R-2556

UCID- 18939

MASTER

DESIGN OF A MeV, 4kA LINEAR INDUCTION ACCELERATOR FOR FLASH RADIOGRAPHY

B. Kulke, R. Brier, W. Chapin,
R. Kihara, R. Kuenning,
B. McFarlane, G. North, K. North,
C. Parkison, D. Ravenscroft, G. Russell,
R. Scarpetti, I. Smith, G. Vogtlin,
J. Wagner, K. Wong

February 10, 1981

Lawrence Livermore Laboratory

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore Laboratory under Contract W-7405-Eng-48.

DESIGN OF A MeV, 4kA LINEAR INDUCTION ACCELERATOR FOR FLASH RADIOGRAPHY*

B. Kulke, R. Brier, W. Chapin, R. Kihara, R. Kuenning,
B. McFarlane, G. North, K. North, C. Parkison, D. Ravenscroft,
G. Russell, R. Scarpetti, I. Smith, G. Vogtlin, J. Wagner, K. Wong

Lawrence Livermore National Laboratory
Livermore, California 94550

FOREWORD

The following report covers the content of a presentation given at the 1980 IEEE International Conference on Plasma Science in Madison, Wisconsin, on May 19-21, 1980.

ABSTRACT

For verifying the hydrodynamics of nuclear weapons design it is useful to have flash x-ray machines that can deliver a maximum dose in a minimum pulse length and with very high reliability. At LLNL, such a requirement was identified some years ago as 500 roentgens at one meter, in a 60 nsec pulse length. In response to this requirement, a linear induction accelerator was proposed to and funded by DOE in 1977. The design of this machine, called FXR, has now been completed and construction has begun.

The FXR design extends the parameters of a similar machine that had been built and operated at LBL, Berkeley, some ten years ago. Using a cold cathode injector followed by 48 accelerator modules rated at 400 kV each, the FXR machine will accelerate a 4 kA electron beam pulse to 20 MeV final energy. Key design features are the generation and the stable transport of a low emittance (100 mr-cm) beam from a field emitter diode, the design of reliable, compact energy storage components such as Blumleins, feedlines and accelerator modules, and a computer-assisted control system.

*Work performed under the auspices of the U.S. Department of Energy under contract No. W-7405-Eng-48.

Introduction

Modern nuclear weapons design involves an immense amount of numerical simulation that predicts the radius-time history of imploding spherical objects. At some point in the design it becomes necessary to validate the computational model experimentally. One method of doing this is by taking a flash x-ray picture; i.e., by producing a radiographic record of the imploding geometry at one instant of time. In order to penetrate the large final material densities resulting from the implosion, on a time scale that is short enough to stop the rapid radial motion of the boundary surfaces, one requires a very large x-ray dose in a small fraction of a microsecond. The FXR linear induction accelerator, scheduled for completion in late 1981, is designed to deliver an x-ray does of 500 roentgen at a distance of one meter from the beam target, within a 60 ns time span. This dose is five times greater than the existing flash x-ray capability at LLNL, and the time interval is two to three times shorter, thus enabling radiographers to look through greater material densities with less motion smear than before. Moreover, the modular construction of the FXR machine will allow later expansion to produce radiographic capabilities on the order of 5000 roentgen at one meter.

For tuning convenience, the FXR machine is designed for a 1/3 Hz pulse repetition rate. Moreover, the high cost of fielding an explosive experiment demands exceptionally high reliability for the single radiography pulse on the order of one failure in 10^5 pulses. Both requirements are unusual for high-voltage pulsed power equipment. As part of the FXR design effort, prototype tests have therefore been carried out in order to reduce or remove uncertainties concerning the basic block of four pulsed power modules, including the accelerating cell itself, that will be replicated 12 times in the actual accelerator.

This paper will summarize the design and development of the FXR accelerator. Some results from the prototype component and subsystem tests also will be given.

