Pulse stretching in a Q-switched ruby laser for bubble chamber holography

G. Harigel, C. Baltay, M. Bregman, M. Hibbs, A. Schaffer, H. Bjelkhagen, J. Hawkins, W. Williams, P. Nailor, R. Michaels, and H. Akbari

In testing a holgraphic particle track recording system for the Fermilab 15-ft bubble chamber, it was shown that the peak power of Q-switched laser pulses (~50-ns duration) at the required energy gave rise to boiling during the chamber expansion. A pulse stretching technique is described which was developed to reduce the peak power. Applied to a ruby laser (oscillator and three amplifiers) with a maximum Q-switched output of 30 J, pulses of up to 100-μs duration with coherence up to and exceeding 11 m at 2.5 μs were produced. These pulses were amplified to ~5 J without shape degradation. The considerably increased coherence length will find applications in many fields of pulsed holography, and its use with fiber optics is particularily promising.

I. Introduction

An initial test of holographic recording of particle tracks in a 35-m^3 cryogenic bubble chamber at CERN (BEBC) was successful.[1] However, use of a powerful Q-switched ruby laser produced as an unwanted aftereffect boiling of the chamber liquid which adversely affects the quality of the conventional photographs taken some 10 ms later. This boiling is in all probability due to the absorption of light on small impurities (with diameters of a few micrometers or even fractions of a micrometer), which float in the bubble chamber liquid.[2-4] Their heating gives rise to bubble nucleation during the expansion cycle. In this first test it was demonstrated that, at a given energy (~5 J), the boiling is suppressed by using a free-lasing pulse (~1 ms) instead of the Q-switched pulse ($\leq$50 ns). However, the 1-ms operation mode of the laser is unsuitable for our purpose because of the bubble movement and size variation during illumination. Furthermore, it may not provide reliably enough the necessary coherence length. We, therefore, have to aim for an intermediate pulse duration with good beam quality, as proposed earlier.[1] It is the purpose of this paper to describe our technique, which reduces the instantaneous power at constant energy and solves, at least partially, the boiling problem. Parallel approaches, not the subject of this paper, consist of the reduction of the overall energy requirement by the increase of the sensitivity of existing holographic emulsions[5] and the decrease of impurities by filtering the liquid.[6] The stretched pulse system was used in the Fermilab 15-ft bubble chamber to record high energy neutrino interactions.

Various methods for obtaining stretched pulses have been reviewed both from the experimental and theoretical point of view[7] (sixty references). Any application requires a specific shape and a certain energy of stretched pulses, which may then be obtained with one of the following techniques.

Lengthening of the cavity of a Q-switched laser, introducing nonlinear materials into its cavity, or use of a feedback loop to control switching of an electrooptic shutter was used to obtain long pulses. The first two methods produce light pulses whose time variation is either almost Gaussian or very asymmetric and fairly short: they will not be considered further, since the pulse for our application must be reasonably flat over at least several microseconds, and the rise and decay

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G. Harigel is with CERN, CH-1211 Geneva 23, Switzerland. When this work was done C. Baltay, M. Bregman, M. Hibbs, and A. Schaffer were with Columbia University, Nevis Laboratories, Irvington, New York 10533; M. Bregman and M. Hibbs are now with IBM T.J. Watson Research Center, Yorktown Heights, New York 10598, and A. Schaffer is now with CERN, CH-1211 Geneva 23, Switzerland. H. Bjelkhagen, J. Hawkins, and W. Williams were all with Fermilab, Batavia, Illinois 60510 when this work was done; H. Bjelkhagen is now with Northwestern University, Evanston, Illinois 60201.[2] When this work was done P. Nailor was with Imperial College, London, SW7, U.K.; he is now with P. A. Technology, Cambridge Laboratory, Melbourn, Herts. SG8 6DP, U.K. When this work was done R. Michaels was with Rutgers University, New Brunswick, New Jersey 08903; he is now with Hewlett Packard, Palo Alto, California 94304. H. Akbari is with Tufts University, Medford, Massachusetts 02155.

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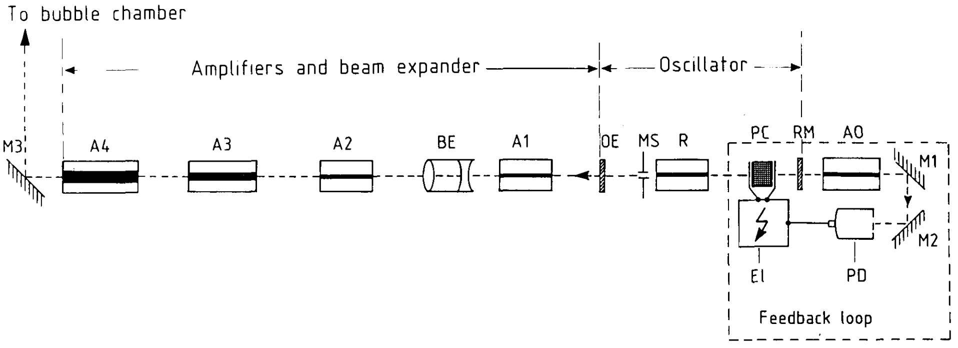

Fig. 1. Layout of the KORAD oscillator stage with feedback optics and four amplifiers (schematic): *OE*, output etalon; *MS*, mode selection aperture; *R*, ruby rod; *PC*, Pockels cell; *RM*, rear mirror; *AO*, amplifier; *M*1, *M*2, *M*3, mirrors; *PD*, photodiode, *E*1, feedback electronics; *A*1, *A*2, *A*3, *A*4, amplifiers; *BE*, beam expander.

times are short compared with the flattop. Therefore, we pursue only the third method and discuss aspects of a few earlier technical approaches in view of their suitability.

