SLAC–PUB–5806
April 1992
(A)

Review of Pulsed RF Power Generation†

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I am going to talk about pulsed high-power rf generation for normal-conducting electron and positron linacs suitable for application to high-energy physics in the Next Linear Collider, or NLC. The talk will cover some basic rf system design issues, klystrons and other microwave power sources, rf pulse-compression devices, and test facilities for system-integration studies.

NLC RF SYSTEM DESIGN ISSUES

The NLC, as envisioned at SLAC, KEK, IHEP, DESY, and CERN, is a phased development for electron-positron colliding-beam linacs starting at 250 GeV per beam (five times SLC), which is too high to reach with a circular machine. The ultimate goal is to reach 500 to 750 GeV per beam (10 to 15 times SLC) after upgrades to the rf system. The rf power required to achieve even the phase-one goal exceeds the capabilities of presently available accelerator rf systems. The magnitude of the rf requirement is illustrated by Table 1 for the existing SLAC Linear Collider (SLC), and for the NLC proposals being discussed by the DESY-THD collaboration[1] and at SLAC.

Table 1. RF Power Requirements.

	Existing SLAC SLC	Proposed DESY NLC Phase I	Proposed SLAC NLC Phase I
Beam energy (GeV)	50	250	250
Accel. grad. (MV/m)	17	17	50
Total linac length (m)	3000*	30 000‡	10 000‡
Rf wavelength (cm)	10.5	10	2.6
Klystron tubes	240	2450	2800
Pk pwr per tube (MW)	60	150	50
Peak power total (GW)	36	300	600
Average power (MW)	10	100	25

*One linac for both beams. ‡Sum of two linacs.

Satisfying the power requirement will require a large number of discrete high-efficiency ($\geq$ 50%) high-gain ($> 10^5$) rf power amplifiers, possibly with further peak power multiplication by rf pulse compression. Alternatively, exotic two-beam accelerator schemes are contemplated in which rf is continually extracted and transferred from a re-accelerated drive beam to the high-energy beam. In either scenario, there is general agreement that the rf system will be the most expensive component of the NLC.

† Work supported by the U.S. Department of Energy under contract DE-AC03-76SF00515.

There is much debate over the choice of rf wavelength due to its widespread implications for linac power consumption, rf field gradients, wakefields, and alignment tolerances, etc. In general, the rf system designers favor shorter wavelengths in order to reduce average power consumption by reducing the volume and surface area of the accelerator structure. The wavelength choices that have been made in different development projects are listed in Table 2.

Table 2. Choices of rf wavelengths.

Group	Wavelength (cm)	Frequency (GHz)
DESY-THD[1]	10	3
SLAC, KEK[2]	2.6	11
VLEPP[3]	2.1	14
LLNL, MIT[4]	1.8	17
CERN CLIC	1.0	30

In the rest of this talk, we will focus on rf sources now under engineering development that may be ready for systems proposals in the near future (say, three years). This choice eliminates from the discussion two-beam accelerators including CLIC (which cannot be prototyped in modular form), free-electron lasers, cyclotron auto-resonance masers,[4] and other exotic devices that may be applicable to the higher-energy linear colliders of the more distant future.

HIGH-POWER PULSED RF SOURCES

In high-gain, high-power, rf amplifiers, such as klystrons, a beam typically is modulated at radio-frequency, the modulation is permitted to grow, then power is extracted from the modulated beam. In klystrons, the modulation is given to the beam velocity, and as the beam drifts, the longitudinal bunch intensity grows. In klystrons, rf power is extracted from the bunched beam as it traverses a resonant cavity shaped to present a narrow gap to the beam. The rf voltage induced across the gap must be approximately equal to the beam's voltage if the transfer of power from the beam to the output circuit is to be efficient. In klystrons, and many other rf amplifiers, the best attainable beam-to-rf efficiency is approximately 50%. Beam power, and hence output power, can be increased by striving for higher cathode-anode voltages. Increased beam voltage alleviates the intra-beam space-charge forces which limit the achievable output power, thus permitting greater beam current and power. Increasing the voltage can permit a tube to operate at reduced perveance (current/voltage$^{3/2}$) which can improve the beam-to-rf efficiency. An empirical demonstration of the inverse relationship between efficiency and perveance is shown for a

Invited talk presented at the 3rd European Particle Accelerator Conference, Berlin, Germany, March 24–28, 1992

