Femtosecond Laser Micromachining Manual

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Contents

Description of the micromachining setup

The schematic of the optical path is shown in FIGURE 1. The beam from the 120 fs Spitfire, the sub 50fs Spitfire or the OPA is directed to the ablation setup typically by three mirrors (M1-M3) not shown in the figure. Mirror M4 is mounted on a kinematic base plate and allows one to easily select either the OPA or Spitfire beam. The beam from the Spitfire is initially ≈10 mm in diameter, and it is reduced in size by a beam condenser, constructed from a f = 50 cm achromatic doublet (L1), and a f = - 20 cm plano-concave singlet lens (L2), to a diameter of ≈ 4 mm. Reducing the beam size eliminates clipping of the beam on thin film polarizers, spinning wave plates and other small-aperture optics. The pulse energy of the Spitfire is typically between 100 – 800 µJ, which is significantly higher than required for most experiments. The initial pulse energy of 800 nm beam is typically adjusted to 1 – 20 µJ with a zero order half wave plate (HWP - 0RP44-3, Newport) and a thin film polarizer (TFP - 11B00UP.26, Newport).   After the polarizer, the dielectric mirrors M5 and M6 are used to align the beam through irises I1 and I2 before the main setup to ensure that the beam is straight. During the experiments, the pulse energy is controlled with a set of 1 mm thick, reflective, neutral density filters (Model 5249, New Focus). The filters are mounted in two filter wheels and allow power adjustments in optical density steps (OD) of 0.1 (OD = $\log(I/I_o)$ where I is the laser intensity). The two filter wheels are mounted on custom-built rotation stages and the position of each of the wheels can be controlled manually or by computer via an RS-232 interface (connected to COM1 of the PC).

A portion of the laser beam is reflected onto a photodiode by an uncoated pellicle beam splitter (PBS). The photodiode monitors the laser energy during experiments. The calibration procedure of the photodiode is discussed in subsequent sections. The laser exposure time (or the number of pulses delivered to the sample) is controlled by a mechanical shutter (VS25 with VMM-D1 controller, Uniblitz). The shutter has a minimum exposure time of 3 ms. Beyond the shutter, the beam is delivered to the focusing optic by mirrors M7 – M9. Historically in most of the experiments the focusing optic was a 5× microscope objective (M - 5×, Newport). The use of this objective allowed focusing of the laser to a spot diameter of approximately 10 µm, with a working distance of roughly 1.5 cm. The long working distance was required for focusing the beam inside of the vacuum chamber through the chamber window. Mitutoyo objectives provide longest working distance and maximum flexibility when used with the microscope revolver.

The vacuum chamber is a custom machined, aluminum vessel with three lids for 1" and 2" windows. The sample chamber is mounted on XY translation stages (UTM150PE.1, Newport) and the focusing objective is mounted on a separate Z translation stage (M-MFN25PP, Newport). The stages are controlled by ESP300 controller (Newport) via GPIB interface. The timing, synchronization and data acquisition are performed by a computer through general purpose data acquisition card (PCI-6025E, National Instrument).   A dielectric mirror M9 is a high reflector at a laser wavelength but transparent in the visible region. A confocal CCD camera arrangement, aligned through the dielectric mirror M9, is used to monitor the sample alignment and the machining process during the course of the experiments.
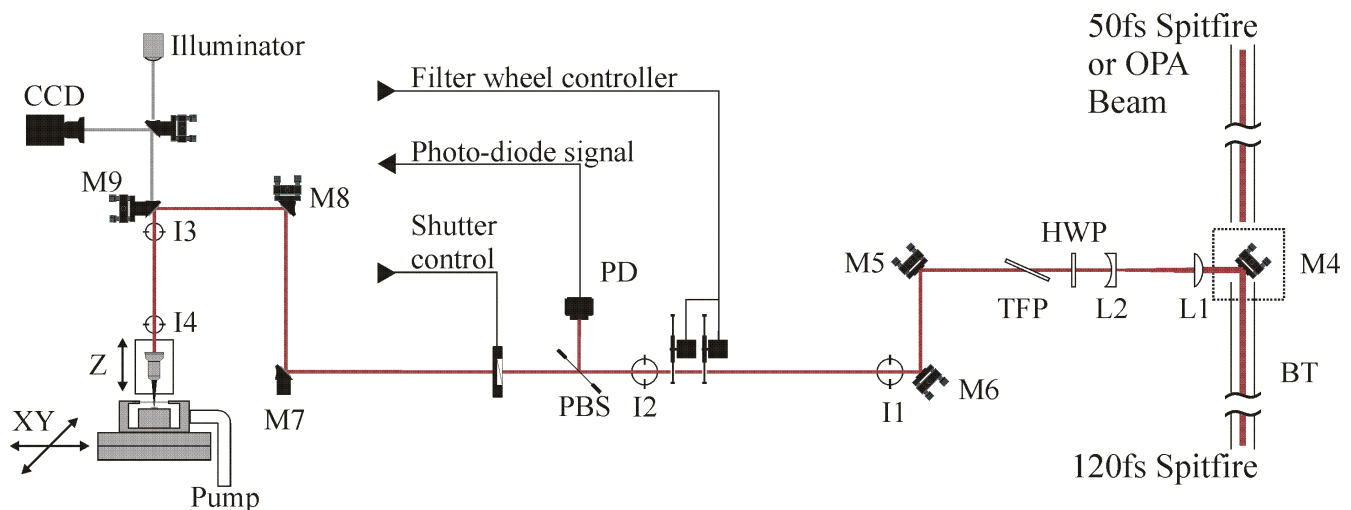
FIGURE 1: Schematic of the laser micromachining setup.

1. Complete micromachining alignment procedure

This section presents a guide to realignment of the entire optical path. Complete realignment should not be necessary on day-to-day basis. **For daily alignment procedures skip on ahead to Section 2**. The procedure assumes that the beam is delivered from the either of laser systems or the OPA to the turning mirror M4.

IMPORTANT: to avoid damaging optics or other equipment, such as beam profiler or spectrometer, *use minimum laser power for the laser alignment*. Reducing laser power is most easily accomplished by ejecting a weak pulse out of the laser cavity. FIGURE 2 shows a late pulse ejected out of 120 fs Spitfire used for alignment. Full beam power can be used with caution.
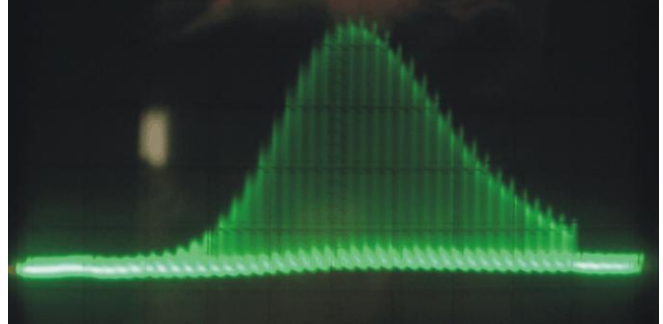

FIGURE 2: Oscilloscope trace of buildup time of 120 fs Spitfire laser.

1. Block the laser beam and remove the beam telescope (Lenses L1 and L2), the half-wave plate (HWP), the thin-film polarizer (TFP) and mirror M5 from the beam path.
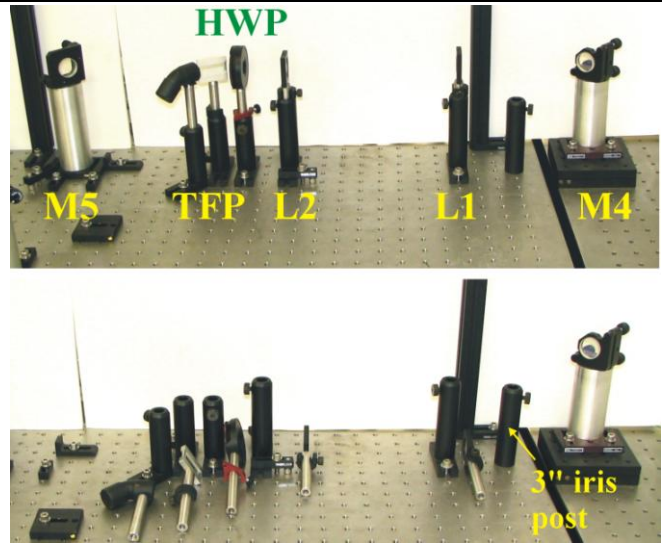

FIGURE 3:

2. Place 15.5 mm alignment iris, marked with yellow label, into the 3" post holder (shown in FIGURE 3) in front of L1 post holder.
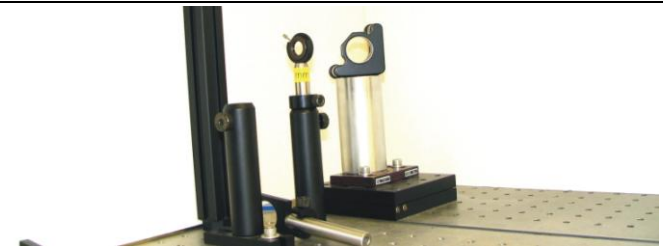

FIGURE 4:

3. Screw a second 3" post holder directly into the table along the same row of holes as L1, L2, TFP ~ 1 m away from the first iris and place the second iris labeled 15.5 mm into that holder. This will define the optical axis for the beam telescope.
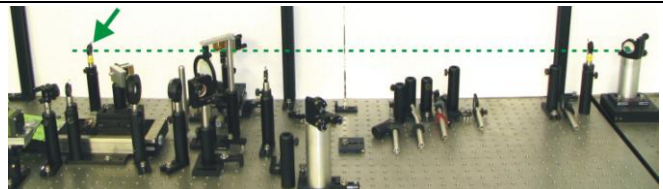

FIGURE 5:

4. Align the beam through both 15.5 mm alignment irises using mirror M3 and M4. (M3 is not shown in any of the figures. It is the turning mirror which precedes M4) Use M3 to center the beam on iris 1 and M4 to center the beam on iris 2. Repeat this process several times until the beam passes through the center of both irises. Use an IR viewer or IR viewing card for the initial alignment.

FIGURE 6:

5. Lunch the beam CCD Profiler software and use the CCD beam profiler, placed behind each aperture, to check the final alignment as shown in FIGURE 6:; this will improve the accuracy. The use of CCD profiler is very convenient especially since M3 is far away from iris 1.
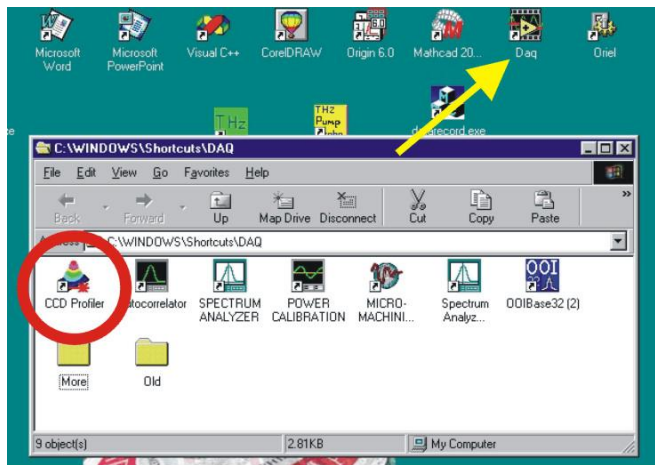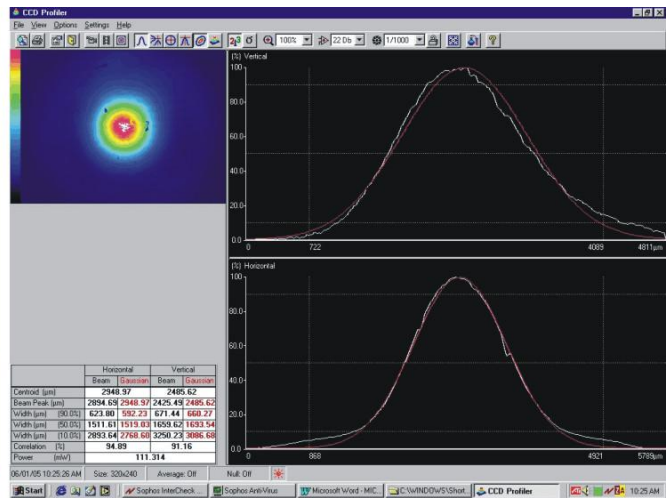

FIGURE 7

6. If the CCD is saturating, decrease the gain to 5dB and increase the shutter speed to 1/1000. If the CCD is still saturating then place an additional neutral density filter in front of the CCD. Conversely if the beam profile is very faint then increase the gain or decrease the shutter speed.

Note: If the beam profiler is not inserted upright then the orientation of the beam on the screen may not be as expected (i.e. a lateral correction of the mirrors may correspond to a vertical correction on the screen).
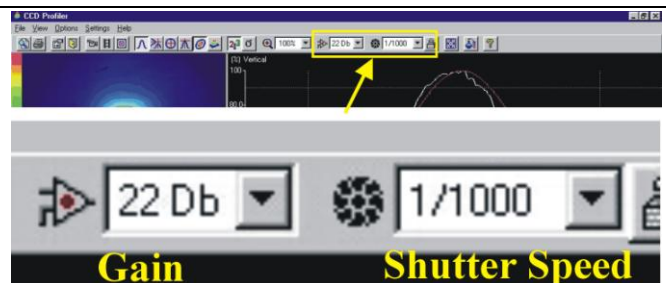

FIGURE 8

7. FIGURE 9 shows beam profile taken with the CCD beam profiler placed behind the alignment iris 2 with the iris (a) fully open and (b) (c) partially closed. The beam profile is concentric with the iris, which is indication of good alignment. (If the beam profile is not concentric, then adjust M3 and M4 as in step 4 until it resembles Figure 7).
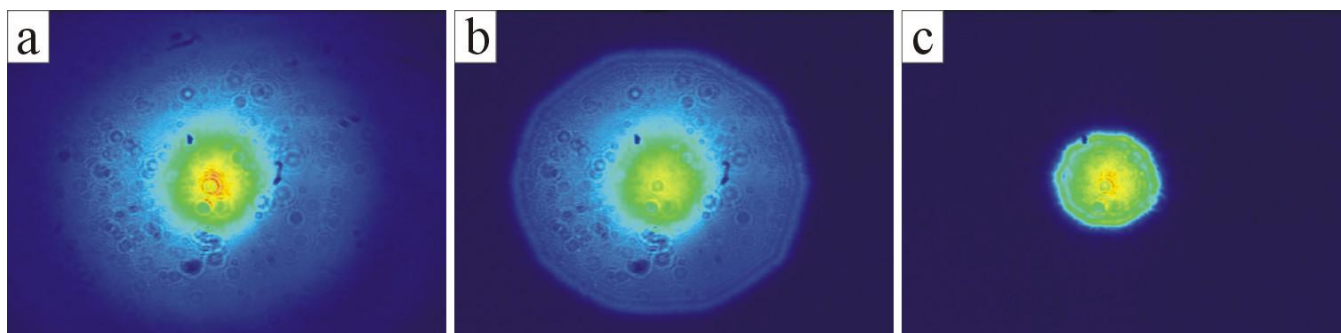

FIGURE 9:

8. Leave the beam profiler behind the second iris for the next step and put a beam block in front of iris 2. Remove iris 1 from the post holder and return the lens L1 back to its post holder (FIGURE 10).

