



A P E

## PULSE MEASUREMENT SYSTEM

FC SPIDER

Manual



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## 1 Introduction

The acronym SPIDER stands for “Spectral Phase Interferometry for Direct Electric-field Reconstruction” [1]. It was invented in 1998 as a nonlinear type of Spectral Interferometry (SI) to get direct access to the spectral phase of an ultrashort laser pulse [2]. In the meantime it evolved to a standard technique for the measurement and full characterization of the shortest optical pulses that encompass only few cycles (FC) of the carrier wave.

With this technique the laser pulse is measured completely in the spectral domain by analyzing the modulation structure of a spectral interferogram. The result allows for the reconstruction of the temporal pulse shape. In contrast to autocorrelation based techniques (e.g. FROG) SPIDER is an intrinsic single-shot method that delivers both the amplitude and phase of the ultrashort pulse without the need for an iterative reconstruction algorithm. This makes SPIDER the method of choice for real-time pulse characterization or the real-time alignment of laser systems.

In addition to the common advantages of the SPIDER technique, the APE FC SPIDER comprises extra features on the hardware side to facilitate the alignment and to enable a robust measurement of the spectrum:

- Internal camera assisted alignment,
- Automated change-over between phase and calibration measurement,
- Choice between one common input port and two independent input ports for separate intensity and phase measurements.
- Optional beam routing kit (including beam splitting and attenuation) for usage of two input ports

On the software side - besides the spectral and temporal intensity and phase information - additional routines were implemented to exploit all accessible information on the pulse:

- Electric-field plot,
- Precise peak power calculation,
- Difference phase measurement,
- Spectral phase derivation to monitor the pulse chirp up to third order,
- Temporal evolution of the carrier frequency,
- Spectrogram, SHG FROG and Wigner representation of the pulse,
- Possibility of adding theoretical dispersion up to the fourth order to simulate arbitrary dispersive influence.

## 2 Description of the optics unit

The FC SPIDER enables robust single shot pulse characterization by combining two independent simultaneous measurements, the spectral amplitude and the spectral phase measurement. For this, two main optical beam lines and two internal spectrometers are installed within the optics unit.

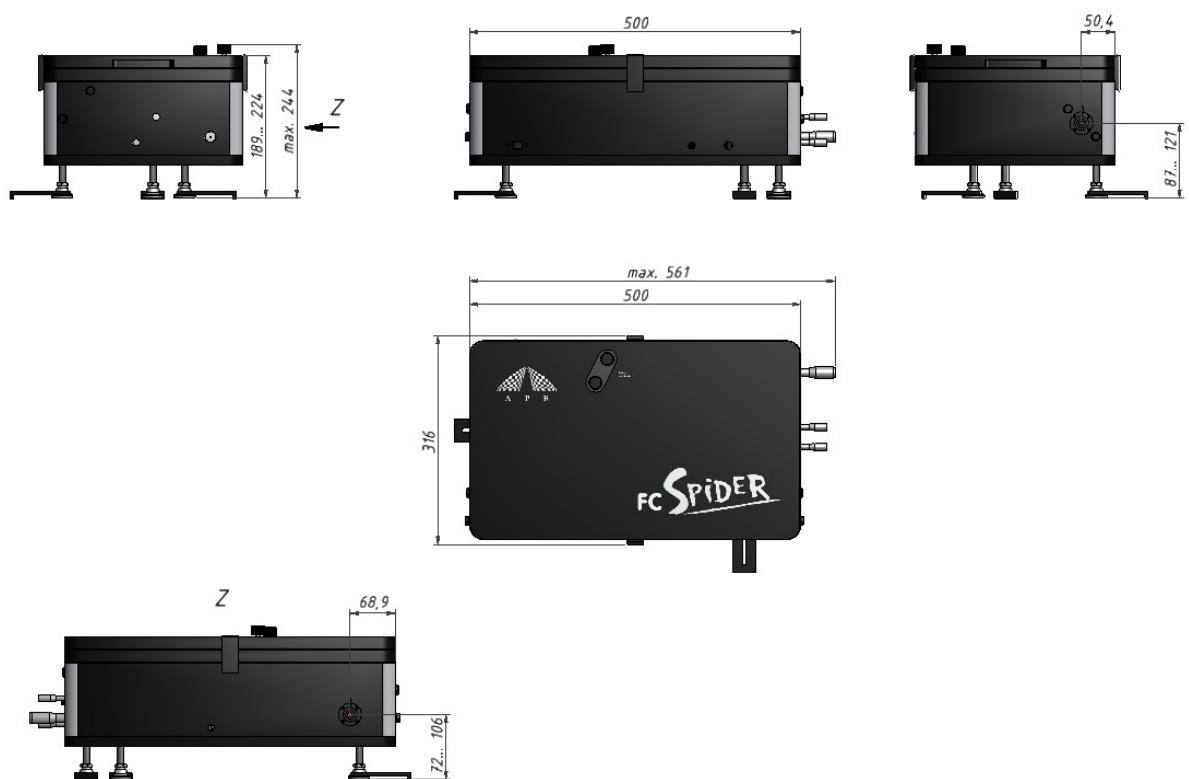


Fig. 1: The APE FC SPiDER optics unit and dimensions.

The optics unit has to be fixed with three foot clamps on an optical table. By screwing the three foots inside the device the beam height of the main input 1 can be varied between 72 and 106 mm (See Fig. 1). After this adaption of the device's height the foot screws need to be locked by their adjacent locking screws.

To continue with the alignment and measurement, power and USB connection as well as software installation on a separate computer is necessary.

### Attention:

**Do not connect the FC SPiDER device to a computer prior to the installation of the APE FC SPiDER control software!**

## 2.1 Schematic Setup

Figure 2 shows a top view schematic setup of the APE FC SPIDER device. The beam path splits into a spectral amplitude characterization part with a fundamental spectrometer (spectrometer 1) and a spectral phase characterization part with a second spectrometer (spectrometer 2) for recording the up-converted pulses. The latter part features an etalon based interferometer, a material dispersion stretcher for the up-converter pulse, and a dispersion minimized beam path for the two test pulses. The introduction of the spectral shear between the two test pulses is realized by their non-collinear type-II interaction with the stretched pulse inside a nonlinear crystal. The resulting SFG signal is detected by a UV sensitive spectrometer. A high degree of motorized automation for software assisted device calibration and alignment is implemented to improve usability. To support the robustness of the measurement, especially in case of strongly fluctuating single-shot laser sources, the spectral power density can be measured independently, yet synchronously with the spectral phase.

The implementation of the patented SPIDER technique is shown in Figure 2 as a scheme of the optical setup. The functionality of important optical components is listed below:

- |                       |  |
|-----------------------|--|
| 1. Input 1:           | Beam entrance aperture (5mm maximum beam diameter for characterization, horizontal input polarization)   |
| 2. Beam splitter BS1: | Two positions: <ul style="list-style-type: none"> <li>• BS1 in the beam path: Reflection is used for measurement of the fundamental spectrum with spectrometer 1. The transmitted beam enters the phase characterization setup.</li> <li>• BS1 outside the beam path: All input 1 power is sent into the phase characterization scheme (enhanced sensitivity, no dispersion correction). To get access to the spectral amplitude for pulse reconstruction, either save spectrum prior to removing the BS1 or use additional beam entrance port “Input 2” and flip the turning mirror M10.</li> </ul> |

# Pulse Measurement System

**FC SPiDER**

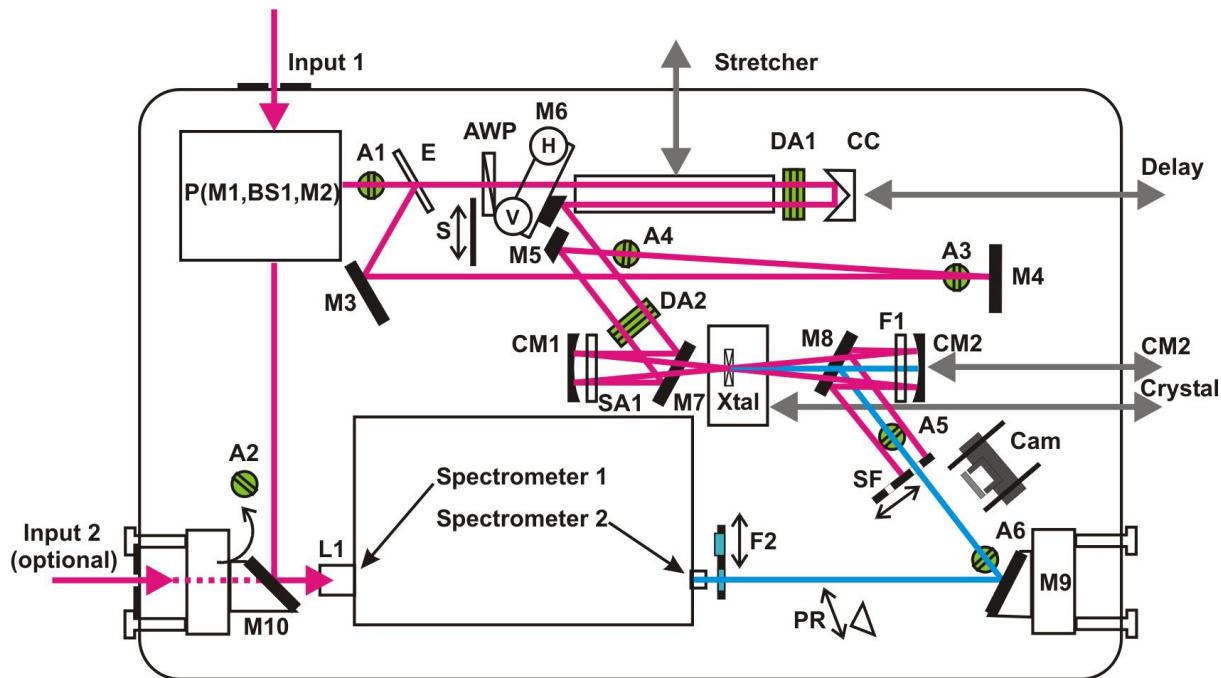


Fig. 2: Scheme of the FC SPiDER (top view) including beam path.

Input 1 and 2: beam entrance apertures; P: periscope with turning mirrors M1, M2 and beam splitter BS1; A1 – A6: positions of single-hole alignment aperture; M1 – M10: turning mirrors (M10: flipping mirror); E: etalon; S: shutter; AWP: half-wave plate; Stretcher: single or double beam pass; DA1, DA2: positions of double-hole alignment aperture; CC: corner cube; CM1, CM2: focusing mirrors; Xtal: nonlinear crystal; SA1: slit-aperture position 1; F1: alignment color filter position / slit-aperture position 2; SF: spatial filter; PR: prism insertion; Cam: alignment camera; F2: color filter.

### Amplitude measurement beam line:

3. Turning mirror M10: Turns the BS1-reflection onto the entrance of spectrometer 1. M10 can be aligned from outside. In case of using the optional entrance port “Input 2” the user has to flip M10 out of the beam path. Then, a fundamental beam has to be externally aligned directly through the input aperture “Input 2” onto the entrance of spectrometer 1 (See Appendix 11.3).

### Phase measurement beam line:

4. Shutter S: Motor driven shutter to block either the stretcher or the double pulse beam path.  
 5. Stretcher: By lateral movement of the rod the user can choose between two configurations: single or double pass transmission. The amount of chirp introduced by the stretcher affects the spectral shear value.

6. Delay: The corner cube for back reflection of the stretched pulse is mounted on a manual delay stage to adjust the temporal delay between the two replica pulses and the stretched pulse.
7. Top adjustable mirror M6: The turning mirror M6 can be handled from outside to align the spatial beam overlap of the two replica pulses and the stretched pulse at the position of the nonlinear crystal.
8. Crystal: The position of the crystal collinear to the beam path can be changed from the outside by a micrometer screw. From inside the user can change the height of the crystal in case of local damage as well as the  $\phi$  and  $\theta$  angles.
9. CM2: Re-focuses the signal beam. The position of CM2 collinear to the beam path can be changed from the outside by a micrometer screw. It depends on the beam overlap alignment and the micrometer position of the nonlinear crystal.
10. Spatial filter SF: Motor driven aperture to block the two fundamental beams and to transmit the centered blue SPIDER signal. The user can choose between two aperture diameters for further suppression of residual fundamental transmission. Signal alignment onto the entrance slit of spectrometer 2 can be handled from outside.
11. Turning mirror M9:
12. Color filter F2: Motor driven color filter insertion to suppress fundamental signal. Two different filter thicknesses can be chosen by the user.

## 3 Specifications

Wavelength range of spectrometer			
Standard			550 nm ... 1050 nm (standard)
Optional			500 nm ... 1000 nm 660 nm ... 1160 nm
Measurement range			
Config. 1 <sup>1)</sup>	Pulse bandwidth > 80 nm	Transform limit 12 fs ... 5 fs	Maximum pulse duration (chirped) < 60 fs
Config. 2 <sup>1)</sup>	35 nm ... 90 nm	30 fs ... 10 fs	< 120 fs
Minimum required input power			100 mW (at 100 nm bandwidth, 10 fs pulse duration, 80 MHz rep. rate)
Input polarization		linear / horizontal	
Input beam height		72 ... 106 mm (spectral phase and intensity) 87 ... 121 mm (spectral intensity)	

### Input laser pulse energy:

Laser repetition rate	Pulse energy
Oscillators, $\sim 10^7$ pulses/sec, (MHz)	$0.2 \text{ nJ} < E_P < 8 \text{ nJ}$
Amplifiers, $\sim 1000$ pulses/sec, (kHz)	$< 10 \mu\text{J}$
Single shot systems, (Hz)	$\sim 10 \mu\text{J}$

### Spectral resolution:

Spectrometer 1 (fundamental range):      0.32 nm  
 Spectrometer 2 (second harmonic range):    0.07 – 0.13 nm

### Electrical parameters:

Power supply (AC/DC converter)      Input: 100 – 240 V AC, 50 – 60 Hz, max. 0.6 A  
 Output: 9V DC, 3A

**Use only the delivered power supply!**

Interface	USB 2.0
Trigger input	TTL, for laser repetition rates < 1 kHz

## 4 Installation

The FC SPIDER comes ready to use with all necessary optics already installed. Before using the device, please pay attention to the following important procedure:

**Do not connect the FC SPIDER device to a computer prior to the installation of the APE FC SPIDER control software!**

- Check contents of delivery for completeness.
- Place the FC SPIDER device on an optical table and fix all three mounting feet with the delivered foot clamps.
- Open the optics unit and remove all transportation locks.
- Screw the optics unit to the desired beam height and fix the threaded rods of the feet with the adjacent locking screws (See Fig. 4).
- Install all the software (FC SPIDER control software, spectrometer and camera software) on a computer (Windows XP or higher recommended, min. 60 MB additional memory / 300 MB additional memory for working wavelet based retrieval)
- Connect the AC/DC converter to the optics unit (Power)
- Connect the optics unit to the computer via USB 2.0 cable (USB)
- Install all internal “devices” on your computer (“FC SPIDER”, 2 “Avantes spectrometers”, possibly deactivate a computer integrated webcam). Check the device manager of the computer for correct recognition of the additional devices.
- Start the APE FC SPIDER control software (FC SPIDER.exe)

### 4.1 Laser Safety

For the application of lasers or laser radiation you have to pay attention to safety rules according to the used laser class! Incorrect handling and operation of lasers can be hazardous to your health.

Take care! There might be back-reflected laser radiation of the laser beam that enters the FC SPIDER optical unit!

Protect the FC SPIDER from humidity, because the nonlinear crystal is hygroscopic.

## 4.2 Contents of Delivery

The following components are delivered:

1. FC SPIDER optics unit:
  - Optics unit with two internal spectrometers and an internal camera
2. Tools (See Fig. 3):
  - 3 foot clamps
  - 1 internal single-hole alignment aperture (A)
  - 1 internal double-hole alignment aperture (DA)
  - 1 internal slit alignment aperture (SA)
  - 1 internal alignment color filter (F1)
3. Cables:
  - AC/DC adaptor (to connect to the optics unit “Power” connector)
  - Power cord (to connect with AC/DC adaptor)
  - USB cable (to link the computer to the optics unit “USB” connector)
4. Software on CD:
  - FC SPIDER control software
  - Webcam C200 software
  - AvaSoft7USB2 software
5. FC SPIDER manual

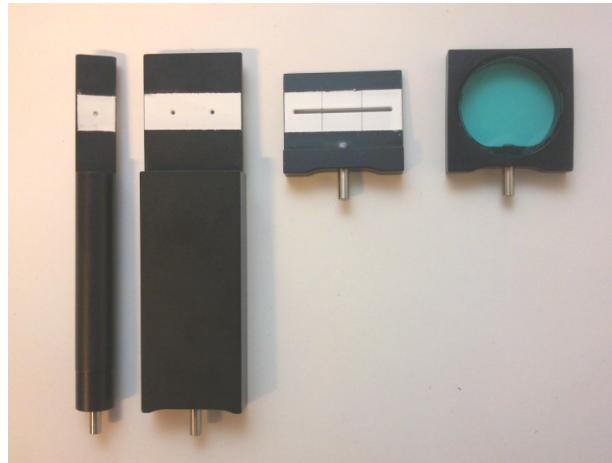


Fig. 3: FC SPIDER set of alignment tools. Left through right: Single-hole alignment aperture (for positions A1 – A6), Double-hole alignment aperture (for positions DA1 and DA2), Slit aperture (for positions SA1 and F1), Alignment color filter (for position F1).