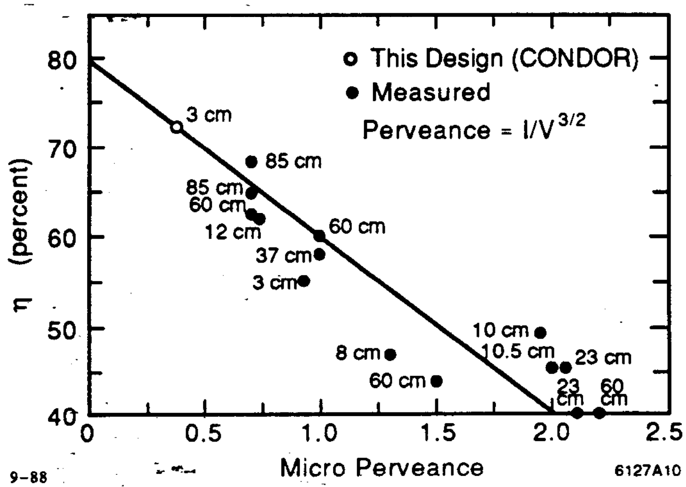

Figure 1. Efficiency vs. perveance for an ensemble of operational and simulated rf sources. (From reference 5.)

large ensemble of operational rf sources at different wavelengths in Figure 1.

Unbounded increases in beam voltage and power are undesirable because too high an rf gradient across the output gap may lead to electrical breakdown. The breakdown limit is a function of vacuum and surface conditions at the rf gap. Gap voltages can be reduced by replacing the resonant cavity gap by a multiple gaps, or by a multicell extended interaction output structure. At voltages approaching a megavolt, additional complications arise from the problems of DC hold-off in the gun, and from potential damage to the output circuit that can be caused by partial loss of the high-power beam into the walls of the drift tube.

Some of the characteristics of high-power klystron development projects are summarized in Table 3. The projects are discussed in more detail below.

The SLAC Linear Collider (SLC) is powered by 240 high-power "5045" klystrons[6] with 10.5-cm-wavelength (2.856 GHz). These tubes were developed, engineered, and mass-produced at SLAC. They reliably produce 67 MW of peak power in 3.5-μsec pulses and have long lifetimes. For the SLC, the rf is compressed (by SLED) into 180-MW pulses of 0.83-μsec duration, suitable for filling the SLAC SLC linac structure and attaining a 17-MV/m acceleration gradient. As an alternative strategy to pulse compression, an experimental 150-MW klystron was also developed at the same frequency, but with only 1-μsec pulsewidth.[7] The 10-cm-wavelength (3-GHz) NLC contemplated by the DESY-THD collaboration would require 150-MW klystrons with 2.8-μsec pulses to achieve a 17-MV/m acceleration gradient.[1] While these tubes would be similar to the experimental tube developed at SLAC but never employed, the pulselength would have to be nearly tripled, which may be a difficult task at such high power.

For the 2.6-cm-wavelength (11.4-GHz) NLC contemplated at SLAC,[2] an X-band klystron with a 1-μsec pulse is being developed.[8,9] The project so far has achieved only 40-MW, 0.8-μsec pulses. At shorter pulselength, 0.1 μsec, 72 MW has been achieved. Some data from the first tubes, "XC1" and "XC2", is shown in Figure 2. Performance so far is limited by rf breakdown in the double-gap output circuit at rf voltage levels sufficiently low that small amounts of beam interception are suspected of stimulating

Table 3. High-power klystron projects.

Klystron	Wave-length cm	Power Out MW	Pulse-length μs	Volt-age kV	Microper-veance $\mu A/V^{3/2}$
SLAC 5045[6]	10.5	67	3.5	350	2.0
SLAC[7]	10.5	150	1.0	450	2.0
SLAC XC[8,9]	2.6	100	1	550	1.2
KEK	2.6	120	1	550	1.2
VLEPP[3]	2.1	150	1	1000	0.3
Cluster[5]	2.6	1680	1	400	0.4

the breakdown. Remedies being developed include reducing the microperveance from 1.8 to 1.2 by increasing the beam voltage from 450 to 550 kV, and reducing the rf electric fields by installing a multi-cell extended-interaction output structure. While the ultimate goal of these improvements is to obtain a 100-MW, 1-μsec klystron pulse, the interim goal of 50 MW for 0.8 μsec, which has nearly been achieved, is sufficient (with pulse compression) to attain a 50-MV/m gradient in a 250-GeV Phase-I NLC linac. For Phase II (500-GeV beams), it is hoped to make a 100-MW tube.