   CAUTION: L1 is a positive lens with focal length of approximately 50 cm, therefore *make sure that the beam path is clear before putting the lens in the beam*. If the laser pulse energy is sufficiently high air brake-down will occur in the focus. (Although this is a really cool effect it is thoroughly undesirable for the alignment procedure, hence the pulse energy should be reduced while aligning the beam.)
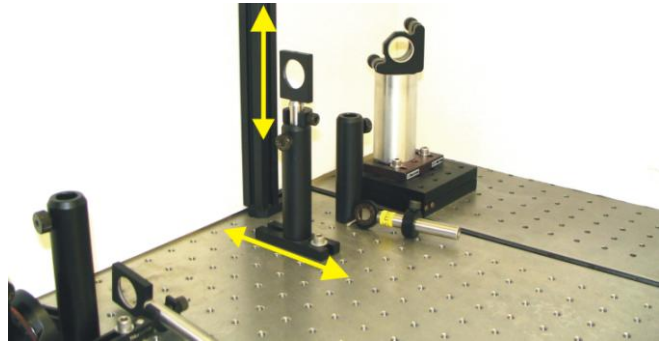

FIGURE 10

9. The beam diverges beyond its focus and it should pass through the center of iris 2. If it does not the lateral and vertical positions of L1 must be adjusted. FIGURE 11: shows (a) the beam profile before L1 is inserted into the beam, the beam is concentric with the iris, and (b) the beam profile immediately after L1 is inserted into the beam. The beam does not pass through the middle of the lens leading to misalignment on iris 2. FIGURE 11: (c) shows the beam profile after the lateral position of the lens has been adjusted and the beam is once again concentric with the iris.
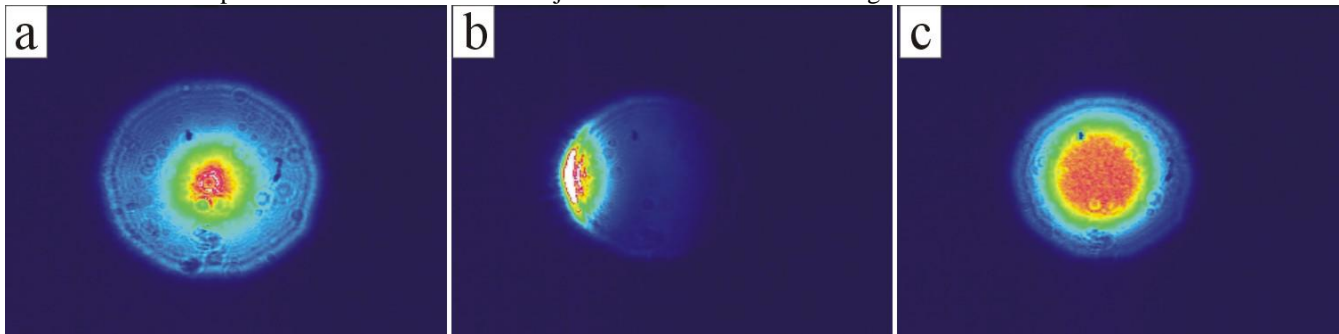
FIGURE 11:

10. Return the negative lens L2 into it's post holder. L2 will re-collimate the beam, and the beam should pass through the middle of the second alignment iris. If necessary adjust the lateral and vertical position of L2 as in step 9.

FIGURE 12

11. Make sure that the beam is collimated and does not come to the focus at any point beyond L2. If the beam continues to converge adjust the separation between L2 and L1 such that the beam size remains approximately constant beyond L2.

FIGURE 13

12. Remove the second 3" post holder from the table once the beam is reduced in size, collimated and aligned through both irises. Return mirror M5 to its original position (against the kinematic stops on the table as shown in FIGURE 14), and return the half-wave plate (HWP) into its post holders. Make sure that the beam passes through the middle of HWP and hits the center of M5. If necessary adjust the lateral position of M5 and height of the HWP.
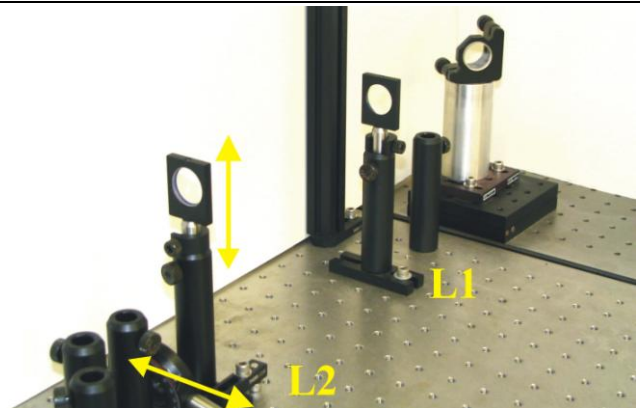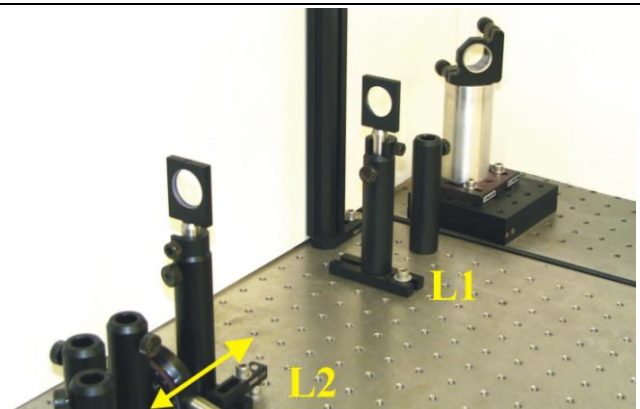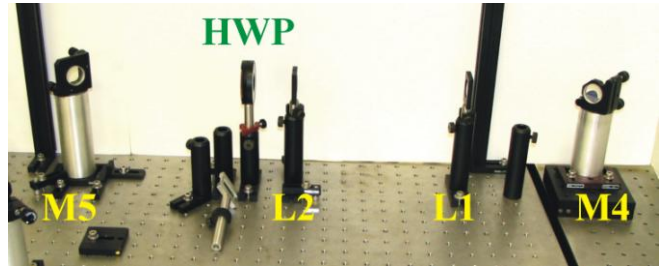

FIGURE 14

13. Place the thin-film polarizer (TFP) in the beam and make sure that the beam passes through the middle of TFP. Any clipping at the edges will show up as diffraction fringes in the beam profile. The TFP should be at approximately 60º relative to the beam axis.

    Note: that TFP will offset the beam from the optical axis defined by the apertures. Make sure that the residual beam is reflected into the beam dump shown in FIGURE 15.
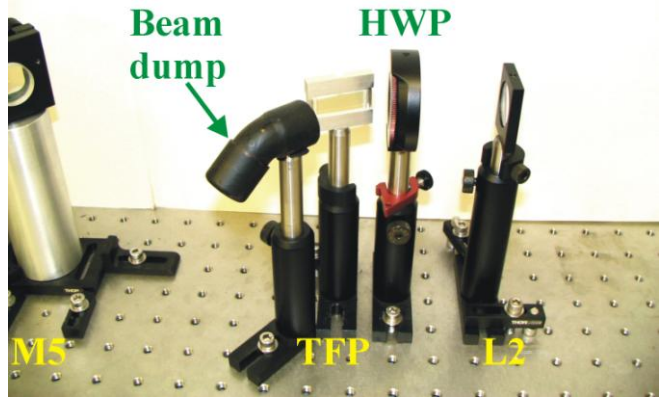
FIGURE 15

14. Now we need to ensure that the TFP is placed properly. Block the beam with a business card placed at a convenient spot beyond TFP. Set up a photodiode and an oscilloscope to look at the scattered light from the business card. Make sure that the photodiode is not saturating. Rotate the HWP to obtain maximum transmission through the TFP, then rotate the TFP about it's axis to maximize the transmission (photodiode signal).

15. Place one iris labeled 15.5 mm in the 3" post holder located after mirror M6 and the second iris in the post holder immediately after the filter wheel.

    Note: make sure that both filter wheels are set to clear (ND = 00).
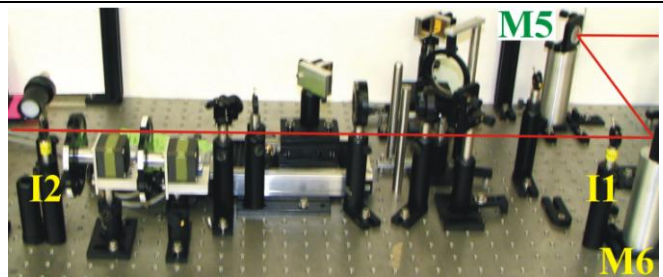
FIGURE 16

16. Use M5 to center the beam on iris I1 and M6 to center the beam on the iris I2. Iterate several times until the beam passes through the center of both irises. The alignment is most effective with the use of beam profiler placed behind I2.

FIGURE 17

17. Note: Historically a pellicle beam splitter (PBS) was used to sample a fraction of the beam energy with a photodiode (PD). However since Dec. 2010 an AR coated (for 800 nm) 1 mm thick φ1.0" fused silica window has been in use for the sampling. An alternative solution will have to be used to sample beams at different wavelengths. The term "PBS" will be left in the rest of this procedure to refer to the beam splitter in general to match the figure, since Eugene is too lazy to label another picture.
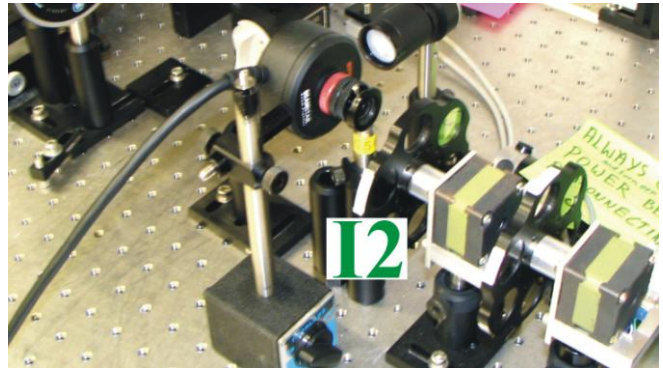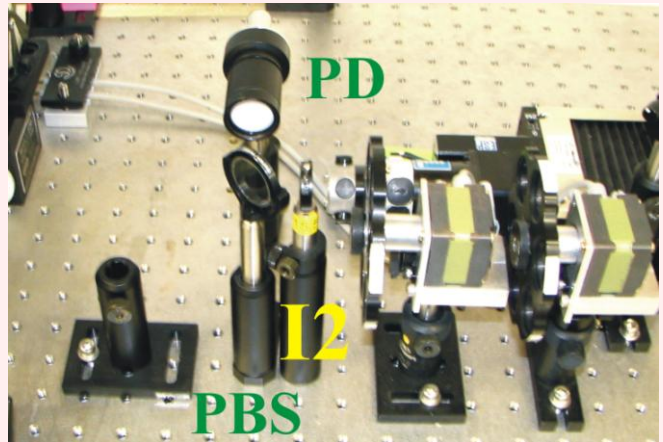
Insert PBS into the 3" post holder located behind I2. The PBS should be inserted at approximately 45 deg. Fraction of the beam will be reflected onto the photodiode. At this point the photodiode can be connected to the box-car to check for the signal levels and angle of PBS can be adjusted to maximize the signal. Position and pointing angle of the photodiode can be fine tuned to optimize the signal. If the photodiode saturates neutral density filters can be inserted in addition to the opal diffuser. This step can also be left till after the alignment stage when configuring the box-car.

Note: The box-car integrator input is switched between this photodiode and the one used in the autocorrelator setup. Make sure the switch is at the appropriate position to work with the signal.

FIGURE 18

18. In some machining experiments it is desirable to use rotating polarization for machining, especially in drilling and cutting of thin foils. The use of rotating polarization leads to substantial improvements in quality and geometry of the exit hole. Rotating polarization is implemented by inserting of a hollow shaft motor with the HWP attached. Insert the rotating wave plate assembly after PBS. Use the beam profiler placed in front of the shutter to make sure that the beam is not being clipped inside of the hollow shaft.

The frequency of the rotating HWP can be adjusted by turning S3 trim pot on the motor controller box. Historically the value was set to 160 Hz.

FIGURE 19

19. Lift up the protective beam tube, which covers mirror M7 and remove the dust caps (shown with arrows in FIGURE 20). Set the microscope objective revolver head to a slot containing SM1 tube with an iris. There should be enough clearance between the vacuum chamber and the iris for the CCD profiler.

    Note: If all microscope spots are used up or the iris is not in the revolver free up one slot and screw in the SM compatible iris (also shown in FIGURE 22).

FIGURE 20

20. Lower the beam power all the way down. Turn on the shutter control box, with the switch located on the back side of the box (upper left). Open the shutter by switching the toggle switch from Normally Closed (N.C.) position to Normally Open (N.O.) on the shutter controller unit. A green LED will be on when the shutter is open.

FIGURE 21

21. Follow the beam with an IR viewing card through the beam path from the shutter to M7, M8, M9 and the microscope head assembly (see FIGURE 22). Close the shutter and place the beam profiler below the lens tube with the iris.

22. Open the shutter and use mirror M8 to center the beam on the first iris I3 and mirror M9 to center the beam on I4. Iterate several times until the beam passes through the center of both irises. Save the beam profile for future reference.

    Note: that in a day-to-day operation good alignment through irises I1 and I2 in steps 15 should guarantee good alignment through the microscope head.

FIGURE 22

23. Close the shutter.

Following beam path alignment you can follow steps for laser beam diagnostics, power adjustment and calibration.

2. Daily micromachining alignment procedure

This section presents a guide to realignment of the entire optical path. Complete realignment should not be necessary on day-to-day basis. The procedure assumes that the beam is delivered from the either of laser systems or the OPA to the turning mirror M4.

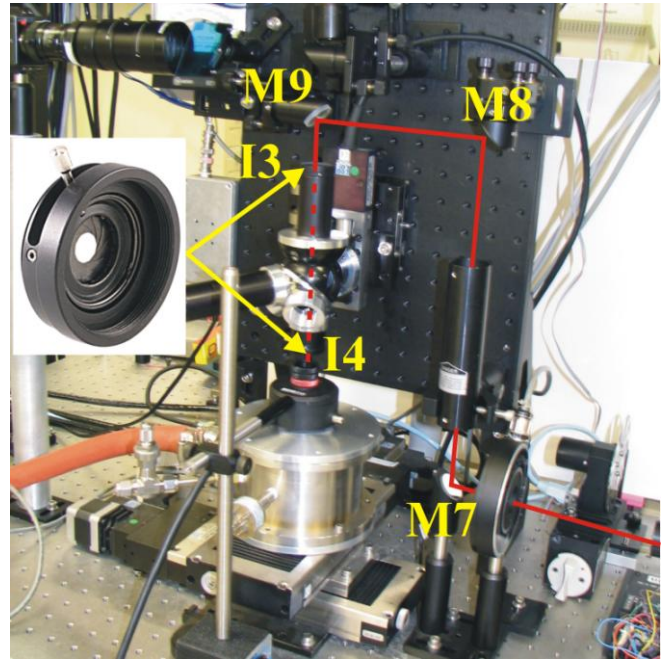**IMPORTANT:** to avoid damaging optics or other equipment, such as beam profiler or spectrometer, *use minimum laser power for the laser alignment*. Reducing laser power is most easily accomplished by ejecting a weak pulse out of the laser cavity. FIGURE 2 shows a late pulse ejected out of 120 fs Spitfire used for alignment. Full beam power can be used with caution.
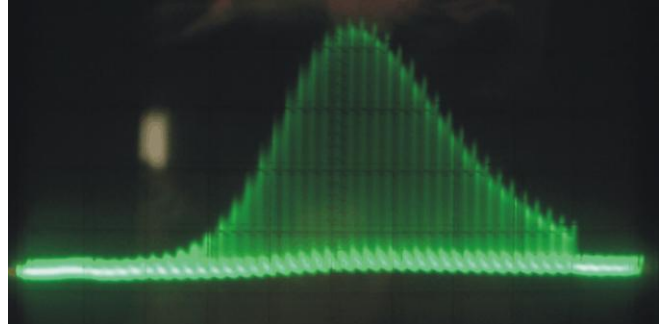
FIGURE 23: Oscilloscope trace of buildup time of 120 fs Spitfire laser.

1. a) **If not using the spatial filter:**

Place one iris labeled 15.5 mm in the 3" post holder located after mirror M6 and the second iris in the post holder immediately after the filter wheel.