## 4.3 Alignment

### 4.3.1 Status

- The FC SPIDER optics unit is fixed on an optical table, and the feet height is set for the desired input beam height with locked thread rods of the feet (See Fig. 4).

Threaded rod of the foot to change height of the device above the optical table

Locking screw to fix the threaded rod of the foot

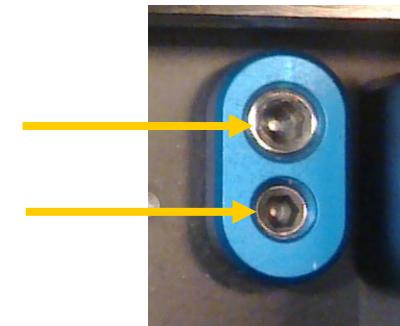


Fig. 4: Foot locking inside the optics unit

- All software components are installed on the computer,
- Pre-aligned, beam path to the Input 1 aperture: Please, use at least two turning mirrors with one of them as close as possible in front of the Input 1 aperture (See Fig. 5). The input beam is horizontally polarized.
- Power is supplied to the FC SPIDER optics unit via the delivered AC/DC adaptor
- The FC SPIDER optics unit is connected to the computer via USB 2.0 cable,

#### 4.3.2 Preparation

1. Attenuate the laser beam to pulse energy levels as defined under “Specifications”, (Keep in mind that depending on the method of attenuation the pulse shape might be changed due to attenuation optics.)
2. Pre-align the input laser beam to travel at constant height (height of the FC SPIDER Input 1 aperture) above the optical table and enters the optics unit at a right angle (maximum input beam diameter / aperture acceptance for characterization is 5 mm),
3. Take care that the height of all three feet of the optics unit is equal.
4. Start the FC SPIDER control software on the computer, check for proper operation of the spectrometers (complete initialization procedure) and switch to the “Alignment” software tab (See chapter “Description of the FC SPIDER software”, for internal optical configuration, see Appendix 11.4.),
5. Set the micrometer screws for the Delay, the Crystal and the CM2 position to the default values as displayed at the software’s “Alignment” tab.

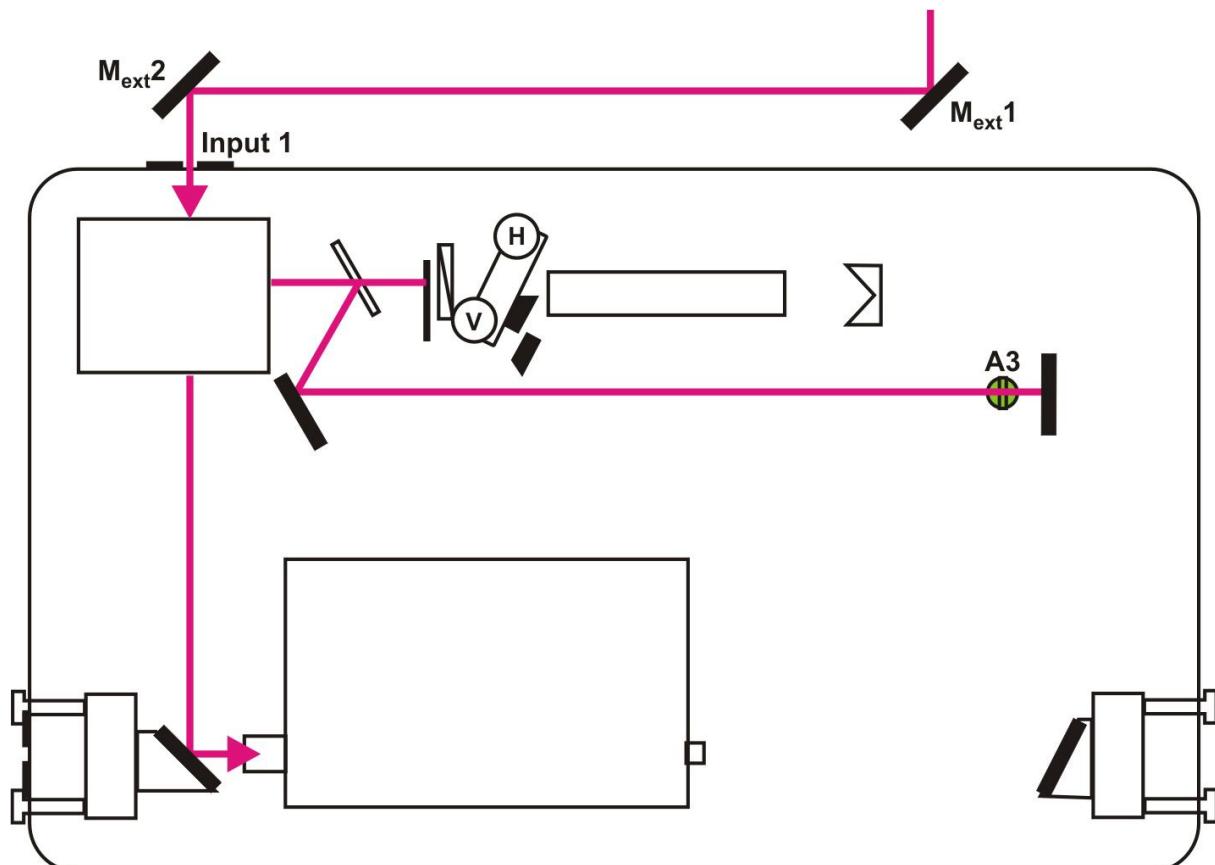


Fig. 5: Setup for initial FC SPIDER alignment with at least two external turning mirrors  $M_{ext}1$  and  $M_{ext}2$ . Center input beam with  $M_{ext}1$  onto Input 1 aperture and with  $M_{ext}2$  onto  $A3$ .

### 4.3.3 Initial FC SPiDER Alignment

1. Set the iris aperture of Input 1 to a diameter of ~5mm.
2. Use a distant mirror (e.g.  $M_{ext1}$  of Fig. 5) to center the laser beam onto the Input 1 aperture.
3. Block the chirped pulse beam path with the motor driven device shutter to suppress parasitic reflections (Press software button “Block chirped pulse” to show “Shutter In”).
4. Place the separately delivered single hole alignment aperture at position A3 in front of mirror M4.
5. Close the iris of the “Input 1” aperture to a diameter <1 mm.
6. Use the external turning mirror in front of the “Input 1” aperture to align the spot onto the hole of the single-hole alignment aperture at A3.
7. Open the iris of “Input 1” and check / use a distant mirror to align for a centered beam. If alignment is still necessary, repeat step 5 through 7.
8. Keep the “Input 1” iris closed at a diameter ~1 mm. Remove the alignment aperture in front of M4. Unblock the chirped pulse beam path with the motor driven device shutter (Press software button “Block chirped pulse” to show “Shutter Out”).
9. Monitor the internal alignment camera picture of the software (“Alignment” tab). It should display a picture similar to Fig. 6a). If there are no spots visible, please increase sensitivity and exposure time of the internal camera (See Fig. 7) to get a picture similar to Fig. 6a). [If there are still no spots visible or the camera is saturated exchange the attenuator filter in front of the alignment camera detector.]

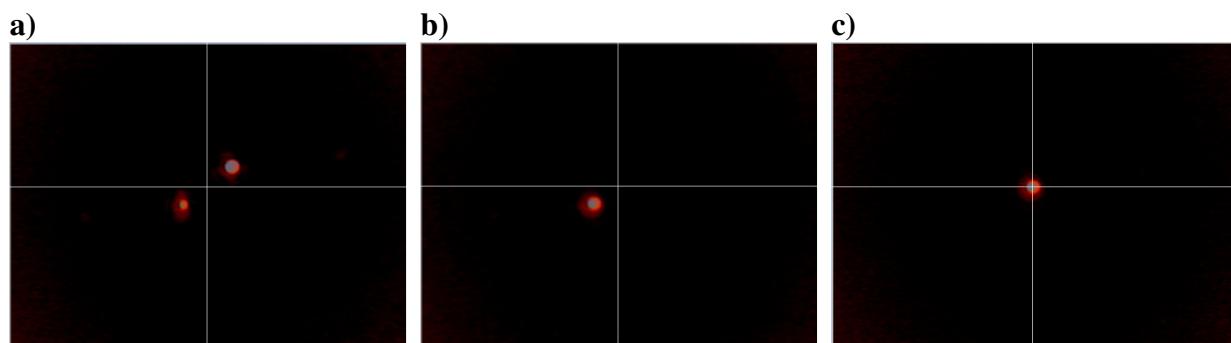
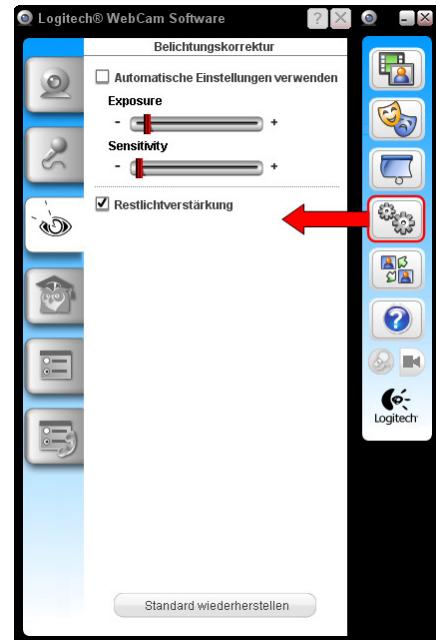


Fig. 6: Alignment camera picture to monitor the 2 beam overlap at the nonlinear crystal: a) After initial alignment into the optics unit both beams do not overlap spatially; b) With the top adjust  $M_6$  alignment the more intense beam of the stretcher beam line can be spatially overlapped with the double pulse beam; c) With alignment of the turning mirror  $M_9$  both beams can be centered at the cross hairs of the alignment camera to pre-align the coupling into the spectrometer 2.

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Fig. 7: Screen shot of the internal camera's software: Use exposure and sensitivity slider controls to adapt the camera signal to the given power level of the input laser beam.



10. Use the top adjust mirror M6 to align the more intense spot of the stretcher beam path onto the second weaker spot of the double pulse beam (See Fig. 6b).
11. Align turning mirror M9 to center both spots at the cross hairs of the camera picture (to pre-align the signal coupling into spectrometer 2).
12. Open the “Input 1” iris to ~5mm diameter.
13. Use the control software and switch to the “Display Raw Data” tab.
14. Increase exposure time of spectrometer 2 and make changes to the “Delay” in case no SPiDER interferogram is detected.
15. Close the optics unit if a SPiDER interferogram is already detected by the spectrometer 2.
16. Use the “Exposure” slider of “Settings Spectrometer 2” (Control software tab “Display Raw Data” / sub-tab “Online” [See Fig. 9a]) to exploit all the dynamic range of the spectrometer without clipping high signals.

If there is no SPiDER signal, please refer to the chapter “Find the SPiDER sum-frequency signal”.

#### 4.3.4 Signal Optimization

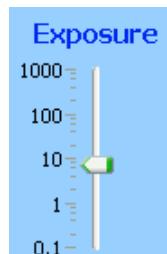
In case of standard performance of the optics unit all signal alignment and optimization can be done with the software controls and the adjustment knobs from the outside.

1. Maximize the SPIDER interferogram signal by optimizing the coupling into spectrometer 2: **Align mirror M9**.
2. Maximize the SPIDER interferogram signal by optimizing the beam overlap at the crystal: **Align top adjust mirror M6**.
3. **Change the “Delay”** to find position of maximum signal and best interferogram modulation contrast.
4. **Change “Crystal” position** with the external micrometer screw to find a higher signal.
5. **Change “Input 1” iris diameter** to improve the SPIDER signal.

In case of a successful initial alignment of the optics unit the FC SPIDER software should display the 2 spectrometers readout similar to Figure 8.

## 5 Brief Instruction: Necessary Software Steps

1. Start the APE FC SPIDER control software.
2. The “**Display Raw Data**” tab is active. Optimize the alignment and set both “Exposure” sliders of spectrometer 1 and 2 for optimal use of the dynamic detector range. Avoid detector saturation.
3. Switch to “**Prepare Spectral Amplitude**” tab and press “Auto Settings” software button:



- (If necessary, adapt the width of the Super-Gaussian low-pass filter [red cursor position] in the FFT graph and the spectrum apodization limits [two blue cursor positions] in the “Fundamental Spectrum” graph.)
4. Switch to “**Measure Calibration and SPIDER**” tab, choose the “Calib” sub-tab and press “Load Calibration”:

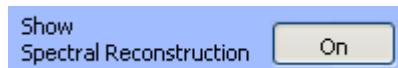


The software screen will look similar to Fig. 14. (Alternatively, take a calibration measurement as described in chapter “Measure a Calibration Trace”.)

5. Press the “Auto Settings” software button and check for the following:
  - a. FFT graphs: Are the side bands fully within the Super-Gaussian filter limits? (If not, manually change the filter limits.)
  - b. Is the spectral interferogram phase of the calibration measurement flat and free of distortions and covers at least the spectral range of the SPIDER interferogram? (If not, choose or measure a new calibration trace or press the “Extrapolate Calibration Phase” software button.)
  - c. Is there a spectrally continuous modulation of the SPIDER interferogram over the full range of the proposed red envelope curve? (If not, try to change the micrometer “Delay” screw for a better interferogram.)
6. Switch to the “Reconstr” sub-tab and check if the “Theoretical Envelope” red curve has the correct spectral position with respect to the SPIDER interferogram. Optionally, correct the “Shift (THz)” value for a better match between the interferogram and the proposed envelope.



7. Set a check mark in the “Lock Settings” check box for robust reconstruction (not necessary in case of a stable and noise-free signal).
8. Display Options: Press the “Show Spectral Reconstruction” software button to show “On”.



Use the zoom option (magnifying lens symbol) for a proper display of the spectral pulse reconstruction and position the vertical blue cursors (cross hairs symbol) for an appropriate fitting range of the spectral phase (or press “Auto Settings” software button after zooming in).



9. Switch to “**Pulse Reconstruction**” tab to monitor the reconstruction results.
10. Press the “Save” software button to save the results.
11. Press the “Stop” button or close the software (cross) if finished.

## 6 Description of the FC SPIDER Software

The FC SPIDER software is based on an automated data evaluation that follows the shown pages (tab structure) from left through right. The user starts with the “Display Raw Data” tab and ends up with the “Pulse Reconstruction” tab. This procedure makes sure that – in spite of the automated parameter choice – the user is forced to monitor the automated reconstruction procedure and can take action if a display shows up an error source. The latter is more and more important the more broadband and structured the spectrum of a pulse gets.

If the FC SPIDER optics unit is recognized properly by the computer the software starts in “Online” mode otherwise the “Offline” mode is chosen (no device connected) and loading of previously saved data is requested.

### 6.1 The “Display Raw Data” tab

Initially, the FC SPIDER software starts with the “Display Raw Data” tab for choosing the right settings of the two spectrometers. Figure 8 already shows proper measurement signals of both spectrometers for complete pulse reconstruction. The upper graph of Figure 8 depicts the measurement of spectrometer 1 which takes the fundamental spectrum of the pulse. The lower graph shows the SPIDER interferogram taken by the SHG spectrometer 2. The control structure of the “Display Raw Data” tab is distributed over three sub-tabs (See Fig. 9) and offers to switch between the “Online” and an “Offline” mode. In Addition, the “Options” sub-tab allows for a selective use of the motorized device components.

#### 6.1.1 The “Online” Sub-Tab

The “Online” mode is only activated if the optics unit is connected to the computer and properly recognized (See device manager).

