DASEL Laser Fiber Transport Feasibility Report
Engineering and Test Report

SPECIFICATIONS
To Satisfy requirements of SLAC 0000172746 Purchase Order
September 21, 2017

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COMPANY OVERVIEW

Amplitude Systemes, located near Bordeaux, France, develops and manufactures diode-pumped ultrafast solid-state lasers for scientific and industrial applications.

In the early 90s a first generation of commercial ultrafast lasers featuring Titanium doped Sapphire (Ti:Sapphire) as the active material was introduced allowing researchers in different fields (biology, chemistry, spectroscopy) to take advantage of the very short pulse durations these systems offered. This first generation of femtosecond lasers, although well suited to a research environment, exhibited limitations which prevented them from being used in an industrial environment.

Consequently,a new generation of ultrafast lasers was developed in the mid 90s and they experienced rapid growth. Using a rare-earth dopant, such as Neodymium or Ytterbium, these lasers could be directly diode-pumped, exhibited excellent optical performances and were fully compatible with highly reliable telecom-class laser diodes. These new diode-pumped femtosecond lasers were compact, highly reliable, and more cost effective than their predecessors.

Amplitude Systemes is a leading company in this field of diode-pumped ultrafast lasers and has pioneered many new products:

- 2001: First high average power (>1W) diode-pumped femtosecond oscillator.
- 2002: First diode pumped Ytterbium amplified femtosecond laser.
- 2002: First demonstration of a sub-40fs non collinear OPA pumped by an Yb amplifier (CLEO 2002)
- 2002: First tuneable infrared femtosecond system for multiphoton microscopy.
- 2003: First high energy (> 200 nJ) diode-pumped femtosecond oscillator.
- 2004: First high repetition rate (100 kHz) diode pumped amplified femtosecond laser.
- 2005: First micro-Joule from a fibre amplifier.
- 2008: Compact air-cooled diode-pumped femtosecond oscillator.
- 2006: 60W average power femtosecond oscillator and fiber amplifier.
- 2009: 2mJ diode pumped femtosecond amplifier. 50µJ, 400 kHz fiber amplifier.

- 2010: 5W 10 µJ Satsuma Fiber laser, 100µJ, 200kHz version of the Tangerine Fiber Amplifier.
- 2011: 10W 20 µJ Satsuma HP Fiber laser
- 2012: 20 W 40 µJ Satsuma HP2
- 2013: High average power > 30W industrial bulk regenerative amplifier
- 2014: 35 W 200 µJ Tangerine HP
- 2015: 50 W 40 µJ Satsuma HP3
- 2016 100W Tangor Ultrafast Laser

Amplitude Systemes maintains an intense and active R&D policy. This offers our customers the guarantee that any current investment will be supported in the future.

t-Pulse 20

Satsuma

Tangerine

MANUFACTURING CAPABILITY

Amplitude Systemes is located near Bordeaux in the south west of France. Amplitude Systemes' production facility is a 25000 sq ft building, featuring state-of-the-art optical labs and production space. Amplitude Systemes has two off-site dedicated R&D laboratories. Amplitude Systemes employs more than 150 people, 80% of whom are highly trained technicians and engineers.

The company benefits from its proximity to a high caliber university campus which in combination with attractive living conditions, allows recruitment of high level engineers and technicians. Amplitude Systemes has experienced a very low personnel turnover since its creation in 2001.

In 2017 Amplitude completed an expansion into a custom designed, state of the art laser manufacturing facility, doubling its manufacturing space to 2500 square meters.

Further facilities expansion is possible due to the favorable real estate environment and local institutional support in the Bordeaux area.

The company is currently working as an OEM manufacturer for several industrial and medical customers, and is experienced with industrial requirements and continues its constant involvement and efforts into delivering systems for cutting edge applications.

The company is ISO 9001:2008 certified. The internal quality assurance system ensures consistent manufacturing quality, as well as traceability and records management. Amplitude Systemes is ISO13485 certified since 2011.

R&D CAPABILITY

Amplitude Systemes benefits from a strong scientific and industrial environment due to its close proximity to a high level scientific campus and to the "Laser MegaJoule" project currently being developed for inertial fusion research. Amplitude Systèmes is an active member of the "Route des Lasers", the only French competitiveness cluster dedicated to high power lasers.

This attractive environment offers significant advantages in terms of R&D capability. Amplitude Systemes has many active R&D projects which are either funded internally, or in collaboration with leading universities or industrial partners worldwide. Amplitude Systèmes is also a partner and coordinator in several national or European projects.

Amplitude Systemes is as an example the prime partner and coordinator in FemtoPlus, a research project solely dedicated to ultrafast laser development, as well as SFERA, a European Union project dedicated to industrial applications of ultrafast lasers in pharmaceutical anticounterfeiting applications.

Amplitude Systemes' strong R&D capability guarantees the company's long term commitment and guarantees that any investment made today in a fast-moving field will be supported in the future.

SERVICE CAPABILITY

Amplitude Systemes has a dedicated service team, able to offer high quality service worldwide with a short response time. To guarantee efficient support, we rely on experienced direct technical support in Germany, Asia, and the United States.

In other countries, Amplitude Systemes has a network of sales and support partners, able to offer first tier service and diagnostics.

In the US, service support is dispatched from our San Jose California facility at 140 Baytech Drive.

OBJECTIVE: Feasibility study laser for DASEL project

PARTICIPANTS: MNA, YZA, FGU, LLA

AUTHOR: MNA

TO: SLAC in response to purchase order 172746

DATE : 31/03/2016

This report aims to demonstrate the feasibility of a laser system able to cope with the requirement of the DASEL project at SLAC as per the SOW.

1 BACKGROUND

Amplitude Systemes has manufactured the photocathode and laser heater lasers for LCLS-II. This twin laser system consists of two identical lasers each featuring an oscillator locked to the LCLS-II master clock and a high power Tangerine amplifier. The DASEL project requires a laser delivering a small amount of UV light onto the photocathode of LCLS-II at very high repetition rates. Therefore, it must be synchronized to LCLS-II.

