IEEE Transactions on Nuclear Science, Vol.NS-22, No.3, June 1975

PULSERAD 1480--A 9 MV PULSED ELECTRON ACCELERATOR WITH AN INTENSELY FOCUSED BEAM

P. CHAMPNEY AND P. SPENCE
Physics International Company
2700 Merced Street
San Leandro, California 94577

The Pulserad 1480 is a flash X-ray generator designed to take time-synchronized radiographs through large objects containing high atomic number materials moving at high velocity.

An X-ray dose of approximately 400 R is produced 1 meter from the anode during a 150-nsec time interval. The X-ray dose is produced by a pulsed 200 kA beam of 7 MV mean energy electrons impinging on a tungsten target. The 125 kJ electron beam is delivered to the target in a graded plastic-insulated tube by a field emission cathode operating in a focused flow mode. The effective X-ray spot size has been radiographically determined to be approximately 3 to 4 mm in diameter. Closure velocities involving anode and cathode plasma motion >3×10^7 cm/sec have been inferred from impedance versus time histories, suggesting peak current densities of several tens of MA/cm^2. An oil-insulated coaxial Blumlein circuit supplies the electrical pulse to the tube structure after being pulse charged to 8.2 MV in approximately 1 µsec by an 80-stage oil-immersed Marx generator. The time jitter between the 10 volt command signal and the X-ray output is less than 100 nsec (rms).

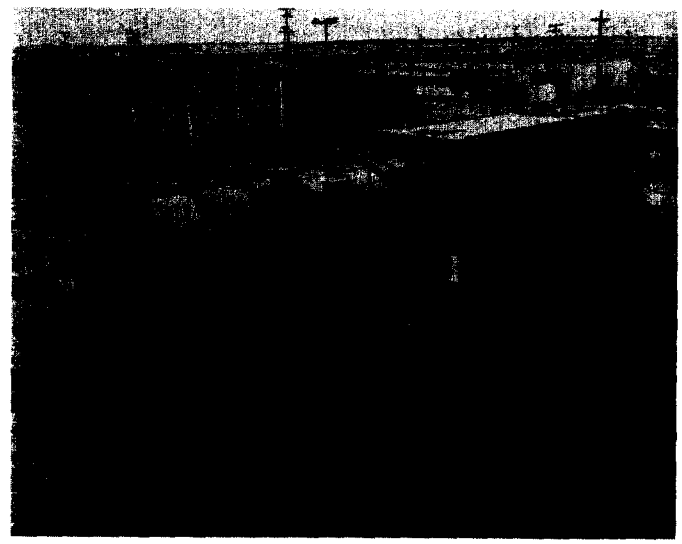

Figure 1. Pulserad 1480.

General Description

The Pulserad 1480 is housed in a single tank structure (Fig. 1). The tank structure comprises a cylindrical section (14.6 meters long and 4.7 meters in diameter) in line with a rectangular section (17.3 meters long, 5.1 meters wide, and 5.6 meters high). The overall maximum generator dimensions are 32.46 meters long, 5.74 meters wide, and 5.79 meters high. During operation, the entire tank structure is filled with 520 cubic meters of insulating oil to provide electrical insulation. The entire assembly, excluding oil, weighs approximately 118,000 kg. The total weight, including oil, is approximately 580,000 kg. The generator tank is mounted on wheels enabling it to roll on rails. A hydraulic positioning system allows the generator to be moved even when full of oil.

Marx Generator

The Marx generator is a series parallel assembly of one hundred and sixty 1.85 µF, 60 kV capacitors, associated gas-pressurized spark-gap switches, and charging and trigger resistors. Electrically, a Marx generator consists of a charging and triggering circuit and a discharge circuit. Two 1.85 µF capacitors, stacked together mechanically, form one stage of the Marx generator. The capacitor stages are charged in parallel, triggered, and discharged in series. The negative high voltage developed by the series erection of the Marx is applied to the intermediate coaxial cylinder of the Blumlein via series resistance. Figure 2 is a photograph of the Marx generator. The Marx generator is suspended in the insulating oil by nylon straps attached to pipes running lengthwise along the ceiling of the rectangular tank. The individual capacitor stages are supported in columns one above the other, by short nylon straps.

The Marx is charged by a power supply located outside the tank. Each stage is charged plus and minus, with the capacitor cases remaining at ground potential during the charge.