##### Controls:

- **“Exposure” sliders:** For proper operation and an increased robustness of the reconstruction it is important that the user chooses the right exposure times to exploit all the dynamic range of the spectrometers without clipping high signals. The actually chosen exposure time is displayed on the “ms” indicator below the respective slider. The update rate of the spectrometer’s read out can be monitored at the “Hz” indicator.
- **Average:** The spectrometer signal is averaged over the given number of exposure cycles.
- **Dynamic Dark Correction:** Activates dynamic dark signal subtraction. This option has to remain activated at the fundamental spectrometer 1 for the irradiance calibration to work.
- **High Dynamic Range:** If activated the dynamic range of the spectrometers’ read out is changed from 14 bit to 16 bit which slightly slows down the software.
- **Trigger mode:** The user can switch between “Free Running” for high repetition rate lasers and “External Trigger”. The latter has to be used if the repetition rate of the laser system under test is below ~500 Hz.

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**FC SPiDER**

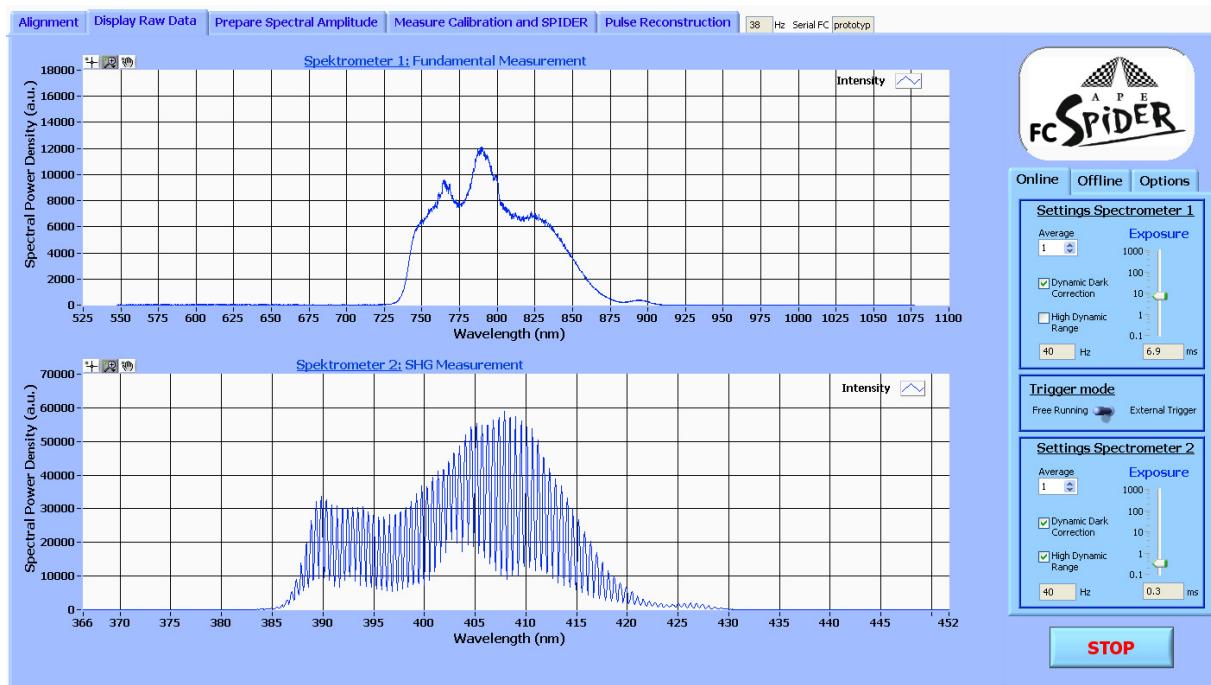


Fig. 8: Screen shot of the FC SPiDER control software: The “Display Raw Data” tab is initially shown by default.

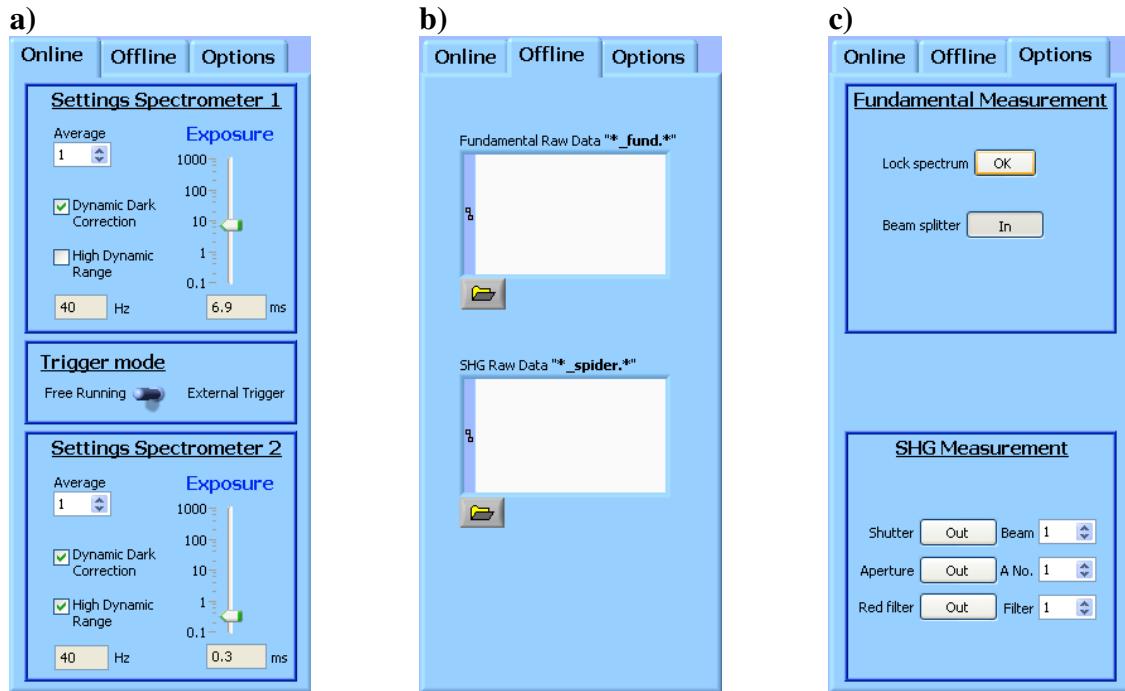


Fig. 9: Sub-tab structure of the “Display Raw Data” window; a) The “Online” tab is used to change the settings of the two spectrometer cameras; b) An “Offline” mode offers pulse reconstruction based on previously saved raw data, also without connected optics unit; c) The “Options” tab allows the user to set the motorized components of the device.

In such a case, a TTL trigger signal has to be provided via the “Trigger” BNC input port to initiate a synchronized read out of the two spectrometer cameras. In case of a TTL signal with a retardation exceeding the exposure time of the spectrometer camera, an external delay generator has to be used to shift the laser pulse into the exposure time window.

## 6.1.2 The “Offline” Sub-Tab

The FC SPIDER control software can also be used as pulse reconstruction software based on previously saved raw data. The user can switch to this tab to load the data and continue the reconstruction procedure as in a real measurement.

## 6.1.3 The “Options” Sub-Tab

This control panel allows the user to set the motorized components of the device. It is split in two parts: one concerns the “Fundamental Measurement” the other the “SHG Measurement” configuration for the phase reconstruction.

### Options of Fundamental Measurement:

- **Lock Spectrum:** Press “OK” to freeze the current read out of spectrometer 1. This saved pulse spectrum is used for all further pulse reconstructions until this software button is unlocked again.
- **Beam Splitter:** Defines the position of the beam splitter inside the periscope: “In” for “In the beam path”, and “Out” for “Outside the beam path”. If the beam splitter is in the beam path, its surface reflection is used to measure the fundamental spectrum. (Because the spectral phase of the transmitted pulse is measured, the dispersive influence of the beam splitter is subtracted from the result by the software.) In case the beam splitter is moved out of the beam path, pulse reconstruction is only possible if:
  - the fundamental spectrum was “locked” (saved) before, or
  - the additional “Input 2” entrance port is used to align a second beam (from the same source) onto the diffuser of spectrometer 1. For this, the flipping mirror M10 has to be turned by 90° out of the beam path (See Fig. 2).

### Options of SHG Measurement:

- **Shutter:** “In”/”Out” moves the motor driven shutter (S, see Fig. 2) in or out of the beam path with respect to the beam number (Beam 1: stretcher beam; Beam 2: double pulse beam)
- **Aperture:** “In”/”Out” moves the motor driven aperture (SF, see Fig. 2) in or out of the beam path. For the “In” position the user can choose between two different aperture diameters (aperture number 1 or 2). The large diameter aperture is used for faint SPIDER signals to avoid blocking some of the SFG light. The small aperture diameter can be used to suppress parasitic fundamental stray light.
- **Red filter:** In case of taking a calibration measurement the co-propagating fundamental beam has to be blocked by a color filter. This software button allows for moving the color filter F2 into the beam path in front of the input port of spectrometer 2. The filter number concerns two color filters that differ in thickness.

## 6.2 The “Alignment” tab

By switching to the “Alignment” tab the two spectrometers are deactivated and an internal alignment camera is activated instead. The picture of this alignment camera is displayed on the left hand side of the window (See Fig. 10). It allows for monitoring the positions of the stretcher beam and of the double-pulse beam in the plane of the crystal. With the top adjustable mirror M6 the stretcher beam can be aligned to spatially overlap with the double pulse beam (Refer to Fig. 6). In a second step, M9 adjustment allows to center the spots at the cross hairs of the camera picture to align proper coupling into spectrometer 2.

At the right hand side two software buttons control the position of the beam shutter S to distinguish the visible spot of the stretcher beam from the spot of the double pulse beam. The additional indicators display the factory settings of the respective micrometer screws for which the displayed spatial beam overlap is valid. It means, only for the given “Crystal position” and “CM2 position” settings a beam overlap displayed on the alignment camera picture also exists in the plane of the crystal. The “Delay position” marks the micrometer screw value for temporal overlap of stretcher pulse and double pulses around a center wavelength of 800 nm. This “Delay position” value differs with respect to the configuration of the optics unit (single or double stretcher pass).

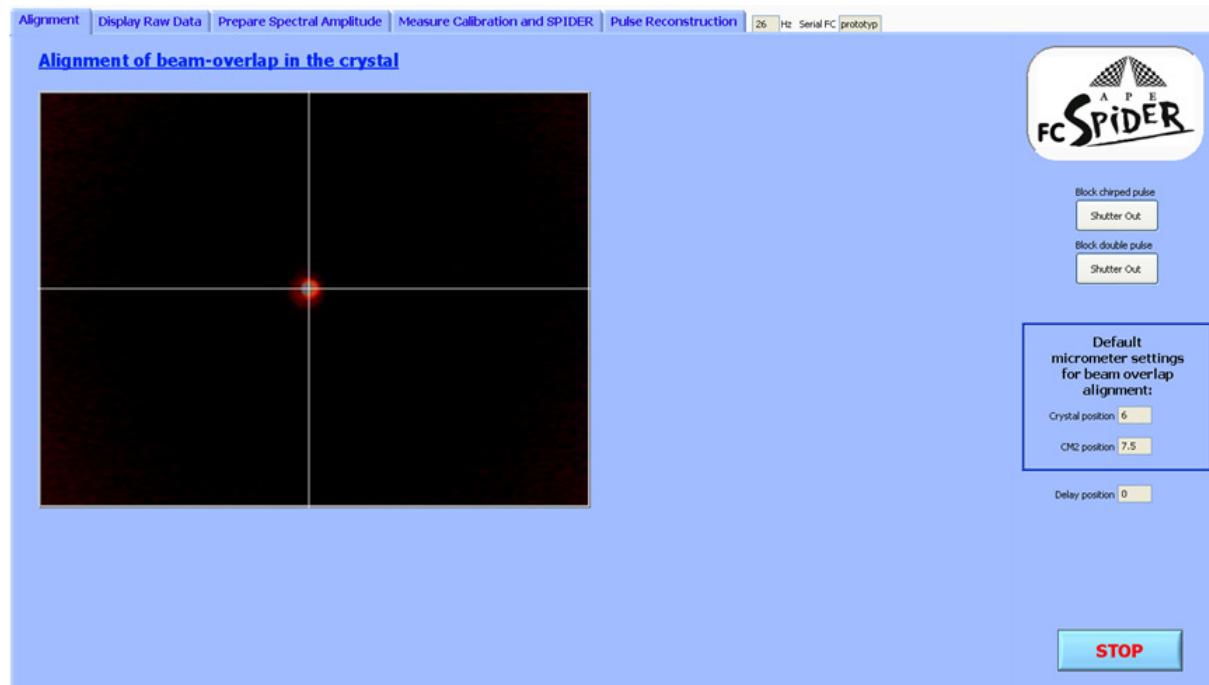


Fig. 10: Screen shot of the FC SPiDER control software: The “Alignment” tab displays the live picture of the internal alignment camera.

## 6.3 The “Prepare Spectral Amplitude” tab

Pulse reconstruction requires two types of datasets, the spectral amplitude of the pulse (as the square root of the spectral power density) and its spectral phase. This step of the pulse reconstruction software concerns the preparation of the amplitude part (See Fig. 11). It includes:

- Spectral amplitude corrections (e.g. based on factory calibration of the nonlinear detector response and irradiance calibration),
- Low pass Fourier-filtering of the spectrum (See bottom graph of Fig. 11), and
- Super-Gaussian apodization of the spectrum to prevent non-zero camera signal beyond the range of the pulse spectrum to contribute to the pulse reconstruction.

In addition, the user can monitor key values such as the spectral “Center of Gravity” of the pulse and the FWHM bandwidth of the pulse spectrum.

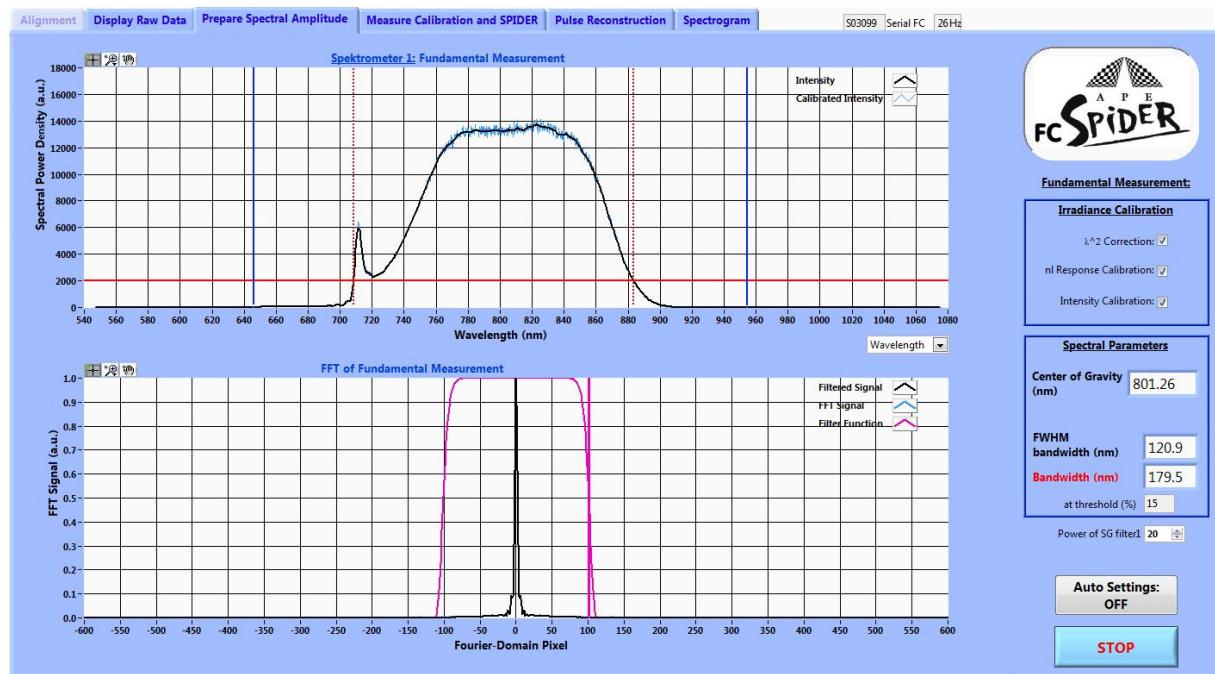


Fig. 11: Screen shot of the FC SPiDER control software: The “Prepare Spectral Amplitude” tab allows for low pass filtering and super-Gaussian apodization of the measured spectral power density.

The top graph of Fig. 11 displays the measured and calibrated spectral power density of the pulse (blue curve) and a black curve that is taken for the pulse reconstruction. This black curve should follow the blue data curve and shows the result after low-pass Fourier filtering and Super-Gaussian apodization. The raw data of the spectrum after Fourier transformation is shown in the bottom graph of Figure 11 (black curve) along with the Super-Gaussian filter function (red curve).