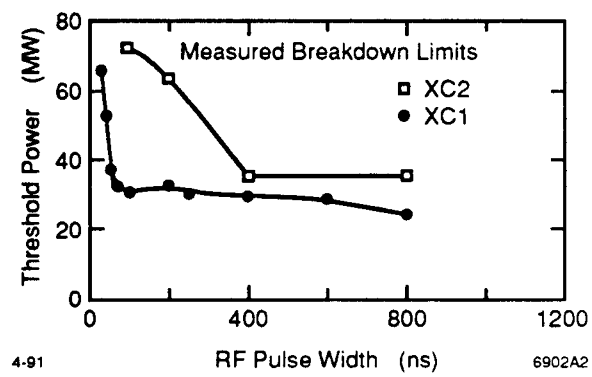

Figure 2. Performance of the first SLAC X-Band klystrons.

For the 2.6-cm-wavelength (11.4-GHz) Japanese NLC, called the "JLC," contemplated at KEK,[2] a 120-MW, X-band klystron is being developed with 1-μsec pulsewidth and microperveance of 1.2. So far, only 22 MW has been achieved, limited most recently by failure of the gun ceramic insulator.

For the 2.1-cm-wavelength (14-GHz) Russian NLC, called VLEPP, contemplated in Protvino, a 150-MW, X-band klystron is being developed[3] with 1-μsec pulsewidth and microperveance of 0.3. So far, only 50 MW has been achieved, limited by substantial beam loss (70 out of 200 Amps). This development project has several intricate and rather elegant features: The perveance is very low due to very high voltage, 1000 kV. The low perveance permits periodic permanent magnet focusing. The klystron gun voltage is divided by many intermediate anodes. The klystron beam is composed of many separate "beamlets" produced by separate emitting regions of a coated oxide cathode, and is switched by a non-intercepting control electrode. A sketch of the gridded gun is shown in Figure 3.

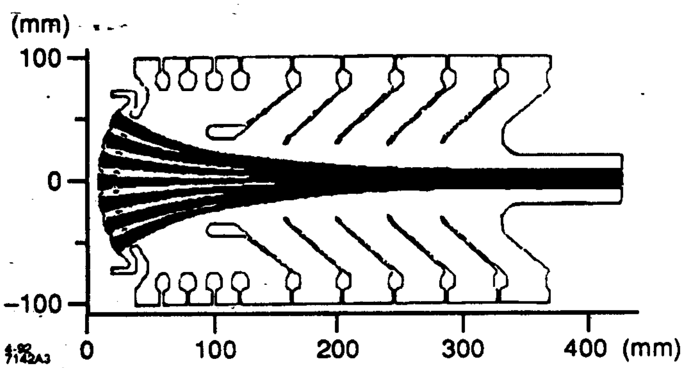

Figure 3. The VLEPP X-band klystron's 1000-kV gun, featuring a segmented cathode, non-intercepting control electrode, and intermediate anodes. The beam goes to the right in the picture.

Another very low perveance klystron design at 2.6-cm wavelength is the "Cluster Klystron" which is being designed by a Brookhaven-SLAC collaboration.[5] The Cluster Klystron design calls for a collection of 42 separate beams, each of which comprises a 40-MW klystron, all sharing a common (superconducting) solenoid. The 42 beams are generated by an array of magnetron injection guns, and are switched by a 400-kV mod-anode. The microperveance of the design is 0.4, implying the potential for high efficiency. If the details of beam dynamics, spurious rf mode control, and packaging can be overcome, the designers of this tube hope to produce up to 1680 MW of peak power from one cluster!

Still other klystron variations with very low perveance have been considered in the form of sheet-beam[10] and annular-beam tubes.[11] The general problem with these designs, as with the cluster klystron, is the control of spurious modes.

Microwave amplifiers based on rotational deflection and modulation in some ways are attractive alternatives to klystrons because they offer the prospect of reduced rf gradients at gaps of larger longitudinal dimensions compared to klystrons. One such tube, the gyroklystron, which is under development at University of Maryland for NLC application, has so-far achieved 24 MW of peak power at 3-cm wavelength (10 GHz). However, gyroklystrons, and other devices based on rotational deflection of a beam, have overmoded drift tubes which do not cut off feedback from unwanted deflecting modes. Consequently, these devices are plagued by oscillations, which sometimes can be overcome with difficulty by placing microwave absorbers in the drift tubes. For the present, klystrons seem to dominate the field of practical high-power rf sources.