The synchrolock oscillator of LCLS-II contains the optical cavity, all necessary actuators (one piezoelectric transducer and one stepper motor) to minimize the phase drift with respect to the provided master clock and a photodiode used as input signal for the feedback control electronics. The oscillator is separate and independent from the Tangerine laser head to prevent noise contamination due to any cooling and fan vibrations within the power amplifier contained in the laser head. The mechanical interface is shown below. The size of the oscillator is 330 x 250 x 137.5 mm.

The oscillator has three fiber coupled outputs. All have 3 m long protected single mode fibers with FC/APC terminations. The first output is directly connected to the Tangerine front-end and is situated in the primary power supply. It is used to seed the amplifier. The second fiber is used to seed a short pulse option used for cross-correlation purposes. The third output is available for the seeding of a DASEL amplifier.

One major goal of the DASEL system is the delivery of laser radiation to the gun which is located approximately 60 m away from the LCLS-II lasers in sector 0. Amplitude Systemes has proposed to decouple the oscillator and the main amplifier head. Each sub-component would then be linked by a long optical fiber.

2 DASEL LASER SPECIFICATIONS

The DASEL laser is required to operate in the UV at ~260 nm owing to the material used in the gun. The nominal wavelength of Amplitude Systemes' lasers is 1030 nm; therefore, it is necessary to shift the 1030 nm output to 257 nm by fourth harmonic generation. An optical average power of 1 mW is sufficient.

	DASEL	Amplitude Systemes' goal
Distance between oscillator and amplifier	>60m	>60m
Average power at 1030 nm	>1 W	>2W
Beam quality at 1030 nm	N/A	M^2 <1.2
Average power stability at 1030 nm	N/A	<1% rms
Pulse duration at 1030 nm	N/A	<250 fs
Average power at 257 nm	>1mW	>5mW

3 BEAM DELIVERY SCENARIOS

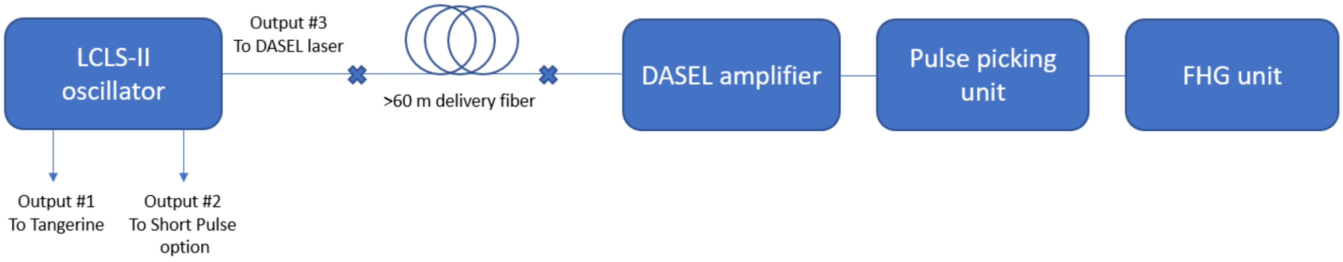
Two major scenarios for beam propagation were initially proposed.

The first scenario consists in the delivery of either the full IR power or the full FHG power through a 60 m long fiber. However, lack of proper fibers, dispersion issues and overall cost of such a solution makes this scenario very complicated. Consequently we decided to focus on the second scenario.

The second scenario consists in the delivery of low power 1030nm seed pulses from the LCLS-II oscillator through 60 m of step index fiber to a compact amplifier laser head located close to the gun. The seed pulses are then amplified and then this amplified output is frequency quadrupled in appropriate nonlinear crystals. The major concerns of this scenario are compressibility of the pulses in the IR and conversion efficiency of the FHG.

4 DASEL LASER ARCHITECTURE

The following figure shows the conceptual layout of the laser we propose.



The fiber coupled output #3 of LCLS-II oscillator is connected to the 60 m delivery fiber. This long delivery fiber allows for propagation of the pulses down to the DASEL amplifier located close to the gun. DASEL amplifier is comprised of a custom laser head that includes all necessary components to manage the dispersion of the pulses, the amplification and the compression to sub-250 fs pulse duration. Since DASEL pulses are to be separated from the main LCLS-II pulses, a pulse picker will be used to create a burst of pulses. Finally, the pulses will be directed to a fourth harmonic unit specifically designed to operate at very high repetition frequencies (i.e. with very limited pick intensity).

5 PERFORMANCE DEMONSTRATION

5.1 REALISATION AND CHARATERISATION OF THE AMPLIFIER

For this demonstration, we used a standard Amplitude Systemes' oscillator running at 40 MHz repetition rate. This oscillator emits pulses at comparable specifications to the output #3 of the LCLS-II oscillator. Any remaining differences between this demonstration oscillator and the LCLS-II oscillator are not expected to influence the results that we are presenting hereafter.

The pulses from the oscillator are coupled into a >60m long fiber that acts as the delivery fiber. This fiber is then connected to an amplifier that was built for the study. The pulses are dispersion managed and amplified in a series of core and clad pumped fiber amplifiers. Due to the moderate energy and average power needed, the propagation and amplification of the pulses were realized in an all-fiber format. Finally, the pulses are optically isolated and compressed using a pair of diffraction gratings.

