IEEE Transactions on Nuclear Science, Vol. NS-26, No. 3, June 1979

EXPERIENCE WITH THE LAMPF LINE D FAST KICKER SYSTEM*

C. Thompson
Los Alamos Scientific Laboratory, Los Alamos, NM 87545

Abstract

In a paper presented at the 1977 Particle Accelerator Conference, R. Faulkner and R. Cooper outlined the design of the LAMPF Line D Fast Kicker System. At that time the prototype had been constructed and initial tests were complete. After the Kicker was reassembled in final operating configuration, some components were extensively modified, and considerable operational experience has since been obtained. The system has now operated in production for over 500 hours.

The modifications made to the original design were few but important in terms of reaching the system design objectives. Much of the continuing component development program has centered on upgrading reliability at sustained high average power levels.

The Kicker is presently capable of delivering 7-μs-long pulses at a 120-Hz repetition rate with a peak current of 5800 A. It has operated for complete LAMPF production cycles without maintenance.

Continued development work has concentrated on the high power load resistor, the pulse forming network (PFN) capacitor bank, the charging inductor, and the elimination of component failure caused by high voltage/current discharges. This paper discusses Kicker problem areas and solutions.

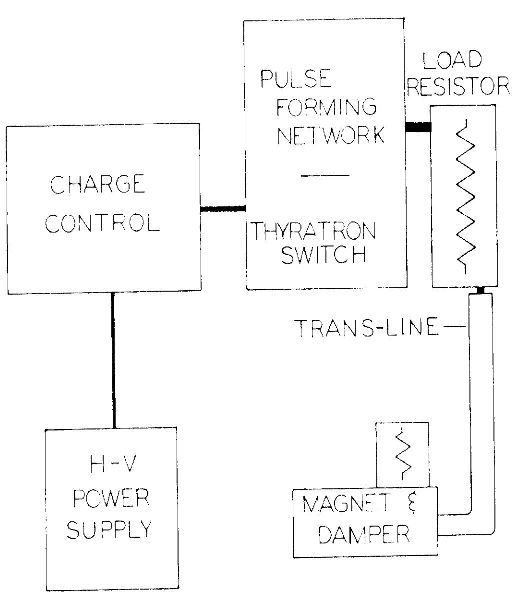
Introduction

The LAMPF Line D Fast Kicker switches short pulses of 800-MeV protons into the beam transport system leading to the Weapons Neutron Research (WNR) Facility. To accomplish this, the Kicker power supply must deliver nearly 6000-A pulses at high repetition rates into a ferrite magnet excited by a single turn coil. The magnet, which is treated in the circuit as an element of the lumped element PFN, has a 2.67-μH inductance. The network design impedance is 2 Ω. The magnet is separated from the PFN by 20 meters of transmission line.

The Fast Kicker can be broken down into seven main elements. These are: (a) the dc power supply, (b) the charge control circuit, (c) the PFN, (d) the thyratron switch, (e) the high-current load resistor, (f) the transmission line, and (g) the magnet and the magnet damping resistor. A block diagram of the functional connection of these elements is provided in Fig. 1. The Kicker pulse shape and quality are controlled by the specific makeup of elements (c), (e), (f), and (g). Computer modeling was used to optimize the relative locations of the load resistor and damping resistor (R1 and R6 in Fig. 2) to determine the best combination for the desired waveform. This model was then used to optimize the rest of the system to reduce ringing, to establish the smallest ripple on the pulse flat top, and to minimize pulse rise and fall times.

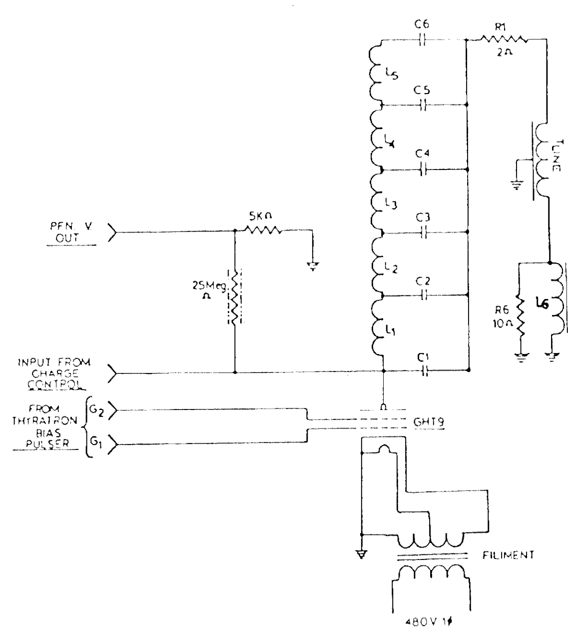
After the system design refinements were complete and the Kicker had been installed in its final operating configuration, it was then put through long term, full-power tests. During these tests and early stages of production usage, several design weaknesses came to light. A program of continued component

*Work supported by U.S. Department of Energy.



