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LONG-PULSE APPLICATIONS OF PULSE-FORMING LINES FOR HIGH-POWER LINAC APPLICATION*+

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Summary

The ever present demands for high efficiency in the RF power stations for particle accelerators has caused increased interest in longer RF pulses (ten's of microseconds) for linacs such as the Pion Generator for Medical Irradiation (PIGMI) and Free Electron Laser (FEL). For either RF power station, a fundamental decision is whether to use a modulating anode/hard-tube driver or pulsed cathode/line-type pulser configuration. The choices in the extremes of low power for very long pulses or for very-high-power, short pulses are, respectively, a modulated anode/hard tube modulator and pulsed cathode/pulse forming line. However, the demarcation between these two extremes is not clearcut. The criteria (cost, flexibility performance, reliability, efficiency) that resulted in the RF station definition of these two specific systems will be described.

Introduction

The choice of RF power-station design establishes in large measure the ultimate efficiency in the wave-type accelerator. The initial choice of the RF power station (pulse length, RF drive control, klystron, average power, etc.) for a particular accelerator application represents a costly investment in hardware that is not easily retrofitted. The overall cost of the RF power station is a linear combination of the initial developmental cost, fabrication, and operational cost over the lifetime of each RF power station. Some of the overall costs for an RF power station cannot be projected accurately over the useful life of the device (typically, 20 or more years). These include technician hourly operation costs, component replacement costs and useful lifetimes, and electrical-energy costs. One example of this uncertainty is the costing of vacuum switch tubes that have seen a four-fold price increase, which is double the inflation rate. As an initial step in developing a reasonable RF power station, it is necessary to compare the purchase price for the two basic types of RF power stations that can meet the specifications set by the particular accelerator application. During the last three months, the RF power stations for two accelerators, PIGMI[1] and FEL[2], have been designed. Both of these operate at 1300 MHz and have a requirement for long-pulse operation and the same peak and average power. However, after evaluation of both the hard-tube modulator and pulse-forming network (PFN), a different choice was made for each system.

Discussion

The major specifications for the two RF power stations are shown in Table I. The choice of operating frequencies arises for very different reasons in the two systems: the FEL electron accelerator at 1300 MHz benefits from the reduced size of the accelerating structure while remaining compatible with existing electron-injector peak currents and dimensions of the components to be machined. The PIGMI system requires a match (with harmonic injection) of a low-beta structure for protons produced in the radio frequency quadrupole (RFQ).[3,4,5] The first RF band of suitable klystrons occurs around 400 MHz, and the third harmonic also is in a favorable band for developed and reliable klystrons.

TABLE I
Major RF Power Station Design Specifications

Frequency (MHz)	1300	1300
Pulse length (μs)	68	100
Pulse repitition frequency (Hz)	30	10
Peak power (MW)	7	7
Average power (kW)	14	7
Amplitude variation (during pulse)	±1/2%	±1/2%

The hard-tube modulator design is shown schematically in Fig. 1. The requirements for high power and low phase shift during the pulse forced the design toward high voltage and massive energy storage in the main capacitor bank. The air-insulated bank has four tiers of capacitors, with the voltage resistively graded to ground. The total capacitance in the bank of 36 μF results in a 9-μF net capacitance and a 25.3-kJ stored energy. The individual capacitors are protected from catastrophic failure by a series connected resistor that acts as a fuse in case of an internal capacitor arc. The resistor opens and takes the capacitor out of service. We anticipate that the high voltage required to meet the power requirement will severely impact the switch triode lifetime. This triode will be operated near its absolute voltage and dissipation ratings. This triode also is used on the LAMPF 805-MHz modulators at 83 kV and 1-ms pulse length. On the LAMPF line, the expected lifetime is 13 400 filament hours[7] for a triode that is preconditioned on a separate test fixture. Extrapolating this to the present case, we would estimate the lifetime to be reduced by at least a factor of two, and will probably require special selection from the available triodes. Cable failures at the higher voltage also are anticipated to increase, although the low overall voltage swing (~2%) will help minimize this problem. The klystron is one of the most vulnerable components in the system; a gun arc presents the opportunity to discharge the whole capacitor bank energy between the cathode and one of the guard rings. The klystron gun is protected by a triggered vacuum-gap crowbar switch in the high-voltage capacitor bank. A gun arc is sensed with a current-viewing transformer on the current-return line. The current-viewing transformer is used to minimize ground loops. The 30-Ω resistor in the high-voltage output then allows the bank energy to be shunted directly to ground. The gap switching is very fast typically less than half a microsecond. The bank's power supply is individually protected from over-currents; also, the crowbar opens the interlock chain to turn off the power supply. The series high-voltage resistor causes a small, but continual, (<kW) loss in the system. Klystron window arcs and high VSWR also are continually monitored. These faults can inhibit the trigger pulse when necessary. The oil-insulated modulator tank appears satisfactory for the present voltage and heat load, and keeps all of the modulator high voltage inside the tank (~3 cubic meters). The overall floor space required for the capacitor room klystron tank and klystron is twenty square meters.