The longest pulse was achieved with a feedback circuit using a Kerr electrooptic shutter.[8] The intensity distribution was highly asymmetric, reaching its maximum at $\sim$150 μs, and fell smoothly to zero at $\sim$1.8 ms. An attempt to obtain a rectangular pulse of 5–10 μs in a feedback circuit, using a Kerr cell,[9] resulted only in asymmetric pulses of $\leq$5-μs duration with heavy intensity instabilities at 0.6 μs. A negative feedback system using a Pockels cell gave pulses of almost 1-μs duration, however, with a spike twice the average intensity at the beginning.[10] This pulse was amplified without shape distortion to an energy of $\sim$0.6 J. This technique was further investigated, both experimentally and with computer simulation of the electronic circuit and of the laser rate equations, aiming for several hundred nanosecond flattop pulses.[11] This concept appeared the most promising with which to obtain flat pulses of tens of microseconds duration.

In the relevant papers[7–11] the effect of pulse stretching on the coherence length and the TEM$_{00}$ mode, important for our application, has not been discussed.

II. Feedback-Controlled Laser Systems and Experimental Results

For the illumination of $\leq$10 m^3 of the fiducial volume of the 15-ft (4.5-m) bubble chamber at Fermilab, a system similar to that described in Ref. 1 with light energy up to $\sim$30 J is needed.[12] This energy will be obtained with an oscillator stage followed by several amplifiers with increasing ruby rod and laser beam diameter. Since we expect no serious deterioration of the quality of the initial light pulse going through these amplifiers[11] (for effects of high pumping of amplifier rods and backreflections see Appendix), we can limit ourselves to a description of the oscillator.

The original development was carried out on a modified KORAD laser with a feedback circuit similar to Ref. 11 and tested during a technical run of the Fermilab 4.5-m bubble chamber; the system used later in the physics run was a new design, adapted to the JK Laser System 2000.

A. KORAD Laser

For the layout of the cavity we used various elements from a KORAD K-1000 ruby laser system given to us by Columbia University's Radiation Laboratory. Figure 1 shows the geometrical arrangement. The length of the cavity is chosen to be 100 cm, similar to the layout described in Ref. 11. To keep the cavity as simple as possible we extract the light needed for the feedback loop through the rear 95% reflector rather than from a beam splitter placed inside. The outgoing 5% of the light passes through a ruby amplifier to give sufficient intensity and flexibility for operation of the feedback electronics. After only some 30-cm path length (1-ns delay) the light hits a 45-mm diam. phototube (ITT FW114A), which acts, through the electronic circuit shown in Fig. 2(a) on the Pockels cell. The left side of the circuit serves to adapt the trigger to the KORAD power supply. We chose a KD*P Pockels cell (Quantum Technology model QK-10) with a low quarterwave voltage (2100 V) and low capacitance (6 pF); the connecting wires were kept short to minimize the stray capacitance of the circuit. The fire pulse from the laser control system triggers a Kryton switch (EG&G type KN6B), which drops the bias voltage across the Pockels cell to zero in a time of $\sim$1 ns. As laser oscillation begins, the phototube starts to conduct. Voltage is produced across the 200-Ω load resistor, rebiasing the Pockels cell. This negative feedback inhibits the buildup of oscillation. To prevent the complete extinction of laser action, positive feedback is applied via the inductor, causing the differential voltage across the Pockels cell to drop again. This allows oscillation to build up, and sustained laser action is ensured by the balance between the negative and positive feedback. For further theoretical details, see Ref. 11.

Typical stretched pulses (with some mode-beating) are shown in the oscilloscope picture of Fig. 3. About 20% of all pulses exhibit an overshoot (maximum about twice the average height) at the beginning of the pulse, which does not affect significantly our application. About 2 μs after the Kryton fired, the differential Pockels cell potential rose rapidly closing off all lasing. The output from the circuit was only marginally effective given the 2.1-kV quarterwave potential of the Pockels cell. To produce $\sim$1-kV modulations from the

