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An ultrashort-pulse reconstruction software: GROG, applied to the FLAME laser system

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Summary. — The GRENOUILLE traces of FLAME Probe line pulses (60 mJ, 10 mJ after compression, 70 fs, 1 cm FWHM, 10 Hz) were acquired in the FLAME Front End Area (FFEA) at the Laboratori Nazionali di Frascati (LNF), Instituto Nazionale di Fisica Nucleare (INFN). The complete characterization of the laser pulse parameters was made using a new algorithm: GRenouille/FrOG (GROG). A characterization with a commercial algorithm, QUICKFrog, was also made. The temporal and spectral parameters came out to be in great agreement for the two kinds of algorithms. In this experimental campaign the Probe line of FLAME has been completely characterized and it has been showed how GROG, the developed algorithm, works as well as QuickFrog algorithm with this type of pulse class.

1. – Introduction

The knowledge of the pulse parameters in both temporal and spectral domain is essential for studying many physical processes like: photo-dissociation that is more efficient in the case of using chirped pulse; non-linear processes like self-focusing (SF), self-phase modulation (SPM) and others which modify the laser beam parameters and so on. Moreover, the complete characterization of this type of pulses is useful to test the theoretical models about the laser physics and to succeed in the possible production of even shorter pulses. One of our major interest in the characterization of ultrashort high-power laser pulses is the valuation of the pulse temporal shape (presence of pedestal, pre-pulses, etc.) for the employment of this type of pulses in the plasma physics experiments related to the inertial confinement fusion (ICF, [1]), laser plasma acceleration (LPA, [2, 3]), and other applications. The characterization of the ultrashort high-power laser pulses has always been a challenge. It requires using the same pulse to measure itself, because a shorter event to compare it to does not exist. Moreover, there are many other difficulties to

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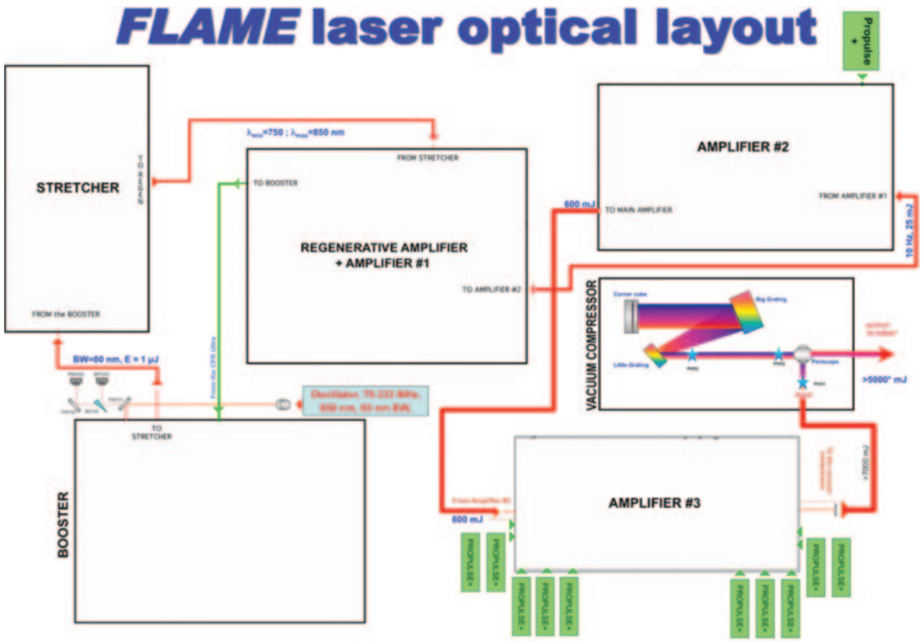

Fig. 1. – FLAME experimental set-up, taken from the web site `http://ilil.ino.it/flame/`.