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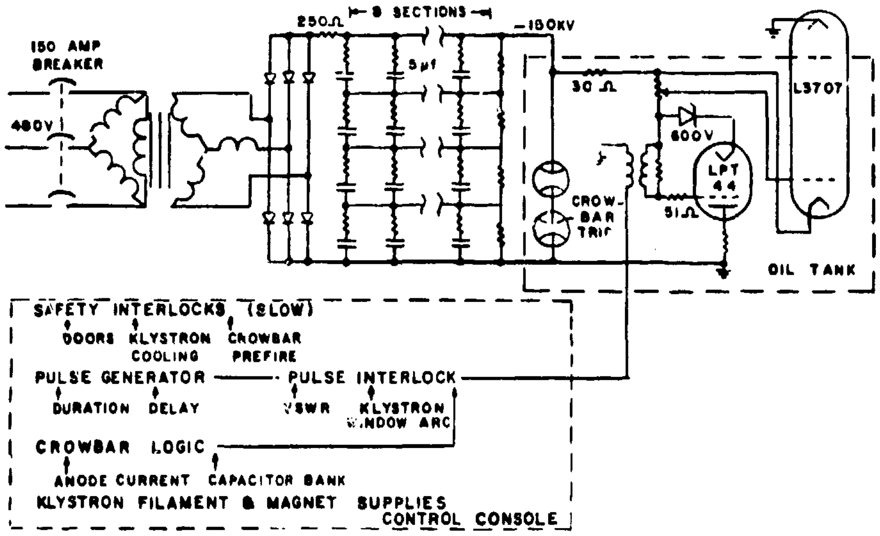

Fig. 1. Hard-tube modulator RF power station.

The PFN approach results in the electrical design shown in Fig. 2. The klystron cathode is directly pulsed by use of a switched, lumped-element, pulse-forming line through a step-up transformer. This approach allows for the use of relatively low-voltage (50-kV) capacitors and a well characterized thyratron. When the thyratron is triggered by the optical link, a short occurs at one end of the line. The energy stored in the line can be regarded as the superposition of two traveling waves, each of magnitude one-half the charged voltage, running in opposite directions. The wave traveling towards the transformer causes voltage to occur on the primary, one transit time after the thyratron fires. The wave traveling towards the thyratron cannot dissipate significant energy (shorted condition) and is reflected back to the transformer. As a result, the transformer is pulsed with a voltage of one-half the intrapulse charged voltage, with a pulse length twice the electrical length of the line. The transformer is bifilar wound, so that the klystron heater is at the same potential as the cathode, and the unit is inan oil tank (~1.5-m^3). The transformer introduces some additional risetime to the pulse (approximately a microsecond), which is less than a third of the risetime caused by the pulse-forming line. The pulse transformer droop is less than 1% over the 100 μs. This sag can be corrected by the tuning of the pulse line, and is not a constraint on the pulse shape. The transformer's finite risetime (bandwidth) is useful to the operation of the system. The fast switching of the thyratron introduces high-frequency noise in the primary side of the circuit. The transformer then serves to keep some of the reflections from ringing back through the circuit. The use of a secondary winding on the resonant charging choke has been previously used on the Stanford Linear Accelerator (SLAC) and has the advantage of keeping the D-Quing[5] circuit at a few kilovolts, instead of at the high voltage. Resonant charging with diodes has the advantage of not incurring the 50% energy loss of resistive charging.