The following parameters can be changed by the user:

- The width of the Fourier filter can be set with the red cursor position (bottom graph).
- The steepness of the filter slopes are changed with the “Power of SG filter1” control.
- The apodization limits of the pulse spectrum can be set with the two blue cursor positions (top graph).
- The position of the horizontal red cursor (top graph) defines the threshold for the red “Bandwidth” indicator.
- The scaling of the top graph can be switched between “Wavelength (nm)” and “Frequency (THz)”.

Pressing the “Auto Settings: Off” software button to show “On” sets all vertical cursors to their default values.

## 6.4 The “Measure Calibration and SPIDER” tab

This tab contains the main features of the phase reconstruction and is, therefore, the most important window. It combines graphical displays of the interferogram raw data along with the Fourier-domain representation and the final spectral phase reconstruction (See Fig. 12, 14 and 15). Similar to the previous tab the display is structured in a top graph, showing the raw data along with intermediate, Fourier-filtering results, and a bottom graph that either shows the raw data after Fourier transformation or already the pulse reconstruction in the spectral domain. At the right hand side of the display a sub-tab structure separates several control and display options (See Fig. 13).

For the reconstruction of the pulse’s phase, the SPIDER algorithm processes the spectral phases of two interferograms, the calibration interferogram (as a reference) and the SPIDER interferogram (as sensitive to the chirp of the pulse). The software offers two alternative methods to retrieve the spectral phase of an interferogram. The default method is based on Fourier analysis (Fourier filtering, [Ref. 3]). Optionally, the customer can switch to an interferogram modulation analysis that uses Gabor transformations (Wavelet based analysis, [Ref. 5]). This choice can be made on the “Analysis” sub-tab [See Fig. 13 c)].

The calibration interferogram phase has only to be taken once for the desired spectral range. Such a calibration can be saved and loaded by using the “Calib” sub-tab [See Fig. 13 a)].

Besides the two interferogram phases a third experimental parameter has to be determined to complete the data for proper pulse reconstruction. This parameter is the exact spectral “Shift (THz)” value between the spectral phase of the pulse (reconstructed on the second harmonic frequency axis) and the fundamental amplitude of the pulse (measured on the fundamental frequency axis). On the “Reconstr” sub-tab, the calculated “Shift (THz)” value can be corrected by the user if necessary [See Fig. 13 b)].

# Pulse Measurement System

**FC SPIDER**

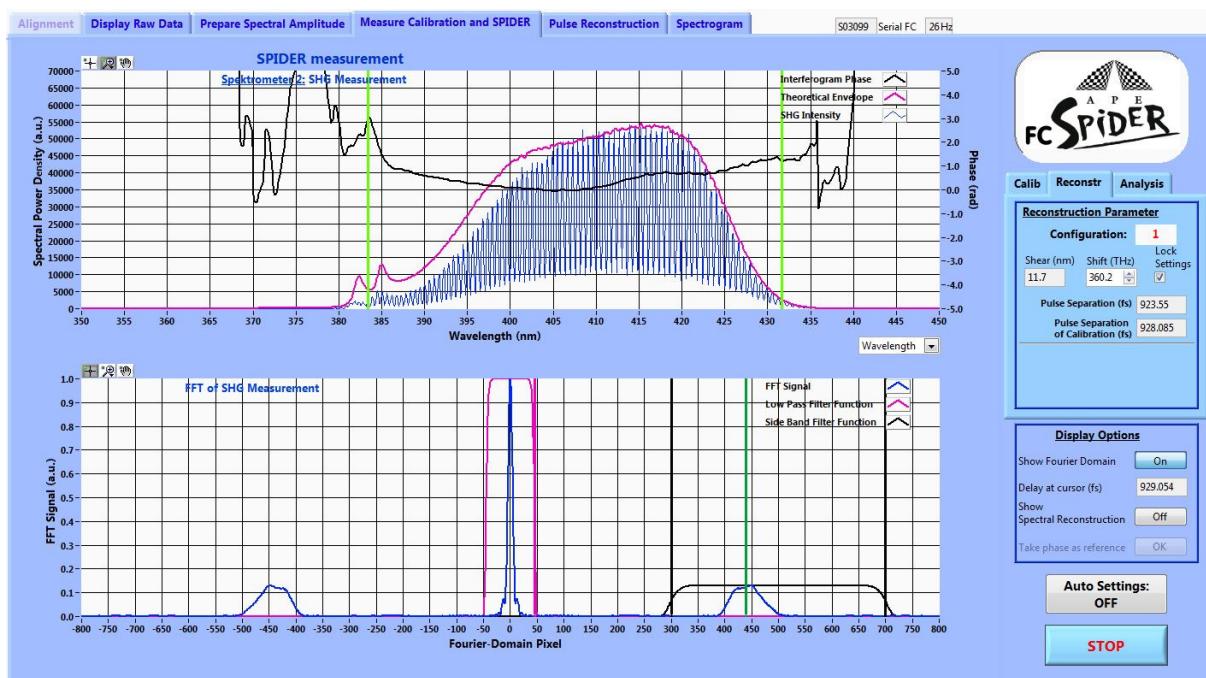


Fig. 12: Screen shot of the FC SPIDER control software: The “Measure Calibration and SPIDER” tab is most important display to check for proper measurement conditions and pulse reconstruction.

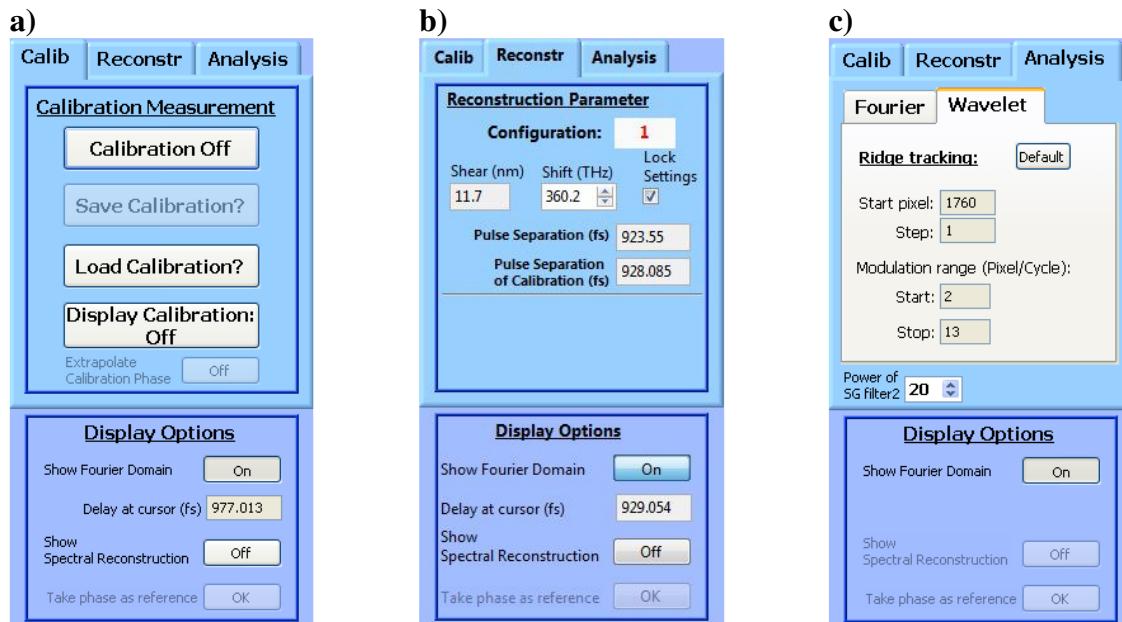


Fig. 13: Sub-tab structure of the “Measure Calibration and SPIDER” window; a) The “Calib” tab allows to switch between SPIDER and Calibration measurement device configuration. In addition, the user can save, load and display a calibration measurement; b) The “Reconstr” tab displays important reconstruction parameters; c) Optionally, on the “Analysis” tab the user can choose between two different interferogram analysis methods.

### 6.4.1 The “Calib” Sub-Tab

#### Calibration Measurement

Description of the control software buttons:

- “**Calibration OFF**” / “**Calibration ON**”: By pressing this software button all motorized shutters and filters are set for the respective measurement configuration (SPIDER measurement / Calibration measurement) that is indicated as the headline of the “Spectrometer 2: SHG Measurement” graph. To find and optimize the related signal, please follow the description of the chapter “Measure a Calibration Trace”.
- “**Save Calibration?**”: This software button is enabled if the upper software button is switched to show “Calibration ON”. A robust and representative calibration interferogram of the spectral range of interest should be saved for future use.
- “**Load Calibration?**”: This software button is enabled if the upper software button is switched to show “Calibration Off”. **For phase reconstruction the SPIDER algorithm needs the information of the calibration interferogram. Therefore, it is necessary to either measure a calibration trace or load a saved one.**
- “**Display Calibration: Off / On**”: Press this software button to show the actual used calibration interferogram and the respective Fourier domain graph beneath the “SPIDER measurement” plot (See Fig. 14). Zooming of the wavelength or frequency axis of either the SPIDER or the Calibration interferogram rescales the other interferogram graph accordingly. This function helps to monitor the quality of both interferogram phases over the same spectral range. **In addition, it is important to check if the calibration interferogram phase is free of distortions and flat over at least the same spectral range as the present SPIDER interferogram phase.**

### 6.4.2 The “Reconstr” Sub-Tab

#### Reconstruction Parameter

Description of the software indicators and control buttons:

- “**Configuration**” **1 or 2**: The software recognizes the actual stretcher configuration of the optics unit via end stop sensors. After change of the configuration by the user (See chapter “Change of Device Configuration”) this alteration is only updated in the software if the user switches from a different tab to the “Measure Calibration and SPIDER” tab. The detected configuration affects the spectral “Shear” value.
- “**Shear**”: This value determines the spectral sampling step of the pulse’s phase and the time window for pulse reconstruction for which the pulse structure has “full spectral support”. The limits of the resulting time window are marked by two vertical blue cursors in the “Pulse: Time Domain” graph of Fig. 14. The shear is calculated with the known stretcher dispersion and the measured center wavelength (Center of Gravity) of the pulse spectrum.

- “**Shift**”: This value determines the frequency shift between the spectral phase of the pulse (measured in the SHG spectral range) and the spectral power density (measured in the fundamental spectral range). Though the software proposes a value derived by cross correlation calculation between the fundamental spectrum and the envelope of the SPIDER interferogram, the user should check for its accuracy and, optionally, correct the value with the up/down arrows. As an indication for the shift value, the theoretical envelope of the SPIDER interferogram is calculated from the measured fundamental spectrum and plotted as a red curve in the “SPIDER measurement” graph: “Spectrometer 2: SHG Measurement” (See top graph of Fig. 12, 14 and 15). The shift value is consistent if the SPIDER interferogram follows this separately measured envelope. (It is not important that the modulation amplitude of the blue interferogram fits to the amplitude of the proposed red envelope. Only the amplitude structure is unambiguously tied to the interferogram and has to be shifted to match it.) In addition, the user can and should check if all the fundamental spectral bandwidth is up-converted to show a SPIDER interferogram, i.e. if there is a modulated SPIDER signal (blue curve) beneath the whole spectral range of the proposed envelope (red curve).
- “**Lock Settings**”: Set this check mark if the right spectral “Shift” value is chosen and the alignment and signal optimization is finished. The check mark blocks further automatic parameter setting (cursor position, reevaluation of the “Shear” and “Shift” value) to avoid noisy pulse reconstruction.  
Remove the check mark to start automatic parameter setting again (e.g. in case the user tunes the center wavelength of the laser or the “Delay” of the stretcher pulse is changed by the micrometer screw.)
- “**Pulse Separation (fs)**”: The linear slope of the phase of the interferogram determines the average temporal separation of the two test pulse replicas. This slope is analyzed by a linear phase fit between the two vertical green cursors of the interferogram plots (See Fig. 12, 14 and 15) and shown as a numerical value (in femtoseconds) for both cases: SPIDER and Calibration interferogram. The interferogram phase is plotted as a black curve after subtraction of the respective slope. The positions of the vertical green cursors that define the fitting range can be changed manually if the “Lock Settings” check mark is set. For automatic setting of cursor positions, press the “Auto settings: OFF” software button to show “ON”.

### 6.4.3 The “Analysis” Sub-Tab

On this tab the user can choose the interferogram evaluation method to retrieve the spectral phase of an interferogram. The default method is based on Fourier analysis (Fourier filtering, [Ref. 3]). Optionally, the customer can switch to an interferogram modulation analysis that uses Gabor transformations (Wavelet based analysis, [Ref. 5]). This option is disabled if the computer does not offer enough memory (additional ~500 MB) for the necessary look-up table of wavelets during software initialization.

- **“Fourier”** method: A robust way for phase analysis of an interferogram can be realized by filtering the modulation side band of the Fourier-transformed interferogram data. Therefore, one Super-Gaussian filter function is set by default around the side band at the right hand side of the Fourier domain representation “FFT of SHG Measurement” and “FFT of Calibration Measurement” (See e.g. bottom graph of Fig. 12). The limits of the Super-Gaussian Filter are given by the two vertical black cursors. The position of these cursors can be changed by the user and be set back to their default values by pressing the “Auto Settings: OFF” software button to show “ON”. Also, the steepness of the Super-Gaussian filter function can be changed with the “Power of SG filter2” control. The centered DC-band is filtered as well (red Super-Gaussian filter function) to get the envelope of the interferogram (not shown in the “Spectrometer 2: SHG Measurement” graph).
- **“Wavelet”** method: A further way for phase reconstruction of an interferogram is implemented by comparing the local spectral modulation of the interferogram with a set of Gaussian-shaped Wavelets. Changing two parameters, the center frequency and the modulation frequency of the Wavelet adds up to a 2D plot with a local amplitude that corresponds to the conformity between a specific Wavelet modulation and the actual interferogram modulation. A ridge-tracking algorithm allows for a fast and robust evaluation of the interferogram phase. This phase extraction method proofs to be more robust than the “Fourier” method in case of weak and noisy modulation amplitudes. Also, the result of this method is quite independent on initial parameters.

**It is important not to mix up the analysis methods: Use the same method for evaluating the calibration and the SPiDER measurement!**

#### 6.4.4 Display Options

The “Display Options” box below the sub-tab structure allows for changing the combination of displayed graphs (See Fig. 14 and 15):

- **“Show Fourier Domain”:** The graphs showing the measurement after Fourier transformation can be switched on and off.
- **“Delay at cursor (fs)”:** The “Fourier-Domain Pixel” value of the position of the green cursor (graph “FFT of SHG Measurement”, see Fig. 12) is converted to a delay value in femtoseconds. (Zoom in to get a more precise result.)
- **“Show Spectral Reconstruction”:** The graph showing the spectral reconstruction of the pulse (spectral intensity and phase) can be displayed instead of the saved calibration measurement (See Fig. 15).
  - **Blue vertical cursors:** Set the limit for a linear phase fit to determine the slope of the spectral phase (refers to an arbitrary group delay). The depicted spectral phase (red curve in bottom graph of Fig .15) shows the result after subtraction of this slope. The fitting range (cursor position) can be adapted by the user (set to default by pressing “Auto Settings” software button).
  - **Green vertical cursors:** These cursors are only indicators for the evaluated spectral position of the two test pulses on the stretched up-converter pulse. They change with the “Delay” set with the micrometer screw. Their interspace is given by the “Shear” value.
- **“Take phase as reference”:** By pressing this software button the current phase is saved and taken as a reference for all future phases. As long as this button is pressed the reference phase is subtracted from all further measured phases to show dispersive changes. The dispersion analysis described in section 6.5.1 is then applied to the new difference phase.

