Study and applications of THz and Lasers pulses for accelerator physics

SAPIENZA
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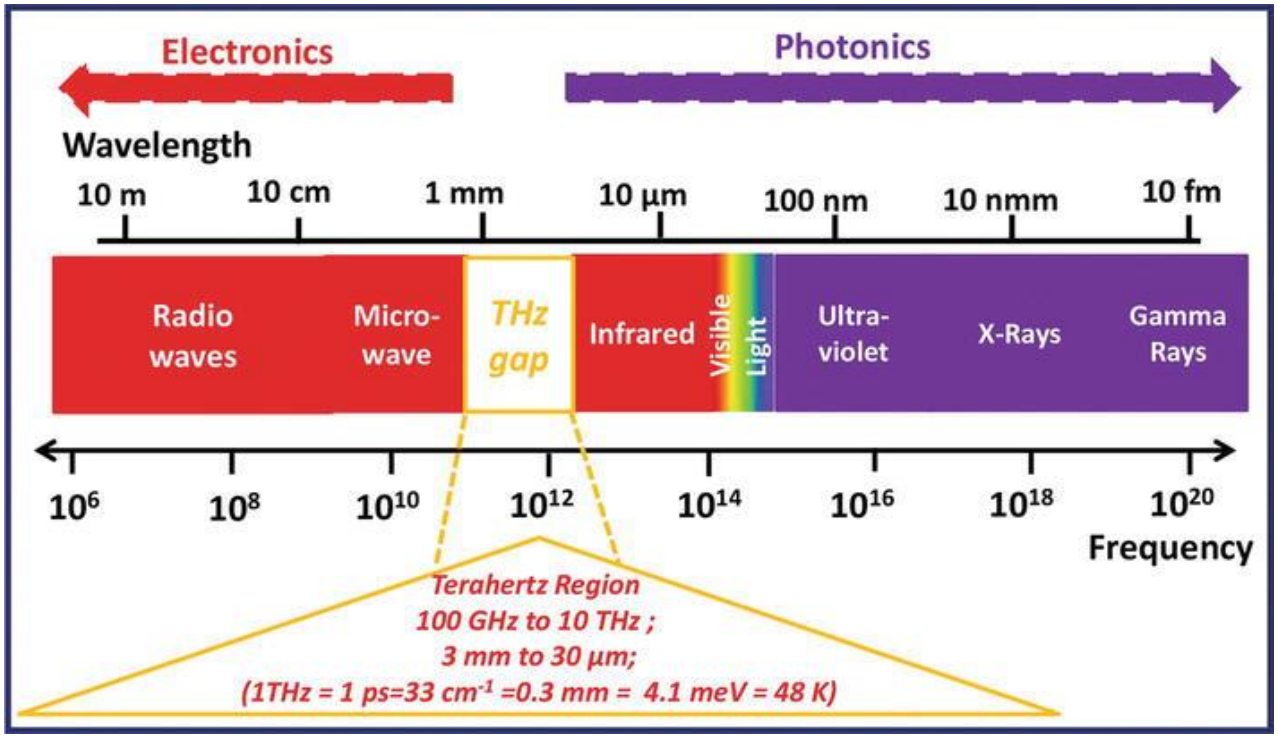
Presentation outline

- Terahertz overview: generation and detection
- Coherent control of intense THz field
    - THz shaping
    - Laser diagnostics
- Optical properties of organic crystals
    - DSTMS and HMQ-TMS
- THz-Plasma interaction for accelerator physics
    - THz-Plasma acceleration
    - Plasma diagnostics
- THz generation by electron bunches at CLEAR
- Laser Comb study

Introduction THz

Terahertz radiation (1 THz corresponds to ~ 4 meV photon energy, or ~ 300 µm radiation wavelength) has a strong impact in many areas of research. In literature, proof of principle electron acceleration experiments induced by THz pulses have been reported, therein showing that a strong THz field can be used to boost the electron energy in a short space interval.



THz generation and detection used during my PhD

THz generation can be achieved with different mechanisms:

- Laser based sources
    - Semiconductor sources: photoantenna
    - Crystals sources: Optical Rectification (OR)
    - Two-Colours Plasma THz generation
- Particle based
    - Coherent Transition Radiation (CTR) and Diffraction Radiation

THz detection can be divided in two branch:

- Coherent detection
    - Electro Optical Sampling EOS
    - Photoconductive sampling
- Energy detection: pyroelectric or pyrocam

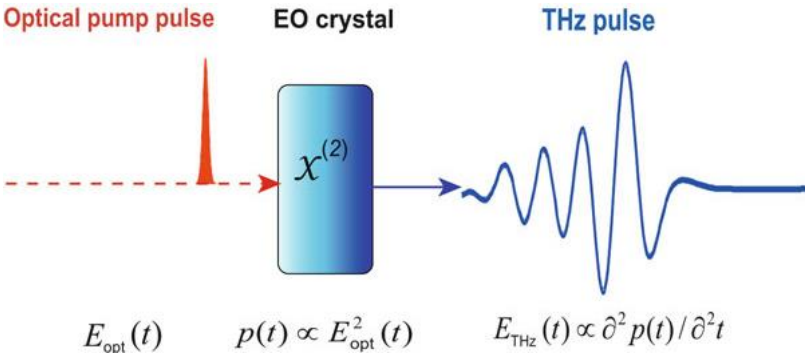
Coherent control of intense THz field

Optical Rectification in non-linear crystals

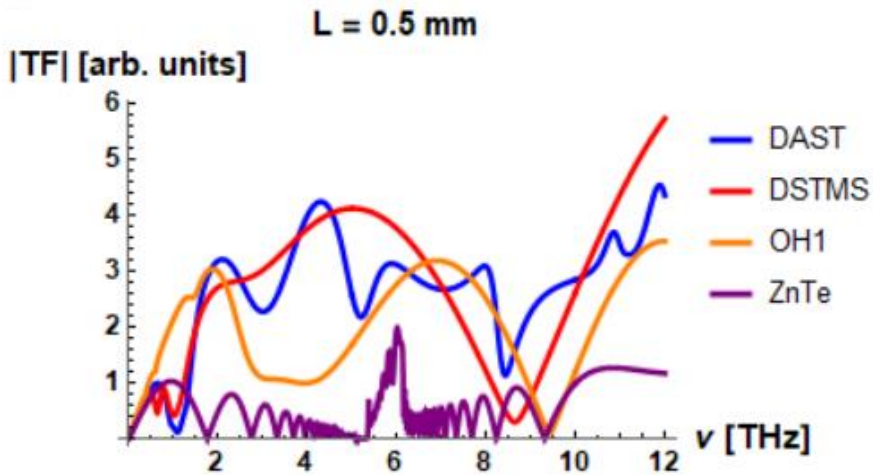
$$E_{THz}(z,\omega) = TF(z,\omega)\cdot\left(E_p \star E_p^*\right)(\omega)$$

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

$$L_c = \frac{1}{2}\frac{c}{\nu_{THz}(ng_{pump}-n_{THz})}$$



The THz field generated in OR process depends upon the convolution of the electric field of the pump pulse with itself and from the Transfer Function (TF) of the crystal in use (the transfer function from some crystals is plotted in the figure on the right). The TF of a crystal depend only upon its optical properties both in the THz frequency and at the pump wavelength.



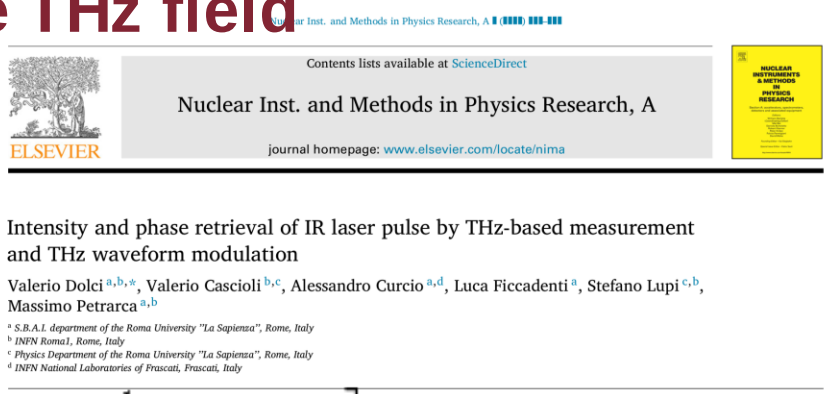
It is possible to observe that the organic crystals (DAST,DSTMS,OH1 in the plot) have a broader *TF.* The higher conversion factor in THz generation is reported for the DSTMS crystal 3% circa.

