LABORATORY CHARACTERIZATION OF ELECTRO OPTICAL SAMPLING (EOS) AND THz DIAGNOSTICS FOR FERMI BY MEANS OF A LASER DRIVEN PULSED THz SOURCE

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Abstract

EOS and coherent radiation-based diagnostics of sub-psec electron bunches are longitudinal diagnostics that have been adopted for use at FERMI and other 4th generation light sources. The performance of both kind of diagnostics depends on the material properties in the THz spectral range. There is a need to characterise the transmission of windows materials and to understand the absolute efficiency of electro-optic detectors. This requirement for absolute EO efficiency is particularly important given observed variations between individual crystals with nominally identical specifications. In this paper we report measurements with THz pulses produced with photoconductive emitters. Our main goal was the characterization of EO crystals such as ZnTe and GaP for EOS and THz windows materials and humidity absorption. Good agreement is found for the EO results between experimental results and theoretical calculations concerning temporal resolution.

MACHINE PARAMETERS

FERMI@Elettra is an single-pass seeded FEL presently under construction at the Sincrotrone Trieste Laboratory. It is based on a UCLA photoinjector gun with design emittance of 2 mm-mrad and charge per bunch in the range from 0.1nC to 1nC. The normal-conducting Linac will operate at 50Hz delivering a final beam energy of 1.5GeV. Two bunch compressors (BC1 and BC2) will compress the bunch length in a range from 5ps to 0.15ps FW (Full Width). The two FEL chains (FEL1 and FEL2) are designed to cover a total range from 100nm to 4nm delivering peak power of the order of GWs. A description of the facility is presented in the FERMI Conceptual Design Report [1]. Diagnostic are of crucial importance to meet the FERMI@ELETTRA needs in term of performances. Non destructive longitudinal diagnostics are foreseen: two Electro Optical Sampling (EOS) stations, one for each FEL chain and two Bunch Length Monitors (BLM) one at the exit of each bunch compressor. The EOS will provide a high-resolution, single-shot, non-destructive longitudinal profile and bunch arrival time measurement. The BLMs will provide a relative bunch length measurements, information that is required by the longitudinal feedback system that is designed to stabilize the final output peak power of the FELs by stabilizing the electron beam peak current. These two crucial systems share a common fundamental aspect in their underlying physics: their performance is based on material response in the THz spectral range that is defined by the temporal duration of the electron bunches. EOS relies on the frequency response of the optical properties of the EO crystals used to map the electron bunch longitudinal profile. The BLMs are based on coherent radiations emitted in the THz because the coherent onset depends on the electron bunch FW. They employ materials, transport systems and detectors that have to be optimized for this spectral range. In this paper we report measurement comparing the performance of EO crystals of different materials and thickness with reference ones. Moreover we have characterized the transmission in the THz range of BLMS components such as windows (z-cut quartz and glass and windows) and quantified the impact of water absorption in humid air. All these measurements were performed with a laboratory apparatus based on a compact femtosecond fiber laser oscillator and a photoconductive THz emitter that has been developed with the aim of supporting the development of both EOS and BLM diagnostics for FERMI.

SETUP

The apparatus is based on a TC780 Menlosystems laser. It is a frequency doubled 1560nm femtosecond fiber laser emitting at 780nm with a repetition rate of 78.89MHz, an energy per pulse of 0.8nJ and a pulse duration of 110fsec FW. The laser beam is split into pump beam and probe beam via a pellicle beam splitter (PBS) with 92% of the power in the pump beam and 8% in the probe beam. The pump beam is focused on a Terased3 photoconductive emitter (produced by Gigaoptics GmbH) and THz pulses are emitted by the surface recombination current induced by the laser on the biased semiconductor emitter. This kind of emitter is well suited for oscillator lasers compared to optical rectification emitters since it can operate with energy per pulse as low as 100pJ thus avoiding the need of an amplified laser system. Another advantage is that the emitter requires a low voltage modulation to be applied avoiding the need of a HV pulsed amplifier. If the laser pulses are sufficiently short, as in our case, the Terased emitter produces THz radiation centered around one THz. This radiation has an angular opening of about 7° degrees and it

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is collimated by a first aluminum off axis parabolic mirror, transported and then refocused on the EO crystal with a second parabolic off axis mirror. The probe beam passes through a motorized delay line so that its arrival time can be changed and it is refocused and recoupled via reflection on a 55% /45% PBS on the EO crystal. The PBS acts as a combiner since its transmission in the THz range is so high that the THz beam passes undisturbed, while the probe beam is reflected onto the EO crystal. Finally the probe laser reaches the balanced detection system: a $\lambda/4$ wave plate followed by a Wollaston prism where the two almost balanced beams are detected by a balanced photodetector equipped with bandpass filters.