The FXR Facility

The overall layout of the FXR facility is shown in Fig. 1. The machine is configured in basic blocks of four accelerator modules, together with their associated drive circuitry. The 45 m long building will accommodate a 64 module machine, as shown, although the presently planned installation consists of only 48 accelerator modules and six injector modules. After acceleration, the beam is transported through a forward diagnostic area prior to final focusing into a bremsstrahlung target. The massive concrete bunker protects both the machine and the operators from the blast of the test shot on the firing table; internal concrete shielding is provided for radiation protection of personnel working in the electronics corridor while the machine is running. A large underground optics room contains high-speed cameras that will be synchronized with the FXR radiography pulse. As seen in Fig. 2, the beam line elements are mounted on six transverse, steel beams spanning the 6.7 m wide accelerator bay. Two longitudinal, aluminum I beams support the

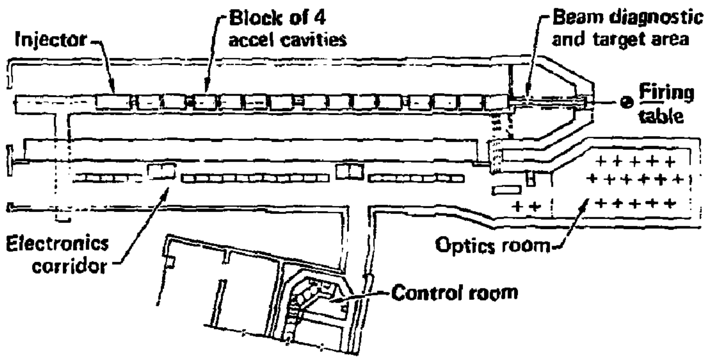

Figure 1. FXR Facility, plan view

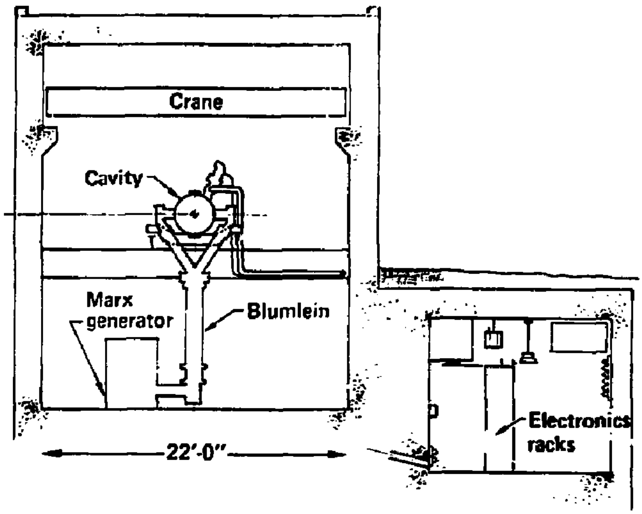

Figure 2. FXR Facility, rear elevation

cavities directly. Each accelerator module is driven from a water-filled, Blumlein pulse forming line, with intermediate energy storage provided through a bank of Marx generators.

The FXR Design

The accelerator module design (Fig. 3) follows that of a reentrant coaxial cavity with the center post pulsed negatively; the accelerating potential appears across the 45 mm wide gap. In order to prevent the applied voltage pulse from being shorted out through the center post, the latter is loaded with 14 ferrite toroids, thus supporting a 400 kV pulse for 90 ns, FWHM. The evacuated beam chamber is separated from the oil-filled volume containing the ferrite and the feed terminals, by an epoxy insulator. The four terminals for the two feed lines and the two ballast loads are spaced symmetrically around the periphery of the center post, in order to provide a balanced distribution of return currents when the cavity is loaded by the electron beam. The purpose of the ballast loads is primarily to match the 10 ohm pulse source to the 100 ohm beam impedance; in addition, some pulse shaping is possible, if necessary, by adding reactive elements to the ballast loads. The ballast loads consist of $CuSO_4$ columns, with the liquid recirculated; this allows energy dissipation as well as continuous monitoring of the resistivity. Each column typically has a resistance of 40 ohms. The mismatch provides voltage gain, i.e., the pulse source typically is charged to 300 kV for a desired accelerating voltage at the gap of 400 kV. All edges are radiused to maintain the field stresses on negative surfaces below 200 kV/cm, both in the oil and