Coherent control of intense THz field

THz shaping

Using a pump pulse with a chirp (*a*) and a third order phase (*b*) it is possible to shape the THz field generated in OR. In the frequency domain it is possible to write the complete pump field in Taylor expansion a field as:

$$E_p(\omega) = \frac{E_0\tau}{2\sqrt{\log 2}} \cdot \exp\left[-\frac{\tau^2(\omega-\omega_0)^2}{8\log 2} + i\frac{a}{2}(\omega-\omega_0)^2 + i\frac{b}{6}(\omega-\omega_0)^3\right]$$


Contents lists available at ScienceDirect

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Intensity and phase retrieval of IR laser pulse by THz-based measurement and THz waveform modulation

Valerio Dolci [a,b,*], Valerio Cascioli [b,c], Alessandro Curcio [a,d], Luca Ficcadenti [a], Stefano Lupi [c,b], Massimo Petrarca [a,b]

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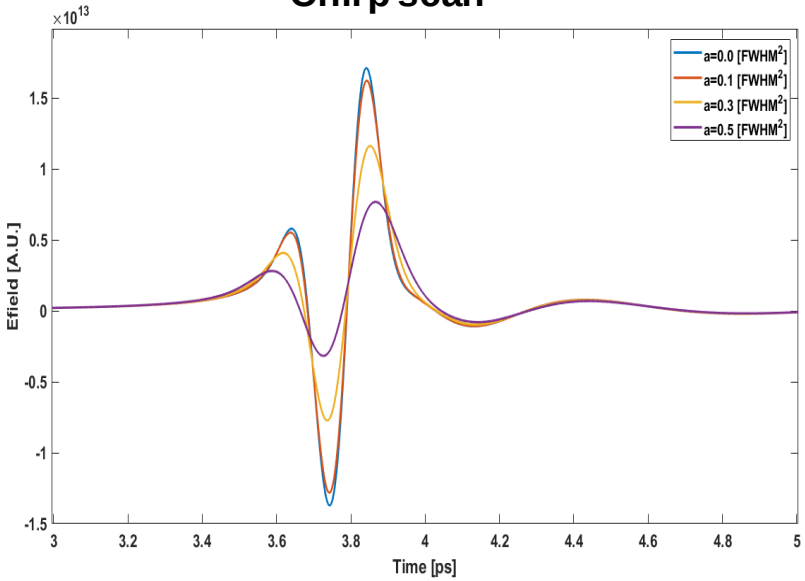
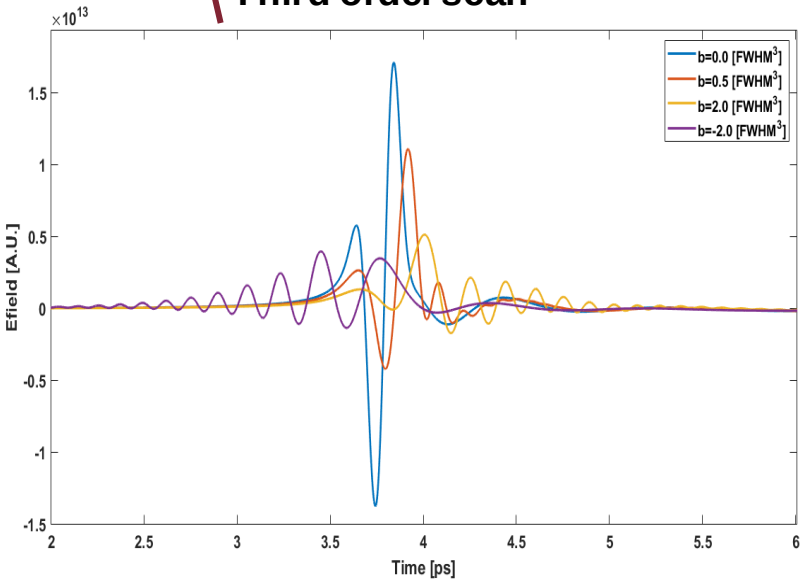
Chirp scan



Third order scan



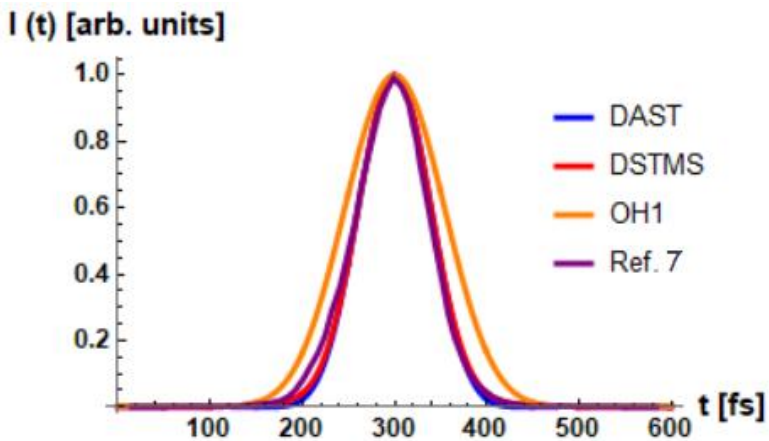
Coherent control of intense THz field

Laser diagnostic

Inverting the equation for the THz generation in OR it is possible to retrieve the initial parameters of the pump laser. The model was tested on published data.

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

Measuring the THz field (E_{THz}) and knowing the TF of the crystal in use, by its optical properties, it is possible to retrive the pump intensity profile.



Terahertz-based retrieval of the spectral phase and amplitude of ultrashort laser pulses

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[2]S.B.A.I. Department of the Rome University "La Sapienza", Rome, Italy
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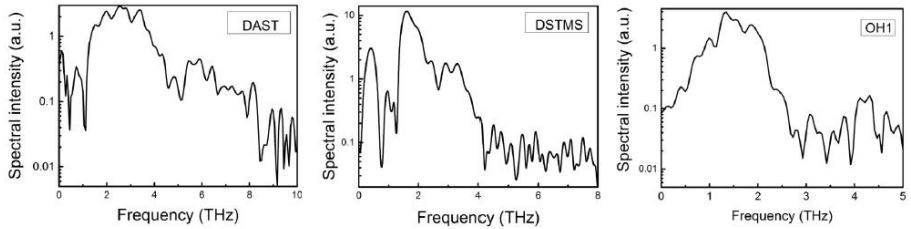
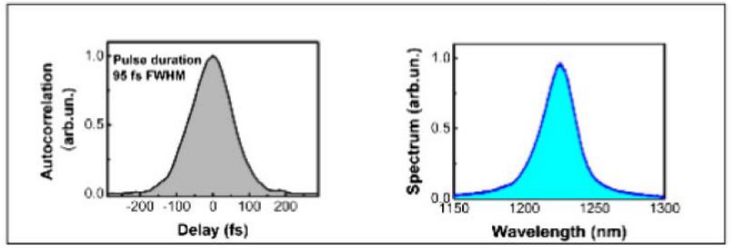


Cr:Forsterite laser output



Optical properties of organic crystals

measured crystals 1/3

1) V. Dolci, P. Di Pietro, A. Perucchi, S. Piccirilli and Lupi, and M. Petrarca. "Broadband optical properties of terahertz generator DSTMS organic crystal". *under publication* (2019).
2) V. Dolci et al. "Broadband optical properties of terahertz generator HMQTMS organic crystal". *under publication* (2019).

The crystals optical properties were measured in the range 50-36000 cm-1 for both Reflectance (R) and Transmittance (T) at room temperature. The measure was done for both the optical axis, ordinary and extraordinary. To achieve this large spectrum I made the measure using different instruments:

- MIR data at SISSI Infrared beamline at Elettra Synchrotron through a Bruker Vertex 70 V Michelson interferometer
- NIR to UV data have been measured at the Department of Physics, Sapienza University of Rome through a JASCO V50 spectrometer

To retrieve the complex refractive index, I have used an analytical model and a Kramers-Kronig transformation. The analytical model was needed for the correction of the multiple reflection inside the crystals. The measured reflectance can be corrected using the equation:

$$R(R_m, T_m) = \frac{2 + T_m^2 - (1 - R_m)^2 - \sqrt{[2 + T_m^2 - (1 - R_m)^2]^2 - 4R_m(2 - R_m)}}{2(2 - R_m)}$$

Where R_m and T_m are the measured quantities and the result is the reflettance of the single crystal slab. **Right:** the dependance of T and R upon the complex refractive index *(n,k)*.

