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ADVANCED RF POWER SOURCES FOR LINACS*

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In order to maintain a reasonable over-all length at high center-of-mass energy, the main linac of an electron-positron linear collider must operate at a high accelerating gradient. For copper (non-superconducting) accelerator structures, this implies a high peak power per unit length and a high peak power per RF source, assuming a limited number of discrete sources are used. To provide this power, a number of devices are currently under active development or conceptual consideration: conventional klystrons with multi-cavity output structures, gyroklystrons, magnicons, sheet-beam klystrons, multiple-beam klystrons and amplifiers based on the FEL principle. To enhance the peak power produced by an rf source, the SLED rf pulse compression scheme is currently in use on existing linacs, and new compression methods that produce a flatter output pulse are being considered for future linear colliders. This paper covers the present status and future outlook for the more important rf power sources and pulse compression systems. It should be noted that high gradient electron linacs have applications in addition to high-energy linear colliders; they can, for example, serve as compact injectors for FEL's and storage rings.

1. Overview

In this report we consider the current status of pulsed high power rf sources for linacs with copper (non-superconducting) accelerating structures. The desired peak output power from these sources is driven in large part by the requirements of electron-positron linear colliders which are currently under active design and development at various laboratories around the world. Some basic rf-related parameters for these machines are given in Table 1. This table is based on data contained in the December, 1995, report of the International Linear Collider Technical Review Committee [1]. This report is primarily concerned with the details of linear colliders designs at 500 GeV center-of-mass (c.m.) energy; upgrade paths to 1 TeV c.m. are only briefly considered. However, we have selected the 1 TeV parameters because particle physicists strongly urge that the collider designs should include the potential for an upgrade to reach this energy. Two of the machines in Table 1 (JLC-X and VLEPP) propose upgrades to 1.0 TeV c.m. simply by doubling the active accelerator length. In the other three designs a higher accelerating gradient, with a correspondingly greater power demand from the rf source, is proposed for the upgrade. In addition to the linear collider designs shown in Table 1, two other designs have been proposed which are based on the two-beam accelerator approach: CLIC at CERN and the Two-Beam NLC proposed by LBNL and LLNL as an alternative rf power source for the NLC. Although the drive beam of a two beam accelerator is capable of producing copious amounts of rf power at good efficiency, we will consider only discrete rf sources here.

Although phase-locked oscillators have been proposed as possible rf sources for powering linear colliders, we consider only amplifiers here because of their higher gain and greater stability. Among the potential candidates for a high power microwave amplifier, klystrons, gyroklystrons and magnicons have demonstrated the capability to produce power in the 3-17 Ghz frequency range at a level of interest for linear colliders. Details concerning current performance of these devices are presented in Sections 2 and 3 of this report.

RF pulse compression, using passive microwave components, can enhance the peak power from a microwave tube by a factor of 2-1/2 to 5 or so with reasonable efficiency. Current pulse compression methods are discussed in Section 4. Some future possibilities for pulse compression, including the use of loaded delay lines to reduce delay line length and the use of active switching to increase power gain and efficiency, are discussed in Section 5.

Looking to the longer-range future, there is interest in how to reach energies well beyond the 1 TeV energy provided by the designs in the Technical Review Committee Report. To reach higher energies within a reasonable overall accelerator length, a higher accelerating gradient will be needed. Significantly higher gradients can only be achieved by increasing the rf frequency. Some scaling relations for the variation of rf power requirements with frequency and gradient are given in Section 6. As an example, by extrapolating 11.4 GHz technology to 34 GHz, a 5 TeV collider could be built with an unloaded gradient of 250 MV/m and an active structure length of about 30 km. However, the required peak rf power is about 800 MW per meter at a pulse length of about 60 ns. Even with rf pulse compression, it will be difficult to obtain the required power from a conventional round-beam 34 GHz klystron. Some limitations on the power that can be reached by round-beam klystrons, and how this maximum power output might scale with frequency, are also discussed. Some possible microwave devices that might provide power adequate to drive a 5 TeV collider at 34 GHz are described in Section 7.

2. Klystrons

The workhorse of the world's high power klystrons at S-band is the SLAC 5045 klystron [2] currently in use as the power source for the SLC. Approximately 240 of these tubes have been in use on the SLAC linac for about 10 years. Some of these tubes have now accumulated over 65,000 hours of operating time. The specifications for the 5045 klystron, the mean time to failure, and some of the failure modes together with the number of tubes that have failed in each mode over a ten-year period, are given in Table 2. An outstanding feature of the 5045 klystron its reliability and long lifetime. To be successful in a linear collider application, where several thousand tubes are used, a klystron will need to approach the reliability and lifetime of the 5045.