Note: make sure that both filter wheels are set to clear (ND = 00).
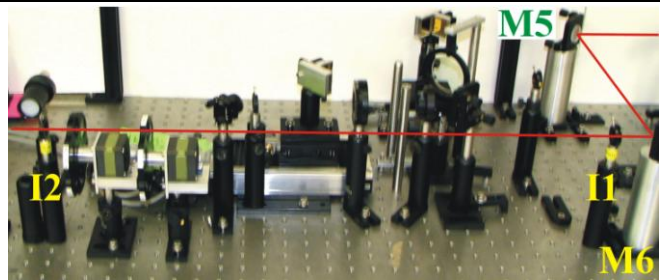
FIGURE 24

b) **If using the spatial filter:**

Place the spatial filter in place. Positioning of the spatial filter is pre-set by the two post holders. Remove the spatial filter pinhole by unscrewing the ½" lens tube holder from the assembly (H).

Use the screw-on irises I3 and I4 at the entrance and the exit port in place of I1 and I2 in steps 1 for the following steps.
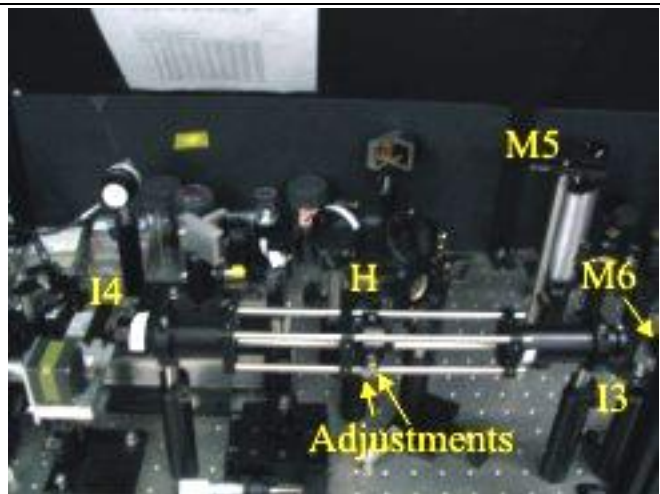
Figure 25

2. Use M5 to center the beam on iris I1 (I3 if using spatial filter) and M6 to center the beam on the iris I2 (I4 if using spatial filter). Note due to the use of lenses in the spatial filter, to align the beam through I4 the beam is moved opposite to the direction of where we would intuitively move it in a clear beam path.

Iterate several times until the beam passes through the center of both irises. The alignment is most effective with the use of beam profiler placed behind I2, if space allows..

Alternatively the beam profile can be placed at the position in step 8 and use the iris shadow and diffraction pattern to center the beam. This may take a bit of getting used-to to master.

If using the spatial filter: Lower to the power all way as to not machine the pinhole. Re-insert the pinhole into the holder assembly. Position the pinhole in the focal plane of the spatial filter by using the vertical and horizontal adjustments to center the pinhole on the beam. If the beam can not be easily found one may slide the entire holder assembly (H) down towards I3 to section out a portion of the beam, and iteratively slide the pinhole towards the focal plane of the spatial filter lens ($f = 175$ mm) in small steps while adjust the vertical and horizontal placement to track the beam at each step. Adjust the beam power as needed but use the lowest power useable for alignment to avoid machining the pinhole.
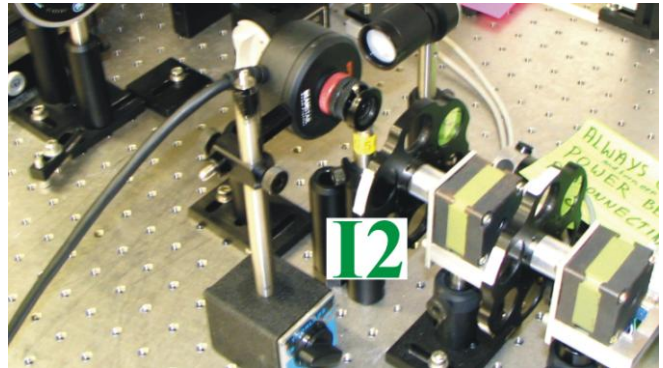
FIGURE 26

3. In some machining experiments it is desirable to use rotating polarization for machining, especially in drilling and cutting of thin foils. The use of rotating polarization leads to substantial improvements in quality and geometry of the exit hole. Rotating polarization is implemented by inserting of a hollow shaft motor with the HWP attached. Insert the rotating wave plate assembly after PBS. Use the beam profiler placed in front of the shutter to make sure that the beam is not being clipped inside of the hollow shaft.

The frequency of the rotating HWP can be adjusted by turning S3 trim pot on the motor controller box. Historically the value was set to 160 Hz.

FIGURE 27

4. In some experiments it is desirable to use a slower repetition rate than the 1 kHz Spitfire output. A 10-blade chopper with 9 out of 10 slots blocked is used to slow down the repetition rate to 50 Hz. This is required to acquire less than 20 laser pulses, since the mechanical shutter has a finite minimum open-close rate (say ~20 ms).

The positioning of the chopper is pre-set by butting its side against a base plate right downstream from the rotating HWP mount. The magnetic base should be engaged to secure the chopper to the table.
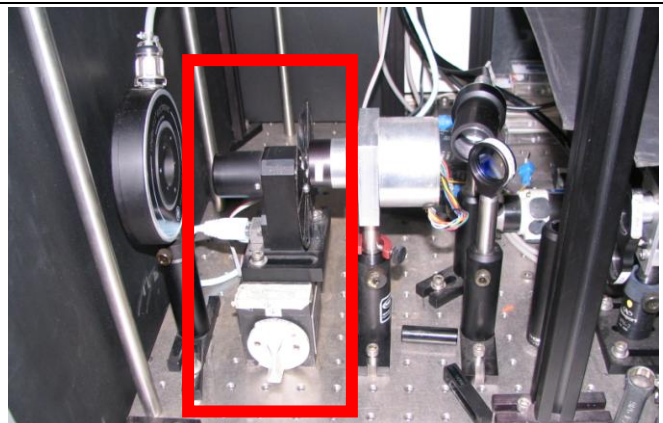
Figure 28

4 (con't) The chopper requires the trigger LED to be turned on, and the controller should be synchronized to the kHz trigger from the CPA by making sure the Ext En light is on the chopper controller

Figure 29

Figure 30

5. Lift up the protective beam tube, which covers mirror M7 and remove the dust caps (shown with arrows in FIGURE 20). Set the microscope objective revolver head to a slot containing SM1 tube with an iris. There should be enough clearance between the vacuum chamber and the iris for the CCD profiler.

Note: If all microscope spots are used up or the iris is not in the revolver free up one slot and screw in the SM compatible iris (also shown in FIGURE 22).
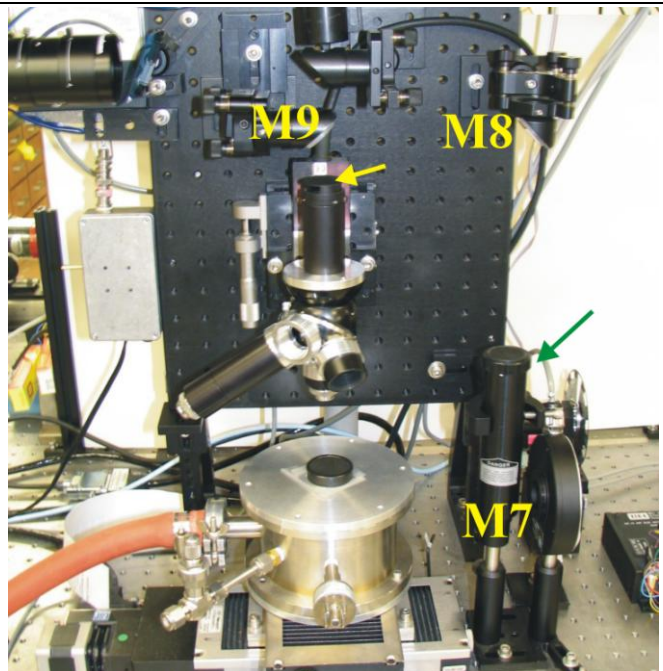
FIGURE 31

6. Lower the beam power all the way down. Turn on the shutter control box, with the switch located on the back side of the box (upper left). Open the shutter by switching the toggle switch from Normally Closed (N.C.) position to Normally Open (N.O.) on the shutter controller unit. A green LED will be on when the shutter is open.

FIGURE 32

7. Follow the beam with an IR viewing card through the beam path from the shutter to M7, M8, M9 and the microscope head assembly (see FIGURE 22). Close the shutter and place the beam profiler below the lens tube with the iris.

8. Open the shutter and use mirror M8 to center the beam on the first iris I3 and mirror M9 to center the beam on I4. Iterate several times until the beam passes through the center of both irises. Save the beam profile for future reference.

Note: that in a day-to-day operation good alignment through irises I1 and I2 in steps 15 should guarantee good alignment through the microscope head.
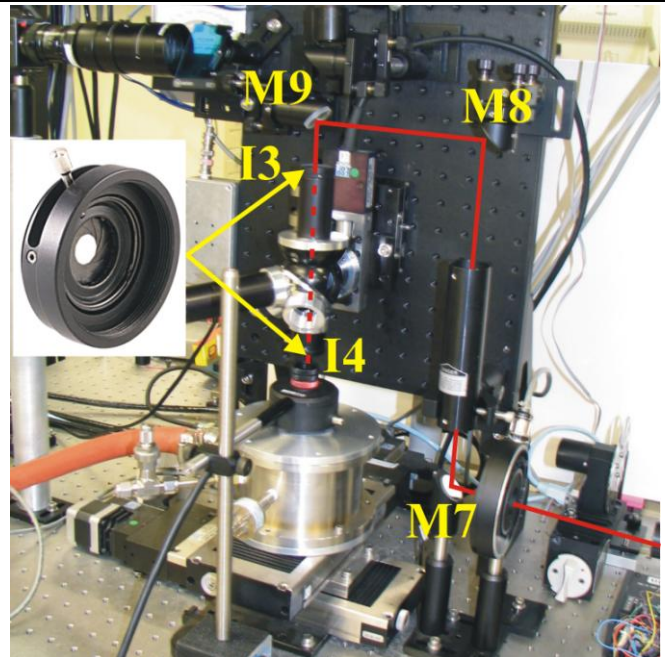
FIGURE 33

9. Close the shutter.

Following beam path alignment you can follow steps for laser beam diagnostics, power adjustment and calibration.

3. Box-car Setup

The box car integrator measures the integrated signal of a wave form in specified window (GATE) and outputs a DC value proportional to "area" below the waveform. The box-car is used for autocorrelation measurements and for measurement of the pulse energy during the experiments. The following procedure outlines steps in the box-car setup. All instructions refer to the figure below.

FIGURE 34

NOTE: Numbers show in red correspond to the steps in the box-car setup procedure.

1. Turn ON the Box-car instrument crate and the oscilloscope.
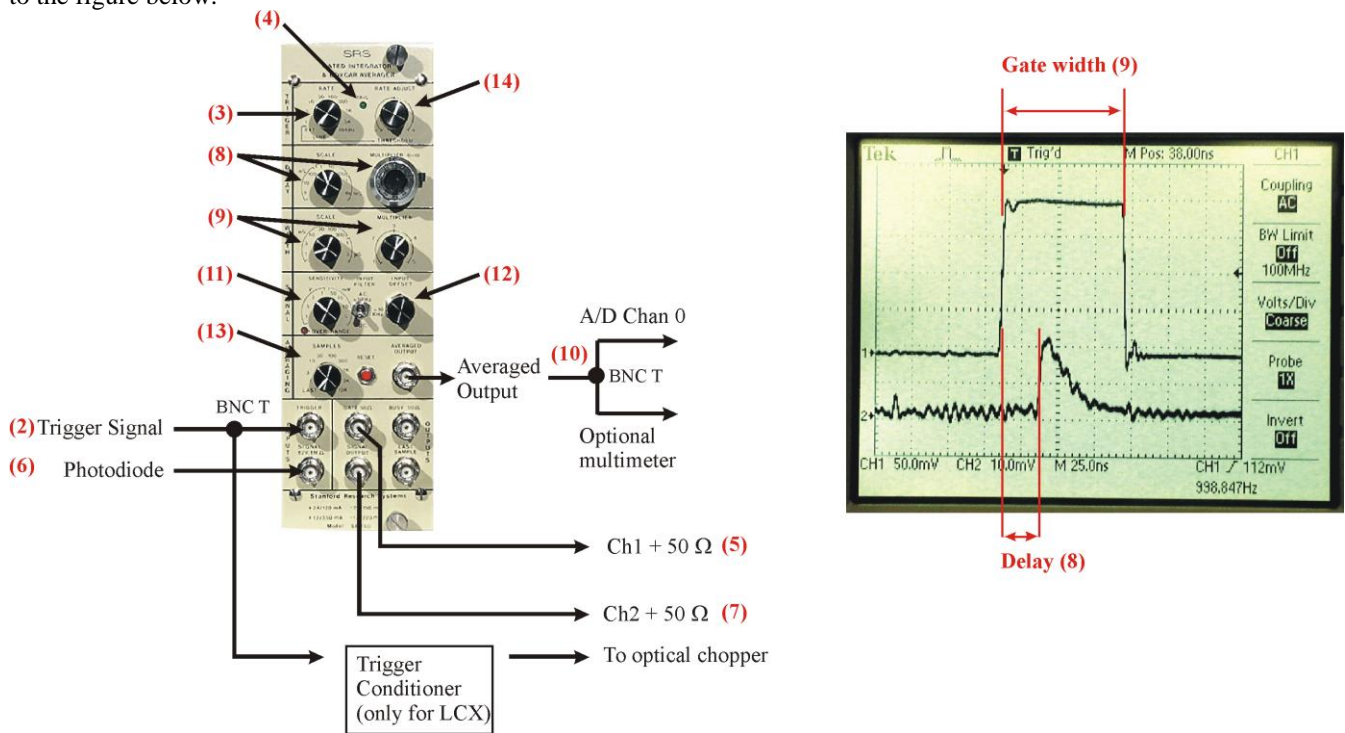2. Connect the trigger signal from the Spitfire to input BNC. The BNC can be connected directly into the instrument or via BNC-T connector. The trigger is often used for synchronization of the mechanical chopper in single pulse ablation experiments.
3. Make sure that the **RATE** knob is selected to **EXT** (external trigger).
4. If the trigger is detected the green **TRIG LED** should be ON
   NOTE: Under most circumstances the box car should not have any problems with triggering. If there are problems, first plug the trigger BNC to the scope and examine the signal. Make sure that the trigger signal is present and signal levels are normal. Normal trigger for Spitfire LCX (a.k.a old system) resembles a decaying exponential with the peak voltage in excess of 10V. The trigger signal from the Sub 50fs Spitfire (a.k.a the new system) is a standard 5 V TTL square pulse. If the trigger signal is absent that may indicate problems with the laser. If the trigger signal is present but the box-car does not trigger, the trigger level might have to be adjusted. Plug the trigger BNC back to the box car and adjustment the THRESHOLD control (14) until the box car trigger and gate waveform can be seen on the scope. Note that you want to trigger on the rising edge of the trigger pulse so make sure that the THRESHOLD knob is on the positive side. It the threshold is set too high or too low multiple gates can be generated. This situation does not occur often but tends to be problematic if it does.
5. Connect **GATE** output to the scope; make sure to use 50 Ω terminator. Adjust the scope settings such that the gate is seen on the screen.
6. Turn the photodiode ON and connect the photodiode signal to the input BNC.
7. Connect **SIGNAL OUTPUT** to the scope; make sure to use 50 Ω terminator. Adjust scope settings such that **GATE** waveform and SIGNAL waveform are both visible. It is most convenient to trigger the scope on the GATE signal. Make sure that the photodiode signal is not saturated. If the signal is saturated you will have to insert additional

neutral density filters in front of the photodiode. In many cases it is beneficial to use the opal beam diffuser in front of the photodiode.