The electric field of the THz beam induces birefringence in the EO crystal acting much in the same way the electric field of the electron beam will. In the final EOS systems amplitudes will be of the order MV/m producing large birefringence effects that allow for single-shot measurements. In the present setup the magnitude of the electric field is orders of magnitude lower and the signal from the balanced detector has to be acquired through a Lock-in amplifier. Scanning the delay of the probe beam a measurement of the time profile of the THz pulses is obtained. The spectrum of the radiation can be obtained via an FFT of the measured time profile data. Following [3] EO signal with this kind of setup is proportional to $\sin(\Gamma)$ where Γ is the phase retardation induced by the electric field of the electron beam as from eq. 1.

$$\Gamma = \frac{\pi d}{\lambda_0} n_0^3 E r_{41} \sqrt{1 + 3\cos^2(\alpha)} \quad (1)$$

Here d is the thickness of the crystal, λ_0 is the laser wavelength in vacuum, E is the electric field due to the electron beam, r_{41} is the only independent element of the electro-optic tensor for the zincblende crystal structure, and finally α is the angle between the electric field of the THz field and the $[-1, 1, 0]$ direction. This equation is often used in literature to show the dependence of the EO signal on the main parameters involved.

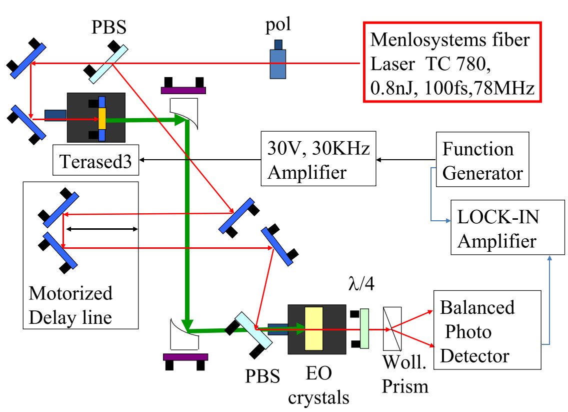

Figure 1: Laboratory system layout.

EO CRYSTALS

The EOS diagnostics performances rely intrinsically on the capability of the EO crystals to map the electric field of the electron beam. The frequency dependence of the optical properties of the EO crystals (like ZnTe and GaP) plays a central role. Several authors investigated analytically and numerically the problem using for the index of refraction n and for the electro-optic coefficient r_{41} values from the literature [3]. The available data for these quantities are not sufficient to calculate reliably the expected EO signals in all cases. There is also some evidence for performance variations between crystals with nominally identical specifications. In the final EOS electron beam diagnostics application it has been common to find for the amplitude of the EO effect lower values than the expected from calculations. The reason of this can be attributed to variable crystals quality and thus values for n and r_{41} varying from sample to sample. To predict the EO signal magnitude and system resolution of an EOS diagnostics and so overcome these difficulties, one could in principle measure $n(f)$ and $r_{41}(f)$ for the specific samples. But this kind of measurements is difficult for several reasons e.g. for GaP the quantities should be measured up at least to TO (Transverse Optical) resonances around 11THz. We opted for a different approach: the direct comparison of the EO signal for the electro optic crystals foreseen for FERMI FEL1 (ZnTe 3mm, ZnTe 1mm, Gap 1mm and GaP 0.4mm all (110) cut) with a reference crystal. The reference crystal is a ZnTe (110) high resistivity crystal of 1mm thickness from Ingcrys Ltd that have been extensively used in previous EOS experiments.

The first measurement was performed with a ZnTe (110) 3mm thick crystal meant for the initial FERMI EOS operation to have a maximum EO signal without requirements on the resolution. The crystal should have an EO effect three times larger than the reference crystal due to the linear dependence on the thickness in eq.1. Unfortunately the crystal showed an extremely weak non-linear EO effect and non-isotropic behavior for rotation of the polarization of the incoming laser in the absence of the THz field. It was discarded for detection in the EOS and instead used for optical rectification experiments.

The second comparison was performed with a ZnTe (110) 1mm thick high resistivity crystal also from Ingcrys Ltd. The EO signal of this sample is plotted together with that of the reference crystal in Figure 2. The EO amplitude of the 1 mm thick ZnTe is 20% lower than the reference crystal and can be interpreted as a difference of magnitude of the r_{41} electro-optic coefficient or due to variations in the optical or THz transmission properties. The inset in Figure 2 shows the same data normalized in amplitude to enhance the similarity of the EO signal shape for the two crystals, indicating the same effective time resolution when employed in the EOS diagnostics.