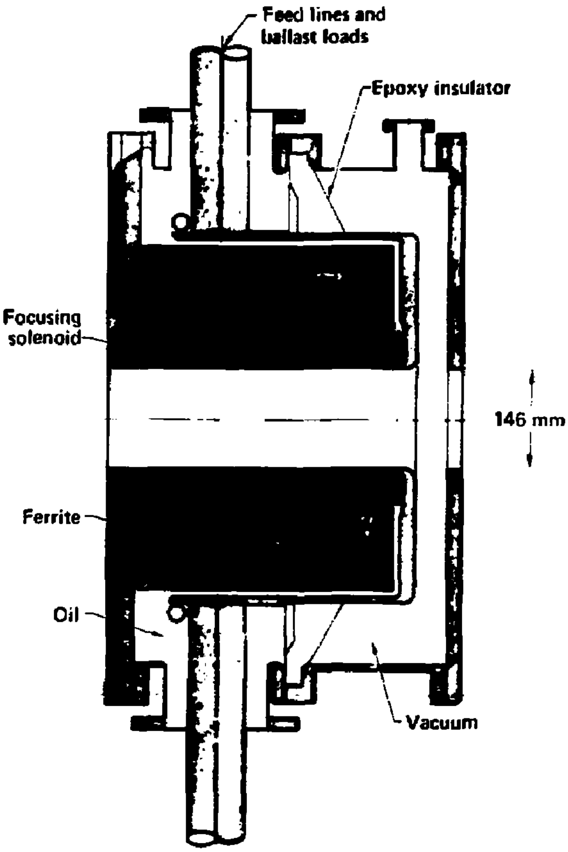

Figure 3. Simplified Cross Section of FXR Accelerator Cavity

in the vacuum, with 400 kV applied across the gap. The vacuum in the 146 mm dia beam tunnel is held in the mid 10^{-6} torr range by means of a cryopump shared with one other cavity. An integral focusing solenoid is capable of generating 2000 Gauss on axis, continuously.

Each accelerator module is driven symmetrically from a 10 ohm, Blumlein pulse forming line (Fig. 4), with a 90 ns nominal pulse length. Water dielectric is used both in the Blumlein proper and over part of the two symmetrical 20 ohm feed lines. This reduces the physical length compared to an oil filled Blumlein; at the same time the resulting time domain isolation tends to suppress interference between the Blumlein and the accelerator module. The Blumlein is fired through a switch gap pressurized to 60 psig of SF_6; this is a recirculated system, with the gas filtered continuously. The final part of the feed line, near the 120 degree bend, uses oil rather than water in order to minimize the discontinuity capacitance at this point; this oil volume connects directly with the cavity.

The choice of a relatively low surge impedance for the pulse forming line was made for several reasons. First, because water dielectric is used in the Blumleins, it was difficult to realize an impedance much higher than 10 ohms; second, the large ballast current into a linear load tends to mask the nonlinear beam loading and hence, any regenerative effects between the beam current and the accelerating voltage pulse; and third, the large ballast current leaves room for later growth in the beam current if beam stability permits.