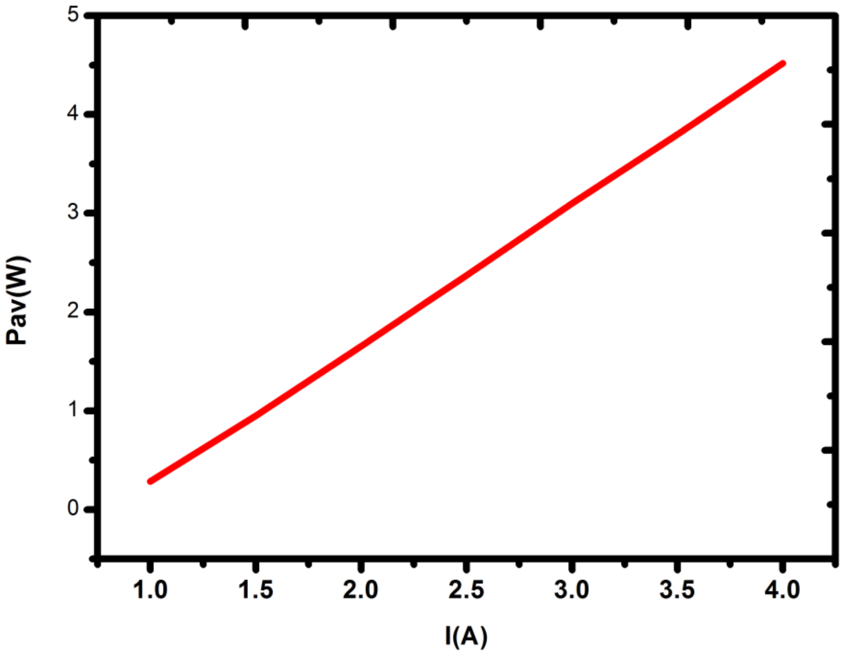
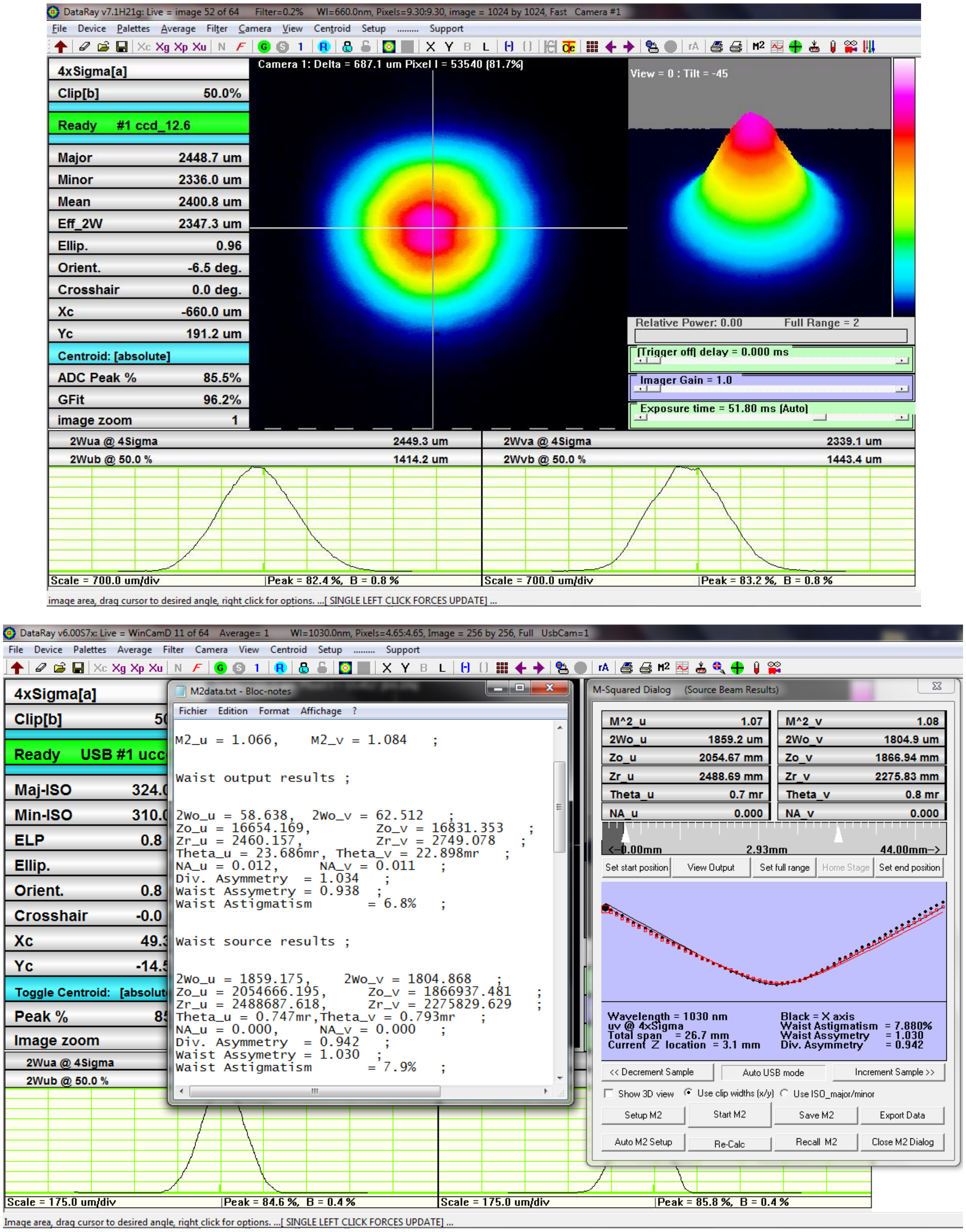


Figure 1 : Average power of the fiber amplifier prior to pulse picking and frequency conversion

Figure 1 shows the average power extracted from the laser head with respect to the current applied to the power amplifier diode laser. The laser head delivers 4.6W of average power for the maximum current applied to the diode. Considering the above-mentioned projects goals, the laser will be characterized next at an operating current of 2A, corresponding to 2W of IR power.