RF PULSE COMPRESSION

Radio-frequency pulse compression can be used to attain higher peak power than an rf amplifier can deliver. To reach the power level required for the SLAC 11.4-GHz NLC, 200 MW per meter of accelerator in 150-nsec pulses, one can imagine the straightforward task of generating the power directly using some form of high-power rf source switched-on for 150 nsec by a series switch-tube, a magnetically-saturable modulator, a mod-anode, a switched grid, or an rf-switched cathode.[12] Alternatively, one could ease the requirements on the rf amplifiers by demanding just 50 MW per meter for a pulselength of 900 nsec, and then compressing the rf pulses by $\frac{1}{6}$ with an efficiency of $\frac{2}{3}$. The compressed pulses then would have pulselenghs of ($\frac{1}{6} \times 900 =$) 150 nsec and peak power of ($6 \times \frac{2}{3} \times 50 =$) 200 MW per meter.

The advantages of rf pulse compression are many. The demand on the klystrons, or other source tubes, for peak power is reduced. Consequently, the tubes can be operated at lower voltage and at lower perveance, possibly allowing increased efficiency. Pulse compression devices can be passive microwave networks without a beam, and hence are not as sensitive to peak power problems as are rf power amplifiers based on beam-rf interaction. Also, the use of longer-duration pulses in klystrons reduces the inefficiencies due to finite rise- and fall-times in the pulse modulators and in other components of the rf system.

The type of S-band rf pulse compression used in the SLC is SLED, the SLAC Energy Doubler.[13] As illustrated in Figure 4, SLED consists of a pair of cylindrical resonant energy storage cavities connected to a klystron's output by a 3-dB hybrid. Energy from the klystron goes into filling the storage cavities until the klystron phase is reversed (at the low-power driver), whence the power from the cavities is combined constructively with the klystron (reversed-phase) power and directed into the accelerator. A graphical analysis of the SLED pulse is shown in Figure 5. The LIPS (LEP Injector Power Saver) rf pulse compressor is similar to SLED.[14]

The exponentially decaying SLED rf pulse is undesirable for multi-bunch energy compensation, as required by SLAC's design for the NLC, and for other applications of rf compression. Hence, an rf pulse compressor with flat output pulses is desirable. There has been great interest recently, at SLAC, CERN, IHEP, and the Moscow Engineering Physics Institute, in developing SLED-like schemes with the goal of producing flat pulses. These SLED-like schemes replace the SLED storage cavities by either single-mode delay lines, multi-mode coupled resonators, or resonant-ring energy stores, as discussed in several papers in these proceedings.[15–19] As an example, the flat-top SLED-II scheme being developed at SLAC[15,20] is illustrated, and compared to SLED, in Figures 6 and 7.

An alternate method of flat-top rf-pulse compression is Binary Pulse Compression, in which the leading half of a klystron pulse is switched into a long delay path so it can be made coincident with the trailing half of the pulse. In this way, pulselength can be reduced by half while peak power is multiplied by two, less any losses. A high-power three-stage 11.4-GHz binary compressor was implemented in low-loss overmoded circular waveguide at SLAC, to produce high peak power for X-Band accelerator structure tests. Pulse lengths have been compressed by ($2^3 =$) 8, and peak power has been increased from 25 MW to 125 MW, limited by klystron power, not by pulse compression.[21]