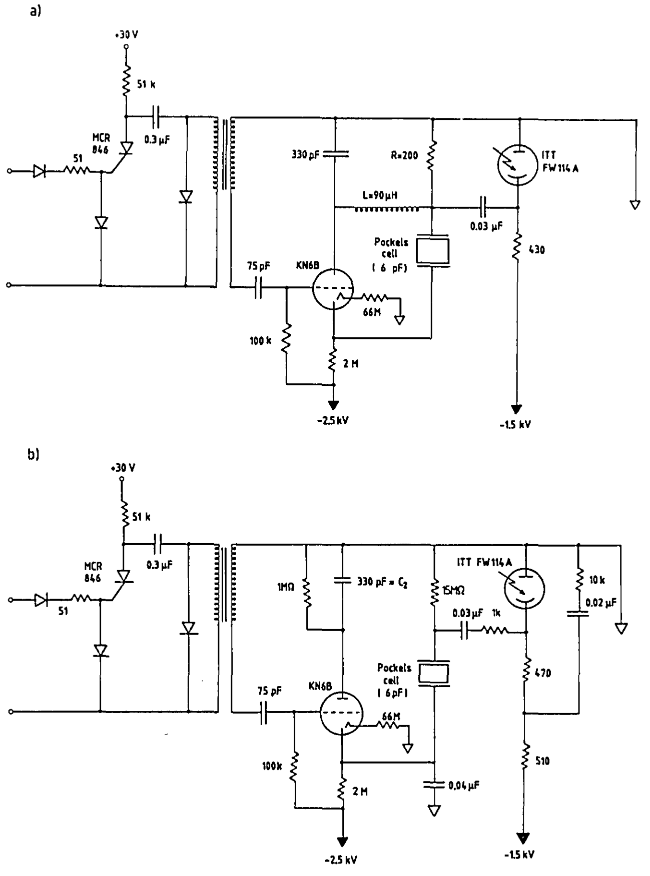

Fig. 2. Feedback electronics: FW114A, phototube, KN6B, Krytron: (a) Lovberg circuit, KORAD Laser, pulse duration, ≤2.5 µs; (b) modified circuit, KORAD Laser, pulse duration, ≤5 µs; improved version used initially with JK laser, pulse duration, ≤10 µs.

phototube output, it was necessary to increase the stored charge associated with it. Current flows as this charge decays through the conducting phototube, producing voltage across the Pockels cell (as explained before). The inductor was also removed again to allow greater initial voltage modulation and improved control over the overshoot at the start of the pulse. With these modifications repeatable 5-µs pulses were produced. Conventional Q-switched pulses with ~100 ns FWHM could be easily produced by blocking the light pass to the phototube. As reported in Ref. 11, also our stretched pulses contained 80–90% of the energy of these Q-switched pulses.

To get good coherence length the oscillator stage was equipped with a temperature stabilized intracavity etalon (<0.1°C). A 2-mm aperture was used to obtain the TEM_{00} mode. At this stage it was demonstrated that the action of the stretching circuitry improved the coherence length (e.g., coherence lengths of up to ~4 m were observed).

After field tests in the bubble chamber, boiling was noticeably reduced for prolonged pulses up to 3 µs compared with the Q-switched pulse.[13] However, the level of boiling was still unacceptable, so supplementary research was conducted to try to increase the pulse length further, thereby reducing the peak power.

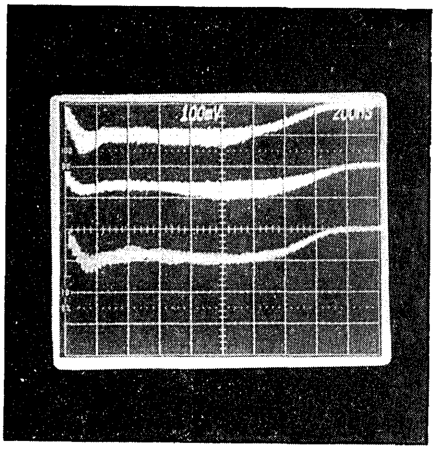

Fig. 3. Typical stretched pulses obtained with the KORAD laser with electronic circuit [Fig. 2(a)] 200 ns/div.

B. JK Laser

A commercially available holographic ruby laser system (JK Laser System 2000) was adapted to our application. The oscillator has high mechanical stability, a higher gain than in the KORAD laser, and is equipped with two tilted intracavity etalons, which are thermally locked into the cooling system of the ruby rod to ensure maximum mode stability. Our alterations of the oscillator stage consisted in the use of a 80% rear mirror (instead of the supplied 100% mirror) and in replacing the Pockels cell supplied by JK by one from Lasermetrics with a quarterwave voltage of 1.15 kV. Nominal values of the JK 2000 system are a 30-J Q-switched pulse of 30-ns duration, which is obtained by the oscillator, followed by three amplifiers. An apparently uniform spatial energy distribution after the last amplifier in the near field is observed, as is customary for holographic lasers. It deteriorates in the far field, still giving a fairly homogeneous central region, but is surrounded by a hot ring of irregular shape (see Appendix). We did not observe any significant dependence of the spatial light distribution in the far field (~28 m) on pulse duration.

The feedback circuit of Fig. 2(b) was used initially to stretch laser pulses with the new JK laser. However, after field testing it was obvious that the circuit must be modified for our application to reduce the light spike at the beginning of the pulse and inhibit post lasing for ~1 ms (i.e., until the population inversion is depleted through spontaneous emissions). Also, ~10–20% of the stretched pulses showed ripple with a magnitude of >50%.

As with the compound feedback circuit of Lovberg *et al.*[11] stray capacitance is a significant factor that governs the response time of this circuit. Consequently, a stray capacitance of 20–50 pF can cause destabilizing delays of 50–100 ns. This allows the beginning of the laser pulse to pass through the Pockels cell without negative feedback. We reduced the initial light spike by shortening the RG58 cable length between the phototube and the feedback circuit: the effect of the reduction of the stray capacitance by ~30 pF on the laser light flux vs time was calculated by solving the laser rate equations and the Ohms law circuit and is shown in Fig. 4. For this calculation an algorithm called DVERK[14] was used. To improve further the bandpass characteristics of this system we removed the 1-kΩ resistor in series with the 0.03-μF capacitor on the feedback side of the Pockels cell [Fig. 2(b)].