8. Adjust the **DELAY** such that the photodiode signal is inside of the gate.
9. Adjust the **WIDTH** of the gate to capture the entire pulse shape.
10. Connect the **AVERAGED OUTPUT** to PC and to a multimeter (use BNC T connector).
11. Adjust **SENSITIVITY** to level where the full scale reading is less than 5V.
12. Block the laser beam and adjust the **INPUT OFFSET** such that the **AVERAGED OUTPUT** is ~ 0mV on the multimeter. Note that this knob is very sensitive.
13. Make sure that the **AVERAGING** is set to 1 sample (SAMPLES knob).
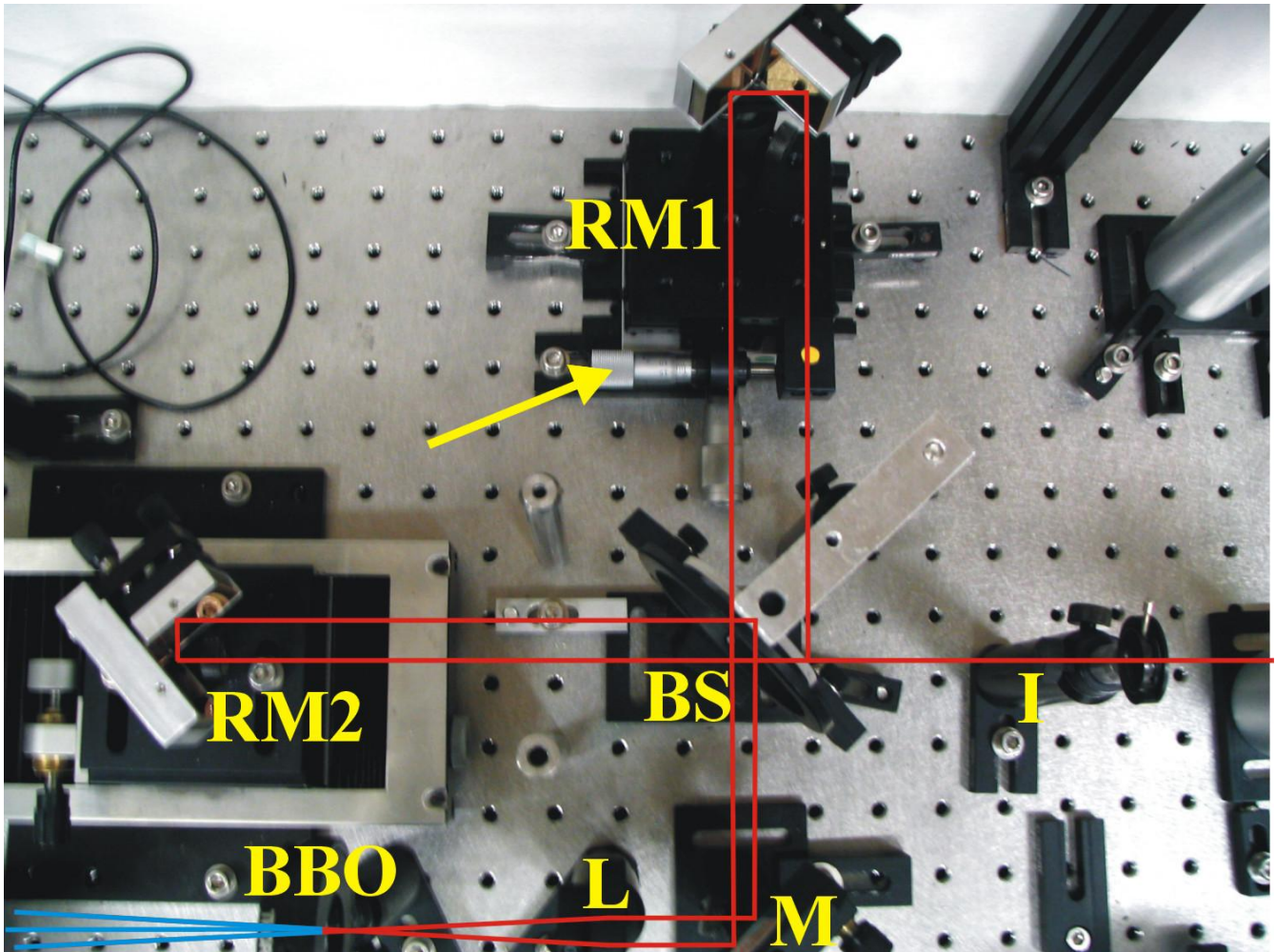
4. Autocorrelator Setup

4.1.   Introduction

The measurement and characterization of ultrashort laser pulses is a non-trivial problem and it has been an active field of research in itself. The majority of measurement techniques rely on various autocorrelation schemes. A very good overview of these techniques can be found in a number of textbooks [i,ii]. A micromachining setup includes an autocorrelator that can be configured to operate in interferometric or intensity modes. Intensity autocorrelation is used for most routine measurements as it is the fastest and most practical.

The autocorrelator is based on a Michelson interferometer configuration. FIGURE 35 shows a schematic of interferometric (a) and intensity (b) autocorrelator configurations and typical autocorrelation traces of the Spitfire pulses obtained in each configuration. FIGURE 36 shows the picture of the setup in intensity or background free configuration. The input beam is split into two replicas by a broadband, 2", 3 mm thick beam splitter (BS). The beam in each arm is retro-reflected by a gold mirror roof mirror (RM1 and RM2) and the same beam splitter recombines the two beams. A dielectric mirror (M) directs the two beams through a lens (L), which focuses the beams in a nonlinear crystal (BBO). In the interferometric configuration the position of RM1 is adjusted with the micrometer (indicated by an arrow in the picture), such that the two beams are superimposed and sent through a nonlinear crystal. In the interferometric configuration the focusing lens (L) can be removed. In the intensity or background free configuration the beam in one arm (RM1) is horizontally displaced by ~ 4 mm relative to the other beam. The two parallel beams are recombined by the same beam splitter and focused in the nonlinear crystal at a shallow angle by a lens. The path length of one arm is scanned by a translation stage (Newport). The signal from the detector is acquired with at box-car integrator (SR250, SRS) and computer acquisition card (PCI-6025E, National Instruments).
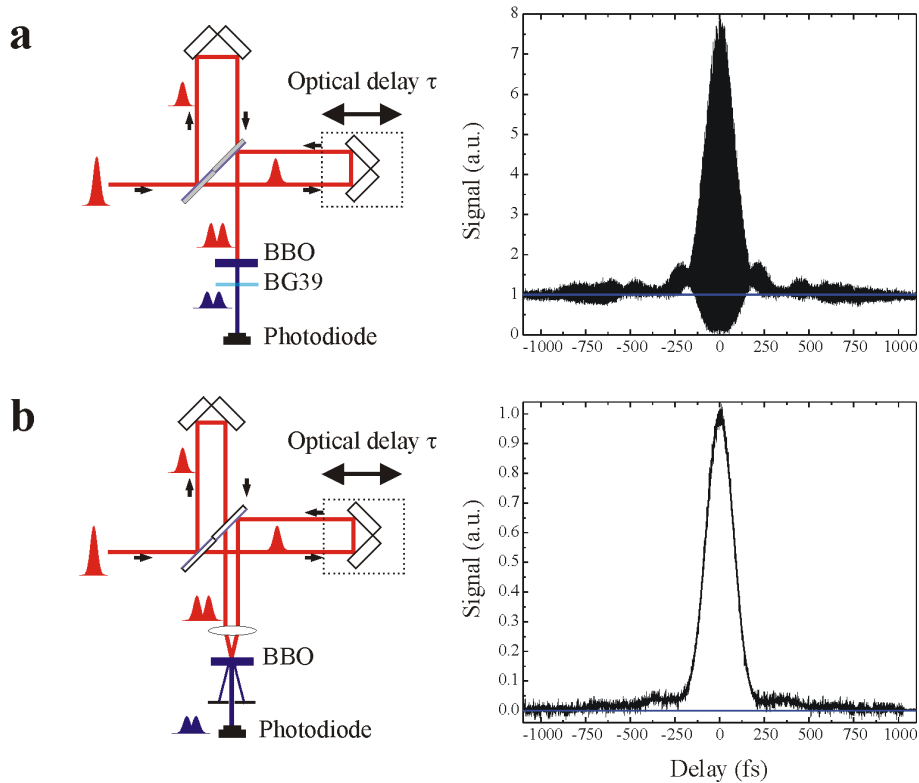
FIGURE 35 : Schematic of (a) an interferometric and (b) intensity autocorrelator geometry along with typical autocorrelation traces of 130 fs Spitfire beam.

FIGURE 36: Picture of the autocorrelator setup shown in intensity or background free configuration.

4.2. Autocorrelator Alignment

1. First align the beam through the micromachining setup.
   (See section 1 or 2)

---

2. Reduce the laser energy to minimum with HWP.

---

3. Make sure that the iris (I) in front of the autocorrelator is closed to ~1 mm.
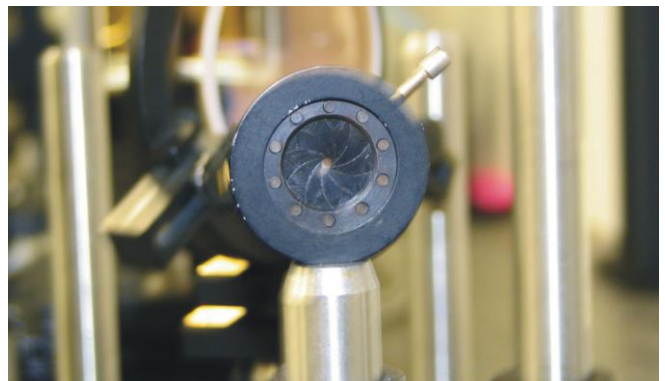
FIGURE 37

4. Flip up the mirror directing the beam into the autocorrelator setup, located between mirrors M5 and M6. (Location shown with arrows in FIGURE 38, but a mirror mounted flip-mount has been in use since).
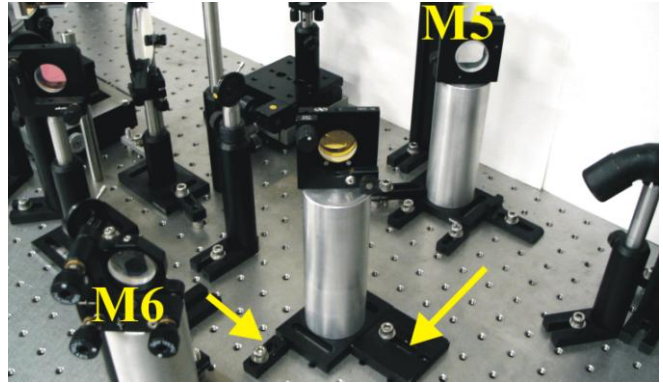
FIGURE 38

5. Place a business card after the BBO crystal and slowly increase laser power by rotating HWP until you see blue light on the business card. If everything is aligned correctly you should see 3 blue spots on the business card. The middle spot should be the brightest one of the three.

If this is not the case realignment of the autocorrelator might be required. The instruction on autocorrelator realignment is beyond the scope of this manual and should be performed by a laser jock.
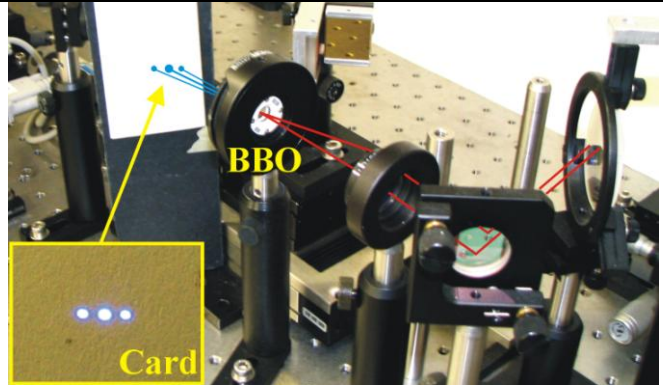
FIGURE 39

6. Beyond BBO blue beams are directed onto the Si photodiode with the silver mirror. The silver mirror should be adjusted such that the middle beam passes through the paper mask as shown in FIGURE 40. The two outside beam should be visible on either side of the card.
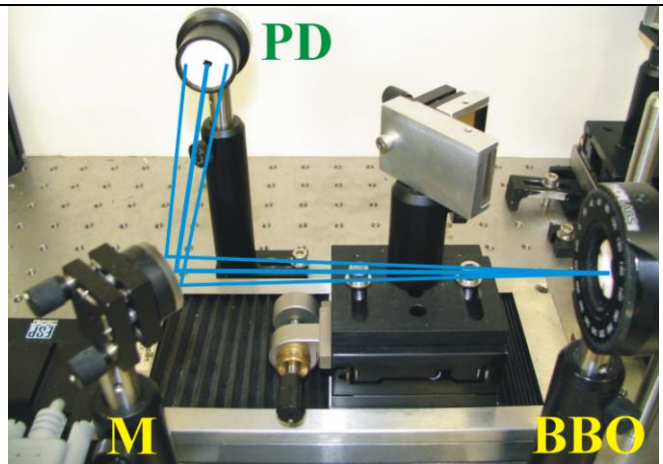
FIGURE 40

7. Make sure that the photodiode is ON and connected to the input of the box car (follow the box car setup instructions in the previous section).

8. Adjust the laser power with the half wave plate to a level where the diode is not saturating. (signal level should be ~ 100 - 200 mV (peak-to-peak).
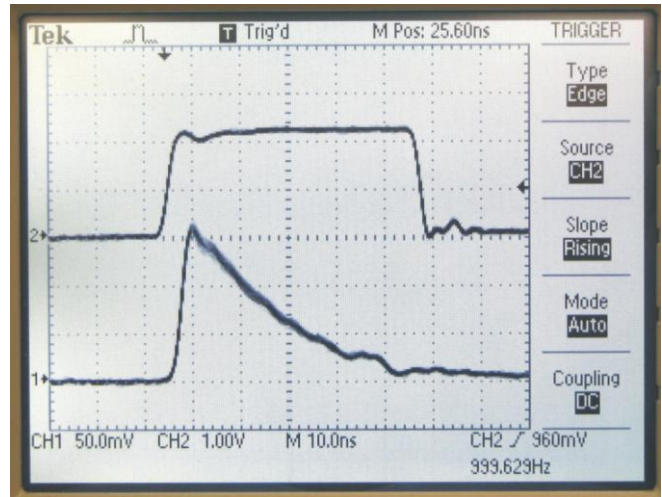
FIGURE 41

9. If necessary, maximize the photodiode signal by adjusting the delay line in RM1 arm with the micrometer indicated with the arrow.

   The positioning and the rotation of the BBO crystal can be adjusted as well by adjusting the translation stage on which the BBO is mounted on to further peak the signal.

   These steps should not be necessary on day-to-day operation.
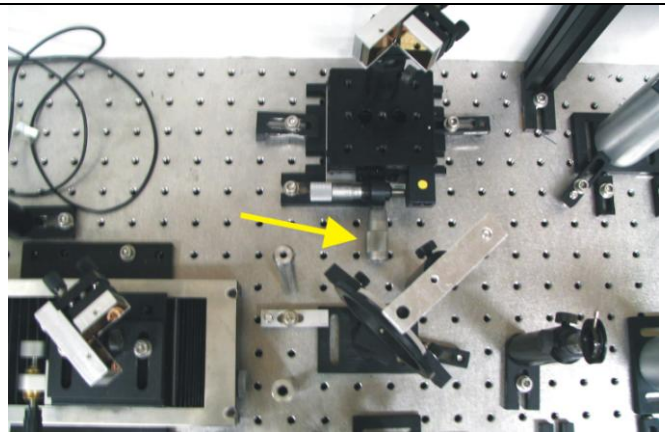
FIGURE 42

10. Note: The box-car integrator input is switched between this photodiode and the one used in the autocorrelator setup. Make sure the switch is at the appropriate position to work with the signal.