FAST KICKER BLOCK DIAGRAM

FIG 1



KICKER SCHEMATIC DIAGRAM

FIG 2

0018-9499/79/0600-3913$00.75 © 1979 IEEE

improvement and modification to correct these weaknesses has now resulted in a high degree of operational reliability.

Computer Modeling

From the beginning of the Kicker development project, computer modeling of the circuit has been used as a primary analysis tool. Initial construction and testing of the system was carried out at a site remote from its final location in the LAMPF switchyard. Following these prototype tests, the system was disassembled, moved to the WNR facility, and then reconstructed in a special building adjacent to the LAMPF switchyard service aisle.

The magnet is located in the main LAMPF beam line, more than 20-m distant from the Kicker power supply, for geometrical and access reasons. This distance is bridged by a transmission line composed of several parallel 14-Ω power transmission coaxial cables. Therefore, line impedance could be adjusted in 14-Ω parallel increments. The final arrangement uses seven cables to produce a 2-Ω impedance.

Prototype tests had been conducted using short cables connecting the PFN to the magnet and load resistor. When the system was reassembled and tested with full-length cables, output pulse characteristics were observed to be considerably degraded. Computer modeling, using the LASL program NET-2, determined the circuit modifications needed to correct this.

The six-section PFN uses multiple arrays of foil type, oil-filled capacitors. By changing individual capacitors it was feasible to fine-tune the waveshape produced by the PFN. The magnet damping resistor could be adjusted to any desired value.

Adjustable circuit parameters, therefore, consisted of (a) transmission line impedance, (b) PFN capacitance values, and (c) damping resistor value. The load resistor was, in practice, essentially a fixed resistance; it also contained a sizable parasitic inductance (3.8 μH). The magnet inductance and resistance were fixed parameters. With these variables and constraints the computer model produced with NET-2 was used to optimize the circuit.

Development Work

The Fast Kicker, when operating at the normal repetition rate (120 Hz), dissipates a large amount of power (100 kW) in the load resistor. This element must also handle pulsed power levels of about 125 MW. Ideally, the load resistor should have a minimum inductance, be able to dissipate these power levels, and have a suitably long lifetime (thousands of hours). Proper design of this power resistor is critical to the operation of the whole system. To get an adequate performance from this component required considerable development work.

The present resistor has a 3.8-μH inductance. This inductance limits the Kicker pulse rise/fall times to about 3 μs. Faster transition times could be obtained with a special low-inductance resistor, which has been designed but not constructed. Although the load resistor inductance has a strong impact on circuit performance, it has been treated as a relatively fixed parameter during development work because of the difficulty and expense of fabricating a new low-inductance resistor.

Early computer modeling confirmed the initial impression that a reactive load (the magnet itself) would not serve as a proper termination for the 2-Ω transmission line. Placing a damping resistor in parallel with the magnet improves the situation, making the termination appear more resistive and less reactive. The program NET-2 showed that a 10-Ω resistor in parallel with the magnet would provide an optimum termination. In practice, the damping resistor consists of a water-cooled, circuit-board-mounted array of 2-W resistors, which dissipates about 8-kW average power. It performs satisfactorily.

The coaxial cables used for the transmission line have a high-loss layer in the dielectric to attenuate high frequencies encountered in power industry applications. This charcteristic fortuitously assists in damping some of the ringing at the PFN end of the cable. Pulse profiles observed at the magnet end of the line show much less high-frequency content than those seen at the PFN end. Pulse risetime is 3 to 4 μs; no appreciable signal attenuation in the cable is observed. The cables reach a temperature of about 120°F after many hours of operation, which is quite acceptable.

Load Resistor

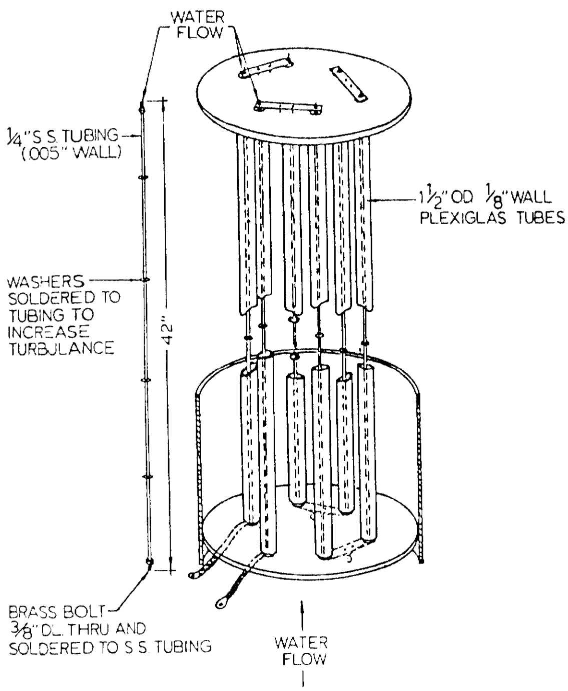
The load resistor is constructed from thin-walled stainless steel tubing, (0.005-in. wall, 0.25-in. diam). The thin wall is required to obtain a high resistance per unit length, and thereby to minimize the inductance. Because of the fragility of this tubing, the development of the load resistor became largely a problem in mechanical engineering. Two major design problems were the dissipation of peak power and vibration damping.