take into account, for example those related to the pulse itself to characterize (non-linear effects, distortion, tilt, etc.) and the complexity of the diagnostic tool set-up required to perform the measurements. One of the most promising and exploited techniques for the complete characterization of the ultrashort laser pulses is GRating-Eliminated No-nonsense Observation of Ultrafast Incident Laser Light E-fields (GRENOUILLE) [4], whose set-up is much simpler than popular techniques like Frequency-Resolved Optical Gating (FROG) [5-8] and others. GRENOUILLE is considerably sensitive, extremely easy to set-up (reducing the optical elements) and to align (it is already spatially and temporally aligned on the contrary of other tools). It is based on the FROG technique, a spectrally resolved autocorrelation, in respect to which the experimental configuration provides simple changes. The simplification of the pulse splitting and of the recombination line is obtained by replacing the structure beam splitter (BS) - delay line (DL) - optical recombination of the two pulse copies (OR) with a Fresnel biprism and the easiness to generate the GRENOUILLE trace (GRENOUILLE measurement) is obtained by replacing the thin crystal for the second harmonic generation (SHG) and the related spectrometer with a thick crystal. This last choice also has the advantage of reaching a more intense SHG signal because it depends on the thickness of the crystal frequency doubler according to the dependence $S \sim L^2$. At the end of the diagnostic tool set-up, the output trace is acquired by a CCD camera. It provides a spectrally resolved autocorrelation that involves temporal and frequency resolution simultaneously. In order to retrieve the pulse parameters from the GRENOUILLE traces, we employ an algorithm based on the 1-D conjugate gradient minimization method [9-11], instead of other algorithms [5] like: the Basic Frog algorithm [7, 8, 12]; General Projection algorithm [5, 13]; Composite algorithm [13, 14] or commercial software (like Quick Frog or Video Frog). The reason for this choice is because of many problems related to: i) the algorithm convergence, ii) the convergence velocity and iii) the capability to work with single shot. This innovative pulse software [9] for the laser diagnostics is based on the acquisition of an experimental image, which is subtracted from the background, calibrated and rescaled before being used in the reconstruction program. At this point, the experimental trace can be compared to the calculated analytic image produced by starting from an arbitrary reasonable pulse field as initial guess. Using a suitable algorithm that proposes to vary at each step the initial arbitrary pulse, we minimize the distance between the two images, finally succeeding in obtaining a reconstructed pulse as similar as possible to the real one. The software has been validated on experimental images acquired in the laser Vulcan Front End (Low Power) at the Central Laser Facility (CLF) at Rutherford Appleton Laboratory (RAL). Afterwards the same measurements have been performed in the Target Area Petawatt (TAP), with the laser Vulcan (400 J, 400 fs, one shot per 10 min; in our studied case 10 μJ, 1 ps, 2 Hz) at full power [10, 14] and in the Gemini Target Area (GTA), with the Gemini laser at full power (15 J, 30 fs, one shot per 20 s) [12]. In this paper we present a complete characterization of the FLAME Probe line pulses using the GROG algorithm; employing the line as a probe line in the acceleration experiments performed, we needed to know all the pulse parameters. Moreover, we present a comparison between the characterizations of the laser pulse parameters retrieved by using two different types of algorithms: a multi-shot one, QUICKFrog, and a single-shot one, GROG. The temporal and spectral parameters came out to be in great agreement for the two type of algorithms. GROG, this developed algorithm, works as well as the previous one. The advantage of working in single-shot is underlined when one integrates the diagnostic on a low repetition rate laser as Vulcan and Gemini at CLS, RAL.

2. – Description: FLAME Front End Area experimental set-up and data acquisition

The FLAME laser is based upon a Ti:Sa, chirped pulse amplification (CPA) system that will deliver 35 fs up to 300 TW laser pulses with a 10 Hz repetition rate at a fundamental wavelength of 800 nm. The system features a high, sub-ns contrast ratio ($> 10^{10}$) and has a fully remotely controlled operation mode. The system includes a front-end with pulse contrast enhancement (booster), bandwidth control and regenerative amplifier and yields pulses with 0.7 mJ in 80 nm bandwidth. These pulses are then further amplified by the first amplifier to the 25 mJ level while the second amplifier brings the energy to the 600 mJ level. The third cryogenic amplifier is based upon a 50 mm Ti:Sa crystal pumped by 10 Nd:YAG lasers for a total of up to 20 J of energy. The extraction energy is as high as 35%, leading to a final energy in the stretched pulses in excess of 7 J. Pulses are then transported in air to the vacuum compressor placed in the underground target area. Once compressed, the pulse in transported under vacuum to the target chamber. A schematic layout of the laser system is given in fig. 1.

A fraction of the main beam is sampled after the second amplifier by a 10% beam splitter. The Probe line pulses have the following characteristics: an energy of 60 mJ, a temporal length of about 70–80 fs, a beam radius of about 1 cm and a repetition rate of 10 Hz. The diagnostic measurements of the pulse paramenters have been made after the amplifier and the compressor. The laser beam after the optical compressor propagates in air. The use of mirrors allows to direct the beam towards the diagnostic, in our case the GRENOUILLE one, as we can see in fig. 2.

