FSAC

Interferometric Autocorrelator

User Guide

Table of Contents

Chapter 1 Warning Symbol Definitions

Below is a list of warning symbols you may encounter in this manual or on your device.

Symbol	Description
	Direct Current
	Alternating Current
	Both Direct and Alternating Current
	Earth Ground Terminal
	Protective Conductor Terminal
	Frame or Chassis Terminal
	Equipotentiality
	On (Supply)
	Off (Supply)
	In Position of a Bi-Stable Push Control
	Out Position of a Bi-Stable Push Control
	Caution: Risk of Electric Shock
	Caution: Hot Surface
	Caution: Risk of Danger
	Warning: Laser Radiation
	Caution: Spinning Blades May Cause Harm

Chapter 2 Safety

All statements regarding operational safety and technical data in this manual will only apply when the unit is operated correctly.

WARNING

Always wear appropriate laser safety eyewear during laser setup and operation.

WARNING

Use Appropriate Laser Safety Eyewear when Working with Lasers

WARNING

Visible and invisible radiation may be present.

Please note that while this is a passive device, lasers that emit high-power radiation are used in conjunction with this device. Safe practices and proper usage of safety equipment should be taken into consideration when operating lasers. The eye is susceptible to injury, even from very low levels of laser light. Laser emission in the visible and near infrared spectral ranges has the greatest potential for retinal injury, as the cornea and lens are transparent to those wavelengths, and the lens can focus the laser energy onto the retina. Follow all safety precautions in the operator's manual.

1. Never aim any laser at a person's eye, skin, or clothes.
2. Always use proper laser safety eyewear.
3. Avoid wearing watches, jewelry, or other objects that may reflect or scatter the laser beam.
4. Keep the laser beam paths above or below eye level for both sitting and standing positions.
5. Ensure that individuals do not look directly into a laser beam.
6. Eliminate all unnecessary reflective surfaces from the vicinity of the laser beam path.
7. Ensure that all individuals who operate lasers are trained in laser safety and authorized to operate a laser. Do not leave a running laser unattended if there is a chance that an unauthorized user may attempt to operate the laser. A key switch should be used if untrained persons may gain access to the laser. A warning light or buzzer should be used to indicate when the laser is operating.
8. Use low power settings, beam shutters, and laser output filters to reduce the beam power to less hazardous levels when the full output power is not required.
9. Make sure that spectators are not exposed to hazardous conditions.

Chapter 3 Description

3.1. Introduction

Thorlabs' FSAC is an interferometric autocorrelator capable of quantitative and qualitative monitoring of ultrafast pulses from tens of femtoseconds to 1 picosecond. A modified Michelson interferometer splits an input pulse into two copies, modulates the delay between them, and recombines the pulses at a photodiode. Because the photodiode is not responsive over the fundamental wavelength band of typical Ti:sapphire lasers, two-photon absorption is required to generate photocurrent. This results in nonlinear responsivity in the detector which enables the interferometric autocorrelation.

3.2. Shipping List

The FSAC consists of the following components:

- FSAC Autocorrelator
- CL5 Mounting Clamps (Qty. 2)
- 5/32" Stubby Hex Key
- VRC2SM1 Fluorescent Alignment Disk
- SM1CP2 End Cap
- R1DS3N Alignment Reticle
- LDS1212 Power Supply

Chapter 4 Setup and Operation

Environmental Requirements

The FSAC is intended for use in a laboratory setting, mounted on an optical bench, and should be operated under controlled conditions to achieve stable performance. Humidity control is required to prevent condensation from forming on optical surfaces. Keep the system away from air conditioning vents, which can cause sudden humidity and temperature changes.

Electrical Requirements

The following table lists the electrical requirements of the FSAC.

Electrical Requirements	
Input Voltage	±12 VDC
Power Consumption	6 W (Max)

The FSAC is designed to use the included Thorlabs LDS1212 power supply, which meets these requirements.

4.1. Optical Requirements

The FSAC is designed for horizontally polarized light (i.e., parallel to the plane of the table). In addition to allowing the beam height to be adapted to the FSAC input aperture height (3"), a periscope such as Thorlabs' RS99 (Figure 2) may be used to rotate the laser polarization by 90 degrees, if necessary. Alternatively, if additional dispersion is acceptable, a half-wave plate may be used to rotate the polarization.

The noise equivalent sensitivity of the FSAC is approximately $10^{-1}\ \mathrm{W}^2$ (found by multiplying the average laser power by the peak power) at 800 nm for a 1 mm beam diameter ($1/e^2$). For the same beam parameters, the response of the photodiode saturates at about $10^3\ \mathrm{W}^2$. Thus, for an 800 nm, Ø1 mm beam, the peak-average power product should fall between 1 and $10^3\ \mathrm{W}^2$. If the peak-average power exceeds this level, then the average laser power of the beam entering the FSAC should be attenuated (by using a neutral density filter or a Fresnel reflection from an uncoated window, for example). The peak-average power product is roughly inversely proportional to the square of the beam size, and may be scaled accordingly to roughly estimate the usable peak-average power range. For example, with a Ø4 mm beam, the peak-average power product will decrease by a factor of roughly 16 compared to that for a Ø1 mm beam.

To avoid damaging the FSAC optics, the average power of the input laser should not exceed 150 mW.

The FSAC is designed for lasers with transform-limited pulse durations ranging from 40 fs to 1 ps, but may be used for measuring pulses as short at 15 fs with dispersion compensation. See Section 4.5 for more details.

4.2. Setup and Coarse Optical Alignment

WARNING

Always wear appropriate laser safety eyewear during laser setup and operation.

The FSAC is roughly 7" x 6" (18 cm x 14 cm) in size and requires about 10" x 6" (25 cm x 14 cm) of optical table space when two CL5 mounting clamps are used to secure the FSAC to the table (see Figure 1). In this configuration, the autocorrelator beam height is 3" (76.2 mm) from the table surface. Alternatively, three 1/4"-20 and three M6 x 1.0 tapped holes on the bottom of the FSAC allow mounting with Thorlabs' RS pedestal posts (not included) or other mounting configurations. Ensure that that LDS1212 power supply is set to the appropriate line voltage, then connect the LDS1212 power supply to the autocorrelator and set the power switch on the LDS1212 to 'On.' Next, use the FSAC power switch to turn the autocorrelator on.