DataRay v7.1H21g: Live = image 52 of 64 Filter=0.2% Wl=660.0nm, Pixels=9.30:9.30, image = 1024 by 1024, Fast Camera #1

4xSigma[a]
Clip[b] 50.0%
Ready #1 ccd_12.6
Major 2448.7 um
Minor 2336.0 um
Mean 2400.8 um
Eff_2W 2347.3 um
Ellip. 0.96
Orient. -6.5 deg.
Crosshair 0.0 deg.
Xc -660.0 um
Yc 191.2 um
Centroid: [absolute]
ADC Peak % 85.5%
GFit 96.2%
image zoom 1

Camera 1: Delta = 687.1 um Pixel I = 53540 (81.7%)
View = 0 : Tilt = -45
Relative Power: 0.00 Full Range = 2
[Trigger off] delay = 0.000 ms
Imager Gain = 1.0
Exposure time = 51.80 ms [Auto]

2Wua @ 4Sigma 2449.3 um
2Wub @ 50.0 % 1414.2 um
2Wva @ 4Sigma 2339.1 um
2Wvb @ 50.0 % 1443.4 um
Scale = 700.0 um/div Peak = 82.4 %, B = 0.8 %
Scale = 700.0 um/div Peak = 83.2 %, B = 0.8 %
image area, drag cursor to desired angle, right click for options. ...[SINGLE LEFT CLICK FORCES UPDATE] ...

DataRay v6.00S7x: Live = WinCamD 11 of 64 Average= 1 Wl=1030.0nm, Pixels=4.65:4.65, Image = 256 by 256, Full UsbCam=1

4xSigma[a]
Clip[b] 50
Ready USB #1 ucc
Maj-ISO 324.0
Min-ISO 310.0
ELP 0.8
Ellip.
Orient. 0.8
Crosshair -0.0
Xc 49.3
Yc -14.5
Toggle Centroid: [absolut
Peak % 85
Image zoom
2Wua @ 4Sigma
2Wub @ 50.0 %

M2data.txt - Bloc-notes

```
M2_u = 1.066,    M2_v = 1.084   ;


Waist output results ;


2Wo_u = 58.638,  2Wo_v = 62.512   ;
Zo_u = 16654.169,        Zo_v = 16831.353   ;
Zr_u = 2460.157,         Zr_v = 2749.078   ;
Theta_u = 23.686mr, Theta_v = 22.898mr   ;
NA_u = 0.012,      NA_v = 0.011   ;
Div. Asymmetry  = 1.034   ;
Waist Assymetry = 0.938  ;
Waist Astigmatism       = 6.8%   ;


Waist source results ;


2Wo_u = 1859.175,    2Wo_v = 1804.868   ;
Zo_u = 2054666.195,      Zo_v = 1866937.481   ;
Zr_u = 2488687.618,      Zr_v = 2275829.629   ;
Theta_u = 0.747mr,Theta_v = 0.793mr   ;
NA_u = 0.000,      NA_v = 0.000   ;
Div. Asymmetry  = 0.942   ;
Waist Assymetry = 1.030  ;
Waist Astigmatism       = 7.9%   ;
```

M-Squared Dialog (Source Beam Results)

M^2_u	1.07	M^2_v	1.08
2Wo_u	1859.2 um	2Wo_v	1804.9 um
Zo_u	2054.67 mm	Zo_v	1866.94 mm
Zr_u	2488.69 mm	Zr_v	2275.83 mm
Theta_u	0.7 mr	Theta_v	0.8 mr
NA_u	0.000	NA_v	0.000

<-0.00mm 2.93mm 44.00mm->

Wavelength = 1030 nm
uv @ 4xSigma
Total span = 26.7 mm
Current Z location = 3.1 mm
Black = X axis
Waist Astigmatism = 7.880%
Waist Assymetry = 1.030
Div. Asymmetry = 0.942

☐ Show 3D view ● Use clip widths (x/y) ○ Use ISO_major/minor

Scale = 175.0 um/div Peak = 84.6 %, B = 0.4 %
Scale = 175.0 um/div Peak = 85.8 %, B = 0.4 %
Image area, drag cursor to desired angle, right click for options. ...[SINGLE LEFT CLICK FORCES UPDATE] ...

Figure 2 : Typical beam profile and M² measurment of the output of the laser

Figure 2, shows the beam profile and M2 measurement of this laser system. The beam profile is Gaussian, as expected, considering being the output of the fiber. The M2 measurement confirms the beam quality with a value less than 1.1 that perfectly matches the required performances.

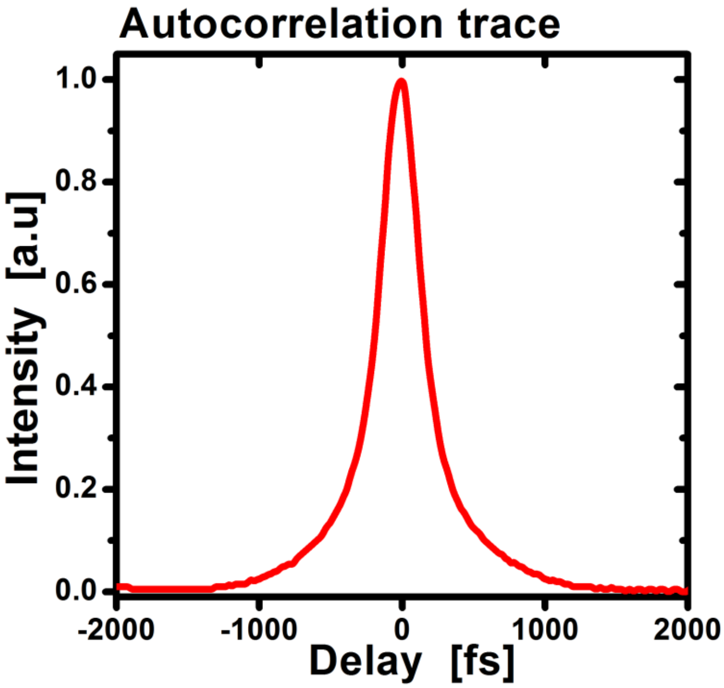


Figure 3 : Autocorrelation trace of the compressed pulses at 2 W of output average power

Figure 3 shows the autocorrelation obtained at 2 W and 40 MHz repetition rate. The autocorrelation FWHM is 370 fs, and its shape is slightly Lorentzian. This reveals the presence of (a theoretically predicted) remaining third order dispersion. This shape is typical from the remaining third order phase that originates from the dispersion mismatch between the stretcher (dominated by the dispersion of the delivery fiber) and the compressor of the laser.

