Development And Advances In Conventional High Power RF Systems*

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The development of rf systems capable of producing high peak power (hundreds of megawatts) at relatively short pulse lengths (0.1-5 microseconds) is currently being driven mainly by the requirements of future high energy linear colliders, although there may be applications to industrial, medical and research linacs as well. The production of high peak power rf typically involves four basic elements: a power supply to convert ac from the "wall plug" to dc; a modulator, or some sort of switching element, to produce pulsed dc power; an rf source to convert the pulsed dc to pulsed rf power; and possibly an rf pulse compression system to further enhance the peak rf power. Each element in this rf chain from wall plug to accelerating structure must perform with high efficiency in a linear collider application, such that the overall system efficiency is 30% or more. Basic design concepts are discussed for klystrons, modulators and rf pulse compression systems, and their present design status is summarized for applications to proposed linear colliders.

I. INTRODUCTION

There now exists an *Interlaboratory Collaboration for R&D Toward TeV-Scale Electron-Positron Linear Colliders*. The collaboration consists of some 23 member institutions in Europe, Asia and the United States with an interest in linear collider development. The Council of the Collaboration (consisting of one representative from each member institution) met at EPAC'94, and decided to appoint a Technical Review Committee (TRC). This committee was charged with preparing a report on the present status of linear collider technology, and the further R&D needed over the next few years to reach these design goals: an initial luminosity in excess of 10^{33}cm^{-2}s^{-1} at a center-of-mass energy of 500 GeV, with the capability of being expanded in energy and luminosity to reach 1 TeV center-of-mass energy with a luminosity of 10^{34}cm^{-2}s^{-1}. A draft of the report will be submitted to the Collaboration Council in June, 1995. This paper is based in large part on material collected for Chapter 3 (Linac Technology) of the TRC report.

The major proposals for future linear colliders have been described in detail elsewhere (see for example the survey talks in [1]). TESLA (TeV Superconducting Linear Accelerator) is a proposal for a linear collider based on the use of superconducting accelerating cavities at 1.3 GHz. The TESLA R&D program is an international collaboration of about a dozen laboratories, coordinated by the DESY laboratory in Hamburg, Germany. Use of a superconducting cavity avoids the need for very high peak rf power. Such a cavity is in essence an rf pulse compressor, storing energy over a relatively long time period (on the order of a millisecond) from an RF pulse with a relatively low peak power. An advantage of the low TESLA rf frequency is a larger beam cross-section and looser tolerances on construction and alignment. The SBLC (S-Band Linear Collider) is a proposal, also based at DESY, for a linear collider with an rf frequency of 3 GHz. Because of the relatively low rf frequency, the SBLC also has comparatively loose tolerances. A strong point of this proposal is that it is supported by a wide base of existing S-band accelerator technology, in particular the SLC prototype linear collider at SLAC. The NLC (Next Linear Collider) is a proposal by SLAC for a linear collider at 11.4 GHz, exactly four times the SLC frequency. The principal advantage of a higher rf frequency is that a higher accelerating gradient can be obtained for the same ac input power, resulting in a shorter length and possibly lower cost for the main linac. A major disadvantage is that tighter tolerances are required for the construction and alignment of the accelerating sections and focusing magnets. Also, higher peak power is required from the rf sources, with a consequence that some form of rf pulse compression is necessary. The KEK laboratory in Tsukuba, Japan, has proposed the JLC (Japan Linear Collider), also at 11.4 GHz; it is quite similar to the NLC in its main design parameters. VLEPP (standing for "Colliding Linear Electron-Positron Beams" in Russian) is a proposal for a linear collider at 14 GHz, which originated at the Institute of Nuclear Physics (INP) in Novosibirsk, Russia. The R&D for the collider is actually taking place at Protvino, Russia, near Serpukhov (about 100 km south of Moscow). It is being carried out by personnel from a Branch of the above institute (BINP). Unfortunately, the economic situation in present-day Russia is such that a full-scale VLEPP will probably not be funded. However, a strong R&D program is still going forward at Protvino; this work will provide useful results which can expedite the other collider programs. CLIC (CERN Linear Collider) is a proposal for a two-beam linear collider based at CERN in Geneva, Switzerland. In the CLIC design (see paper by K. Hübner in [1]), 350 MHz superconducting cavities are used to accelerate a high-current drive beam to 3 GeV. The drive beam consists of trains of bunches in which the spacing between bunches in each train is the rf wavelength at 30 GHz. These trains pass through a series of low impedance "transfer structures", where they induce about 90 MW of peak rf power for a pulse duration of 12 ns. This power is then transferred through waveguides (two for each transfer structure) to the accelerating sections in the main linac. The TBNLC (Two-Beam NLC), proposed by a group at LBL and LLNL, is also a two-beam accelerator scheme, but in this case the drive beam is powered by induction linac modules. The TBNLC is proposed as an alternative power source for the NLC, in particular as a high-gradient upgrade to 1 TeV. Instead, of a single drive beam per main linac, as in the case of CLIC, the TBNLC would consist of 18 separate drive beam units for each of the two main linacs. There would be 150 transfer structures per drive beam, each supplying 360 MW of power to a single 1.8 m NLC accelerating section.