The components and specifications of the two systems have much in common; however, the process of detailed design has pointed out some significant differences between the modulated anode/hard tube modulator and the pulsed cathode/pulse-forming line.

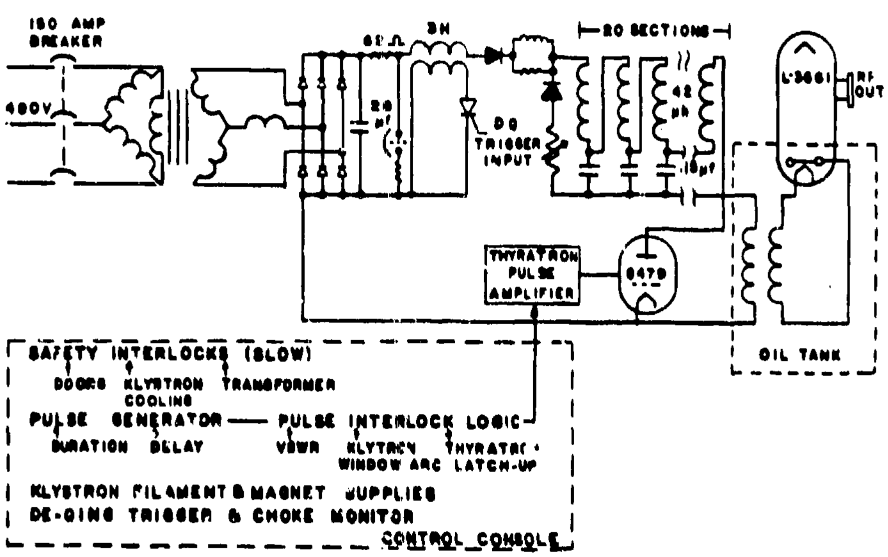

Fig. 2. Pulse forming network RF power station.

Reliability. The components, with the exception of the klystron (see below), of the pulse-line modulator are much more thoroughly developed and tested at these voltages. The experience of SLAC in testing thyratrons and forcing tube development greatly improved the state of technology. One side benefit is that the only component that showed no increase in cost for the last four years was the thyratron for the PFN.

Maintainability. This only is estimated, but the number of components at high voltage of the pulse-forming line is smaller (45 vs 100), and the number of critical components also is fewer. In the case of the pulse-line system, the weakest component is the klystron; in the case of the hard-tube modulator, the weakest component is the switch triode.

Cost. The cost for the two systems is itemized in Table II. The major difference in design cost estimates occurs in the actual hardware cost. Much of the assembly and checkout cost is very similar.

TABLE II
Cost Comparison

	Hard-Tube Modulator (K$)	PFN (K$)
High voltage (dc) & assembly	59.9	47.5
High voltage (pulsed) & assembly	64.1	64.5
Klystron drive & frequency	28.5	19.8
Crowbar	17.2	5.7
Klystron & magnet fields	135.2	93.0
Electrical & run controls	19.5	18.4
Trigger interlocks	22.8	13.7
Total	$347.2K	$262.6K

Future versions of both these systems will have much lower design costs. The philosophy of costing both systems was to use proven components operating near the limit of their specifications; modules already proven by fifteen years of operation at LAMPF were used when possible.

Klystrons. In both cases, the klystrons are not proven at this pulse length and 7-MW peak-power output. Each klystron has been tested to the greatest extent possible with existing hardware, but neither has worked (or failed) at these parameters.

Size and Weight. Where these are a constraint, the pulse-forming-line system is at an advantage, being approximately 40% smaller and lighter. In large measure, this is because of the more compact design (and support structures) allowed by the operation at primarily 25 to 50 kV, as opposed to most of the hard-tube modulator being at 150 kV.