Since any energy contained outside the main pulse is unavailable for frequency conversion, we used an SHG-FROG measurement to retrieve the intensity profile of the pulse and quantify the energy located in the post-pulses. Figure 4 shows the intensity profile retrieved from the SHG-FROG. The pulse FWHM is 277fs. As discussed in the previous paragraph, we see a clear temporal signature of a third order remaining phase. Hence, a series of post-pulses is clearly visible in Figure 4. The main pulse contains 85.3 % of the total energy which gives a measured peak power of 0.154 MW at 2W and 40 MHz.

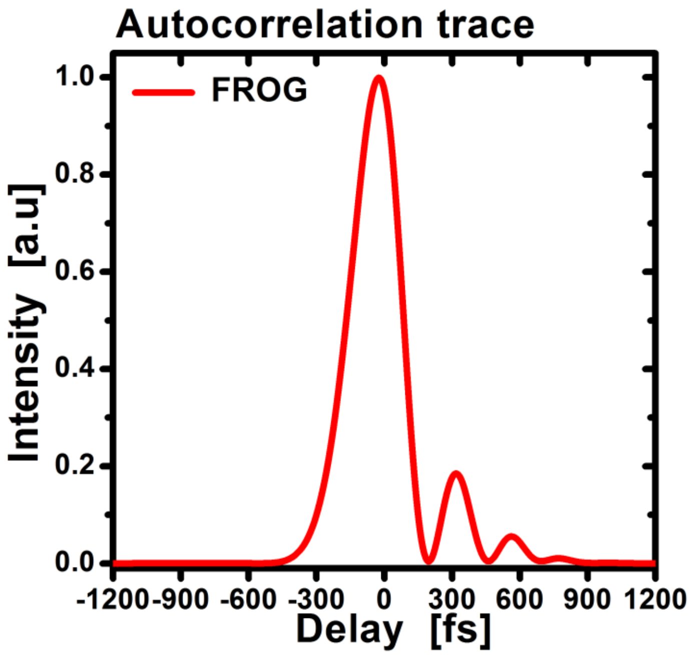


Figure 4 : SHG-FROG retrieved pulse duration of the laser

5.2 FREQUENCY CONVERSION IN THE UV

We then consider sufficient generation of UV. The requested wavelength necessary for the DASEL project requires the 1030nm output from the amplifier be converted by fourth harmonic generation to UV. However, the generation of FHG with the low peak power pulses is challenging. Simulation of the conversion processes reveals that SHG in a type-I 4mm-long LBO crystal followed by FHG in a 3mm-long type-I BBO crystal is the most promising approach to generate the UV radiation required.

To achieve sufficient intensity in the crystals, beam propagation from the laser has to be carefully managed. Figure 5 shows the beam propagation from the laser output to the waist location around which the nonlinear crystals will be placed. Considering the propagating beam at 1030nm, the simulation shows a waist located at 350mm with a Rayleigh length of 3.6mm. We carefully matched focus diameter and Rayleigh length with the correct crystal length for best conversion. For example, considering the beam at 515nm, the resulting Rayleigh length is 7.1mm. The waist is 120µm in diameter, and the position of LBO and BBO crystal is shown in green and blue, respectively.

Figure 6 shows the evolution of the SHG and FHG power with respect to the IR laser average power. The SHG average power has been measured after two dichroic mirrors (HT1030nm HR515nm). The SHG efficiency plot shows a monotonic increasing behavior. The maximum efficiency of 25% is consistent with our simulation and is limited by the temporal quality of the IR pulse but should be sufficient for the subsequent FHG conversion. The FHG efficiency behavior is positively monotonic along all the characteristic range of the laser. The average FHG power has been detected after three mirrors (HR 257nm HT 515nm+1030nm). This result, in connection with what has been said for the SHG, represents the optimum FHG efficiency available with the demonstrated focusing optics configuration. An average power of 43mW at 257nm for 2W of IR power was measured and corresponds to a 2.1% of efficiency. This value completely satisfies the goal in terms of FHG power.

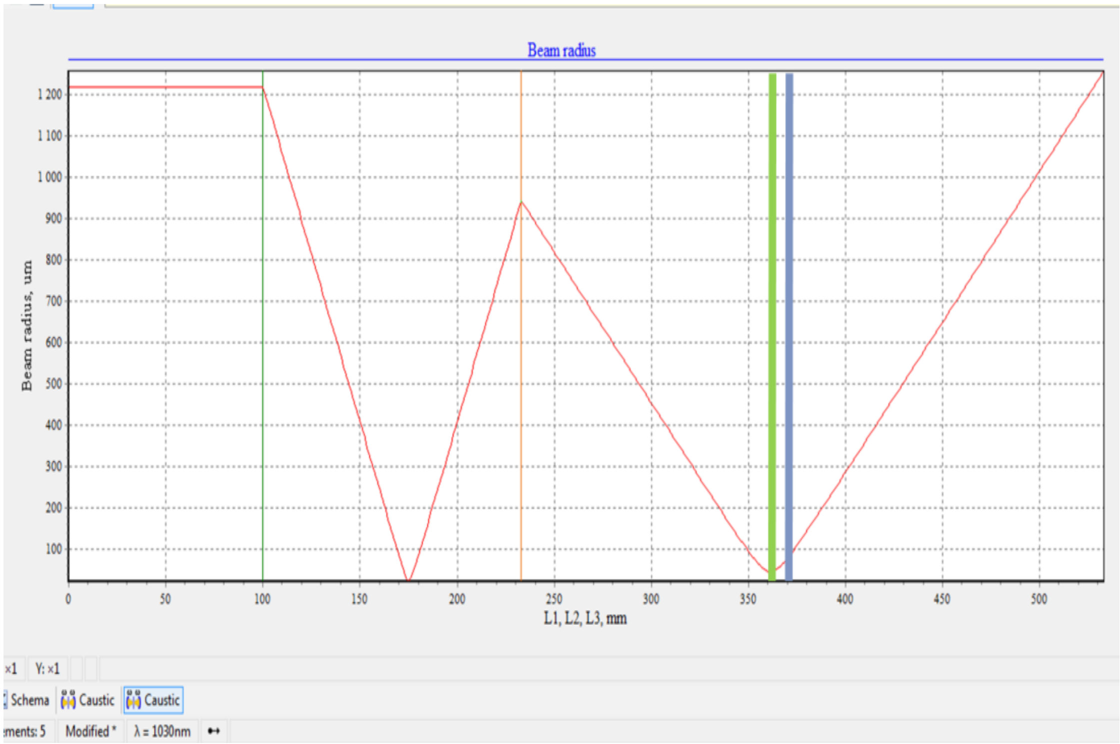


Figure 5 : Beam propagation from the laser to the FHG frequency conversion stage. Green line is the LBO position, blue the BBO position.