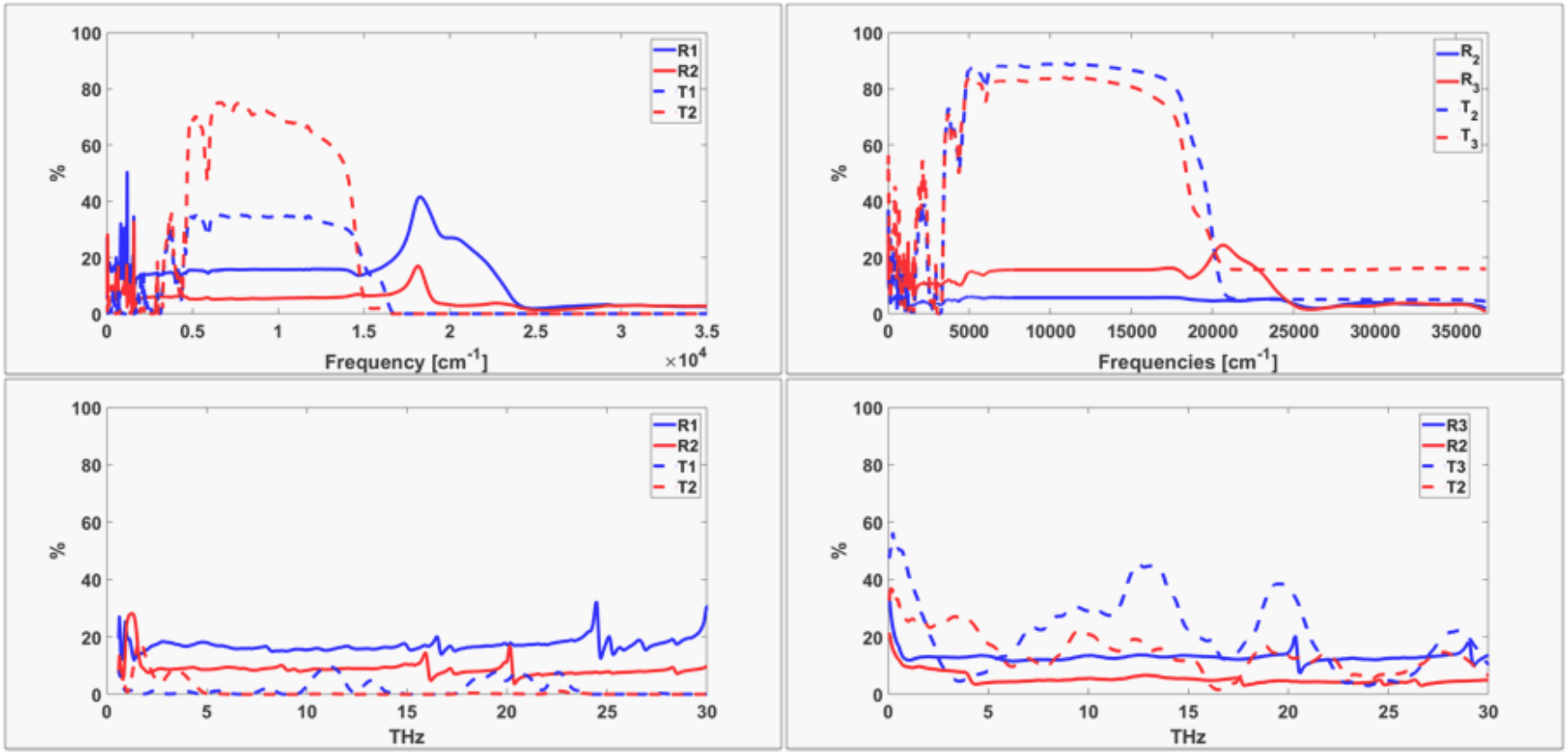
$$R = \left|\frac{n - ik - 1}{n - ik + 1}\right|^2$$

$$T = \frac{4n}{|n - ik + 1|^2}$$

Optical properties of organic crystals

DSTMS and HMQ-TMS measured R and T 2/3

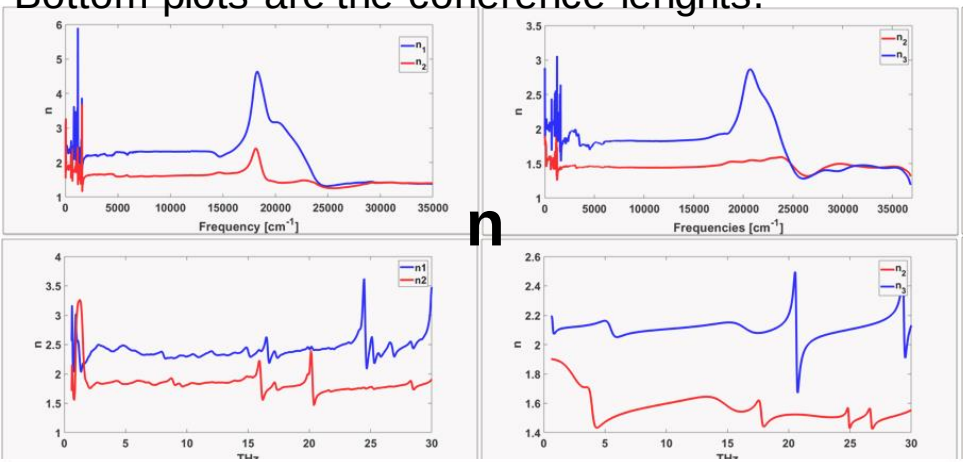
DSTMS on the left and HMQ on the right, where continuous lines are for Reflettance and dashed lines for the Transmittance. The bottom plots are a zoom of the low frequency in the THz region.

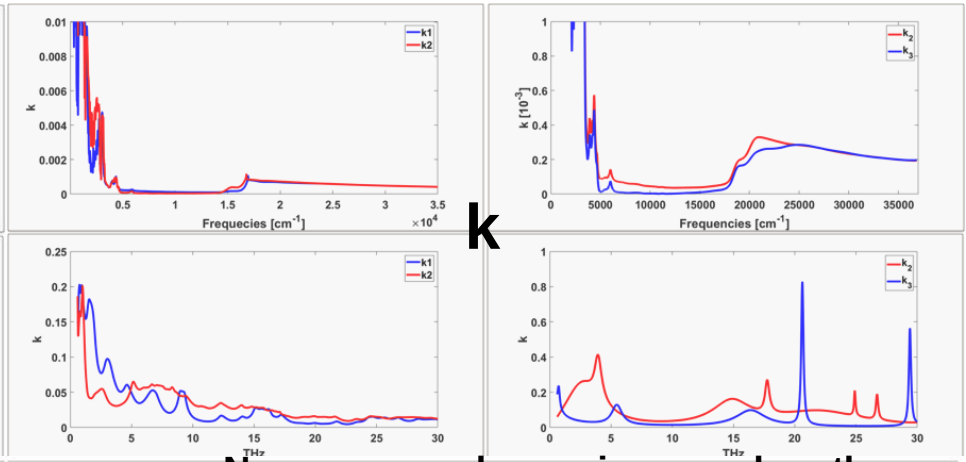


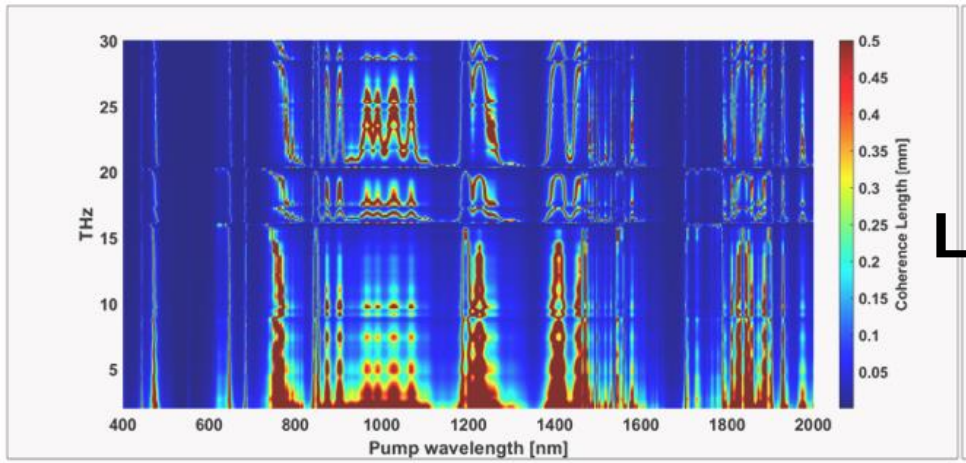
Optical properties of organic crystals

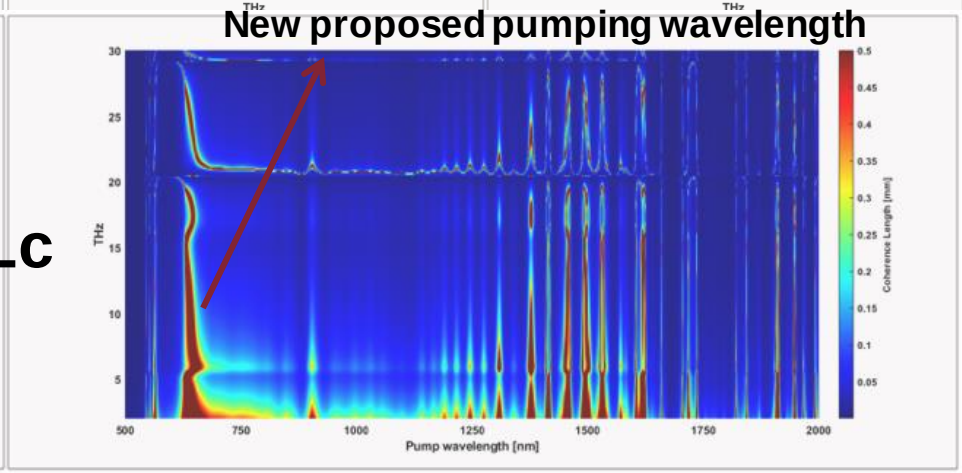
Complex refractive index for DSTMS and HMQ-TMS 3/3

Real part of the refractive index n (left) and complex part k (right), with the zoom in the THz region, for both crystals, DSTMS (left) and HMQ-TMS(right) the polar axis is in blue for both crystals. Bottom plots are the coherence lenghts.