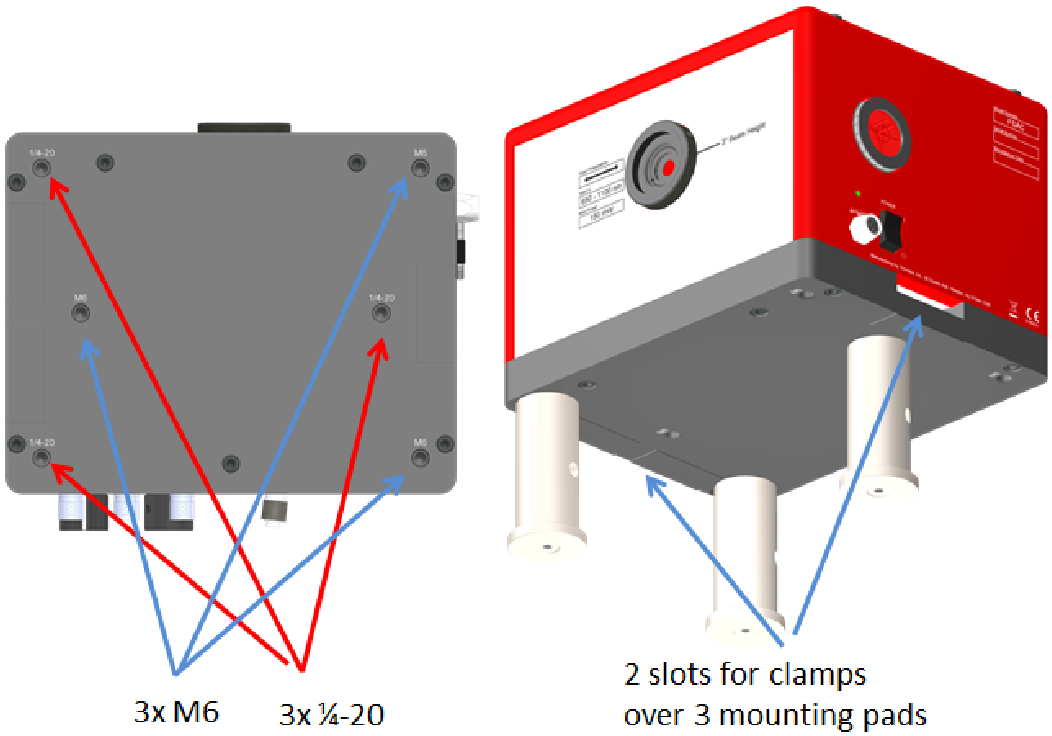


Figure 1 FSAC Mounting Features

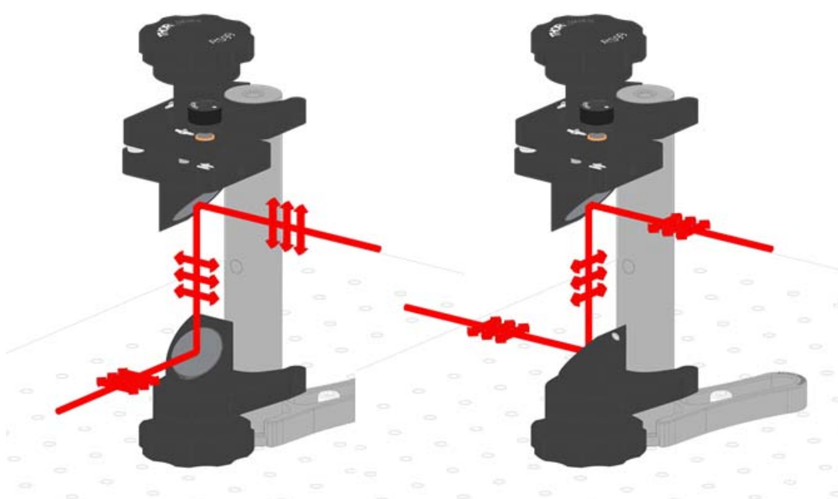


Figure 2 Thorlabs' RS99 Periscope may be used to change the beam height while either maintaining the beam polarization or rotating it by 90 degrees.

Attach the VRC2SM1 fluorescent alignment target to the alignment aperture of the FSAC (Figure 3). The input aperture iris and the fluorescent alignment target provide two points which define the optical axis of the autocorrelator. When the input beam is centered on both points, the system will be close to optimal alignment. To achieve this, use two steering mirrors with tip and tilt adjustment in front of the autocorrelator as shown in Figure 4.

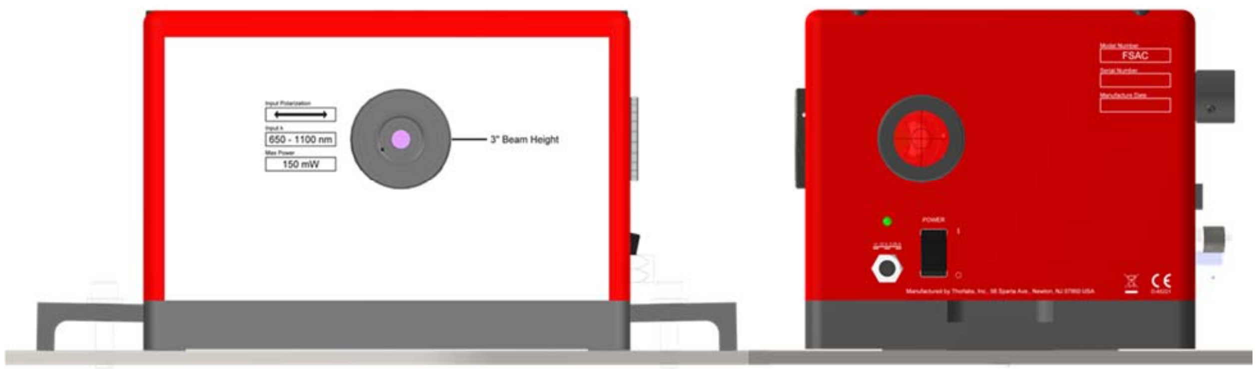


Figure 3 Front and Side Views Showing the Input Aperture (Left) and Alignment Aperture (Right)

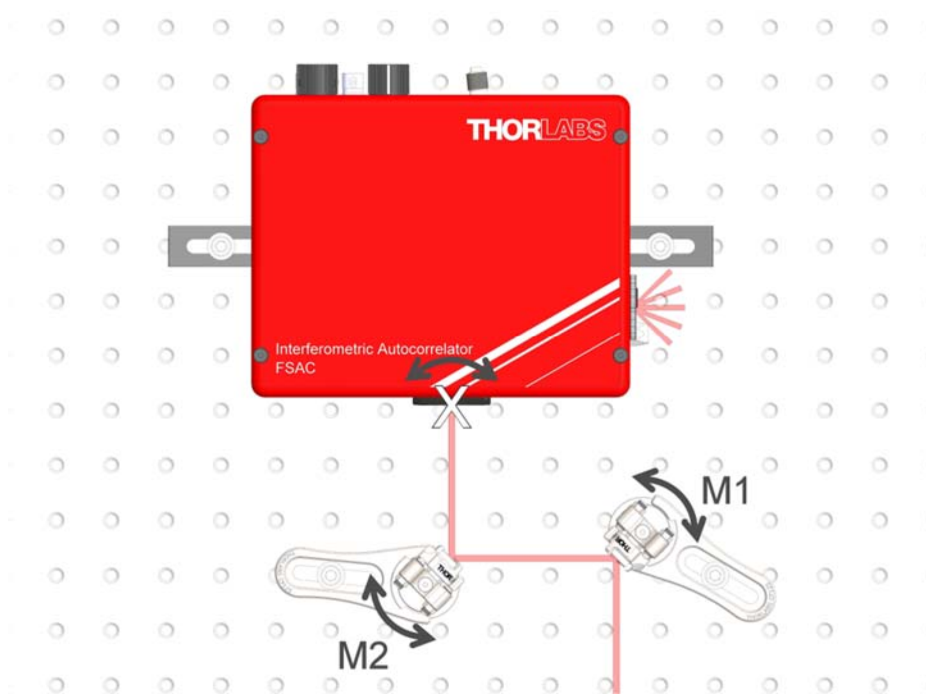


Figure 4 Use two mirrors to center the beam on the input port and alignment aperture.

The easiest way to complete the coarse alignment of the FSAC is to start by using the steering mirror to set the beam height to that of the autocorrelator input aperture, and ensure that the beam is parallel (level) to the table. M1 is adjusted to set the height of the beam, and M2 is used to level the beam, usually in alternating fashion. The FSAC may be moved towards M2 to check the height, and away from M2 to check the level. Several iterations may be required. Once the beam is level, place the FSAC at the desired location so that the beam is centered on the aperture. Open the aperture so that the beam just passes, then carefully rotate the entire FSAC about the input aperture (marked by the white X in Figure 4) until the beam spot on the alignment target is roughly centered. Make minor adjustments until the beam is roughly centered on both the input aperture and the VRC2SM1 alignment target. Note that when the FSAC is grossly misaligned, spurious reflections may appear on the alignment target, so be sure to look for the brightest spot.

