# Autocorrelation measurements of bursts of picosecond pulses

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In a master oscillator power amplifier system a powerful train of pulses can be generated. A simple method is described to measure the duration of these pulses. The measurements have been performed both at the fundamental frequency (1053 nm) and at the second harmonic (527 nm). In accordance with theoretical expectations we have observed a narrowing of the pulse owing to frequency doubling. © 1996 Optical Society of America

## 1. Introduction

A prerequisite for building a high-quality free electron laser is the use of a high-current, high-brightness electron beam with a low-energy spread. The best way to produce such a beam is with a radio-frequency linear accelerator with a photocathode. Such a photocathode (in our case an alkali-antimonide cathode) must be illuminated by a train of short pulses produced in a master oscillator power amplifier (MOPA) laser system. Because the temporal shape of the electron pulse is determined by the temporal shape of the laser beam, it is essential to have a reliable tool to measure the duration of the pulses.

Our MOPA laser system uses a Nd:YLF laser. The pulses from this laser are amplified in two double-pass Nd:YLF amplifiers. A calculation shows that a 20-ps pulse is broadened to 20.5 ps because of the finite bandwidth of the amplifier medium. So it is important to measure the pulse duration of the pulses in the amplified pulse train. This pulse train is several microseconds long, and the pulses have an energy of ~10 μJ (at 1053 nm). There is no easy-to-use autocorrelator available to measure the duration of these pulses.

A simple method is described to determine the autocorrelation signal of short trains of pulses with intermediate energies. The method is compared with a conventional autocorrelation technique, and the results of the measurements in the IR and the green are presented.

## 2. Experimental Setup

Our MOPA system consists of a cw mode-locked Nd:YLF laser that produces a continuous train of 50-ps pulses at 1053-nm wavelength with a repetition rate of 81.25 MHz, a fiber-grating pulse compressor, an acousto-optic modulator (AOM) that slices out a short train of pulses, two double-pass pulsed Nd:YLF amplifiers in which sub nanojouls pulses are amplified to the 10-μJ level, and a lithium triborate crystal in which noncritically phase-matched frequency doubling takes place. A more detailed description of the system can be found in Ref. 1.

The temporal structure of the beam is as follows: It consists of 15-μs-long pulse trains called macropulses. The repetition rate of these macropulses is adjustable from 0 to 10 Hz. The individual pulses from the Nd:YLF laser are called micropulses. These pulses are ~20 ps long and are spaced 12.3 ns apart.

It is important in the application to determine experimentally the time shape of the output beam at different places in the system. The duration of the micropulses before the AOM, thus before the macropulses are formed, has been measured with a commercially available autocorrelator (Inrad Model 514B). The operating principle of this autocorrelator is as follows: The incoming beam is split into two equal parts, each following a different path in the autocorrelator. The two parts are recombined in the nonlinear crystal where they generate the autocorrelation signal (see also Fig. 1).

In each optical path a rotating block is present. In the equilibrium position the optical lengths of both paths are equal. For a certain angular deviation from the equilibrium position, a delay advance of $\tau/2$

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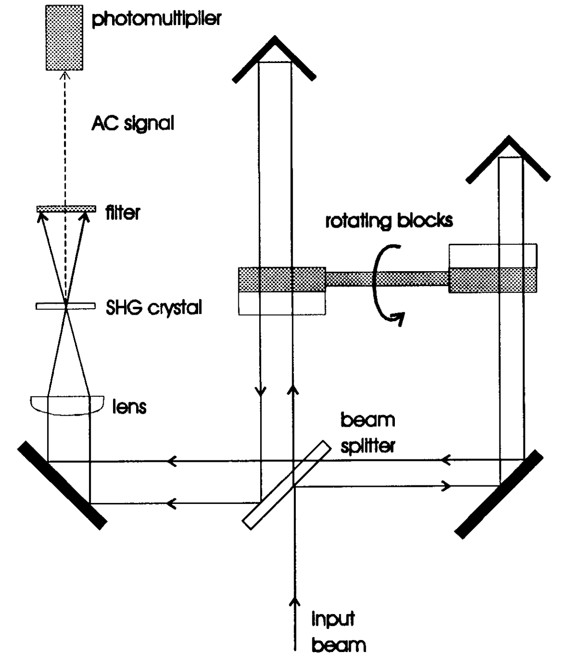

Fig. 1. Alignment of the Inrad Model 514B autocorrelator. The photomultiplier is a Hamamatsu Model R212UH. SHG, second harmonic generation.

is introduced into each path. Because of the relatively low rotation frequency of the delay blocks (15 Hz) it takes ~2 ms to vary the delay longer than 20 ps, which means that each measurement requires at least a 2-ms-long train of pulses.