THz-plasma interactions for accelerator physics

THz-plasma acceleration 1/2

The work was done mainly using Particle In a Cell (PIC) simulations with already achieved parameters for the THz pulse and for the plasma. We did a complete scan over the THz and plasma parameters, showing that the scaling law for the maximal longitudinal electric field generated in the wakefield is in good agreement with the well known scaling law for the laser-plasma interaction in the 1D linear case.

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SCIENTIFIC REPORTS

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Resonant plasma excitation by single-cycle THz pulses

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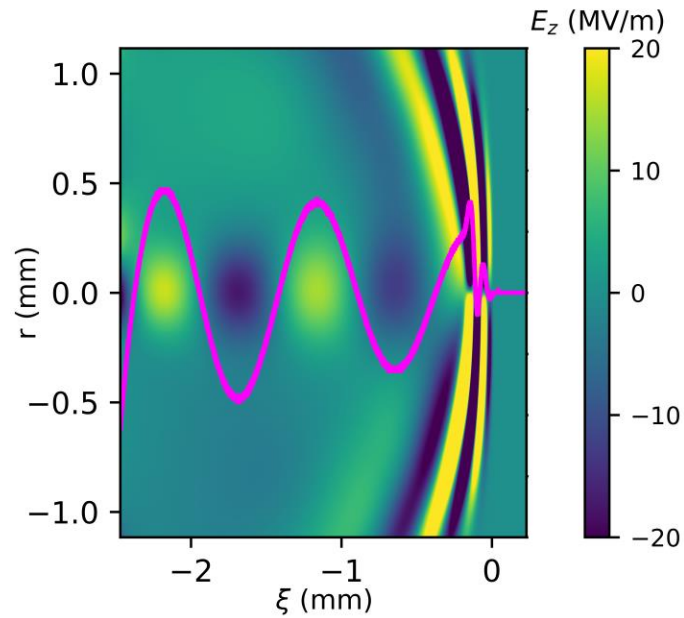
Published online: 18 January 2018

In this paper, an alternative perspective for the generation of millimetric high-gradient resonant plasma waves is discussed. This method is based on the plasma-wave excitation by energetic single-cycle THz pulses whose temporal length is comparable to the plasma wavelength. The excitation regime discussed in this paper is the quasi-nonlinear regime that can be achieved when the normalized vector potential of the driving THz pulse is on the order of unity. To investigate this regime and determine the



Background and mesh setup:	
Longitudinal cell resolution:	0.2 μm
Transversal cell resolution:	1.6 μm
Longitudinal point:	51000
Transversal point:	1440
Particle per cell:	25

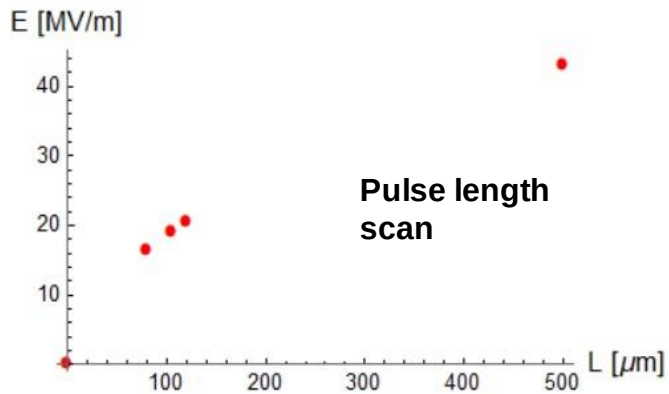
TeraHertz pulse working point:	
Pulse central frequency:	$\nu_0 \simeq 3$ THz
Pulse length:	$L \simeq 105\ \mu m \simeq \lambda_p/10$
Plasma density:	$n_0 = 1 \times 10^{15} cm^{-3}$
Radial width:	$w_0 = 270\ \mu m$