For normal Q-switched operation of the laser, the delay between receiving the fire pulse and opening the Pockels cell is $\Delta \simeq 1.2$ ms. This is the time taken for sufficient population inversion to be built up in the oscillator, and it is set by the flashlamp characteristic. As part of the high energy physics experiment, the laser is used to make holograms of bubble chamber tracks of ~100-μm diameter. The fire pulse is derived from trigger electronics that detect when an interaction has taken place in the chamber. If we delay the laser pulse by 1.2 ms with respect to this trigger pulse, the bubbles will have grown to ~200 μm and will be too large for high resolution studies. It was thus necessary to find a way to operate the laser at reduced delay. Earlier work with the stretching circuitry also showed that operating the laser at delays of 0.8–1.0 ms reduced the initial pulse overshoot. At these short delays, higher pumping levels are needed and the pulse is extracted before the peak of the flashlamp output. Consequently, a large amount of the population inversion remains in the rod after pulse extraction, and we require that it decay by spontaneous emission. This means that the Pockels cell must be shut after the pulse is extracted so that no postlasing results.

We used a second Krytron to switch or clamp the Pockels cell voltage on the nonfeedback side to its quarterwave value. But we found that the KN6B Krytrons would fail in 1–2 days if they were triggered 3 times/min and held on for ~3 ms/trigger, not unexpectedly, since Krytons are not dc switches. Thus we developed a clamp that could switch ~1.2 kV in ~0.1–0.2 μs using a SCR (2N5207). In this slow turn-on circuit lasing did not occur until 1–2 μs after the start pulse triggered the feedback Krytron. Thus we replaced both the feedback and clamp Krytrons with 1.2 kV SCRs. Figure 5 shows the general layout of the JK laser system, feedback optics, and block diagram of the pulse stretching electronics with the clamping circuit, as used for the physics run. Figure 6 gives details of the electronics.

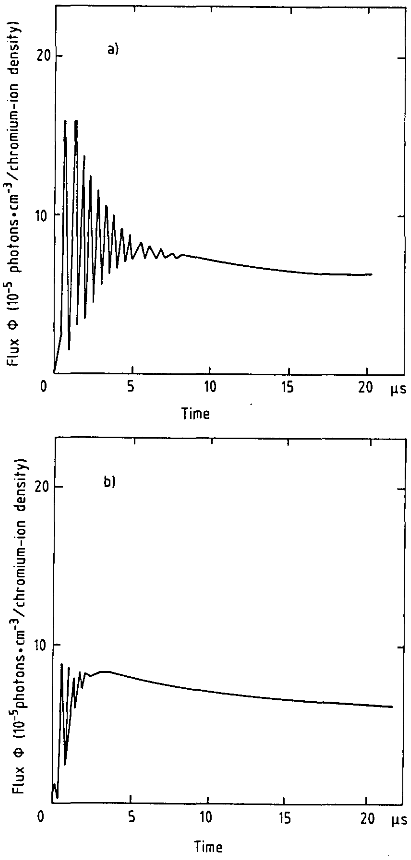

Fig. 4. Laser flux vs time calculated for feedback circuit shown in Fig. 2: (a) with 50-pF stray capacitance; (b) with 20-pF stray capacitance.

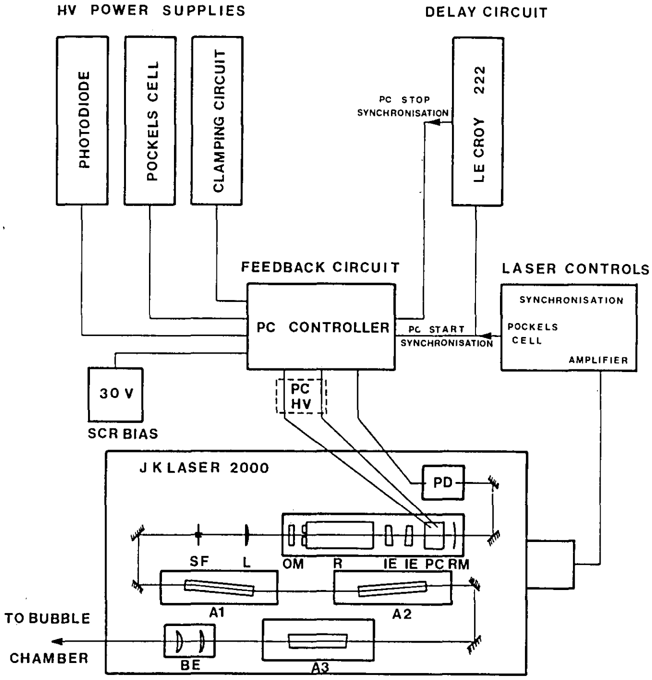

Fig. 5. Layout of the JK laser system 2000, feedback optics, and block diagram of the pulse stretching electronics (schematic): *PD*, phototube; *RM*, 80% reflective rear mirror ($r = 5$ m); *PC*, Pockels cell; *IE*, tilted etalons; *R*, ruby oscillator; *OM*, output mirror; *L*, focusing lens; *SF*, spatial filter; *A*1, *A*2, *A*3, amplifiers; *BE*, beam expander.

