficient high average power modulators at these high voltages remains an important task for a realizable collider design. Considerable effort is presently devoted to shortening the voltage pulse rise and fall times. Several approaches are possible. At SLAC, a three-stage Darlington pulse-forming network coupled to the klystron load by a 6:1 pulse transformer has been chosen [8]. The distributed capacitance of conventional pulse transformers yields a limit on the achievable voltage rise time; alternative transformers, such as the transmission line transformer, do not suffer from this limitation and have been used successfully in high efficiency short pulse modulators for induction linacs [11]. Though modulator development and advances merit more discussion, these issues will not be further discussed here.

As an alternative to pulsed modulators, some RF source schemes now under investigation would utilize grided guns and DC power supplies in an effort to increase the efficiency of power transfer from the AC grid to the electron beam in the RF source.

SLOW-WAVE AMPLIFIER ADVANCES

The largest amount of RF source development effort has centered on improvement of RF amplifiers based on a slow-wave interaction between beam and wave (linear beam tubes), and this effort has lead to greatly increased performance of klystrons and their varients.

Klystrons

Dramatic improvements in klystron performance have been demonstrated at several laboratories during the past several years. The majority of the work has been carried out at SLAC, KEK, and BINP (Protvino), with smaller efforts at universities and small companies. Representative advances for slow-wave amplifiers are summarized in Table 1.

SLAC has substantially improved klystron performance over the original 2.856 GHz tubes used in the SLC. Initial development work proceeded towards the goal of producing a 100 MW tube at 11.424 GHz with a relatively high gun perveance of 1.8 μP. The perveance of an electron gun of current I_b and voltage V_b operating under space-charge limited flow is given by $I_b/V_b^{3/2}$ with $1\,\mathrm{P} \equiv 1\,\mathrm{A/V}^{3/2}$. These XC-series tubes demonstrated up to 87 MW for 200 ns and 50 MW for 700 ns at this frequency (XC6) [12, 13]. This tube employed four output couplers and four output windows in an attempt to maintain an acceptable RF loading on the window. Subsequently, the SLAC klystron department turned their focus to development of a 50 MW class tube (XL-series) for use with the Next-Linear-Collider Test Accelerator (NLCTA) being built at SLAC. For this series of tubes, the electron gun perveance has been reduced to 1.2 μP and a design voltage of 440 kV has been chosen for the XL-series tubes, in an attempt to improve the efficiency. The first of these tubes, the

Group	Frequency [GHz]	Power [MW]	Pulse Length [ns]	V_b [kV]	PERV [μP]	η_{RF} [%]	Gain [dB]	Device Type
LANL	1.3	450	500	600	8.6	19	34	K (Annular)
SLAC	2.856	65	3500	350	1.9	45	51	K (5045)
Cornell	9	200	100	850	1.15	26	40	TWT
SLAC	11.424	52	1000	440	1.8	29	50	K (XC5)
SLAC	11.424	87	200	440	1.8	36	60	K (XC6)
KEK	11.424	78	50	600	1.2	26	53	K (XB72K)
SLAC	11.444	58	500	415	1.2	44	58	K (XL1)
SLAC	11.444	51	1500	415	1.2	38	57	K (XL1)
LLNL/LBL/HRC	11.424	420	12	2500	500A†	34	–	RKA-TBA
HRC(SRL/MIT)	11.424	100	45	550	1.2	45	50	K (X791)
BINP	14	60	700	1000	0.12	35	75	K
HRC(MIT)	17.136	16	150	550	0.25	37	61	K (X7100)

Table 1: Recent Advances in Linear-Beam Tubes: Klystrons, Relativistic Klystrons, Twystrons, TWTs. Device type and tube designation is also given. †Current is given rather than perveance for the RKA/TBA.

XL1 klystron, has recently demonstrated operation at the 58 MW power level for 500 ns at 11.424 GHz [14]. The beam parameters for this operation are 415 kV, 1.2 μP (321 A), yielding an efficiency of 44%. This same tube has run at 51 MW output power for increased pulse widths of 1.5 μs. Operation at this longer pulse width was limited by an instability in the buncher cavities, believed to be due to TE_{11} mode excitation. This tube employed a three-cell standing-wave output cavity with π-phase advance per cell. In this tube, dual windows on dual output arms were employed, with each window a $\mathrm{TE}_{01}^{\mathrm{O}}$ half-wave resonant window. Planned future tubes, XL2 and XL3, will employ a 3-cell standing-wave output circuit and a 4-cell traveling-wave $\pi/2$-phase advance output circuit, respectively [14]. The XL2 tube will also employ a new ultra-pure Al_2O_3 ceramic window formed by a hot-isostatic pressing of the alumina ceramic. Such windows are believed to be largely free of tiny voids where RF breakdown can occur, and experimental evidence suggests greatly increased RF breakdown thresholds for this type of window [15].