11. Turnrn on the ESP 300 controller for the autocorrelator motor. As of Dec. 2010 this would be the controller on top.

12. Start the autocorrelation software.
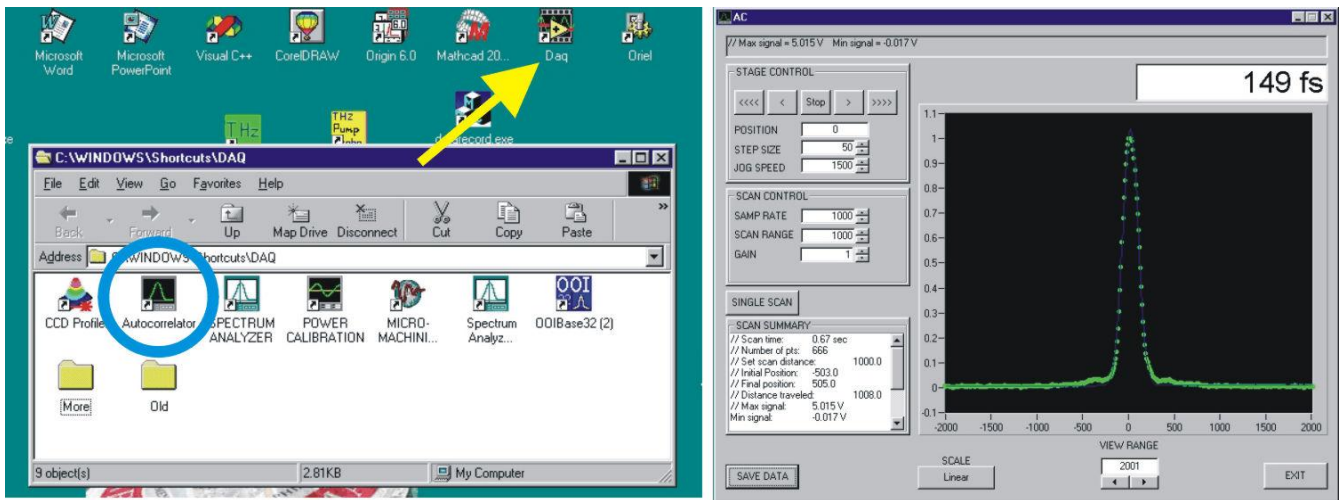
FIGURE 43

13. Press *SINGLE SCAN* to scan and obtain the autocorrelation trace. The Y-axis can be viewed on a linear or log scale. Log scale is useful for visualizing "wings" of the pulse. If necessary adjust compression of the laser to minimize pulse duration and repeat the scan.

When the desired pulse duration/compression is obtained, perform a long base line scan to make sure there are no ancillary pulses. The stage is capable of a 10 cm travel (100 000 um scan range), corresponding to a ± ~333 ps delay rnage.

When finished press *SAVE DATA* to record the trace. The data is saved in TAB delaminated ASCII format with the header summarizing the scan conditions. With every scan the data is automatically saved in E:\Laser_Log directory.
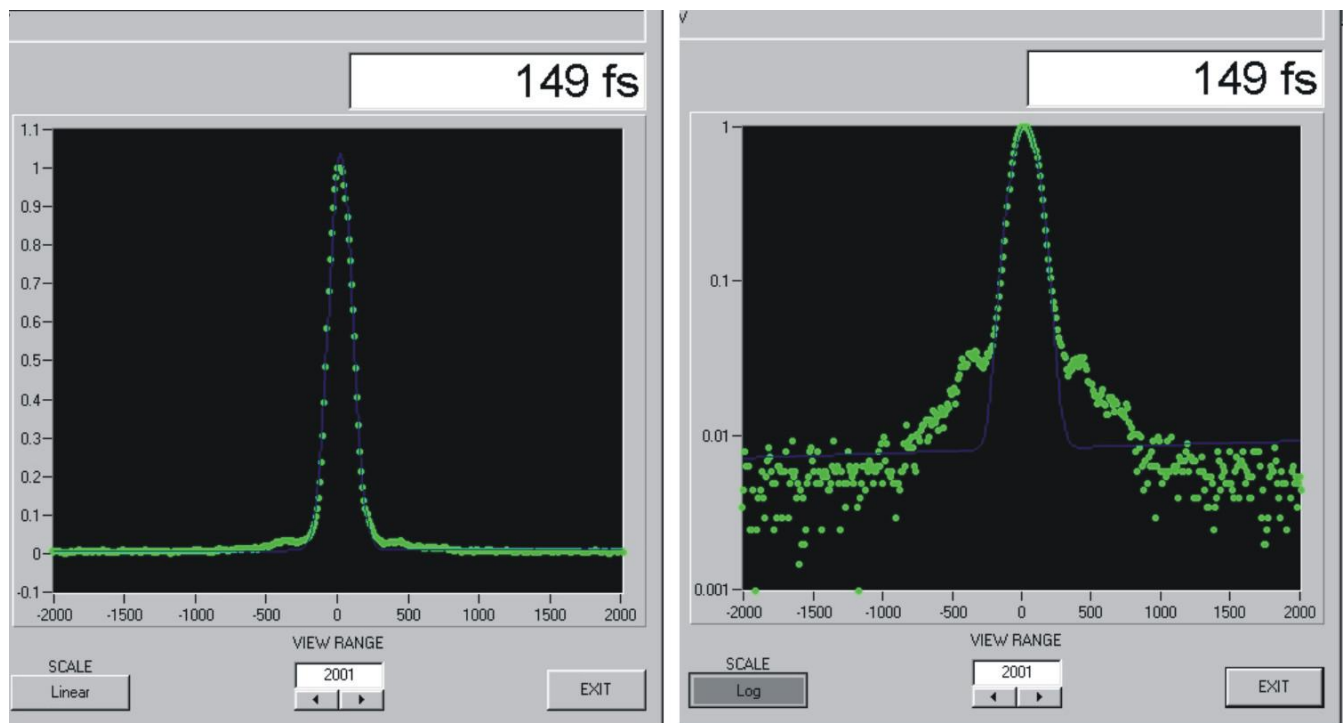
14. Turn the beam power all the way down using the HWP. Flip the the gold mirror from the beam path to direct the beam towards the micromachining setup.

5. Spectrum Measurement

1. Place a business card in the beam at 45º angle and scatter the beam onto the fiber coupled spectrometer.
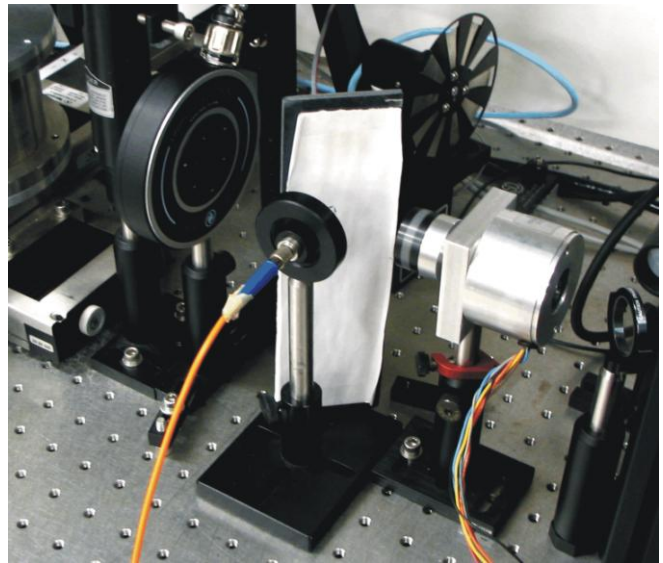
FIGURE 44

2. Start the SPECTRUM ANALYZER software
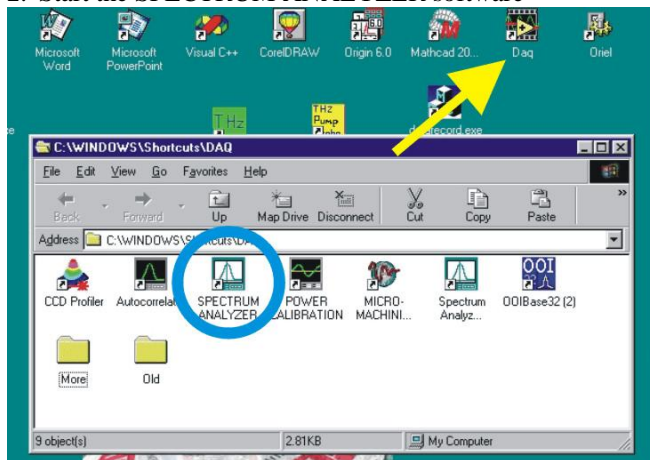
FIGURE 45

3. Press **START Spectrometer** to begin acquisition. The **Max Signal** level should be between 500 – 4000 counts. If the spectrum looks noisy or the signal level is low it is usually sufficient to move around the business card and/or spectrometer.
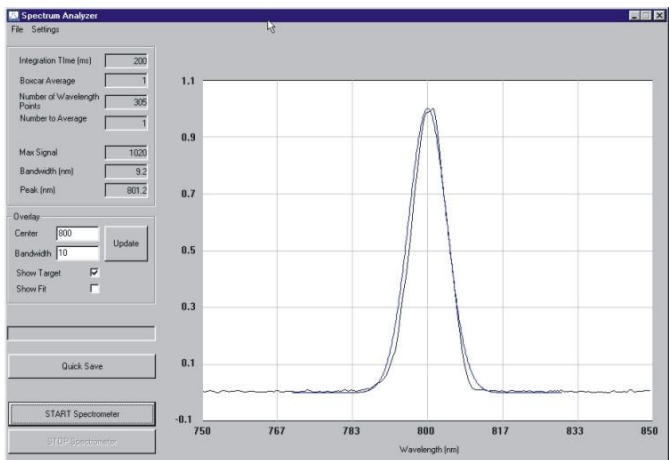
FIGURE 46

4. Press **STOP Spectrometer** to stop acquisition and save the data in a file (FILE → Save Spectrum). You can also press **Quick Save** to save the data in the E:\Laser_Log directory. The fill will be called 200Y_MM_DD_Spectrum. The data is two column TAB separated ASCII format. The first column is wavelength in nm and the second is signal level in arbitrary units.
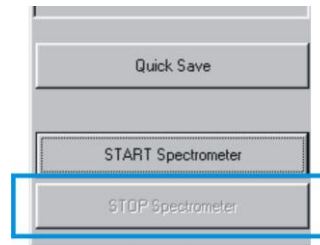
FIGURE 47

6. Setting up for Laser Micromachining

1. Place the sample inside of the chamber. The type of sample mount will vary depending on the sample processed. A variety of mounting options are available.
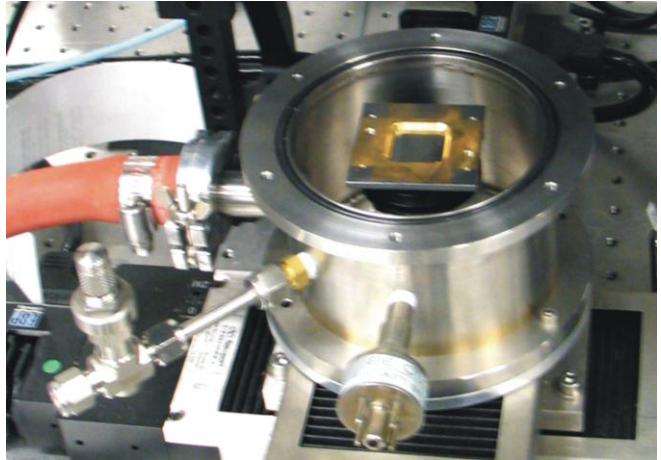
FIGURE 48

2. Rotate the microscope revolver with an appropriate objective into the beam. Historically Newport 5x objective was the workhorse, however other objectives and lenses can by used for machining, for example Mituooyo objectives, and various lenses mounted in the ThorLabs SM1 tubes.
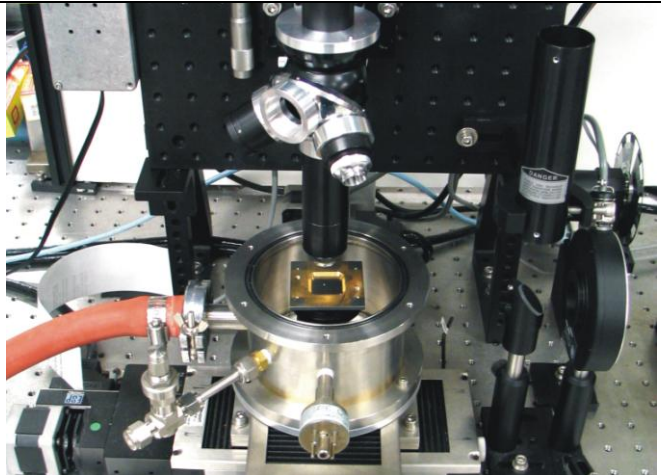
FIGURE 49

3. Turn the LED illumination ON and the TV monitor.

Figure 50

4. Adjust the manual-focussing micrometer such that the image appears in focus on the monitor.

Figure 51

5. Note: This step is omitted for experiments where we would want as close to a pure single-pulse as possible for the irradiation (e.g., single-shot, threshold/incubation experiments.)

Tape a 1x1" microscope glass slide to the back side of the vacuum chamber lid. This slide protects the window from debris and might have to be changed regularly especial when processing in vacuum. The lid with 2" window can be protected with the 2x1" cover slips side by side.
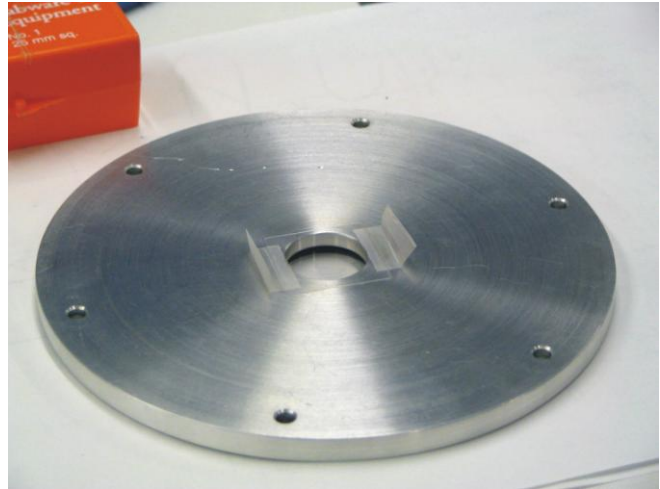
FIGURE 52

6. Place the lid over the vacuum chamber. You will notice that the camera will have to be refocused when the lid is placed over the chamber.

7. Connect the vacuum gauge, close the air admit valve on the chamber and turn on the vacuum pump. The vacuum pump is located under the optical bench under the micromachining chamber area.
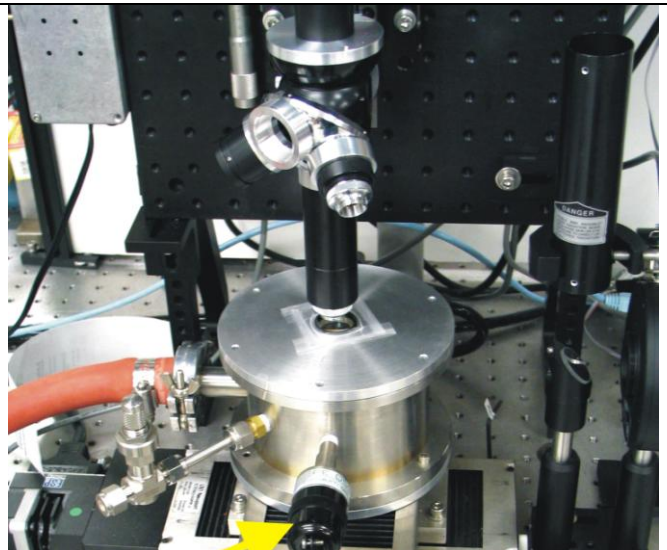
FIGURE 53

15. Turn on the ESP 300 controller for the autocorrelator motor. As of Dec. 2010 this would be the controller at the bottom, Launch the MICROMACHINING CONTROL software. Rock and roll!

FIGURE 54

7. Matching camera focus to laser focus

When performing an experiment a convenient to locate the laser focus is to match the viewing camera focus to the laser focus. This is done by performing very low power scans on the sample surface such that observable damage or modifications occur at the focal plane. The camera focus is then matched to the laser focus at this point.