A 150 MW S-band klystron for powering the DESY S-band linear collider (SBLC) has been designed and engineered at SLAC [3]. Table 3 gives the design specifications and the performance of the first two prototype tubes. The design philosophy for these tubes followed a conservative approach

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Table 1
Linear Collider RF Parameters at 1 TeV Center-of-Mass Energy

	SBLC (DESY)	JLC-C (KEK)	JLC-X (KEK)	NLC (SLAC)	VLEPP (BINP)
RF Frequency (GHz)	3.0	5.7	11.4	11.4	14.0
Accelerating Gradient Unloaded/Loaded (MV/m)	42/36	58/47	73/58	85/63	100/91
Dark Current Capture Gradient (MV/m)	16	31	61	61	75
Peak Power per Meter at Structure input (MV/m)	49	97	100	145	120
Klystron Peak Power (MW)	150	100	135	75	150
Klystron Pulse Length (μs)	2.8	2.4	0.5	1.0	0.5
Repetition Rate (Hz)	50	50	150	120	300
Pulse Compression Type	SLED	SLED	DLDS	BPC	VPM
Compression Ratio	≈3.5	5.0	2.0	4.0	4.6
Compression Power Gain	2.0	3.5	1.95	3.5	3.3
Compression Efficiency (%)	≈60	70	98	87	73
RF System Efficiency (%)	23	26	31	34	40
Number of Klystrons	4900	6200	6900	9500	2800
Active Length (km)	29	22	18	17	12
Wall Plug Power (MW)	285	200	220	190	115

Table 2
The SLAC 5045 Klystron

Specifications	
Operating Frequency	2856 MHz
Beam Voltage	350 kV
Beam Current	414 A
Microperveance	2.0
Output Power	67 MW
Pulsewidth	3.3μs
Repetition Rate	180 Hz
Efficiency	46 %
Gain	53 db
Number of Cavities	6
Cathode Loading	8 A/cm^2
Area Convergence	19
Lifetime	
Mean Time to Failure	≈ 50,000 hrs
Cause of Failure (403 tubes : 1984-1994)	
Window failure	89
Gun ceramic	82
Unstable or low rf output	68
Arcing	57
Gassy	46
Vacuum Leak	24
Low Emission	16
Water Leak	14
Faulty parts	7

Table 3
SLAC/DESY 150 MW S-Band (2998 Mhz) Klystron

	Design	Performance I	Performance II
Beam Voltage (kV)	535	536	520
Beam Current (A)	700	720	670
Microperveance	1.8	1.83	1.78
Cathode Loading (Max A/cm^2)	6		
Area Convergence	40:1		
Output Power (MW)	150	160	156
Pulsewidth (μs)	3	3	3
Repetition Rate (Hz)	50	60	60
Electronic Effic. (%)	>40	41.5	45
Gain (db)	>55	62	58
Output circuit		1 cell	2 cell
Focusing type	Solenoid		
Solenoid Power (kW)	1.5		
Output Window Type	TE_{11} pillbox		
No. Windows per Kly.	4		

Table 4
SLAC X-Band (11.4 Ghz) Klystrons

	XL-4		X5011	
	Design	Achieved	Design	Achieved
Gun				
Beam Voltage (kV)	440	450	465	480
Beam Current (A)	350		190	
Microperveance	1.2	1.15	0.6	0.65
Cathode Loading (A/cm^2)	8.75		7.4	
Area Convergence	125		140	
RF				
Output Power (MW)	50	75	50	62
Pulsewidth (μs)	1.5	1.1	1.2	0.6
Repetition Rate (Hz)	180	120	180	60
Electronic Eff. (%).	52 (sim)	48	63 (sim)	60
Gain (db)	>50	55	55	55
Output circuit	4 cell TW		5 cell TW	
Focusing				
Type	Solenoid (0.47 T)		PPM	
Solenoid Power (kW)	15		----	
Output Window				
Type	TE_{01}-TW		TE_{01}-TW	
No. Windows per Klystron	1		1	