Once the beam is centered on both the input aperture and target, use the CL5 clamps (or other mechanism) to secure the FSAC to the table. Finally, alternate between using the adjustment on M1 to align the beam to the input aperture and using M2 to align the beam to the alignment target, stopping when it is very well centered in both places. The coarse alignment is complete.

WARNING

Up to 100% of the input light may exit the alignment aperture if it is not blocked by the fluorescent target or an end cap.

Alternatively, if space is constrained or the position of the FSAC is fixed, M1 and M2 may be used to perform the full alignment. The input beam should first be aligned so that it is centered on the input aperture, and approximately perpendicular to the input aperture of the autocorrelator. Attaching the R1DS3N negative crosshair reticle to the input port and using the back reflection can help with this coarse alignment (you may need to take care that the beam is not perfectly retroreflected back to the laser cavity). Alternating between the two, the first mirror (M1 in the diagram) should be used to roughly center the beam on the reticle, and the second mirror (M2 in the diagram) should be used to adjust the reflected angle to within a few degrees of the incident beam. Next, remove the reticle from the input aperture. The beam should now appear on the VRC2SM1 fluorescent target. If not, try scanning M2 until it appears. If it still does not appear, confirm that the beam is very close to perpendicular to the FSAC input surface. Once the beam is visible on the alignment target, alternate between using M1 to center the beam on the input aperture and using M2 to center the beam on the fluorescent alignment disk. Note that when the FSAC is grossly misaligned, spurious reflections may appear on the alignment target, so be sure to look for the brightest spot.

4.3. Operation and Fine Optical Alignment

4.3.1. Power

Figure 3 shows the side panels for the FSAC. Ensure that the LDS1212 power supply is on and connected. Push the power switch on the FSAC up to turn the device on. The momentary switch will return to the neutral position, and the power LED will turn green to indicate that the device is on. Push the power switch down to turn the power off.

4.3.2. Auto Shut Off

When not in use, the FSAC should be turned off by the user. In order to preserve the lifetime of the device, the FSAC is equipped with an auto-shut-off feature. Once the device is turned on, it will automatically turn off after approximately 12 hours.

4.3.3. Output Signals

Trigger, delay reference, and photodiode BNC outputs are available on the control panel as shown in Figure 5. The trigger signal is a 5 Hz, 5 V TTL signal synchronized with the delay scan rate which may be used to trigger acquisition by an oscilloscope or a digital acquisition (DAQ) card. This signal is particularly useful during setup and alignment. Once the autocorrelation trace is visible, triggering off of the autocorrelation signal itself allows for a more stable view. The delay reference output provides a voltage between -5 and +5 V that is proportional to the delay position, which can be helpful when setting up the autocorrelation trace (discussed below). The photodiode output provides the voltage signal from a variable-gain transimpedance amplifier connected to the photodiode. The output signal will contain the autocorrelation trace, and is between 0 and +10 V.

4.3.4. Controls

In addition to the BNC outputs, the control panel also provides four controls as shown in Figure 5. The delay stage is driven with a sinusoidal wave that is nominally centered about the zero-delay point (the center of the autocorrelation trace). The amplitude knob is connected to a 3-turn potentiometer which controls the amplitude of this drive wave, allowing the full delay scan range to be adjusted from 50 fs to 10 ps (i.e., ±25 fs to ±5 ps). The offset knob is also a 3-turn potentiometer. It adds an overall offset to the sine wave, which in effect moves the average position of the sine wave with respect to the zero-delay point. Its use is described in further detail below. The photodiode focus knob physically moves the position of the photodiode along the optical axis so it can be moved precisely to the focal point of the FSAC. A final knob switches the photodiode transimpedance amplifier gain from 0 to 70 dB in 10 dB steps.

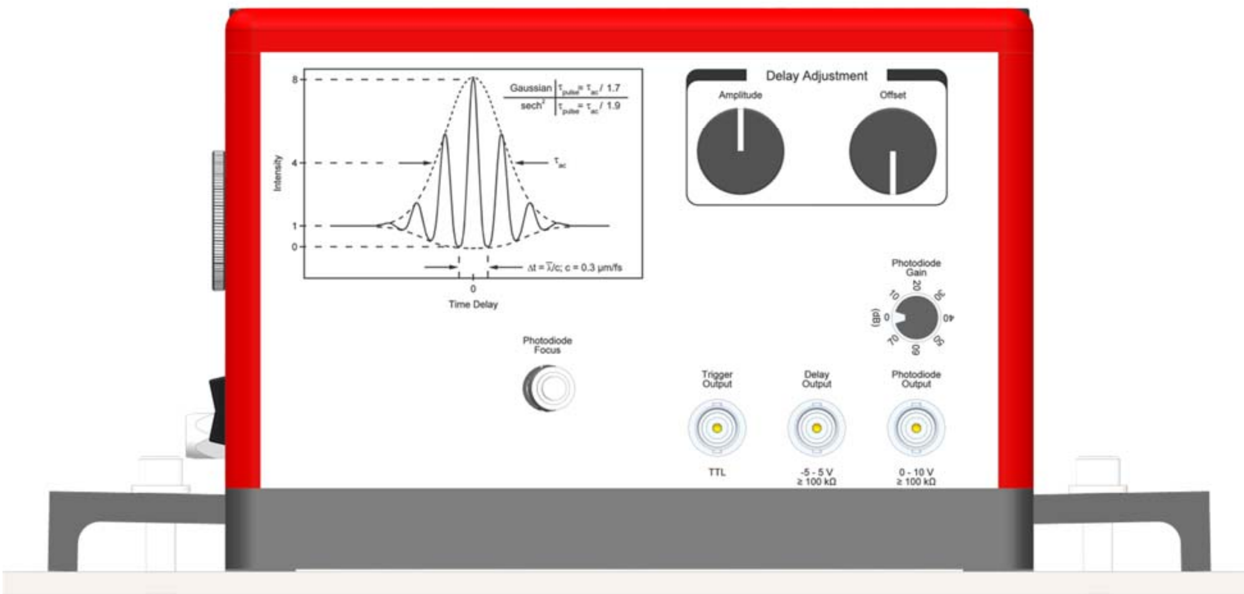


Figure 5 FSAC Control Panel

4.3.5. Fine Optical Alignment

After completing the coarse alignment procedure (Section 4.2), start by ensuring that the laser to be measured is mode locked. Next, turn the delay amplitude to its maximum value and monitor the delay output to verify that the stage is moving. The delay output should be roughly sinusoidal, though it may be somewhat distorted due to nonlinear coupling between the drive mechanism and the stage. Next, set the delay offset to approximately zero by turning the offset knob all the way in one direction, and then turning 1.5 turns in the opposite direction so that the indicator line is pointing up. The average voltage of the Delay Output should be near zero. Next, increase the photodiode gain as high as it can go without saturating any signal that may be present (the highest voltage should be less than +10 V). Adjust the photodiode focus position using the photodiode focus knob to maximize the photodiode output signal. You may need to decrease the photodiode gain as the signal increases. When the photodiode position is far from optimal, you can use the DC background of the photodiode signal for optimizing the position until the autocorrelation trace appears, at which point the peak signal of the autocorrelation trace may be used to optimize the position.