The SCR circuit functions in the following manner: Initially the feedback side of the Pockels cell ($V1$) is at ground level, and the nonfeedback side ($V2$) is biased to a negative 1.1 kV, its quarterwave potential. Then a CMOS pulse from the JK controls, called the Pockels cell synchronization (sync), triggers the feedback SCR causing it to close and allowing the voltage at $V2$ to decay exponentially to ground with an RC time determined by the 500-Ω resistor and the 0.03-μF capacitor at $V2$. As lasing begins the voltage at $V1$ swings positive and tries to follow the laser light hitting the feedback phototube. The magnitude of this positive voltage at $V1$ can be adjusted by the bias voltage across the phototube. The bias level typically ran between 250

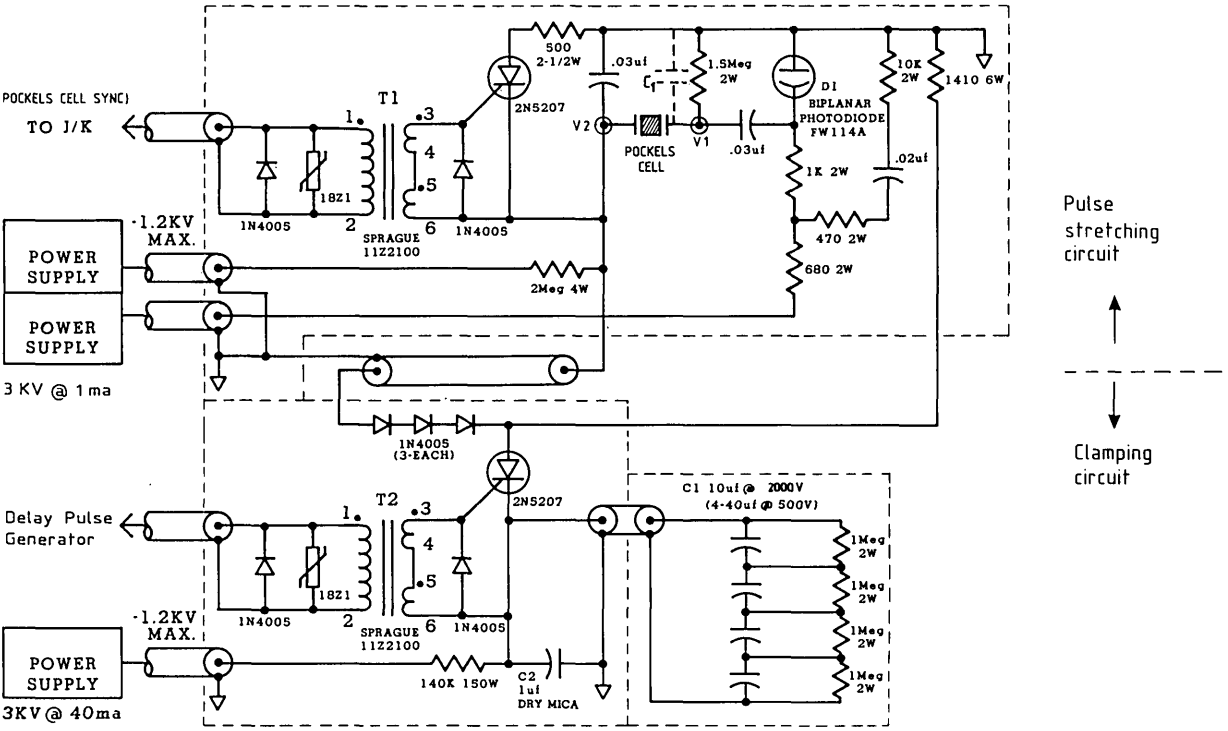

Fig. 6. Pulse stretching and clamping circuit electronics for the JK laser system: upper part, stretching system; lower part, clamping system.

and 400 V. If a 20-μs pulse is desired, 20 μs after the Pockels cell sync occurs a second TTL pulse is produced by a LeCroy 222 delay pulse generator. This triggers the clamp SCR and closes it so that $V2$ now sees −1.1 kV within ~0.2 μs. Since the holding current for the 2N5207 SCRs is ~40 mA we needed to supply a stored charge source capable of providing an average current of 40 mA for ~3 ms that would not trip off while providing initially much higher instantaneous peak currents. Thus the 10-μF capacitor bank was added, ensuring that the clamping circuit was effective for ~1 ms after the pulse is extracted. This allows the oscillator rod inversion to decay harmlessly by spontaneous emission. After ~3 ms the current through the two SCRs drops below the holding level, and both switches turn off. At this point the various HV power supplies begin recharging the circuit. A typical voltage waveform at $V2$ and $V1$ is shown in Fig. 7. The minimum switching time (set by the RC constant for the top SCR) is ~1 μs, which results in a minimum reliable pulse length of ≥ 2.5 μs. For pulse durations of ≤ 20 μs we must change the RC for the top SCR as it now switches the Pockels cell on in ~20 μs (for 40-μs pulses).

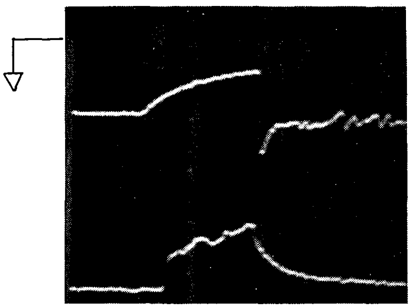

Fig. 7. Voltage waveform on the two sides of the Pockels cell (10 μs/div): The upper trace is the monotonically decreasing voltage $V2$ (500 V/div). The initial value of $V2$ is −1000 V. The lower trace is the feedback voltage $V1$ (200 V/div).