# Pulse Measurement System

**FC SPiDER**

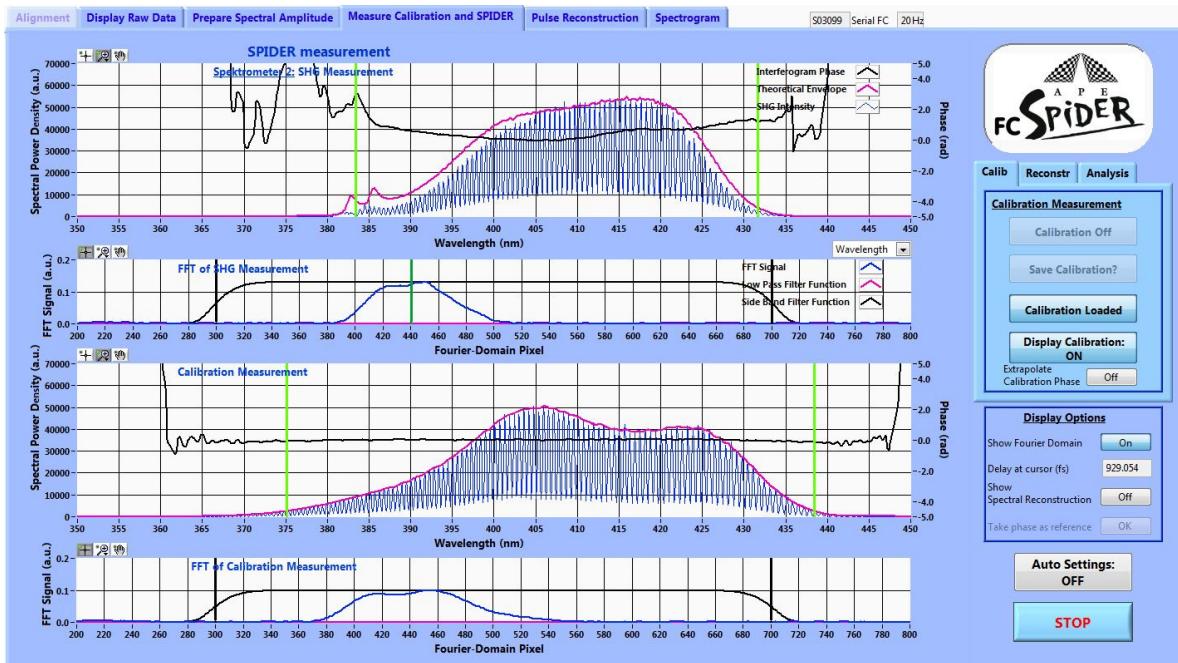


Fig. 14: Screen shot of the FC SPiDER control software: On the “Measure Calibration and SPiDER” tab both relevant measurements for phase reconstruction, the SPiDER interferogram and the SHG calibration interferogram, can be displayed simultaneously along with their Fourier-transform.

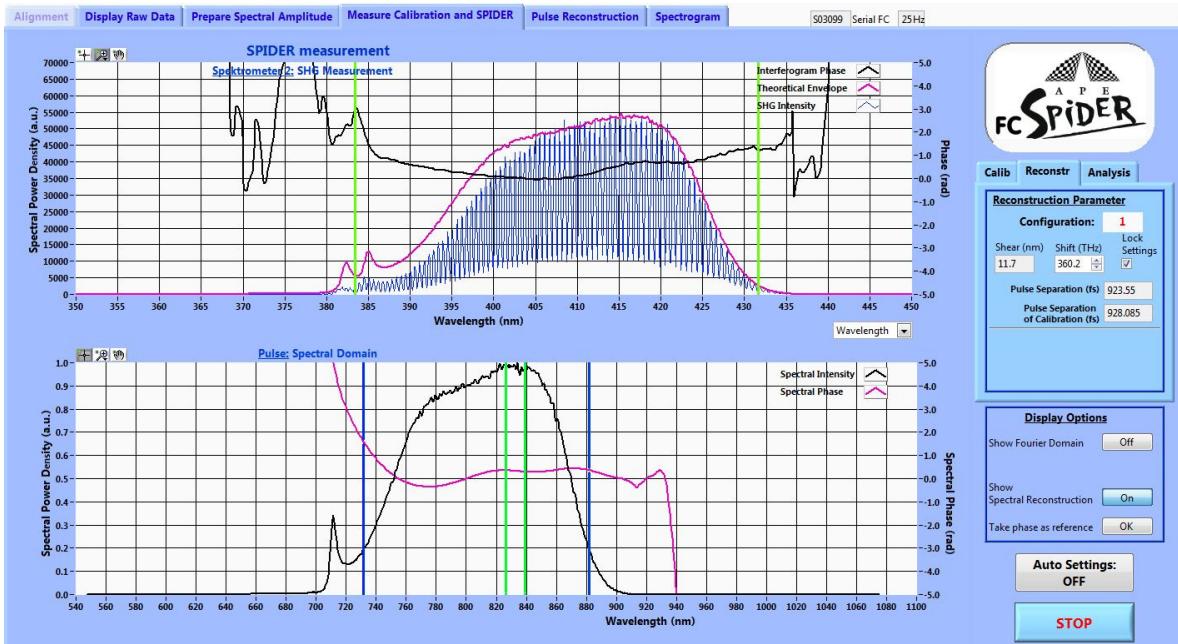


Fig. 15: Screen shot of the FC SPiDER control software: On the “Measure Calibration and SPiDER” tab the online evaluated SPiDER interferogram and the spectral reconstruction of the laser pulse (intensity and phase) can be displayed simultaneously.

# Pulse Measurement System

**FC SPiDER**

## 6.5 The “Pulse Reconstruction” tab

This tab purely shows the results of the measurement (See Fig. 16): The top graph displays the temporal intensity structure of the pulse whereas the bottom graph is the spectral representation of the pulse (same graph as Spectral Reconstruction of the “Measure Calibration and SPIDER” tab). Both pictures are equivalent and linked via Fourier transformation.

- **Pulse: Time Domain:** The upper display of Fig. 16 shows the “Time Domain” picture of the laser pulse (black line: intensity pulse shape, blue line: intensity pulse shape of the Fourier limit [or transform limit], red line: “temporal phase” or its derivative, the “carrier frequency”). The two vertical blue cursors indicate the time window for precise field reconstruction. If the pulse’s intensity structure stretches beyond these limits the pulse reconstruction is considered to be without full spectral support.
- **Pulse: Spectral Domain:** The bottom display of Fig. 16 shows the same graph as already described in the previous caption (See “Measure Calibration and SPIDER” tab \ Display Options: “Show Spectral Reconstruction”). In addition, the “Spectral phase” curve can be replaced by a curve that depicts its derivative up to fourth order.

The sub-tab structure on the right hand side of the “Pulse Reconstruction” tab displays the main results as numerical values and allows the user to change characteristics of the “Pulse: Time Domain” depiction (See Fig. 17).

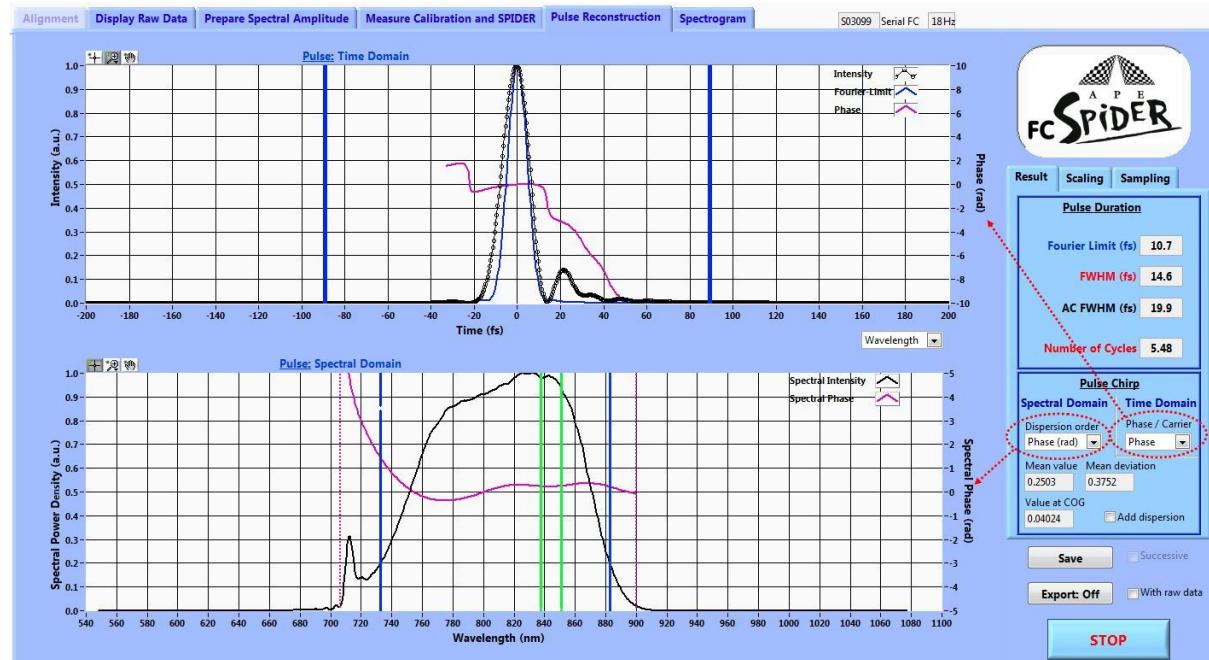


Fig. 16: Screen shot of the FC SPiDER control software: The “Pulse Reconstruction” window displays the online result of the pulse reconstruction: Temporal intensity and phase as well as spectral intensity and phase.

# Pulse Measurement System

FC SPiDER

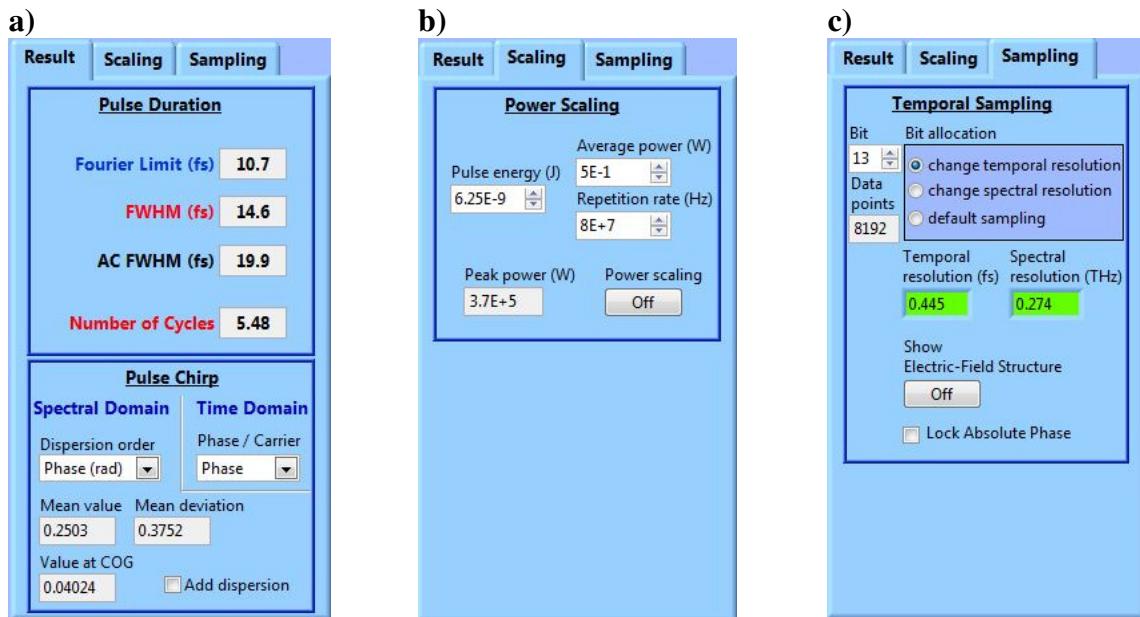


Fig. 17: Sub-tab structure of the “Pulse Reconstruction” window; a) The “Result” tab shows important resulting values of the reconstructed pulse profile such as the FWHM pulse duration; b) On the “Scaling” tab the user can calculate the exact peak power and replace the arbitrary intensity scaling by a power scaling. c) On the “Sampling” tab the resolution and data range of the temporal pulse reconstruction can be changed.

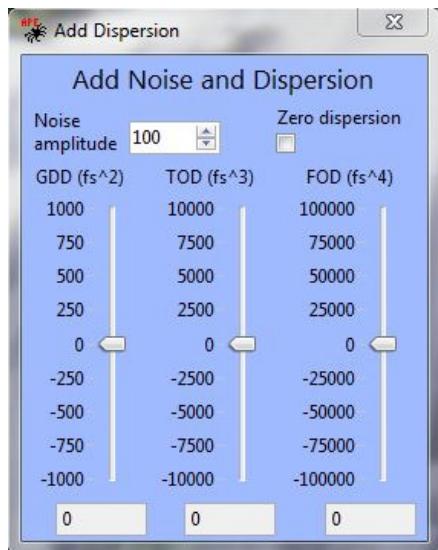


Fig. 18: The “Add Dispersion” option: By setting a check mark in the “Add dispersion” check box [See Fig. 17 a) / “Pulse Chirp”] a second window opens to add noise (only in the “Offline” mode) and dispersion (Group Delay - , Third Order – and Fourth Order Dispersion) to the measurement. This option allows for simulating the dispersive influence of arbitrary material in the beam path of the pulse. Set a check mark in the “Zero dispersion” check box to cancel the introduced artificial dispersion.

### 6.5.1 The “Result” Sub-Tab

- **Pulse Duration:**

- “**Fourier Limit (fs)**”: Displays the FWHM of the intensity pulse shape of the Fourier limit (blue curve of the “Pulse: Time Domain” graph).
- “**FWHM (fs)**”: Displays the FWHM of the intensity pulse shape (black curve of the “Pulse: Time Domain” graph).
- “**AC FWHM (fs)**”: Displays the FWHM of a simulated intensity autocorrelation trace (not shown).
- “**Number of Cycles**”: Displays the number of electric-field cycles over the temporal range of the FWHM of the intensity pulse shape.

- **Pulse Chirp:**

The pulse chirp can be visualized in the “Time Domain” and in the “Spectral Domain” representation of the pulse.

“**Phase / Carrier**” control: In the “Pulse: Time Domain” graph (Fig. 16, upper graph) the user can choose between the depiction of a phase and a carrier frequency or carrier wavelength curve.

“**Dispersion order**” control: The user can change the red curve in the “Pulse: Spectral Domain” graph (Fig. 16, bottom graph) to show the spectral phase or a higher derivative [GD: Group Delay (fs), GDD: Group Delay Dispersion ( $\text{fs}^2$ ), TOD: Third Order Dispersion ( $\text{fs}^3$ ) and FOD: Fourth Order Dispersion ( $\text{fs}^4$ )].

The plot range of the red curve is limited by two vertical, red dotted cursors that can be positioned by the user.

“**Mean value**”: Numerical value of the intensity weighted mean of the depicted red curve (spectrally resolved dispersion) within the two limiting cursors.

“**Mean deviation**”: Numerical value of the intensity weighted deviation of the red curve from the mean value.

“**Value at COG**”: Phase, group delay or dispersion value at the center wavelength of the pulse spectrum.

“**Add dispersion**”: Set a check mark opens a new window with slider controls to add or subtract GDD, TOD and FOD values to the measurement (See Fig. 18). With this tool the user can simulate or compensate dispersive influence of arbitrary material in the beam path of the pulse. Setting a check mark in the “Zero dispersion” check box cancels the introduced artificial dispersion.

“**Noise amplitude**”: In “Offline” reconstruction mode the user can add noise to a saved measurement.

## 6.5.2 The “Scaling” Sub-Tab

**Power Scaling:** The scaling of the “Intensity (a.u.)” axis of the “Pulse: Time Domain” graph (Fig. 16) can be replaced by a “Power (W)” axis. To calculate this scaling the user has to enter either a pulse energy value or the average power together with the repetition rate of the laser.

Press “Power Scaling” software button to switch between the two scales.

## 6.5.3 The “Sampling” Sub-Tab

**Temporal Sampling:** The density and range of data points in the “Pulse: Time Domain” graph can be changed to balance between precision of the results and speed of the reconstruction. An appropriate temporal step length is set by the software according to the spectral bandwidth of the pulse.

- **“Bit”:** The number of data points can be changed with this control. If “Bit allocation” is set for “change temporal resolution” the density of data points varies with the Bit value. If “change spectral resolution” is chosen the temporal span of data points resizes with the Bit value while the density remains constant. The “default sampling” sets the data grid back to the spectrometer given one that is independent on the pulse bandwidth.
- **“Temporal resolution (fs)” / “Spectral resolution (THz)”** denote the current resolution with respect to the “Bit” value and the “Bit allocation” choice.
- **“Show Electric-Field Structure”:** If the temporal resolution is high enough this software button is enabled. Press this button to replace the “Pulse: Time Domain” intensity plot by a “Pulse: Electric Field” plot (See Fig. 19). Because the Carrier-Envelope Offset phase of the Pulse cannot be determined by the SPIDER method the software adds an arbitrary  $\varphi_{CEO}$  to the measured phase. The  $\varphi_{CEO}$  can be set to zero by setting a check mark in the “Lock Absolute Phase” check box.

**Save:** Press this software button to save all data and reconstruction results of the current measurement. Choose a name for the data and a directory. For each saved measurement six files are created that are marked with their characteristic abbreviation:

- name\_calib.dat Calibration interferogram raw data used
- name\_spider.dat SPIDER interferogram raw data
- name\_fund.dat Raw data of the fundamental spectrum
- name\_freq.dat Pulse reconstruction in the spectral domain (e.g. spectral phase)
- name\_time.dat Pulse reconstruction in the time domain (e.g. pulse shape)
- name\_values.dat Characteristic reconstruction values

The first three files are needed for offline pulse reconstruction.