The development of a PPM-focused (periodic-permanent-magnet focused) klystron is also proceeding at SLAC. The objective is to replace the solenoid with a PPM stack, thereby eliminating the power consumption of the copper solenoid. Klystrons with PPM focusing are the main effort at BINP, Protvino, Russia (see below). At SLAC, the use of PPM focusing in future klystrons will require a decrease of the gun perveance to 0.6 μP in order to achieve acceptable beam confinement [14].

At KEK, output powers of 78 MW for 50 ns pulse width at 11.424 GHz and an efficiency of 26% (beam 570 keV) has been obtained with the XB72K klystron [16]. The design beam parameters for this tube are 600 kV, 550 A (1.2 μP). This tube failed due to RF window breakage when the RF pulse width was lengthened.

Output power of 65 MW (60 dB gain) at 14.0 GHz for 700 ns has been obtained at

BINP, Protvino [17], where the objective is to obtain a 50% efficient tube with 80 dB gain for 500 ns at 14 GHz, using a gridded electron gun operating at 1 MV, 300 A. The motivation for employing a gridded gun for this tube is nothing less than the complete elimination of the modulator and its associated inefficiency. The VLEPP klystrons are to be provided power from high voltage capacitors DC-charged to 1 MV. This tube is at present the only high power klystron to employ PPM focusing. The principle development issues associated with this tube are the development of this gridded gun and supression of instabilities in the klystron drift tube. The usual difficulty with high power klystron stabilization is exacerbated by the planned 80 dB gain. Nevertheless, provided the technical difficulties can be surmounted such a klystron power system is attractive as a collider RF source.

RF pulse compression technologies have also improved substantially, with the advent of SLED-II (or Resonant-Line SLED) and Binary Pulse Compression (BPC) techniques at SLAC [4]. The NLCTA at SLAC will employ SLED-II pulse compression, which has been demonstrated at high power levels. In high power BPC experiments at SLAC, gains of 5.2 in power have been obtained with input powers of 20 MW at 11.424 GHz with three-stage BPC [18]. RF pulse compression has and will continue to play an important role in future RF systems, but efficiencies and power gains will require further improvement. Details of recent developments in this area are given in this proceedings in the article by P. Wilson [4].

Linear-Beam Tubes (TWT, Twystron)

Smaller research efforts at universities and small companies have also contributed to advances in this field. At Cornell University, TWT development has yielded 160 MW at 9 GHz for 50 ns [19]. Studies there have centered on the investigation of sideband instabilities and the use of low group velocity structures. At LANL, an RF power of 450 MW has been obtained from an annular beam klystron at 1.3 GHz [20]. Such a klystron employs the enhanced bunching associated with propagation of a beam past an RF gap with beam current near the limiting current. Such gate-effect or relativistic klystrons were first investigated by Friedman and coworkers at NRL [21], and are now under investigation at several laboratories [20, 22].

Haimson Research Corp. has developed two relativistic klystrons with impressive performance. The first tube, the X791 klystron, achieved 100 MW at 11.424 GHz for 50 ns pulses in tests carried out on the SNOMAD-II induction accelerator in collaboration with Science Research Laboratory and MIT [23, 24]. The second tube, the X7100 Traveling-Wave Relativistic Klystron, which has been designed for 20 MW operation at 17.136 GHz with 1 μs pulses, has achieved 16 MW for 150 ns at 17.136 GHz in preliminary tests at MIT [25]. In these preliminary tests, the pulse width and beam voltage were intentionally limited. This klystron employs a 580 kV, 0.27 μP electron gun and high-voltage modulator in place at the MIT Plasma Fusion Center. Principal design features of these klystrons are the use of distributed, tapered phase velocity, and traveling wave output circuits to permit optimal bunching of the electrons, while at the same time limiting field stresses to acceptable values. These tubes are perhaps more acurately termed twystrons due to their use of standing wave bunching cavities and traveling wave output circuits.

One general trend in klystron development is towards the use of lower perveance guns.