The various proposed colliders and their operating frequencies are listed in Table I, along with other basic

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parameters to be discussed in the following sections. The SLC is listed for comparison.

II. SCALING COLLIDER PARAMETERS WITH FREQUENCY

All of the proposed linear collide designs are based on the production and manipulation of RF power in the frequency range 1.3-30 GHz. The rf system itself must convert power from the ac mains (wall plug) to rf power at the input of the accelerating structure with the greatest possible efficiency. In general, it is easier to attain a high accelerating gradient at a higher rf frequency. Nature has, however, imposed a powerful limitation on the gradient achievable for routine operation of a copper accelerating structure --- the dark current capture threshold. This threshold is given by

$$G_{th}\lambda = 1.605\,\mathrm{MV} \qquad (1)$$

where λ is the RF wavelength. The threshold gradients for the various colliders are listed in Table I, together with the design gradients for a 500 GeV machine. It is indeed possible to exceed this threshold gradient by some reasonable factor; for example the SLC routinely operates 30% above it with barely detectable dark current. However, the dark current beam power dissipation, and hence the difficulty in processing a structure to a given gradient level, tends to become worse exponentially as the capture threshold is exceeded by a still larger factor. In the case of a superconducting structure, field emission will necessarily be reduced to a low level by special cleaning and processing techniques to avoid unacceptable power dissipation at low temperature. Perhaps these heroic cleaning and handling procedures can be adapted to copper structures as well. But in any case, if operation is planned at a gradient significantly above the capture threshold, dark current effects must be carefully studied in an appropriate test facility (such as the TESLA Test Facility under construction at DESY).

For a high frequency high gradient linear collider with a copper accelerating structure, nature has unfortunately imposed another limitation on the rf system. The energy stored per unit length on the accelerating structure will scale roughly as $G^2\lambda^2$. If the gradient is set at some factor times the capture threshold gradient, then the stored energy per unit length remains roughly constant, independent of frequency. However, the time allowed for this energy to be collected in the accelerating structure depends on the energy decrement time,

$$\tau_d = Q/\omega \sim \omega^{-3/2} \qquad (2)$$

Thus the RF pulse length will also tend to scale as $\omega^{-3/2}$, and since the stored energy per meter is roughly constant under the above scaling assumption, the peak power required per meter will tend to scale as $\omega^{3/2}$. Unfortunately, the maximum output power available from a klystron tends to decrease rather than increase as frequency increase. Therefore high frequency RF systems using klystrons to generate the RF power (NLC, JLC, VLEPP) require some sort of pulse compression to enhance the peak power output. However, the additional loss associated with the compression process tends to lower the overall efficiency of the RF system. The two-beam accelerator concept (TBNLC, CLIC) bypasses the limitations imposed by conventional klystrons in producing high frequency, high peak power at short pulse lengths. The drive beam in a two-beam accelerator is, in fact, equivalent to the beam in a klystron, and the TBA scheme is also called a “relativistic klystron.” A collider using a superconducting accelerating structure (TESLA) increases the Q/ω limitation on energy collection time by a large factor over that of copper, allowing a long pulse, low peak power, efficient RF system. (As will be discussed later, a long pulse modulator tends to be more efficient than one which must produce short, very high peak power pulses). However, this gain in the efficiency of RF power generation is offset to a large extent by the additional power required by the refrigeration system.