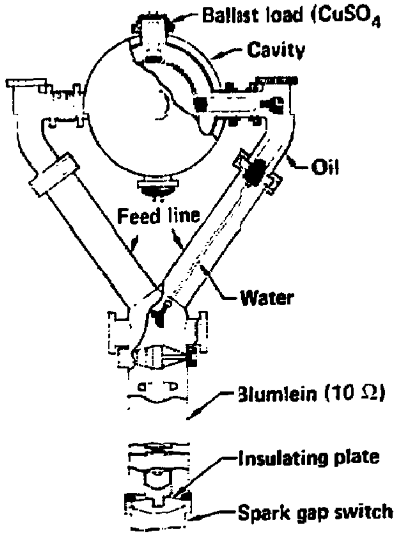

Figure 4. Accelerator Cavity with its Driver Module

Using J. C. Martin's empirical formulas (Ref. 1) for voltage breakdown in a water dielectric, both Blumlein and feedlines were designed to hold off 400 kV within the 1.8 μsec charging interval, with a safety margin in excess of 1.5. The water dielectric is recirculated to allow continuous filtering and degassing, with the resistivity held near 10 Megohm-cm.

The 54 Blumleins are charged from 13 Marx banks, with each bank charging four pulse lines, or six in the case of the injector group. These are five-stage capacitors banks, where each stage consists of a 2x1uF capacitor pair, bipolar charged. The nominal erected capacitance is 100 nF. The Blumleins are charged through individual inductors to provide isolation during charging. The modularity of the capacitive storage is designed to enhance the reliability of the machine, that is, if one Marx fails, only four Blumleins are out of commission, resulting in a tolerable 8% energy loss to the beam. The Marx bank switch gaps are pressurized with 50 psi of dry air. Nominal capacitor life at 1/3 Hz repetition rate and less than 20% voltage reversal is on the order of one million charge-discharge cycles. The Marx banks are charged in sets of four from 80 kV, 300 mA dc power supplies.

The FXR injector utilizes a cold cathode diode to generate the electron beam. An important requirement is the upper limit on initial beam emittance (100 mr-cm) which is related to the 3-6 mm spot size that has been specified for the accelerated beam at the point where it finally strikes the high-Z target to generate bremsstrahlung. In order to verify just what emittance values could be obtained with the cold cathode approach, a series of measurements was carried out earlier on the Berkeley ERA injector (Refs. 2, 3) which showed that over a fairly wide range of current and of diode potentials, the emittance can be reduced linearly by collimating the beam. The planned FXR parameters are 10-20 kA emitted, 4 kA collimated beam current.

The overall injector configuration is shown in Fig. 5. For economy and commonality, we are using six voltage modules that are similar to the basic accelerator module used elsewhere in the machine, to generate the nominal 1.5 MV voltage pulse appearing across the diode. The voltage contributions from the different modules are summed by a metallic cathode stem that links four modules, and a hollow anode stem that links two modules. The driving pulse sources have an effective internal impedance of 8 ohms, which includes the loading by ballast resistors, and thus there is a mismatch between the pulse sources and the 80 ohm diode load. In order to help absorb reflected voltage waves, both the cathode and the anode stems are tapered so as to provide an optimal surge impedance at each point. At the same time, stray field emission from negative surfaces is rendered negligibly small by reducing all field stresses to well below the 200 kV/cm level.

Extensive computer simulation was used to arrive at the injector diode geometry. The cathode is a foil edge emitter consisting of a spiral of 0.5 mil tantalum foil, inlaid on an 80 mm diameter, convex spherical cap. The nominal emitted current density of the solid beam is 350 A/cm^2. The anode is formed by a tungsten mesh that is stretched over the beam aperture; immediately behind the mesh there is a watercooled collimator which reduces

Figure 5. The FXR Injector System

the beam current to a 4 kA level in a 36 mm diameter. Magnetic focusing is utilized to generate approximate Brillouin flow, and a bucking coil is used to produce zero magnetic field at the cathode. The beam is then injected into an approximately solenoidal field that is generated by a succession of focus coils.