Best pulses with shorter delays are obtained by matching the Pockels cell voltage V_{PC} with the oscillator voltage V_{osc} and the Pockels cell delay Δ. These can be adjusted so that there is no prelasing or postlasing and no overshoot on the pulse to obtain the required energy in the pulse. These adjustments depend on the pulse duration, i.e., on the time dependence of the rod-inversion depletion. For shorter pulses, a longer delay must be used to extract the same energy. An alternative is to pump the amplifiers harder, but there is an upper limit due to saturation. Once the delay is set, the combination of V_{osc} and V_{PC} can control the overshoot of the pulse by sitting on the threshold for prelasing. If, for typical values of Δ and V_{osc}, the Pockels cell is shut too hard before the open signal from the circuit, an overshoot results due to the higher inversion buildup before punch-through initiates the pulse. Hence the Pockels cell is used as a threshold device at 60–80% of the quarterwave voltage. This allows for more easily controlled pulse buildup and may explain the increased coherence length. Reducing the delay further results in postlasing and the deficiency of required energy in the pulse. An alternative to reduce this delay further is to reduce the buildup time of the laser by reconfiguring the inductance/capacitance circuit.

If the delay is set so that the Pockels cell is shut ($V_{PC} \simeq 1.1$ kV) throughout the peak of the flashlamp output (e.g., $\Delta \geq 1.55$ ms) and if the oscillator is run hard ($V_{osc} \simeq 2.3$ kV), a giant (Q-switched) pulse is extracted. This pulse has FWHM of ~220 ns and is extracted at ~0.9 ms after the fire pulse when the flashlamp cycle begins. As punch-through begins and it detects the laser light, the phototube supplies a large voltage spike to the Pockels cell. This then opens the cell allowing a giant pulse to build up from the peaked inversion. The circuit is behaving like an electronic passive Q-switch where the onset of punch-through causes the Pockels cell/phototube combination to bleach. There is sometimes a small amount of postlasing, but this contains ≤1% of the total energy of the pulse and is not a worrying effect. A clamping circuit could be built to cure this if necessary. The coherence length was 1–1.5 m due to the high pumping level allowing several longitudinal modes to oscillate. This form of pulse was useful, however, as it enabled us to switch easily between stretched and short pulse operation.

Figure 8 shows pulses of various duration, measured after the last amplifier to have better control over the effects of the amplifiers on the form of the pulse. A small part of the light scattered from one of the beam handling mirrors is detected with an ultrafast silicon photodiode (FND-100). Seventy-five percent of these pulses are remarkably flat with no spike at the beginning. The other 25% of the pulses develop a spike usually in the beginning of the pulse. This spike is only 1.5 times bigger in magnitude than the rest of the pulse and has a FWHM of ~100 ns. The overshoot is a result of a sudden higher buildup of the oscillator gain and seems to be unavoidable. None of the pulses exhibit mode beating; and there was no prelasing or postlasing 95% of the time. For very long pulse durations depletion of the ruby rods becomes apparent [Fig. 8(d)]. Typical output energies of the oscillator were 20–25% mJ, which could be amplified up to 5 J, while retaining smooth output energy waveform in time. Pumping the amplifier rods beyond this energy has negative effects on the pulse shape as does any backreflection from the optical surfaces in the system (see the Appendix). Longer pulses are more reproducible. The amplitude of 40-μs pulses has a jitter of ±5% measured at the output energy of 2.5 J, while that of 4-μs pulses is as high as ±10% measured at the same energy. Stretching beyond 100 μs does not appear to be desirable for our application due to vibration and bubble movement. The maximum repetition rate of the laser with output energies of ≤8 J is about once every 8 s.

A remarkable asset of stretched pulses is the considerably increased coherence length compared with the Q-switched operation (~1–2 m). It was measured in the laboratory with a layout shown in Fig. 9. Replayed holograms are displayed in Fig. 10 where the field visible has a depth of ~4–5 m.

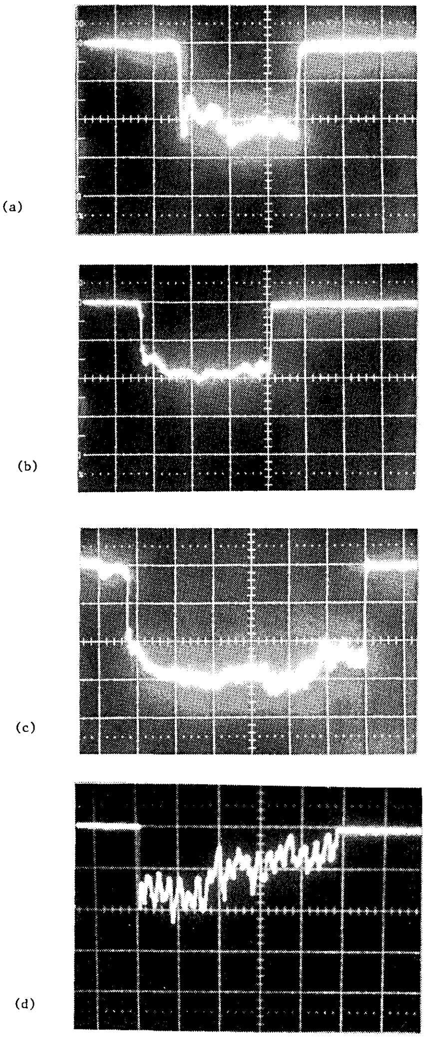

Fig. 8. Typical light pulses obtained in the JK laser with the compound feedback and clamping circuit: V_{osc}, oscillator voltage; V_{PC}, Pockels cell voltage; V_{cl}, clamping circuit voltage; Δ, delay between firing of flashlamp and opening of the Pockels cell.