---

1. Reduce the laser power all the way down by either using the HWP or the NDFs, if the NDFs are still in use.

2. Insert all of the optical elements to be used in th experiment, downstream for the camera viewing mirror in the beam path, as they will affect how the laser and the camera would focus.

   This may include a focusing element, micromachining chamber lid window, waveplate and/or a coverslip etc..

3. As the laser beam is scanned on the test sample surface using the "Linear Grating" routine, preferably in the same ambient condition as the experiment to be ran, slowly ramp up the power until damage/modification is just observable under the viewing setup in the micromachining setup.

4. Adjust the manual-focussing micrometer to find a working distance for the lens/objective such that the most laser damage is visible for a given power setting. Reduce the power as necessary to keep the ablation/modification in the gentle regime.
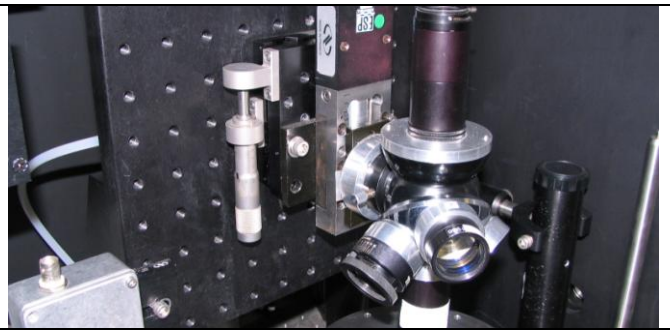
5. Iteratively reduce the laser power and re-adjust the manual focusing micrometer until the lowest power can be used to achieve visible changes to the test sample surface at the given working distance. If the focus between the laser and the camera started off really far, one may need to adjust the camera focus periodically in this step (see the next step for camera focus adjustment).

   At this point lowering the power or moving changing the working distance of the objective will cause observable damage/modifications to seize. This will indicate the laser focus is just at the sample surface.

6. The focus of the camera is adjusted by loosening the setscrew and adjusting the outer most ring on the camera.

   Note: Other adjustment rings on the camera shouldn't need to be adjusted on a day to day basis. The camera only samples a small area and it is easy to lose the laser irradiation point as we are adjusting the focus. One could easily spend more than an hour just trying to find where the laser irradiates the sample if they are lost.
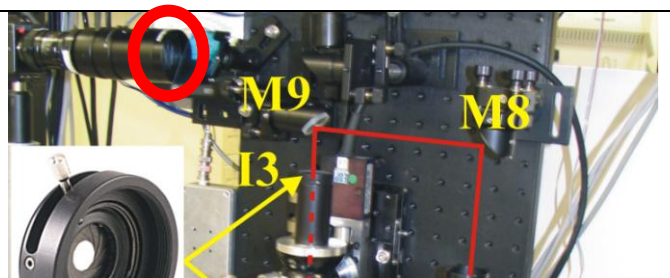
7. If need be, adjust the positioning of the camera viewing area on the sample by adjusting the viewing mirror.

   NOTE: Do not confuse the laser alignment mirror(s) with the camera mirror, or the alignment procedure will have to be performed again.
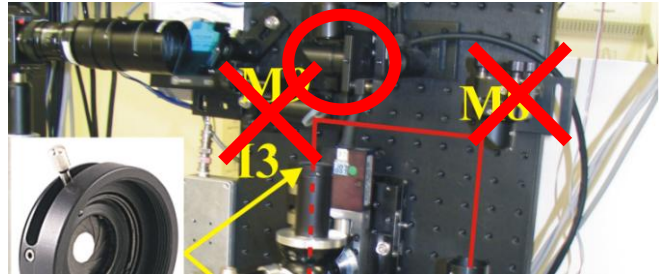
Figure 55

8. Power Measurement and Photodiode Calibration

This section describes method for adjusting the power level and calibrating the monitor photodiode. Power calibration should be performed as a last step, after optical alignment, pulse-width, spectrum and beam profile measurements.

1. If not already done so turn on the filter wheel control box. The toggle switch is located at the rear of the controller on the upper right.

FIGURE 56

2. Make sure that the power meter is connected to the PC serial port COM2. Turn on the power meter and ensure that the WAVELENGTH is set to appropriate value, in most circumstances is should be 800 nm. Also check if the FILTER is in or out (this only applies to the silicon photodetector head).

FIGURE 57

3. Connect the photodiode (PD), monitoring the reflection from the pellicle beam splitter (PBS), to the box-car integrator and follow the box-car integrator setup procedure. Make sure that PD is not saturating. In case of saturation add appropriate neutral density filter.
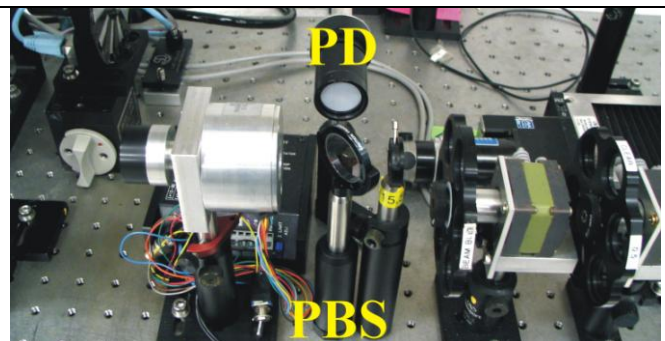
FIGURE 58

4. Note: The box-car integrator input is switched between this photodiode and the one used in the autocorrelator setup. Make sure the switch is at the appropriate position to work with the signal.

5. Place the power meter after the focusing optic. **IMPORTANT:** The beam should never focus on the active element of the power meter as this can lead to permanent damage of the detector or in a less sever case saturation of the detector which will lead to inaccurate power reading. At the other extreme you also want to ensure that the beam does not overfill the detector TIPS:
Place the detector as close as possible to the objective or focusing optics. This will capture the entire beam well before it comes to focus. Focusing beams with pulse energy in excess of 10 uJ will lead to air break-down, therefore measuring the power below the focus can lead to inaccurate power measurements.
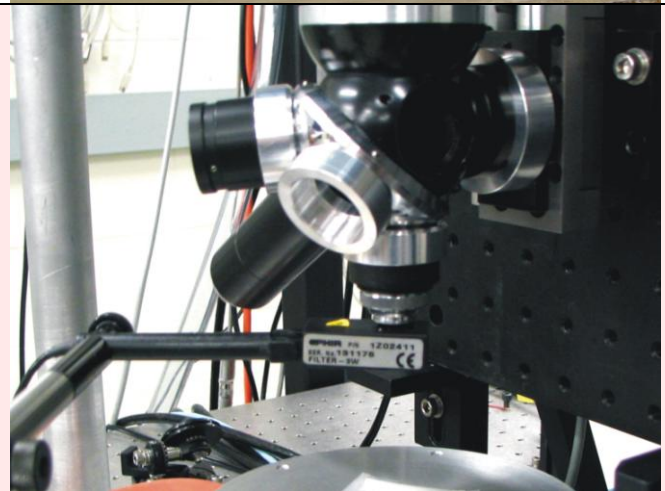
FIGURE 59

6. If the samples are processed inside of the vacuum chamber one has to account for Fresnel losses as the beam passes through the chamber window. Place the window along with the protective microscope glass slide on top of the detector or the iris I3. This will account for all throughput losses when the beam is delivered into the vacuum chamber.

FIGURE 60

7. Start the Power Meter Calibration software.
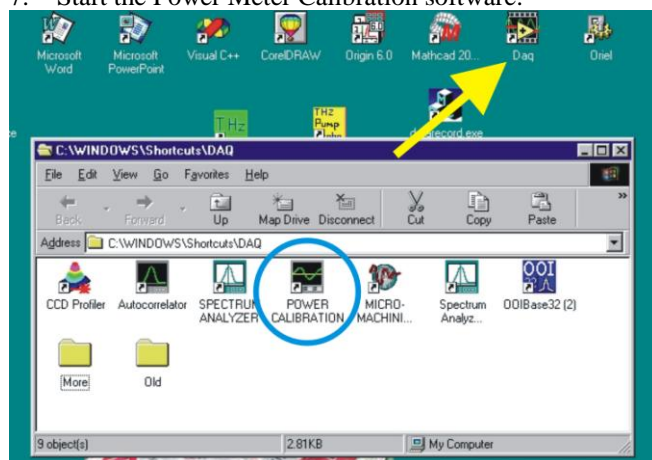
FIGURE 61
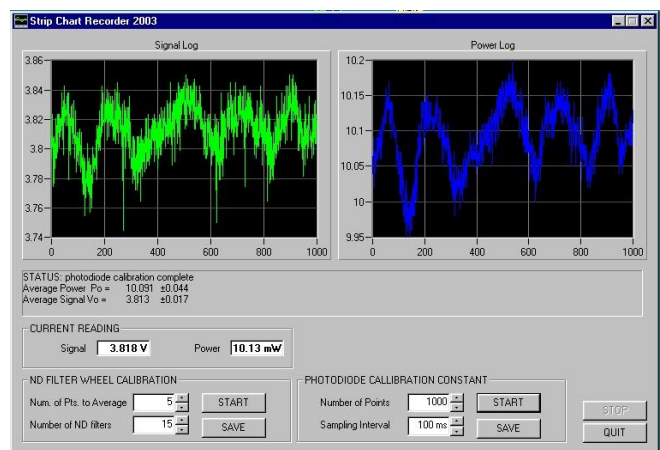
FIGURE 62

8. Follow the box-car setup instructions and connect the AVERAGED OUTUPT to CHAN 0 on the BNC AD card.

9. Adjust the laser power to minimum using HWP.	
10. Open the laser shutter and increase the laser power by rotating the wave plate until a desired power level is reached. For example, typical power levels for single and multiple pulse ablation of semiconductors with a 5x objective are on the order of 1 uJ (1 mW). Drilling and cutting of grooves in metals typically require pulse energy of ~ 10 uJ (10 mW).	
11. Double check to make sure that the offset on the box car is set to 0. That is when the laser is blocked the output of the box-car should read approximately 0. With the full power the signal should not exceed 5V.	
12. Once the power meter and the box-car are set up you can start the calibration sequence.	
13. In the software window, under PHOTODIODE CALLIBRATION CONSTANT choose number of samples to be acquired and sampling interval, the default values are 2000 and 100 ms respectively. Press **START** to begin acquisition process. The program will simultaneously sample photodiode and power meter. The current values will be plotted on the two plots and current readings will be displayed on screen below the STATUS window.
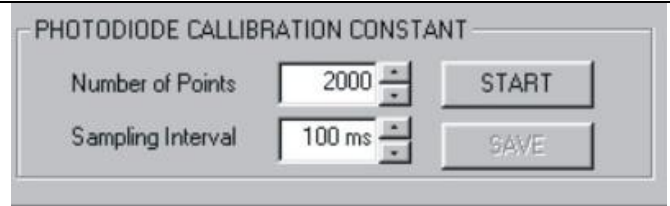
FIGURE 63 |
| 14. After completion of acquisition mean and standard deviation of the signals will be calculated and displayed in the STATUS window – note these values in your notes.

The calibration constant is given by:

$C = P_o/V_o$ mW/V

You can also save the raw data for future reference. The last scan is always saved automatically in E:\Laser_Log directory under the name 200Y_MM_DD_Photodiode_Calibration_AUTOSAVE |
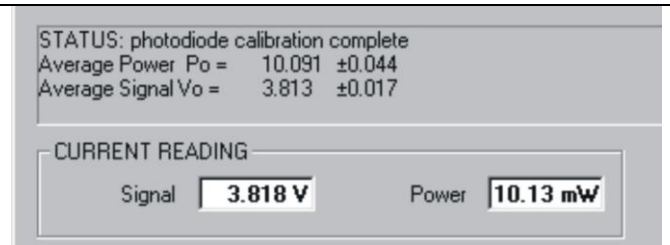
FIGURE 64 |
| 15. If you are performing measurements where certain parameter is investigated as a function of pulse energy, use Filter wheel calibration function to measure the power and the signal level at all filter wheel values. | |
| 16. First select the number of OD filters to be measured (default value is 15) and number of consecutive measurements at each OD setting (default value is 5). If the value is set to 5, then 5 consecutive voltage and power meter readings are taken at each OD filter and the average value of those readings is recorded in the file. |
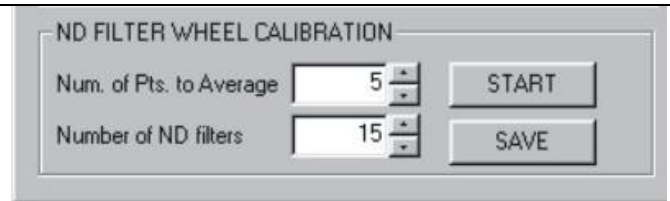
FIGURE 65 |
| 17. To begin the measurement press START. Status of the measurement is shown in the STATUS window. At the end of acquisition a dialog box will appear allowing the user to save the data to a file. The data file contains three columns: Nominal OD, Measured Power, and Photodiode Signal. In addition the last photodiode calibration measurement is saved in E:\Laser_Log directory. | |

9. Generation of different repetition rates

On Laser Repetition Rate:

In experiments dealing with single and multiple pulse ablation, it is necessary to select a known number of pulses from the 1 kHz pulse train. The number of pulses delivered can be controlled in a several ways, for example, by using a combination of a Pockels cell and a polarizer; a fast mechanical shutter with minimum exposure time less than 1 ms; or by reducing the repetition rate of the amplifier to 100 or 10 Hz and using a slower mechanical shutter. Initially, the last method was adapted as it is the easiest and, by far, the least expensive. However, reducing the repetition rate of the amplifier to 10 Hz changes the thermal loading of the amplifier and leads to a decrease in the output pulse energy, and may require a subtle, longer-term stabilization period, which may affect the power calibration for a long experiment. A decrease of pulse energy in the range of few percent is not too problematic in experiments utilizing pulses from the Spitfire LCX amplifier. The change in steady state conditions of the sub-50 fs Spitfire is a greater concern since that system was used to pump the OPA. The OPA is very sensitive to laser intensity fluctuations since it relies on nonlinear processes for wavelength conversion. A decrease of the OPA pump pulse energy by a few percent can translate into a decrease in the OPA output pulse energy by as much a 50%. To avoid problems associated with changing the steady state condition of the laser caused by reducing the repetition rate, the repetition rate is decreased by using a phase locked optical chopper. The optical chopper (MC1000, ThorLabs) with a 10 slot wheel is phase locked to a sub-harmonic of the amplifier repetition rate yielding a 500 Hz pulse train. Blocking 9 out of 10 slots in the chopper wheel further reduced the repetition rate to 50 Hz allowing for the use of a slower mechanical shutter, while maintaining 1 kHz amplifier operation. Further reduction of the repetition rate is achieved by programming the shutter to repeatedly open at a definable rate that is < 10 Hz to avoid damage of the shutter, as per the shutter manual. The repetition rate is programmed via the micromachining control program, in the main menu where we can choose between "normal rep. rate" and "slow rep rate."
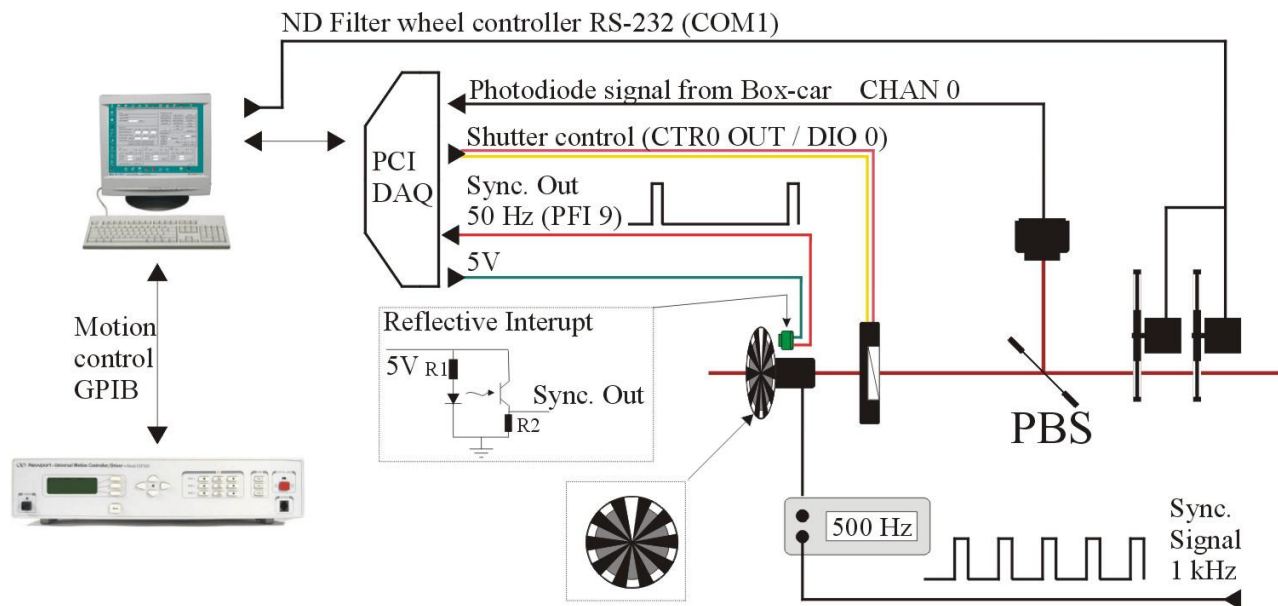
FIGURE 66: Schematic of synchronization and acquisition connections.