The autocorrelation trace should now be visible. Decrease the delay amplitude to better resolve the autocorrelation. You may now make small adjustments to M2 and the photodiode focus to optimize the signal. When the signal is optimized, it may no longer be perfectly centered on the alignment target. This is normal. The spot on the alignment target may also appear to oscillate at 5 Hz. This is inherent to the design of the device, and is also normal.

4.3.6. Optimizing the Autocorrelation Trace

The delay output (Figure 5) provides a voltage that is proportional to the position of the delay mirror with respect to its nominal equilibrium position. The delay mirror is driven with a sinusoidal wave, but due to friction in the stage bearings, the motion may deviate significantly from sinusoidal, especially near the turning points. Use the amplitude and offset knobs to place the autocorrelation where the delay stage motion is linear, as shown in Figure 6. The linearity may be verified by checking that the fringe spacing is the same at several positions in the interferometric trace.

Sometimes triggering the oscilloscope off of the photodiode channel can create a more stable view. Be sure to set the trigger holdoff on the oscilloscope to ~100 ms to avoid triggering off of both the forward and backward scan.

Next, adjust the photodiode amplifier gain to maximize the signal-to-noise ratio without saturating the photodiode. Higher gains (>40 dB) reduce the detection bandwidth which may distort the signal. Also, ensure that the sampling rate of the oscilloscope or DAQ is sufficient to resolve the fringes. In some cases of insufficient sampling, the trace may appear normal but yield unexpectedly short pulse width measurements, since the fringe frequency is aliased to a lower frequency. See Section Figure 6 for further details.

Finally, verify that the peak-to-background ratio (refer to Figure 12) is at least 7:1. Note that there may be a small, non-zero offset when the laser is blocked, and that this should be subtracted from the peak and background measurements. If this is not the case, please see Section 4.4.5.

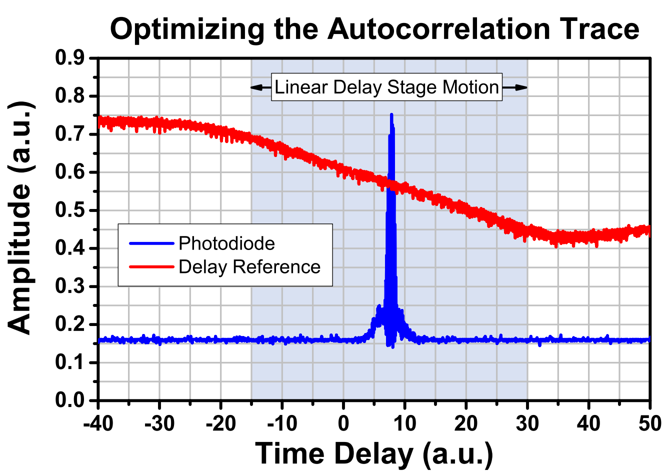


***Figure 6** Delay offset and amplitude are adjusted until the autocorrelation trace appears within the linear region of the delay line, shaded in blue.*

4.4. Common Problems

4.4.1. Sampling Rate

As discussed in Chapter 5, the interferometric autocorrelation contains a term oscillating at a rate corresponding to the central wavelength of the pulse, and another term corresponding to the the second harmonic. The maximum frequency component, f_2, in the interferometric autocorrelation trace corresponding to the second harmonic can be derived from the fact that the delay mirror motion is roughly sinusoidal:

$$f_2 \approx 2\pi f_0 \tau_{full} \frac{c}{\lambda_0}$$

Here, $f_0 = 5\ \mathrm{Hz}$ is the mirror scanning frequency, τ_{full} is the the peak-to-peak time delay of the delay mirror (typically greater than 5 times the expected pulse duration in order to operate within the linear range of the delay stage), $c = 300\ \mathrm{nm/fs}$ is the speed of light, and λ_0 is the central wavelength of the input laser. According to the Nyquist sampling theorem, the sampling rate must be at least twice f_2 in order to avoid aliasing, otherwise the fringes may be detected at a lower frequency resulting in an underestimated pulse duration. If the full envelope of the interferometric autocorrelation trace is to be inferred without the aid of post-processing, then the sampling rate should be on the order of 10 or more times f_2. For example, to measure a 100 fs pulse with a central wavelength of 800 nm, a conservative delay of 1 ps might be used. f_2 is calculated to be about 12 kHz, meaning the sampling rate must be 24 kHz in order to detect the highest frequency in the interferometric autocorrelation without aliasing, and 120 kHz in order to adequately resolve the envelope to estimate the pulse width.

4.4.2. Photodiode and Amplifier Bandwidth

The nominal detector bandwidth for each gain setting is shown in Table 1. For low gain settings the bandwidth is limited by the photodiode, and for high gain it is limited by the transimpedance amplifier. Signal frequencies, as described in Section 4.4.1, that are higher than the bandwidth for a given gain setting will be highly attenuated. This results in distortion of the interferometric autocorrelation. In more extreme cases, like that shown in Figure 7, the fringe contrast will be reduced—i.e., the peak will not be as high, and the signal will fail to go to zero near the center of the trace. A quick way to check if the bandwidth is sufficient is to lower the gain setting to see if the contrast improves. For a proper autocorrelation trace, ensure that the highest signal frequency (as described in Section 4.4.1) is below the bandwidth for the chosen gain setting.

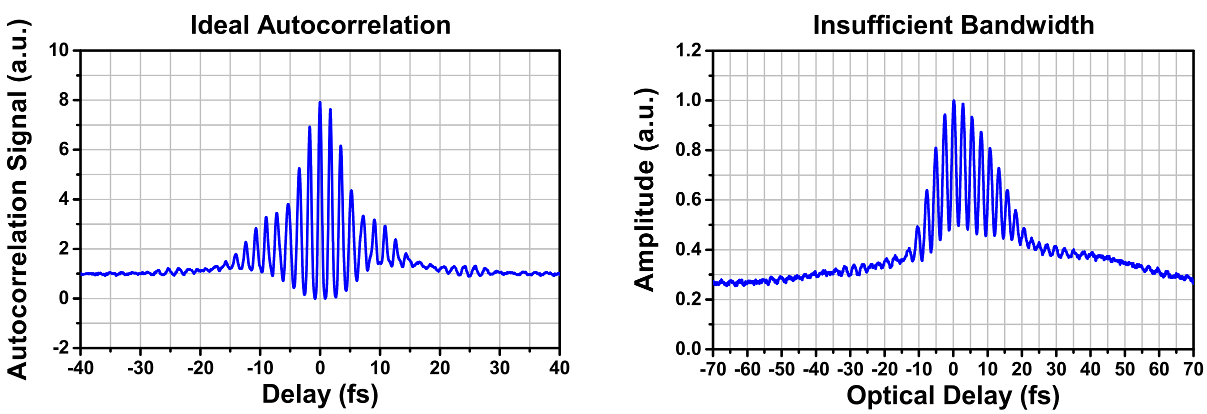


Figure 7 **Left:** ***An autocorrelation with an ideal 8:1 peak-to-background ratio.***
Right: ***The autocorrelation signal fails to go to zero near the center of the trace and the fringe contrast is low, both symptoms of insufficient bandwidth.***

Gain Setting (dB)	Bandwidth (kHz)
0	120
10	120
20	120
30	120
40	100
50	32
60	11
70	3.3

Table 1 Detector Bandwidth Settings

For pulse width measurements, post-processing of the interferometric trace may be used to attain the intensity autocorrelation. In this case, it is not necessary to detect the second harmonic frequency, and significant attenuation of the fundamental frequency may be tolerated. See Chapter 5 for more details.