	V_{osc} (kV)	V_{cl} (kV)	V_{PC} (kV)	Δ (ms)
(a) 6.5-μs pulse (2 μs/div)	1.68	1.20	0.80	1.06
(b) 35-μs pulse (10 μs/div)	1.80	1.15	0.95	0.98
(c) 63-μs pulse (10 μs/div)	1.82	1.15	0.95	0.95
(d) 95-μs pulse (20 μs/div)	1.65	1.15	0.93	0.95

The coherence length for each pulse duration was measured for a sample of ten pulses separated by 60 s and twelve pulses separated by 10 s: no dependence on the repetition rate was observed. The energy of the pulses of various durations was set to 150 mJ: no change for higher energy is expected. The results of all measurements are shown graphically in Fig. 11. The ordinate is the observed white light diffraction from the holograms. This coherence length is defined as the path difference between the reference and object beams for which the diffraction efficiency on reconstruction is observed to fall to ~10% of its peak value. Running with a single Q-switched pulse of $\tau_{FWHM} = 85$ ns (derived using an 80% rear reflector in the cavity and the reinstalled proprietary Q-switching

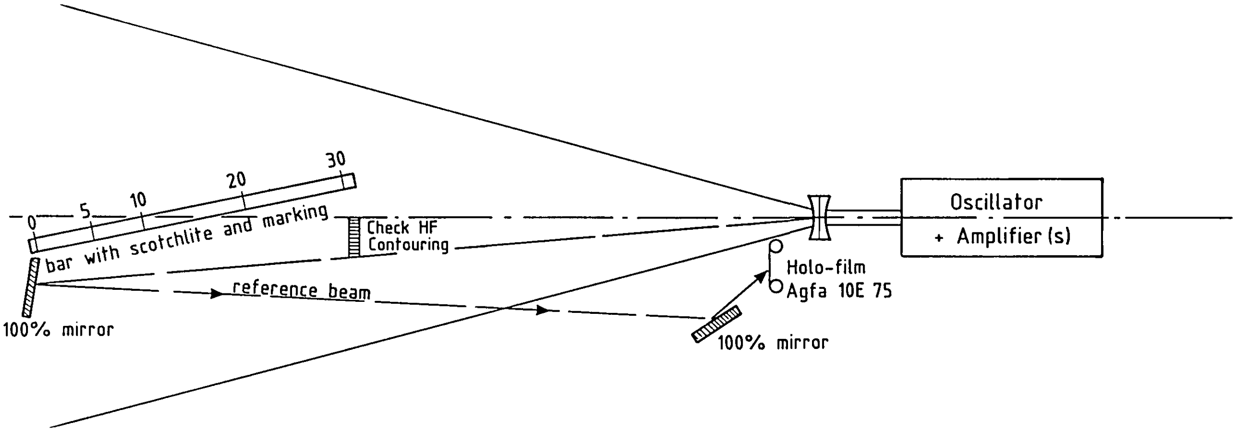

Fig. 9. Layout for the holographic measurement of the coherence length (schematic). The small bar perpendicular to the beam serves for checking the high frequency contouring.


(a) (b)

Fig. 10. Replayed holograms of stretched pulses from the JK laser obtained with the setup of Fig. 9. The mark 30 on the Scotchlite bar corresponds to 3-m length: (a) 2.5-μs pulse duration; (b) 10-μs pulse duration.

system), we obtained ~1.5–2-m coherence length. By using the double pulsing feature of the oscillator with the least possible pulse separation (~20 μs) and the bias set to produce the most power in the second pulse ($\geq$95%), the coherence length is observed to increase in ~60% of the pulses to nearer 3–3.5 m but in the rest of the pulses is ~1.2 m. As with pulse stretching the mechanism for this is prevention of the high gain oscillator cavity latching onto several modes at the onset of the pulse, as the first pulse is of small amplitude. This double pulsing technique needs further investigation to obtain reliable results.

The coherence length for 2.5 μs $< \tau_p \leq$ 15 μs is consistently in excess of 8 m, and that for τ_p = 2.5 μs is even in excess of 11 m. This latter result arose by putting in an extra 3 m of path length for the reference beam keeping the geometry otherwise the same as for the other measurements. Due to the layout of the room, we were unable to increase further the path difference, and so the figure of 11 m is only a lower