Energy decrement times and peak RF power requirements for the collider designs are listed in Table I. For machines with copper structures, the structure filling times (except for CLIC) are quite close to the values given for τ_d; the RF pulse lengths are typically several times longer to allow for acceleration of a bunch train. The pulse lengths at the accelerating structure (in nanoseconds) are: SBLC (2800); JLC (230); NLC (240); VLEPP (110); CLIC (12). In the case of TESLA, the pulse length (1.3 ms) is reduced below the decrement time approximately by the ratio of the refrigeration power required per Watt of power dissipated at 4.2°K (≈ 300). The peak powers do not scale as $\omega^{3/2}$ as discussed above, because the actual design gradients do not closely follow a G_{th} scaling. However, as seen in Table I, the peak power per meter does increase rapidly with increasing frequency. Likewise, the linac length would be roughly proportional to λ for $G \sim G_{th}$ scaling. The actual design lengths do show a strong correlation with frequency. Since the stored energy per meter remains approximately constant for $G \sim G_{th}$ scaling, the average AC wall-plug power should scale roughly as $\overline{P}_{AC} \sim f_r\lambda/\eta_{rf}$, where f_r is the repetition rate and η_{rf} is the RF system efficiency. As frequency increases, the colliders in Table I trade at least part of their wavelength advantage for a higher repetition rate. These rates are (in Hz): TESLA (10); SBLC (50); JLC (150); NLC (180); VLEPP (300).

III. RF SYSTEM TECHNOLOGY

A. Klystrons

At a constant beam voltage, the RF output of a klystron (or other microwave power source) increases as the beam current increases. However, a higher beam current, I_b, at a given beam voltage, V_b, inevitably lead to a lower efficiency because of the detrimental effects of space charge forces. These forces tend to blow apart the sharply defined bunches needed for high output efficiency. The microperveance (defined by $K_\mu = I_b/V_b^{3/2} \times 10^{6}$) is commonly taken as a measure of these space charge effects. If klystron efficiencies, obtained from both measured performance and simulations, are plotted as a function of microperveance, it is found that the collection of points (see for example [2], Fig. 3) is quite sharply bounded by the line

$$\eta_{kly} \approx 0.80 - 0.15 K_{\mu} \ . \qquad (2)$$

Low frequency, long pulse or CW klystrons tend to fall closer to this performance limit than high frequency, high peak power tubes. The intercept at zero perveance has some theoretical justification. A 100% efficiency implies that all the electrons in the beam are just brought to rest by the RF voltage of the output circuit. This is not possible in a real klystron because there is an energy spread in the beam due to the bunching process, and because the RF voltage varies with radius across the gap. Also, even a single electron cannot be stopped in a gridless gap; an electron on axis can lose at most about 85% of its energy [3].

There is also the perennial question concerning limitations on peak klystron output power as a function of frequency. This can be roughly estimated as follows. First, the beam radius is limited to something like $\lambda/8$ to allow for reasonable gap coupling. Second, the current density per unit area from the cathode (cathode loading, I_A) is limited to about 10 A/cm^2 for good cathode lifetime. Third, the area compression ratio, C_A, of the beam in the gun region is limited by optics and tolerances to perhaps 150. Putting these factors together gives

$$P_{max} \approx \eta V_b \left[I_A C_A \pi (\lambda / 8)^2 \right] = 74 \eta V_b (\lambda / cm)^2 \quad (3)$$

where η is the electronic efficiency. If the tube is to be efficient, and if we apply Eq. (2) conservatively, then the microperveance for an efficiency of 50-60% is limited to $K_{\mu} \leq 1$. Using Eq. (2) together with $P_K = \eta \left(K_{\mu} \times 10^6 \right) V_b^{5/2}$, we find that for V_b = 500 kV the maximum output power is about l00 MW up to 14 GHz, then falls off as λ^2 above this frequency.