4.4.3. Saturation

If the 2-photon signal is too high, the top of the autocorrelation trace may appear distorted as shown in Figure 8. This is independent of the voltage output of the photodiode, so it may be observed even for low output signal levels. If this is found to be the case, then the average laser power of the beam entering the FSAC must be attenuated (by using a neutral density filter or a Fresnel reflection from an uncoated window, for example). For an 800 nm, Ø1 mm $(1/e^2)$ beam, saturation occurs when the product of the average and peak power of the laser is around $10^3\ \mathrm{W}^2$.

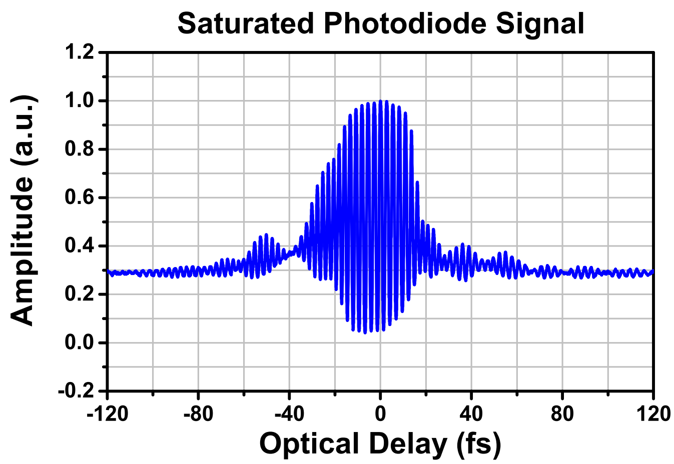


Figure 8 When the 2-photon signal becomes too high, the top of the waveform may be flattened, resulting in an erroneous measurement.

4.4.4. Excessive Chirp

When a pulse is highly dispersed, the interferometric autocorrelation may appear as in Figure 13, where the tails of the trace lie outside of the coherence length of the pulse and are equivalent to an intensity autocorrelation, and the center of the trace coherently interferes, creating a spike. In this case, using the interferometric autocorrelation alone will underestimate the pulse width. However, post-processing may still be used to find the intensity autocorrelation trace from which the pulse width may be more accurately estimated. See Chapter 5 for more details.

4.4.5. Peak to Background Ratio Too High/Low

WARNING

Use Appropriate Laser Safety Eyewear when Working with Lasers

As discussed in Section 5.2, the theoretical peak to background ratio is 8:1. However, due to imperfect beamsplitting and phase errors between the two arms of the FSAC interferometer, the peak to background ratio may be lower (~7:1). If this ratio is very low (<6:1), check that the signal is not saturated (Section 4.4.3), and that the sampling rate (Section 4.4.1) and detector bandwidth (Section 4.4.2) are sufficient. Also note that there is typically a small, but non-zero offset in the signal that depends on the gain setting of the FSAC detector and the oscilloscope or DAQ card. This level can be measured by blocking the input to the FSAC, and then the level may be subtracted from the entire interferometric autocorrelation trace.

The alignment between the two arms of the interferometer is quite sensitive, and may drift over time, especially when subjected to strong temperature fluctuations (like during shipping). It may be necessary to periodically readjust the reference mirror alignment in order maximize the peak to background ratio. To do this, begin by removing the FSAC lid using a 5/32" balldriver, or the included 5/32" stubby hex key. Next, with the device on, monitor the autocorrelation trace (be sure to take proper laser safety precautions) and adjust the tip and tilt actuators on the reference mirror (Figure 9) using the included 5/32" stubby hex key. The required adjustment is typically very small, less than 1/8 of a turn. Also, be extremely careful not to damage the beamsplitter, or perturb any of the other optical components. If the alignment is so far off that no autocorrelation signal is present, rough alignment may be achieved by adjusting the reference mirror so that the delay and reference beams are overlapped on the alignment target (Figure 3). Make fine adjustments until the peak to background ratio is optimized.

Figure 9 **Left:** ***Inside of the FSAC. The reference mirror is indicated by the red box.***
Right: ***Adjusters on the reference mirror are indicated by boxes and adjuster locking screws are indicated by circles.***

If the peak to background ratio is too high, it is likely that the signal to noise ratio of the background signal is insufficient to accurately measure the background level. Try increasing the gain setting of the FSAC, or increasing the average power of the input laser beam.

4.5. Measuring Short (<40 fs) Pulses

It is important to understand that the measured pulse width using the FSAC is the width of the pulse just before the photodetector. Dispersion in media causes broadening in unchirped and positively chirped pulses. For a Gaussian pulse whose unchirped pulse duration is τ_0, the pulse duration will be increased as approximated by

$$\tau = \tau_0 \sqrt{1 + \left(4 \ln 2 \frac{D_2}{\tau_0^2}\right)^2} \approx 4 \ln \frac{D_2}{\tau_0},$$

where τ is the new pulse duration, D_2 is the total group delay dispersion (GDD) experienced by the pulse, and the approximation holds when $D_2 \gg \tau_0^2$. The nominal GDD within the FSAC before reaching the photodetector is 230 fs^2. For measuring short pulses where broadening becomes significant, dispersion-compensating optics such as Thorlabs' DCMP175 and Thorlabs' UMC10-15FS chirped mirrors may be used to compensate for internal dispersion from within the FSAC.

Alternatively, if the pulse bandwidth and, consequently, the transform-limited pulse duration τ_0 are already known, then a system of equations can be derived and solved to estimate the pulse width entering the FSAC. Referring to Figure 10, a bandwidth-limited pulse of duration τ_0 will be broadened by various optics of total dispersion D_0 prior to the FSAC to a duration of $\tau_0{}'$, for which we wish to solve. The pulse duration at the FSAC detector is the result of broadening caused by optics prior to the FSAC, as well as optics internal to the FSAC, which have dispersion $\mathrm{D_{ac}} \approx 230\ \mathrm{fs}^2$. This gives two equations:

$$\tau = \tau_0 \sqrt{1 + \left(4 \ln 2 \frac{D_0 + D_{ac}}{\tau_0^2}\right)^2}$$

$$\tau_0{}' = \tau_0 \sqrt{1 + \left(4 \ln 2 \frac{D_0}{\tau_0^2}\right)^2} = \tau_0.$$

The first equation may be solved for the total dispersion prior to the FSAC,

$$D_0 = \pm \frac{\tau_0 \sqrt{\tau^2 - \tau_0^2}}{4 \ln 2} - D_{ac},$$

the results of which may be plugged into the second equation to estimate $\tau_0{}'$.

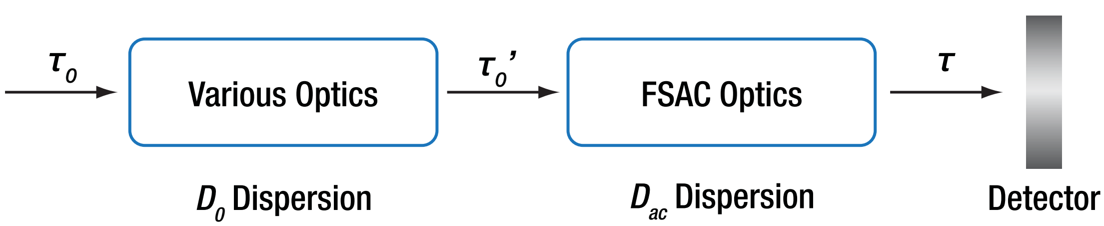


Figure 10 Diagram of a typical pulse measurement setup. τ_0, $\tau_0{}'$, and τ are the FWHM bandwidth-limited pulse duration, the pulse duration prior to the FSAC, and the pulse duration at the FSAC detector, respectively. D_0 is the total dispersion introduced into the beam prior to the FSAC, and D_{ac} is the dispersion inherent in the FSAC design.

