A FEMTOSECOND RESOLUTION ELECTRO-OPTIC DIAGNOSTIC USING A NANOSECOND-PULSE LASER

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Abstract

Electro-optic diagnostics with a target time resolution of 20fs RMS, and with intrinsically improved stability and reliability, are being developed. The new system is based on explicit temporal measurement of an electro-optically upconverted pulse, following interaction of the bunch with a quasi-CW probe pulse. The electro-optic effect generates an "optical-replica" of the longitudinal charge distribution from the narrow-bandwidth probe, simultaneously up-converting the bunch spectrum to optical frequencies. By using Frequency Resolved Optical Gating (FROG), an extension of autocorrelation, the optical replica can then be characterised on a femtosecond time scale. This scheme therefore bypasses the requirement for unreliable femtosecond laser systems. The high pulse energy required for single-shot pulse measurement via FROG will be produced through optical parametric amplification of the optical-replica pulses. The complete system will be based on a single nanosecond-pulse laser – resulting in a reliable system with greatly relaxed timing requirements.

INTRODUCTION

Electro-optic (EO) techniques have for some time held the promise of high time resolution non-destructive bunch longitudinal profile diagnostics. A range of EO diagnostic systems has been developed and demonstrated, such as Spectral Decoding [1], Spatial Encoding [2], Temporal Decoding [3], and Spectral Upconversion [4], although all have the same underlying physical principle of encoding the temporal or spectral information of the bunch profile into an optical signal via the second order non-linear (EO) interaction. Despite the large number of demonstrations of EO diagnostic concepts, there are only a very limited number of examples of EO diagnostics being integrated into operational accelerator diagnostic systems [5-7]. This can at least partially be attributed to the increasing demands for the time resolution, now reaching down to the sub 10 fs level for FELs, which remain beyond state-of-the-art EO systems. Where lower, demonstrated, time resolutions are acceptable, there is also a significant barrier to operational implementation due to the complexity and reliability of the ultrafast laser systems that have until now been necessary.

Here we describe the development of a new variant of EO diagnostic, which we term 'Electro-Optic Transposition' (EOT) [8], that has the potential for both high time resolution and robust implementation. The system requires no ultrafast lasers and can be based on narrowband nanosecond lasers that have reached a mature level of 'industrial' reliability. The development described here relates to the laser system and optical characterisation. For higher time resolution, a parallel improvement in EO materials is also required, and while not described here this is the subject of a separate research project in our group.

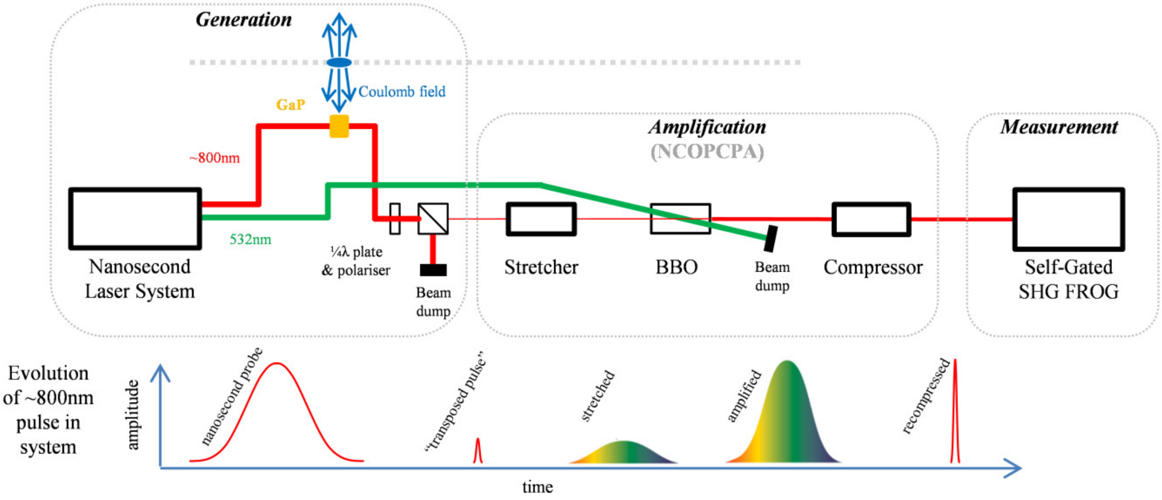

Figure 1: Schematic of the electro-optic transposition system. The system can be considered as 3 separate stages: generation of the optical probe and subsequent up-converted signal pulse; amplification of the signal pulse to a level that can be characterised, and finally measurement of the signal to reveal its temporal structure.