The next step was to compare ZnTe and GaP. ZnTe is expected to offer a higher EO magnitude compared to GaP

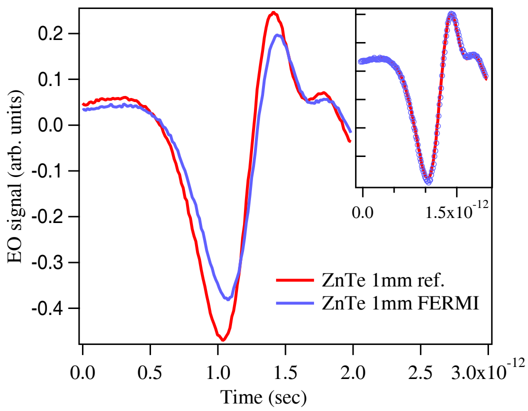

Figure 2: EO signal from ZnTe 1mm (blue) and refer. ZnTe 1mm (red). Inset: signals normalized in amplitude.

for the same thickness while it is generally agreed that GaP offers higher temporal resolution due to its TO vibrational resonances being at higher frequencies with respect to ZnTe. The EO signal from the 1mm ZnTe reference crystal is plotted in Figure 3 together with the EO signal from GaP crystals with thicknesses of 1mm and 0.4 mm. The measured amplitude of the EO signal of GaP 1mm is 5.6 times lower compared to the reference 1mm ZnTe. Following equation 1 which does not include phase matching effects one would expect a factor of 4 due to the fact that $r_{41}^{ZnTe}/r_{41}^{GaP}$ is approximately equal to 4. The data from GaP 0.4mm show an amplitude of the EO signal which is almost the same compared to the GaP 1mm while it should scale linearly with the thickness and due to the combined effect of thickness and r_{41} should be 10% of the EO signal from the reference 1mm ZnTe crystal. These measurements demonstrate the importance of phase matching considerations in assessing the expected signal magnitude. Increasing the GaP thickness from 0.4 mm to 1.0 mm does not increase the (time domain) signal magnitude but does increase its duration due to phase slippage between

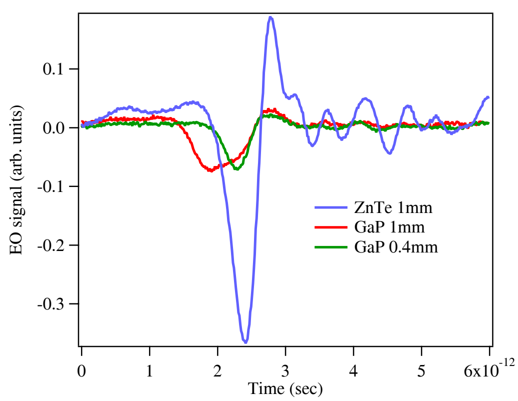

Figure 3: EO signal from reference ZnTe crystal (blue), and GaP crystals with thickness 1mm (red) and 0.4mm (green).

the THz and the probe pulses. Conversely, in the frequency domain this longer duration signal would correspond to an increased magnitude in the detected low frequency components. Simulations were performed to confirm this idea, following the approach described in [4] that offers a more accurate evaluation of the electro-optical effect and allows off-normal incidence EO calculations. The results are presented in Figure 4. The electric field of the e-beam is plotted in red while the simulated EO profile is plotted in blue. The calculation shows that the EO signal for 1mm ZnTe (top left graph) has a smaller FW than for the 0.4mm GaP (top right graph) and the predicted EO signal temporal dependence is qualitatively in agreement with the experimental data for 0.4mm GaP. It is also interesting to perform fur-

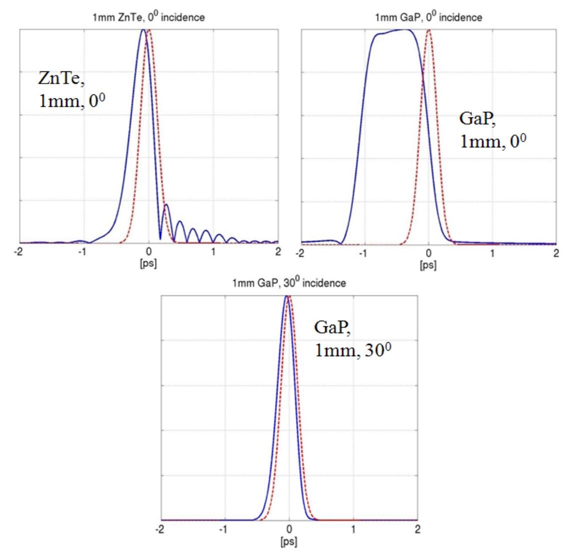

Figure 4: EO signal calculated for 1mm ZnTe (Top Left) at normal incidence, 1 mm GaP at normal incidence (Top Right) and 1 mm GaP at 30° off normal incidence (Bottom).

ther the calculations using the capability to evaluate also off normal incidence geometries. As shown in Figure 4 (Bottom plot), going to a larger angle of incidence it is possible to mitigate the resolution problem. In the present case for 1mm thick GaP at 30^o the effective time resolution is significantly improved.