If the FC SPIDER is used in triggered mode the “Successive” check box at the right hand side of the “Save” software button can be used.

# Pulse Measurement System

**FC SPIDER**

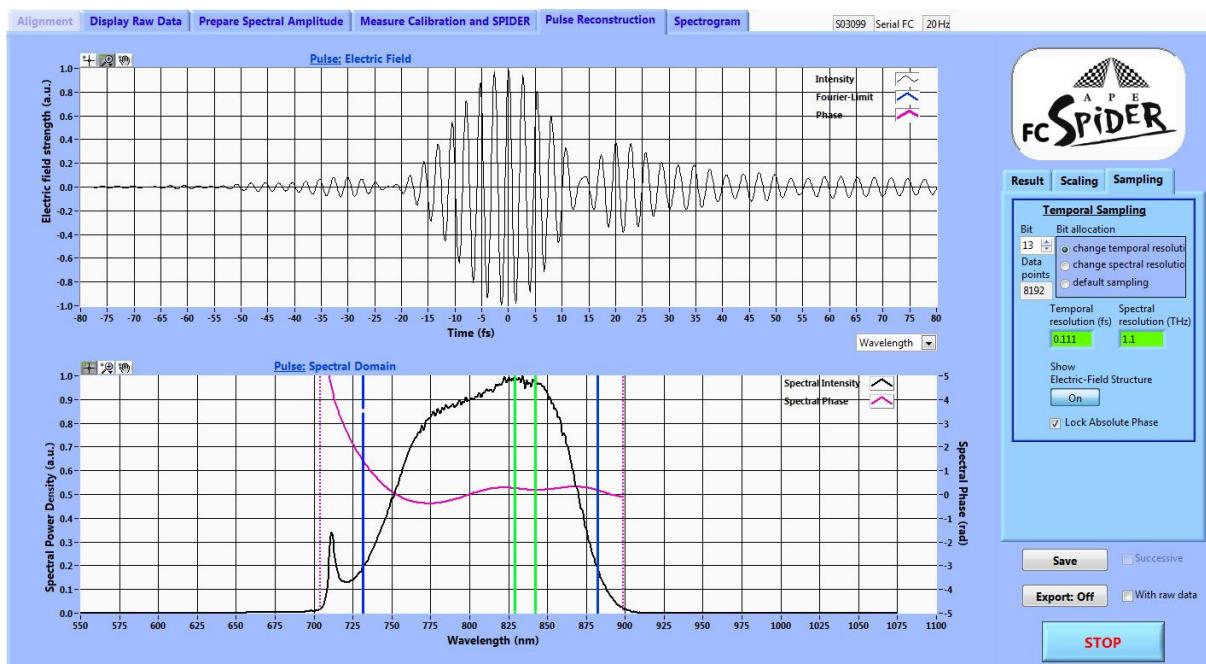


Fig. 19: Screen shot of the FC SPIDER control software with activated “Show Electric-Field Structure”: The “Pulse Reconstruction” window displays the online result of the electric-field of the pulse (arbitrary absolute phase offset assumed) as well as spectral intensity and phase.

Each successive pulse reconstruction (each analyzed camera shot) is saved automatically in case of activated check box followed by pressing the “Save” button.

## Export: Off / On

Press this software button to activate a data socket server (co-installed with the control software) for online data export of the spectral intensity and phase. This data can be imported simultaneously in an additional open source LabView vi for further evaluation. If the “With raw data” check box is checked the raw data of spectrometer 1 and 2 are exported as well.

## 6.6 The “Spectrogram” tab

This tab features additional real-time visualization of the measured laser pulse.

### Spectrogram:

A spectrogram visualizes the frequency distribution of the pulse over time. Figure 20 shows an example of a spectrogram plot of the measured pulse. To calculate such a frequency-time-distribution picture the pulse has to be mathematically sampled by a second pulse that does not introduce any additional chirp information. The duration of the sampling pulse is initially set to the same duration as the test pulse but can be changed by the user. The speed of the software can be increased by lowering the bit rate of the sampling (decreased temporal and spectral resolution).

Please, keep in mind the uncertainty principle! The longer the sampling pulse the more washed-out the temporal pulse structure gets, whereas the frequency distribution gains in preciseness.

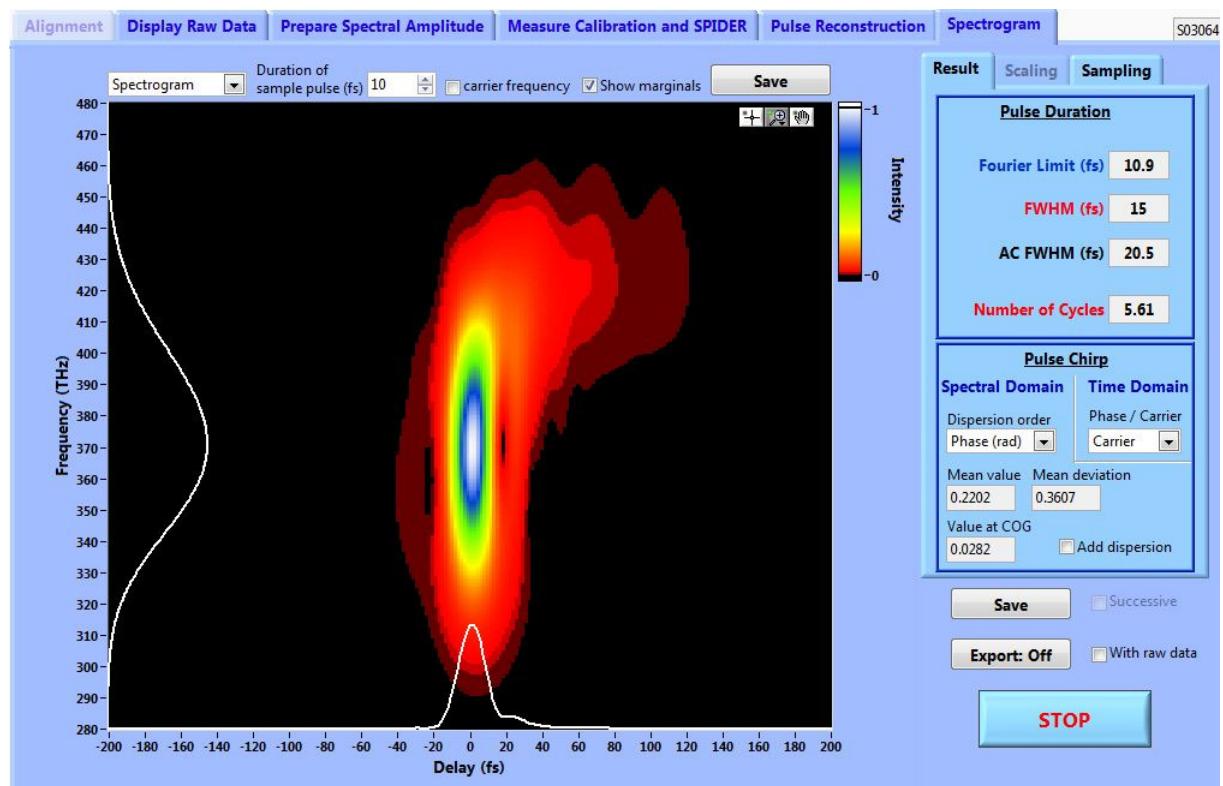


Fig. 20: Screen shot of the FC SPiDER control software with “Spectrogram” option activated. The sampling pulse has a duration of 10 fs.

# Pulse Measurement System

**FC SPiDER**

**“Show marginals”:** If this check box is activated the “frequency marginal” (spectral intensity pattern that results from integration of the spectrogram along the delay axis) and the “delay marginal” (temporal intensity pattern that results from integration of the spectrogram along the frequency axis) is plotted on top of the respective axis of the 2D picture.

**“carrier frequency”:** If this check box is activated the carrier frequency of the measured pulse is inserted into the spectrogram plot as a dotted line (See Fig. 21).

**“Save”:** The user can save the 2D data of the spectrogram independently from common save routine. The abbreviation (“name\_frog.dat”, “name\_spectrogram.dat”, “name\_wigner.dat”) to the chosen file name represents the used 2D visualization.

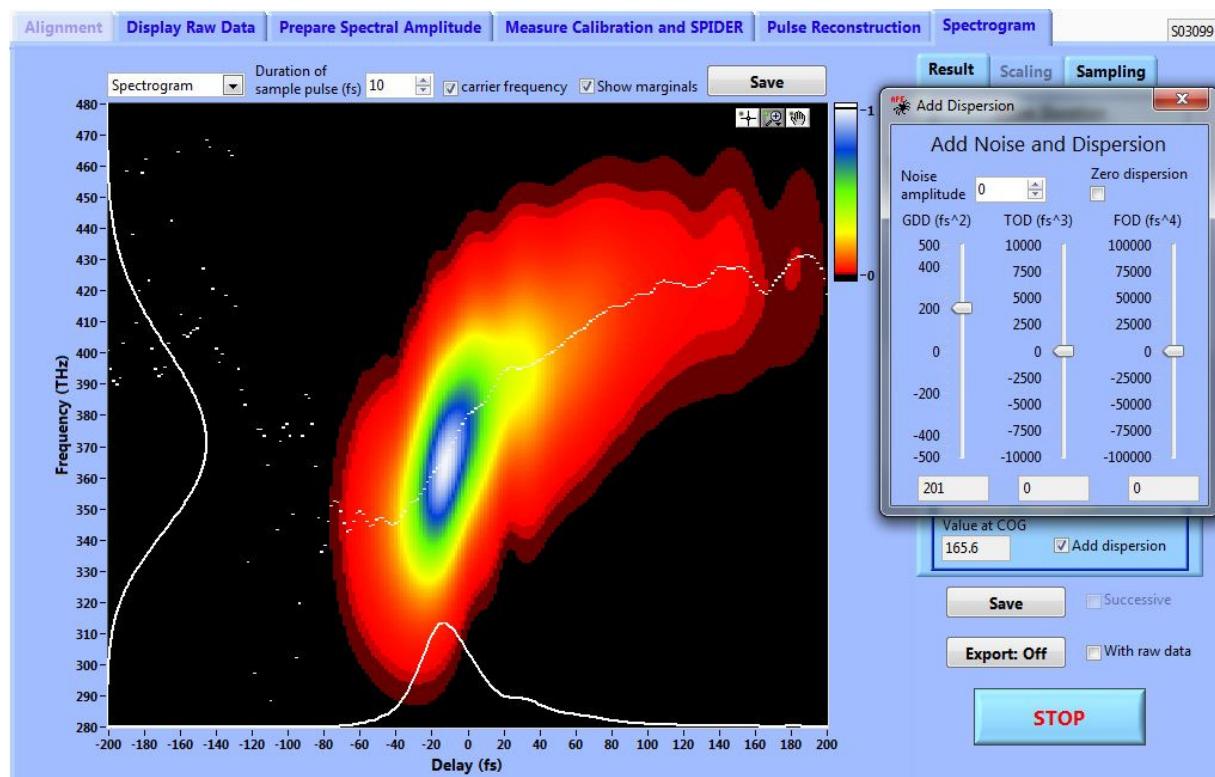


Fig. 21: Screen shot of the FC SPiDER control software with “Spectrogram” option activated. With the “Add dispersion” option a value of GDD~200fs<sup>2</sup> was added to the pulse measurement shown in Fig. 20.

# Pulse Measurement System

**FC SPiDER**

## SHG FROG:

A “Frequency-Resolved Optical Gating” measurement of the pulse is a spectrally resolved autocorrelation measurement of its second harmonic signal. Based on the SPIDER results such a FROG trace is calculated online (See Fig. 22). In contrast to the “Spectrogram” picture, the FROG trace is always symmetric along the delay axis and shows no direct chirp information.

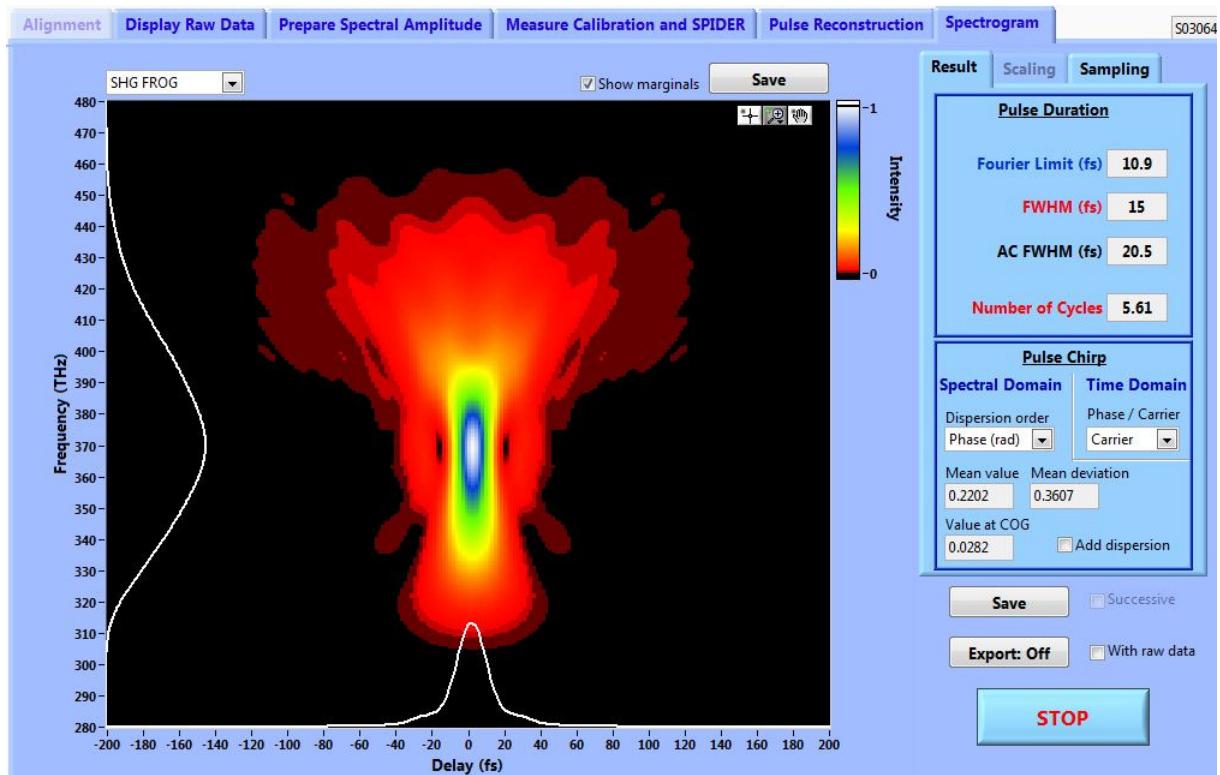


Fig. 22: Screen shot of the FC SPiDER control software with “SHG FROG” visualization activated. The FROG trace represents the same pulse as shown in Fig. 20.

# Pulse Measurement System

FC SPIDER

## Wigner trace:

The Wigner trace of a pulse is a sensitive method to visualize the impact of the phase on the pulse structure (Fig. 23). The dominate order of the chirp can be recognized along with the spectral and temporal intensity pattern of the pulse in one graph. The Wigner marginals are the pulse spectrum and the temporal pulse shape [6].