From the injector, the beam is transported in a 147 mm diameter beam tunnel through successive accelerator modules, by means of built-in solenoids, designed to give a peak field of 2000 Gauss on axis. This is roughly double the field intensity that would nominally be required to confine a well-behaved beam in Brillouin flow; the strong focusing capability is intended as insurance against beam instabilities. The field ripple of ± 30% which is inherent in the spacing of the solenoids, is reduced to ± 10% in the injector and in the first 12 accelerator modules by utilizing nonuniformly wound solenoids. After every four modules, there appears a 28 cm space; focusing field continuity here is maintained by an additional set of bridging solenoids. In this space there is also a set of x-y steering coils which serve to correct the beam trajectory when necessary. Beam current and beam position are measured here also, with a current viewing resistor divided into four quadrants; the four signals are summed to indicate total beam current, and compared to indicate beam position.

On leaving the last set of accelerator modules, the beam is allowed to expand to a 4-6 cm diameter and then is transported through a drift section towards the bremsstrahlung target. Lens focusing is used in this section, utilizing four solenoids, including a final lens that focuses the beam down to the desired 3-6 mm final spot size. A beam analyzer is included which has a 5% energy resolution. Because of the beam perturbation that would result from unsymmetrically distributed wall currents the analyzer enclosure was designed to keep the wall currents normally symmetrical. When the analyzer is activated, a small portion of the beam is sampled through an axial slit in the beam tunnel wall. Provision also is made for inserting a perforated, mask-type emittance tester, but this device is not normally left in the beam path.

The x-ray production target consists of a tungsten rim that is mounted on a rotatable wheel; because the beam is expected to puncture the target with each shot, a new target area is rotated into position for each successive x-ray pulse. After traversing the target, the attenuated electrons are absorbed totally in a 3 cm thickness of water-cooled aluminum, which at the same time forms the vacuum boundary. A lead collimator serves to define the cone angle of the emerging x-ray beam. A retractible beam stop made of high-Z material is lowered into position when the machine is being tuned in order to prevent inadvertent fogging of film that may already be on the firing table. A retractable plug built into the lead collimator is lowered automatically after each firing event to protect the beam line from possible shrapnel damage. Finally, a Compton detector serves as a final diagnostic of the radiation flux.

Fig. 6 shows the overall switching system (Ref. 4). This is essentially a two part system, one half triggering the charging Marx generators and the other half, the Blumleins. Accurately cut lengths of charged cables are used to