To generate different repetition rates:

Chances are if you are a keen experimentalist you have understandably skipped the blurb on the repetition rates on the previous page. So, here is a short version on how to generate the different repetition rates and use them in experiments.

- 1000 Hz: This is the typical operation repetition rate for the Spifire, nothing needs to be done to obtain this.
- 500 Hz: Can be obtained by using a 10-blade chopper with the Thorlabs chopper controller.
- 250 Hz: Can be obtained by blocking out every two slots on the chopper blade, presumably.
- 100 Hz: Can be obtained by blocking out 8/10 slots so that the two open slots are opposite each other.
- **50 Hz: This is the typical repetition rate used with the single-/multiple-shot routines in the micromachining program, and is obtained by taking a 10-blade chopper blade and blocking out 9/10 slots.**
- ≤ 10 Hz: Can be obtained by using the 50 Hz chopper setup in conjunction with the routine in the micromachining control program where the shutter can be switched repeatedly to slow down the repetition rate.

NOTE: The use of trigger is required with chopper to ensure the shutter opening is synchronized with the arrival of the laser pulses to ensure the pulses are not clipped by the shutter.

10. Using the micromachining control program

The routines to be used is chosen in the drop down menu below the "Pattern Settings" tab. Details of the routines can be found under the "Patterns Settings" tab.
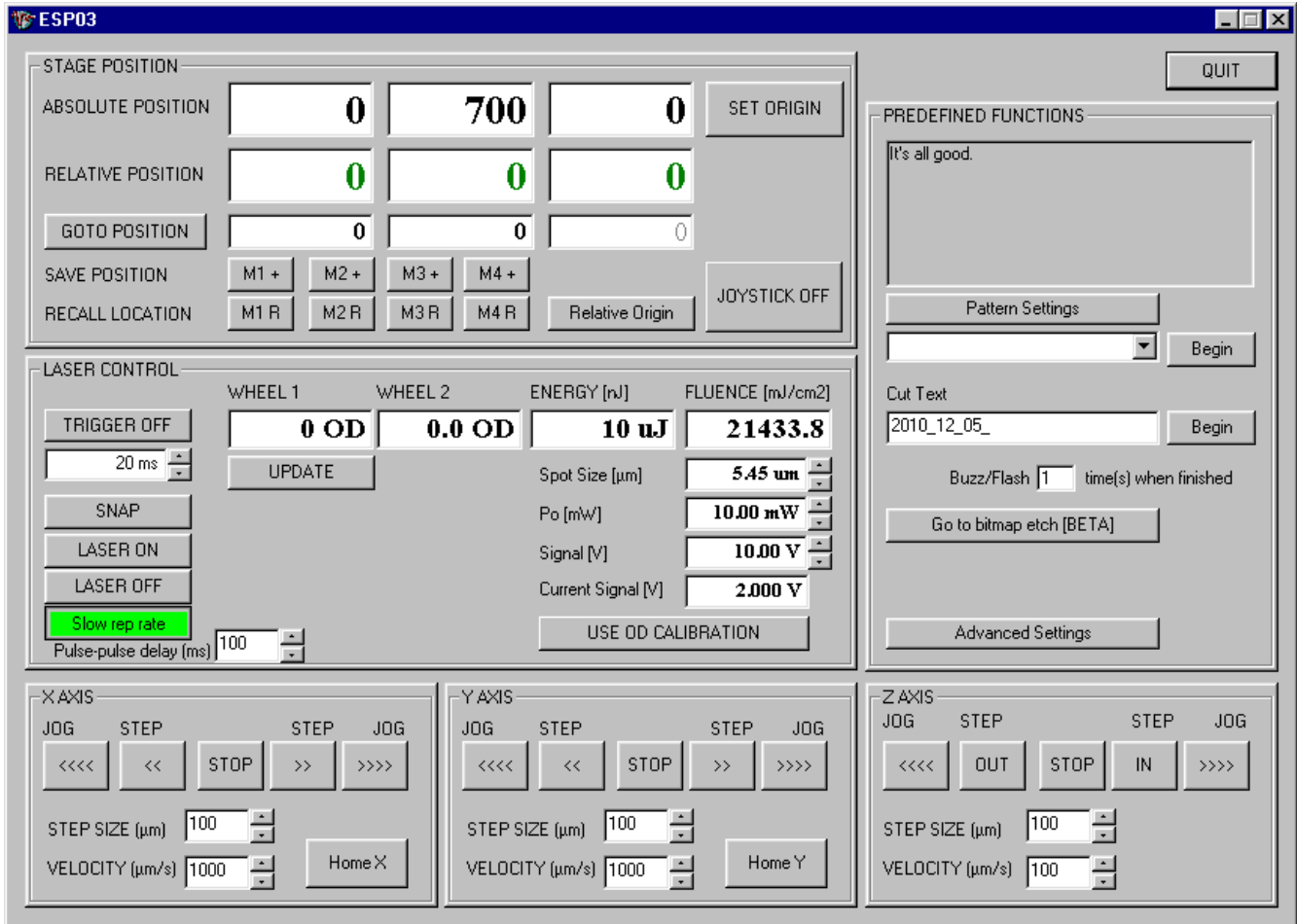
The micromachining control program's front menu are divided into the following sections:

STAGE POSITION

ABSOLUTE POSITION: This is the read out for the current location in the absolute location coordinate.

RELATIVE POSITION: This is the read out for the current location as the relative location. The relative origin is set when the ESP 300 is turned on. After which the relative origin can be set any time with the SET ORIGIN switch.

SET ORIGIN: Sets the current location as the relative origin.

SAVE POSITION: Saves the current location in the memory. As can be seen we can save up to 4 locations.

RECALL LOCATION: Calls up the memory location stored in the slot (M1, M2, M3 or M4). The coordinates of the recalled location is displayed in the third row of text boxes.

RELATIVE ORIGIN: Funky laser ninja dance…je ne sais pas.

JOYSTICK ON/OFF: Switches between using the micromachining control program (and/or the front panel of ESP 300) XOR the joystick to control the positioning of the stages.

LASER CONTROL

TRIGGER ON/OFF: Turns the trigger on/off, which is required to synchronize the shutter opening time to the chopper rotation to avoid clipping pulses when the chopper is in use.

SNAP: Opens the shutter for the amount of time indicated in the text box right above the snap button.

LASER ON: Opens the shutter.

LASER OFF: Closes the shutter.

SLOW REP RATE: Allows the use of a slower rep. rate, in conjunction with a chopper. It requires the trigger to be on. The pulse-to-pulse delay is entered at the text box below this switch. The maximum safe continuous operating frequency for the shutter is 10 Hz (corresponds to a minimum pulse-pulse delay of 100 ms).

OTHER POWER READOUT STUFF: Shows the CALCULATED energy and fluence at different ODs when the maximum power (i.e., at OD of 0.0 in this imaginary situation) is set at P_o.

X/Y/Z-AXIS

These settings allow control of the movements of the stages.

STEP: Move the stage by one STEP SIZE.

JOG: Move the stage indefinitely until the STOP button is pushed.

STOP: Stops the movement of the stage in JOG mode.

STEP SIZE: The distance to move in one STEP.

VELOCITY: Sets the translation speed of the STEP or JOG movements.

PREDEFINED FUNCTIONS

Detailed descriptions for the pre-defined patterns and their settings are provided in the next section.

PATTERN SETTINGS: Sets the details of the selected pattern.

PATTERNS SELECTION: (Text label not shown.) The drop down menu allows the user to choose a pre-defined setting.

CUT TEXT: Cuts the text entered into the text field onto the sample. Some of the lesser used symbols/punctuations are not defined as one of the pre-defined patterns, yet.

BITMAP ETCH: Takes a monochromatic bit map and ablates pixels that are black. The shutter opens for the "on" spots of the bitmap as the target positioning is raster scanned across the sample. Basically this turns the laser system into a half-a-million-dollar dot matrix etching printer.

ADVANCED SETTINGS: Contains control parameters for motion controller and DAQ board.

11.   Descriptions of micromachining program routines

The routines to be used is chosen in the drop down menu below the "Pattern Settings" tab. Details of the routines can be found under the "Patterns Settings" tab.

Select desired routine in this drop down menu. Descriptions for more common routines are below in this manual.

Cutting of texts are set/performed in a separate menu.

Modifiable details for each routine are access through this "Pattern Settings" tab.
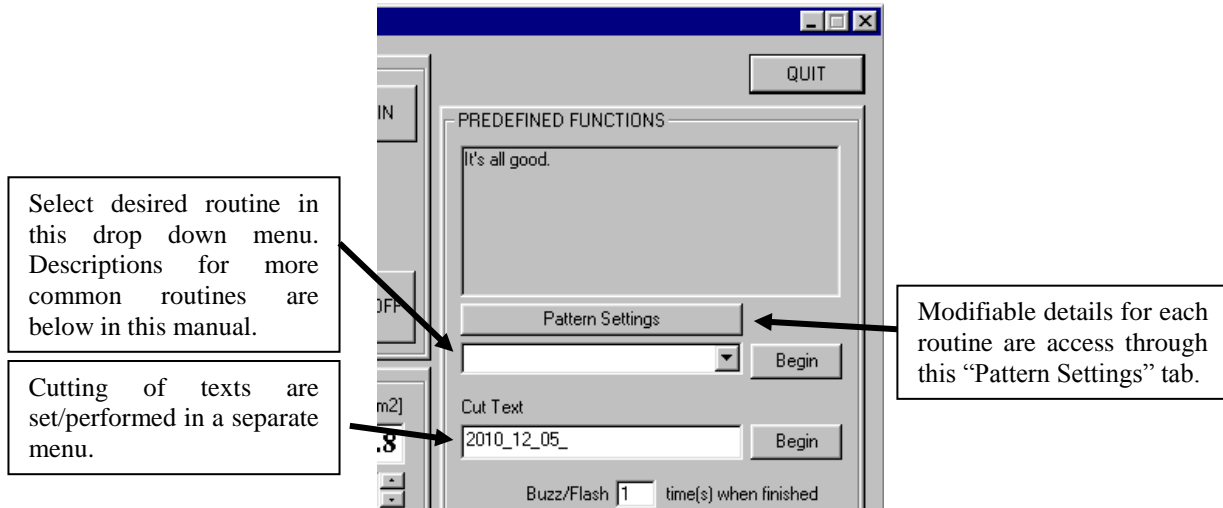
Cutting text: The text to be etched onto the sample is entered into the text field under the label "Cut Text". The dimensions of the text is set under "Pattern Settings" → "Other Figures"

1. **Single Shot**: This routine ablates rows of spots with decreasing laser energy/increasing OD. It starts at the real life left of the sample (as right on the micromachining camera) and the craters with increasing OD is cut subsequently to the right. With a chopper slowing the repetition down to 50 Hz and the shutter time set to 20 ms, single-pulse irradiation is achieved.
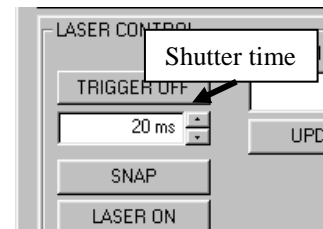
    Shutter time

    Parameters (in "Pattern Settings" → "Single and Multiple Pulse"):
    "SINGLE PULSE" column:
    *   **Number of holes**: Number of different energies/OD's to do for each row.
    *   **Number of rows**: Number of rows to repeat the same run.
    *   **Hole spacing**: Lateral hole-hole spacing.
    *   **Row spacing**: Vertical row-row/hole-hole spacing.
    *   **Z-step between holes**: Not sure. Presumably something to do with moving the focal plane in and/or out, either between holes or between rows of holes. Feel free to explore.
    *   **Pulses per hole**: The number of pulses to be used per hole. This assumes that "a pulse" means the shutter opens once, as defined by the shutter time in the main menu, and multiples the shutter time by the number input in this field to get a total amount of time the shutter is opened for. For example, with the 50 Hz chopper in place the shutter time will be set to 20 ms for each pulses, and if we input 5 pulse we will have the shutter opening at 100 ms per irradiation spot. Any arbitrary combinations of shutter time and pulses per hole can be used to obtain a total shutter opening time.
    *   **# holes before space**: At times it may be desirable to leave an extra step of hole/row spacing between holes to facilitate easier positioning on the samples, for example, when viewing the sample under the microscope. If extra spacing is not desired simply set this number to a larger number than the number of holes/rows to be used in the experiment.

2. **Multiple Pulse**: This routine ablates rows (and columns) of spots with decreasing laser energy/increasing OD at rows of different numbers of shots. It starts at the real life bottom left of the sample (appears as bottom right on the micromachining camera) and at the same OD cuts all the subsequent numbers of shot at this OD stepping upwards for each number of shots, then moves to the real life right and back down for the next column/OD setting. Presumably it takes the "Shutter Time" from the main menu of the control program and multiplies it by the entries in the "MULTI PULSE" column under "Pattern Settings" → "Single and Multiple Pulse", and *maybe* by the "Pulses per hole" entry in the "SINGLE PULSE" column under "Pattern Settings" → "Single and Multiple Pulse".

NOTE: One may have to check if this routine is hard coded to work at 50 Hz. If it does then the "Shutter Time" entry will be ignored and 20 ms will always be used as the shutter time entry.

Parameters (in "Pattern Settings" → "Single and Multiple Pulse"):

Note: Parameters in the "SINGLE PULSE" column are still used to control most of the parameters used in the the "MULTIPLE PULSE" routine.

"SINGLE PULSE" column:
- **Number of holes**: Number of different energies/OD's to do for each row.
- **Number of rows**: Number of rows **to repeat each number-of-pulses settings.**
- **Hole spacing**: Lateral hole-hole spacing.
- **Row spacing**: Vertical row-row/hole-hole spacing.
- **Z-step between holes**: Not sure. Presumably something to do with moving the focal plane in and/or out, either between holes or between rows of holes. Feel free to explore.
- **Pulses per hole**: The number of pulses to be used per hole. This assumes that "a pulse" means the shutter opens once, as defined by the shutter time in the main menu, and multiples the shutter time by the number input in this field to get a total amount of time the shutter is opened for. For example, with the 50 Hz chopper in place the shutter time will be set to 20 ms for each pulses, and if we input 5 pulse we will have the shutter opening at 100 ms per irradiation spot. Any arbitrary combinations of shutter time and pulses per hole can be used to obtain a total shutter opening time.
- **# holes before space**: At times it may be desirable to leave an extra step of hole/row spacing between holes to facilitate easier positioning on the samples, for example, when viewing the sample under the microscope. If extra spacing is not desired simply set this number to a larger number than the number of holes/rows to be used in the experiment.