Table 5
Parameters for the KEK/Toshiba and BINP/VLEPP Klystrons

	KEK/Toshiba		BINP/VLEPP	
	Design	Achieved	Design	Achieved
RF Frequency (GHz)	11.4		14	
Output Power (MW)	135	96/50	150	60
Pulsewidth (μs)	0.75	0.1/0.2	0.5	0.7
Repetition Rate (Hz)	150	100	300	2
Microperveance	1.2	1.2	0.25	0.15
Electronic Efficiency (%)	45	33	60	40
Beam Voltage (kV)	600	620	1000	1000
Cathode Loading (A/cm^2)	13.5	13.5	5	5
Output Circuit	4-cell TW	single gap	14-cell TW	
Gain (db)	53-56		75	90
Focusing Type	SC Magnet	Solenoid	PPM	PPM
Solenoid/Cryogenic Power (kW)	1	40	----	----
Output Window	TE_{11}-TW	TE_{11}-$\lambda/2$	TE_{11}-TW	

in which existing 5045 technology was extended to higher beam currents and rf power densities. In the first tube an 8.56 Ghz oscillation proved troublesome. In the second tube, two copper drift tubes were replaced by stainless steel drift tubes. The second klystron processed quickly and showed no instabilities.

Table 3 gives design and performance parameters for two X-band klystrons designed and built at SLAC (see [4] for an overview of the X-band klystron program at SLAC). Four klystrons in the XL series [5] have been produced. XL-1 and XL-2 have 3-section standing-wave output circuits and the other two tubes have four-cell traveling-wave outputs. The first three tubes produced the specified 50 MW at 1.5 μs but were troubled by instabilities unless the focusing strength was increased at the cost of reduced efficiency. Several design changes were incorporated in XL-4, including adjustments in the spacing and tuning of the bunching cavities, fabrication of the last three drift tubes from stainless steel, and coating the output circuit with titanium nitride. This klystron has produced 50 MW at 1.5 μs and 120 pps at a beam voltage of 400 kV with 43% efficiency; at a somewhat shorter pulse width (1.1 μs) it has reached 75 MW at an efficiency of 48%. It is essentially free of oscillations, pulse-shortening or missing pulse phenomena that have been observed in all previous X-band klystrons built at SLAC.

The second column in Table 4 shows design parameters [6] and achieved performance for the first Periodic Permanent Magnet (PPM) focused klystron built at SLAC. This tube has produced over 60 MW at 0.6 μs with an efficiency of 60%. At a pulse length of 1.2 μs it has reached the design power output of 50 MW at somewhat lower efficiency. Although the output rf pulse is stable, a complex phenomenon takes place as a function of drive power which is not yet fully understood. In any case, this is the only klystron of this design that will be built. The program effort will be directed to the design of a 75 MW PPM tube with a microperveance of 0.75.

There are two additional programs for the development of high power klystrons for linear collider service. At KEK, a klystron is being developed in collaboration with Toshiba for the X-band JLC collider. The first tube achieve the performance shown in Table 5 at short pulse lengths, but could not sustain higher power levels or longer pulse lengths due to breakdown in the single output gap. To reduce the field level, the klystron has been redesigned with a 4-cell TW circuit; this new tube is currently under test.

At the Protvino Branch of the Budker Institute of Nuclear Physics, a prototype rf system for the VLEPP collider project is being designed and tested. A novel feature of this klsytron is a gridded gun, which allows the beam to be switched directly from a pulse-forming line without the need for a pulse transformer and its attendant inefficiencies. Further information on this klystron is given in [1] and [7], and on the KEK klystron in [1] and [8].

3. Magnicons and Gyroklystrons

A magnicon is a scanning-beam microwave amplifier in which a rotating electron beam interacts synchronously with a rotating TM-mode in a cylindrical output cavity.It is capable of high efficiency, and has been proposed as an alternative to klystrons for powering linear colliders. At the Budker Institute of Nuclear Physics (Novosibirsk), a 7 Ghz magnicon has produced 30 MW at 35% effiiciency [9]. The efficiency was limited by an oversized electron beam diameter (4 vs 3 mm). At the Naval Research Laboratory, an 11.4 Ghz magnicon is under design with a simulated output of 58 MW at 58% efficiency [10]. By using the TM_{210} mode in the output cavity, this magnicon also acts as frequency doubler from 5.7 to 11.4 Ghz. For high efficiency in a magnicon it is necessary to keep the beam diameter (e.g. ≈ 2 mm in the NRL design) small relative to the rf wavelength. It will be difficult therefore to achieve high power in a magnicon at a frequency which is substantially higher than the 11 Ghz of the NRL design.