Table II lists klystron parameters for the five collider proposals that use klystrons as an RF source. Both design parameters and values actually achieved to date are shown. The numbers given for "scaled maximum efficiency" are obtained from Eq. (2). Note that the design values for efficiency are all well below these maximum values, except for the low frequency, long pulse TESLA klystron where good efficiency should be relatively easy to achieve. Two of the klystrons have achieved the design peak power. The SBLC S-band klystron, designed in collaboration with SLAC, has reached 150 MW at a 2.8 µs pulse length [4]. The NLC X-band klystron has achieved 50 MW at 1.5 µs [5]. Both klystrons still fall short in efficiency, and both must eventually replace power-consuming solenoids with PPM (periodic permanent magnet) focusing or superconducting solenoids.

B. Modulators

The rise time of a modulator pulse is an important parameter in determining the modulator efficiency. In a conventional modulator, the pulse forming network (PFN) capacitance is charged by a DC power supply to a voltage V_{PFN}. This network can be either a length of smooth transmission line, or a series of discrete capacitors and inductors which model such a line. The line is then discharged by a switching device, usually a thyratron, through the primary of a pulse transformer with a turns ratio n. The output of the pulse transformer produces a voltage $nV_{PFN}/2$ (single stage PFN), or nV_{PFN} (two stage, or Blumlein PFN). In the case of the TESLA modulator, an energy storage capacitor is partially discharged through the primary of the pulse transformer. The switching is done by solid state devices (thyristors). A "bouncer" circuit is used to compensate for voltage droop.

The energy efficiency, η_E, of the pulse transformer is defined as the useful energy in the flat-top portion of the pulse divided by the total energy in the pulse. The energy in the fall-time portion of the pulse tends to scale in proportion to the rise time, T_R, so that the energy efficiency can be written as $\eta_E \equiv T_K/T_E = T_K/(T_K + \alpha T_R)$, where T_K is the useful flat-top pulse width, T_E is the energy width, and α is a coefficient between 1.0 and 1.2 which depends on the pulse shape and the definition of rise time. In turn, a simple physical argument [6] leads to the scaling $T_R \sim nT_E^{1/2}$. Combined with the preceding relation, this gives

$$T_E = \frac{1}{4} \left[\beta n + (\beta^2 n^2 + 4 T_K)^{1/2} \right]^2 \qquad (4)$$

where β is a constant that can be obtained by fitting to existing pulse transformer designs. For the pulse transformer driving the 5045 SLAC klystrons, β = 0.033 $(\mu s)^{1/2}$. It is found that the above expression then gives a good fit to a number of other pulse transformers measured at SLAC having a variety of turns ratios and pulse lengths. Using Eq. (4), the energy efficiency is plotted in Fig. 1.

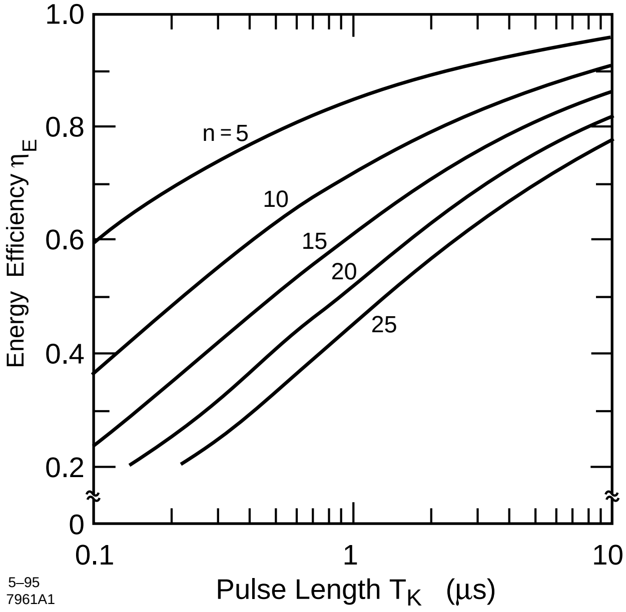

Figure 1 - Energy Efficiency for a typical pulse transformer as a function of pulse length and turns ration n.