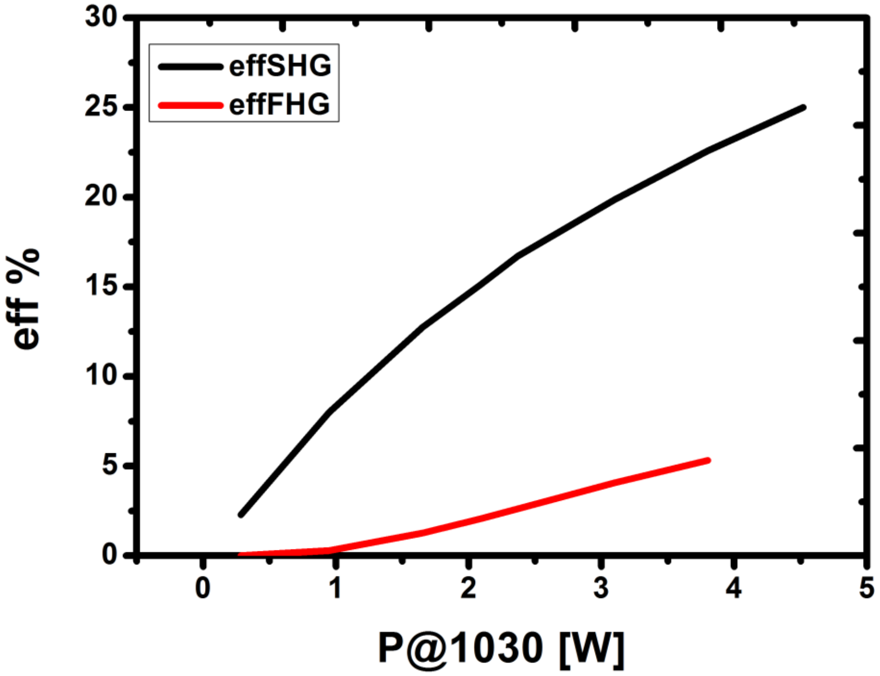
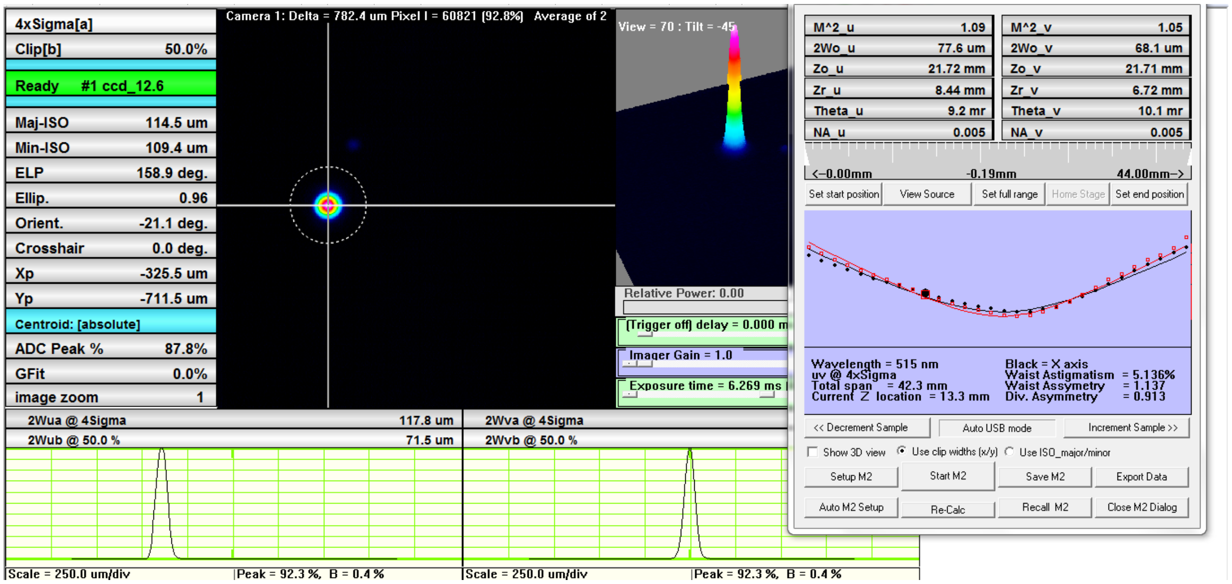


Figure 6 : Efficiency plot of SHG (black) and FHG (red) respect to 1030nm average power.