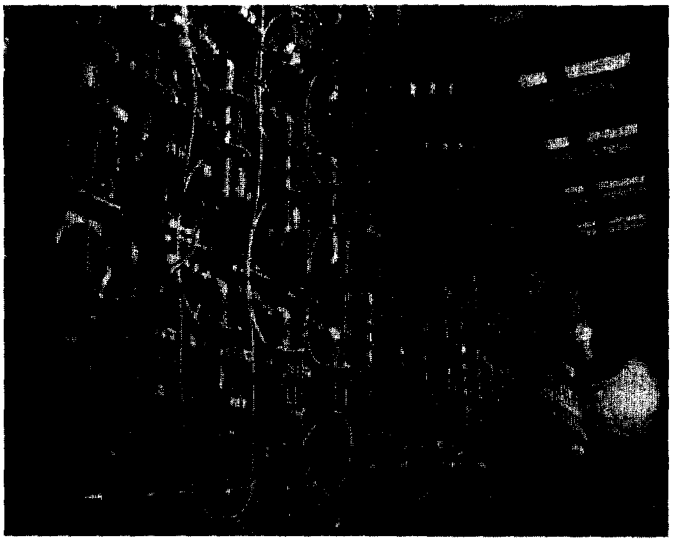

Figure 2. Pulserad 1480 Marx generator.

The Marx generator is initiated by triggering the first four spark gaps at the low-voltage end using a trigger pulse of approximately 400 kV. This trigger pulse is derived from a small Marx preceded by a master trigger switch and two stages of command signal amplification.

Blumlein Coaxial Transmission Lines

The Blumlein consists of three concentric cylinders (Fig. 3). The 4.42 meter-diameter outer cylinder forms the cylindrical tank wall which serves as the oil-air interface. The diameters of the intermediate and inner cylinders are arranged to provide a Blumlein output impedance of 26 ohms. The length of these cylinders is approximately 7 meters, to give an electrical pulse length of 75 nsec.

A self-breaking oil spark gap is used to switch the Blumlein. A hydraulically adjustable electrode mounted on the semi-elliptical head of the intermediate cylinder allows the switch spacing to be varied from 0 to 30 cm. Under normal operating conditions the oil switch is adjusted to close at approximately 90 to 95% of the peak of the charging waveform. After a firing, an oil pump is activated, which injects fresh oil into the Blumlein switch region.

A hydraulically actuated short is provided between the outer and intermediate Blumlein cylinders during Marx charge. This short, or Marx clamp, is removed after Marx charge and immediately prior to the command firing of the Marx. In the event of a Marx pre-fire during charging, the Marx is discharged through this short via a series resistor.

Figure 3. Blumlein conductors.

Prepulse Isolation Switch.

The prepulse is the voltage produced across the diode in advance of the main pulse; it results from the charging of the Blumlein by the Marx. It has serious effects upon the ability of the diode to pinch and maintain impedance, and to a lesser degree affects the ability of the tube envelope to withstand vacuum breakdown. A length of matching transmission line is attached to the tube assembly (Fig. 4). Six adjustable symmetrically positioned switch electrodes project from the toroidal circumference of this transmission line, facing the end of the inner Blumlein cylinder. These switches protect the tube assembly against application of excessive prepulse voltages.

The length of matching transmission line between the prepulse switch and the tube assembly provides substantial capacity between the tube assembly and ground. This reduces the voltage that is capacitively coupled across the prepulse switches. Arrival of the fast rising, high voltage Blumlein output pulse causes the prepulse isolation switches to break down. Closure of all the switches, assured by transit time isolation, produces a low overall switch inductance. After a firing, fresh oil is injected into the prepulse switch region.

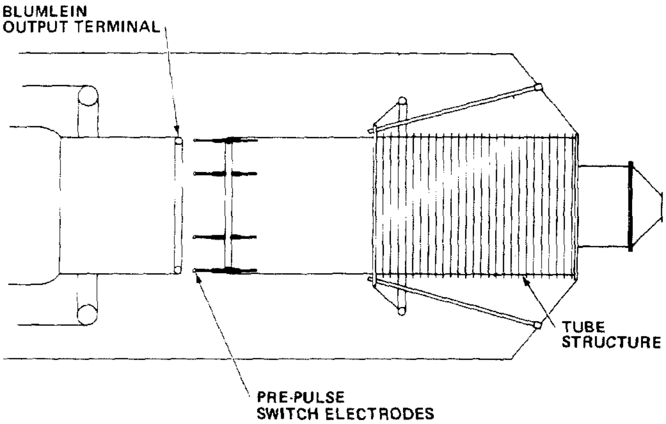

Figure 4. Prepulse switch.

Tube Assembly.