THz-plasma interactions for accelerator physics

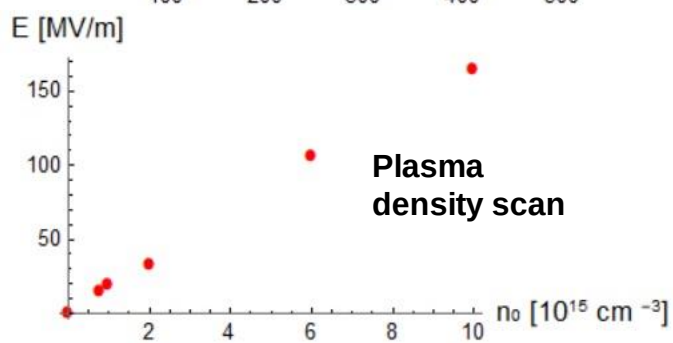
THz-plasma acceleration 2/2

$$E_N(V/m) = E_{wb}\frac{a_0^2}{2\sqrt{1+\frac{a_0^2}{2}}}$$

$$E_{wb} = m_e\omega_p c/e \sim 96\sqrt{n_0(cm^{-3})}[V/m]$$

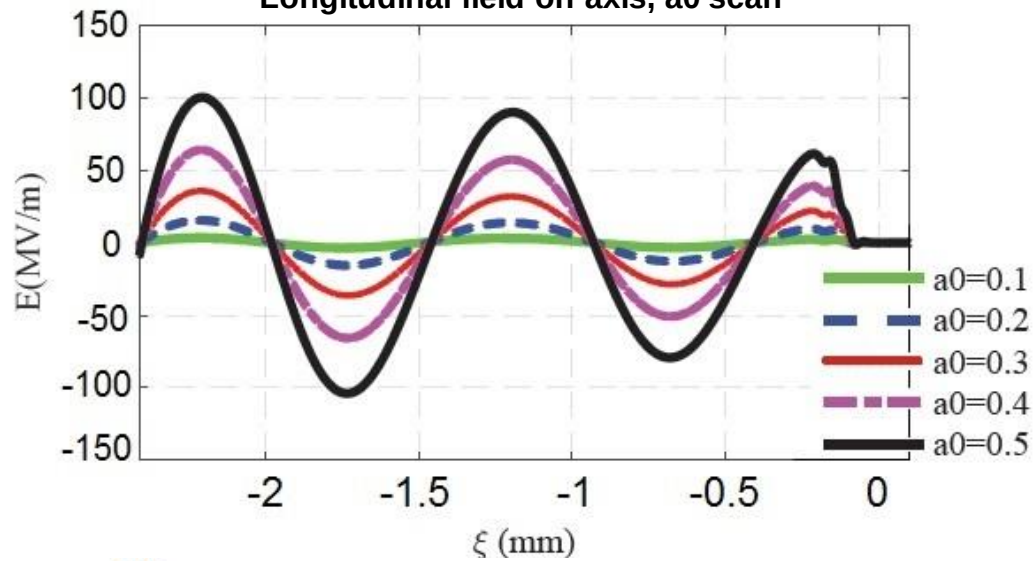


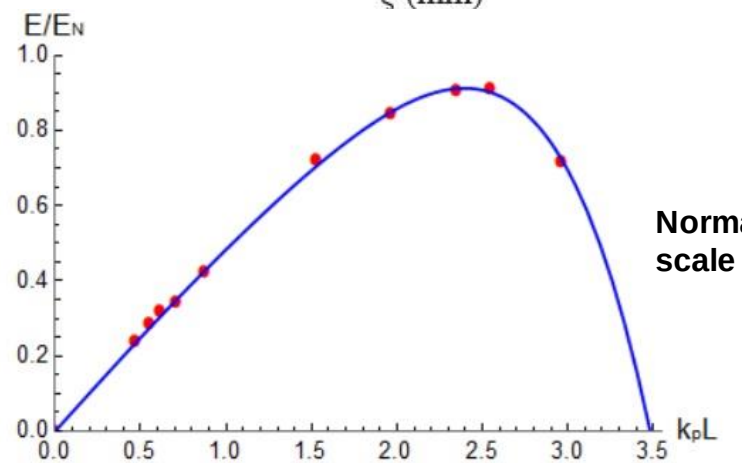
Pulse length scan



Plasma density scan

Longitudinal field on axis, a0 scan





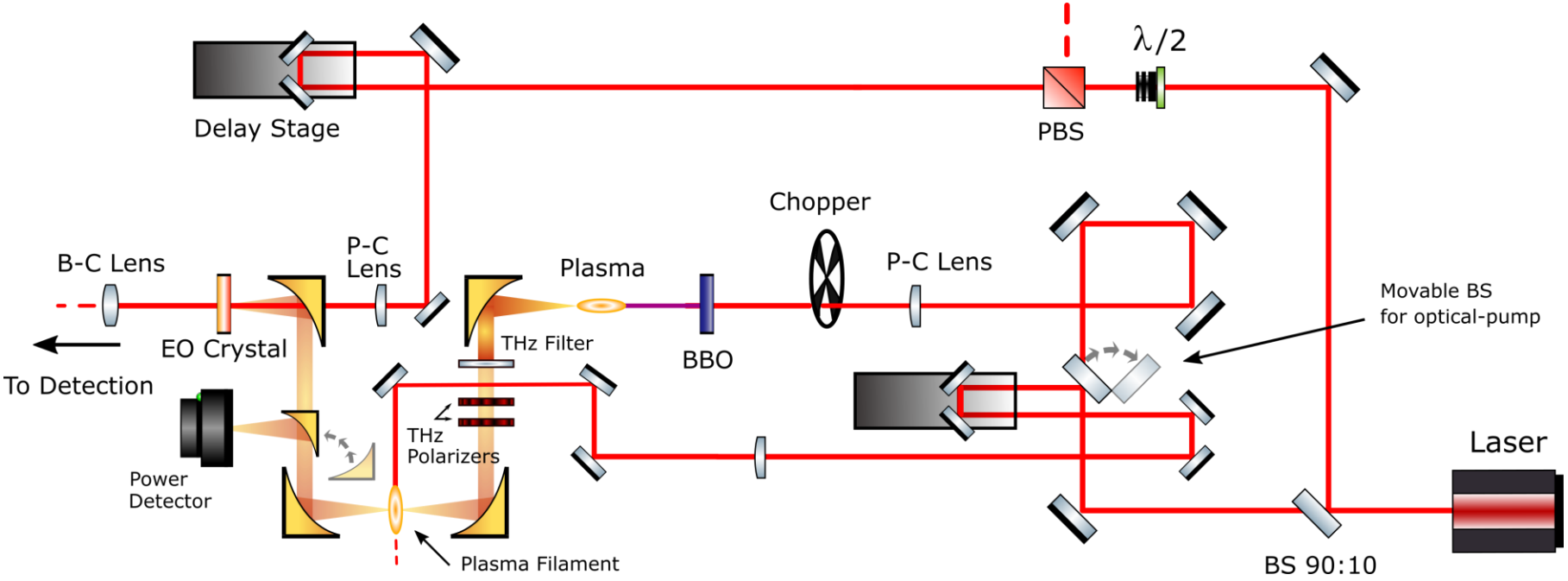
Normalized scale law

THz-plasma interactions for accelerator physics

Plasma diagnostic 1/4, setup

Following the work in [1], I have built a plasma diagnostic setup at the TeraHertz Sapienza laboratory, for INFN call, CSN5, persons in charge: M. Petrarca and S. Lupi. The laser is a Ti:Sa laser chain at 780 *nm* with 7 *mJ* and 35 *fs@FWHM* having 1 *KHz* repetition rate.

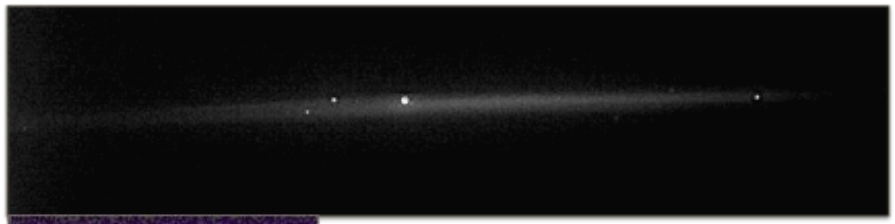
[1] A. Curcio and M. Petrarca. "Diagnosing plasmas with wideband terahertz pulses". In: *Optics letters* 44.4 (2019), pp. 1011–1014.

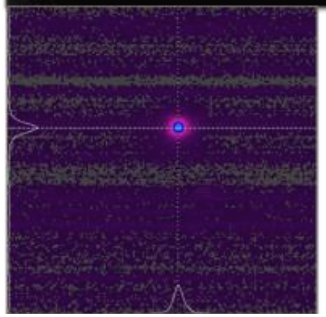


THz-plasma interactions for accelerator physics

Plasma diagnostic 2/4, preliminary measures

Plasma filament photo from above. The plasma dimensions are 5.50 mm @FWHM length and 0.3 mm @FWHM with nearly gaussian profile.

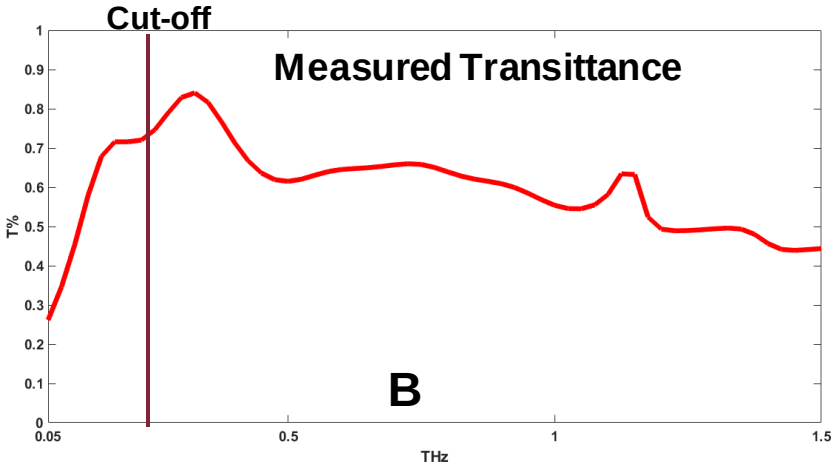


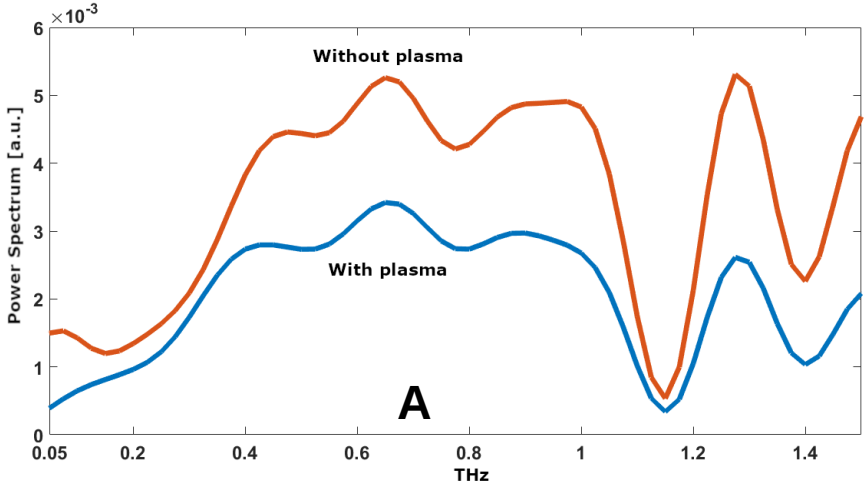


THz transverse profile in the interaction point measured with a pyrocam. Near gaussian profile with 2 *mm* FWHM in both *x* and *y* direction.

A) THz measured power spectrum, using EOS detection, with the plasma and without the plasma.

B) Transmittance of the previous measures showing a cut in low THz frequencies.