Along with T_K and n, values of η_E from Eq. (4) are listed in Table III (as the scaled energy efficiency) for the modulator designs for the various collider proposals. An accurate calculation of energy efficiency must also include the effect of the load (klystron) capacitance, the series inductance of the thyratron, transformer core losses, and the inductances of the cables and leads connecting the components. Of course, the best efficiency is obtained by eliminating the modulator entirely by using a klystron with a gridded gun to switch the beam, as proposed for VLEPP.

C. RF Pulse Compression

RF pulse compression is a method of enhancing klystron output power at the expense of pulse width. Although some energy is lost in the compression process, the efficiency can in principle be quite high. High-Q energy storage elements are required to achieve efficient pulse compression; these can be either resonant cavities or lengths of shorted delay line.

RF pulse compression is used in three of the 500 GeV collider designs. VLEPP and NLC use a SLED-type scheme (SBLC plans to use a SLED system in a 1 TeV upgrade). In a SLED pulse compression system [7], energy builds up in a storage element (resonant cavity or resonant delay line) over the major part of the klystron output pulse. During the final part of the pulse, equal to the desired output pulse length, a phase reversal at the klystron input triggers a discharge of this stored energy, which then adds to the energy coming directly from the klystron. During the filling time of the storage device, there is an unavoidable power reflection; in addition, some energy is left behind in the storage element. Together, these factors lead to a maximum intrinsic efficiency for a SLED system on the order of 80%, even assuming lossless components. Taking losses into account reduces the efficiency to approximately 75%. On the other hand, the JLC uses a compression method, the Delay Line Distribution System (DLDS), which is inherently 100% efficient. Although related to Binary Pulse Compression [8], the DLDS system uses less delay line pipe by feeding power in the up-stream beam direction, thus taking advantage of the beam transit time to achieve a factor of two reduction in the required delay line length. Both the DLDS and the SLED-II compression systems have the advantage or producing a flat output pulse. This is a necessity for accelerating long bunch trains (the beam pulse length is about 120 ns for JLC and NLC). The VLEPP compression system is based on the use of a single traveling-wave “open” cavity resonator of unique design [9], and is therefore very compact. Although the output pulse is not inherently flat, this is of no consequence for the acceleration of a single bunch, as is the case for VLEPP. Parameters for the three pulse compression systems are given in Table IV.

IV. RF SYSTEM EFFICIENCY

The overall RF system efficiency is an important parameter for a linear collider. The AC power requirements (see Table I) for the various collider proposals range from 60-150 MW. Thus a 1% improvement in efficiency can reduce the AC power consumption by a megawatt or more. The net system efficiency, shown in the last column in Table I, is the product of the separate efficiencies of the klystron, modulator, and pulse compression systems. If there is no compression system, the efficiency for transmitting power from the klystron to the accelerating structure must be included instead. The system efficiency can be calculated with and without auxiliary power. This includes power for the klystron cathode heater, klystron focusing solenoid, thyratron cathode and reservoir heaters, and power for the cryogenic systems in TESLA and CLIC (which uses superconducting cavities to accelerate the drive beam). The net RF system efficiency is, on the average, about one-third.

It is obviously highly desirable to increase the net RF system efficiency. For example, one can think of eliminating the pulse compression system and the losses associated with it. However, more dc pulse compression must then be carried out in the modulator (or in the induction linac modules in the case of the TBNLC). As another example, a better klystron efficiency can be obtained by raising the beam voltage and lowering the perveance. Again, this implies a lower modulator efficiency because a pulse transformer with a larger turns ratio will be required (or a higher V_{PFN} could be used, which is more expensive and technically difficult). There are losses and inefficiencies in each stage of the power handling and processing chain between the AC wall plug and RF at the input to the accelerating structure. Care must be taken that an efficiency improvement at one step in this chain is not made at the expense of increases loss at another stage.

A long-range expectation for the efficiency of the RF system for a linear collider might be on the order of 50%. This efficiency could be attained by a low perveance, high efficiency klystron (65%) with grid switching (95% efficient), and a high-gain Binary Pulse Compression system (81% efficient including power transmission). The BPC system would use 10 or so discrete cavities per stage to eliminate long delay lines.