The tube assembly has three principal regions (see Figs. 5 and 6); the tube insulator, the coaxial transmission line, and the diode. The first region, tube insulator, is a plastic structure separating the vacuum region from the oil that fills the Blumlein. The output pulse of the Blumlein passes through the insulator, then travels through the second region, a vacuum filled coaxial transmission line. This transmission line contains an additional prepulse isolation switch, which is a vacuum insulated surface flashover switch. The vacuum coax terminates, physically and electrically, in the third region, the diode. Here the electron beam is accelerated from the cathode and stopped by the target.

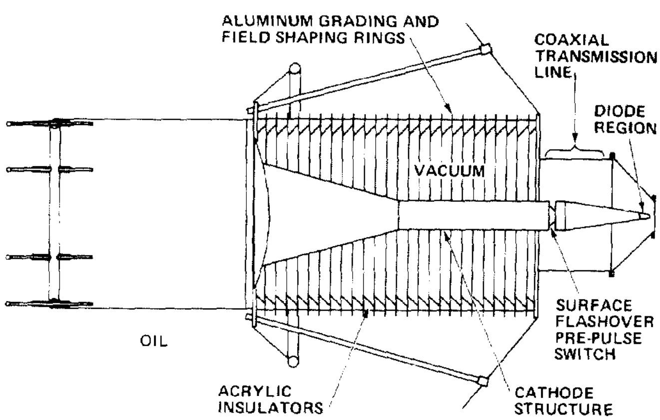

Figure 5. Tube assembly.

The oil-vacuum boundary formed by the tube insulator has the shape of a 3-meter-long cylinder, 2 meters in diameter, whose axis coincides with that of the Blumlein. The cylinder is formed from 26 identical acrylic rings, about 2 meters in diameter and 10-cm thick. These are separated by 1.27-cm-thick aluminum rings.

The aluminum rings keep the electric field in the acrylic nearly axial on average. The field is thus inclined at about 45 degrees to the actual plastic-vacuum interface, which is machined to form a smooth, conical bore. The field that the interface withstands is maximized by the choice of the 45-degree angle; this angle helps direct electrons emitted from the plastic or aluminum surface away from the acrylic and thus avoid electron multiplication. Even so, a total length of 3.7 meters of plastic is required to withstand a 10 MV, 75 nsec pulse reliably.

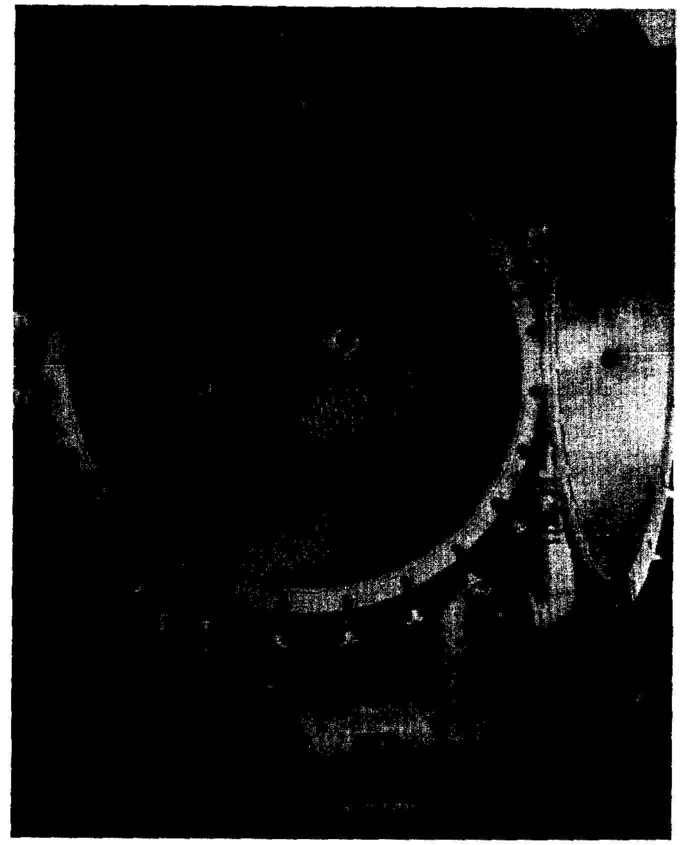

Figure 6. Interior of tube assembly.

The cathode plate (located at the high voltage end of the tube) was tapered down to a 12-inch-diameter cylindrical shank which extended forward into a 44-inch-diameter cylindrical anode extension. A 5-cm thick, hard nylon, angled surface, prepulse (flashover type) switch was placed between the 12-inch-diameter cathode shank and the final conical cathode piece. This reduced the prepulse voltage on the cathode tip to about one-third of the tube prepulse voltage or ~100 kV (calculated) as compared to the measured ~300 kV tube prepulse voltage.