Figure 3 reports one of the modified Probe line traces, previously taken with the GRENOUILLE tool.

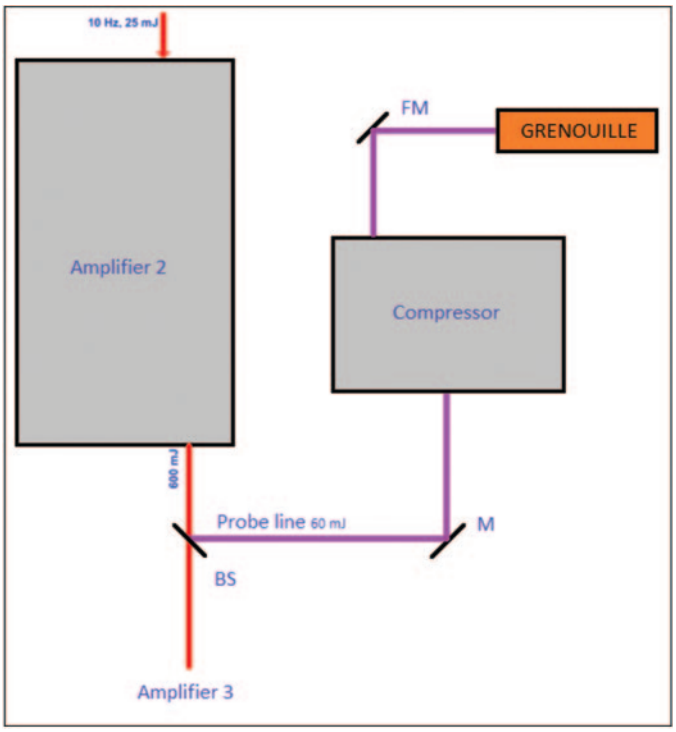

Fig. 2. – FLAME Probe line diagnostic experimental set-up. BS: beam splitter, M: mirror, FM: flip mirror.

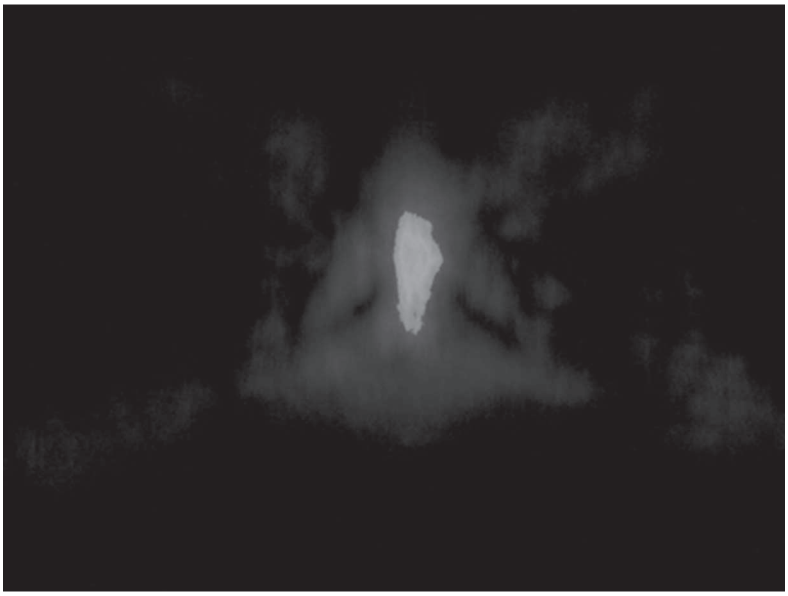

Fig. 3. – Modified FLAME Probe pulse GRENOUILLE trace.

3. – Data processing of FLAME Probe line pulse

The GRENOUILLE trace is analysed by the above-mentioned reconstruction software. The analysis carried out allows to obtain the intensity and phase in both temporal and spectral domains and the χ^2 distance that indicates the difference between the pixel values of the input experimental trace and the reconstructed one. The GRENOUILLE images were reconstructed taking as the initial possible guess of the pulse electric field:

$$E(t) = e^{-\frac{t}{B}^2} e^{-iat^2},$$

with the parameters a (Gaussian second-order temporal phase) and B (Gaussian FWHM) reported in table I.

In fig. 4 the reconstructed image corresponding to the experimental GRENOUILLE trace, showed in fig. 2, is reported.

