Envelope and phase reconstruction of ultra-short pump lasers by optical rectification measurements

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Abstract: THz radiation is of great interest for a variety of applications. Simultaneously with the demonstration of high-intensity THz sources the idea to use this radiation for particle acceleration started to be investigated. THz accelerating gradients up to GV/m have been demonstrated in laboratory. THz radiation can be generated through the optical rectification process induced in non-linear crystals by a pump laser. The temporal shape of the pump laser and in general its characteristics are important aspects to be known in order to produce THz radiation via optical rectification in a controlled way, especially for single shot experiments. Here we present a technique that can be used to retrieve the temporal profile characteristics (envelope and phase) of the pump laser, starting from the detection of the THz waveform/spectrum and the knowledge of the physical/optical properties of the crystal used to produce it. This work shows also that the THz field can be shaped by properly acting on the pump laser phase. The possibility to opportunely shape the THz field is of great importance for many applications and THz based particle accelerator is one of those. Therefore this work paves the wave to the possibility to coherently and dynamically control the THz field shape optimising therefore the acceleration process.

Nonlinear wave equation for the THz field generated via optic rectification:

$$\nabla^2 E_{THz} - \frac{\varepsilon}{c^2}\frac{\partial^2 E_{THz}}{\partial t^2} = \frac{1}{\varepsilon_0 c^2}\frac{\partial^2 P_{OR}}{\partial t^2}$$

Fourier transform with respect of the time variable:

$$\nabla^2 E(z,\omega) - \frac{\omega^2\varepsilon(\omega)}{c^2}E(z,\omega) = -\frac{4d\omega^2}{c^2}\left(E_p \star E_p^*\right)(\omega)e^{i\frac{\omega z}{v_g}}e^{-\alpha z}$$

The THz electric field as function of the medium optical characteristics:

$$E(z,\omega) = \frac{2d\omega^2 e^{ik(\omega)z}}{k(\omega)c^2}\frac{\left(e^{i\left(\frac{\omega}{v_g}+i\alpha-k(\omega)\right)z}-1\right)}{\frac{\omega}{v_g}+i\alpha-k(\omega)}\left(E_p \star E_p^*\right)(\omega)$$

Generic pump electric field:

$$E_p(\omega) \propto E_0 f(\omega-\omega_0)\tau \exp\left[i\frac{a}{2}(\omega-\omega_0)^2 + i\frac{b}{3}(\omega-\omega_0)^3\right]$$

Chirp coefficient (a); Third order dispersion coefficient (b); Transform-limit FWHM (τ)

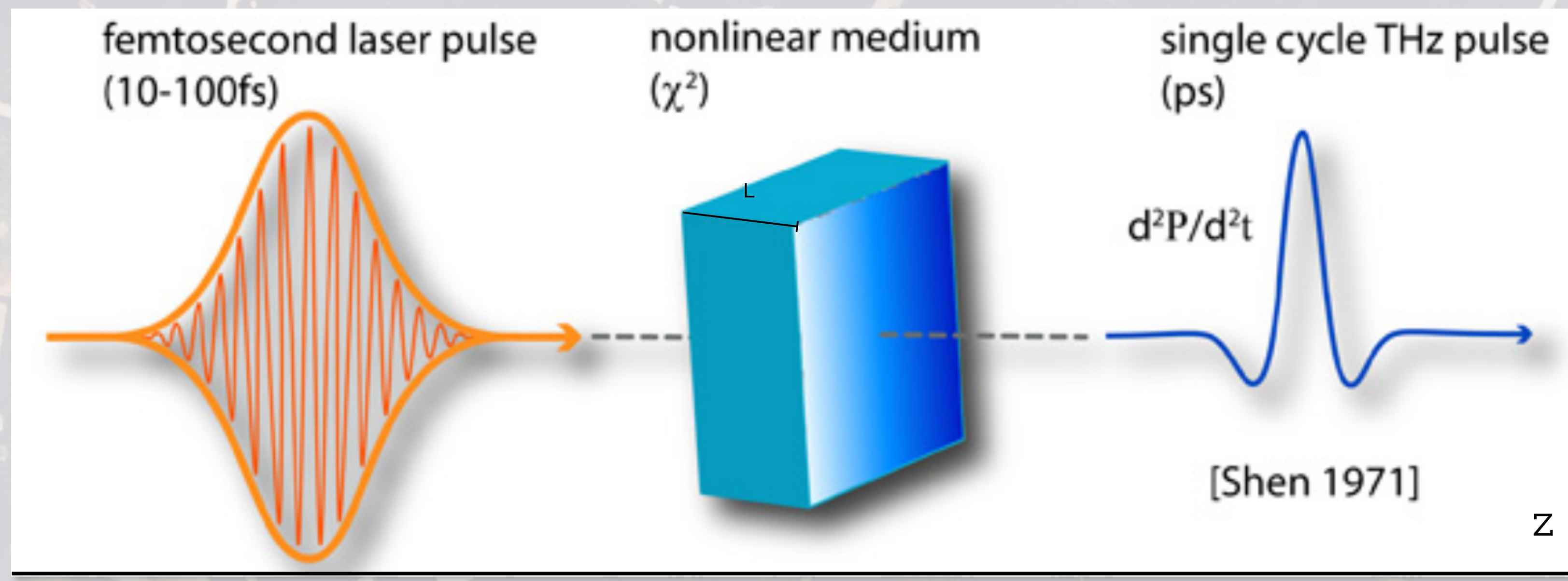
Optical rectification term of the 2nd order nonlinear polarisation of the medium:

$$P_{OR}(z,t) = 4\varepsilon_0 d E_p\left(t-\frac{z}{v_g}\right)E_p^*\left(t-\frac{z}{v_g}\right)e^{-\alpha z}$$

$$k^2(\omega) = \frac{\omega^2\varepsilon(\omega)}{c^2}$$

The pump convolution is directly related to the Fourier transform of the pump intensity:

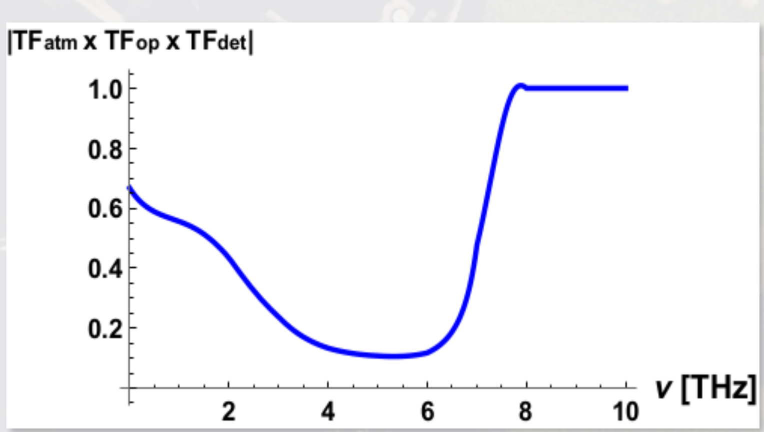
$$\left(E_p \star E_p^*\right)(\omega) = \frac{2I(\omega)}{\varepsilon_0 n(\omega_0)c}$$



Correction to transfer function for the reconstruction

$$TF_{eff} = TF_{atm}(z_{atm},\omega) \times TF_{op}(\omega) \times TF_{det}(\omega) \times TF(z,\omega)$$

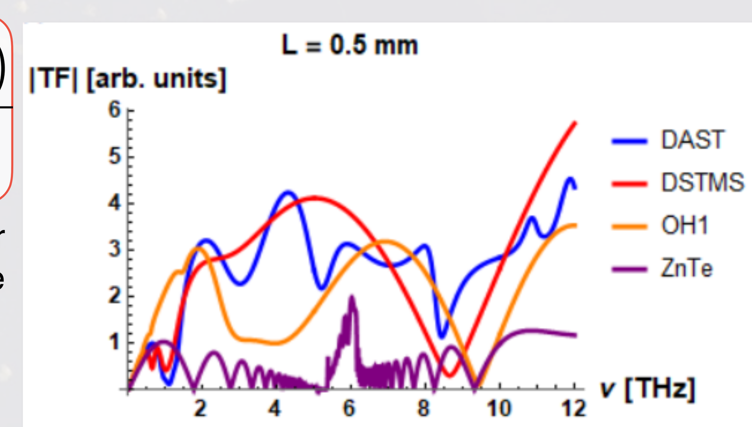
Right: Modulus of the reconstructed function *TF_{atm} x TF_{op} x TF_{det}* relative to the pump retrievement.
This include the THz absorption from the water in air (*TF_{atm}*) Ref. [9], the losses due to the finite acceptance/chromatic effects associated to the optics (*TF_{op}*) on the THz beam path and also the limited spectral response of the THz detector (*TF_{det}*).