The final cathode tip is sketched in Fig. 7. A 5-cm diameter, hollow, radiused steel cathode at a 7.62 cm gap spacing was found to give the desired 35 to 45 ohm impedance in the focused beam mode. Smaller diameter cathode tips (down to 2.5 cm diameter, at A-K gaps of ~3.8 cm) performed well at lower voltage levels, but were found to produce poor beam pinch characteristics and exhibit early impedance collapse (shorting) at normal voltage output levels. These observations suggest that prepulse, whose amplitude in this case is proportional to the pulse-charge voltage, sets a limit on the physical dimensions of the diode electrodes independent of the main pulse diode characteristics. Thus at full voltage it was necessary to use the smooth radius 2-inch-diameter cathode shown in Fig. 7. In practice it was also found that a light coating of DC 704 oil applied to the cathode tip improved the diode reproducibility, again emphasizing the importance of preventing current emission during pre-pulse.

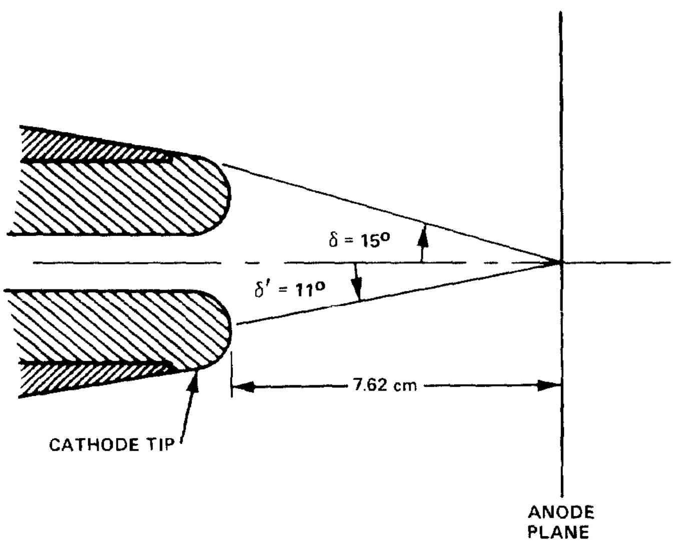

Figure 7. Cathode tip.

Diode Impedance Characteristics

Typical diode voltage (corrected for L dI/dt at the monitor point) and current waveforms are given in Fig. 8 for a 130 kJ shot. Figure 9 shows the impedance (V/I) time history with limits corresponding to a 5 nsec relative uncertainty in V and I phasing. Following an initial high impedance turn-on phase, the impedance tends to remain relatively constant at 40 ohm (±20%) until 30 to 40 nsec past peak power at which time it collapses toward zero in ~80 nsec.

Observed impedance levels can be compared with the predictions of Creedon's parapotential flow model[1] which has been useful in the past in predicting impedance for lower voltage (≤ 3 MV) higher current focused flow diodes. In its general formulation (when the A-K gap spacing is larger than the cathode radius), Creedon's expression for the saturated parapotential current becomes:

$$I_p = 8500\, \gamma_o \ln\left[\gamma_o + (\gamma_o^2 - 1)^{1/2}\right] \frac{(-1)}{\ln\left[\tan \delta/2\right]} \quad \text{(AMPS)}$$

where γ_o is the usual relativistic factor and δ is the angle shown in Fig. 7. In this case the geometric factor $[-\ln(\tan \delta/2)]^{-1}$ could range from 0.49 (δ=15°) to 0.43 (δ=11°) depending on the location of dominant electron emission. Calculated saturated parapotential impedances for g = 0.49 and g = 0.43 are shown in the wavy lines superimposed on Fig. 9. The agreement with experimental data is good, particularly near the times of peak power. At 30 to 40 nsec past the peak power point, the observed rapid impedance collapse is not consistent with Creedon's model, indicating a possible late time dominance of conductive plasma motion in the A-K gap.

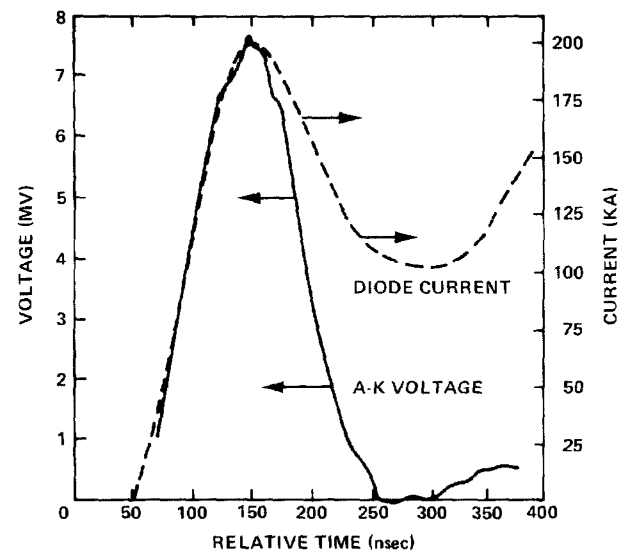

Figure 8. Diode current and voltage versus time.