The above-mentioned technique cannot be used directly to measure the pulse duration after the amplifiers or after frequency doubling because the macropulses are only 15 μs long, which is ~2 orders of magnitude too short. On the other hand, a single-pulse autocorrelation technique as originally developed by Wyatt and Marinero[2] also cannot be used because a much larger energy per micropulse (at least 35 μJ/micropulse) is necessary to obtain a reasonable signal-to-noise ratio.

## 3. Autocorrelation Measurements of Bursts of Pulses

The usual technique for measuring autocorrelation traces of bursts of pulses is to vary the delay between the two pulses manually and then take an autocorrelation measurement while keeping the delay fixed in time. However, if the bursts of pulses come regularly with a fixed repetition frequency $f_b$, a very simple autocorrelation technique can be used with the help of the Inrad autocorrelator. In this autocorrelator an autocorrelation measurement is performed at each rotation of the delay blocks. A trigger pulse is generated at the start of the autocorrelation trace. Suppose the rotation frequency of the blocks is $f_{\mathrm{rot}}$. The phase $\phi$ between the rotation frequency and the macropulse repetition frequency is given by

$$\phi = (f_{\mathrm{rot}} - n f_b)t, \tag{1}$$

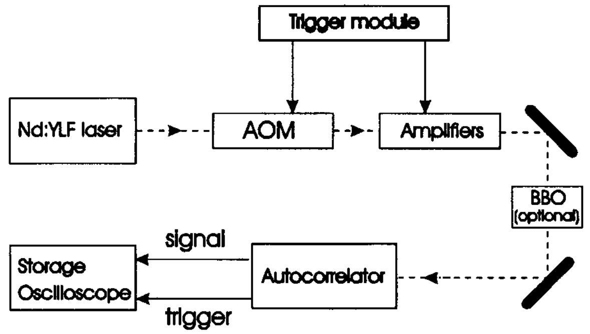

Fig. 2. Schematic of the experimental setup that was used to measure the duration of the micropulses after amplification. The optional BBO crystal can be used to frequency double the pulses.

where $t$ is the time at which the phase is determined. Suppose the rotation frequency $f_{\mathrm{rot}}$ equals $f_b$ or is the $n$th subharmonic of $f_b$, then each autocorrelation measurement is done at the same phase difference $\phi$ between the two frequencies and thus at the same optical delay time. However, if $f_b$ is not exactly equal to $f_{\mathrm{rot}}$ or a subharmonic of $f_{\mathrm{rot}}$, each measurement is performed at a different phase $\phi$ and thus at a different optical delay time between the two pulses.

Each micropulse yields one point in the autocorrelation trace. A macropulse consists of 1200 micropulses and will therefore yield 1200 points in the trace. These points are indistinguishable owing to the finite bandwidth of the photomultiplier and the electronics. The resulting point in the autocorrelation trace is an average of greater than one macropulse. Using a storage oscilloscope, we can measure a complete autocorrelation trace. As can be seen from Eq. (1), $\mathrm{d}\phi/\mathrm{d}t$ can be adjusted by changing $f_b$. Hence the time required for measuring a complete autocorrelation trace can be chosen by changing $f_b$. In our experiment $f_{\mathrm{rot}}$ is a fixed frequency and equals 15 Hz and $f_b$ can be set to a value close to 7.5 Hz. A schematic of the experimental setup is shown in Fig. 2.

## 4. Results

The pulse duration has been measured at three positions in the beam line: once before slicing out the macropulse, once again after amplification of the macropulse, and finally after frequency doubling the macropulse. To measure the autocorrelation pulse duration in the visible, the $\mathrm{LiIO_3}$ crystal was replaced by a 1-mm β barium borate (BBO) crystal.

The results of these measurements can be found in Fig. 3. These autocorrelation traces are Lorentzian curves, which are deconvolved into Lorentzian pulse shapes. The conventional autocorrelation trace (Fig. 3A) yields a pulse full width at half-maximum (FWHM) of (19.1 ± 0.4) ps. This may be compared with the trace in Fig. 3B, which was measured after the macropulse had been sliced out. The FWHM of these pulses was (17.6 ± 1.6) ps, which is within the margin of error equal to the result obtained with the conventional autocorrelation method.