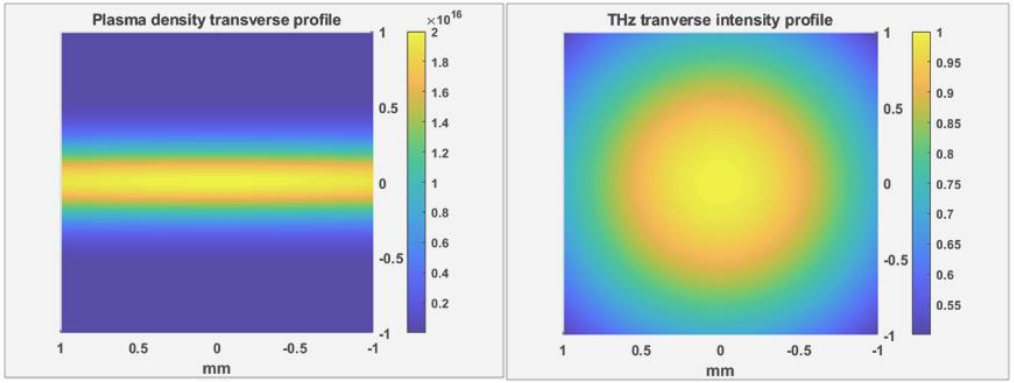


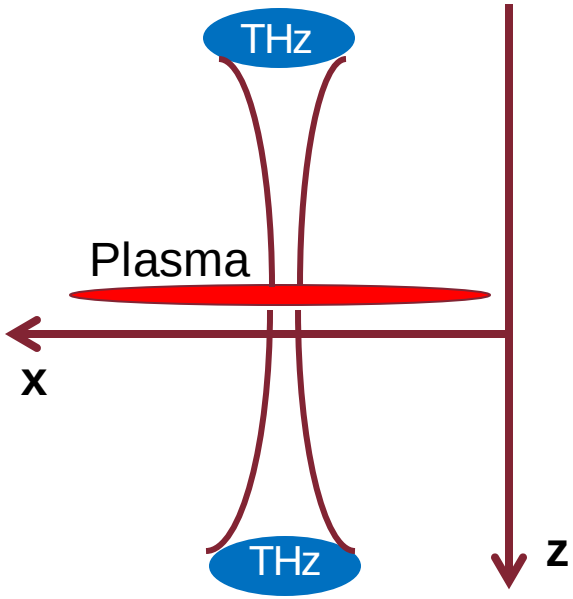


THz-plasma interactions for accelerator physics

Plasma diagnostic 3/4, simulations

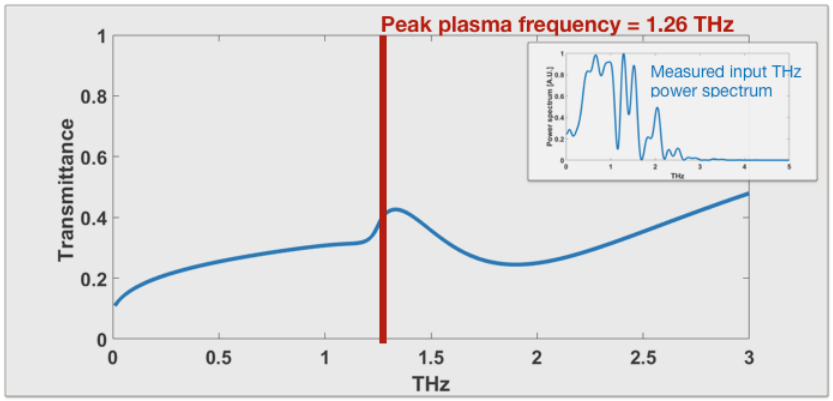
Simulated transverse profile for the plasma filament and the THz pulse in the interaction point. The THz is propagated in the longitudinal direction (exiting the screen), then, as a simple approximation, all the THz transverse rays are summed in the time domain giving the output THz field.





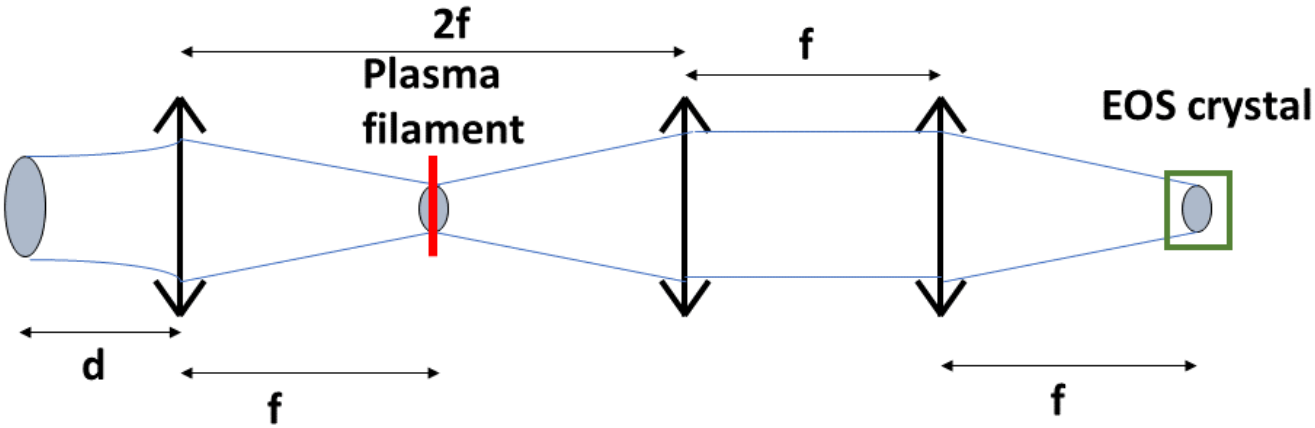
The transmittance obtained from the previous simulation using as peak plasma density *2*10^16 cm^-3*, resulting in a plasma frequency of 1.26 THz.

This results show a cut in the lower frequencies, but also a modulation in the higher frequencies due to the interference of different THz rays.



THz-plasma interactions for accelerator physics

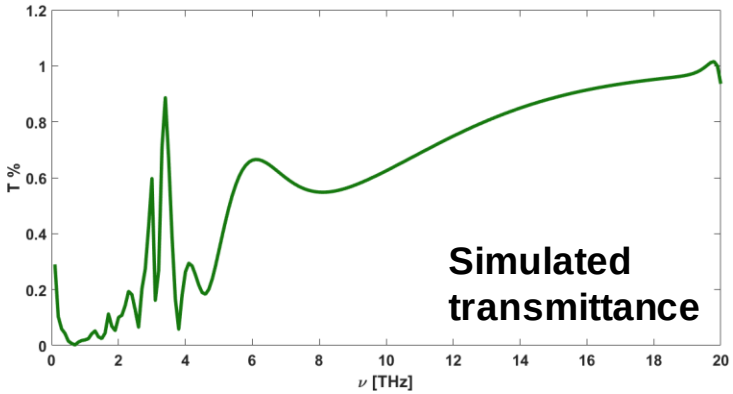
Plasma diagnostic 4/4, start-to-end simulations



Simulation that uses a Fresnel transfer function to propagate a 3D THz pulse from the generation to the detection in a EOS crystal. This scheme is a simulation of our experimental setup, where the parabolic mirrors are approximated as thin lenses. The EOS detection is simulated using the following equation:

$$I_{signal}(\tau) = \int I^{y}_{probe}(x,y,\tau)dxdy = \int I_0(x,y) * j * \frac{\Gamma(x,y,\tau)}{2} dxdy$$

$$\Gamma(x,y,\tau) = \frac{2\pi L}{\lambda} n^3_{\omega} r_{41} E_{THz}(x,y,\tau)$$



THz generation by electron bunches at CLEAR 1/2

The THz radiation can also be used as diagnostics for charged particles bunches. The radiation generated from the interaction of an electron bunch with solid target will generate radiations via Coherent Transition Radiation or Diffraction Radiation.
The spectrum of this emitted radiation can span in the THz region and so can be used as measure for the charge, energy and lenght of the particle bunch. The work was done at the CLEAR collaboration at CERN, using different kinds of targets for the generation of CTR and CDR.

PHYSICAL REVIEW ACCELERATORS AND BEAMS **22,** 020402 (2019)

Beam-based sub-THz source at the CERN linac electron accelerator for research facility

A. Curcio,* M. Bergamaschi, R. Corsini, D. Gamba, W. Farabolini, T. Lefevre, and S. Mazzoni
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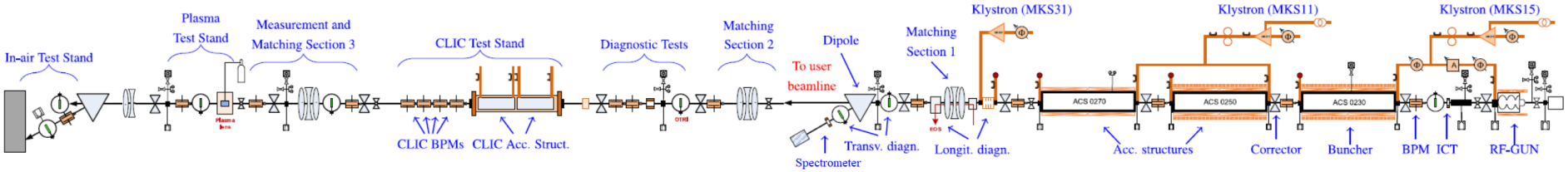
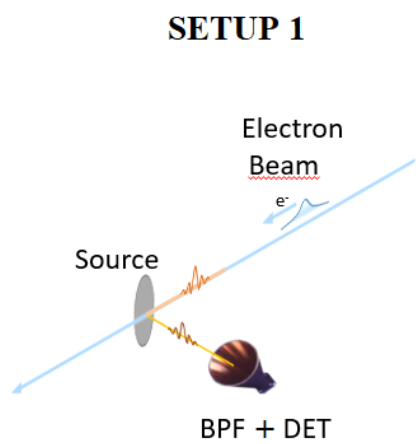
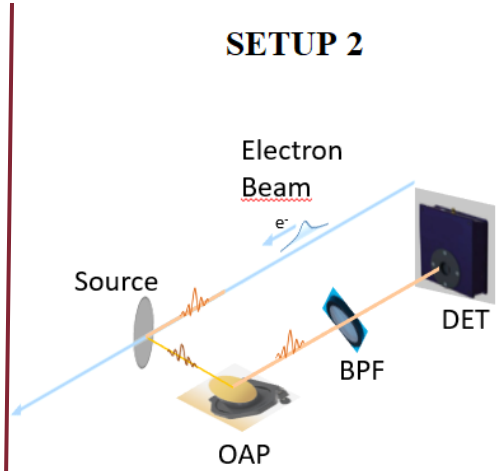
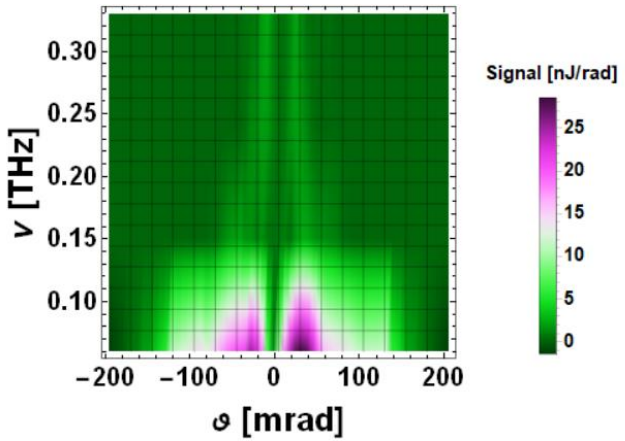
(Received 1 November 2018; published 4 February 2019)