The general principle is shown in Fig. 1. A narrow bandwidth, long duration laser probe interacts with the bunch Coulomb field, preferably within the beamline. In this context the electro-optic effect is best described as a process of sum-frequency and difference-frequency mixing between the Coulomb field pulse and the optical probe, resulting in Spectral Upconversion as detailed in [9]. The direct measurement of the upconverted spectrum provides significant information about the bunch profile, but as with other spectral measurements such as CTR spectra [10] and Smith Purcell [11] measurements, lacks the phase information for an unambiguous temporal profile. However, the upconverted optical signal also contains sought after temporal information, with the optical temporal envelope following the Coulomb field time profile. To measure this time profile, our proposed system uses Frequency Resolved Optical Gating (FROG), an established laser technique which allows unambiguous retrieval of the optical pulse envelope with resolution better than 10 fs [12, 13]. As the FROG measurement will be a self-referenced spectrally resolved autocorrelation, it requires no additional ultrafast lasers and is inherently insensitive to timing jitter. This enables the technique to be used for characterising very weak, high repetition rate pulses (bunches) having a significant timing jitter that prevents their measurement in another way. For single-shot diagnostics however, a signal pulse energy of significantly greater than >10 nJ is required, dependent on pulse profile. Such optical signal pulse energies are not realistically achievable directly from the EO process, due to both EO material damage limitations and reasonable constraints on the input probe pulse. To overcome this problem, our scheme includes an integrated optical amplification stage for the signal; the amplification stage is driven by the same nanosecond laser system that produces the input probe, maintaining the overall laser system robustness and expected system reliability.

A complete prototype system has been designed with a resolution approaching 50 fs FWHM. Referring to Fig. 1, the base laser system is a robust Q-switched Nd:YAG with frequency-doubled 532 nm output of 10 ns duration and >10 mJ energy. Part of this pulse will be used to pump an integrated optical parametric oscillator, producing a narrow line-width (<1 cm^{-1}) pulse at ~830 nm with an energy of around 1 mJ, which is to be used as the probe wave. The remaining Nd:YAG 532 nm output will pump post-interaction optical parametric amplification, raising the signal levels to that necessary for single-shot FROG.

The design has been informed and confirmed by experimental tests on the upconversion efficiency and the non-collinear amplification gain and bandwidth, results of which are presented.

SYSTEM DESIGN & VERIFICATION

Optical Upconversion and EO Transposition

In order to verify and examine various stages of the system design, a test bed has been built around a regeneratively amplified femtosecond Ti:Sapphire laser-driven terahertz source. In this system, shown schematically in Fig. 2, terahertz pulses were emitted from a large area photoconductive antenna (PCA) [14] excited by the ultrafast Ti:Sapphire pulses, providing a pulsed field as a mimic of the bunch Coulomb field. In our setup, peak THz electric field strengths of up to ~130 kV/m were available. A synchronised narrow bandwidth optical probe was obtained by spectrally filtering a fraction of the 50 fs, 800 nm pulses that excited the PCA. The spectral filter was tunable in both bandwidth and wavelength, and was free from angular, spatial and temporal chirp. Transform limited 10 ps pulses were used for the narrow band probe results described here, with the pulse duration verified via autocorrelation.

