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RADIAL COMPRESSION OF PICOSECOND ELECTRICAL PULSES

C. BAMBER, W. DONALDSON, T. JUHASZ, L. KINGSLEY, and A. C. MELISSINOS

Department of Physics & Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14627

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We used 1-ps, 1-mJ pulses from a Nd:glass laser system to produce kilovolt electrical pulses with rise time of order ~15 ps. The pulses propagated radially between two circular discs resulting in a voltage gain of 2 at the center of the discs as compared to the circumference, in qualitative agreement with calculations. Such structures can be used to produce very-high-gradient accelerating fields.

1. INTRODUCTION

Acceleration of electrons and positrons in conventional rf linacs is presently limited to gradients of order 20 MV/m. To extend e^+e^- collisions to the TeV region it is necessary to achieve gradients at least an order of magnitude larger, and several promising proposals are being explored.[1,2,3,4] The high electric field at the focus of intense lasers[5] provides a suitable gradient, but so far no practical geometry has been found for efficient particle acceleration.

Recently, Willis[6] suggested the use of ultrafast lasers to switch power from a dc high-voltage source to an accelerating structure. The proposed structure consists of circular discs and thus acts as a radial transformer. If the rise time of the electrical pulse is of the order of the gap spacing (~1 mm) a voltage gain of a factor of 10 can be achieved. Furthermore, because of the small gap spacing a very high gradient is, in principle, attainable.

Radial compression of electrical pulses had been considered[7] in the 1960s and is used in accelerators such as the PBFA.[8] More recently studies on a large-scale model have been reported by Aronson *et al.*[9] For a high-energy accelerator a compact structure is needed, and this is now possible because of the availability of fast pulsed lasers driving the high-voltage switch. Willis and his group are working on laser-triggered photoemission from a wire cathode[10]; Villa proposed a laser-triggered spark gap.[11,12] Here we report on results obtained using photoconductive switching of high-resistivity silicon.

Using a high-power picosecond laser developed at the Laboratory for Laser Energetics[13] we were able to demonstrate voltage gain in a structure with outer radius R = 3 cm and gap $g = 2$ mm. Since the field at the center of the disc must be measured with picosecond time resolution, we measured the electro-optical effect and sampled the waveform by varying the delay between the probe and switching pulses. A hard-tube pulser provided the high voltage that was applied on the edge of the discs 10–100 ns before switching. The observed waveforms and their amplitudes are in qualitative agreement with the calculated values.

2. PROTOTYPE STRUCTURE

The structure used in this investigation is shown in Fig. 1. The lower, grounded disc is brass, and the upper disc is a silicon wafer 500 μm thick. A gold coating on the inner side of the silicon serves as the "anode" to provide the conducting structure in which the pulse propagates. A circular ring of gold was deposited on the outer side of the silicon disc at its edge. This ring was connected to the high-voltage feed. The two discs were separated by 2 mm and had a 1-mm-diameter hole at their centers. A KDP crystal 1 cm square and 2 mm thick was placed at the center between the discs and was probed in reflection.

The equivalent electric current is shown in Fig. 2. The disc structure is represented by C_2 even though at these frequencies it is a distributed system; C_1 is the charging capacity, ~20 pF, and R_1 represents the ohmic impedance across the silicon disc between the conducting coatings, ~10 kΩ ($\rho = 7000$ Ω-cm); S_2 represents the photoconductive switch that shorts R_1. When the charging pulse $-V_0$ is applied at C_1, the upper plate of C_2 floats towards $-V_0$ charging C_2; to prevent this, a small conducting spring was inserted between the discs. This is indicated by the inductance L_1.

The waveform at the charging electrode (i.e., the C_1, R_1 node) is shown in Fig. 3a. Because of the impedance mismatch the voltage builds up to $-V_0$ by successive reflections; the IR switching beam is blocked. Figure 3b shows the waveform when switching is accomplished by the IR pulse, whose timing is indicated on the lower trace.