"MULTI PULSE" column:
Simply indicate if each of the rows will be processed by using the check boxes, and enter the number of shots desired for each row.

3. **Multiple Pulse Horiz**: This routine ablates rows (and columns) of spots with decreasing laser energy/increasing OD at rows of different numbers of shots. It starts at the real life bottom left of the sample (appears as bottom right on the micromachining camera) and at the same numbers of shots cuts all the subsequent ODs stepping to the right each time. Then it will cut the next row at the next numbers-of-pulses setting. **When the trigger is on**, presumably it assumes a 20 ms "single-pulse time" and multiplies it by the entries in the "MULTI PULSE" column under "Pattern Settings" → "Single and Multiple Pulse", and *maybe* by the "Pulses per hole" entry in the "SINGLE PULSE" column under "Pattern Settings" → "Single and Multiple Pulse" **When the trigger is off**: presumably it assumes a 1 kHz repetition rate and opens the shutter for the corresponding durations to obtain the entered number of shots.

The key difference between this routine and the "Multiple Pulse" routine is that this one cuts row by row, while the "Multiple Pulse" routine cuts column by column, which may be undesirable when going up to high number of shots is used due to debris concerns.

Parameters (in "Pattern Settings" → "Single and Multiple Pulse"):
Note: Parameters in the "SINGLE PULSE" column are still used to control most of the parameters used in the the "MULTIPLE PULSE" routine.

"SINGLE PULSE" column:
- **Number of holes**: Number of different energies/OD's to do for each row.
- **Number of rows**: Number of rows **to repeat each number-of-pulses settings.**
- **Hole spacing**: Lateral hole-hole spacing.
- **Row spacing**: Vertical row-row/hole-hole spacing.
- **Z-step between holes**: Not sure. Presumably something to do with moving the focal plane in and/or out, either between holes or between rows of holes. Feel free to explore.
- **Pulses per hole**: The number of pulses to be used per hole. This assumes that "a pulse" means the shutter opens once, as defined by the shutter time in the main menu, and multiples the shutter time by the number input in this field to get a total amount of time the shutter is opened for. For example, with the 50 Hz chopper in place the shutter time will be set to 20 ms for each pulses, and if we input 5 pulse we will have

the shutter opening at 100 ms per irradiation spot. Any arbitrary combinations of shutter time and pulses per hole can be used to obtain a total shutter opening time.

- **# holes before space**: At times it may be desirable to leave an extra step of hole/row spacing between holes to facilitate easier positioning on the samples, for example, when viewing the sample under the microscope. If extra spacing is not desired simply set this number to a larger number than the number of holes/rows to be used in the experiment.

"MULTI PULSE" column:
Simply indicate if each of the rows will be processed by using the check boxes, and enter the number of shots desired for each row.

4. **Depth vs. Energy**: This routine cuts parallel lines at different energies, stepping down in energy/stepping up in OD from line to line. The default setting is cutting the lines in the y-direction, and steps to the (real life) right for each line.

One special parameter in "Pattern Settings" → "Single and Multiple Pulse"
- **# holes before space**: At times it may be desirable to leave an extra step of line spacing between lines to facilitate easier positioning on the samples, for example, when viewing the sample under the microscope. If extra spacing is not desired simply set this number to a larger number than the number of holes/rows to be used in the experiment.

Parameters (in "Pattern Settings" → "Grooves"):
Machine grooves in X direction: Cut the lines in the X-direction instead of the Y-direction as in the default setting. The grooves will be cut from (real life) left to right. Each subsequent line is then cut above the previous one.

"DEPTH VS ENERGY" field
- **Number of lines**: Number of different ODs to cut on the sample.
- **Line length**: The length of each line to be cut.
- **Line spacing**: Spacing between the parallel lines
- **Line Z step**: Not sure. Presumably it would step the focus in or out of the sample between each line. Feel free to explore.
- **Feed rate**: Translation speed of the sample relative to the beam, in μm/s.

5. **Depth vs. Cutting Speed**: This routine cuts parallel lines at different feed rates.. The default setting is probably cutting the lines in the y-direction, and steps to the (real life) right for each line for the next feed rate. Presumably the entire routine is carried out at a manually pre-set OD setting.

One special parameter in "Pattern Settings" → "Single and Multiple Pulse"
- **# holes before space**: At times it may be desirable to leave an extra step of line spacing between lines to facilitate easier positioning on the samples, for example, when viewing the sample under the microscope. If extra spacing is not desired simply set this number to a larger number than the number of holes/rows to be used in the experiment.

Parameters (in "Pattern Settings" → "Grooves"):
Machine grooves in X direction: Cut the lines in the X-direction instead of the Y-direction as in the default setting. The grooves will be cut from (real life) left to right. Each subsequent line is then cut above the previous one.

"DEPTH VS ENERGY" field
- **Line length**: The length of each line to be cut.
- **Line spacing**: Spacing between the parallel lines
- **Line Z step**: Not sure. Presumably it would step the focus in or out of the sample between each line. Feel free to explore.

"DEPTH VS FEED RATE" field
- **Starting speed**: The cutting speed of the first line
- **Final speed**: The cutting speed of the last line to be cut.
- **Increment**: The increment in speed from one line to the next.

6. **Depth vs. Number of Passes:** This routine cuts parallel lines at different numbers of passes. The default setting is probably cutting the lines in the y-direction, and steps to the (real life) right for each line for the next number of passes settings. Presumably the entire routine is carried out at a manually pre-set OD.

   One special parameter in "Pattern Settings" → "Single and Multiple Pulse"
   - **# holes before space**: At times it may be desirable to leave an extra step of line spacing between lines to facilitate easier positioning on the samples, for example, when viewing the sample under the microscope. If extra spacing is not desired simply set this number to a larger number than the number of holes/rows to be used in the experiment.

   Parameters (in "Pattern Settings" → "Grooves"):
   Machine grooves in X direction: Cut the lines in the X-direction instead of the Y-direction as in the default setting. The grooves will be cut from (real life) left to right. Each subsequent line is then cut above the previous one.

   "DEPTH VS ENERGY" field
   - **Line length**: The length of each line to be cut.
   - **Line spacing**: Spacing between the parallel lines
   - **Line Z step**: Not sure. Presumably it would step the focus in or out of the sample between each line. Feel free to explore.

   "DEPTH VS NUMBER OF PASSES" field
   Simply indicate if each of the line will be processed by using the check boxes, and enter the number of passes desired for each line.

7. **Array of Holes**: This routine cuts an array of holes at a manually pre-set OD setting.

   Parameters (front menu of the control program):
   Shutter time: Used to determine the number of shots used for each hole.

   Parameters (in "Pattern Settings" → "Single and Multiple Pulse"):
   "SINGLE PULSE" column:
   - **Number of holes**: Number of columns to be cut.
   - **Number of rows**: Number of rows to be cut.
   - **Hole spacing**: Lateral column-column spacing.
   - **Row spacing**: Vertical row-row spacing.
   - **Z-step between holes**: Not sure. Presumably something to do with moving the focal plane in and/or out, either between holes or between rows of holes. Feel free to explore.
   - **Pulses per hole**: The number of pulses to be used per hole. This assumes that "a pulse" means the shutter opens once, as defined by the shutter time in the main menu, and multiples the shutter time by the number input in this field to get a total amount of time the shutter is opened for. For example, with the 50 Hz chopper in place the shutter time will be set to 20 ms for each pulses, and if we input 5 pulse we will have the shutter opening at 100 ms per irradiation spot. Any arbitrary combinations of shutter time and pulses per hole can be used to obtain a total shutter opening time.

8. **Array of Holes (requires File Input)**: This routine cuts an array or pattern of holes at a manually pre-set OD. The locations of the holes are read from an input file, which the user can browse and choose after hitting begin. The starting point is used as the origin for the input files, and the input file will simply have a column of X and a column of Y values to indicate the positions of the holes. These coordinates are in μs. Try it out to see if the positive/negative corresponds to the orientation of camera view or in real life.

   Parameters (front menu of the control program):
   Shutter time: Used to determine the number of shots used for each hole.

9. **Linear Grating**: This routine cuts multiple parallel lines at a manually pre-set OD setting. Starts at the (real life) bottom left, and cuts to the right/up depending on if the lines are in the x- or y-direction.

   Parameters (in "Pattern Settings" → "Other Figures"):
   Cutting speed (all patterns): Controls the feed rate for the lines in the gratings.

   "LINEAR GRATING" field

- **X Axis/Y Axis check boxes**: Indicates if the lines in the gratings are long the x- or y-direction, respectively.
- **Line length**: Indicates the length of the lines.
- **Line spacing:** Indicates the line-to-line spacing.
- **Tilt:** Not sure. Funky dance ninja action perhaps.
- **Break every (blank) lines:** At times in experiments it is desirable to program a periodic break every so often. This field is used to program pre-determined breaks after so many lines. A dialogue will pop up and cutting of the rest of the grating will resume once the user clicks the OK button.

10. **Circular Grating**: This routine cuts a circular grating/multiple circles at a manually pre-set OD setting. By default the circles are lined up on the left.

    Parameters (in "Pattern Settings" → "Other Figures"):
    Cutting speed (all patterns): Controls the tangential cutting speed for cutting of the circles.

    "CIRCLE" field:
    - **Centre on current point**: By default the circles are lined up on the (real life) left. Use this option if concentric circles are desired. This may be reprogrammed to have the concentric circles as the default or only mode for this routine.

    "CIRCULAR GRATING" field:
    - **Number of circles:** The number of circles to cut with this routine.
    - **Initial radius:** The starting radius of the first circle..
    - **Radius increment:** The increment in the radius from one circle to the next.

11. **Circle:** This routine cuts an arc, circle, or multiple circles at the same spot, at a manually pre-set OD setting. By default the circles are lined up on the left.

    Parameters (in "Pattern Settings" → "Other Figures"):
    Cutting speed (all patterns): Controls the tangential cutting speed for cutting of the circles.

    "CIRCLE" field:
    - **Radius**: Radius of the arc/circle
    - **Sweep angle**: Angle of the arc to be swept.
    - **Centre on current point**: By default the circles are lined up on the (real life) left. Use this option if concentric circles are desired. This may be reprogrammed to have the concentric circles as the default or only mode for this routine by the time you are reading this. Try it out.

12. **Rectangle:** This routine cuts a rectangle, at a manually pre-set OD setting. By default the cutting of the rectangle uses the current position as the bottom left corner.

    Parameters (in "Pattern Settings" → "Other Figures"):
    Cutting speed (all patterns): Controls the cutting speed.

    "RECTANGLE" field:
    - **Height**: Height of the rectangle. What did you think it does?
    - **Width**: Width of the rectangle. Surprise surprise.
    - **Centre on current point**: By default the cutting of the rectangle uses the current position as the bottom left corner. Use this option if it is desired to have the rectangle centered on the current spot.

13. **Triangle:** This routine cuts a triangle with the base parallel to the horizontal axis, at a manually pre-set OD setting. By default the cutting of the triangle uses the current position as the bottom left corner.

    Parameters (in "Pattern Settings" → "Other Figures"):
    Cutting speed (all patterns): Controls the cutting speed.

    "RECTANGLE" field:
    - **Height**: Height of the triangle.
    - **Width**: Width of the triangle.

- **Centre on current point**: By default the cutting of the triangle uses the current position as the bottom left corner. Use this option if it is desired to have the triangle centered on the current spot.
- **Centre on current point**: By default the triangle points up. This function allows the cutting of a downward pointing triangle.

14. **Wide Trench:** Deciphering the C++ source code, it seems like this routine cuts multiple side-by-side wide trenches/patches at a manually pre-set OD setting, so each wide trench or patch can be made up of multiple lines. As of Dec. 2010 it is hard-coded that the lines of the trenches will be cut in the Y-direction.

    Parameters (in "Pattern Settings" → "Grooves"):
    "DEPTH VS ENERGY" field
    - **Number of lines**: Number of trenches/patches to be cut..

    "LINEAR GRATING" field
    - **X Axis/Y Axis check boxes**: NOT USED! This routine is hard-coded to cut the lines in the Y-direction.
    - **Line length**: Indicates the length of the lines.
    - **Line spacing:** Indicates the line-to-line spacing within each wide trench/patch.

15. **Custom:** Funky laser ninja dance! …or maybe Eugene's too lazy to go in and decipher the code since this routine's almost never used.

16. **Mask (Requires File Input)**: This routine cuts rectangles with centers (x, y), widths (w) and heights (h) are defined in an input file in rows of:
    x y w h
    The files will be in standard ASCII format (e.g., plain text, .txt or .dat).

17. **ShutterAcquire**: This routine was written to work with a photodiode placed below a sample such that when the sample is drilled through a signal is received and sampled on the photodiode. A high optical density filter (e.g., OD of 4 had been used) is likely required to avoid saturation and damage to the photodiode.

    This routine first does a calibration run with 1000 shots with no sample in the beam path to see what is the maximum signal the photodiode would see at each OD. It then asks for the sample to be inserted in place and does a real run, basically a multiple-pulse run while acquiring the photodiode data, then asks for a post-run calibration again.

    A standard passive reverse bias scheme is adequate for the photodiode, and its input is fed as the signal into the boxcar integrator for processing and synchronization. The output of the boxcar integrator is fed into input ACH1 on the National Instrument DAQ board (the module mounted on the right side of the micromachining control computer cart with a bunch of BNC connectors).

    The sampling rate of the diode is at 1000 Hz unless if more than 10000 laser pulses were selected, then 500 Hz is used to reduce the memory buffer size.

    Parameters (in the front menu):
    "Shutter time": Defines how long the shutter is opened for each hole.

    Parameters (in "Pattern Settings" → "Single and Multiple Pulse"):
    "SINGLE PULSE" column:
    - **Number of holes**: Number of different energies/OD's to do for each row.
    - **Number of rows**: Number of rows to repeat the same run.

18. **ShutterAcquireGrid**: This routine was written to work with a photodiode placed below a sample such that when the sample is drilled through a signal is received and sampled on the photodiode. A high optical density filter (e.g., OD of 4 had been used) is likely required to avoid saturation and damage to the photodiode.

    A standard passive reverse bias scheme is adequate for the photodiode, and its input is fed as the signal into the boxcar integrator for processing and synchronization. The output of the boxcar integrator is fed into input ACH1 on the National Instrument DAQ board (the module mounted on the right side of the micromachining control computer cart with a bunch of BNC connectors).

The sampling rate of the diode is at 1000 Hz unless if more than 10000 laser pulses were selected, then 500 Hz is used to reduce the memory buffer size.

Parameters (in the front menu):
    "Shutter time": Defines how long the shutter is opened for each hole.

Parameters (in "Pattern Settings" → "Single and Multiple Pulse"):
    "SINGLE PULSE" column:
- **Number of holes**: Number of holes to do for each row.
- **Number of rows**: Number of rows to repeat.

19. **Array of Circles**: This routine cuts an array of arcs/circles at a manually pre-set OD setting. By default the circles are lined up on the left at where the cursor is.

    Parameters (in "Pattern Settings" → "Single and Multiple Pulse"):
    "SINGLE PULSE" column:
- **Number of holes**: Sets the number of circles in each row.
- **Number of rows**: Sets the number of rows to cut.
- **Hole spacing**: Sets the lateral spacing between each (column) circles.
- **Row spacing**: sets the vertical spacing between each (row) of circles.

    Parameters (in "Pattern Settings" → "Other Figures"):
    Cutting speed (all patterns): Controls the tangential cutting speed for cutting of the circles.

    "CIRCLE" field:
- **Radius**: Radius of each of the arc/circle
- **Sweep angle**: Angle of the arc to be swept.
- **Centre on current point**: By default the circles are lined up on the (real life) left. Use this option if concentric circles are desired. This may be reprogrammed to have the concentric circles as the default or only mode for this routine by the time you are reading this. Try it out.

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[i]   J. C. Diels, W. Rudolph: "Ultrashort laser pulse phenomena" Academic Press (1996)

[ii]   R. Trebino: "Frequency-Resolved Optical Grating: The Measurement of Ultrashort Laser Pulses", Kluwer Academic Publishers, Boston 2000