Characteristic transfer function of the crystal

$$TF(z,\omega) = \frac{2d\omega^2 e^{ik(\omega)z}}{k(\omega)c^2}\frac{\left(e^{i\left(\frac{\omega}{v_g}+i\alpha-k(\omega)\right)z}-1\right)}{\frac{\omega}{v_g}+i\alpha-k(\omega)}$$

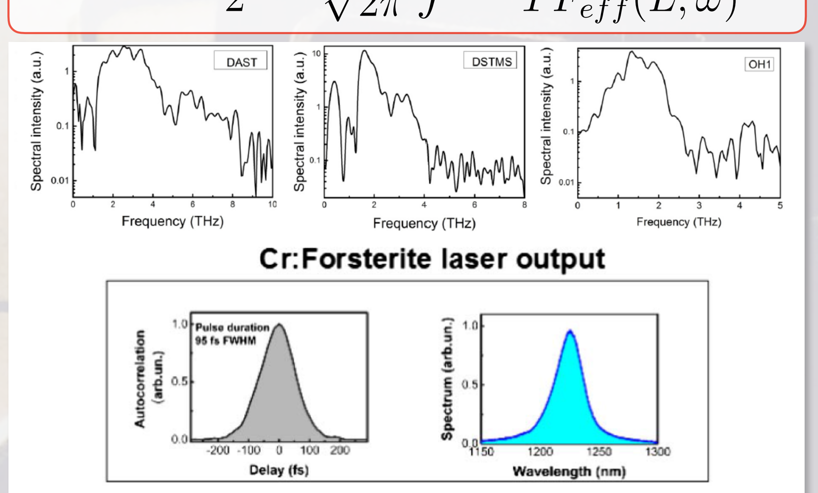
Right: Modulus of the transfer function (in arbitrary units) for the crystals ZnTe, DAST, DSTMS and OH1. The crystals have same length L=0,5 mm and the pump wavelength is 1250nm.

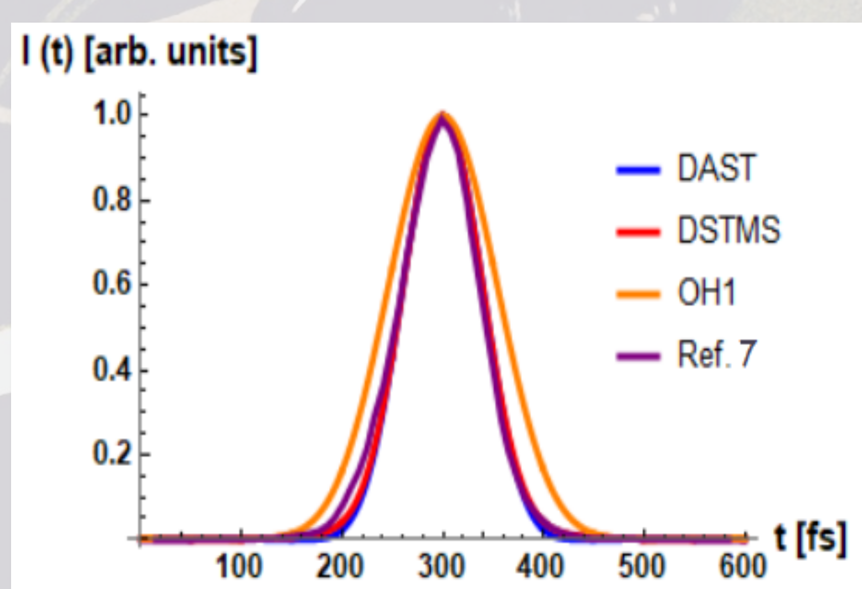


Laser diagnostics

By measuring the electric field of the THz wave it is possible to retrive the intensity profile and the phase of the pump laser.
We test our technique on the experimental results of Ref [6,7] where Terahertz spectrum emitted by DAST, DSTMS and OH1 were measured (THz Michelson interferometer).

$$I_p(t) = \frac{\varepsilon_0 n(\omega_0)c}{2}\frac{1}{\sqrt{2\pi}}\int d\omega \frac{E_{THz}(L,\omega)}{TF_{eff}(L,\omega)}e^{i\omega t}$$





An almost perfect matching between the pump pulse envelope as measured in [6,7] with the envelope retrieved by our technique can be obtained exploiting DAST (180μm) and DSTMS (900 μm) crystals; FWHM: 95±15 fs, in agreement with the temporal duration measured in [7]. The FWHM of the pump laser as retrieved when considering the OH1 (440 μm) THz spectrum was 126±21 fs.
Our methodology allows to retrive the phase of the pump pulse.