V. ACKNOWLEDGMENT

The principal results on the status and development of high power RF systems, as reported here, are contained in Tables I through IV. These tables are the result of hard work over many months by members of the Linac Technology working group of the Technical Review Committee mentioned in the Introduction. In particular D. Proch (TESLA), N. Holtkamp (SBLC), T. Higo and H. Mizuno (JLC), N. Solyak (VLEPP), G. Westenskow (TBNLC) and I. Wilson (CLIC) were responsible for the major portion of this effort, with substantial input from A. Gamp on the TESLA rf system.

VI. REFERENCES

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Table I Basic Parameters for Proposed Linear Colliders Designs at 500 GeV

Collider Proposal	Type$^{(1)}$	RF Freq (GHz)	G_{th} from Eq. (1) (MV/m)	Gradient$^{(2)}$ (MV/m)	Decrement Time τ_d (ns)	Peak Power per meter (MW/m)	Active Length$^{(3)}$ (km)	AC Power$^{(4)}$ (MW)	RF System Efficiency$^{(5)}$ (%)
TESLA	SCA	1.3	7	25/25	0.6×10^9	0.21	20	154	35/58
SLC	Cu	2.856	15	20/21	730	12	2.8	24	13.6/14.5
SBLC	Cu	3.0	16	17/21	720	12	30	139	37/38
JLC	Cu	11.4	61	53/73	95	100	10	114	30/34
NLC	Cu	11.4	61	37/50	98	50	14	103	30/31
VLEPP	Cu	14	75	91/100	68	120	6	57	39/40
TBNLC	TBA	11.4	61	74/100	98	200	7	106	39/40
CLIC	TBA	30	160	78/80	22	144	6	100	26/35

(1) SCA = superconducting accelerating structure; Cu = copper accelerating structure; TBA = two-beam accelerator (with copper main linac structure).
(2) Design gradient with/without beam loading (bunch on crest).
(3) Includes overhead for BNS damping and energy management (see text).
(4) AC power required for producing main linac RF; includes cryogenic and auxiliary power (see text).
(5) Efficiencies are given with/without cryogenic and auxiliary power included.

Table II Klystron Parameters: Design Goals and Achieved to Date

	TESLA		SBLC		JLC		NLC		VLEPP	
	Design	Ach.'d	Design	Ach.'d	Design	Ach.'d	Design	Ach.'d	Design	Ach.'d
RF Frequency (GHz)	1.3	1.3	3.0	3.0	11.4	11.4	11.4	11.4	14	14
Peak Output Pwr. (MW)	7.1	5.0	150	150	135	96/50	50	58/52	150	60
Pulse Length (μs)	1314	2010	2.8	3	0.5	0.1/0.2	1.2	0.2/1.5	0.50	0.7
Repetition Rate (Hz)	10	10	50	60	150		180	60	300	2
Ave. Output Pwr. (kW)	93		21	27	10		11	1/5	24	
Microperveance	0.5$^{1)}$	2.0	1.2	1.8	1.2	1.2	0.6	1.2	0.25	0.15
Electronic Effic. (%)	70	45	50	42	45	33	60	43/37	60	40
Scaled Max. Effic.$^{2)}$ (%)	73	50	62	53	62	62	71	62	76	78
Beam Voltage (kV)	110	130	575	528	600	620	455	400	1000	1000
Beam Energy/Pulse$^{3)}$ (J)	13,300	10,100	840	1070	150	170	100		125	
Cathode Load(A/cm^2)	3.1		6	6	13.5	13.5	7.4	7.6.	5	5
Cathode Heat Pwr. (kW)	0.5		1	2	0.5	0.5	0.4		1.0	1.0
Focusing Type	Sol.	Sol.	PPM	Sol.	SCM	Sol.	PPM	Sol.	PPM	PPM
Solenoid Power (kW)	4	4	---	15	1	40	---	≈ 20	---	---
Output Window Type	Coax	Pillbox	Pillbox	Pillbox	TE_{11} TW	TE_{11} λ/2	TE_{01} TW	TE_{01} TW	TE_{11} TW	TE_{11}
Windows/Klystron	1	1	2	4	2	2	1	1	2	2
Overall Length (m)		2.0	2.5	2.5	1.5	1.5	1.3	1.3	1.46	1.46

(1) Perveance per beam in multibeam klystron. (2) $\eta(\text{Max}) \approx 0.80 - 0.15 \times \text{Microperveance}$. (3) In flat-top portion of pulse.