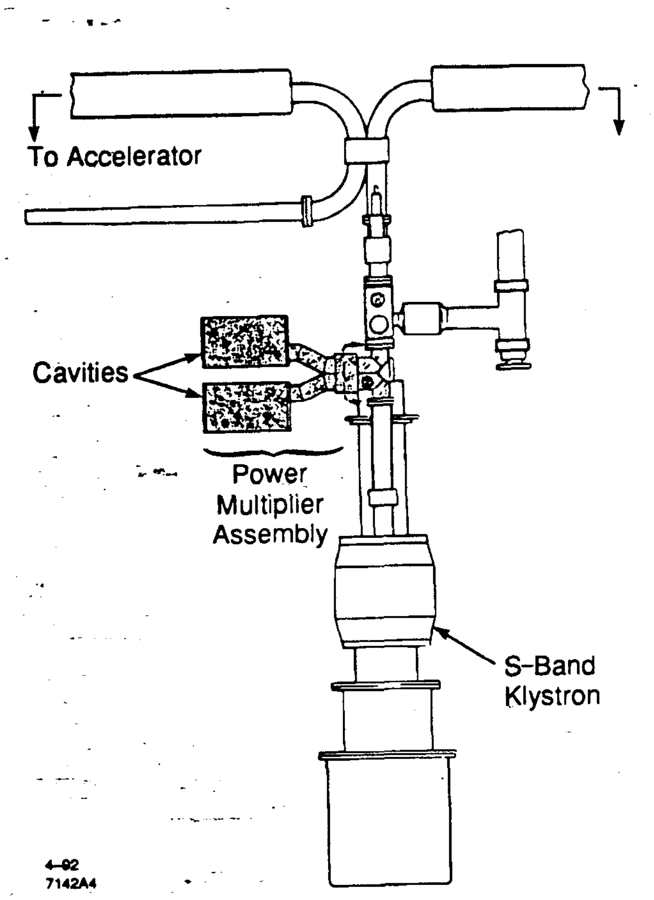

Figure 4. View of a SLAC S-band klystron plus SLED pulse compressor.

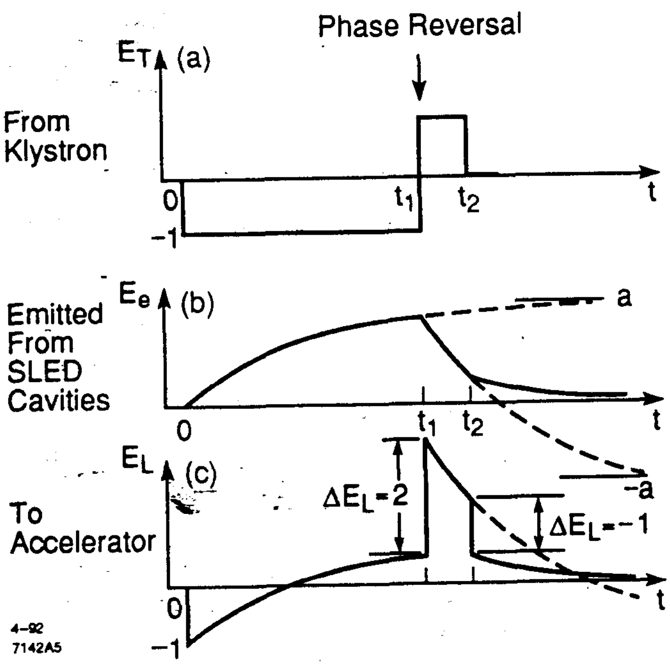

Figure 5. Graphical analysis of the S-band SLED pulse.

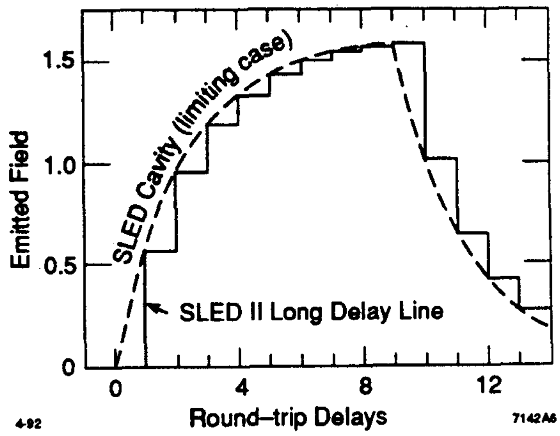

Figure 6. Field emitted from X-Band SLEDII long delay-lines as they fill-up with microwave energy. Each flat-top bin represents one round-trip delay-time in a shorted delay line. (See reference 15.)