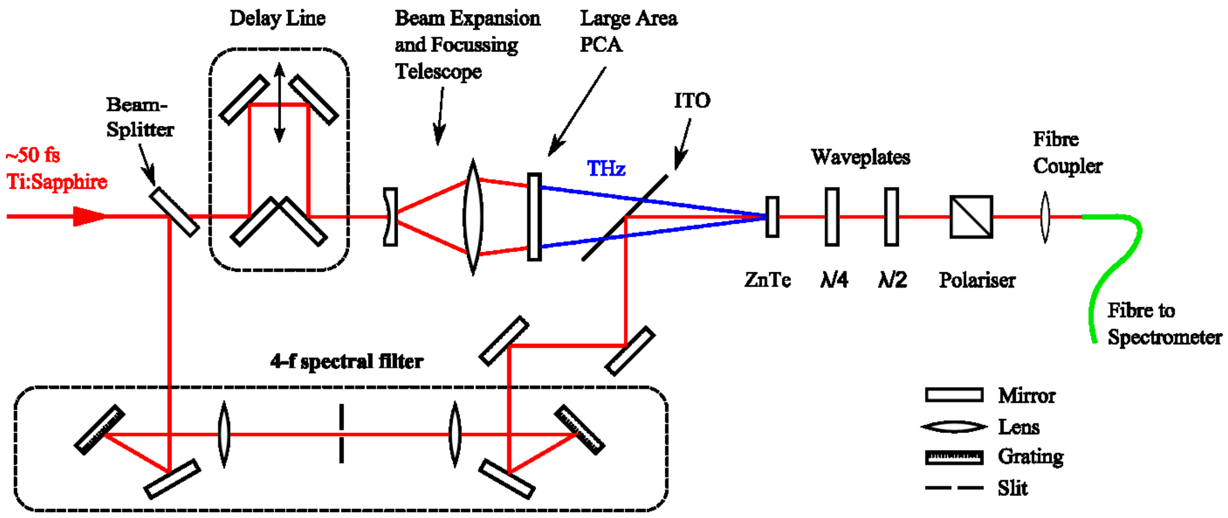

Figure 2: Experimental arrangement for the lab-based testing of efficiency of Spectral Upconversion, the first stage of the EO Transposition scheme.

To generate an electro-optically transposed pulse, the optical probe was mixed with the terahertz pulse in a 4mm thick ZnTe crystal; the higher bandwidth response achievable with alternative EO materials was not necessary because of the ~3 THz bandwidth of the PCA emission. The electro-optically transposed pulses were then separated from the input probe through polarisation selection, and coupled into a spectrometer for analysis via an optical fibre. In this system the spectral filter could be fully opened to allow the 50 fs pulses through, allowing a conventional terahertz time domain spectroscopy (THz-TDS) measurement of the pulse temporal profile, and hence spectrum, to be taken as a reference.

Figure 3 shows the electro-optically transposed spectrum obtained with a narrow bandwidth probe, with and without the THz pulse Coulomb field mimic. The terahertz spectrum is closely replicated in the optical domain as sidebands on the probe, with the fundamental probe attenuated through polarisation rejection.

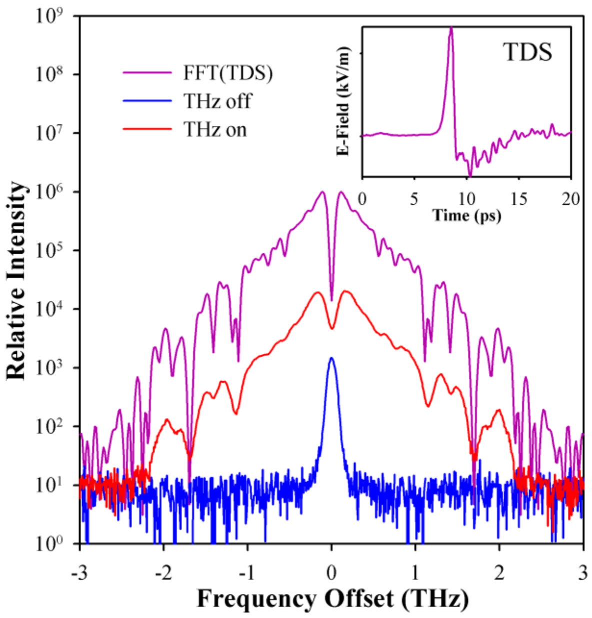

Figure 3: Sideband spectra as measured by EO upconversion, and as inferred from THz-TDS. The TDS spectrum has been offset to enable a clear comparison with the upconverted spectrum.