A well known empirical scaling for klystron efficiency versus beam perveance predicts higher maximum attainable device efficiency at lower beam perveances. This scaling is not without physical justification, for the lowered space charge forces associated with lower perveance beams permit the formation of more compact (in phase) bunches on the beam, with a resulting greater extraction efficiency in the output circuit.

Cluster and Sheet-Beam Klystrons

Concepts such as the cluster klystron and the sheet-beam klystron may significantly improve the overall RF system efficiency by permitting operation at lower beam current densities, thereby permitting the use of highly optimized extraction circuits which should yield high (approaching 60-70%) RF efficiencies. Moreover, in some systems, modulating grids (as in the BINP klystrons) or non-intercepting modulating-anodes (cluster klystron guns) would permit a rapid modulation of the klystron beam pulses, thereby permitting the use of DC power supplies and a concomitant increase in modulator effciency.

In order to take advantage of the general klystron scaling of efficiency with beam perveance, several efforts have begun to scale up klystron power at low beam perveance through the use of either multiple low perveance beams in the same focusing system or use of a sheet electron beam. In the cluster klystron concept [26] multiple electron beams produced from an array of electron guns interact with individual circuits in the same focusing solenoid. The use of magnetron injection guns with modulating anodes for the formation of the beam would permit the rapid modulation of the beam, and thereby obviate the need for a pulsed high-voltage modulator. Rather, the guns would be connected directly to a high voltage DC source, and the beam would be switched by the modulating anode. This power supply configuration, together with the anticipated high efficiency obtainable for low perveance beams would yield an RF system with high overall efficiency (> 70%). The principal difficulties for this type of device are the beam formation; very high cathode current densities are required because the magnetic flux on the gun is the same as that in the interaction circuit (immersed flow).

The sheet beam klystron is another concept for increasing klystron output power at high efficiency [27]. In this concept, rather than using a cluster of individual beams, one employs a sheet electron beam. High beam currents are obtained without unduely large space-charge forces by spreading the beam into a sheet in one transverse direction.

Neither of these klystron concepts have been demonstrated experimentally at the power levels required for colliders, although multiple beam klystrons at lower powers are readily available from industry, and have been investigated since early work at General Electric Company [28]. Collider relevant klystron development in this area is being actively persued by a group at Brookhaven National Laboratory and SLAC.

Remaining Difficulties

The principal technical difficulties remaining for klystron development are numerous. RF breakdown in the klystron output gaps is a continuing problem, as the fields in these cavities are very high. Output window breakage continues to plague high peak power tubes under development. However, the recent trend towards overmoded TE_{01} circular windows should lead to reduced field stress on the windows. Suppression of dipole modes in the tubes is a continuing issue; the beam current densities presently used exceed the threshold current density ($\sim 2\,\mathrm{A/mm^2}$ for $1\,\mu$s) for single pulse melting of copper. The trend towards lower perveance has lead to increased gun voltages, and put more of a burden on the gun and modulator designer. Furthermore, the development of very high efficiency klystron designs is not without associated problems in other areas; the tube efficiency becomes a very sensitive function of the load mismatch [29].

FAST-WAVE AMPLIFIER ADVANCES

High peak power amplifiers based on fast-wave devices have also made important advances during the past several years, and as a result of these advances these devices are now serious contenders to be the RF source for the next collider. Fast-wave amplifiers are distinguished from slow-wave amplifiers in that the synchronism between the beam and RF is achieved by modification of the beam dispersion characteristic rather than a modification of the wave dispersion characteristic. There are many techniques for achieving this synchronism, the most common being 1) introduction of an axial guide magnetic field (this leads to the cyclotron maser or gyrotron instability) or 2) introduction of a periodic transverse magnetic (wiggler) field (which leads to the FEL or ubitron interaction).

Cyclotron-Resonance Masers

The cyclotron maser interaction occurs for electrons undergoing cyclotron motion about an axial magnetic field, and the transfer of energy from the beam to RF results from an azimuthal bunching of electrons in their cyclotron orbits due to the negative mass instability. The resonance condition for gyrotrons is thus given by $\omega - k_{||}v_{||} = s\Omega_c$, where s is the harmonic number and $\Omega_c = eB/\gamma m$ is the relativistic cyclotron frequency. This resonance condition is often rewritten as $\omega = s\Omega_c/(1 - \beta_{||}/\beta_{ph})$, where the normalized wave phase velocity is $\beta_{ph} \equiv \omega/ck_{||}$.