Gyroklystrons, having extended annular beams, are capable of producing high rf power at high frequencies. The most extensive work on the development of high power gyroklystrons has taken place at the University of Maryland. In past experiments, 27 MW at 9.9 Ghz has been produced with an efficiency of 32 %, and 32 MW at 19.7 Ghz (2^{nd} harmonic) at an efficiency of 29%; the pulse length was about 1 μs (see references in [11]). A new gyroklystron testbed has recently been completed with a higher power modulator capability (800A at 500 kV). A coaxial gyroklystron is now under construction which will eventually reach a simulated output power of 160 MW at 17.1 Ghz (2^{nd} harmonic) at an efficiency of 41% [11]. Use of a single-stage depressed collector could increase this efficiency to 55%.

4. RF Pulse Compression

An rf pulse compression system can enhance the peak power output from a microwave tube by trading reduced pulsewidth for increased peak power. The power gain is given by the compression ratio, R, in pulsewidth times a compression efficiency which takes account of intrinsic losses (e.g., reflected power), resistive (copper) losses, and the effect of a non-flat output pulse. Pulse compression reduces the burden on the rf power source and helps to match the modulator pulse length) to the accelerator structure filling time. It is especially important at higher frequencies where the structure filling time, which scales as $\omega^{-3/2}$, is short and the production of peak rf power is more difficult. A pulse compression system always involves an energy storage element of some sort to delay or transfer energy from the early portion of the rf pulse into the compressed output pulse.

The first large-scale pulse compression system for an accelerator application was the SLED scheme, implemented on the SLAC linac in the late 1970's. Using a pair of TE_{015} cylindrical cavities ($Q_0 \approx 1\times10^5$) as energy storage elements, SLED produces a power gain of about 2.7 with a compression efficiency of 62% (R = 4.4). A distinguishing feature of the SLED compression method is a 180^0 phase reversal in the klystron drive, which triggers the release of the energy stored in the high Q cavities. Two cavities and a 3 db coupler are used so that the energy reflected and emitted from the cavities will not return to the klystron but will be directed into the transmission line to the accelerator.

Because the SLED output pulse has a shape which is dominated by the exponential decay of energy in the storage cavities, it is poorly adapted for powering a linear collider with long bunch trains. The pulse shape problem can be solved by replacing the two storage cavities with shorted delay lines. In this scheme, called SLED-II, the delay line length (in travel time) is equal to one-half the desired output pulse length. The power gain is optimized by adjusting the reflection coefficient of an iris at the entrance to the delay lines. Assuming lossless components, the power gains (and efficiencies) for a SLED-II system with compression ratios of 4, 5 and 6 are 3.44 (86%), 4.0 (80%) and 4.5 (75%).

A program has been in progress at SLAC for a number of years to develop the necessary components for a high power SLED-II pulse compression system. To keep losses low, overmoded TE_{01} circular waveguide is used for the SLED-II delay lines and for power transmission over distances greater than a meter or so. A low loss (3/4%) mode converter [12] has been developed which makes it possible to couple efficiently to the circular guide from standard WR90 rectangular guide. This so-called "flower petal" mode converter also makes it possible to manipulate rf power using relatively simple rectangular waveguide components. For example, a 90^0 bend is constructed from a mitered rectangular waveguide bend and two mode transducers.

A complete SLED-II compression system has been implemented on the NLC Test Accelerator at SLAC, and tested at both low and high power [12]. The measured efficiency of the SLED-II system was 68% at R=6 (power gain of 4.05). The intrinsic Q for the delay lines (12.07 cm diameter) was measured to be 1.05×10^6, which is 76% of theoretical. This corresponds to a roundtrip power loss of 1.5% for a delay of 225 ns. The power transmission system connecting the SLED-II compressor to the NLCTA injector consists of 20 m of 7.4 cm diameter circular waveguide, two 90^0 bends and mode converters at each end. The measured one-way loss is 5.8%. The system is currently delivering an output power of about 150 MW; this power level is still increasing as the injector accelerating structures continue to process, and is expected to reach about 200 MW.

5. Future Possibilities for Pulse Compression

Several possibilities exist for improving pulse compression systems beyond SLED-II. First of all, the intrinsic inefficiency of a SLED-II system translates to a 30-40 MW increase in ac wall plug power for a 1 TeV collider. The Binary Pulse Compression (BPC) scheme, which compresses by a factor of $R=2^n$, is inherently 100% efficient, but unfortunately needs a total delay line length of $(R-1)T_p$, where T_p is the output pulse length . This can be compared to a length Tp for a SLED-II system.