Chapter 5 Theory and Interpretation

5.1. Working Principle

Figure 11 shows the optical layout of the FSAC. The input beam pulse is split and copies are reflected from a delay mirror and a reference mirror and then recombined at the beamsplitter. The recombined beam is focused onto the detector. When the delay and reference path lengths are exactly equal so that the optical path difference (OPD) is zero, the pulses overlap in time and add constructively to produce the maximum possible signal on the detector. When the OPD exceeds the full width of the pulse so that the pulses no longer overlap in the combined beam, there is no interference and the photodiode signal is at a minimum.

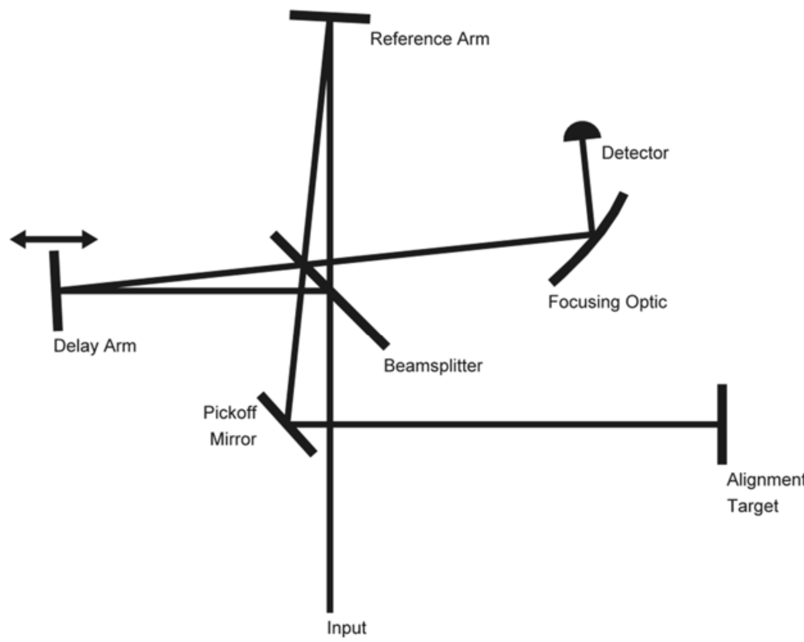


Figure 11 FSAC Optical Layout

As photocurrent in the FSAC is generated by a two-photon process, the output signal is proportional to the square of the irradiance incident on the detector, which in turn is proportional to the square of the total electric field amplitude. And since the speed of the photodiode is several orders of magnitude longer than pulse width, it must be time integrated. This is written as

$$I_{AC}(\tau) = \int_{-\infty}^{\infty} |[\boldsymbol{E}(t) + \boldsymbol{E}(t-\tau)]^2|^2 \mathrm{d}t \,,$$

where $\boldsymbol{E}(t)$ is the complex electric field of the pulse and τ is the time delay between the two pulses arriving at the detector[1]. The integrand may be expanded to give

[1] *Rulliere, Claude.* Femtosecond laser pulses*. Springer Science+ Business Media, Incorporated, 2005.*

$$I_{AC}(\tau) = \int_{-\infty}^{\infty} [I(t)^2 + I(t-\tau)^2]\,\mathrm{d}t + 4\int_{-\infty}^{\infty} [I(t) + I(t-\tau)\mathrm{Re}\{\boldsymbol{E}(t)\boldsymbol{E}^*(t-\tau)\}]\,\mathrm{d}t + 2\int_{-\infty}^{\infty} Re\{\boldsymbol{E}(t)^2\boldsymbol{E}^*(t-\tau)^2\}dt + 4\int_{-\infty}^{\infty} \mathrm{I(t)I(t-\tau)}\,\mathrm{d}t\,,$$

where $*$ denotes the complex conjugate. The first term is a constant background. The second term is a modified interferogram of $\boldsymbol{E}(t)$ which is responsible for fringes at the central frequency of its spectrum. The third term is the interferogram of the second harmonic of $\boldsymbol{E}(t)$, and the fourth term is the intensity autocorrelation.

5.2. Interferometric Autocorrelation Trace

Figure 12 shows an ideal autocorrelation trace and envelope for a well-behaved (secant-squared) pulse. The signal to background ratio is expected to be 8:1, but is typically lower (~7:1) due to non-ideal conditions such as beam alignment and imperfect beamsplitting. The fringe spacing is proportional to the central wavelength of the input beam, so this can be used to calibrate the time axis of the autocorrelation trace. Typically the input pulse is assumed to be either a Gaussian or secant-squared shape, in which case the full width half maximum (FWHM) of the upper envelope[2] of the autocorrelation trace will be directly proportional to the FWHM of the input pulse according to the values listed in Figure 12. The pulse should be symmetric, though for short pulses, small dispersion and balance errors between the two arms may introduce some asymmetry.

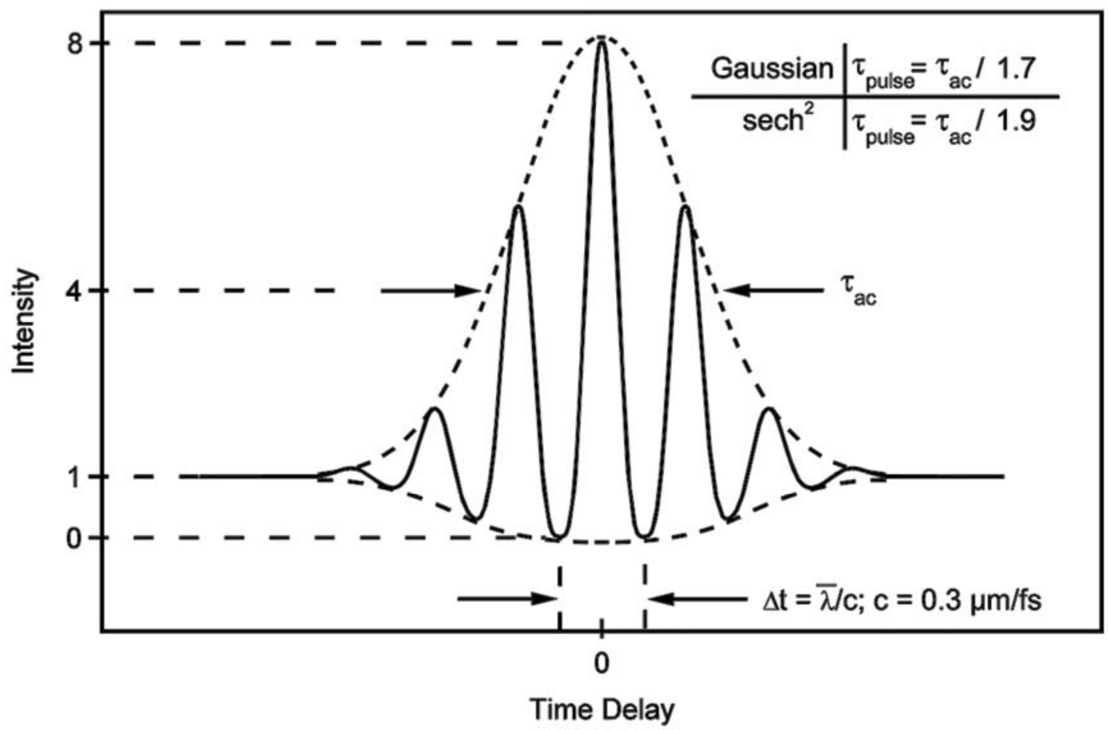


Figure 12 Ideal Interferometric Autocorrelation Trace

5.3. Intensity Autocorrelation Trace

If the fringes are filtered out (either by insufficient response time of the detector and electronics, or by post-processing) so that the second and third terms in the equation above integrate to zero, an intensity autocorrelation with a peak to background ratio of 3:1 is produced. In this case, if the background is also removed and a Gaussian or secant-squared pulse shape is assumed, then the FWHM of the background-free intensity autocorrelation trace