We can see that the reconstruction does not reproduce faithfully all the little structures appearing in the corresponding experimental image. However, one has to note that the experimental image does not appear to be symmetrical, as it should be for the GRENOUILLE images. This discrepancy may be due to the presence of chromatic aberrations of the beam and/or to the problem connected to the optical system. In any case, the analysis program can extract the useful signal component from the experimental image, thanks to the research of maximum similarity between the experimental and the simulated image. In figs. 5 and 6 we present the intensity and the phase in both temporal and spectral domain retrieved by our algorithm, GROG.

One can note that the temporal and spectral phase are treated with the unwrapping scheme and they are not constant, which is the proof of a non-perfect pulse compression. As predicted by the theory the temporal and spectral phase have opposite trends about the maximum value of the intensity and spectrum, respectively. We report the temporal and spectral length in table II.

Furthermore, we installed a commercial software QUICKFrog and we made also the complete characterization with it. Here we present the comparison between the results by the two types of algorithm QUICKFrog and the developed one. We report the snapshots of the QUICKFrog measurements in figs. 7 and 8 in both the temporal and spectral domains.

TABLE I. – *Initial Values of B (temporal length) and a (quadratic phase) for the Gaussian shape used in the analysis of the Gemini pulses.*

	Temporal domain	
B	$\dfrac{\sqrt{2}\text{par}_{\text{sample}}\Delta_{\text{pix}[t]}}{2.355} =$	$= 203.352$
Temporal calibration	$\text{par}_{\text{sample}} =$	$= 4.58\,\frac{\text{fs}}{\text{px}}$
Temporal pixel length	$\Delta_{\text{pix}[t]} =$	$= 74\,\text{px}$
	Spectral domain	
a	$\dfrac{\Delta_{\text{pix}[s]}\text{ss}_{\text{fft}}B}{2.355\sqrt{2}B^2} =$	$= 188384 \times 10^{-9}$
Spectral calibration	$\text{ss}_{\text{fft}} =$	$= 1.33972 \times 10^{-3}\,\frac{\text{rad}}{\text{fs px}}$
Spectral pixel length	$\Delta_{\text{pix}[s]} =$	$= 96\,\text{px}$

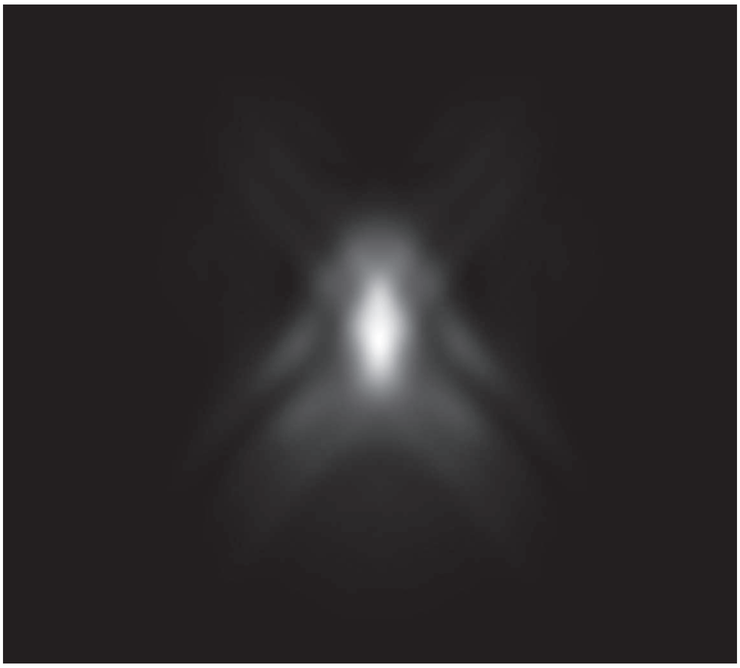

Fig. 4. – Reconstructed GRENOUILLE trace corresponding to fig. 3.