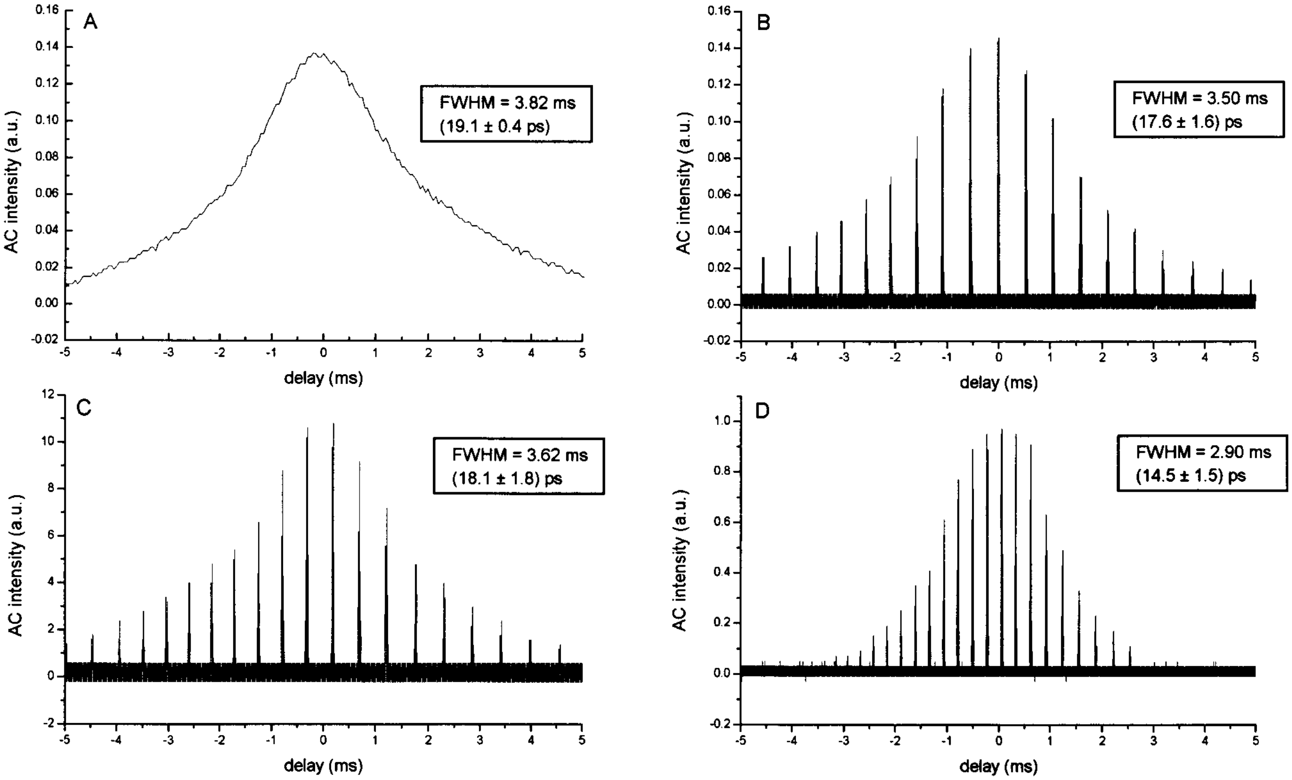

Fig. 3. A, ac trace from an infinitely long pulse train, measured before the macropulse is sliced out. B, ac trace measured after the macropulse has been sliced out. C, ac trace measured after the macropulses have been amplified. D, ac trace of the pulses after the amplified macropulses have been frequency doubled.

Further measurements yield FWHM = (18.1 ± 1.8) ps after the macropulse has been sliced out and amplified (see Fig. 3C) and FWHM = (14.5 ± 1.5) ps after frequency doubling the amplified macropulse (see Fig. 3D).

The trace in Fig. 3A, measured before the macropulse was sliced out of the continuous pulse train, appears to be a continuous trace. This is because the bandwidth of the electronics behind the photomultiplier is too small to resolve the individual micropulses. The peaks that are shown in the other traces in Fig. 3 originate from the 15-$\mu$s-long macropulses. The delay difference between these macropulses can be adjusted by changing $d\phi/dt$ according to Eq. (1). Because the autocorrelation curve is composed of several macropulses, it is essential that the fluctuation in the amplitude of these macropulses be small. In our case this fluctuation is less than 1%.

## 5. Conclusions

We have successfully demonstrated a technique for measuring the autocorrelation traces of bursts of picosecond pulses. This technique has been used to measure the duration of pulses in short-pulse trains of intermediate energy (of the order of 1 $\mu$J/micropulse). The results from this method are comparable with those obtained by more conventional techniques.

According to the measurements presented in this paper, the pulses that are generated by our MOPA system are of the correct duration to be used in free electron laser experiment. The predicted increase in pulse duration owing to the amplification of the macropulse was well within the experimental margin of error, and hence it was not observed.

The traces shown in Fig. 3 were not measured simultaneously. Because the autocorrelation curves have been measured at several positions in the beamline, the autocorrelator had to be repositioned and realigned between measurements. It is possible that during this realignment the duration of the Nd:YLF laser pulse has changed owing to cavity detuning caused by temperature effects. This may account for the observed variations in the pulse duration.

We have also found within the experimental error the ratio of $\sqrt{2}$ in the duration of the pulses in the IR and the visible.

## References

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