The impedance seen by the electrical pulse that propagates between the two discs is a function of the radius r; it is given (approximately) by $Z(r) =$

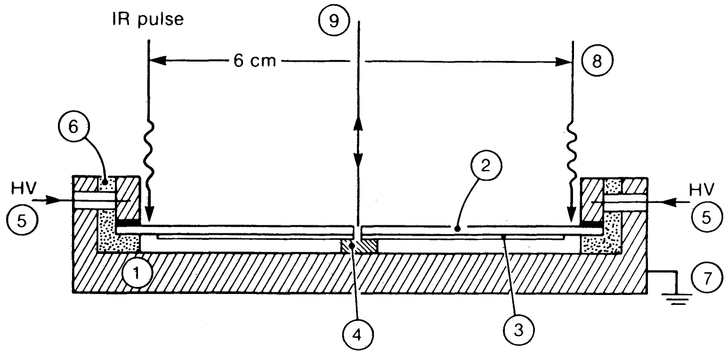


FIGURE 1 Cross section of the disc structure: (1) cathode brass disc, (2) silicon wafer, (3) gold coating, (4) KDP crystal, (5) HV feed, (6) insulator, (7) ground, (8) IR pulse, (9) probe pulse.

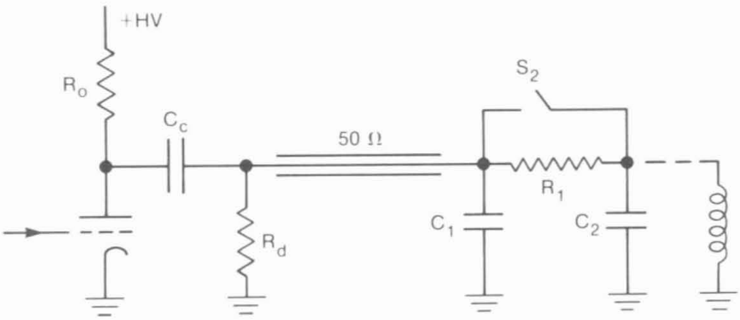
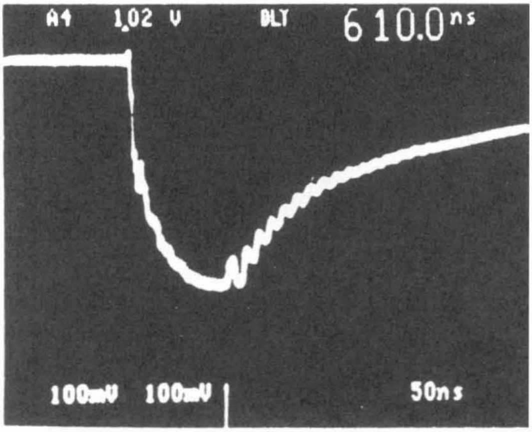
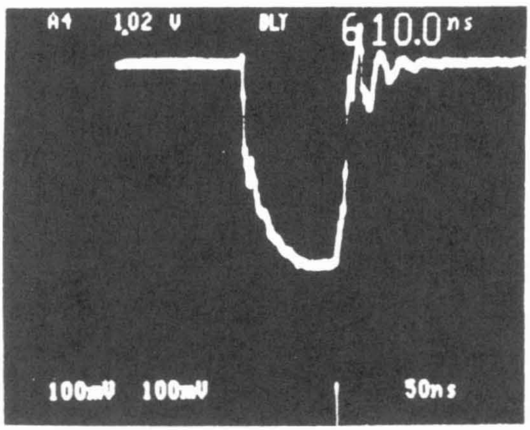


FIGURE 2 The equivalent circuit for the structure.



(a)



(b)

FIGURE 3 The waveform at the HV feed point: (a) without switching (b) with switching.