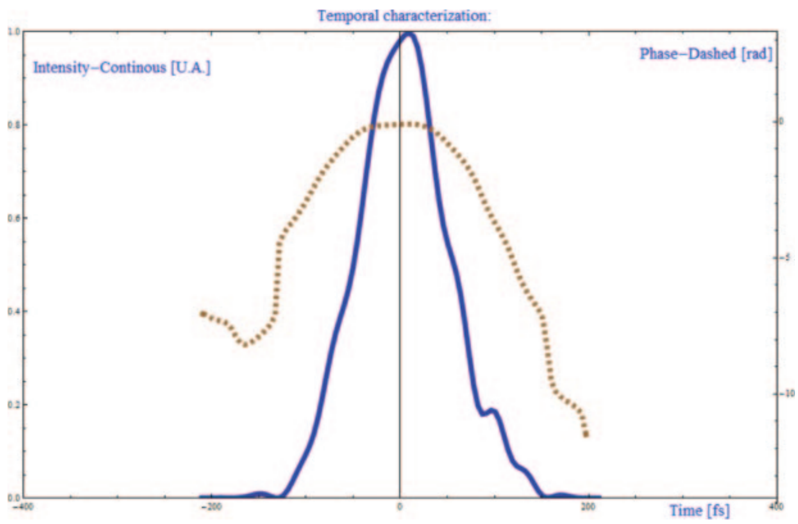

Fig. 5. – Intensity and phase in the temporal domain retrieved by GROG.

TABLE II. – *Values of FWHM length in both domains for the "Gaussian" shape.*

Temporal length	77.86 fs
Spectral length	13.45 nm

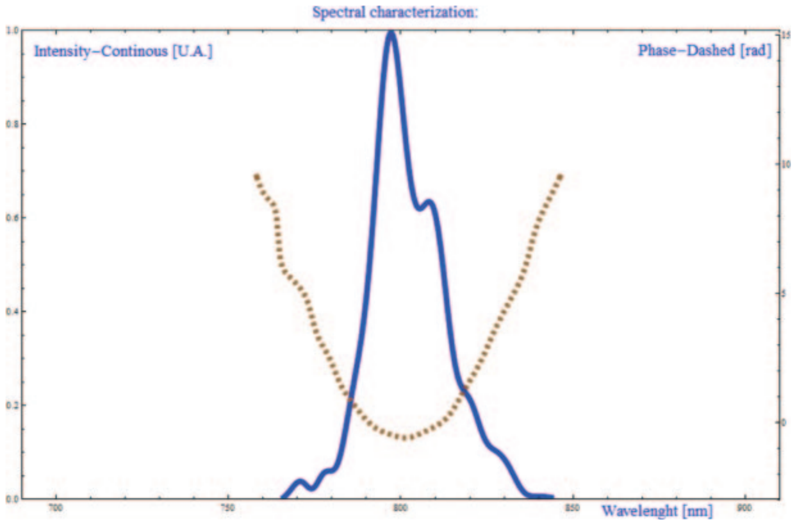

Fig. 6. – Intensity and phase in the spectral domain retrieved by GROG.

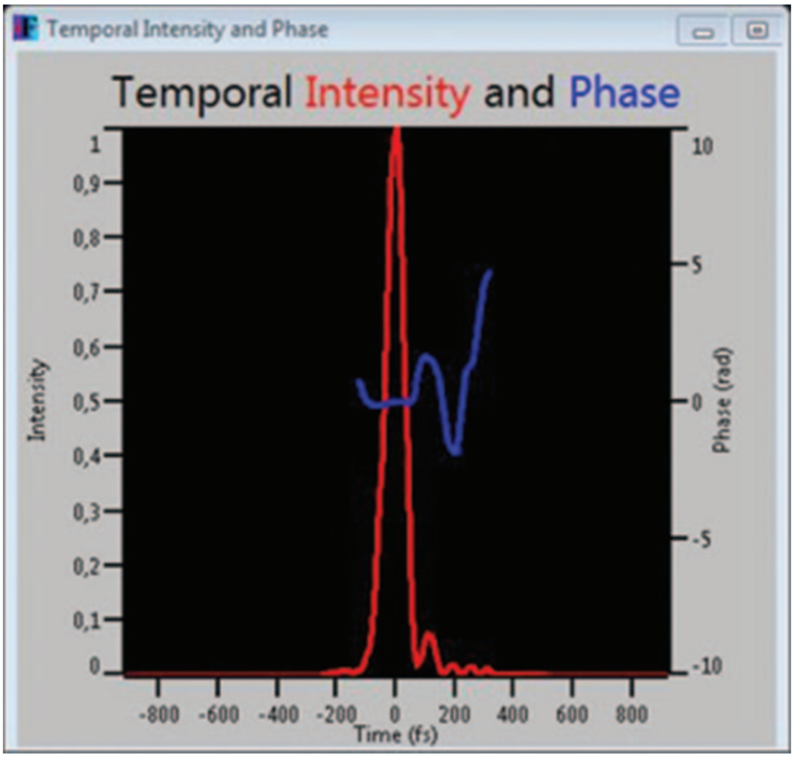

Fig. 7. – Intensity and phase in the temporal domain retrieved by QUICKFrog.