Two ways have been suggested for reducing the delay line length for a BPC system. In the DLDS (Delay Line Distribution System) scheme proposed at KEK, the rf is sent up-stream toward the gun for one-half of the delay, and the transit time of the returning beam provides the other half. This reduces the length of delay line pipe by about a factor of two (see [1] and [8] for more details on DLDS). A second method being considered for reducing delay line length is to replace the lines by a chain of N coupled resonators, where N is of the order 3 to 10. Larger values of N will give a flatter pulse and greater pulse shape efficiency. For a delay of one microsecond, a Q on the order of 10^6 is required for good transmission efficiency. This can be achieved in a TE_{onm}-mode cavity on the order of 1.5 m long, but because of the high mode density coupling to parasitic modes is a problem. Active R&D on such loaded delay lines is underway at SLAC and elsewhere.

Use of an active device to switch the effective reflection coefficient of the irises at the entrance to the delay lines can improve the efficiency and power gain of a SLED-II system. Such a switch, based on changing the conductivity of a silicon wafer with a laser beam, is under investigation at SLAC [13].

6. Limitations on Klystron Power

If all dimensions of an accelerating structure are scaled in proportion to the rf wavelength λ, the energy stored per unit length varies as $U_m \sim G^2\lambda^2$, where G is the accelerating gradient.

Therefore, assuming a fixed repetition rate and ratio of pulse length to filling time, the gradient and the total machine energy can be increased in direct proportion to the rf frequency while maintaining a fixed active structure length and ac power. It is interesting to note that the gradient for capture of an electron at rest (dark current capture threshold) is also proportional to frequency (G_{th}=1.605 MV/λ). Operational difficulties, such as the interference of dark current with beam position monitoring, can also be expected to scale with G_{th}. While the dark current capture threshold does not impose an absolute limit on accelerating gradient, it is dangerous to assume it can be exceeded by too wide a margin. Values of G_{th} are listed in Table I for the various collider designs.

The accelerators listed in Table I were not designed with any particular frequency scaling law in mind. However, there is a consistant trend toward higher gradients at higher frequencies. If the unloaded gradients for the 500 GeV c.m. designs (not listed) are plotted vs. frequency, they fall roughly on a straight line parallel to and 35% above the line $G_{th}\sim\omega$. If we extrapolate this trend to 34 Ghz (12 times SLC), we obtain an unloaded gradient of 250 MV/m. This frequency and gradient can serve as the basis for a 5 TeV linear collider design with a reasonable length ($\approx$ 30 km of active structure) and ac power ($\approx$ 250 MW).

The peak rf power required per meter of structure length scales as $U_m/T_F \sim G^2\lambda^{1/2}$. Assuming an NLC accelerating structure with somewhat higher group velocity (vg/c = 0.09) scaled to 34 Ghz, the peak power per meter will scale to $\approx$ 800 MW/m. In a scenario using a 3-stage BPC compression scheme and two 0.6 m accelerating structures per klystron, the peak klystron power required would be 150 MW. We conider next the limitations on obtaining this kind of power from a 34 Ghz microwave source.

It is well known that the efficiency of conventional round-beam klystrons depends on the microperveance, K_m. This dependence is not sharply defined, but the expression η = 0.75–0.17 K_m gives approximate efficiencies for the X-band klystrons simulated at SLAC (assuming modest future improvements). To obtain an overall rf system efficiency of 50%, a klystron with an efficiency in the range 65–70% is needed. To achieve such efficiencies, the microperveance will need to be in the range 0.3–0.6. Assuming a beam voltage of 500 kV, the maximum output power will be in the range 35–70 MW.

Another limitation on klystron power depends on the acceptable cathode loading per square centimeter, I_A , the maximum area convergence ratio A_c (dictated by the gun optics) and the need for good coupling to the beam in the rf gaps (maximum beam radius $\approx\lambda/8$). Putting these factors together, the maximum output power is $P\approx\eta V_b I_A A_c\cdot\pi(\lambda/8)^2$.The maximum area convergence is limited by the beam perveance: $A_c\approx 150/K^2_m$ [14]. For I_A = 8A/cm^2, a beam voltage of 500 kV and a microperveance in the range 0.3–0.6, the maximum klystron power is in the range 180–40 MW at 34 Ghz.