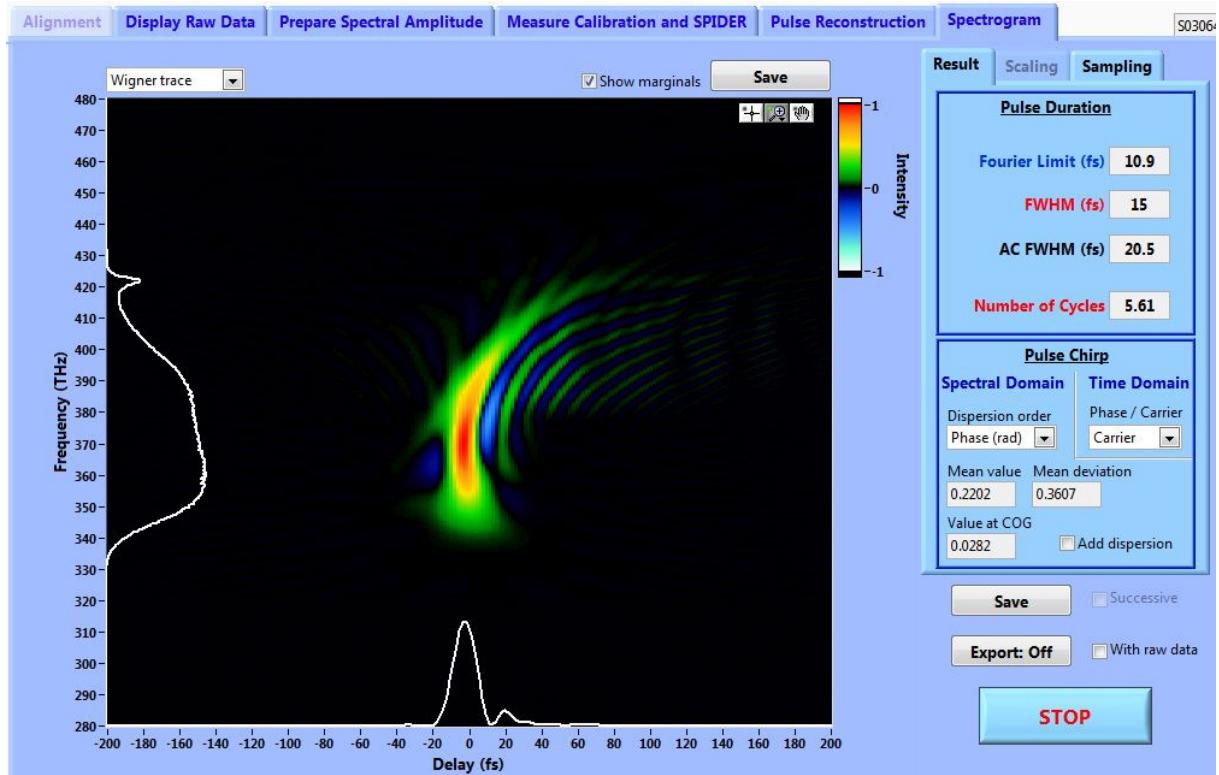


Fig. 23: Screen shot of the FC SPIDER control software with “Wigner trace” visualization activated. The Wigner trace represents the same pulse as shown in Fig. 20.

## 7 Measure a Calibration Trace

The calibration measurement is a very important part of the spectral phase reconstruction procedure. Its quality contributes to the accuracy of the retrieved spectral phase to the same amount as the online SPIDER measurement does. In first order, the calibration interferogram delivers the temporal distance between the two test pulses without a spectral shear between them. This distance is on the order of 1 ps. This value contributes to the spectral shear calculation. For the spectral phase reconstruction the whole phase of the calibration interferogram or its extrapolated fit is used together with the phase of the SPIDER interferogram. However, in contrast to the phase of the SPIDER interferogram the respective phase of the calibration interferogram is expected to show an absolutely flat and undisturbed gradient (Compare Fig. 14). Deviation from such a behavior is a hint for a bad calibration measurement.

Because the FC SPIDER is based on a drift-free, etalon-based interferometer, it is not necessary to take a new calibration measurement as long as:

- the etalon or its alignment was not changed,
- the calibration interferogram covers at least the same wavelength range (or more) as the SPIDER interferogram.

In case of ultra broadband laser sources, the type-II phase-matched SPIDER signal can show a spectrally more broadband interferogram than the associated type-I phase-matched calibration signal. In such a case it is reasonable to use the “Extrapolate Calibration Phase” software option [See Fig. 13 a)].

To measure a calibration interferogram, please, act according to the following steps:

1. Control software: Switch to the “Measure Calibration and SPIDER” tab
2. Control software: Switch to the “Calib” sub-tab [See Fig. 13 a)]
3. Press the “Calibration Off” software button to show “Calibration On”. All necessary motor driven shutters and filters are set to the right positions for a calibration measurement (See Appendix 11.2).
4. Open the optics unit and turn the nonlinear crystal in  $\varphi$ -direction from  $0^\circ$  to  $45^\circ$  according to Figure 24 a) and b).
5. Control software: Switch to the “Display Raw Data” tab
6. Optimize / maximize the calibration interferogram with turning mirror M9.
7. Try to maximize the signal with small  $\varphi$  and  $\theta$  adjustments of the crystal tilt or even with the “Crystal” micrometer position (from outside). (Look for sufficient spectral bandwidth to cover at least the same spectral range as the SPIDER interferogram.)
8. In case of residual disturbing background from fundamental radiation, use a thicker color filter in front of the entrance of spectrometer 2 (Control software tab “Display Raw Data” / sub-tab “Options” / Red filter: In, choose Filter no. 2 [See Fig. 9c])

# Pulse Measurement System

FC SPiDER

9. Use the “Exposure” slider of “Settings Spectrometer 2” (Control software tab “Display Raw Data” / sub-tab “Online” [See Fig. 9a]) to exploit all the dynamic range of the spectrometer without clipping high signals.
10. Control software: Switch to the “Measure Calibration and SPiDER” tab / “Calib” sub-tab and save the calibration interferogram by pressing the “Save Calibration?” software button [See Fig. 13a)]

To continue with the pulse characterization switch back to the SPiDER measurement configuration:

1. Press the “Calibration On” software button to show “Calibration Off”.
2. Turn the nonlinear crystal back to  $\varphi = 0^\circ$ .
3. Maximize / optimize the SPiDER interferogram according to “Initial FC SPiDER alignment” starting at step 11.

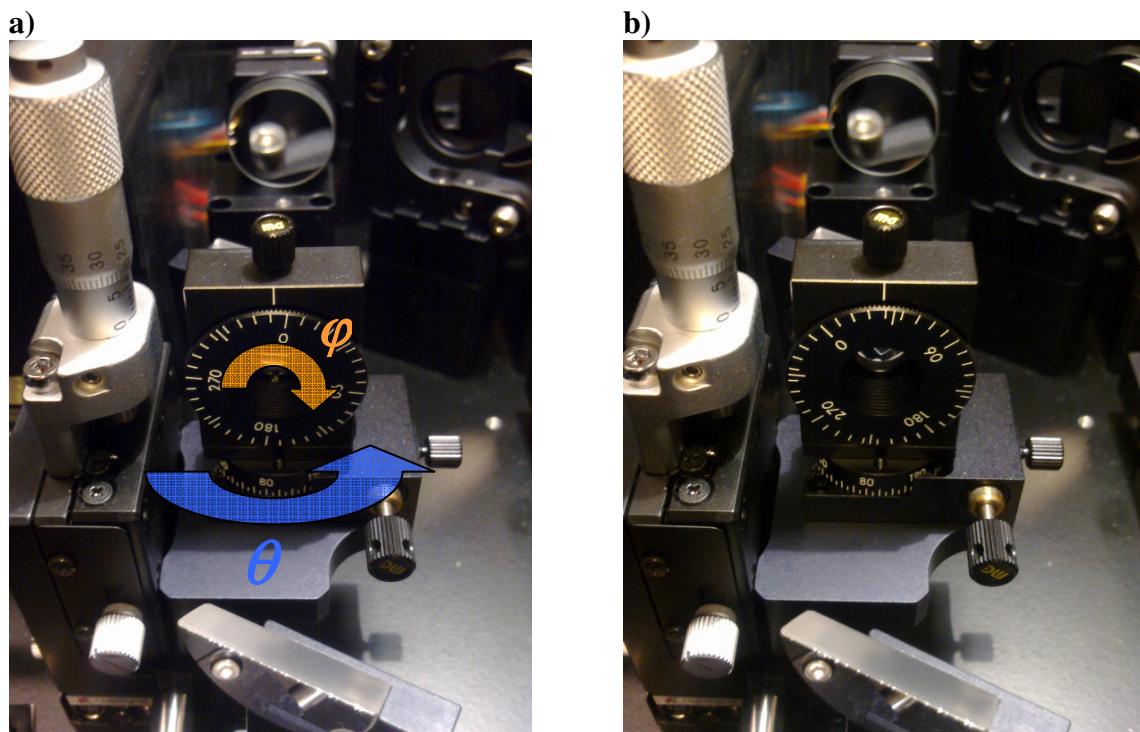


Fig. 24: Difference of crystal  $\varphi$ -angle for SPiDER and Calibration measurement: a) For a SPiDER measurement the crystal angle is set to approximately  $\varphi = 0^\circ$  for type-II SFG; b) For a Calibration measurement the crystal angle has to be changed by  $\varphi = 45^\circ$  to yield maximum type-I SHG signal of the double pulse.

## 8 Change of Device Configuration

To switch between the two device configurations for the different pulse bandwidth ranges, please, act according to the following steps:

1. Release the locking screws [See Fig. 25 a)],
2. Change the positions of the dispersive glass rod and the corner cube to the desired configuration according to Fig. 25 a) for device configuration 1 and according to Fig. 25 b) for device configuration 2.  
**Do not touch any optical components! Use the external plunger to change the dispersive glass rod position! [See Fig. 25 b) and d)]**
3. Tighten the locking screws (only necessary for the corner cube).
4. Control software: Switch to the “Alignment” tab
5. Change the micrometer “Delay” position according to the configuration dependent value that is displayed on the “Alignment” tab.
6. Use the top adjust mirror M6 to re-align the beam overlap (Refer to Fig. 6).
7. Control software: Switch to the “Display Raw Data” tab and maximize / optimize the SPiDER interferogram;

Continue with step 13 of the “Initial FC SPiDER Alignment”.

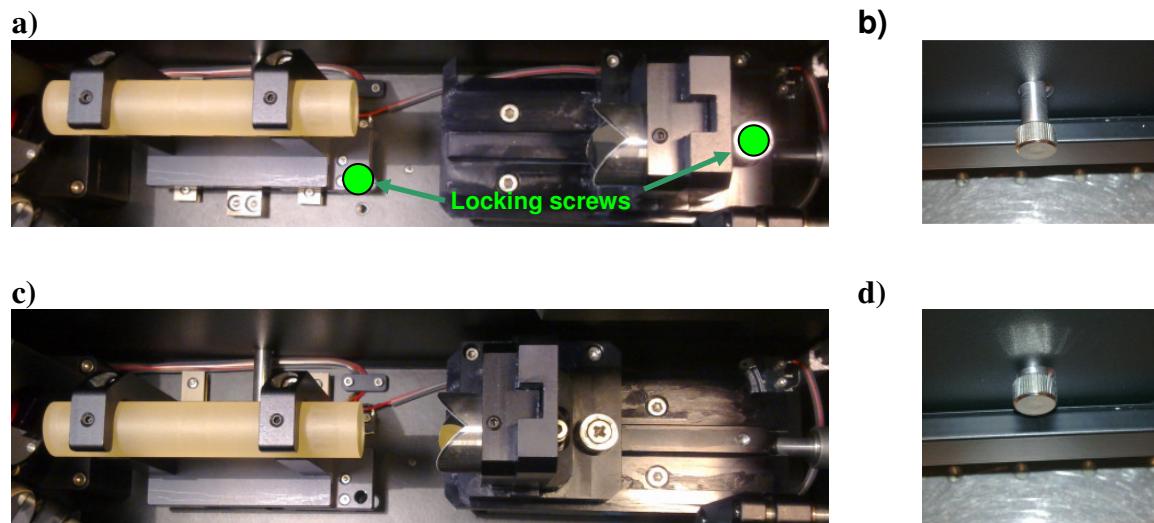


Fig. 25: Setup of the two device configurations for the two accessible pulse bandwidth ranges; a) Configuration 1: single transmission pass through the dispersive glass rod with the corner cube fixed at the distant position; b) plunger position for configuration 1 (pull to switch from configuration 2 to 1); c) Configuration 2: double transmission pass through the dispersive glass rod with the corner cube fixed at the close position; d) plunger position for configuration 2 (push to switch from configuration 1 to 2).

## 9 Find the SPIDER sum-frequency signal

**First, always try to detect the SPIDER signal with the default routine:**

- Adjust the micrometer screw of the “Delay”, the “Crystal” and “CM2” to their default values that are displayed on the “Alignment” tab of the software. (The values are valid only if the specific device configuration file is loaded.)
- Use the software’s alignment option (“Alignment” tab) to align the overlap of the two beams with M6.
- Use M9 to align both overlapping beam spots on the cross hairs of the alignment camera display (for proper coupling into spectrometer 2).
- If no SPIDER interferogram is detected by spectrometer 2 at the “Display Raw Data” tab increase the exposure time of spectrometer 2 for more sensitivity. Change the “Delay” with the micrometer screw and monitor the signal graph of spectrometer 2 for an interferogram to appear.

In case no SPIDER signal is visible continue as follows:

1. Check if the laser is mode-locking (look at fundamental spectrum measured with spectrometer 1).
2. Check for correct basic alignment:
  - a) Make sure that the optics unit and the beam path to the entrance aperture “Input 1” is prepared according to the description “Prepare” of the chapter “Alignment”.
  - b) Check if the beam is centered at the alignment aperture holes: Use the single-hole alignment aperture at positions A1, A3 and A4, the double-hole alignment aperture at positions DA1 and DA2, and the slit-aperture SA in front of CM1 and CM2. (If there is severe discrepancy, please, call for instructions.)
3. Place a card in front of the motorized spatial filter SF (It is recommended to use a fluorescent (e.g. green) card for a better visibility of the blue SFG signal).
4. Check CM2-alignment: Both fundamental beams should be reflected by M8 onto the card (Refer to Fig. 2).
5. Move the CM2 position (micrometer screw) to a larger distance to the crystal (distance between the crystal and the CM2 surface >95mm).
6. Check crystal orientation: turned for a vertical incidence of the beams and an angle of  $\varphi=0^\circ$  [See Fig. 24a)]. Move the crystal position with the micrometer screw to the default value (displayed on the “Alignment” tab of the software). The distance between the surface of CM1 mirror and the crystal should be 75mm.
7. Place the additional alignment filter at F1 position in front of CM2. The two fundamental beams are suppressed. However, a faint blue type-I SHG signal should be visible in both beams. (If this is not the case, check for proper mode-locking and/or increase input power).
8. Move the crystal in the focus of the beams: Change “Crystal” position to maximize the two visible blue SHG signal spots (For low divergent laser beams the optimum crystal position should remain approximately at 75mm distance to CM1).

9. Turn the  $\phi$ -angle of the crystal to minimum intensity of the visible SHG signal spots  
(The angle value should be around  $\phi=0^\circ$ .)
10. Check and optimize the overlap of the two beams at the crystal by M6 alignment.  
Carefully use a white card close to the crystal surface to estimate the beam overlap or try an IR-viewer to look at the crystal's surface.
11. Remove the (green) card at SF position. Further use M6 to optimize the beam overlap by monitoring its image behind CM2 in front of the spectrometer 2 entrance slit.

At this state – if no SPIDER signal is visible – two parameters might be off:

- The crystal position is still not at the overlap of the two beams.
  - The “Delay” position that depends on the center wavelength of the pulse is still off.
12. Slightly change the “Crystal” position and monitor the card placed in front of SF for a blue SPIDER signal to appear between the two beams.
  13. In case of being unsuccessful: Move the crystal to the estimated position for beam overlap. Change the “Delay” and monitor the card for a blue SPIDER signal to appear between the two beams.
  14. In case of being unsuccessful: Change “Crystal” position iteratively. Each iteration scan the “Delay” and look for the SPIDER signal.

## 9.1 Alignment of the SPIDER signal beam path

15. Use CM2 to center the SPIDER signal on the spatial filter hole of the motorized aperture SF. Align M8 to center the SPIDER beam on the single-hole alignment aperture at A6. Repeat this step if necessary (See Fig. 2).
16. Align M9 to couple the SPIDER signal into spectrometer 2.
17. Maximize the SPIDER interferogram by changing CM2 position. Recover the signal decrease due to beam displacement by M9 re-alignment. (Maximize interferogram by alternating CM2 positioning and M9 re-alignment.)
18. If the new optimal “Crystal” and “CM2” positions differ much from the factory settings (See values on “Alignment” tab display.) the automatic alignment tool (internal camera) have to be rearranged for further use:  
**Attention! Factory settings for automated alignment help are changed by the following procedure!**
  - a) Set the software to the “Alignment” tab. Unlock camera position (loose top set screws of “Cam”) and move the camera-plate along the four posts to a position where both beam spots spatially overlap on the camera picture.
  - b) Align prism (PR) mount to center the beam overlap spot in the center of the cross hairs of the camera picture.
  - c) Make a note of the “Crystal” and “CM2” micrometer screw positions for the new arrangement of the alignment camera.

Continue with signal optimization as described in the chapter “Installation” \ ”Alignment” \ ”Signal Optimization”.