The spectrum retrieved via THz-TDS is also shown, and comparison verifies that the upconversion process is faithfully encoding the THz pulse. Measurements of the energy conversion efficiency in the electro-optically transposed pulse, combined with the properties of the rest of the system, have allowed us to estimate that for CLIC bunch parameters a transposed pulse energy of ~15 nJ should be produced for an input probe intensity of 100 kW (or 1 mJ in 10 nS). Similar levels are expected for FEL bunch parameters (say 200 pC in 200 fs or 20 pC in 20 fs).

Amplification

The electro-optically transposed pulse energy obtained directly from the EO interaction is insufficient for the implementation of a single-shot FROG [15]. Our system will use Non-Collinear Optical Parametric Chirped Pulse Amplification (NCOPCPA) to overcome this problem. NCOPCPA is a commonly used technique for the amplification of ultrashort pulses and is regularly used to amplify Fourier-transform-limited pulses by 6 or 7 orders of magnitude with minimal distortion.

In chirped pulse parametric amplification, efficient amplification of a sub-picosecond pulse by the few-nanoseconds duration parametric amplifier pump is achieved by stretching the seed pulse in time to improve pulse overlap. With a subsequent compensating pulse-compressor, the original input pulse duration can be regained post-amplification. Such temporal manipulation is readily achieved through the spectral dispersion induced by a pair of diffraction gratings. This non-collinear amplification geometry has an additional benefit of a broad bandwidth gain (in this case spanning ~60 THz), allowing for amplification of the spectral content associated with sub 10 fs duration pulses. An even broader bandwidth could be arranged at the expense of a greater phase distortion, but is unnecessary in this case.

For the EOT diagnostic, an NCOPCPA system based around a type 1 phasematched BBO crystal has been designed with the following parameters: crystal length 20 mm, crystal cut at 23.81° to the optic axis, pump to signal angle of 2.25°, and a pump wavelength 532 nm. The gain bandwidth is sufficiently large to amplify 8 THz bandwidth optical replica pulses, and to allow the system to be readily used for a broader bandwidth (shorter pulse) signal. The gain (G) for such an arrangement is easily calculated via

$$G = \cosh^2(\Gamma L) \tag{1}$$

where

$$\Gamma = \sqrt{\frac{2\omega_s \omega_i {d_{eff}}^2 I_p}{n_s n_i n_p \varepsilon_0 c^3}} \tag{2}$$

where ω_s and ω_i are the frequencies of the amplified wavelengths, d_{eff} is the effective nonlinear coefficient (~2pm/V), I_p is the pump intensity, L is the crystal length, ε_0 is the permittivity of free space, c is the speed of light, and n_s, n_i, and n_p are the refractive indices for the pump and amplified waves. When pumped with pulses of ~10 mJ and duration 10 ns with a beam diameter of 0.9 mm, the expected gain of an input pulse is greater than a factor of 1000.

The impact on the spectral phase of the amplified pulse must also be considered. In the general case where NCOPCPA is used to generate very high energy pulses, systems are often operated such that the energy of the

ISBN 978-3-95450-126-7

amplified pulse becomes large enough to cause a significant depletion of the pump pulse. In this regime the phase change induced through the nonlinear process is sensitive to the level of pump depletion, which is in turn sensitive to the amplitude jitter of the input pulses. However, it is possible to amplify without significant depletion, and in this situation the phase shift of the amplified pulse is quite insensitive to input pulse amplitude jitter. In the system we have designed the pulse will be amplified to ~1 μJ, sufficiently small when compared to the pump pulse energy of 10 mJ for the depletion induced phase distortion to be negligible. For this condition, where the pulse to be amplified is much smaller than the pump pulse, the spectral phase change (φ_s) is [16, 17]

$$\varphi_s = \frac{B\sin A\cosh B - A\cos A\sinh B}{B\cos A\cosh B + A\sin A\sinh B} \tag{3}$$

where

$$A = \frac{\Delta kL}{2}, B = \sqrt{(\Gamma L)^2 - \left(\frac{\Delta kL}{2}\right)^2} \tag{4}$$