7. RF Sources for 34 Ghz

In the previous section it was found that efficiency and cathode loading and area convergence considerations limited the power of a conventional klystron to about 40 MW at 34 Ghz. Four such beams packaged together in the same vacuum envelope could produce the desired 150 MW. Such a multibeam klystron having common rf cavities but separate PPM-focused beam tubes has indeed been proposed [14]. Klystrons using a sheet beam, essentially equivalent to many round beams in parallel, are also capable (in simulations) of producing 150 MW at 34 Ghz with good efficiency [15].

As discussed in Sec. 3, gyroklystrons are capable of producing high power at high frequency. At the University of Maryland, a coaxial-circuit gyroklystron frequency doubled to 34 Ghz has been designed which produces an power output of 150 MW at a simulated efficiency of 42% [16]. A single-stage depressed collector can increase this to 56%.

Another annular-beam device capable of delivering high power output at high frequencies is the ubitron FEL proposed by McDermott et al. [17]. Using a TE_{01} -mode coaxial cavity with PPM focusing, it produces a simulated output power of 250 MW at 11.4 Ghz with an efficiency of 50%.

References

A number of papers relevant to high power rf sources and pulse compression systems for linacs were presented at the recent meeting on Pulsed RF Sources for Linear Colliders (RF96), April 8-12, 1996, Shonan Village Center, Hayama, Japan. In the following, a reference to RF96 indicates a paper to be published in the proceedings of this conference.

[1] G. A. Loew, ed, *International Linear Collider Technical Review Report, 1995;* SLAC-R-95-471, Stanford Linear Accelerator Center, Stanford, CA (December 1995).

[2] M. A. Allen et al., "Performance of the SLAC Linear Collider Klystrons", Proceedings of the 1987 IEEE Particle Accelerator Conference, p. 1713. Failure data provided by G. Caryotakis (private communication).

[3] D. Sprehn, G. Caryotakis and R. M. Phillips, "150-MW S-Band Klystron Program at the Stanford Linear Accelerator Center", RF96; also SLAC-PUB-7232 (1996).

[4] George Caryotakis, "The X-Band Klystron Program at SLAC", RF96; also SLAC-PUB-7146 (1996).

[5] E. Wright et al., "Design of a 50 MW Klystron at X-Band", Presented at RF94, published in *AIP Conference Proceedings* 337 (1995), p. 58; also SLAC-PUB-95-6676 (1995).

[6] D. Sprehn et al., "PPM Focused X-Band Klystron Development at the Stanford Linear Accelerator Center", RF96; also SLAC-PUB-7231 (1996).

[7] G. Dolbilov, "Development Status of Wide Aperture 14 Ghz VLEPP Klystron with Distributed Suppression of Parasitic Modes", RF96.

[8] H. Mizuno, "X-Band RF System for JLC", RF96.

[9] E. Kozyrev et al., "Performance of High Power 7 Ghz Magnicon Amplifier", *Particle Accelerators*, in press.

[10] S. Gold, O. Nezhevenko and B. Hafizi, "Design of a High Power Thermionic Magnicon Amplifier at 11.4 Ghz", Naval Research Laboratory Report NRL/MR/6790-96-7857.

[11] W. Lawson et al., "Initial Operation of a 100 MW X-Band Gyroklystron for Collider Applications", paper MOP62, this conference.

[12] S. G. Tantawi et al., "The Next Linear Collider Test Accelerator's RF Pulse Compression and Transmission Systems", presented at EPAC'96, Sitge, Spain, June 1996; also SLAC-PUB-7247.

[13] S. G. Tantawi et al., "Active Radio Frequency Pulse Compression Using Switched Resonant Delay Lines", *Nuclear Instr. Meth.* 370 (1996), p. 297.

[14] R. Phillips, private communication.

[15] D.U.L. Yu, J. S. Kim and P. B. Wilson, "Design of a High Power Sheet Beam Klystron", Fifth Advanced Accelerator Concepts Workshop, Port Jefferson, NY, (*AIP Conference Proceedings* 279, 1993), p.85.

[16] Girish Saraph, private communication.

[17] D. B. McDermott et al., "Periodic Permanent Magnet Focusing of an Annular Electron Beam and its Application to a 250 MW Ubitron FEL"; submitted to *Physics of Plasmas* (1995).