(377 Ω)($g/2\pi r$), with g being the gap spacing. For constant power, the voltage squared is proportional to the impedance, so that one can expect a gain of order $V(r_0)/V_0 = \sqrt{R/r_0}$, where r_0 is the radius of the central aperture. The propagation of a pulse of finite rise time can be calculated analytically,[11,12] and one obtains for the voltage at the center of the discs

$$V_c = 2V_0\sqrt{\frac{2R}{g + c\tau_R}}. \tag{1}$$

Here V_0 is the voltage at radius R, and τ_R is the rise time of the pulse. Equation (1) shows the importance of ultrafast switching if one wishes to maintain a small gap between the discs.

3. OPTICAL SYSTEM

The pulsed laser used in this investigation was a combination of a Nd:YLF oscillator and a Nd:glass amplifier ($\lambda = 1.054\,\mu$m) producing pulses of a few millijoules with 1–3 ps duration[13] at a repetition rate of 5 Hz. The system is capable of 1 J in 1 ps, at a repetition rate of one pulse per 20 s. Pulses from a Nd:YLF mode-locked oscillator are stretched to 300 ps and chirped in a 1.5-km optical fiber and injected into a regenerative amplifier. The pulse is then amplified to saturation and ejected from the optical cavity. Reflection gratings, arranged to compensate for the optical chirp, compress the pulse to 1 ps. This sequence is shown schematically in Fig. 4.

The spatial profile of the IR pulse was modified by an optical system incorporating a toroidal lens. The annulus of IR light was focused onto the silicon switch at the periphery of the radial transmission line. The attenuation length at $\lambda = 1.054\,\mu$m is of order of 1 mm, so that carriers are being produced throughout the bulk of the silicon wafer. A fraction of the pulse was split off, frequency doubled, and used to probe the KDP crystal at the center of the discs. A variable delay in the pump beam provided the temporal scanning.

The sampling system is shown schematically in Fig. 5. The frequency-doubled green beam is passed through a Glan–Thompson polarizer followed by a

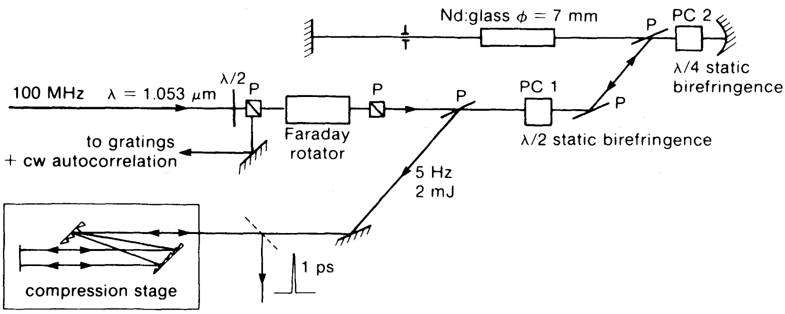


FIGURE 4 Schematic of optical pulse amplification and compression.

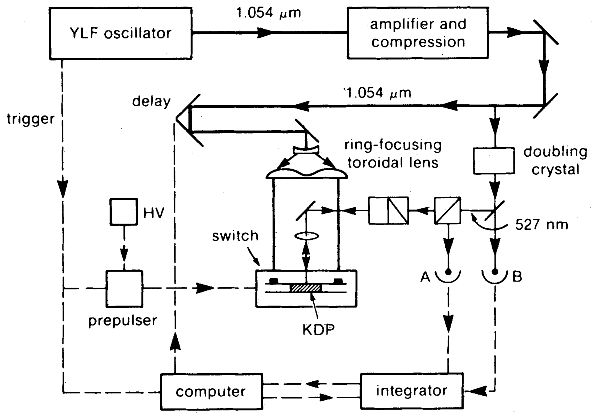
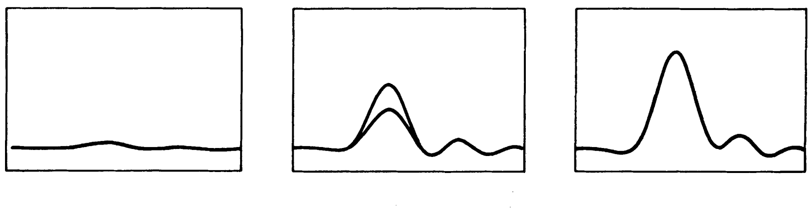