Δk is the phase mismatch, and Γ is the nonlinear gain coefficient, and in this case is around 207 m^{-1}. The calculated phasematching bandwidth and phase distortion are shown in Fig. 4.

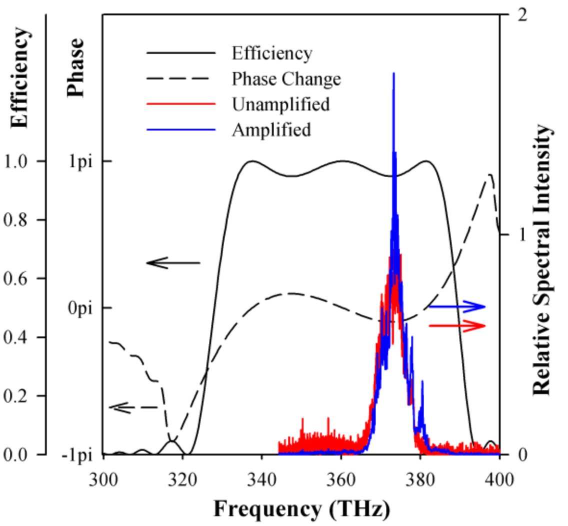

Figure 4: The spectra of a 50 fs FWHM 800 nm pulse before and after non-collinear parametric amplification superimposed on the phasematching efficiency and phase change. The “Amplified” trace depicts the spectrum of a 50 fs FWHM pulse that was first attenuated by 1000x using ND filters, and subsequently amplified back to the original level. The difference in background noise in the spectra is due to differing levels of signal averaging.

The gain and bandwidth of the amplification stage has been tested through its ability to amplify 50 fs FWHM pulses obtained directly from a synchronised Ti:Sapphire laser. In using the laser pulse directly the seed bandwidth is significantly larger than would be available from the signal generated by EO transposition of our PCA derived pulses, and better determines capability for sub 50 fs duration bunch diagnostics. The parametric amplification was generated in a single pass through a 20 mm long BBO crystal, as described in the previous section. As the goal was to confirm the gain and bandwidth, the stretcher and compressor were not implemented in these experiments. The amplifier was pumped by a custom-modified Continuum Leopard Nd:YAG laser delivering 532 nm pulses of 50 ps duration and up to 30 mJ energy. The Nd:YAG was seeded by a 50 ps Nd:YVO_4 oscillator which was synchronised with the Ti:Sapphire laser oscillator to approximately 300 fs. These pulses were attenuated to provide the same irradiance as a 10 mJ, 10 ns pulse of 0.9 mm diameter. Fig. 4 shows the pulse spectra before and after amplification, indicating that the bandwidth has been preserved and confirming that the technique has sufficient bandwidth as an EO transposition diagnostic with target time resolution of 20 fs rms. The predicted gain was verified by re-amplification of the 50 fs pulse to its original energy, as measured on a spectrometer and also a separate photodiode, after being attenuated by 1000x with calibrated ND filters.

CONCLUSIONS

We have described the underlying principles and layout of an electro-optic detection system that will be capable of measuring relativistic bunch longitudinal profiles in a non-destructive manner without the need for femtosecond laser systems. Experiments have been carried out to verify design parameters. A complete prototype, based on an industrial, reliable, nanosecond Nd:YAG laser is currently in the final stages of development.

ACKNOWLEDGMENTS

This work was conducted as part of an on-going project to develop an EO profile monitor suitable for characterising the 150 fs rms bunches of CLIC with a resolution approaching 20 fs rns. Funding was provided by CERN through CLIC Contract Number KE1865/DG/CLIC.

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