Pump phase reconstruction

If the pump pulse has a phase expressed as in Eq. 4, the convolution for the generic pump laser electric field is given by:

$$\left(E_p \star E_p^*\right)(\omega) \propto \frac{E_0^2\tau^2 g(\omega)}{(2b)^{\frac{1}{3}}}\exp\left[-i\frac{a}{2}\omega^2 - i\frac{b}{3}\omega^3 + i\frac{2}{3}bq\right]Ai\left(\frac{2^{\frac{2}{3}}b^{\frac{2}{3}}p}{3}\right)$$

Airy function of first kind (Ai)

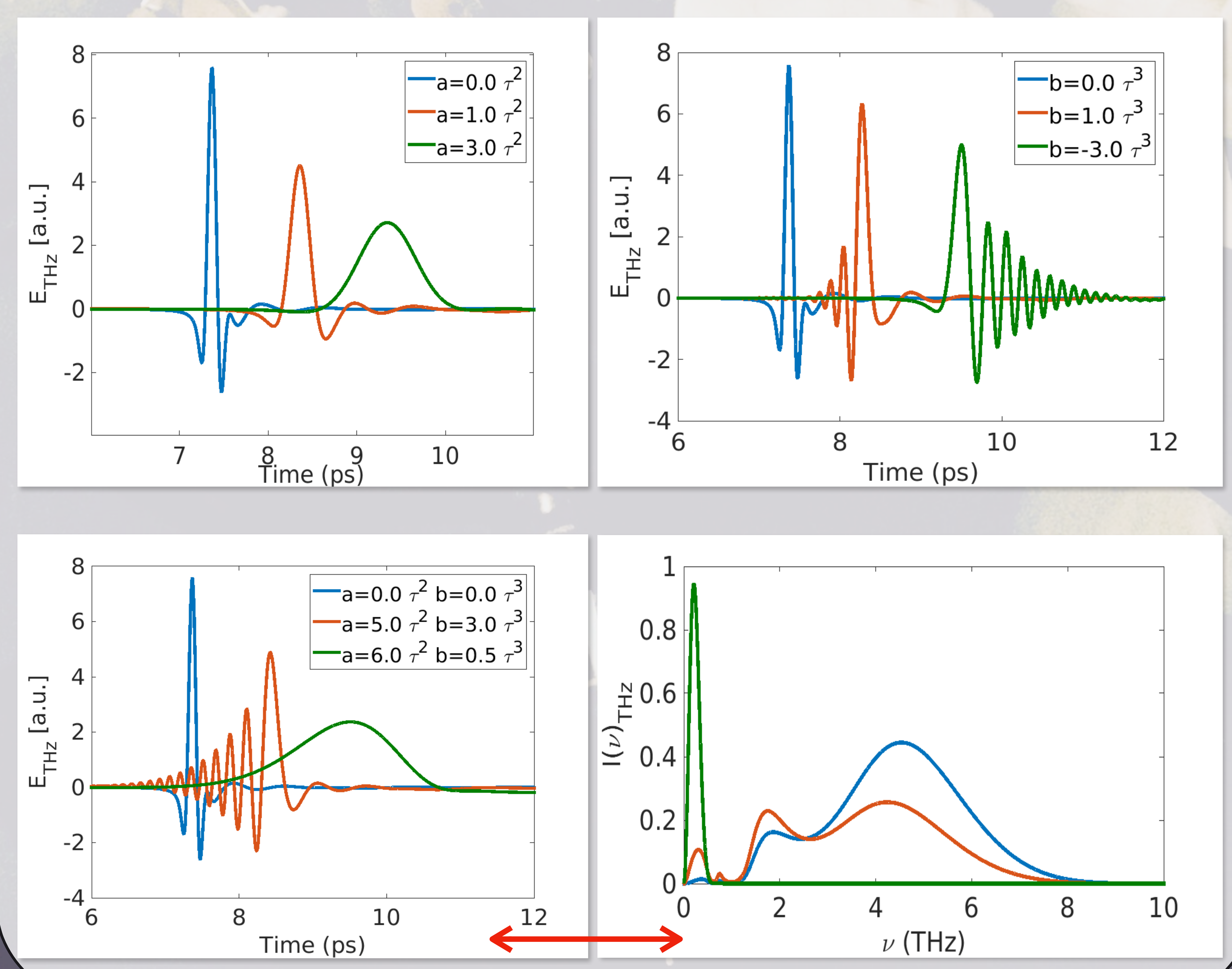
$$c_1 = \omega\tau^2/2 + ib\omega^2 + ia\omega \quad p = c_1 - c_2^2/3$$
$$c_2 = 3(i\tau^2/2 - b\omega)/2b \quad q = -c_1c_2/3 + 2c_2^2/27$$