Diode Pinch Characteristics

Limited data were collected on the effective spot size (pinch diameter) using X-ray shadowgraph techniques which were sensitive to the high energy γ components of the electron bremsstrahlung spectrum produced when the focused beam was stopped in a tantalum (converter) anode.

Shadowgraphs of a 4-cm-thick uranium block (with a series of cylindrical holes ranging from 2 mm diameter by 1 mm deep to 4 mm diameter by 3 mm deep) placed 3 meters from the source were taken at source-to-object distance over object-to-film distance ratios of 150 and 2. The 150/1 ratio exposures

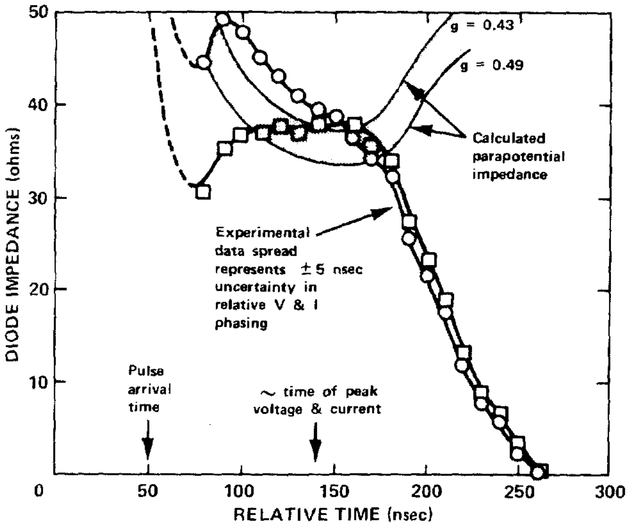

Figure 9. Impedance versus time history.

served to measure the film blur and scattering caused by the image intensifying screens adjacent to the film. Comparison of the 150/1 and 2/1 exposures enabled the effective source diameter to be determined by simple geometric expressions.

A typical source diameter of 3.5 mm was inferred by the shadowgraph technique with most shots falling within a 3 to 4 mm band. These measurements suggest average pinch current densities of 1 to 2 MA/cm^2 and power densities of 0.8-1.6x10^{13} W/cm^2 during the high voltage portion of the pulse. Independent measurements performed by the Lawrence Livermore Laboratory personnel (viewing the γ source with less filtering than the above shadowgraph technique) indicate time integrated spot diameters of ~10 mm, thus suggesting that the pinch diameter is smallest only during the higher voltage (and current) portion of the pulse.

Peak current densities at the center of the pinch were not directly measured, however they likely exceed the 1 to 2 MA/cm^2 average levels implied by the shadowgraphs. An approximate, qualified estimate on the peak current density can be obtained from the observed impedance collapse rate (Fig. 9) of ~40 cm/μsec.

Upper bound estimates of the cathode plasma closure contribution [using a maximum observed cathode closure of 8 cm/μsec at 1 MV (Ref. 2) and an assumed $V^{1/2}$ voltage dependence on cathode plasma closure[3]] leave an anode plasma closure contribution of ~15 cm/μsec. This implies dose levels in the anode plasma of ~10^7 J/gm. If anode return current heating is ignored, these dose levels corresponding to peak current densities of 5 to 10 MA/cm^2 depending on the dose/fluence coupling coefficient characteristic of such a high voltage, high transverse temperature electron beam. The above arguments are by no means conclusive due to uncertainties in the various assumptions, however, they do suggest the possibility of 10^7 A/cm^2 peak current densities and the need for further study to determine the limits of achievable current density in focused multi-megavolt electron beams.

REFERENCES

1. J. Creedon, "Relativistic Electron Flow," PIIR-17-72A, Physics International Company San Leandro, California, October (1972). A version of this paper has been submitted to J. Appl. Phys.

2. J. Creedon, P. Spence, and R. Huff, "Anode Cathode Plasma Motion in High ν/γ Diodes," Bull. Am. Phys. Soc. 18, 1310 (1973).

3. I. Smith, Physics International Company, Private Communication.