THz generation by electron bunches at CLEAR 2/2

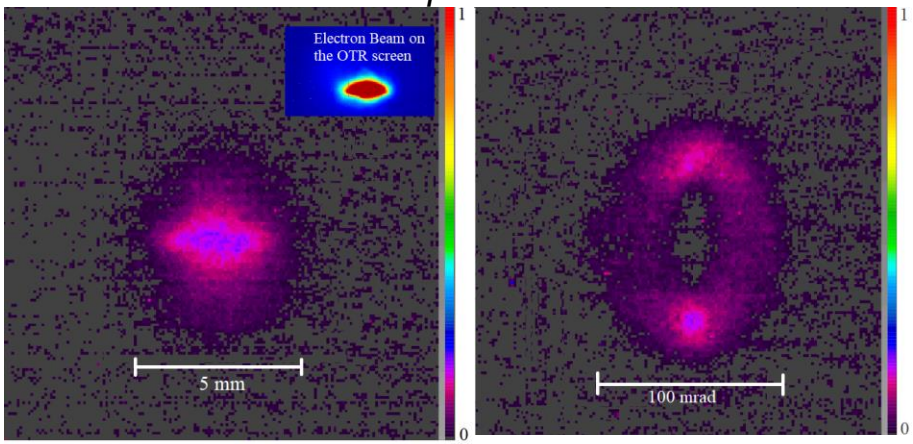






Top: Smoothed representation of the experimental results on spectral-angular characterization of the CTR light emitted by a 215 *MeV*, 40 *pC*, 1.5 *ps* long electron bunch at 30 *cm* from the source.

Bottom: Far Field and Near Field images (color palette in arbitrary units) of CTR over the whole spectral range of emission. These images demonstrate the possibility to control the energy distribution of the radiation shaping the bunch (size and divergence at the source plane). Electron beam parameters (per single bunch): 215 *MeV*, 1.5 *ps*, 40 *pC*.



Laser COMB study

Generation of UV flat-top pulses for electron gun 1/4

I have studied the generation of a flat-top pulse, with 8 to 12 *ps* time duration, using a COMB scheme. The starting UV pulses used are in fig. (**a**). The blue line stands for the 18 *nm* bandwidth, the red line stands for the 35 *nm* bandwidth. The aim was to achieve a flat-top pulse with less than 20% ripple.

For the study I have used the birefringent alpha-BBO crystal, taking into account up to the second order phase in the propagation.

A generic scheme for this technique can be found in Fig. (**b**). In my research, I used a different number of crystals, 4/5/6, where each *n* crystal has an angle of 45° in respect of the *n-1,* so the scheme is 45/90/135/ecc. The lenght of each *n* crystal is the half of the *n-1.*

$$E^N(\omega, L_N) = E^{N-1}(\omega) e^{i(K_0 + K_1(\omega-\omega_0) + \frac{K_2}{2}(\omega-\omega_0)^2)L_N}$$

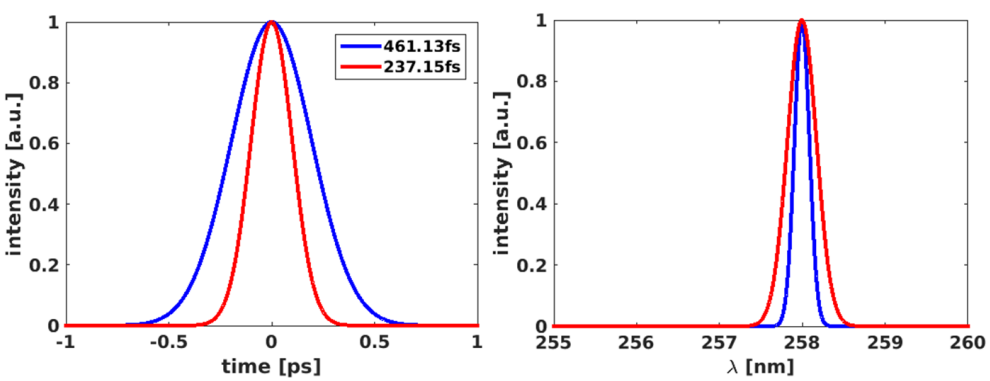


Fig. (a)

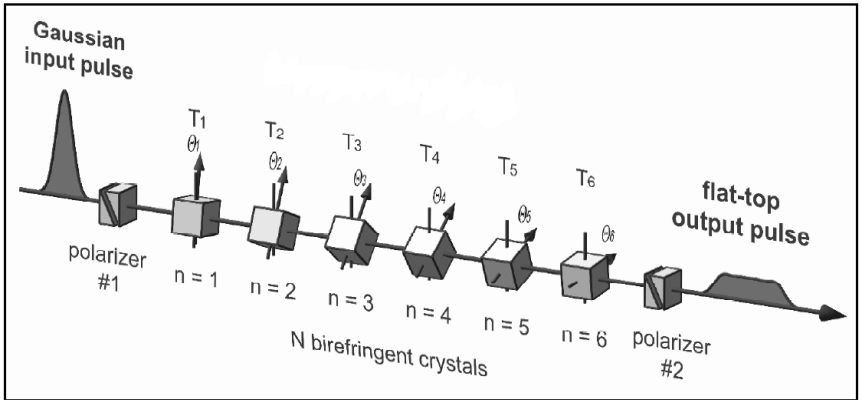
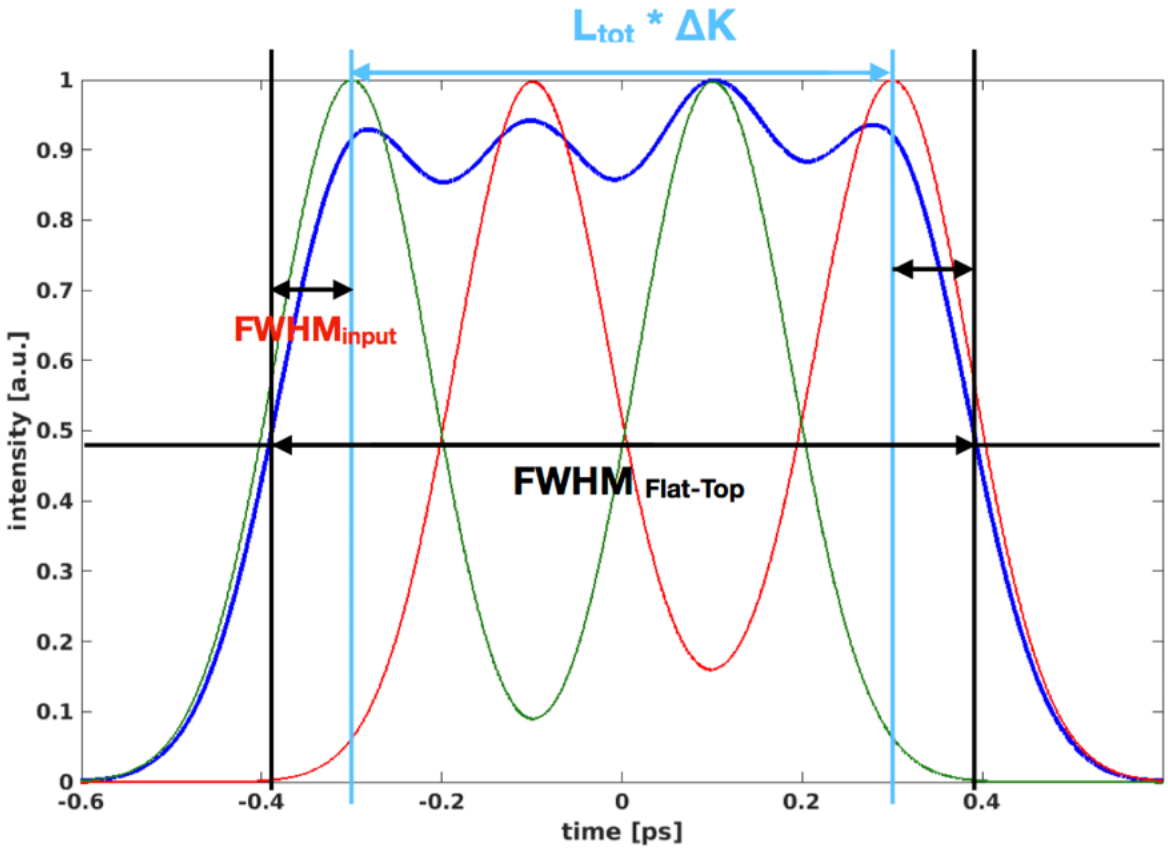