	$f(\omega-\omega_0)$	$g(\omega)$	FWHM error
Gaussian	$\mathrm{Exp}\left[-\frac{\tau^2(\omega-\omega_0)^2}{8\log 2}\right]$	$\mathrm{Exp}\left[-\frac{\tau^2\omega^2}{8\log 2}\right]$	0%
Sech^2	$\mathrm{Cosech}\left[\frac{(\omega-\omega_0)\tau}{3.52}\right]$	$\mathrm{Cosech}\left[\frac{\omega\tau}{3.52}\right]$	8%
Sinc^2	$\mathrm{Tri}\left[\frac{(\omega-\omega_0)\tau}{4\log 2}\right]$	$\mathrm{Tri}\left[\frac{\omega\tau}{4\log 2}\right]$	3%

The parameters *a* and *b* can be retrieved by fitting the above equation on the experimental *E_{THz}/TF_{eff}*, using as functions *f* and *g* the expression given in the tabular for a gaussian, sech² or sinc² pump pulses shape. The results are exact for a gaussian pulse. If a non gaussian shape is required it is not obvious to obtain an analytical expression and therefore a small error on the retrieved FWHM is expected. We denoted by tri(x) the triangular function.

THz shaping

By modulating the non-linear phase of the pump laser field is possible to dynamically modify the shape of the THz electric field optimising it for the experiment under consideration. Therefore this methodology is particularly suitable to optimise the THz based acceleration process.
Shaping simulation using a laser pump of: λ=1500nm, 100 fs FWHM and a crystal of DSTMS 1mm thick:



Conclusion: We introduced a non-intercepting, single-shot technique to retrieve the temporal profile of ultra-short pump lasers (100 fs and below) used to produce THz pulses via OR.
We have shown experimental examples of THz production and how to reconstruct the pump temporal profile and phase.
Finally we discussed the effects of the second and third order dispersion of the pump pulse on the THz production and temporal shaping. The shaping of THz pulses could be of great utility for many applications, included the most recent ones related to electron acceleration experiments Ref[10].
Therefore this work paves the wave to the possibility dynamically control the acceleration process by opportunely shaping the THz field.

Reference:

[1]Sansone, Giuseppe, Luca Poletto, and Mauro Nisoli. "High-energy attosecond light sources." Nature Photonics 5.11 (2011): 655-663.
[2]Krogen, Peter, et al. "Generation and multi-octave shaping of mid-infrared intense single-cycle pulses." Nature Photonics 11.4 (2017): 222-226.
[3]Vicario, Carlo, Balazs Monoszlai, and Christoph P. Hauri. "GV/m single-cycle terahertz fields from a laser-driven large-size partitioned organic crystal." Physical Review Letters 112.21 (2014): 213901.
[4]Boyd, Robert W. Nonlinear optics. Academic press, 2003.
[5]Shan, Jie, et al. "Single-shot measurement of terahertz electromagnetic pulses by use of electro-optic sampling." Optics letters 25.6 (2000): 426-428.
[6]Vicario, C., Jazbinsek, M., Ovchinnikov, A. V., Chefonov, O. V., Ashitkov, S. I., Agranat, M. B., & Hauri, C. P. (2015). High efficiency THz generation in DSTMS, DAST and OH1 pumped by Cr: forsterite laser. Optics express, 23(4), 4573-4580.
[7]Vicario, C., et al. "Generation of 0.9-mJ THz pulses in DSTMS pumped by a Cr: Mg 2 SiO 4 laser." Optics letters 39.23 (2014): 6632-6635.
[8]Slocum, David M., et al. "Atmospheric absorption of terahertz radiation and water vapor continuum effects." Journal of Quantitative Spectroscopy and Radiative Transfer 127 (2013): 49-63.
[9]Tomasino, A., et al. "Wideband THz time domain spectroscopy based on optical rectification and electro-optic sampling." Scientific reports 3 (2013): 3116.
[10]Nanni, Emilio A., et al. "Terahertz-driven linear electron acceleration." Nature communications 6 (2015): 8486.