4xSigma[a]
Clip[b] 50.0%
Ready #1 ccd_12.6
Maj-ISO 114.5 um
Min-ISO 109.4 um
ELP 158.9 deg.
Ellip. 0.96
Orient. -21.1 deg.
Crosshair 0.0 deg.
Xp -325.5 um
Yp -711.5 um
Centroid: [absolute]
ADC Peak % 87.8%
GFit 0.0%
image zoom 1

Camera 1: Delta = 782.4 um Pixel I = 60821 (92.8%) Average of 2
View = 70 : Tilt = -45
Relative Power: 0.00
(Trigger off) delay = 0.000 m
Imager Gain = 1.0
Exposure time = 6.269 ms

2Wua @ 4Sigma 117.8 um
2Wub @ 50.0 % 71.5 um
2Wva @ 4Sigma
2Wvb @ 50.0 %
Scale = 250.0 um/div
Peak = 92.3 %, B = 0.4 %
Scale = 250.0 um/div
Peak = 92.3 %, B = 0.4 %

M^2_u	1.09	M^2_v	1.05
2Wo_u	77.6 um	2Wo_v	68.1 um
Zo_u	21.72 mm	Zo_v	21.71 mm
Zr_u	8.44 mm	Zr_v	6.72 mm
Theta_u	9.2 mr	Theta_v	10.1 mr
NA_u	0.005	NA_v	0.005

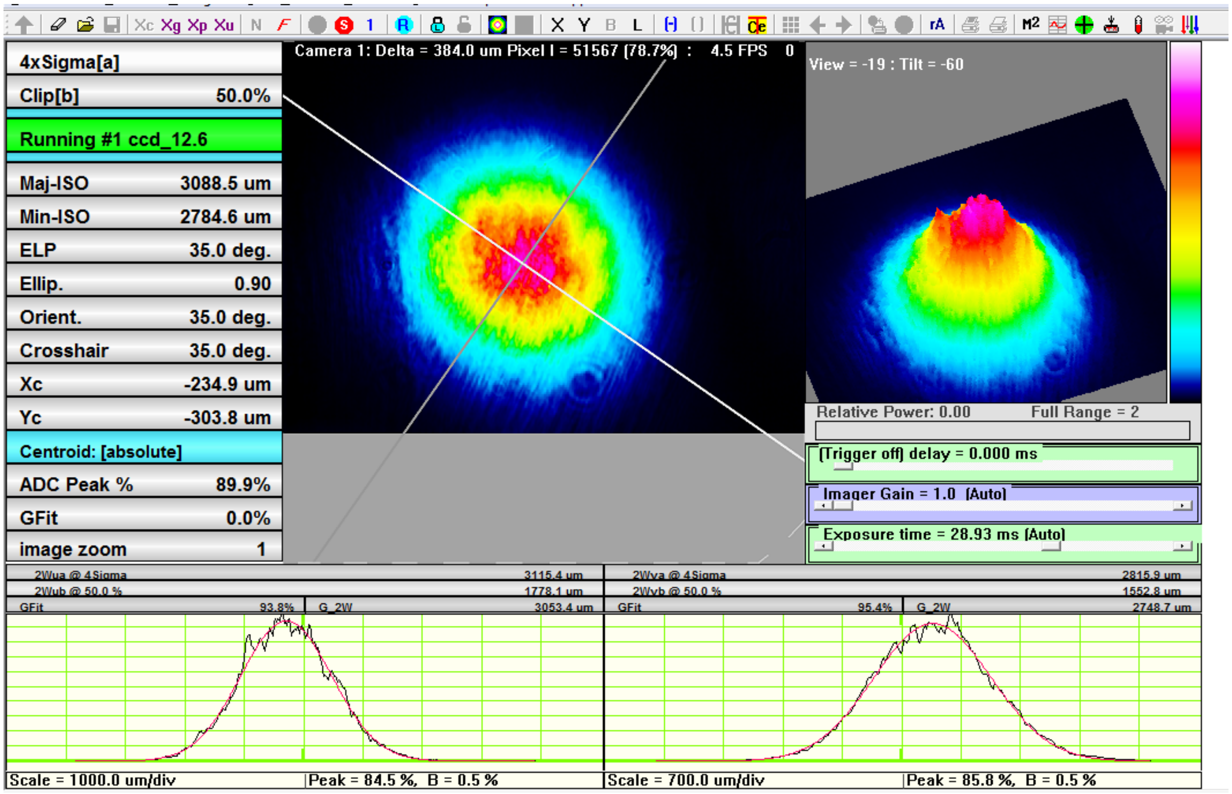
<–0.00mm -0.19mm 44.00mm–>

Wavelength = 515 nm
uv @ 4xSigma
Total span = 42.3 mm
Current Z location = 13.3 mm

Black = X axis
Waist Astigmatism = 5.136%
Waist Assymetry = 1.137
Div. Asymmetry = 0.913

☐ Show 3D view ● Use clip widths (x/y) ○ Use ISO_major/minor

Figure 7: M2 measurement for the SHG beam.



4xSigma[a]
Clip[b] 50.0%
Running #1 ccd_12.6
Maj-ISO 3088.5 um
Min-ISO 2784.6 um
ELP 35.0 deg.
Ellip. 0.90
Orient. 35.0 deg.
Crosshair 35.0 deg.
Xc -234.9 um
Yc -303.8 um
Centroid: [absolute]
ADC Peak % 89.9%
GFit 0.0%
image zoom 1

Camera 1: Delta = 384.0 um Pixel I = 51567 (78.7%) : 4.5 FPS 0
View = -19 : Tilt = -60
Relative Power: 0.00 Full Range = 2
(Trigger off) delay = 0.000 ms
Imager Gain = 1.0 (Auto)
Exposure time = 28.93 ms (Auto)

2Wua @ 4Sigma 3115.4 um
2Wub @ 50.0 % 1778.1 um
GFit 93.8% G_2W 3053.4 um
2Wva @ 4Sigma 2815.9 um
2Wvb @ 50.0 % 1552.8 um
GFit 95.4% G_2W 2748.7 um
Scale = 1000.0 um/div
Peak = 84.5 %, B = 0.5 %
Scale = 700.0 um/div
Peak = 85.8 %, B = 0.5 %

Figure 8 : FHG Beam profile.