TableIII. Modulator Parameters: Design Goals and Achieved to Date

	TESLA		SBLC		JLC		NLC		VLEPP	
Modulator Type1)	Storage cap. with bouncer		PFN		Blumlein PFN		Blumlein PFL		Gridded Gun see 6)	
	Design	Ach.'d	Design	Ach.'d	Design	Ach.'d	Design	Ach.5)	Design	Ach.'d
Flat Top Pulse Length, Tk (µs)	1314	2010	2.8	3.0	0.5	0.7	1.2	1.5	0.50	0.50
PFN Voltage (kV)	9	10	65	43	120	80	455	400	1000	960
Transformer Ratio n	1:13	1:13	1:18	1:23	1:5	1:7	1:7	1:20	---	---
Rise/Fall Energy Effic (%)			86.5	≈ 65	89	70	80	≈ 60		
Scaled Energy Effic.2) (%)	99	---	70	65	79	70	81	58	---	---
I^2R/Thy./Core Loss Effic. (%)			97	95	97		97			
Energy Stored on PFN3) (J)			1000	l650	174		258			
Power Supply Efficiency (%)			95	90	95		93	≈ 90		
Mod. Eff. without Aux. Power (%)			79.5	≈ 60	82		72	≈ 52	95	
Auxiliary Power4) (kW)			1.5	3	1.5		1.5	1.5	0.3	
Net Modulator Efficiency (%)	86	86	77.5	59	80		70		92.5	
Ave. AC Input Power (kW) (Including Auxiliary Power)	155		54.2	88	29		51.5		40.5	

(1) PFN = lumped element pulse forming network; PFL = pulse forming line (transmission line).
(2) See text.
(3) Energy switched per pulse from storage element for TESLA and VLEPP.
(4) Includes thyratron cathode heater and reservoir heater power.
(5) With standard (not Blumlein) PFN.
(6) Uses a PFL as energy storage element.

Table IV. RF Pulse Compression and Power Transmission: Design and Achieved to Date

	JLC		NLC		VLEPP	
Type of Pulse Comp. System1)	DLDS		SLED-II		SLED-I (VPM)	
	Design	Ach.'d	Design	Ach.'d	Design	Ach.'d
Compression Ratio	2		5	6	4.55	4.55
Input/Output Pulse Length (ns)	500/250		1200/240	900/150	500/110	500/110
Compression Efficiency (%)	98		76.5	73	74	72
Power Gain	1.96		3.83	3.7	3.37	3.3
Power Transmission Efficiency (%)2)	95		94	84	95	95
Power Gain Including Transmission Loss	1.86		3.60	3.0	3.20	3.1
Net Efficiency Including Trans. Loss (%)	93		72		70	
Length of Structure per Power Unit (m)3)	5.24		7.20		4.00	
Power at Structure per Power Unit (MW)	524		360	150	480	
Maximum Power in P.C. System (MW)	282		380	205	250	150
Required Klystron Power (MW)	2 × 141		2 × 50		2 × 75	

(1) DLDS = Delay Line Distribution System; VPM = VLEPP Power Multiplier.
(2) The power transmission efficiency in percent for TESLA, SBLC, TBNLC and CLIC are, respectively, 96, 97,98, and 90.
(3) A power unit is: TESLA, one klystron with modulator feeding thirty-two 1.04 m accelerating sections; SBLC, one klystron with modulator feeding two 6.0 m sections; JLC, two klystrons with two modulators driving one pulse compression unit which feeds four 1.31 m sections; NLC, one modulator driving two klystrons which together drive one pulse compression unit feeding four 1.8 m sections; TBNLC, one transfer structure for each 1.8 m section; VLEPP, one grid-modulated klystron driving two VPM cavities which together feed four 1.0 m sections; CLIC, one transfer structure driving two 0.28 m sections. The total number of power units (2 linacs) are: TESLA, 604; SBLC, 2517; JLC, 1804; NLC, 1968; TBNLC, 3938; VLEPP, 1400; CLIC, 11233.