## 10 Theory of Operation: Principle of SPIDER

### 10.1 Spectral Interferometry

Spectral Interferometry (SI) is an established method to measure the phase difference between two optical paths in the frequency domain. The appropriate experiment only consists of an interferometer and a spectrometer that detects the spectral intensity of two recombined laser pulses after each one had traveled along a different path. The spectrum of such a double pulse is called a spectral interferogram because – in most cases – it exhibits a strong intensity modulation along the frequency axis. The modulation period of length  $\Delta\omega_l$  at a certain frequency  $\omega_l$  of the spectrum encodes the temporal separation  $\tau_l=2\pi/\Delta\omega_l$  between the two pulses at this frequency. If one of the two pulses has been additionally chirped due to a dispersive element in its beam path the spectral interferogram deviates from even periodicity. Now, the change in the period length of the modulation along the frequency axis reveals the spectral dependence of the temporal distance between the “test” pulse and the “reference” pulse:  $\tau=\tau(\omega)$ . This function arises from the actual measured difference in the spectral group delay (GD) of the two pulses:

$$2\pi/\Delta\omega(\omega) = GD_{pulse1}(\omega) - GD_{pulse2}(\omega)$$

with

$$GD(\omega) = d\phi/d\omega,$$

with  $\phi(\omega)$  as the spectral phase of the pulse. Integration gives the information about the phase difference between the two beam paths, i.e. the phase added by the additional dispersive element in one interferometer arm. However, the information about the actual spectral characteristic of the group delay of the pulse is lost.

## 10.2 Spectral shearing Interferometry

In 1998 C. Iaconis and I. A. Walmsley introduced “Spectral Phase Interferometry for Direct Electric-field Reconstruction” as a modification of SI [2]. Because they were not interested in the phase difference of two primarily identical pulses but in the phase of a pulse itself they had to use an additional trick. Frequency shifting two identical copies of the input pulse by a small amount  $\Omega$  (about 10% of the pulse’s bandwidth) with respect to each other and analyzing their spectral interferogram gives direct access to the group delay  $GD(\omega)$  of the input pulse (See Fig. 26).

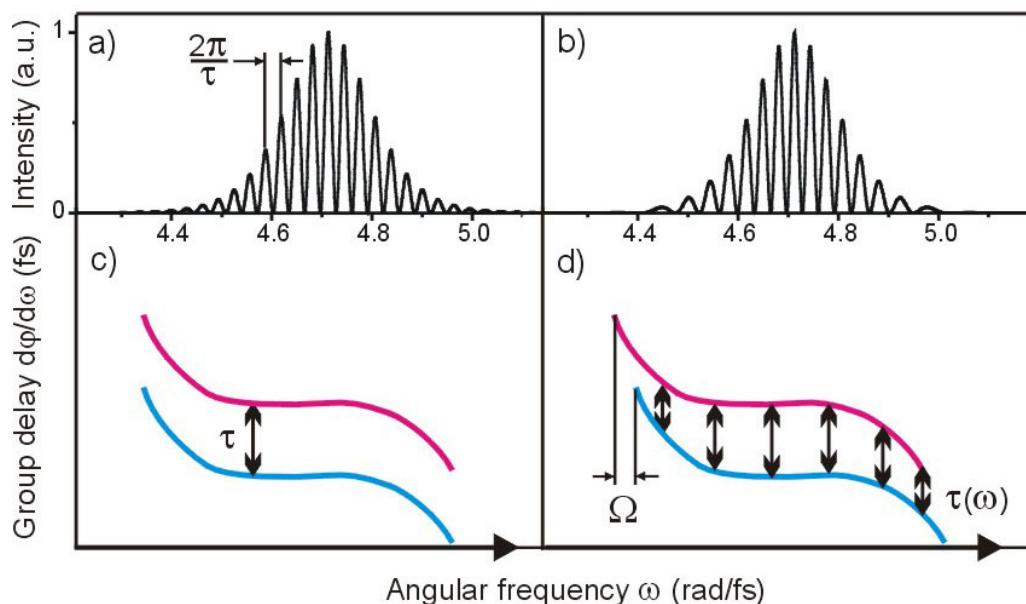


Fig.26: *Principle of spectral shearing Interferometry;*

- a) Delaying two identical replica pulses with respect to each other results in equidistant fringe spacing in their interferogram.
- b) Applying a spectral shear between the pulses causes a deviation from the calibration fringe spacing shown in a).
- c) Without a shear the temporal separation of the group fronts remains constant along the frequency axis.
- d) A spectral shear  $\Omega$  yields a change or even a spectral dependence of the temporal separation of the group fronts that can be directly retrieved from the spectral interferogram. This information encodes the change of the spectral pulse phase in steps  $\Omega$  along the frequency axis.

Full information on the spectral behavior of the group delay is sufficient to reconstruct the spectral phase of the pulse except for a constant offset (the carrier-envelope offset phase). Together with a measured spectrum of the pulse one is able to calculate its electric field in the time domain just by means of Fourier transformation.

The different types of SPIDER mainly vary in the method how the frequency shear  $\Omega$  is generated. Especially, in case of characterization of ultrashort pulses each of the two replica pulses is up-converted with a different monochromatic frequency component. The traditional way of doing this is to split the incoming pulse in three replica pulses. Whereas two are delayed with respect to each other in some sort of interferometer (Michelson or an etalon) the third one is strongly chirped and stretched. Recombining all three pulses in a thin nonlinear crystal is followed by Sum Frequency Generation (SFG) of the whole spectrum of the two replica pulses with the respective frequency component of the stretched pulse that lies in the time window of the replica. In this way, both pulses are frequency shifted to the second harmonic frequency range by a slightly different amount resulting in the necessary frequency shear (See Fig.27).

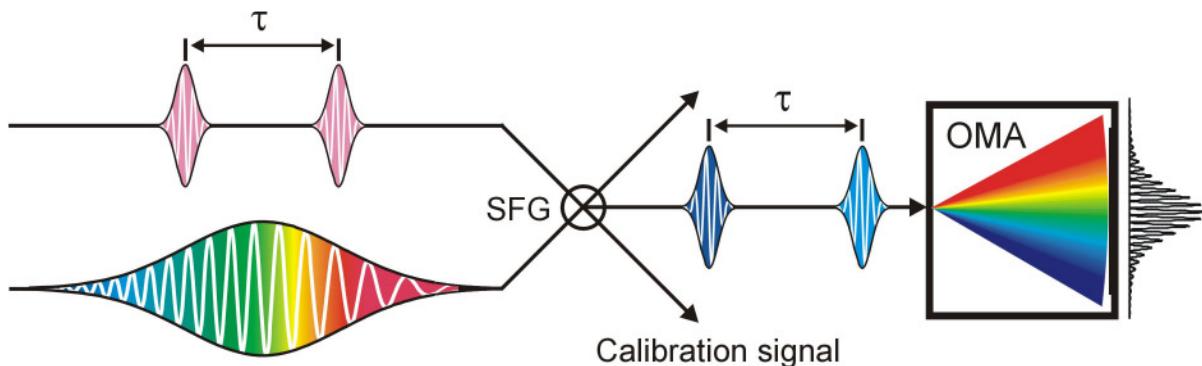
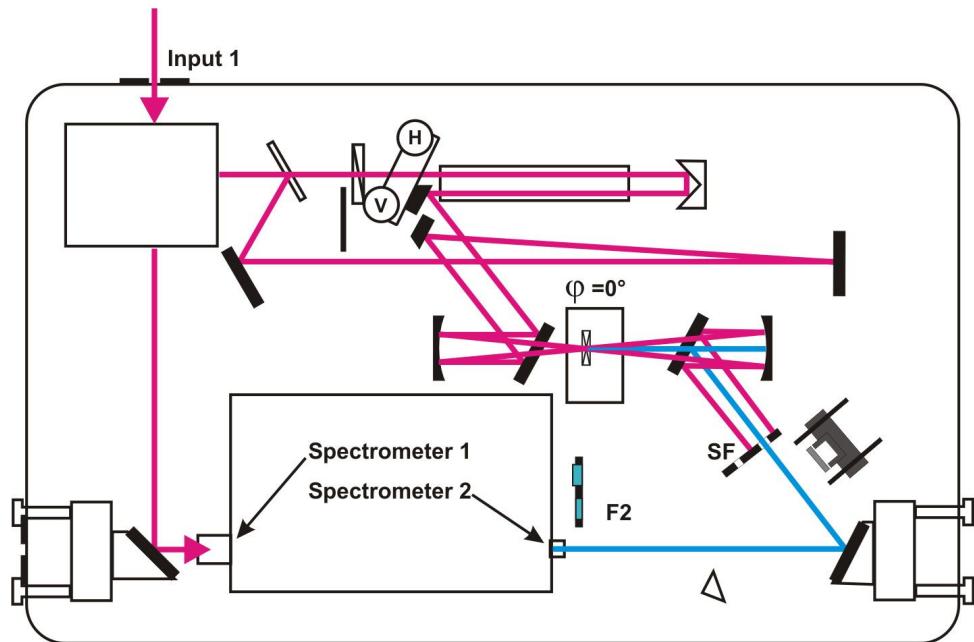


Fig. 27: Schematic setup of traditional SPIDER;

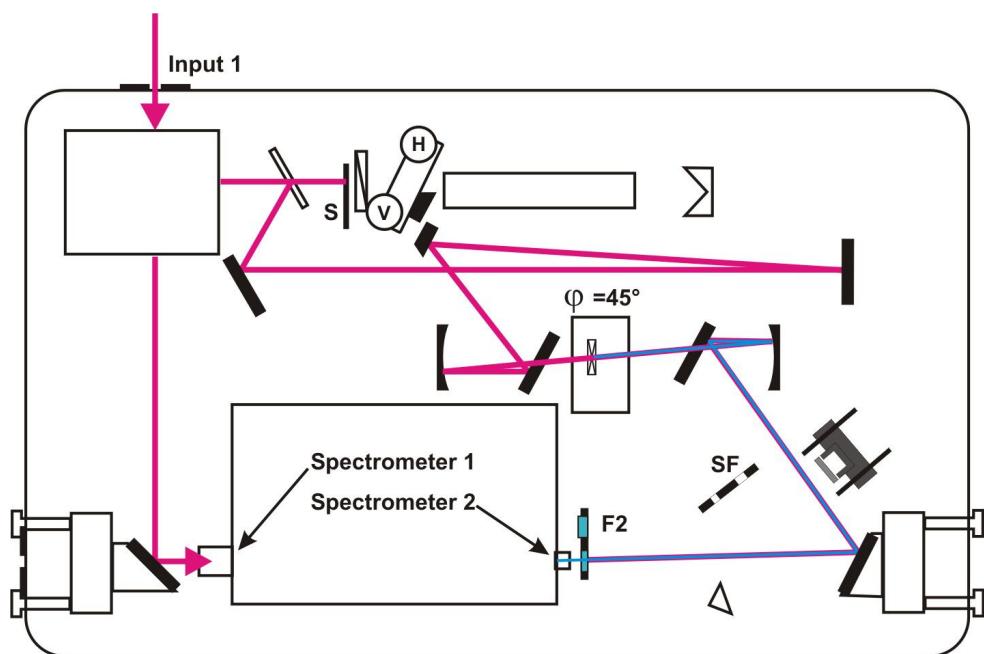
Two identical replica pulses of the input pulse are separated in time by a constant delay  $\tau$  and spatially / temporally overlapped with a third strongly chirped pulse inside a thin nonlinear crystal. Sum-Frequency Generation (SFG) of the whole spectrum of each pulse replica with different quasi-monochromatic components of the chirped pulse translates the delay  $\tau$  into a spectral shear  $\Omega$  between the two up-converted replica pulses. The spectrometer (OMA: Optical Multi-channel Analyzer) signal of these two replica pulses manifests as a spectral interferogram that is spectrally analyzed. The calibration signal gives an interferogram of the two replica pulses without shear. It enables the determination of the delay  $\tau$ .

## 11 Appendix: Measurement Arrangements

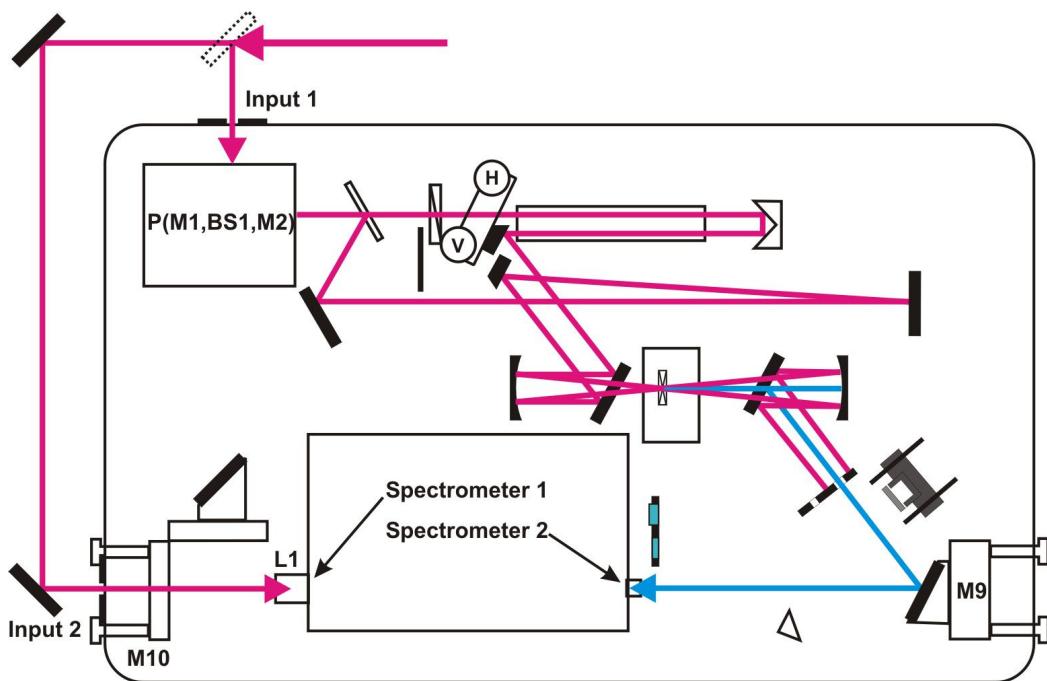
### 11.1 SPiDER Measurement for High Repetition Rate Laser Systems



### 11.2 Calibration Measurement

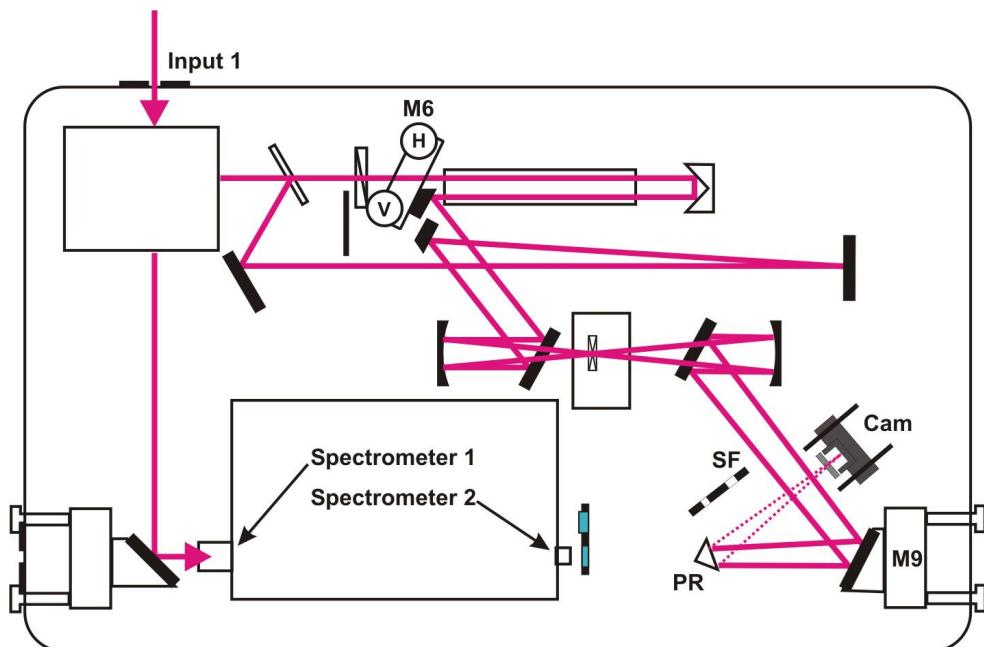


### 11.3 SPiDER Measurement for Low Repetition Rate Laser Systems (“Single Shot” measurement setup\*)



(\* The external beam routing – including beam splitting and attenuation – is optionally available.)

### 11.4 Two-Beam Overlap Alignment (With Internal Camera)



## References

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- [6] L. Cohen, "Time-frequency distributions – a review," *Proc. IEEE* **77**, 941 (1989)