[2] Diels, Jean-Claude M., et al. "Control and measurement of ultrashort pulse shapes (in amplitude and phase) with femtosecond accuracy." Applied Optics 24.9 (1985): 1270-1282.

is proportional to the input pulse FWHM by the factors in Table 2. Search for “FSAC” at Thorlabs’ website to find a sample MATLAB or Python script for converting interferometric autocorrelation data to an intensity autocorrelation trace. The script performs the following functions:

1. Load interferometric autocorrelation data.
2. Load offset data (data taken with laser blocked).
3. Subtract mean offset from interferometric autocorrelation data.
4. Shift time axis data, *t*, so that *t* = 0 corresponds to the peak autocorrelation signal.
5. Determine the fundamental fringe frequency, f_1, from the magnitude of the Fourier transform data.
6. Use the fundamental frequency to convert the time axis, t, to a delay axis using the central wavelength of the input laser, λ, and the speed of light, c.

$$\text{Delay} = t \times \mathrm{f}_1 \times \lambda \,/\, c$$

7. Set all frequencies outside of $\pm\mathrm{f}_1/2$ to zero to remove all fringes.
8. Perform an inverse Fourier transform on the filtered data to get an intensity autocorrelation with background.
9. Using points near the beginning and end of the trace, estimate the background and subtract it from the intensity autocorrelation trace to get the background free intensity autocorrelation trace.
10. Determine the background-free intensity autocorrelation FWHM.
11. Convert to a pulse FWHM by assuming a pulse shape and using the values in Table 2.

Intensity (Non-Interferometric) Autocorrelation FWHM Relations[3]	
Gaussian	$\tau_{\text{pulse}} = \tau_{ac} \,/\, 1.414$
sech^2	$\tau_{\text{pulse}} = \tau_{ac} \,/\, 1.543$

Table 2

5.4. Excessive Chirp

If the pulse is significantly chirped so that the pulse length greatly exceeds the coherence length of the laser, then the autocorrelation will appear as in Figure 13. The wings of the autocorrelation are identical to those of an intensity autocorrelation, and the point at which the trace transitions to an interferometric autocorrelation can be used to quantify the chirp[4]. In this case, it is not straightforward to interpret the pulse width without additional post-processing (i.e., filtering out the fringes as described above). See the cited references for more information on interpreting autocorrelation traces.

[3] *Diels, Jean-Claude, and Wolfgang Rudolph. Ultrashort laser pulse phenomena. Academic press, 2006.*
[4] *Ibid.*

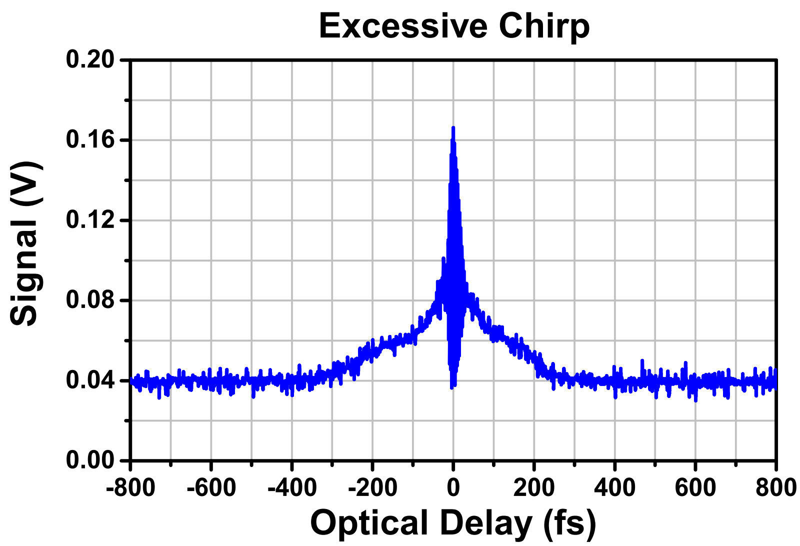


Figure 13 ***An interferometric autocorrelation of a chirped pulse transitions to an intensity autocorrelation in the wings. Pulse width estimation, in this case, is not straightforward.***

Chapter 6 Maintenance

The FSAC does not require regular maintenance. To maximize lifetime of the device, be sure it is powered off when not in use.

Chapter 7 Warranty

Thorlabs warrants to the buyer of the system described in this manual that it conforms to the published specifications and is free from defects in materials and workmanship for a period of 12 months. The warranty period begins at installation or thirty days from shipment, whichever occurs first. For systems which do not include installation, this warranty begins at the date of shipment.

On-site warranty services are provided only at the installation point. In order to keep the warranty in effect the buyer needs to purchase additional installation or inspection services if the system is moved from the original installation point.

The buyer must provide the appropriate utilities and operating environment as outlined in Chapter 4 of this manual. Damage to the laser system caused by failure of the buyer's utilities is solely the responsibility of the buyer and is specifically excluded from any warranty.

The obligations of Thorlabs are limited to repairing or replacing, without charge, equipment which proves to be defective during the warranty period. Repaired or replaced parts are warranted for the duration of the original warranty period only. This warranty does not cover damage due to misuse, negligence, or damage due to installations, repairs or adjustments not specifically authorized by Thorlabs.

Chapter 8 Specifications

8.1. General Specifications

General Specifications		
Full Scan Range	50 fs to 10 ps	
Input Pulse Duration	Without Precompensation	40 fs - 1 ps (FWHM)
	With Precompensation[5]	15 fs - 1 ps (FWHM)
Full Scan Rate	5 Hz	
Noise-Equivalent Sensitivity	10^{-1} W^2 at 800 nm for Ø1 mm Beam $(1/e^2)$[6]	
Input Wavelength Range	650 nm to 1100 nm	
Input Polarization	Horizontal	
Input Beam Diameter	<Ø4 mm $(1/e^2)$	
Input Repetition Rate	>300 kHz[7]	
Required Sampling Rate	>1.5 MHz for 10 ps Delay at 650 nm >150 kHz for 1 ps Delay at 650 nm	
Internal Dispersion	GDD	230 fs^2 at 800 nm (Nominal)
	TOD	345 fs^3 at 800 nm (Nominal)
Maximum Average Power	150 mW	
Dimensions	6.90" x 5.53" x 4.82" (175.3 mm x 140.4 mm x 122.4 mm)	

8.2. Electrical Requirements

Electrical Requirements	
Input Voltage	±12 VDC
Power Consumption	6 W (Max)
Connector	Lumberg RSV3-657/2M Female Connector