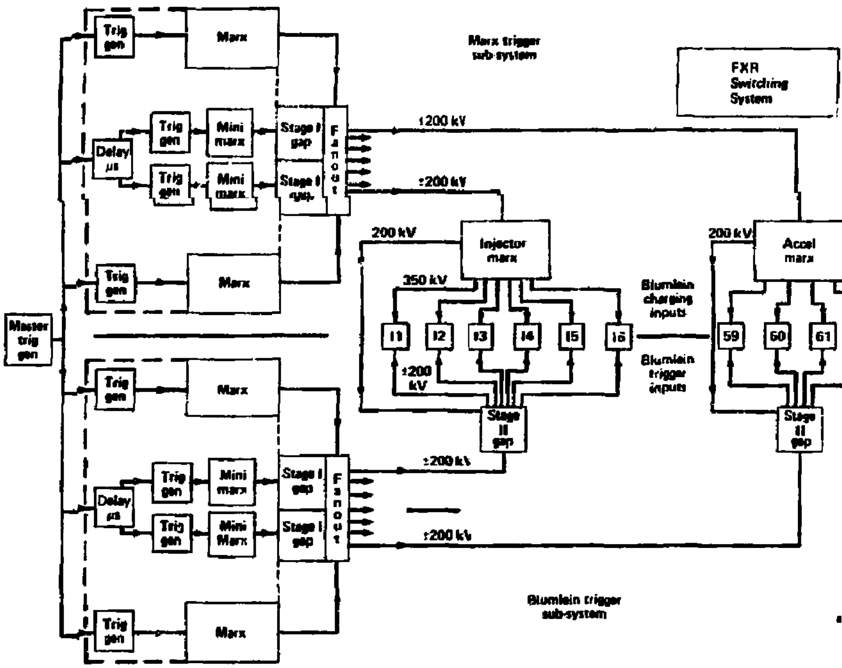

Figure 6. FXR Switching System

distribute and amplify the trigger pulses, using the inherent voltage reversal that results from shorting the cable ends. Several stages are used in order to get from the 100 volt command pulse to the final trigger pulse which is on the order of 300 kV for the Blumlein gaps. Wherever practical, redundant switch gaps have been either included or allowed for. For example, the Stage I amplifier gap is duplicated by a parallel, identical gap. Both gaps will be triggered simultaneously, and both will generally fire; if only one should fire, the degradation in the output trigger pulse would be negligible.

Control of the FXR machine should ideally be by a single button which is pushed when a radiograph of a firing event is desired. The machine performance for this event must be ultrareliable; this implies that all machine components should be monitored closely for incipient failure or degradation, during the tuning process. Fig. 7 shows the microprocessor-based monitoring and control system (Ref. 5). The system is designed so that while an operator is required to actually tune and run the machine, routine monitoring and control functions are performed automatically, with abnormal timing and amplitude occurrences on key signals being flagged to the operator. On c and, key signals can be made available to the operator in either analog or digital form. Redundant CPU's are used so that machine downtime should almost never be due to a control system failure. Sensor signals generally are digitized close to the source and then are transmitted through fiber optic links to the control room; similarly, control signals are transmitted digitally. In order to enable analog observation of specific signals by the operator when desired, matrix switches are provided that will

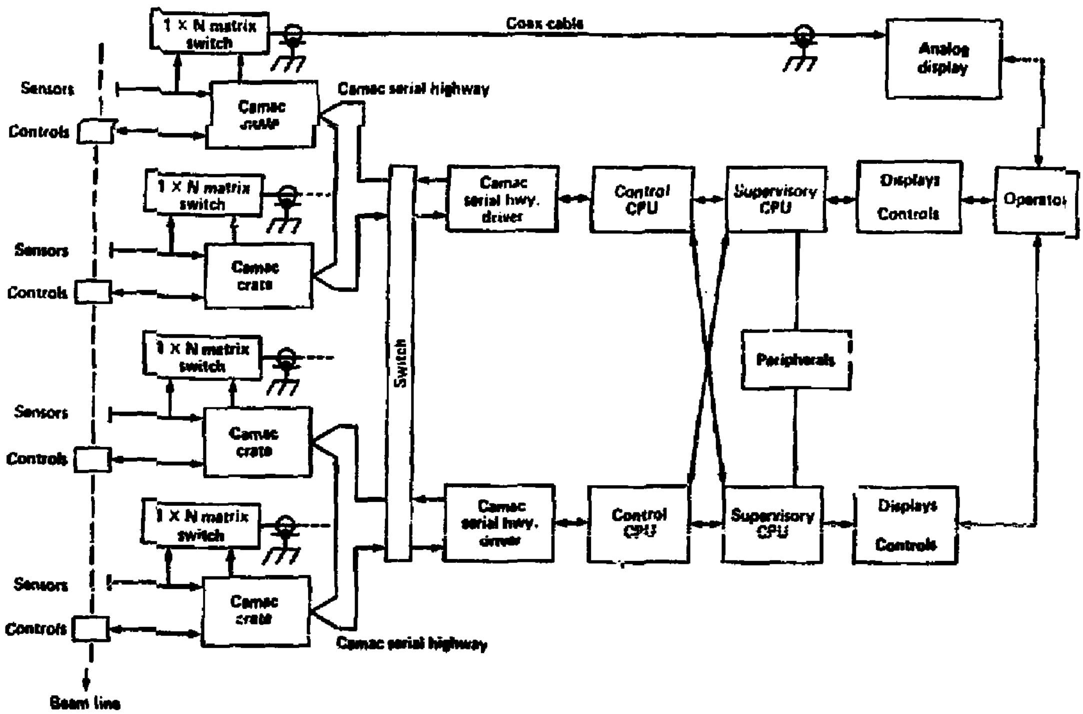

Figure 7. Computer-based Control System for FXR

connect certain sensors directly to a shielded coaxial link and hence, to the control console. The system will be expandable when needed, as application software may be added that will serve to relegate increasingly responsible functions to computer control, with only casual operator supervision. All safety interlocks will be hardwired.