Cooling the average heat load deposited in the resistor posed no particular problem. However, proper heat transfer of the peak power load caused serious difficulties. It was necessary to maintain high velocity turbulent water flow over the entire tubing surface to prevent local burnout. Because stainless steel is a poor heat conductor, hot spots quickly developed in areas of low turbulence or coolant velocity. These hot spots produced surface vaporization (local boiling) that further reduced the available heat transfer at these points. The usual result was thermal runaway and failure of the tubing. The final design, shown in Fig. 3, uses Plexiglas baffles and shrouds to force the water flow more directly around the tubing. This restricted flow technique has proved successful in eliminating resistor failure caused by peak power local heating.

The second cause of load resistor failure was vibrational stress. Mechanical ringing induced by the repetitive, high intensity current pulses was sufficient to eventually break the tubing or loosen the suspension framework. The final cure for this problem was to suspend the stainless steel tube lengths on beryllium copper plates using rubber grommets as vibration dampers.

Capacitor Experience

Occasional PFN capacitor failure was observed early in the development of the Fast Kicker. The Tobe Deutschmann capacitors initially used were constructed with a dielectric stressed at 1200 V/mil (considering 40 kV dc across the capacitor). Dielectric heating caused by the repetitive transient pulse operation caused a need for significant heat removal from the capacitor. New capacitors were made with both a lower stress (V/mil of dielectric) and with larger terminal headers for more efficient heat extraction. Only the largest size (0.05-μf) PFN capa-



100KW CW (120 M.W. PULSE) 2Ω LOAD RESISTOR
(IN PLACE AT WNR FAST KICKER)

FIG 3

citor needed this change. Capacitor failure was radically reduced with the new series of 0.05 μf capacitors. After long operation of the PFN the next smaller size capacitor (0.02 μf) also began to show a higher than normal failure rate. These failures occurred mainly in the first PFN section, (see Fig. 2, C_1). Computer model review showed considerably faster risetime for the incremental pulse waveform in this section, C_1) than in any of the following PFN sections. This faster risetime creates greater dielectric heating in the first section capacitors than in those of subsequent sections. Using the computer model, a new distribution of these capacitors which is less sensitive to heat buildup in the dielectric has been obtained.

Control Systems

Several improvements have been made in the Kicker control circuits since initial full-power tests. Originally the Kicker was to be simply switched on when the WNR Facility was ready for beam delivery. Under these conditions the PFN and charge-control circuits were charged to a voltage level 50% higher than is encountered during normal running. Higher than normal voltage stress was therefore applied to many circuit components during the period following turn-on of the high voltage but prior to normal pulse firing. This caused frequent failure of some of these components.

The Kicker pulse peak intensity is controlled by the charge control feedback loop. The damping time of this loop is much greater than the pulse repetition interval. In fact, several hundred Kicker pulses are delivered before the feedback loop settles down. As a result of this long control time-constant, many proton beam pulses were spilled in the switchyard or inaccurately deflected in the magnet during the Kicker startup transient, before stable regulation was reached.

Because of these two problems a different method of initiating and terminating beam delivery to WNR was devised. The present system provides for continuous operation of the PFN and charge-control circuits at the correct voltage, with beam delivery effected by controlling the timing of the Kicker pulse relative to the LAMPF macropulse timing. When beam is not required at the WNR target, the Kicker firing time is shifted backward about 100 μs. This is sufficient to place the magnet pulse well into the empty interval between macropulses. When experimenters are ready for beam, the Kicker firing phase is simply shifted forward to properly bracket the portion of the macropulse intended for line D. When the Kicker is first turned on, the PFN voltage is manually adjusted at a normal pulse repetition rate and brought gradually into regulation. No overvoltage then occurs.

Conclusions

The LAMPF Line D Fast Kicker is now a reliably operating element of the WNR beam transport system. Development of this high-power system has involved the solution of many problems. Computer modeling of the Kicker has proven particularly invaluable in making a number of necessary circuit modifications to obtain the desired pulse performance. Much of the recent development work has centered on upgrading specific component performance. Design of a long-life reliable high power load resistor has been the most challenging of these concerns.

Acknowledgments

The final development phases of the Fast Kicker project have involved the efforts of many people. Ross Faulkner and Richard Cooper, as designers of the original system, were instrumental in achieving performance goals. James Lunsford was project leader for assembly and testing of the system in final location and configuration. David Oschwald was centrally involved in the component upgrading program and in full power system tests. Others who contributed significantly to the effort were: Richard Ryder, Joseph Van Dyke, David Keffler, and Robert Sturgess.

References

1. "LAMPF Line D Fast Deflector System," R. K. Cooper and J. R. Faulkner, Los Alamos Scientific Laboratory report LA-6748-MS, (May 1977).
2. "Net-2; A Fortran Network Analysis Program," prepared by Allan F. Malmberg, Braddock, Dunn and McDonald, Inc., 6500 Convair Rd., El Paso, TX 79925 (September 1973).