A representative sample of recent advances in high power gyroamplifier research is shown in Table 2. The large effort at U. Maryland on gyroklystron development has lead to impressive results, including the generation of 31 MW output power and 27 dB gain at 19.8 GHz for 800 ns with a second harmonic gyroklystron [30, 31]. An output power of 24 MW at 9.87 GHz, with 34% efficiency and 34 dB gain with a gyroklystron operating at the fundamental of the cyclotron frequency has also been demonstrated [32, 33]. In three cavity gyroklystron experiments, gains of up to 50 dB have been obtained with 20 MW output power and 28% efficiency. In gyrotwystron experiments, the U. Maryland group has generated 22 MW at 9.8 GHz with 22% efficiency [34] and 9 MW at 19.8 GHz with 10% efficiency in a second harmonic gyrotwystron. In future experiments, this group plans to develop both a 100 MW, 8.57 GHz fundamental and a 100 MW, 17 GHz second harmonic gyroklystron amplifier.

Smaller efforts at other universities and laboratories have also demonstrated the promise of fast-wave amplifiers based on the gyrotron or cyclotron resonance maser interaction. Operation of a large orbit gyroklystron at LANL has demonstrated an output power of

Group	Frequency [GHz]	Power [MW]	Pulse Length [ns]	V_b [kV]	I_b [A]	η_{RF} [%]	Gain [dB]	Device Type
LANL	1.3	100	40	850	2500	5	40	GK
U.Md.	9.87	24	1000	425	190	34	34	GK Ω_c Tube 6
U.Md.	9.87	27	1000	425	200	32	36	GK Ω_c Tube 8
U.Md.	9.87	20	1000	425	200	28	50	GK Ω_c Tube 8
U.Md.	9.858	21.6	1000	440	220	22	24	GTWY Ω_c
MIT	17.136	4	20	380	180	6	40	GTWT $3\Omega_c$
U.Md.	19.76	31	800	440	270	28	27	GK $2\Omega_c$ Tube 4
U.Md.	19.772	12	500	457	244	11	21	GTWY $2\Omega_c$

Table 2: Recent Advances in Gyro-Amplifiers. The following abbreviations are used in the table: GK = Gyroklystron, GTWY = Gyrotwystron, GTWT = Gyro-TWT, Ω_c= Relativistic Cyclotron Frequency

100 MW at 1.3 GHz with a field emission diode produced electron beam [35]. A third harmonic gyro-TWT amplifier at MIT has generated 4 MW power at 17.1 GHz in the TE_{31} mode with over 40 dB gain [36]. A cyclotron autoresonance maser (CARM) amplifier experiment was also carried out at the MIT Plasma Fusion Center, but inadequate beam quality prevented the device from operating on the Doppler upshifted TE_{11} mode at 17 GHz. However, successful operation of the amplifier on second and third harmonics in the TE_{21} and TE_{31} modes was obtained. In this experiment, these modes operated closer to cutoff of the waveguide (i.e. in the gyrotron regime of the cyclotron maser instability), and, due to their increased coupling to the beam and smaller Doppler shift, they were less sensitive to beam velocity spread. CARMs may yet prove attractive for a collider RF source, provided the difficult problem of the production of an electron beam with sufficient beam quality can be solved. However, the gyroklystron and gyro-twystron are clearly the best contenders for a fast-wave amplifier for collider applications at the present time.

Several important development tasks remain for gyroklystron and gyrotwystron amplifiers. These tasks include increasing the gain, efficiency, and output power of the tubes, and demonstration of the tube stability when operating into an actual accelerator load. These are all areas in which klystrons remain superior at frequencies up to X-band.

Free-Electron Masers

The free-electron maser or ubitron is capable of generating considerable power in the microwave and millimeter wave bands. Pioneering experiments carried out by Phillips in the early 1960's succeeded in demonstrating an output of 1.65 MW at 15.7 GHz with a ubitron amplifier [37]. The large electron laser facility (ELF) program at LLNL during the 1980's succeeded in generating 1 GW performance at short ($\sim$ 50 ns) pulse widths at 35 GHz, albeit with a very large induction accelerator to generate the beam [38]. More recently, ubitron amplifiers have successfully generated 0.8 MW at 35 GHz with 26 dB gain and 8.6% efficiency (400 ns pulse) at MIT [39], and 4.2 MW at 16.6 GHz with 29 dB gain and 18% efficiency (~ 1 μs pulse) at NRL [40]. FEL Experiments with field emission diodes have generated 61 MW at 33.3 GHz with 27% efficiency (30 ns pulse) at MIT [41]. FEL experiments at KEK have produced 30 MW with 30 dB gain for a 60 ns pulse at 9.6 GHz with 6% efficiency [42]. All of these experiments have spurred renewed interest in the development of FEL amplifiers for linear collider applications, not only in two-beam accelerator configurations but also as stand-alone RF sources.