Fig. (b)

Laser COMB study

Generation of UV flat-top pulses for electron gun 2/4

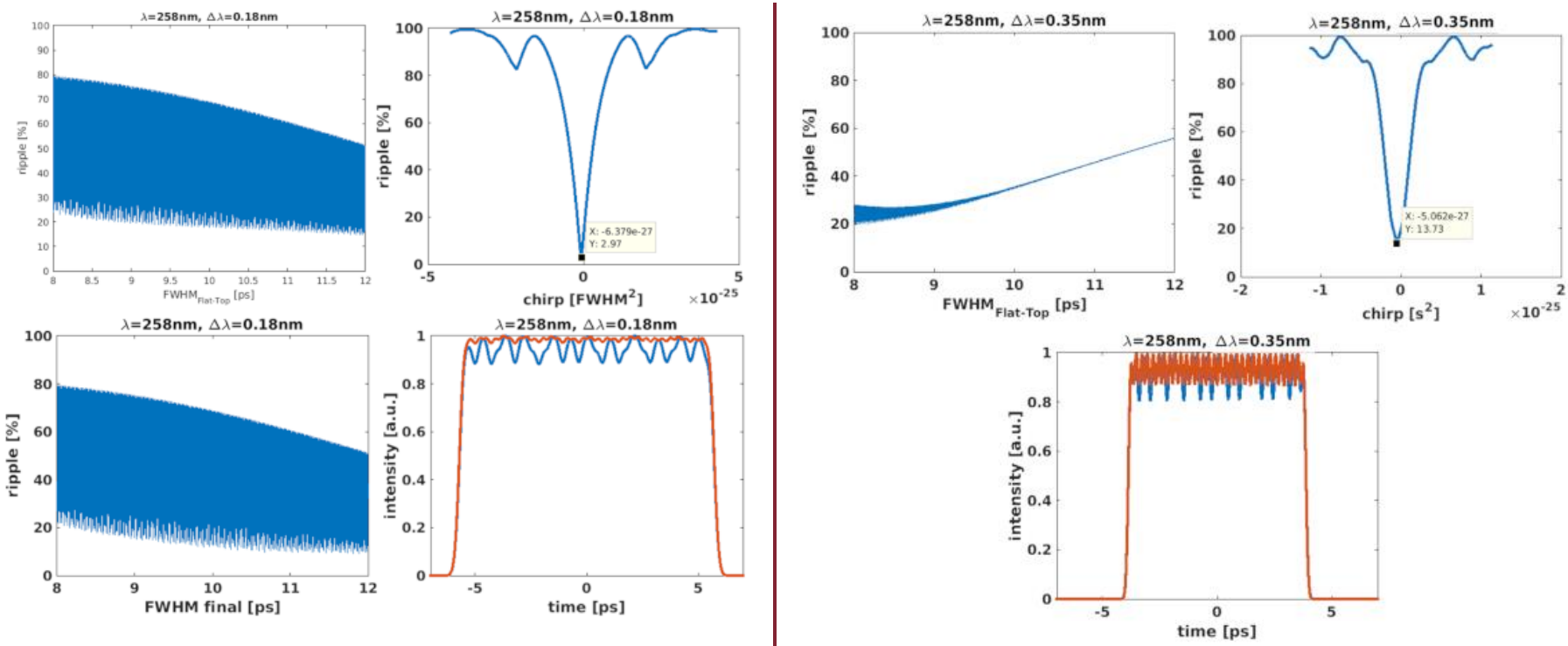
On the right, an example of the generation of a flat-top pulse using only two crystals with the previous considerations. Red and green lineas stand for the two orthogonal polarizations, the blue line stands for the combination of the two in the last polarizer. The asymmetry in the reconstructed blue line is due to the effects of the interference with pulses that have experienced a different phase delay in the propagation.



Laser COMB study

Generation of UV flat-top pulses for electron gun 3/4

The figures below show the results for the best case scenario for both the initial pulse time bandwidth. The 5 crystals setup is shown to be the most effective for both the initial pulse, giving the possibility to achieve the desired final time duration of the flat-top pulse. The use of an initial negative chirp for the UV pulse allows a reduction in the ripple. The last images show the best position with and without the initial chirp.

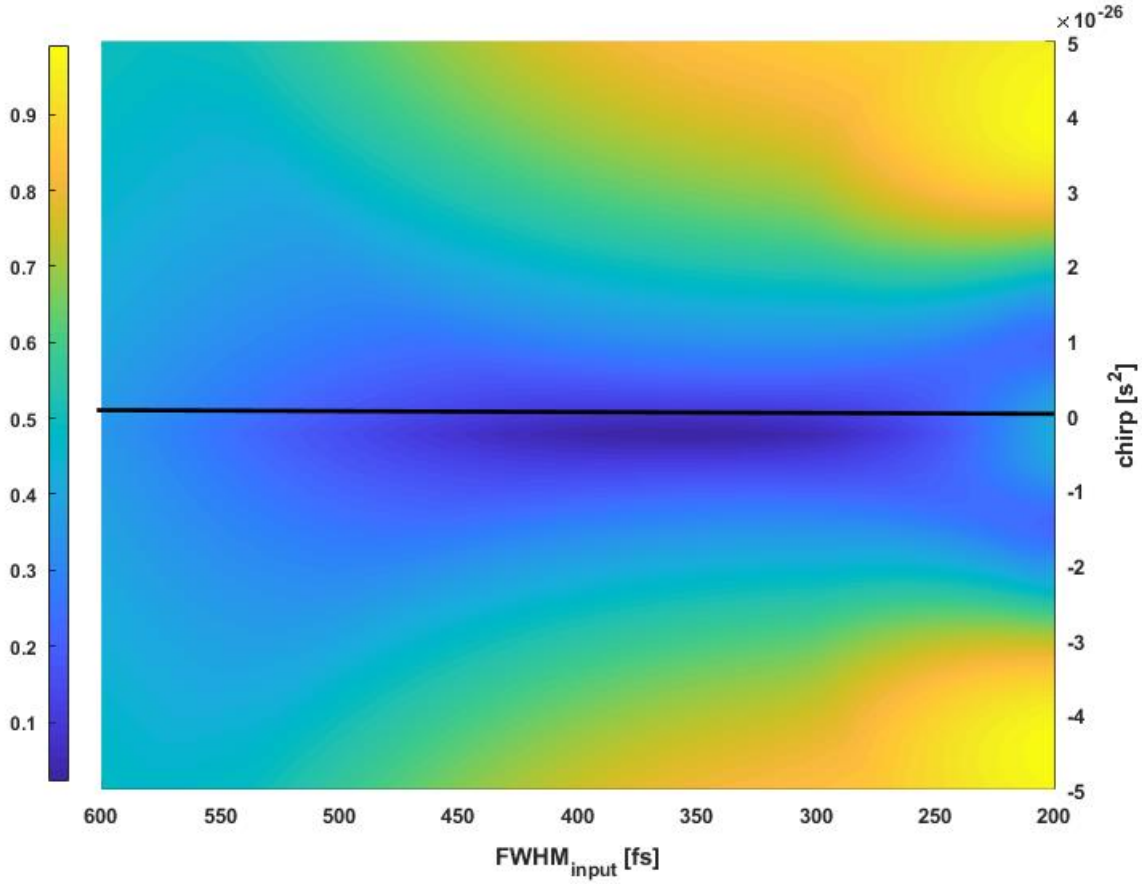


Laser COMB study

Generation of UV flat-top pulses for electron gun 4/4

For the 5 crystals setup, and for 8,5 *ps* flat-top, I have done a 2D scan over the initial UV pulse time duration and chirp. The color code stands for the % of the ripple, deep blue is near 0% where yellow istand for 100% ripple.

From those results it is clear that is possible to achive high quality flat-top pulse with a span of initial pulse length, 270 to 420 *fs* in this configuration, using a initial negative chirp.



Conclusions

During my PhD thesis, I have worked on different topics, aiming to improve some aspects of the use of lasers and THz radiation in accelerator physics. Some of the key points are:

- The characterization of non-linear crystals for the Optical Rectification for higher energy conversion efficiency.

- Showing the possibility to shape the THz field generated by OR, allowing higher field in the interaction point.

- The studies on the use of high energy THz pulse for Laser WakeField Acceleration complementary to existing Laser based one.

- THz diagnostic of plasma channel for the extraction of the plasma density and temperature profiles in the LWFA schemes.

- Experimental work in the THz generation using Coherent Transition and Diffraction Radiation, at the CLEAR linar at CERN, aiming at the use of this radiation as electron bunches diagnostic for bunches length and charge.

- Complete simulations and studies on a laser COMB technique, showing the possibility to obtain high quality UV flat-top pulses for their use in electron guns.