FIGURE 5 Schematic arrangement of the switching and electro-optical sampling layout.

compensator (variable retardation device) so that elliptically polarized light is incident on the electro-optical crystal. After reflection, the beam retraces its path, and the component orthogonal to the original polarization direction is detected by a photodiode. The compensator is set so that after the double traversal the light is circularly polarized, and the detector is biased to half its maximum intensity.

The electro-optical effect was longitudinal and thus independent of crystal thickness, yielding a half-wave voltage[14] $V_\pi = 10\,\text{kV}$ at $\lambda \sim 530\,\text{nm}$. To improve signal-to-noise ratio, the electrical pulse was applied for every second laser pulse, and the difference between 20 consecutive pulses was averaged in a boxcar integrator. Furthermore, the incident pulse intensity was monitored and used for normalization. The output of the laser varies significantly from pulse to pulse, and thus it is necessary to use averaging techniques. The crystal was calibrated by applying a (quasi) static voltage (1.5 kV) across the discs. The results are shown in Fig. 6 and correspond to a bias of $\phi = 0°$, 45°, and 90°. At 45° the rotation induced by the voltage pulse, which is applied for every *second* laser pulse, is clearly shown. At 0° and 90° the signal is quadratic in the optical rotation angle and beyond our resolution.

When fast switching is desired it is important to prevent any type of prepulse from accompanying the main pulse. The prepulses bleed the voltage across the



(a) $\phi = 0°$ (b) $\phi = 45°$ (c) $\phi = 90°$

FIGURE 6 Calibration of the electro-optical effect. The voltage is applied only for every second laser pulse: (a) bias $\phi = 0°$, (b) bias $\phi = 45°$, (c) bias $\phi = 90°$. At $\phi = 45°$ the signal is proportional to Γ the optical rotation; at $\phi = 0°$, 90° it is proportional to Γ^2 and therefore too small to be observed.

switch and can completely distort the rise time of the electrical pulse. Evidence for such prepulses can be seen in the trailing edge of the waveform of Fig. 3b. The optical delay line had a travel distance of ~9.4 cm and a step size of 6.25 μm. In this experiment data were taken every 25 steps (1.04 ps). However, the time resolution of the system is set by the thickness of the crystal. Since the probe beam traverses the 2-mm-thick crystal twice, the resolution is of order $\delta t = 18$ ps, given a refractive index $n = 1.5$.

RESULTS

In our first measurements a Teflon insert ~1.5 cm in diameter was used to hold the crystal at the center of the discs. This insert produced significant reflections and had to be removed. Distortions of the waveform were also seen in connection with prepulses; these were reduced by tuning the laser. The best waveform observed is shown in Fig. 7.

The measured rise time (10–90%) is $\tau_m = 24$ ps; this is a convolution of the actual rise time with the time resolution of the probe, $\delta t = 18$ ps. By simple quadrature, the true rise time is $\tau_R = 16$ ps, and it is therefore probable that the peak amplitude exceeds the measured value by a factor of 1.5–2. A reflected pulse appears ~300 ps after the initial pulse. This corresponds roughly to the transit time for the trip from the center of the disc to the edge of the structure and back (8 cm).