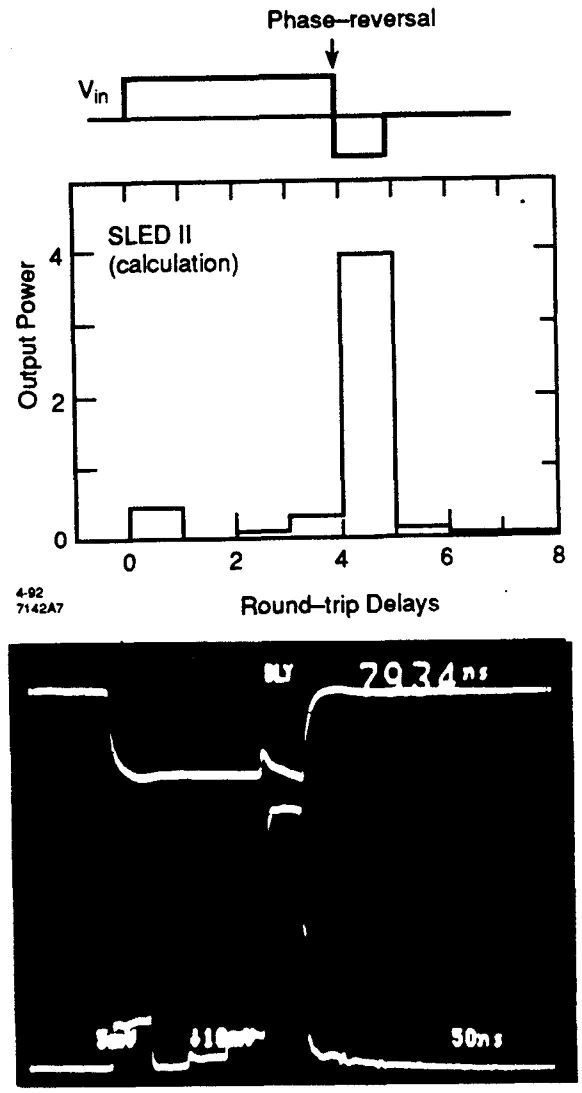

Figure 7. The X-Band SLED-II output pulse from calculation (above) and low-power prototype testing (below).

RF SYSTEM INTEGRATION TESTS

System-integration tests for the prospective NLC rf systems are being proposed and implemented at the various laboratories.

At SLAC, a short high-gradient rf linac is being proposed in order to gain experience with real operation of X-band accelerators and rf systems. SLAC's "Next Linear Collider Test Accelerator" (NLCTA) will be composed of six 1.8-meter long sections of 11.4-GHz linac structure. The goal is to energize this structure to an accelerating gradient of 50 MV/m and to produce a beam energy of 540 MeV. A higher-gradient upgrade option will make it possible to increase the accelerating gradient to 100 MV/m and the beam energy to 1.1 GeV. The primary goal of the NLC Test Accelerator is to construct and operate reliably a short high-gradient X-Band linac in order to integrate the accelerator structures, rf sources, and rf systems being developed for the NLC. The NLCTA will serve as a test bed as the design of the NLC evolves, and will provide a model upon which a reliable cost estimate for an NLC can be based. The secondary goal of the NLCTA is to study the dynamics of the beam during the high-gradient acceleration of many bunches on each rf fill of the structure.

A similar X-band accelerator test facility is under construction at the Institute for High Energy Physics in Protvino, Russia.

A CLIC test facility is becoming operational at CERN. It will test the 30-GHz rf technology. However, it can not test the drive-beam re-acceleration aspect of the CLIC two-beam accelerator concept over long distances.

CONCLUSIONS

Rf systems for 250-GeV linacs seem feasible within three years. Reasonable power sources are being engineered today, such as the 50-MW, 11.4-GHz, 1-μsec klystron developments at SLAC and KEK. These tube projects, in combination with the companion rf-pulse compression development projects, should result in an rf system sufficient to attain 50 MV/m gradients in the 11.4-GHz structures being developed at these laboratories. The DESY proposal to use 150-MW, 3-GHz klystrons for 250-GeV linacs, will be most challenged by the 2.8-μsec pulselength demanded from tubes that have never exceeded 1-μsec pulselength.

Prospects for the upgrade to 500-GeV beam energies are more distant. This upgrade requires quadrupling the peak power in order to double the gradient. The approach of quadrupling the number of sources will surely be very expensive. The approach of quadrupling the amount of pulse compression will greatly reduce the efficiency. The approach of replacing the Phase-I sources with new ones having four times more peak power per source (or per meter) will require a new generation of challenging tube development projects. However, a good prospect for this four-times higher-power source is a modest technological leap to a multiple-beam, low-perveance cluster klystron, as is presently being considered at Brookhaven and SLAC.[5]

I would like to thank V. Balakin, G. Caryotakis, J. Haimson, N. Kroll, H. Kumpfert, R. H. Miller, R. B. Palmer, R. Ruth, S. Takeda, A. Vlieks, and P. B. Wilson for interesting and helpful discussions.

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