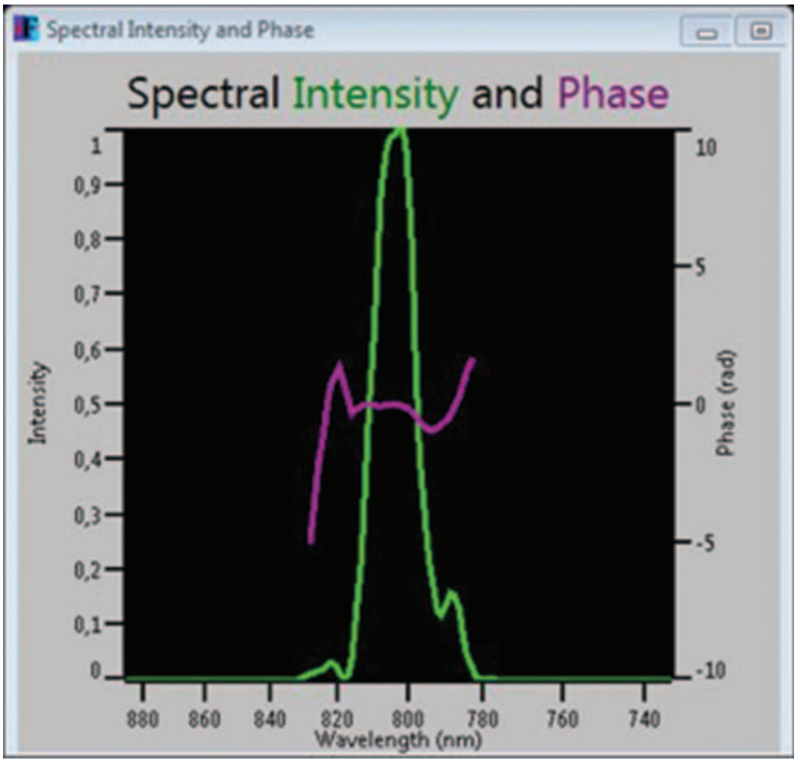

Fig. 8. – Intensity and phase in the spectral domain retrieved by QUICKFrog.

At the same time, also in the retrieved QUICKFrog one can see the presence of a non-constant phase in time, which is an evidence of a non-perfect pulse compression. As predicted by the theory the temporal and spectral phases have opposite trend about the maximum value of the intensity and spectrum, respectively. The retrieved QUICKFrog temporal length (Full Width Half Maximum - FWHM) is 77.86 fs while the reconstructed temporal length (FWHM) by the developed algorithm is 73.50 fs (fig. 6, table II). The retrieved QUICKFrog spectral length (FWHM) is 13.45 nm while the reconstructed spectral length (FWHM) is 13.35 nm (fig. 6, table II). The results show an excellent agreement between the two types of measurements, summarized in table III.

4. – Conclusion and perspectives

From the analysis of the experimental GRENOUILLE traces [10, 11, 15] it was verified that the software program is reliable and it is able to completely reconstruct the

Table III. – *Measurements with the two different diagnostic software.*

Diagnostic software	GROG	QUICKFrog
Temporal length	77.86 fs	73.50 fs
Spectral length	13.45 nm	13.35 nm

ultrashort pulse in a fast and accurate way. Analysing the results of the QUICKFrog and those of GROG, relative to the estimation of the intensity and the phase, we note that the obtained lengths in both domains are comparable so as validating the accuracy of the characterization of ultrashort pulses by the software developed. After this experimental campaign, we have an accurate characterization of the FLAME Probe line and of the Main line (this will be presented in a future article [16]) so now we know with which pulses we will be dealing during the LPA experiments that will be done at LNF with the FLAME laser. In the near future the analysis will be extended to other data taken at full power related to laser pulses and also to Free-Electron Laser (FEL) pulses [17], implementing some modifications to the presented algorithm. The implementation of functions analysing information derived by other diagnostic tools (Spider [18], Spectrum [6], Auto-Correlation [6], Transient-Gradient FROG (TG FROG) [19,20], etc.) will permit us to obtain more reliable and precise pulse complete characterization. Furthermore, the improved algorithm can be made faster and it could be used to make on-line measurements really useful for plasma physics experimental campaigns that will be unrolled at the CLF facilities at the Rutherford Appleton Laboratory (RAL, Oxford) and at the INFN Laboratori Nazionali di Frascati (LNF, Rome).

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