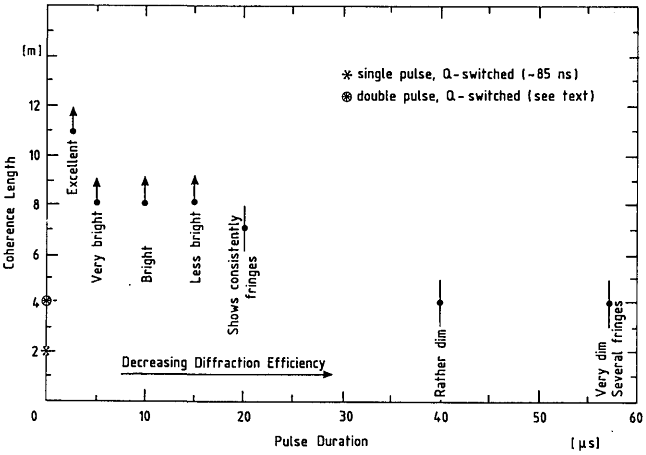

Fig. 11. Dependence of coherence length on pulse duration of the stretched pulse obtained with the feedback circuit in the JK laser. ↑ Lower limit on the value of the coherence length. The path difference is limited by laboratory layout as explained in the text.

bound on the coherence length of the 2.5-μs pulses. No fringes are present in the whole recorded field, and there is no discernible loss of brightness in the reconstruction due to coherence effects from the recording laser.

The gradual decrease in diffraction efficiency observed for 5 μs ≤ τ_p ≤ 40 μs is almost certainly due to movement of the reference beam during exposure, and the fringes observed in the longer pulses due to mode mixing from the oscillator caused by either the oscillator movements and/or the temperature instability of the etalons during these long exposures.

Pulse stretching is also desirable for transporting high energy laser light for use in holography through optical fibers since they are easily destroyed at high power densities. It might find application in a two-beam technique for large bubble chambers[15] proposed as an alternative to the one-beam holography.

III. Conclusions

It has been shown that stretched pulses with adjustable duration up to 100 μs in the TEM_{00} mode can be obtained from a ruby oscillator stage, which is equipped with a negative feedback system and clamping circuit. This increase in pulse length from 30 ns to 40 μs at the energy level of a few joules suppressed boiling in the bubble chamber liquid. The stretching also considerably increased the coherence length, and the time structure and duration of the pulse remained essentially unchanged after passage through three amplifiers. Future applications of stretched pulses may include the transport of high intensity laser light through fibers and the holography of volumes larger than previously possible with a Q-switched ruby laser due to increased coherence length.

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G. Harigel also holds an appointment with Columbia University. H. Bjelkhagen is on leave of absence from the Division of Production Engineering of the Royal Institute of Technology (Sweden).

Appendix: Effects from Amplifiers and Backreflections

Laser light from a ruby oscillator stage will suffer (some) spatial and temporal distortions after passage through amplifiers. These effects are discussed in detail in textbooks (see, e.g., Ref. 16).

In our tests, we were able to produce flat stretched pulses through the amplifiers only if they were pumped moderately, that is, ≤ 5 J. Pumping the rods above this energy caused nonuniformity and high modulations in the pulses. It is not certain whether these variations are only due to nonlinearities in the amplifier rods, which become important for high pumping voltages or amplification of backreflections from the optical surfaces in the laser system which are negligible for lower energies. This could be determined by using an optical isolator just after the oscillator. Yet we were able to study the effect of backreflections from the optical surfaces after the last amplifier, which is similar to the effect of high pumping of amplifiers.

Any laser light reflected from downstream beam elements (mirrors, apertures) is amplified backward and will reach the phototube of the feedback circuit. It can change the time structure of the stretched pulse considerably: Figs. 12(a) and (b) show the light output from the laser and the voltage response of the fast photodiode for a pulse stopped immediately behind the last amplifier and one going all the way to the bubble chamber. Such an unwanted effect can be suppressed to a large extent by proper antireflection coating of optical elements in the beam path by baffles to absorb straylight and by an optical isolator installed behind the last amplifier.

Spatial distortions arise from nonuniform pumping, nonuniformities in the active material, gain saturation, diffraction effects, and thermal distortions. We attribute the observed far-field structure of our beam essentially to the nonuniform pumping of the rods with symmetrically arranged linear flashbtubes: the oscillator has two, the first and second amplifier four, and the third amplifier six such tubes. The almost hexagonal structure of the hot ring of the beam in the far field (28 m), observed only after focusing the beam once in vacuum and not present otherwise, indicates that the

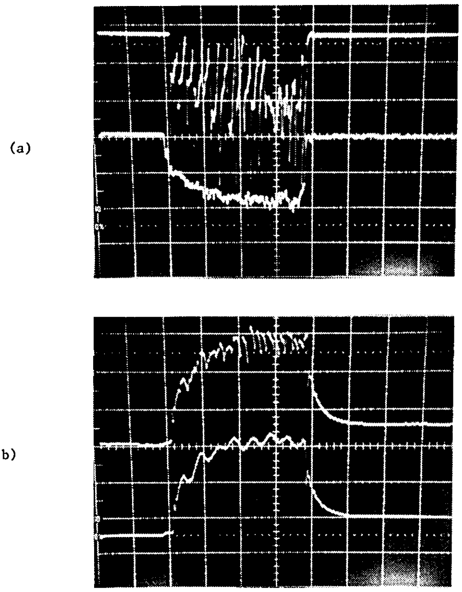

Fig. 12. Effect of backreflections (10 μs/div). Upper trace: pulse going into bubble chamber; lower trace: pulse stopped after last amplifier: (a) light output from laser; (b) voltage response of feedback phototube.

deviation from Gaussian profile originates mostly from nonuniform pumping of the amplifiers.

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