Magnicons

The magnicon has attracted considerable interest in recent years due to the impressive performance of early experiments carried out at INP in Novosibirsk at 915 MHz frequency. This first magnicon delivered 2.6 MW at 915 MHz with an efficiency of 85% [43]. The beam voltage and current for this experiment were 300 keV and 12 A, respectively, and the RF pulse length was 30 μs. The magnicon is one of a class of scanned electron beam devices, in which an initially longitudinally directed beam is deflected in a transverse direction, usually by a TM_{110} mode in a field-free region. Following this deflection, the beam enters a solenoidal magnetic field region, wherein the beam couples to a TM_{110} cavity mode for synchronous energy extraction at the drive frequency. Extraction may also occur at harmonic m of the local cyclotron frequency, provided the deflection cavities are operated at frequency $1/m$ times the cyclotron frequency. In this case the output cavity mode is usually the TM_{m10} mode [44]. Several programs directed towards scaling magnicon operation to higher frequencies have followed this early result. Recent experiments at INP in Novosibirsk have yielded 20 MW output power at 7 GHz with 25% efficiency, and 47 dB gain [44, 45]. Similar experiments at Los Alamos National Laboratory and the Naval Research Laboratory in the US are also underway [46, 47]. The principle technical difficulties for the magnicon are the need for very small beam diameters in the interaction region, necessitating the use of guns with very high area convergence (e.g. a factor of 2000 in the Novosibirsk gun), the effects of space charge, and the large beam loadings.

TWO-BEAM ACCELERATORS

Two-beam accelerator (TBA) schemes (e.g. CLIC and LBL/LLNL TBA project) generally envision maintaining high efficiency with short pulsed (few 100 ns) beams by repeated reacceleration and periodic RF extraction of a bunched drive beam. In experiments at LLNL on the ATA induction linac injector, an RF choppertron [48] has produced a bunched beam at 11.424 GHz [49], from which up to 180 MW power has been obtained from a single structure and from which up to 420 MW RF power (at 12 ns pulse length) has been extracted from two traveling wave disk loaded structures [50]. The efficiency for extraction of the RF energy from the bunched beam is the relevant figure of merit for a TBA scheme, and this efficiency was 34% in this case [50, 51]. These initial TBA experiments have proved promising, but important questions about the beam stability to BBU remain to be addressed. Costing studies of a 0.5 TeV class collider based on this TBA scheme show costs competitive with the cost of a conventional klystron-powered collider [52]. Future TBA concepts may employ a standing wave FEL interaction for RF extraction from the drive beam [53].

At the CERN linear collider (CLIC) test facility, a multi-bunch train of 8 bunches separated by 333 ps has been injected into a 30 GHz transfer structure, where up to 16 MW has been generated. This RF is then employed to power a 30 GHz accelerating structure. The bunched drive beam in these experiments was produced by an RF gun, and in the final collider design would be produced by many RF guns operating in tandem. The difficulties associated with this configuration has lead to consideration being given to use of an induction linac driven FEL at 30 GHz for formation of the drive beam for the CLIC structures [54].

FUTURE DIRECTIONS

In spite of these advances, much work remains to be done in the areas of modulator development and RF source development. In the near term, klystrons appear to be viable RF sources for colliders at frequencies up to X-Band (11.4 GHz); however, future collider designs at even higher frequencies will almost certainly require a new RF source technology. Certainly at much higher frequencies, fast-wave devices such as the gyroklystron and ubitron (FEL) will likely be the RF source of choice. However, in spite of the impressive advances of these sources, the efficiency, gain, and phase stability of klystrons has yet to be matched by that of a fast-wave source. The frequency at which the benefits of fast-wave technology outweigh the benefits of klystron technology remains a contentious issue. Nevertheless, fast-wave devices are certain to play an increasingly important role as drivers for future high-gradient colliders.

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