Based on the calibration of the crystal, the observed peak field is $V_c = 1.0$ kV. The charging voltage was $V_0 = 480$ V so that the observed gain is $V_c/V_0 \sim 2$. To predict the gain from Eq. (1) we use $\tau_R = 16$ ps, $R = 3$ cm, and $g = 0.2$ cm. The calculated gain is then

$$V_c = 2V_0\sqrt{8.7} = 5.9V_0. \tag{2}$$

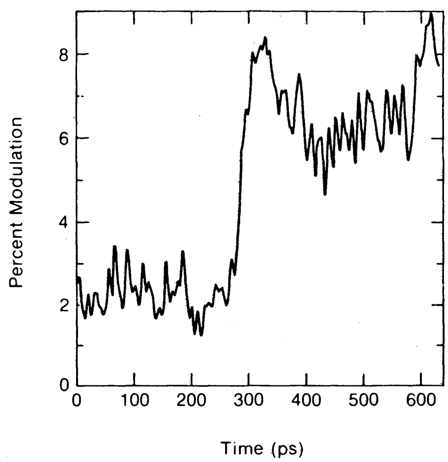


FIGURE 7 The waveform observed at the center of the discs. The observed rise time is 24 ps with a resolution of 18 ps.

There are two good reasons why the observed gain cannot be compared directly with the value of Eq. (1). The KPD crystal used to sample the field introduces a discontinuity, and part of the propagating pulse is reflected. If the dielectric constant of KDP is taken to be $\varepsilon_r \simeq 20$, only 0.37 of the incident pulse is transmitted into the crystal. This suffices to bring the result of Eq. (2) into good agreement with observation. Another effect is the time resolution (18 ps) of the probe, which prevents us from measuring the peak value of V_c for a very narrow pulse.

The propagation of the pulse on the structure has been calculated in detail by R. Barker using the 2-D, electromagnetic simulation code MAGIC.[15] In that model, 10 kV was applied at the outer radius of about 3.6 cm, and the silicon switch was closed with a 0.5-ps rise time, but the measurements have *not* been smeared by finite resolution. The fields are calculated as a function of radius and time; the voltage waveform near the center of the discs ($r = 0.8$ mm) is shown in Fig. 8. We note that despite the effects of experimental resolution, the calculated waveform qualitatively matches the observation very closely.[16] The peak gain V_c/V_0 is seen to be about 6.6; from Eq. (1) we find for $\tau_R = 0.5$ ps, $g = 2$ mm, and $R = 3$ cm, that $V_c/V_0 = 10.3$.

In conclusion, we have demonstrated that we can generate kilovolt electrical pulses with a rise time $\tau_R \sim 16$ ps using a circular photoconductive switch. The propagation of this circular pulse toward the center gives rise to a voltage gain in reasonable agreement with calculation. The energy in the switching pulse used for this investigation was ~1 mJ; we did, however, observe successful switching at significantly lower power levels as well.

Our present goal is to improve on these measurements and observe gains of order ~10, while also increasing the supply voltage to a few tens of kV. We can then attempt to accelerate electrons photoemitted from the cathode; in that case

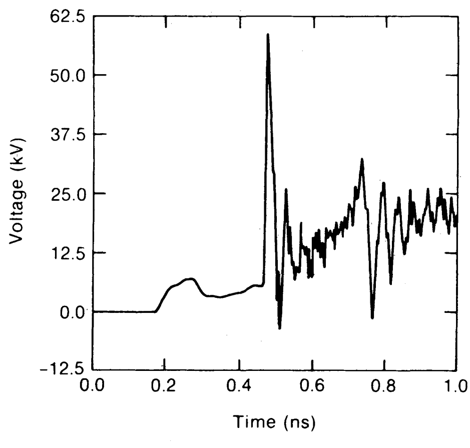


FIGURE 8 The waveform at the center of the discs are calculated in Ref. 15 for 0.5-ps closing of the switch. Note the qualitative agreement with the observed data.

the KDP crystal is removed, and the probe beam is frequency doubled once more so that the cathode is illuminated by a UV pulse. We believe that we can achieve gradients of 0.2–0.5 MV/mm, and that one can stack several discs to make a structure of finite length. Such a device would make an electron source of high brilliance and could eventually be used for acceleration to TeV energies.

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