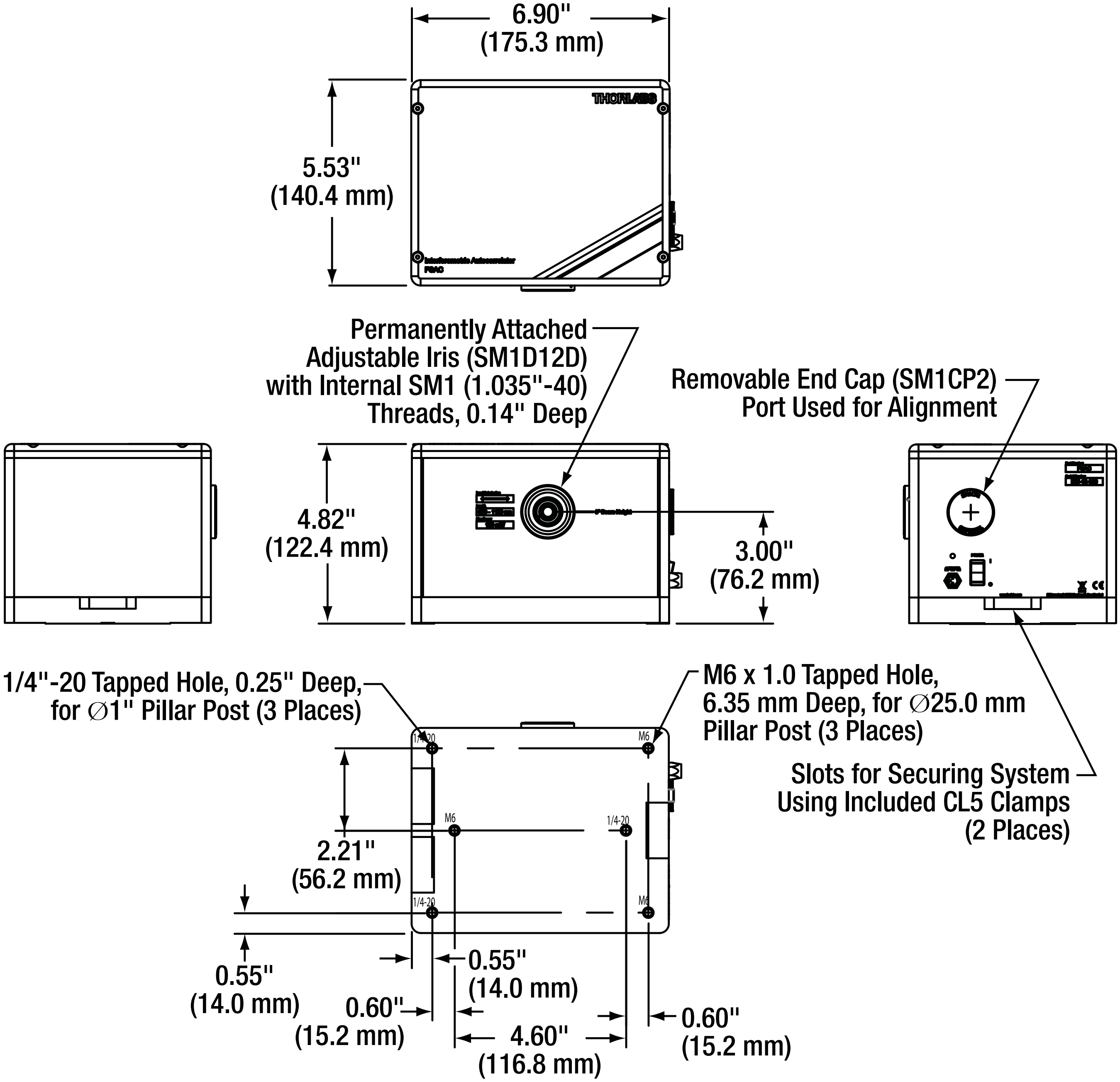
FSAC is designed to use the included Thorlabs LDS1212 power supply, which meets these requirements.

8.3. Environmental Requirements

Environmental Requirements	
Room Temperature Range	17 °C to 25 °C

[5] Pulses as low as 15 fs may be measured with use of dispersion compensation.
[6] Sensitivity is defined as the noise-equivalent product of the average power and the peak power of the laser.
[7] Lower repetition rates are possible when using triggered acquisition.

8.4. Mechanical Drawings



Chapter 9 Declaration of Conformity

THORLABS
www.thorlabs.com

EU Declaration of Conformity

in accordance with EN ISO 17050-1:2010

We: Thorlabs Inc.

Of: 56 Sparta Avenue, Newton, New Jersey, 07860, USA

in accordance with the following Directive(s):

2014/35/EU	Low Voltage Directive (LVD)
2014/30/EU	Electromagnetic Compatibility (EMC) Directive
2011/65/EU	Restriction of Use of Certain Hazardous Substances (RoHS)

hereby declare that:

Model: ***FSAC***

Equipment: ***Interferometric Autocorrelator***

is in conformity with the applicable requirements of the following documents:

EN 61010-1	Safety Requirements for Electrical Equipment for Measurement, Control and Laboratory Use.	2010
EN 61326-1	Electrical Equipment for Measurement, Control and Laboratory Use - EMC Requirements	2013

and which, issued under the sole responsibility of Thorlabs, is in conformity with Directive 2011/65/EU of the European Parliament and of the Council of 8th June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment, for the reason stated below:

does not contain substances in excess of the maximum concentration values tolerated by weight in homogenous materials as listed in Annex II of the Directive

I hereby declare that the equipment named has been designed to comply with the relevant sections of the above referenced specifications, and complies with all applicable Essential Requirements of the Directives.

Signed: *On:* 18 May 2017

Name: Ann Strachan

Position: Compliance Manager

EDC - FSAC -2017-05-18

CE 17

Chapter 10 Regulatory

As required by the WEEE (Waste Electrical and Electronic Equipment Directive) of the European Community and the corresponding national laws, Thorlabs offers all end users in the EC the possibility to return "end of life" units without incurring disposal charges.

- This offer is valid for Thorlabs electrical and electronic equipment:
- Sold after August 13, 2005
- Marked correspondingly with the crossed out "wheelie bin" logo (see right)
- Sold to a company or institute within the EC
- Currently owned by a company or institute within the EC
- Still complete, not disassembled and not contaminated

Wheelie Bin Logo

As the WEEE directive applies to self-contained operational electrical and electronic products, this end of life take back service does not refer to other Thorlabs products, such as:

- Pure OEM products, that means assemblies to be built into a unit by the user (e. g. OEM laser driver cards)
- Components
- Mechanics and optics
- Left over parts of units disassembled by the user (PCB's, housings etc.).

If you wish to return a Thorlabs unit for waste recovery, please contact Thorlabs or your nearest dealer for further information.

Waste Treatment is Your Own Responsibility

If you do not return an "end of life" unit to Thorlabs, you must hand it to a company specialized in waste recovery. Do not dispose of the unit in a litter bin or at a public waste disposal site.

Ecological Background

It is well known that WEEE pollutes the environment by releasing toxic products during decomposition. The aim of the European RoHS directive is to reduce the content of toxic substances in electronic products in the future.

The intent of the WEEE directive is to enforce the recycling of WEEE. A controlled recycling of end of life products will thereby avoid negative impacts on the environment.

Chapter 11 Thorlabs Worldwide Contacts

For technical support or sales inquiries, please visit us at www.thorlabs.com/contact for our most up-to-date contact information.

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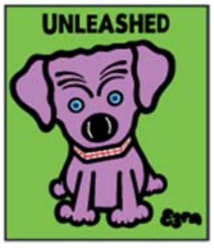
China
Thorlabs China
chinasales@thorlabs.com



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