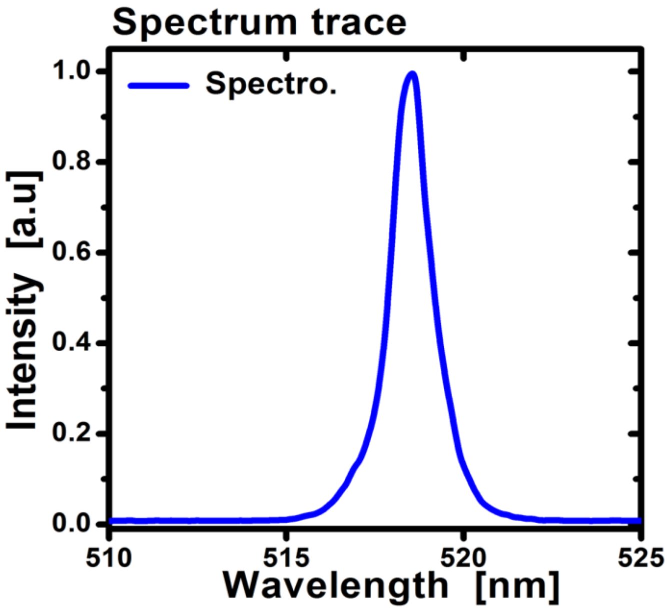


Figure 9: Typical spectrum after the SHG conversion

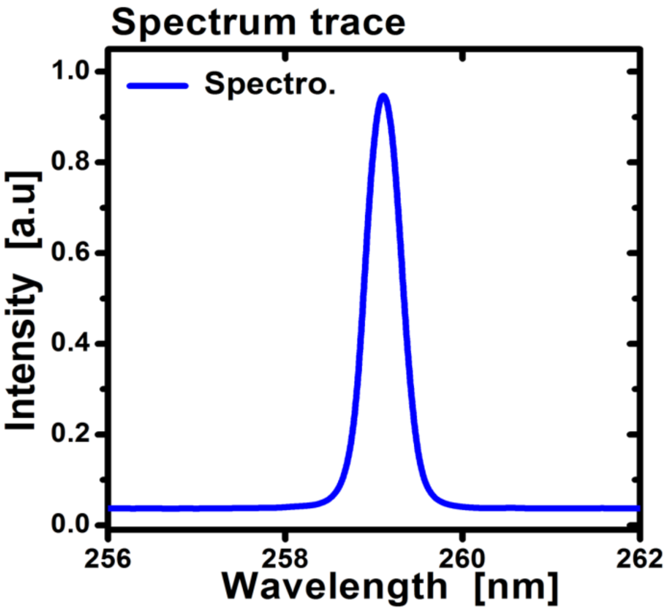


Figure 10: Typical spectrum after the FHG conversion

Figure 7 and 8 shows the beam profile of the SHG and FHG beams obtained. A Gaussian profile with an ellipticity of 0.90 is also maintained for the FHG beam. The measurement has been realized by taking a reflection from a wedge after the three dichroic mirrors used for the power measurement. A 257 nm-centered bandpass filter and a CCD camera (DataRay) have been used for imaging the beam profile.

Figure 9 and 10 also shows the optical spectrum of the SHG and FHG beams.

5.3 PULSE PICKING OF THE LASER

We also verified the ability to create a burst of pulses at the output of the laser. To do so, we implemented a fast AOM pulse picker based on a TeO_2 cell. Figure 11 shows the oscilloscope traces for a 600ns width defined burst. The rising

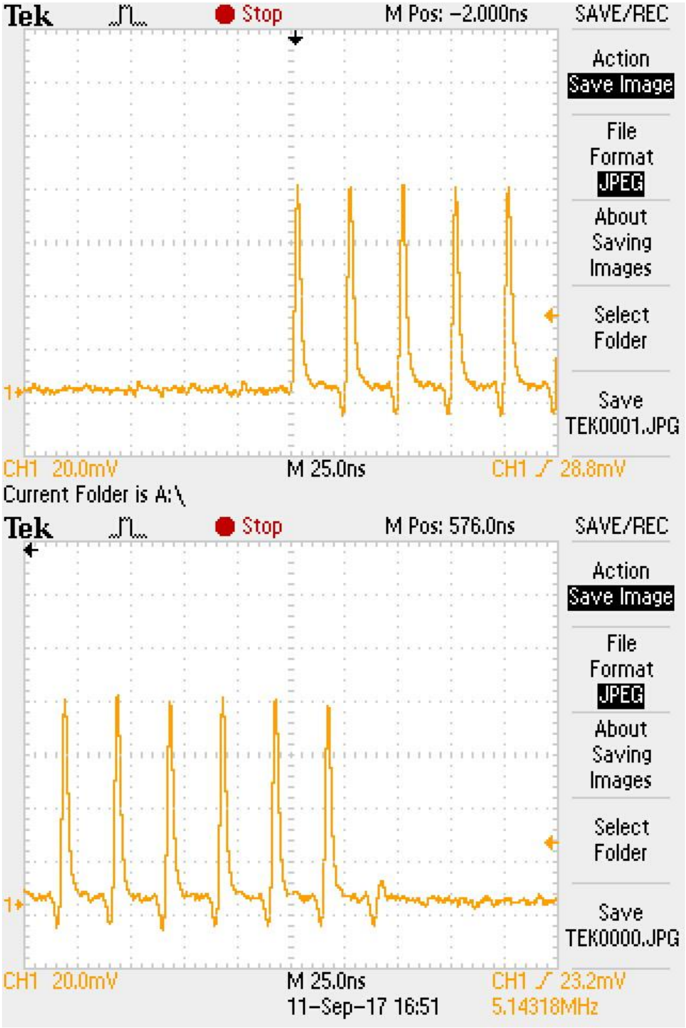


Figure 11. Top: Rising edge of the burst; Bottom: Falling edge of the burst.

and the falling edges are shown respectively. The rising and falling time of the AOM pulse picker are also sufficiently fast to form a clean burst of pulse without pre and post pulses.

A long term test did not reveal any damage of change in diffraction efficiency from th TeO2 AOM cell.

6 CONCLUSION

In conclusion, the tests conducted reveal that we can exceed the requirement for the DASEL project. We were able to generate >40 mW of fourth harmonics with ~2 W of IR average power. We have also shown that the use of a TeO_2 AOM pulse picker allows the creation of a burst of pulses with clean rising and falling edges.