The FXR machine will use roughly 4,500 gallons of high purity water (as a dielectric in the Blumlein/feedline systems), and about 15,000 gallons of transformer oil, as a dielectric in the accelerator modules and Marx tanks. It will contain a total of 58 switchgaps pressurized with SF_6 gas, and 13 switchgaps pressurized with dry air, not counting the Marx bank switches. In addition, there is a total flow of 250 gpm of cooling water, assuming all solenoid magnets to run at full power. The total beam pipe volume is 3,000 ℓ, evacuated to the mid 10^{-6} torr range, utilizing 16 cryopumps. Thus there is a considerable part of the machine devoted to pumping, recirculating, purging, and monitoring the flow and status of these various systems.

In order to validate certain design parameters as the design has progressed, a number of tests have been carried out on prototype components and subsystems. For example, a complete four module set was run to over 105 shots at 400 kV per module. A typical 10-shot overlay of cavity voltage pulses, at the 400 kV level, is shown in Fig. 8, illustrating the low jitter in time and amplitude that is obtainable with this system. The jitter was also measured independently by using an automated data acquisition system to collect 250 shot samples and to perform regression analyses on them, yielding one-sigma

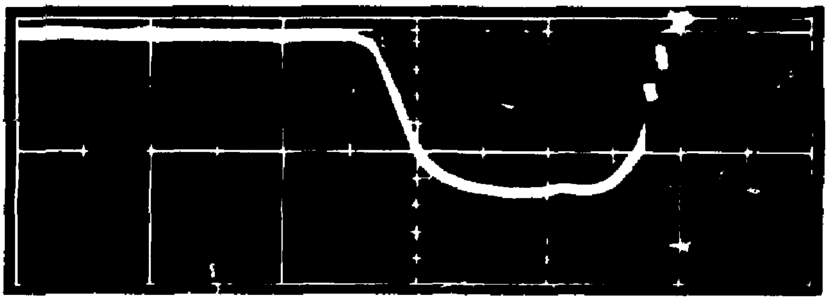

Figure 8. Ten Shot Overlay of Single-cavity Accelerating Voltage Pulse.
(Peak voltage 400 kV, at 50 ns/division)

limits as low as 0.35 ns, with a range of 2 ns. The reliable acquisition of the jitter data simultaneously provided a good indication of the expected performance of the FXR monitoring and control system in a high EMI environment.

Conclusion

The FXR machine will constitute a powerful new source for LLNL flash radiography. The design phase has been completed and the machine is expected to be operational by September, 1981. Major prototype components and subsystems have been tested and have validated the design.

REFERENCES

1. Pulsed Electrical Power Dielectric Strength Notes. PEP 5-1, AFWL TR 73-167, Air Force Weapons Laboratory, Kirtland AFB, NM 87117 (April 1973).

2. Avery, R. et al., The ERA 4-MeV Injector, Trans. IEEE NS-13, pp. 479-483 (1971).

3. Kulke, B. and R. Kihara, Emittance Measurements on Field Emitter Diodes, Proc. 2nd IEE Int. Pulsed Power Conference, Lubbock, TX, June 12-14, 1979, pp. 209-213.

4. Scarpetti, R. D. and C. D. Parkison, Switching System for the FXR Accelerator, 14th Pulse Power Modulator Symposium, Orlando, FL, June 3-5, 1980.

5. Brier, R. L., FXR Monitoring and Control System Requirements, Internal Memorandum #FXR 1307, LLNL, October 23, 1980.