BLM COMPONENTS

The bunch-length monitors (BLMs) design for FERMI are based on two systems for the large range of bunch lengths that translates into a spectral range from 150 GHz to 3 THz and also for redundancy. As with the LCLS BC1 BLM, the sources are coherent edge radiation (CER) emitted from the bunch compressors and wake fields diffraction radiation emitted through a ceramic gap. The optimization of the CER system includes an analysis of the transmission of the whole transport systems. Limitations in the transmission for low frequencies arise from the large emission angles, that are larger the longer the wavelength of the radiation is, while at high frequencies limitations arise from the transmission of the vacuum windows used to extract the radiation and from water absorption related to humidity in the air. For this reason we decided to investigated the properties of the vacuum windows and the effect of humidity with the setup previously described. The possible choice of materials for the UHV vacuum windows includes silicon, diamond and z-cut quartz while TPX (Polymethylpentene) and Tsurupica should be discarded if as in our case vacuum baking procedures are to be used. Diamond is the best material but it is too expensive for the size of windows needed for the FERMI BLMs, while silicon is not transparent in the visible and an optical alignment of the components is required. For these reason z-cut quartz has been chosen as the window material. In Figure 5 we show the transmission of a z-cut quartz window and of a standard glass Kodial 7056 UHV window for comparison. The z-cut quartz transmission is around 80 %t from 180 GHz to 2.2 THz then it starts degradating, reaching 40 % around 3 THz. The standard Kodial 7056 glass shows much poorer transmission. Significant transmission occurs only below 0.5 THz and the transmission is lower than 10% up to 3 THz. Another problem encountered in transporting the

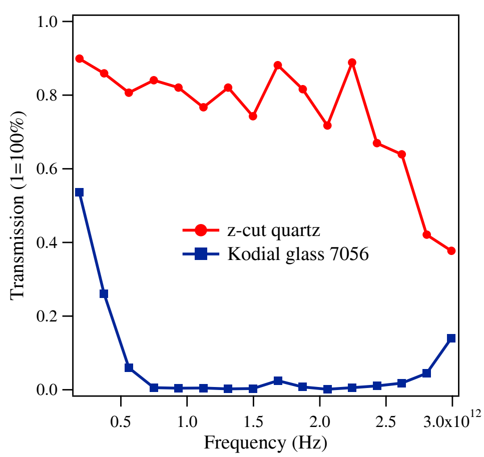

Figure 5: Transmission of z-cut quartz and Kodial 7056 glass windows.

THz radiation in ambient air is the absorption due to water present in the air. Water absorptions will decrease the total coherent power measured by the BLMs detectors. To evaluate specifically this problem we have studied the effect of water absorption by changing the relative humidity (RH) present in the atmosphere of the setup held at 22^{o}C. The RH was changed by enclosing the whole system in a box and flowing in dry nitrogen. In the setup the length of the air path is of about 50cm, comparable to the one used in the coherent BLM transport outside the vacuum chamber. Figure 6 shows two EO measurements for 40% RH and 15% RH and their spectrum obtained via FFT of the time domain data.

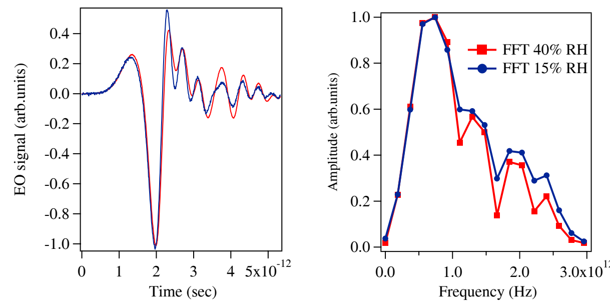

Figure 6: EO signal (left) and $|FFT_{EOsignal}|$ right for RH of 40% and 15%.

As expected the major absorptions are clearly seen at 1.1THz, 1.6THz and 2.2THz. Above 2.4THz water absorption is also important but no sharp absorption lines are evident. Water absorption seems negligible below 0.8THz. These measurements clarify that to suppress water absorption to a negligible level, the system should be designed for an RH lower than 5%.

CONCLUSIONS

We have presented measurements of key element of the EOS and BLMs longitudinal diagnostics of FERMI@Elettra by means of a THz pulsed laboratory system based on a femtosecond fiber oscillator. The EO crystals foreseen to be used in the FERMI EOS FEL1 have been characterized against a reference crystal. The results of the measurements stress the importance of an experimental determination of the EOS crystal properties in order to optimize the EOS SNR (Signal to Noise Ratio) and time resolution. Finally the transmission of windows used for BLMs as well as the effect of water absorption on the BLMs has been studied.

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