Efficiency. In large measure, this is set by the klystrons in use--35% vs 38%. The overall modulator efficiencies are not expected to be substantially different.

Areas of Improvement. For both systems the klystron development remains the key issue. The doubling in efficiency for either klystron will substantially impact the long-term system cost. Also, redesigning the gun of either klystron will substantially improve reliability in long-pulse operation.

Extension to Higher Power. The pulse-forming line-type system has the definite advantage here, the relevant klystron having been tested at 30 MW (14.4-μs pulse length). If fewer drivers are needed for the particular accelerator, this can have a dramatic effect on overall system cost and reliability.

Flexibility. This includes all the changes to the operating point that occur in a laboratory environment. The pulse length control is the only major difference between the two systems and entails a mechanical change in the case of the pulse-forming line.

Conclusions

The initial costs for these circuits is not substantially different, although the pulse-forming-line system is lower in initial cost. Operating costs also favor the pulse-forming line, because of the fewer components, and having all components except the transformer in air. The pulse-forming line was chosen for PIGMI and permits future increase in the peak power output to 30 MW. This could ultimately be very cost-effective to the hospital unit. The hard-tube modulator was chosen for the FEL and will allow for greater flexibility in laser development.

Acknowledgments

The continuing discussions with Don Reid, Tom Boyd, Jr., and Bob Cady have added substance to the design of these systems and is gratefully acknowledged. The previous work of Carl Olson at SLAC, to improve pulse-line RF power stations, was a major factor in gaining acceptance of these devices in the design and construction of such a unit; his interest and valuable comments are most appreciated.

References

1. T. J. Boyd, Jr., K. R. Crandall, R. W. Hamm, L. D. Hansborough, R. F. Hoeberling, D. W. Mueller, J. M. Potter, R. H. Stokes, J. E. Stovall, R. G. Sturgess, D. A. Swenson, P. J. Tallerico, T. P. Wangler, and L. C. Wilkerson, "The PIGMI Technology," Los Alamos Nat. Lab. report LA-UR-80-3561 (1980).
2. C. A. Brau, "Free Electron Lasers Overview: Fundamentals and Application," Los Alamos Nat. Lab. report LA-UR-80-185 (1980).
3. R. H. Stokes, K. R. Crandall, R. W. Hamm, F. J. Humphry, R. A. Jameson, E. A. Knapp, J. M. Potter, G. W. Rodenz, J. E. Stovall, D. A. Swenson, and T. P. Wangler, "The Radio-Frequency Quadrupole: General Properties and Specific Applications," Proc. XIth Conf. on High Energy Accelerators, CERN, Geneva, July 7-11, 1980.
4. J. M. Potter, S. W. Williams, F. J. Humphry, G. W. Rodenz, "Radio-Frequency Quadrupole Accelerating Structure Research at Los Alamos," Proc. 1979 Particle Accelerator Conf., San Francisco, California, March 12-14, 1979.
5. J. E. Stovall, K. R. Crandall, and R. W. Hamm, "Performance Characteristics of a 425-MHz RFQ Linac," Proc. Conf. on Application of Accelerators in Research and Industry, Denton Texas, Nov. 1980.
6. P. J. Tallerico, R. L. Cady, and J. D. Doss, "Design and Performance of the LAMPF 1-1/4-MW Klystron Modulator," IEEE Conference Record of the 1973 Eleventh Modulator Symposium, New York, New York, 55-60.
7. P. J. Tallerico, "Reliability and Operating Experience of the LAMPF 805-MHz RF System," Conference Proceedings, 6th European Microwave Conference, September 14-17, Rome, Italy, 1973, 55-60.
8. R. W. Bradford, P. C. Edwards, C. W. Olson, R. B. Neal, R. M. Rowe, W. T. Tomlin, F. T. Veldhuizen, and A. L. Williams, "The Stanford Two-Mile Accelerator", edited by R. B. Neal (W. A. Benjamin, Inc., NY 1968).